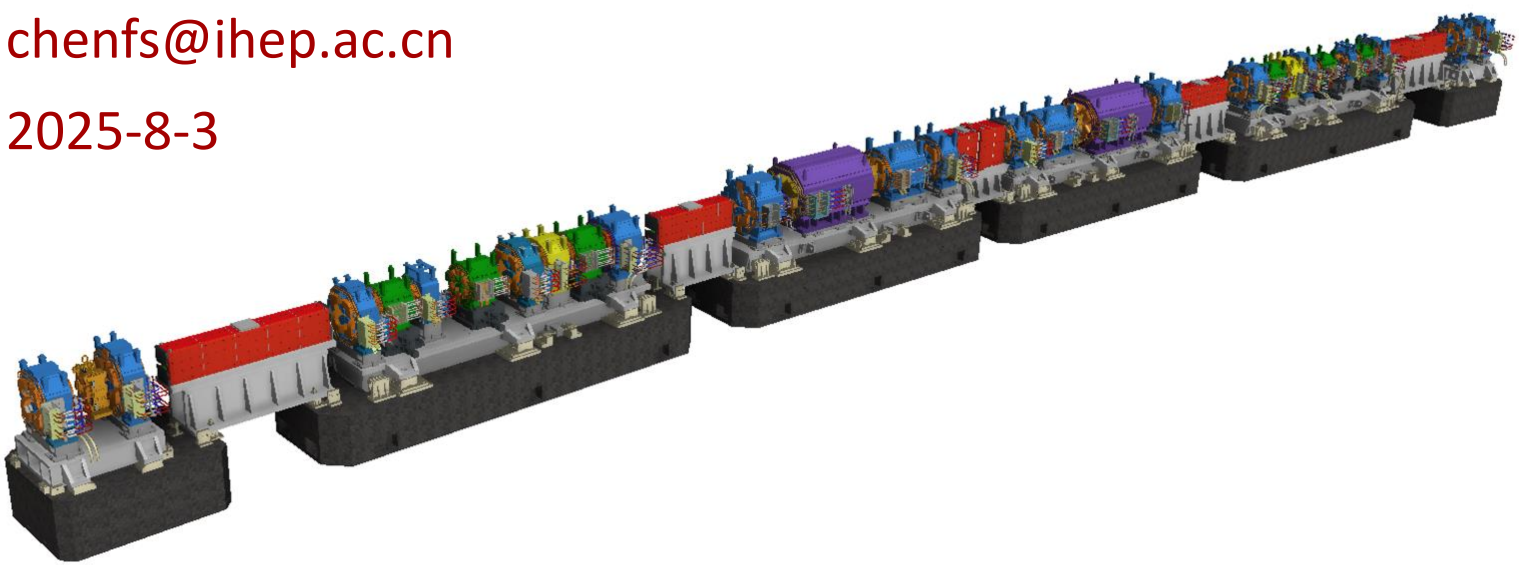
中国科学院高能物理研究所

Magnet Technology

CHEN, Fusan 陈福三

chenfs@ihep.ac.cn

2025-8-3



Contents

1 Introduction and basic theories

2 Iron dominated electromagnet

3 Superconducting magnet

4 Permanent magnet

5 Magnetic field measurement

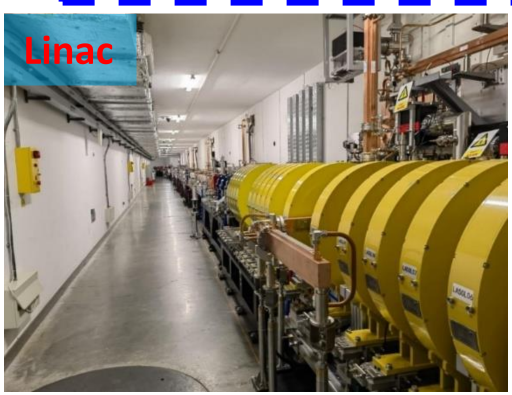
6 Special topics

Introduction

- **Magnet system – the foundation of accelerator**
  - Only multipole magnet for Lattice is discussed in this lecture.
  - High Energy Photon Source (HEPS) magnets as examples.

Accelerator Magnet

- Multipole magnet for Lattice
  - Dipole (Bending magnet)
  - Quadrupole (Focus magnet)
  - Sextupole
  - Octupole
- Insertion devices
  - Wiggler
  - Undulator
- Inj/extraction magnet



Functions of magnets

- Lorentz force

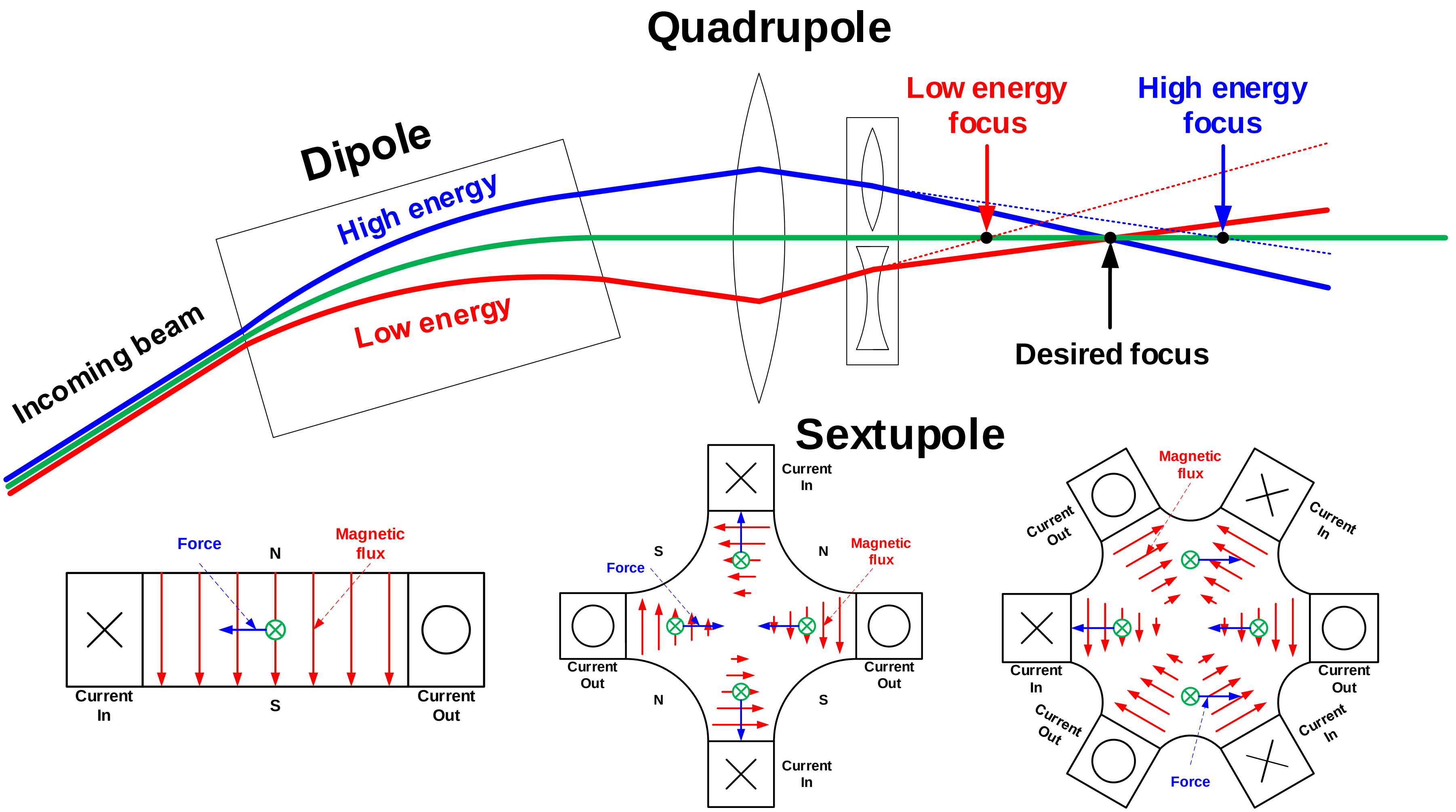
$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

For particles with velocity of light (c), 1T of magnetic field is equivalent to 300 MV/m of electric field.

- Magnet types
  - Dipole: bend the beam and generate synchrotron radiation
  - Quadrupole: focus/defocus the beam
  - Sextupole: chromaticity correction
  - Octupole: Landau damping
  - Insertion devices: a series of periodically arranged dipole to generate high quality synchrotron radiation

Functions of magnets

- Magnet functions diagrammatic sketch



Maxwell's equations

- Differential form of Maxwell's equations

$$\vec{\nabla}\cdot\vec{D}=\rho$$

$$\vec{\nabla}\cdot\vec{B}=0$$

$$\vec{\nabla}\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}$$

$$\vec{\nabla}\times\vec{H}=\vec{J}+\frac{\partial\vec{D}}{\partial t}$$

$\vec{D}$	Electric displacement
$\vec{B}$	Magnetic flux density, magnetic induction
$\vec{E}$	Electric field strength
$\vec{H}$	Magnetic intensity
$\vec{J}$	Current density
ρ	Charge density

$$\vec{D}=\varepsilon\vec{E},\quad \vec{B}=\mu\vec{H},\quad \vec{J}=\sigma\vec{E}$$

ε	Electric permittivity
μ	Magnetic permeability
σ	Conductivity

$$\mu_0=4\pi\times10^{-7}[\text{H/m}]$$

$$\varepsilon_0=\frac{1}{\mu_0 c^2}\approx\frac{1}{36\pi}\times10^{-9}[\text{F/m}]$$

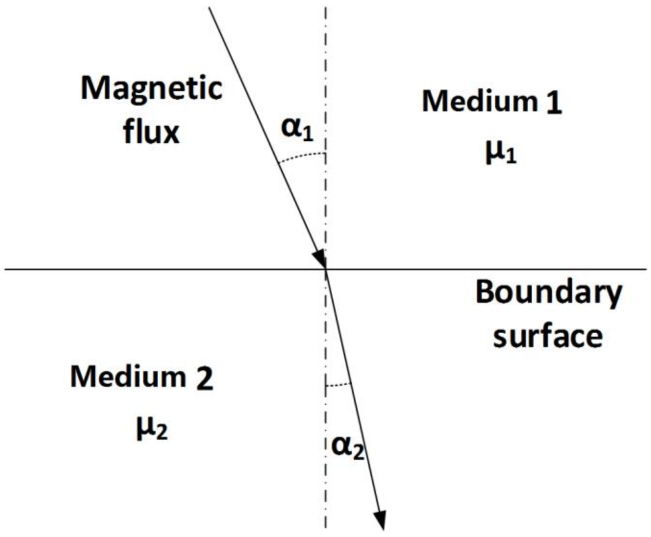
Principles of magnetic field

- Ampere's law **for static magnetic field generated by constant current**

$$\int_l \vec{H}\cdot d\vec{l} = \int_S (\vec{\nabla}\times\vec{H})\cdot d\vec{S} = \int_S \vec{J}\cdot d\vec{S} + \frac{\partial}{\partial t}\int_S \vec{D}\cdot d\vec{S} = I$$

=0

- Boundary condition between two materials



$$B_{1\perp} = B_{2\perp} \qquad H_{1||} = H_{2||}$$

Normal component of the magnetic flux density and tangential component of the magnetic intensity are continuous across a boundary.

For the incident angle α_1 and exit angle α_2:

$$\frac{\tan\alpha_1}{\tan\alpha_2} = \frac{\mu_1}{\mu_2}$$ **and** $\tan\alpha_2 \approx 0$ **if** $\mu_1 \gg \mu_2$

Scalar potential and vector potential

- Magnetic scalar potential:

For a static magnetic field with <u>no current in the region</u>:

For example: in vacuum chamber

$$\vec{\nabla}\times\vec{B} = \mu\vec{\nabla}\times\vec{H} = \mu\vec{J} + \mu\frac{\partial\vec{D}}{\partial t} = 0$$

Curl

The magnet flux density can be described with the gradient of a scalar field:

$$\vec{B} = -\vec{\nabla}\varphi = -\frac{\partial\varphi}{\partial x}\hat{x} - \frac{\partial\varphi}{\partial y}\hat{y} - \frac{\partial\varphi}{\partial z}\hat{z}$$

- Magnetic vector potential:

For any vector field $\vec{A}$: $\vec{\nabla}\cdot(\vec{\nabla}\times\vec{A}) \equiv 0$ **and** $\vec{\nabla}\cdot\vec{B} = 0$

The magnet flux density can be derived from the curl of a vector field:

$$\vec{B} = \vec{\nabla}\times\vec{A} = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ A_x & A_y & A_z \end{vmatrix} = \left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}\right)\hat{x} + \left(\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x}\right)\hat{y} + \left(\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y}\right)\hat{z}$$

Laplace equation and Poisson equation

- Laplace equation in the region with no current:

$$\vec{\nabla}\cdot\vec{B} = -\vec{\nabla}\cdot(\vec{\nabla}\varphi) = -\nabla^2\varphi = 0 \Rightarrow \nabla^2\varphi = \frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2} + \frac{\partial^2\varphi}{\partial z^2} = 0$$

$$\vec{\nabla}\times\vec{B} = \vec{\nabla}\times(\vec{\nabla}\times\vec{A}) = \vec{\nabla}(\vec{\nabla}\cdot\vec{A}) - \nabla^2\vec{A} = 0 \Rightarrow \nabla^2\vec{A} = 0$$

Coulomb gauge used here: $\vec{\nabla}\cdot\vec{A} = 0$

- Poisson equation in the region with current:

$$\vec{\nabla}\times\vec{B} = \vec{\nabla}\times(\vec{\nabla}\times\vec{A}) = \vec{\nabla}(\vec{\nabla}\cdot\vec{A}) - \nabla^2\vec{A} = \mu\vec{J} \Rightarrow \nabla^2\vec{A} = -\mu\vec{J}$$

The solution of the Poisson equation is: $\vec{A}(\vec{r}) = -\frac{\mu}{4\pi}\int\frac{\vec{J}(\vec{r}')}{|\vec{r}-\vec{r}'|}d^3r'$

Two-dimensional field

- Simplify 3-d problem to 2-d cause:
  - The particle feels integral field along z direction.
  - For most magnet, stray field is quite small to integral field.
- 2-d variables represented by complex number:
  - Coordinate: $x + iy = re^{i\theta}$
  - Constant: $C = a + ib = \left|C\right| e^{i\phi}$
  - Magnet field: $B_y + iB_x = (B_\theta + iB_r)e^{-i\theta}$
  - Differential operator: $\frac{\partial}{\partial x} + i\frac{\partial}{\partial y} = e^{i\theta}\left(\frac{\partial}{\partial r} + \frac{i}{r}\frac{\partial}{\partial \theta}\right)$

Multipole magnetic field

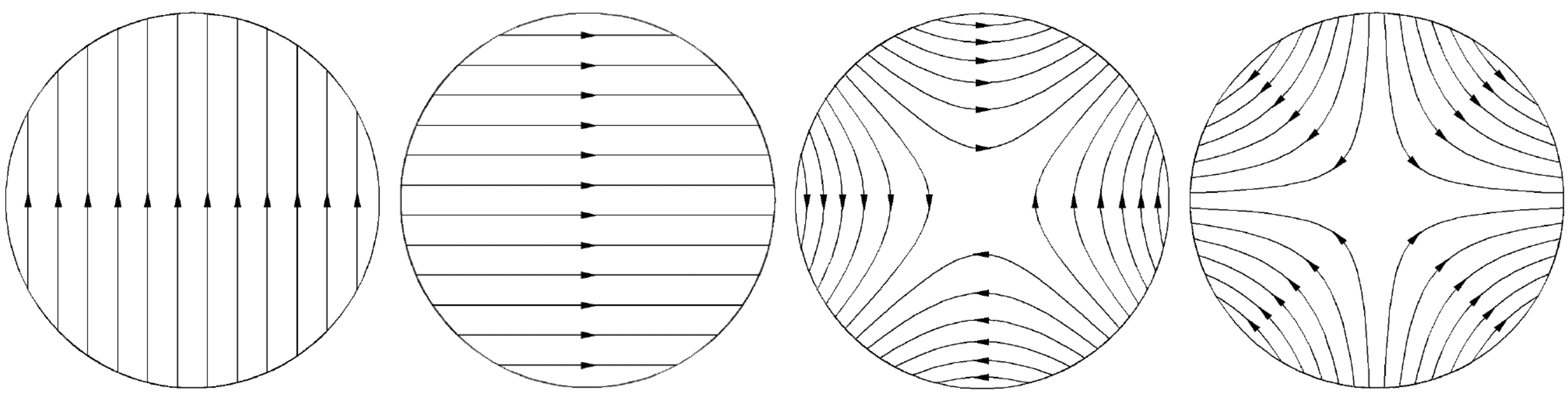
- Consider the field $\vec{B} = (B_x, B_y, 0) = (B_r, B_\theta, 0)$ satisfy:

$$B_y + iB_x = \sum_{n=1}^{\infty} C_n (x+iy)^{n-1} \quad \xleftrightarrow{\text{equivalent}} \quad B_\theta + iB_r = \sum_{n=1}^{\infty} \left|C_n\right| r^{n-1} e^{i(n\theta + \phi_n)}$$

Phase

  - **It is demonstrable that $\vec{B}$ is a solution of Maxwell's equations and a possible physical magnetic field, which is know as multipole fields.**

- Magnetic flux of multipole fields with different orders:



$n=1, \phi_1 = 0, b_1 = 0$ **Normal dipole** | $n=1, \phi_1 = \pi/2, a_1 = 0$ **Skew dipole** | $n=2, \phi_2 = 0, b_2 = 0$ **Normal quadrupole** | $n=2, \phi_2 = \pi/2, a_2 = 0$ **Skew quadrupole**

Magnetic scalar equipotential

- Consider the scalar potential $\varphi = -\left|C_n\right| \frac{r^n}{n} \sin(n\theta + \phi_n)$

$$\vec{B} = -\vec{\nabla}\varphi = -\frac{\partial\varphi}{\partial r}\hat{r} - \frac{1}{r}\frac{\partial\varphi}{\partial\theta}\hat{\theta} = \left|C_n\right| r^{n-1}\left[\sin(n\theta+\phi_n)\hat{r} + \cos(n\theta+\phi_n)\hat{\theta}\right]$$

Here we get the n-order multipole field: $B_\theta + iB_r = \left|C_n\right| r^{n-1} e^{i(n\theta+\phi_n)}$

- The n-order magnetic scalar equipotential is:

$$-\left|C_n\right| \frac{r^n}{n} \sin(n\theta + \phi_n) = \varphi_0$$

Let: $r_0^{\ n} = -\frac{n}{\left|C_n\right|}\varphi_0$

We get: $r^n \sin(n\theta + \phi_n) = r_0^{\ n}$

The magnetic scalar equipotential is a series of curve which is perpendicular to the magnetic flux, where r_0 gives the minimum distance from the origin to the equipotential curve.

Contents

1 Introduction and basic theories

2 Iron dominated electromagnet

3 Superconducting magnet

4 Permanent magnet

5 Magnetic field measurement

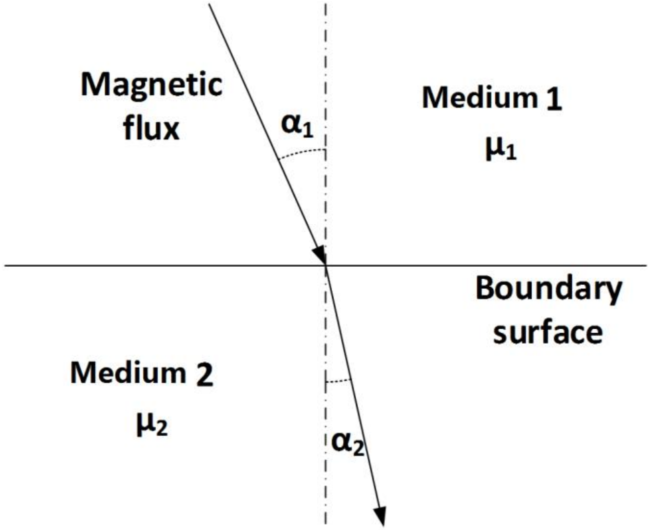
6 Special topics

Generate multipole with Iron

- Recall the boundary condition:

$$\tan\alpha_2 \approx 0 \quad \text{if} \quad \mu_1 \gg \mu_2$$

Consider medium 1 is a high permeability material such as pure iron or silicon steel, and medium 2 is vacuum or air, so that above condition satisfied. The magnetic flux is perpendicular to the boundary surface.

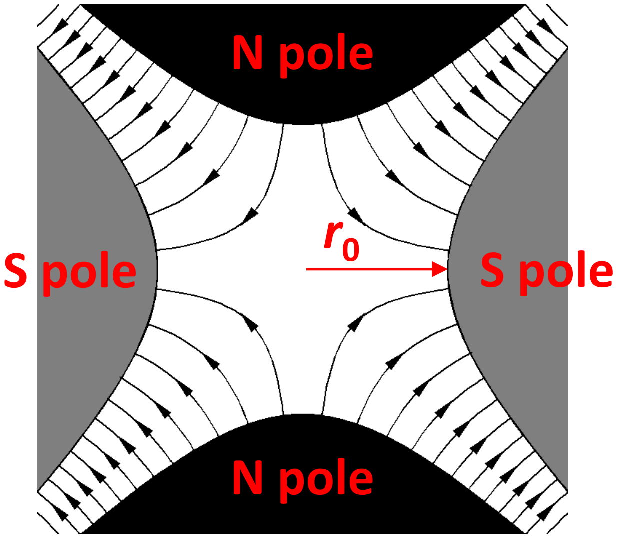


- Generate field with Iron

Make high permeability material (Iron) surface fitting the equipotential, the so-called magnet pole, and we will get desired field between the poles.

For example: skew quad.

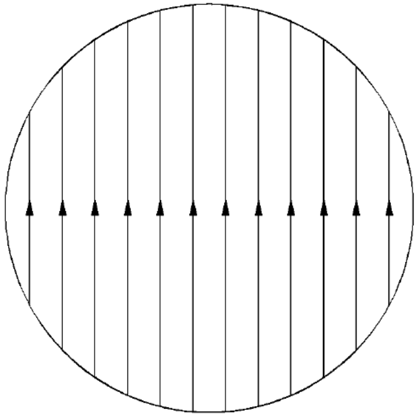
$$r^2 \sin(2\theta + \pi / 2) = r_0^2$$



Characteristics of multipoles

- For n-order multipole fields $\left|\vec{B}_n\right| = \left|B_{n,\theta} + iB_{n,r}\right| = \left|C_n\right| r^{n-1}$

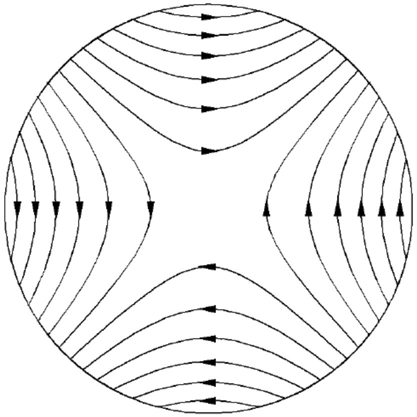
Normal dipole



$$\left|\vec{B}_1\right| = \left|C_1\right| = B$$

n=1, dipole has uniform field with no field center

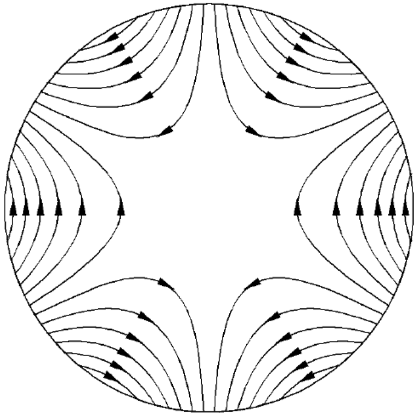
Normal quadrupole



$$\left|\vec{B}_2\right| = \left|C_2\right| r = B' r$$

n=2, the strength of a quadrupole is proportional to the distance to the origin.

Normal sextupole



$$\left|\vec{B}_3\right| = \left|C_3\right| r^2 = \frac{1}{2} B'' r^2$$

n=3, the strength of a sextupole is proportional to the square of the distance to the origin.

Real magnet

- Ideal magnet has only specified multipoles
  - The poles profile fits the equation, $r^2 \sin(2\theta + \pi / 2) = r_0^{\ 2}$ so the poles expand to infinity while $2\theta + \pi / 2 = m\pi,\ m \in \mathbb{Z}$
  - The length of the magnet is infinite.
  - The permeability is infinite high. $\mu \mapsto \infty$
  - The pole surface is absolutely smooth.
  - The excitation coil is infinite away from the center.
- All above conditions can not be satisfied. So real multipole magnet consists of main component and infinite number of other multipole fields.

Field error – high order harmonics

- High order field are categorized into:

  - Systematic errors: have the same symmetry as main field.

$$\vec{B}_n(\theta + \frac{\pi}{N}) = -\vec{B}_n(\theta) \quad \Rightarrow \quad \sin\frac{n\pi}{N} = 0 \quad \textbf{and} \quad \cos\frac{n\pi}{N} = -1$$

$$n_{systematic} = (2m+1)N, \quad m = 1,2,3,\cdots$$

Systematic errors can be optimized on the design stage

Main field	Systematic error
N=1, dipole	n=3,5,7,…
N=2, quadrupole	n=6,10,14,…
N=3, sextupole	n=9,15,21,…

  - Nonsystematic errors:

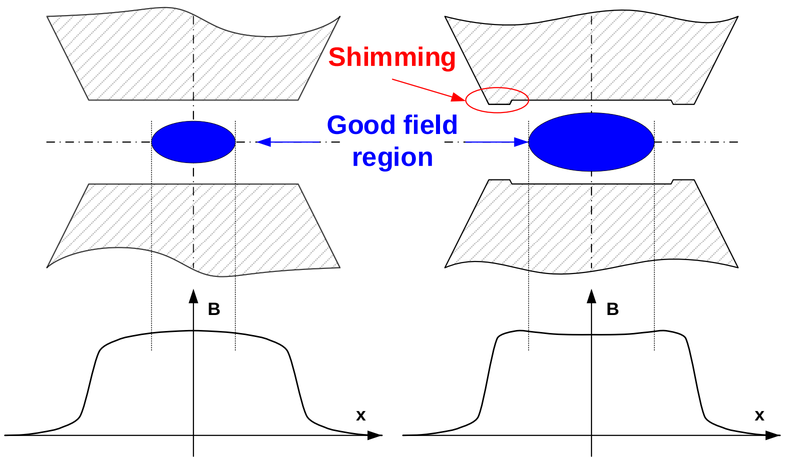
Nonsystematic errors are zero on the design stage, and come from the imperfection of material and fabrication.

  - Field quality evaluation:

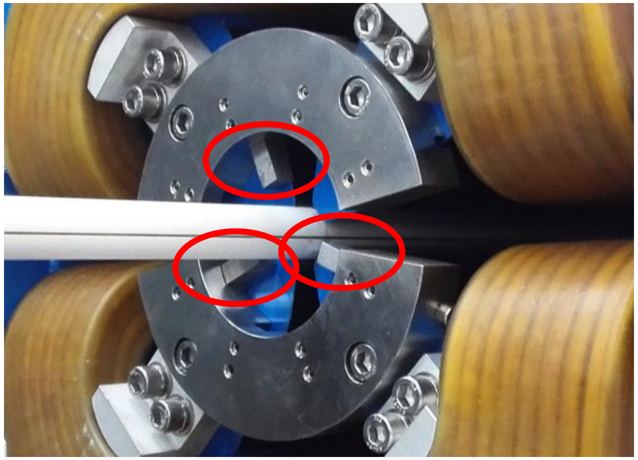
$$\frac{|B_n|}{|B_N|} = \frac{|C_n|}{|C_N|} r^{n-N}$$

Shimming and Chamfering

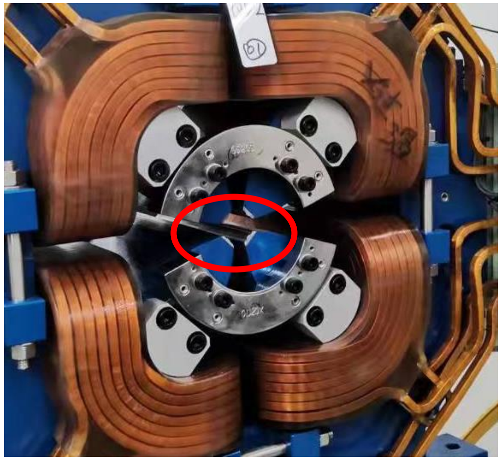
- Pole profile shimming
  - Compensate the systematic errors and widen the good field region
- Pole end shimming
  - Correct the nonsystematic errors according to the measurement result



- Pole chamfering



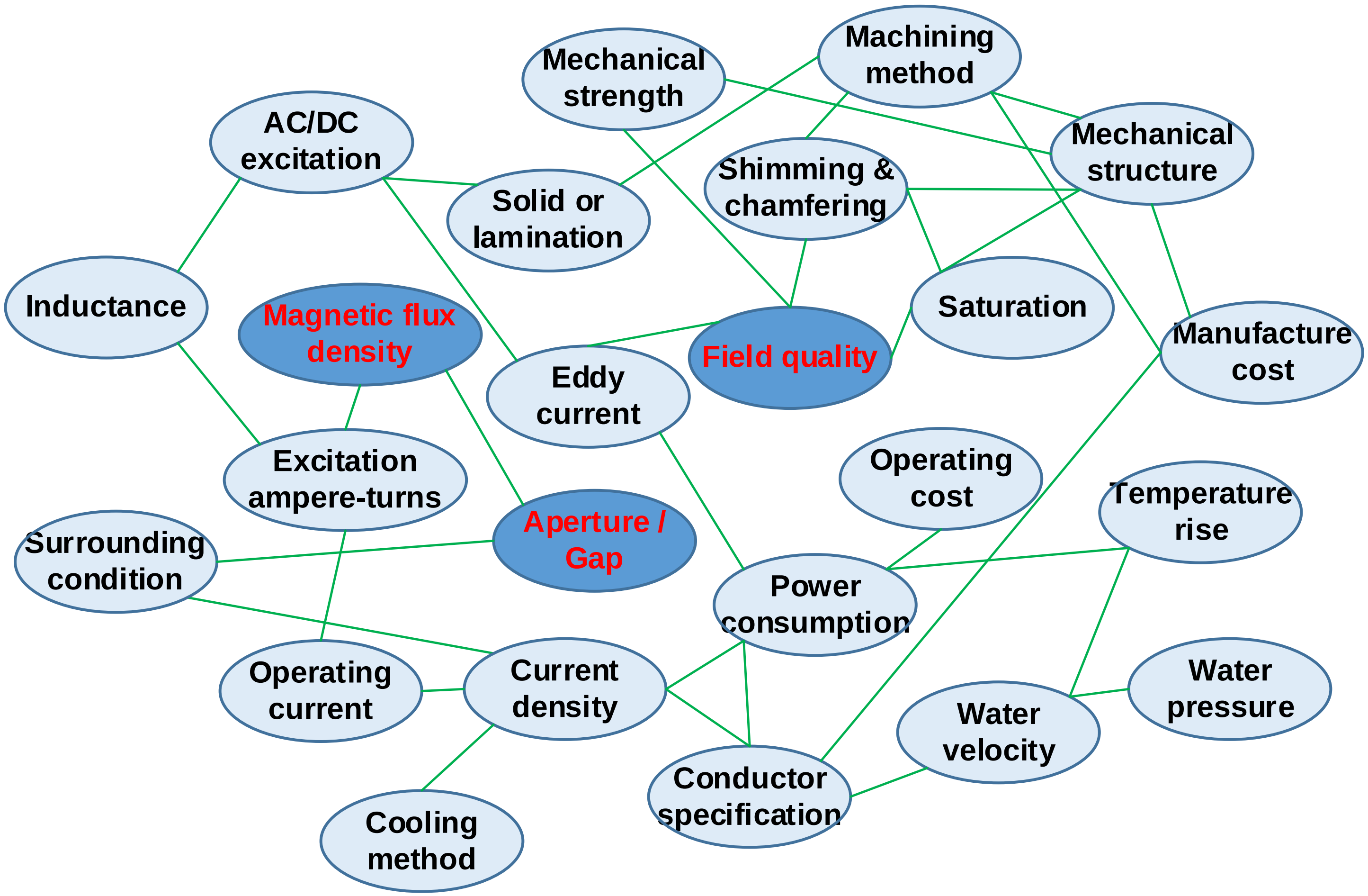
'Magic finger' used for HEPS magnet



Chamfering on the pole end can correct the field errors as well as reduce the saturation of the pole corner.

Magnet design – considerations

- Compromise of various factors



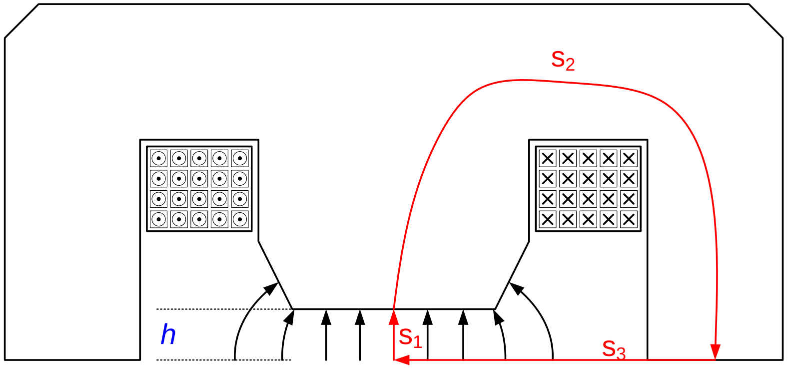
Magnet design – excitation current

- **Dipole**：**Ampere's law** $\int_l \vec{H}\cdot d\vec{l} = I$

Divide the integral path into 3 segments:

$$\int_{s_1} \frac{\vec{B}}{\mu_0}\cdot d\vec{l} + \int_{s_2} \frac{\vec{B}_{iron}}{\mu_{iron}}\cdot d\vec{l} + \int_{s_3} \vec{H}\cdot d\vec{l} = I$$

I_{iron}, **a small value**   **Zero**

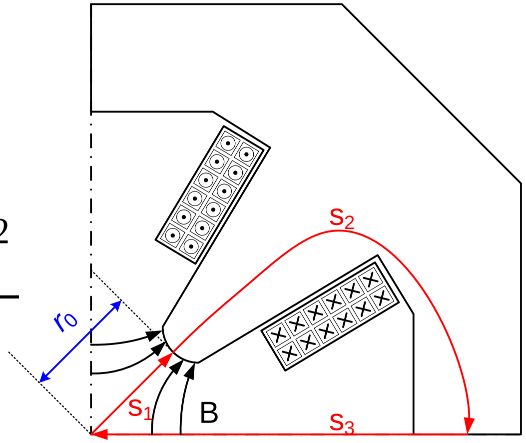


$$I = \frac{Bh}{\mu_0} + I_{iron} = f\,\frac{Bh}{\mu_0}$$

***f*, ampere factor, about 1.01~1.06 for unsaturated magnet**

- **Quadrupole**：

$$I = \int_{s_1} \frac{\vec{B}}{\mu_0}\cdot d\vec{l} + I_{iron} = f\,\frac{B' r_0^{\,2}}{2\mu_0}$$



Use same method to calculate the excitation current of sextupole, noting that

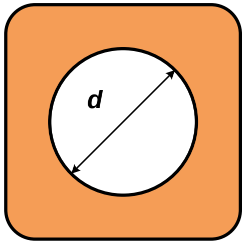
$$B = \frac{1}{2} B'' r^2$$

Magnet design – cooling water

- For the current density J of coil

$J < 1\,[\mathrm{A/mm^2}]$ **Air cooling**

$J > 1.5\,[\mathrm{A/mm^2}]$ **Water cooling**



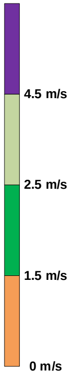
The water cooling coil is made of hollow copper conductor

- Cooling water calculation

$$V^{1.75} = \left(\frac{\Delta p \cdot d^{1.25}}{0.28L} \right)$$

$$\Delta T = \frac{4 \times 10^{-3} P}{4.2 \pi d^2 V}$$

V	**Water flow velocity**	**[m/s]**
Δp	**Water pressure drop**	**[kg/cm²]**
d	**Hole diameter of conductor**	**[mm]**
L	**Length of cooling loop**	**[m]**
Q	**Flow rate of water**	**[l/s]**
ΔT	**Temperature rise of water**	**[°C]**
P	**Power consumption of coil**	**[kW]**



Too fast leading to vibration

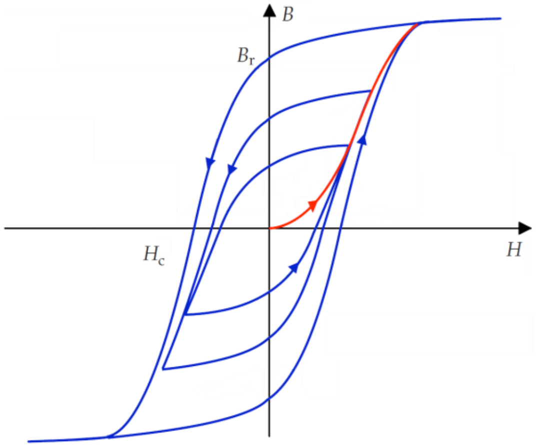
Acceptable velocity range

Good velocity range

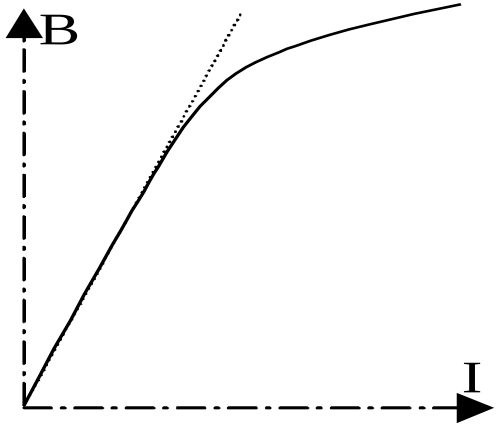
Too slow to form turbulence

Standardization and I-B curve

- The magnet core material has hysteresis loop:
  - Ramping up and down have different path
  - Magnetic flux density is nonlinear to current



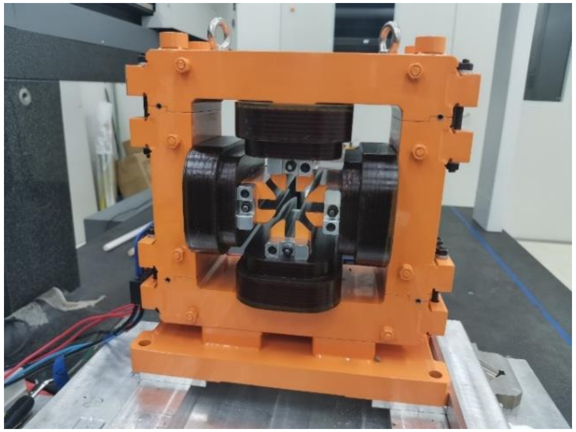
- Standardization and I-B curve
  - Power the magnet by 0 → I_{max} → 0 for 3 times, then ramp to I_{op1}. If next operation current $I_{op2} > I_{op1}$, ramp to I_{op2} directly; if $I_{op2} < I_{op1}$, ramp to I_{max} → 0 → I_{op2}.
  - Only ramping up I-B curve is adopted.
  - I-B curve is measured in 10~20 points and interpolation is used for other values



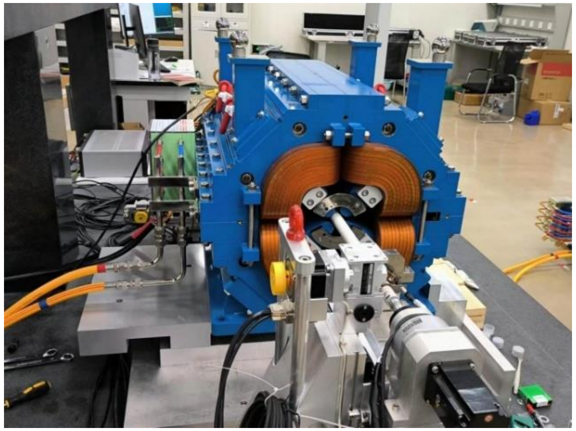
Photos of HEPS magnets

HEPS booster dipole

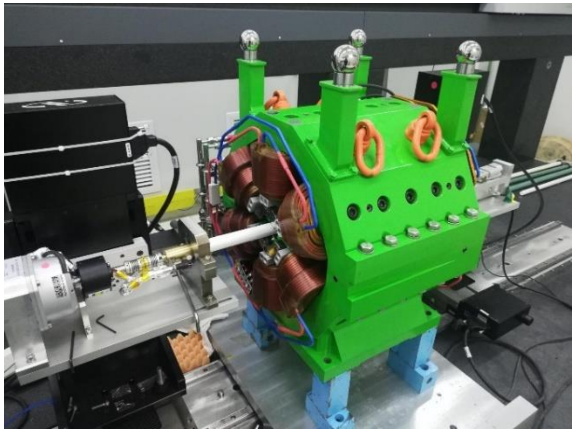
HEPS storage ring dipole prototype



HEPS storage ring fast corrector



HEPS storage ring quadrupole



HEPS storage ring sextupole

HEPS storage ring octupole

Contents

1 Introduction and basic theories
2 Iron dominated electromagnet
3 Superconducting magnet
4 Permanent magnet
5 Magnetic field measurement
6 Special topics

Superconducting materials

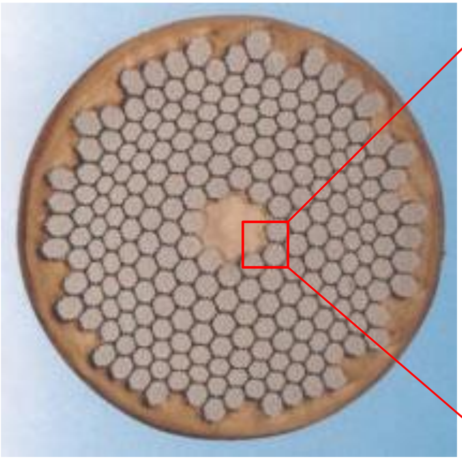
- NbTi is the most widely used SC material

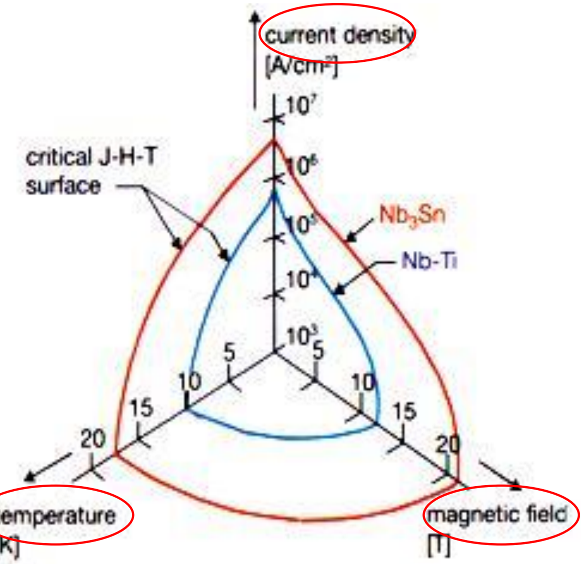
- Low temperature superconductor
  - **NbTi**
  - Nb_3Sn, Nb_3Al
  - Metal compounds
    - MgB2, …

Tc < 77K cooled with liquid Helium

- High temperature superconductor
  - Copper based materials
    - ReBCO
    - BSCCO
  - Iron based materials

Tc > 77K cooled with liquid Nitrogen

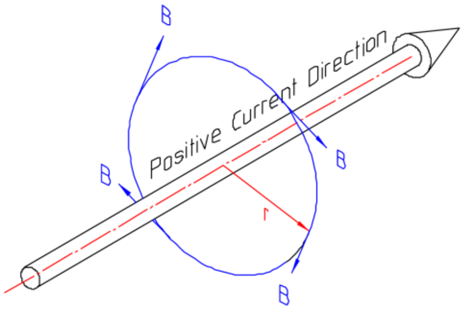




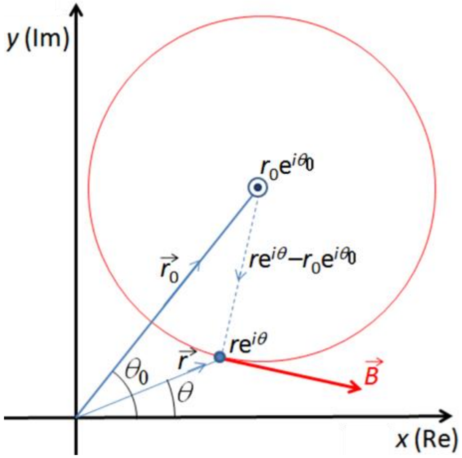
Three critical conditions for SC material

Generate multipoles with current

- Magnetic field from a line current



$$\oint \vec{H}\cdot d\vec{l} = \frac{B}{\mu_0}2\pi r = I \Rightarrow B = \frac{\mu_0 I}{2\pi r}$$



$$B_x + iB_y = i\frac{\mu_0 I}{2\pi}\frac{re^{i\theta} - r_0 e^{i\theta_0}}{\left|re^{i\theta} - r_0 e^{i\theta_0}\right|^2}$$

$$B_\theta + iB_r = (B_y + iB_x)e^{i\theta} = -\frac{\mu_0 I}{2\pi r_0}\frac{e^{-i(\theta_0-\theta)}}{1-(\frac{r}{r_0})e^{-i(\theta_0-\theta)}}$$

Generate multipoles with current

Use Tayler series expansion $\frac{1}{1-\zeta}=\sum_{n=1}^{\infty}\zeta^{n-1}$ **where** $|\zeta|<1$

For the region $r<r_0$ **we get** $B_\theta+iB_r=-\frac{\mu_0 I}{2\pi r_0}\sum_{n=1}^{\infty}(\frac{r}{r_0})^{n-1}e^{-in(\theta_0-\theta)}$

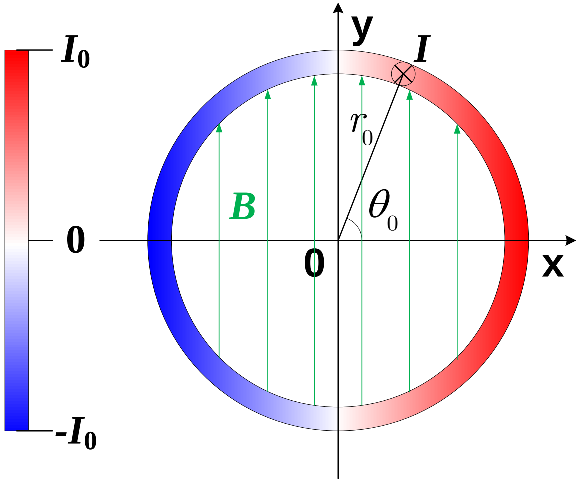
Consider the current distributed on a circle of radius r_0 satisfy

$$I=I_0\cos(N\theta_0),\ N=1,2,3,\cdots$$

The integral field generated in the circle is:

$$B_\theta+iB_r=-\frac{\mu_0 I_0}{2r_0}(\frac{r}{r_0})^{N-1}e^{iN\theta}$$

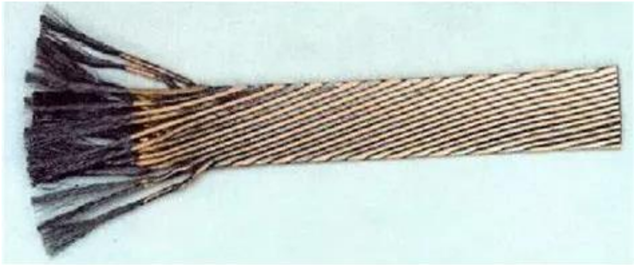
This is a typical 2N-pole magnetic field.



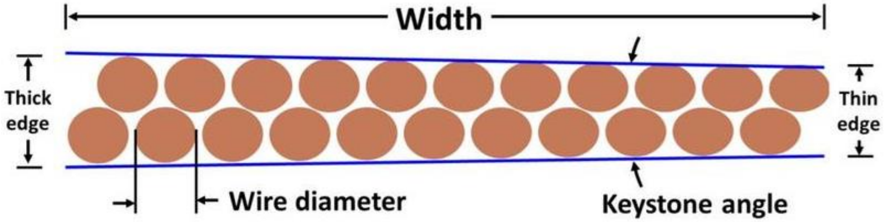
Dipole field with $N=1$

Superconducting magnet type

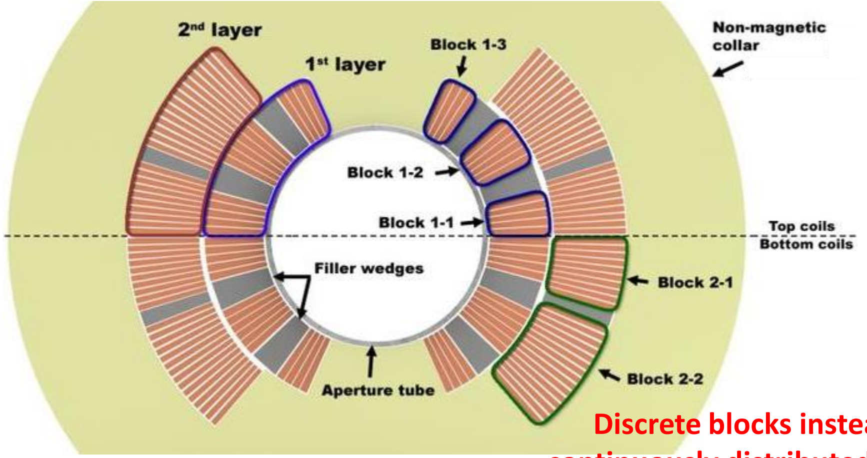
- Cosine theta with Rutherford cable



Rutherford cable

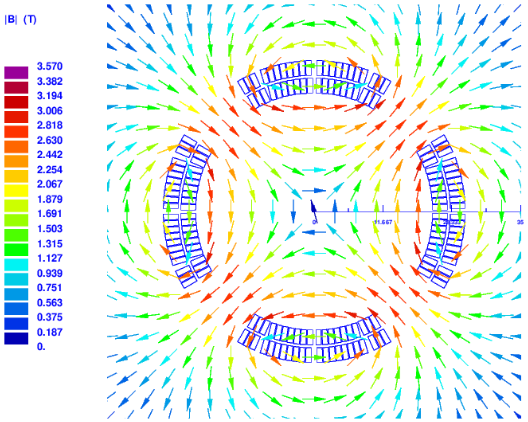


Cross section of Rutherford cable



Discrete blocks instead of continuously distributed current

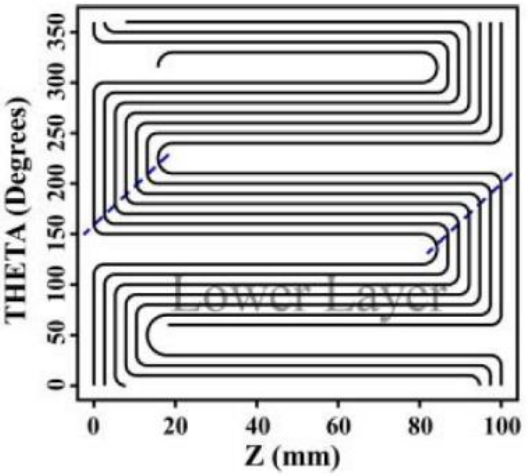
Cross section of dipole

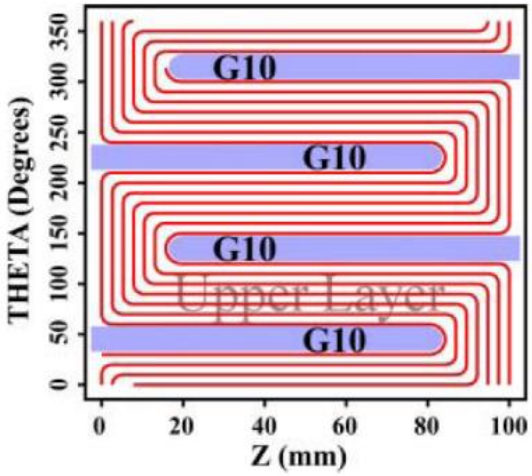


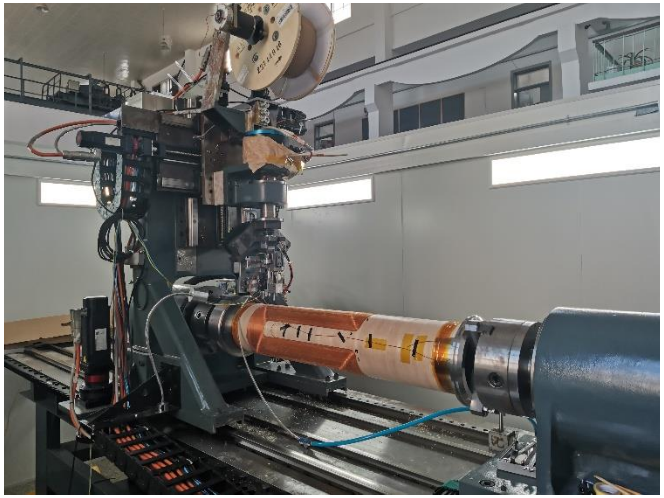
Field distribution of quadrupole

Superconducting magnet type

- Serpentine style cosine theta type magnet







- The straight segments have the same length → 2d simulation has the same result as 3d simulation → Fast and easy design
- Double layers form a complete multipole field.
- Suitable for fabrication with direct winding machine.

Superconducting magnet type

- Canted cosine theta (CCT)

Two tilted solenoid with transverse components superposed and longitudinal component cancelled.

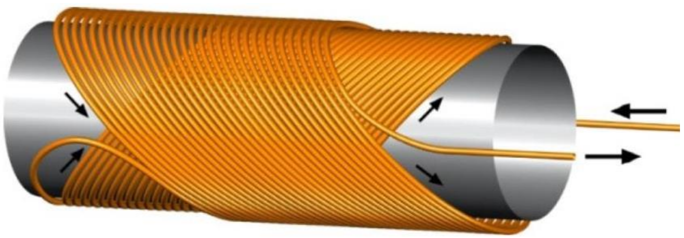
The wire path defined by:

$$x = R\cos\theta$$

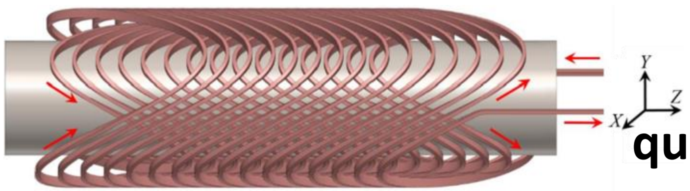
$$y = R\sin\theta$$

$$z = \frac{w\theta}{2\pi} + \frac{R\sin(n\theta)}{n\tan\alpha}$$

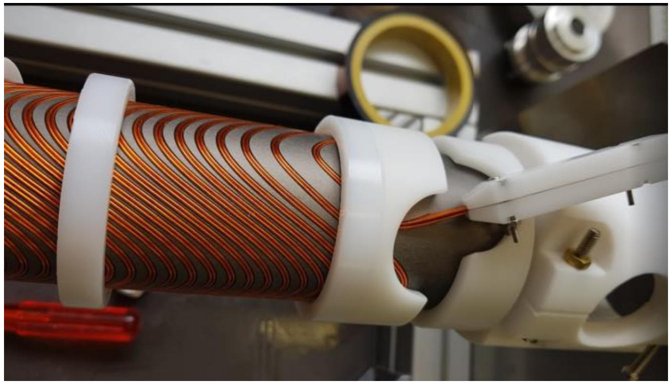
Double layers form complete field



CCT dipole

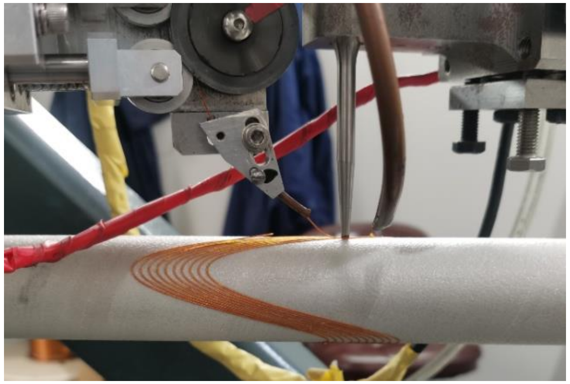


CCT quadrupole



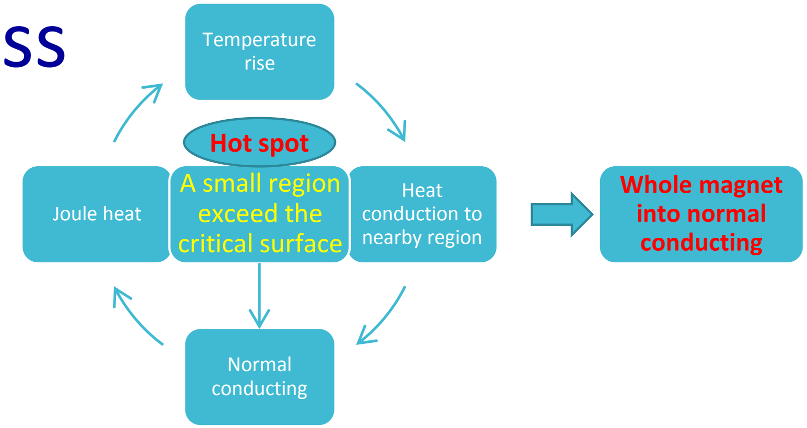
Quadrupole prototype for FCC-ee, wires-in-groove technology.

Quadrupole prototype for CEPC, direct winding technology.



Quench and quench protection

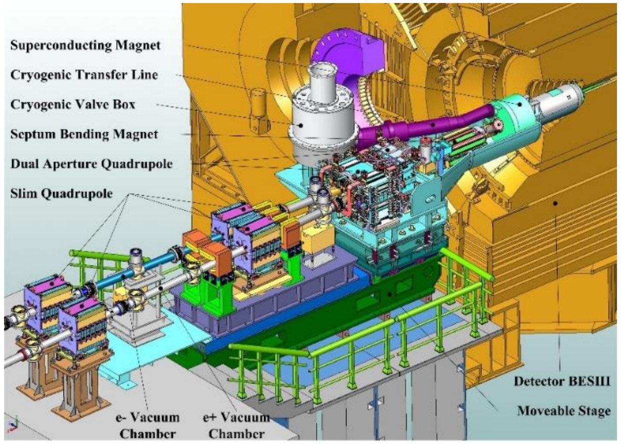
- Quench: a sustaining process brings whole magnet into normal conducting state.



- Potential risks:
  - Wire performance decline, insulation damage, magnet burnt out.
- Quench protection system (QPS):
  - Dump the stored energy outside or scattered inside to avoid hot spot over-heated. → < 300K.
    - Quench detector identifies the quench, QPS shuts down the power supply, switches to the protection circuit and triggers the quench heater.
    - QPS needs to record all the quench data for diagnostics.

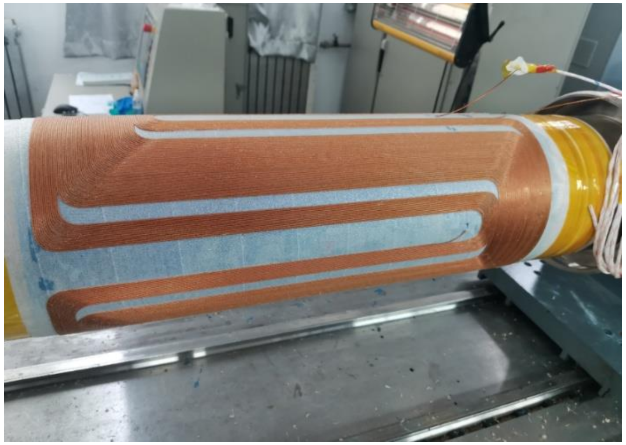
Superconducting magnet of BEPCII

- Two SC magnets are installed on each side of the BEPCII interaction point as final focus magnet.



The interaction region SC magnet of BEPCII is inserted into the detector.

BEPCII SC magnet has 3 anti-solenoids to compensate the detector's field.



The main coil is a 10-layers quadrupole which can provide 25T/m field.

Horizontal cryogenic test with field measurement.

Contents

1 Introduction and basic theories

2 Iron dominated electromagnet

3 Superconducting magnet

4 Permanent magnet

5 Magnetic field measurement

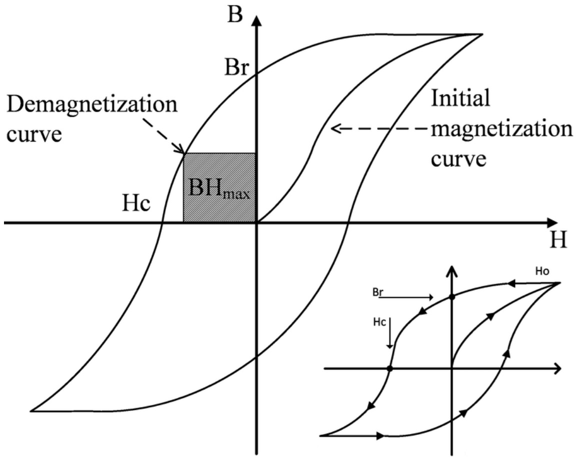
6 Special topics

Permanent magnet materials

•Permanent magnet material characteristics:

- High remanence & high coercivity → High energy product BH_{max}
- Demagnetization in high temperature and irradiation condition
- Permeability is close to μ_0 (vacuum)
- Easy axis: the direction of the remanence B_r points to.

Materials	Remanence	BH_{max}	Work temperature	Temperature coefficient
Unit	T	KJ/m^3	°C	10^{-4}/°C
AlNiCo	0.7~1.3	30~100	<550	1
Ferrite	0.3~0.4	10~30	<250	13
SmCo	1.0~1.3	180~250	<500	3
NdFeB	1.1~1.4	240~440	<220	10



Advantage and disadvantage of PM

- Comparing to the electromagnet

	Electromagnet	Permanent magnet
Advantage	☑ Tuning field by changing current ☑ High field achieved with SC magnet ☑ Improve field quality by shimming and chamfering	☑ No power consumption, low operating cost ☑ Compact structure, saving longitudinal space without coils ☑ No need for power supply and cooling water system
Disadvantage	☒ Power consumption ☒ Need auxiliary systems including power supply, power cables and cooling water system	☒ Field is not easy to change ☒ Large dispersion for material property and field quality is not so good ☒ Temperature coefficient demands stable operating condition ☒ Demagnetization by heat or radiation

Generate multipole with pure PM

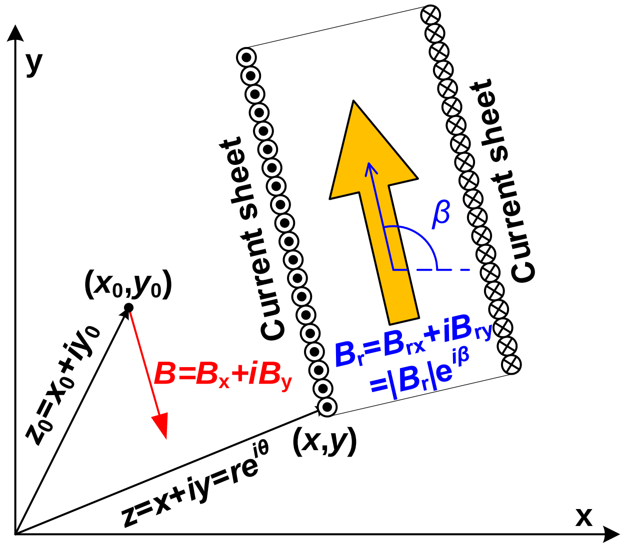
- Current sheet equivalent model (CSEM)

Complex conjugate B* is used cause it is analytic

$$B^* = B_x - iB_y = \frac{\mu_0}{2\pi i}\iint \frac{j dx dy}{z_0 - z}$$

$$B_r = B_{rx} + iB_{ry} \qquad \mu_0 j = \nabla \times B_r$$

Here is remanence, not the radial component



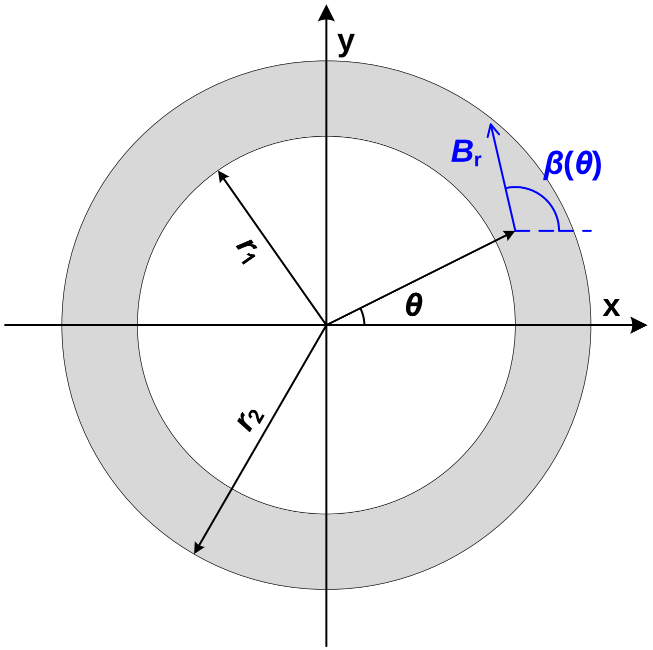
$$\frac{1}{(z_0 - z)^2} = \sum_{n=1}^{\infty} \frac{n z_0^{\,n-1}}{z^{n+1}} \quad \textbf{for} \quad |z_0| < |z|$$

$$B^* = \frac{1}{2\pi}\iint \frac{B_r dx dy}{(z_0 - z)^2} = \frac{n}{2\pi}\sum_{n=1}^{\infty}\iint \frac{|B_r| e^{i[\beta(\theta)-(n+1)\theta]} z_0^{\,n-1}}{r^n} dr d\theta$$

Generate multipole with pure PM

- Consider a PM ring with the easy axis satisfy:

$$\beta(\theta) = (N+1)\theta,\ N = 1, 2, 3, \cdots$$



Inside the ring:

$$N = 1 \qquad B^* = B_r \ln(\frac{r_2}{r_1})$$

$$N > 1 \qquad B^* = \frac{N}{N-1}\left|B_r\right|\left[(\frac{1}{r_1})^{N-1} - (\frac{1}{r_2})^{N-1}\right] z_0^{N-1} = C_N z_0^{N-1}$$

This is a N-order multipole field.

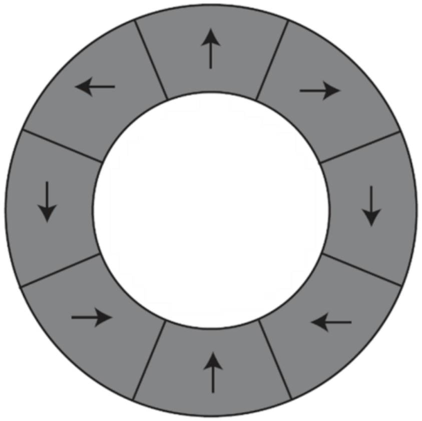
It can be proved that the field outside the ring is zero.

Field errors and correction method

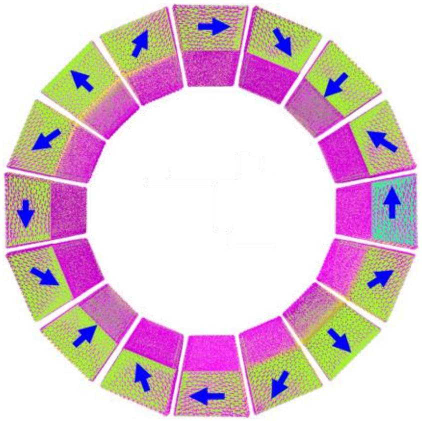
•Simplify for practice

Halbach array

- Idea distribution → Discrete distribution → Wedges assembly

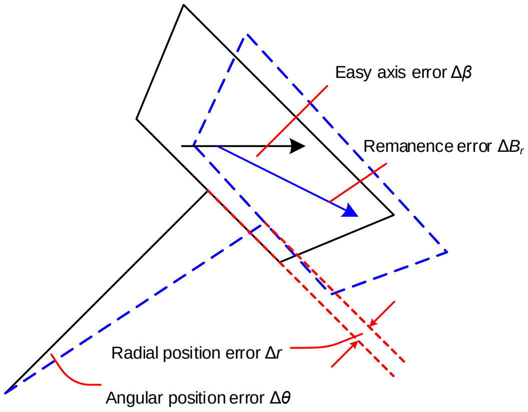


Dipole with 8 pieces



Quad. with 16 wedges

Photo of a quad.

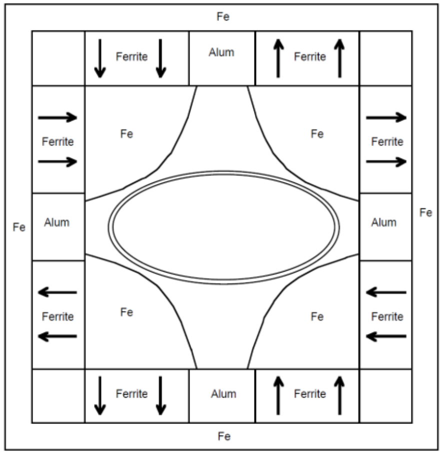


Errors for one wedge

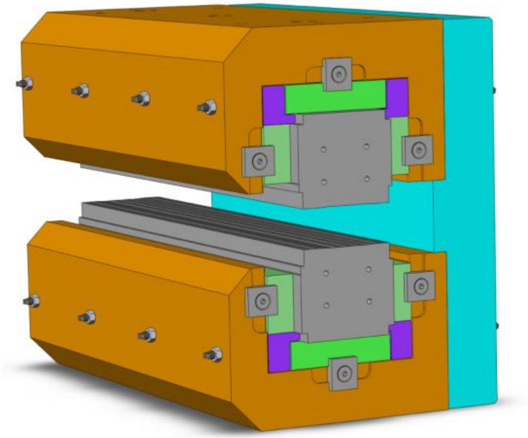
- The field quality is not ideal because of various of errors.
- Correction method: change the radial position of the wedges Intentionally to induce the multipoles opposite to the errors.

Hybrid magnet: PM+Iron

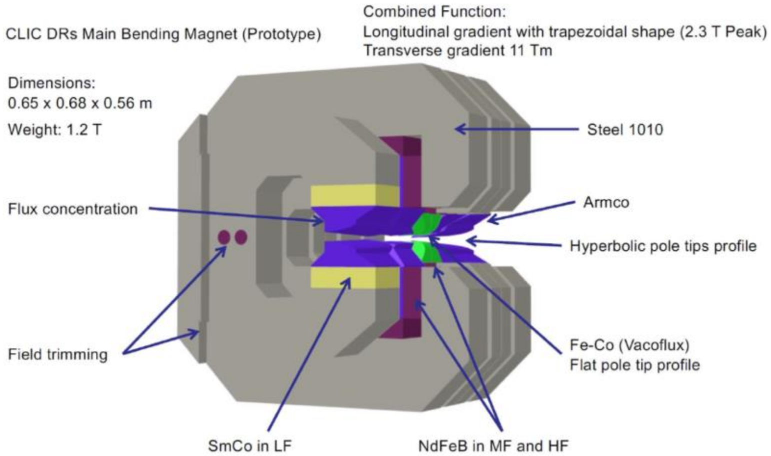
- PM substitute for the coils of iron-based magnet



Fermilab Recycler Ring quadrupole, made of ferrite.



Dipole of ESRF-EBS storage ring, made of Samarium Cobalt.



Prototype of CLIC bending magnet designed by ALBA, both Neodymium Ferrum Boron and Samarium Cobalt are used.

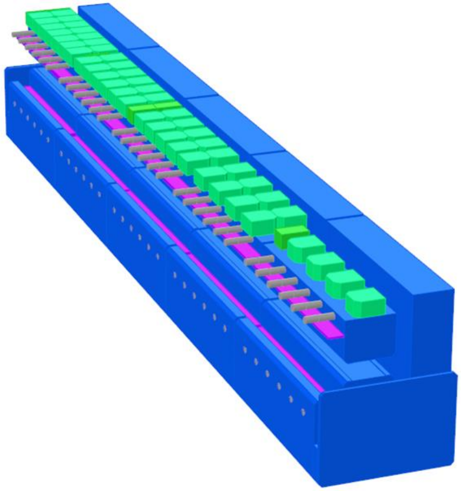
All these magnets have Iron poles to form desired multipole field just like electromagnet.

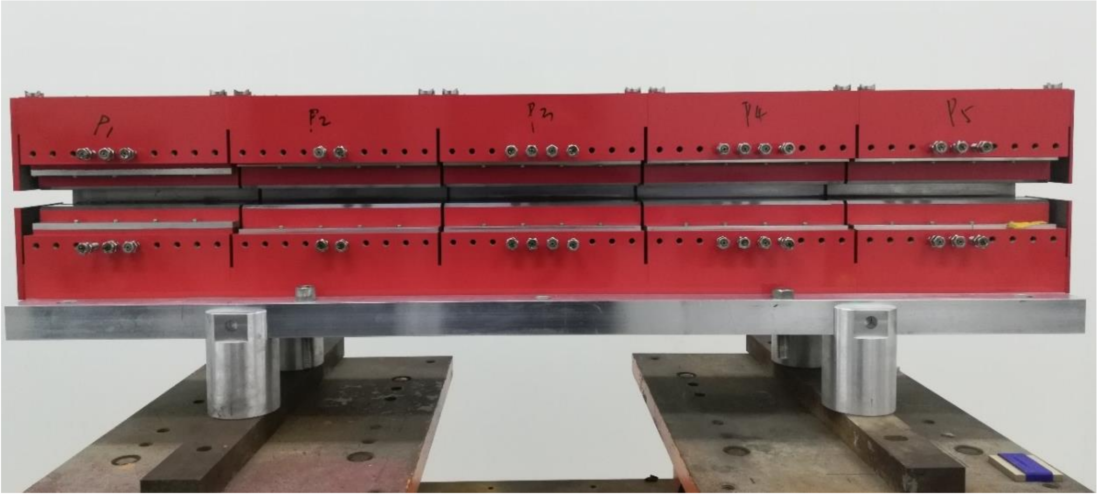
BLG magnet of HEPS

- 240 longitudinal gradient PM dipoles used for HEPS storage ring.

  - FeNi alloy is used to compensate the temperature coefficient to less than 50ppm/°C
  - Adjusting bolts are used to tuning the integral field in ±50ppm

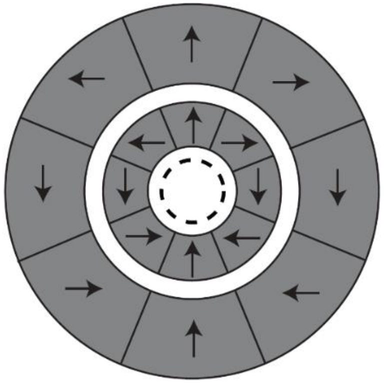
Offline tuning during field measurement

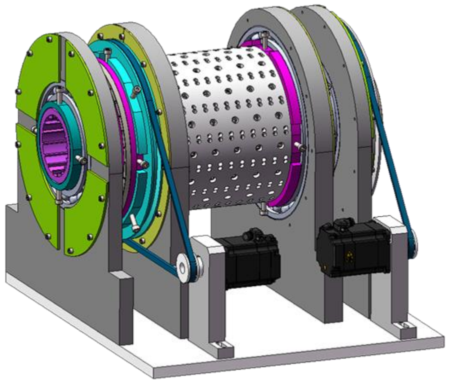




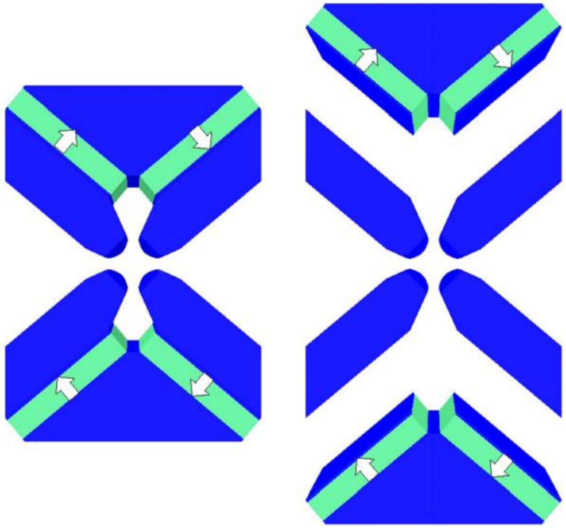
Future technology: strength tunable

- On-line tunable is necessary for quad. and sext.
  - Hybrid magnet with trim coil: tuning ratio <10%.
  - Large scale tunable method:
    - Change the flux path
    - Change the superposition

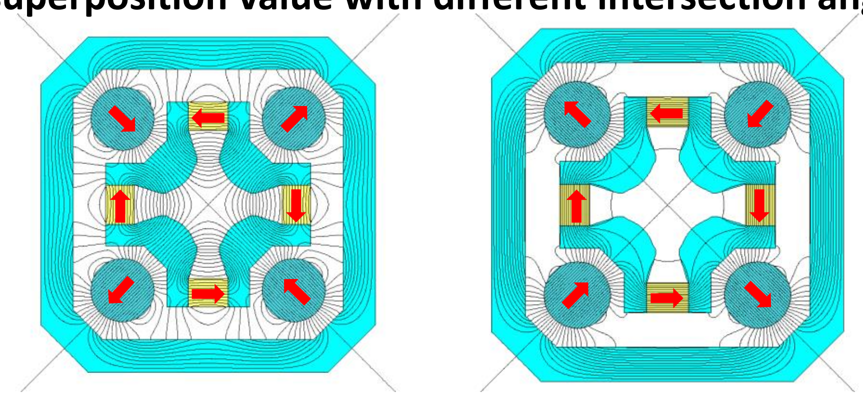




Rotate the inner and outer Halbach ring to change the superposition value with different intersection angle



Pull open the PM and pole to add air gap in the integral path of ampere's law



Rotate the cylinders to change the field at the center

Contents

1 Introduction and basic theories

2 Iron dominated electromagnet

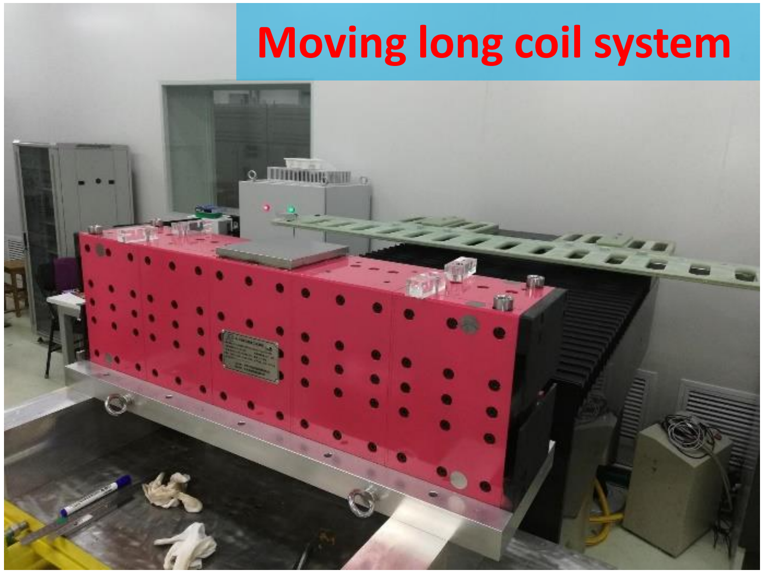
3 Superconducting magnet

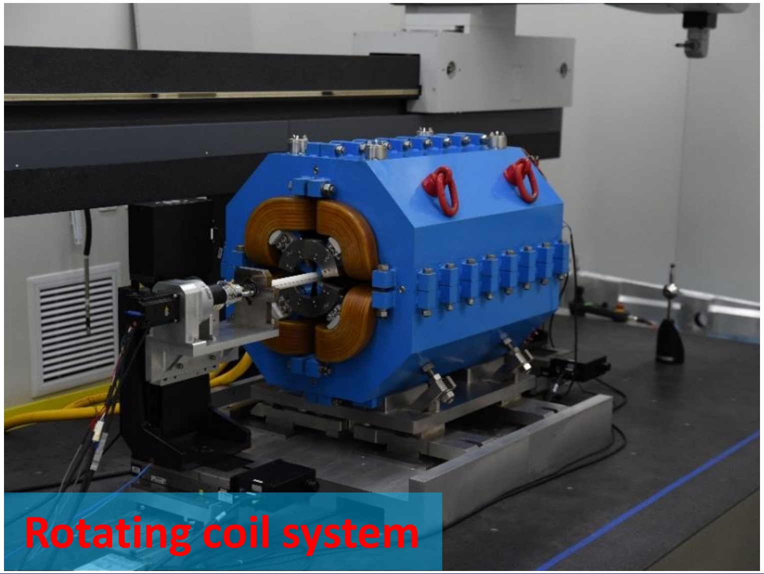
4 Permanent magnet

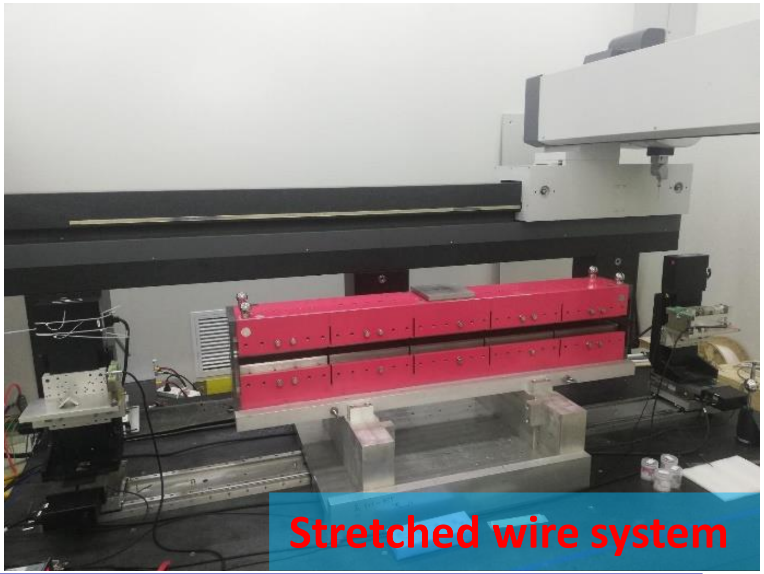
5 Magnetic field measurement

6 Special topics

Photos of measurement system







NMR & Hall probe system

- Absolute measurement with probe

	NMR system	Hall probe system
Principle	Nuclear magnetic resonance	Hall effect
Accuracy	$5*10^{-7}$ T	0.01% of reading
Measuring speed	10 s/sample	0.1 s/sample
Field gradient	< 1000 ppm/cm	-
Sensor size	~ 10*10 mm	~ 0.15*0.15 mm
Temperature effect	no	yes

- NMR system has very high accuracy independent to temperature, but the operation condition is very strict.
- Hall probe system is used for general purpose, and has very precise positioning.
- NMR system is used to calibrate the Hall probe system.

Rotating coil system

- Induced voltage of coil moving in the multipole

Consider the multipole field:

$$B_\theta + iB_r = \sum_{n=1}^{\infty} \left|C_n\right| r^{n-1} e^{i(n\theta+\phi_n)}$$

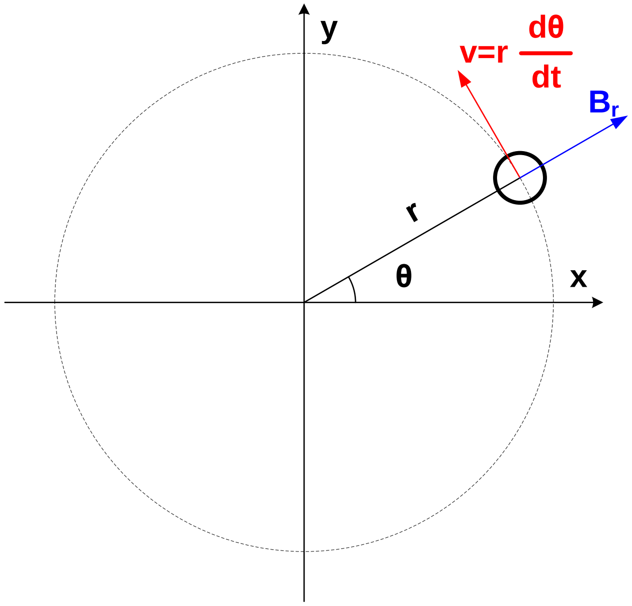
The radial component is:

$$B_r(\theta) = \sum_{n=1}^{\infty} \left|C_n\right| r^{n-1} \sin(n\theta + \phi_n)$$

The voltage induced by a one-turn coil perpendicular to the paper surface moving around the origin is:

$$V(\theta) = \left|\vec{v} \times \vec{B} L_{eff}\right| = B_r(\theta) L_{eff} r \frac{d\theta}{dt}$$

$$= \sum_{n=1}^{\infty} \left|C_n\right| L_{eff} r^n \sin(n\theta + \phi_n) \frac{d\theta}{dt}$$



Rotating coil system

Integrate the voltage over time:

After integration, the function no more depends on the rotating speed.

$$f(\theta) = \int V(\theta)dt = \int B_r(\theta) L_{eff} r d\theta = \sum_{n=1}^{\infty} -\frac{1}{n} \left| C_n \right| L_{eff} r^n \cos(n\theta + \phi_n)$$

On the other hand, use Fourier Series to express the periodic function:

Ignore the imaginary part and take symmetry into account.

$$f(\theta) = \sum_{n=-\infty}^{\infty} F(n) e^{i(n\theta + \phi_n)} \doteq \sum_{n=1}^{\infty} 2F(n)\cos(n\theta + \phi_n)$$

So the amplitude of n-order multipole is:

$$\left| B_n L_{eff} \right| = \left\| C_n \right| r^{n-1} L_{eff} \right| = \frac{2nF(n)}{r}$$

Of which: $F(n) = \frac{1}{2\pi} \int_0^{2\pi} f(\theta) e^{-in\theta} d\theta$

It means, using Fourier Transform on integral of the induced voltage of rotating coil, we will get the amplitude of multipoles from the coefficients of the Transform.

Rotating coil system

- Rotating coil system is used to measure the multipoles, usually the ratio to main component of integral field.
- 'Spill-down' field and the magnetic center

The n-order (n>=2) multipole:

$$(B_\theta + iB_r)_n = \left|C_n\right| r^{n-1} e^{i(n\theta+\phi_n)} = \left|C_n\right| (re^{i\theta})^{n-1} e^{i(\theta+\phi_n)}$$

If the magnet center shift: $\Delta r e^{i\delta}$

$$\begin{aligned}(B_\theta + iB_r)_m &= \left|C_n\right| (re^{i\theta} + \Delta r e^{i\delta})^{n-1} e^{i(\theta+\phi_n)} \\ &\approx \left|C_n\right| \left[(re^{i\theta})^{n-1} + (n-1)\Delta r e^{i\delta} (re^{i\theta})^{n-2}\right] e^{i(\theta+\phi_n)} \\ &= \left|C_n\right| (re^{i\theta})^{n-1} e^{i(\theta+\phi_n)} + \left|C_n\right| (n-1)\Delta r (re^{i\theta})^{n-2} e^{i(\theta+\phi_n+\delta)} \\ &= (B_\theta + iB_r)_n + (B_\theta + iB_r)_{n-1}\end{aligned}$$

A n-1 order field induced, so called 'spill down' field

$$\Delta r = \frac{\left|B_{n-1}\right| r}{(n-1)\left|B_n\right|}$$

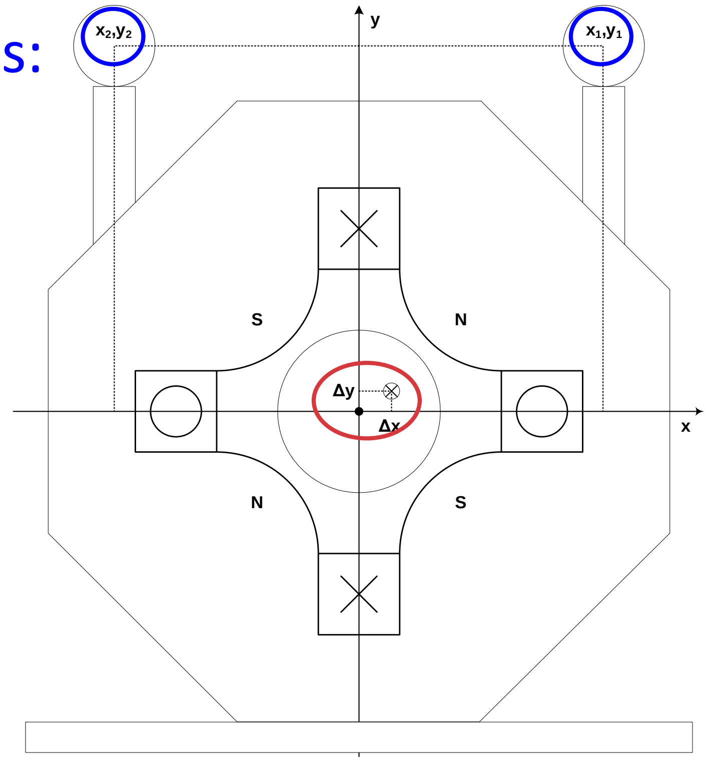
So we can calculate the offset of magnetic center to rotating axis according to the 'spill down' field.

Alignment in field measurement

- Align the magnetic center to the fiducial targets.
  - The magnetic center to the rotating coil axis, from field measurement:

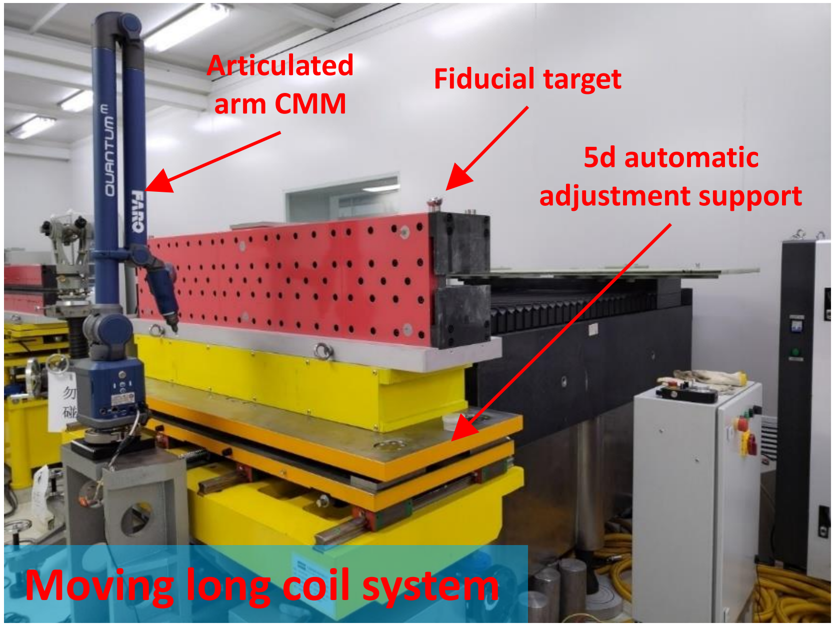
$$\Delta x = -\frac{B_{1y}}{B_2}, \quad \Delta y = -\frac{B_{1x}}{B_2}$$

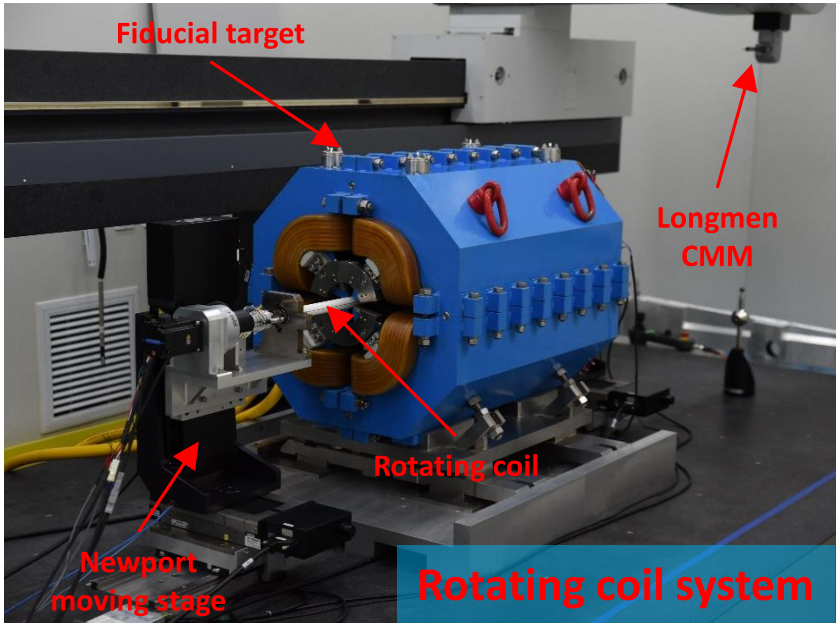
  - The rotating coil axis to fiducial targets:
    - Optical instruments such as theodolite, precision: 30~50 µm
    - Laser tracker, precision: 20~25 µm
    - Coordinate measuring machine, precision: 5~7 µm
  - 4^{th} generation light source alignment requirement: 30 µm on same girder.



Automation in magnet measurement

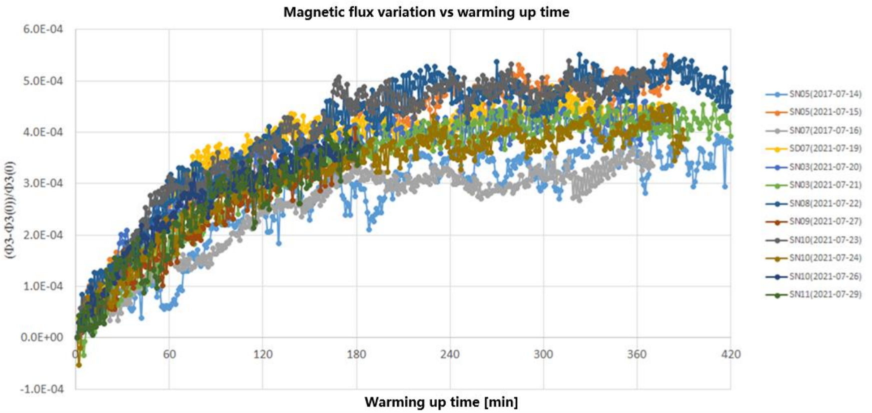
- By programming the alignment and motion devices, alignment process is implemented automatically.
  - Magnet to measuring coil or measuring coil to magnet.
  - Improve the measurement efficiency and precision dramatically.

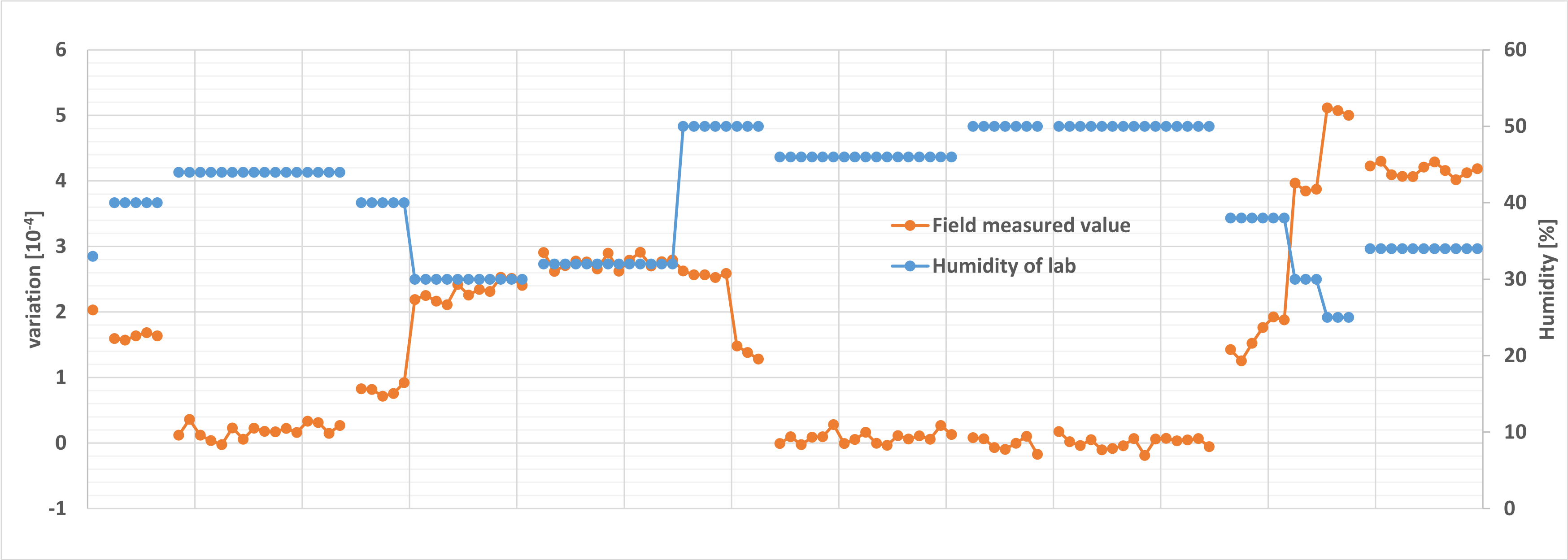




Effect of lab environment

- Warming up before measurement
- Keep the temperature and humidity steady.





Contents

1 Introduction and basic theories

2 Iron dominated electromagnet

3 Superconducting magnet

4 Permanent magnet

5 Magnetic field measurement

6 Special topics

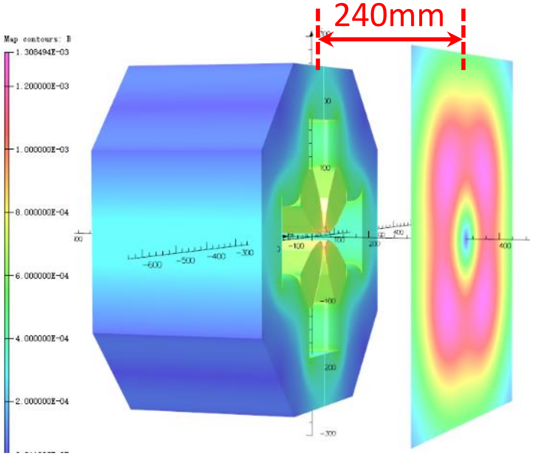
Crosstalk studies in HEPS

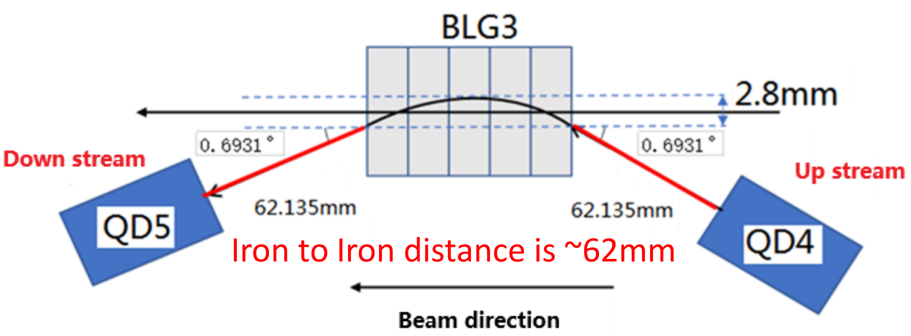
- Cross-talk is caused by leakage field

Magnet type	BLG3	BD1/2	QD5	SD2/3	OCT1/2
Magnet aperture[mm]	26	45	26	26.6	30
Influence range [mm] *	30 **	260	240	130	145

* Influence range is defined by leakage field < 10Gs

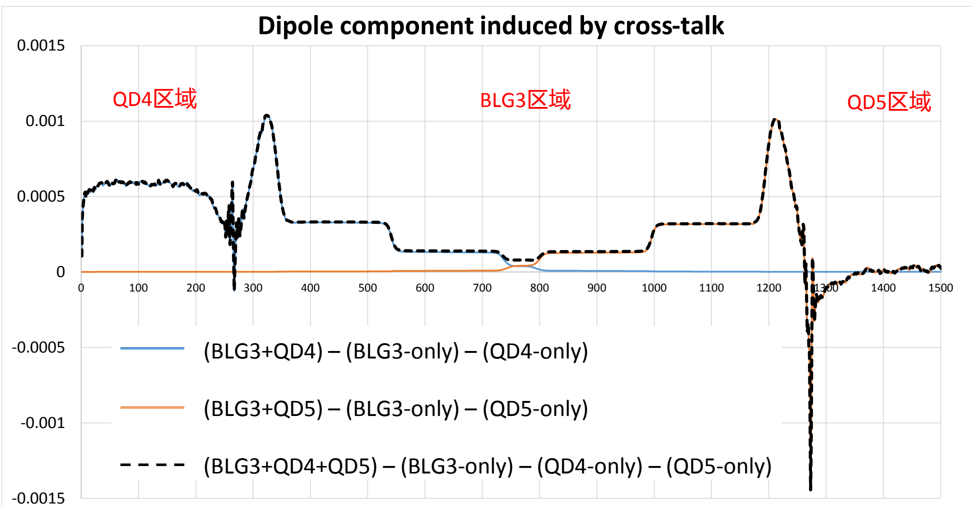
** Leakage field of BLG magnet is suppressed by end shielding plate

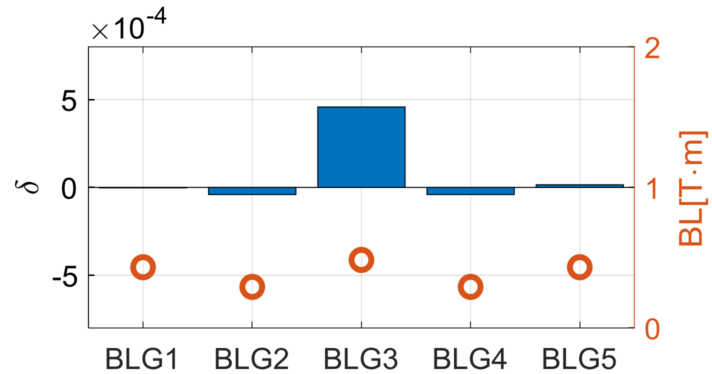




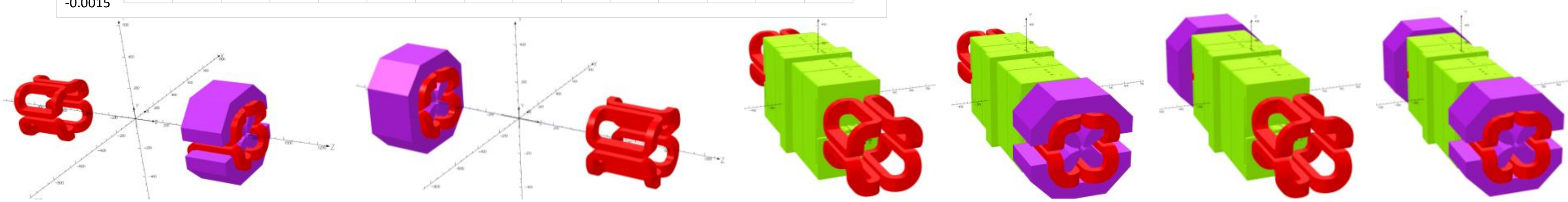
Crosstalk simulation and correction

- Modelling for different situations in OPERA-3d and Calculating the variations of dipole and quadrupole along the beam direction





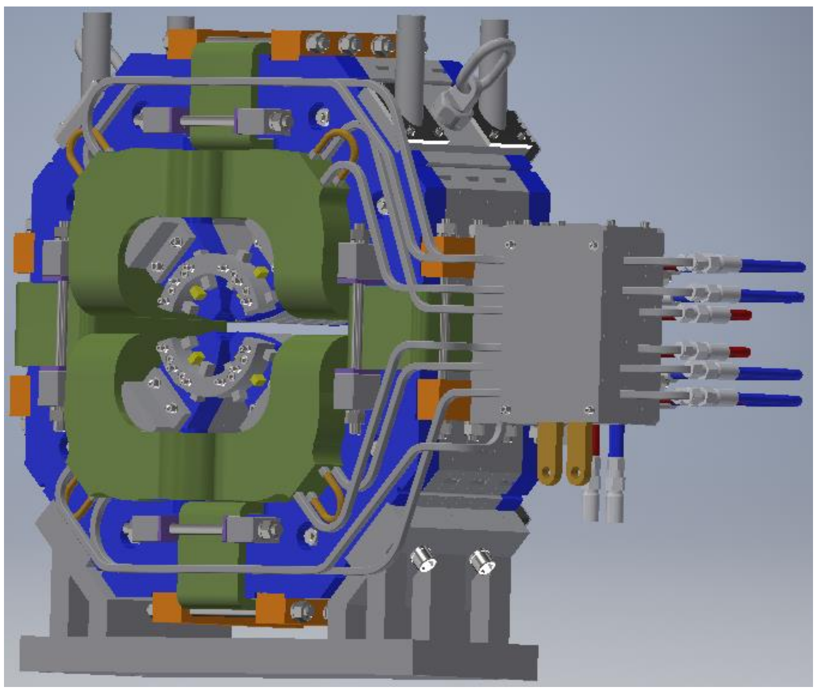
For permanent magnet, the crosstalk induced variation must be corrected before the magnet installed into tunnel.

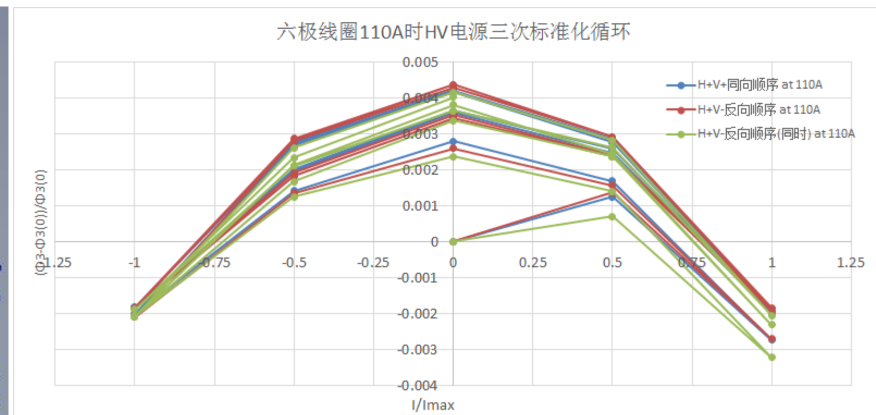


QD4-only **QD5-only** **BLG3-only** **BLG3+QD4** **BLG3+QD5** **BLG3+QD4+QD5**

Interference of trim coil & main coil

- To save space, some quad. and sext. have trim coils to provide horizontal or vertical beam orbit correction.
- The main field changes when trim coils are powered.



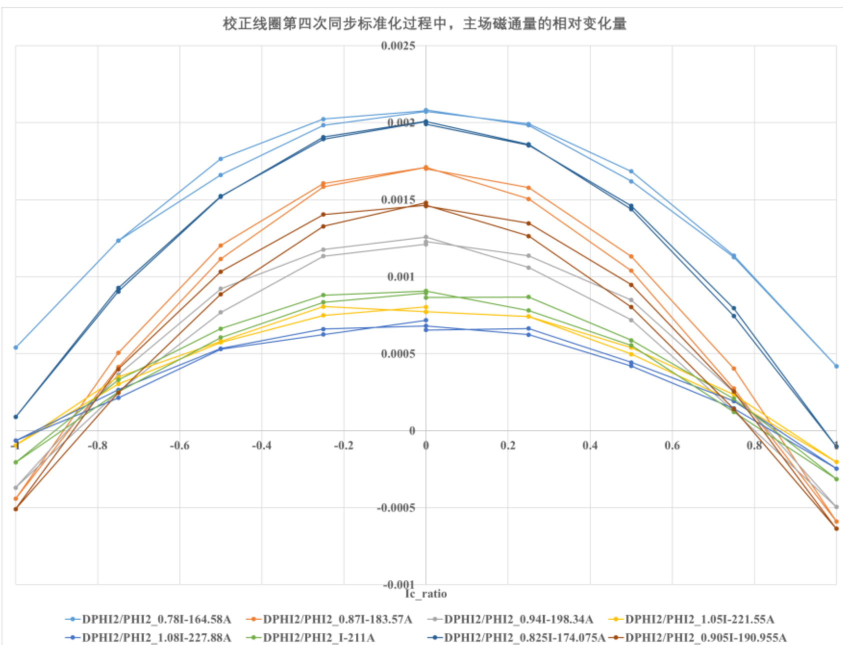


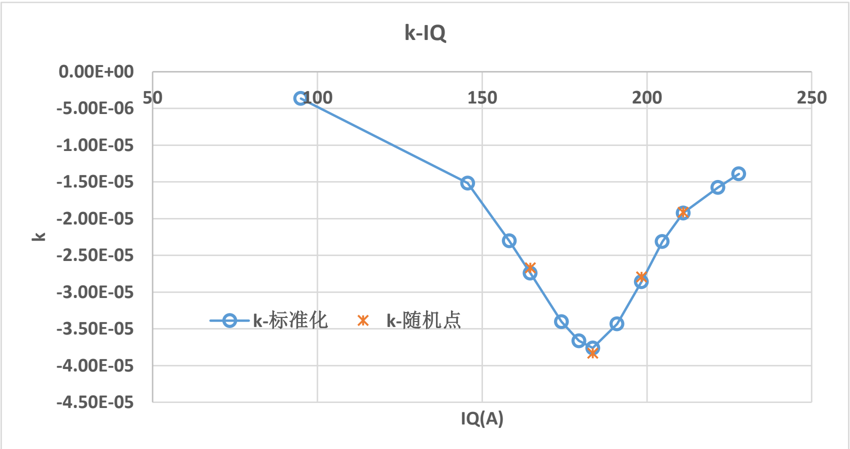
In case of sextupole, the change ratio of the main field is up to 0.45% and depends on the current of trim coils.

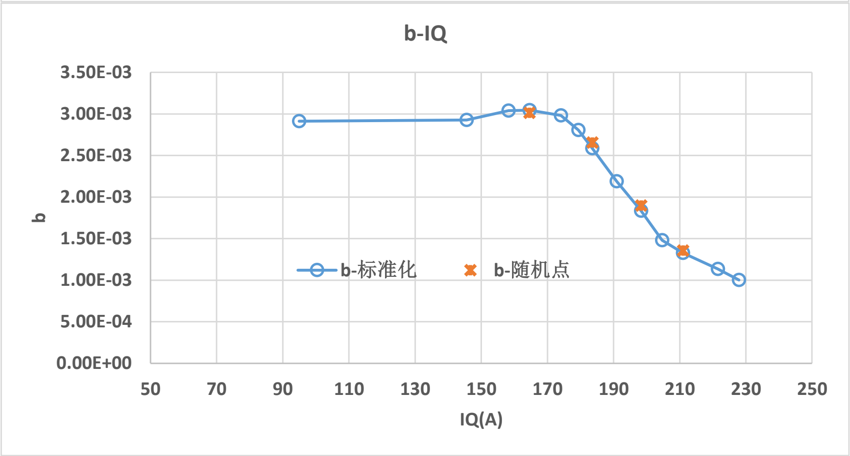
Trim coil effect

- The change ratio of main field $\delta\varphi$ depends on main coil current (I_M) and trim coil currents (I_H/I_V).

$$\delta\varphi = k_{I_M}\left(I_H{}^2 + I_V{}^2\right) + b_{I_M}$$







Codes for magnet design

Code Name	Description
Poisson	A free 2d code package developed by Los Alamos National Lab and still be often used for quick rough simulation and iteration.
OPERA (CST)	A powerful commercial 3d code package developed by a British company and now belongs to a French company DASSAULT. This code is widely used for magnet design. The simulation result is highly consistent to the real magnet.
RADIA	A professional free 3d code package based on a commercial software Mathematics and developed by a French laboratory ESRF. This code is widely used for permanent magnet design as well as electromagnet.
ROXIE	A 3d program developed by CERN and dedicated to electro-magnet, especially to superconducting magnet simulation. A one-off fee is required for non-profit institutions such as universities and labs.

References

- Iron dominated electromagnets design, fabrication, assembly and measurements, Jack Tanabe, Jan. 6, 2005.
- Proceedings of the CAS – CERN Accelerator School: Magnets, 16-25 Jun 2009, CERN-2010-004.
- Field computation for accelerator magnets, Stephan Russenschuck.
- Magnet technology, 10th OCPA accelerator school, Jyh-Chyuan Jan, 2018.

Thanks for your attention

Welcome to HEPS, the first 4th Generation light source in Asia