PSI Center for Accelerator Science and Engineering

Room temperature Accelerator Magnets
An introduction in 60 min

CAS Mechanical & Materials Engineering for Particle Accelerators and Detectors
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A magnet is a material or a technological system that produces a magnetic field

Scope and limitations

PSI

Topics:

Object of the course: Magnets for <u>accelerators</u>

Types of magnets and function

Characteristics of three types of magnets (permanent; electro-magnets; superconducting → next course)

Magnet construction cycle : overview for the design, assembly and magnetic tests

Examples taken with magnets designed at the Paul Scherrer Institut

Not in this course :

- electromagnetic theory
- a course on superconductivity
- dynamic effects (eddy current effects, loss….)

Recommended Reading

conventional magnets

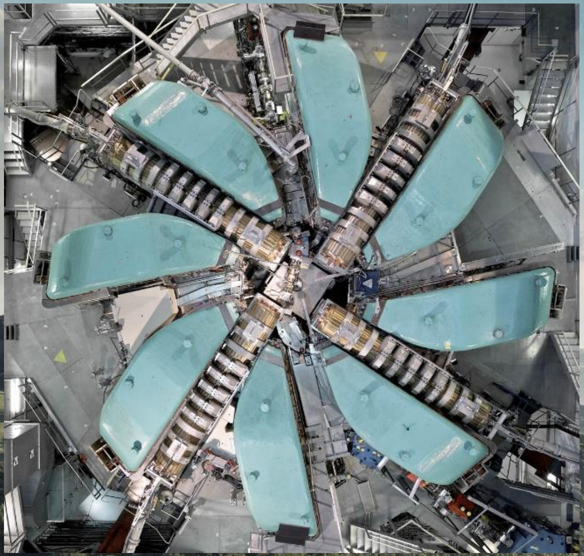
- CAS Bruges, 2009, specialized course on magnets, 2009, CERN-2010-004
- “Warm magnets”, D. Tommasini, CAS, Varna, 2010
- “Normal Conducting magnets”, Th. Zickler, JUAS, 2018
- “Permanent Magnets”, G. Le Bec, CAS course on Normal- and Superconcting magnets; St Pölten, *2023*
- “Conventional Magnets for Accelerators”, Ben Shepherd , https://www.cockcroft.ac.uk/wp-content/uploads/2016/07/Magnets-basic-course-Lecture-2-BJAS-2016.pdf, 2016
- “Resistive & Permanent Magnets for Accelerators”, J. G. Weisend https://indico.cern.ch/event/78565/contributions/2089949/attachments/1058809/1509743/Resistive_Magnets_for_Accelerators.pdf
- Iron Dominated Electromagnets, J. T. Tanabe, World Scientific, 2005
- Field computation for accelerator magnets, S. Russenschuck, Wiley, 2011

Aknowledgement

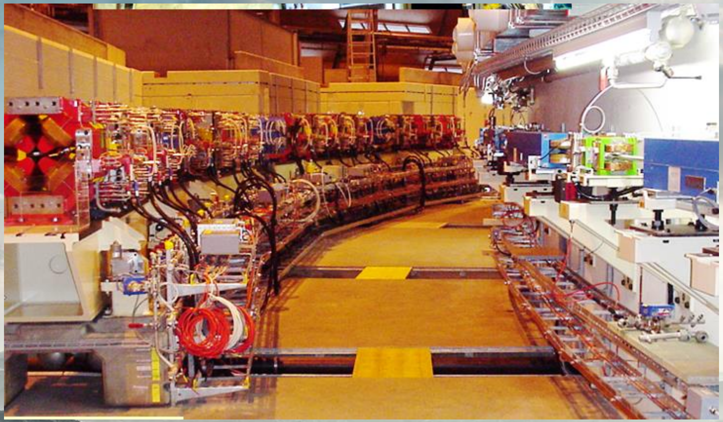
- The information and results reported here are based on the collective work of the Magnet Section Team at PSI

- Special thanks to my CERN colleagues *M. Buzio, L. Bottura, A. Milanese, D. Tommasini, Th. Zickler* , to my ESRF colleagues *G. Lebec, C. Benabderrahmane and J. Chavanne* for providing information, material and discussions during many years.

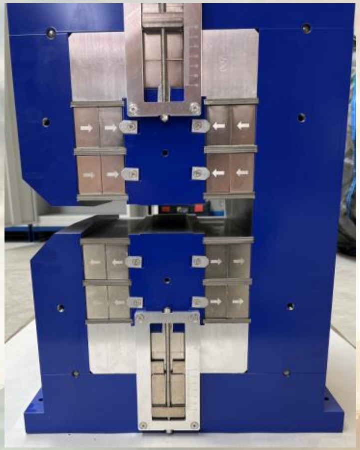
Conventional Magnets for Large Research Facilities



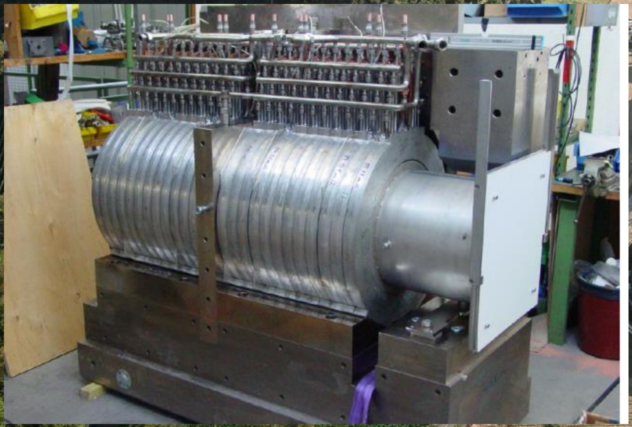
PSI – Dipoles
High Intensity ring cyclotron



PSI – Electro-quadrupoles
(SLS)



PSI – Superbend with Permanent
Magnets: Upgrade SLS



PSI – Double solenoid
High Intensity ring cyclotron

PSI – Electro-dipole
Gantry II (protontherapy)

PSI – Sextupole & Octupole
Upgrade SLS

Role of magnets in the accelerator

Magnets are an important part of accelerator components

Particle accelerators operate with charged particle beams (e.g. electron, protons, ions, positrons, antiprotons etc)

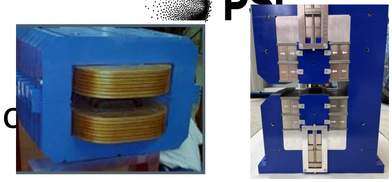
Interaction of these charged particles and the magnet field allows manipulation of the beam

$$\overrightarrow{F} = e\vec{v} \times \vec{B}$$

Uses of Magnets in Accelerators

Bending: Magnets can bend the paths of charged particles, allowing them to travel alo curved paths as required by the accelerator's design

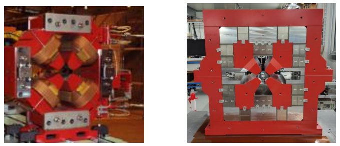
- Dipoles



Dipoles

Focusing of Beam: Magnets are used to focus beams in the arcs and at interaction points where particles collide, enhancing collision rates and experimental efficiency

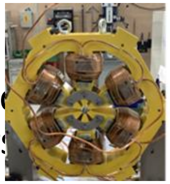
- Quadrupoles



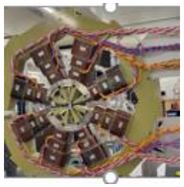
Quadrupoles

Beam Correction

- Sextupoles, octupoles, decapoles….



6-poles



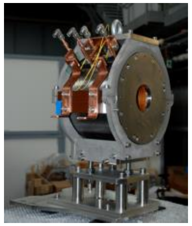
8-poles

Beam "Compression" or Energy Selection: used to select particles of a specifi energy range by bending trajectories of particles of certain energies while allowing other continue straight.

- Chicanes using dipoles

Focusing and guiding charged particle beams, particularly in experiments where precise control over the beam's trajectory and shape is required. over the beam's trajectory and shape

- Solenoids



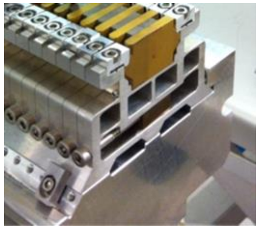
Solenoid

Beam direction for application: Magnets are utilized to extract particle beams from accelerators for various applications, such as medical therapy, materials processing

- Undulators

Inducing oscillations in the particle beam to create synchrotron light

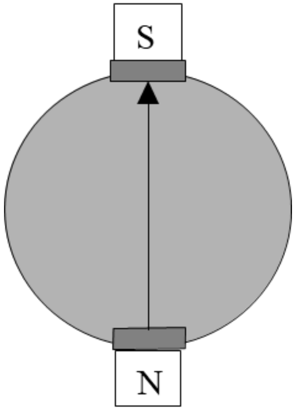
- Permanent Magnets in Undulators (Insertion Devices)



U15 ID

Magnet types

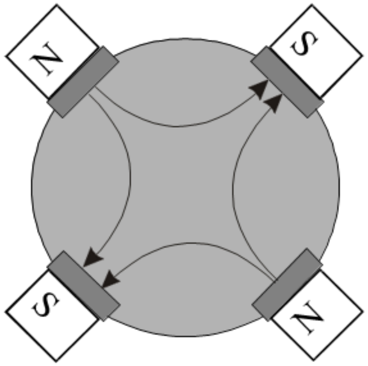
NORMAL: vertical field on mid-plane



Dipole

$|B|=const$

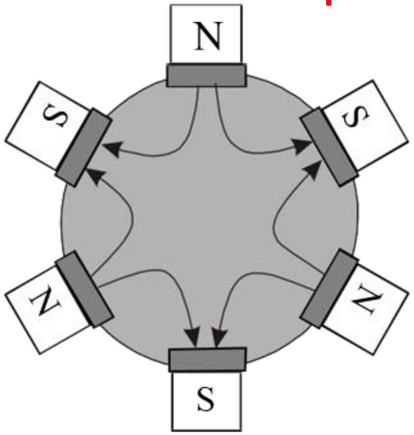
Bending



Quadrupole

$|B|=G\cdot r$

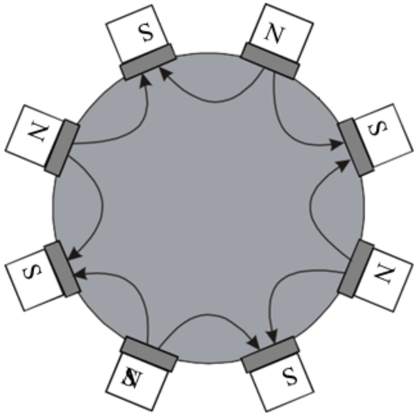
Focussing/ defocussing



Sextupole

$|B|=1/2\cdot B''\cdot r^2$

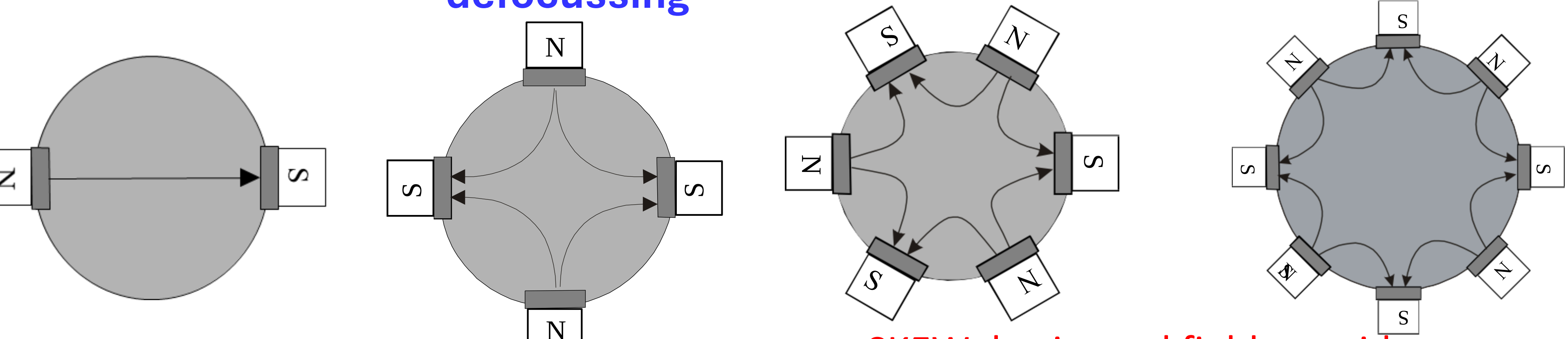
Chromaticity



Octupole

$|B|=1/6\cdot B'''\cdot r^3$

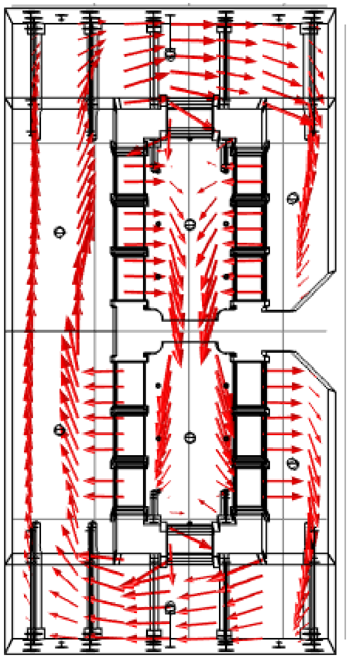
Correction errors



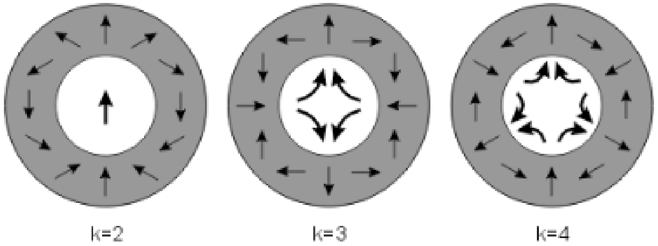
SKEW: horizontal field on mid-plane (rotation by π/n)

Davide Tomasini (CERN) –CAS Introduction to particle physics- Magnets Varna, 2010

Magnet geometries

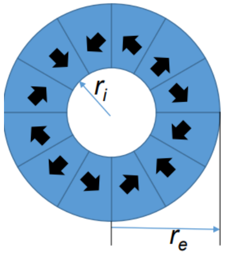


PM Dipole (SLS2.0 dipole)

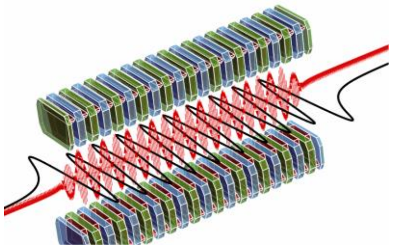


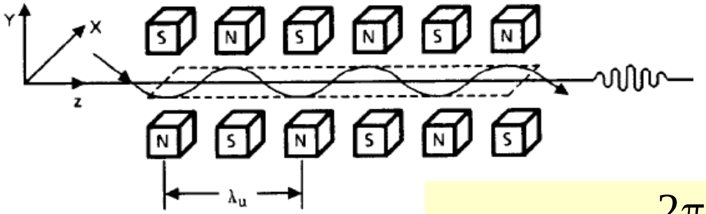
Halbach arrangement Dipole, quadrupole, Sextupole (no yoke!, verstatility, tunability)

$$G = 2B_r K \left(\frac{1}{r_i} - \frac{1}{r_e}\right)$$



Halbach, NIM 169, p. 1-10 (1980)





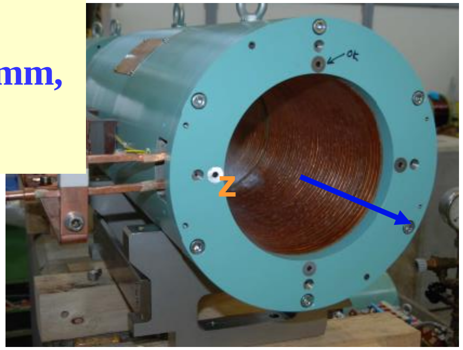
$$B_y = B_0 \sin\frac{2\pi s}{\lambda_u}$$

Insertion device U15 (arrays of NdFeB magnets with permendur poles)

SwissFEL Solenoid

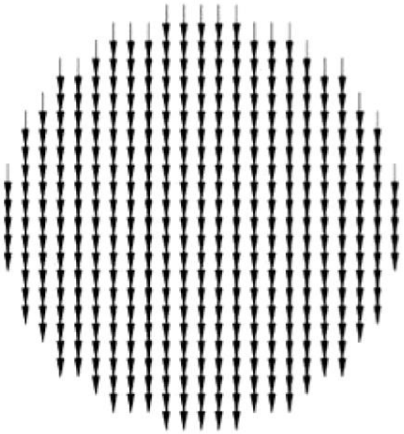
0.1 T, Φ=220mm,

l=0.75 m

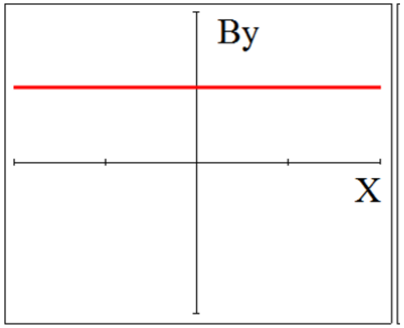


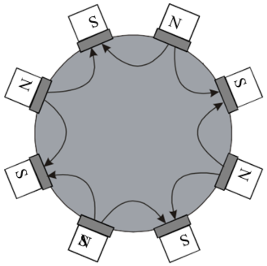
Main field component in z-direction, focusing by end fields

Field Distribution



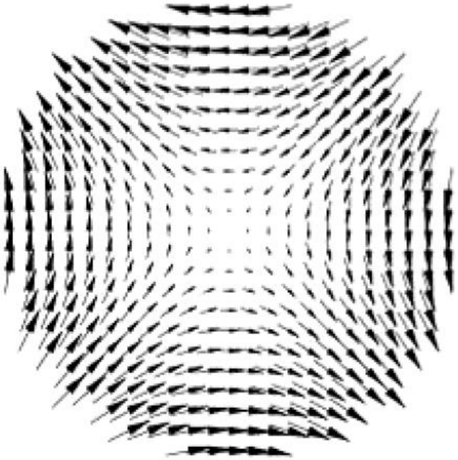
constant field



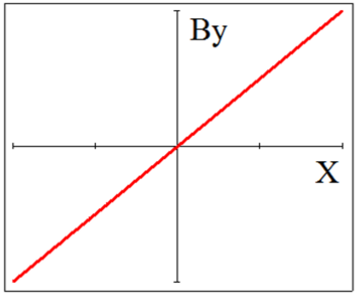


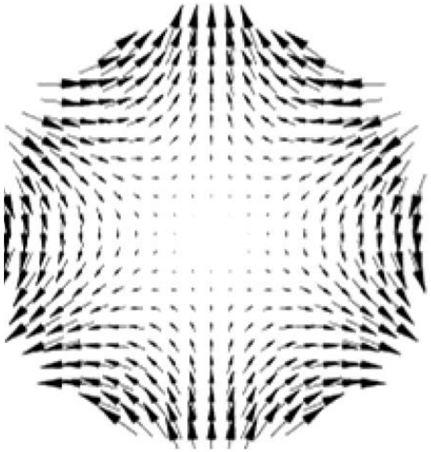
Octupole

$|B|=1/6\cdot B'''\cdot r^3$

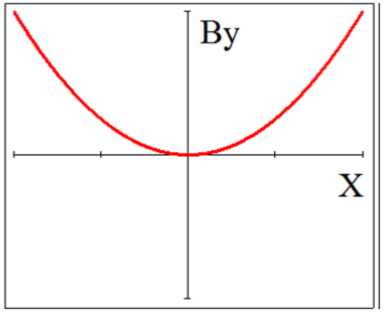


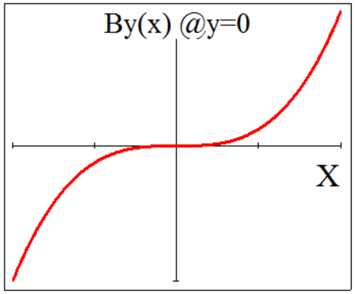
Field varies linearly with the distance from the magnet center





The field varies quadratically with the distance from the magnet center





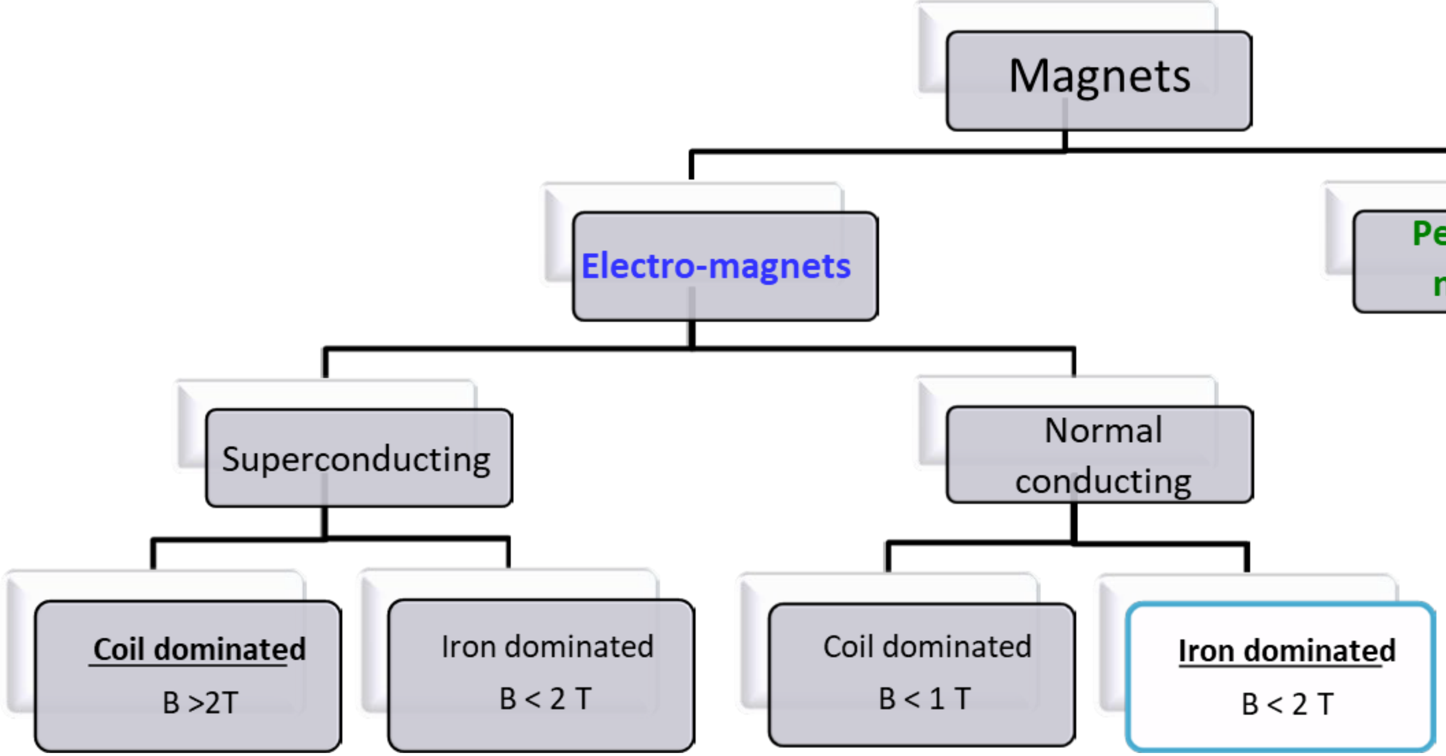
The field varies in a cubic way with the distance from the magnet center

Requirements of an accelerator magnet

- operation mode (continuous, pulsed, ramp rate T/s)
- physical constraints (space, transport, weight ...)
- physical aperture
- strength (field integral)
- good field region (the region where the field quality has to be within certain tolerances- in general a typical value of 2/3 of the physical aperture radius.)
- field quality at the different working conditions
- alignment (mag/mech axis position)
- power supply
- cooling
- radiation exposure
- reliability

Davide Tomasini (CERN) –CAS Introduction to particle physics- Magnets Varna, 2010

Magnet technology choice



- Magnets
  - Electro-magnets
    - Superconducting
      - **Coil dominated** B >2T
      - Iron dominated B < 2 T
    - Normal conducting
      - Coil dominated B < 1 T
      - **Iron dominated** B < 2 T
  - Permanent magnets

Next course

- Permanent magnets provide only constant magnetic fields
- Electro-magnets can provide adjustable magnetic fields
- Superconducting magnets: B >>2 T
- B<2T : the field dis dominated by the iron yoke
- B>2 T : the field is dominated by the current coils

Magnet technologies: Figures of merit

Type	Advantages	Disadvantages
Permanent technology	+ Compact and Lightweight (no coils, no water pipes) + No power supply + Low operation costs (zero power consumption, no water) + No maintenance (water pipes) + Less control systems, cables, noise + high reliability and robustness + Long operational life time*	– Constant field (tuning; 1-2 %) – Limited in field strength (1-2T) – Permanent magnet magnetization variability (~2 %) – Thermal stabilization needed – Radiation effect (performance)? – Magnetic coupling difficult to compute and correct at the 0.1 % level
Normal conducting (electro)magnets	+ Flexibility - Variable field + Moderate field (up to 2 T) + No need for complicated cryogenic or vacuum systems + Well know technology	– Larger transverse size – Limited in field (up to ~ 2 T) – Moderate operating costs for power & water – Maintenance required
Superconducting technology	+ High fields & Variable fields + Can be made compact + Low power consumption Often for high fields (>>2T)	– Complex design – High costs for the manufacturing and cryogenic system – complicated cryogenics, vacuum, quench protection

*** Except in radiation environment**

SLS2.0 vs SLS: Permanent magnets for energy savings

alexander.gabard@psi.ch

SLS2.0 Triplet = VB-BN-VB

Total number of triplets: 60

BN: By=1.35 T; VB: GdL=-40.64 T/m

Total Weight=1250 kg

60 Triplets ~Total P=0 W

SLS BX Dipole

Total number of BXs:12
By=1.39 T ; I=407 A; R= 58 mΩ;
Weight=2950 kg
Cooling= 16 l/min

BX: P= 58 mΩ x (407 A)^2= ~9.6 kW

12 BX ~ Total P: 116 kW

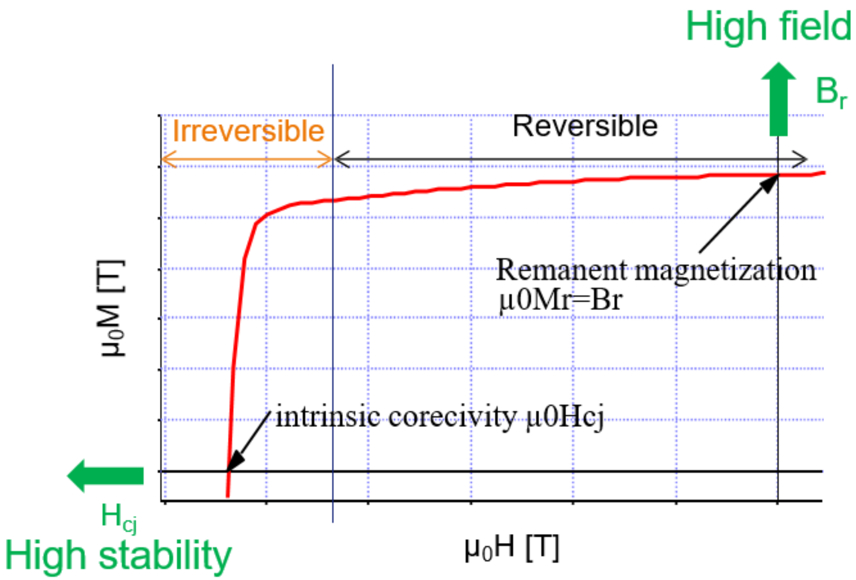
SLS dipoles : 116 kW x 6800 operating hours ; 789 MWh per year

Savings for 15 Years : 11.83 GWh

Permanent magnet components

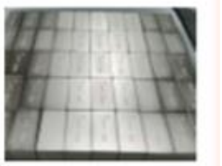
- Permanent magnet are ferromagnetic materials with high coercitivity and High Magnetization values along an Easy Axis
- The magneto-motive force comes from intrinsic material properties

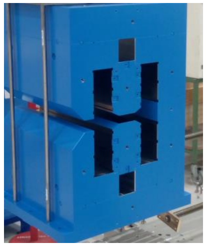
Type	B_r (T)	H_{cj} (kA/m)
Sm_2Co_{17}	1.05 – 1.15	1500 – 2100
$Nd_2Fe_{14}B$	1.06 – 1.45	900 - 3000

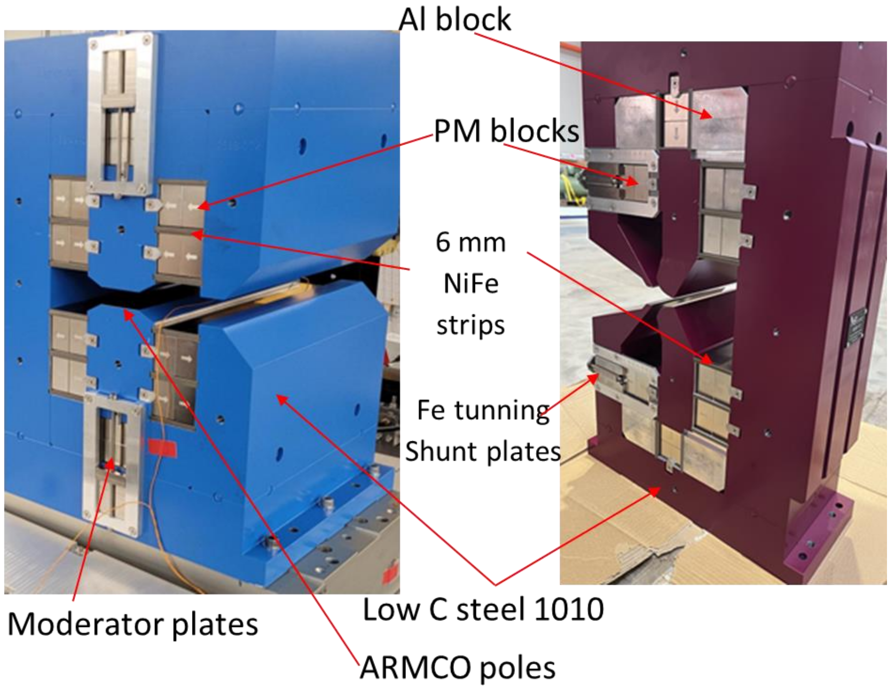


Courtesy: Chamseddine BENABDERRAHMANE

Permanent magnet for accelerator:
- PM blocks
- Thermal shunts
- Yoke (low C-steel)
- Shims, moderator plates for tuning the field integral (~up to few %)

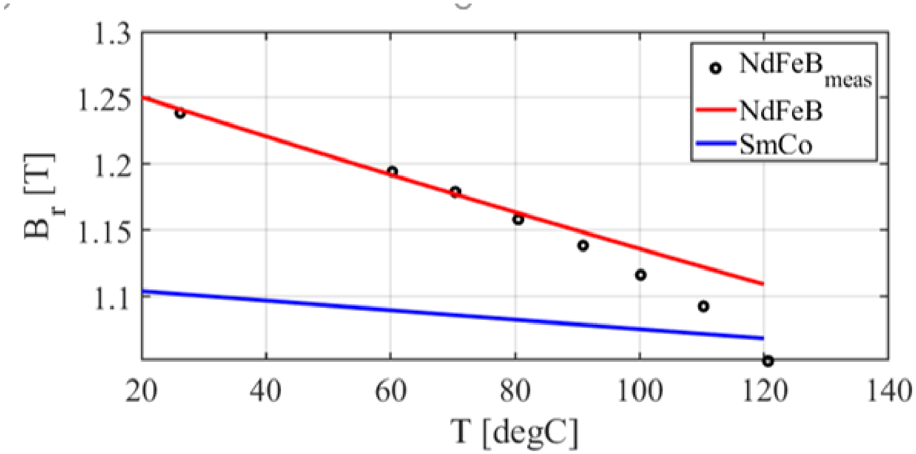






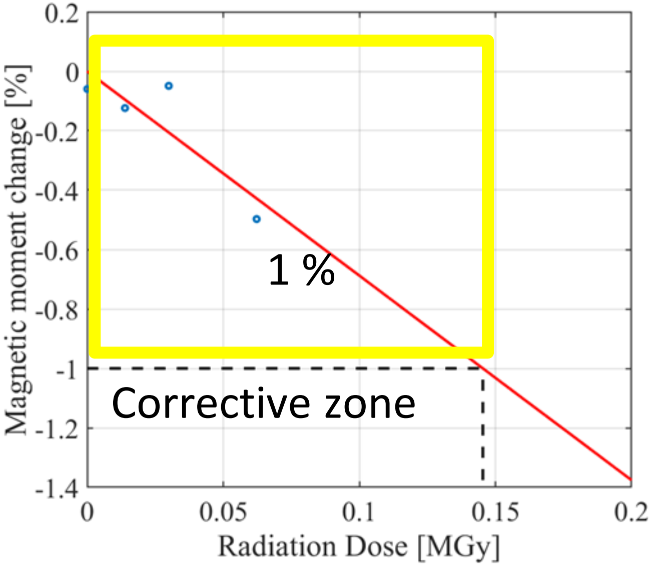
Permanent magnet blocks -magnetisation control

Temperature stability :
dominated by the material temperature coefficient (dB/B)/dT



(Linear) reduction of 0.12 %/°C for NdFeB

Radiation damage with time (litterature-A. Temnykh)



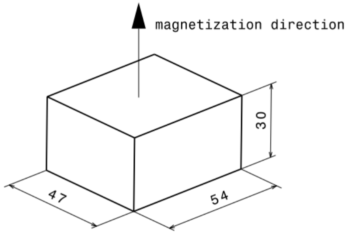
Temperature stabilisation with **passive NiFe shunts**
for a relative field integral variation ~ **0.015%/°C**

Problem after a cumulative dose of **0.15 MGy** ?

But: PM blocks are not close to the beam pipe

the dose is mostly onto the iron poles

Example: Magnets with $Nd_2Fe_{14}B$ for the blocks (SLS2.0 light source)



- block size for all magnets: 30 mm x 47 mm x 54 mm

(30 mm : direction of the magnetization)

- Rare earth : **$Nd_2Fe_{14}B$** (Remanent field : ~1.3 T)
- Weight : 0.57 kg
- Coercive field : 1015 kA/m
- Temperature dependence : 0.12 %/°C

  (thermal stabilization needed)

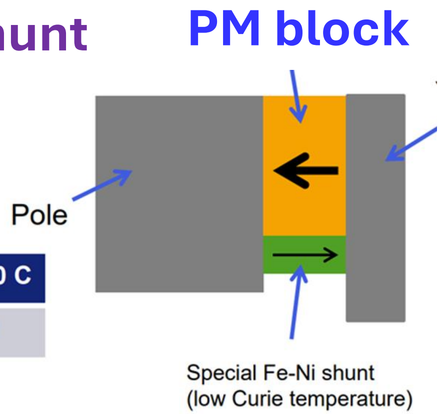
  passive thermal shunts→ reduced magnetization for the same cross-section

Thermal shunt

$$\Phi_{gap} = \Phi_{PM} - \Phi_{shunt}$$

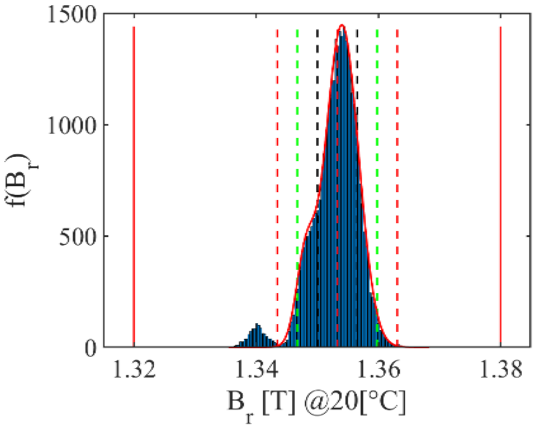
Material	Curie T	B at 20 C
55/100 G	55	0.22

THERMOFLUX (VACUUMSCHMELZE)



G.W. Foster et al., EPAC98, Stockholm, Sweden, 1998

Stabilization up to 0.01 %/K with 6 mm thick NiFe strips



34000 blocks

Magnetization distribution within +/-2 %

PM sorting and distribution before the PM insertion in the yoke

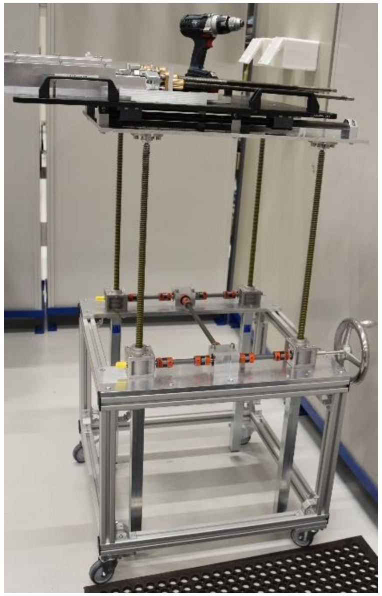
SLS 2.0 Magnets:

~90 NdFeB blocks in average

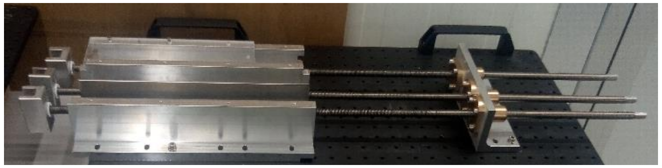
Permanent magnets assembly: Safety warning in handling strong PM magnets

strong forces of PM-blocks require **special tools** and **procedures** for assembly and handling

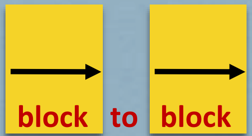
Lifting table



Detail of the insertion rods.



PM-block sizes:
30 mm x 47 mm x 54 mm

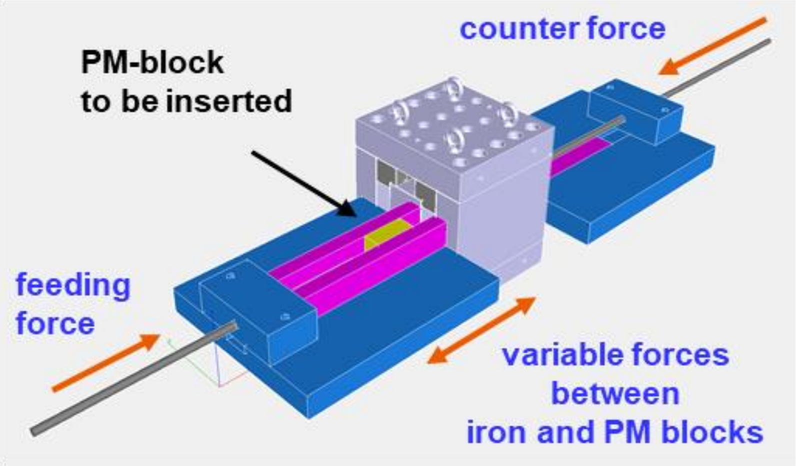


block to block
magnetic pull ≈ 180 kg

Assembly table mounted around the BN magnet.

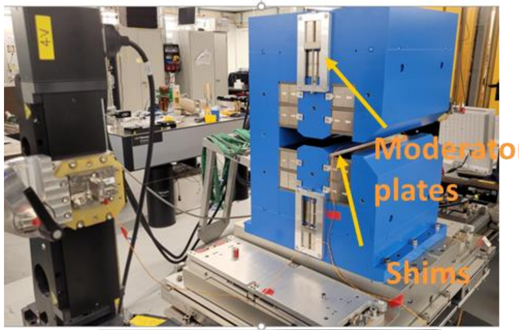
Compensating screws

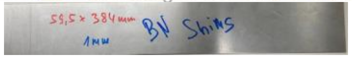
Forward screws

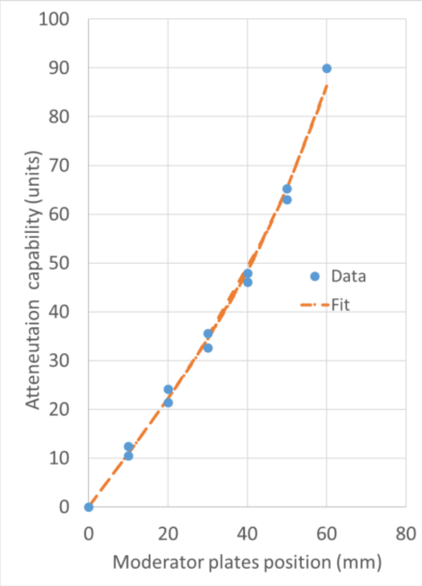


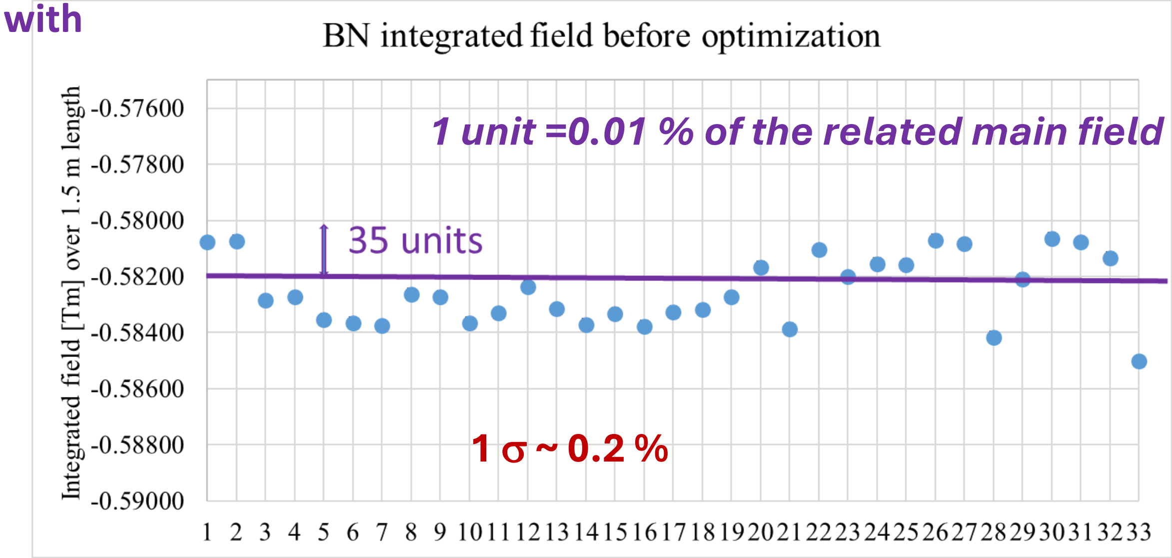
Tunability of the Field integral of a dipole tuning using shims and moderator plates

Single magnets measured/optimized with the moving wire (Field Strength)









Measured field integral of 33 dipoles before optimization

Field Integral	Not Optimized SLS2.0 dipole	Optimized SLS2.0 Dipole
Average	-0.5823 Tm	-0.5724 Tm
σ (% of the main field)	0.2	0.01

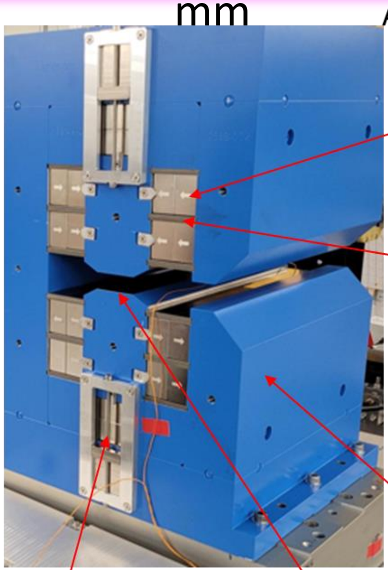
Optimization with (0.75 -1 mm thick) shims +moderator plates successful

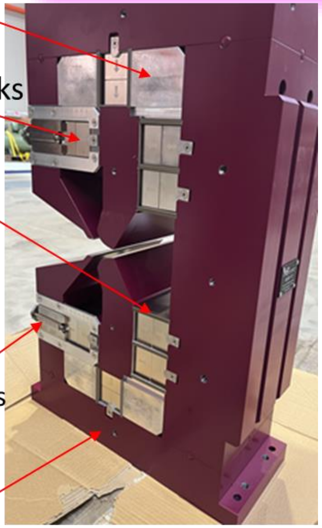
The field integral of a SLS2.0 dipole can be tuned at ~0.01 % level

Examples : SLS2.0 permanent magnets

Dipole BN (56)
1.35 T; L=405 mm; G=22 mm

VB (120)
0.84 T
40.6 T/m





Al block

PM blocks

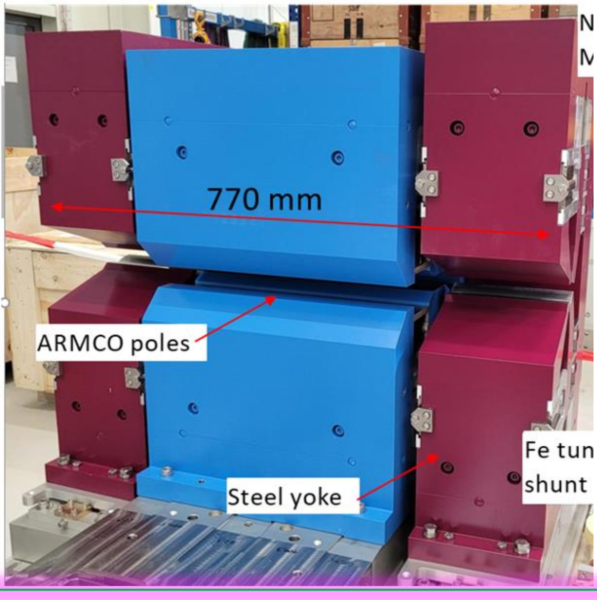
6 mm NiFe strips

Fe tunning Shunt plates

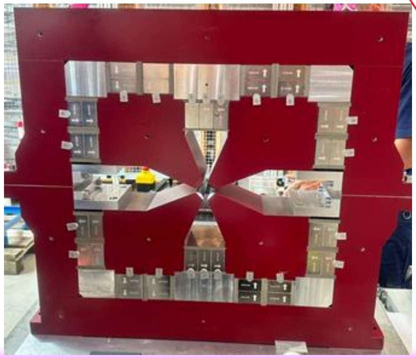
Low C steel 1010

Moderator plates

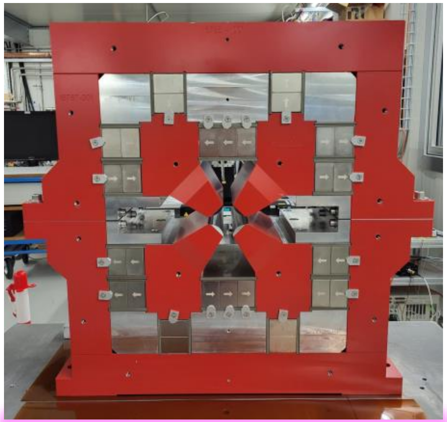
ARMCO poles



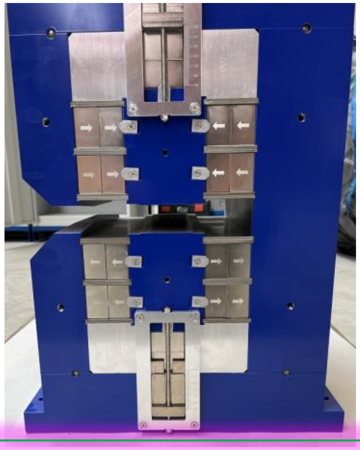
Triplet VB/BN/VB (60) , 0.861 Tm



Quadrupole AN(M) (148)
72.5-78 T/m ; Ø=22 mm

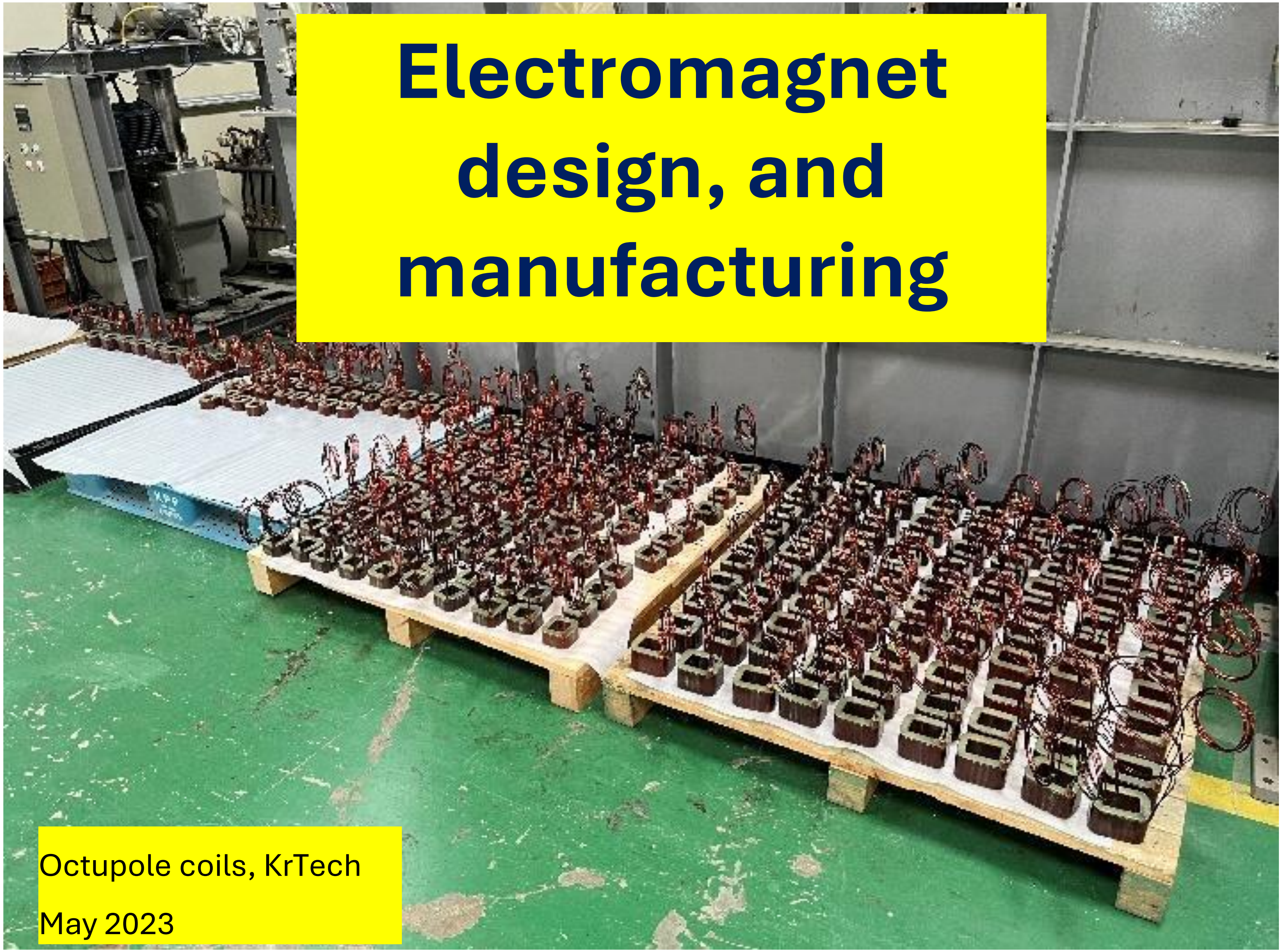


Quadrupole VE (24)
45.8 T/m; Ø=22 mm



2.1 T Superbend (4)
Gap =14 mm; L=405 mm

Electromagnet design, and manufacturing



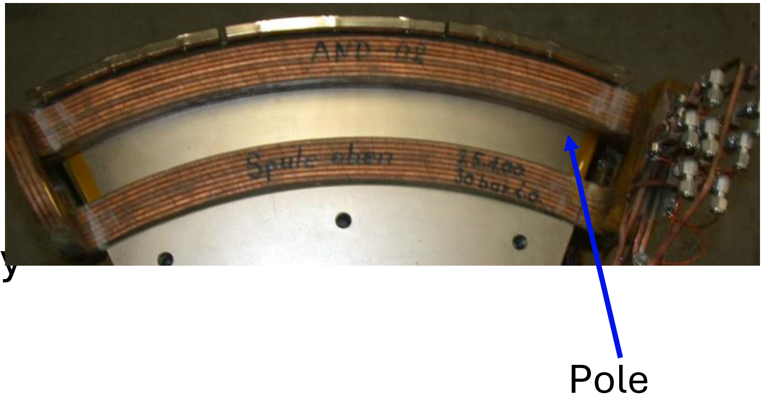
Octupole coils, KrTech

May 2023

Electromagnets

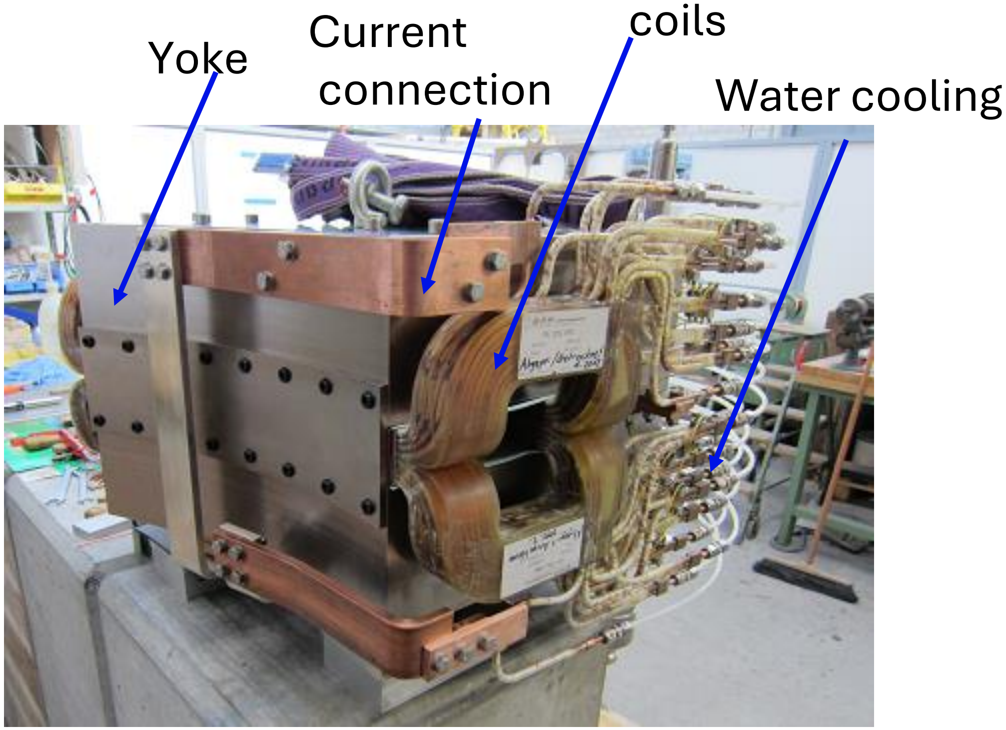
- Excitation is provided by current carrying conductors (generally Cu Coils)
- Field lines is closed by an iron yoke and shaped by iron poles
- Resistive losses in the conductor frequently require water cooling
- Basis of electromagnets is the Biot-Savart law

$$B = \frac{\mu_0 I}{2\pi R}$$



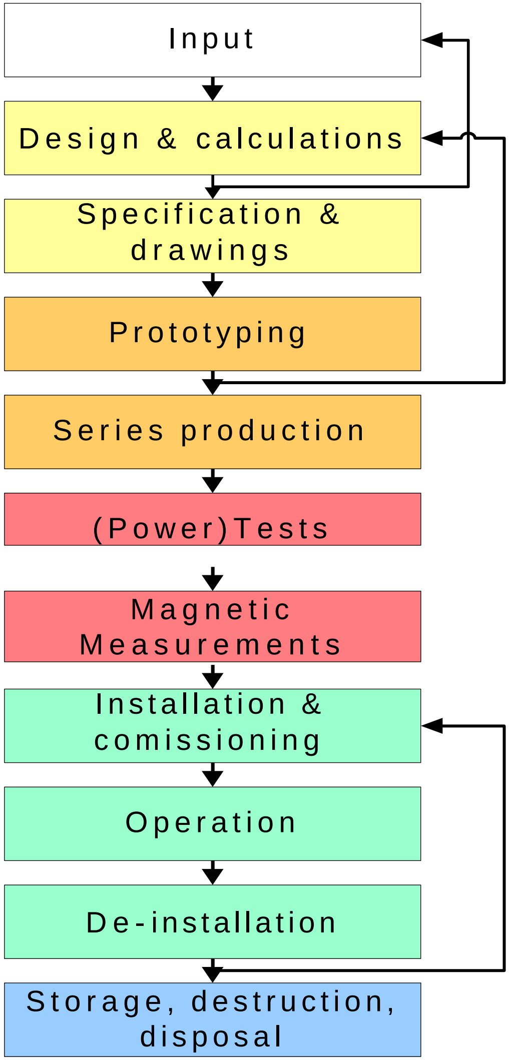
Resistive magnet:

- Copper coils
- Insulation
- Water cooling (if J> 1 A/mm^2)
- Poles (low C-steel)
- Yoke (low C-steel)
- Powering connection



Magnets for accelerators : a complex technological product

Steps in process



Input

Design & calculations

Specification & drawings

Prototyping

Series production

(Power)Tests

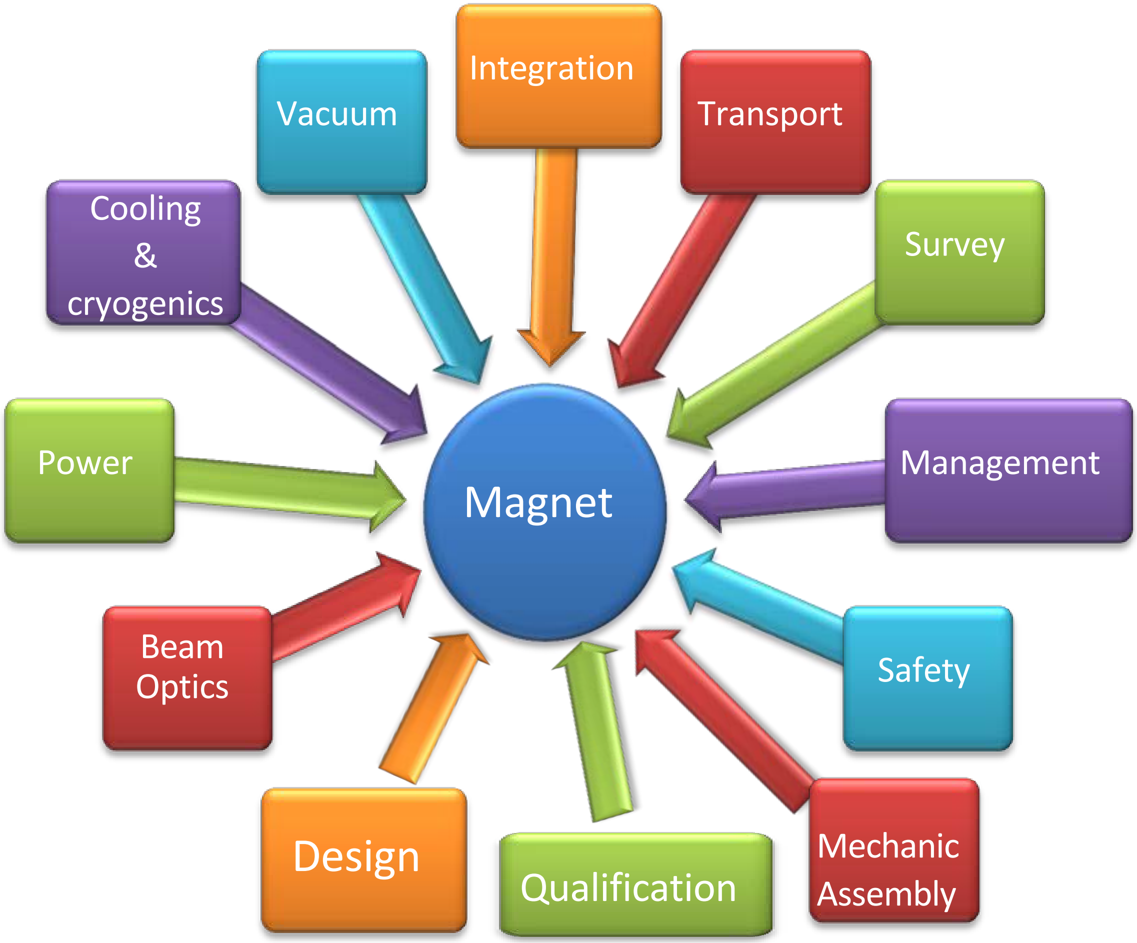
Magnetic Measurements

Installation & comissioning

Operation

De-installation

Storage, destruction, disposal



Magnet

Integration

Vacuum

Transport

Cooling & cryogenics

Survey

Power

Management

Beam Optics

Safety

Design

Qualification

Mechanic Assembly

Magnet life cycle

From Thomas Zickler (CERN) –Normal Conducting Accelerator Magnets Juas 2013

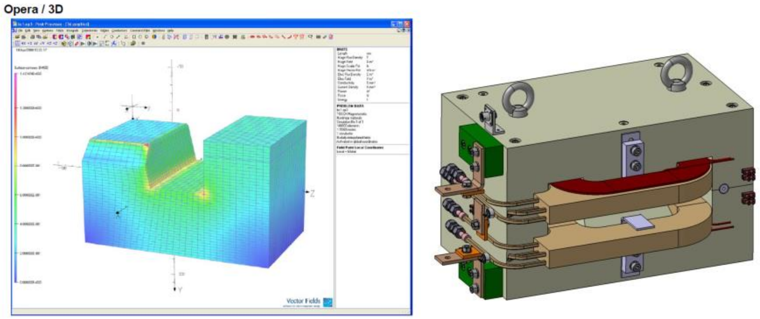
Simple illustration: Electromagnet Dipole used for the SwissFEL at PSI

- ○ Magnet specifications from the optic (Field, Size, aperture, length, field quality, uncertainty)
- ○ Numerical Design (OPERA 3D™-COMSOL™)
- ○ Mechanical Design
- ○ Prototypes production and magnetic measurements
- ○ Construction plans (CATIA V6) & technical specifications
- ○ Call for tender and contract award
- ○ Assembly (if only coils are ordered in companies)
- ○ Reception tests and magnetic measurements

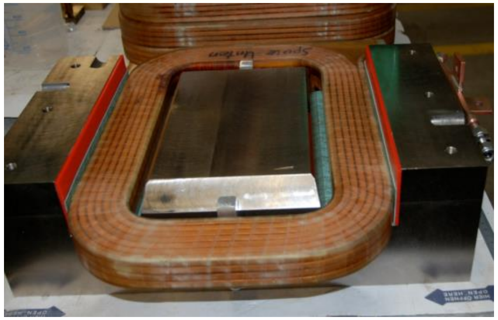
maximum current	200 A
magnetic flux density	0.46 T
bending angle	5 degree
yoke dimensions	L: 250 mm, W: 400 mm, H: 228 mm
Weight	200 kg
Uncertainty (field integral)	<0.1%
ΔB/B (GFR)	<0.05 %

Schedule for design assembly and tests

Example : Dipole for the bunch compressor of one PSI SwissFEL line



Magnetic & construction design



Assembly

Magnetic Measurements

Steps in the Magnet Design, Manufacturing & tests (1)

Steps in the process:

1. Specifications

- **Physical Size**: Overall dimensions of the magnet and good field region
- **Aperture**: Diameter of the opening through which the beam passes.
- **Field** : Magnetic field strength and homogeneity in the good field region
- **Harmonics**: Tolerance to harmonics

2. Material Choice

- **Conductor**: Selection of material for the coils (copper, aluminum).
- **Insulation**: Materials for insulating the conductors.
- **Steel**: Type of steel for the magnetic core.
- **Pole and Yoke**: Materials and shapes of the poles and yoke.

3. Detailed Design

- **FE Model Optimization**: Use finite element modeling to optimize the design.
- **Coil Cross-Section Geometry & Cooling**: Design the geometry of the coil cross-section and its cooling system.
- **Yoke Shape (C vs. H), Pole Shape , yoke & pole ends**: Optimal shape for the yoke and poles for an optimization of the field quality

Steps in the Magnet Design, Manufacturing & tests (2)

5. Coil Manufacturing

Manufacturing Process: Techniques for winding the coils.

Insulation: Methods for insulating the coils.

Impregnation: Process for impregnating the coils to enhance insulation and mechanical stability.

6. Yoke Manufacturing

Tolerance and Precision: Define manufacturing tolerances and precision requirements.

Machining Methods: Techniques for machining the yoke to achieve the required specifications

7. Reception tests (visual, hydraulic, electrical)

8. Magnetic qualification (field strength & field quality & magnetic axis)

Some points detailled in the next slides……

Magnetic design with Finite Elements

Translate the beam optic requirements into a magnetic design

- Aim of the electromagnetic FE models:
  - Magnetic Field computation: Field integral, field distribution, yoke geometry, minimize high saturation zones, adjust pole shape for multipoles
  - Optimization of magnet design: Coil geometry, material selection, minimize the total steel amount (magnet weight, raw material cost)
  - Thermal analysis: Heat generation, cooling requirements

- Some FE software packages that are often used:
  - Opera from Dassault Systems: 2D and 3D commercial electromagnetic simulation software see: https://www.3ds.com/products/simulia/opera
  - Simulation ROXIE (CERN) 2D and 3D, specialized for accelerator magnets; single fee license for labs & universities see: ttps://espace.cern.ch/roxie/default.aspx
  - ANSYS Maxwell: 2D and 3D engineering simulation software (commercial)

    see: http://www.ansys.com/Products/Electronics/ANSYS-Maxwell
  - COMSOL Multiphysics® Simulation :commercial multiphysics software see: https://www.comsol.com/comsol-multiphysics

Key Aspects of Magnet Design using Finite Element Analysis (FEA)

- **Codes:**

– finite elements with various mesh types (triangular, quadrilateral, tetrahedral,….)
– multiple iterations to simulate steel nonlinearity
– Preprocessing (Setting up the model, defining material properties, boundary conditions, and meshing) and post-processing (Analyzing results, visualizing field distributions, ..)

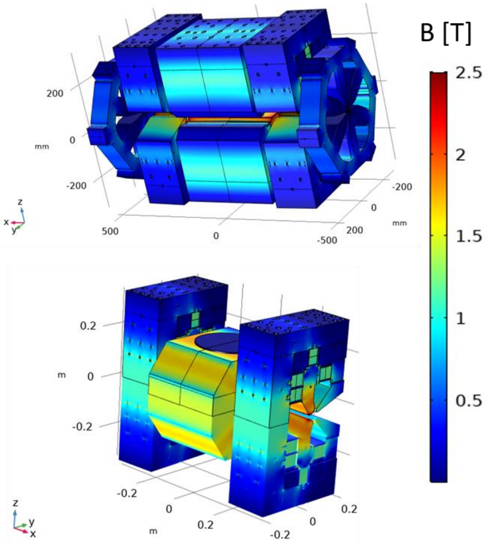
- **Technique is iterative :**

– calculate field generated by an initial geometry
– adjust geometry until desired distribution is achieved

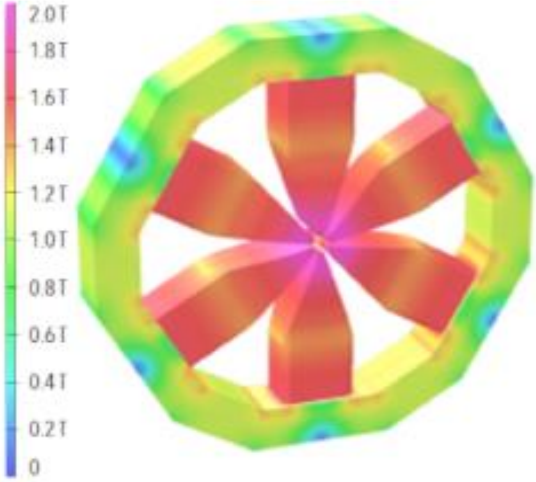
- **Non-Linear modeling solver:**

+Accurate modeling of magnetic models.
- Long meshing time and long solve time.

- **Software choices dependent on cost, desired accuracy, and calculation time.**

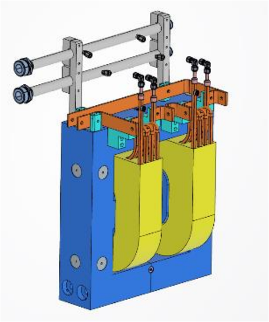


Magnetic field map of a Permanent Magnet triplet- OPERA 3D

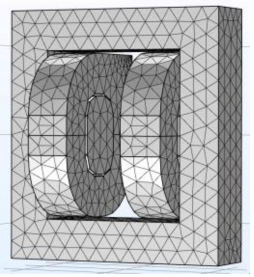


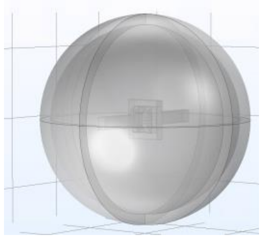
Field distribution of a sextupole magne

Magnetic design-
Finite Element Analysis (F.E.A.)

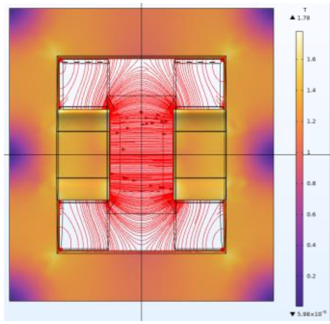


○ **Step 1: Modeling and mesh generation (pre processing)**
- Define geometry of all the regions (Coil, Iron, Air)
- Modeling coils with specified current density
- Incorporate regions made of steel to guide the magnetic field lines
- Use the symmetry constraints on the boundaries to reduce the complexity of the model
- Apply the B-H curves for the steel and any other relevant materials





○ **Step 2: Solver based calculation**
- Linearization of the Maxwell equations
- Definition of magnetic potential (thus flux density) in the mesh nodes
- mode first with a pre-defined permeability curve
- Optimization with the B-H curve specific, taking into account non-linear behavior of permeability



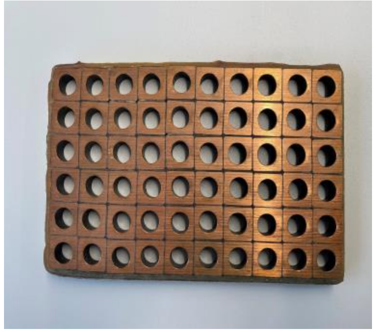
○ **Step 3: Post processing analysis**
- Field line visualization & graphs : the field distribution and magnetic flux density and field strength across different regions
- Contours & gradients: Field intensity and uniformity across the modeled area
- harmonics (from a Fourier analysis around a circular path) for field quality

Conductor materials and coil geometry

Material : "Oxygen-free" copper grades, such as CDA 10200, : high electrical and thermal conductivity due to their lack of oxygen content, better brazeability and weldability

Standard design : rectangular hollow design with cooling water tube, 0.5 mm glass tape insulation. Coils are potted in epoxy to prevent damage

Purity (%)	99.95
Melting point	1083 °C
Resistivity @ 20°C	1.73 mΩ.cm
Thermal Conductivity	3.91 W/cm K
Density	8.94 g/cm^3



$j = NI/A$

j: current density
N : Number of turns
I current
A : copper surface

Bedstead coil

- ✓ Low j → low power loss, less heat
- ✓ High j→ small coil, small magnets
- ✓ N high →High voltage power supply
- ✓ N low →High current power supply

solenoid

Tapered coil

Racetrack coil

<u>**Economic** criteria !</u>

Ben Shepherd (2016)
Conventional Magnets for Accelerators

Water cooling : key issues

Goal: Define diameter $d_{cooling}$ and length L of cooling tube, pressure drop ΔP [bar], temperature increase ΔT [K], flow rate Q [l/min] taking into account the power in the coil

Cooling with water: Guidelines for efficient cooling

- Coils with current density < 1 A/mm^2 may not need cooling
- Max. current density for cooled conductor is ~ 10 A/mm^2
- The pressure drop: $1 \leq \Delta P \leq 100$ bar
- Water flow should be moderately turbulent (v > 1.5-2 m/s) to improve heat transfer (heat transfer through the thin film separating the conductor surface): Reynolds > 2000
- flow velocity should be lower than 5 m/s to avoid erosion and vibrations
- The temperature rise: $\Delta T \leq 30$ °C

$$\Delta P[bar] = 60L[m]\frac{Q[l\ \ min]^{1.75}}{d[mm]^{4.75}}$$

Blasius law

Water properties

- demineralized water :minimal ionic content and thereby reducing the risk of mineral deposits
- resistivity ≥ 0.1 MΩ m, indicative of the water's purity and low ionic concentration
- narrow acidic window with **pH of 6 to 6.5**, optimizing the conditions to prevent corrosion and scaling
- Filters (reverse osmosis) to remove particles to avoid cooling ducts obstruction

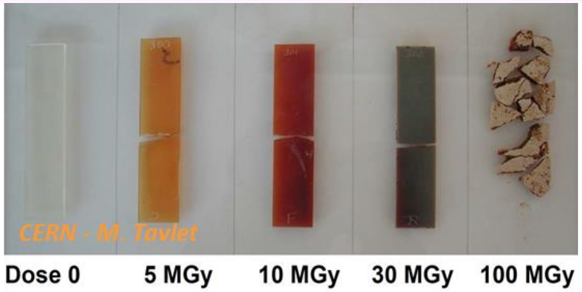
Mineral Insulated Conductors for radiation hard magnets

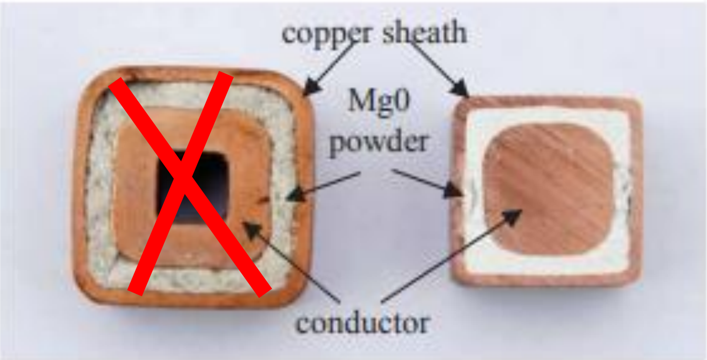
At PSI magnets close to the targets: up to 7 MGy /week !

high energy gamma, neutrons, other hadrons (p+, α, π ...)

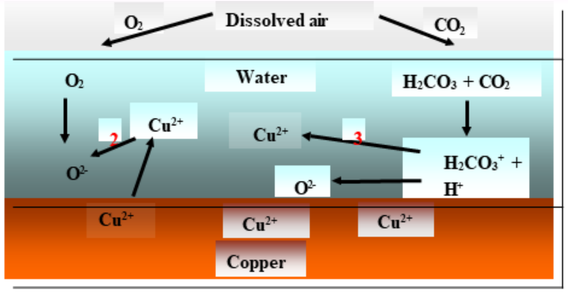
- avoid organic materials
- Metals, ceramics only

Radiation damage on Epoxy





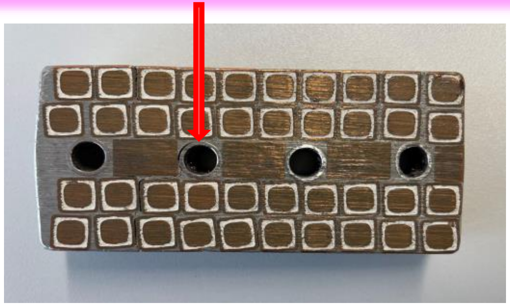
Increase copper corrosion



Copper corrosion

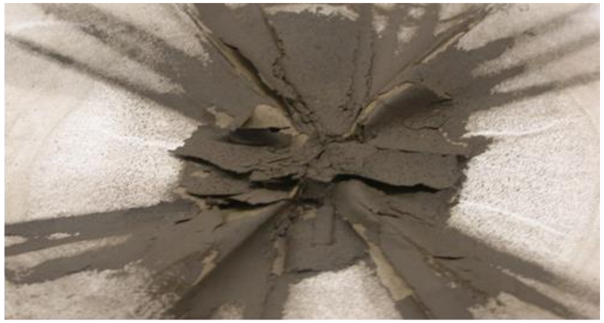
corrosion increased further due to radiation

Indirect cooling and mineral insulated cable (MIC)



MIC: Copper + MgO

- inorganic
- hygroscopic
- Fragile
- Prone to short-to-ground



Copper oxide obstructs cooling channels

« Radiation hard magnets at the Paul Scherrer Institute », A. Gabard et al., Proceedings of IPAC2012

Iron Yokes- key functions

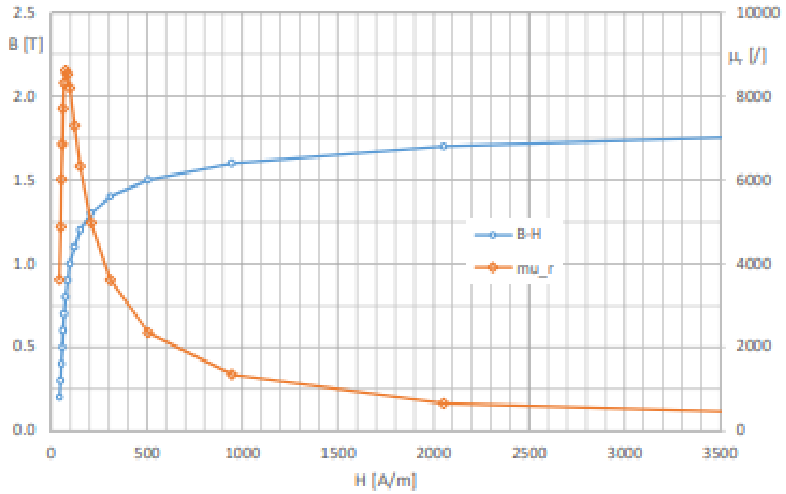
1. Magnetic Field Enhancement: Concentrate the magnetic flux produced by the coils, effectively increasing the field strength within the desired regions. High-permeability material, provides an easier path for magnetic lines

B-H curves and saturation effect

Magnet steel begins to saturate around 1.5 T

for $B \ll 2$ T, one has $\mu \gg 1$ ($\mu \sim 10^3$-10^4), and the iron increase the magnetic field value

for $B > 2$ T, $\mu \rightarrow 1$, and the iron becomes “transparent” (no effect on field)



curves for typical M1200-100 A electrical steel

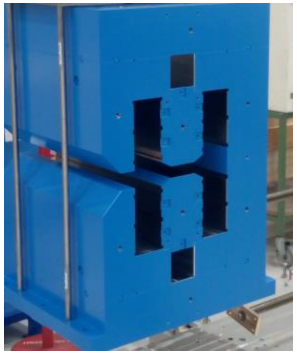
Attilio Milanese
An introduction to Magnets for Accelerators (2022)

2. Uniform Distribution: Yoke distributes the magnetic field more uniformly across the required areas

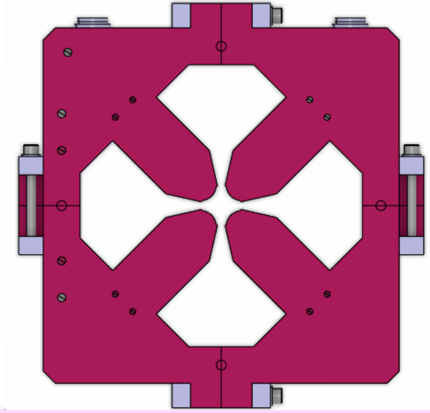
3.Minimizing Leakage: The yoke reduces magnetic leakage, closing the flux lines: essential for the efficiency and safety.

4.Structural Support: the iron yoke also provides mechanical strength and support to the magnet structure..

Yokes: Solid cores vs laminated cores



Iron yokes (Low C-steel)
for SLS2.0 permanent magnets



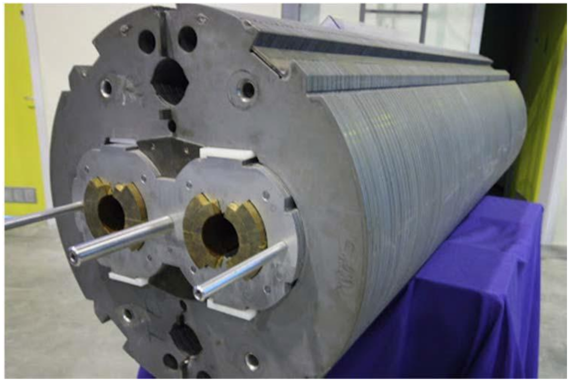
1 min thick lamination
for SwissFEL quadrupoles

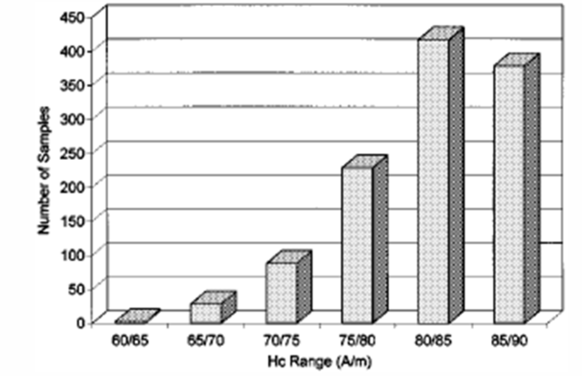
Solid Cores : **Steady state magnets**, high magnetic permeability **(+)**, simple manufacturing **(+)**, Generates eddy currents **(-)**, hinder heat dissipation leading to potential thermal stresses **(-)**, high weight and size **(-),** lower field uniformity ~ 0.1% **(-)**
Laminated Cores : **for time varying field magnets**, reduced eddy currents **(+)**, better heat dissipation **(+)**, higher field uniformity ~ 0.01% **(+)**
Complex manufacturing **(-)**, delamination **(-)**

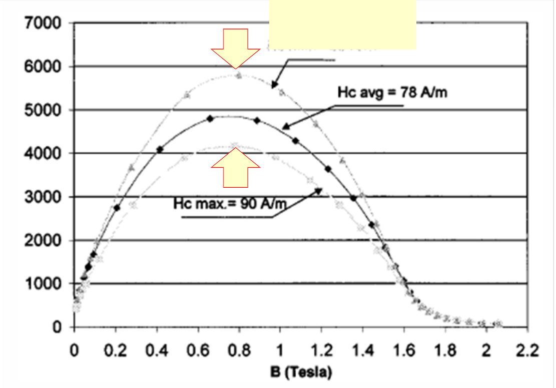
Most typical material for magnet fabrication: 1010 Steel, low carbon contents << 0.1%: High saturation field, High permeability

Steel Laminations: Laminations coated with an inorganic (oxidation, phosphating, Carlite) or organic (epoxy) layer to increase the resistance. These steels have good electrical resistivity and magnetic permeability (from 0.5 mm to 6 mm thick).

Example of material uncertainties in the iron yokes

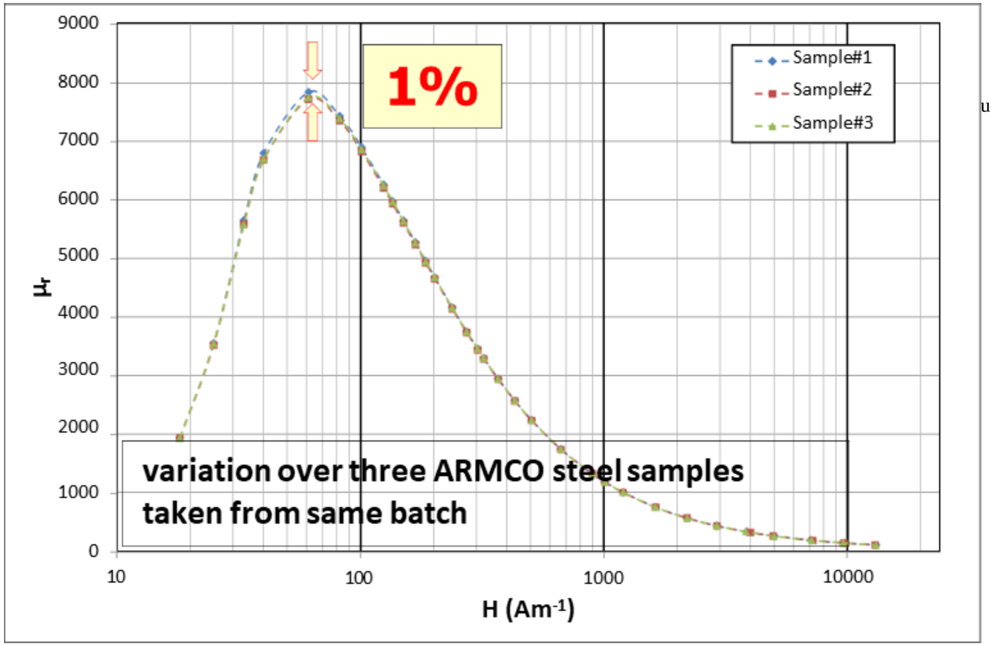






variation of the coercivity over 50 ktons of MAGNETIL steel sheets for LHC cryomagnets

useppe Peiro *et al.*, Toward the Production of 50 000 Tonnes of Low-Carbon Steel Sheet for the LHC Superconducting Dipole and Quadrupole Magnets, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 12, NO. 1, MARCH 2002



1%

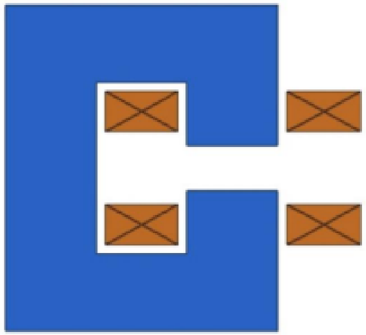
variation over three ARMCO steel samples taken from same batch

M. Buzio (CERN) –"Magnetic Measurements for Particle Accelerators", 2013

Courtesy Giuseppe Montenero, CERN

Typical absolute uncertainty on permeability values up to 3-5%

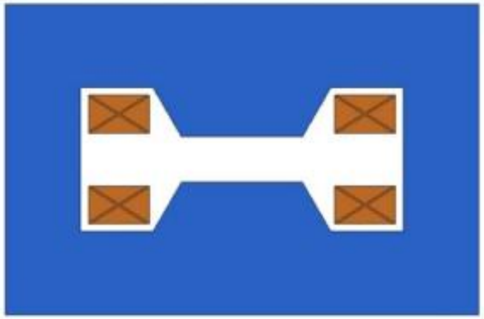
Common Magnet geometries (dipoles, quadrupoles)



C shape magnet

⊕ Accessibility

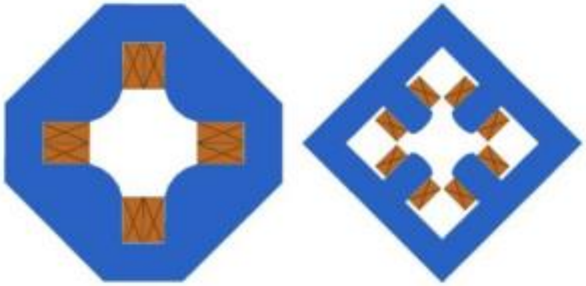
⊖ Field quality



H shape magnet

⊕ Mechanic, Field quality

⊖ Accessibility



Close quadrupoles

⊕Less saturation

⊖ Large coils

Open type quadrupoles

⊕ Accessibility

⊖ Manufacturing work

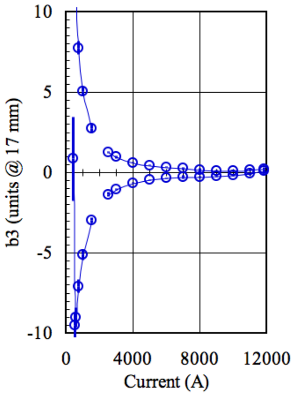
Drawings from "Iron Dominated Magnets", Luis Garabito

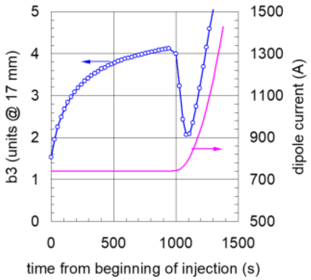
Field quality measurements

Sources of magnetic field errors

(conventional and superconducting magnets)

- **Manufacturing errors & mechanical tolerance:** typically 20-50 μm for electromagnets and permanent magnets yokes
- **Errors in coil geometry w.r.t to ideal case** (→superconducting magnets)
- **Magnetic properties of the materials** (permeability yoke, permanent magnets, variability of few %)
- **Hysteretic behavior of magnetic materials** (non reproducible magnetic state)
- **Magnetic coupling** (multi function magnets, high density of magnets)
- **Magnetic & mechanic deformations**
- **Eddy currents** (fast current ramp rates)
- Persistent current hysteresis (Magnetization related to the Jc)
- Current redistribution
- Change of the magnetization in time at low field and 1.9 K (decay)





Superconductivity

Why to measure?

Aim: know the magnetic field in the volume occupied by the beam

- Acceptance tests : verifification of the respect of tolerances imposed by the machine optic
- To provide fiducialization data for installation and (pre) alignment
- magnetic measurements speed-up machine commissioning : get as much information as possible
- To confirm the magnetic models obtained by computer simulations
- To provide magnetic parameters to beam simulation
- To monitor production quality of the magnet series and steer manufacturing

Computer simulation targeting 0.01 % accuracy are difficult and expensive

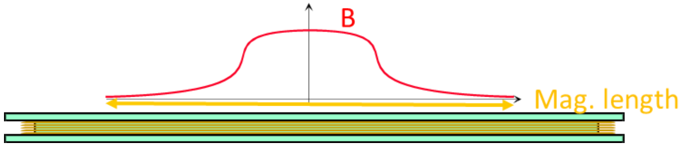
- Geometrical uncertainty (mechanical tolerances, assembly errors)→50 micrometers, 0.5 % of error typically
- **Material properties uncertainty** (e.g. iron yokes properties, NdFeB blocks, ARMCO poles….)- uncertainty **ranging from 1-3% (μ (H) variability)**
- Magnetic coupling time-consuming and sometimes difficult to simulate

Experimental verification of the magnetic field quality is mandatory !

Specific Quantities Measured for Accelerator Magnets

Field integral : $\int B dl\ (dipole); \int g dl\ (quadrupole); \int B_3 dl\ (sextupole); \ldots$

➡ **Field integrated along the magnetic length (what the beam sees including stray fields)**



Field quality : **field errors with respect to the main field expressed in terms of harmonics**

ex dipole (b_1) errors: b_2,a_2 (quadrupolar), b_3,a_3 (sextupolar),b_4,a_4 (octupolar)

Field Maps (2D,3D) : **Point like & line measurements for field quality homogeneity**

Magnetic axis location : **locus of the zero field (n-poles, n≥2) + fiducialisation**

= measuring the magnetic axis w.r.t. a set of references (mechanical surfaces or optical targets) as required for alignment in the machine

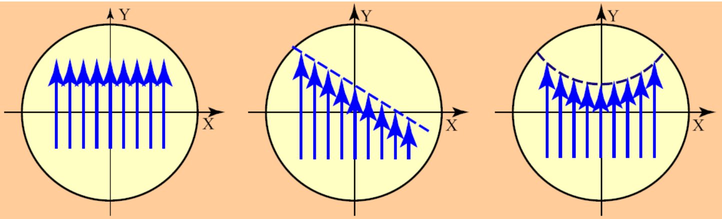
Combined techniques to measure field integral, field maps, the field quality and the axis location and….. cross-check calibrations

Specificity of fields in accelerator magnets
Harmonic errors (multipoles)

○ Beam is in a beam pipe: the shape of the field area in the magnets is a cylindrical volume with long length w.r.t aperture (2D approximation)

$$B_y + iB_x = \sum_{n=1}^{\infty} \mathbf{C}_n \left(\frac{\mathbf{s}}{R_{ref}} \right)^{n-1}$$

- Complex multipoles coefficients : $\mathbf{C}_n = B_n + iA_n$
- The magnetic field is expressed in terms of field harmonics (main, multipoles)



$B_y = B_0$ (Constant) — Normal Dipole

$B_y = B_0 + G.x$ — Normal Dipole + Normal Quadrupole

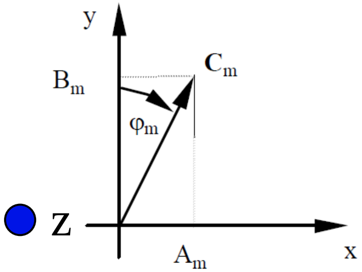
$B_y = B_0 + A.x^2$ — Normal Dipole + Normal Sextupole

n=1, b_1 normal dipole, a_1 skew dipole

n=2, b_2 normal quadrupole, a_2 skew quadrupole

n= 3, b_3 normal sextupole……

C_n scales as z_{ref}^{n-1}



$$\boxed{B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}} \quad \boxed{b_n = \frac{B_n}{B_{ref}}} \quad \boxed{a_n = \frac{A_n}{B_{ref}}}$$

- We factorize the main component (B_1 for dipoles, B_2 for quadrupoles)
- We introduce a reference radius R_{ref} for dimensionless coefficients (R_{ref}~2/3 aperture magnet)
- We factorize 10^{-4} since the deviations from ideal field are ~0.01%

$$\boxed{b_n\,(unit) = \frac{B_n}{B_{ref}} * 10^4}$$

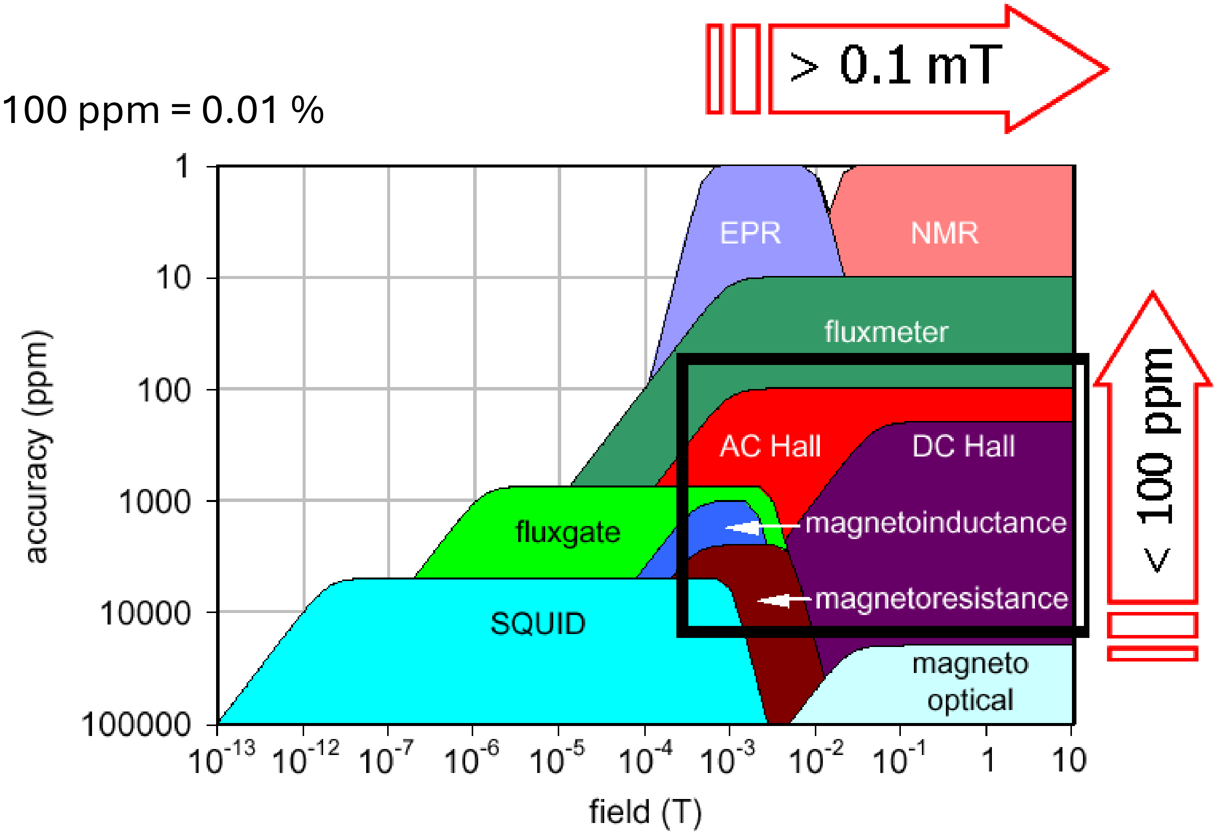
The coefficients b_n, a_n are called <u>normalized multipoles</u>

b_n are the <u>normal</u>, a_n are the <u>skew</u> (adimensional)

Selecting Appropriate Magnetic Field Measurement Techniques

Questions to answer:

- **Measurements**: Field component, total (Bx,By,Bz), field integral to measure ?
- **Field characteristics**: Strength, uniformity, AC/DC?
- **Accuracy needed:** % or 0.01%?
- **Access:** What access do you have to the region measured? Precision and reproducibility of the positioning?
- **Environment:** cryogenic, room temperature?
- **Constraints:** Time schedule, cost, human resources..

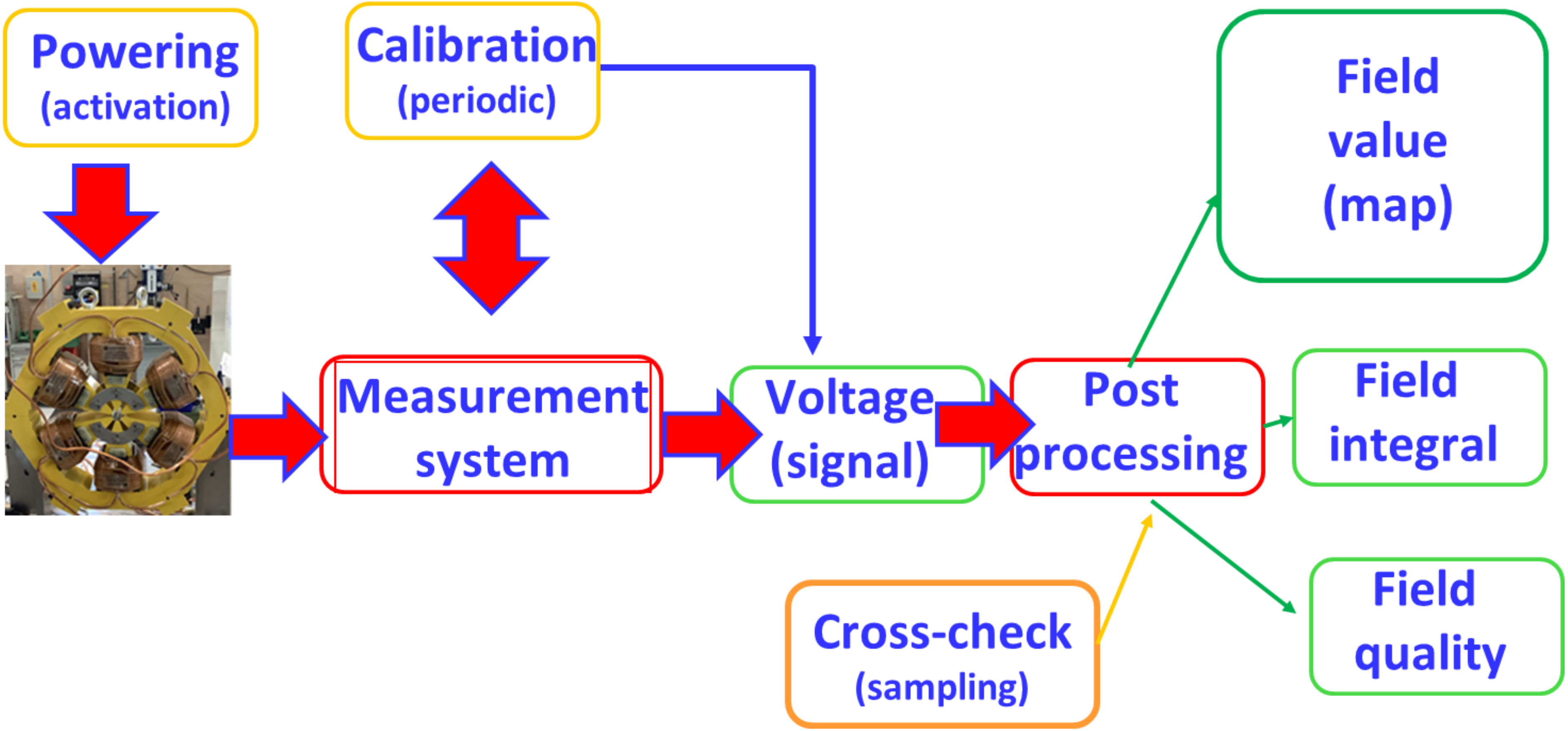


100 ppm = 0.01 %

From L.Bottura (CAS 2002)

B~0.01T ………10T, accuracy: 10^{-2} to 10^{-5} of the reading

Simplified Measurement chain



Powering
(activation)

Calibration
(periodic)

Measurement system

Voltage
(signal)

Post processing

Field value (map)

Field integral

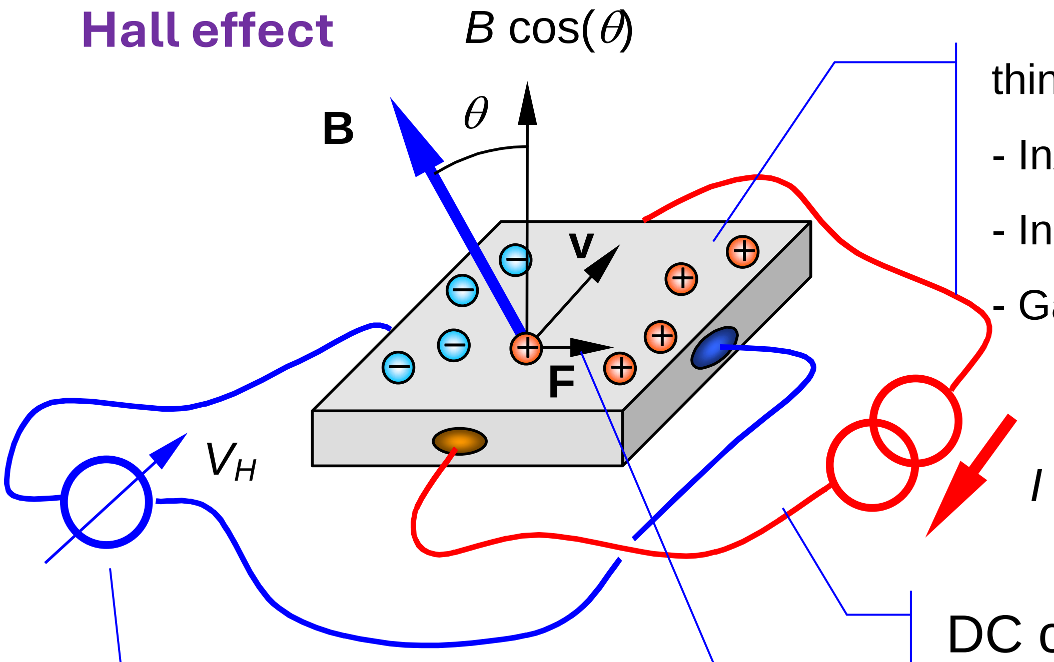
Field quality

Cross-check
(sampling)

Measured value: Voltage

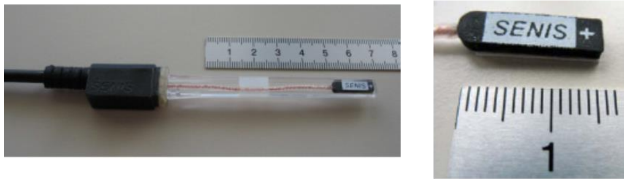
Hall probes

Hall effect



thin slab of semiconducting material

- InAs
- InSb
- GaAs



Sensor IC: 16x4x2 mm³

3D sensor from SENIS

DC current

Lorentz force F = v x B

transverse DC (Hall) voltage

Lorentz force ⟶ Steady state voltage V_H

$V_H = G.\ R_H.\ I.\ B.\ \cos\theta$ **G=Geometric factor, R_H= hall coefficient**

Hall probes : Field mapping, field integral, magnetic length

Fluxmeters

$$V_C = -\frac{d\Phi}{dt} = -\frac{d}{dt}\iint_A \mathbf{B}\cdot\mathbf{n}\,dA = -\iint_A \frac{\partial \mathbf{B}}{\partial t}\cdot\mathbf{n}\,dA - \oint_{\partial A} \mathbf{v}\times\mathbf{B}\,d\ell$$

Faraday’s law (total derivative)

fixed-coil,
time-varying field

coil rotating, translating
(wire)

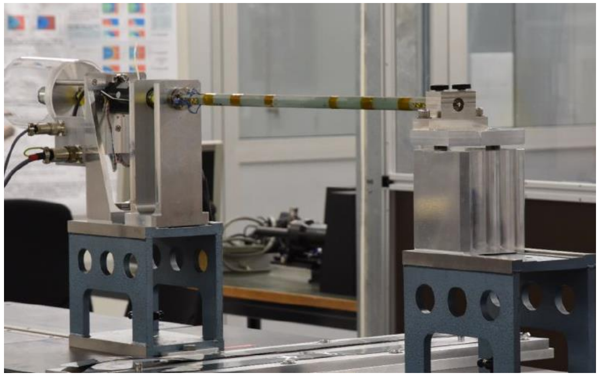
Voltage (integration) → Discrete sampling of flux → Fourier components → main field + field harmonics

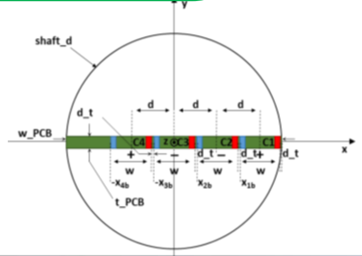
- ○ Pick up coils
  - Rotating (change of surface dA)
  - Fixed coils (B change in time, $\frac{\partial B}{\partial t}$)
- ○ Wires (coil made of 1 loop)
  - Translating, rotating (change of surface dA)

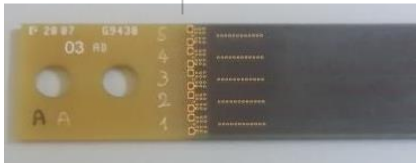
$$-V_c = \frac{\partial\Phi}{\partial t} = \begin{cases} A_c\dot{B} \\ A_c B\omega \\ A_c\nabla B v \end{cases}$$

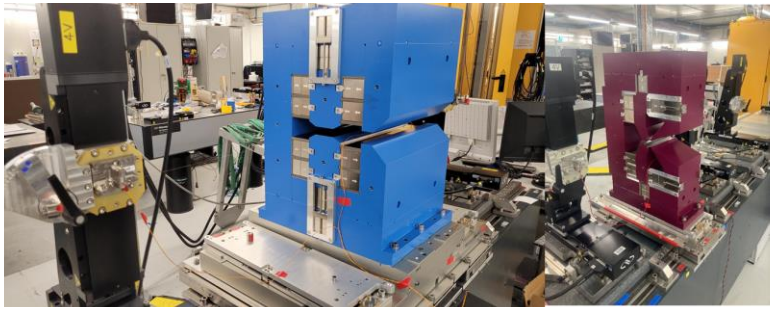
A_c : pick-up coil surface

ω rotation speed







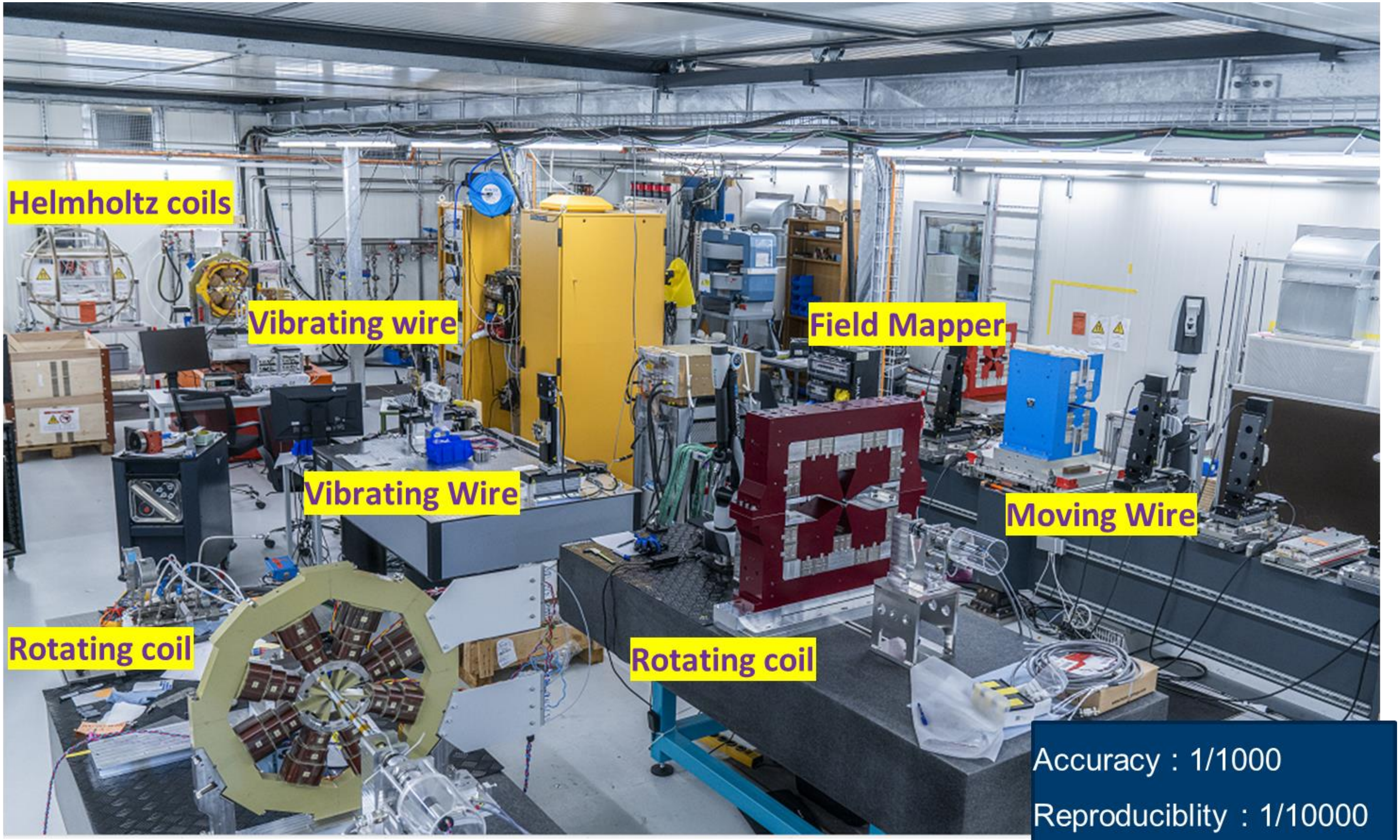


400 mm long-rotating coils (PSI/Elettra/CERN) made of 5 PCB coils

Moving wire measurement of dipole/ quadrupole at PSI

Rotating (coils, wire): Field integral, harmonics, magnetic center

Magnet measurements at the Paul Scherrer Institut



Accuracy : 1/1000

Reproduciblity : 1/10000

Axis : < 30 micrometers

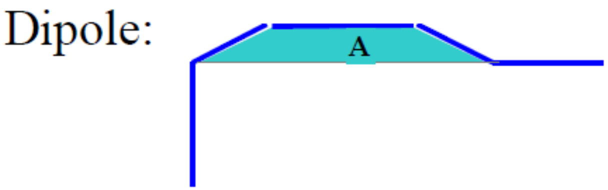
Field quality tuning in conventional magnets

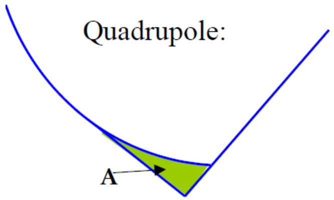
It depends on the design and shape of the pole

The designer optimises the pole by ‘predicting’ the field resulting from a given pole geometry and then adjusting it to give the required quality.

Shims : The ‘shim’ is a small, additional piece of ferromagnetic material added on each side of the poles – it compensates for the finite cut-off of the pole to reduce “allowed” harmonics

The area and shape of the shims determine the amplitude of error harmonics which will be present. **<u>The field will rise and then fall</u>**





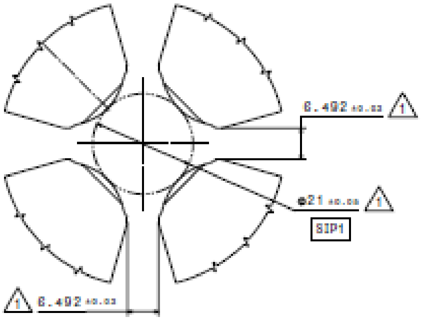
Chamfers (cut of the poles)-Control of the longitudinal field at magnet end Magnetic length better defined & **<u>prevent saturation</u>**

Allowed harmonics : errors because the poles are finite
For the dipole, $N=1$, the allowed error multipoles are $n=3, 5, 7, 9, 11, 13, 15, \ldots$
For the quadrupole, $N=2$, the allowed error multipoles are $n=6, 10, 14, 18, 22, \ldots$

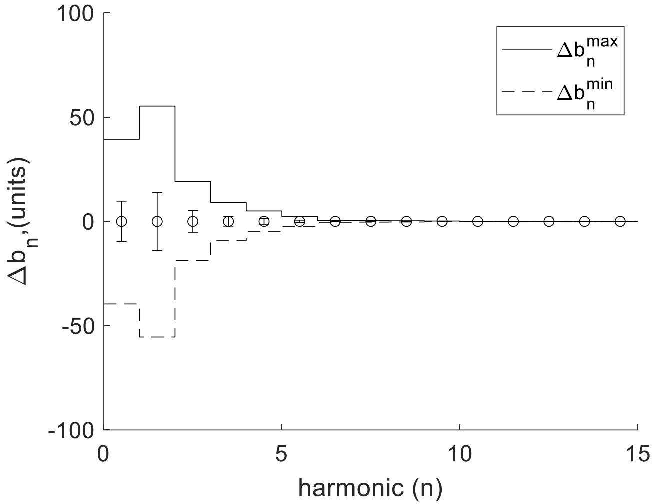
Non allowed harmonics (normal and skew)*: Non ideal geometry (mechanical tolerances, assembly default, non homogeneity of the yoke….*

CAS 2009- Antoine DAËL

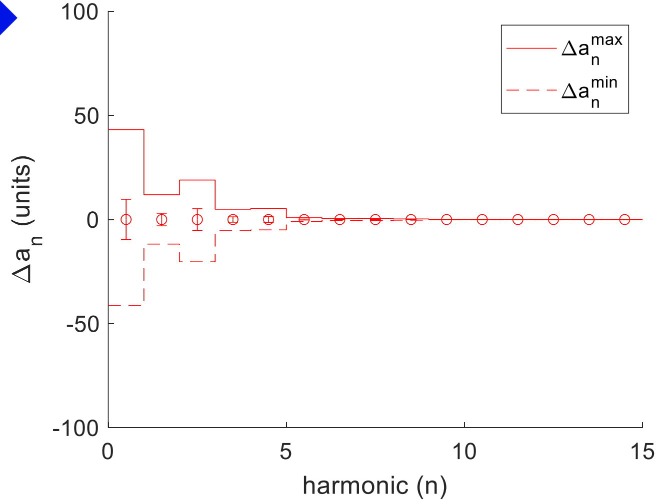
Simulated vs. measured harmonics errors coming from manufacturing tolerances- SLS2.0 electro-quad



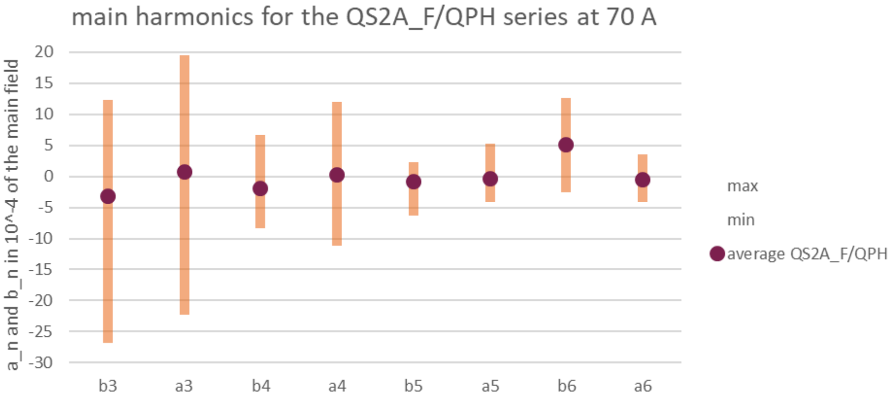
Inter-pole distance : 6 mm +/- 30 μm
Aperture tolerance : 21 mm +/-50 μm



Two sets of monte-carlo simulations are carried out with 10000 runs

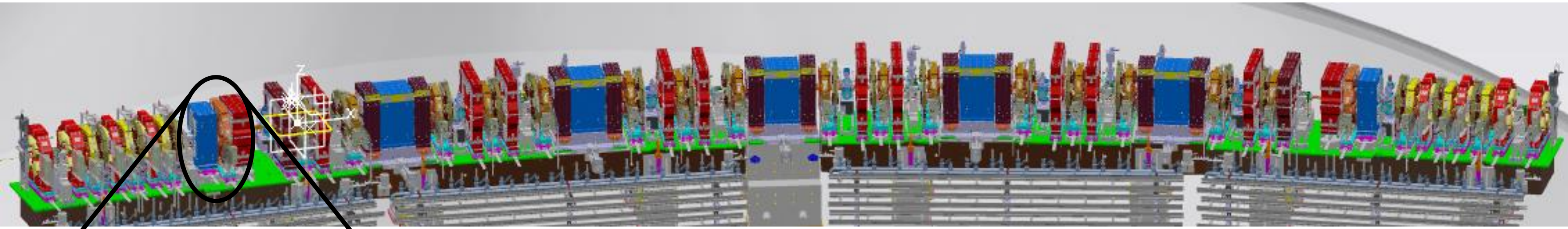


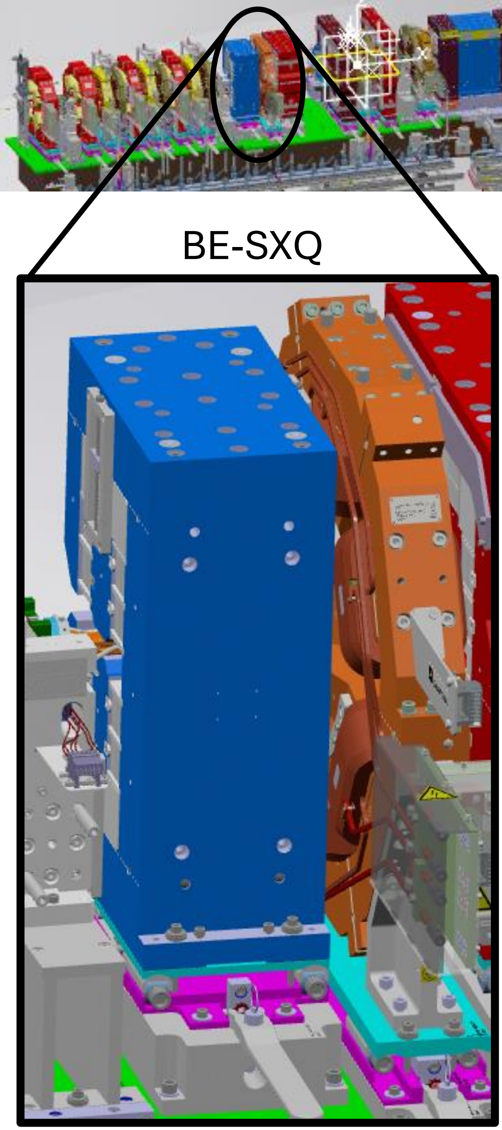
Rotating coils measurements on 55 magnets



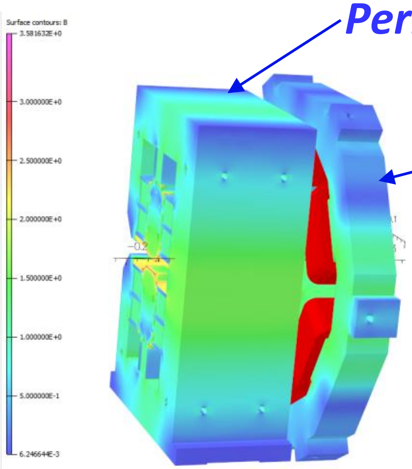
Calculated and measured allowed and non allowed harmonic errors match quite well

Field quality errors coming from magnetic coupling – the example of BE-SXQ SLS2.0 magnets





BE-Field integral (Tm)	BEI alone	BEI & SXQ on (38 A)	Attenuation
Computed (Tm)	0.2563	0.2463	3.83 %
Measured (Tm)	0.2562	0.2447	4.6%
Δ [%]	0.03		



Permanent magnet dipole

Sextupole (electro-magnet)

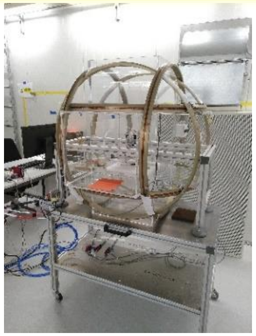
OPERA simulation

The sextupole SXQ is reducing the field strength of the PM dipole BE by 4.6 % (calculation : 3.8 %)

Summary

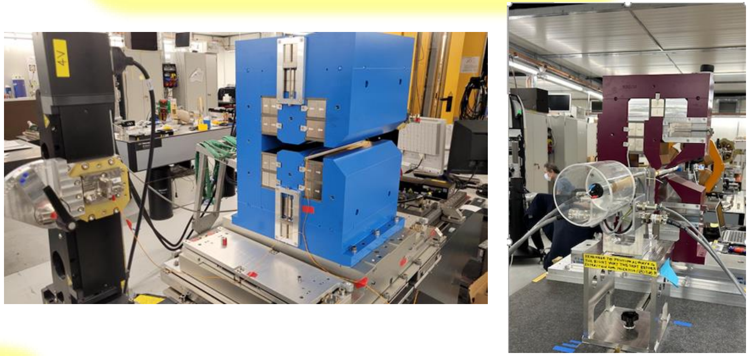
Path for a permanent based SLS2.0 magnet: case of a triplet Quad (VB)/Dipole (BN)/Quad (VB)

PM block measurements (cross-check 0.5-1%) with Helmholtz coils

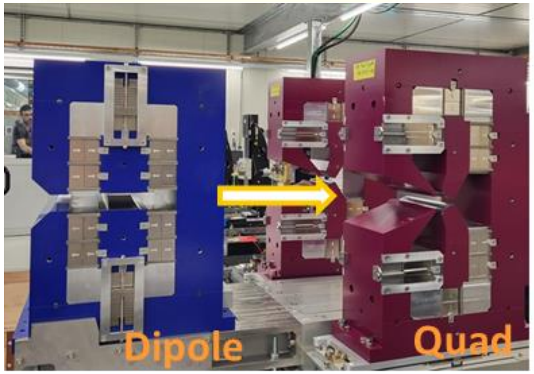


Insertion of the blocks in the yoke

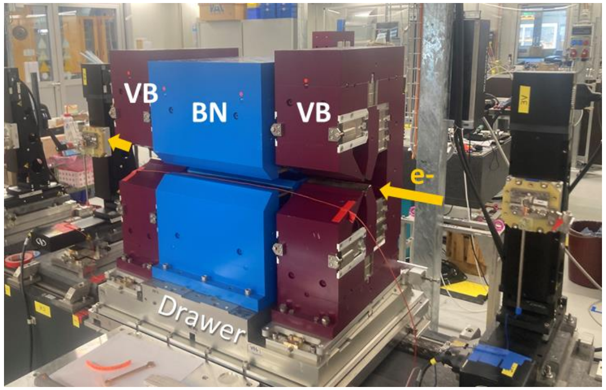
Individual measurements : and field integral tuning (0.01% level)



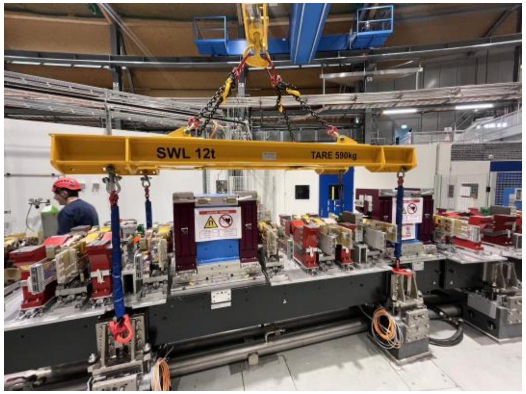
Assembly of the three magnets and fiducialisation



Magnetic measurements and tuning of the triplet magnets together (0.2 % level)



Transport and Installation on the girder

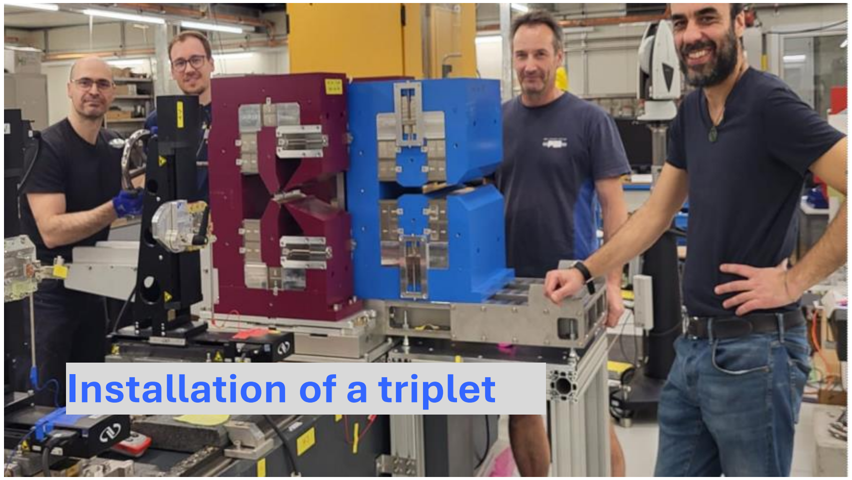


Training of the team for rotating coils

HIPA magnet

Quad reception tests

Successful measurement of Sextupoles Octupoles axis



Installation of a triplet

Dedication, Setbacks, Unexpected Turns, Achievements, and…. Challenges

Join the magnet section

Thank you for your attention

Annexes

Nomenclatures

Magnetic Field: (the magneto-motive force produced by electric currents)

symbol is **H** (as a vector); units are Amps/metre in S.I units;

Magnetic Induction or **Flux Density:** (the density of magnetic flux driven through a medium by the magnetic field)

symbol is **B** (as a vector); units are Tesla (Webers/m^2)

Permeability of free space:

symbol is μ_0 ; $\mu_0 = 4\pi * 10^{-7}$;units are Henries/metre;

Permeability (abbreviation of **relative permeability**):

symbol is μ_r; the quantity is dimensionless;

$$\overrightarrow{B} = \mu_0 \mu_r \overrightarrow{H} \qquad \mu_r = \frac{\mu}{\mu_0}$$

Magnetic field errors & Impact on the beam

Generalities Mag. Meas

- random errors in the integral of field in bending magnets : <ΔBL/BL> ≈ a few **10^{-4}**
- random errors in the integral of gradient of quadrupoles : <ΔGL/GL> ≈ a few **10^{-4}**
- horizontal or vertical mis-positioning of magnets (dipoles, quadrupoles, sextupoles)

  <ΔxQ> and <ΔyQ> ≈ **0.03-0.05 mm**
- roll errors : 0.1 – 0.2 mrad

- Close orbit distorsion & focusing errors→ Blow up of the beam size and emittances, loss of particles
- Multipoles errors → non linear resonance and loss of particles

Measure field integral, the field quality (multipoles) and the axis location

Measurement techniques summary

Method	B [T]	Sensor size	Uncertainty abs / rel	Remarks
Rotating-coil fluxmeter	$>10^{-4}$	Ø8-100 mm 30 mm – 15 m	$10^{-4}/10^{-6}$	• strength, axis and field direction • high accuracy multipoles • quick measurements • complex mechanics (encoder, motor) • not suited to strongly curved, rectangular aperture magnets
Fixed-coil fluxmeter	$>10^{-4}$	< 3 m	$10^{-4}/10^{-5}$	• only option for curved, pulsed magnets • field uniformity
Stretched wire (moving)	$>10^{-2}$	Ø 0.1 mm < 20 m	$10^{-4}/10^{-4}$	• calibration reference for integrals • 1-turn, suitable for strong fields
Stretched wire (vibrating)	$>10^{-2}$	Ø 0.1 mm < 20 m	$10^{-3}/10^{-5}$	• extremely sensitive for magnetic axis • only option for harmonics in small gaps
Hall probe	$>10^{-4}$	$1\ \mathrm{mm}^3$	$10^{-3}/10^{-4}$	• simple, cheap, commercially available • T-sensitive, Hall planar effects • accuracy requires laborious calibration

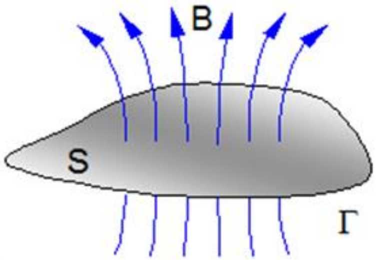
From M. Buzio (CERN) , “Magnetic Measurements for Particle Accelerators”
International Master in Hadrontherapy, Pavia, 10 May 2013

Measurements with Rotating Coils

Based on flux measurements and Induction Law

$$\varphi = \int_S \mathbf{B}\, d\mathbf{S}$$

Flux through a surface S of a pick-up coil



$$V = -\frac{d\varphi}{dt}$$

Time dependence (B or S variation) ➡ Voltage

$$\varphi_{end} - \varphi_{start} = -\int_{t_{start}}^{t_{end}} V\, dt$$

Change of flux measured by integrating the voltage

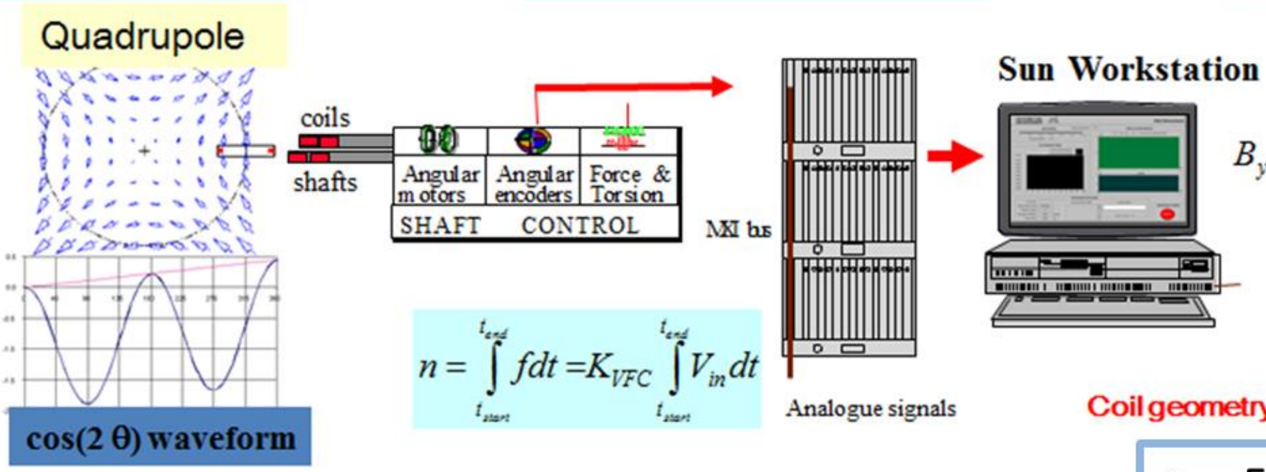
$$\boxed{B_{end} - B_{start} = \frac{\varphi_{end} - \varphi_{start}}{\kappa}}$$

To know : φ_{start} and **pick up coil geometry** (**<u>surface, radius</u>**)
Accuracy depends on their knowledge!

a) shaft rotation

b) Digital integration of V

c) Fourier analysis



$$n = \int_{t_{start}}^{t_{end}} f dt = K_{VFC} \int_{t_{start}}^{t_{end}} V_{in} dt$$

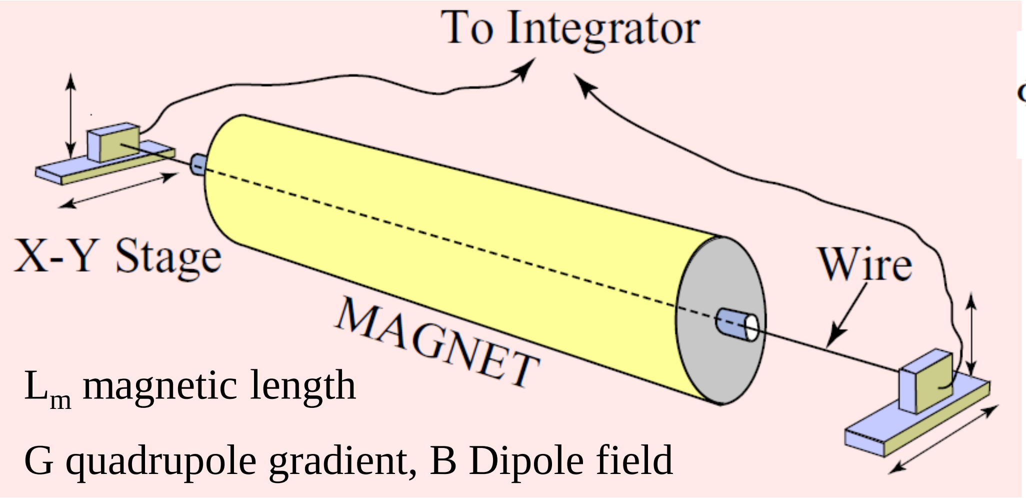
$$B_y + iB_x = \sum_{n=1}^{\infty} \mathbf{C}_n \left(\frac{\mathbf{s}}{R_{ref}} \right)^{n-1}$$

Coil geometry ➡ $\boxed{\mathbf{C}_n = \frac{\boldsymbol{\Psi}_n}{\boldsymbol{\kappa}_n}}$

κ_n= F(coil area A, radius R_0^{n-1})

The accuracy in the knowledge of the κ_n is fundamental

Single stretched and moving wire technique



L_m magnetic length

G quadrupole gradient, B Dipole field

- 0.1 mm single CuBe wire moved by 2× XY translation stages with µm resolution
- geometrical reference provided by retro-reflector optical targets
- Change in flux for a horizontal wire motion from x =0 to ±D and y =0 to ±D :
- variable wire tension to measure and compensate sag effects

- **1σ repeatability ~ 0.01 % at 1 T field**
- **Accuracy on integral field ~ 0.1 %**
- **Axis position uncertainty ~ few µms**

Horizontal movement

$$\Phi_H^{\pm} = L_m \int_0^{\pm D} B_y \cdot dx = L_m G \left[b_2 \frac{D^2}{2} \mp (b_2 x_0 + a_2 y - a_2 y_0) D \right]$$

Vertical movement

$$\Phi_V^{\pm} = L_m \int_0^{\pm D} B_x \cdot dy = L_m G \left[b_2 \frac{D^2}{2} \mp (b_2 y_0 - a_2 x + a_2 x_0) D \right]$$

Integrated Field Dipole

$$Lm\ B = \frac{\Phi_{H,V}^{+} - \Phi_{H,V}^{-}}{D}$$

Integrated Field Gradient

$$L_m . G = \frac{\Phi_H^{+} + \Phi_H^{-}}{D^2} = \frac{\Phi_V^{+} + \Phi_V^{-}}{D^2}$$

Magnetic axis

$$x_0' = -\left(\frac{D}{2}\right)\left(\frac{\Phi_H^{+} - \Phi_H^{-}}{\Phi_H^{+} + \Phi_H^{-}}\right)$$

$$y_0' = -\left(\frac{D}{2}\right)\left(\frac{\Phi_V^{+} - \Phi_V^{-}}{\Phi_V^{+} + \Phi_V^{-}}\right)$$