VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
STATE RESEARCH INSTITUTE
CENTER FOR PHYSICAL SCIENCES AND TECHNOLOGY

Oliver LIEBFRIED

THE INVESTIGATION
OF ELECTROMAGNETIC PROCESSES
IN ELECTROMAGNETIC LAUNCHERS
USING COLOSSAL
MAGNETORESISTANCE SENSORS

DOCTORAL DISSERTATION

PHYSICAL SCIENCES, PHYSICS (02P),
CONDENSED MATTER: ELECTRONIC STRUCTURE; ELECTRICAL,
MAGNETIC AND OPTICAL PROPERTIES; SUPERCONDUCTORS;
MAGNETIC RESONANCE; RELAXATION; SPECTROSCOPY (P260)

Vilnius LEIDYKLA TECHNICA 2011

Doctoral dissertation was prepared at the State Research Institute Center for Physical Sciences and Technology (former – Semiconductor Physics Institute) and the French-German Research Institute of Saint-Louis in 2007–2011.

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VG TU leidyklos TECHNIKA 1880-M mokslo literatūros knyga
<http://leidykla.vgtu.lt>

Parengta L^AT_EX2_ε sistema

ISBN 978-9955-28-800-8

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS
VALSTYBINIS MOKSLINIŲ TYRIMŲ INSTITUTAS
FIZINIŲ IR TECHNOLOGIJOS MOKSLŲ CENTRAS

Oliver LIEBFRIED

ELEKTROMAGNETINIŲ PROCESŲ TYRIMAS ELEKTROMAGNETINĖSE SVAIDYKLĖSE NAUDOJANT MILŽINIŠKOS MAGNETOVARŽOS JUTIKLIUS

DAKTARO DISERTACIJA

FIZINIAI MOKSLAI, FIZIKA (02P),
KONDENSUOTOS MEDŽIAGOS: ELEKTRONINĖ STRUKTŪRA,
ELEKTRINĖS, MAGNETINĖS IR OPTINĖS SAVYBĖS,
SUPERLAIDININKAI, MAGNETINIS REZONANSAS, RELAKSACIJA,
SPEKTROSKOPIJA (P260)

Vilnius LEIDYKLA TECHNICA 2011

Disertacija rengta 2007–2011 metais Valstybiniame mokslinių tyrimų institute Fizinių ir technologijos mokslų centre (anksčiau – Puslaidininkių fizikos institutas) ir Saint-Louiso Prancūzijos-Vokietijos tyrimų institute.

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For **Rasa** and **Lukas**

Abstract

The development of rails and armatures which ensure a sliding solid-to-solid contact during the whole projectile acceleration is a great challenge in the field of railgun technology. Multifaceted physics exists at the sliding contact interface: The current concentrates at the rear of the interface due to magnetic diffusion processes and the fast armature movement. Consequently, Joule heating leads to enhanced wear in this region. In this dissertation, magnetic diffusion in railguns is investigated by means of measuring magnetic fields with CMR-B-scalar sensors at static and dynamic experimental conditions. These novel sensors, based on $\text{La}_{0.83}\text{Sr}_{0.17}\text{MnO}_3$ thin films exhibiting colossal magnetoresistance were adapted for the use at railguns.

It was found that these sensors are effective tools to measure the magnitude of high pulsed magnetic fields independent of the field orientation. Magnetic field distributions influenced by proximity and velocity skin effect could be measured in the harsh railgun environment. The obtained results allowed to estimate the skin depth in the rails at the sliding interface of a fast moving armature (>1500 m/s). Furthermore experiments with fixed multiple brush armatures showed that front brushes can have contact problems in case of missing contact pressure.

The dissertation consists of an Abstract, an Introduction, 6 chapters, General Conclusions, References, a List of Publications and 2 Appendices.

The introduction reveals the investigated problem, the importance of the thesis and describes the purpose and tasks of the work. Furthermore, it presents the research methodology, the scientific novelty, the practical significance of results, the defended statements and the acknowledgement.

Chapter 1 gives a literature review and introduces the field of railgun research and the idea behind this dissertation. Chapter 2 describes the experimental setups and main equipment. Chapter 3 deals with the CMR-B-scalar sensor and related metrological questions. The use of the sensor in static and dynamic coilgun experiments is presented in chapter 4. Chapter 5 deals with the investigation of magnetic diffusion and the current distribution in the rails of a railgun. Chapter 6 is about the current distribution in brush armatures.

Seven articles focusing on the subject of the discussed dissertation have been published so far: Six articles in Journals listed in the Thomson ISI Web of Science and one article in the proceedings of an international conference. Seven presentations of the subject have been given at 5 international conferences.

Santrauka

Pagrindiniai bėgių tipo elektromagnetinių svaidyklių technologijos uždaviniai yra susiję su daugybe fizikinių reikinių, vykstančių sviedinio kontaktų sąlyčio su bėgiais riboje. Todėl elektromagnetinių procesų, atsirandančių dėl didelių elektros srovės tankių ir slydimo greičių tyrimas yra svarbus šios srities uždavinys. Dėl magnetinės difuzijos ir greito sviedinio judėjimo, srovė koncentruojasi galinėje kontakto dalyje, kuri dėl stipraus Joule šilimo greitai susidėvi, o tai apriboja svaidyklės efektyvumą. Disertacijoje pateikiami magnetinio lauko difuzijos tyrimai bėgių tipo svaidyklėse panaudojant specialius jutiklius magnetinių laukų matavimui. Šie nauji jutikliai, pagaminti iš plonų $\text{La}_{0,83}\text{Sr}_{0,17}\text{MnO}_3$ sluoksnių, pasižyminčių milžiniškos magnetovaržos (MM) reiškiniu (MM-B-skaliariniai jutikliai), buvo pritaikyti svaidyklėse, veikiančiose statiniame ir dinamiame režime, esant dideliems elektromagnetinių triukšmų lygiams ir mechaniniams įtėmams.

Darbo metu buvo nustatyta, jog šiais jutikliais galima išmatuoti stipraus magnetinio lauko impulso amplitudę, kai nėra žinoma šių laukų kryptis. Buvo ištirti nevienalyčių magnetinių laukų pasiskirstymai bėgiuose, atsirandantys dėl artumo efekto bei greičio skinefekto, sviediniui judant greičiau nei 1500 m/s. Bandymai su įtvirtintu daugelio šepetėlių konstrukcijos sviediniu parodė, kad priekiniai šepetėliai, dėl nepakankamo Lorencio jėgos sukuriama slėgio, gali pararasti elektarinį kontaktą su bėgiais.

Disertaciją sudaro reziumė anglų, lietuvių ir vokiečių kalbomis, įvadas, 6 skyriai, išvados, nuorodos, straipsnių sąrašas ir 2 priedai.

Įvade aptariama tiriamoji problema ir disertacijos svarba, pateikiami darbo tikslai, uždaviniai, tyrimų metodologija, mokslinis naujumas, praktinė vertė ir ginamieji teiginiai. Pirmame skyriuje pateikta literatūros analizė ir suformuluojami darbo uždaviniai. Antrame skyriuje aprašoma elektromagnetinių svaidyklių įranga ir tyrimo įtaisai. Trečiame skyriuje aptariamos milžiniškos magnetovaržos jutiklių konstrukcijos, o ketvirtame – magnetinio lauko tyrimai ritės tipo svaidyklėje. Penktame skyriuje aprašomi magnetinio lauko difuzijos tyrimai bėgių tipo svaidyklės veikimo metu. Šeštame – elektros srovės ir magnetinio lauko pasiskirstymo tyrimai sviedinio kontaktų aplinkoje.

Disertacijos tema publikuoti 7 straipsniai: šeši iš jų žurnaluose, įtrauktuose į Thomson ISI sąrašą, vienas straipsnis – tarptautinės konferencijos darbuose. 7 pranešimai pristatyti 5 tarptautinėse konferencijose.

Zusammenfassung

Eine große Herausforderung im Gebiet der Schienenbeschleunigertechnologie besteht in der Realisierung von Gleitkontakten, die durch vielfältige physikalische Phänomene beeinflusst werden: Aufgrund magnetischer Diffusion und der Bewegung der Strombrücke ist die Stromverteilung auf den hinteren Abschnitt der Kontaktzone konzentriert. Infolgedessen führt ohmsche Aufheizung dort zu erhöhter Abnutzung. In dieser Dissertation wird die magnetische Diffusion in Schienenkanonen anhand von Magnetfeldmessungen mit CMR-B-skalaren Sensoren unter statischen und dynamischen Versuchsbedingungen untersucht. Diese neuartigen Sensoren, die auf $\text{La}_{0.83}\text{Sr}_{0.17}\text{MnO}_3$ Dünnschichten basieren und einen kolossalen Magnetowiderstand aufweisen, wurden eigens für die Benutzung an Schienenbeschleunigern angepasst.

Es konnte gezeigt werden, dass diese Sensoren ein effektives Werkzeug sind, um die Amplituden von hohen und dynamischen Magnetfeldpulsen unabhängig von der Feldorientierung zu messen. Magnetfeldverteilungen, die vom Proximity und Velocity Skin Effekt beeinflusst wurden, konnten erstmalig unter den metrologisch anspruchsvollen Bedingungen gemessen werden. Aufgrund der erzielten Ergebnisse bei dynamischen Experimenten konnte die Skintiefe in den Schienen bei hohen Gleitgeschwindigkeit ($> 1500 \text{ m/s}$) bestimmt werden. Experimente mit festgehaltenen multiplen Bürstenstrombrücken zeigen, dass im Fall von fehlendem Anpressdruck die vorderen Bürsten Kontaktprobleme bekommen können.

Die Dissertation besteht aus einer Zusammenfassung, einer Einleitung, 6 Kapiteln, Schlussfolgerungen, einer Literaturliste, einer Liste der Publikationen sowie 2 Anhängen.

Kapitel 1 gibt einen Überblick über die Technology der Schienenkanonen und deren Erforschung und hebt die Idee hinter der Dissertation hervor. Kapitel 2 beschreibt die Versuchsaufbauten und Geräte. Kapitel 3 handelt vom CMR-B-Skalar Sensor und messtechnischen Fragen. In Kapitel 4 werden die CMR-B-Skalar Sensoren in statischen und dynamischen Versuchen mit einem Spulenbeschleuniger genutzt. Kapitel 5 handelt von Untersuchungen der Magnetischen Diffusion und Stromverteilung in den Schienen einer Schienenkanone. Kapitel 6 behandelt die Stromverteilung in den Bürstenstrombrücken.

Sieben Artikel zum Thema dieser Dissertation wurden bis jetzt veröffentlicht: 6 Artikel davon in Journalen, die im Thomson ISI Web of Science gelistet sind und ein Artikel im Tagungsband einer internationalen Konferenz. 7 Präsentationen zum Thema wurden auf 5 internationalen Konferenzen gehalten.

Abbreviations

A/D	–	Analog-Digital
Ag	–	Silver
CMR	–	Colossal MagnetoResistance
Cr	–	Chromium
Cu-Cd	–	Copper-Cadmium
Cu-Cr	–	Copper-Chromium
DC	–	Direct Current
DE	–	Double Exchange
DES	–	Distributed Energy Supply
Du	–	Dural
EM	–	ElectroMagnetic
EMA	–	ElectroMagnetic Accelerator
FEM	–	Finite Element Method
FM	–	Ferromagnetic Metal
GBs	–	Grain Boundaries
GRP	–	Glass fibre Reinforced Plastic
HFMR	–	High Field Magnetoresistance
HMFC	–	High Magnetic Field Coil
HMFG	–	High Magnetic Field Generator
HMFM	–	High Magnetic Field Measurement
HS	–	High Speed
ISL	–	French-German Research Institute of Saint-Louis
LCMO	–	$\text{La}_{1-x}\text{Ca}_x\text{MnO}_3$
LFMR	–	Low Field Magnetoresistance
LSMO	–	$\text{La}_{1-x}\text{Sr}_x\text{MnO}_3$
MR	–	Magnetoresistance
PF	–	Pulse Forming
PFU	–	Pulse Forming Unit
PI	–	Paramagnetic Insulator
RAFIRA	–	Rapid Fire Railgun
SPI	–	Center for Physical Science and Technology, Semiconductor Physics Institute
STL	–	Steel
UK	–	United Kingdom
URL	–	Uniform Resource Locator
U.S.	–	United States
USA	–	United States of America

VSE – Velocity Skin Effect

WWII – Second World War

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Introduction

Problem under Investigation

Electromagnetic (EM) launchers convert electrical energy into kinetic energy by application of Lorentz forces. Recent developments focus on solid armature railguns which are able to accelerate massive projectiles to velocities of more than 2 km/s. The armature is a solid work piece which serves as sliding contact between the two rails and has to conduct currents of up to several MA. The electromagnetic acceleration force of the projectile acts solely on its armature and therefore one of the central technological challenges of this launcher type is the realization of appropriate armatures. The motion of the armature and magnetic diffusion lead to a current accumulation at the rear part of the sliding contact interface. Very high current densities result in phase transitions and exceptional wear at the interface during acceleration. Therefore, quantitative information about the current distribution in the vicinity of the sliding contact interface are of greatest interest. The measurement of the magnetic field distribution is one method to gather this information. Corresponding measurement techniques should have high spatial resolution and should also be able to measure highly dynamic magnetic fields. Such a technique, based on a new type of magnetic field sensor was developed in this work.

Certain manganites exhibit a very large ("colossal") magnetoresistance (CMR).

This magnetoresistive effect is characterized by a spin-polarized electron transport behaviour. CMR in polycrystalline films depends mainly on the magnitude of the applied magnetic field and not on its direction. Moreover, very large amplitudes (50 T) may be recorded. Based on thin manganite films, CMR-B-scalar sensors with very small active volume ($0.4\text{ mm} \times 50\text{ }\mu\text{m} \times 0.4\text{ }\mu\text{m}$) can be produced. In this work, they have been adapted for measurements of the magnetic field distribution in EM launchers.

Topicality of the Research Work

The current accumulation at the rear part of the sliding contact interface appears due to the so called "velocity skin effect" (VSE). Since more than 30 years, asymmetric wear has been observed at the rear parts of recovered armatures, but the corresponding current profiles have never been measured during dynamic railgun experiments. This work presents for the first time measurements of the magnetic field distribution allowing to estimate the VSE during dynamic experiments.

Furthermore, the measurement of magnetic fields with high spatial resolution for moving conductor problems are very important for the validation of simulation codes for numerous applications.

Research Object

The objects of investigations are the CMR-B-scalar sensor based on thin manganite films and electromagnetic processes, in particular at the contact interface of railguns with multiple brush armatures.

The Aim of the work

The goal of this effort was to develop the CMR-B-scalar sensor for measurements at EM launchers and to use it for investigations of the magnetic field distribution at railguns related to magnetic diffusion at static and dynamic conditions.

Tasks of the Work

1. To develop the CMR-B-scalar sensors for magnetic field measurements at EM launchers with a high level of electromagnetic interferences.
2. Testing of the CMR-B-scalar sensor at dynamic magnetic field measurement in a coilgun.
3. Investigation of magnetic diffusion in static and dynamic railgun experiments.
4. Investigation of force and current densities acting on the sliding contacts of the railgun armatures.

Applied Methods

Pulsed high magnetic fields, currents and voltages were measured at coil and rail launchers. The results were analysed and discussed by several numerical simulations performed with the codes *COMSOL Multiphysics*, *Mathematica*, *MEGA* and *PSpice*.

Scientific Novelty and its Importance

The contribution to the field of physical sciences involves:

1. The development of a new pulsed high magnetic field measurement system for EM launchers based on CMR-B-scalar sensors having an active volume of $0.4 \text{ mm} \times 50 \text{ }\mu\text{m} \times 0.4 \text{ }\mu\text{m}$ and being able to measure absolute values of magnetic flux density of pulses with amplitudes up to 20 T in a frequency range from 0 to 10 kHz.
2. Studies of magnetic field distribution during static and dynamic operation of coilgun and railgun type electromagnetic launchers using unique 2D and 3D arrays of CMR-B-scalar sensors.
3. The measurement of magnetic field diffusion process characteristics in static railgun experiments with different rail materials (steel, Dural and copper) and at dynamic railgun conditions with high projectile velocities (up to 2200 m/s).
4. Investigations of the VSE influence on the current distribution in the rails

of a railgun at high projectile velocities (1500 m/s) and static investigation of current distributions in the case of projectiles equipped with multiple brush armatures.

Practical Value of the Work Results

The performed work led to the development of an unique and advanced system for the measurement of high pulsed magnetic fields independent from their direction. It operates in a measurement range of 20 T, a frequency range of 0–10 kHz and its features are galvanic separation, shielding against electromagnetic fields and the possibility for stand-alone operation. The achieved results improve the understanding of physical processes at the sliding contact interface of railguns and can be used to validate numerical simulations.

Statements Presented for Defense

1. The magnetic field sensor based on polycrystalline $\text{La}_{0.83}\text{Sr}_{0.17}\text{MnO}_3$ thin films is an effective tool for studies of electromagnetic processes in EM launchers. It is able to measure the magnitude of the magnetic induction from 0.5 T to 20 T in the frequency range from DC to 10 kHz with an error smaller than $\pm 10\%$.
2. The local maxima of the gradients of the magnetic field distribution between the inner and outer edges of the rails appearing due to proximity and skin effect during static operation of the railgun EMA3 ($15 \times 30 \text{ mm}^2$ calibre, 150 kA peak current) are equal to 0.1 T/mm, 0.09 T/mm and 0.056 T/mm for copper, Dural and steel rails, respectively.
3. The skin depth of 1.7 mm determined at a dynamic operation of the railgun RAFIRA ($25 \times 25 \text{ mm}^2$ calibre) with a projectile velocity of 750 m/s by analysing magnetic field measurement data using finite element method simulations in a harmonic oscillation approach is greater than a skin depth of 0.5 mm at a velocity of 1500 m/s due to a more pronounced velocity skin effect in the latter case.
4. The distributions of magnetic field and current measured in the vicinity of multiple brush armatures during static railgun experiments with energies of 150 kJ show that the front brush can lose electrical contact with the rails due to missing Lorentz force even their length is still greater than

the distance between the rails. The solid contact formation appearing after 500 μ s is accompanied by material melting in the contact zone.

Approval of the Work Results

Seven conference contributions to five conferences dealt with the content of this dissertation. Five of them were selected for publication in Journals listed in the Thomson ISI list. One was published in the corresponding conference proceedings and the remaining one is available as abstract form. One additional paper was published directly in a ISI listed journal.

The work was presented on following conferences:

- 1st Euro-Asian Pulsed-Power Conference, 18–22 September 2006, Chengdu, China.
- 14th Symposium on Electromagnetic Launch, 10–13 March 2008, Victoria, Canada.
- 2nd Euro-Asian Pulsed-Power Conference, 22–26 September 2008, Vilnius, Lithuania.
- ISP-PhD Congress, 17–18 February 2010, Karlsruhe, Germany.
- 15th Symposium on Electromagnetic Launch, 17–20 May 2010, Brussels, Belgium.

Author's Contribution

The findings presented in this thesis were obtained by the author in cooperation with the co-authors of the publications listed in the bibliography. The author's contributions to these findings include autonomous experimental work at coilgun and static railgun facilities; including data acquisition and signal processing. He further worked out methods to apply CMR-B-scalar sensors at dynamic railgun experiments and controlled the corresponding data acquisition. Besides the experimental work, he performed simulations with the codes *COMSOL*, *Mathematica* and *PSpice*. The corresponding results helped to interpret the observed phenomena in discussions with his co-authors. The author also made essential contributions in preparing and writing of scientific papers.

The Scope of the Scientific Work

The dissertation consists of an introduction, 6 chapter, references, list of publications and 2 appendices. The chapters include literature review, description of experimental setups, experimental and computational results. This work includes 106 pages, 21 numbered formulas and 140 bibliographical references.

Acknowledgements

This thesis would not have been possible without the help and encouragement of many people during the past four years.

I had not started and finished a PhD without the encouragement and support of my supervisor Prof Dr Habil Saulius Balevičius. The same holds true for Dr Markus Schneider who offered me the interesting theme, several hours of his time for discussions, education and encouragement. I am very grateful to Prof Dr Markus Löffler for his support and the initiation of the German-Lithuanian student exchange program which influenced the rest of my life.

I like to thank all my Lithuanian colleagues for theirs constant support and encouragement. Especially I want to thank Prof Dr Nerija Žurauskienė for valuable discussions, Dr Voitech Stankevič also for the discussions and for fabricating the CMR-B-scalar sensors, Tomas Stankevič and Lukas Medišauskas for the development of the CMR-B-scalar measurement system and Dr Skirmantas Keršulis, Dr Česlovas Šimkevičius and Lina Belkevičienė for their help at administrative issues.

I am grateful for many help from my colleagues at the French-German Research Institute: Farid Alouahabi, Thierry Steiblin, Phillip Baumann, David Blunzner and Mirko Wötzel for their help related to the railgun experiments. Raymond Specklin and Yannik Foerry for preparing several projectiles and measurement blocks in cumbersome legwork. Dr Stephan Hundertmark and Dr Christian Schuppler for English corrections, fruitful discussions and many advices. Lothar Gernandt for fruitful discussion and for sharing his experience about pulsed power coils with me. Christine Dietlin, who was always very helpful regarding PC issues. Gregory Vincent, Volker Brommer, Caroline Gauthier-Blum, Dr Emil Spahn, Dr Christophe Avril, Georg Zettler, Isabelle Metzger, Laurent Sinninger, Dr Bernd Fischer, Dr Yäel Demarty for several kinds of support provided during my time at ISL.

I want to express my heartfelt gratitude to my family. The support of my

wife Rasa and my son Lukas was priceless. I am grateful to my parents Josef and Hildegard for their support during my life and education. I also appreciate the support of my parents in law, Algimantas and Albina during my stays in Lithuania.

I am thankful to my friends and former fellows, Thorbjörn Siaenen, Sylvain Pinguet and Sonja Podjawerschek, for their repeated encouragement and moral support.

Electromagnetic Launchers and their Metrology

1.1. A Brief History of Electromagnetic Launch

The first ideas to convert electric energy to kinetic energy arose in the 19th century. However, the first serious experiments were performed by the Norwegian scientist Kristian Birkeland in 1901 who built a coilgun (Egeland 1989). The concept of a railgun was invented first by the French Andre Louis Octave Fauchon-Villeplee during World War I but the program was stopped with the end of the war. During World War II, the Germans and the Japanese performed research programs to develop long range weapons. These and other efforts of the early electric gun research were of limited success (McNab 1999: and the references therein). They mainly suffered from the lack of suitable power supplies.

In the following years after the WWII, research in UK and USA did not surpass the efforts of their former enemies. This led to the conclusion of the U.S. Airforce that this technology will not be successful in the near future (Meinel 2007). Based on this conclusion, funding for EM launch research ceased everywhere. However, small groups remained and in 1978, the Australian Richard Marshall reported of a railgun shot with a 3 gram lexan projectile, accelerated to a speed of 5.9 km/s (Ying *et al.* 2004). Since then, the interest in EM launchers rose again and the first IEEE EML Symposium took place in 1980 (*IEEE Transactions on Magnetics* 1982). In the following decade, many countries established

their own EML research projects. So did Germany and France within the French-German Research Institute of Saint-Louis (ISL). In recent years, the Interest of China and of the U.S. Navy in EM launch technology is responsible for a renewed boom of research in this field (Fair 2007).

1.2. The Principle of Operation of Electromagnetic Launchers

In general, electromagnetic launchers are devices which convert electric energy to kinetic energy. Theirs principle of operation is based on the Lorentz force which acts on an electric charge q moving in a magnetic field $\vec{B}$ with velocity $\vec{v}$. The Lorentz force is expressed by

$$\vec{F} = q (\vec{v} \times \vec{B}). \quad (1.1)$$

The force $\vec{f} = d\vec{F}/d\vec{V}$ per unit volume dV containing $N \cdot q$ charges which move with velocity $\vec{v}$ in a magnetic field $\vec{B}$ is then

$$\vec{f} = \vec{j} \times \vec{B} \quad (1.2)$$

with the current density $\vec{j} = N \cdot q \cdot \vec{v}$. This formula will be referred to as the "J-cross-B" force.

Considering the corresponding force $d\vec{F}$ acting on $N \cdot q$ charges confined in a wire of unit length $d\vec{l}$ with cross-sectional area A leads to

$$d\vec{F} = I (d\vec{l} \times \vec{B}). \quad (1.3)$$

Here, the current $I = N \cdot q \cdot \vec{v} \cdot A$ flows in the direction of the wire element $d\vec{l}$.

This work deals with two kinds of launchers which operate according to the just presented principle. Both will be explained next.

1.2.1. The EM Coil Launcher

An EM coil launcher consists basically of a primary coil and an armature. The term "armature" denotes a work piece which experiences the accelerating force by an interaction with a magnetic field. It consists of a conductive or a ferromagnetic material (Gernandt and Nett 1999). Fig. 1.1 shows a classical coil launcher with a conductive ring armature. A time varying current in the primary

Fig. 1.1. 3D sketch of an axial coilgun

coil creates a magnetic field which induces a secondary current in the armature according to Lenz's law. A Lorentz force is acting on the secondary current and repels the armature from the coil.

In case the armature consists of a ferromagnetic material, it is magnetized and attracted toward the coil. The primary coil current has to be switched off when the armature passes through the coil. Otherwise, the armature would be retarded by inverted attraction forces. This method is limited by the saturation of the ferromagnetic armature. Therefore high velocity launchers use conductive armatures. However, both cases require several coils placed along the path of the armature motion in order to reach high velocities. A challenge hereby is the exact switching of the coils. Coil accelerator can be realized in a wide range of possible arrangement (Ying *et al.* 2004).

1.2.2. The EM Rail Launcher

The EM rail launcher (also known as railgun) consists of two rails which are electrically connected by a sliding armature (see Fig. 1.2). A pulsed current I generated by an appropriate energy source (e.g. capacitors) creates a magnetic field as indicated in Fig. 1.2. The interaction of the magnetic field with the current in the armature results in a Lorentz force F_z in forward direction. This force can be described by the railgun force law (Löffler 1988; Marshall and Ying 2004; Ying *et al.* 2004) which is expressed by

$$F_z = \frac{1}{2} L' \cdot I^2. \quad (1.4)$$

$L' = dL/dz$ is the inductive gradient of the rails. Note that a corresponding repelling force acting on the rails has to be compensated by an appropriate mechanical setup.

Fig. 1.2. Main components of a railgun and its principle of operation

Related to the kind of armature, railguns can be classified in two categories: plasma armature railguns and solid armature railguns. In the first case, the plasma is usually ignited by a current past through a thin aluminium foil. This creates a plasma cloud which continues to conduct the current between the rails and is accelerated by the Lorentz force. A projectile in front of the plasma must have a design which prevents the passage of it. Generally, the plasma arc consumes power in the range of tens of megawatt which produces heat of several thousand degree Kelvin (Parker 1989). This makes the plasma railgun less efficient than solid armature rail or coil launchers.

In case of the solid armature railgun, a low resistive metal is usually used to conduct the current via a sliding contact at the armature-rail interface. The most common design is the so-called C-shape armature (Satapathy *et al.* 2007) which is made of one solid machined part. An alternative solution is used at the ISL. The armatures used here consist of bundles of copper filaments, also called brushes (Peter and Charon 1997; Schneider *et al.* 2005).

1.3. Motivation for Electromagnetic Launch Research

EM launchers offer in principle the possibility of hypervelocity (velocities > 3 km/s) launch. There is no physical limitation like the stagnation sound velocity of burning powder gases in conventional guns (Huebschman 1993). The generation of muzzle velocities of 3 km/s or more is possible with conventional guns but very inefficient (Horst 2005). Therefore, high performance tank guns

provide velocities in the range of 1700 m/s. Railguns with a distributed energy supply offer already today efficiencies of more than 30 % at velocities higher than 2 km/s (Lehmann *et al.* 2001). Furthermore, projectile acceleration and velocity can be controlled quite accurately with the applied current (Geng and Xu 2010; Sjaenen *et al.* 2011). Additionally, EM launchers use fossil fuel as primary energy source which is much safer than the explosive propellants of rockets and guns. In addition, EM launchers offer several other advantages depending on the application (Ying *et al.* 2004).

1.4. Electromagnetic Launch Applications

Since the 70's of the last century, the transport of men and payload to space by EM launcher is an ongoing topic in the community (Bolonkin and Krinker 2010; Fair *et al.* 1989; Meinel 2007). Currently, a scientific collaboration of American institutions is working on a railgun system able to accelerate nano-satellites to space from an airborne platform (McNab 2007; Wetz *et al.* 2009). Other scientists prefer a hybrid system of a conventional rocket, pre-accelerated by a railgun (Božić *et al.* 2010; Schneider *et al.* 2011). The costs per gram of payload could be reduced remarkably by use of an EM launcher due to less parasitic mass (fuel).

EM launchers are also seen as a tool for hypervelocity impact studies (Schneider 2010). One goal of such studies is the improvement of the hulls of space ships or space stations in order to protect them from increasing space debris. The hypervelocity impact is also a possibility to study very high pressures in materials similar to the pressure inside the earth. In general, hypervelocity gives new possibilities in physical and material research.

The ability of the precise control of the muzzle velocity and the acceleration profile is also interesting for material research. The Taylor test, where specimens of different materials are launched against a solid wall with identical test conditions, should be named in this respect (Sjaenen *et al.* 2009; 2011).

Another interesting idea is to inject fuel pellets into a nuclear fusion reactor by EM launchers (Onozuka *et al.* 1993).

Nevertheless, the most promising applications are seen in the military field. Hypervelocity means an increased launch distance, higher penetration depth into a target, faster and more steady flight of projectiles and therefore an increased probability to hit a target (Schneider *et al.* 1995). This and other advantages of EM launchers compared to conventional guns make the technology very attractive for various military scenarios. Currently the U.S. Navy runs a research project

with a budget of several 10 million U.S. \$ per year (U.S. Department of Defense 2011) to develop an EM gun for its all electric ships, which should be able to attack targets in excess of 500-km distance (Fair 2007; McNab *et al.* 2005).

1.5. Limits and Challenges of Electromagnetic Launch

Reaching extremely high velocities with EM launchers requires currents, magnetic fields and forces in the range of megaamperes, tens of teslas and meganewtons. Therefore, the materials of EM launchers are exposed to extreme stresses and the technological challenges are manifold.

High velocity coil launcher have to consist of multiple coils along the path of acceleration. The accurate switching of them is a very complex task. Railguns are more simple in this context. Therefore the contributions to the field of coil-guns are comparatively small (Haghmaram and Shoulaie 2004). Experimental efforts with coilguns achieved velocities ≤ 1 km/s for medium scaled projectiles. A major challenge of this technology is the mechanical integrity of the coils and the armature (Cowan 1987; Gernandt and Nett 2000). Ohmic heating and the requirement of very short and high magnetic field pulses at high velocities are the problematic.

Higher velocities were already realized with railguns. Plasma railguns are able to accelerate projectiles of a few grams to velocities exceeding 6 km/s (Drobyshewski *et al.* 1995; Hawke *et al.* 1986; Tower and Haight 1984). However, it exists currently a technical velocity barrier at around 7 km/s which is related to arc re-strikes (Parker 1989). That is a phenomenon, in which the rails are short-circuited by a voltage breakdown in the hot gas behind the plasma armature. This shunts the armature current and the Lorentz force on the main plasma is reduced. Current investigations are promising to overcome this barrier by the use of multiple current injections along the railgun bore (Distributed Energy Supply) (Karhi *et al.* 2009, 2011).

The acceleration of higher masses (hundreds of gram up to several kilograms) to velocities between 2 and 3 km/s are the goal of several investigations of solid armature railguns (e.g. McNab *et al.* 2005; Reck *et al.* 2009; Satapathy *et al.* 2005; Schneider *et al.* 2009a). Major problems of launchers in this respect are gouging (Watt and Bourell 2011) and contact transition (see section 1.8). Both phenomena appear at the sliding contact interface causing damage to the rails. Their physical origins are not fully understood yet.

Fig. 1.3. Magnetic diffusion into a conducting half-space (Knoepfel 2000)

Gouging is the creation of eyedrop-shaped sink-holes at the rail surface. It appears when the sliding velocity is above a critical value for a particular combination of rail and armature material. It is seen as a pure mechanical phenomenon because it is also observed in non-current carrying rocket sledges (Graff and Dettloff 1969). The current explanation for the occurrence of the eyedrop-shaped sink-holes is the interaction between surface asperities of the sliding members which is strongly influenced by inertial forces, the wave nature of stress propagation and local impact stresses Watt and Bourell (2011).

Because this thesis focuses on the VSE which is also considered as a major reason for contact transitions, the physics leading to the VSE will be introduced within the next sections. Afterwards, contact transition will be explained.

1.6. Magnetic Diffusion

Magnetic diffusion means that a magnetic field diffuses into an electric conductive material. Various textbooks (Knoepfel 2000; Lehner 1996; Löffler 2005) introduce this topic by one dimensional diffusion of a magnetic field into an infinite conducting half-space (see Fig. 1.3). In this example, a magnetic field $B_y = B_0$ in z -direction is applied at $t = 0$ to the surface of a conducting area with infinite size in all direction except $x < 0$. The conductivity σ , the permeability μ and B_0 are assumed to be constant. This situation can theoretically be described by the magnetic diffusion formula which can be derived from Maxwell's equations. According to (Knoepfel 2000: p. 156) it is

$$\Delta \vec{B} = \mu \sigma \frac{\partial \vec{B}}{\partial t}. \quad (1.5)$$

(a) Magnetic field depending on x -location and time (b) Current density depending on x -location and time

Fig. 1.4. One-dimensional diffusion process into a half-space like shown in Fig. 1.3 (the half-space is assumed to be copper)

The one dimensional solution of the half-space can be written as (Lehner 1996)

$$B_z(x, t) = B_0 \operatorname{erfc} \left(\frac{x \sqrt{\sigma \mu}}{2 \sqrt{t}} \right), \quad (1.6)$$

where erfc is the complementary error function. Next, the corresponding current density j_y induced by the varying magnetic field can be found by applying the law of Ampère (Knoepfel 2000):

$$j_y(x, t) = \frac{B_0}{\mu} e^{-\frac{x^2 \mu \sigma}{4t}} \sqrt{\frac{\mu \sigma}{\pi t}}. \quad (1.7)$$

In order to illustrate the magnetic diffusion process, Fig. 1.4 gives solutions for (1.6) and (1.7). Here, the conductive material is assumed to be copper. Fig. 1.4a demonstrates how the magnetic field B_0 penetrates the copper, starting at the surface at $t = 0$. According to Lenz law, a surface current is produced which acts against the penetration of the field. Fig. 1.4b shows nicely how the current is located near the surface at the beginning and how it expands into the copper.

In the case when the applied magnetic field B_z is harmonically oscillating with an angular frequency $\omega = 2\pi f$, the solution of equation (1.5) is according to (Knoepfel 2000)

$$B_z(x, t) = B_0 e^{-x \sqrt{\omega \mu \sigma / 2}} \sin \left(\omega t - x \sqrt{\frac{\omega \mu \sigma}{2}} \right) \quad (1.8)$$

and the corresponding current density becomes

$$j_y(x, t) = j_0 e^{-x\sqrt{\omega\mu\sigma/2}} \sin\left(\omega t - x\sqrt{\frac{\omega\mu\sigma}{2}} + \frac{\pi}{4}\right). \quad (1.9)$$

The dependence of both quantities on $e^{-x\sqrt{\omega\mu\sigma/2}}$ means that the magnetic field and the current concentrates near the surface of the conducting half-space. The oscillation of the applied field induces currents which limit the diffusion of the magnetic field into the conductor. At high frequencies, the diffusion depth is very small and the induced currents flow in a thin layer at the surface. This is called the **skin effect**. The width of the layer is defined by the skin depth δ . It is the depth (measured from the surface of the conductor) at which the amplitude of the magnetic field and current density is decreased to B_0/e or j_0/e , respectively (Knoepfel 2000). B_0/e equal the amplitude of equation (1.9) leads to the harmonic skin depth for the conducting half-space:

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}. \quad (1.10)$$

Although this equation is valid only for this particular case of an harmonically oscillating magnetic field applied to a conductive half-space, it is broadly used to get an impression for the depth of the current carrying layer in many other cases.

The simple skin effect occurs at single conductors and leads to an increased current density at the surface. In case a conductor is positioned in the vicinity of another current carrying conductor like in railguns, the current distribution in both conductors is influenced by the magnetic field caused by the current in the other one (Berleze and Robert 2003). This interaction is widely called the **proximity effect**. In the case of railguns, the J-cross-B interaction leads to an increased current flow at the surface facing the other rail because the currents flow in opposite directions.

In Railguns, magnetic diffusion is important due to the application of short pulsed currents. The current conducted by the rails is not using the total available cross-section which results in higher rail resistance, increased current densities, increased ohmic heating and reduced efficiency (Johnson and Bauer 1989). It also has considerable influence on the inductance gradient of the railgun (Kerrisk 1981; Keshtkar 2005). In Fig. 1.5, equation (1.5) was solved for a half of a two dimensional railgun. It illustrates the magnetic diffusion into the rails and a solid armature.

(a) Transient diffusion pattern $60\mu\text{s}$ after switch on of a constant magnetic field between the rails

(b) Steady state diffusion pattern

Fig. 1.5. 2D examples of magnetic diffusion in the half of a simple railgun (static). The curved lines represent 20 %, 40 %, 60 % and 80 % of the total DC current (Long and Weldon 1989)

1.7. Velocity Skin Effect

In the case of a railgun, the magnetic field volume between the rails grows with the position of the armature. Consequently, parts of the rail are subjected to a magnetic field which were not beforehand. Similar to the process explained in section 1.6, the magnetic field diffuses into the rail volume. This plays an important role with respect to the current distribution in the rails and the contact behaviour at the rail-armature interface. The diffusion equation (1.5) has to be extended by a second term to consider the motion of the magnetic field behind the armature. According to (Knoepfel 2000: p. 442) the general diffusion equation becomes in this case

$$\mu\sigma\frac{\partial\vec{B}}{\partial t} = \Delta\vec{B} + \mu\sigma\vec{\nabla} \times (\vec{v} \times \vec{B}). \quad (1.11)$$

Young and Hughes (1982) solved this equation theoretically for a simple railgun geometry in two dimension. An illustration of the VSE is shown in Fig. 1.6, which was computed years later by Long and Weldon (1989). It can be seen that the current distribution depends on the distance to the armature in shot direction resulting in a current accumulation at the rear part of the rail-armature interface. Note the difference to the current distribution due to the skin / proximity effect in Fig. 1.5. In reality, both effects take place at once.

Fig. 1.6. 2D examples for magnetic diffusion process in the half of a simple railgun. The curved lines represent 20 %, 40 %, 60 % and 80 % of the total DC current (Long and Weldon 1989)

1.8. Contact Transition

The VSE attracts much attention since erosion especially at the trailing edge of solid armatures was observed (Barber *et al.* 1974; Price *et al.* 1989). Today, the VSE is seen as one of the major reasons for the loss of the solid contact at the rail-armature interface (Chen *et al.* 2007). The consequence of this event is the occurrence of plasma arcs which is also referred to as “contact transition”.

In railguns with C-shape armature, transition is explained by the current melt-wave erosion model (Barber *et al.* 2003; Stefani *et al.* 2005). This model assumes that the strong current concentration at the trailing edge of the armature results in melting of the material due to Joule heating. Hence, material is removed from the rear part of the armature and deposited on the rail surface behind the projectile. Thus, a gap at the rail-armature interface appears which grows from rear to front. Contact transition occurs in connection with other processes like magnetic blow off (Barber and McNab 2003) when this melt-wave reaches the front edge of the armature-rail interface.

In principle, this model can also be applied to brush armatures. However, there are differences. Schneider *et al.* (2003a; 2009) explained that the rear brushes loose mass first due to the VSE and Joule heating. Within this process, the brushes straighten up due to the J-cross-B forces until the brushes are shorter than the rails separation. Next, transition arcs occur for a very short time until the current commutates to the next row of brushes in the front. Finally, contact transition occurs when all brushes are too short to establish a good contact.

1.9. The Investigation of the Current Distribution in Railguns

Up to now, several scientists computed the current distribution in simple railguns using a two dimensional approach (Kerrisk 1984; Long and Weldon 1989; Schoolderman *et al.* 1993). Due to progress in computing power, researchers are constantly improving the computation methods. In the last two decades, computers became powerful enough to compute the magnetic diffusion effects in realistic 3D arrangements under stationary conditions. So did the researcher at ISL with the finite element code *MEGA*, developed by the university of Bath (Reck 2005; Rodger and Leonard 1993; Wey *et al.* 1999) and latterly with *COMSOL Multiphysics* (*Comsol Multiphysics 3.5* 2008). In recent years, computer models exist which include several physical processes at once like EM diffusion, thermal diffusion, material melting and material loss, and other aspects (Liu and Lewis 2009; Shvetsov and Stankevich 2011; Stefani *et al.* 2005). Although the models became more realistic with time, simulations with armature velocities close to today's contact transition velocities (>1500 m/s) are not available yet. Successful Simulations of the VSE in railguns were published at velocities below 500 m/s (Hsieh *et al.* 2001; Li and Weng 2008) only.

Despite this background railgun research relies on experimental results in order to investigate the current distribution at the sliding armature-rail interface. In particular, it is required for the validation of existing computer models. The investigation of the Current distribution in armatures and rails is very complex because of the armature movement. However, several authors were had limited success in this respect.

Schmitt *et al.* (1998; 1997), for example, investigated the current distribution between brush armatures with Rogowski coils¹ in a static setup. They observed a current concentration of 70 % in the rear brush and influenced it by the use of different materials for the brush armatures.

Kondratenko *et al.* (1997) investigated the current distribution at the contact interface of a solid block armature during a static approach. They found that the current density at the rear is about 3.5 times higher than the average current density when the applied current pulse rises. They also found that the current density decreases below the average when the total current decays. They stated that the results are in agreement with three dimensional magnetic diffusion considerations. Similar current density profiles were obtained in (Koops and Karthaus 1995) in

¹A Rogowski coil is a toroidal air coil, which can be used for the measurement of a transient current if applied around the current conductor (Nyholm *et al.* 2002; Ward and Exon 1993).

their armature test bed. They used B-dots² and voltage probes between a split block armature.

Kondratenko *et al.* (1997) investigated also the current distribution in a C-shape armature during dynamic experiments by using B-dots along the railgun bore. They observed a maxima of the current density in y-direction (see Fig. 1.2) at the contact interface which is shifted forward while the armature travels along the bore. Kondratenko *et al.* obtained a maximal velocity of 1100 m/s in their experiments. A very similar approach was presented in Crawford *et al.* (2010). He prepared small Bdots on printed circuit boards and performed reference measurements with defined current paths in order to compare future measurement results to it.

On the other hand, Wey *et al.* (1999) conducted experiments with miniaturized Rogowski coils around the brushes of a moving projectile. The Rogowski coils were connected to a recording system by long twisted pair wires placed ahead of the projectile in the bore. This effort was successful up to a projectile velocity of 260 m/s. The measured results differed slightly from calculated current profiles. The difference was explained by the VSE which was not taken into consideration during the static FEM-simulations. The authors stated that this measurement method is limited due to the failure of the signal transmitting wires.

Another methods was conducted in (Schneider *et al.* 2003a). They estimated from flash radiographs and rail traces the current distribution between brushes of a multiple brush armature. They observed that only the brushes in the rear are straighten up due to the Lorentz force. Later on, he investigated a method using voltage probes with compensation loop sensors to measure the ohmic voltage drop at a part of the rails. Here, he found that the current is mainly conducted by the rear brushes (70 %) which was a strong deviation to his static FEM-simulations (Schneider and Schneider 2004a, 2009).

It can be concluded that the methods to perform a direct measurement of the current distribution in armatures and rails are limited to static conditions or require a perturbation of the conductor which leads to a distortion of the current paths. Therefore, a contact free measurements of the magnetic field is required in order to draw conclusions about the current distribution.

There is a wide range of magnetic field sensors available (Caruso *et al.* 1998; Lenz and Edelstein 2006), but the application of most of these sensors is not possible due to exceptional operation conditions at railguns. These are magnetic fields exceeding 3 T, EM interferences, high current and voltages and a rough

²The term "B-dot" is deduced from the time derivative of the magnetic induction, $\dot{B} = dB/dt$, and means a simple coil or loop sensor (Tumanski 2007).

mechanical and thermal environment. Up to now, B-dot sensors are the preferred tools for magnetic field sensing at railguns. They are widely used for velocity measurement (Wang *et al.* 2009), measurement of EM emissions (Ciolini *et al.* 2009), triggering of distributed energy supply (DES) stages and secondary diagnostics such as flash radiographs (Jamet and Thomer 1976). However, B-dots are not suitable to measure the magnetic field distribution at the vicinity of the rail. There, large gradients of the field are present due to magnetic diffusion. This kind of measurement requires very small probes (volume $< 1 \text{ mm}^3$) (Schneider *et al.* 2007) and small sized B-dots are very inaccurate. Moreover, the signal recorded from B-dot sensor depend on magnitude and direction of the magnetic field. During railgun operation both these parameters change simultaneously in time. Therefore it is impossible to obtain high accurate measurements with a B-dot probe in this respect. Earlier efforts to design a 3D sensor made from three B-dot sensors demonstrated that minimal effective volume of measured magnetic field is in the order of few cubic mm or larger (Schilstra and van Hateren 1998; Smith 2011). Conventional magnetic field measurement devices based on the Hall effect exhibit the same limitations in respect of anisotropy. The volume of available 3D-Hall probes exceed several cubic mm (Yilmazoglu *et al.* 2001).

In summary, several authors presented measurements which reveal a current concentration at the rear of the contact interface. No measurement techniques were found in the literature, which can obtain quantitative information about the velocity skin effect at high speed experiments. But this is of great importance for the progress in EML research in order to validate existing computer models and to design appropriate armatures and rails which can ensure a solid-to-solid sliding contact.

1.10. Colossal Magnetoresistance

Due to the lack of appropriate diagnostics for observing the VSE, it is obvious to watch out for new methods and techniques. A sensor based on the Colossal Magnetoresistance (CMR) phenomenon is a promising candidate for this task. CMR is an effect which can exhibit a much larger Magnetoresistance (MR) than the giant MR whose discovery made the significant increase of capacity of modern hard disks possible (Nobelprize.org 2007). When a MR above $10^5 \%$ was observed (Jin *et al.* 1994; Xiong *et al.* 1995) (compared to 30% for GMR) the effect was named "colossal". MR was defined by the change in resistance related

to an applied magnetic field in relation to its initial value and can be expressed by

$$MR = \frac{\rho(H) - \rho(0)}{\rho(0)} \times 100\%. \quad (1.12)$$

Here, $\rho(H)$ is the resistivity in presence of a magnetic field of strength H and $\rho(0)$ is the resistivity in the absence of a magnetic field.

The discussions how the CMR effect can be used for high pulsed magnetic field measurement (HMFM) started around 1997 (Smith and Schneider 1997). Balevičius *et al.* suggested in 1998 to use thin polycrystalline films made from La-Ca-MnO for HMFM in magnetic flux compression generators. Then, Xu *et al.* (2001) investigated magnetic field sensor based on bulk polycrystalline manganites and proposed to use it for the manufacture of sensors which measure the magnetic field independently of the direction. Short time later, Balevičius *et al.* (2002) suggested a sensor made from La-Sr-MnO thin polycrystalline films to measure pulsed magnetic fields with amplitudes up to 20T. In the following he could demonstrate that these sensors are able to measure pulsed magnetic field amplitude during coil-gun operation (Balevičius *et al.* 2004). Encouraged by these results, the CMR sensor was first time used at railgun experiments (Schneider and Schneider 2007) and promising results were achieved.

1.10.1. The CMR Effect

Jonker and Santen discovered in 1950 that manganite materials like LaMnO_3 which is an antiferromagnetic insulator, gains metallic behaviour when Lanthan (La) is replaced by Strontium (Sr). Furthermore, they discovered that these materials show a phase transition from paramagnetic-insulating (PI) to ferromagnetic-conducting (FM) depending on the temperature and the presence of an external magnetic field. Manganites crystallizes in a perovskite structure which is shown in Fig. 1.7. In case of $\text{La}_{1-x}\text{Sr}_x\text{MnO}$ (LSMO), a Manganese (Mn) atom in the centre is surrounded by 6 oxygen atoms and a mix of 8 La and Sr atoms. The ratio between La and Sr depends on the doping factor x . The replacement of La by Sr atoms introduces holes on the Mn site because La exhibit 3 and Sr only 2 electrons on the outer electron shell. Therefore, an electron can hop from an Mn^{+3} -ion to the oxygen atom and simultaneously another electron from the oxygen atom to a Mn^{+4} -ion (see Fig. 1.8). This process is known as the double-exchange (DE) mechanism (Zener 1951a,b,c) and describes basically the electron transfer in manganites. The transfer probability is influenced by the orientation of the magnetic spins of the Mn-ions (Anderson and Hasegawa 1955). If the spins

Fig. 1.7. Crystal structure of perovskite (Dagotto 2003)

Fig. 1.8. Synchronous hopping of electrons according to the DE model (Mathews 2007)

of the Mn-ions are not aligned, the moving electrons loose kinetic energy because the spin of the electrons have to adjust to the spin of the ion. The conductivity of the manganite is largest, if the spins of the Mn-ions are aligned. This can be performed by cooling or by applying a magnetic field.

This model alone does not completely explain all aspects of the CMR (Dagotto 2003; Dörr 2006; Haghiri-Gosnet and Renard 2003; Millis *et al.* 1995) but it is precise enough to give a basic understanding of the CMR effect required for this work.

1.10.2. Basic Properties of the CMR Effect

Figure 1.9 shows a characteristic temperature dependence of the CMR effect. The CMR is largest around T_m , the temperature of maximal resistivity ρ_m . This temperature is typically close to the Curie temperature T_C which is the temperature where a ferromagnetic material becomes paramagnetic. These two temperatures are very similar for monocrystalline materials.

In case a magnetic field is applied to a manganite the resistivity decreases and T_m shifts to higher temperatures. Fig. 1.10 shows such a behaviour for a monocrystalline LSMO bulk material. The highest MR (here 90 %) occurs typically at the ferromagnetic phase transition.

The properties of manganites and therefore the characteristic curves depend on many parameters. The most fundamental ones are the composition of the used manganite material (Gangineni *et al.* 2006) and the doping factor x (Urushibara *et al.* 1995; Žurauskienė *et al.* 2009). A large MR at room temperature was found for example in $\text{La}_{1-x}\text{Sr}_x\text{MnO}$ with doping factors around $x = 30\%$ (Haghiri-Gosnet and Renard 2003). Otherwise, the CMR effect is more pronounced in thin films than in bulk materials, because ρ_m and MR increase whereas T_m decreases with decreasing thickness of the film (Dörr 2006; Ziese *et al.* 2002). However, ul-

Fig. 1.9. Typical temperature dependence of resistivity and magnetization of ferromagnetic manganites (Cimpmperman 2006)

Fig. 1.10. Temperature dependence of resistivity for LSMO crystals under various magnetic fields. Open circles represent the magnitude of the neg. MR at 15 T (Urushibara *et al.* 1995).

Fig. 1.11. LFMR in FM (curves 1 & 2) and PM state (curves 3 & 4) (Žurauskienė *et al.* 2011).

tra thin films (< 3.5 nm) show significant different behaviour than bulk materials (Ziese *et al.* 2003).

Considering the properties of thin films, epitaxial films are more sensitive to temperature and magnetic fields than polycrystalline films (Stankevič *et al.* 2005). The behaviour of the latter can be further influenced by controlling the crystal growth conditions [i.e. substrate material (Cimpmperman *et al.* 2004), grain size (Balcells *et al.* 2000; Gupta and Sun 1999; Kameli *et al.* 2008), growth orientation (Infante *et al.* 2007), deposition temperature (Žurauskienė *et al.* 2011) and so on].

It was found that the magnetoresistive behaviour of polycrystalline films can

be separated in two categories: the low field (LFMR) and the high field magnetoresistance (HFMR) (Ju *et al.* 2002; Kozlova 2005) which dominate at fields below and above ~ 1 T, respectively. The LFMR originates from tunnelling (or hopping) of spin-polarized electrons through the grain boundaries (GBs), while HFMR is related to the electron transport within the GBs of polycrystalline films (Dörr 2006). An important difference between both is the anisotropic behaviour at low fields. Fig. 1.11 shows the influence of the magnetic field direction on the MR (compare dashed and straight line, respectively). Note that for larger fields the curves are parallel to each other which means that the anisotropy disappears at large fields. The anisotropic behaviour can be influenced by shifting T_m with methods already mentioned. A good compromise between anisotropy and sensitivity has to be found.

For sensor applications for instance, the use of polycrystalline films is preferable because they show isotropic behaviour for high magnetic fields (Stankevič *et al.* 2005). A further advantage of polycrystalline films over epitaxial films is that they show a more linear dependency at high fields (Lee *et al.* 1999) and that no saturation tendencies show up at magnetic fields up to 57 T (Kozlova 2005).

An important property with respect to high pulse magnetic field measurement is the ordering and disordering processes of the magnetic system. The speed of these processes has to be much faster than the rise and decay time of the measured magnetic field pulse. Xiong *et al.* (1995) found that manganites exhibit a slow resistance relaxation at $T < T_m$ after a magnetic field was switched off. The reason for that was explained by a magnetic "memory effect". Fig. 1.12 shows evidence of a memory effect by separating curves for the increasing and decreasing part of the applied magnetic field pulse. Balevičius *et al.* (1998, 1999, 2000) investigated polycrystalline La-Ca-MnO₃ films at high pulsed magnetic field with amplitudes up to 45 T and a duration of 1 ms in this respect. It was demonstrated that the resistance relaxation of this films contains two terms: a fast one (less than few μ s) and a slow one. The slow one is well described by the following empirical formula (Balevičius *et al.* 2000):

$$R(t) = R(t_1) - [R(t_1) - R(0)] \cdot \exp(-t/\tau). \quad (1.13)$$

Here, the time of observation t_1 was much greater than the characteristic time τ which changes in the range from 0.1 to 1 ms if the temperature is varied between 77 and 300 K. At room temperature, the relaxation process can be neglected because the term $[R(t_1) - R(0)]$ decreases with increased temperature. This result allows the use of polycrystalline manganite films for HMFM at room temperatures.

Fig. 1.12. Field dependence of the MR of a polycrystalline $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ film. Branches for increasing and decreasing pulsed magnetic field parts are plotted (Kozlova *et al.* 2003)

1.11. Conclusions of chapter 1 and Motivation for the Research

The interest in EM launchers lasts already more than 100 years and is based on the wish to accelerate payloads to higher velocities than with today's conventional gas driven launching systems. Most research in this respect is focusing on the railgun concept due to its simple operational principle compared to others. However, several physical processes limit the performance and lifetime of today's railguns. In particular the VSE due to magnetic diffusion and the fast movement of the armature is seen as a major reason for rail damaging and performance limiting contact transitions at the sliding contact interface in a railgun. Although the VSE is already known since more than 30 years, corresponding current profiles have never been measured during dynamic railgun experiments with velocities above 1 km/s according to the author's knowledge. In this respect, measurements are very important for validating available simulation codes. An idea in this respect is to measure the magnetic field distribution in the vicinity of the rails in order to estimate the VSE during dynamic experiments. This kind of measurement requires very small sensors which can measure magnetic fields independent of the orientation.

Several authors proposed the use of sensors based on the CMR effect for direction independent measurements of magnetic fields. The successful application of sensors based on polycrystalline LSMO thin films at railguns led this work.

Experimental Setups

2.1. Pulsed Power Technology

EM launchers are pulsed power devices which release very high energies in very short time. In case of railguns, energy storages like capacitors or rotating machines deliver current pulses with amplitudes of megaamperes in very short time (milliseconds). The preceding charge of laboratory energy storage is usually performed at moderate power levels (few kilowatts) and time scales around few minutes. The EM launchers at the ISL are powered by capacitor banks and therefore a corresponding pulsed power circuit shall be explained by means of Fig. 2.1.

A principle pulsed power circuit consists of an energy source (charger), a capacitor bank, a load, two switches and an impedance Z_0 . A pulse forming inductance and a crowbar diode are optional components. Special properties like high blocking voltage, high current leading capability and fast switching time are required for switch S_2 . Today, these requirements are usually fulfilled by spark gaps or thyristors. The impedance Z_0 takes the electrical properties of additional components like cables into account, which in most cases cannot be neglected. A crowbar diode short-circuits the capacitors at the maximum of the current pulse and prevents a recharge of the capacitors in opposite direction. By this, the requirements for the capacitors and the switches can be reduced. A

Fig. 2.1. Principle pulsed power circuit

pulse forming inductance can be used to reduce and prolong the current pulse and thereby control the acceleration behaviour in case of EM launchers. Additionally, it limits the current in case of a failure. Experience showed that a connection to earth potential is useful in order to prevent undefined high voltages.

A modular assembly of capacitors, thyristors, crowbar diodes and an inductance represent a pulse forming unit (PFU). Several of such units can be connected in parallel and triggered independently in such a way that a desired current pulse can be shaped.

2.2. High Magnetic Field Generator

The high magnetic field generator (HMFG) at the SPI consists of a charger, a 2240 μF capacitor bank, a high-current semiconductor switch (S_2) and a high magnetic field coil (HMFC). The charger consists basically of a high voltage transformer, a rectifier diode and a charging resistor and is placed together with the capacitors in a common housing. The capacitors are connected by conductive rails to the coil in a low inductive arrangement. The corresponding impedance is ohm-inductive and was defined by short-circuit measurements. Table 2.1 gives the characteristics of the generator according to the circuit diagram in Fig. 2.1. Here, no crowbar diode and pulse forming inductance exist.

Pulsed magnetic fields can be generated by the HMFC which consists of 52 windings of copper-niobium wire in four layers. The outer diameter is 36 mm, the length 50 mm and the inner diameter is 18 mm (see Fig. 2.2). The windings have an oval cross-section with an area of 6.25 mm². For the purpose of ensuring mechanical stability the coil was surrounded by a 60-mm-long metallic case with

Table 2.1. Characteristics of the HMFG power supply

Component	Property	Value
Capacitor bank	Rated capacitance C	2240 μ F
	Max. charging voltage U_{max}	5 kV
Switches	S_2	Thyristors
	Crowbar diodes	None
impedance Z_0	Resistance R_0	0.1 m Ω
	Inductance L_0	50 mH

Fig. 2.2. Longitudinal section of the electromagnetic coil test arrangement: 1 – hollow copper cylinder; 2 – guiding tube; 3 – left stopper; 3' – right stopper; 4 – plastic tube; 5 – coil; 6 – metallic casing (all dimensions in mm, 1-4 are optional). For simulation, 1 and 6 are imaginary discretized in square-shaped rings (see chapter 4)

a 36 mm inner diameter and a 58 mm outer one. The conductivity of the case material was assumed to be $5 \cdot 10^6$ S/m. For safety reasons, the coil is maintained in a steel container with double-walls of 10-mm-thick steel plates. The magnetic field pulses created by this HMFG have a half-period sinusoidal shape with amplitudes up to 20 T and a duration of 600 μ s.

As shown in Fig. 2.2 the HMFC can be used to place a hollow cylinder concentrically inside the coil. Copper or aluminium cylinders are accelerated according to the coilgun principle, if they are not fixed by stoppers at the sides. The hollow cylinder and the stoppers have an inner diameter of 3 mm and fit exactly on the hollow guiding tube. The outer diameter of both, the cylinder and the stoppers, is 4.9 mm. The stoppers and the guiding tube are made from tex-

Fig. 2.3. 3D sketch of EMA3 (cut) with fixed projectile (the GRP stopper is optional)

tolit. The length of the cylinder can be varied but the experiments presented later it was 8.8 mm. Sensors can be placed within the hollow guiding tube or within a plastic tube which can be placed in a radial distance of 7 mm to the centre of the coil.

2.3. Static Railgun EMA3

At the time being, the 3 m-long ISL railgun EMA3 is out of service and parts of it are available for static investigations. The parts are 270 mm or 1370 mm long and can be equipped with rails made from copper-chromium (Cu-Cr), Dural (Du) or steel (STL) with conductivities of 50 MS/m, 20 MS/m and 0.36 MS/m, respectively. The rails have a 15 mm × 30 mm cross section and are separated by 15 mm if mounted on the containment structure made from glass fibre reinforced plastic (GRP). Fig. 2.3 shows a part of EMA3 with cut-outs. The containment is made of two GRP bars, GRP distance keepers, threaded steel rods and screw-nuts. A GRP stopper bar can be mounted between the rails to keep a projectile in place at any position along the rails. A inductance gradient of 0.3 $\mu\text{H/m}$ was calculated for a frequency of 1 kHz (Schneider *et al.* 2003a). Two different PFUs were used to supply the static EMA3 setup. Due to space restrictions, they cannot be used simultaneously. In the following it will be referred to the grey and the yellow

PFU. Both are based on the pulsed power circuit of Fig. 2.1. Corresponding parameters are presented in Table 2.2. Except that the yellow bank consists of more modern components, the principle difference between both is the kind of S2. The grey PFU operates with a spark gap whereas each capacitor of the yellow PFU is equipped with a thyristor switch. Additionally, the maximal energy of 178 kJ which can be provided by the grey PFU is slightly more the 150 kJ of the yellow PFU.

Table 2.2. Characteristics of the yellow and grey PFUs

Item		Grey PFU	Yellow PFU
Rated capacitance	C	$8 \times 385 \mu\text{F}$	$3 \times 925 \mu\text{F}$
Max. voltage	U_{max}	10.75 kV	10.4 kV
Switch S_2		Spark gap	$3 \times \text{ABB 5SPY36L4500}$ thyristors per capacitor
Crowbar diodes		$24 \times \text{ABB}$ 5SDA27F2002	$1 \times \text{ABB 5SDA27Z1202}$ diode per capacitor
PF Inductance	L_P	$4 \mu\text{H}$	$4 \mu\text{H}$
	R_P	$280 \mu\Omega$	$280 \mu\Omega$
Coaxial cable	L_0	$0.27 \mu\text{H/m}$	$0.27 \mu\text{H/m}$
	R_0	$0.7 \text{m}\Omega/\text{m}$	$0.7 \text{m}\Omega/\text{m}$

2.4. Rapid Fire Railgun RAFIRA

The ISL railgun RAFIRA was built to investigate the multishot capacity of the brush armature technology (Schneider *et al.* 2009a,b). Based on experiences with EMA3, RAFIRA is made by the same GRP open bore construction. Here, the calibre is $25 \text{ mm} \times 25 \text{ mm}$ with a rail cross-section of $25 \text{ mm} \times 20 \text{ mm}$. An inductance gradient of $0.45 \mu\text{H/m}$ was calculated at a frequency of 100 kHz (Schneider *et al.* 2009b). RAFIRA consists of a main launcher and two pre-accelerators. The rails of the main launcher and the pre-accelerator are made from Dural and Cu-Cr and have a length of 3 m and 30 cm, respectively. The rails of the main launcher are vertically oriented whereas the rails of the pre-accelerator are horizontally mounted (see Schneider *et al.* (2009b)). Like this, the pre-accelerators and the main launcher use different brushes. At a multishot, RAFIRA operates as follows: the main launcher and both pre-accelerators are loaded with projectiles. At first, the projectile in the main launcher is shot out. Then the first pre-accelerator shoots the second projectile into the main launcher

Fig. 2.4. ISL pulse forming units (see Table 2.2 for characteristics)

Fig. 2.5. ISL railgun RAFIRA

before the main launcher shoots out this projectile. The same procedure is performed with the third projectile in the second pre-accelerator. It has to be noted that this projectile have to pass the first pre-accelerator before it enters the main launcher.

Maximal 18 grey PFU's are available for the power supply. Each PFU can be triggered separately to form a desired current pulse shape. In case of a multi-shot, the number of PFU's has to be divided by the number of shots because the capacitor banks cannot be recharged intermediately. The time between two shots is an order of magnitude below the time needed to charge the capacitor bank. Moreover, one PFU is required for each pre-accelerator. Therefore, five PFU's per shot were connected to the main accelerator during a multishot. Up to 10 grey PFUs providing a maximal energy of 1.78 MJ were used for single shots during

(a) Projectile with a horizontal brush for the pre-accelerator and a payload (copper bar) (b) Separating projectile for single shot

Fig. 2.6. RAFIRA projectiles

Fig. 2.7. A multiple brush projectile at different states: (a) before insertion, (b) before the shot, (c-e) during shot. At (e), the rear brush is disconnected due to wear

the preparation time of this work.

RAFIRA projectiles are based on the ISL multiple brush armature technique. Usually ten brushes made from copper-cadmium (Cu-Cd) filaments are incorporated in a GRP body (sabot). Multishot projectiles exhibit one vertical brush for the pre-accelerator (see Fig. 2.6a). If a payload is desired, the projectile is usually equipped with a metallic bar.

A particular feature of the multiple brush technology is that the brushes bend backwards if they are inserted between the rails (see Fig. 2.7). The brushes are initially longer than the distance between the rails and the sabot provides small free space behind each brush, called reservoir in the following. The brush over-length provides a good initial contact force and the brushes can straighten up if they become shorter due to wear and erosion until they disconnect from the rails. Then the current commutates to the brushes in the front. This mechanism is used in projectiles for high-speed shot experiments (Schneider and Schneider 2004b; Schneider *et al.* 2005). Fig. 2.6b shows a separating projectile for single shots. The rear part of the projectile stays behind when its brushes disconnect

from the rails. This reduces the parasitic mass and higher muzzle velocities can be obtained than with projectiles like shown in Fig. 2.6a.

2.5. Diagnostics

2.5.1. Voltage Measurement

The Voltage measurement between the rails of a railgun is regularly performed at the breech and at the muzzle of railguns. At ISL, the measurements are performed using voltage dividers, opto-electronic transmitters and oscilloscopes (Wey *et al.* 1995). Such a measurement gives valuable information on the contact behaviour between the armature and the rails. For example, transition is accompanied with suddenly rising voltage due to the increased resistance of a plasma arc (Melton and Stefani 2005). A similar behaviour occurs if the armature leaves the railgun and the current is not yet completely decayed. Then, a muzzle arc occurs which also results in a high breech and muzzle voltage. The origin and meaning of the muzzle voltage were explained in (Dreizin and Barber 1995; Parker 1999)

2.5.2. Current Measurement

At RAFIRA, currents are measured by Rogowski coils (Nyholm *et al.* 2002; Tumanski 2007; Ward and Exon 1993) like shown in Fig. 2.8. Such coils are installed at each of the grey capacitor banks. They were developed to fit perfectly to the current feeds and are connected to a passive filter and the recording system inside a Faraday cage. The integration is performed by numerical computation (Clements 1992; Wey *et al.* 1995).

The calibration of ISL Rogowski coils is performed with a small pulsed power circuit and a Pearson probe (Waters 1986). The pulsed power circuit consists of three 150 J capacitors, a standard DC power supply, a crowbar diode, a thyristor and a 2-m-long twisted pair cable. A current pulse with amplitudes in the range of few kiloamperes is measured by the Pearson probe and the Rogowski coil under test. The signal of the Rogowski coil is numerically integrated and compared to the signal from the Pearson probe. A calibration factor around 200 MA/Vs is usually determined at the pulse maximum for the Rogowski coils installed at the grey PFU's for RAFIRA. The error of these coils is below 1 %.

At EMA3, a commercially available "clip-on" Rogowski coils (PEMUK 2010) within an active integrator was used.

Fig. 2.8. ISL B-dots on the left and a Rogowski coil on the right

2.5.3. B-dot sensors

B-dot sensors (B-dots) are better known as loop sensors or search coils (Tumanski 2007). At RAFIRA, B-dots are located in vertically centred positions along the bore ($z = 20, 1000, 2000$ and 3000 mm) with the area being in plane with the sides of the rails. Therefore, the magnetic field created by the current in the armature induces a voltage in a B-dot which changes its polarity when the armature passes the measurement position. The axis crossing of the signal can be detected and is used for armature position detection. The signal is also used to trigger X-ray flash tubes. The B-dots are not calibrated and their signal is not integrated. Fig. 2.8 shows two ISL B-dots with different orientation of the windings.

2.5.4. Doppler radar

A Doppler radar is used for continuous velocity measurement of the projectile accelerated by RAFIRA (Eckenfels *et al.* 2004; Schneider *et al.* 2003b, 2005). Because RAFIRA has an open bore at the muzzle and at the breech, it is possible to place a Doppler radar at both positions, see Fig. 2.9. The radar signal at the muzzle is usually deflected by a mirror made from aluminium foil on paper board.

Fig. 2.9. Principle of the Doppler radar installation

The projectile can easily perforate the mirror when it leaves the bore. The front, the back or both sides of the projectile is usually coated by an aluminium colour to increase the reflection of the radar signal (see Fig. 2.6b).

The Doppler radar system is more precise than other velocity measurement techniques but fails when plasma arcs occur. Therefore, B-dots are used as additional measurement tool.

2.6. Conclusions of Chapter 2

Testing and calibrating high magnetic field sensors requires high pulsed magnetic field sources with a known magnetic field regarding amplitude and direction. Such magnetic field pulses of half-period sinusoidal shape with 600 μs duration and amplitude of up to 20 T can be generated with a high magnetic field coil described in this chapter. The coil can be used for the acceleration of a conducting cylinder in order to test a magnetic field sensor array at dynamic coilgun experiments.

The railgun EMA3 presented in this chapter can be used to perform magnetic field and current distribution measurement at static railgun experiments with a maximum energy of 178 kJ. This setup allows an easy variation of several parameters (i.e. rail material, energy and armature geometry). The railgun RAFIRA presented here was available for the investigation of magnetic diffusion and current distributions at dynamic experiments.

Magnetic Field Sensor based on the Colossal Magnetoresistance Phenomenon

This chapter deals with the preparation and development of the CMR-B-scalar magnetic field sensor and dedicated electronics. Parts of this chapter were presented in (Balevičius 2009) and (Žurauskienė 2011).

3.1. Sensor Preparation

The magnetic field sensors were made by growing 400 nm thick polycrystalline $\text{La}_{0.83}\text{Sr}_{0.17}\text{MnO}_3$ films on Lucalox substrates. The method used to produce the LSMO film was the pulsed injection metal organic chemical vapour deposition technique (Abrutis *et al.* 2002). Note that the growth rate and substrate temperature during the deposition influences the properties of the sensor in respect of its sensitivity and anisotropy. In the following, arrays of $0.4 \text{ mm} \times 0.2 \text{ mm}$ big areas were formed by using standard photolithography and by etching the unnecessary film. Two square electrical contact layers with an edge length of 0.4 mm were added by thermal deposition of silver (Ag) on the LSMO film using a chromium (Cr) sublayer. The gap distance between the Ag layer was $50 \mu\text{m}$. Then, the contacts were annealed in argon atmosphere for 40 minutes at 420°C . It was found that contacts made from Ag exhibit a contact resistance which is more than 10 000 times smaller than the resistance of the LSMO thin film.

Fig. 3.1a shows a sketch of a prepared sensor sample. Such samples with a

Fig. 3.1. The CMR-B-scalar sensor

Fig. 3.2. CMR-B-scalar sensor array with removed wire screen

size of $0.5 \text{ mm} \times 1 \text{ mm}$ were cut from the array. The Ag contact layer partially covers the LSMO film like shown. The size of the sensor's active volume is then $0.4 \times 50 \times 400 \text{ } \mu\text{m}^3$. It means that magnetic field which direction is unknown in advance could be measured locally in the effective volume of $\approx 3 \times 10^{-2} \text{ mm}^3$. In the next step, two copper wires were twisted and soldered to the contacts perpendicular to the film surface. Then, the active area was sealed with special thermo glue to prevent an ageing of the LCMO film. After this, the wires were placed in a wire screen covered by a flexible isolating tube. The sensor and wires were mechanically fixed to the wire screen and the flexible tube by epoxy. Finally, the cable had a length of approximately 1 m. A coaxial plug is used to connect the sensor wires to the measurement electronics. Fig. 3.1b shows a close-up view of the sensor. The rectangular piece on the tip is the substrate.

3.2. Sensor Array

An array of four CMR-B-scalar sensors was prepared in order to measure the magnetic field distribution in the HMFC. The sensors were positioned in a flexible tube in distances of 5 mm each to the other and fixed by customary glue. In order to protect the sensor from high frequency noise, the flexible tube together with the sensors array and twisted wires were coated by a wire screen. Fig. 3.2 shows the sensor array with removed wire screen.

Fig. 3.3. Connection scheme of the CMR-B-scalar sensor (generation I)

Fig. 3.4. CMR-B-scalar sensor system of generation I

3.3. Measurement System

The sensor is an electronic device which magnetoresistance can be measured by applying a constant voltage or current source and measuring the resistance change due to an applied magnetic field. A simple electrical circuit used to power a CMR-B-scalar sensor is shown in Fig. 3.3. The power supply E consists of two AA batteries which provide a voltage of 3 V. The voltage stabilizer V consists of two diodes in forward direction which reduce the voltage to 1.4 V. Thereby, the ballast resistor $R_2 = 1 \text{ k}\Omega$ limits the maximum current to 3.6 mA. Resistor $R_1 = 3.6 \text{ k}\Omega$ is connected in series to the sensor. The voltage across R_1 is measured by the recording system, i.e. an oscilloscope. In order to protect the electrical circuit from high frequency noise, the circuit was installed in an aluminium box and the wires were screened (see Fig. 3.4). The sensor wire screen, the sensor's low potential lead, the aluminium shielding box of the circuit and the outer conductor of the coaxial cable were connected to the ground potential of the recording system. The application of the CMR-B-scalar sensor at railguns with high EM interferences led to the development of a standalone measurement system (see Fig. 3.5a). This system is characterized by improved EM shielding, galvanic separation, and an implemented recording system. It consists of max-

Fig. 3.5. CMR-B-scalar sensor system of generation II

imum four magnetic field sensors and B-scalar meters, a fibre optic hub and a software package (see Fig. 3.5).

The B-scalar meter is a high-speed electronic device for high resolution measurement, data storage and transmission. It consists basically of a high speed digital data processor, a similar circuit as shown in Fig. 3.3 which is connected to an Analog to Digital (A/D) converter, a data storage for one measurement, PC communication circuits and the power management including a lithium-ion rechargeable battery.

The B-scalar meter can be either connected by a fibre optic cable, a fibre optic hub and a USB cable or directly by USB cable to a PC. The software package controls the B-scalar meter, converts the recorded raw signals into units of Tesla and provides several data post-processing tools. Maximal four B-scalar meter can be connected to the optic fibre hub and simultaneously controlled by the software.

During operation, the measurement parameters like measurement or trigger time have to be set by using the PC. Depending on the settings, the B-scalar meter can either be triggered by an external 5 V-signal or by the detected signal itself. Thereafter, the meter performs the measurement of the sensor resistance, digitalizes it and stores it in the internal memory. Next, the data are requested by the software installed at the PC. Next, the software converts the data into magnetic field values.

A 4-mm-thick steel and 1-mm-thick aluminium casings are protecting the electronic circuit from EM interferences. Furthermore, the circuit is based on SMD technology in order to minimize its EM susceptibility. In addition to the galvanic separation, the fibre optic cable provides also data transmission over large distances (> 5 m) which is not possible with a direct USB connection.

The detailed characteristics of this system are listed in Appendix B.

Fig. 3.6. Temperature sensitivity vs. magnetic flux density for three sensor samples

3.4. Temperature Sensitivity

As mentioned in chapter 1.10 the CMR effect depends on an applied magnetic field and on the temperature. In order to characterize the temperature sensitivity, a coefficient is defined as follows:

$$\beta = \frac{\Delta MR_{max}}{MR_{0T} \cdot \Delta T} \cdot 100\%. \quad (3.1)$$

Here, ΔMR_{max} is the maximal change of magnetoresistance in the temperature range $\Delta T = T_2 - T_1$ (here it is $T_2 = 40^\circ\text{C}$, $T_1 = 0^\circ\text{C}$), MR_{0T} is MR at a given magnetic flux density measured at middle temperature $T_{op} = (T_1 + T_2)/2 = 20^\circ\text{C}$. Fig. 3.6 presents the dependence on the magnetic field amplitude for different sensor samples which were grown at 750°C (S-750), 700°C (S-700) and 650°C (S-650). It can be seen that the magnetic field measurement of all sensor samples is influenced by the temperature by more than 2%. This has to be taken into account during the calibration of the sensors.

3.5. Calibration

The CMR-B-scalar sensors are calibrated in order to take the non-linear magnetic field dependence and the temperature sensitivity into account. The measured voltage across R_1 (see Fig. 3.3) can be separated into the offset voltage V_0 and the voltage change ΔV during a measured magnetic field pulse. V_0 is the voltage at zero magnetic field and is related to the sensor's temperature. ΔV occurs due to the resistance change of the sensor in a magnetic field. In order to

Fig. 3.7. Calibration curves for different temperatures

measure the magnetic field, each sensor was calibrated at temperatures ranging from 10 to 40 °C.

The calibrations were performed within the HMFC. A sensor was placed in the homogeneous magnetic field in the centre of the coil together with an axial B-dot. The calibration of the B-dot was performed by a magneto-optical sensor which operation is based on the Faraday effect. The B-dot signal was integrated by a passive integrator consisting of a 120 k Ω resistor and a 339 nF capacitor. During the calibration of the sensors, the HMFC was cooled by filling the inner container maintaining the HMFC with liquid nitrogen. Then, magnetic field pulses of half sinusoidal shape and amplitudes of maximal 20 T were generated. The measurement location was warmed up by ohmic heating of the HMFC and additionally by ohmic heating in a nichrome wire, which is wound around the guiding tube shown Fig. 2.2. The current in the nichrome wire was digitally controlled in order to repeat the calibration measurements in steps of 3 °C.

Fig. 3.7 presents corresponding calibration curves of one sensor. These curves are stored in a file which is used by the software to convert measured data of voltage change into magnetic field values by linear interpolation. The offset voltage is usually measured shortly before the triggering of the measurement device. It is assumed that the temperature of the sensor does not change during the time of measurement of a pulsed magnetic field ($t < 10$ ms).

3.6. Loop Effect

It has to be noted that a time-varying magnetic field induces a parasitic voltage $V_{loop} = S \cdot \frac{dB}{dt}$ into the transmission line acting as a closed loop. The magni-

(a) Sensor's response to sinus waveform magnetic field pulses having different $\hat{B}$: 1–0.46 T, 2–1.13 T and 3–1.28 T

(b) Analysis of (a): $\hat{V}$ and $\hat{V}_{loop} (\times 5)$ as functions of $\hat{B}$

Fig. 3.8. Loop effect measurement

tude depends on the loop area S and the derivative of the magnetic field dB/dt . The wire leads of the sensor were twisted in order to minimize the loop area S and therefore V_{loop} . Hereby, the voltages induced in neighbouring loops compensate each other if the magnetic field is homogeneous and the loops are perfectly uniform. The magnetic field created by a current in a straight wire decreases with distance r to the wire by $1/r$ (Wolff 1997). In railguns, the decrease of the magnetic field is even more pronounced due to the superposition of the magnetic field created by the opposed currents in the rails. In this case an induced voltage which interferes with the measurement signal can not be avoided.

To make an error estimation, the magnetic field created by a high sinusoidal current pulse in a 10 cm long straight wire was measured by a CMR-B-scalar sensor. The sensor was placed near the cable with its twisted wire perpendicular to it in order to simulate the conditions at railgun experiments. The diameter of the sensor wires and the thickness of its isolation was 0.1 mm and 0.05 mm, respectively. The length of each loop of the wire was 2.5 mm.

Fig. 3.8a shows three corresponding measurement results. Here, the voltage measured across R_1 (see Fig. 3.3) is shown. It can be seen that the measured magnetic field pulses have a half-sinusoidal shape. Therefore, the maximum amplitude of an induced voltage ($\hat{V}_{loop}$) appears at $t = 0$ ms because the derivative of it has a cosinusoidal character. ΔV is the part of the voltage which is related to the resistive change of the CMR-B-scalar sensor due to the magnetic field pulse. Its maximal amplitude is $\Delta \hat{V}$ which corresponds to the magnetic field amplitude $\hat{B}$. In order to obtain an accuracy of $\pm 5\%$, the ratio $\Delta \hat{V} / \hat{V}_{loop}$ is 10.

In Fig. 3.8a, $\hat{V}_{loop}$ can be determined for each pulse by a small negative peak

Fig. 3.9. I-V-characteristic curve of a CMR-B-scalar sensor

which appears just after $t = 0 \text{ ms}$. Corresponding values depending on $\widehat{B}$ are plotted in curve 2 of Fig. 3.8b. Note, that a multiplication by a factor 5 was performed. Curve 1 shows likewise a $\Delta\widehat{V}$ dependence on $\widehat{B}$. Now, the coefficients $k_1 = \Delta\widehat{V}/\widehat{B}$ and $k_2 = \widehat{V}_{loop}/\widehat{B}$ can be obtained by the slope of these curves. Here, k_1 and k_2 are 11.34 mV/T and 0.625 mV/T, respectively. Then, the maximal possible frequency f_{max} within an accuracy of 5 % can be calculated by

$$f_{max} = 0.1(k_1/k_2)f_m. \quad (3.2)$$

Here, f_m is the fundamental frequency of the magnetic field pulse. Equation (3.2) states that the maximum attainable frequency is reached by f_m when the ratio k_1/k_2 is 10. Applying the values of Fig. 3.8b, $f_{max} \approx 1.5 \text{ kHz}$.

One way to increase f_{max} is to improve the signal-to-noise ratio by increasing k_1 . This can be performed by increasing the voltage applied to the sensor. However, the voltage is limited by Joule heating. This voltage was found to be 2.5 V at 300 K (see Fig. 3.9). By increasing the voltage from $\sim 0.8 \text{ V}$ to 2.5 V, f_{max} can be increased to $\sim 5 \text{ kHz}$.

In order to reduce the loop effect in the wires, they can be twisted with non-uniform loop size. The size of the loops (loop steps) have to increase with the distance to the sensor in order to take the gradient of the magnetic field into account. Fig. 3.10 shows the induced signals into three wires which were differently twisted and applied to the before mentioned magnetic field pulse. Two wires were uniformly twisted with 1 mm and 17 mm step size. The other one was twisted with varying step sizes from 1 mm to 17 mm. In this case a theoretical simulation has been carried out in order to calculate the loop length distribution along the length of the leads. Fig. 3.10 shows that gradually twisted wires give the best result if

Fig. 3.10. Induced voltage in the loops of bifilar twisted wires with different loop steps

the wires of the sensor are placed in a gradient of the measured magnetic field. An upper frequency limit of 10 kHz was found in this case.

3.7. Response Time of the CMR-B-scalar Sensor

The response time of the CMR-B-scalar sensors depends on the ordering and disordering processes of the magnetic spins. The ordering process in a ferromagnetic material usually occurs during subnanosecond time whereas the disordering process depends on the temperature. The relaxation time increase with lower temperatures and a memory effect occurs. To overcome this drawback, the sensor was made from a film which is in the paramagnetic state at operation temperature (room temperature). It means that T_m (see Fig. 1.9) was significantly below the room temperature.

The response of sensors was tested by measuring a damped sine waveform magnetic field with a frequency of 71 kHz and a maximum amplitude of 4 T. After the compensation of the loop effect, it was found that the sensors response fully coincide with the measured current waveform. This result shows that the operational speed is not limited by a memory effect of the LSMO film to frequencies of approximately 100 kHz.

3.8. Anisotropy

Anisotropy is the sensor's response dependency on the direction of the measured magnetic field. As already mentioned in chapter 1.10, CMR sensor exhibits an anisotropic behaviour at low magnetic fields. Because the CMR-B-scalar sen-

(a) Sensor's response dependence on magnetic flux density when magnetic field was applied in film plane (parallel to the current J) and perpendicular to the plane

(b) Sensor's measurement relative error vs. magnetic flux density

Fig. 3.11. Anisotropy measurement

sor is designed to measure the magnetic field independently from its direction, the anisotropy is the main reason for the error at low magnetic fields (< 1 T).

For investigation of the LFMR, the MR was measured in the same magnetic field for two different configurations: when B is parallel ($B_{\parallel}$) and perpendicular ($B_{\perp}$) to the film plane of the sensor. Fig. 3.11a shows an according measurement at 290 K. It can be seen that a difference in the MR occurs at low magnetic field and stays constant for higher magnitudes. In order to decrease the anisotropy related error, the average value ($B_{av} = (B_{\parallel} + B_{\perp})/2$) was taken for calibration. The absolute error due to anisotropy effect is then ΔB and the relative error $\delta = (\Delta B/B_{av}) \cdot 100\%$. Fig. 3.11b shows the relative error for magnetic fields up to 800 mT at different temperatures. It can be stated that the relative error at room temperature due to anisotropy is less than 10 % for $0.5 \text{ T} > B > 1 \text{ T}$ and 5 % for $B > 0.5 \text{ T}$.

3.9. Conclusions of Chapter 3

The results presented in this chapter demonstrate that thin polycrystalline $\text{La}_{0.83}\text{Sr}_{0.17}\text{MnO}_3$ films can be used in order to design a sensor which can be used for measurements of strong pulsed magnetic fields. Such sensors are able to measure the absolute value of the magnetic flux density up to 20 T. The sensor exhibits a very small active volume ($\approx 3 \times 10^{-2} \text{ mm}^3$) which can be placed in

the vicinity of an electric current conductor (e.g. the rails of a railgun) with a minimal distance of 0.4 mm to the surface. This is important in order to measure magnetic diffusion with high magnetic field gradients present.

A bifilar wire connecting the sensor twisted with a non-uniform loop size showed the lowest loop effect in a magnetic field which is decreasing with the distance to the sensor location. An upper frequency limit of 10 kHz was found employing these wires.

The sensors inaccuracy due to its strong dependence on temperature can be minimized by a calibration method using data obtained from resistance vs. magnetic field measurements at different temperatures. By taking the magnetoresistance anisotropy effect during the calibration into account, the error induced by it can be reduced to 10 % at $0.5 \text{ T} < B < 1 \text{ T}$ and 5 % at $B > 0.5 \text{ T}$.

Magnetic Field Distribution in a Coilgun

In order to test the CMR-B-scalar sensors, an array of them was used to measure the complicated magnetic field distribution in a coilgun. The results were compared to corresponding simulations in *Mathematica*. The results presented in this chapter were published in (Liebfried 2006; 2009).

4.1. Experimental

Static and dynamic coilgun experiments were performed by using the HMFG equipped with a 8.8-mm-long copper cylinder like specified in Fig. 2.2. During the experiments, the capacitor bank was charged up to 1 kV and sinusoidal magnetic field pulses of 600 μ s duration and amplitudes of maximum 10 T were created in the HMFC.

During the static experiments the cylinder was kept in place by two Textolite stoppers (see Fig. 2.2). In order to measure the magnetic field as close as possible to the hollow cylinder, two CMR-B-scalar sensors (S1, S2) were placed in a groove of the left stopper near the outer and inner radii of the copper cylinder. There they were fixed by ordinary glue. Fig. 4.1 illustrates this situation. The sensor S1 was oriented in the radial direction (film plane was parallel to the centreline), while all the other sensors were axially oriented (film planes were perpendicular to the centreline). The connecting wires of these sensors were also

Fig. 4.1. Section of Fig. 2.2 with CMR-B-scalar sensor positions (arbitrary scale)

placed in the groove of the left stopper and introduced through a drill hole inside the hollow guiding tube. A plastic tube was placed parallel to the axis at a distance of 7 mm in order to position a further sensor (S3). A fourth sensor (S4) was finally positioned on the axis of the coil in the hollow guiding tube. All the sensors were arranged in the same plane at a distance $\Delta z \approx -0.5$ mm from the side of the copper cylinder. The radial positions of the sensors S1, S2, S3 and S4 were 5, 3, 7 and 0 mm from the axis of the coil, respectively.

At dynamic experiments, the sensor array was positioned in the hollow guiding tube on the centreline of the HMFC. In order to obtain the complete field distribution on the axis of the coil, four experiments were made at same experimental conditions. During all four experiments the capacitor bank was initially charged to 1 kV. After each experiment the array of sensors was displaced by a distance of 15 mm. Therefore, the position of the first sensor of the subsequent experiment coincides with the position of the fourth sensor in the previous experiment. In this way, the magnetic field was measured in 5 mm distances from $z = -3$ cm until $z = 3$ cm. Note that the origin of the coordinate system lies at the centre of the coil. The sensors were positioned with an accuracy of 1 mm.

At these experiments, the CMR-B-scalar sensors were connected an oscilloscope as shown in Fig. 3.3.

4.2. Theory and Simulation

Semi-analytic parameter simulations of the experiment using the *Mathematica* code were carried out. The first step was to calculate the currents in the coil, its casing and in the copper cylinder. Subsequently, the movement of the projectile and the magnetic induction at the positions of the sensors was calculated.

In order to calculate the current distribution in the copper cylinder and in the metallic casing, their geometry was discretized: they were split into small rings with square cross sections positioned at a zero distance from each other

Fig. 4.2. Equivalent circuits of four magnetically coupled rings

(see Fig. 2.2). The length of the sides of the squares was chosen to be smaller than the skin depth according to equation (1.10) or maximum half the material thickness. During the performed simulation the occurring skin effect had a skin depth of 2.3 mm (copper cylinder) and 7.8 mm (casing), respectively. In the radial direction the copper cylinder and casing were divided into two layers (see Fig. 2.2).

After discretization, the arrangement corresponds to a system of magnetically coupled conductive rings. Fig. 4.2 shows example of equivalent circuits of such a system with a resistance R_i , an inductance L_i and a voltage source v_i for each ring. Each circuit is coupled by the mutual inductances $M_{i,j}$ to the other circuits. The coil itself was described by one equivalent circuit. According to (Löffler 2005), the complete system can be described by the following equation:

$$\vec{v}(t) = \mathbf{M}(z(t)) \cdot \frac{d}{dt} \vec{i}(t) + \left(\mathbf{R} + \frac{d}{dt} \mathbf{M}(z(t)) \right) \cdot \vec{i}(t). \quad (4.1)$$

The elements with $i = j$ of matrix $\mathbf{R}$ describe the resistivity of the i^{th} ring. The elements are zero in case $i \neq j$. The matrix $\mathbf{M}$ represents the self-inductances of each ring when $i = j$ and the mutual inductances between the i^{th} and the j^{th} ring if $i \neq j$. $\vec{v}(t)$ and $\vec{i}(t)$ are vectors describing the voltages and currents of the equivalent circuits. Here, $z(t)$ is the position of the projectile. Equation (4.1) can be transformed to

$$\vec{v}(t) = \mathbf{M}(z(t)) \cdot \frac{d}{dt} \vec{i}(t) + \left(\mathbf{R} + \frac{d\mathbf{M}(z(t))}{dz} \frac{dz(t)}{dt} \right) \cdot \vec{i}(t). \quad (4.2)$$

Fig. 4.3. Mutual inductivity (a) and its gradient (b) between the coil and one ring of each armature layer in dependence of its position in z direction

Here, $\frac{d\mathbf{M}}{dz}$ is the matrix of gradients of mutual inductivities. The mutual inductivities and their gradients between all circuits were calculated according to (Smythe 1939) for different positions in z -direction. The results were summarized in tables for interpolating. Fig. 4.3 shows the results of the mutual inductivities and the gradients between the coil and a ring of the projectile's inner and outer layer. The acceleration a of the projectile with mass m can be calculated by taking the propelling (Lorentz) force in consideration. Here, the Lorentz force results from the interaction of the currents in the projectile rings, the coil, and the casing. Due to rotational symmetry, the force acts in z -direction. It is described by

$$F_z(t) = m \cdot a_z(t) = \vec{i}_1(t) \cdot \frac{d\mathbf{M}(z(t))}{dt} \cdot \vec{i}_2(t). \quad (4.3)$$

The sum of all forces acting on the single projectile rings gives the resulting force acting on the projectile. The equation

$$a_z(t) = m \frac{d}{dt} u_z(t) = \frac{d^2}{dt^2} z(t) \quad (4.4)$$

with velocity u_z in z -direction completes the equation system.

The calculation of the currents was accomplished applying *Mathematica 5.2*. Geometrical and electrical parameters as presented in chapter 2.2 were used. Instead of an elliptic cross section of the coil winding a circular form with a radius of 1.41 mm was chosen resulting in the same area as in reality. It is assumed, that the conductivity of the coil windings and the projectile is $56 \cdot 10^6$ S/m and of the casing $5 \cdot 10^6$ S/m. The projectile mass of 3.7 g was calculated assuming a density of 8930 kg/m^3 .

For the calculation of the magnetic flux density B at a given point the law of

Biot-Savart was applied resulting in the contribution of the n^{th} ring (radius s_n , current I_n) given in the cylindrical coordinates r and z (Smythe 1939)

$$\begin{aligned} \vec{B}_n(r, \Delta z_n, t) \\ = \begin{pmatrix} B_{n,r} \\ B_{n,\varphi} \\ B_{n,z} \end{pmatrix} = \frac{\mu I_n(t)}{2\pi} \cdot \frac{\Delta z_n k_n}{\sqrt{4s_n r^3}} \cdot \begin{pmatrix} -K(k_n^2) + \frac{s_n^2 + r^2 + \Delta z_n^2}{(s_n - r)^2 + \Delta z_n^2} \cdot E(k_n^2) \\ 0 \\ K(k_n^2) + \frac{s_n^2 - r^2 - \Delta z_n^2}{(s_n - r)^2 + \Delta z_n^2} \cdot E(k_n^2) \end{pmatrix} \end{aligned} \quad (4.5)$$

with $k_n^2 = 4s_n r \cdot [(s_n + r)^2 + \Delta z_n^2]^{-1}$. K and E are the complete elliptic integrals of the first and of the second kind. Here, Δz_n is the axial distance between the n^{th} ring and the point of interest. The superposition of all $\vec{B}_n$ gives the magnetic field at any point of the arrangement. The magnetic field lines in an axially symmetrical system like this one can be obtained according to Smythe (1939) by

$$A(r, \Delta z_n, t) = 2 \cdot \pi \cdot r \cdot A_{n,\varphi}(r, \Delta z_n, t), \quad (4.6)$$

where $A_{n,\varphi}$ is the vector potential of the n^{th} ring defined by

$$A_{n,\varphi}(r, \Delta z_n, t) = \frac{\mu I_n(t)}{\pi k} \cdot \sqrt{\frac{s_n}{r}} \cdot \left[\left(1 - \frac{k^2}{2} \right) K(k^2) - E(k^2) \right]. \quad (4.7)$$

The formula has to be applied to every ring. The superposition of the single contributions onto the vector potential makes it possible to draw the magnetic field lines like contour lines.

4.3. Results

At the beginning, static experiments and simulations were performed in order to verify the simulation results and to gain first insights into the magnetic field distribution. In this case, the z -depending terms in equation (4.2) and the equations (4.3) & (4.4) were neglected. The results are shown in Fig. 4.4a–c at different instants after switching on the thyristor: $t = 100 \mu\text{s}$, $400 \mu\text{s}$ and $600 \mu\text{s}$. A section of the cylinder marked by a rectangle is zoomed in and is presented in Fig. 4.4d–f. The arrows shown in the close-up figures represent the calculated magnetic field vectors in the positions of the sensors S1 and S2 in the static experiments. The lengths of the vectors depend on the magnetic flux density. It should be noted that the direction of the vectors changes in time.

To highlight this change in direction in front of the copper cylinder, Fig. 4.5

Fig. 4.4. Longitudinal cross-section of the arrangement with magnetic field lines at different instants of time (a–c) and corresponding close-up sections (d–f). Magnetic field vectors are shown at the positions of the sensors S1 and S2

shows the simulated magnetic field ($B_{absolute}$) and its axial (B_z) and radial (B_r) components at $z = 0 \text{ mm}$ and $r = 4 \text{ mm}$. This point is the origin of the vectors in the inset. Note the difference between the curves of the absolute value and the curve of B_z . They differ mainly from each other by the buckling of B_z at $t = 0.6 \text{ ms}$.

In the following, the simulation was compared to corresponding experiments. The first experiment was completed without a hollow cylinder. Fig. 4.6 shows the response of the sensors S3 and S4 in comparison to the calculated magnetic field at their position. The location of the sensors can be seen in the inset.

The results of the experiment with the copper cylinder are shown in Fig. 4.7a. Fig. 4.7b presents the results of the respective simulation.

At dynamic experiments, the magnetic field was measured on the centreline when the right stopper was removed. Fig. 4.8 shows the results obtained with the moving projectile. The graphs show the axial distribution of magnetic induction at different time points. The straight lines represent the result of the calculations, the points represent experimental data from different experiments. The results obtained with different experiment are represented by other symbols and colours.

Fig. 4.8a shows the axial magnetic field distribution $50 \mu s$ after current ignition. This corresponds to the increasing part of magnetic field pulse (see Fig. 4.6). The curve has a minimum which coincides with the centre of projectile. The second graph (Fig. 4.8b) shows the distribution of the magnetic field after $250 \mu s$.

Fig. 4.5. Distribution of the magnetic flux density (absolute, radial and axial components)

Fig. 4.6. Magnetic field measurement and simulation in the HMFC. The measurement positions are indicated in the inset

(a) Simulated results

(b) Measured results

Fig. 4.7. Magnetic field pulse in the vicinity of the copper cylinder

At this time the magnetic induction is close to the maximum. In the next graph (Fig. 4.8c) the magnetic field is decreasing again at 500 μs . Here, the magnetic field is a local maximum at the location of the hollow copper cylinder. A similar curve results from the fourth (Fig. 4.8d) graph where at $t = 700 \mu\text{s}$ the coil current is switched-off by the thyristor. At this time the magnetic field is maintained by eddy currents in the projectile and in the casing.

Fig. 4.8. Measurement (symbols) and simulation (curves) of the magnetic field at the axis of the HMFC during acceleration of the hollow copper cylinder

4.4. Discussion

The pictures of Fig. 4.4 reveal a high dynamic magnetic field behaviour in the vicinity of the copper cylinder. The simulation clearly shows a change in the magnetic field direction: at the start of the magnetic field pulse, the magnetic field vector points diagonally outwards and rotates during the pulse clockwise towards the inside of the coil. This is in agreement with the results presented in Fig. 4.5. One can see that the radial component of the magnetic field vector starts with positive values and then becomes negative. This change in the magnetic field direction can be explained by the superposition of two magnetic fields: the magnetic field induced by eddy currents in the cylinder and the external magnetic field created by the coil. During the increasing part of the pulse the eddy currents induce a magnetic field in opposite direction to the external magnetic field. The decreasing part of the pulse ($t > 0.27 \mu\text{s}$, see Fig. 4.5) causes a change in direction of the induced magnetic field, so that it is superimposed on the external field. Due to the closed nature of the induced magnetic field lines, the radial component appears on the edge of the copper cylinder and changes directions in time. Therefore, the magnetic field of the cylinder is responsible for the radial magnetic field component in Fig. 4.5. The absolute magnetic field $B_{abs} = (B_z^2 + B_r^2)^{1/2}$ and B_z differ in time, especially at the end of the pulse (see the circled part in Fig. 4.5).

Moreover, after the switch-off of the coil current, the magnetic field still remains accumulated inside the metallic casing of the coil (see Fig. 4.4 c). This results in the magnetic field "tail" after the switch-off of the current (see Figs. 4.6 & 4.7).

A good agreement between the measured and simulated results of the ar-

rangement without the cylinder (see Fig. 4.6) can be stated. Small differences in the amplitude appear due to the charging accuracy of ± 20 V of the HMFG capacitors and the accuracy of the CMR-B-scalar sensors. A high frequency noise appears due to the small voltage measurement signal (mV-range) of the sensor. The nearly equal amplitudes of the measurements at different radial positions and the appearing sharp bend show that the magnetic field inside the coil without the cylinder is homogeneous and only axially directed (compare to B_z in Fig. 4.5). Furthermore, the experiment shows that the different orientation of the S1 plane has no noticeable influence on the measurement results.

The static experiment with the copper cylinder (Fig. 4.7) also shows very good agreement between measurement and simulation. In particular the similar shapes of the experimental and calculated magnetic induction curves corresponding to the positions of the sensors S1–S4 have to be stressed. The curve of S3 shows a sharp bend at the end of the pulse due to the higher distance to the copper cylinder and the shorter distance to the coil. It indicates a very small influence of the radially directed magnetic field of the cylinder at this position. It is in contrast to the other measurement points which are closer to the cylinder (S1, S2 and S4). The corresponding curves have no visible sharp bend at the end of the pulse.

The superposition of the induced magnetic field of the copper cylinder with the external magnetic field results firstly in a reduction and later ($> 400 \mu\text{s}$) in an amplification of the magnetic field inside the copper cylinder. Therefore, it is possible to identify the motion of the projectile in Fig. 4.8 by the local maxima/minima. Small derivations between the calculation and the measurement appeared because in the calculation effects like friction and heating were neglected and because the measurement tolerance of the position of the sensors and of the projectile was restricted to 1 mm. Additionally, the charging accuracy and the sensor accuracy have also be taken into consideration. The results from the four different experiments are in excellent agreement with the calculations although the magnetic field distribution is complicated.

4.5. Conclusions of Chapter 4

A magnetic field rapidly changing in value and direction was measured using an array of CMR-based magnetic field sensors in a typical electromagnetic launching system – a small coilgun with an inserted hollow copper cylinder. The semi-analytic parameter simulations of magnetic induction inside the coilgun performed by using the *Mathematica* code showed a good agreement with the exper-

imental data for the static and the dynamic case. It demonstrates that the response of the CMR-B-scalar-based sensors to the magnetic field pulse does not depend on their orientation in the magnetic field direction and thus the CMR-B-scalar-sensors measure the absolute value of the magnetic induction.

Finally, it should be concluded that the CMR-based sensors can be used in complicated systems for the local measurement of pulsed magnetic fields with directions, unknown in advance, involving strong field gradients. This is an important feature regarding the measurement of the magnetic field distribution in railguns.

Current and Magnetic Field Distribution in Railguns

The wear behaviour observed at the rail-armature interface in railguns is strongly asymmetric. The wear predominantly takes place at the rearmost part of the interface. This asymmetry was explained by a corresponding current concentration due to the VSE (see chapter 1). This chapter deals with the measurement of the magnetic field distribution at the rail of a railgun by using the CMR-B-scalar sensor. It starts with experiments concerning the measurement of magnetic diffusion in a static setup followed by measurements at dynamic experiments. Together with FEM simulations the results are used to draw conclusions on the current distribution in the conducting rails. The findings presented in this chapter were partially published in (Schneider 2009c) and (Liebfried 2009).

5.1. Magnetic Field Measurements at Static Railgun Experiments

If a short and high current pulse is supplied to an electric conductor, the current will distribute inhomogeneous over its cross section. This effect is caused magnetic diffusion. In the case of the rails of a railgun, the skin and proximity effect leads to current concentrations at the inner rail surface. The goal of the experiments being described here, was to measure the inhomogeneous magnetic

Fig. 5.1. CMR-B-scalar sensors mounted at EMA3

Fig. 5.2. Cross section of EMA3 with indicated positions of the CMR-B-scalar sensors and simulated current density inside the rails (all dimensions in mm)

field distribution in the vicinity of a rail conductor by the use of the CMR-B-scalar sensor. In addition the conducted experiments showed that CMR technology can be applied in the harsh experimental environment being typical for railguns and therefore opening the possibility for follow-up measurements related to the VSE.

5.1.1. Experiments

The static experiments were performed with the 137 cm-long part of EMA3. Three different rail materials were used in order to vary the spatial magnetic field distribution without a significant change of the applied current pulse. Rails made of Cu-Cr, Dural and steel were used. The corresponding material properties are presented in Appendix A. According to equation (1.10) the skin depths at 1 kHz are 2.3 mm, 3.9 mm and 7.4 mm, respectively.

Five CMR-B-scalar sensors with corresponding supply circuits (see Fig. 3.4) were used and mounted in a plastic block close to the upper rail (see Fig. 5.1). Fig. 5.2 shows a cross section of the rails and the position P1–P5 of the sensors. Note, that the distance Δx between the rail and the sensors active area is varied during different experiments. The distances were 0.5 mm, 1.5 mm and 3.5 mm. The error of this sensors was $\pm 10\%$.

5.1.2. Simulation

Measurements are compared to results from simulation performed with the 3-D FEM code *MEGA* (Rodger and Leonard 1993). As input for the simulation the measured current pulse from the experiment was used. A simulated current density distribution in the rails at the time of the current maximum ($I = 140$ kA, $t = 0.2$ ms) in Cu-Cr rails is shown in Fig. 5.2. *MEGA* has a standard post-processing function to evaluate the magnitude of the magnetic flux density, which in the experiment is measured by the CMR-B-scalar sensors.

5.1.3. Results and Discussion

Typical measurements results are presented in Fig. 5.3. Fig. 5.3a shows the first millisecond of the measured magnetic field pulses obtained at a distance of 1.5 mm to a Cu-Cr rail. Fig. 5.3b gives corresponding results obtained at an experiment with steel rails. Error bars have been left out for the purpose of clarity. In both cases, the dashed curves show corresponding simulation results. A good agreement between simulation and measurement can be stated. The measurement of sensor P4 was neglected in Fig. 5.3b due to an error in calibration (see Fig. 5.3a).

A qualitative difference between the two materials is observed by comparing the amplitudes of measured curves. While the difference of the applied current pulses was smaller than 2 %, the occurring maximum magnetic field amplitudes are generally smaller for steel rails. Apart from this, the highest magnetic field in the case of Cu-Cr rails is measured by P2 whereas the signals of P2 and P3 have similar amplitudes in the case of steel rails. This can be explained by magnetic diffusion effects which will be treated in more detail below.

Figs. 5.4a–c show a summary of the performed measurements. They display the measured CMR-B-scalar signal (points) together with simulation results (lines) at the time instant near the current pulse maximum at 250 μ s. Three different colours indicate the magnetic field measurements with different distances between the sensors and the rails. The position of the sensors is shown in the insets again. The position of the upper rail is indicated by two dashed lines in the diagrams. The error bars display an error of ± 10 %.

All three figures show a magnetic field concentration near the inner edge of the rail ($y = 7.5$ mm). This agrees with theory and can be explained by the proximity effect which is responsible for a current concentration at the inner rail edge (see Fig. 5.2). It also explains that the field concentration can be measured only at small distances Δx because the magnetic flux density depends on current

(a) Cu-Cr rails

(b) Steel rails

Fig. 5.3. Transient magnetic fields measured at different positions in the vicinity of different rails and corresponding 3D FEM calculations

density and distance (see the Biot-Savart law (Knoepfel 2000)). Measurements at the distance Δx of 3.5 mm failed to detect effects caused by magnetic diffusion which was also seen by Schneider *et al.* (2007) in preliminary experiments. This shows the importance of small sensors which can be placed very close to the rail surface.

A comparison between experiments with Cu-Cr, Dural and steel rails shows that the B-field at experiments with steel has the lowest magnitudes. Furthermore, a magnetic field gradient between the inner to the outer rail edge can be obtained from Fig. 5.4 for all three materials. The highest gradient appears at

(a) Cu-Cr rails

(b) Dural rails

(c) Steel rails

Fig. 5.4. Spatial field distribution for different rails at $t = 0.25$ ms: Calculations (lines) and experimental data (symbols)

$\Delta x = 0.5$ mm and is 0.1 T/mm, 0.09 T/mm and 0.056 T/mm for Cu-Cr, Dural and steel rails, respectively. The differences in magnitude and of the gradient can be explained by the skin and the proximity effect again because these effects are more pronounced in materials with high conductivity. The corresponding skin depth is directly related to the conductivity of the conductor (see equation (1.10)).

Generally, a good agreement between simulation and measurements can be stated here.

5.2. Magnetic Field Measurement at Dynamic Railgun Experiments

Magnetic field measurements at coilgun and static railgun experiments showed promising results in order to measure the magnetic field distributions related to the VSE at dynamic railgun experiments. Those were realized by using the ISL railgun RAFIRA.

5.2.1. Experiments

The experiments presented here were performed in the multishot and the single shot mode of RAIFRA. Multishot experiments were performed with three projectiles like shown in Fig. 2.6a. An energy of 800 kJ in 5 capacitor banks was applied for the launch of each projectile plus an energy of 170 kJ for each of the two pre-accelerators. The single shot experiments were performed by using up to 10 capacitor banks to supply RAFIRA with a maximum energy of 1.6 MJ. A separating projectile as being shown in Fig. 2.6b was used in this case. In both operational modes, a Doppler radar was used to obtain the velocity profile of the projectile inside the bore. Additionally, light barriers or a high speed (HS) camera was used to detect the passage of the projectile at the CMR-B-scalar sensor position.

CMR-B-scalar sensors were mounted in the plastic sensor mounting block adapted from EMA3. Later on, the sensors were positioned in a GRP block to protect them from electrical, mechanical and thermal damage. The thickness of the protective GRP layer between the sensors and the rails was 0.5 mm, resulting in a total distance of about 1 mm between the sensor's active volume and the rails. The spacing of adjacent sensors was 5 mm in the horizontal plane and 3.12 mm in the vertical (see Fig. 5.6). A light barrier diode can be installed in an additional hole which is located at the centre between the rails and below the CMR-B-scalar

Fig. 5.5. CMR-B-scalar sensors attached to RAFIRA by sensor mounting block

Fig. 5.6. Sketch of the sensor mounting block: View from behind (left) and from the left side (right)

sensor positions (marked as LB in Fig. 5.6).

5.2.2. Results and Discussion

First results with a sensor system as shown in Fig. 3.4 were obtained in a multishot experiment. The measurement of the first shot is shown in Fig. 5.7. Here, a plastic block as adapted from EMA3 experiments was used. The sensor positions are depicted in Fig. 5.7b. The velocity of the projectile increased from around 1020 m/s to 1050 m/s during the time period shown in Fig. 5.7.

The measured curves show a sharp rise after the passage of the projectile. Then the sensors mounted close to the inner rail edge show a similar behaviour as the total current which is also drawn in Fig. 5.7. However, sensor RP2 shows a quite different behaviour. Its amplitude increases with decaying current. This can be understood as magnetic diffusion towards the inner parts of the rails. All curves decrease suddenly at around 4.5 ms due to the projectile exiting the railgun.

However, some aspects of the CMR-B-scalar sensor signals differ remarkably from the current profile and cannot be explained by known EM processes at the railgun. Among them are the small oscillations of RP2 and RP3, the negative magnetic flux density of RP1 and RP2 around 4 ms and the different behaviour of RP4 around 4.5 ms. It is believed that these effects are attributed to EM noise induced into the measurement chain and mechanical vibrations. Note that occurring current, magnetic field and related forces are minimum 5 times higher than in the static experiments before. Furthermore, the magnetic field gradient dB/dt is very high during the passage of the projectile.

(a) Measurement signals

(b) CMR-B-scalar sensor positions of (a)

Fig. 5.7. First magnetic field measurement (a) with CMR-B-scalar sensors at RAFIRA

In order to exclude the influence of possible sources of noise on the signal, several changes in the experimental setup were performed. The loops of the twisted pair cable were decreased (see chapter 3) and the sensor cable was lengthened in order to increase the distance between the supply circuit and the railgun. Additionally, the sensors were mounted in the already mentioned GRP blocks. Fig. 5.8 shows a measurement performed with this system at a high speed shot of RAFIRA. The muzzle velocity obtained was 2280 m/s with an applied energy of 1.6 MJ. The velocity profile measured by the Doppler radar, the muzzle voltage and the current profile are displayed in the upper diagram of Fig. 5.8. Note that

Fig. 5.8. Measurement curves of a RAFIRA single shot (see text for further explanation)

the current is divided by 2. The lower diagram displays the measurement of the four CMR-B-scalar sensors placed in holes RP1 and RP3 of the GRP block (see Fig. 5.6). The position of the sensors is shown in the inset of Fig. 5.8. The distance between active area of the sensors and the rail surface was about 1 mm. Two dashed lines are drawn at $t = 1.86$ ms and $t = 2.389$ ms. These times correspond to the signal interruption from two light barriers which were installed together with the CMR-B-scalar sensors at $z = 1520$ mm and $z = 2665$ mm, respectively. The projectile velocity was 1900 m/s and 2220 m/s when it passed these positions.

The low muzzle voltage for $t < 2$ ms indicates a good solid-to-solid contact at the rail-armature interface until 1.7 ms. The following increase of voltage indicates contact transition meaning that electric arcs are formed at the rail-armature interface, which was confirmed by corresponding traces on the rails (not shown here). The sharp rise of the muzzle voltage at $t = 2.58$ ms corresponds to the exit of the projectile and the creation of a muzzle arc.

While the measured CMR signal quality improved in this experiment compared to the one shown in Fig. 5.7, it still shows interferences. Short high peaks occur for example when the spark gaps of the capacitor banks are triggered. This

is evident by their coincidence with the buckling in the pulse shape of the total current. Distinct interferences can also be identified at the end of the magnetic field pulse when the projectile already left the bore. However, additional interferences on the signal can not be excluded, especially at high magnetic field gradient during the passage of the projectile at the sensors position at $t = 1.86$ ms and 2.39 ms, respectively. In the following the results are discussed

All measured curves start with a steep rise, corresponding to the passage of the projectile indicated by the interrupted signals from the light barriers. The green and blue curves reach a higher maximum amplitude than the red and the black curve. This can be explained by the high current concentration at the inner rail edge due to the VSE. The blue and green sensors are located very close to the current leading path, whereas the red and the black sensors are located at a larger distance to it. With the current diffusing towards the interior of the rails, the detected field becomes spatially more homogeneously distributed. This results in converging magnetic field profiles at later times. This is confirmed by comparing the red and green curve to the blue and black one at $t = 2.39$ ms.

The measured magnetic field behaviour after the projectile left the bore ($t = 2.58$ ms) is rather related to current conduction processes which short-circuits the rails than to magnetic diffusion processes. Therefore it is not discussed in more detail.

In order to confirm the conclusions drawn from these results, additional measurements were performed with the sensor system shown in Fig. 3.5 on page 42. Fig. 5.9a shows the measurement curves of magnetic field, total current and muzzle voltage of a shot with an applied energy of 850 kJ. The voltage scale is divided by two. The CMR-B-scalar sensors were mounted at $z = 1520$ mm at the locations RP1, RP3 and RP5 (as shown in the inset). A time period corresponding to the rising part of the magnetic field measurement is shown in Fig. 5.9b. The results of this shot are in agreement with the results of Fig. 5.8. Here, the signal quality is excellent.

Additional information was obtained by the use of a HS camera. The time of the projectile passage was detected with an accuracy of $\pm 2 \mu\text{s}$. Fig. 5.10 shows two snapshots of the first projectile when it passes the CMR-B-scalar measurement position (left blue line). The snapshots were taken at $t = 3.113$ ms and $t = 3.228$ ms, respectively. The length of the projectile was 86.5 mm and therefore the projectile velocity was 750 m/s.

The instantaneous projectile position regarding to the sensor location in z direction is drawn into the diagram of Fig. 5.9b. It can be seen that the measured magnetic field maximum (dashed line) is reached after the brush armatures have passed the measurement location. This is in agreement with findings of earlier

(a) CMR-B-scalar sensor signals, total current and muzzle voltage

(b) Time segment of (a): The projectile drawing corresponds to its passage of the measurement position

Fig. 5.9. Measurement signals at a RAFIRA shot with projectile velocity of 750 m/s (see text)

works (see chapter 1): a current accumulation in the rear armatures. It also indicates a current path which tapers towards the brushes. Additionally, it should be noted that the real brushes are probably longer and bend further to the rear as being drawn in Fig. 5.9b.

A similar experiment with higher projectile velocity is shown in Fig. 5.11a. The CMR-B-scalar sensor array was installed near the centre of the railgun (see the inset). Additionally, a part of the applied current is displayed in Fig. 5.11a.

Fig. 5.10. Snapshots taken by the HS camera showing the passage of the projectile at the measurement position (left blue line) – only a part of the projectile can be seen (compare to Fig. 2.6a)

Fig. 5.11. Measurement signals at a RAFIRA shot with projectile velocity of 1500 m/s (see text)

Fig. 5.12. Time-harmonic FEM simulated magnetic flux density along the y-axis as shown in the inset for different frequencies. The harmonic skin depth is calculated according to (1.10). The red points and the stars are measured values from Figs. 5.9b & 5.11b at $t = 3.22 \text{ ms}$ and $t = 2.18 \text{ ms}$

In this experiment, the projectile passed the sensor position with a velocity of 1500 m/s and left the railgun with 1690 m/s. The applied energy was 1.13 MJ.

The sensors located next to the inner edge of the upper rail measure the highest amplitudes whereas those further off the rail edge show an in amplitude reduced and in time delayed behaviour. This is displayed in a close-up view in Fig. 5.11b.

For an approximation of the skin depth, the magnetic flux density at the time of its maximum in sensor location RP1 is compared to numerical simulations. Fig. 5.12 shows the results of simulations with the FEM code *COMSOL Multiphysics*. Here, the normalized magnetic flux density was computed for different frequencies along a vertical line between $y = 0 - 32.5 \text{ mm}$ in a distance of 1 mm to the surface of the upper rail (see the inset). The CMR-B-scalar sensor positions in y-direction are indicated by dashed lines. The bold line indicates the rail edge.

It can be seen that the skin and proximity effect result in high magnetic flux densities in the vicinity of the rail corners and in particular at the inner one ($y = 12.5 \text{ mm}$). Here, the curves calculated with higher frequencies ($> 1 \text{ kHz}$) differ most clearly from each other.

The red points in Fig. 5.12 correspond to magnetic field measurement at

$t = 3.22$ ms of Fig. 5.9b. The stars are related to magnetic flux densities shown in Fig. 5.11b at $t = 2.18$ ms. Considering the measurement point at RP1, the measured points correspond to a harmonic oscillation of about 50 kHz and 5 kHz, respectively. These frequencies correspond to a skin depth of 0.5 mm and 1.7 mm.

The disagreement between measurement and simulation at RP5 can be explained by a difference between the current profiles in the static and the dynamic case. The harmonic simulation performed here is not able to match the current distribution to be expected from the convective term in equation (1.11) in every detail. Simulations in the future have to take this into account.

5.3. Conclusions of Chapter 5

CMR-B-scalar sensors were successfully used to measure the magnetic field distribution in the vicinity of the rails at static and dynamic railgun experiments.

The measurements at static conditions agree well with corresponding FEM simulations. The results showed that the measured magnetic field magnitudes and gradients is influenced by the magnetic diffusion. The highest magnetic field gradients for Cu-Cr, Dural and steel rails were 0.1 T/mm, 0.09 T/mm and 0.056 T/mm, respectively. Additionally, the results of the static experiments demonstrated the importance of small sensors which can be positioned at small distances to the rail surface in order to measure magnetic diffusion effects. The application of CMR-B-scalar sensors for the investigation of the magnetic field distribution in the vicinity of the rails at dynamic railgun experiments, clearly indicate an increased current concentration at the rear part of the armature-rail contact interface due to the fast motion of the armature. A velocity-dependent skin depth of 0.5 mm and of 1.5 mm was estimated for projectile velocities of 1500 m/s and 750 m/s, respectively.

Current Distribution and Contact Mechanisms in Multiple Brush Armatures

The brushes of multiple brush armatures wear asymmetrically if they are separated in shot direction (Schneider *et al.* 2003a). The rear brushes wear out first and become disconnected from the rails (see Fig. 2.7). Then the current commutates to the next brushes in front of them and the process repeats until transition occurs. Since ohmic heating plays a key role, the wear process depends strongly on the current distribution. Furthermore, the J-cross-B force is an important part of the normal force which determines the contact quality between armatures and rails.

In this chapter, the mechanisms determining the current distribution of multiple brush armatures are investigated using a static setup. Therefore, the current in the brushes is measured by especially prepared mini Rogowski coils and the magnetic field is measured in the vicinity of the brushes by the CMR-B-scalar sensors. While such an approach differs considerably from launch conditions with regard to sliding contacts, it allows to vary the conditions at the brush-rail interfaces.

The results presented in this chapter are published in (Liebfried 2011).

Fig. 6.1. GRP projectile with front brush (1), rear brush (2), small Rogowski coil (3), drill holes for CMR-B-Scalar sensors (4) and brush reservoirs (5)

6.1. Experiments

Static experiments were performed with the short part of EMA3 (see Fig. 2.3). Several projectiles made from GRP and Cu-Cd brush armatures were prepared (see Fig. 6.1). Two brushes of 7 mm diameter were placed one behind the other in shot direction. The distance between the centres of the brushes was 13 mm. The length of the brushes was different for each prepared projectile. Table 6.1 lists the projectiles with the corresponding brush length parameters. The length of the brushes is defined by the overlength Δz . This overlength corresponds to the length of the front filaments minus the distance between the rails. Note that the brushes are cut in a way that results in longer rear fibres. A negative overlength means that the brush length is shorter than the distance of the rails, resulting in an air gap. If the brushes are cut otherwise, it is noted by an angle (i.e. 0° for a straight cut resulting in equal filament length).

Table 6.1. Projectile setups

	1st brush	2nd brush
No.	Δz	Δz
1	+ 3.3 mm	+ 3.3 mm
2	+ 2 mm	+ 2 mm
3	+ 1 mm	+ 1 mm
4	+ 4.8 mm	+ 3.3 mm
5	+ 4.8 mm	+ 2 mm
6	+ 4.8 mm	+ 1 mm
7	+ 4.8 mm	0 mm
8	+ 4.8 mm	- 0.4 mm (0°)

Before each experiment, the projectile was placed in the railgun according to a fixed procedure, thus ensuring unvaried conditions. First, the surfaces of the rails were cleaned with wet sandpaper. If a surface damage from previous experiments could not be repaired without significant abrasion, the rails were replaced. Then, the projectile was inserted into the opened railgun (without upper rail and the GRP bar). Then, the railgun was closed and the projectile was moved forward alternating with tightening the bolts until the test position in front of the stopper was reached. The procedure guaranteed that the brushes with overlength were pushed back into the reservoir (see Fig. 6.1). The bolts were finally fastened with an 80-N·m torque.

As power supply, the yellow PFU was used (see Table 2.2). The energy and pulse form was varied by variation of the charging voltage and number of applied capacitors (one, two or three). During the experiments, the total current and rail voltages (breech and muzzle) were measured (see section 2.5). Additionally, each projectile was equipped with a very small Rogowski coil in order to record the current distribution between the brushes (see Fig. 6.1). This setup is similar to the experiments described in (Schmitt *et al.* 1997). The coils were hand-twisted around an inner return conductor and afterwards calibrated inside the notch of the sabot with the calibration system described in section 2.5.2. After insertion of the brushes, the coils were embedded into the sabot and permanently fixed using two-component epoxy. The integration of the signal from the coils was performed numerically after the subtraction of the mean value by using the "Origin 7" data processing software. The recorded signals of the coils were in the mV-range at a sensitivity of about 700 MA/Vs. Therefore, the recorded signals were sensitive to noise.

The magnetic field distribution was recorded with the CMR measurement system as shown in Fig. 3.4. Typically six CMR sensors were placed in small holes very close to the brushes (see Fig. 6.1). The holes are 15.5 mm deep while the sabots have a width of around 30 mm. Therefore, the magnetic field was measured along the middle axis (in shot direction) of the sabots.

6.2. Simulation

The experiments were simulated using the *PSpice* code. The part simulating the brush armatures is emulated by a circuit shown in Fig. 6.2. The brush resistances R_{b1} and R_{b2} were estimated by taking into account a fill factor of 70 % and a contact resistance of $15 \mu\Omega$ for both contacts (Schneider and Schneider 2004a).

Fig. 6.2. Part of the *PSpice* circuit simulating the rails and brushes

6.3. Results and Discussion

The results of three experimental series with different parameter variations are presented in this chapter. The first series deals with the variation of the applied electrical energy, the second treats the variation of the rear brush length (projectiles 4–8) and the third considers a variation of both brush lengths (projectiles 1–3).

A typical current characteristic of an experiment with projectile no. 1 (see Table 6.1) is presented in Fig. 6.3. Note that only the current in the front brush (1) is measured. The current in the rear brush (2) is calculated as the difference between total current and the current through the front brush. Projectile no. 1 has an overlength of +3.3 mm. The total energy applied was 150 kJ. The results are compared to a *PSpice* simulation and rather good agreement is observed (see Fig. 6.3). The small deviations after the current maximum are attributed to the neglect of the skin-effect in the model. The idea behind using circuit-based simulation is to detect not simulated phenomena. If experimental variations lead to phenomena not included in a circuit model, e.g. when plasma occurs, a deviation between simulation and experiment will exist. Here, the good agreement between experiment and simulation indicates that the contact qualities at the rail-brush interface during the experiment are not influenced by not simulated phenomena. The mechanical pressure resulting from the overlength of brushes ensures stable conditions. In the following sections, results of the three series of experiments mentioned above are presented and discussed.

Fig. 6.3. Comparison of current profiles for a 150 kJ experiment using projectile no. 1: experimental results (dashed line) and results from the *PSpice* simulation (full line)

6.4. Variation of Energy for a Fixed Brush Configuration

The goal of this series of experiments was to study the effect of the amount of applied energy on a fixed projectile configuration. Projectile no. 6 was selected for this study because its configuration resembles that of the projectiles used in launch experiments where the rear brush wears out at first. The electrical energy was varied stepwise from 50 kJ to 150 kJ by adjusting the charging voltage of the capacitors shown in Fig. 6.4. The experimental results of that series are shown together with a *PSpice* simulation corresponding to an applied energy of 150 kJ. The currents of the front brush are scaled to the total current and drawn versus time. All measured profiles show a similar behaviour and the deviations are smaller than the experimental error. Moreover, the experimental curves agree good with the results of the *PSpice* simulation. The system behaves according to circuit elements included in this *PSpice* model. It can be concluded that interface phenomena not being taken into account in the *PSpice* model do not play a role in this configuration. The asymptotic behaviour of the current distribution corresponds to a resistive divider of two equal resistances.

6.5. Variation of Rear Brush Length

Asymmetric wear of brushes can be observed during launch of projectiles equipped with multiple brush armatures as reported by Schneider *et al.* (2003a).

Fig. 6.4. Scaled current profiles of the front brush (see text)

Rear brushes are worn out first and can be even disconnected from the rails before the projectile exits the muzzle. The idea of the experiments presented in this section is to simulate such an asymmetric wear case.

A series of experiments was performed during which the applied energy (and total current pulse) was kept constant, whereas the length of the rear brush was varied between +3.3 mm overlength and -0.4 mm (air gap). The results are shown in Fig. 6.5. It should be mentioned here that for projectile no. 7, brush no. 2 exhibited overlong fibres in the rear part of the brush due to the cut off angle of the brush surface (see Fig. 6.1). The results for the projectiles with brush lengths between +3.3 mm and 0 mm agree very well with those presented in Fig. 6.3 and in particular with the corresponding *PSpice* simulation. Therefore, it is concluded that stable contact conditions have been realized in all these cases. Moreover, the clearly different mechanical pressure at the contact interface does not influence the current distribution for the current pulses investigated here. As before, the asymptotic behaviour is characterized by a resistive divider in the *PSpice* simulation.

However, the profile of projectile no. 8 differs from those of the others. Note that values above 100 % are due to the error of the small Rogowski coil. Here, the front brush takes over the total current. This behavior was expected since the rear brush is too short to establish a solid contact. Nevertheless, after the experiment molten aluminum was found on the rear part of brush no. 2. Therefore, this experiment is considered more thoroughly in the following paragraph

In Fig. 6.6 the currents of the two brushes are drawn together with the total current. The inset shows one side of the projectile after the experiment. It can be seen that a small current (few kA) flows through the rear brush at the beginning (during the rise time) of the current pulse. This effect was observed in similar

Fig. 6.5. Scaled current in brush no. 1 for varied length of brush no. 2

configurations not reported here. Therefore, a problem in the measurement chain can be excluded. An explanation of this phenomenon has to consider following aspects. While the brush length was prepared to be not sufficient to make solid contact between the rails, single fibres with sufficient length may exist. Furthermore, fibres could come into contact with the rails due to abraded material which is created by the projectile insertion. The mechanical vibration which accompanies the start of the current discharge could also help to form a conducting bridge. The small contact spots soon vanish due to high current concentration and phase transition of the material. The rail surface showed abraded particles and grooves corresponding to the insertion process of the projectile. Abraded aluminium was also seen on the front brush (see the inset of Fig. 6.6). It can be concluded that under the circumstances described here a brush with insufficient length can take a notable part of the current. Note that during a launch abraded material from brushes or rails can lead to conditions similar to those encountered here.

6.6. Variation of Both Brush Lengths

The series of experiments presented in this section was – as in the previous section – motivated by the question how wear influences the current distribution between the brushes. A set of experiments was performed, where the length of both brushes was equally shortened from +3.3 mm to +1 mm. Fig. 6.7(a) shows the corresponding graphs. The current distribution of the first two projectiles (no. 1 & 2) agree with that of the *PSpice* simulation in Fig. 6.3. Therefore, stable solid-solid contacts are to be assumed. However, projectile no. 3 with

Fig. 6.6. Current profiles for an experiment with projectile no. 8. The inset shows the brushes of the projectile after the experiments

a brush overlength of +1 mm shows a different behaviour. In order to clarify this phenomenon, experiments with this projectile and with varying applied energies were performed. Corresponding results with energies ranging from 50 kJ to 150 kJ are presented in Fig. 6.7 (b). A minimum around $t = 300 \mu\text{s}$ can be found for all 3 cases, whereas the corresponding peak increases with increasing energy. Taking into account that the 150 kJ-curve has a measurement error after $t = 200 \mu\text{s}$, it can be assumed that the curve would agree with the other curves in the diagram for $t \geq 500 \mu\text{s}$. Therefore, the general behaviour of all curves can be described as follows: the current in brush no. 1 is about 30 % of the total current at the start, around $200 \mu\text{s}$ later a minimum is observed and afterwards the curves stabilize at around 50 % of total current. In order to explain the minimum of the current curves it is helpful to consider additional experimental information. Firstly, Fig. 6.8 shows a picture of the rail and brush conditions after the experiments with projectile no. 7. Molten aluminium was found on brush 1 (right brush), especially at the rear part of it. This is an indication of contact problems at that brush during the experiment. One of the reasons for a contact problem could be a lack of normal force at the interface. This normal force consists of a mechanical and an electromagnetic component. The mechanical contribution is determined by overlength and geometry of the brushes. Since brushes no. 1 and no. 2 do not differ in that respect, the mechanical component can not explain the observed differences in contact behaviour. Insight with respect to the electromagnetic part of the normal force is offered by considering the magnetic field measurements shown in Fig. 6.9 and the field configuration qualitatively depicted in Fig. 6.10. Note that the CMR sensors measure the absolute value of the mag-

Fig. 6.7. Scaled front brush current for varied brush length of both brushes (a) and varied energies with projectile no. 3 (b)

Fig. 6.8. Contact areas of projectile no. 3 and corresponding rail surface (1 and 2 indicate the front and rear brush)

netic induction. In the beginning, the current in the rear brush is greater than the one in the front brush. Also, the magnetic field at the front brush is much smaller than at the rear brush. Therefore, the electromagnetic normal force is relatively (with respect to the passing current) smaller at the interface of the front brush. A local $\vec{j} \times \vec{B}$ in the inverse direction at the front brush can not be excluded. Finally, the following scenario is conceivable.

At the very beginning, the current is concentrated in the very rear part of both brushes. Later on, it starts diffusing to the surfaces. At the rear brush, the normal forces are sufficient to form a sufficiently large contact zone by deformation of the fibres (or the rail surface). However, the formation of the contact zone at the surfaces of the front brush is accompanied by a phase transition. It needs some molten material until the necessary deformation of the surface can be reached.

Fig. 6.9. Magnetic field measurement with the CMR-B-Scalar sensors at the 150 kJ experiment with projectile no. 3 (the measurement positions are indicated in the inset; sensor 4 had a loose contact)

Fig. 6.10. Principle of the Lorentz force acting on the brushes

The phase transition is accompanied by a temporal re-distribution of the current. This is monitored by the Rogowski coils (see Fig. 6.7) and very nicely by the CMR-B-Scalar sensors (see Fig. 6.9). The CMR-B-Scalar sensors 4 & 5 show an increased magnetic field between both brushes. This agrees with the already mentioned current minimum, which states a current concentration of more than 80 % in the rear brush. Occurring steps/peaks in both measurements can be due to switching of current path inside the brushes. All curves turn back to "normal" after the creation of a good contact ($t > 500 \mu\text{s}$) in the front brush. The current distributes evenly between both brushes and therefore the magnetic field between them becomes very small.

It can be concluded that front brushes with low mechanical contact pressure exhibit contact problems in the beginning of the current pulse ($t < 500 \mu\text{s}$) due

to the missing Lorentz force. Here, the problems were only of short duration. A phase transition of rail material in the contact zone enabled a stable interface with a sufficient area. In the case of sliding contacts, the conditions at the interface are more complicated. Problems can occur during commutation, when the electromagnetic component of the normal force dominates at the interface. This finding can be of importance for dynamic railgun experiments where transition occurs even though the front brushes exhibits an overlength (Schneider *et al.* 2003a).

6.7. Conclusions of Chapter 6

The results obtained with the static experiment setup in order to examine current distribution in the case of multiple brush armatures revealed some interesting findings about their contact behaviour. Although only a maximum energy of 150 kJ per pulse was at disposal, the observed current distributions revealed a qualitatively typical behaviour for multiple brush armatures during launch conditions.

In the case of two brushes being separated in shot direction, the front brush experienced contact problems due to the missing Lorentz force. This was true even for brushes with overlength compared to the distance of the rails. The formation of a good contact took place for 500 μs and includes a current re-distribution phase accompanied by material melting. It ends with the formation of a stable contact zone.

General Conclusions

1. A magnetic field sensor based on polycrystalline $\text{La}_{0.83}\text{Sr}_{0.17}\text{MnO}_3$ thin films (CMR-B-scalar sensor) was developed for studies of electromagnetic processes in EM launchers. It is able to measure the absolute value of magnetic flux density with an accuracy of $\pm 10\%$ in the range from 0.5 to 1 T and $\pm 5\%$ at higher magnetic fields up to 20 T. An array of the sensors was used for the development of a unique and advanced measurement system consisting of four channels which is able to measure high pulsed magnetic fields in the frequency range from 0 to 10 kHz. Its features are galvanic separation, shielding against electromagnetic interference and the possibility of stand-alone operation.
2. The testing of an array made from four CMR-B-scalar magnetic field sensors in a typical electromagnetic launching system – a small coilgun – with an inserted hollow copper cylinder, demonstrated a good agreement of the measurement results with semi-analytical simulations. It was concluded that the CMR-B-scalar sensor can be used for highly local ($0.4 \times 50 \times 400 \mu\text{m}^3$) measurements of a dynamic magnetic field with varying orientation and a large gradient.
3. The measurement of the magnetic field in the vicinity of the rails during static railgun experiments with EMA3 (calibre $15 \times 30 \text{ mm}^2$) by using the CMR-B-scalar sensors showed that the measurements agree well with

corresponding FEM simulation using the *MEGA* code. It was found that the measured magnitudes depend on the spatial current distribution inside the rails which is influenced by diffusion of the magnetic field into the rails. As a result the magnetic field gradient from the inner to the outer rail edge at the time of the current maximum is 0.1 T/mm, 0.09 T/mm and 0.056 T/mm for copper, Dural and steel rails, respectively.

4. The investigation of the magnetic field distribution in the vicinity of the rails at dynamic experiments with the railgun RAFIRA (calibre $25 \times 25 \text{ mm}^2$) clearly indicated a velocity induced current concentration at the rear part of the contact interface. An analysis of magnetic field distribution using the FEM-code *COMSOL Multiphysics* in a harmonic approximation and the comparison between simulation and experiments showed that the velocity-induced skin depths are 0.5 mm and 1.5 mm for projectile velocities of 1500 m/s and 750 m/s, respectively.
5. The investigation of the electrical current and the magnetic field distribution in the vicinity of multiple brush armatures at static experiments with maximum energies of 150 kJ showed a qualitatively typical behaviour for multiple brush armatures during launch conditions. It was found that brushes with a length smaller than the rail distance can be brought back into contact by abraded material. Contact problems were observed for front brushes due to missing Lorentz force even their length was still greater than the distance between the rails. The formation of a good contact took place within $500 \mu\text{s}$ and included a current re-distribution phase accompanied by material melting.

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List of Scientific Publications on the Topic of Dissertation

In the Reviewed Scientific Journals (ISI Web of Science)

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In Other Edition

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Appendices

Appendix A. Material Parameters

Material	Copper-Chrome	Copper-Cadmium	Dural	Steel
Abb.	Cu-Cr	Cu-Cd	Du	STL
δ	8900 kg/m ³	8930 kg/m ³	2800 kg/m ³	7850 kg/m ³
μ_r	1	1	1	1 (assumed)
c	–	340 J/(kg · K)	900 J/(kg · K)	475 J/(kg · K)
α	–	$3.5 \cdot 10^{-3} \text{ K}^{-1}$	$2.3 \cdot 10^{-3} \text{ K}^{-1}$	$12.3 \cdot 10^{-3} \text{ K}^{-1}$
σ	$50 \cdot 10^6 \text{ S/m}$	$36 \cdot 10^6 \text{ S/m}$	$20 \cdot 10^6 \text{ S/m}$	$4 \cdot 10^6 \text{ S/m}$
λ	–	320 W/(m · K)	140 W/(m · K)	44.5 W/(m · K)

Abb. - Abbreviation; δ - Density; μ_r - Relative permeability; c - Specific heat capacity; α - Temperature coefficient; σ - Electrical conductivity; λ - Thermal conductivity

Appendix B. Specifications of the CMR-B-Scalar Sensor System

Sensor dimensions ($w \times l \times h$)	0.5 mm $\times$ 1 mm $\times$ 0.5 mm
Active area ($w \times l \times h$)	400 μ m $\times$ 50 μ m $\times$ 0.4 μ m
Cable length	1 $\pm$ 0.1 m
Cable diameter	2 $\pm$ 0.5 mm
Magnetic field range and accuracy	up to 0.5 T: > 15 %; 1 to 2 T: $\pm$ 10 %; 2 to 20 T: $\pm$ 5 %
Temperature range	10 – 40 °C
Optimal operation temperature	20 °C
Bandwidth (sensor)	0 – 10 kHz
Max. sampling rate (A/D-converter)	0.73 MS/s
Sampling resolution (A/D-converter)	40 μ V
Battery operation time	$\sim$ 24 h
Data transmission	via 25 m–long optic fibre and customary USB cable
PC requirements	min. Windows XP; 20 MB hard disc memory; USB 2.0; min. 256 MB RAM; 2 GHz processor

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THE INVESTIGATION
OF ELECTROMAGNETIC PROCESSES
IN ELECTROMAGNETIC LAUNCHERS
USING COLOSSAL MAGNETORESISTANCE SENSORS

Doctoral Dissertation

Physical Sciences, Physics (02P),

Condensed Matter: electronic structure; electrical, magnetic and optical properties; superconductors; magnetic resonance; relaxation; spectroscopy (P260)

ELEKTROMAGNETINIŲ PROCESŲ
TYRIMAS ELEKTROMAGNETINĖSE
SVAIDYKLĖSE NAUDOJANT MILŽINIŠKOS
MAGNETOVARŽOS JUTIKLIUS

Daktaro disertacija

Fiziniai mokslai, Fizika (02P),

Kondensuotos medžiagos: elektroninė struktūra, elektrinės, magnetinės ir optinės savybės, superlaidininkai, magnetinis rezonansas, relaksacija, spektroskopija (P260)

2011 04 26. 10,25 sp. l. Tiražas 20 egz.

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