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MAGNET TECHNOLOGY

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Physics Design

Danfysik A/S, Denmark

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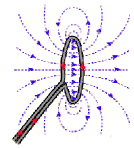
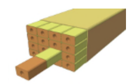
Outline

- Basic magnet concepts
  - Magnetic field and basic magnet types



  - Pole shapes and magnetic steel

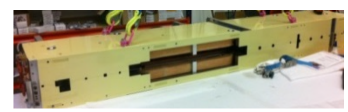
  - Excitation current



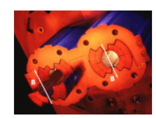
  - Ramped or pulsed magnets

- Magnetic field measurement

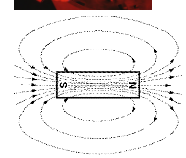
- Maxlab compact girder concept



- Superconducting magnets



- Permanent magnet technology



- Insertion devices

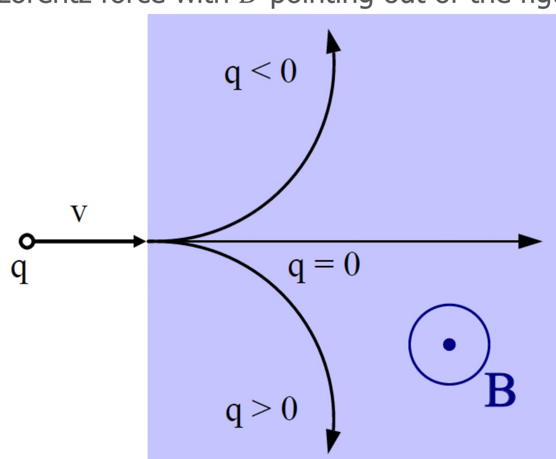
Beam deflection in a magnetic field

Lorentz force on a charged beam in a magnetic field

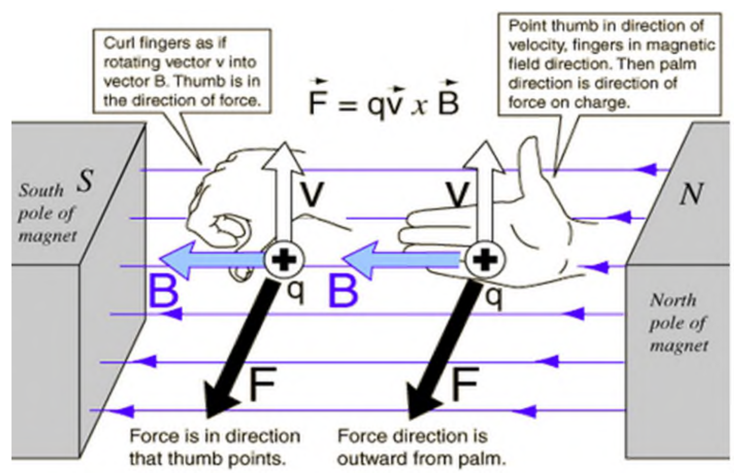
$$\vec{F} = q(\vec{v}\; x\; \vec{B})$$

q = charge [C]
v = velocity [m/s]
B = magnetic field induction [Tesla]

Lorentz force with $\vec{B}$ pointing out of the figure

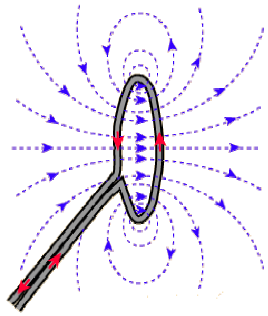


Right hand rule for the Lorentz force direction

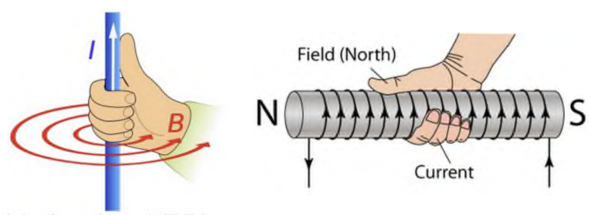


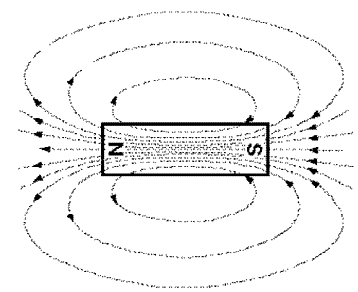
Magnetic field generation

Accelerator magnets are usually made as electromagnets with the magnetic field generated by a current through a conductor but permanent magnets can also be used



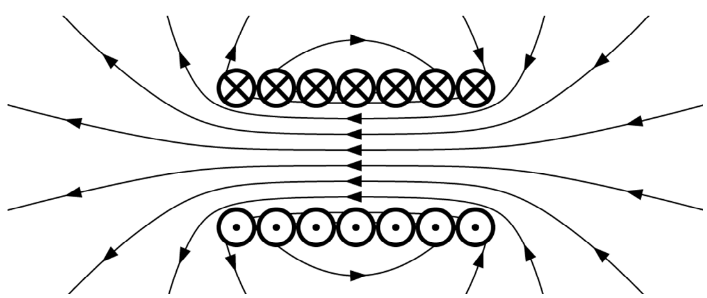
The right-hand rule is useful



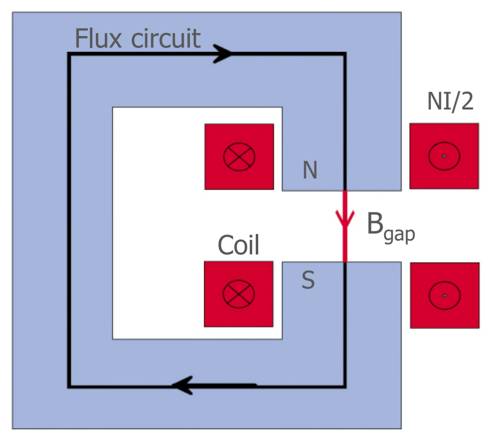


Low field accelerator magnets can be made as air core magnets but normal conducting magnets are typically iron dominated with iron cores as this gives a higher magnetic field B_{gap} for given Ampere-turns and good field homogeneity in is easy to achieve

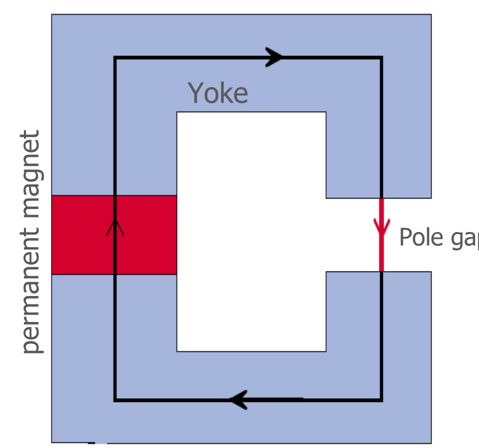
Air core electromagnet



Iron dominated electromagnet



Iron dominated permanent magnet



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Magnetic field

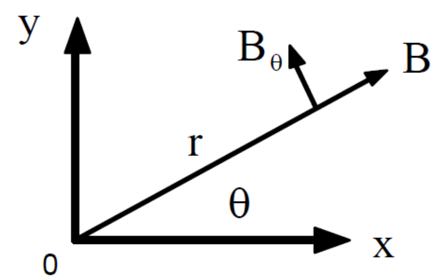
Spherical field harmonics from Maxwell's equation in polar coordinates

$$B_r = B_0 \sum_{n=1}^{\infty} (b_n \sin n\theta + a_n \cos n\theta) \left(\frac{r}{r_0}\right)^{n-1}$$

Complete field description in current & iron free region

$$B_\theta = B_0 \sum_{n=1}^{\infty} (b_n \cos n\theta - a_n \sin n\theta) \left(\frac{r}{r_0}\right)^{n-1}$$

Multipole coefficients:
b_n: normal, a_n: skew



Multipole expansion in Cartesian coordinates

$$B_y + iB_x = B_0 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{r_0}\right)^{n-1} = \sum_{n=1}^{\infty} (B_n + iA_n)(x+iy)^{n-1}$$

$$B_x = B_r \cos\theta - B_\theta \sin\theta,$$

$$B_y = B_r \sin\theta + B_\theta \cos\theta,$$

Vertical field for simplified case without skew A_n terms

$$B_y = B_1 + B_2\, x + B_3(x^2 - y^2) + B_4(x^3 - 3xy^2) + \ldots..$$

Taylor series in the y=0 center plane

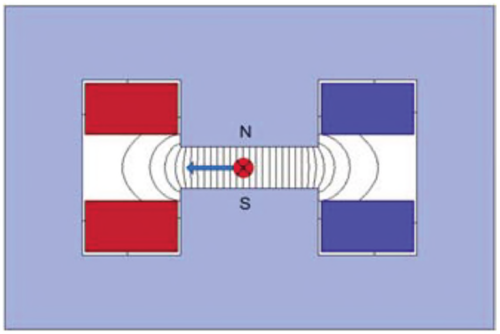
$$B_y = B_0 + \frac{\partial B_y}{\partial x} x + \frac{1}{2}\frac{\partial^2 B_y}{\partial x^2} x^2 + \frac{1}{6}\frac{\partial^3 B_y}{\partial x^3} x^3 + \ldots..$$

Dipole Quadrupole Sextupole Octupole

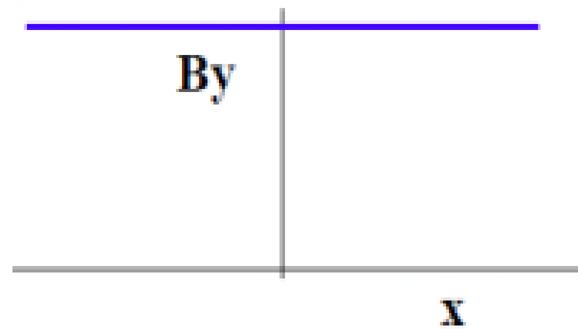
Dipole magnet

Dipole magnets are used to bend or steer the beam

Pole equation: $y = \pm r$ (fixed gap $h = 2r$)

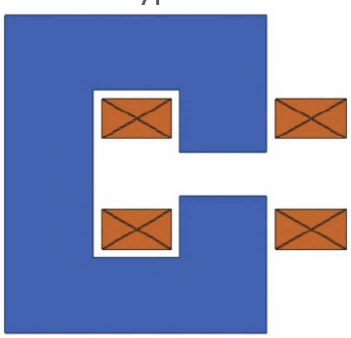


Constant field: $B_y = B_o$

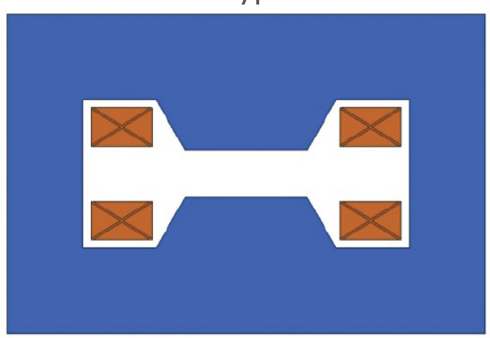


Classic dipole types:

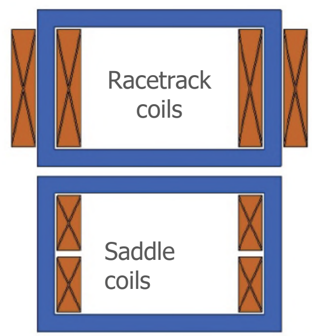
C-type



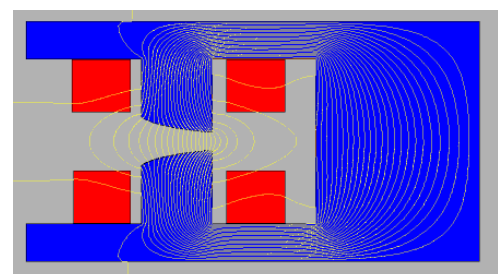
H-type



O-type or Window frame



Combined function: dipole & gradient $B_y = B_o + x \cdot B'$

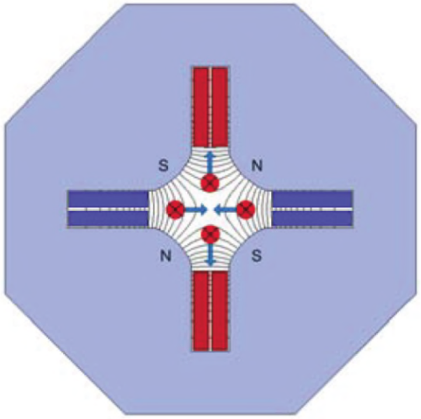


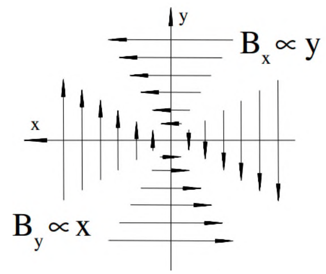
Quadrupole magnet

Quadrupole magnets are used for beam focusing

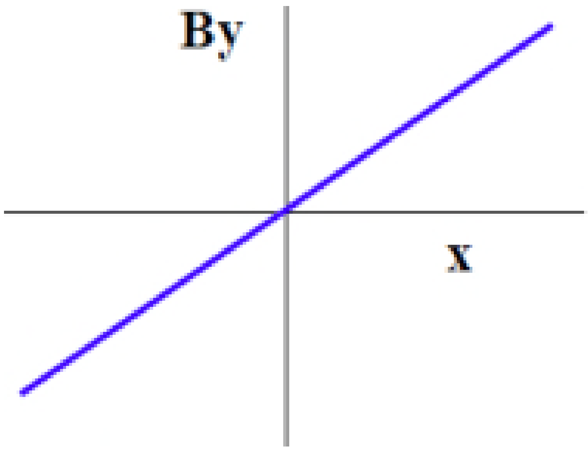
Pole equation: $2xy = \pm r^2$ (r is the aperture radius)

Constant gradient: $B_y = B_2 x$, $B_2 = \frac{\partial B_y}{\partial x}$



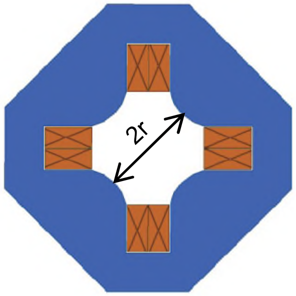


Field amplitude constant on a circle: $|B| = \frac{\partial B_y}{\partial x} \cdot r$



Classic quadrupole types:

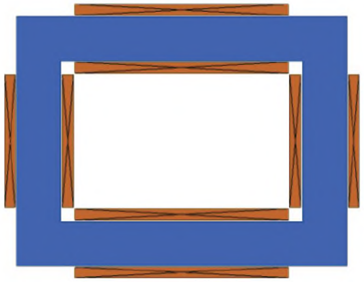
High field type



Cost optimal

Figure-8

Panofsky quadrupole



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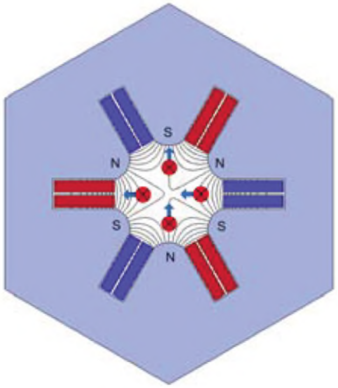
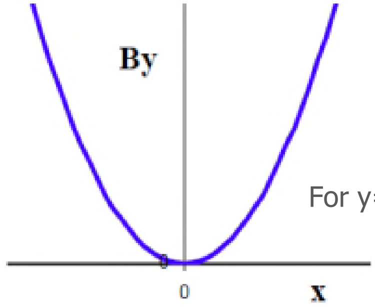
Sextupole and octupole magnets

Sextupole magnets for beam chromaticity correction:

Pole equation, sextupole: $3x^2y - y^3 = \pm r^3$

Constant sextupole gradient: $B_y = B_3(x^2 - y^2)$, $B_3 = \frac{1}{2}\frac{\partial^2 B_y}{\partial x^2}$



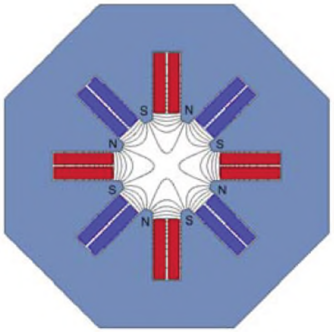


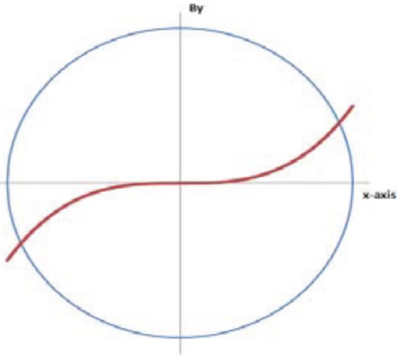
For y=0: $B_y = \frac{1}{2}\frac{\partial^2 B_y}{\partial x^2}x^2$

Octupole magnets for higher order corrections:

Pole equation: $4(x^3y - xy^3) = \pm r^4$

Constant octupole gradient: $B_y = B_4(x^3 - 3xy^2)$, $B_4 = \frac{1}{6}\frac{\partial^3 B_y}{\partial x^3}$



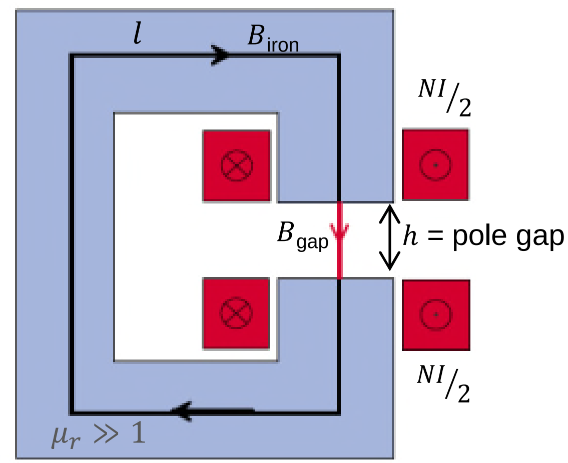


Excitation current for a dipole

We use Ampère's law $\oint \vec{H} \cdot d\vec{l} = NI$, where $\vec{B} = \mu\vec{H}$ and $\mu = \mu_0\mu_r$

Assuming B is constant (i.e. B_{gap}=B_{iron}) around the loop l and h this gives

$$NI = \oint \frac{\vec{B}}{\mu} \cdot d\vec{l} = \frac{hB_{gap}}{\mu_0} + \frac{lB_{iron}}{\mu_0\mu_r} = \frac{B_{gap}}{\mu_0}\left(h + \frac{l}{\mu_r}\right)$$



The pole gap field is therefore

$$B_{gap} = \frac{\mu_0 NI}{h + \frac{l}{\mu_r}}$$

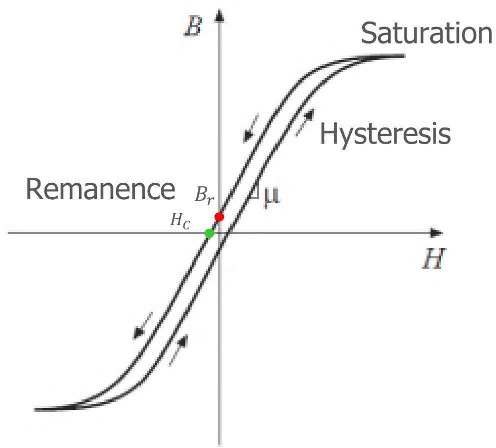
When the relative permeability μ_r is large we can ignore the iron reluctance l/μ_r

$$B_{gap} = \frac{\mu_0 NI}{h} \qquad \mu_r \gg 1$$

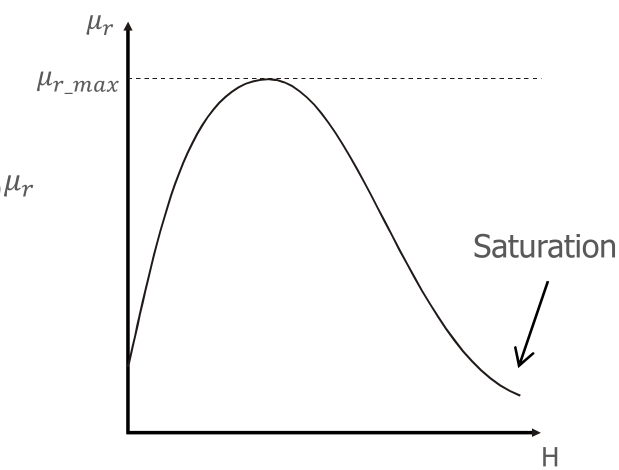
Effect of the magnetic iron yoke

Magnetic soft core material is highly non-linear:

μ_{r_max}: $10^3 - 10^5$, typically 2000-6000

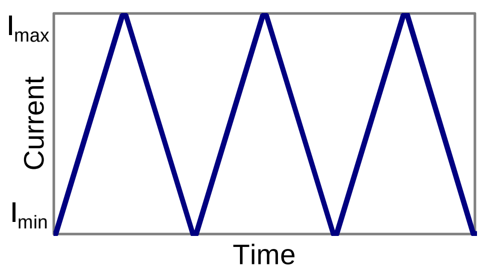


B-H slope: $\mu = \frac{B}{H} = \mu_0 \mu_r$



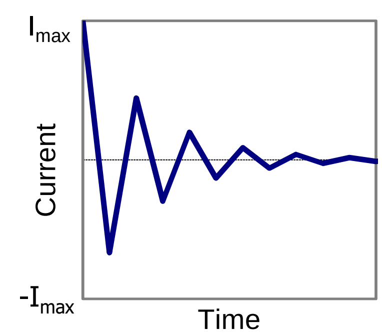
The hysteresis changes typically the magnet field on the 0.1-1% level

To get a stable B(I) the excitation current is cycled up/down 3 times:



At I=0 there is a small residual remanence field on the mT level due to the iron remanence B_r which can be suppressed by degaussing

Degaussing current cycling



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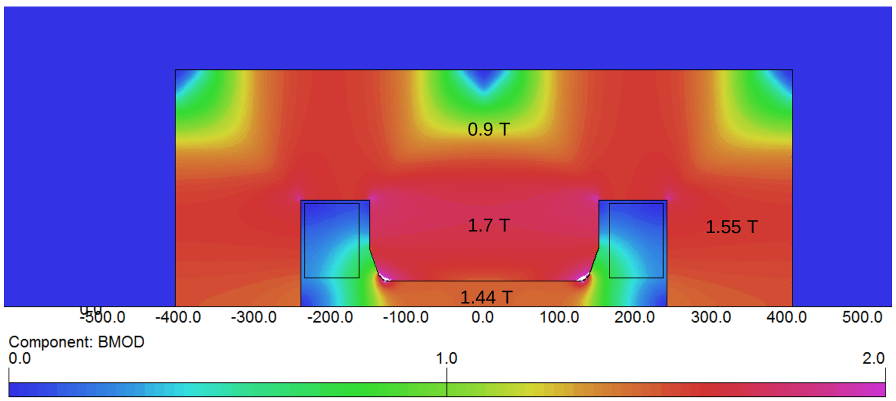
Iron saturation in high field magnets

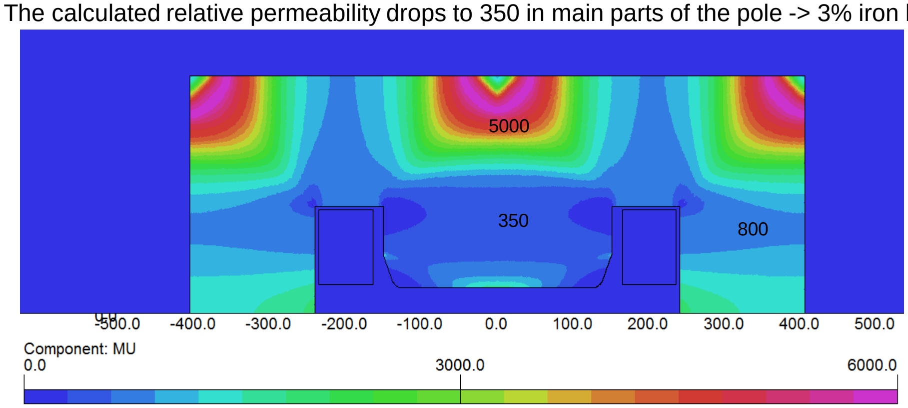
Magnet iron saturates typically at ~2T resulting in a non-linear B(I) decay known as iron loss.

Field levels should if possible be below ~1.5T in the yoke and ~1.8T in the pole

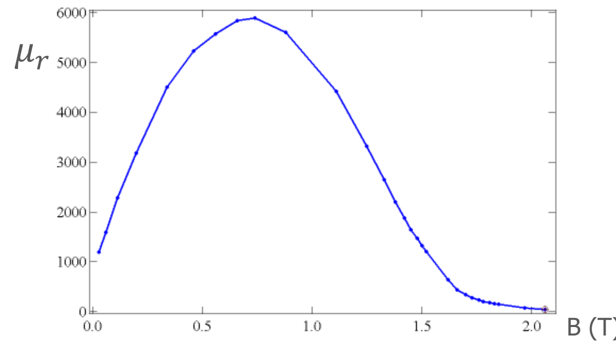
Model calculation of top half of dipole magnet at 1.44 T center field at maximum current



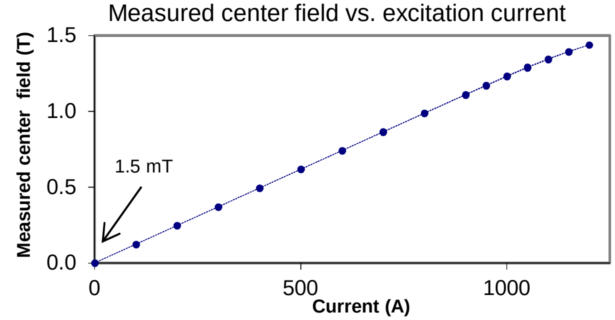
The calculated relative permeability drops to 350 in main parts of the pole -> 3% iron loss



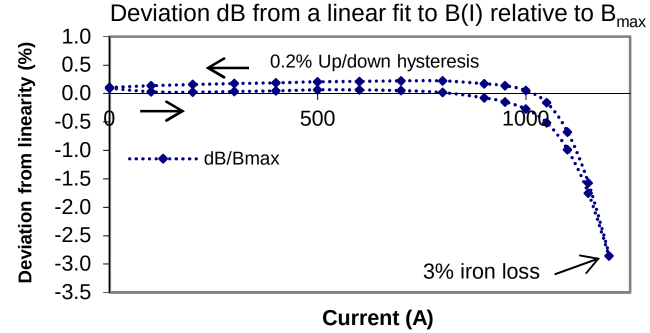
Relative permeability for the steel (EBG 1200)



Measured center field vs. excitation current



Deviation dB from a linear fit to B(I) relative to B_{max}



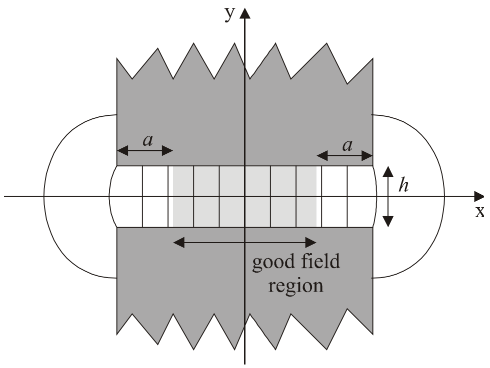
Field quality improvement by pole shimming

The finite pole width reduces the field quality which for a dipole is defined as

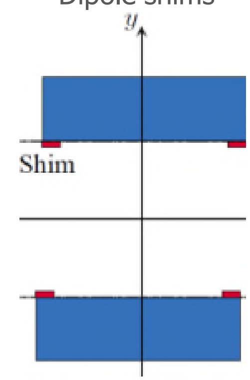
$$dB/B = \left(B_y(x) - B_y(0)\right)/B_y(0)$$

Low dB/B requires pole overhang a which can be estimated as

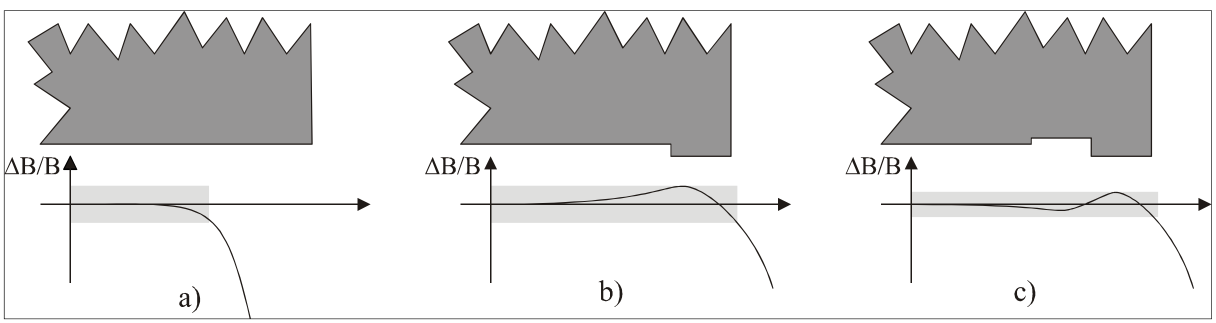
$$\frac{a}{h} \approx -0.18 \cdot \ln(dB/B) - 0.45 \quad \text{(no shims)}$$



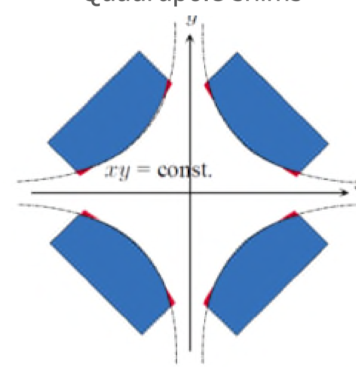
Dipole shims



So-called rose shims can be used to reduce the needed pole width



Quadrupole shims



Fringe field effects

Dipole field integral $\int Bdl$ is important as it determines the beam deflection

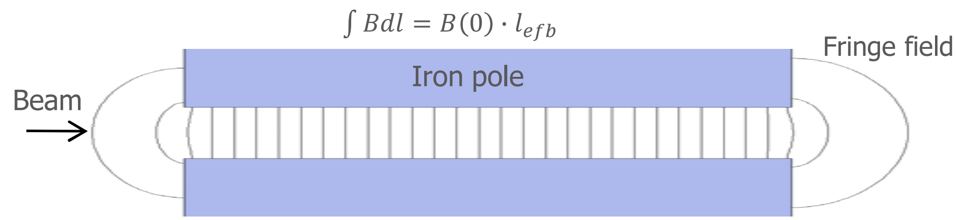
Effective magnetic length:

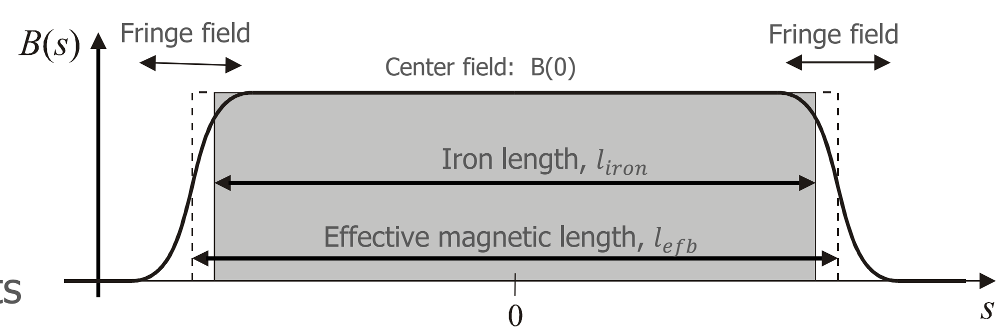
$$l_{efb} = \frac{1}{B(0)} \int_0^{\infty} B(s)ds$$

The magnetic length is longer than the iron length due to the fringe fields:

$l_{efb} \sim l_{iron} + h$ (geometry dependent)

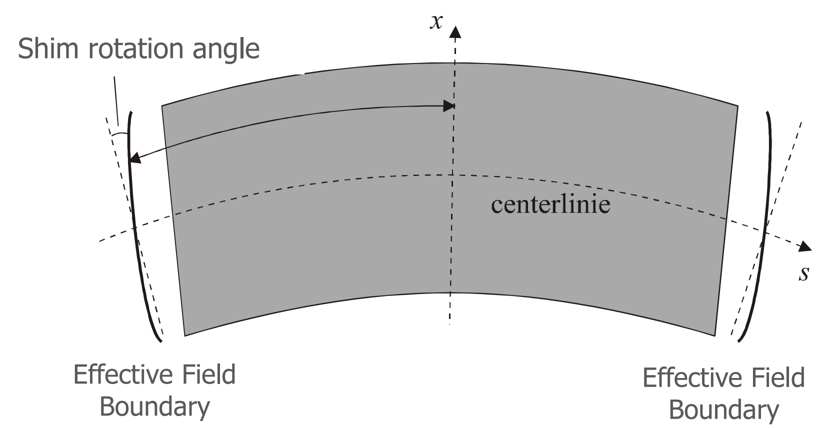
This is very important for short magnets





The magnetic shim rotation angle can be used to optimized the beam focusing

Magnetic field quality should ideally be evaluated based on field integral quality rather than just the center field quality

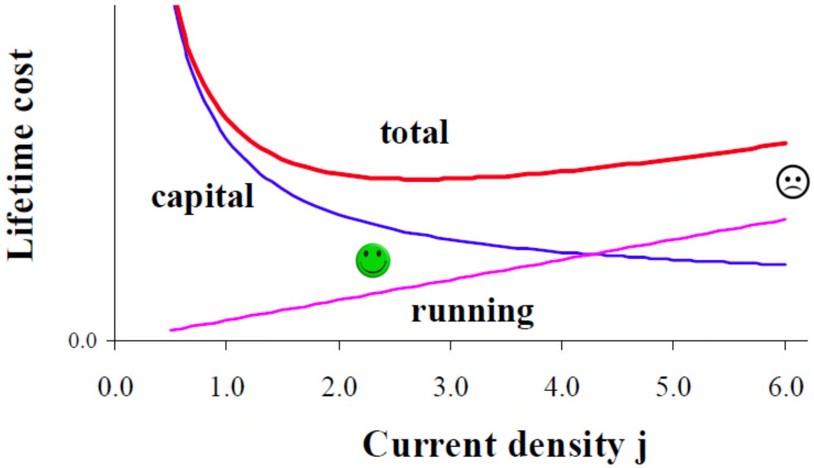


Current conductors

Air cooled coils for current densities of j = 1-2 A/mm^2

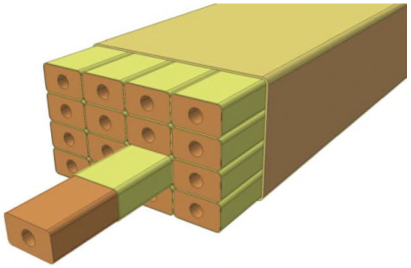
Water cooled coils typical with j of 3-10 A/mm^2
higher values are possible but can be risky

Magnet size and cost is reduced with increasing j but power consumption and running cost increases. Low j value are favored when total lifetime cost is minimized



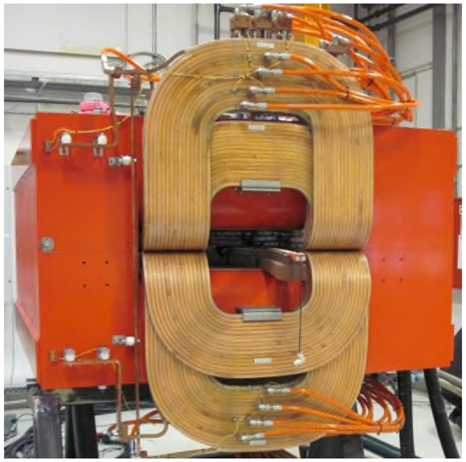
Lacquer insulated solid Cu wire

Glass tape wrapped & epoxy impregnated



1.86 T dipole, 25 ton, j=11 A/mm^2, 300 kW, 170 l/min

High power PT dipole example



AC operation

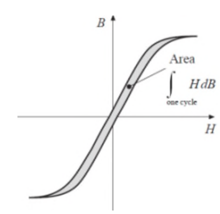
Induction: The needed drive voltage over the coil terminals will increase with ramping speed as U = RI + L$\frac{\partial I}{\partial t}$, where the inductance L is

$$L = \frac{\mu_0 N^2 A}{h + l/\mu_r} \approx \frac{\mu_0 N^2 A}{h} \qquad \mu_r \gg 1$$

where A is the total area of flux, h is the height of the pole gap and l the flux circuit length. N is the number of coil turns.

Power supply: The magnet and its power supply tend to become integrated units. High voltage protection around the current terminals is often needed

Eddy currents: are generated by field ramping and can result in saturation of the yoke and ramping speed dependent field lag both during ramping and some time after end ramping. Eddy currents in, for example, a conductive vacuum pipe can degrade the field quality and result in heating of the pipe



Core loss: In each current cycle there will be hysteresis losses in the core proportional to the enclosed area of the BH-curve resulting in a core heating

Skin-depth: for sinusoidal currents the penetration depth into the conductor will decay with frequency f with a characteristic length $\delta = \sqrt{\rho/(\pi f \mu)}$, ρ is the conductor resistivity. The effective resistance therefore increases when δ becomes smaller than the conductor width. There is also a magnetic field skin-depth effect for the core

For copper at room temperature:

$$\delta = \frac{7.5}{\sqrt{f}}\ \text{cm}$$

Core material options

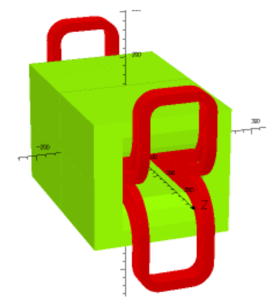
Solid iron magnets: Basically for dc operation with field variation limited to frequencies up to 0.01 - 0.1 Hz due to eddy current effects.

Laminated magnets: Cores of stacked steel laminates that are coated for electrical insulation allow field ramping while limiting eddy current losses. Hysteresis core losses are further minimized by using silicon steel laminates due to its enhanced resistivity. Lamination thickness is usually 0.5 - 1 mm at 10 Hz operation and 0.35 - 0.65 mm at 50 Hz. Faster ramp rates are possible when operated in pulsed operation with time delays between pulses.

Laminates are shuffled during production to get uniform magnet strength for series operation. Laminated magnets are typically costly but can in larger series productions be cost effective.

Lamination direction

Beam dump in 0.2ms with 0.35mm laminate thickness



Power cores: Can be used for intermediate frequency but has reduced saturation fields of 0.6 – 0.8 T.

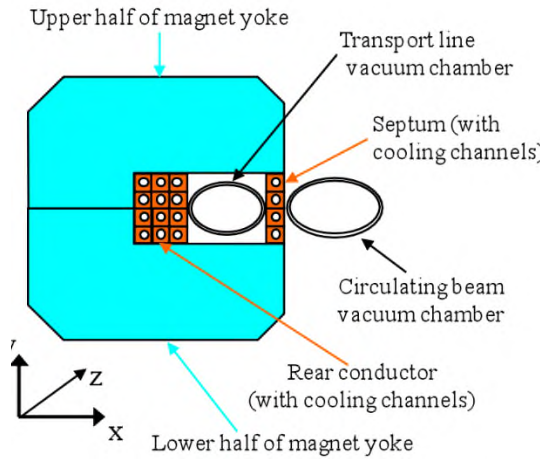
Ferrite magnets: The very high resistivity of ferrite allow MHz operation but the design is limited by the modest 0.25 – 0.5 T saturation magnetization of ferrite. The brittle ceramic ferrite (mostly MnZn or NiZn) core is mostly used in the form of blocks.

Septum and kicker magnets

Septum magnets: DC or pulsed dipole magnets with a thin septum separating the high field from the low field region

1T septum field with <0.1mT leak field driven by a 300μs 10kA current pulse at 530V

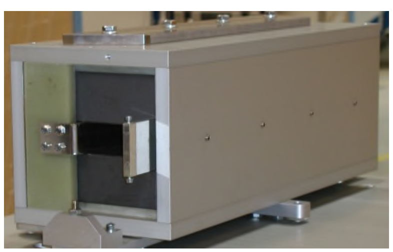
Septum

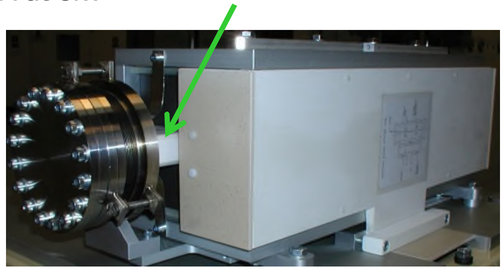


Kicker magnet: pulsed dipole magnet with rapid rise or fall times, typically below ~1μs

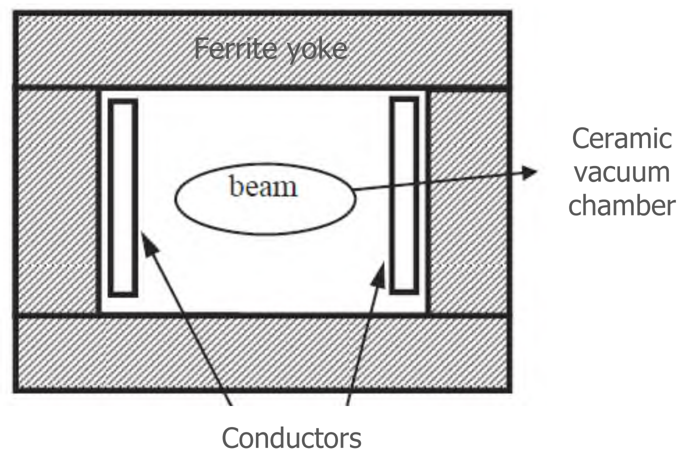
0.2T peak kicker field in a 5μs half-sine pulse driven by a peak current of 6kA at 8kV

Ceramic vacuum chamber





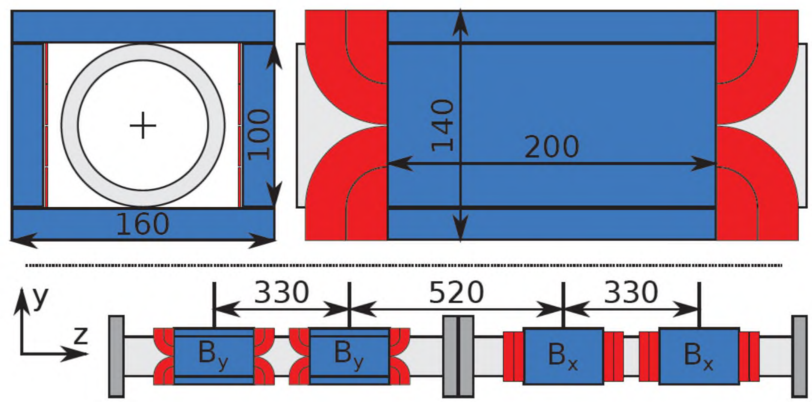
Classic kicker design



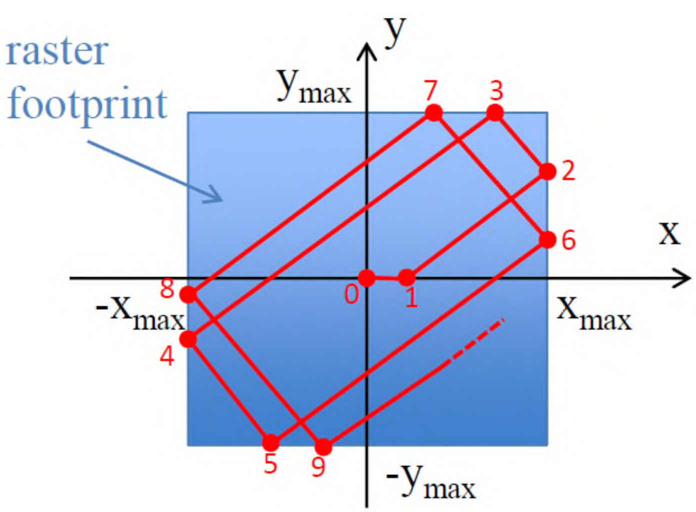
Fast raster scanning magnets for ESS

- The 5MW ESS beam needs to be distribute evenly on the target
- Beam steering with two set of fast 40 kHz ferrite based scanner magnets
- The magnet conductors are only 1mm thick as the current skin depth is only ~0.3mm
- Raster scanning with triangular waveforms
- Smart painting concept with x-y time delay

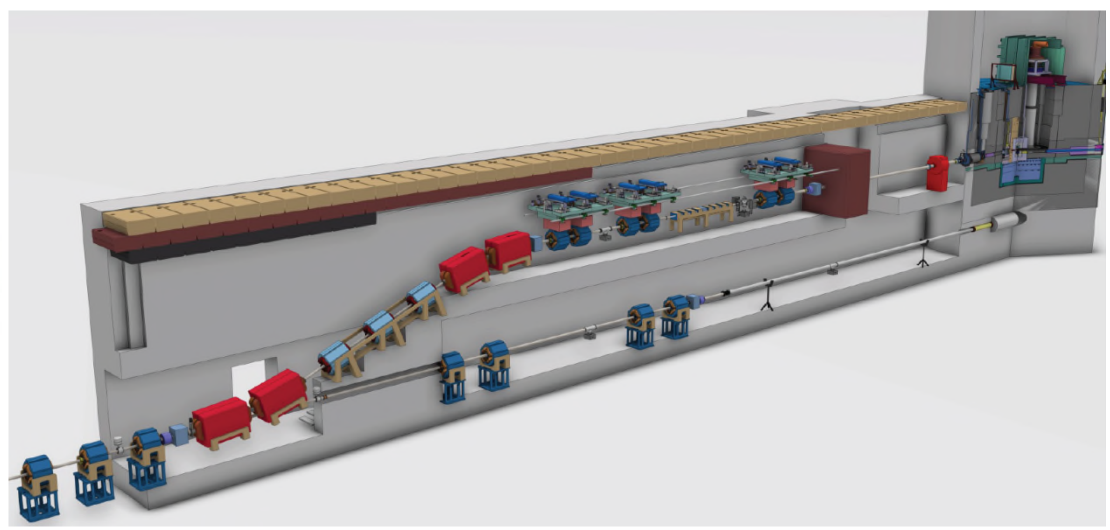
ESS scanner concept



Painting of target for power distribution



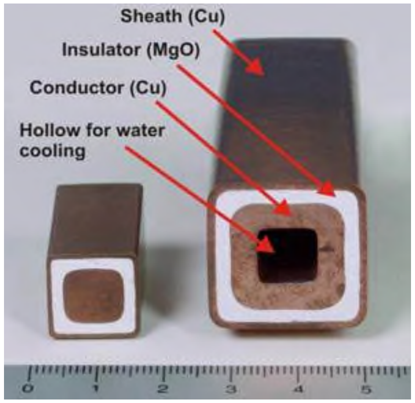
Early concept for last part of the ESS beamline



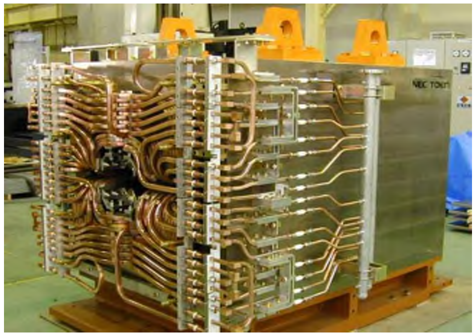
Magnets for high radiation environments

- Standard epoxy resin for max ~$5 \cdot 10^6$ Gy. Best cyanate ester resins up to 10^8 Gy
- Magnets without use of organic materials -> 10^{11} Gy
- All metal conductors can be made using mineral insulated cables (MIC)
- Robust and well proven magnet concept for high radiation levels but expensive

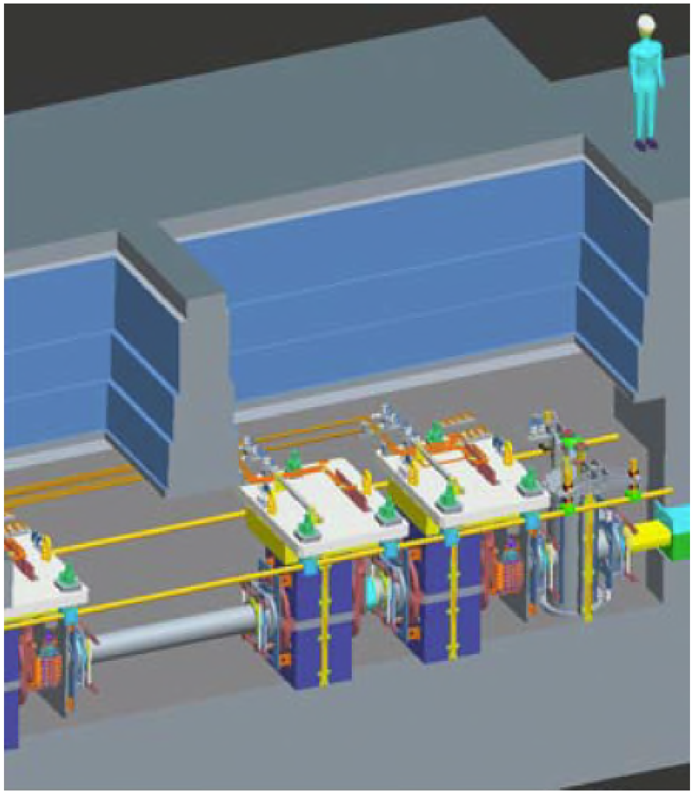
Hitachi MIC cables



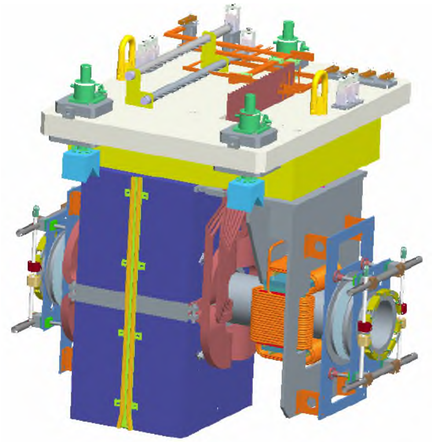
J-PARC magnet



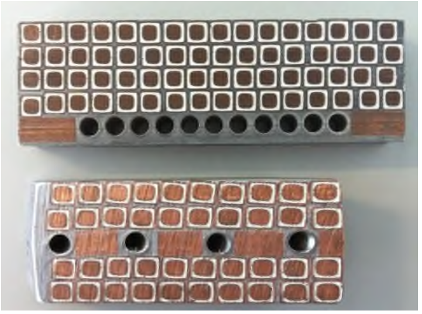
SNS remote handling concept



SNS magnet



MIC coil concept at PSI



Magnet design using computer codes

Several codes available for magnet design such as Opera, RADIA, ROXIE, ANSYS, Poisson. Opera is quite good but costly. Typical magnet design steps:

1) Initial analytical coil calculations:

- Ampere-turns, current density choice, water cooling, conductor resistance,… (consider power supply needs)

2) Magnetic 2D design (could be with Opera-2D):

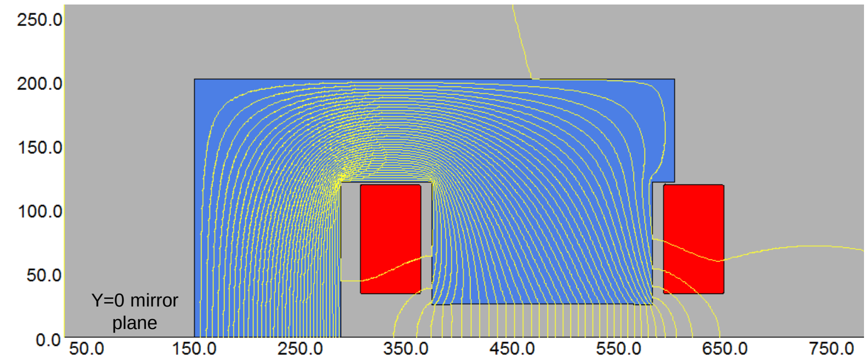
- Pole and yoke width optimized
- Pole profile optimized for needed field quality

3) Magnetic 3D design (could be with Opera-3D):

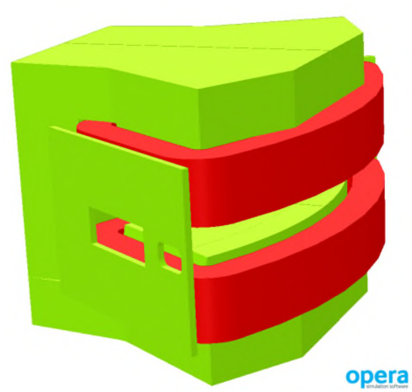
- Build 3D model
- Coil shape can often be approximated
- Finite elements codes like Opera requires good meshing
- Symmetry planes used to reduce model size and thereby the calculation times – which might be several hours
- Verify that the needed center field and effective magnetic length are obtained – avoid large iron loss
- Optimize design for correct field integral performance

4) Final detailed mechanical CAD design

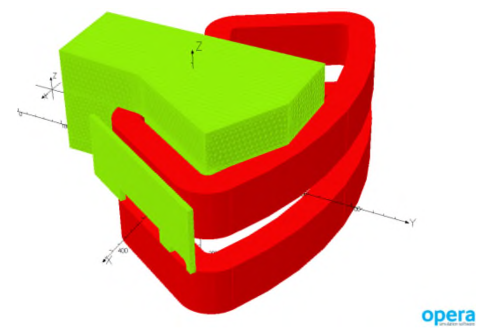
Opera-2D calculations for dipole top half, equipotential lines shown



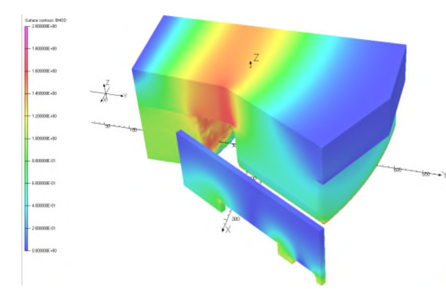
Opera-3D model



Model symmetries used, mesh shown



Field level on iron surface

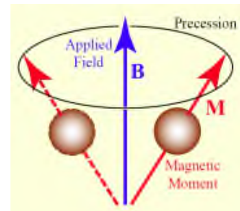


Local magnetic field measurements

NMR probes:

- Requires a uniform field
- Relative slow measurement ~1Hz
- High precision: ppm level (10^{-6})

Spin frequency proportional to field

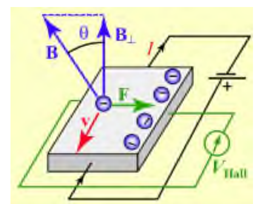


NMR meter with probes

Hall probes:

- Hall-voltage is proportional to the B-field
- Digital probes: slow ~1 Hz data logging
- Analog probes: data logging limit ~10 kHz
- Best precision: ~0.01%

Magnetic forces induces a Hall-voltage



Hall probe

Standard Hall probe field mapping:

- Step-by-step or on-the-fly (analog probe)
- Rectangular 3D measurement grid
- Positioning accuracy: typically 0.1 mm

Standard Hall mapper

High precision Hall probe mapping:

- Granite table with air cushion
- Laser feedback on longitudinal z-axis and linear encoders on transverse x,y-axes
- Positioning accuracy better than 0.01 mm
- Mostly for open C-type of magnets due to short transverse x-range

Precision Hall mapper

Integrating coil measurements

Electromagnetic induction:

Changing flux Φ through a coil induces a voltage:

$$V(t) = -\frac{d\Phi}{dt} = -\frac{d}{dt}\left[\int_S \vec{B} \cdot d\,\vec{S}\right]$$

Rotating harmonic coil:

- Magnetic alignment: ±0.02mm (FARO arm)
- Typical accuracy of the harmonics: $1\text{-}3 \cdot 10^{-4}$
- Typical higher harmonic reproducibility: $0.1 \cdot 10^{-4}$

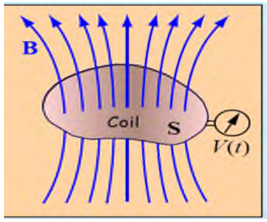
Ramped magnets:

- Multi-turn pick-up coil
- Coil width typically of several mm
- Use integrator or 20 bit data logger
- Field integral at different transverse positions
- Relative stability better than $1 \cdot 10^{-4}$

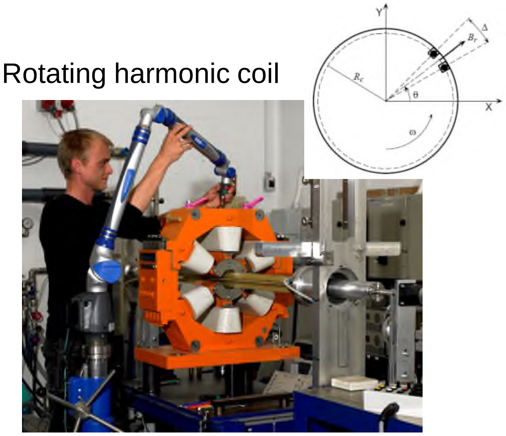
Fast pulsed magnets:

- Single turn strip-line coil
- Ramping times: ≥ a few ns
- Use fast oscilloscope or 20bit data logger

One turn coil with area S

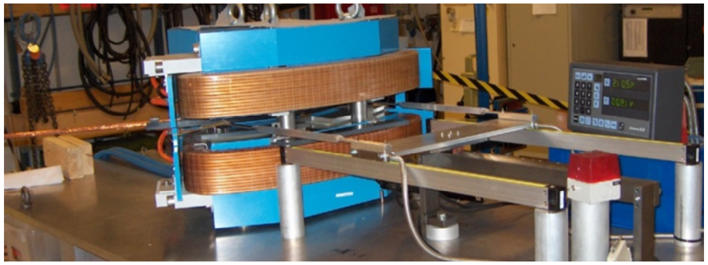


Rotating harmonic coil



Multi-turn integrating coil bend along the nominal trajectory

Pick-up coil



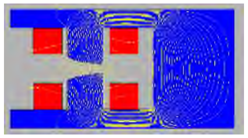
Single turn strip-line coil

Strip-line coil pair in kicker

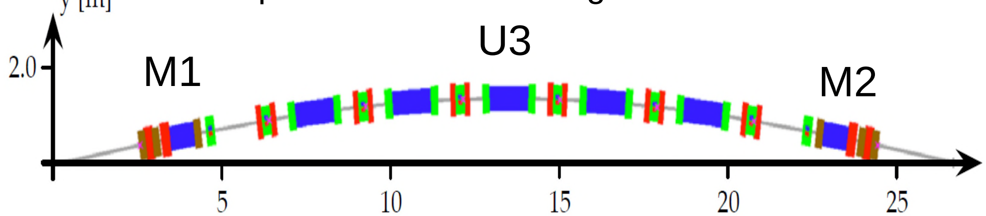
Magnet girders for the 3GeV MAX-IV synchrotron

- New unique concept developed at MAX-Lab for very low emittance
- Girders with up to 12 magnetic elements in a common steel yoke
- Small Ø25 mm aperture in the multipoles
- Combined function dipoles with build-in gradients
- The girders have been produced by Danfysik and Scanditronix

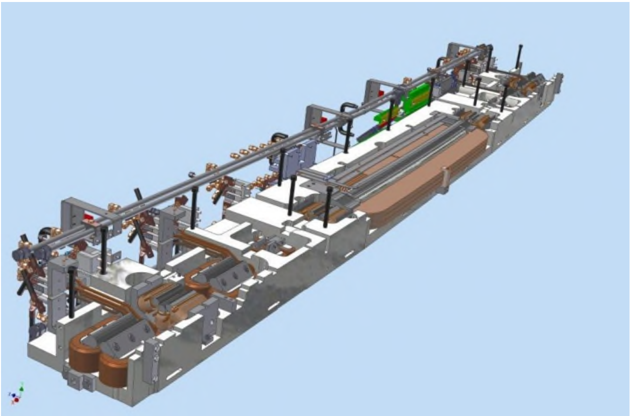
Combined function dipole



Girder positions in the 20 ring achromats

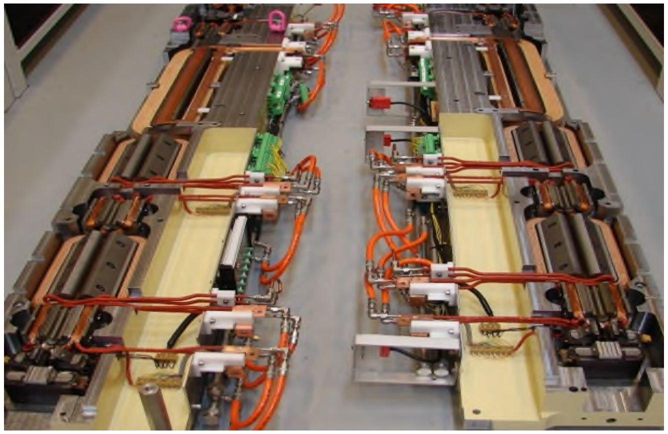


CAD model of the M1 bottom girder



Yokes machined out of one solid piece of steel

Top/bottom half's



Machining and production

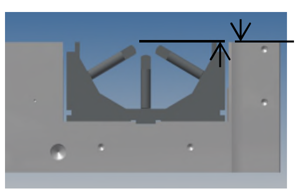
- Challenging tolerances of ±0.02 mm over full length
- Iterative machining refinement and 3D measurement campaign
- Machining performed to the satisfaction of MAX-lab

Main body → Rough machining → Heat treatment → Fine machining → 3D measuring → Fine machining → 3D re-measuring → Assembly

Multipole inserts → Rough machining → Heat treatment → Fine machining → Sub-assembling → Wire erosion → 3D measuring → Fine machining → 3D re-measuring → Assembly

Assembly

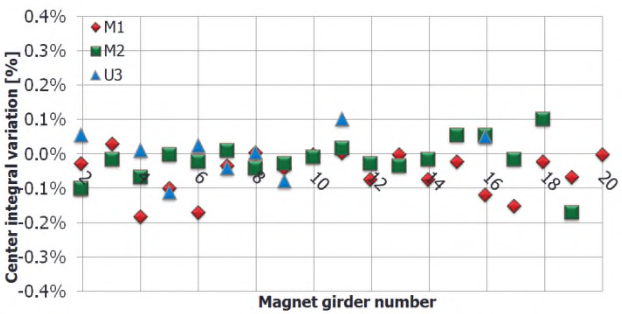
Multipole mid-plane flush to mid-plane within +0.00 / -0.01 mm



Hall probe measurements

- Precision Hall mapper on long granite table
- Usual probe positioning not possible without line-of-sight though magnet
- Alignment by scanning over magnetic pins at know positions
- Fast on-the-fly field mapping using analog Hall probes
- Dipole strength variation is in agreement with ±0.02mm mechanical tolerance

Measured relative on-axis field integral



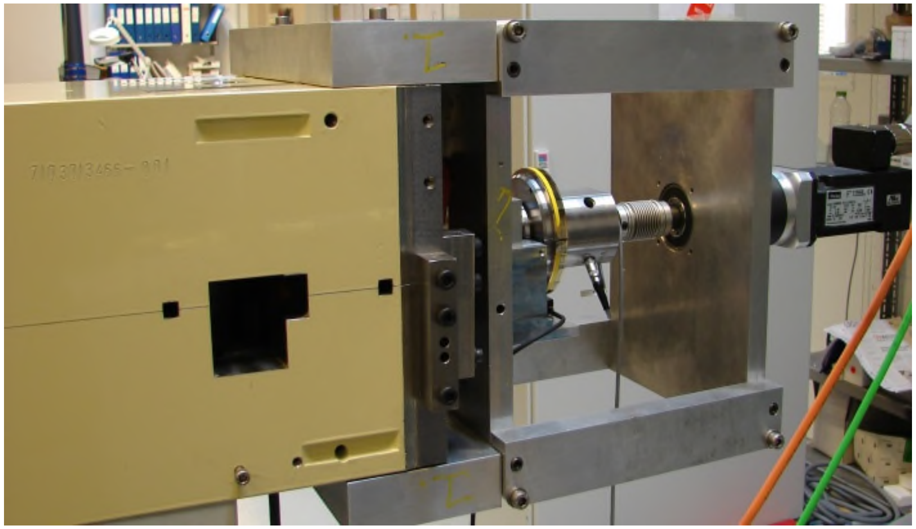
Alignment with magnet tip within 10 µm

Scanning dipole from side & quadrupoles through small holes in yoke

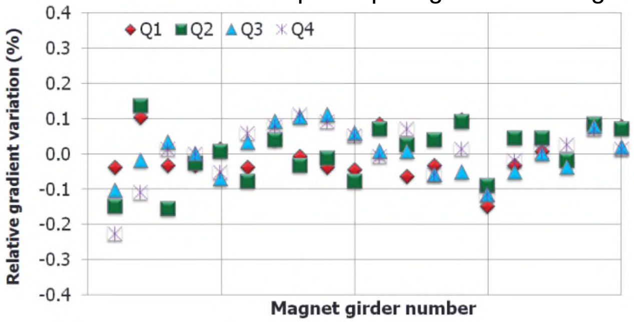
Harmonic insertion coil concept

- Harmonic measuring coil concept made specially for these magnets
- Coil inserted from girder end with external encoder and motor
- Rotating harmonic coil with a 10.7 mm measurement radius
- One short coil segment for each magnet on a support rod
- Multipole performance in agreement with the ±0.02 mm tolerance limit

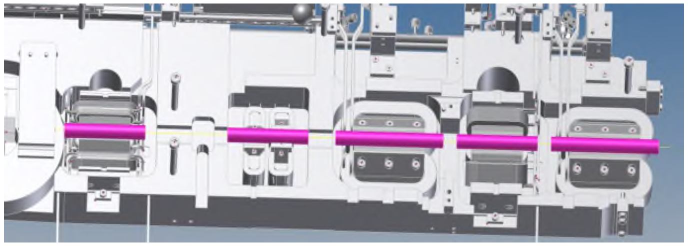
Rotating harmonic coil measuring system inserted at one girder end



Measured relative quadrupole gradient strength



Coil segment positions for U3 (symmetrical ends)



Superconducting technology

LTS-wire: Accelerator rings have so far been made with NbTi which is a ductile and robust alloy while $NbSn_3$ is brittle and difficult

HTS-wire: Expensive prototype wires

- BSCCO wire for high temperature or high field
- YBCO for high temperature & field, but there is a problematic grain boundary alignment issue

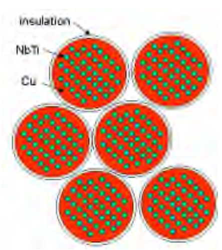
Effective current density: is typically only 15 – 30% of the values for the SC material due to the presence of stabilization cobber, insulation and the packing fraction of the wires

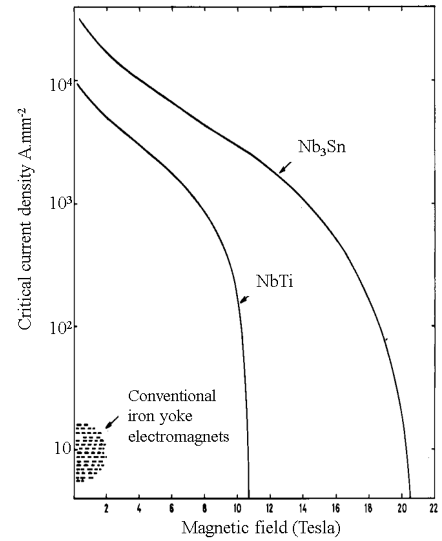
Cooling: bath of liquid helium or with cryo-coolers

Magnetic forces: proportional to B^2 and therefore large. The wires have to be fixed to avoid movement

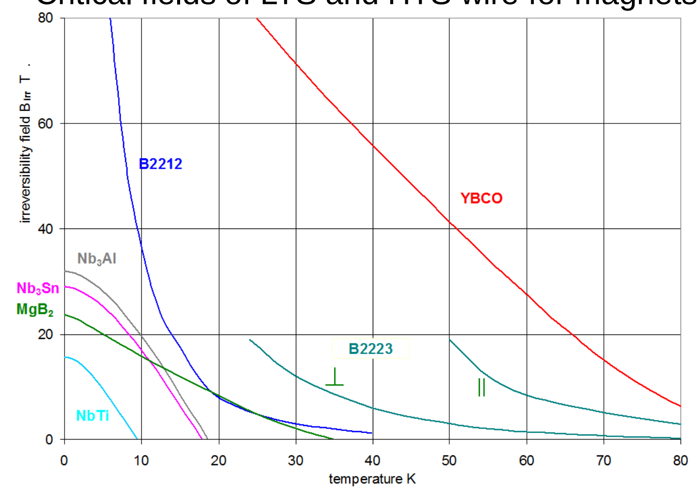
Quench: When the SC goes normal -> energy dump in external resistor

Critical current of metallic SC at 4.2 K



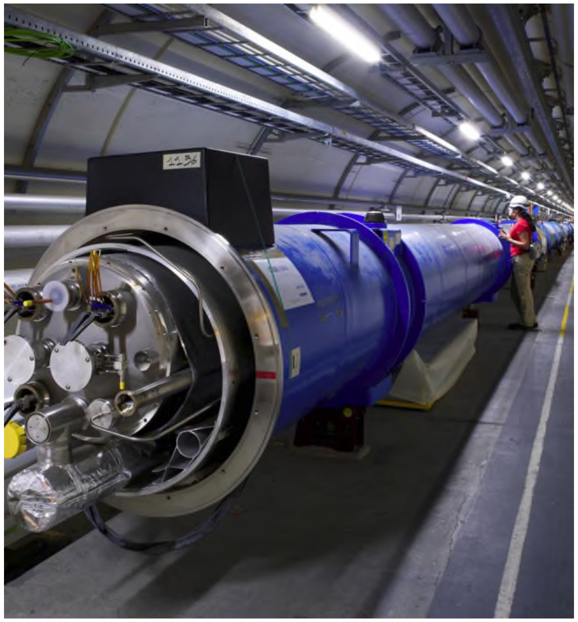


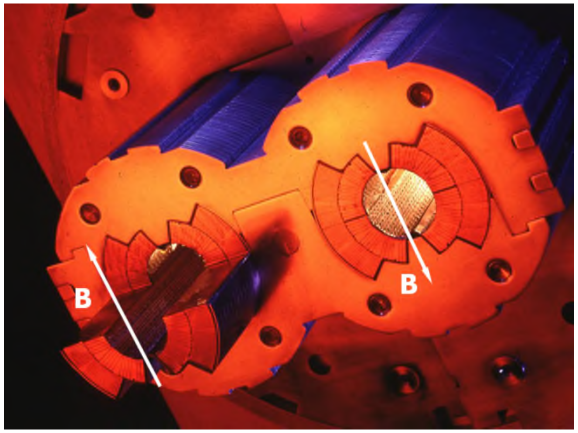
Critical fields of LTS and HTS wire for magnets



Superconducting accelerator magnets

SC dipole in the 27km LHC collider at CERN





Advantages:

- No significant power consumption in coils, but power needed for refrigeration
- Ampere-turns are cheap so less iron is needed
- Higher magnetic fields allowed shorter magnets and therefore smaller accelerator rings

Challenges:

- Field mainly defined by coils
- SC magnets are complex with higher risk involved
- Demanding infrastructure and labor force requirement
- For magnets up to ~2T there is typically no effective energy saving due to cooling needs

Motivation:

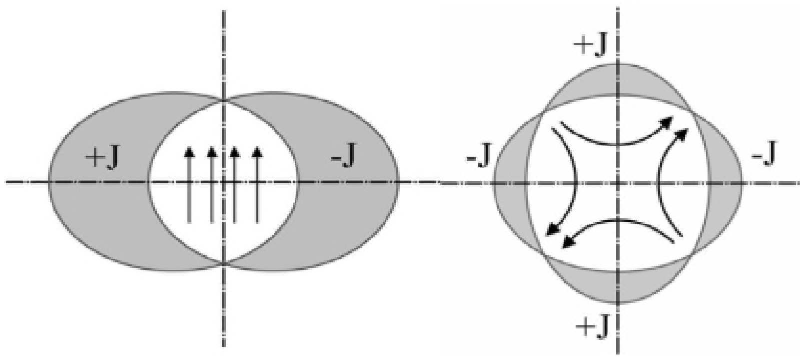
Use SC technology mainly when it is the only option or when a smaller accelerator ring lowers the total facility cost

SC magnets

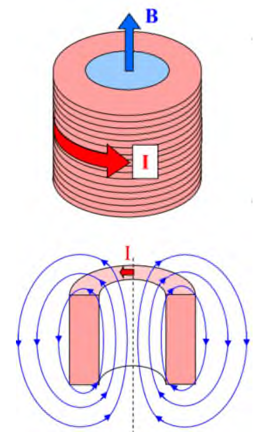
Overlapping elliptical conductor sections with constant current density – this is the cosine-theta types

Dipole

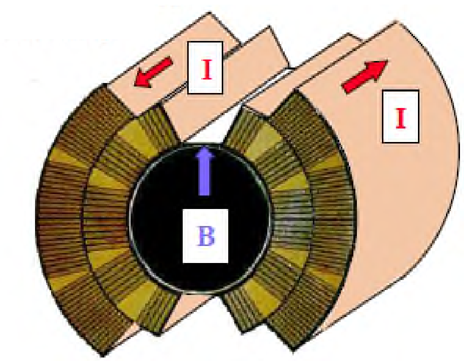
Quadrupole



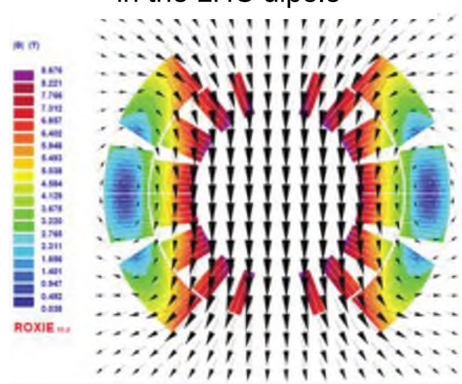
Solenoid made with cylindrical windings



8.3T LHC dipole, J_e= 375A/mm^2



Calculated field distribution in the LHC dipole



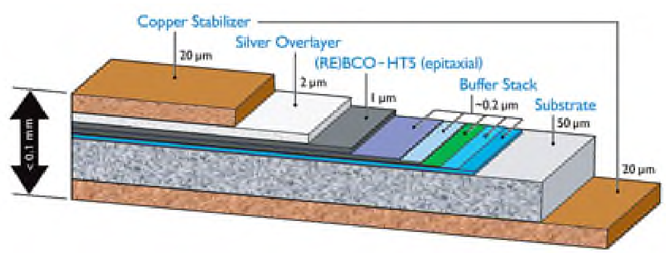
DANFYSIK

HTS-solenoid for University of Wisconsin

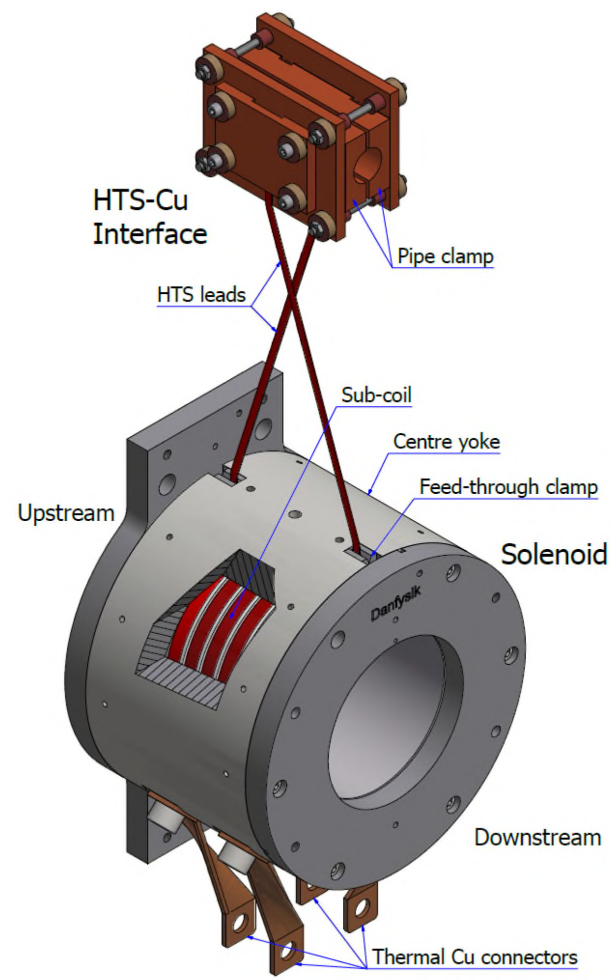
Compact HTS solenoid

- Centerfield 0.2 T
- Operation up to 70 K
- Bore diameter 92 mm
- 8 double pancake coils

2G HTS tape, coated $YBa_2Cu_3O_7$ conductor
Critical current > 100 A at 78 K and 0 T



Coil with 8 sub-coils



DANFYSIK

Green permanent magnet concept

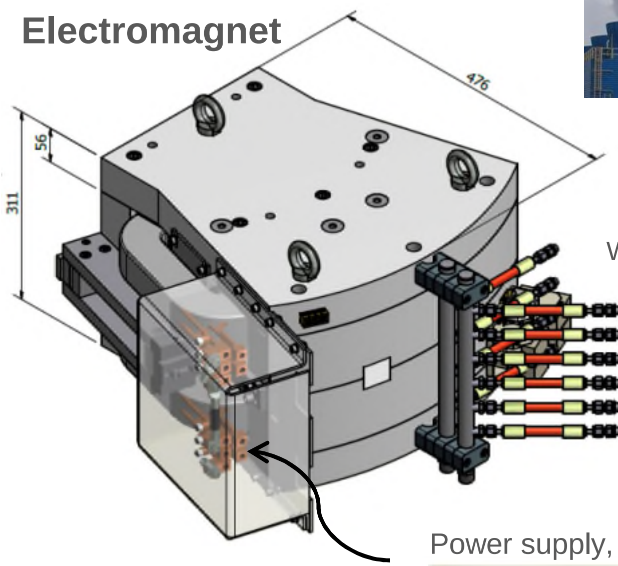
Electromagnet:
- Field generated by current
- Water cooled coils
- High stability 200A power supply

=> Power consumption

Green magnet:
- Fixed field based on permanent magnets
- Air cooled coils for small field adjustments
- Small simple trim 10A power supply

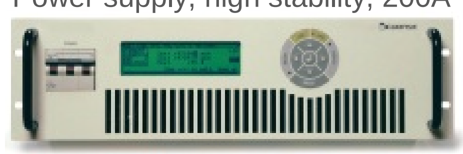
=> Negligible power consumption

Electromagnet



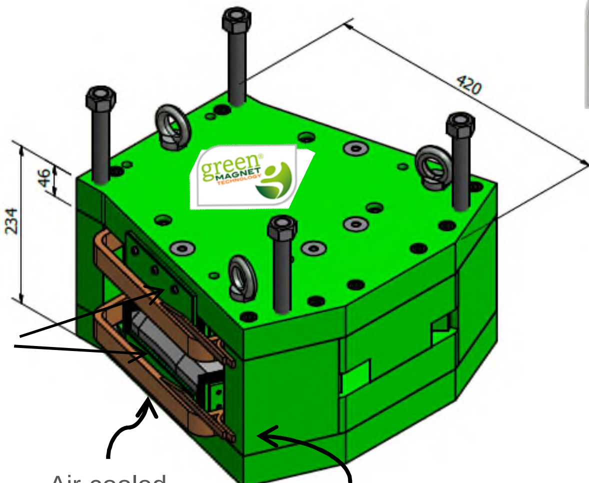
Water cooling

Power supply, high stability, 200A



3year project supported by the Danish HTF

Green magnet



Permanent magnets

Air cooled trim coil

Simple trim supply, 10A

Permanent magnet theory (approximated)

Work point (B_m,H_m): flux density and magnetic field inside the permanent magnet

Gauss's flux theorem: $B_m A_m = B_g A_g$ cross sections: A_m= magnet, A_g= gap

Ampère's law: $H_m l_m + H_g l_g = 0$ path lengths: l_m= magnet, l_g= gap

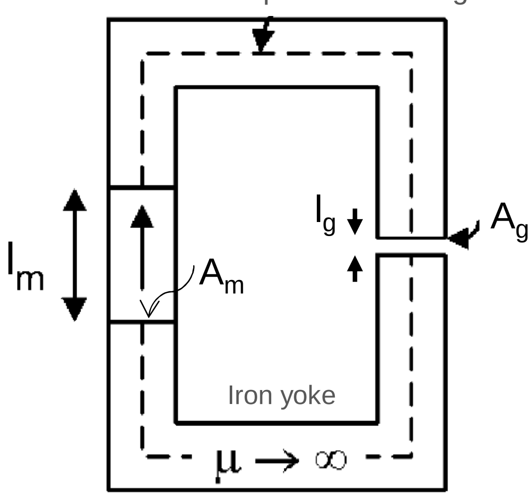
Combining these two relations together with $B_g = \mu_0 H_g$ gives

Load line equation: $B_m = -\mu_0 \left(\frac{l_m A_g}{l_g A_m}\right) H_m$, with slope $-\mu_0 \frac{l_m A_g}{l_g A_m}$

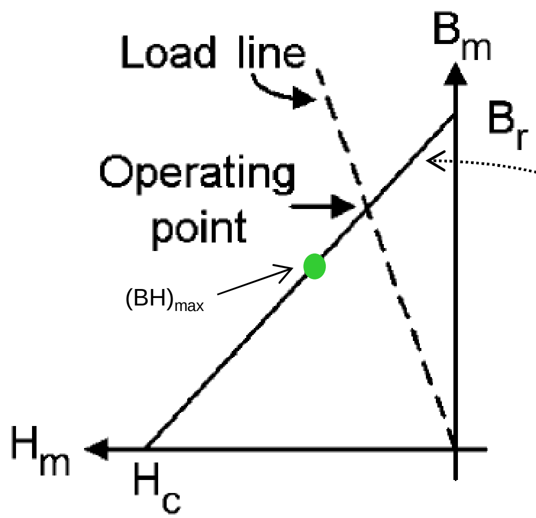
The intercept between the load line and the demagnetizing curve gives the work point

The ideal work point is typically at $(BH)_{max}$ where the magnetic energy generated by the magnet is maximized. For NdFeB and SmCo this is for $B_m \approx B_r/2$

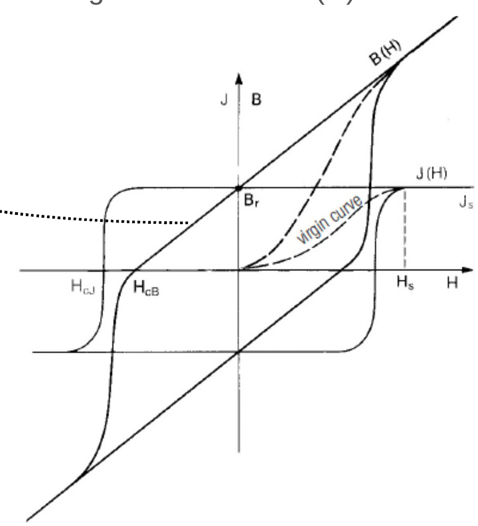
Flux circuit with permanent magnet



Demagnetizing B(H) curve



Magnetization and B(H) curves



Permanent magnets

The Fermilab Recycler from 1997 is the only accelerator facility based mainly permanent magnets

Pure permanent Halbach quadrupoles is the only permanent magnet type in common use in todays accelerators

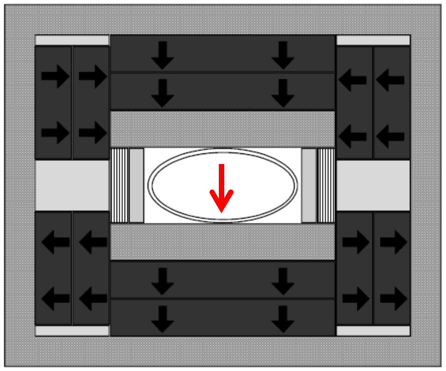
The following table shows typical parameters for the most common permanent magnetic materials

$Nd_2Fe_{14}B$ is favored for strong accelerator magnets, but in environments with significant radiation levels Sm_2Co_{17} is safer

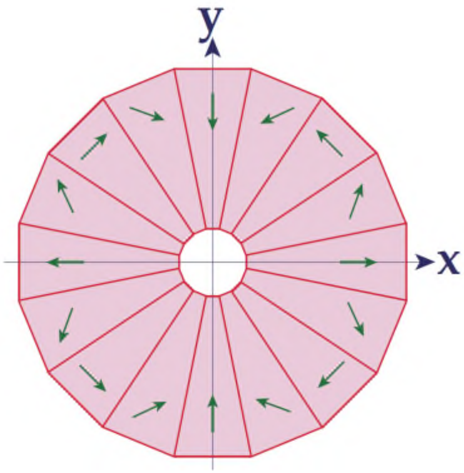
Composition	Fe-alloy	$SrO \cdot 6Fe_2O_3$	$SmCo_5$	Sm_2Co_{17}	$Nd_2Fe_{14}B$
B_r (T)	1.3	0.4	0.9	1.1	1.2
Temp.coeff. of B_r	-0.02	-0.2	-0.06	-0.04	-0.12
H_{cJ} (kA/m)	150	320	2400	2000	1400
$(BH)_{max}$ (kJ/cm³)	50	25	170	250	300
Curie-point (°C)	800	450	750	800	300
Density (g/cm³)	7.2	5.0	8.2	8.4	7.4

Long strait ferrite based

0.23T dipole for 1.1° bend



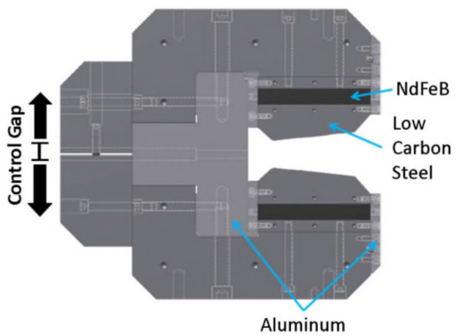
Halbach quadrupole



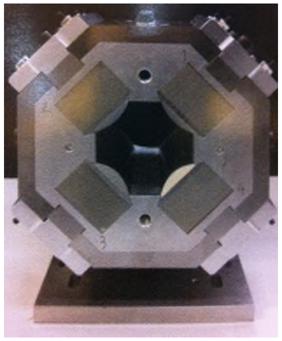
Recent permanent magnet development

- SIRIUS: Brazilian Synchrotron Light Source, focused on energy saving
- LINAC4: Fix field quads – mix EM and PM quads along LINAC
- CLIC: Mainly permanent to avoid problems with tunnel heating
- ESRF: Prototype dipole for ESRF synchrotron being produced: lifetime cost focus

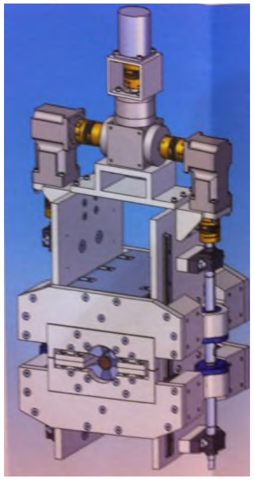
Sirius prototype dipole

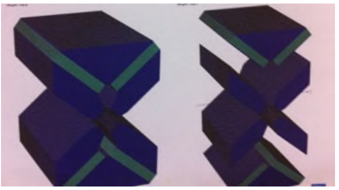


LINAC4 quadrupole

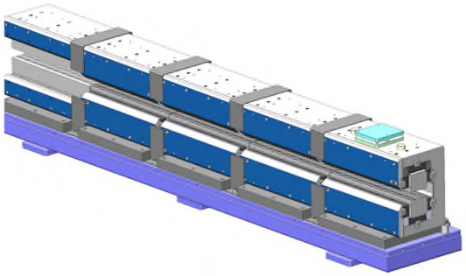


CLIC quadrupole

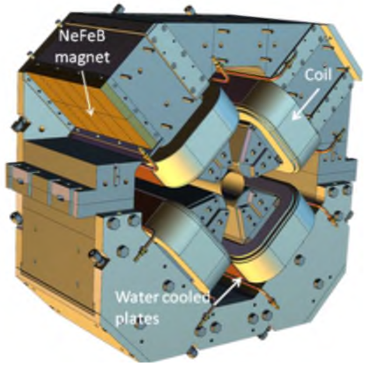




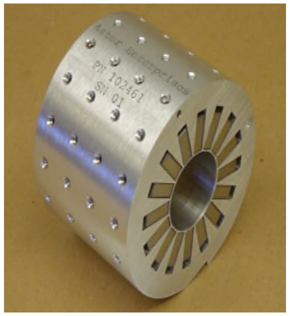
ESRF synchrotron upgrade dipole



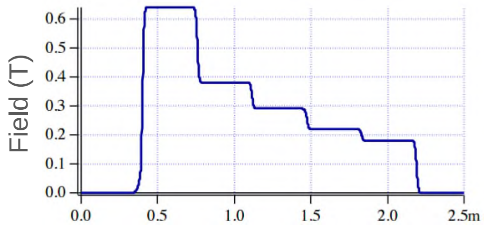
Sirius prototype quadrupole



CERN Halbach quadrupole



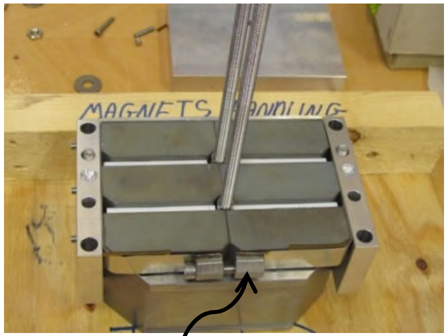
Longitudinal field variation



Test of magnetic forces during assembly

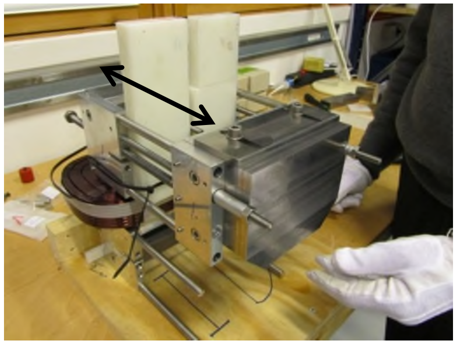
- A small 0.25T test C-magnet was made with 12 spare permanent magnets
- Magnetic forces is a significant issue - we learned mainly how not to do it
- Obtaining a high permanent magnet coverage is an important issue
- A student came up with the needed permanent magnet mounting solution

Test magnet

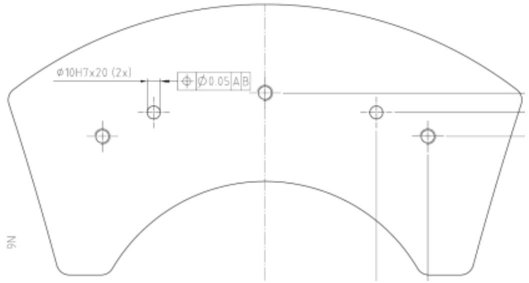


Force between magnets have to be contained

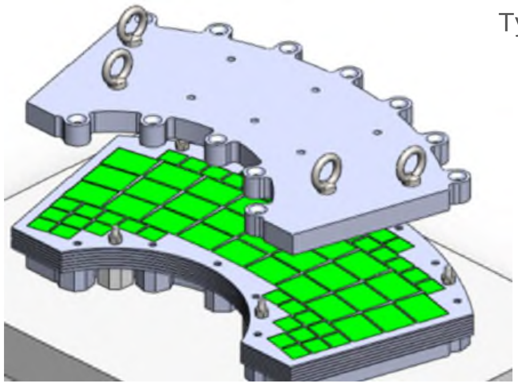
Large force between parts with permanent magnets



Original pole shape for the 90° AMS bending dipole

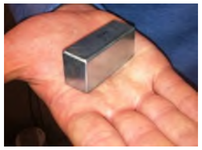


Students project at a Danish university



One of the suggested mounting concepts – not optimal

Typical magnet shape

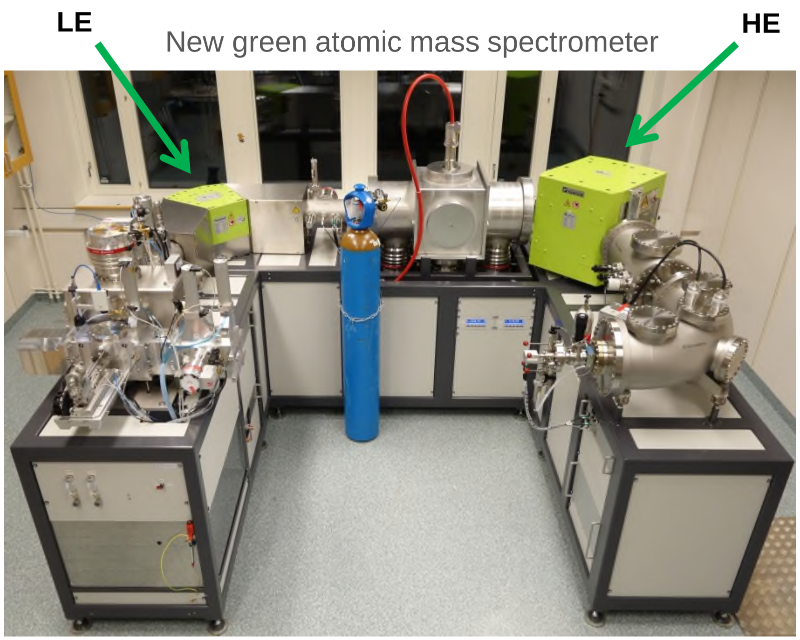


Compact green AMS for carbon dating

- Carbon dating accelerator system at ETH
- Permanent green magnets developed to replace the two 90° bending dipoles
- Field generated by high remanence NdFeB
- No cooling water -> reduced complexity
- Danfysik has produced magnets for 9 facilities

Magnet Parameters, LE	Specification
Deflection angle	90°
Pole gap	38.5 mm
Radius of curvature	250 mm
Magnetic length	393 mm
Center field	0.427 T
Operating range	0 - 2 %
Field homogeneity	$< 1 \cdot 10^{-3}$
Fringe field shim angle	28.5 ± 0.1°
Thermal stability	< 50 ppm/°C

New green atomic mass spectrometer



Prototype LE magnet was installed 2013 at ETH, Zürich

Water hoses and thick power cable needed for the original conventional electromagnet

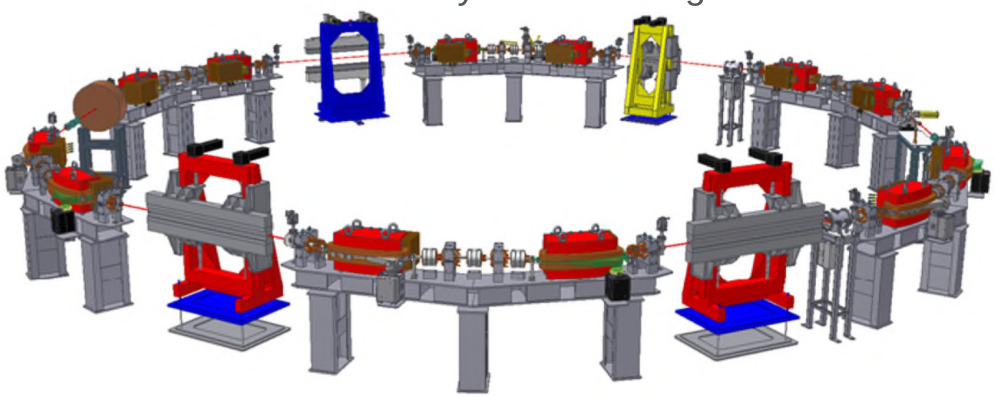
Green magnet alternative for ASTRID2

Fixed beam energy in transfer line and ring

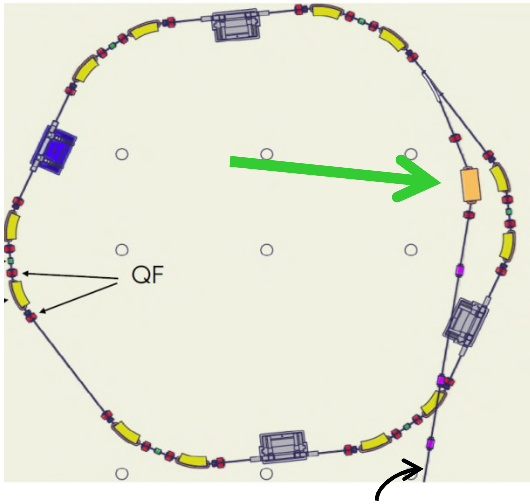
- Fixed field requirement
- 30mm pole gap
- Center field at 1T level
- Modest radiation

=> ideal PM case

ASTRID2 synchrotron ring



One electromagnet has been replaced with a green magnet



Transfer line

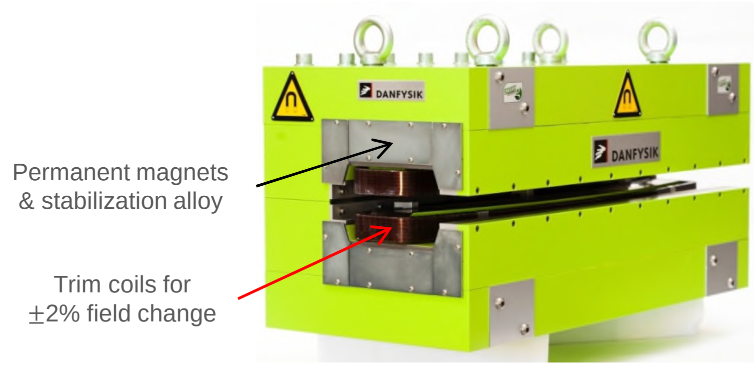
‘Fixed’ field green alternative:

- ASTRID2 requires only ±2% field change
- Small air cooled trim coil with I ≤ 20A
- Power saving: at least 99% of 4 kW

Green magnet prototype for ASTRID2

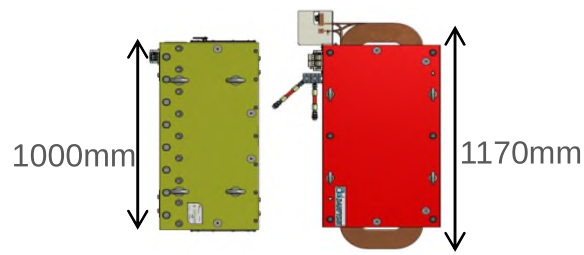
- The magnet fulfill the requirements
- Has been in operation since 2013
- Passive temperature stabilization
- Excellent short and long term stability
- No trim current used so far
- Has been “forgotten” the last few years
- Total magnet length reduced 17%
- Maximum magnetic force 90kN ~ 9 ton

Parameter	Obtained
Beam deflection angle	30°
Pole gap	30.05 mm
Magnetic length	1002.6 mm
Center field	1.015 T
Operating range	±3%
Field homogeneity	< $0.6 \cdot 10^{-3}$
Fringe field shim angle	15.01°
Thermal stability	< 30 ppm/°C



Installation in ASTRID2 transfer line 24-9-2013

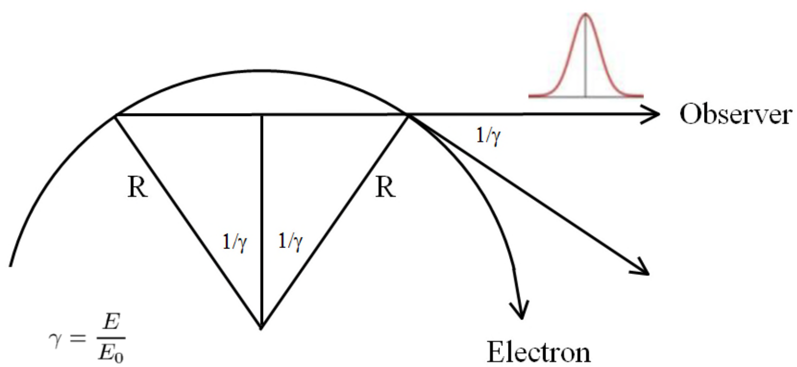
ASTRID2 PM vs EM length



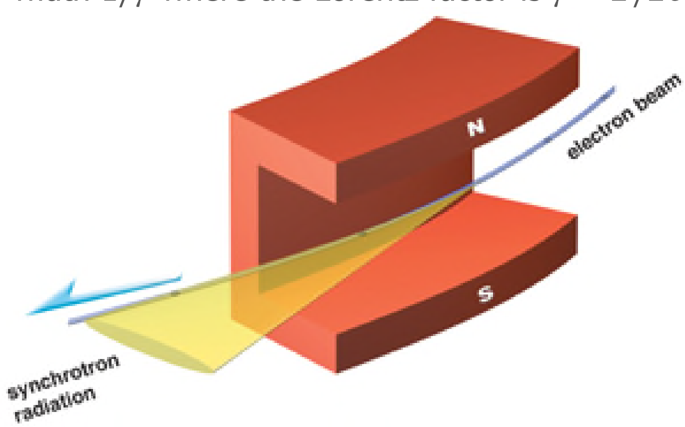
DANFYSIK

Synchrotron spectrum

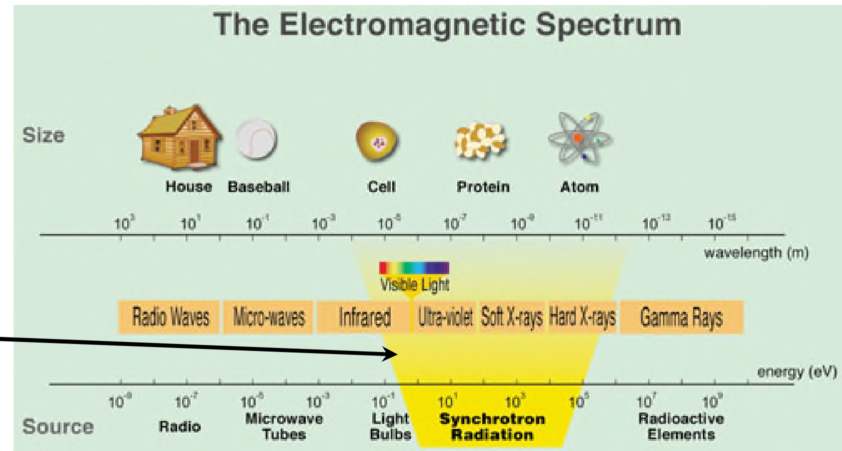
Synchrotron light is generated by electrons that are accelerated when forced on a circular trajectory by the bending magnets



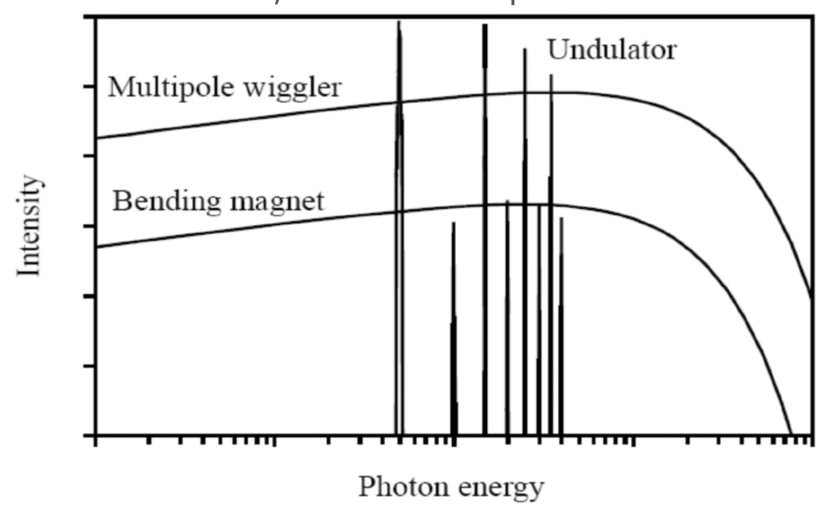
Radiation from a bending magnet, horizontal width $1/\gamma$ where the Lorentz factor is $\gamma = E/Eo$



The spectrum extends over a wide range from infra-red to x-ray



Bending magnet and wiggler spectrum is continues, the undulator spectrum is not



Basic insertion device principles

A fundamental ID parameter: $K = 0.934 \cdot B \cdot \lambda_0$

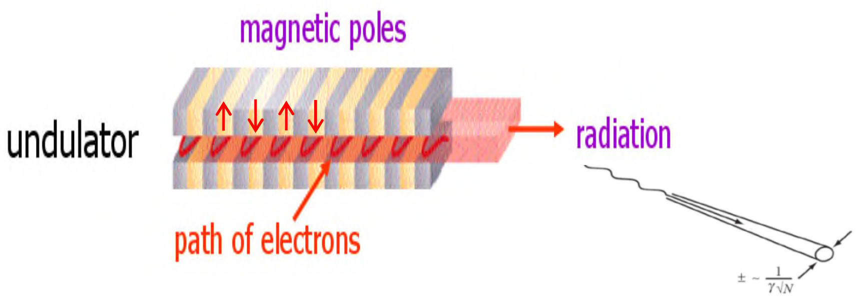
Period length: λ_0 [cm]
Peak field: B [T]

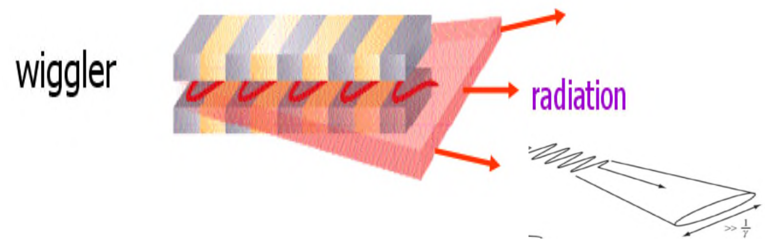
Undulator, $K \leq 3$

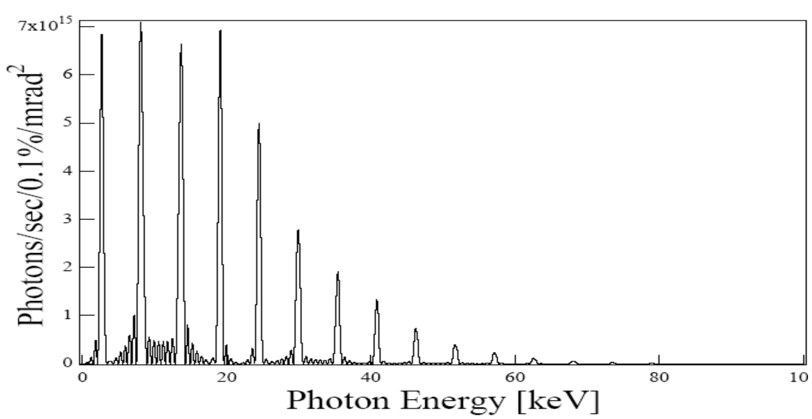
- Discrete radiation

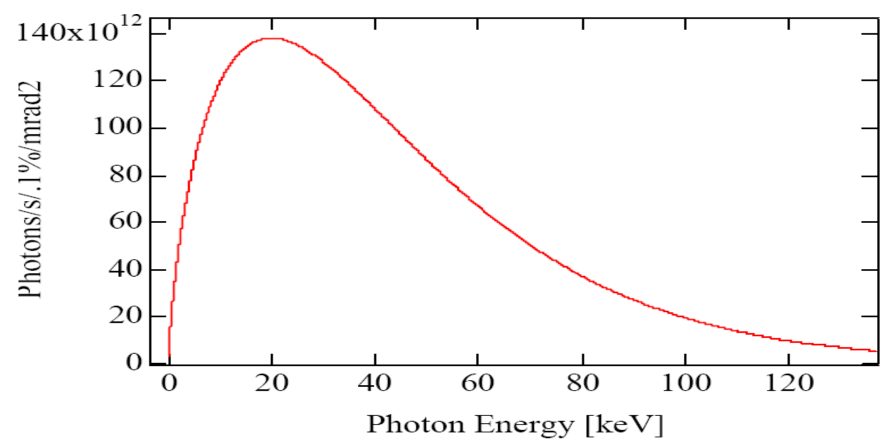
Wiggler, $K \geq 3$

- Smooth radiation spectra









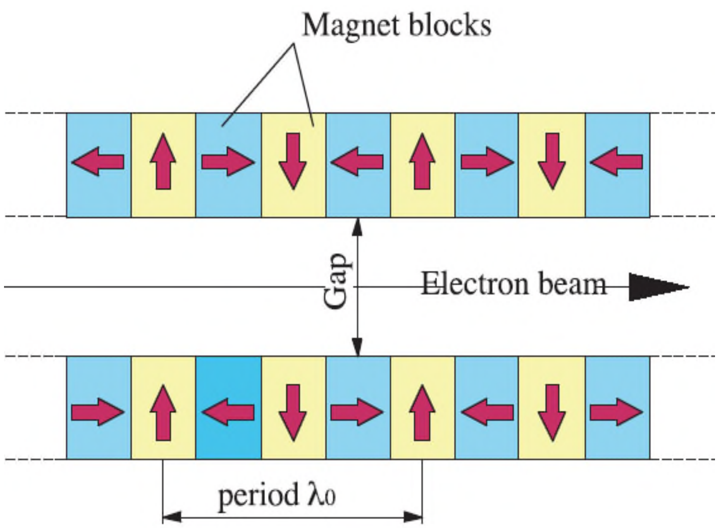
PPM vs. hybrid device

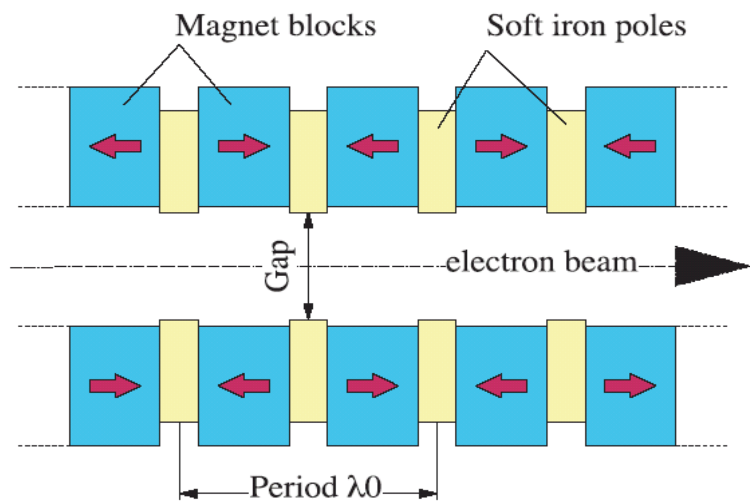
Pure permanent ID:

- Advantages
  - Simple design
  - Simple shimming
  - Robust concept
- Disadvantage
  - Lower peak field

Hybrid ID:

- Advantages
  - Higher field for given period length
  - Half the number of permanent magnets
- Disadvantage
  - More challenging
  - Somewhat sensitive to ambient fields





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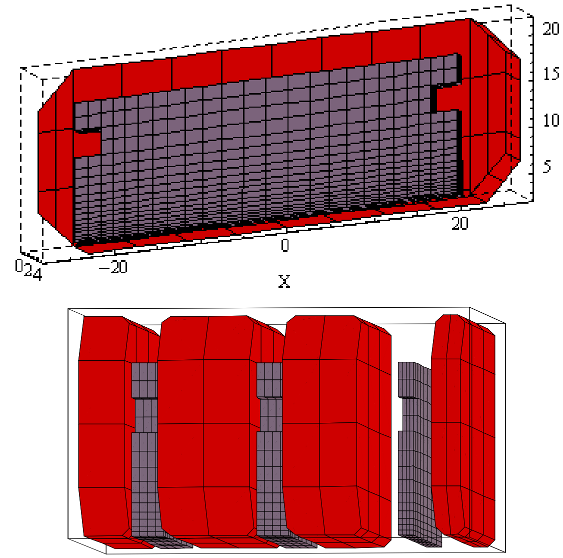
Magnetic design of insertion devices

RADIA: Main center and end design

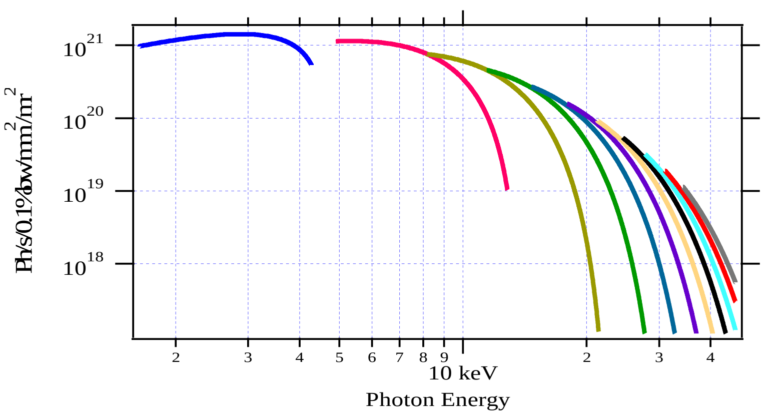
SRW: Radiation spectrum calculation

Opera-3D: Demagnetizing fields calculations

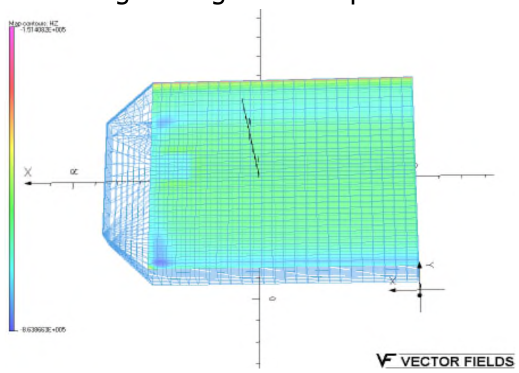
RADIA center and end design



Optical radiation spectrum calculation in SRW



OPERA: demagnetizing fields for permanent magnets



Magnetic testing

Hall probe bench:

- Local field variation along device
- Thin 3D Hall probe
- Laser calibrated position

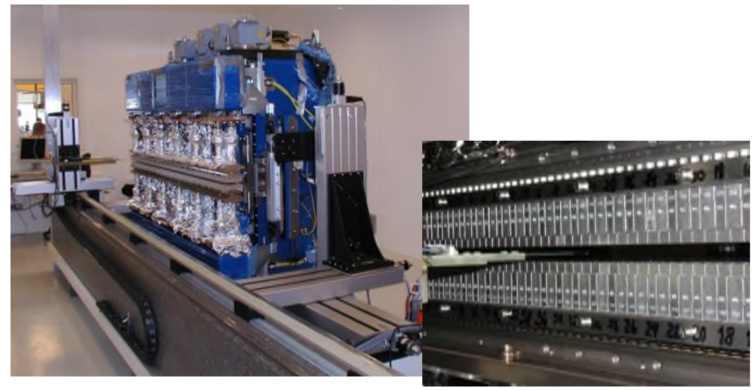
Flip coil bench or stretch wire

- Field integral measurements
- Measurements on individual magnets and on the full device

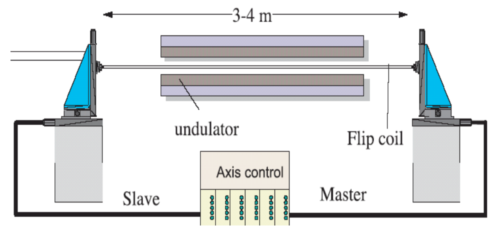
Imperfect permanent magnets

- Strength variations and defects
- A shimming process is needed to correct for magnetic imperfections

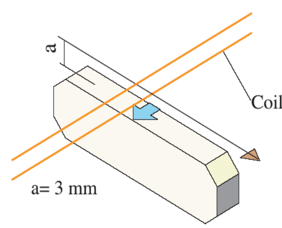
A clean room is need for in-vacuum devices

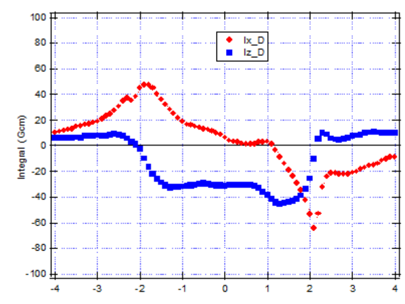


Coil is rotated in undulator gap



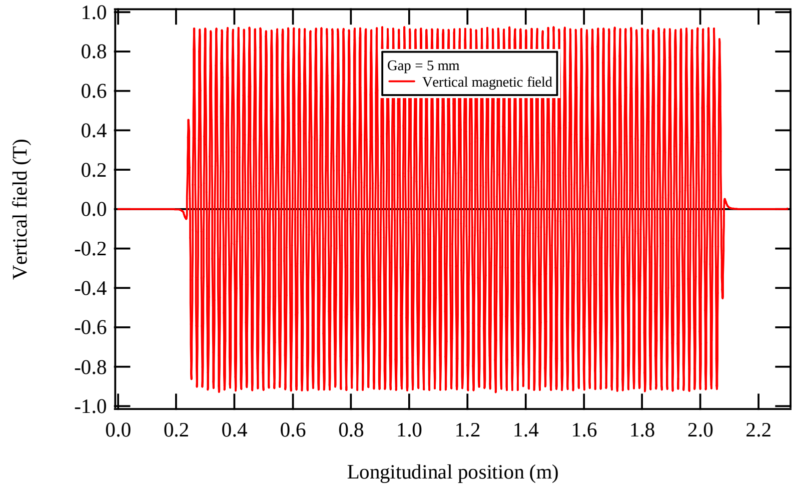
Field integral imperfection measured for each magnet block



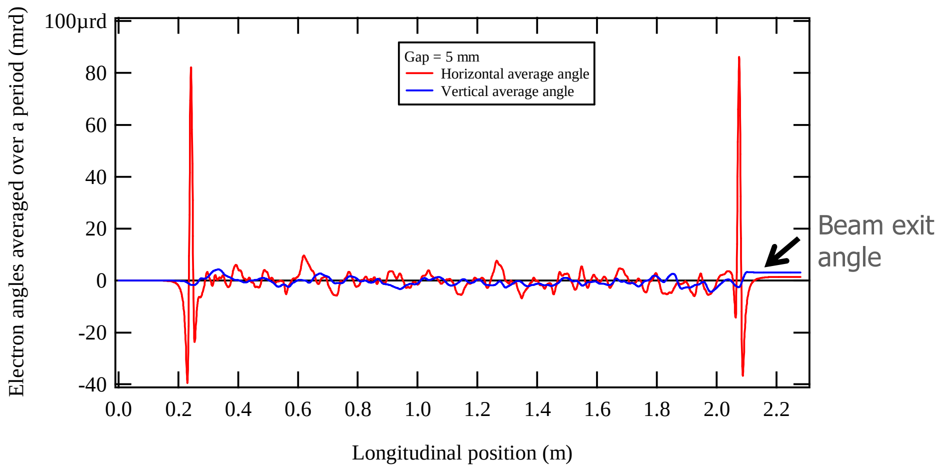


Why shimming

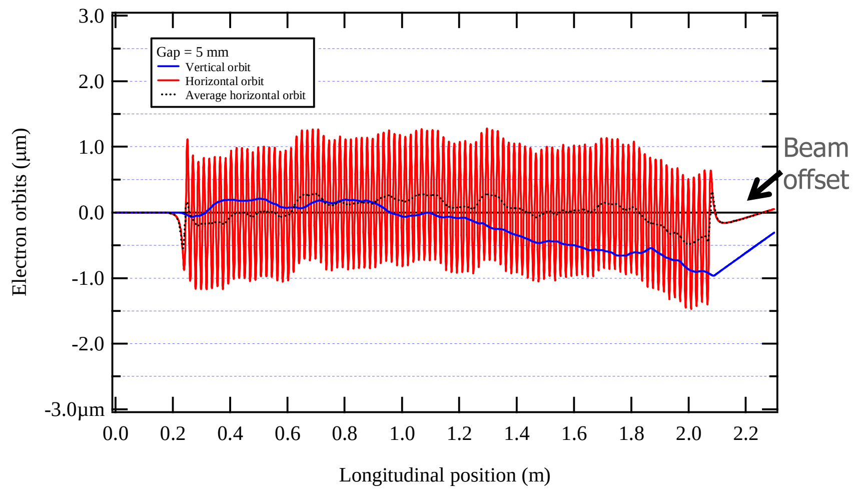
Measured B(x) sinusoidal field along the an undulator



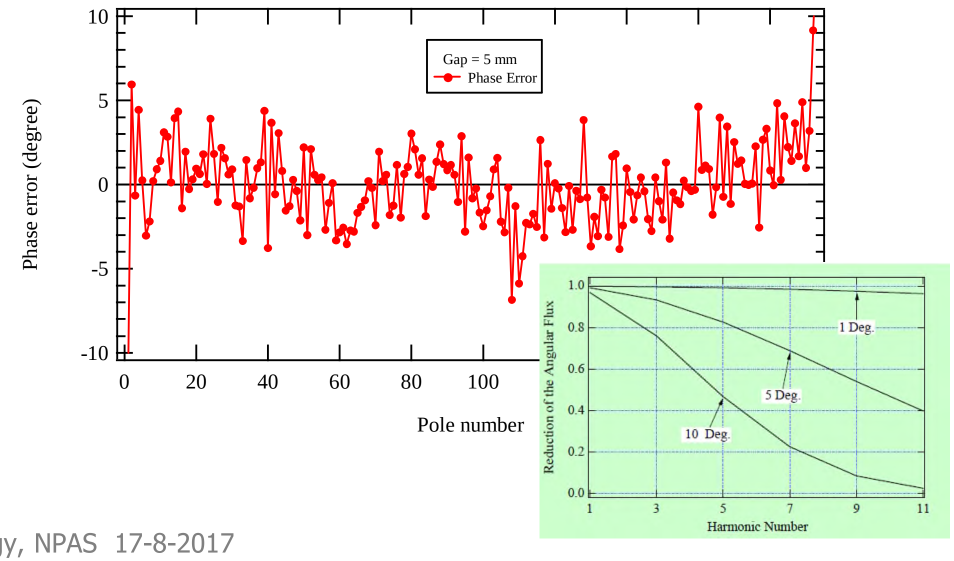
Resulting angular kick on the beam along the device



Beam trajectory calculated from measured field B(z)



Phase error along the undulator - RMS value has to be low



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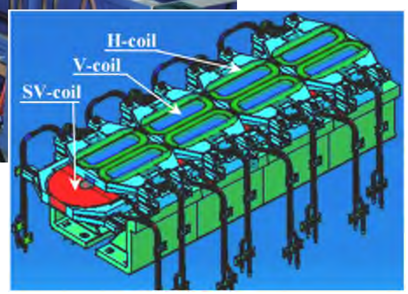
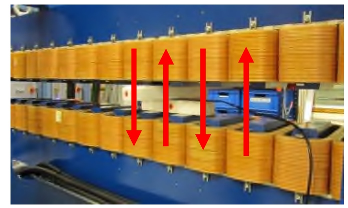
Electromagnetic wiggler examples

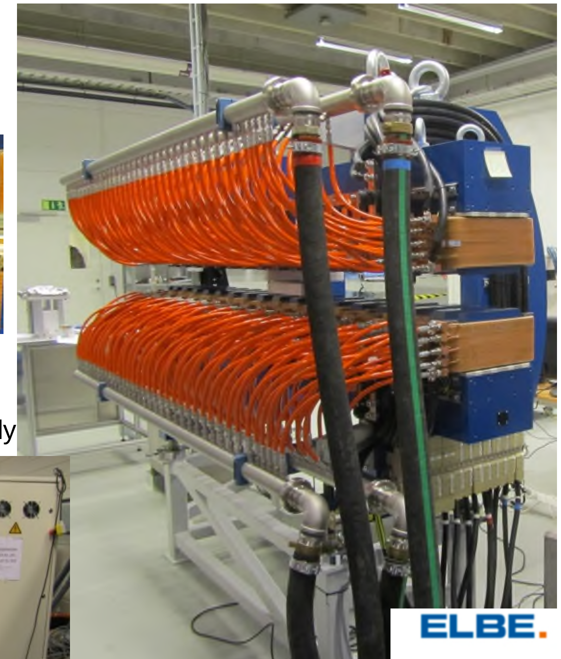
3 sets of coils



Magnetic field orientations



Large 4 cabinet power supply



HELMHOLTZ
ZENTRUM DRESDEN
ROSSENDORF

Low energy 5-40 eV

Variable polarization, 3 coil sets

Fast 1Hz polarization switching

Period length 640 mm

Device length 10 m

Peak field 0.11 T

FEL application

period length 300 mm

Fixed gap 102 mm

Peak field 0.4 T

Water cooled coils

High power consumption: up to 133 kW

High field wiggler example

Classic high field wiggler

- For EXAFS, XAS and Small Angle X-ray Scattering
- Hybrid type
- Peak field 2.0 T
- Period length 230 mm
- Minimum gap 16 mm
- Large glued magnet blocks
- Maximum force of 22 ton
- Produced by Danfysik for SSRL

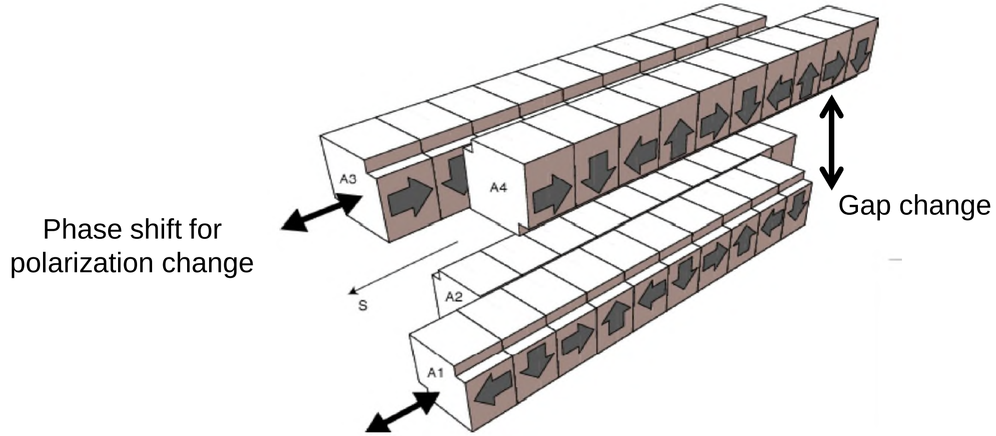
Apple-II undulator

Apple-II

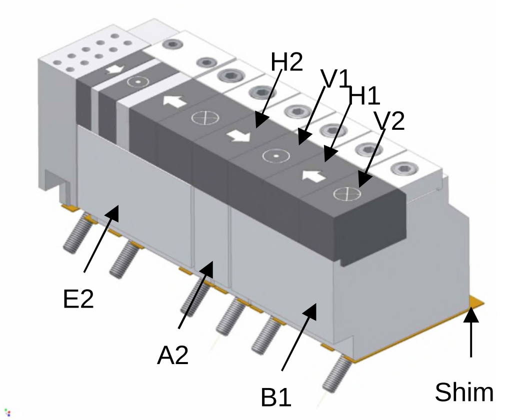
- Variable polarization: circular-elliptical-linear
- Complicated force variation with phase and gap – design mistakes have happened

Main parameters for the shown device:

- Period length 75 mm
- Minimum gap 16 mm
- Peak field 0.7 T

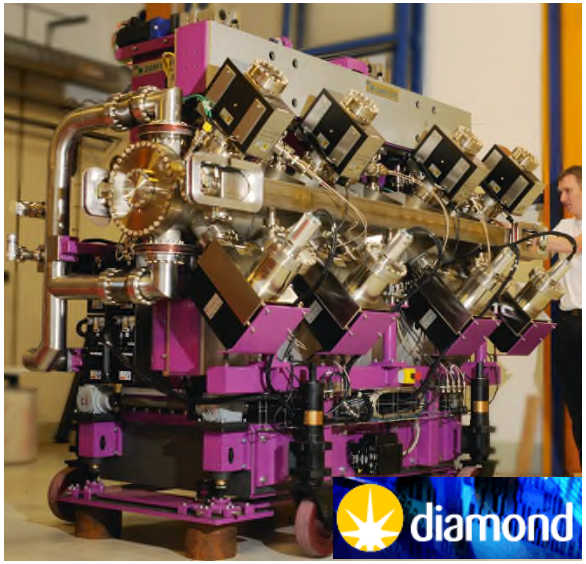


Magnetic keeper modules

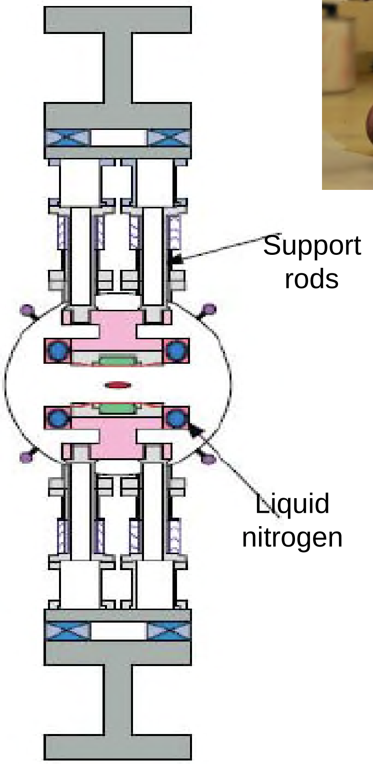


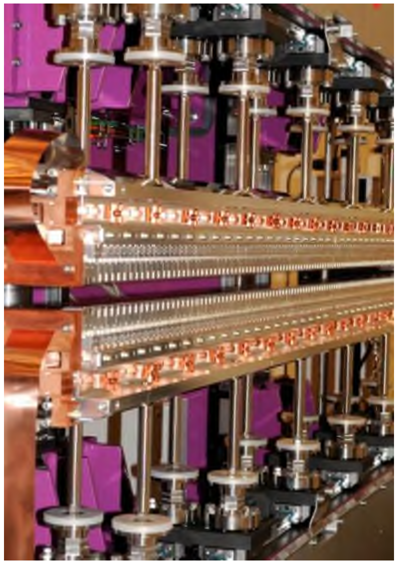
Cryogen in-vacuum undulator

- Hybrid design with NdFeB magnets
- Undulator period 17.7 mm
- Operating temperature 150 K
- Gap range 4 to 30 mm
- Peak field of 1.03 T
- Test system needed for 150 K
- Recent development: PrFeB magnets

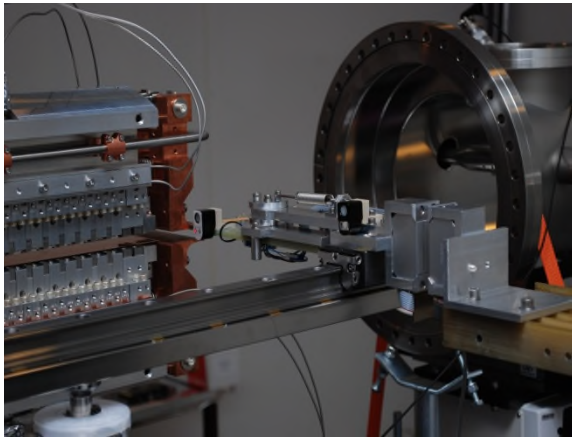


Concept





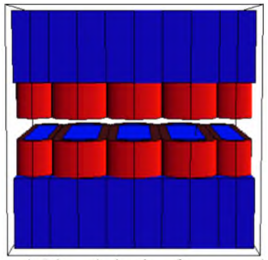
Test system for cryogen in-vacuum measurements



Superconducting insertion devices

SC wigglers with a relative high pole tip field are made using compact superconducting coils

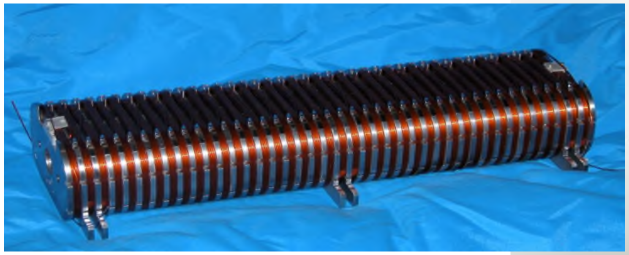
Model of center part



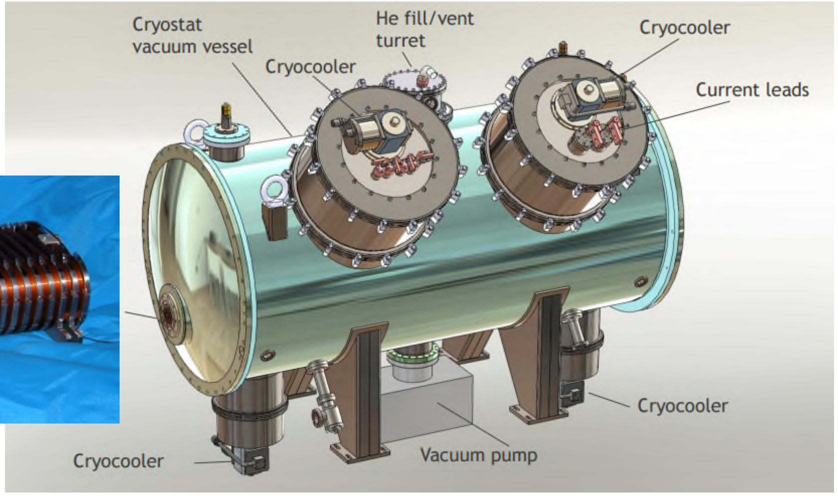
Old MAX-Lab wiggler with 3.5T peak field at 4K

SC undulators have stringent phase requirements. This technology is under development with promising resent advances

Early 42 pole APS test coil



APS cryostat concept



Future developments

- The innovative 7-bend MAX-lab concept have become the new synchrotron design standard which will probably result in an upgrade of many of the existing 2-bend synchrotron facilities
- Compact precision magnets with small magnet apertures will be required for these synchrotron upgrades
- Permanent accelerator magnets are attractive for fixed field synchrotron applications such as the permanent dipole magnets for the ESRF upgrade
- Superconducting magnets will continue towards higher field for very high energy accelerators like LHC. Widespread use will probably require good affordable SC HTS wire at 80K
- Cryogen insertion devices will probably become mainstream and continue to develop. Superconductive undulator technology continue to develop and will probably ensure continual progress