Magnetic field installations and QED

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Magnetic field installations and QED

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Why magnetic fields

Magnetic field generation

state of the art

future developments

High magnetic field facilities

current

future

Why high magnetic fields I ?

- 1) Manipulating matter: deflection
levitation
'engineering' separation
alignment

- 2) Probing matter: the field modifies electronic et magnetic properties:

'materials science' Nuclear magnetic resonance (NMR, MRI)
cyclotron resonance
electron spin resonance (ESR)
Hall effect, dHvA effect, SdH effect,....

- 3) Thermo dynamics; Induce new states of matter:

**'basic solid
state physics'** LT superconductor normal state
Field induced superconductivity
Quantum critical points
Magnetization plateau states
.....

Why high magnetic fields II ?

4) Symmetry

$$\mathbf{B}_0 = \frac{1}{4\pi\epsilon_0} \frac{2\mathbf{I} \times \mathbf{r}}{r^2}$$

$$\mathbf{I} = qN \frac{\partial \mathbf{r}}{\partial t}$$

Parity reversal $P: \mathbf{r} \rightarrow -\mathbf{r}, t \rightarrow t, q \rightarrow q$ so $\mathbf{B} \rightarrow \mathbf{B}$

Charge conjugation $C: \mathbf{r} \rightarrow \mathbf{r}, t \rightarrow t, q \rightarrow -q$ so $\mathbf{B} \rightarrow -\mathbf{B}$

Time reversal $T: \mathbf{r} \rightarrow \mathbf{r}, t \rightarrow -t, q \rightarrow q$ so $\mathbf{B} \rightarrow -\mathbf{B}$

Magnetic field is a time-odd pseudo-vector

Symmetry properties of common physical quantities

		C	P	T
polarization	P	-	-	+
magnetization	M	-	+	-
wavevector	k	+	-	-
electrical current	I	-	-	-
magnetic field	B	-	+	-
electric field	E	-	-	+
linear momentum	p	+	-	-
angular momentum	L	+	+	-

Symmetry and magneto-optics

Perturbation approach:

$$\mathbf{P}^\omega(\mathbf{B}_0) = \chi(\omega, \mathbf{B}_0) \mathbf{E}^\omega \simeq \chi(\omega) \mathbf{E}^\omega + f_1(\mathbf{B}_0, \mathbf{E}^\omega) + f_2(\mathbf{B}_0, \mathbf{B}_0, \mathbf{E}^\omega) + \dots$$

Symmetry:

	C	P	T
P	-	-	+
B	-	+	-
E	-	-	+

Only symmetry allowed form from P and T invariance:

$$\begin{aligned} \mathbf{P}^\omega(\mathbf{B}_0) &\simeq \chi(\omega) \mathbf{E}^\omega + \chi_1 \frac{\partial \mathbf{E}^\omega}{\partial t} \times \mathbf{B}_0 + \chi_2 (\mathbf{B}_0 \cdot \mathbf{B}_0) \mathbf{E}^\omega + \chi_3 (\mathbf{B}_0 \cdot \mathbf{E}^\omega) \mathbf{B}_0 + \dots \\ &\simeq \chi(\omega) \mathbf{E}^\omega + i\omega \chi_1 \mathbf{B}_0 \times \mathbf{E}^\omega + O(B_0^2) \end{aligned}$$

Dielectric constant: $\varepsilon_{ij}(\omega, \mathbf{B}_0) = 1 + 4\pi\chi_{ij} \simeq \varepsilon_{ij}(\omega) + i\gamma(\omega) e_{ijk} B_{0k}$

$$\gamma(\omega) \text{ odd under C}$$

Maxwell:
$$\nabla \times \nabla \times \mathbf{E}^\omega = -\frac{\varepsilon}{c} \frac{\partial^2 \mathbf{E}^\omega}{\partial t^2}$$

Faraday geometry: $\mathbf{k} \uparrow \uparrow \mathbf{B}_0 \equiv \mathbf{z}$

Ansatz:
$$\mathbf{E}^\omega = E^\omega \exp(i\omega t - ikz) \mathbf{x}$$

Solution:
$$\begin{aligned} \mathbf{E}^\omega(z) &= E^\omega \exp(i\omega t) \{ \exp(-ik_+ z) \mathbf{e}_+ + \exp(-ik_- z) \mathbf{e}_- \} \\ &= E^\omega \exp(i\omega t - ikz) \{ \cos(\Delta k z) \mathbf{x} + \sin(\Delta k z) \mathbf{y} \} \end{aligned}$$

Faraday effect (1846)

V = Verdet constant

Verdet constant is the only linear coupling between light and magnetic field in matter.

Why high magnetic fields III?

5) Quantum mechanics

Hamiltonian: $\mathbf{p} \rightarrow \mathbf{p} + q\mathbf{A}$ and $\mathbf{B} = \nabla \times \mathbf{A}$

Energy/time scale: $\hbar\omega_c = \hbar eB / m = 100\mu eV \cdot B$ (Cyclotron energy)

$\hbar\omega_Z = g\mu_B B = 100\mu eV \cdot B$ (Zeeman energy)

Length scale: $\ell = \sqrt{e\hbar / B} = 25,6 nm / \sqrt{B}$ (Cyclotron radius)

Why high magnetic fields III?

6) Quantum electrodynamics

Critical magnetic field $\hbar\omega_c = \hbar e B_{cr} / m = mc^2 \rightarrow B_{cr} = 4,4 \cdot 10^9 \text{ T}$

Magnetic field induced QED effects in the laboratory will be weak and therefore a considerable experimental challenge!

E.g. vacuum polarization: $n(B) - 1 = \frac{\alpha}{6\pi} (B / B_{cr})^2 \approx 10^{-23} B^2$

Why high magnetic fields IV?

7) Beyond the standard model ???

Axion-photon conversion

15 Nobel prizes for magnetic field research

- 1902** Physics H.A. Lorentz & P. Zeeman: Magnetic effects on radiation
- 1922** Chemistry F. Aston: Mass spectrometer
- 1939** Physics E. Lawrence: Development of the cyclotron
- 1943** Physics O. Stern: Magnetic moment of the proton
- 1944** Physics I. Rabi: NMR of atoms and molecules
- 1952** Physics F. Bloch, E. Purcell: Condensed matter NMR
- 1955** Physics P. Kusch: Measurement of the electron magnetic moment
- 1970** Physics L. Neel: Anti-ferromagnetism, ferrimagnetism
- 1977** Physics Anderson, Mott, van Vleck: Magnetic and disordered systems
- 1985** Physics K. von Klitzing: Quantum Hall effect
- 1991** Chemistry R. Ernst: 2D and FT NMR
- 1998** Physics Laughlin, Stormer, Tsui: Fractional quantum Hall effect
- 2002** Chemistry K. Wuthrich: NMR of biological macromolecules
- 2003** Medicine P. Lauterbur, P. Mansfield: Magnetic resonance imaging
- 2007** Physics Fert & Grunberg, Giant magneto-resistance

1 T

30 T

Orders of magnitude of magnetic fields

Orders of magnitude of magnetic fields

enses

Orders of magnitude of magnetic fields

we

Orders of magnitude of magnetic fields

How to generate high magnetic fields for general use?

One solution: circulate a current I in a coil:

$$B \propto I$$

Problem 1: heating $P \propto RI^2 \propto B^2$

Solutions:

- superconductors ($R = 0$)
- cooling: DC fields
- short current pulse (< 1 s): pulsed field

Problem 2: Lorentz forces $\propto \mathbf{B} \times \mathbf{I} \propto B^2$

Solutions:

- strong conductor
- mechanical reinforcement

Magnetic fields for research

Evolution non-destructive high magnetic field generation methods

Static magnetic fields

Faraday 1846

Static magnetic fields

1

10

100

Tesla

Bellevue 1907

Static magnetic fields

1

10

100

Tesla

23,5 T

Static magnetic fields

1

10

100

Tesla

35 T

Static magnetic fields

DC field installation LNCMI Grenoble

24 MW

300 l/s

35 Tesla

State of the art resistive magnet technology

Bitter plates

Poly-helices

Pulsed magnetic fields

Pulsed magnetic fields

Dual coil 100
↑
T

Pulsed magnetic fields

Pulsed magnetic fields

Pulsed magnetic fields

Pulsed magnetic fields

Pulsed field installation LNCMI Toulouse

14 MJ, 24 kV, 1 GW; 80 Tesla

1 GW peak power

0,2 MW average power

Electrical power is not an issue!

HLD: the world's largest capacitor bank : 50 MJ, 5 GW

Semi-destructive fields; installation MegaGauss

2 MA, 60 kV

- Consider a simple disposable coil connected to a capacitor
- The **risetime of the field** is determined by the circuit impedance and capacitance
- The **disintegration of the coil** is determined by its mass and the applied force
- Parameters can be adjusted to make the field risetime faster than the disintegration

Optical experiments in Megagauss

Current limit: 200 T, potentially up to 300 T

Mobile pulsed field installation

The small average power and absence of heavy cooling installations make mobile pulsed high field installations possible:

High field X ray scattering at ESRF (180 kJ, 16 kV, 30 Tesla)

‘Light shining through wall’, LULI

‘X ray scattering’ ESRF

Laser induced plasma in a high magnetic field at LULI

$B=0$

$B = 20 \text{ T} \rightarrow$

Second generation mobile installation:

Elastic neutron scattering in pulsed magnetic fields

1 MJ mobile
generator

IN22 at ILL

40 T magnet

Next generation mobile pulsed field installation

6 MJ, 24 kV in 2 x 20 foot sea containers → 80 T

(under construction, available Feb. 2013)

Future developments in high magnetic field generation

High T_c superconductors

Materials research

Improved cooling techniques

New magnet designs

State of the art technical superconductors

State of the art high T_c superconductor tape

- Phenomenal J_c in the YBCO - $\sim 20 \times 10^6$ A/cm² at 25T

- YBCO is $\sim 1\%$ of cross-section
- 50% is high strength superalloy
- Well suited for high field solenoids

First high T_c superconductor magnet, under construction

Progress HT_c insert coils

NHMFL 32 T HT_c under construction

4 M€, 4 years development

Materials research for resistive magnet technology

Trade-off between mechanical resistance and electrical conductivity

Extensive and very specific materials R&D necessary to make progress

Sub-industrial quantities needed; too big for labs, too small for industry

Dedicated coil designs for scattering experiments

Split coil 30 T, 30 MW

30+ T, 25 MW

40 T, 40 MW

Hybrid magnets

8 meter

Put a resistive magnet inside a large bore superconducting magnet

↓
45 T

Caracteristiques bobine supra

- Diamètre int/ext : 1100/1826 mm
- Hauteur : 1400 mm
- Conducteur : câble NbTi brasé sur profilé Cu
- Nb de couches/galettes : 26/74
- Champ au centre : 8.5 T
- Energie stockée : 76 MJ
- Poids : ~ 20 tonnes
- Fonctionnement à 1.8 K dans bain pressurisé

Ultrarapid cooling of pulsed magnets: Cu-inox polyhelix

Premiers tests: 28 T

Cu-SS polyhelix 40+ T DC magnets

Cu-SS polyhelix hyperrapid cooling pulsed magnets

High magnetic field facilities

Existing facilities

Use of high field facilities

European Magnetic Field Laboratory

International context ; Europe

HLD Dresden

HFML Nijmegen

LNCMI Toulouse

LNCMI Grenoble

International contexte: outside Europe

NHMFL staff 230, core grant 45 M\$/y

Multi-site Facilities: Tallahassee FL, Gainesville FL, Los Alamos NM

Multi-disciplinary and Inter-disciplinary Scientific Research

1.4 GVA Motor-Generator

Los Alamos National Laboratory

100T Pulse
Magnet
15n

11.1T MRI Magnet
400mm warm bore

Florida State University

University of Florida

Advanced Magnetic
Resonance Imaging
and Spectroscopy Facility

45T Hybrid
DC Magnet

High B/T Facility
17T, 6wks at 1mK

900MHz
105mm bore
NMR Magnet

New high field facility in Heifei (China), 26 M€

International user community: LNCMI en 2011

Number of proposals in 2011, by nationality of PI

Traditionally, high magnetic fields are used in condensed matter science

Total 138

LNCMI 2011

Angle dependence of quantum oscillations in $\text{YBa}_2\text{Cu}_3\text{O}_{6.59}$ shows free-spin behaviour of quasiparticles

B. J. Ramshaw¹, Baptiste Vignolle², James Day¹, Ruixing Liang^{1,3}, W. N. Hardy^{1,3}, Cyril Proust^{2,3} and D. A. Bonn^{1,3}★

Stripe-induced Fermi pockets in $\text{YBa}_2\text{Cu}_3\text{O}_y$ Wu et al, Nature 477, 191 (2011)

- *Fermi surface reconstruction from Quantum Oscillation data (LNCMI-T)*
- *High field Cu NMR LNCMI-G:*

Field-induced charge density modulation with period $4a$, correlated with FS reconstruction

EuroMagNET2 FP7-I3: LNCMI +HLD + HFML

A coordinated approach to access, experimental development and scientific exploitation of all European large infrastructures for high magnetic fields

WP Number	Work package title	Type of activity	Lead participant Number	Lead participant short name	Start month	End month	EC contribution (M€)
WP 1	Consortium management	MGT	1	CNRS	1	48	0,4
WP 2	Networking Activities	CORD	3	FZD	1	48	0,9
WP 3	Transnational access static fields CNRS	SUPP	1	CNRS	1	48	2,15
WP 4	Transnational access pulsed fields CNRS	SUPP	1	CNRS	1	48	0,65
WP 5	Transnational access static fields RU	SUPP	2	RU	1	48	1,1
WP 6	Transnational access pulsed fields FZD	SUPP	3	FZD	1	48	0,3
WP 7	JRA High Field User Magnet Technology and Operation	RTD	1	CNRS	1	48	0,8
WP 8	JRA Nano-object measurements and local spectroscopy	RTD	2	RU	1	48	0,6
WP 9	JRA ES ³ -NMR	RTD	2	RU	1	48	0,6
	TOTAL						7,5

ESRFI Project ‘ European Magnetic Field Laboratory’ (EMFL)

Aim: offer to French and European scientist the same opportunities in high magnetic fields as in the USA

1) collaboration, specialisation and coordination between LNCMI, HFML and HLD.

2) Increase investments in Europe’s high field facilities

Intégration on the ESRFI Roadmap 2008

ESFRI

« The European Strategy Forum on Research Infrastructures was launched in April 2002. It brings together representatives of EU Member States and Associated States, appointed by Ministers in charge of Research, and one representative of the European Commission.

The role of ESFRI is to support a coherent approach to policy-making on research infrastructures in Europe, and to act as an incubator for international negotiations about concrete initiatives. «

- First ESFRI Roadmap in 2005, updated in 2008, updated 2010
- So far 240 projects submitted, 44 accepted on the Roadmap

The EMFL Preparatory Phase Proposal outline

Identify legal and governance structure

Funding of investments and operation, staffing

Extension of the EMFL with other partners

Identifying and attracting new user communities

Roadmap for the technical and scientific evolution of the EMFL

Prototyping of new magnets/equipment

.....

Ready-to-sign founding contract

(Starting date 1/1/2011, duration 3 years, 4 M€)

Magnetic fields are a small but well controlled and informative perturbation.

Generating high magnetic fields requires large investments and know how

The EMFL partners welcome requests/proposals for experiments in high magnetic fields.

Calls for proposals: every year May 15th, November 15th

www.emfl.eu

www.euromagnet2.eu