Permanent Magnets
Including Wigglers and Undulators
Part II

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Overview

Part II
Metallurgic aspects of permanent magnets
Magnetic domains
Observation techniques of magnetic domains
New materials
Aging / damage of permanent magnets
Simulation methods
PPM quadrupoles
Unit cell of tetragonal Nd$_2$Fe$_{17}$B
in reality the ratio c/a is smaller

The Fe layers couple antiferromagnetically to the Nd, B layers

Partial substitution of Nd with Dy
  $\rightarrow$ crystal anisotropy increases
  $\rightarrow$ coercivity increases
  Dy atoms couple antiparallel
  $\rightarrow$ saturation magnetization decreases simultaneously

Crystal Structure of RE-Permanent Magnets II

Unit cell of the hexagonal SmCo$_5$ (R=Sm Tm=Co)

Unit cell of rhombohedral Sm$_2$Co$_{17}$ (R=Sm Tm=Co)

Metallurgy: Theoretic Limits of Magnet properties

Theoretical limit of energy product:

\[
(BH)_{\text{max}} = \frac{B_r^2}{\mu}
\]

\[
B_r(20^\circ\text{C}) = B_{r-sat}(20^\circ\text{C}) \cdot \frac{\rho}{\rho_0} \cdot (1 - V_{\text{nonmagnetic}}) \cdot f_\varphi
\]

\[
f_\varphi = \cos(\varphi)
\]

\[
\varphi = \arctan\left(2 \frac{B_{r-perp}}{B_{r-par}}\right)
\]

Typical values for sintered NdFeB magnets

\[
\frac{\rho}{\rho_0} \geq 99\% \quad \text{due to liquid phase sintering}
\]

\[
f_\varphi \geq 98\% \quad \text{alignment coefficient for isostatic pressing}
\]

\(< 2.5 \text{ wt.\% of impurities like Nd-oxide}\)

\(< 2.5 \text{ wt.\% of RE constituents}\quad V_{\text{nonmagnetic}} < 0.05\)

theoretic limit: 63 MGOe (achieved: 59 MGOe)
Typical Structure of Sintered NdFeB Magnets

- Nd$_2$Fe$_{14}$B grains (monocrystalline)
- RE rich constituents containing Nd, Co, Cu, Al, Ga, Dy (area is exaggerated)
- Nd oxides

The interesting effects happen at the boundaries!

- Nd + H$_2$O $\rightarrow$ NdOH + H
- H + Nd $\rightarrow$ NdH

Hydrogen decrepitation destroys magnetic material
- fatal for magnets in operation
- ecologically interesting for decomposition and RE recovery
Coercivity

In the bulk magnetic domains are separated by Bloch walls: below a certain size: no Bloch walls can exist due to energetic considerations above that size several domains in one particle are possible critical size for Fe: 0.01 \( \mu \) m, for Ba ferrite: 1 \( \mu \) m above that size remanence and coercivity follow roughly a 1/size dependence RE-magnets have typical grain sizes that are a bit larger than single domain size

normally, the rotation of the magnetization vector occurs in the boundary plane In thin films: Neel walls, magnetization vector rotates perpendicular to boundary

Reason for coercivity:
- intentionally introduced imperfections (e.g. carbides in steel magnets) impede the movement of Bloch walls
- stable single domain grains which can be switched only completely
- introduction of anisotropy

Basically two types of anisotropy:
- shape of microscopic magnetic parts in non magnetic matrix (needles etc)
- crystal anisotropy
Two Classes of Magnets

A) Small particle magnets with shape anisotropy
   shaped magnetic material in non magnetic matrix
   e.g. FeCo in less magnetic FeNiAl (AlNiCo) or nonmagnetic lead matrix

Shape anisotropy of AlNiCo 5:
Spinodal decomposition
energy product largest along
direction of needles (factor of 10 as
compared to perpendicular direction)

B) Small particle magnets with crystalline anisotropy
   - Nucleation type, e.g. SmCo₅, Nd₂Fe₁₄B, ferrites
     easy motion of domain walls within one domain;
     motion impeded at grain walls

   - Pinning type, e.g. Sm(Co, Fe, Cu, Hf)₇, SmCo₅ + Cu precipitation,
     Sm₂Co₁₇ with SmCo₅ precipitation (size of domain wall thickness)
     Domain walls are pinned to boundaries of precipitations
Initial Magnetization

Nucleation type magnet
- directly after heating: many domain walls inside each grain
- Bloch walls are rather freely movable within grains
- high initial permeability; walls are pushed out of grain bulk at first magnetization
- fixing of walls at the grain boundaries
- usually no domain walls within grain bulk under fully magnetized conditions
- in reverse field most grains switch completely the magnetization

Pinning type magnet
- pinning centers inside grains impede wall movement
- high fields are required to move the walls
Partial replacement of Nd with Dy enhances the anisotropy field and thus the coercivity, however:

Dy is expensive & remanence is reduced

Use all means to enhance coercivity without Dy, e.g. optimizing the grain size

Systematic studies show:
Within the grain size range of 3.9 and 7.6 μm
the coercivity $H_{cj}$ increases with smaller grain size

$$H_{cj}(20^\circ C) \propto (grainsize)^{-0.44}$$

<table>
<thead>
<tr>
<th>Powder size $\mu$ m</th>
<th>Grain size $\mu$ m</th>
<th>$H_{cj}$ (20° C) kA/m</th>
<th>$H_{cj}$ (100° C) kA/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>3.8</td>
<td>1178</td>
<td>581</td>
</tr>
<tr>
<td>2.2</td>
<td>4.3</td>
<td>1162</td>
<td>573</td>
</tr>
<tr>
<td>2.6</td>
<td>4.9</td>
<td>1090</td>
<td>525</td>
</tr>
<tr>
<td>3.0</td>
<td>6.0</td>
<td>971</td>
<td>462</td>
</tr>
<tr>
<td>3.5</td>
<td>7.6</td>
<td>883</td>
<td>414</td>
</tr>
</tbody>
</table>

K. Uestuener, M. Katter, W Rodewald, 2006
with increasing alignment coefficient:
- remanence increases
- coercivity decreases

dependence of coercivity on applied external field direction:

rough approximation: \[ H_{cj} \propto \frac{1}{\cos(\theta)} \]

detailed study at 0°, 45° 90° shows:
- nearly no difference between 0° and 45°
- increase of Hcj by - 30% for axially pressed material
- 70% for isostatically pressed material

in specific cases this enhancement of coercivity can be used.

Linear superposition of PPM fields works within a few percent. For higher accuracy non unity of permeability has to be regarded.

\[ \mu_{par} \text{ depends on fabrication process} \]
\[ 1.05 \text{ axially pressed} \]
\[ 1.03 \text{ isostatically pressed} \]
\[ \text{no correlation with coercivity} \]

\[ \mu_{perp} \text{ decreases with increasing coercivity} \]
\[ 1.17 (H_{cj}=18\text{kOe}), 1.12 (H_{cj}=32\text{kOe}) \]

Metallurgy IV: Grain Growth During Sintering

Study of grain size growth with ASTM E112 (ASTM E112 is a standard for grain size measurement)
the grain radius increases over time approximately with

\[ R(t) = k \cdot t^{1/n} \]

\( n = 2-4 \) for pure metals
\( n = 16-20 \) for sintered NdFeB with \( B < 5.7 \) at.\%
\( n = 7.5 \) for sintered NdFeB magnets with \( B > 5.7 \) at.\%
\( n = 10 \) for sintered NdFeB magnets with RE-contituents > 4wt.\%
sintering time has to be adjusted appropriately
to achieve an optimum grain size of 3-5μm and to avoid giant grains

NdFeB has hexagonal structure
Distribution of numbers of corners changes during sintering
optimization of six corner grains

Grains in a sintered NdFeB magnet,
averaged grain size: 4.6μm;
polished and chemical etched surface as seen with a conventional light microscope

Courtesy of VAC

Johannes Bahrdt, HZB für Materialien und Energie, CERN Accelerator School „Magnets“, June 16th-25th, Bruges, Belgium, 2009
Bitter Patterns
Ferrofluids: fine magnetic grains (a few tens of nm) in a colloid suspension is spread on a polished surface of a magnetic sample magnetic grains are attracted at the domain walls
Resolution: 100nm

Magnetooptical effects:
- Kerr-effect (MOKE), reflection geometry
- Faraday-effect, transmission geometry
Resolution: 150nm, suitable for the detection of fast processes
All magnetooptical effects can be described with a generalized dielectric permittivity tensor which reduces for cubic crystals to:

\[
\tilde{\varepsilon} = \varepsilon \begin{pmatrix}
1 & -iQ_1m_3 & iQ_1m_2 \\
iQ_2m_3 & 1 & -iQ_2m_1 \\
-iQ_3m_2 & iQ_3m_1 & 1
\end{pmatrix}
+ \begin{pmatrix}
B_1m_1^2 & B_2m_1m_2 & B_2m_1m_3 \\
B_2m_1m_2 & B_2m_2^2 & B_2m_2m_3 \\
B_2m_1m_3 & B_2m_2m_3 & B_1m_3^2
\end{pmatrix}
\]

Similarly, a magnetic permeability tensor can be set up, however, the coefficients are 2 orders of magnitude smaller and usually neglected.
Inserting these tensors into Fresnel’s equation describes all effects.
Methods of Magnetic Domain Measurement II

Geometries of magnetooptical Kerr- and Faraday-effect

- linearly polarized light forces charges to vibrational motion
- moving charges experience Lorentz forces
- the additional vibrational motion introduces perpendicular electric field component in reflected / transmitted beam

http://upload.wikimedia.org/wikipedia/commons/b/b4/NdFeB-Domains.jpg

Johannes Bahrdt, HZB für Materialien und Energie, CERN Accelerator School „Magnets“, June 16th-25th, Bruges, Belgium, 2009
X-Ray Magnetic Circular Dichroism (XMCD)
Different absorption coefficients of right / left handed circularly polarized light

Photoelectron emission microscope (PEEM) at BESSY UE56 APPLE

Exchange coupling between magnetic films of Co and Ni separated by a nonmagnetic layer of Cu with variable thickness

X-Ray Holography
No lenses or zone plates are needed
resolution 50nm demonstrated so far

Principle:
absorption of coherent circularly polarized light within an aperture of 1.5μm
reference hole 100-350nm (conical)
coherent overlap of both beams

**Neutron decoherence imaging**

advantage: thick samples (cm range) can be studied

disadvantage: resolution so far 50-100 μm

Principle:
cohensch neutrons from source grating (de Broglie waves)
diffraction of neutrons at magnetic domain walls, distortion of wavefront
Talbot image of distorted wavefront using phase grating
detection of talbot image with sliding absorption grating and detector

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*F. Pfeiffer et al., Phys. Rev. Let. 96. 215505-1-4, 2006*
*C. Grünzweig et al., Phys. Rev. Let. 101, 025504, 2008*
Methods of Magnetic Domain Measurement VI

Transmission electron microscope
Lorentz force microscopy, resolution 10nm

For other domain geometries tilting of the sample may be necessary for a net deflection

Further methods
XMCD in absorption or transmission geometry
Low energy electron diffraction (LEED)
Magnetic force microscope (resolution 10nm)
Spin polarized scanning tunneling microscope (resolution 1nm)

Cryogenic Permanent Magnet Undulators

Proposed by T. Hara, T. Tanaka, H. Kitamura et al.


- 1.5 gain in magnetic field as compared to conventional in-vacuum undulator: mature technology
- 2.0 gain of superconducting ID as compared to conventional in-vacuum undulator: many open questions

New materials:
- No spin reorientation for PrFeB magnets
- Dy can be used as pole material below the phase transition at 80K
- Saturation magnetization >3Tesla
- Dy diffused magnets (Hitachi)

Cryogenic undulator for table top-FEL application
History of sector 3 downstream undulator at APS

the damages are located close to the e-beam

Field retuning has been done with
- undulator tapering
- magnet flipping or
- remagnetizing of magnet blocks

Hall probe scans have been performed at the dismounted magnets along the indicated paths

courtesy of L. Moog, APS, Argonne National Lab., operated by UChicago Argonne for US-DOE, contract DE-AC02-06CH11357
Demagnetization has been observed also at other out of vacuum devices:

ESRF  
*P. Colomp et al., Machine Technical Note 1-1996/ID, 1996*

DESY / PETRA  
*H. Delsim-Hashemi et al., PAC Proceedings, Vancouver BC, Canada 2009*

In-vacuum applications are even more critical usage of SmCo or special grades of NdFeB is required

**Protection of magnets:**

- **Collimator system**
  - dogleg for energy filtering (used in linear accelerators)
  - apertures for off axis particles (LINACS and SR, e.g. SLS-SR)

- **Beam loss detection**
  fast detection
  - scintillators: high sensitivity, medium spatial resolution
  - Cherenkov fibers: medium sensitivity, high spatial resolution
  absolute dose measurements
  - OTDR systems: simple but low dynamic
  - power meter fibers: using several coils: high dynamic
Powermeter fibers

Cherenkov fibers

Fibre position 0° losses 45° losses 90° losses
45° 0.00255 0.00341 0.00277
135° 0.00171 0.00186 0.00286
225° 0.00194 0.00189 0.00286
315° 0.00285 0.00206 0.00191

Number of Cherenkov photons per electron


Powermeter fibers as installed at the MAXlab-HZB HGHG-FEL

Johannes Bahrdt, HZB für Materialien und Energie, CERN Accelerator School „Magnets“, June 16th-25th, Bruges, Belgium, 2009
Equivalent Descriptions of Permanent Magnets

Assuming rectangular magnets with $\mu_{\text{par}} = 1$, $\mu_{\text{perp}} = 0$

\[
\Phi(\vec{r}_0) = -\int \frac{\nabla \cdot \vec{M}(\vec{r}')}{|\vec{r}_0 - \vec{r}'|} dV' = \oint_{\text{surface}} \frac{\vec{n}' \cdot \vec{M}(\vec{r}')}{|\vec{r}_0 - \vec{r}'|} dS' \\
\vec{H}(\vec{r}_0) = -\text{grad}(\Phi(\vec{r}_0))
\]

\[
\vec{B}(\vec{r}_0) = \frac{1}{c} \int \text{Idl} \times \frac{\vec{r}_0 - \vec{r}'}{|\vec{r}_0 - \vec{r}'|^3} \\
\vec{B}(\vec{r}_0) = \int (\nabla \times \vec{M}) \times \frac{\vec{r}_0 - \vec{r}'}{|\vec{r}_0 - \vec{r}'|^3} dV'
\]

This approach is called CSEM which means either
- Current Sheet Equivalent Method or
- Charge Sheet Equivalent Method

Johannes Bahrdt, HZB für Materialien und Energie, CERN Accelerator School „Magnets“, June 16th-25th, Bruges, Belgium, 2009
Based on these equations the fields can be evaluated by analytic integrations over all current carrying surfaces

contribution from surface A:

\[
B_x = \frac{I}{c} \cdot \iint \frac{y - y_0}{\left( (x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 \right)^{3/2}} \, dz \cdot dy
\]

\[
B_y = -\frac{I}{c} \cdot \iint \frac{x - x_0}{\left( (x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 \right)^{3/2}} \, dz \cdot dy
\]

\[
B_z = 0
\]

totally:

\[
\vec{B}(\vec{r}_0) = \overline{\vec{Q}(\vec{r}_0)} \cdot \vec{M}
\]

\[
Q_{xx} = \sum_{ijk=1}^{2} (-1)^{i+j+k+1} \arctan \left( \frac{y_j z_k}{x_i \sqrt{x_i^2 + y_j^2 + z_k^2}} \right)
\]

\[
Q_{xy} = \ln \left( \prod_{ijk=1}^{2} \left( z_k + \sqrt{x_i^2 + y_j^2 + z_k^2} \right)^{(-1)^{i+j+k}} \right)
\]

\[
x_{1,2}(y_{1,2}, z_{1,2}) = x_c(y_c, z_c) - x_0(y_0, z_0) \pm w_{x(y, z)} / 2
\]

\((x_c, y_c, z_c) = \text{center of magnet}\)

\((x_0, y_0, z_0) = \text{point of observation}\)

\((w_x, w_y, w_z) = \text{dimensions of magnet}\)

similarly for all \(Q_{ij}\)
Similarly, the fields and field integrals from arbitrary current carrying planar polygons can be evaluated

Field

\[
\vec{B}(\vec{r}_0) = \overline{Q(\vec{r}_0)} \cdot \vec{M}
\]

\[
\overline{Q(\vec{r}_0)} = \iiint_{\text{surface}} \left( \frac{\vec{r}_0 - \vec{r}'}{\|\vec{r}_0 - \vec{r}'\|^3} \right) \n_{\text{surface}} \, d\vec{r}'
\]

Field integral

\[
\overline{I}(r_0, \vec{v}) = \int_{-\infty}^{\infty} \vec{H}(\vec{r}_0 + \vec{v}) \, dl = \overline{G(\vec{r}_0, \vec{v})} \cdot \vec{M}
\]

\[
\overline{G(\vec{r}_0, \vec{v})} = \frac{1}{2\pi} \iiint_{\text{surface}} \left[ \left( \vec{r}' - \vec{r}_0 \right) \times \vec{v} \right] \n_{\text{surface}} \, d\vec{r}'
\]

\( \overline{Q} \) and \( \overline{G} \) are 3x3 matrices describing the geometric shape of the magnetized cell. They can be evaluated analytically for an arbitrary polyhedron. \( \otimes \) denotes a dyadic product.

Finite Susceptibility Requires Iterative Algorithm

For real magnets: \( \mu_{par} = 1.06, \mu_{perp} = 1.17 \)
Iterative algorithms are required to evaluate the fields.

For pure permanent magnet structures
the finite susceptibility lowers the evaluated undulator fields by a few percent
as compared to zero susceptibility

\[
\vec{B}_i = \sum_{\substack{k=1 \atop k \neq i}}^N Q_{k,i} \cdot \vec{M}_k + Q_{ii} \cdot \vec{M}_i
\]

\[
\vec{H}_i = \vec{B}_i - 4\pi \cdot \vec{M}_i
\]

\[
M_{i-par} = \frac{1}{4\pi} B_r + (\mu_{par} - 1) \cdot H_{i-par}
\]

\[
M_{i-perp} = (\mu_{perp} - 1) \cdot H_{i-perp}
\]
Simulations in the Nonlinear Regime

Linear regime

\[ M_{\text{par}}(H_{\text{par}}) = M_r + \chi_{\text{par}}H_{\text{par}} \]
\[ M_{\text{perp}}(H_{\text{perp}}) = \chi_{\text{perp}}H_{\text{perp}} \]

Including temperature dependence

\[ M_r(T) = M_r(T_0) \cdot (1 + a_1(T - T_0) + a_2(T - T_0)^2 + ...) \]
\[ H_{cj}(T) = H_{cj}(T_0) \cdot (1 + b_1(T - T_0) + b_2(T - T_0)^2 + ...) \]
\[ \chi_{\text{perp}}(T) = \chi_{\text{perp}}(T_0) \cdot (1 + a_1(T - T_0) + a_2(T - T_0)^2 + ...) \]

Magnetization Ansatz

\[ M(H, T) = \alpha(T) \sum_{i=1}^{3} M_{si} \tanh\left( \frac{\chi_i}{M_{si}} (H + H_{cj}(T)) \right) \]

\( a_i, b_i \) from data sheet of magnet supplier
\( M_{si}, \chi_i \) from fit of \( M(H) \) curve at \( T_0 \) (magnet supplier)
\( \alpha(T) \) is determined from
\[ M(H = 0, T) = M_r(T) \]

This model has been implemented into RADIA and tested with a real magnet assembly

J. Chavanne et al., Proc. of EPAC, Vienna, Austria (2000) 2316-2318
2-dimensional Geometries

Use complex notation of fields:

\[ \tilde{B}^*(\tilde{z}_0) = B_x - iB_y \]
\[ \tilde{z}_0 = x_0 + iy_0 = r_0 \cdot e^{i\phi_0} \]

\( \tilde{B}^* \) is an analytic function, \( \tilde{B} \) is not Cauchy Riemann relations are equivalent to Maxwell equations.

Examples:
Current flowing into the plane:

\[ \tilde{B}^*(\tilde{z}_0) = a \int \frac{j_z}{\tilde{z}_0 - \tilde{z}} \cdot dx \cdot dy \]

Permanent magnet with remanence \( \tilde{B}_r \):

\[ \tilde{B}^*(\tilde{z}_0) = b \int \frac{\tilde{B}_r}{(\tilde{z}_0 - \tilde{z})^2} \cdot dx \cdot dy \]

\[ B_r = B_{rx} + iB_{ry} \]

Optimization using conformal mapping (Halbach)

Easy axis rotation theorem:
rotation of all magnetization vectors by (+\( \alpha \))
rotates the field vector B by (- \( \alpha \))

field at the center?
Halbach type multipoles
General segmented multipole with stacking factor $\varepsilon \leq 1$
$v=$harmonic number ($v=0$ describes the fundamental)
$N$=order of multipole, $N=1$: dipole, $N=2$: quadrupole etc
$B_r$=remanence
$r_1$=inner radius
$r_2$=outer radius
$M$=total number of magnets per period
$\alpha = (N+1)2\pi/M = \text{relative angle of magnetization between segments}$

\[
\tilde{B}^* (\tilde{z}) = \tilde{B}_r \sum_{v=0}^{\infty} \left( \frac{\tilde{z}}{r_1} \right)^{n-1} \frac{n}{n-1} \left( 1 - \left( \frac{r_1}{r_2} \right)^{n-1} \right) K_n
\]

\[
K_n = \cos^n \left( \varepsilon \pi / M \right) \frac{\sin(n \varepsilon \pi / M)}{n \pi / M}
\]

\[
n = N + vM
\]

\[
\frac{n}{n-1} \left( 1 - \left( \frac{r_1}{r_2} \right)^{n-1} \right)_{n=1} = \ln(r_2 / r_1)
\]

\[
\tilde{B}^* = B_x - iB_y
\]

\[
\tilde{z} = x + iy = r \cdot e^{i\phi}
\]

$K. \text{ Halbach, Nucl. Instr. and Meth.} \quad 169 \ (1980) \ 1-10$
Example: fundamental of quadrupole: $N=2$, $v=0$, stacking factor $\varepsilon = 1$

$$\bar{B}^* (\bar{z}) = \bar{B}_r \frac{\bar{z}}{r_1} 2(1 - r_1 / r_2)K_2$$

$$K_2 = \cos^2(\pi / M) \frac{\sin(2\pi / M)}{2\pi / M}$$

- **dipole**
  - $N=0$
  - $M=6$
- **quadrupole**
  - $N=1$
  - $M=4$
- **sextupole**
  - $N=3$
  - $M=3$

**Modified Halbach multipoles include Fe**


- **300T/m**
- **radius: 3.5mm**
Continuously adjustable quad for ILC final focus advantages of permanent magnets versus SC solenoid:
- No vibrations due to liquid HE
- Small outer diameter, better geometry for crossing beams

- Effect of a rotated quadrupole is described by a symplectic 4 x 4 matrix $M$ with

$$M^T \Phi M = \Phi$$

$$\Phi = \begin{pmatrix}
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
-1 & 0 & 0 & 0 \\
0 & -1 & 0 & 0
\end{pmatrix}$$

- Off diagonal 2 x 2 matrices describe the coupling between planes
- 5 independent discs can zero the coupling terms and adjust the strength
- Rotation angles of the five discs are symmetric (see figure)


Multipole Magnets for Accelerators IV

Strong focussing ppm quadrupoles (M=3) for table top FEL undulator: Field gradients up to 500T/m at 3mm inner radius

Hall probe measurements

Higher multipole content before (left) and after (right) shimming

Binary stepwise PMQ for ILC


Fermilab 8.9 GeV Antiproton Recycler Ring

3.3 km circumference
344 ppm gradient dipoles
92 ppm quadrupoles
129 powered correctors
material: strontium ferrite

Temperature coefficients:
- remanence of ferrites: -0.19%/deg.
- sat. magnet. of Fe-Ni-alloy: -2%/deg.

Temperature dependent flux shunt

Permanent magnets to be used:
type: hard ferrite
$B_r$: 4.0 KG
$H_{cj}$: 4.5kOe

one of 16 cells of the triple bend achromat (TBA) lattice including three dipole magnets and six quadrupoles

P. Tavares et al, LNLS-2,
Preliminary conceptual design report,
Campinas, April 2009
LNLS II Proposal II

Permanent magnet **dipole** including gradient for focusing

- 32 x 6.5° dipoles
- 16 x 9.5° dipoles
- Peak field: 0.45 T
- Gradient: 1.25 T / m

Permanent magnet **quadrupole** including trim coils for fine tuning

- 96 quadrupoles
- Gradient: 22 T / m
- Integrated gradient: 7.7 T

**Sextupole** magnets will be pure electromagnetic devices