Permanent magnets

Gaël LE BEC

CAS course on Normal- and Superconcting magnets
St Pölten, Austria, 1st December 2023

Outline

1. Introduction
2. Basics
3. Permanent magnet materials
4. Accelerator magnet applications

Introduction

A brief history

- Magnetic stones known since Antiquity
- Compass known in China since 1000 years
- Horseshoe magnet invented in the 18th Century
- AlNiCo developed in Japan in the 1930s
- Ferrite magnets produced in the 1950s
- Rare-earth magnets used since the 1970s (SmCo) and 1980s (NdFeB)

INTRODUCTION

Consumer goods and electronics
Loudspeakers, computers, etc.

Automotive
Motors

Med.

Industry
Motors

Energy
Wind turbine generators

Aero. & Def.

Permanent magnets market (2021)

- USD 21 billions
- 195 000 tons of rare-earth PMs produced in China (95% NdFeB)
- The accelerator market is small and exotic for PM suppliers
  - Biggest order at the ESRF: 6 tons for all the accelerator dipoles
- 60 % of rare-earth material extracted from China
  - The second producer is US
- Cobalt, which is not a rare-earth, is a critical material
- PM recycling being developed by start-ups

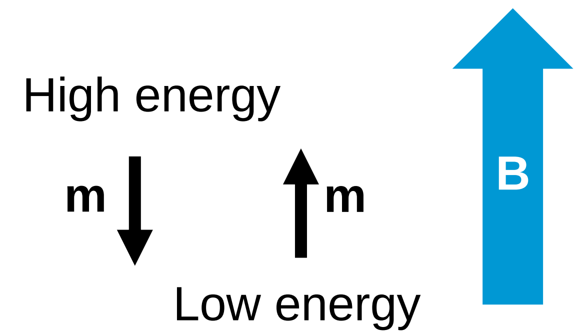
Basics

What is a magnetic moment?

- Some objects have a magnetic moment
- This moment aligns to external magnetic fields

$$\mathbf{T} = \mathbf{m} \times \mathbf{B}$$

Torque — Magnetic moment — External field



- Potential energy

$$U = -\mathbf{m} \cdot \mathbf{B}$$

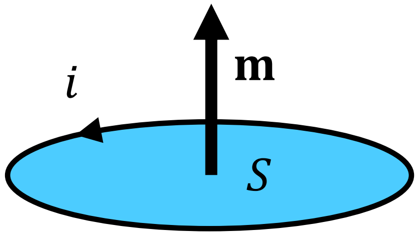
- Force

$$\mathbf{F} = (\mathbf{m} \cdot \nabla)\mathbf{B}$$

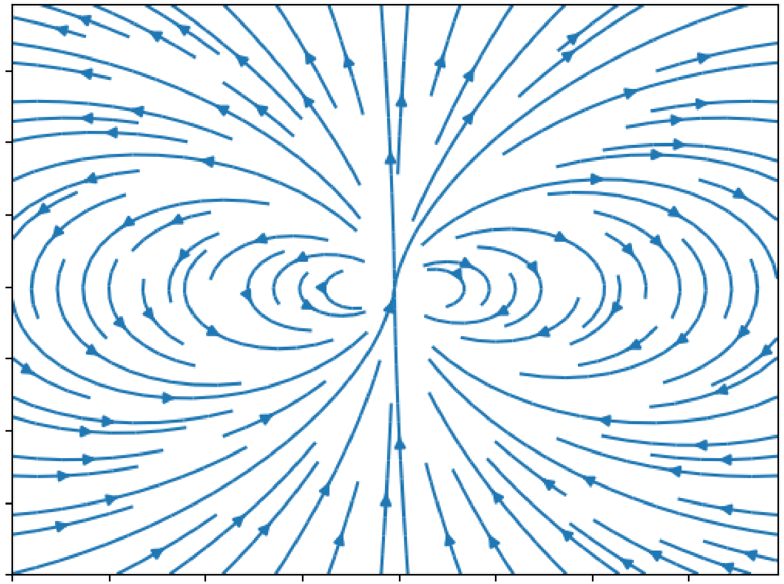
Equivalence with currents

- Magnetic moment of a plannar current loop

$$\mathbf{m} = i\,\mathbf{S}$$



- Magnetic moments can be modeled with current loops



Equivalence with currents

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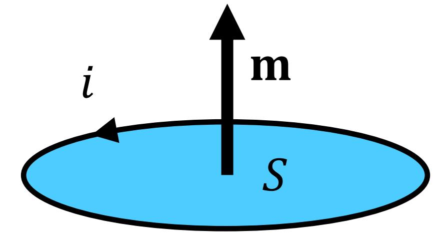

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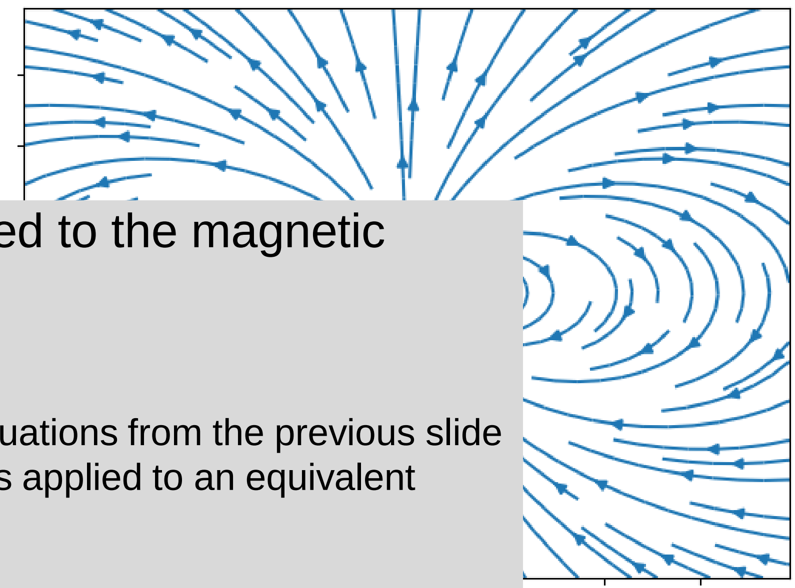
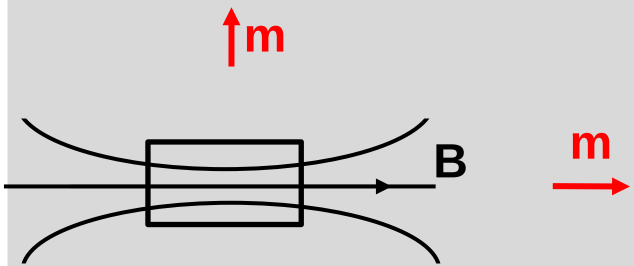


Exercise Draw the forces and torques applied to the magnetic moments in the following cases



(you can use equations from the previous slide or Lorentz forces applied to an equivalent current loop)

What is magnetization?

- The magnetization is the sum of magnetic moments over a volume

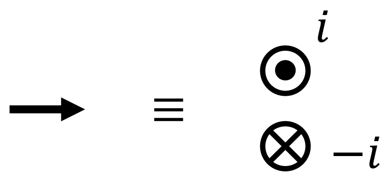
$$\mathbf{M} = \int \mathbf{m} dV$$

The magnetization of a material can be non-null if

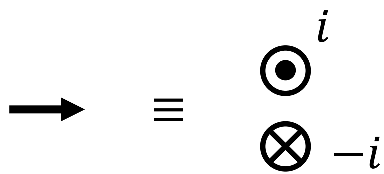
- **m** is non-null, which is the case for ferromagnetic materials
- The material is anisotropic, i.e. the moments are preferably oriented in one direction

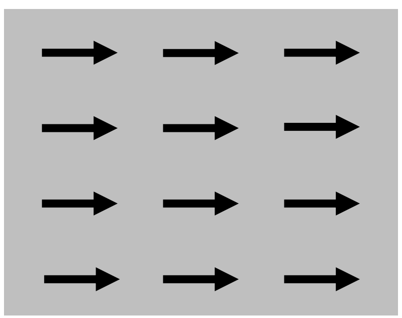
Note: these two conditions does not ensure a non-zero magnetization (e.g. non-magnetized permanent magnets)

Magnetic moments and equivalent currents



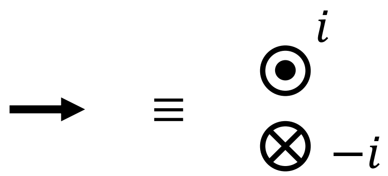
Magnetic moments and equivalent currents

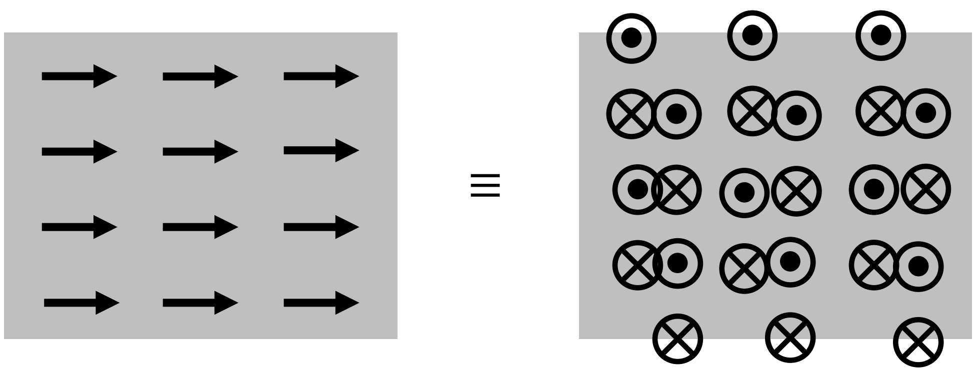




Magnetized material

Magnetic moments and equivalent currents

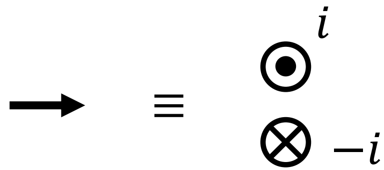


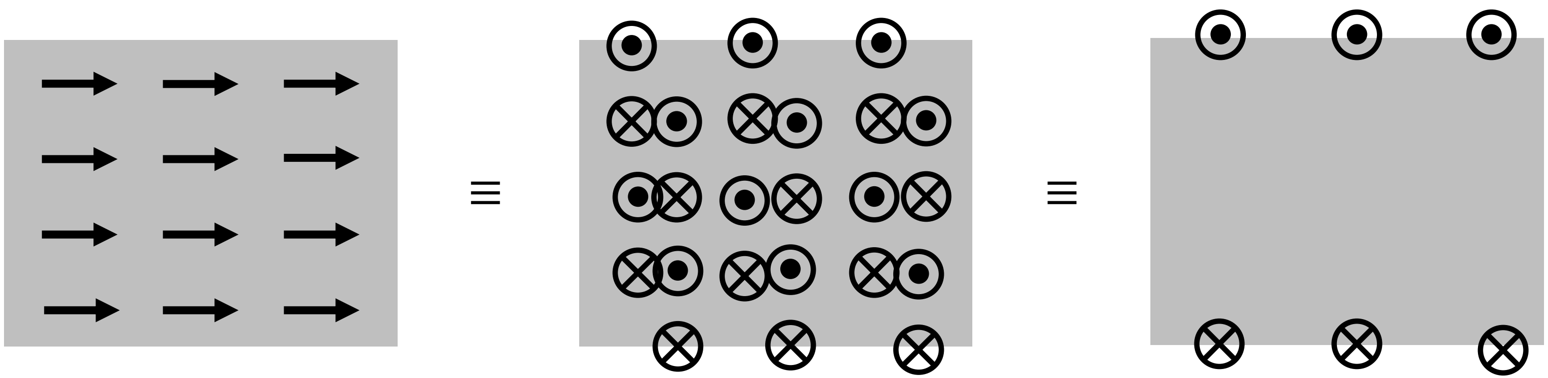


Magnetized material

Equivalent currents

Magnetic moments and equivalent currents





Magnetized material

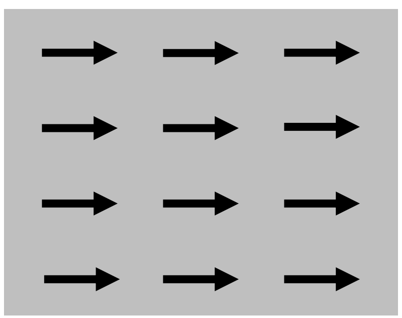
Equivalent currents

Surface currents

Amperian model of magnets

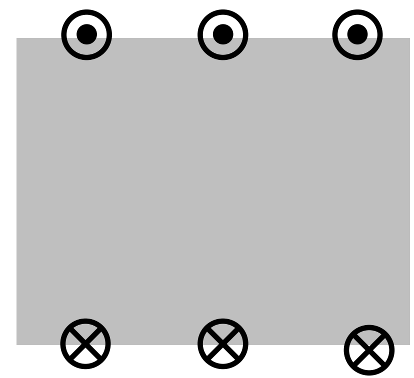
A material with homogeneous magnetization can be modeled by **surface currents**

$$\mathbf{J_S} = \mathbf{M} \times \mathbf{n}$$



Magnetized material

$\equiv$



Surface currents

Amperian model of magnets

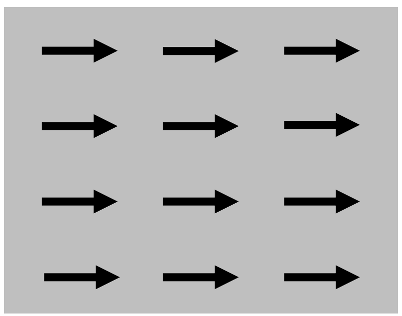
A material with homogeneous magnetization can be modeled by **surface currents**

$$\mathbf{J_S} = \mathbf{M} \times \mathbf{n}$$

Typical values

$$J_S = B_R/\mu_0$$

$$J_S \approx 7.96 \times 10^5 \mathrm{A/m} \text{ if } B_R = 1\ \mathrm{T}$$



Magnetized material

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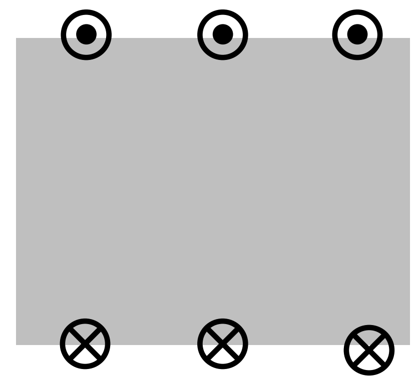


Surface currents

Magnetic field

- In the presence of magnetic material, the magnetic field is

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$$

T

A/m

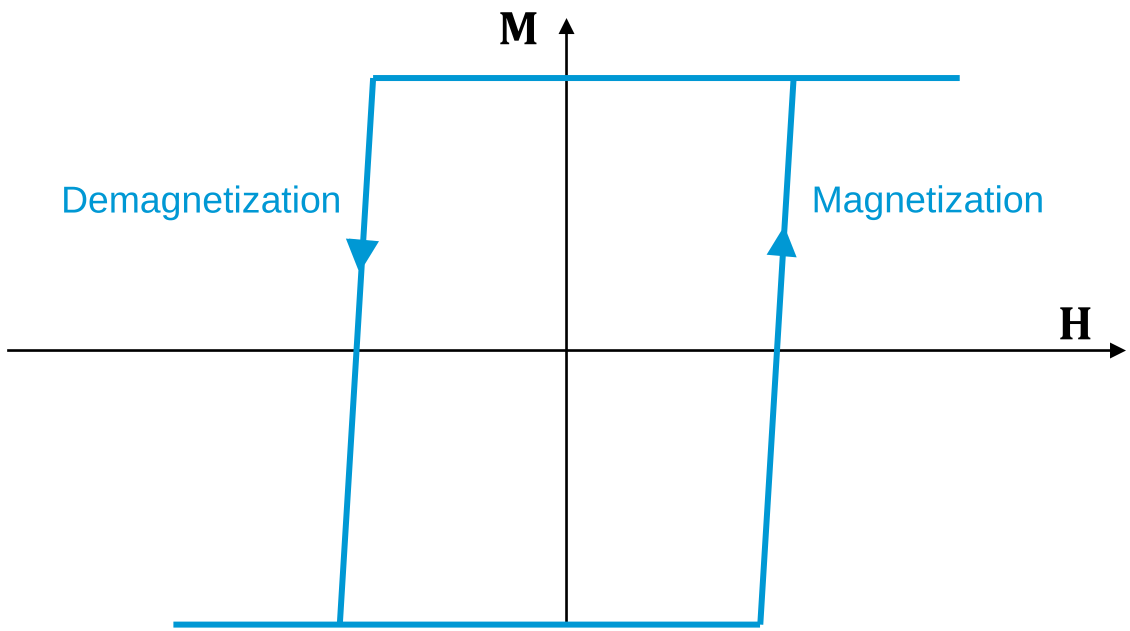
$4\pi \times 10^{-7}$ N/A^2

- The magnetization depends on the H-field

$$\mathbf{M} = \mathbf{M}(\mathbf{H})$$

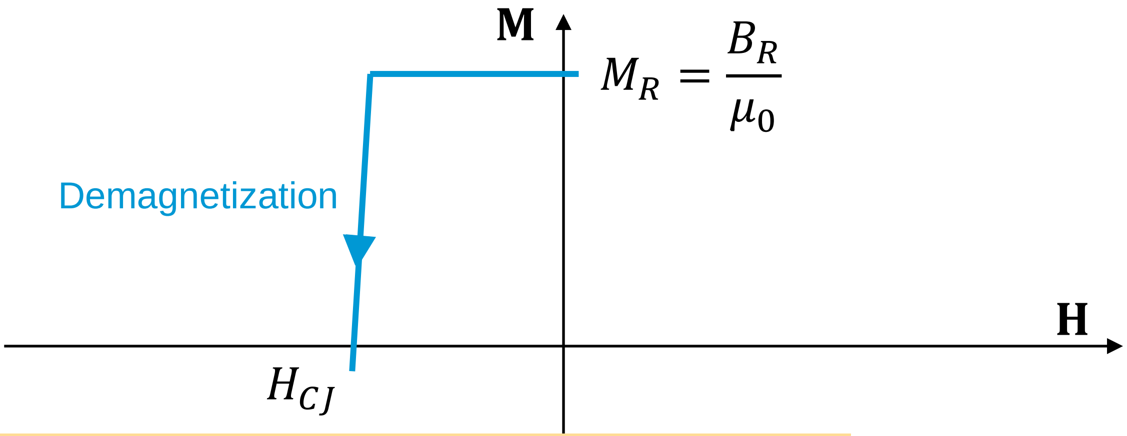
- In permanent magnets, this is the so-called demagnetization curve

Hysteresis in permanent magnet materials



M(H)

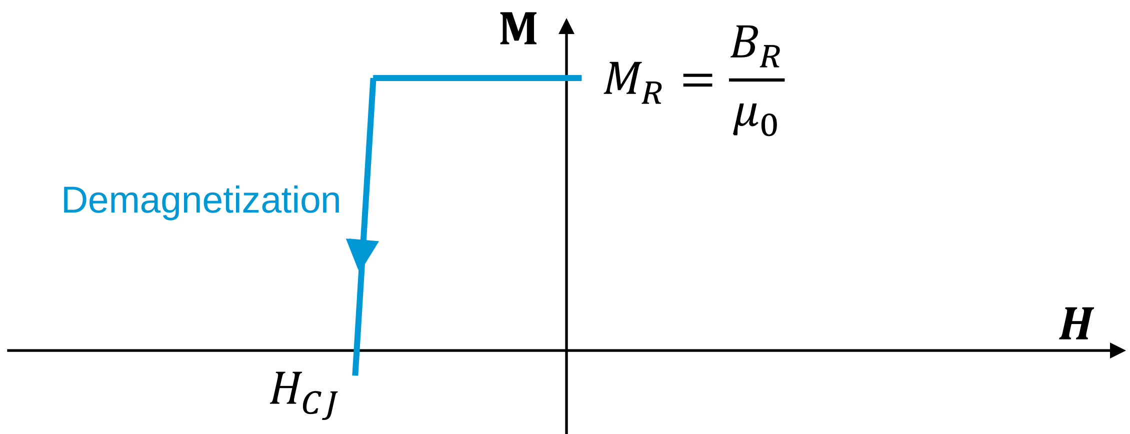
Hysteresis in permanent magnet materials



Demagnetization curve

Remanent field B_R (or remanent magnetization M_R)
Intrinsic coercitive field H_{CJ}

Hysteresis in permanent magnet materials



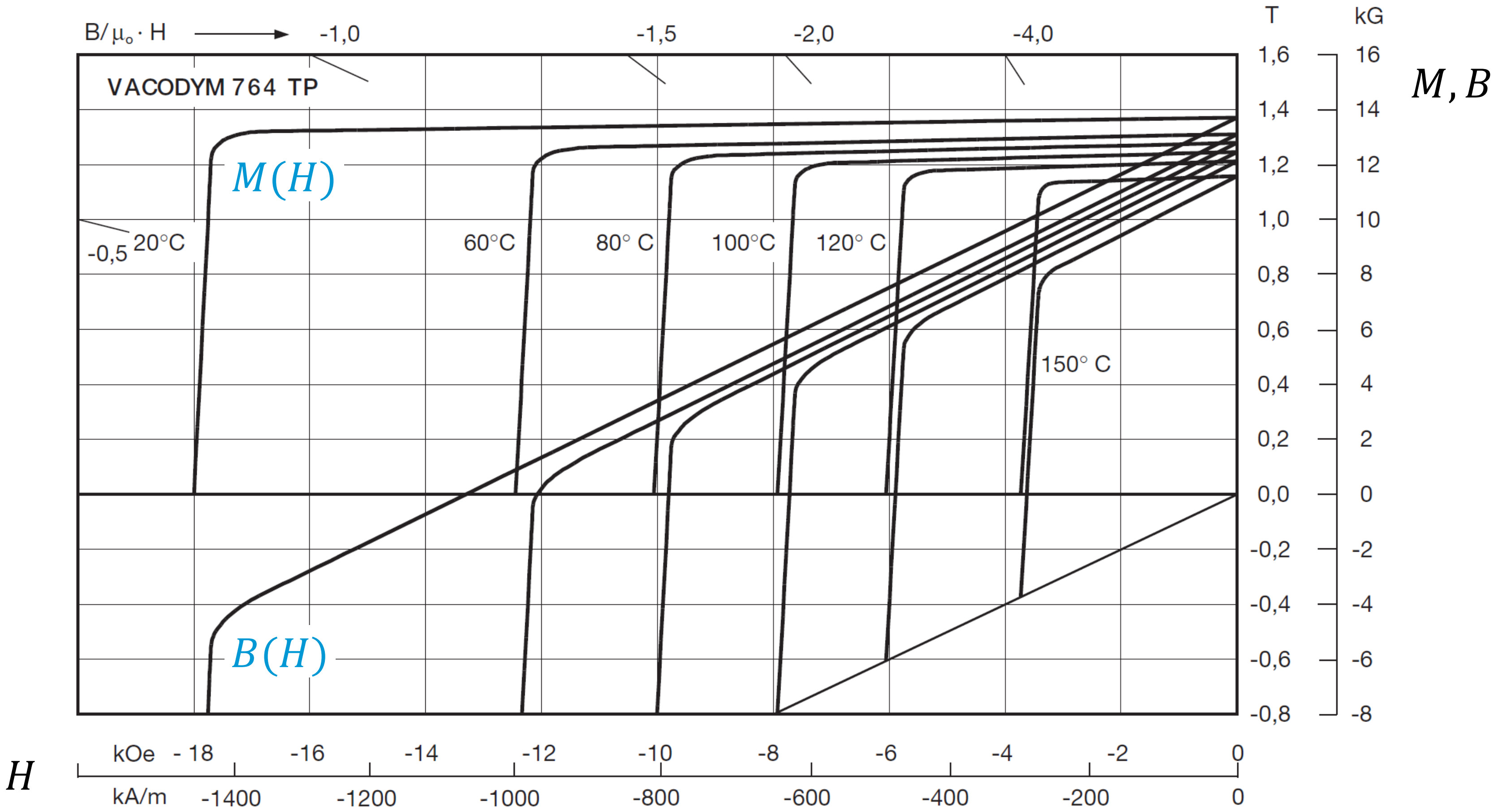
Demagnetization curve

Remanent field B_R (or remanent magnetization M_R)
Intrinsic coercitive field H

High B_R ➔ High magnetization

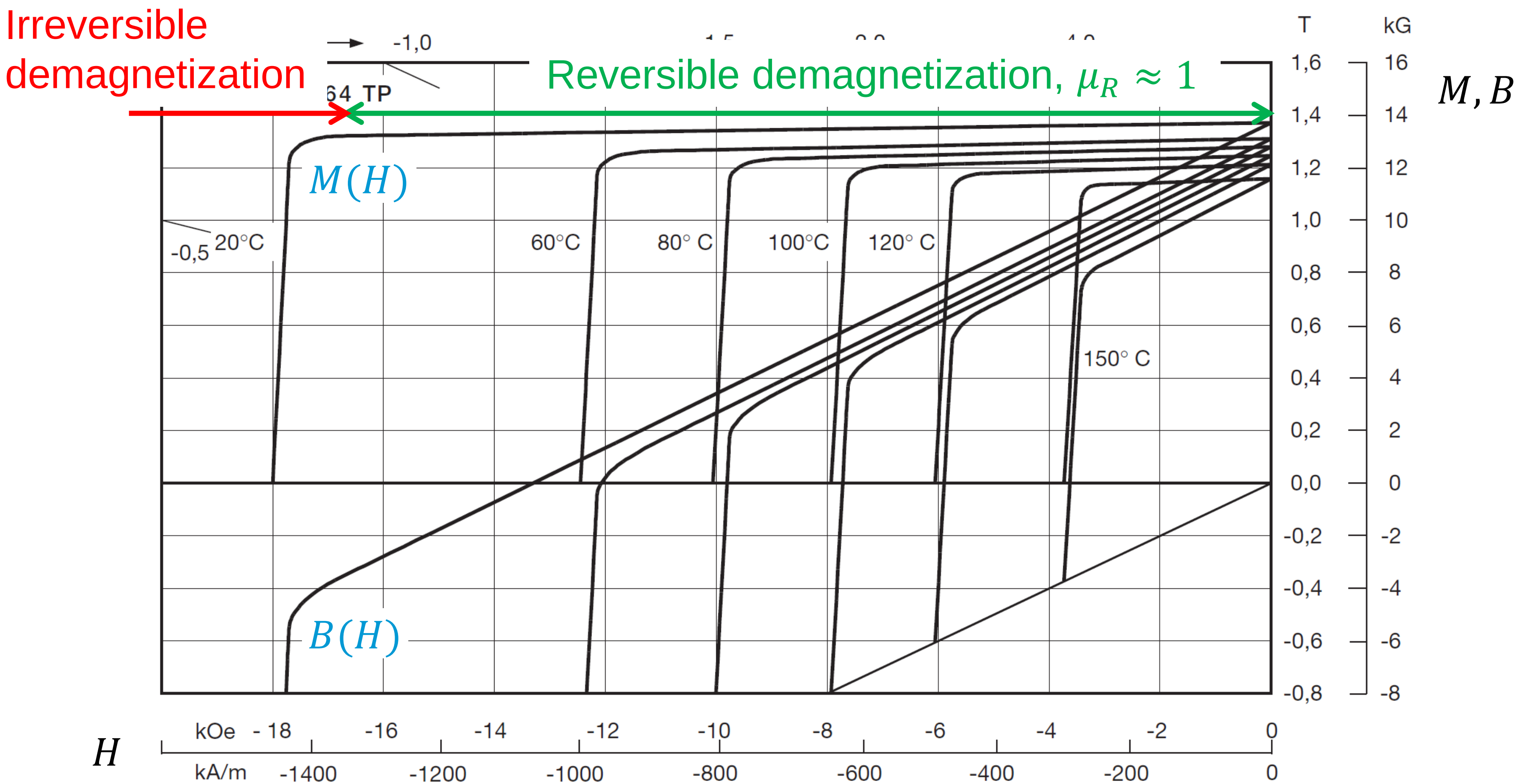
High coercitive field ➔ High resistance to demagnetization

DEMAGNETIZATION CURVE



Source: Vacuumschmelze Vacodym-Vacomax Rare Earth permanent magnets

DEMAGNETIZATION CURVE



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Magnetic H field in a PM material

$$\mathbf{H} = \frac{\mathbf{B}}{\mu_0} - \mathbf{M}$$

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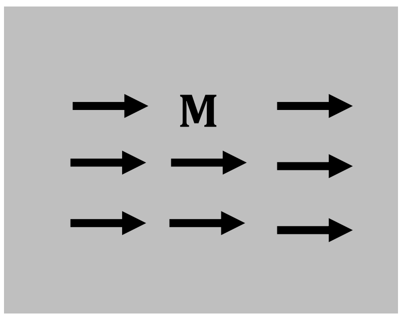

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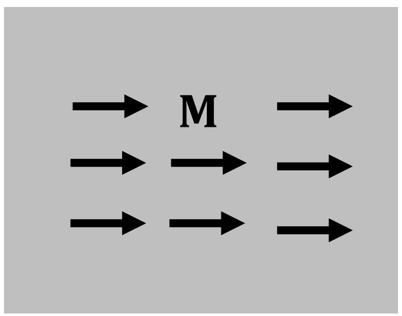
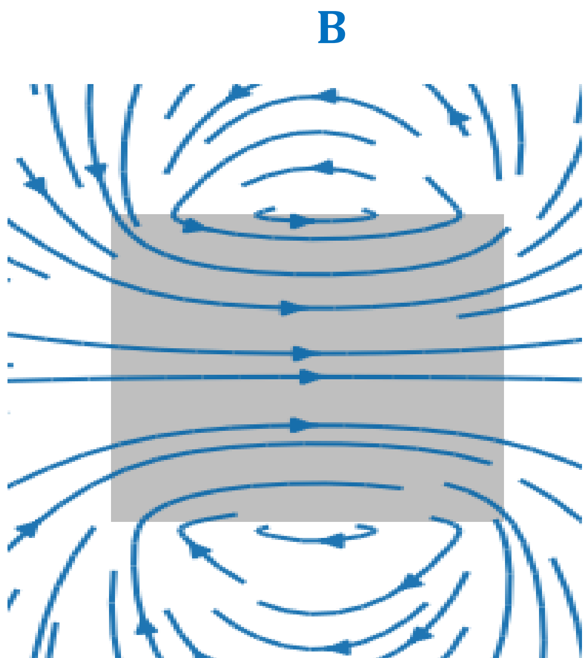
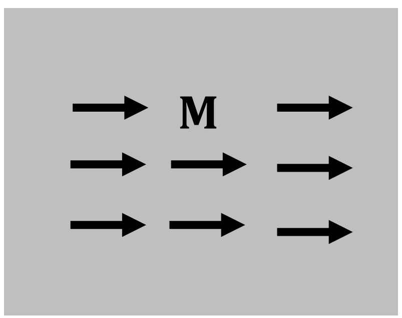




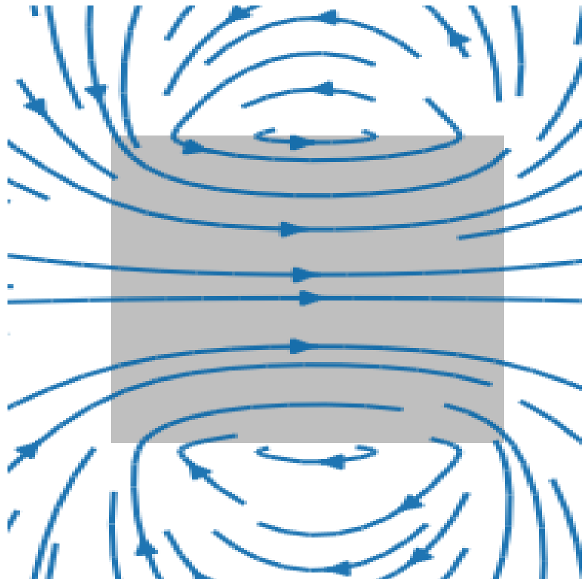
DEMAGNETIZING FIELD

Magnetic H field in a PM material

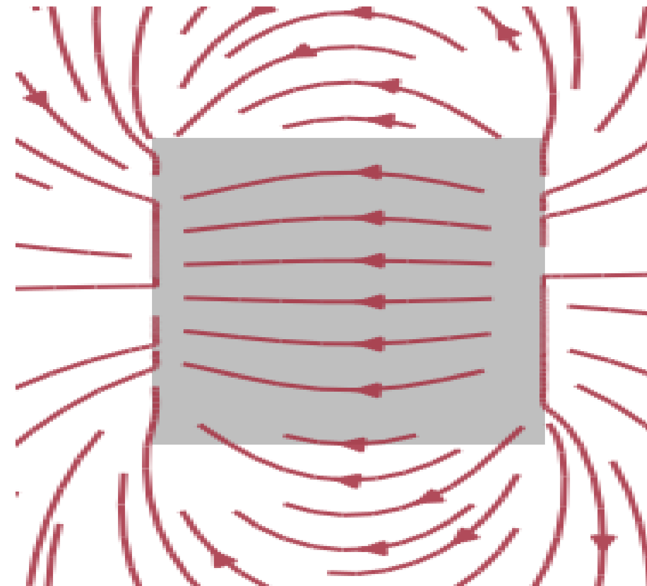
$$\mathbf{H} = \frac{\mathbf{B}}{\mu_0} - \mathbf{M}$$



B



H



Magnetic H field in a PM material

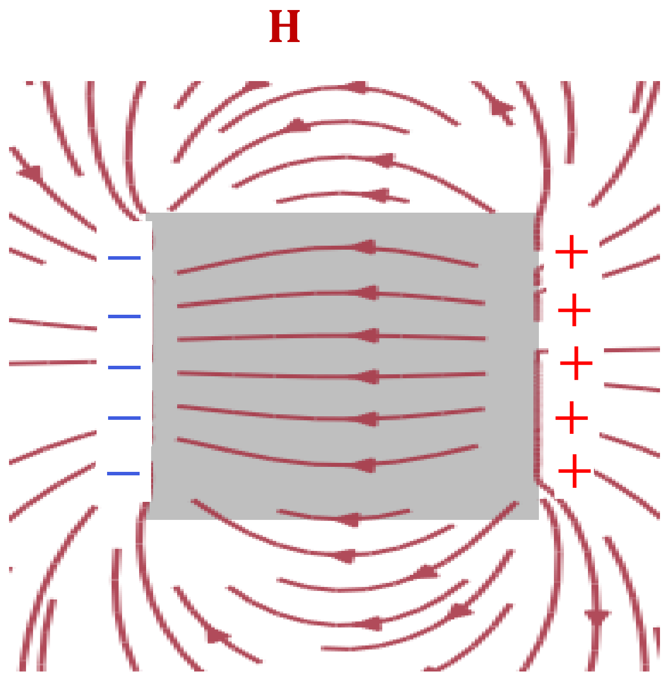
$$\mathbf{H} = \frac{\mathbf{B}}{\mu_0} - \mathbf{M}$$

The H field verifies

$$\mathbf{H} = -\nabla U$$

Same equation as an electric field!

This can be modelled by equivalent **magnetic charges**

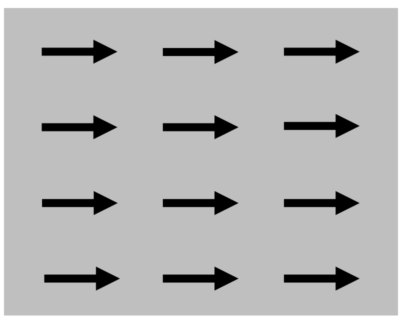


Coulombian model of magnets

An material with homogeneous magnetization can be modeled by equivalent **surface magnetic charges**

$$\sigma_S = \mathbf{M} \cdot \mathbf{n}$$

Note: this model gives **H**, not **B**



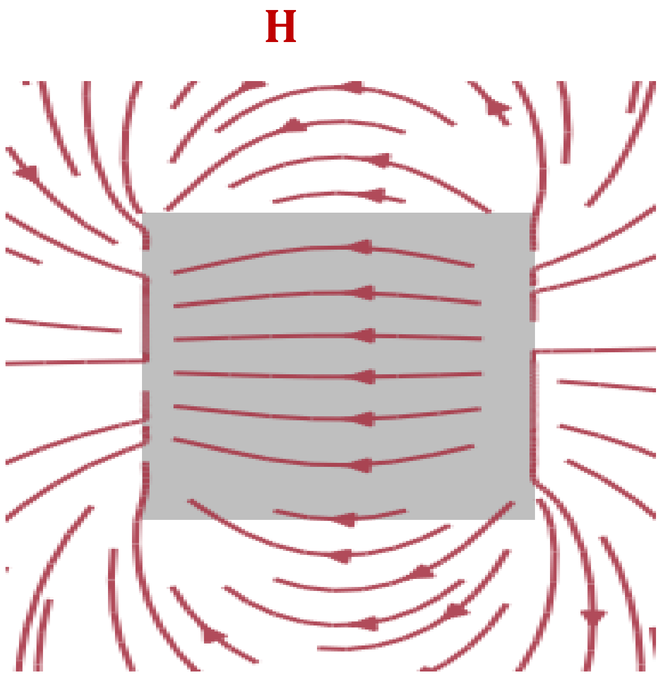
Magnetized material

$\equiv$

Equivalent surface magnetic charges

Inside the magnet

- Magnetization and H-field have opposite direction
- This reduces the magnetization (see the demagnetization curve *M(H)*)



H is called the demagnetizing field

- Its strength depends on the shape
- It is higher for thin magnets
- It is homogeneous for elliptical shapes

Magnetic energy

$$E = \frac{1}{2} \int \mathbf{B} \cdot \mathbf{H} dV$$

➔ $\mathbf{B} \cdot \mathbf{H}$ is a density of energy

➔ $(BH)_{MAX}$ is a figure of merit for PM materials

ENERGY PRODUCT

Magnetic energy

$$E = \frac{1}{2}\int \mathbf{B}\cdot\mathbf{H}dV$$

➔ $\mathbf{B}\cdot\mathbf{H}$ is a density of energy

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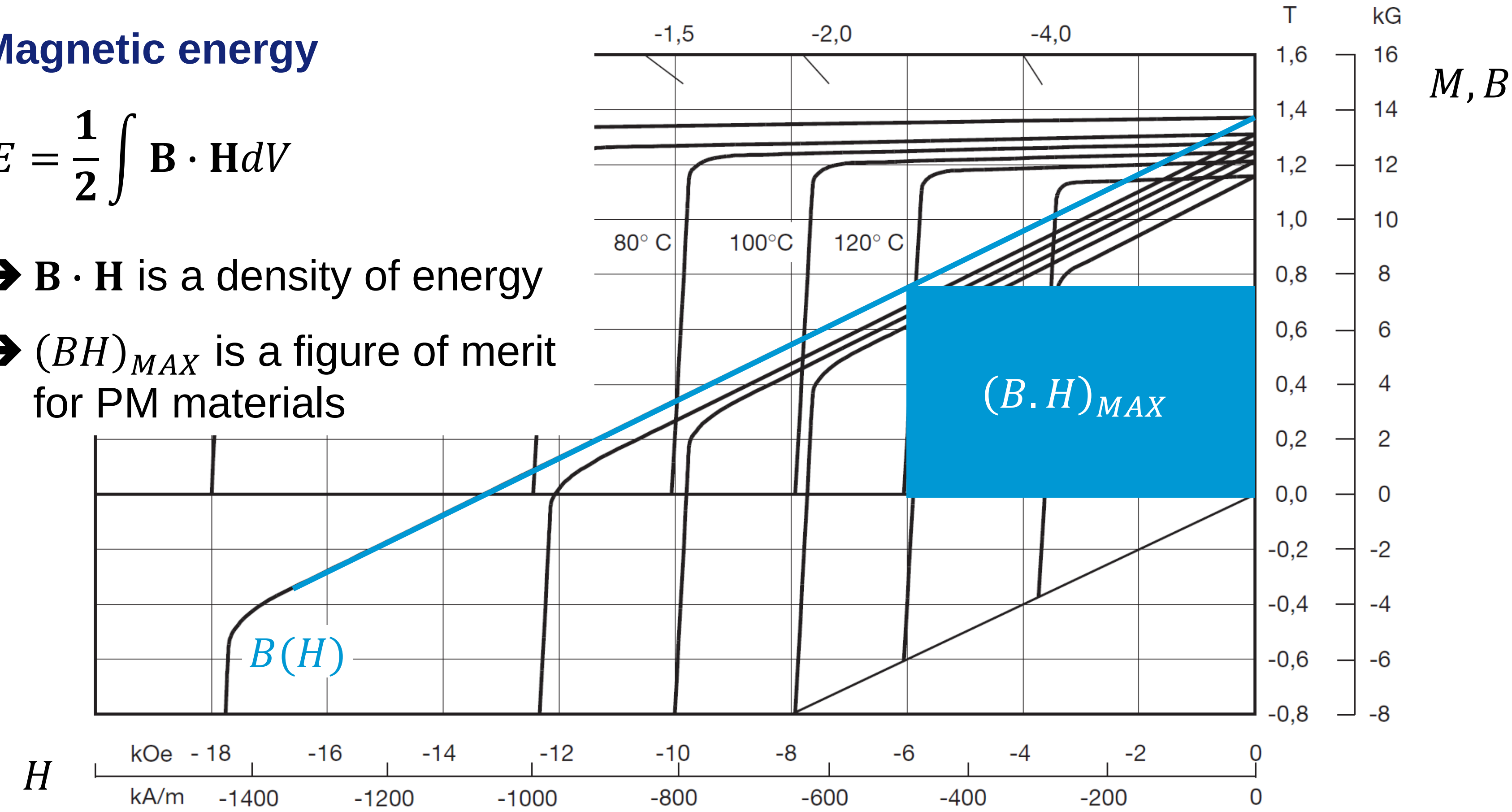
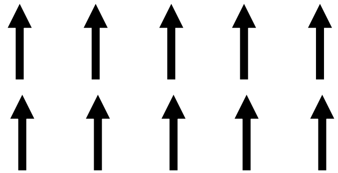


Source: Vacuumschmelze Vacodym-Vacomax Rare Earth permanent magnets

Ferromagnetism

- Magnetic moments from different atoms are parallels



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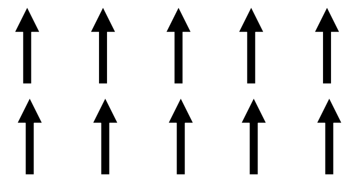
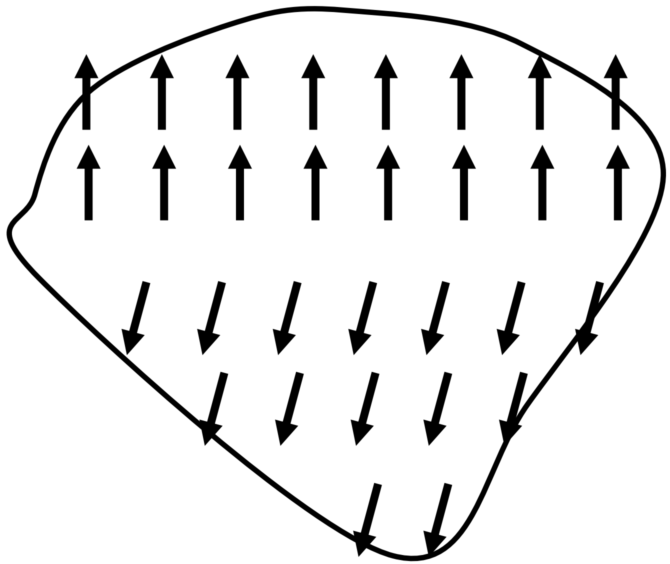


Weiss domains

- The magnetization is homogeneous on domains
- The magnetization axes are differents from domain to domain
- This reduces the magnetic energy



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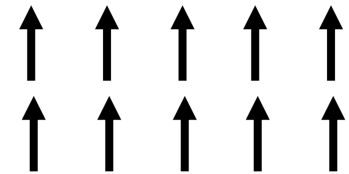

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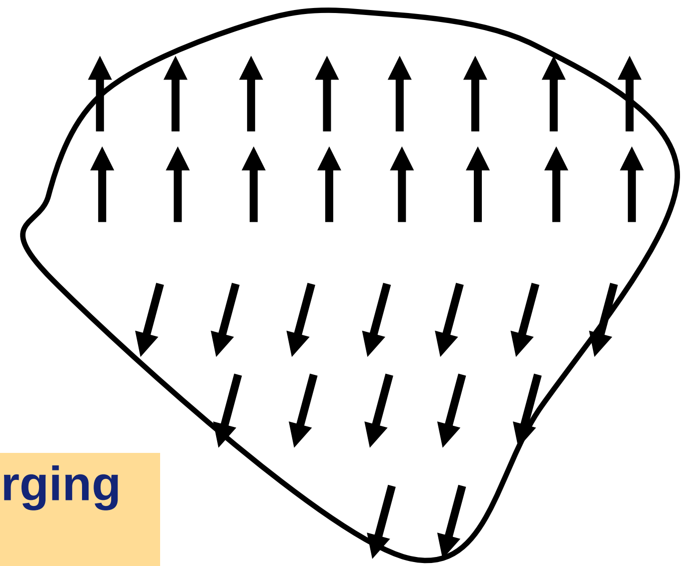
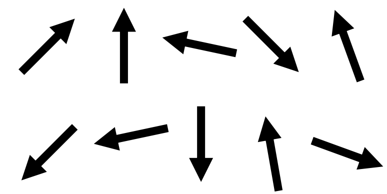


Magnetizing a material means merging the Weiss domains

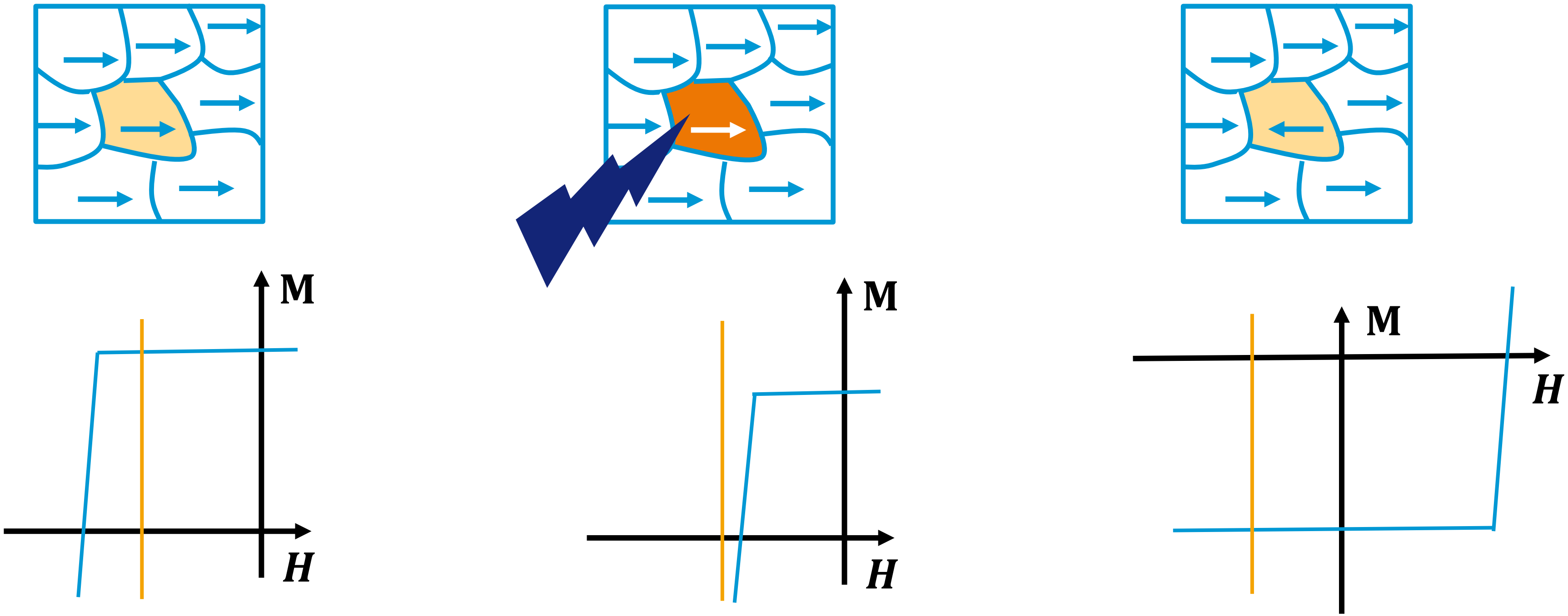
Effect of temperature

- The ferromagnetic order is affected by temperature
- It disappears above the Curie temperature
- This temperature depends on the material



Material	Curie temp. (°C)	${B_R}^{-1} dB_R/dT$ (% / °C)	${H_{cJ}}^{-1} dH_{cJ}/dT$ (% / °C)
NdFeB	310 – 370	– 0.1	– 0.6
Sm_2Co_{17}	800 – 850	– 0.03	– 0.2

RADIATION DAMAGE PROCESS



1 – Magnet polarized at a working point

2 – One grain heated by radiation
This decreases the coercitive field

3 – The grain magnetization is flipped

RADIATION DAMAGE PROCESS

Risk factors of radiation damage

Material properties

- Coercitive field H_{cJ} and its temperature dependence
- Thermal capacity and conductivity

Magnet working point

- Demagnetizing field in the magnet – flat magnets are willing to demagnetize

Radiation dose

RADIATION DAMAGE PROCESS

Risk factors of radiation damage

Material properties

- Coercitive field H_{cJ} and its temperature dependence
- Thermal capacity and conductivity

Magnet working point

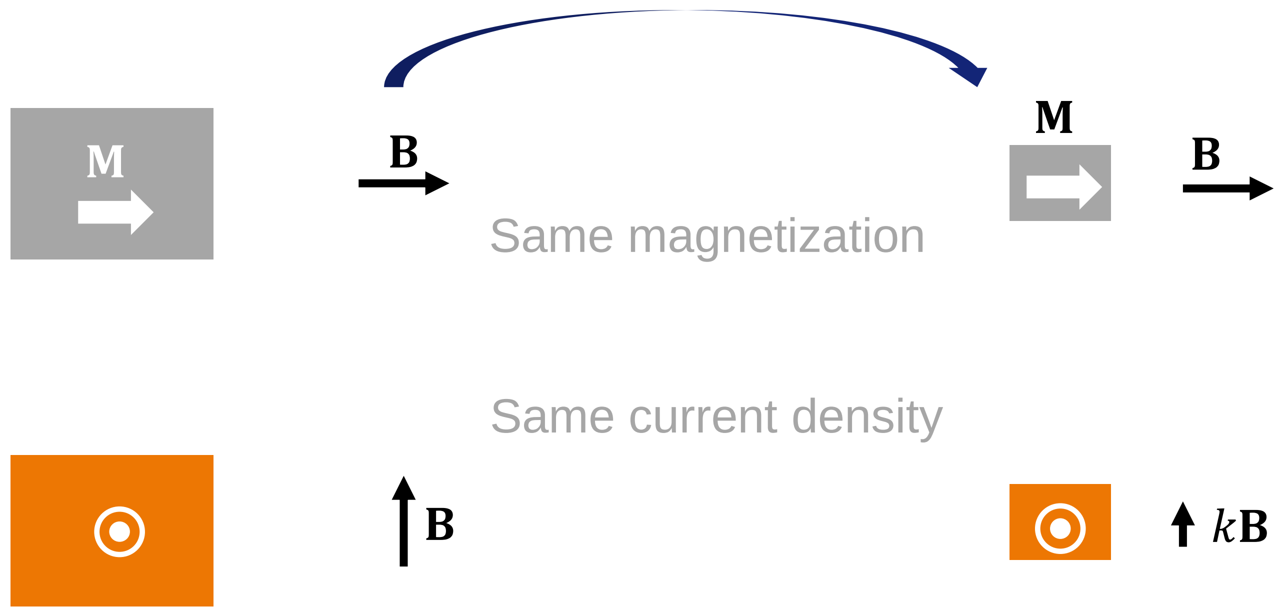
- Demagnetizing field in the magnet – flat magnets are willing to demagnetize

Radiation dose

Sm_2Co_{17} is known to be the most resistant material to radiation damage

SCALE FACTOR

All dimensions and positions divided by k



SCALE FACTOR

Scale factor k on a permanent magnet

- The field is kept constant
- The field gradient scales with $1/k$
- Suitable for multipoles, undulators, small bores magnets, etc

Scale factor k on a electromagnet

- The field scales with k
- The field gradient is kept constant
- More suitable for dipoles, large bores, etc.

BASICS – SUMMARY

Key concepts

- Magnetic moment and magnetization
- Amperian and Coulombian models
- Demagnetization curve $M(H)$, remanence, coercitivity
- Demagnetizing field
- Scale factor benefits to high gradients and small apertures

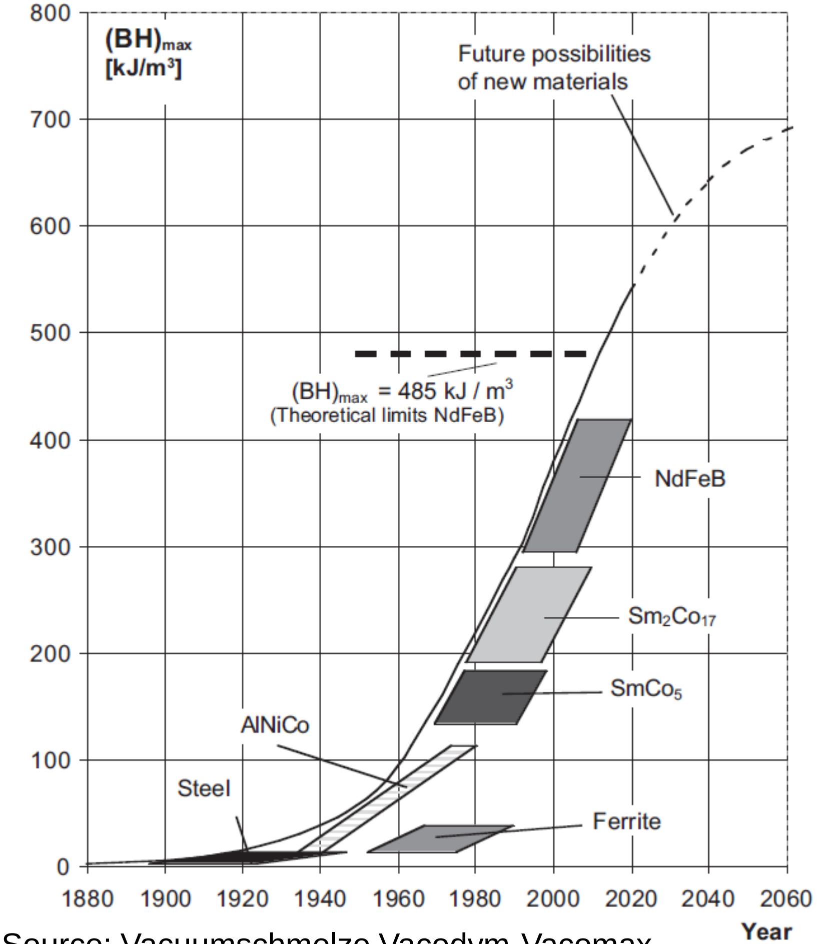
Permanent magnet materials

Materials for accelerator applications

Rare-earth magnets

- Neodymium-iron-boron ($Nd_2Fe_{14}B$)
- Samarium-cobalt ($SmCo_5$, Sm_2Co_{17})

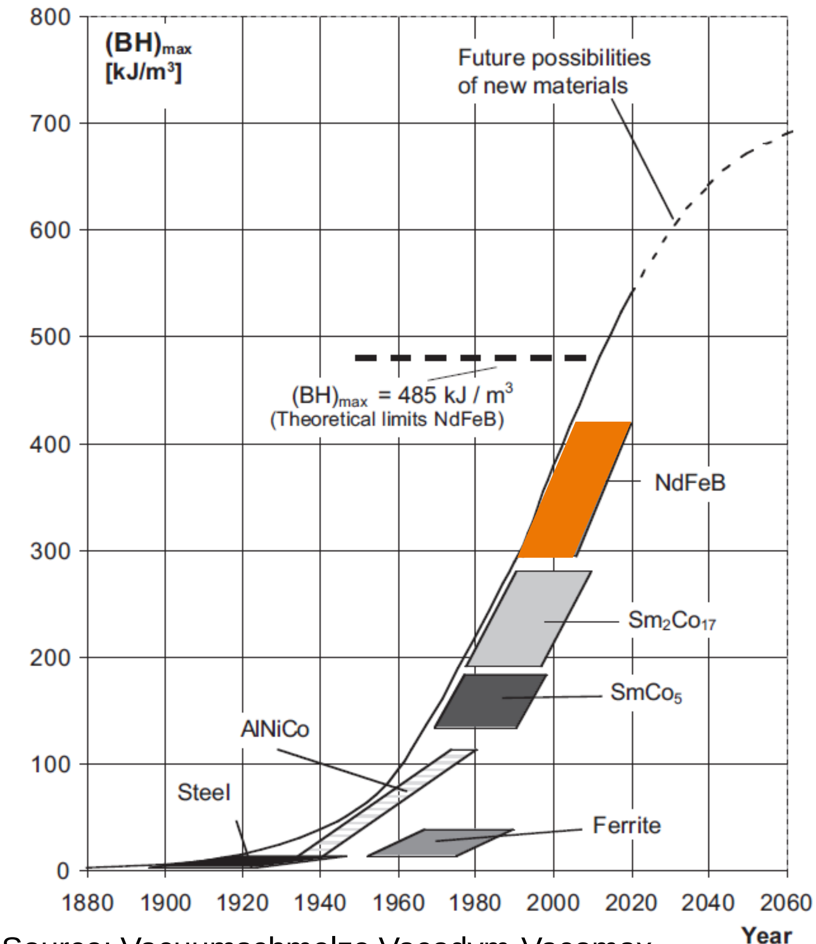
Ferrite magnets



Source: Vacuumschmelze Vacodym-Vacomax Rare Earth permanent magnets

Neodymium-iron-boron

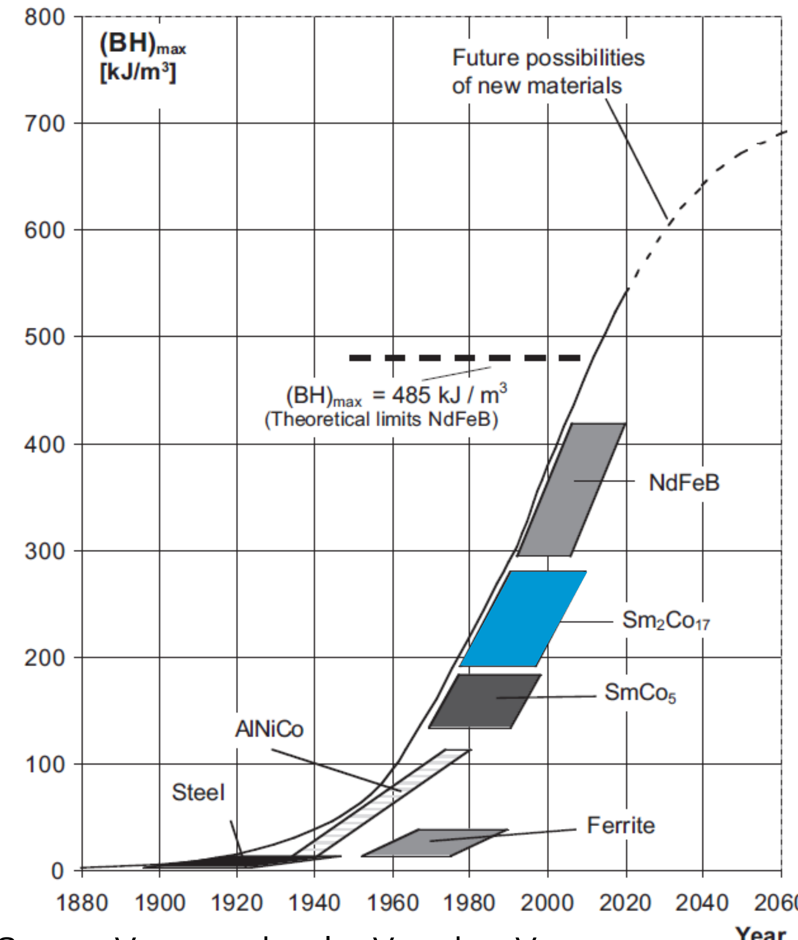
- Highest energy product
- High field applications
- $1.15 < B_R < 1.45$ T
- Applications: undulators, high gradient multipoles



Source: Vacuumschmelze Vacodym-Vacomax Rare Earth permanent magnets

Samarium-cobalt

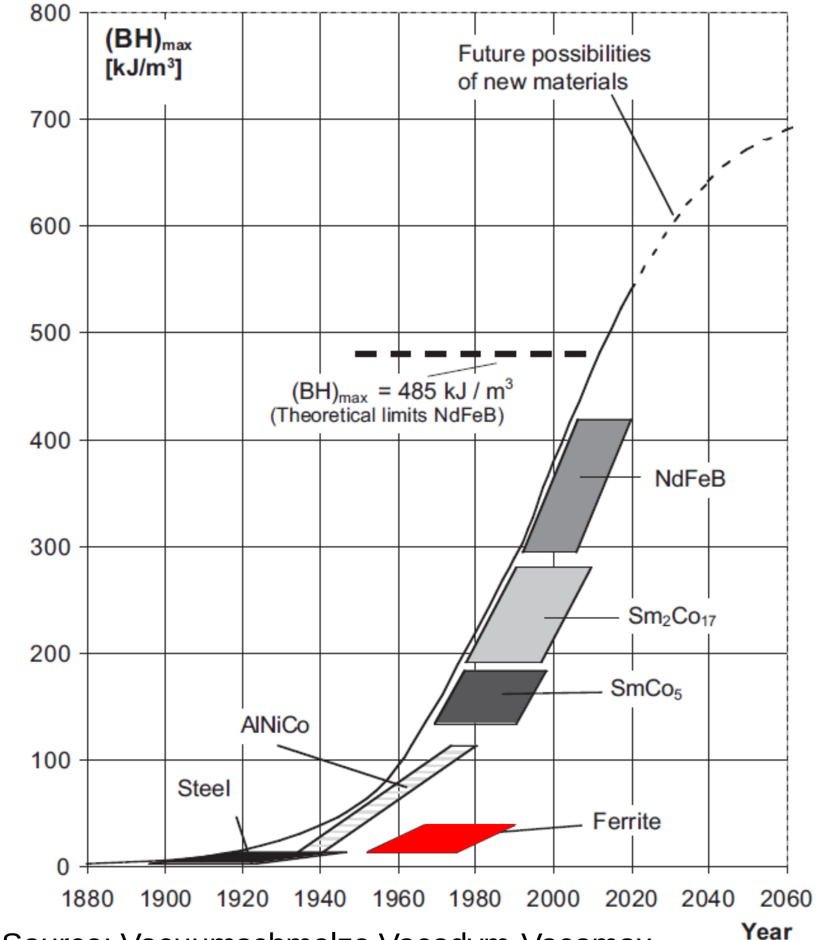
- Energy product is lower
- $1.05 < B_R < 1.15$ T
- More resistant to radiation damages
- 3 x lower temperature coefficient
- Applications: in-vacuum undulators, temperature-stabilized magnets (mainly Sm_2Co_{17})



Source: Vacuumschmelze Vacodym-Vacomax Rare Earth permanent magnets

Strontium ferrites

- Much lower energy product
- $0.2 < B_R < 0.42\ \mathrm{T}$
- Low cost magnets
- Applications: low field magnets (e.g. Fermilab recycler)

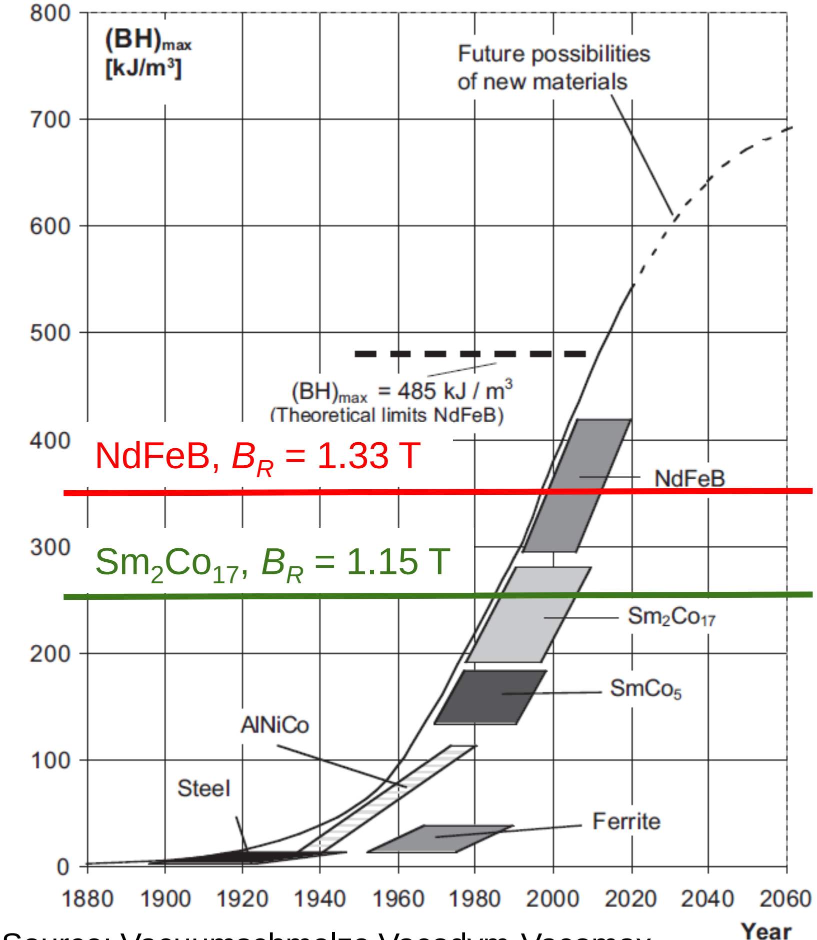


Source: Vacuumschmelze Vacodym-Vacomax Rare Earth permanent magnets

Materials for accelerator applications

Rare-earth magnets

- Neodymium-iron-boron ($Nd_2Fe_{14}B$)
- Samarium-cobalt ($SmCo_5$, Sm_2Co_{17})

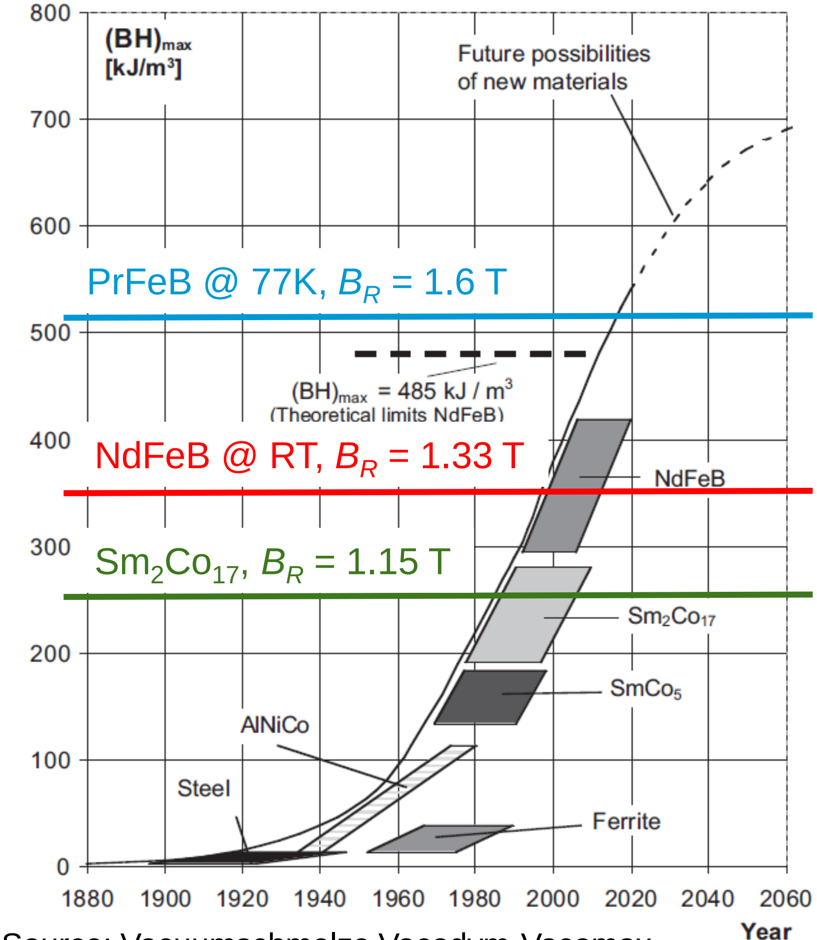


Source: Vacuumschmelze Vacodym-Vacomax Rare Earth permanent magnets

Materials for accelerator applications

Rare-earth magnets

- Neodymium-iron-boron ($Nd_2Fe_{14}B$)
- Samarium-cobalt ($SmCo_5$, Sm_2Co_{17})
- Cold permanent magnets



Source: Vacuumschmelze Vacodym-Vacomax Rare Earth permanent magnets

MANUFACTURING

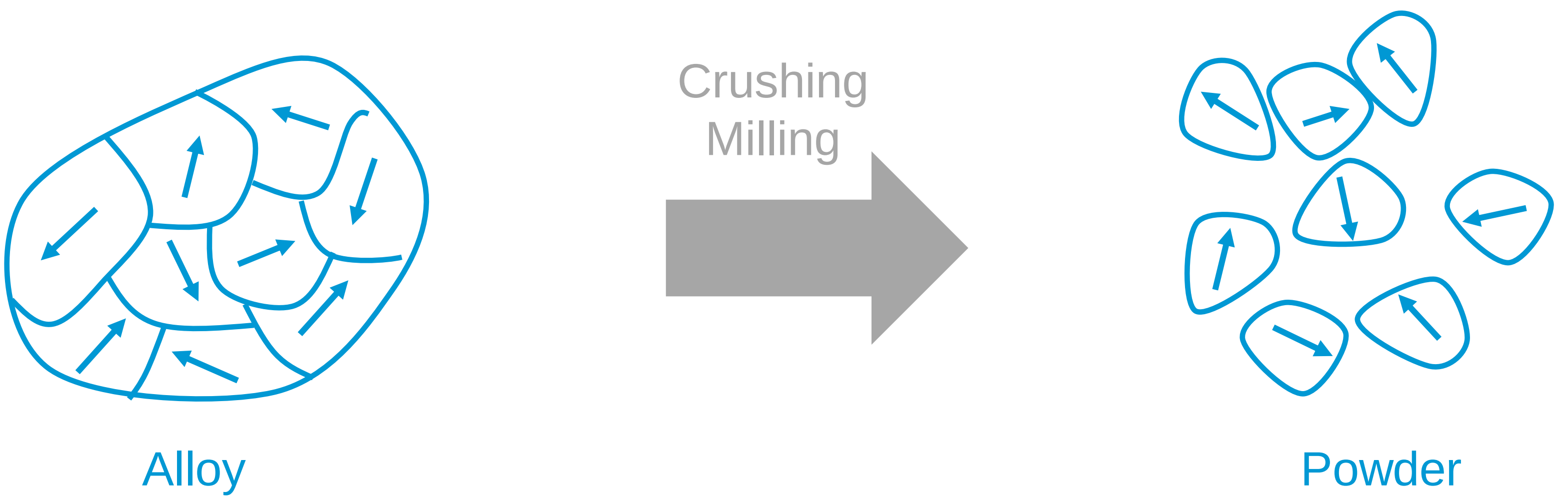
NdFeB and SmCo

- Sintered magnets, see next slides
- Build from powders of magnetic alloys

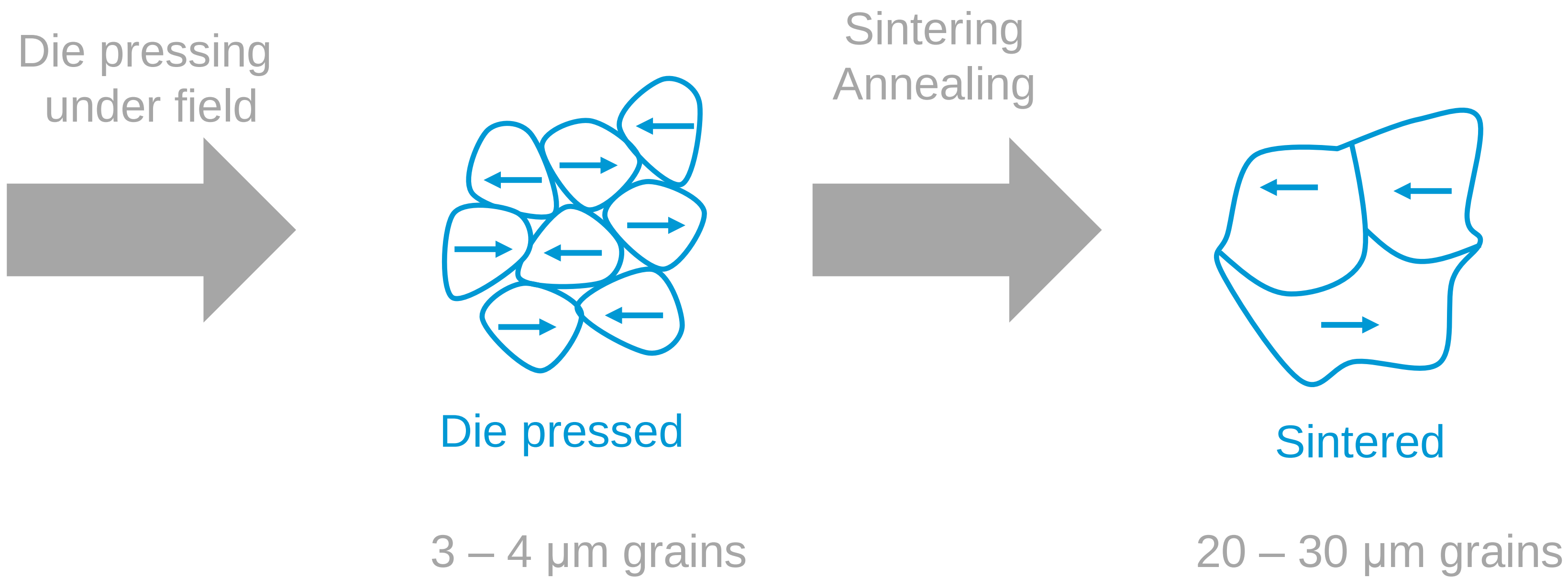
Ferrite

- Ferrite magnets are ceramics

MANUFACTURING OF SINTERED MAGNETS



MANUFACTURING OF SINTERED MAGNETS



MANUFACTURING OF SINTERED MAGNETS

Machining
Coating

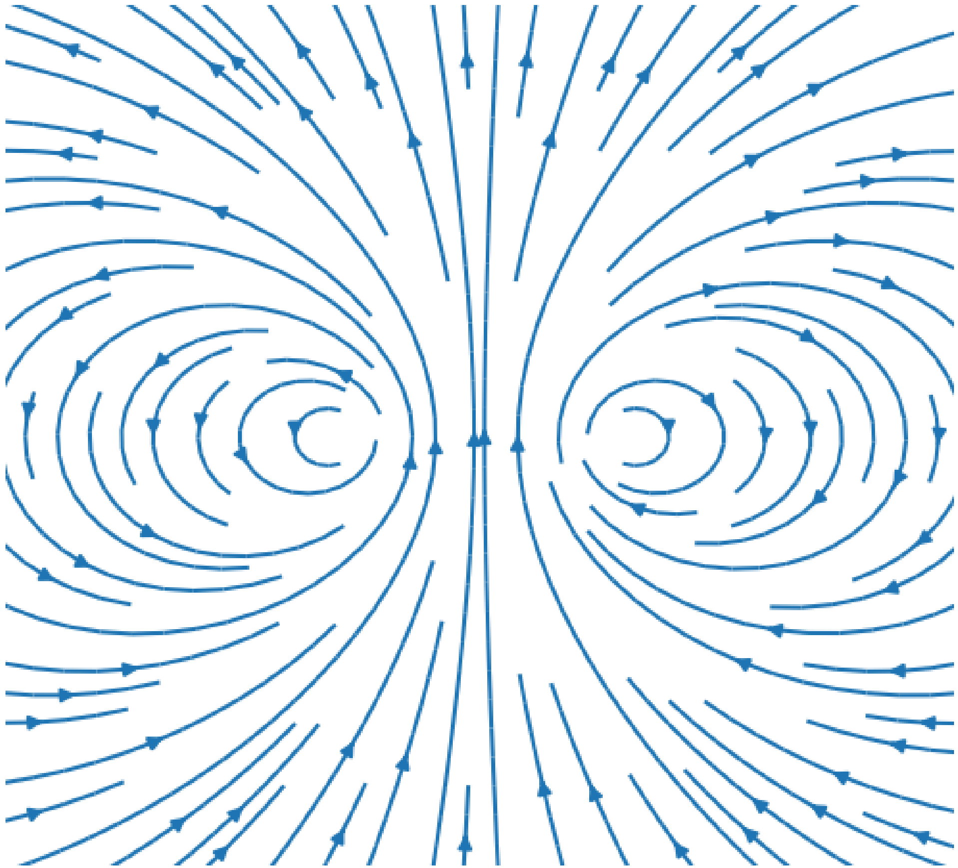
Magnetization

Final shape

Permanent magnet

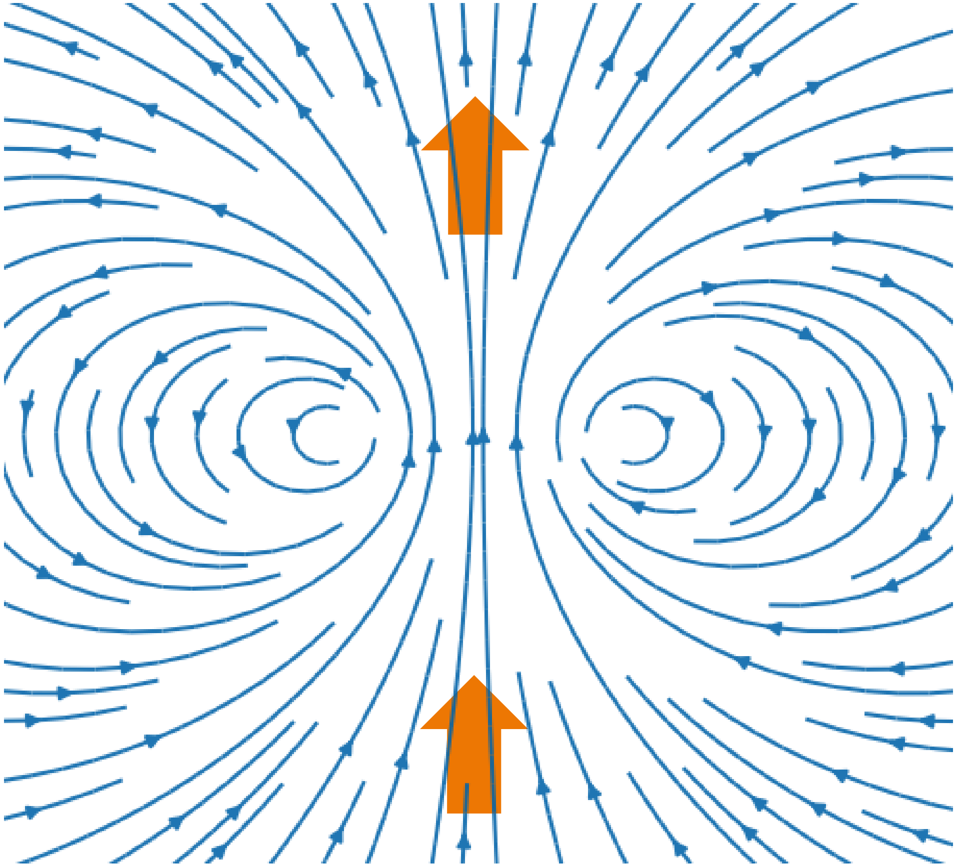
Magnet designs

Let us build a dipole magnet



Let us build a dipole magnet

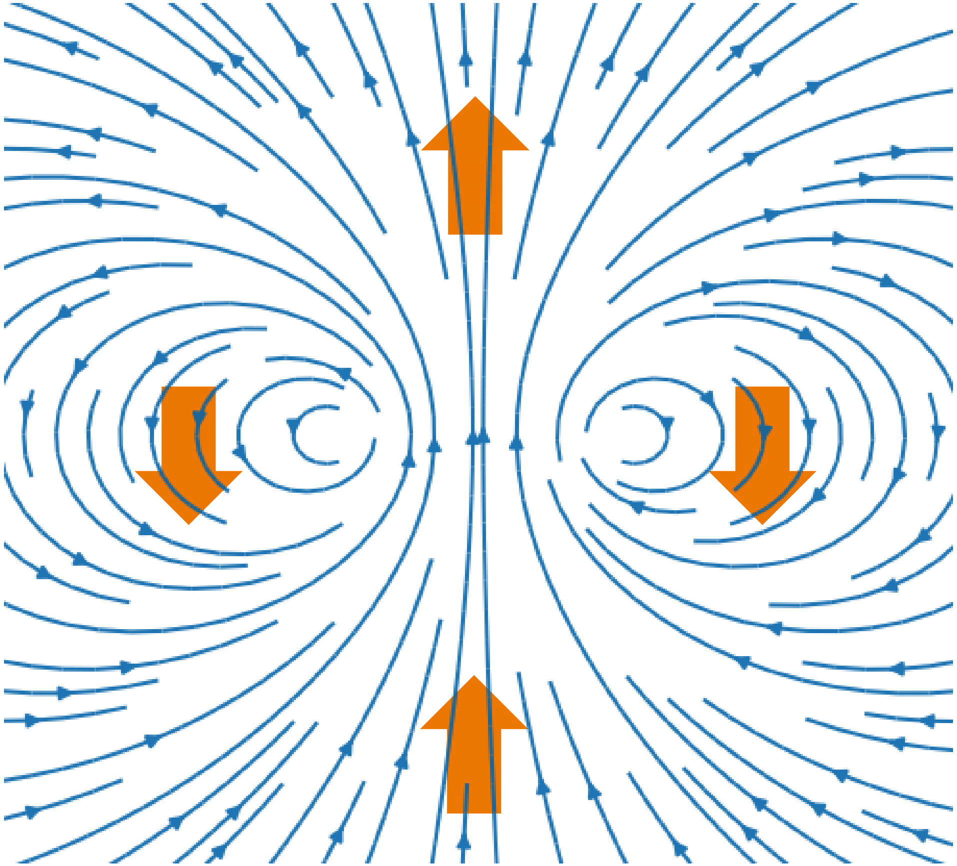
- Place magnets above and below



PERMANENT MAGNET DESIGNS

Let us build a dipole magnet

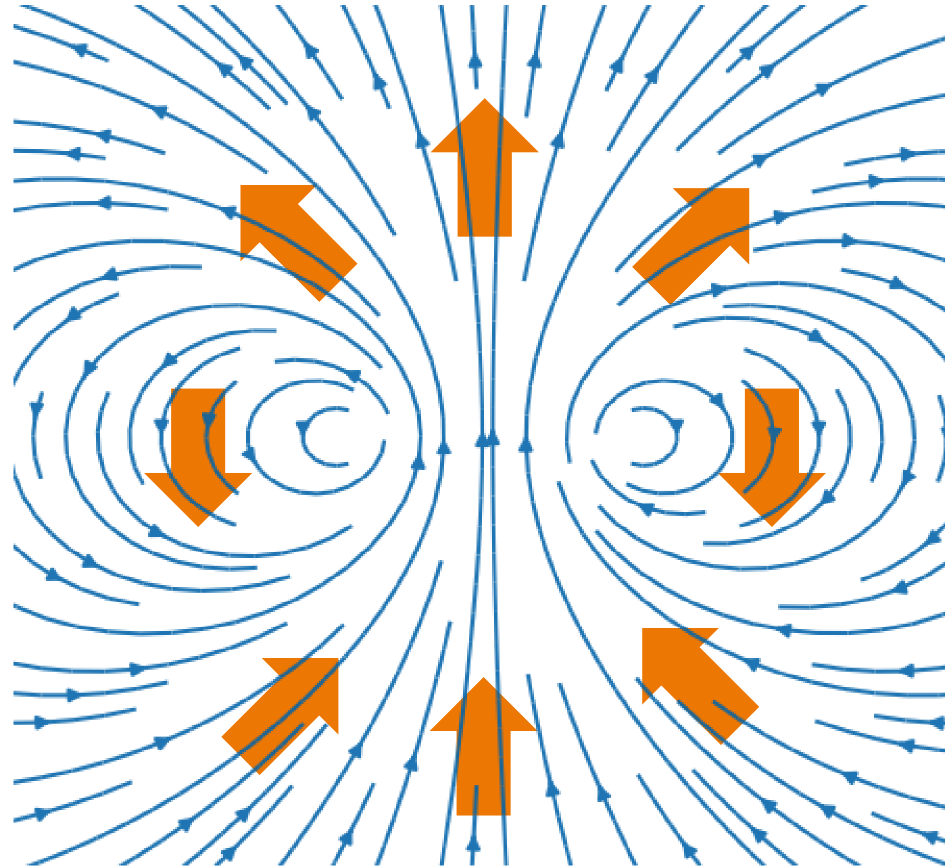
- Place magnets above and below
- Add magnets on the sides



PERMANENT MAGNET DESIGNS

Let us build a dipole magnet

- Place magnets above and below
- Add magnets on the sides
- Continue to add magnets at other angles following the field lines



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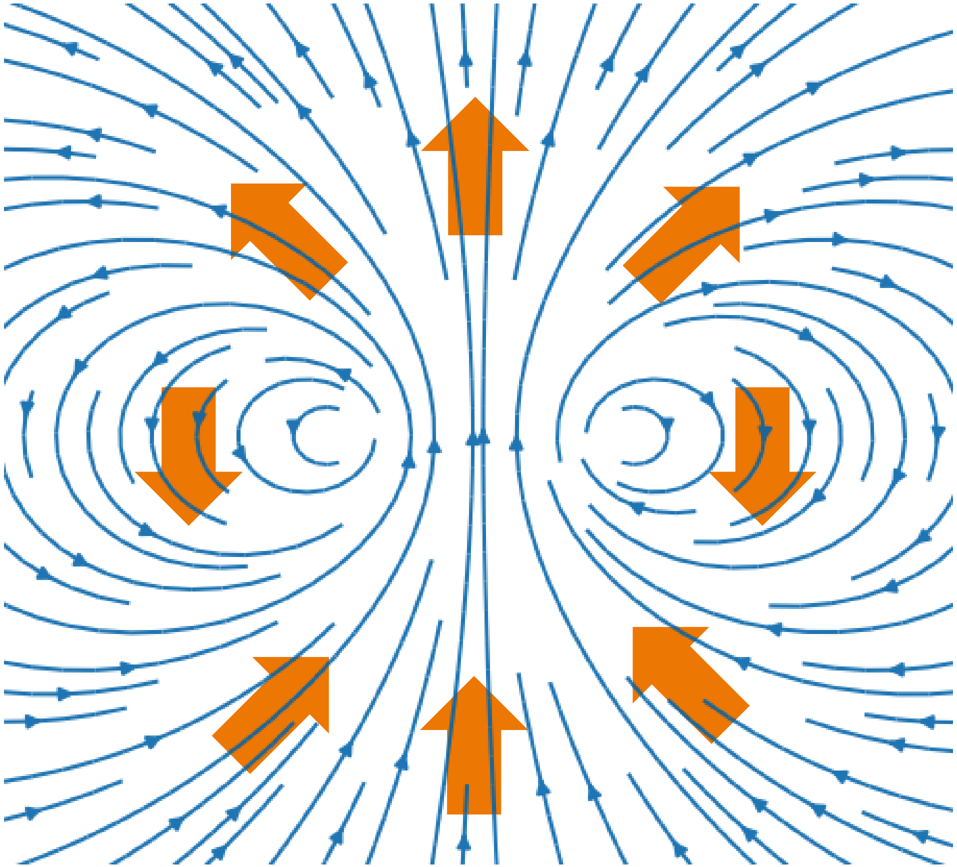


Halbach array

[Halbach, NIM169, 1980]

HALBACH ARRAYS – PURE PERMANENT MAGNETS

Magnetization angles

$$\theta_{Mag} = 2n\theta + \theta_0$$

where n is the multipole order

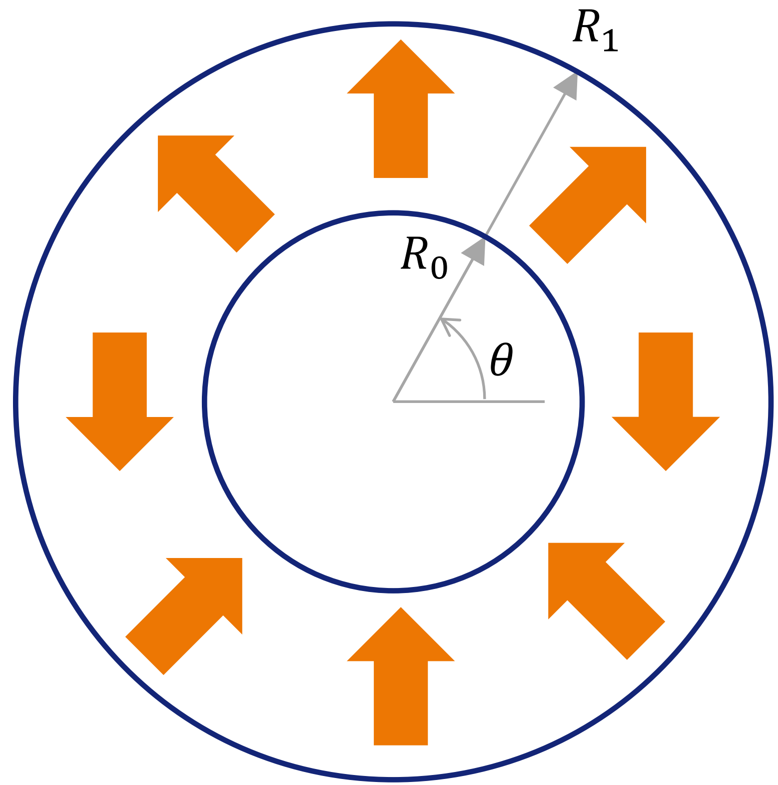
Magnetic field inside

$$B = B_R \ln\frac{R_1}{R_0}$$ for dipoles

$$G = 2\frac{B_R}{R_0}\left(1 - \frac{R_0}{R_1}\right)K$$ for quadrupoles

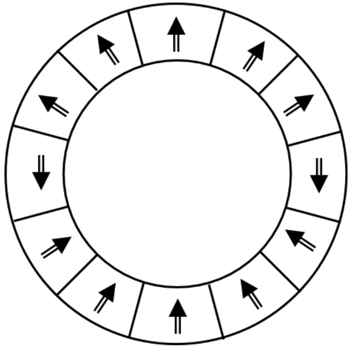
$K < 1$ depends on the number of segments

Magnetic field outside ~ 0

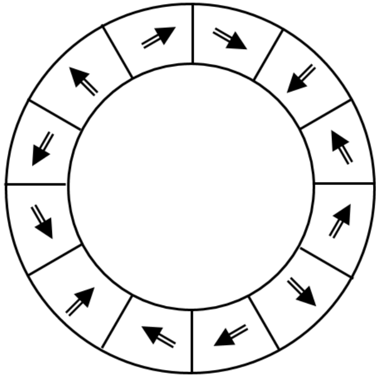


HALBACH ARRAYS – PURE PERMANENT MAGNETS

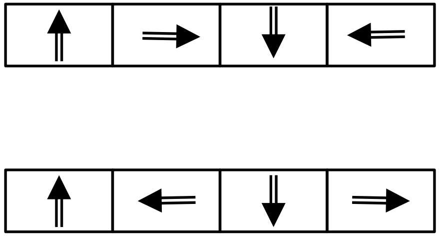
Dipole



Quadrupole

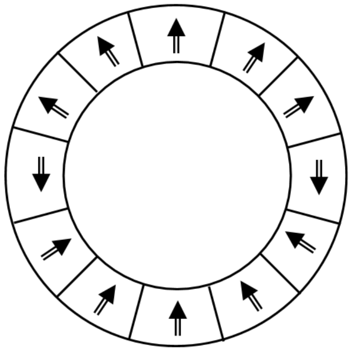


Undulator

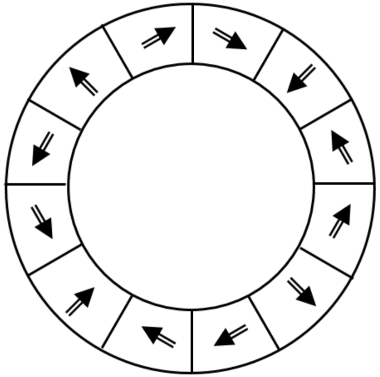


HALBACH ARRAYS – PURE PERMANENT MAGNETS

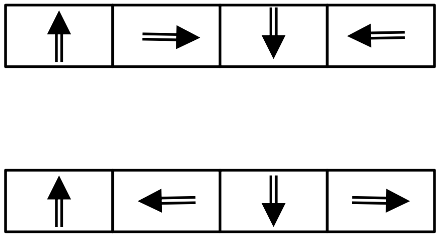
Dipole



Quadrupole



Undulator

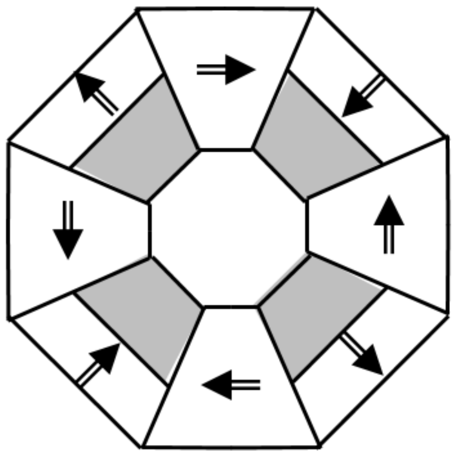


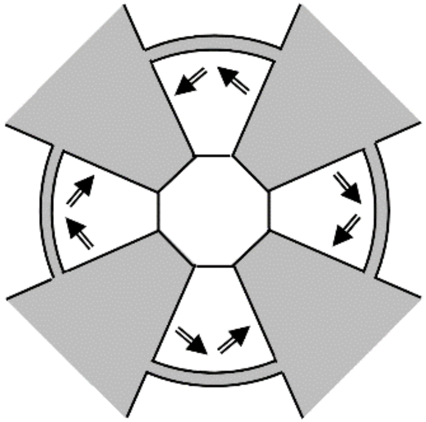
Undulators are the main application of Halbach arrays in accelerators

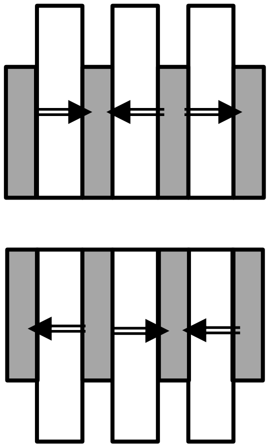
- Homogeneity tolerances are difficult to reach
- Shimming is mandatory

PM dominated hybrid magnets

- The field is increased by poles
- Soft iron or Cobalt iron is used
- A significant part of the flux does not pass through the poles







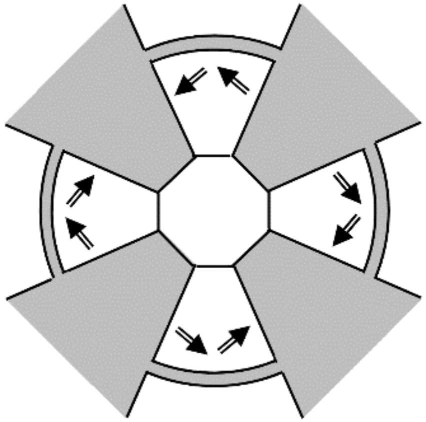
High gradient quad
$G \leq 520$ Tm
$R_0 = 4.12$ mm
[Modena, 2011]

Cryo PM undulator
$B = 1.09$ T
$g = 5$ mm
$\lambda_U = 16.4$ mm
$G = 420$ T/m

HYBRID MAGNETS – PERMANENT MAGNETS AND POLES

PM dominated hybrid magnets

- The field is increased by poles
- Soft iron or Cobalt iron is used
- A significant part of the flux does not pass through the poles



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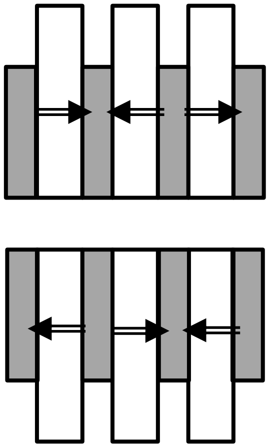
[Modena, 2011]



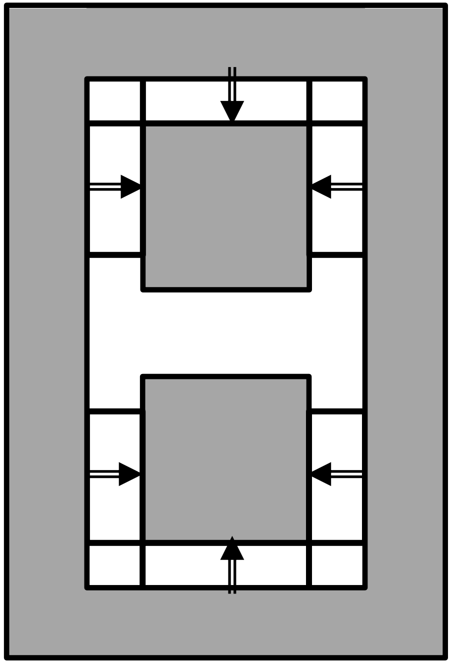
Cryo PM undulator
$B = 1.09$ T
$g = 5$ mm
$\lambda_U = 16.4$ mm
$G = 420$ T/m

Permanent magnets + saturated poles

- Very high gradients
- Long shimming process if tight field tolerances

Iron dominated hybrid magnets

- Replacing coils by permanent magnets
- The magnets are far from the beam axis
- Field tolerances are much easier to reach
- Lower field and gradient
- Compact magnets
- Easy fixed field operation (storage rings, transfer lines)



PM dipole

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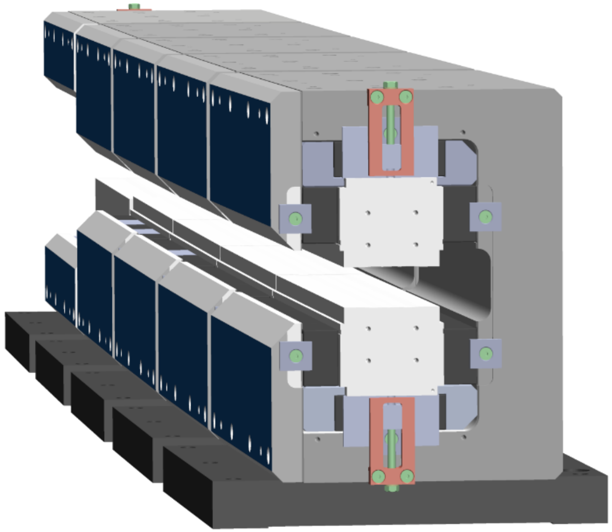


ESRF “DL” dipole

Trimming coils

PM have $\mu_R \approx 1$, same as air gaps

Field (linear regime)

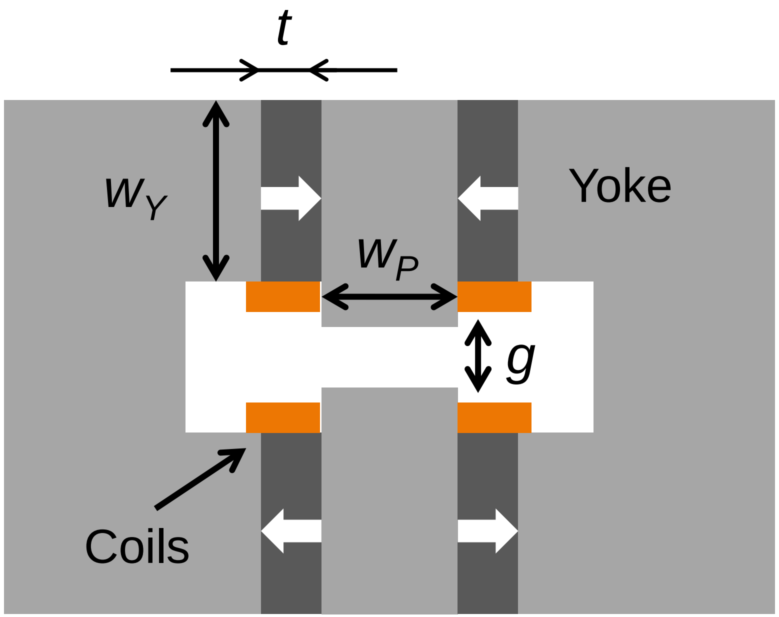
$$B = \mu_0 \frac{NI + Mt}{g + t\frac{w_P}{w_Y}}$$

PM volume minimized for

$$w_Y = \frac{2B_0 w_P}{\mu_0 M} \text{ and } t = \frac{2B_0 g}{\mu_0 M}$$

which gives $B_{NI} = \frac{\mu_0 NI}{2g}$

instead of $B_{NI} = \frac{\mu_0 NI}{g}$ without PMs!



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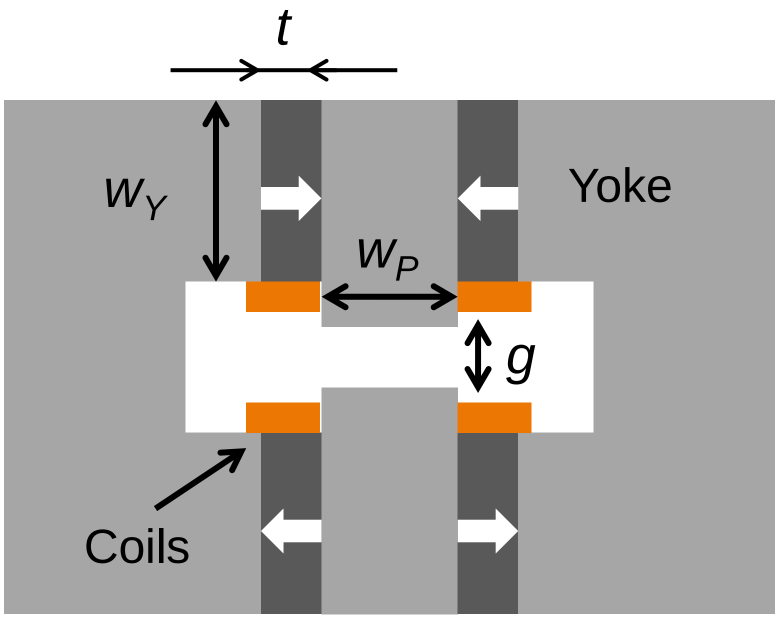
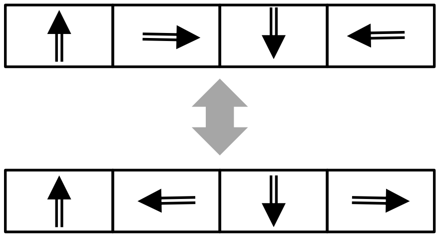


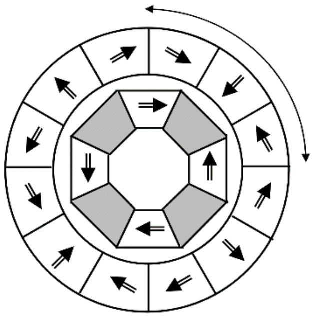
Trimming coils

- Coil efficiency / 2
- Works for low currents / small PM volume

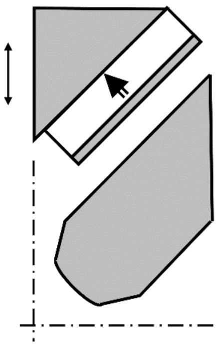
Moving magnets or poles

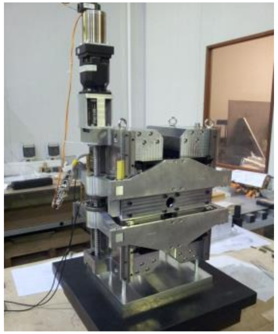


Undulator gap motion

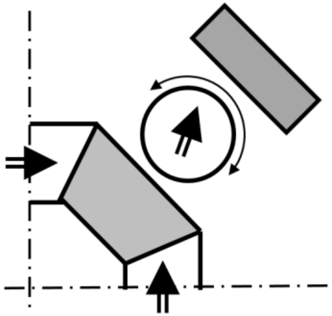


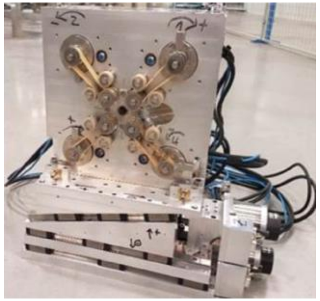
17 T/m < *G* < 120 T/m
[Iwashita 06]





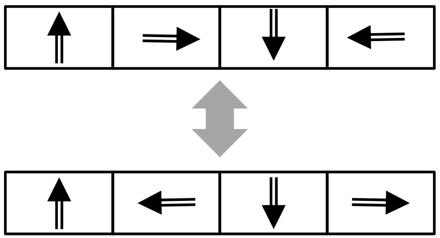
3 T/m < *G* < 44 T/m
[Shephred 14]



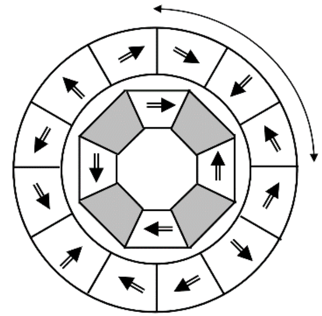


110 T/m < G < 200 T/m
[Marteau 17]

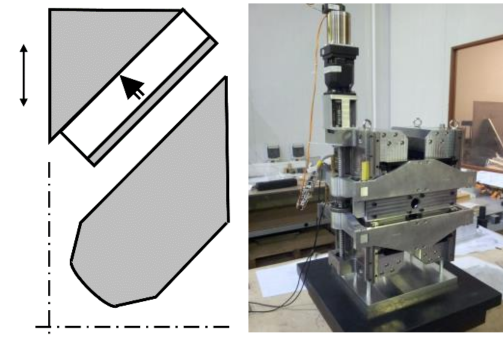
Moving magnets or poles



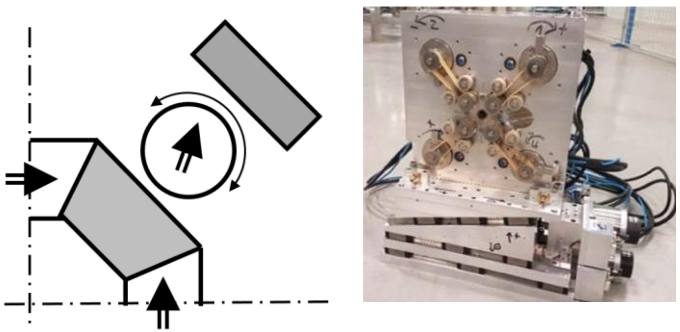
Undulator gap motion



$17\ \text{T/m} < G < 120\ \text{T/m}$
[Iwashita 06]



$3\ \text{T/m} < G < 44\ \text{T/m}$
[Shephred 14]



$110\ \text{T/m} < G < 200\ \text{T/m}$
[Marteau 17]

Mechanical tuning

- Large tuning range
- Complex and cost expensive
- Axis drift can be an issue
- Encoders and drivers can fail

Applications on accelerators

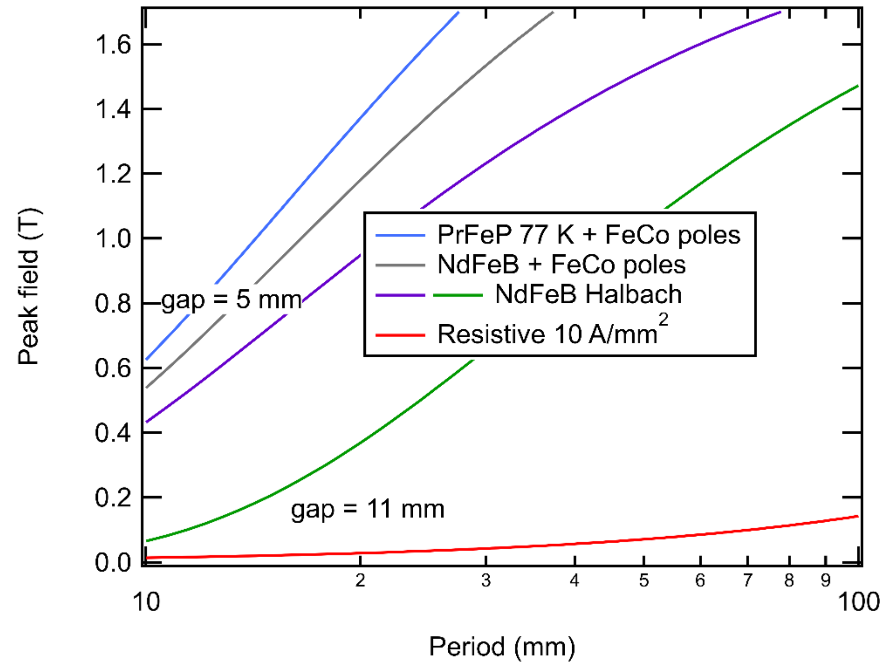
ACCELERATOR APPLICATIONS

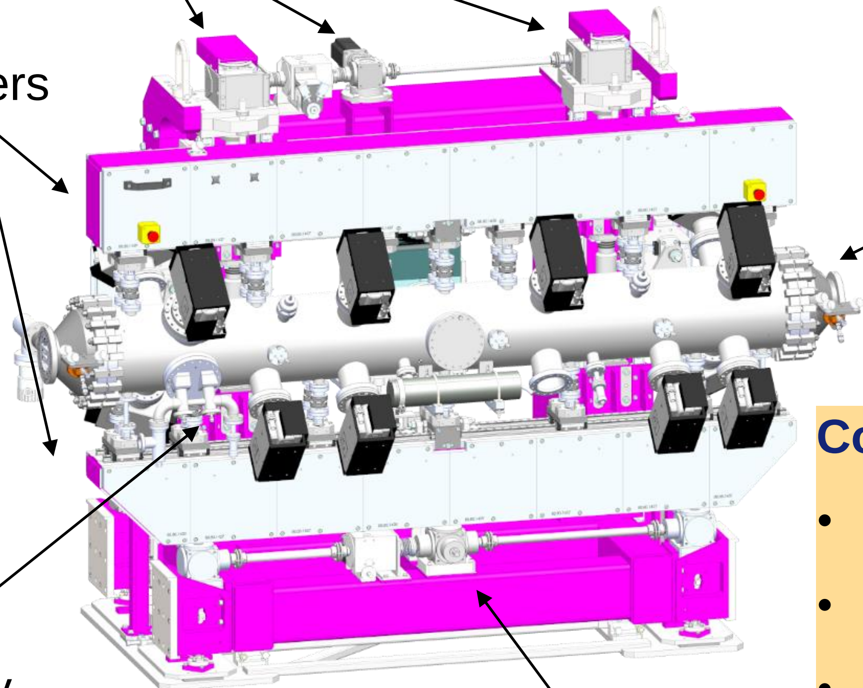
Undulators	**High gradient / high field**
Low power Compactness	**Injection**

Undulator field

$$B \propto e^{-\frac{\pi g}{\lambda}}$$

- Typical strengths cannot be reached with resistive magnets
- Superconducting undulators hardly compete PMs at low periods





Complex systems

- Magnetic forces > 1 ton
- Gap repeatability ~ 10 microns
- Ultra high vacuum

Cryogenic permanent magnet undulator

Quadrupole magnets

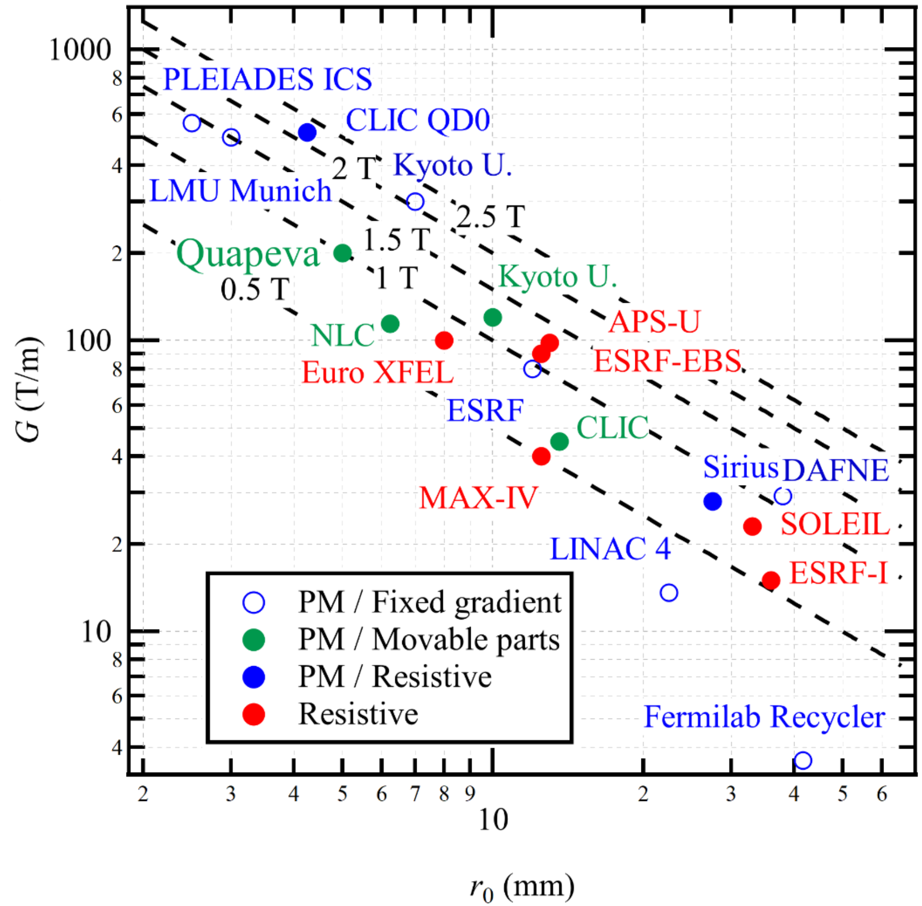
- Several designs and technologies
- Gradients above 500 T/m reached

'pole-tip' field

$$B_p = GR$$

$B_p \approx 1.5\ \mathrm{T}$ for Halbach quads

$B_p > 2\ \mathrm{T}$ for PM + FeCo quads



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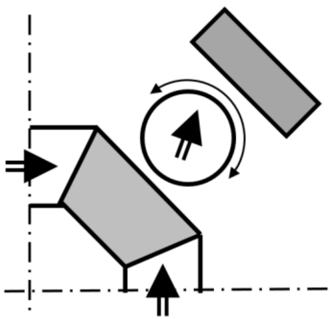
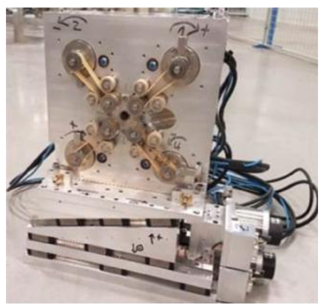
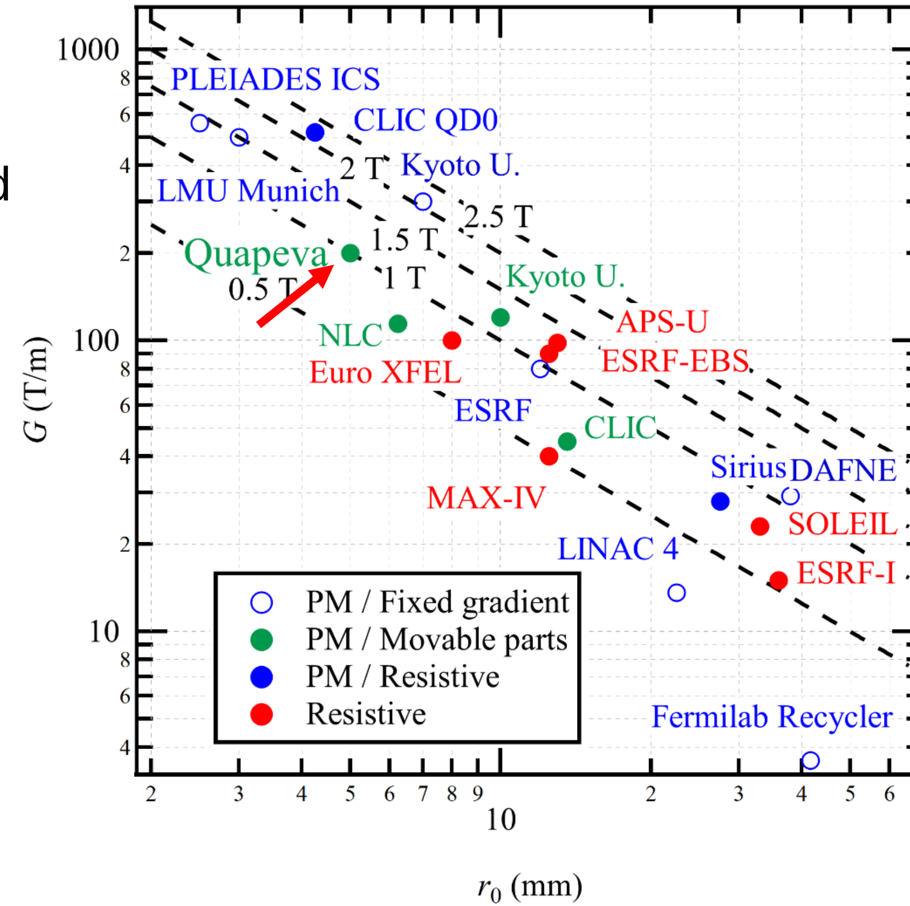




QUAPEVA magnets
Focusing LWFA beam
$110 < G < 200$ T/m
[Marteau 17]



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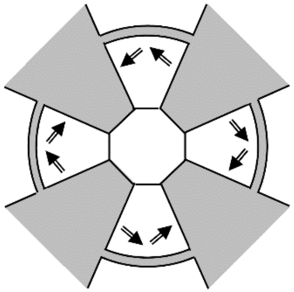
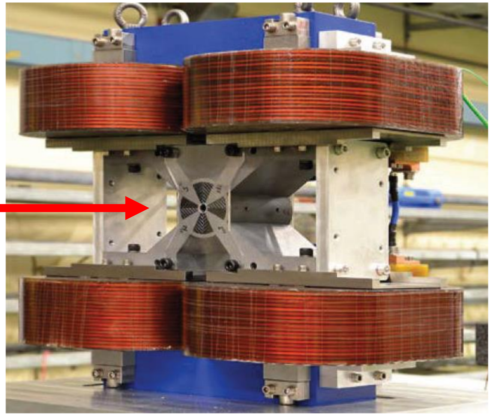
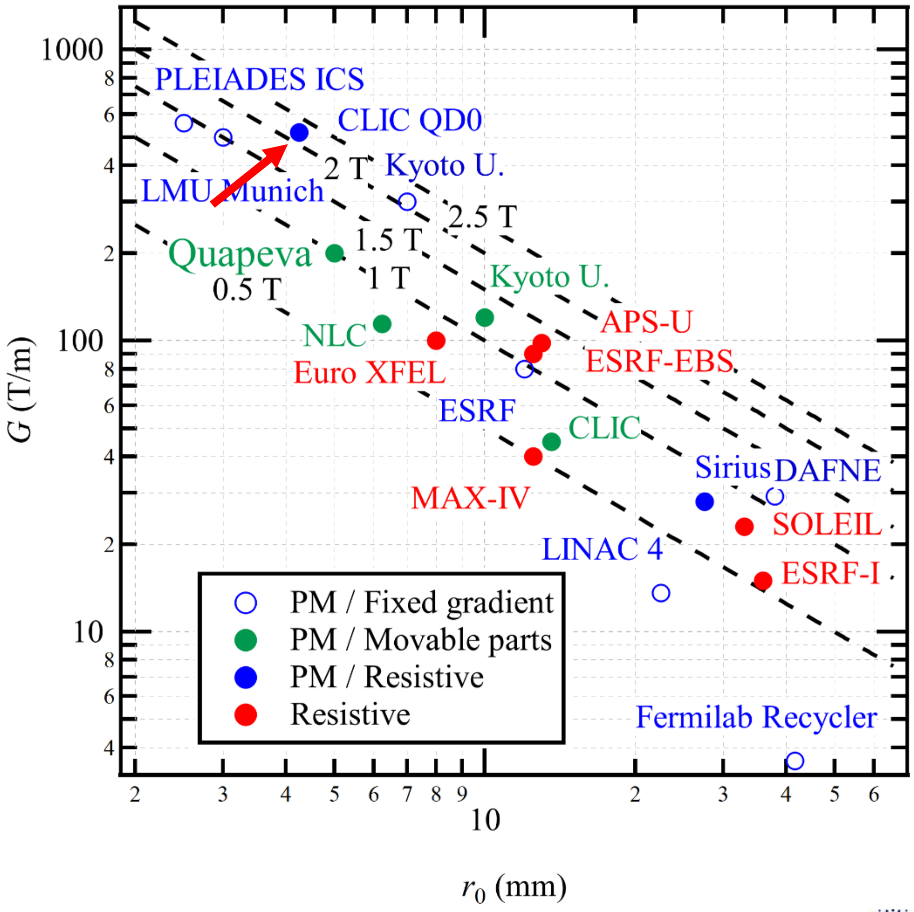


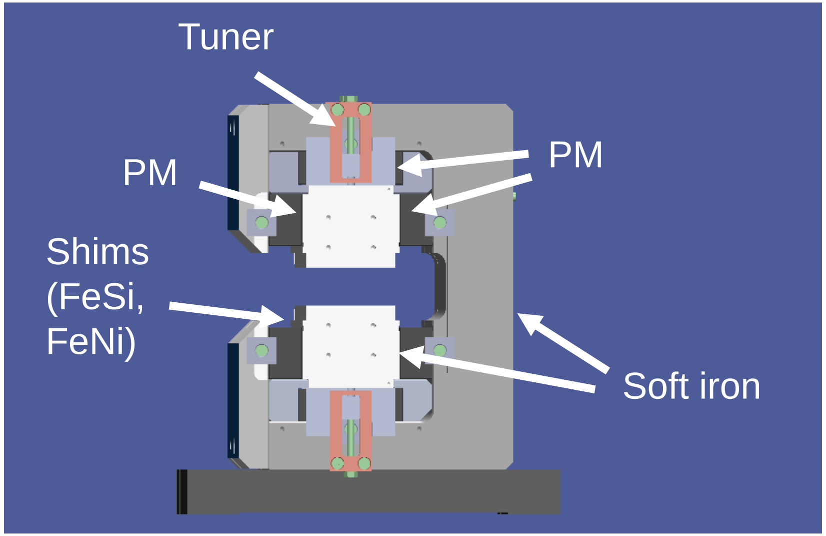


CLIC QD0 prototype
$G \approx 600\ \mathrm{T/m}$
[Modena 12]



ESRF PM dipoles

- Longitudinal field step
- Field: 0.17 – 0.67 T
- Gap: 26 mm
- 132 magnets built

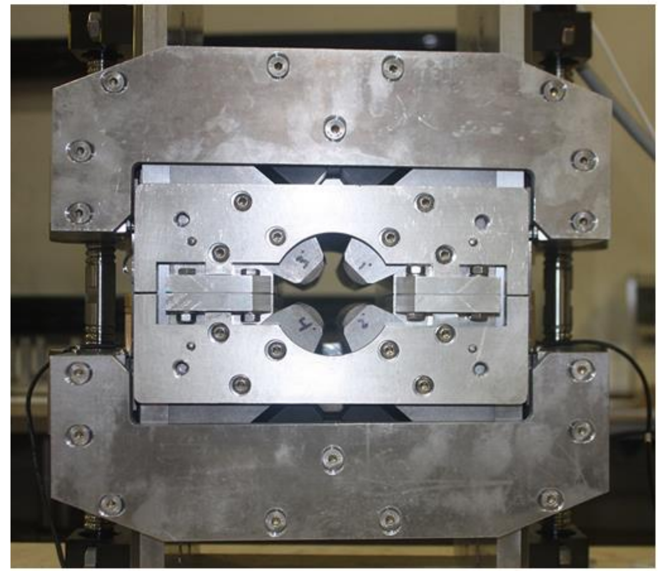


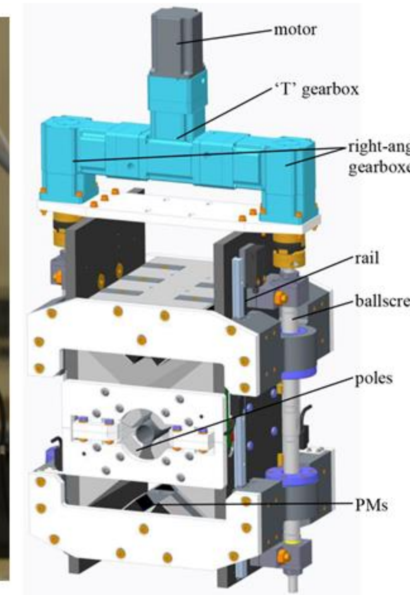
Installed in the SR and forgotten!

- No tuning knob
- No power supply
- No cooling

Zepto quadrupoles (STFC)

- Developed for CLIC
- Gradients 3 – 44 T/m



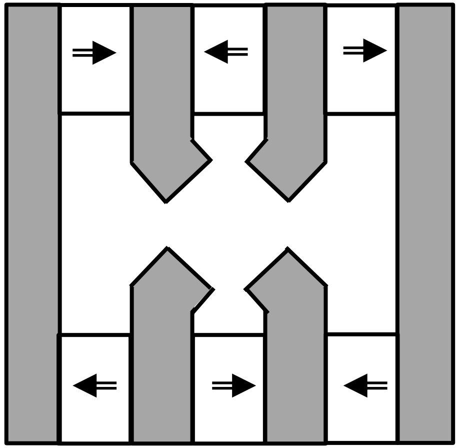


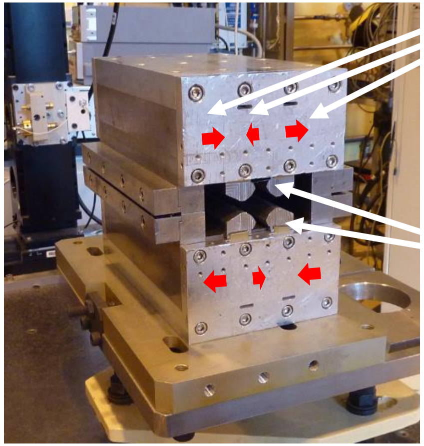
Gradient tuning

- Displacement of PMs and yoke
- The poles does not move

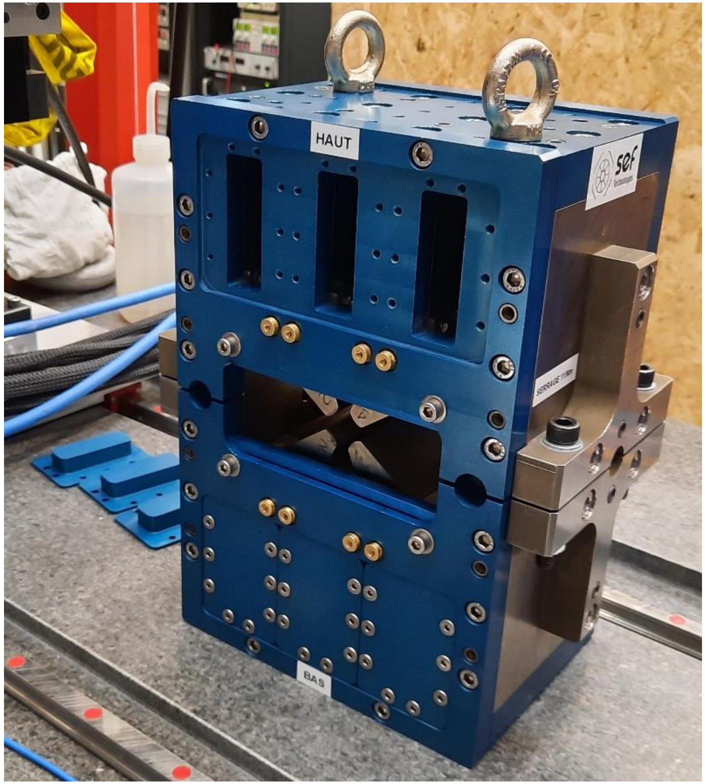
[Shephred 14]

Fixed, moderate gradient quadrupole





‘Plannar’ quadrupole
$G \approx 80\ \mathrm{T/m}, R = 12\ \mathrm{mm}$
[N’gotta 15]



SOLEIL-II PM quad prototype
(Courtesy C Kitegi / F Marteau, Synchrotron SOLEIL)

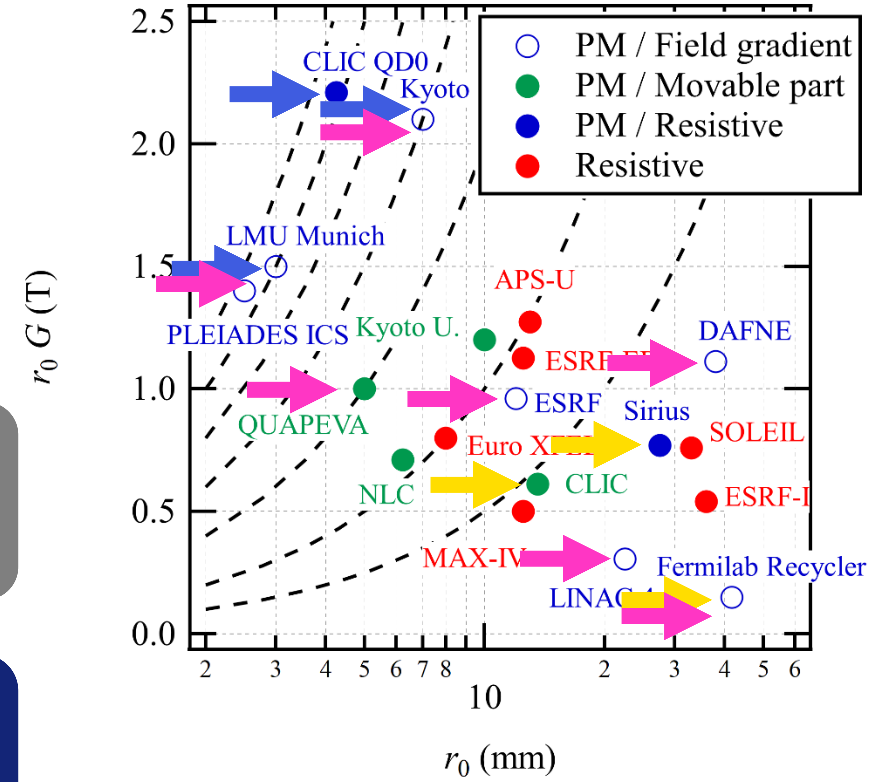
DIFFERENT REASONS TO BUILD PM MAGNETS…

Why building PM quad?

- High gradient / high field
- Power consumption
- Compactness, integration (e.g. in-vacuum)

In most cases, high fields / gradient are not main drivers for PM quads…

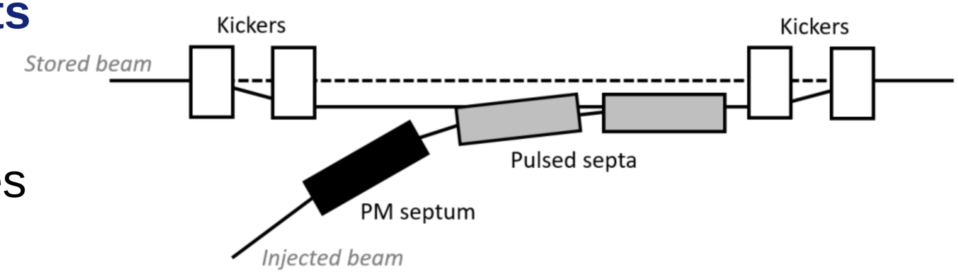
…but it may enable new lattice design



The European Synchrotron | ESRF

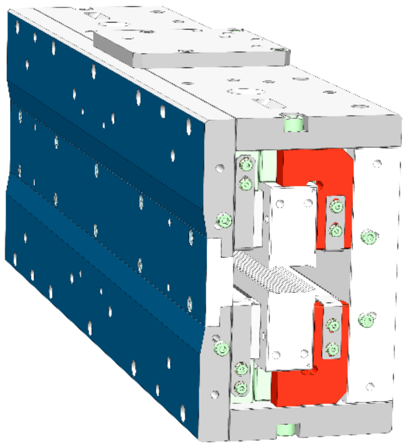
Transfer line and injection magnets

- Injection PM dipole
- Same technology as ESRF dipoles
- 1T field, 13 mm gap



Less compact than pulsed magnets

but **easier stray field compensation**

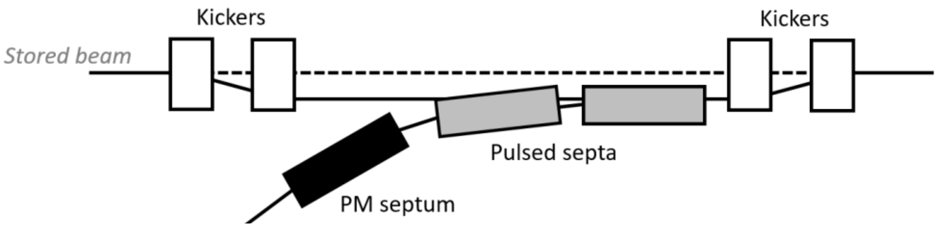


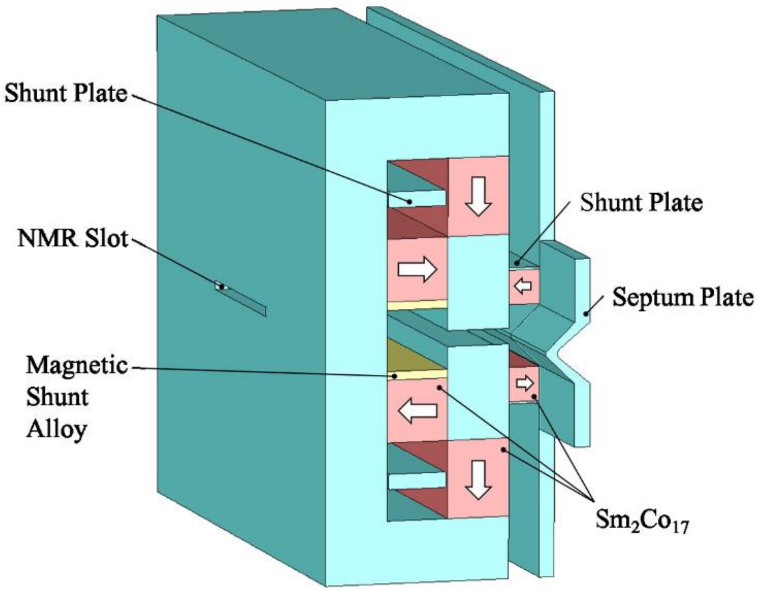
ESRF injection PM dipole

Spring-8 PM septum

- Injected beam field: 1.2 T
- Stored beam field < 1 mT
- Blade thickness 7 mm

[Taniuchi, 2020]





Spring-8 PM septum design

Summary

SUMMARY

Physics

- Equivalent surface currents or equivalent charges
- Demagnetizing field opposite to magnetization
- B_R, H_{cJ}, $M(H)$
- Good scale factor for compact magnets

Materials

- Mainly $Nd_2Fe_{14}B$ and Sm_2Co_{17} for accelerator applications
- Sintered magnets
- Rare-earth and/or critical materials

Different designs

- Halbach
- PM + poles
- PM or iron dominated
- Field / gradient tuning

Accelerator applications

- Compact magnets
- High gradients / high field
- Zero or low power

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