An introduction to Magnets for Accelerators

Attilio Milanese

Attilio.Milanese@cern.ch

CERN

John Adams Institute
Accelerator Course

19 Jan. 2023

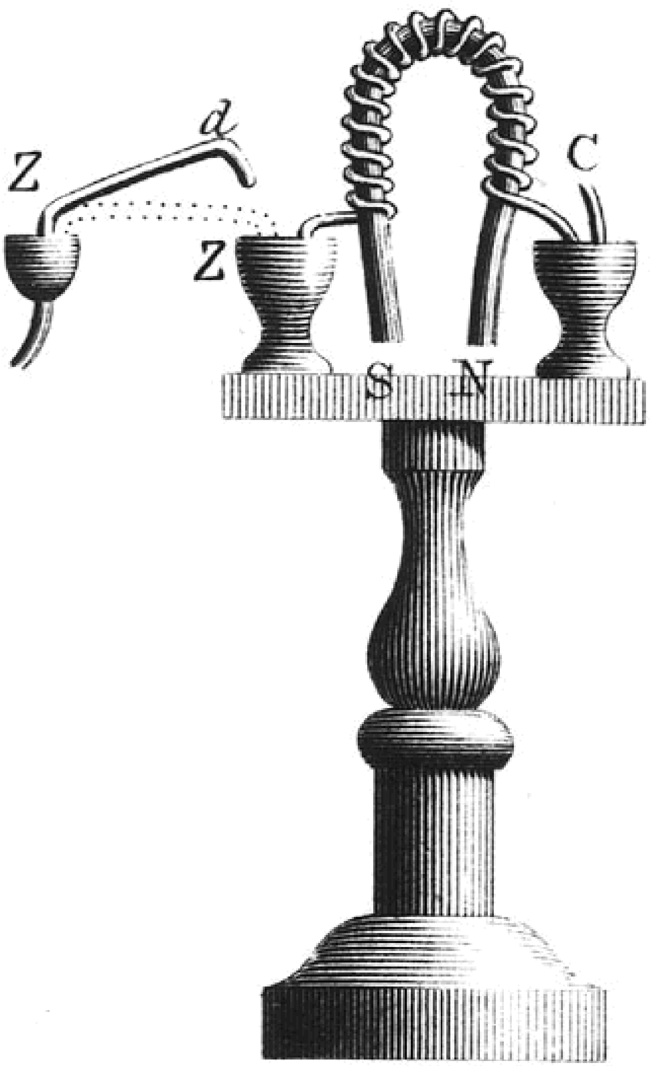
This is an introduction to magnets as building blocks of synchrotrons / transfer lines

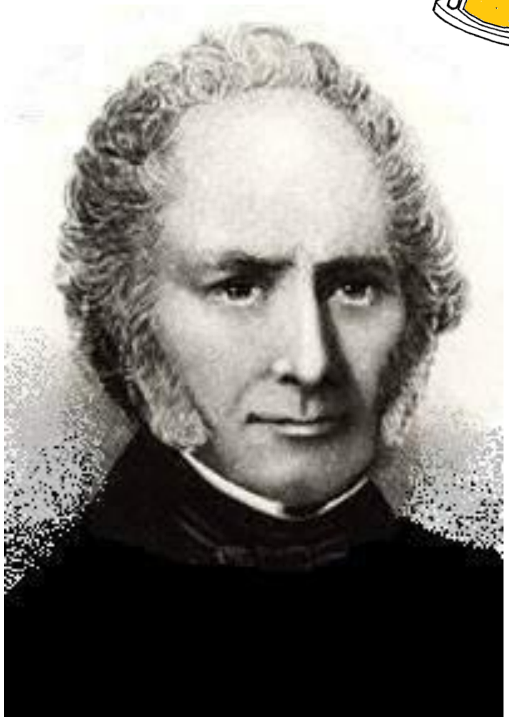
```
//
// MADX Example 2: FODO cell with dipoles
// Author: V. Ziemann, Uppsala University
// Date: 060911

TITLE,'Example 2: FODO2.MADX';

BEAM, PARTICLE=ELECTRON,PC=3.0;

DEGREE:=PI/180.0;

QF: QUADRUPOLE,L=0.5,K1=0.2;
QD: QUADRUPOLE,L=1.0,K1=-0.2;
B: SBEND,L=1.0,ANGLE=15.0*DEGREE;

FODO: SEQUENCE,REFER=ENTRY,L=12.0;
  QF1:   QF,       AT=0.0;
  B1:    B,        AT=2.5;
  QD1:   QD,       AT=5.5;
  B2:    B,        AT=8.5;
  QF2:   QF,       AT=11.5;
ENDSEQUENCE;
```

If you want to know more…

1. N. Marks, Magnets for Accelerators, JAI (John Adams Institute) course, Jan. 2015
2. D. Tommasini, Practical Definitions & Formulae for Normal Conducting Magnets
3. Lectures about magnets in CERN Accelerator Schools
4. Special CAS edition on magnets, Bruges, Jun. 2009
5. Superconducting magnets for particle accelerators in USPAS (U.S. Particle Accelerator Schools)
6. J. Tanabe, Iron Dominated Electromagnets
7. P. Campbell, Permanent Magnet Materials and their Application
8. K.-H. Mess, P. Schmüser, S. Wolff, Superconducting Accelerator Magnets
9. M. N. Wilson, Superconducting Magnets
10. A. Devred, Practical Low-Temperature Superconductors for Electromagnets
11. L. Rossi and E. Todesco, Electromagnetic design of superconducting dipoles based on sector coils

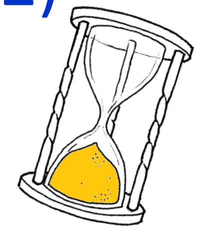
According to history, the first electromagnet (not for an accelerator) was built in England in 1824 by William Sturgeon

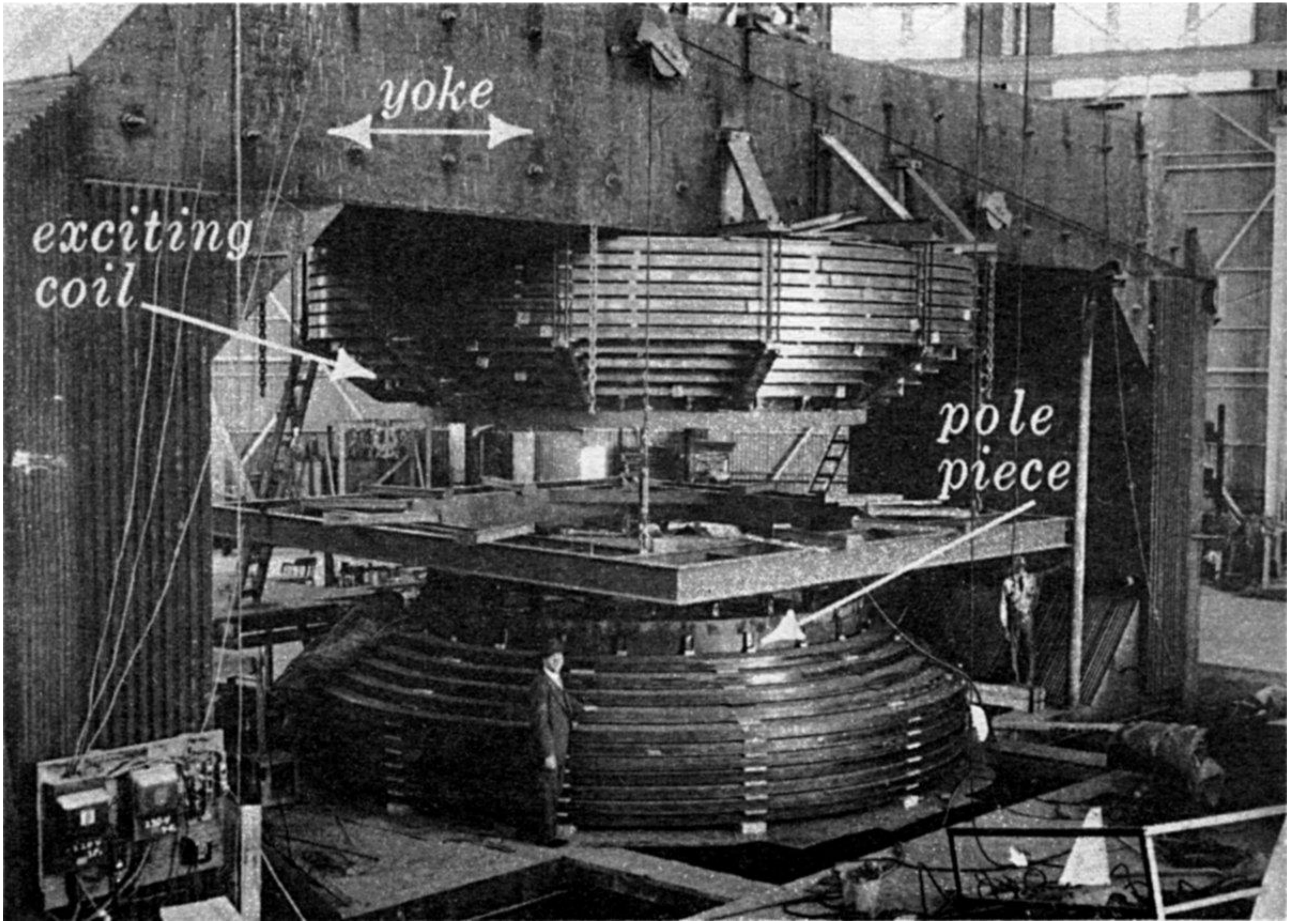




William Sturgeon

The working principle is the same as this large magnet, of the 184'' (4.7 m) cyclotron at Berkeley (picture taken in 1942)





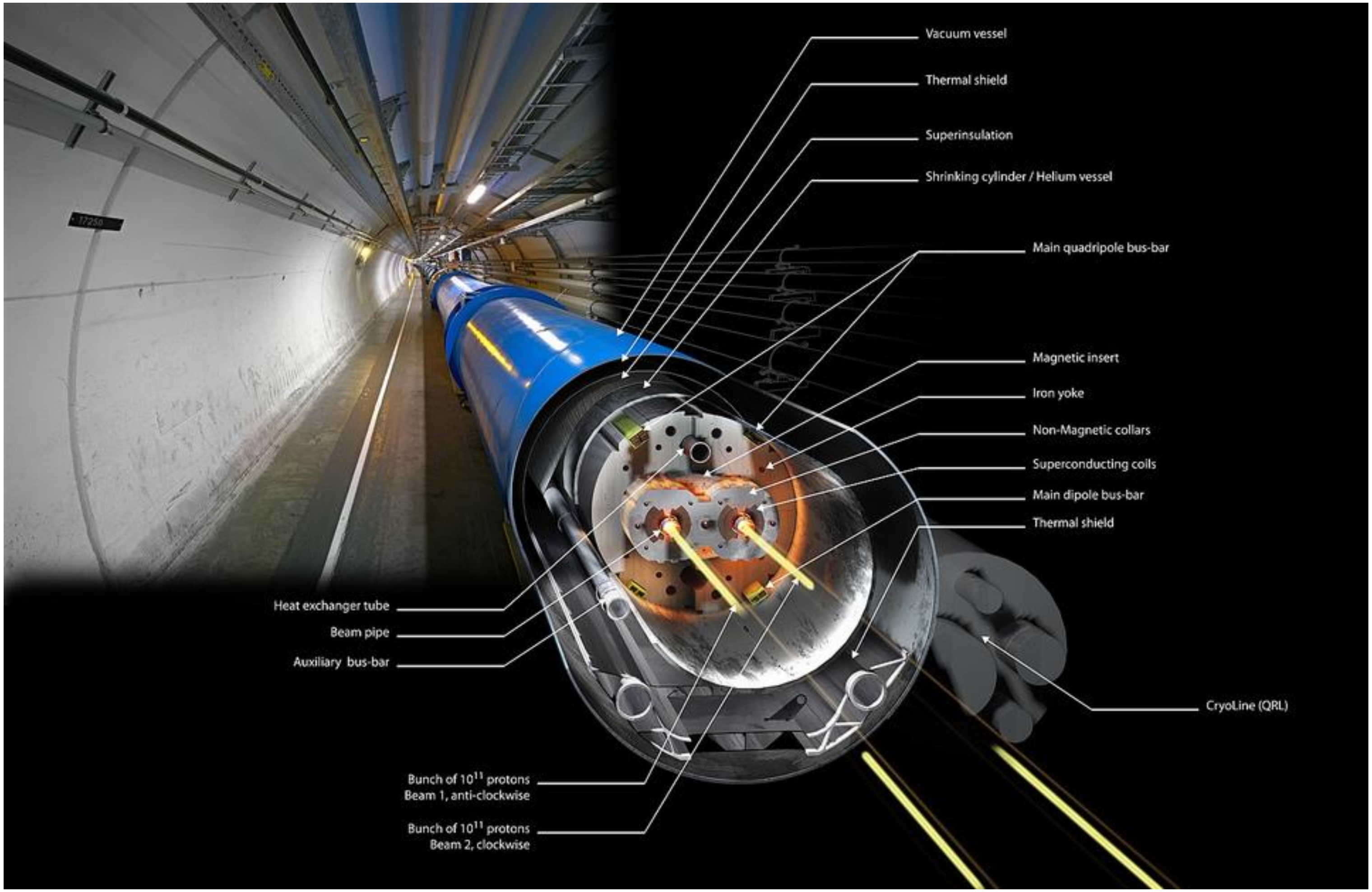
This short course is organized in several blocks

1. Introduction, jargon, general concepts and formulae
2. Resistive magnets
3. Superconducting magnets
4. Tutorial with FEMM

Magnets can be classified based on their geometry / what they do to the beam

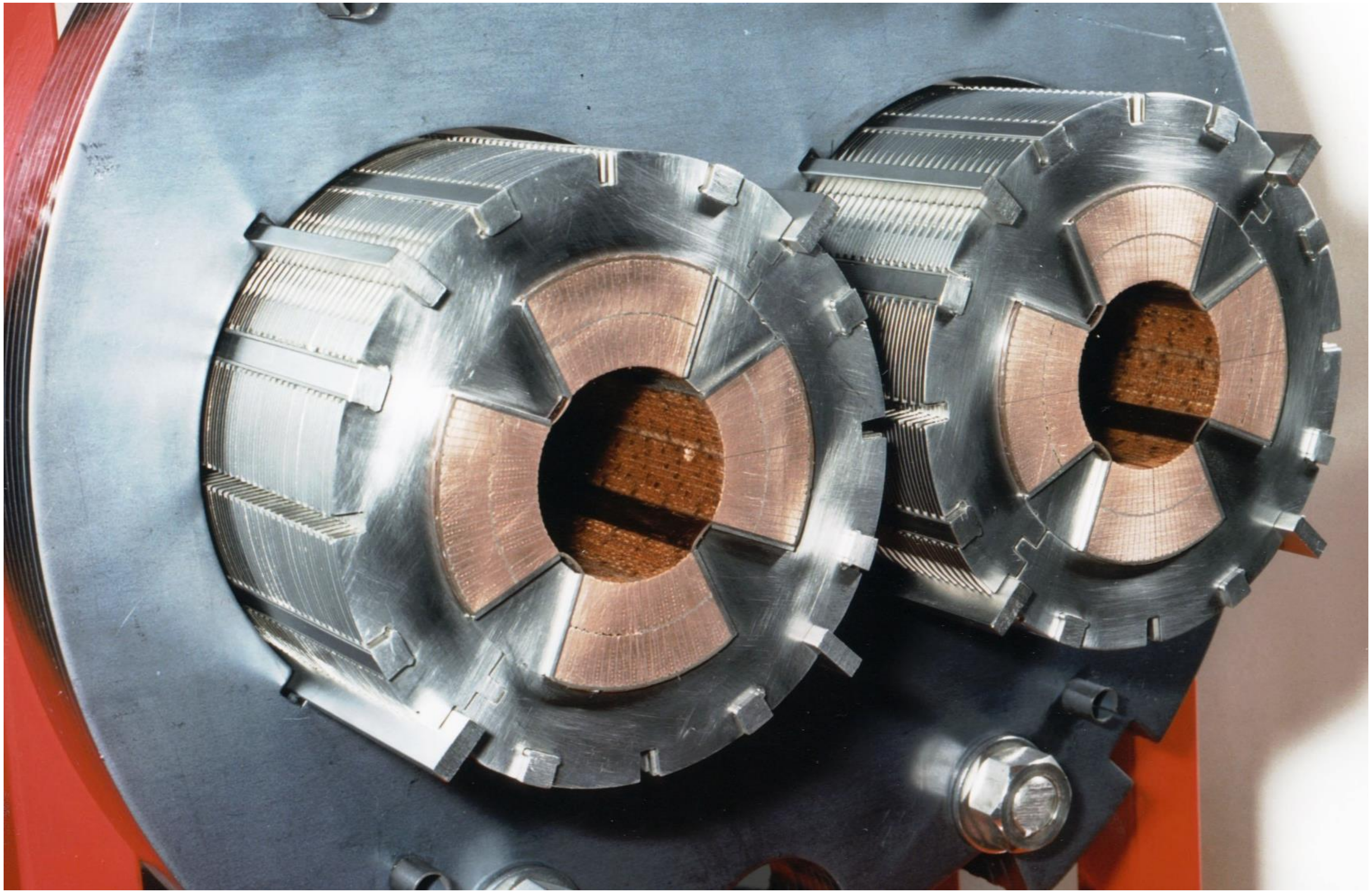
dipole	solenoid
quadrupole	combined function bending
sextupole	corrector
octupole	skew magnet
kicker	undulator / wiggler

This is a main dipole of the LHC at CERN: 8.3 T × 14.3 m



These are main dipoles of the SPS at CERN: 2.0 T × 6.3 m

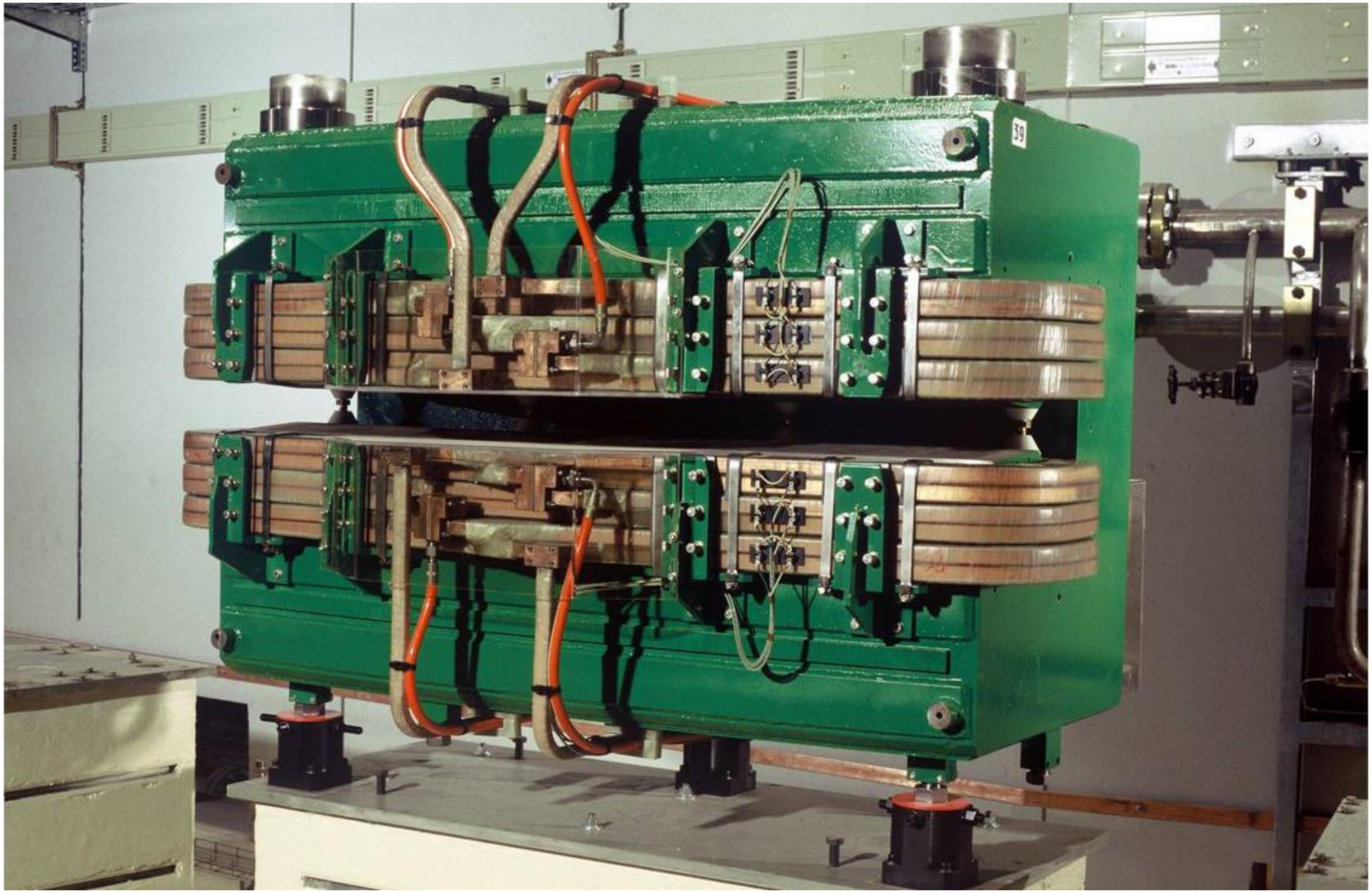
This is a cross section of a main quadrupole of the LHC at CERN: 223 T/m × 3.2 m



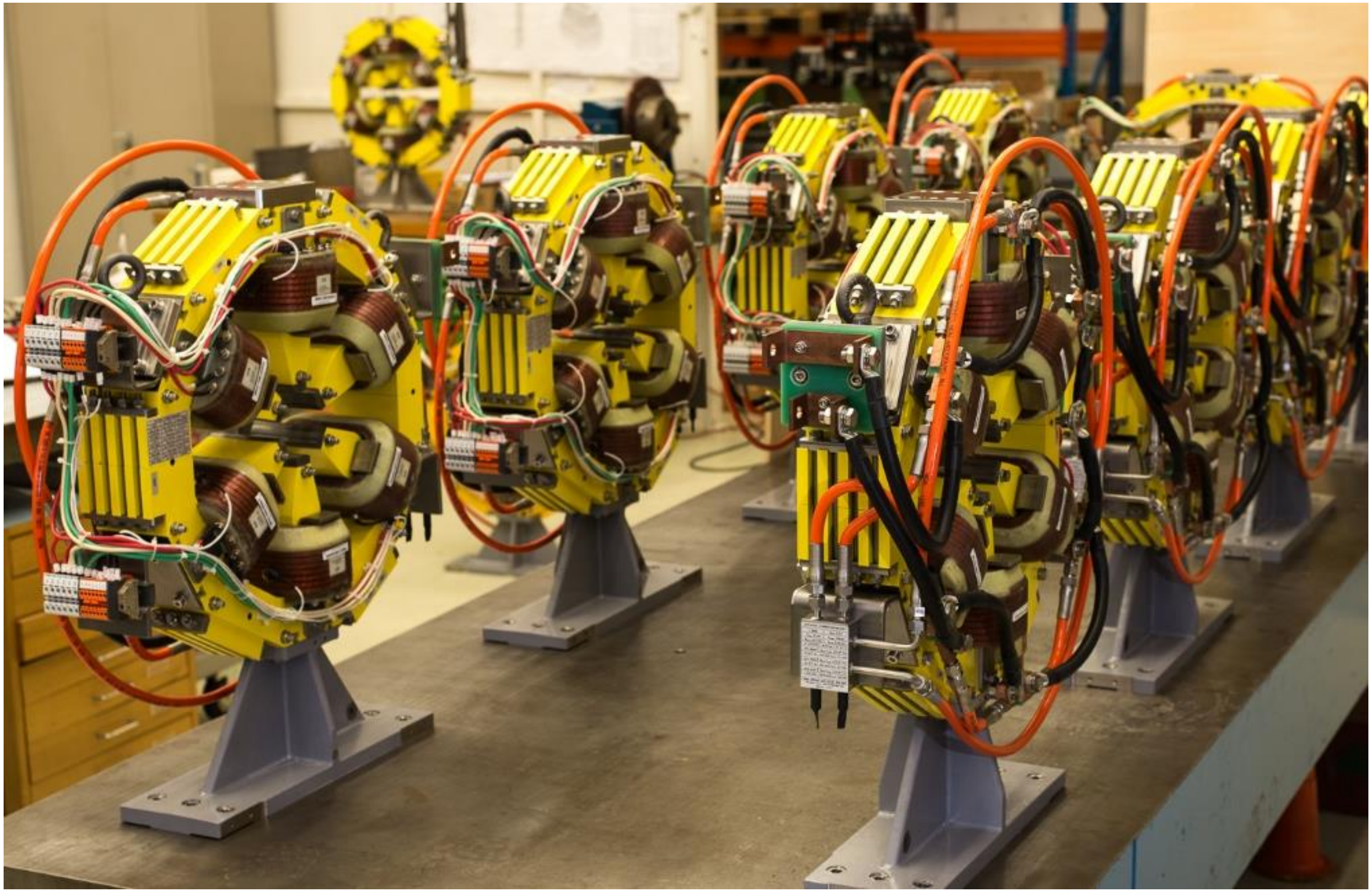
These are main quadrupoles of the SPS at CERN:

22 T/m × 3.2 m

This is a combined function bending magnet of the ELETTRA light source



These are sextupoles (with embedded correctors) of the main ring of the SESAME light source



Magnets can be classified also differently, looking for example at their technology

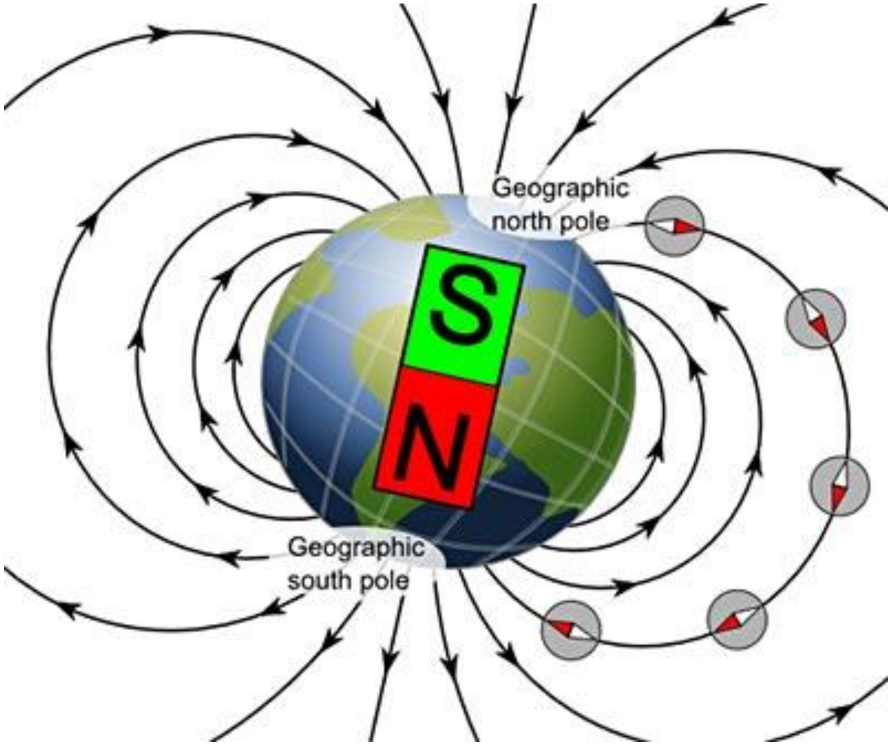
electromagnet	permanent magnet
iron dominated	coil dominated
normal conducting (resistive)	superconducting

static	cycled / ramped slow pulsed	fast pulsed

Nomenclature

B	magnetic field B field magnetic flux density magnetic induction	T (Tesla)
H	H field magnetic field strength magnetic field	A/m (Ampere/m)
μ_0	vacuum permeability	$1.25663706212(19) \cdot 10^{-6}$ H/m $4\pi \cdot 10^{-7}$ H/m (Henry/m)
μ_r	relative permeability	dimensionless
μ	permeability, $\mu = \mu_0 \mu_r$	H/m

The polarity comes from the direction of the flux lines, that go from a North to a South pole



in Oxford, on 25/01/2017

$|B|$ = 48728 nT = 0.048728 mT = 0.000048728 T

Magnetostatic fields are described by Maxwell's equations, coupled with a law describing the material

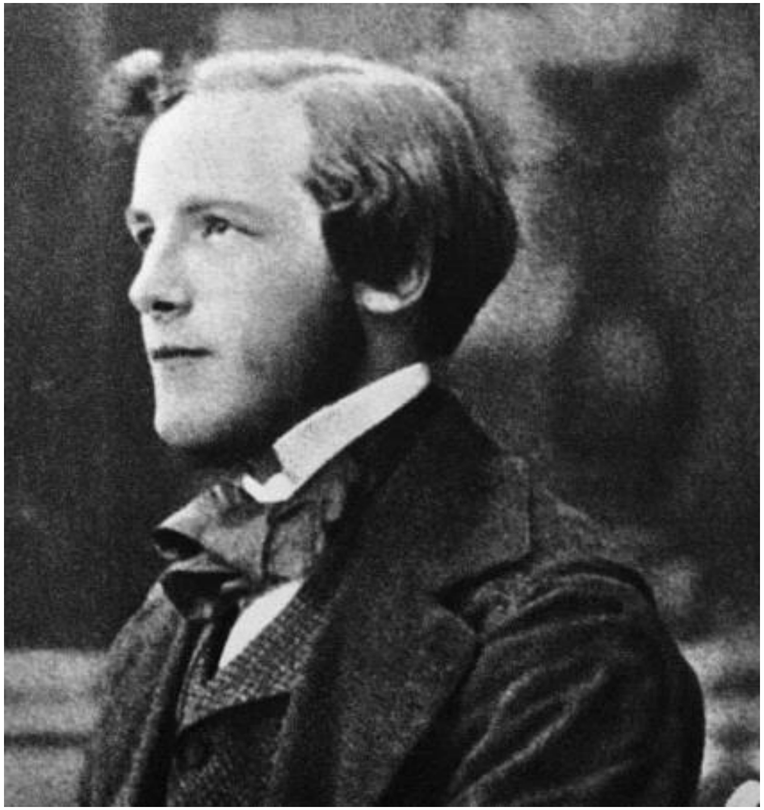
$$\mathrm{div}\,\vec{B} = 0$$

$$\oint_S \vec{B} \cdot \overrightarrow{dS} = 0$$

$$\mathrm{rot}\,\vec{H} = \vec{J}$$

$$\oint_C \vec{H} \cdot \overrightarrow{dl} = \int_S \vec{J} \cdot \overrightarrow{dS} = NI$$

$$\vec{B} = \mu_0 \mu_r \vec{H}$$



James Clerk Maxwell

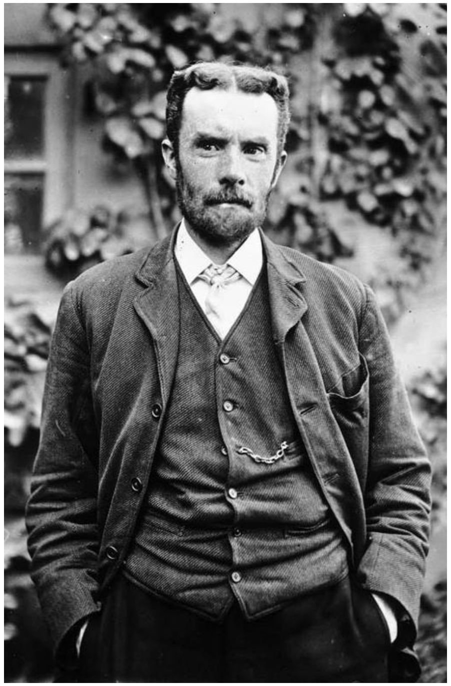
The Lorentz force is the link between electromagnetism and mechanics

$$\vec{F} = q[\vec{E} + (\vec{v} \times \vec{B})]$$

for charged beams

$$\vec{F} = I\vec{\ell} \times \vec{B}$$

for conductors



Oliver Heaviside

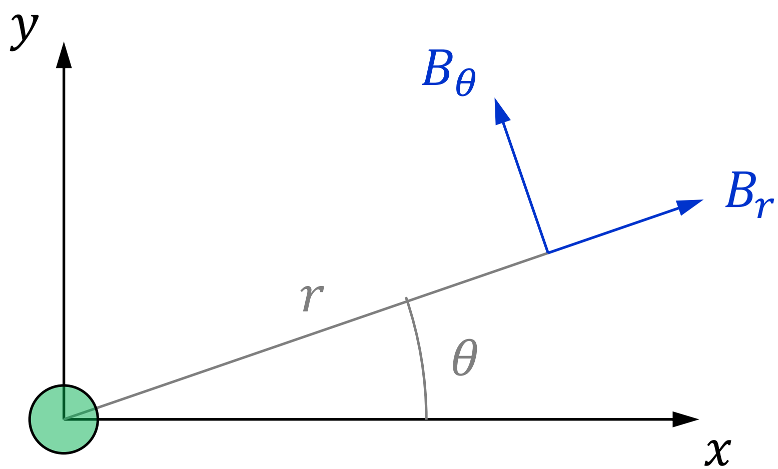
Hendrik Lorentz

Pierre-Simon, marquis de Laplace

In synchrotrons / transfer lines magnets, the B field seen from the beam is often expressed as a series of multipoles

$$B_r = \sum_{n=1}^{\infty} \left(\frac{r}{R}\right)^{n-1} [B_n \sin(n\theta) + A_n \cos(n\theta)]$$

$$B_\theta = \sum_{n=1}^{\infty} \left(\frac{r}{R}\right)^{n-1} [B_n \cos(n\theta) - A_n \sin(n\theta)]$$



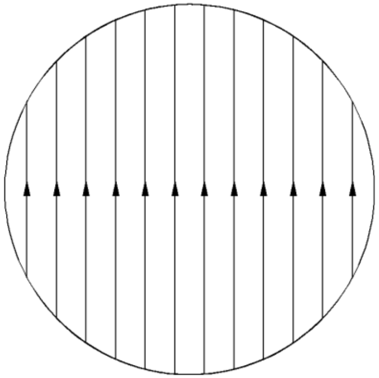
direction of the beam (orthogonal to plane)

$$B_y(z) + iB_x(z) = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{z}{R}\right)^{n-1}$$

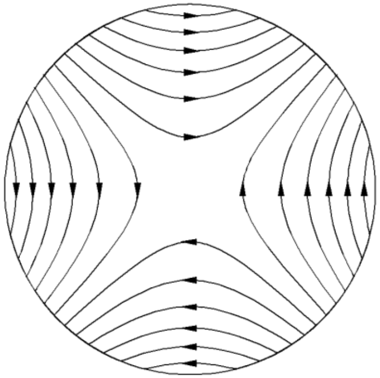
$$z = x + iy = re^{i\theta}$$

Each multipole term corresponds to a field distribution; they can be added up (exploiting linear superposition)

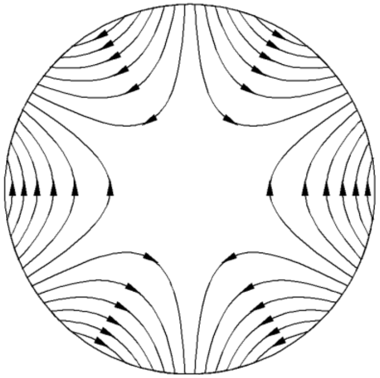
B_1: normal dipole



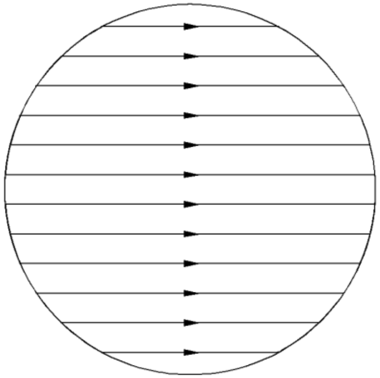
B_2: normal quadrupole



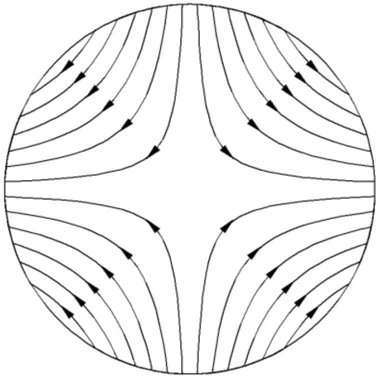
B_3: normal sextupole



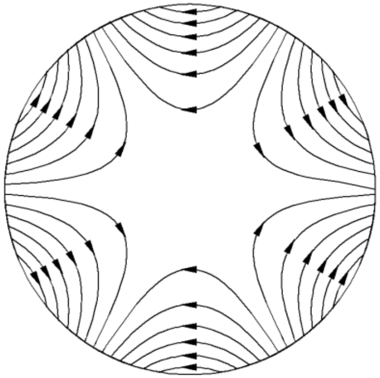
A_1: skew dipole



A_2: skew quadrupole

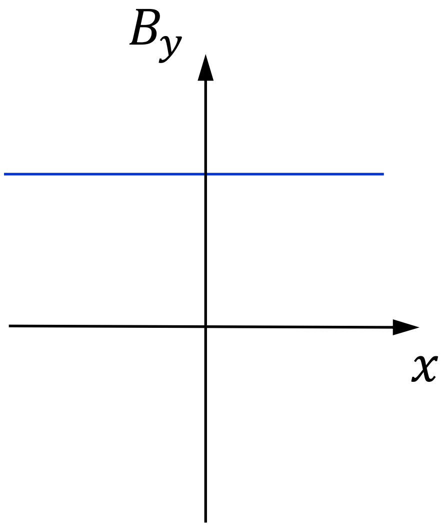


A_3: skew sextupole

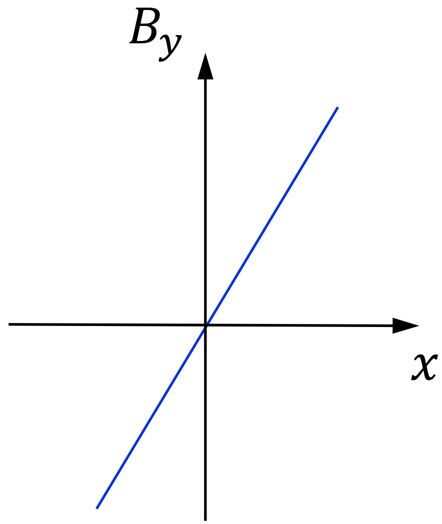


The field profile in the horizontal plane follows a polynomial expansion

$$B_y(x) = \sum_{n=1}^{\infty} B_n \left(\frac{x}{R}\right)^{n-1} = B_1 + B_2\frac{x}{R} + B_3\frac{x^2}{R^2} + \cdots$$

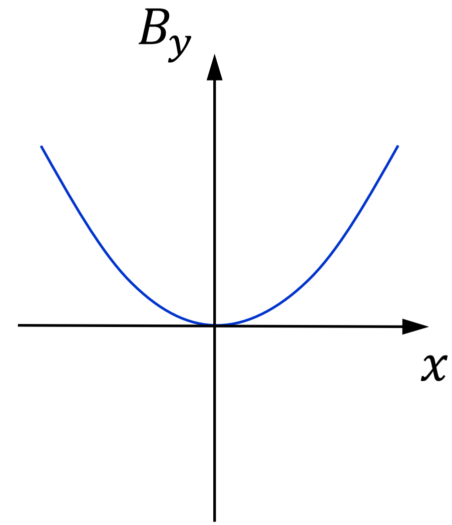


B_1: dipole



B_2: quadrupole

$$G = \frac{B_2}{R} = \frac{\partial B_y}{\partial x}$$



B_3: sextupole

$$B'' = \frac{2B_3}{R^2}$$

For the optics, usually the field or multipole component is given, together with the (magnetic) length: ex. from MAD-X

Dipole

bend angle a [rad] & length L [m]

k_0 [1/m] & length L [m]   obsolete

$k_0 = B / (B\rho)$ $B = B_1$

Quadrupole

quadrupole coefficient k_1 [$1/m^2$] × length L [m]

$k_1 = (dB_y/dx) / (B\rho)$

$G = dB_y/dx = B_2/R$

Sextupole

sextupole coefficient k_2 [$1/m^3$] × length L [m]

$k_2 = (d^2B_y/dx^2) / (B\rho)$

$(d^2B_y/dx^2)/2! = B_3/R^2$

Here is how to compute magnetic quantities from MAD-X entries, and vice versa

```
BEAM, PARTICLE=ELECTRON,PC=3.0;
DEGREE:=PI/180.0;
QF: QUADRUPOLE,L=0.5,K1=0.2;
QD: QUADRUPOLE,L=1.0,K1=-0.2;
B: SBEND,L=1.0,ANGLE=15.0*DEGREE;
```

$(B\rho) = 10^9/c*PC = 10\hat{}9/299792485*3.0 = 10.01$ Tm

<u>dipole</u> (SBEND)

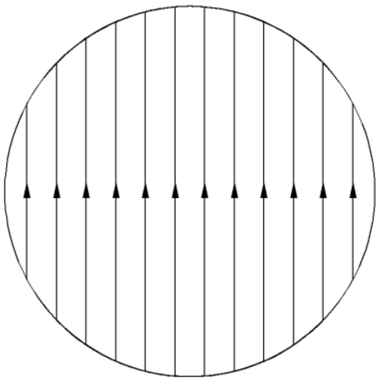
$B = |ANGLE|/L*(B\rho) = (15*pi/180)/1.0*10.01 = 2.62$ T

<u>quadrupole</u>

$G = |K1|*(B\rho) = 0.2*10.01 = 2.00$ T/m

The harmonic decomposition is used also to describe the field quality (or field homogeneity), that is, the deviations of the actual B with respect to the ideal one

(normal) dipole



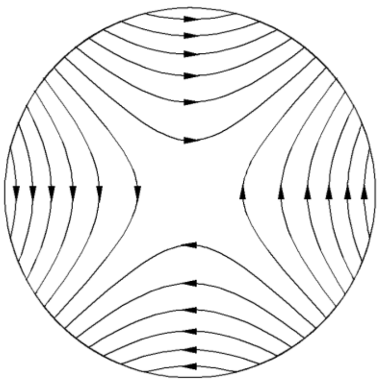
$$\vec{B}_{id}(x,y) = B_1\vec{j}$$

$$B_y(z) + iB_x(z) =$$
$$= B_1 + \frac{B_1}{10000}\left[ia_1 + (b_2 + ia_2)\left(\frac{z}{R}\right) + (b_3 + ia_3)\left(\frac{z}{R}\right)^2 + (b_4 + ia_4)\left(\frac{z}{R}\right)^3 + \cdots\right]$$

$$b_2 = 10000\frac{B_2}{B_1} \quad b_3 = 10000\frac{B_3}{B_1} \quad a_1 = 10000\frac{A_1}{B_1} \quad a_2 = 10000\frac{A_2}{B_1} \quad \ldots$$

The same expression can be written for a quadrupole

(normal) quadrupole



$$\vec{B}_{id}(x,y) = B_2[x\vec{j} + y\vec{i}]\frac{1}{R}$$

$$B_y(z) + iB_x(z) =$$
$$= B_2\frac{z}{R} + \frac{B_2}{10000}\left[ia_2\left(\frac{z}{R}\right) + (b_3 + ia_3)\left(\frac{z}{R}\right)^2 + (b_4 + ia_4)\left(\frac{z}{R}\right)^3 + \cdots\right]$$

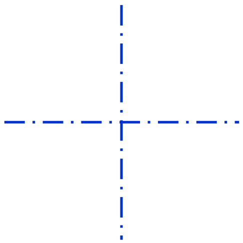
$$b_3 = 10000\frac{B_3}{B_2} \qquad b_4 = 10000\frac{B_4}{B_2} \qquad a_2 = 10000\frac{A_2}{B_2} \qquad \ldots$$

The *allowed* / *not-allowed* harmonics refer to some terms that shall / shall not cancel out thanks to design symmetries

<u>fully symmetric dipoles</u>

allowed: B_1, b_3, b_5, b_7, b_9, etc.

not-allowed: all the others



<u>half symmetric dipoles</u>

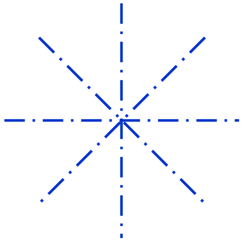
allowed: B_1, b_2, b_3, b_4, b_5, etc.

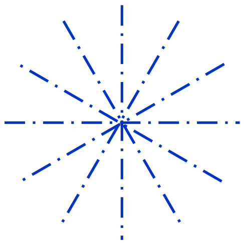
not-allowed: all the others

<u>fully symmetric quadrupoles</u>

allowed: B_2, b_6, b_{10}, b_{14}, b_{18}, etc.

not-allowed: all the others





<u>fully symmetric sextupoles</u>

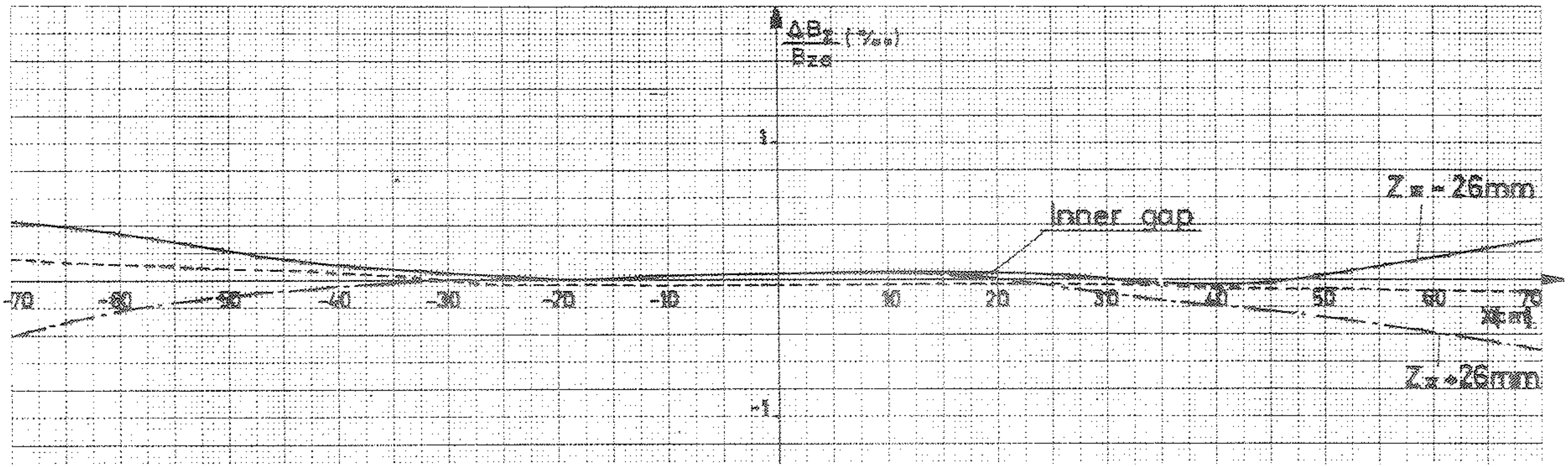
allowed: B_3, b_9, b_{15}, b_{21}, etc.

not-allowed: all the others

The field quality is often also shown with a ΔB/B plot

$$\frac{\Delta B}{B} = \frac{B(x,y) - B_{id}(x,y)}{B_{id}(x,y)}$$

done on one component, usually B_y for a dipole



ΔB/B can (at least locally) be expressed from the harmonics: this is the expansion for a dipole

$$B_{y,id}(x) = B_1$$

$$B_y(x) = B_1 + \frac{B_1}{10000}\left[b_2\left(\frac{x}{R}\right) + b_3\left(\frac{x}{R}\right)^2 + b_4\left(\frac{x}{R}\right)^3 + \cdots\right]$$

$$\frac{\Delta B}{B}(x) = \frac{1}{10000}\left[b_2\left(\frac{x}{R}\right) + b_3\left(\frac{x}{R}\right)^2 + b_4\left(\frac{x}{R}\right)^3 + \cdots\right]$$

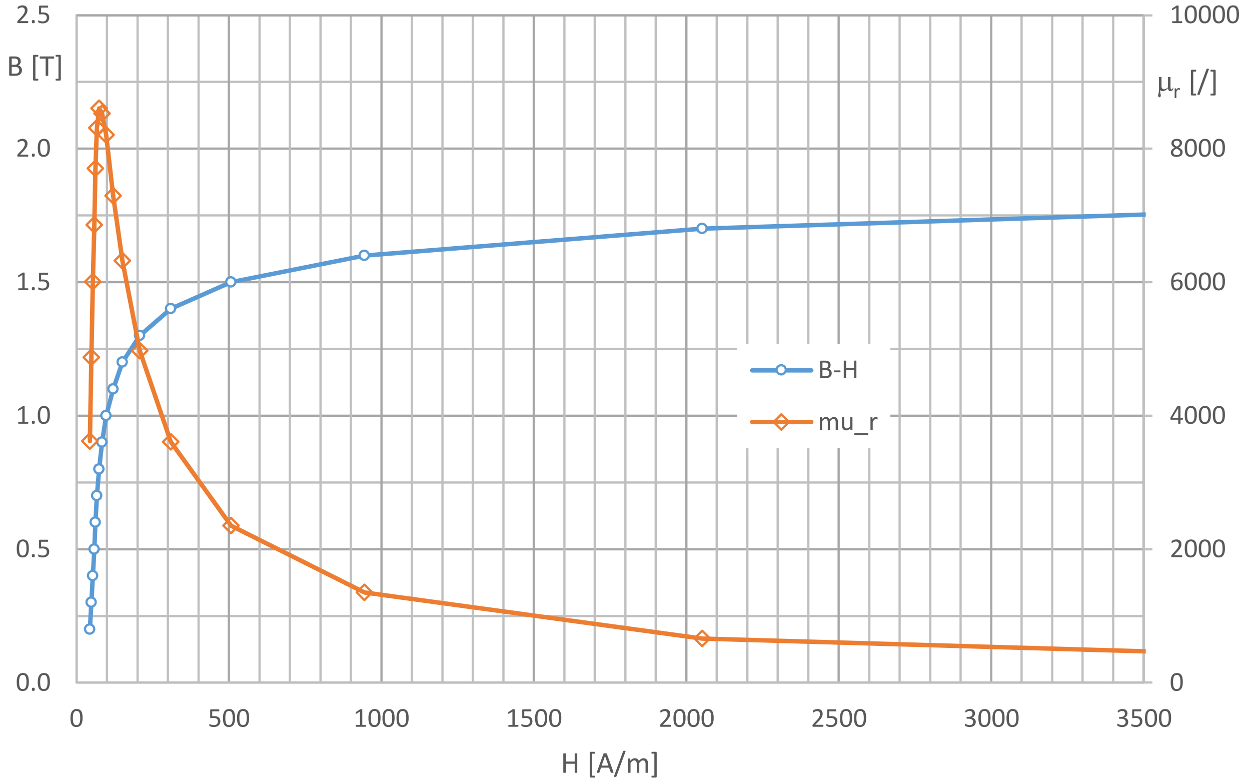
1. Introduction, jargon, general concepts and formulae

2. Resistive magnets

3. Superconducting magnets

4. Tutorial with FEMM

Resistive magnets are in most cases "iron-dominated": the BH response of the yoke material is important



curves for typical M1200-100 A electrical steel

These are typical fields for resistive dipoles and quadrupoles, taken from machines at CERN

<u>PS @ 26 GeV</u>

combined function bending $B = 1.5$ T

<u>SPS @ 450 GeV</u>

bending $B = 2.0$ T

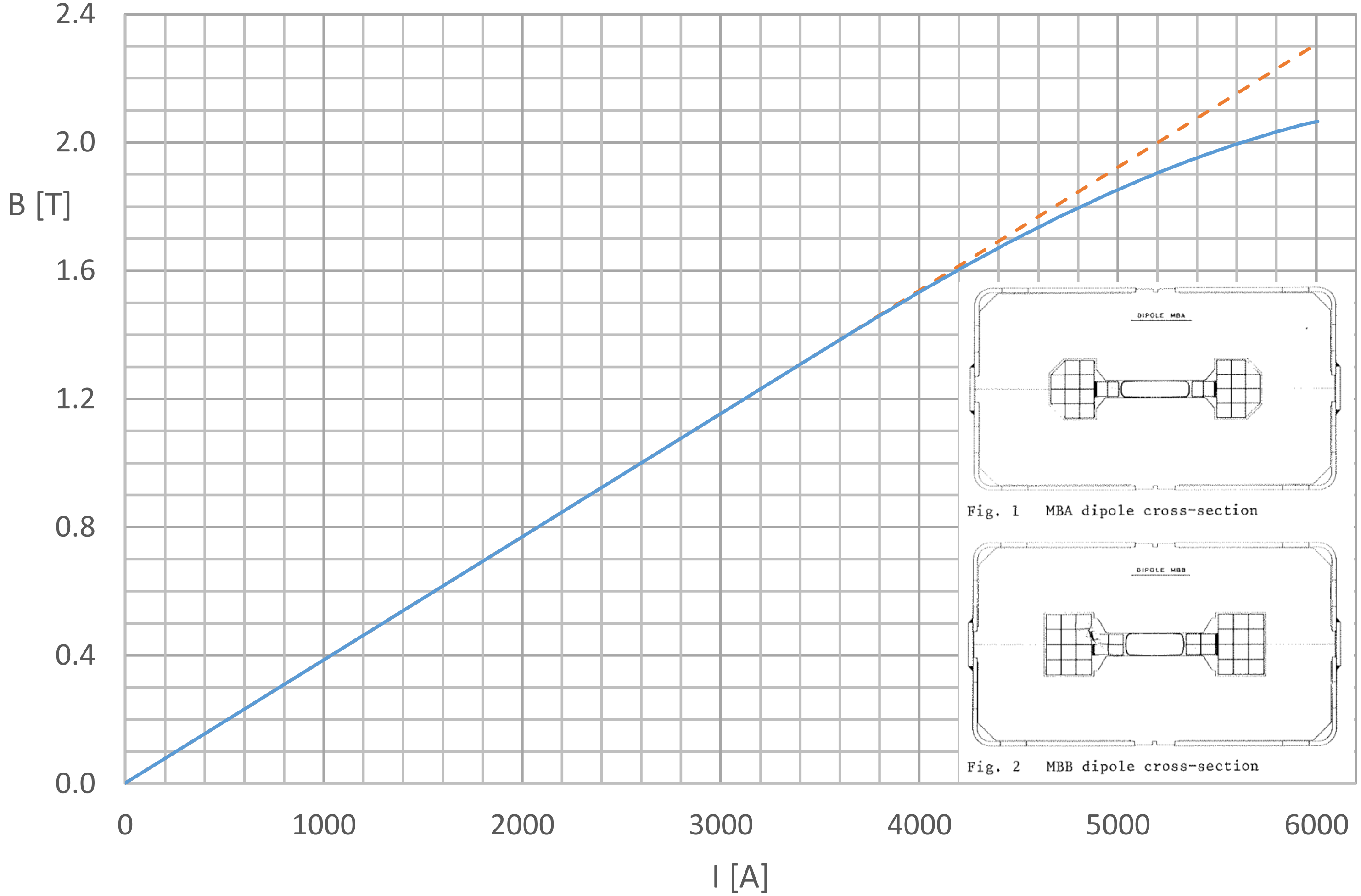
quadrupole $B_{pole} = 21.7*0.044 = 0.95$ T

<u>TI2 / TI8 (transfer lines SPS to LHC, @ 450 GeV)</u>

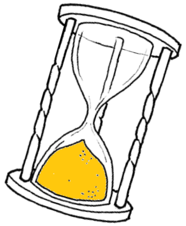
bending $B = 1.8$ T

quadrupole $B_{pole} = 53.5*0.016 = 0.86$ T

This is the (average) transfer function field B vs. current I for the SPS main dipoles



If the magnet is not dc, then an rms power / current is taken, considering the duty cycle

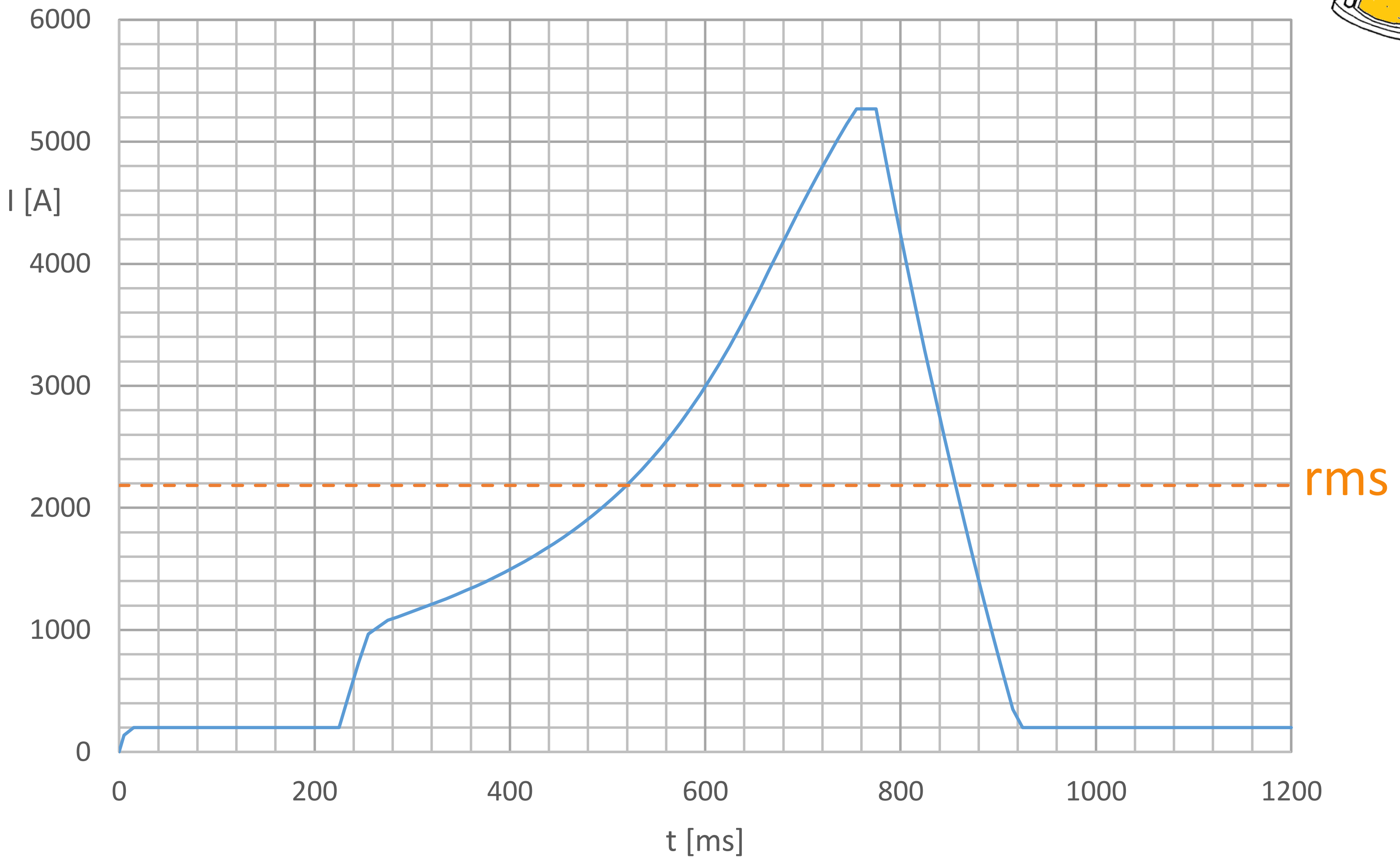


$$P_{rms} = RI_{rms}^2 = \frac{1}{T}\int_0^T R[I(t)]^2 dt$$

for a pure sine wave $$I_{rms} = \frac{I_{peak}}{\sqrt{2}}$$

for a linear ramp from 0 $$I_{rms} = \frac{I_{peak}}{\sqrt{3}}$$

This is a cycle to 2.0 GeV of the PSB at CERN



For resistive coils, the material is most often copper, sometimes aluminum

	Cu	Al
raw metal price	≈ 8400 $/ton	≈ 2300 $/ton
electrical resistivity	$1.72 \cdot 10^{-8}\ \Omega/\mathrm{m}$	$2.65 \cdot 10^{-8}\ \Omega/\mathrm{m}$
density	8.9 kg/dm^3	2.7 kg/dm^3

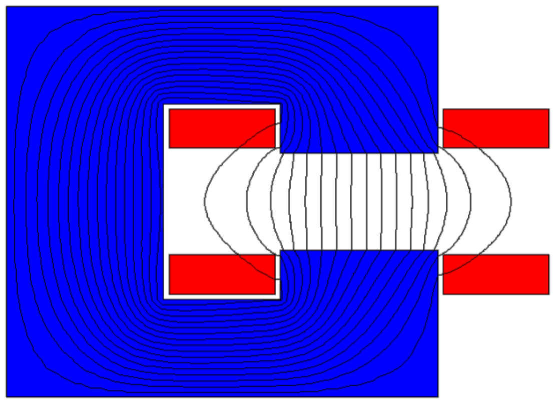
LHCb detector dipole

Al coils

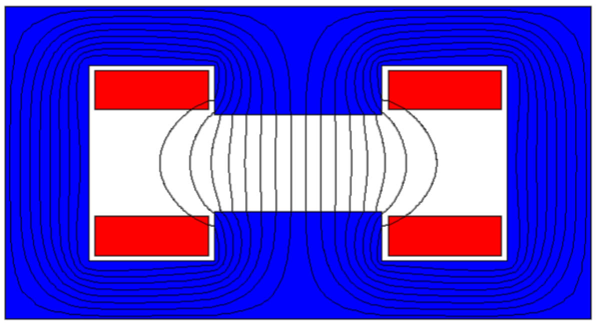
coil mass 2 × 25 t

power 2 × 2.1 MW

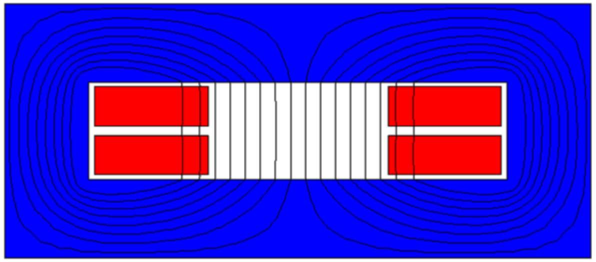
These are the most common types of resistive dipoles



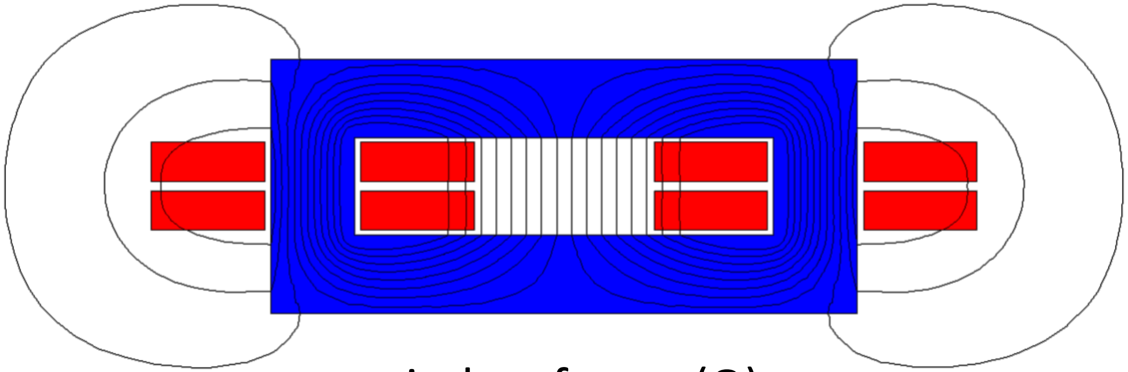
C



H

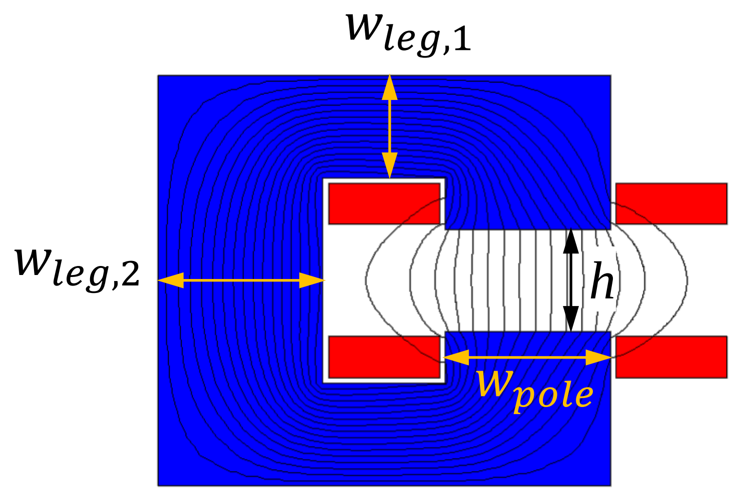


window frame
(O)



window frame (O)
with windings on both backlegs

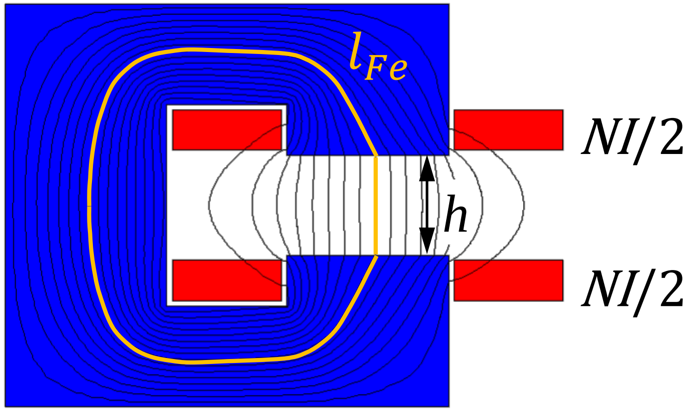
The magnetic circuit is dimensioned so that the pole is wide enough for field quality, and there is enough room for the flux in the return legs



$$w_{pole} \cong w_{GFR} + 2.5h$$

$$B_{leg} \cong B_{gap} \frac{w_{pole} + 1.2h}{w_{leg}}$$

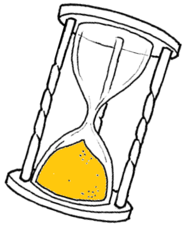
The Ampere-turns are a linear function of the gap and of the B field (at least up to saturation)



$$NI = \oint \vec{H} \cdot \vec{dl} = \frac{B_{Fe}}{\mu_0 \mu_r} \cdot l_{Fe} + \frac{B_{gap}}{\mu_0} \cdot h \cong \frac{B_{gap} h}{\mu_0}$$

$$NI = \frac{Bh}{\eta \mu_0} \qquad \eta = \frac{1}{1 + \frac{1}{\mu_r} \frac{l_{Fe}}{h}}$$

The same can be solved using magnetic reluctances and Hopkinson's law, which is a parallel of Ohm's law



$$\mathcal{R} = \frac{\mathrm{NI}}{\Phi} \qquad \mathrm{R} = \frac{\mathrm{V}}{I}$$

$$\mathcal{R} = \frac{l}{\mu_0 \mu_r A} \qquad \mathrm{R} = \frac{l}{\sigma S}$$

$$\eta = \frac{1}{1 + \frac{\mathcal{R}_{Fe}}{\mathcal{R}_{gap}}}$$

Example of computation of Ampere-turns and current

central field B = 1.5 T
total gap 80 mm

$$NI = \frac{Bh}{\eta\mu_0}$$

$\eta \cong 0.97$

NI = (1.5*0.080)/(0.97*4*pi*10^-7) = 98446 A total

<u>low inductance option</u>

64 turns, I ≅ 98500/64 = 1540 A

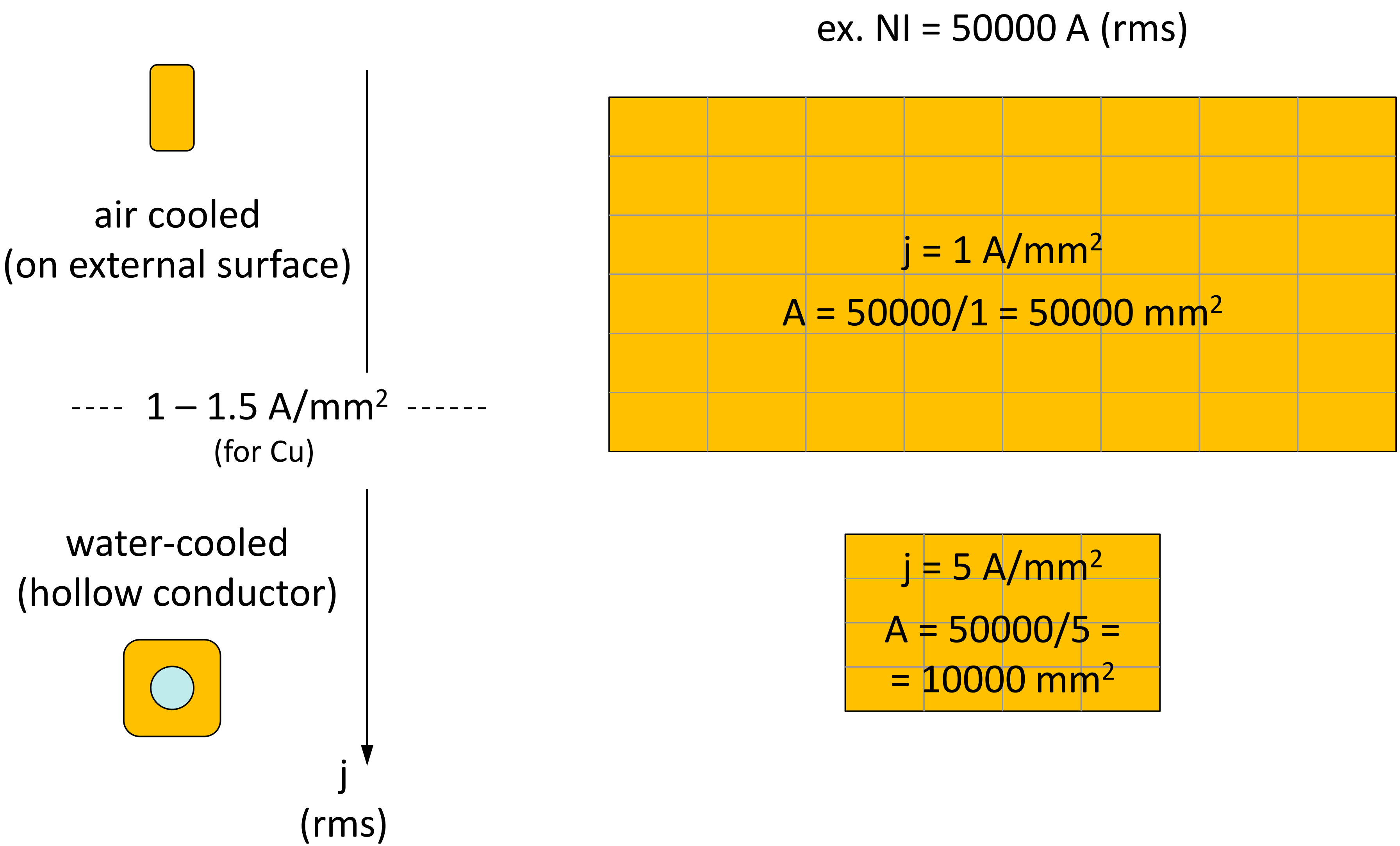
L = 62.9 mH, R = 15.0 mΩ

<u>low current option</u>

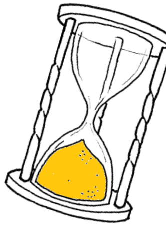
204 turns, I ≅ 98500/204 = 483 A

L = 639 mH, R = 160 mΩ

Besides the number of turns, the overall size of the coil depends on the current density, which drives the resistive power consumption (linearly)



These are common formulae for the main electric parameters of a resistive dipole (1/2)



Ampere-turns (total) $NI = \dfrac{Bh}{\eta\mu_0}$

current $I = \dfrac{(NI)}{N}$

resistance (total) $R = \dfrac{\rho N L_{turn}}{A_{cond}}$

inductance $L \cong \eta\mu_0 N^2 A/h$

$$A \cong (w_{pole} + 1.2h)(l_{Fe} + h)$$

These are common formulae for the main electric parameters of a resistive dipole (2/2)

voltage $$V = RI + L\frac{dI}{dt}$$

resistive power (rms) $$P_{rms} = RI_{rms}^2$$

$$= \rho j_{rms}^2 V_{cond}$$

$$= \frac{\rho L_{turn} B_{rms} h}{\eta \mu_0} j_{rms}$$

magnetic stored energy $$E_m = \frac{1}{2} L I^2$$

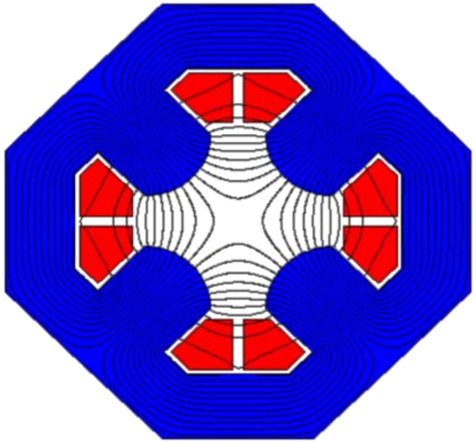
The table describes the field quality – in terms of allowed multipoles – for the different layouts of these examples

	C-shaped	H-shaped	O-shaped
b_2	1.4	0	0
b_3	-88.2	-87.0	0.2
b_4	0.7	0	0
b_5	-31.6	-31.4	-0.1
b_6	0.1	0	0
b_7	-3.8	-3.8	-0.1
b_8	0.0	0	0
b_9	0.0	0.0	0.0

b_n multipoles in units of 10^{-4} at R = 17 mm

NI = 20 kA, h = 50 mm, w_{pole} = 80 mm

These are the most common types of resistive quadrupoles



standard
quadrupole

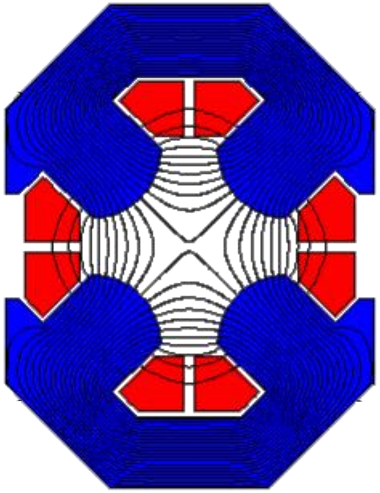
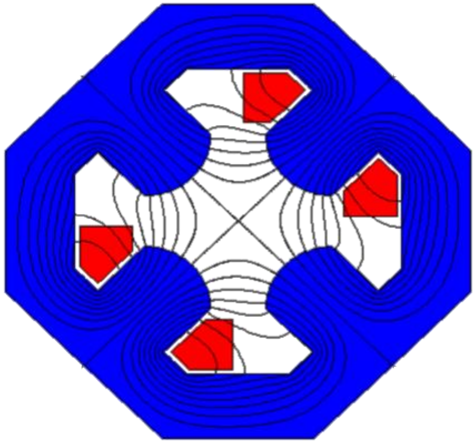
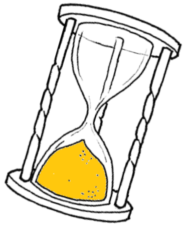


figure-of-8
(useful because
narrow)



quadrupole
with half the coils
(maybe not so common)

These are useful formulae for standard resistive quadrupoles



pole tip field $$B_{pole} = Gr$$

Ampere-turns (per pole) $$NI = \frac{Gr^2}{2\eta\mu_0}$$

current $$I = \frac{(NI)}{N}$$

resistance (total) $$R = 4\frac{\rho N L_{turn}}{A_{cond}}$$

These are useful formulae for the main cooling parameters of a water-cooled resistive magnet

cooling flow $$Q_{tot} \cong 14.3\frac{P}{\Delta T} \qquad Q_{tot} \cong N_{hydr}Q$$

water velocity $$v = \frac{1000}{15\pi d^2}Q$$

Reynolds number $$Re \cong 1400dv$$

pressure drop $$\Delta p = 60L_{hydr}\frac{Q^{1.75}}{d^{4.75}}$$

The *ideal* poles for dipole, quadrupole, sextupole, etc. are lines of constant scalar potential

dipole

$\rho \sin(\theta) = \pm h/2$ $\quad$ $y = \pm h/2$ $\quad$ straight line

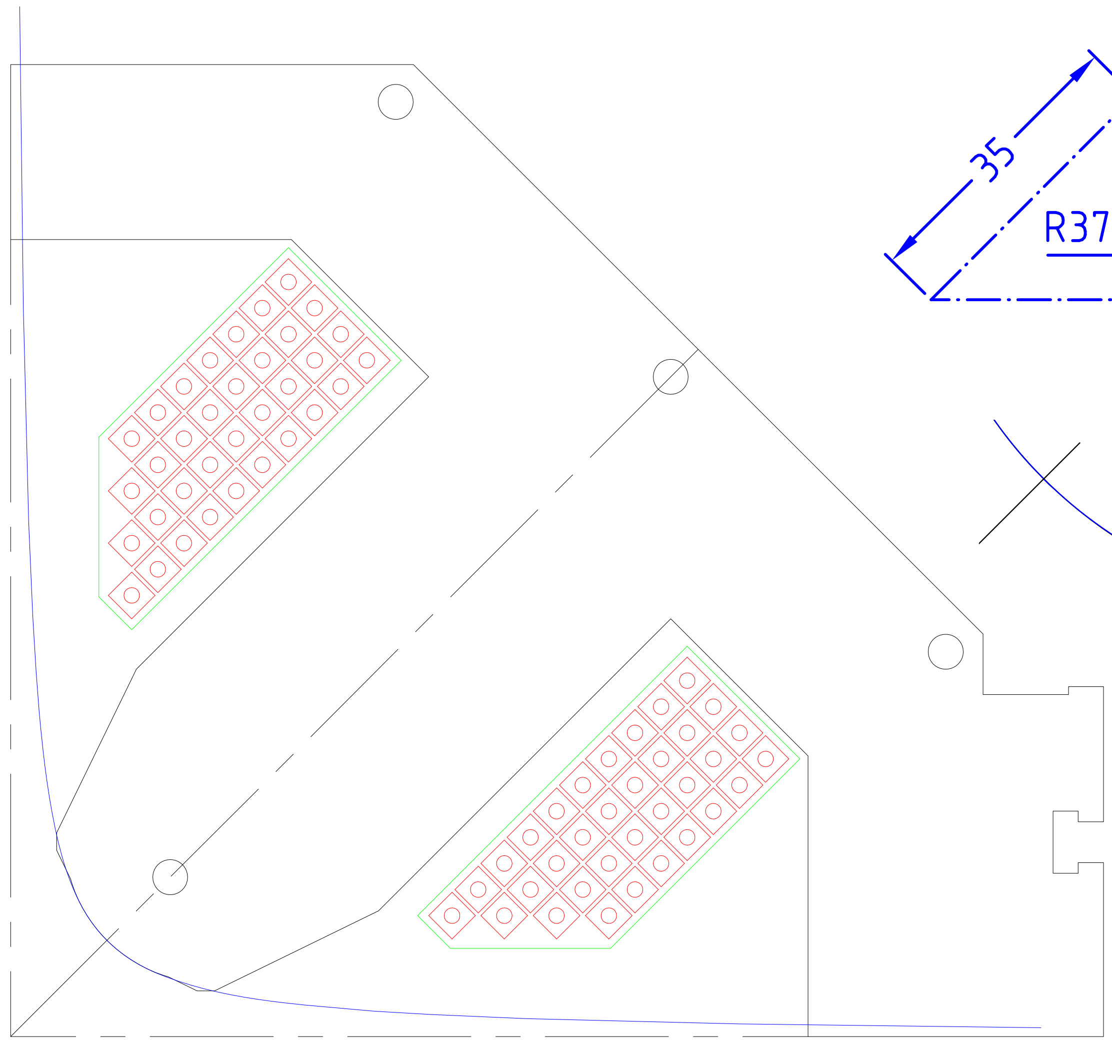
quadrupole

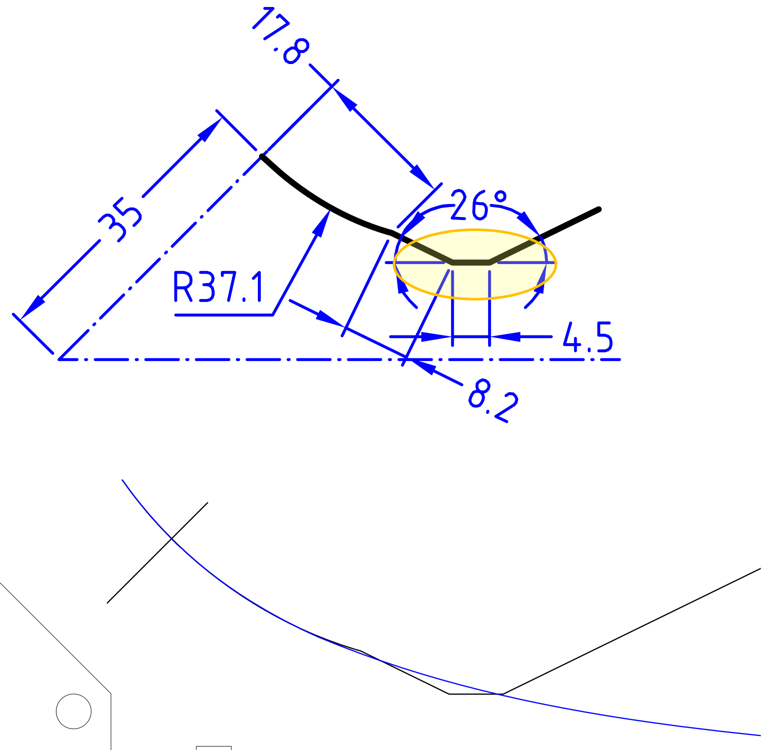
$\rho^2 \sin(2\theta) = \pm r^2$ $\quad$ $2xy = \pm r^2$ $\quad$ hyperbola

sextupole

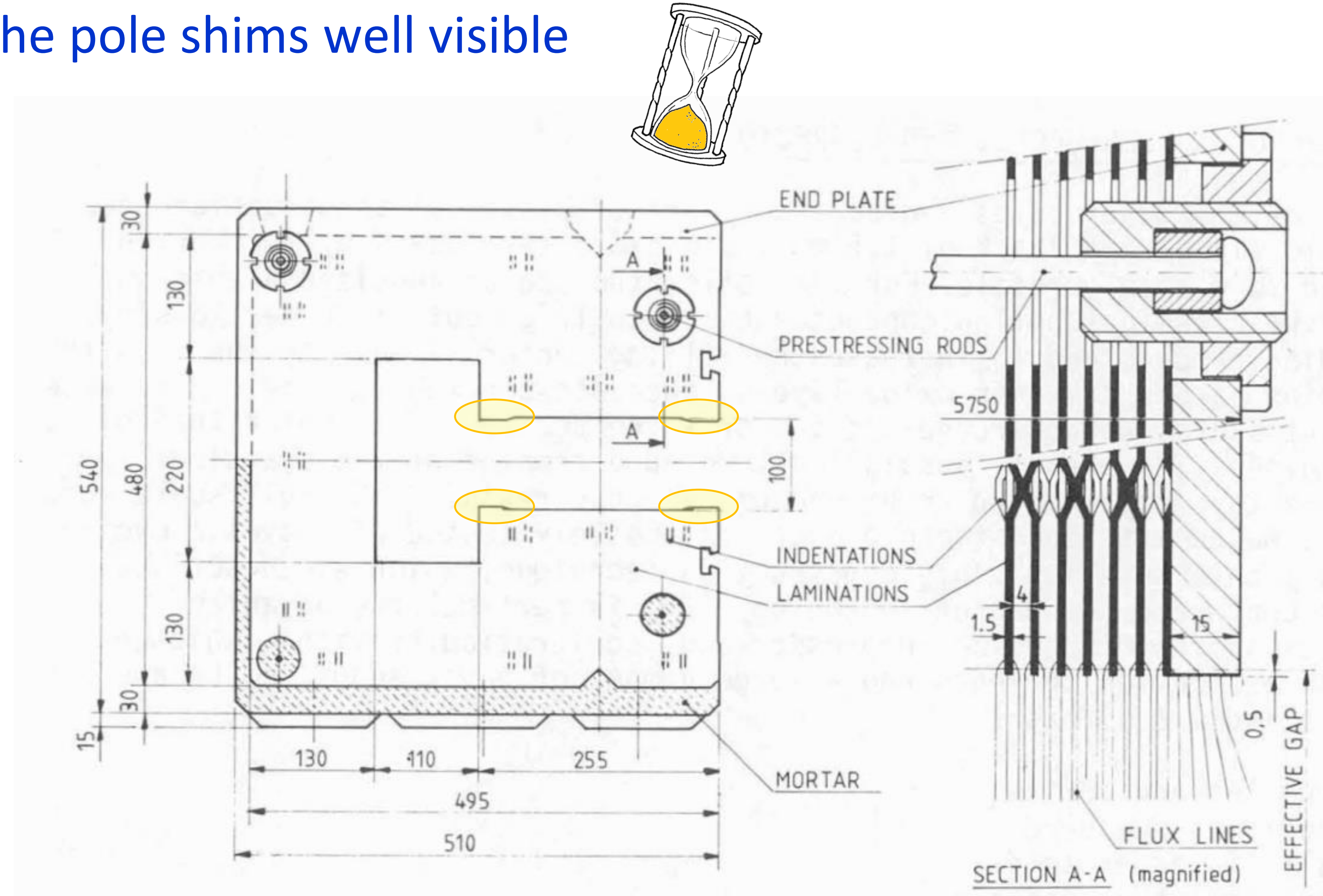
$\rho^3 \sin(3\theta) = \pm r^3$ $\quad$ $3x^2y - y^3 = \pm r^3$

As an example, this is the pole tip used in the SESAME quadrupoles vs. the theoretical hyperbola

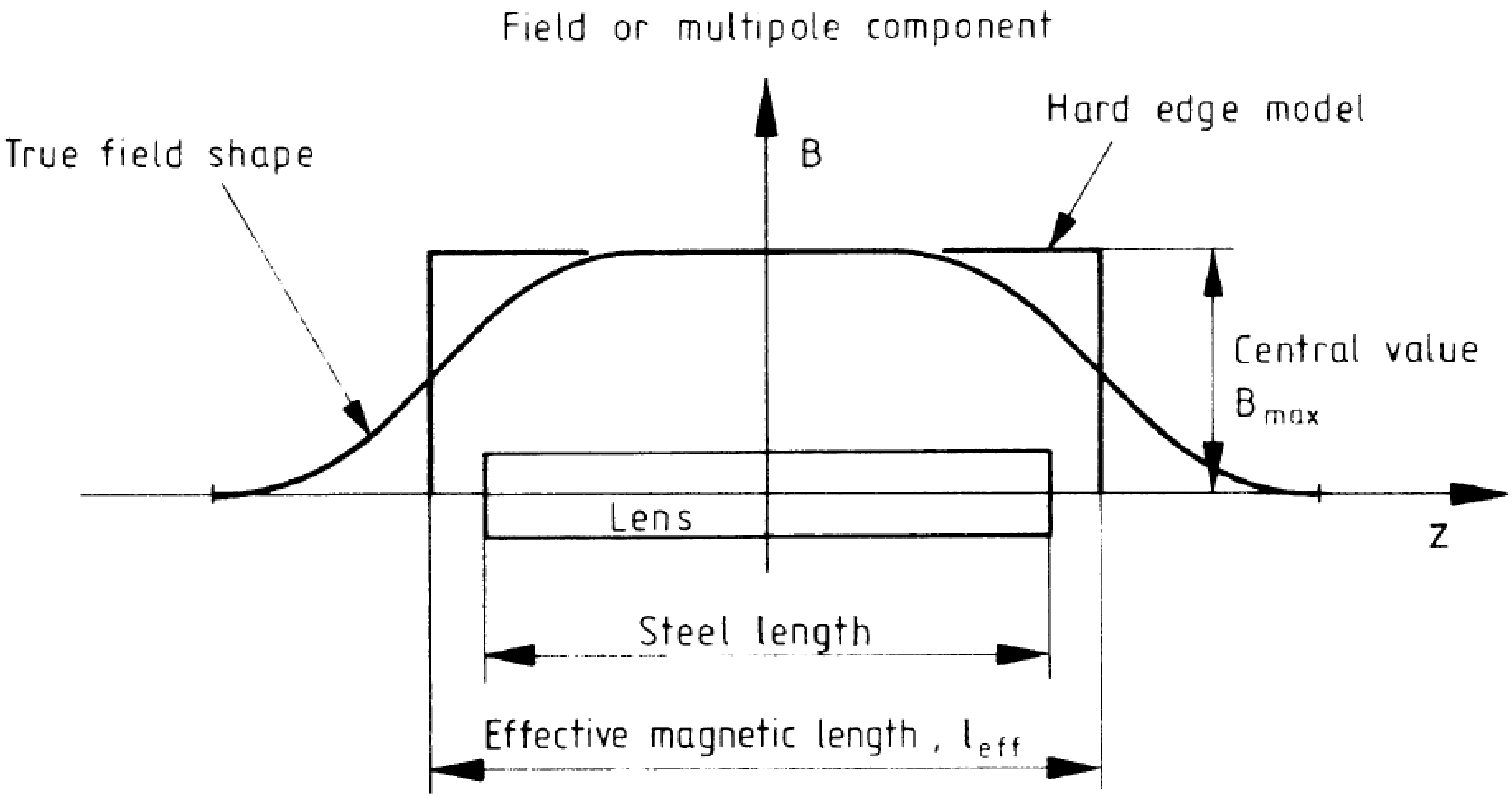




This is the lamination of the LEP main bending magnets, with the pole shims well visible



In 3D, the longitudinal dimension of the magnet is described by a magnetic length



$$l_m B_0 = \int_{-\infty}^{\infty} B(z)dz$$

The magnetic length can be estimated at first order with simple formulae

$$l_m > l_{Fe}$$

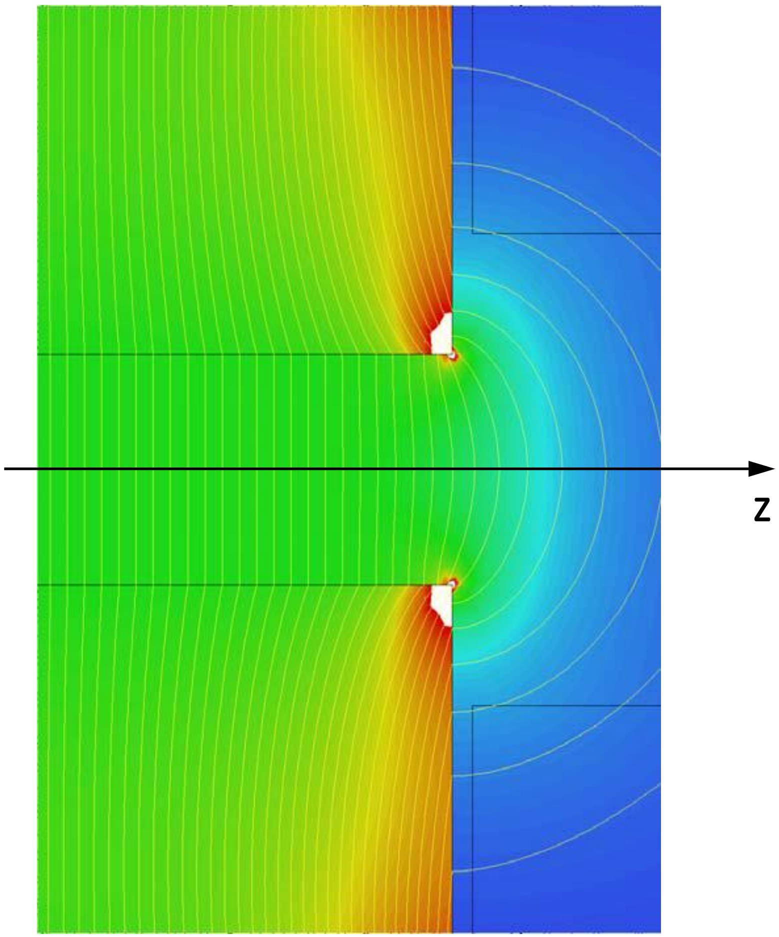
dipole

$$l_m \cong l_{Fe} + h$$

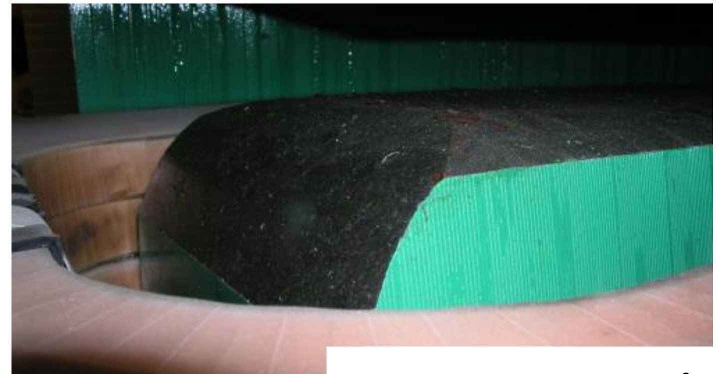
quadrupole

$$l_m \cong l_{Fe} + 0.80r$$

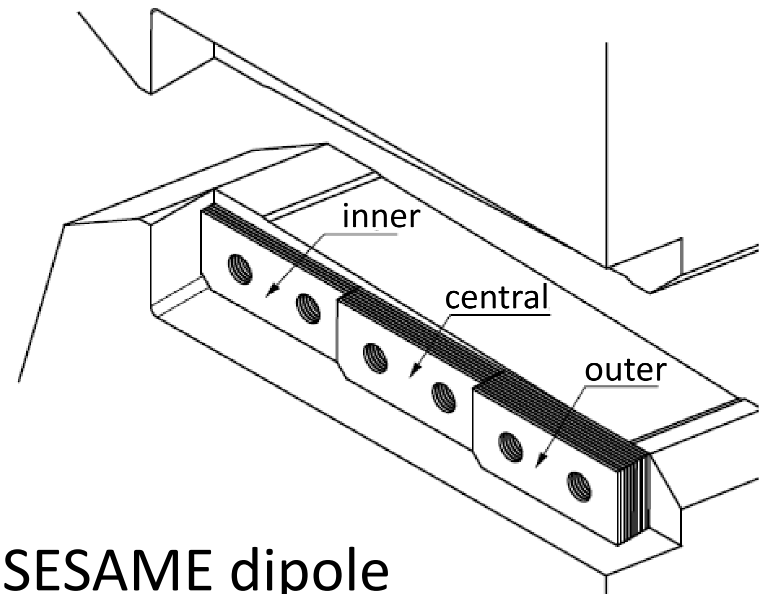
There are many different options to terminate the pole ends, depending on the type of magnet, its field level, etc.



abrupt

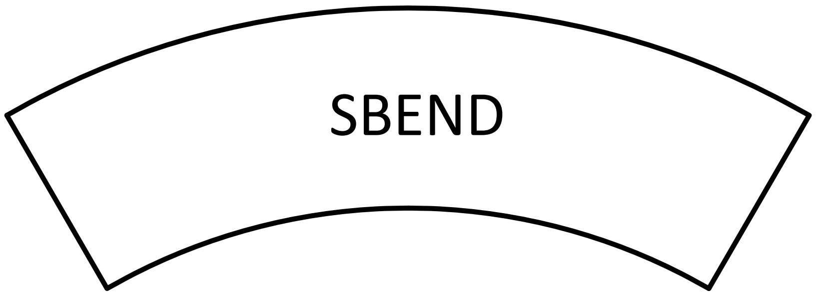


DIAMOND dipole

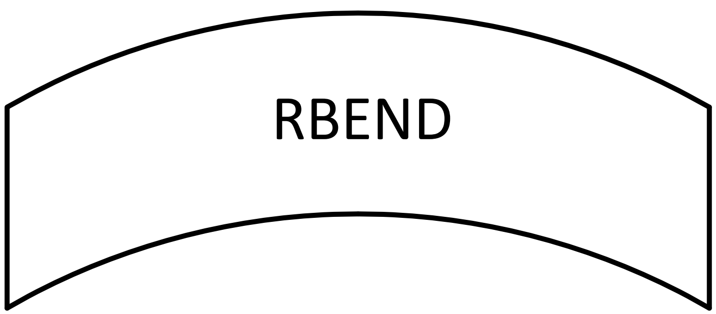


SESAME dipole

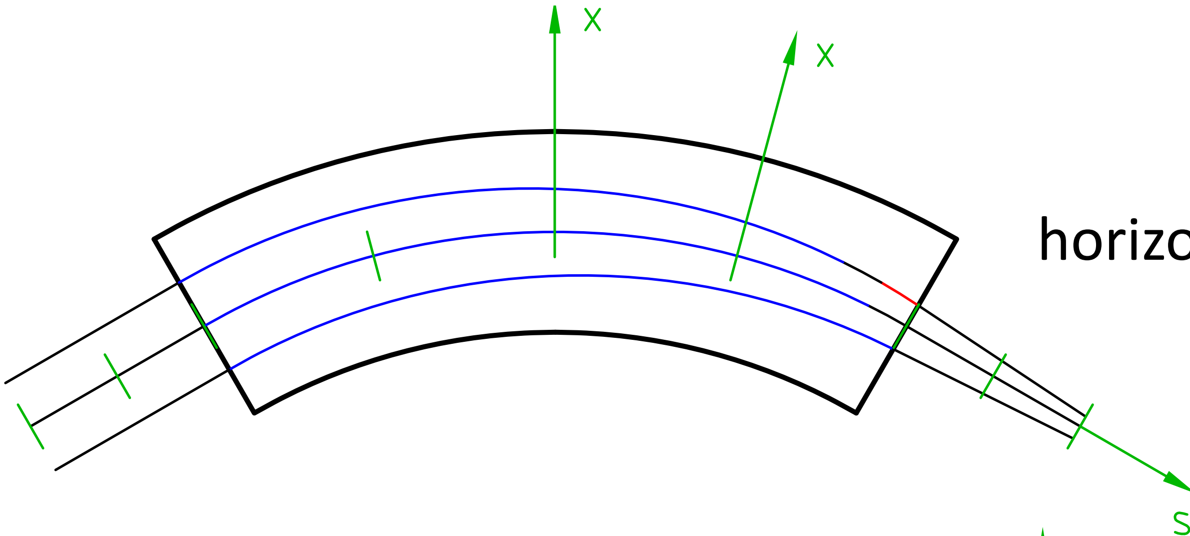
Usually two dipole elements are found in lattice codes: the sector dipole (SBEND) and the parallel faces dipole (RBEND)



top views

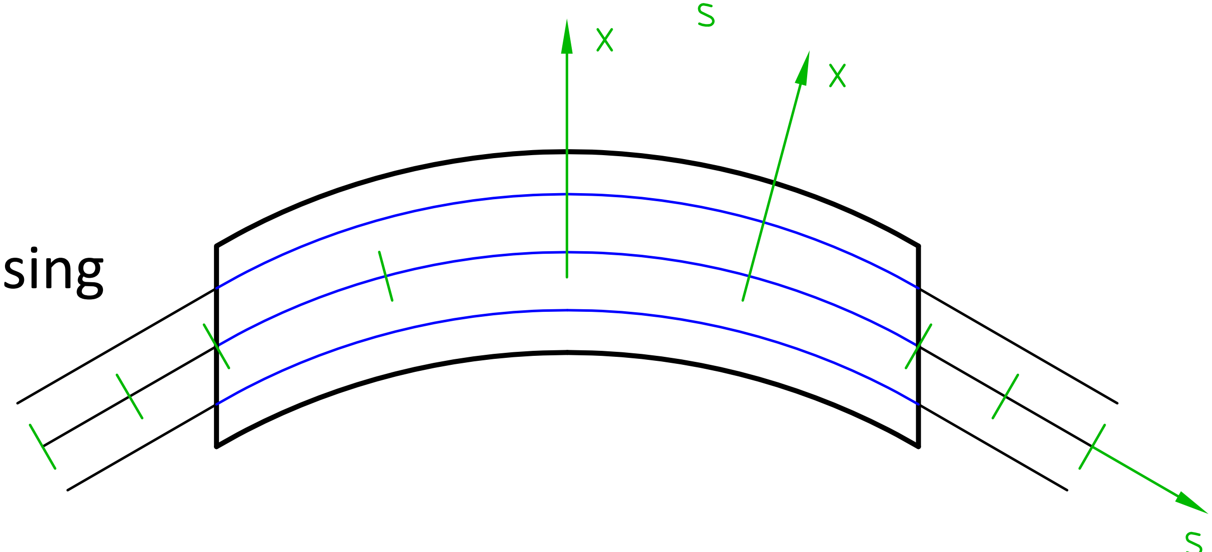


The two types of dipoles are slightly different in terms of focusing, for a geometric effect



SBEND
horizontal focusing

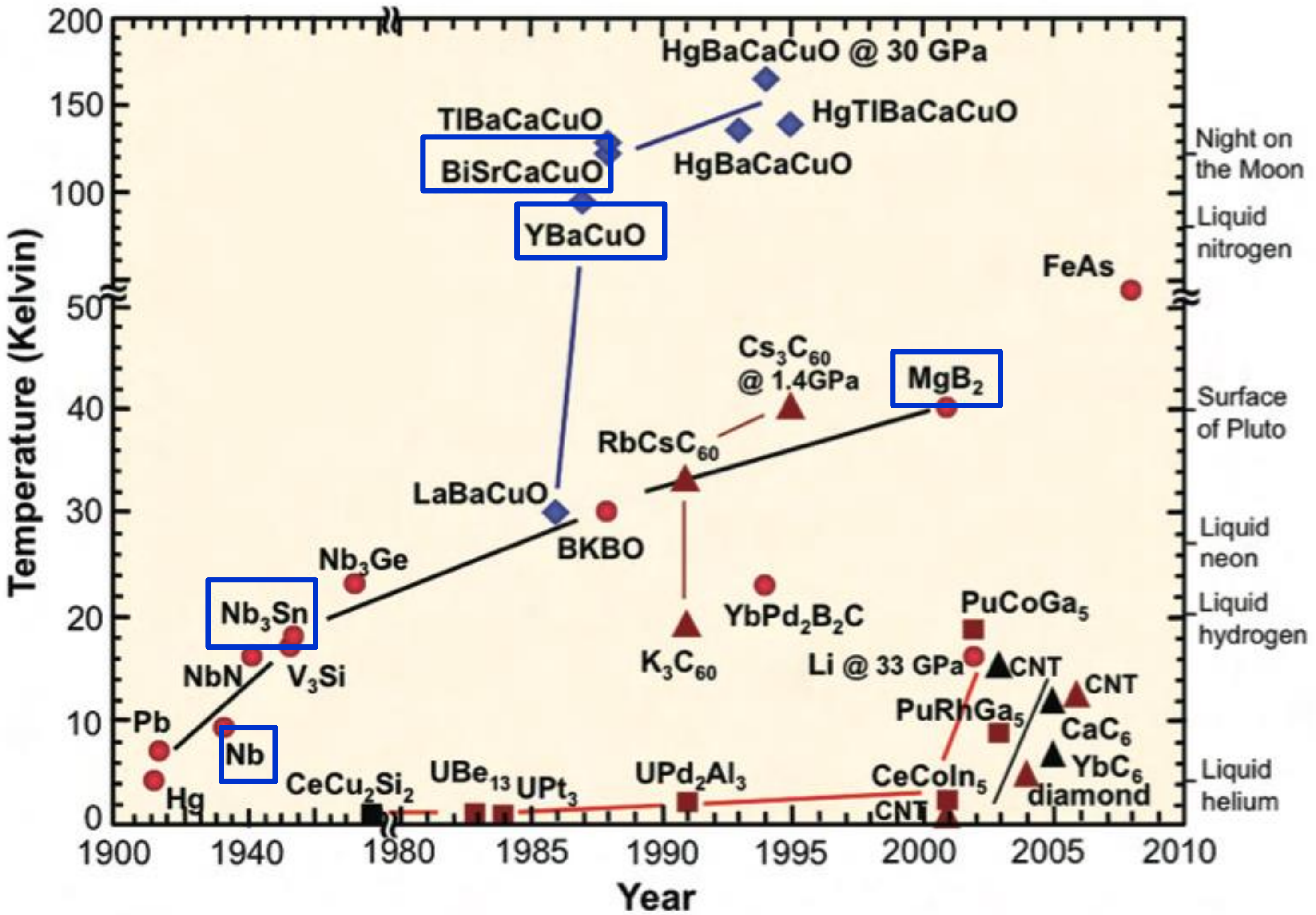
RBEND
vertical edge focusing



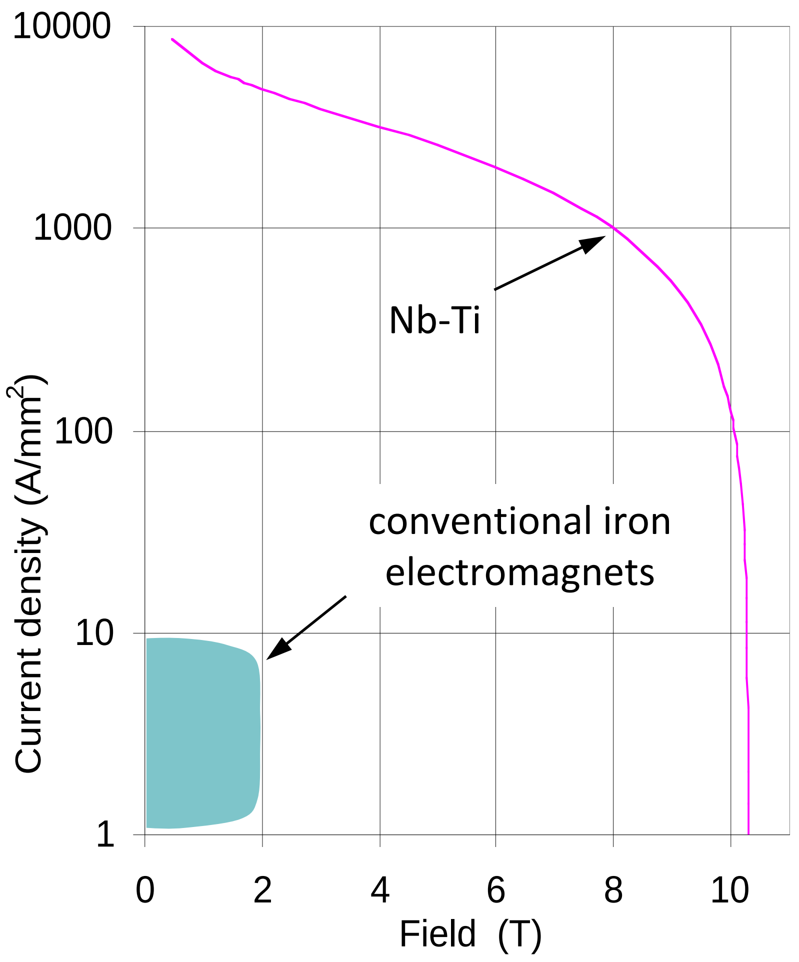
- and anything in between (playing with the edge angles) -

1. Introduction, jargon, general concepts and formulae
2. Resistive magnets
3. Superconducting magnets (thanks to Luca Bottura for the material of many slides)
4. Tutorial with FEMM

This is a history chart of superconductors, starting with Hg all the way to HTS (High Temperature Superconductors)



Superconductivity makes possible large accelerators with fields well above 2 T



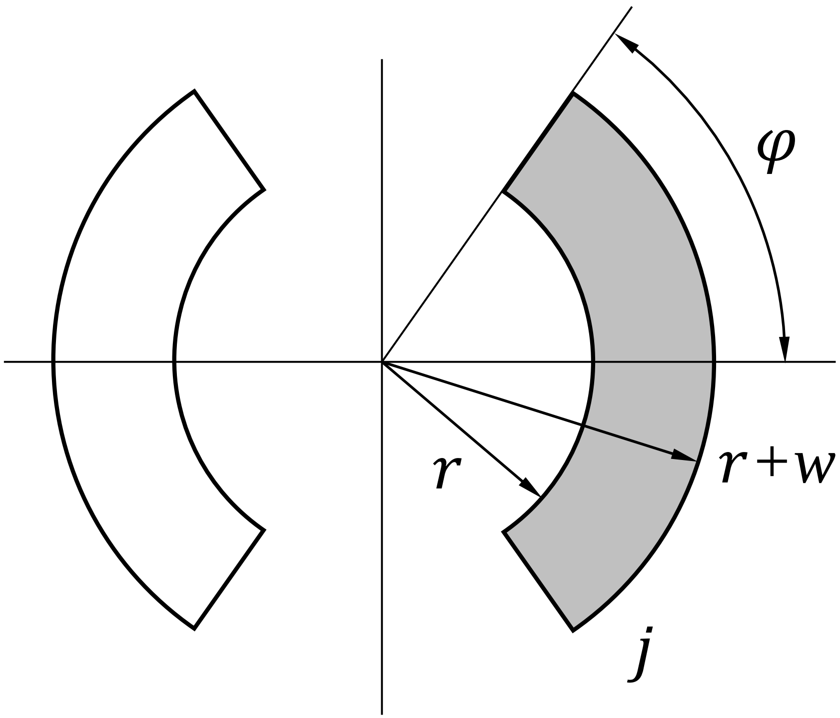
This is a summary of (somehow) practical superconductors

	LTS			HTS		
material	Nb-Ti	Nb_3Sn	MgB_2	REBCO	BSCCO	Fe based
year of discovery	1961	1954	2001	1987	1988	2008
T_c [K]	9.2	18.2	39	≈93	95 / 108	up to 58
B_{c2} [T]	≈14.5	≈30	>30	120…250	≈200	>100

The field in the aperture of a superconducting dipole can be derived using Biot-Savart law (in 2D)

$$B_\theta = \frac{\mu_0 I}{2\pi\rho}$$

Biot-Savart law for an infinite wire



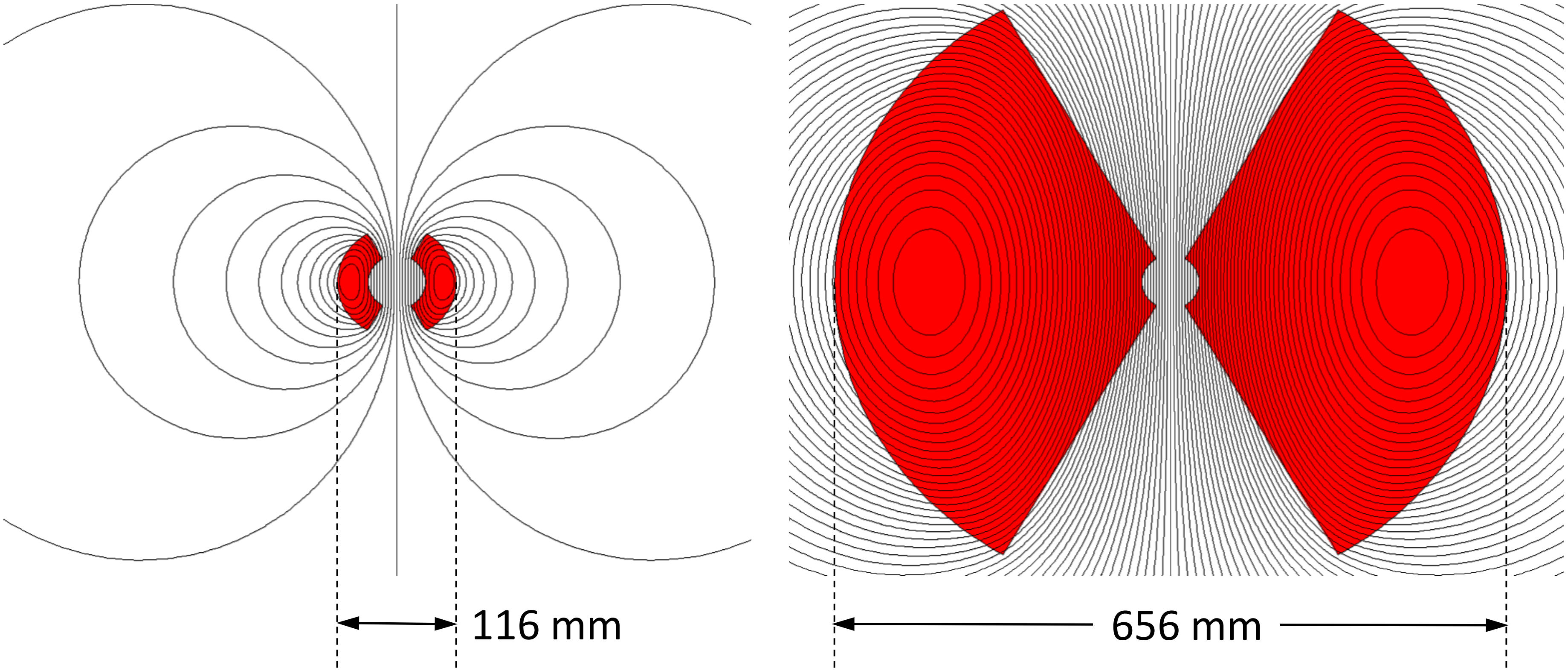
$$B = \frac{2\mu_0 \sin\varphi}{\pi} jw$$

for a sector coil

$$B = \frac{\sqrt{3}\mu_0}{\pi} jw$$

for a 60 deg sector coil

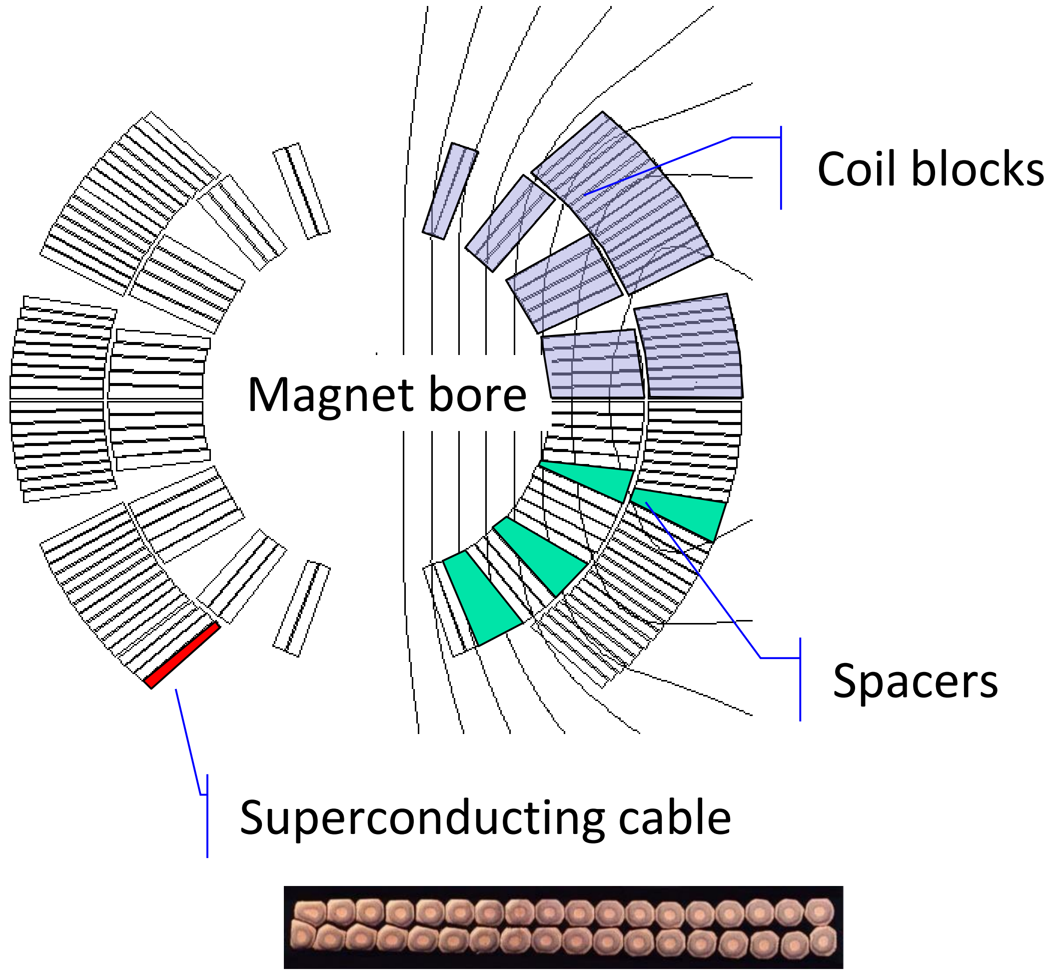
This is how it would look like one aperture of the LHC dipoles at 8.3 T, with two different current densities (without iron)



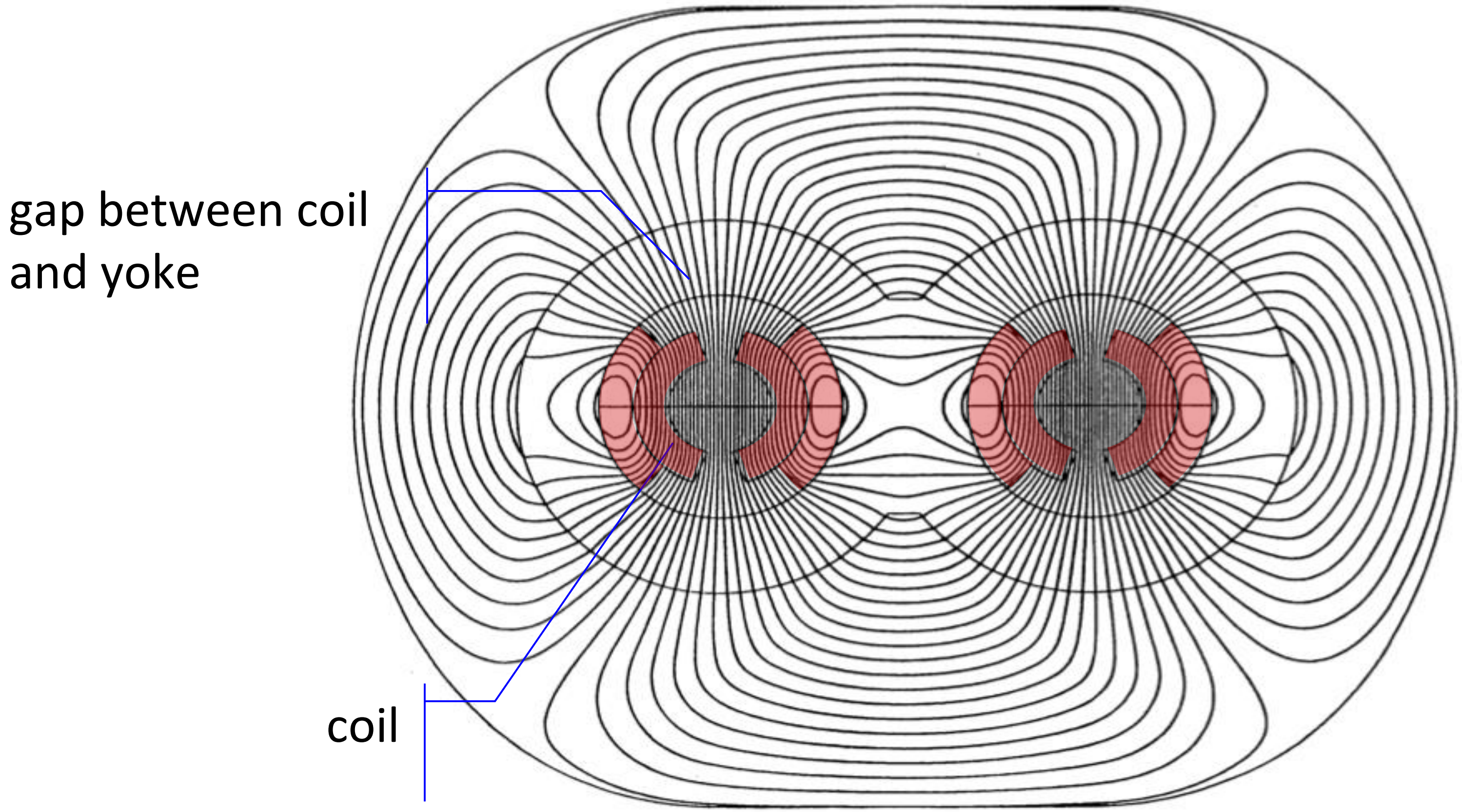
$j = 400$ A/mm^2
w = 30 mm
NI = 1.2 MA
P = 14.9 MW/m (if Cu at room temp.)

$j = 40$ A/mm^2
w = 300 mm
NI = 4.5 MA
P = 6.2 MW/m (if Cu at room temp.)

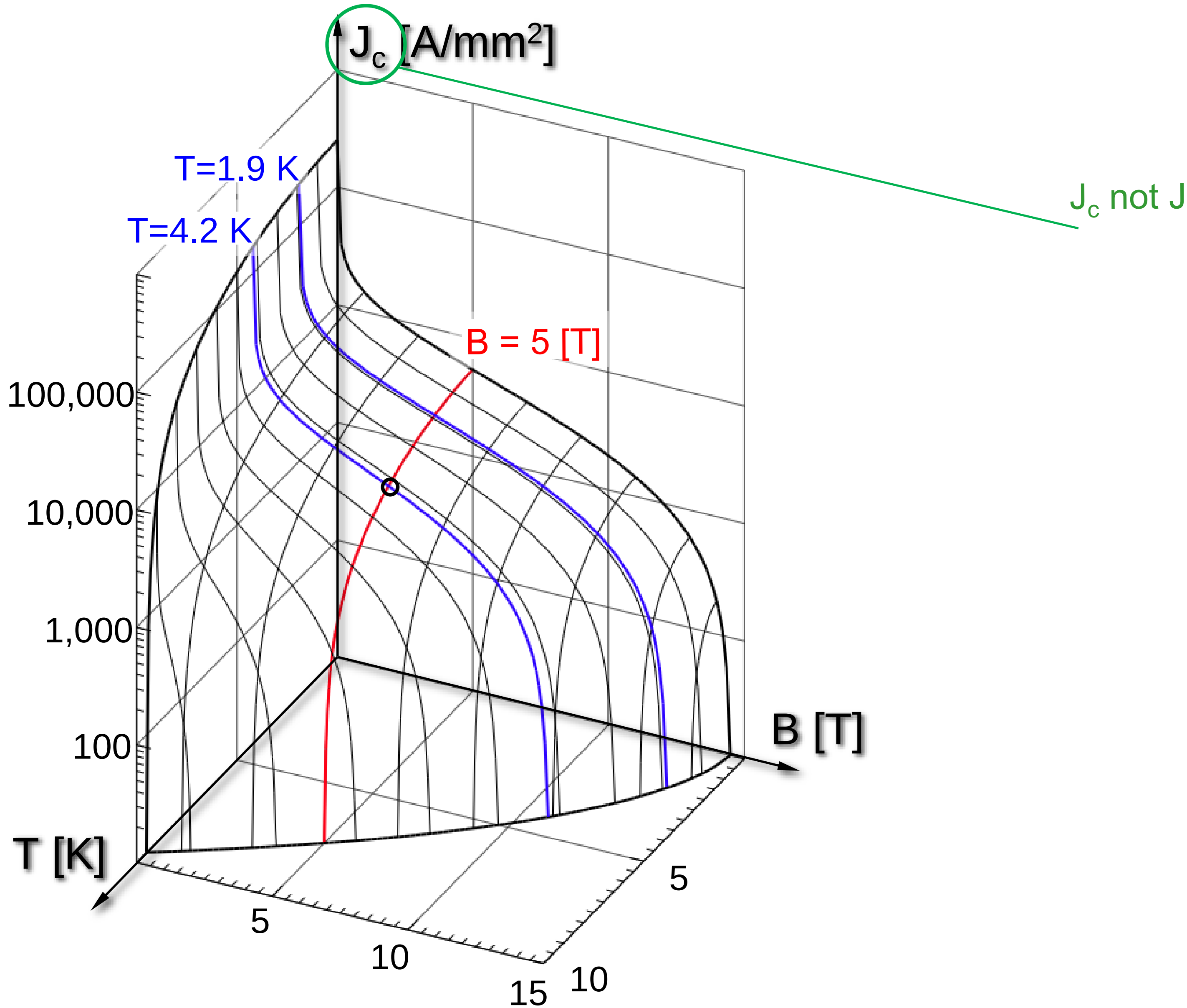
This is the actual coil of the LHC main dipoles (one aperture), showing the position of the superconducting cables



Around the coils, iron is used to close the magnetic circuit

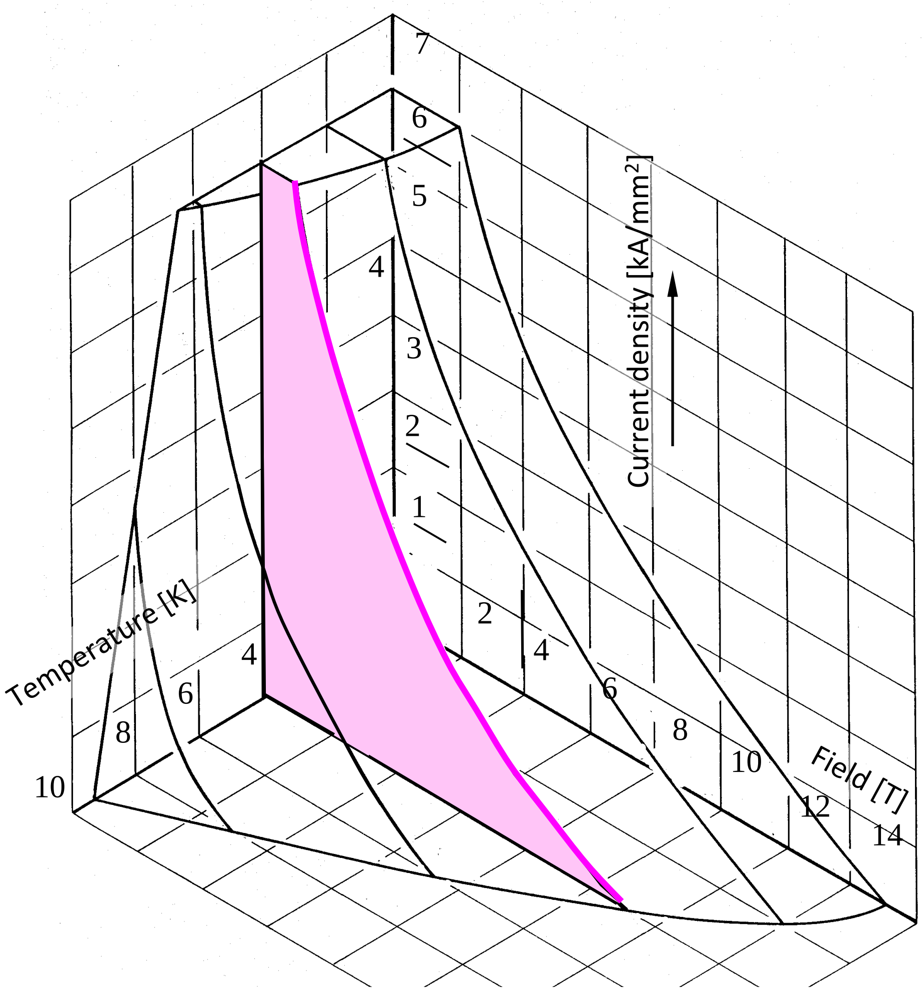


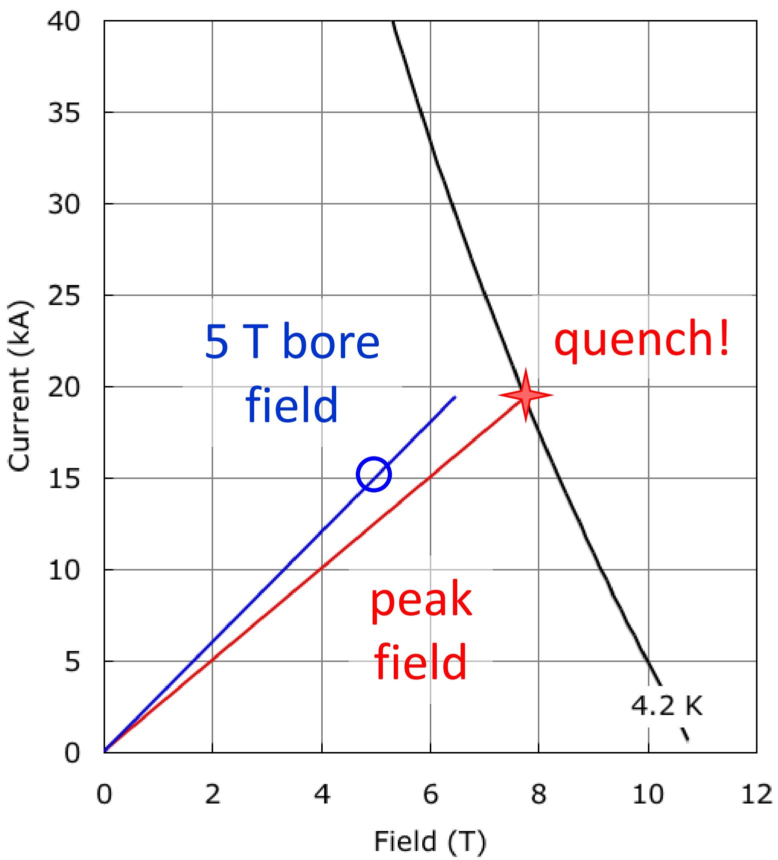
The allowable current density is high – though finite – and it depends on the temperature and the field



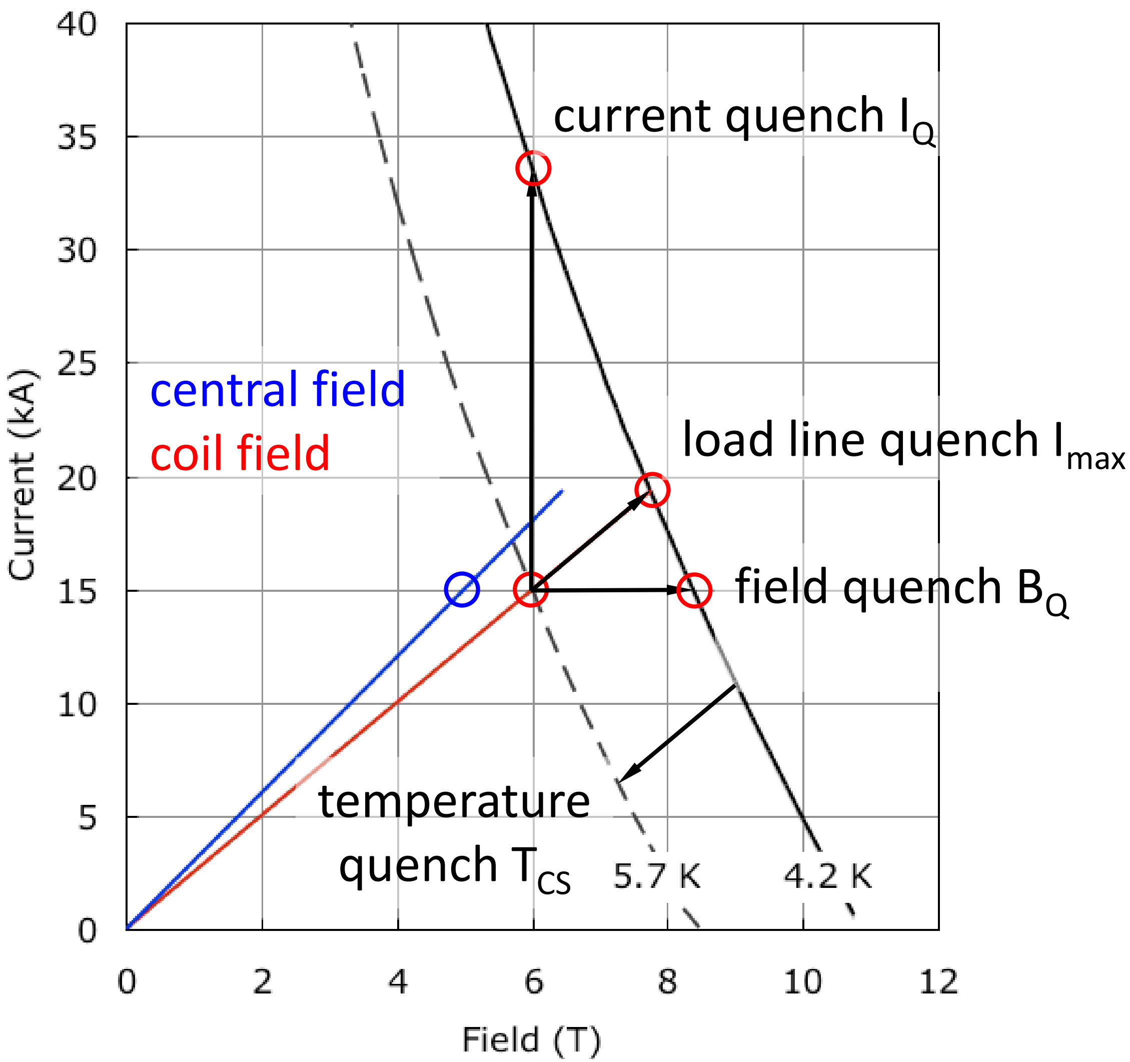
The maximum achievable field (on paper) depends on the amount of conductor and on the superconductor's critical line

Nb-Ti critical surface —— $I_C = J_C \times A_{SC}$ ——→ Nb-Ti critical current I_C (B)



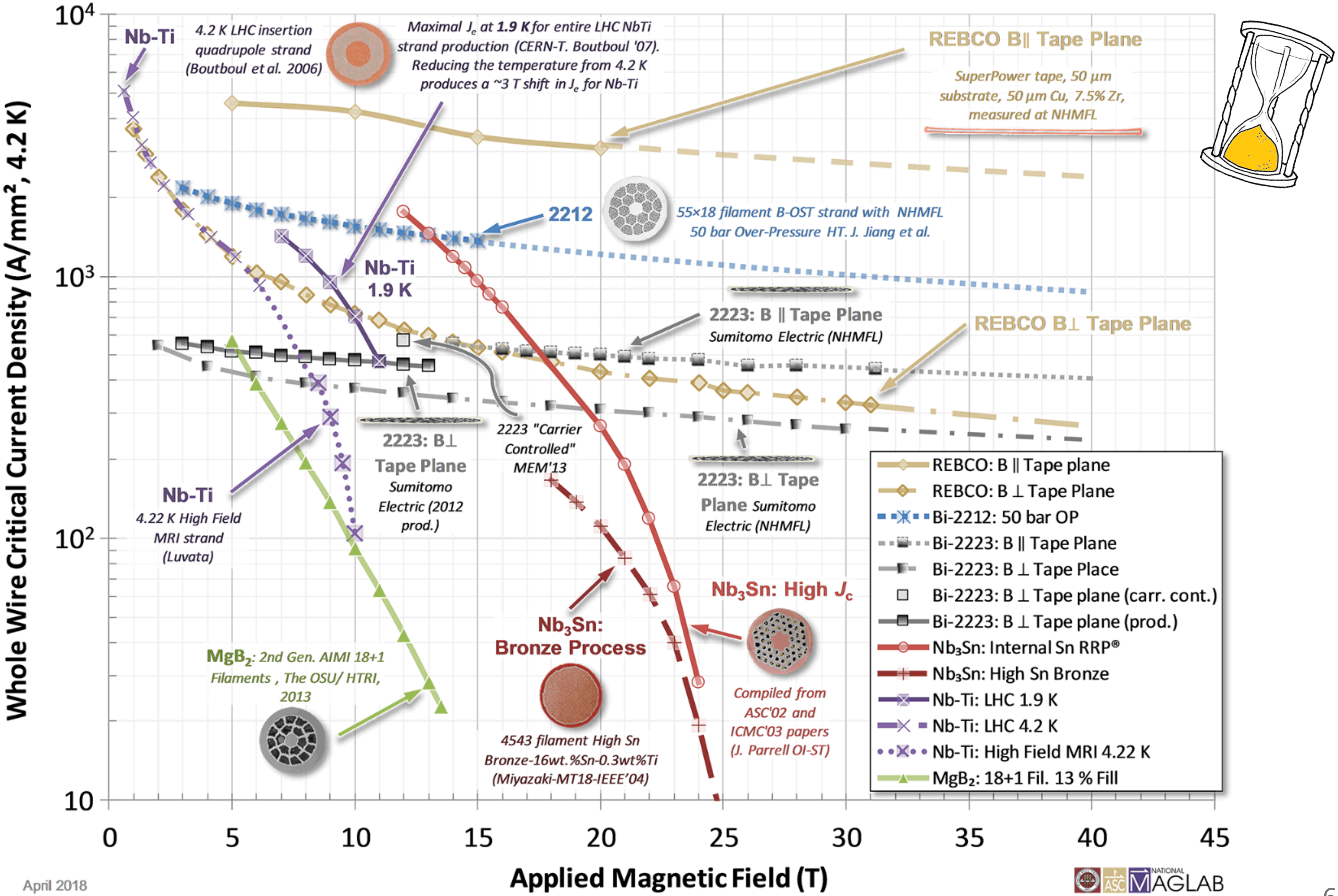


In practical operation, margins are needed with respect to this short sample limit

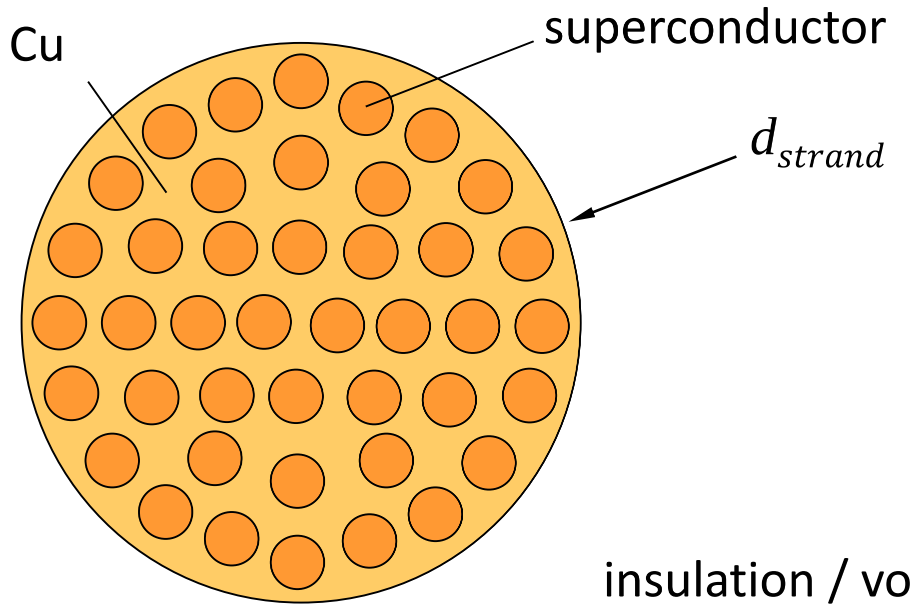


This is the best (Apr. 2018) critical current for several superconductors

Applied Superconductivity Center at NHMFL



The overall current density is lower than the current density on the superconductor

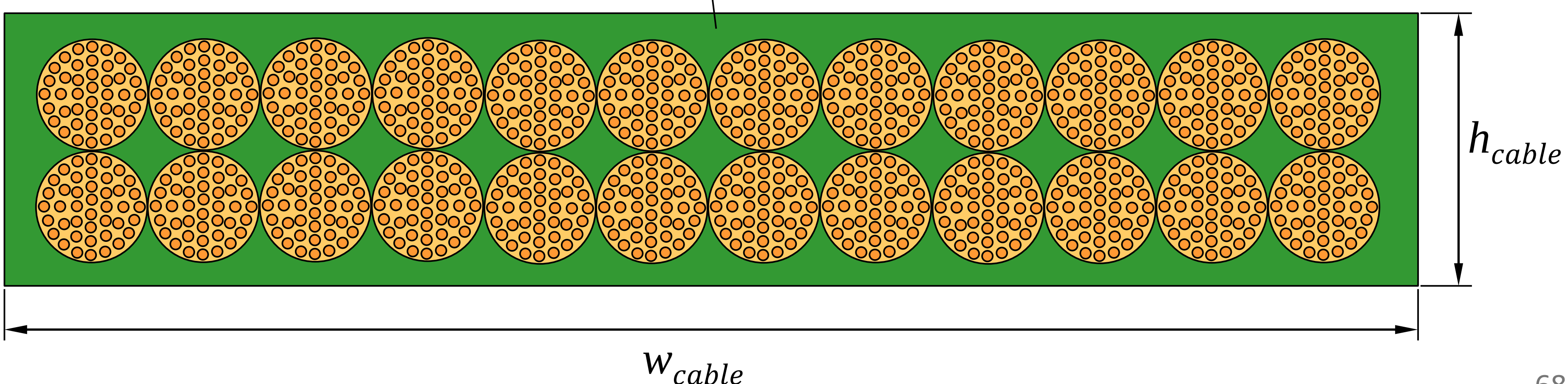


$$j_{overall} = \frac{I}{w_{cable} t_{cable}}$$

$$j_{cond} = \frac{I}{N_{strand} \frac{\pi d_{strand}^2}{4}}$$

$$j_{sc} = (1 + \upsilon_{Cu-sc}) j_{cond}$$

$$\upsilon_{Cu-sc} = \frac{A_{Cu}}{A_{sc}}$$



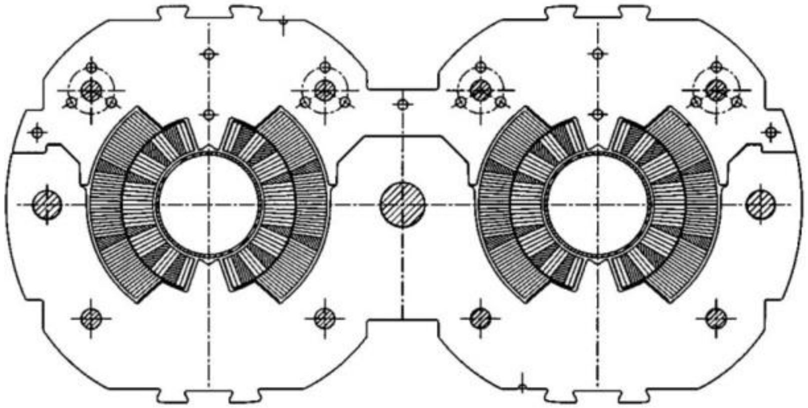
The forces can be very large, so the mechanical design is important

Nb-Ti LHC MB @ 8.3 T

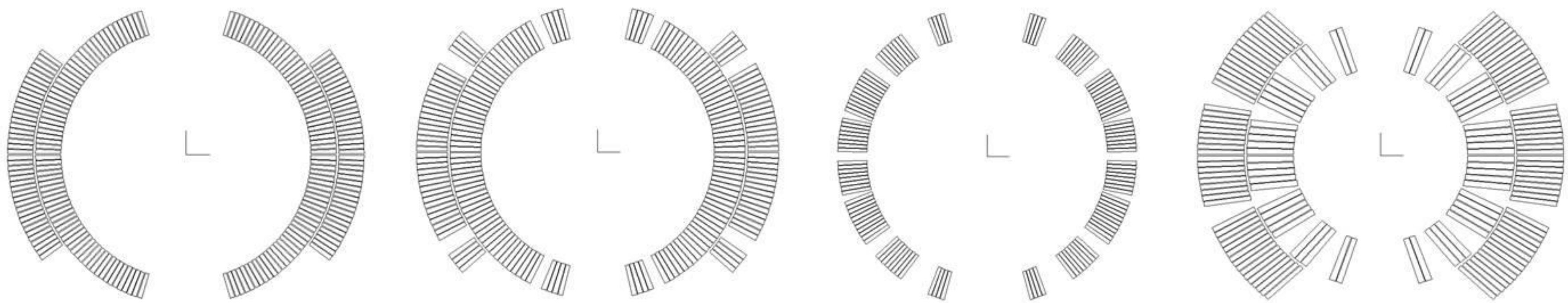
$F_x \approx$ 350 t per meter

precision of coil positioning: 20-50 µm

$F_z \approx$ 40 t

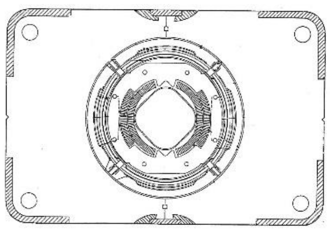


The coil cross sections of several superconducting dipoles show a certain evolution; all were (are) based on Nb-Ti



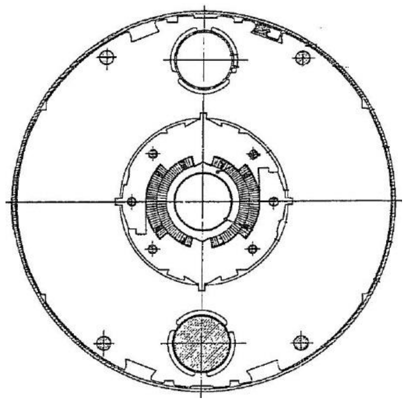
Tevatron HERA RHIC LHC (one aperture)

Also the iron, the mechanical structure and the operating temperature can be quite diverse



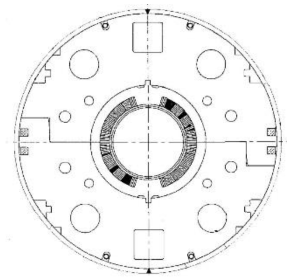
Tevatron

76 mm bore
B = 4.3 T
T = 4.2 K
first beam 1983



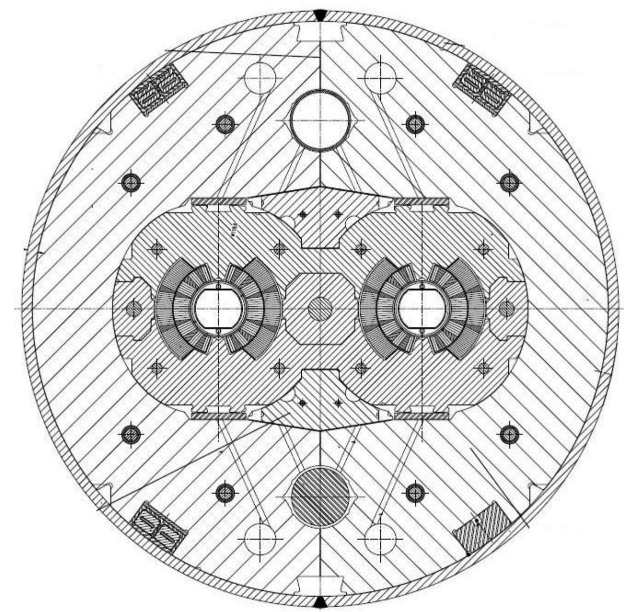
HERA

75 mm bore
B = 5.0 T
T = 4.5 K
first beam 1991



RHIC

80 mm bore
B = 3.5 T
T = 4.3-4.6 K
first beam 2000



LHC

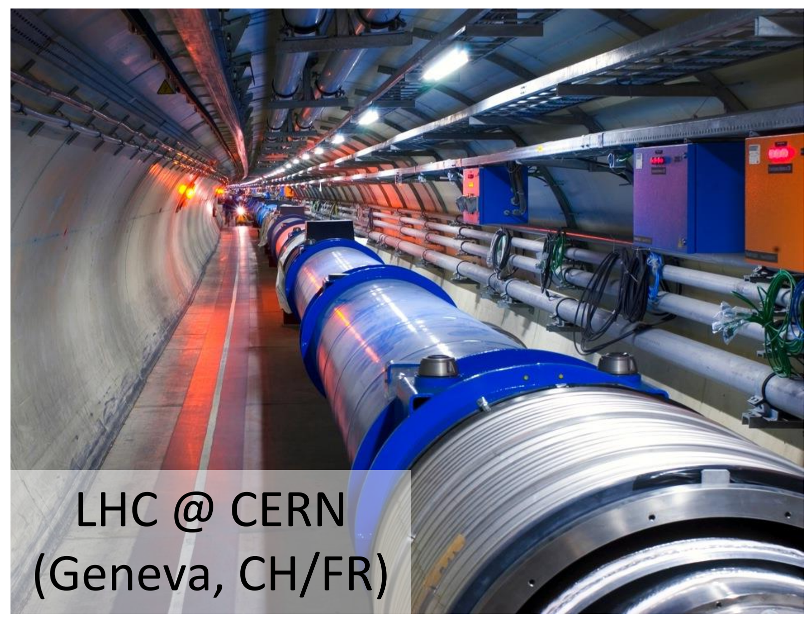
56 mm bore
B = 8.3 T
T = 1.9 K
first beam 2008

This is how they look in their machines


Tevatron @ FNAL
(Chicago, IL, USA)

RHIC @ BNL
(Upton, NY, USA)

HERA @ DESY
(Hamburg, D)


LHC @ CERN
(Geneva, CH/FR)

1. Introduction, jargon, general concepts and formulae

2. Resistive magnets

3. Superconducting magnets

4. Tutorial with FEMM

As an example, we will do a 2D model of a resistive dipole for HIE-ISOLDE

There are different programs used for magnetic simulations

1. OPERA-2D and OPERA-3D, by Dassault Systèmes
2. ROXIE, by CERN
3. POISSON, by Los Alamos
4. FEMM
5. RADIA, by ESRF
6. ANSYS
7. Mermaid, by BINP
8. COMSOL

Here are a few extra references (for FEMM and the magnet of the tutorial)

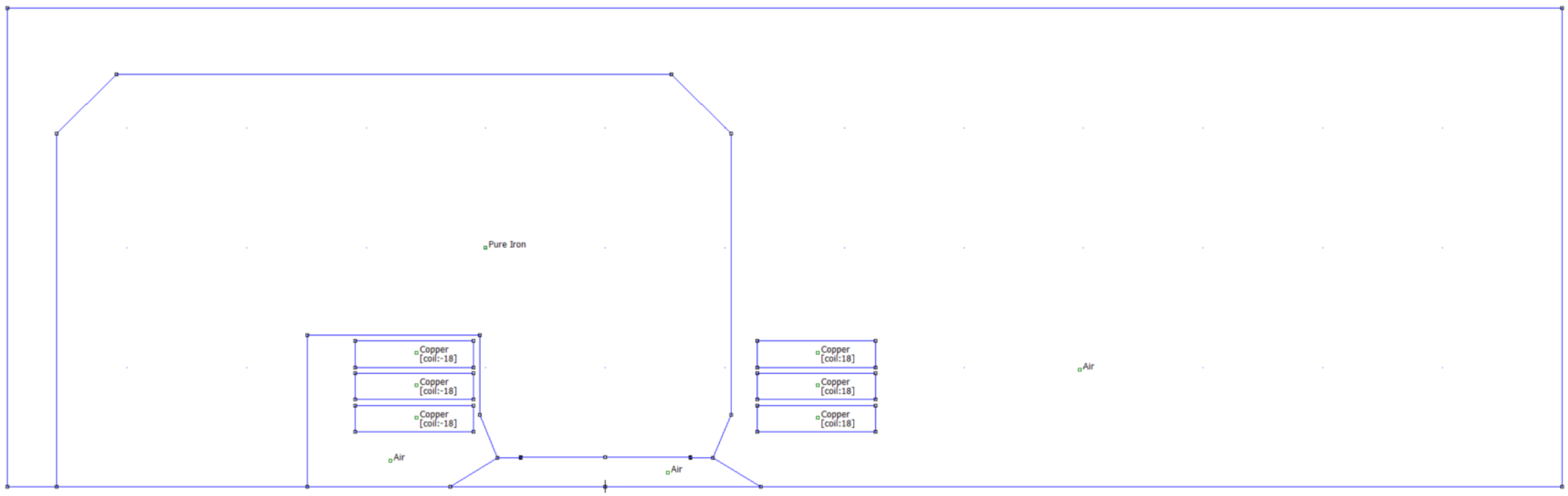
1. Finite Element Method Magnetics
   www.femm.info

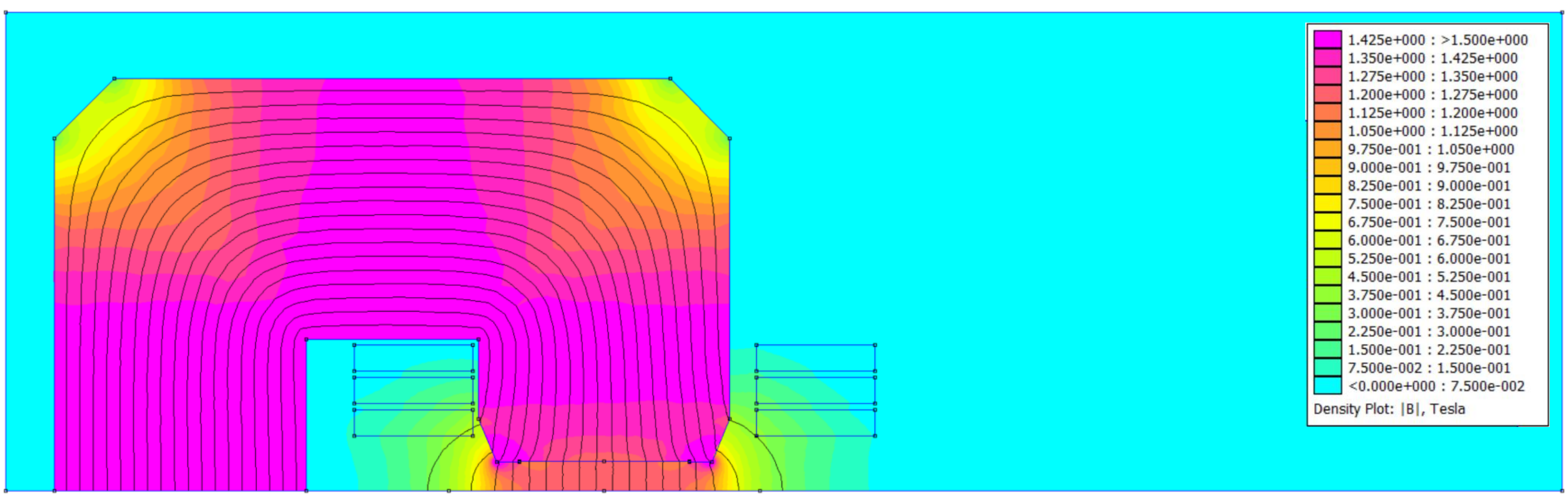
2. T. Zickler, Numerical design of a normal-conducting, iron-dominated electro-magnet using FEMM 4.2, JUAS2016
   https://indico.cern.ch/event/471931/contributions/1149654
   [though you need to ask for access now]

3. J. Bauche and A. Aloev, Design of the beam transfer line magnets for HIE-ISOLDE, IPAC2014 conference, Dresden
   https://accelconf.web.cern.ch/IPAC2014/papers/tupro104.pdf
   This describes the bending magnet of the tutorial

4. For questions specific to latest FCC-ee magnets development
   Jeremie.Bauche@cern.ch

Here is the geometry in the FEMM preprocessor and the solution in the postprocessor of the HIE-ISOLDE dipole (2D)





For convenience, here are a few details about the geometry of the HIE-ISOLDE dipole, for the tutorial

yoke

	x [mm]	y [mm]
1	0	25
2	71	25
3	71	24.2
4	90	24.2
5	105	60
6	105	295
7	55	345
8	-409	345
9	-459	295
10	-459	0
11	-249	0
12	-249	127
13	-105	127

coil

first corner at (127,122) mm

w_{coil} = 99 mm

h_{coil} = 22 mm

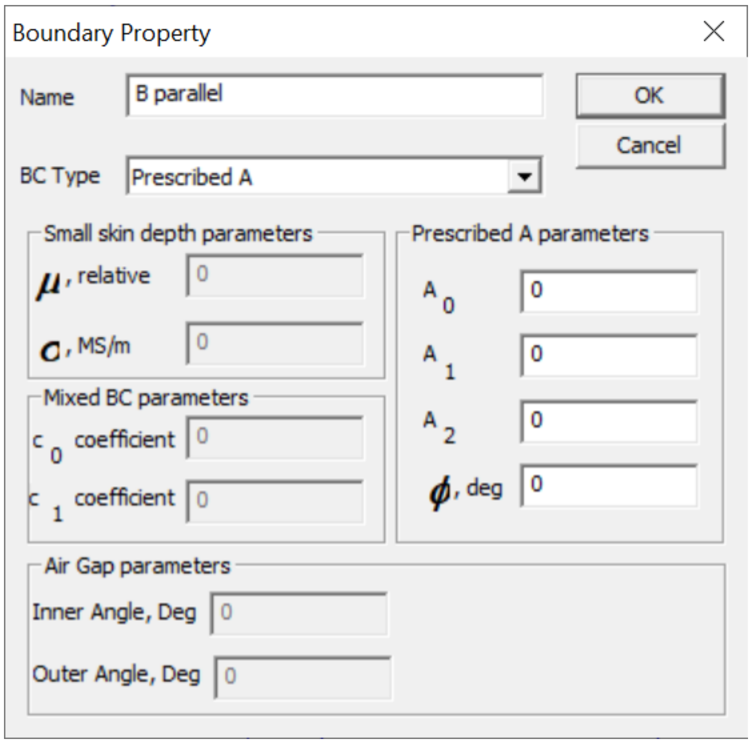
NI = 18 × 450 A

Overall, this is a short decalogue for a FEMM simulation

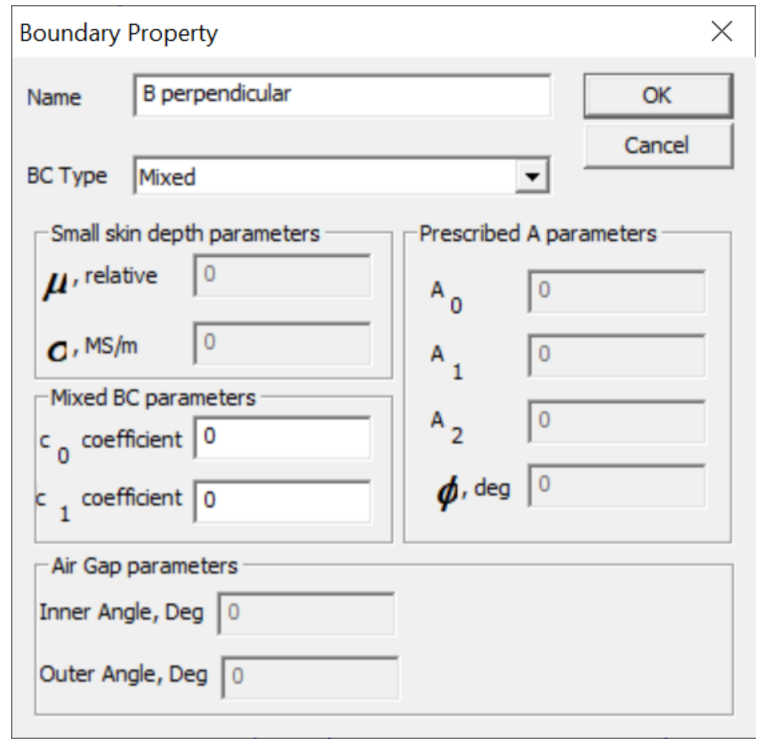
1. Create a new file, “magnetics” category
2. Set main problem parameters (ex. planar, mm, 0 frequency)
3. Define the geometry (iron, coil, air, background)
4. Load and set material properties (on regions)
5. Set circuits properties
6. Set and apply boundary conditions on lines (see next slide)
7. Mesh and refine mesh if needed
8. Solve
9. Postprocess
10. Solve with a different mesh and postprocess to check

Here, as I often forget, the two boundary properties that we use in FEMM

B parallel



B perpendicular



(this is sort of implicit when using linear triangles, see FEMM documentation)

Here, as I often forget as well, some hot keys for the preprocessor (more in the FEMM manual)

Point Mode	
<SPACE>	Edit the properties of selected points
<TAB>	Display dialog for the numerical entry of coordinates for a new point
<ESC>	Unselect all points
<DEL>	Delete selected points

Line / Arc Segment Mode	
<SPACE>	Edit the properties of selected segments
<ESC>	Unselect all segments and line starting points
<DEL>	Delete selected segments

And here some mouse button actions for the preprocessor (more in the FEMM manual)

Point Mode	
L click	Create a new point at the current mouse pointer location
R click	Select the nearest point
R dbl-click	Display coordinates of the nearest point

Line / Arc Segment Mode	
L click	Select a start / end point for a new segment
R click	Select the nearest line / arc segment
R dbl-click	Display length of the nearest arc / line segment

I prepared a short script in LUA to estimate multipoles (beta version, no warranty…)

```
--
-- LUA script to compute multipoles in FEMM (beta version, 16/01/2021)
--
-- Few standard cases are considered:
--   * dipole 180 deg (ex. C shape)
--   * dipole 90 deg (ex. H shape)
--   * quadrupole 45 deg (ex. standard symmetric quadrupole)
--
-- In all cases, the center is 0,0 and the skew coefficients are 0
--
-- The script computes two sets of multipoles:
--   * one from A (the vector potential)
--   * from a radial projection of B
-- They should be the same, so the difference in a way shows
-- how much to trust these numbers; the ones from A should be better,
-- as this is the finite element solution without further manipulations
-- (derivation, radial projection) while B is rougher (linear elements,
-- so B is constant over each triangle), but then it's smoothed out in the postprocessor
--

case_index = 1
-- 1 ===> dipole 180 deg (ex. C shape)
-- 2 ===> dipole 90 deg (ex. H shape)
-- 3 ===> quadrupole 45 deg (ex. standard symmetric quadrupole)

nh = 15 -- number of harmonics
np = 100 -- number of samples points
R = 20 -- reference radius (assumed in mm)
Rs = R -- sampling radius, in most case ok to keep the same as R

if case_index == 1 then
   thmax = pi
   ihmin = 1
   ihstep = 1
   ihfund = 1
elseif case_index == 2 then
   thmax = pi/2
   ihmin = 1
   ihstep = 2
   ihfund = 1
elseif case_index == 3 then
   thmax = pi/4
   ihmin = 2
   ihstep = 4
   ihfund = 2
end
```

file
multipoles_femm.lua

(this is just the start, with the header to set the parameters)