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High Gradient PM Technology for Ultra-High Brightness Rings

Gaël LeBec, J. Chavanne

lebec@esrf.fr

ESRF | The European Synchrotron

OUTLINE

INTRODUCTION – LOW EMITTANCE RINGS

High brightness lightsource rings

- MAX-IV, 3 GeV, 330 pm·rad
  being commissioned in Sweden
- ESRF-EBS, 6 GeV, 135 pm·rad
  Installation planned in 2019 in France
- Sirius, 3 GeV, 280 pm·rad
  Being constructed in Brazil
- APS-U, 6 GeV, 70 pm·rad
  Installation in 2022/2023 in USA
- Spring8 upgrade under study

Other low emittance rings

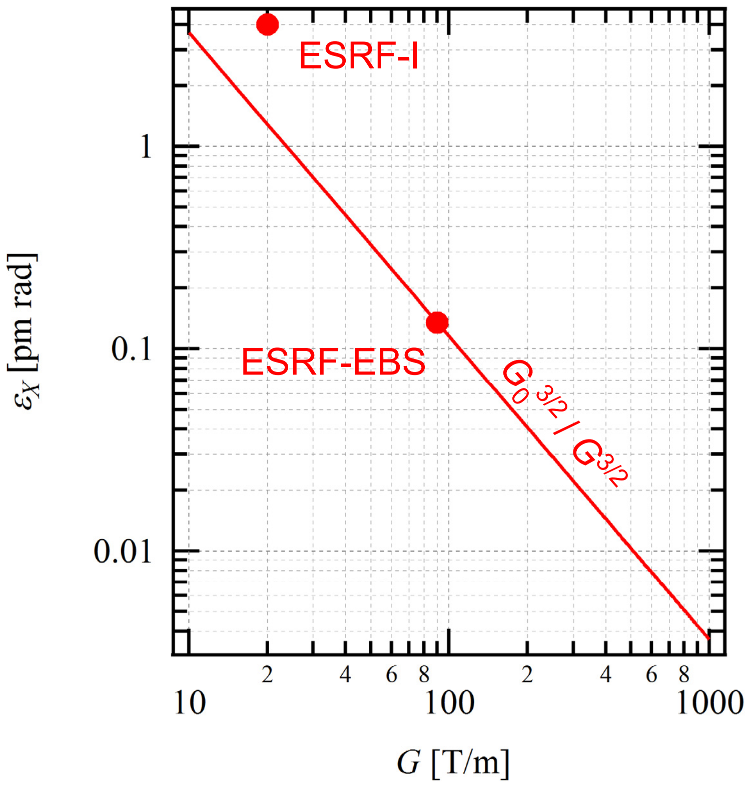
- Damping rings under study, e.g. CLIC

The ESRF lightsource, Grenoble, France

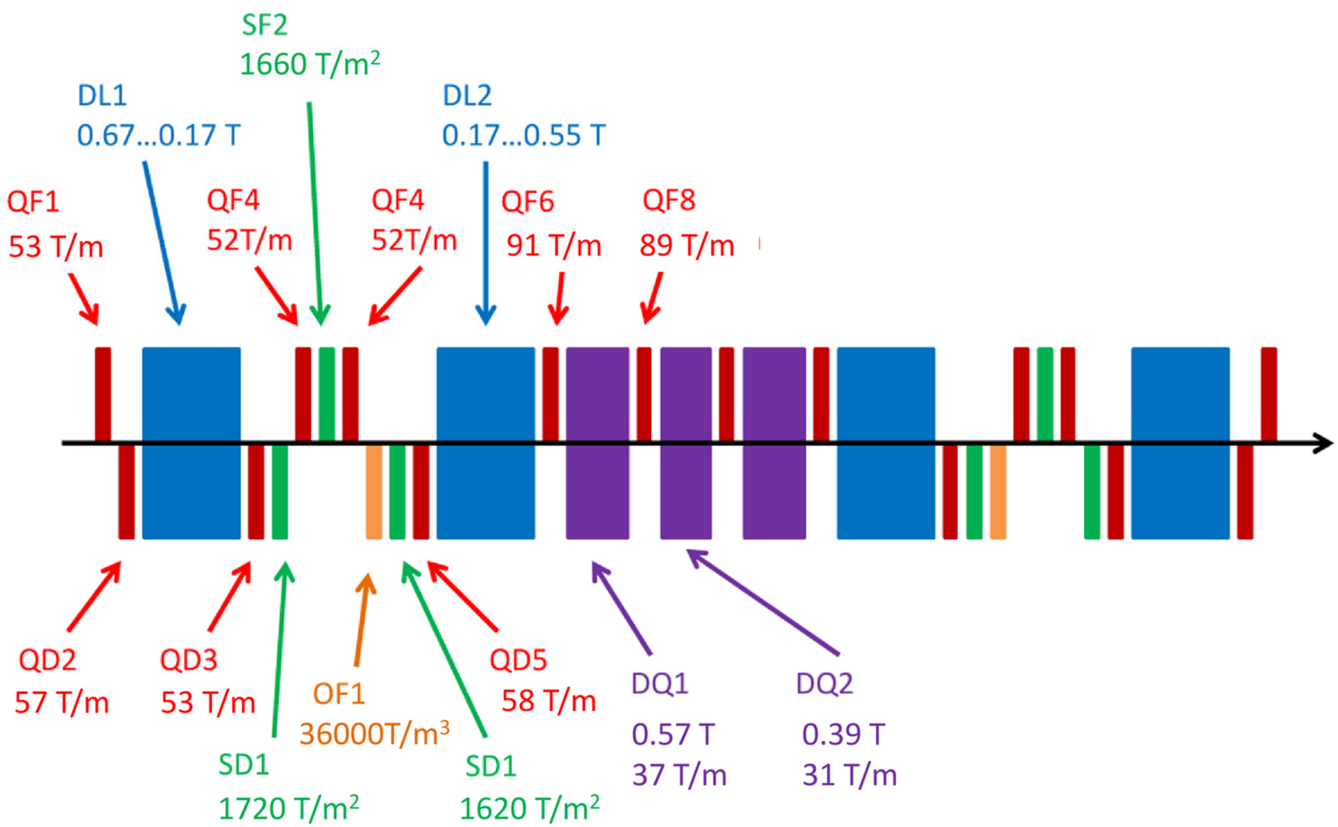
INTRODUCTION – LOW EMITTANCE RINGS

High brightness lightsource rings

- Increased number of dipoles
- 7 bends at MAX-IV, ESRF-EBS and APS-U
- Minimum β_X in dipoles
- Emittance $\propto 1/(N\ Dipoles)^3$ and Gradients $\propto (N\ Dipoles)^2$



One cell of the ESRF-EBS storage ring magnets



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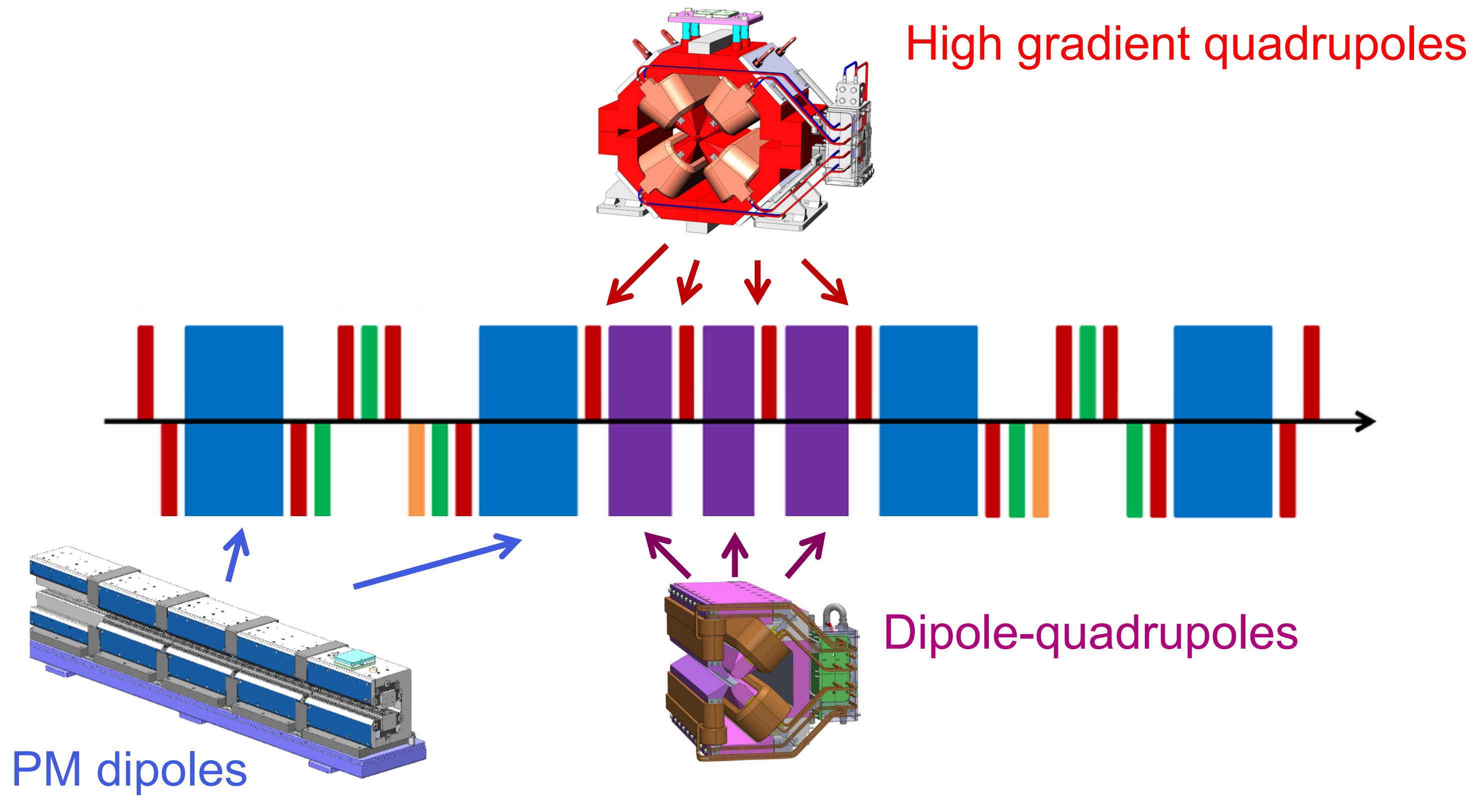
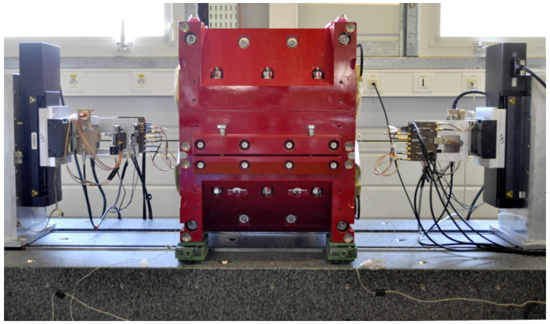


INTRODUCTION – THE ESRF-EBS MAGNETS

High gradient quadrupoles of the ESRF-EBS

- Limited time for R&D
- Development of PM quadrupoles not compatible with the project timescale
- Gradients < 100 T/m was an initial lattice design constraint
- Gradient ~ 90 T/m @ 12.5 mm radius obtained on a prototype, at reasonable power consumption, with soft iron poles [LeBec 16]



Measurement of a resistive high gradient quadrupole prototype

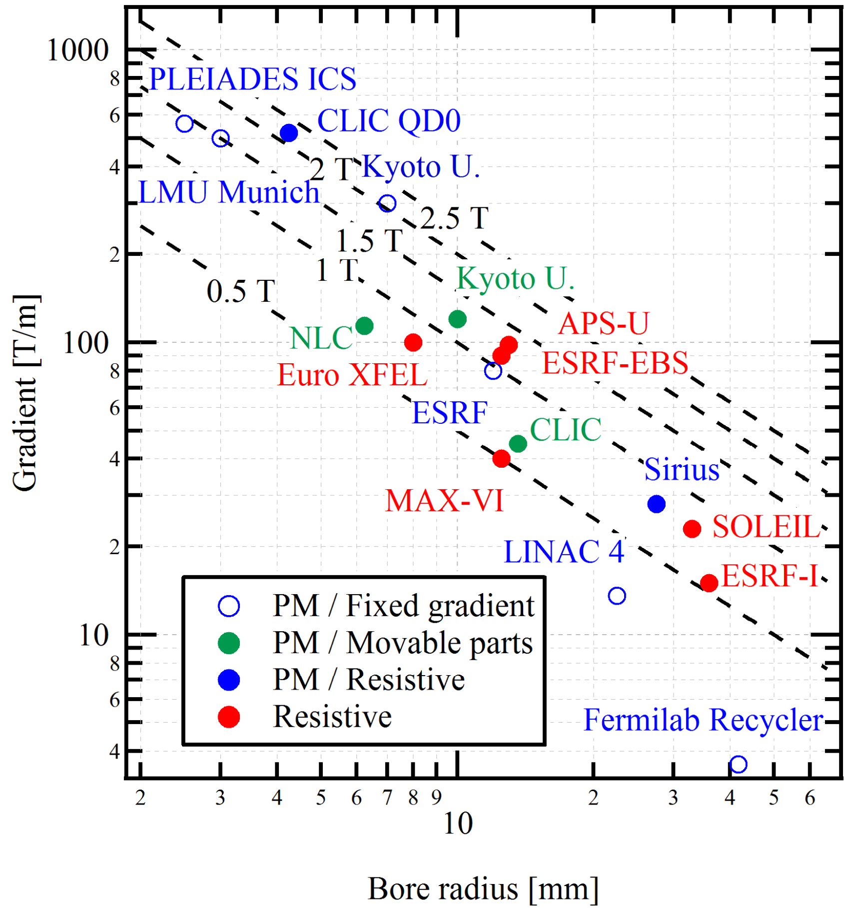
STATE OF THE ART

High Gradient quads

- $G \approx 100$ T/m (resistive)
- $G > 500$ T/m (PM quads, hybrid)

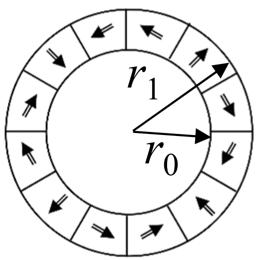
High Field High Gradient quads

- High $G\,r_0$ product
- 1.1T < $G\,r_0$ < 1.3 T at ESRF-EBS and APS-U
- $G\,r_0 \approx 2.2$ T for CLIC QD0



STATE OF THE ART

Fixed gradient PMQ
Halbach magnets



$$G = 2\frac{B_R}{r_0}\left(1 - \frac{r_0}{r_1}\right)K$$

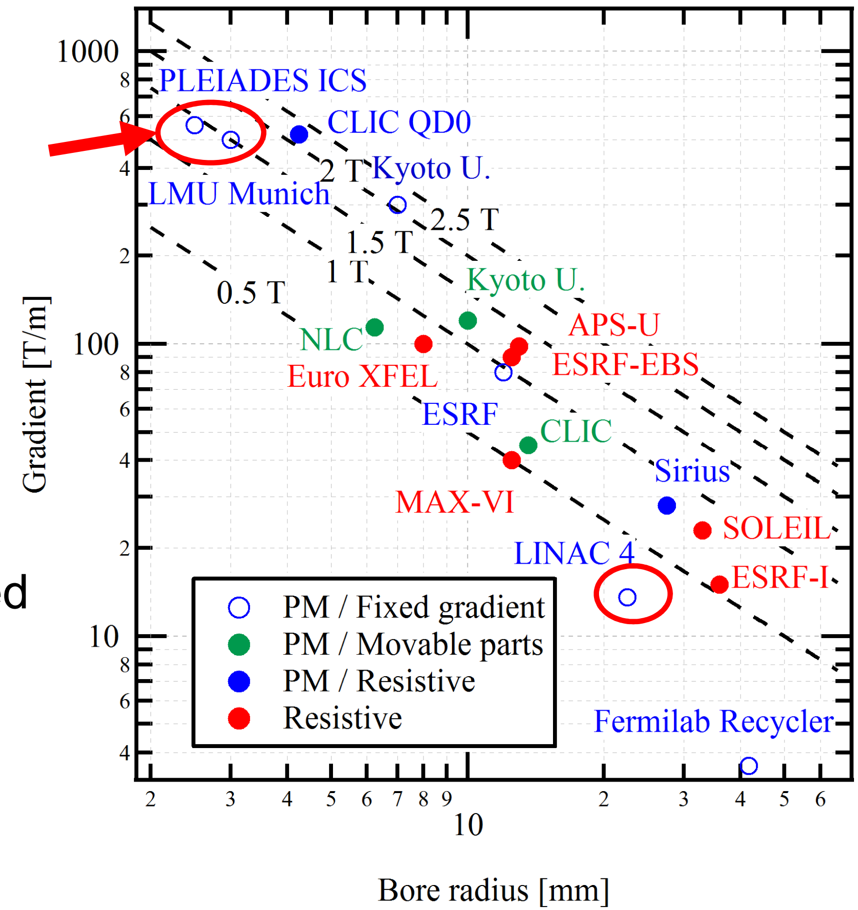
High gradient quads

$G > 500$ T/m and $G\,r_0 \approx 1.5$ T reached

Limitations

Gradient tunability, homogeneity

[Halbach 80, Lim 05, Becker 09]



STATE OF THE ART

Fixed gradient PMQ
Iron dominated magnets

Improved homogeneity

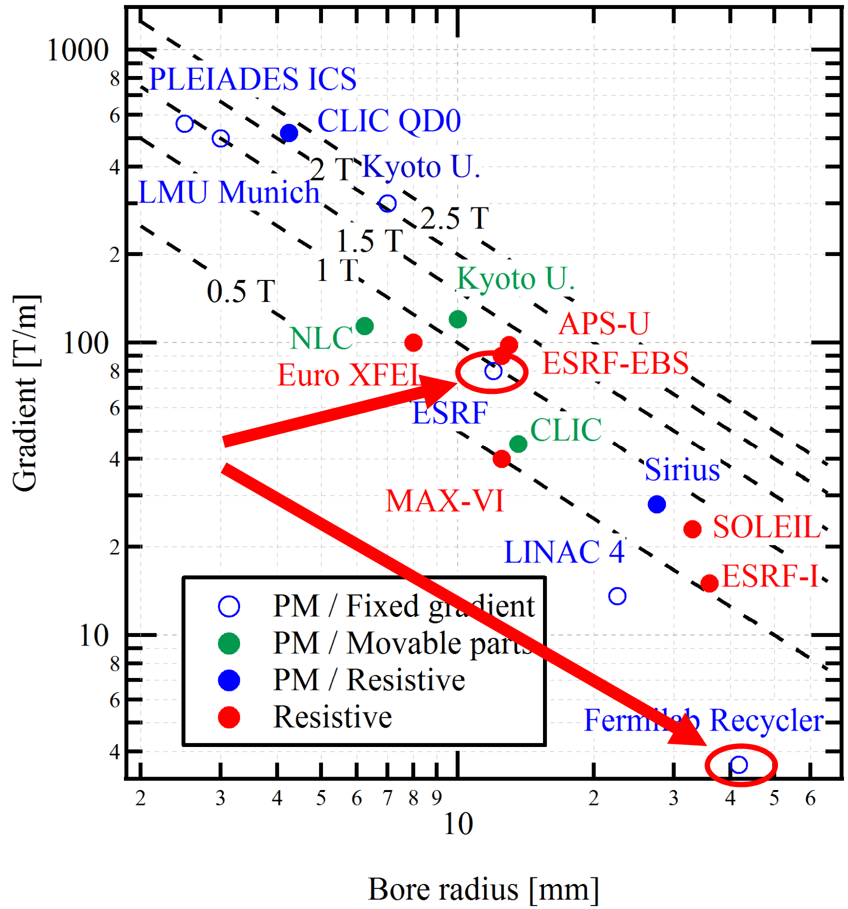
Moderate gradient and field

$G \approx 80$ T/m and $G\, r_0 \approx 1$ T reached

Limitations

Lower gradient and field

[N'gotta 15, Fermilab 96]



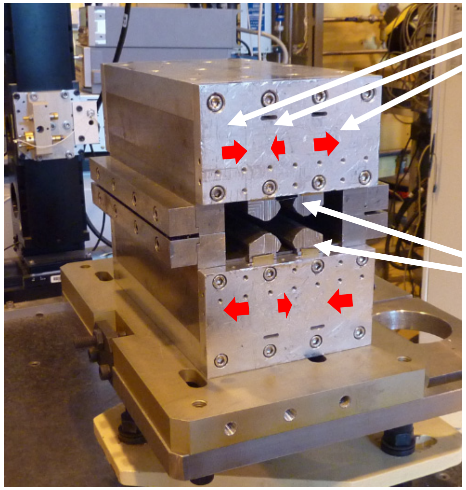
STATE OF THE ART

Fixed gradient PMQ

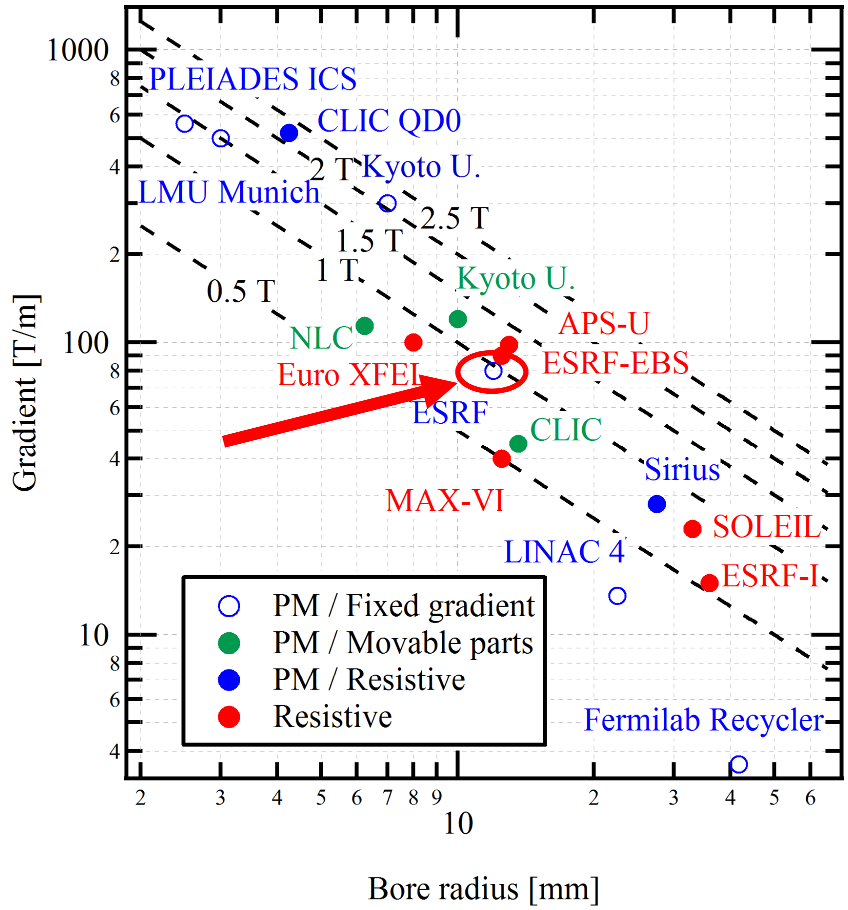
Iron dominated magnets

$G \approx 80$ T/m, r_0=12 mm

$\Delta G/G \approx 10^{-3}$ at $\pm r_0/2$



(Courtesy P. N'gotta [N'gotta 15])

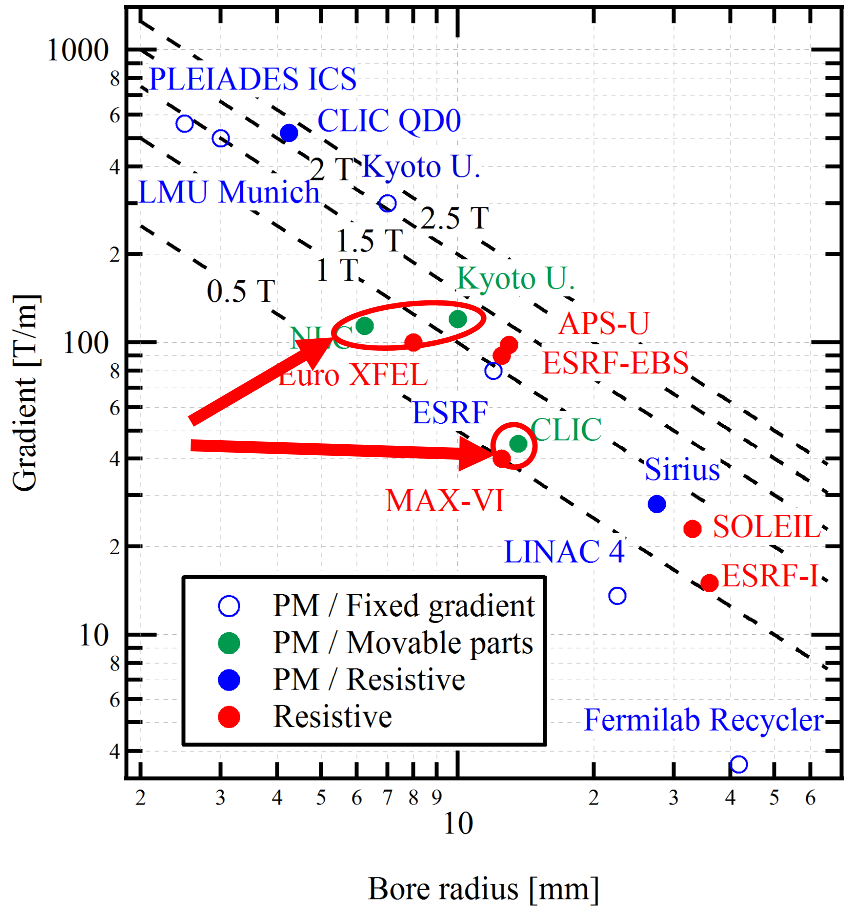


Tunable PMQ
Movable parts

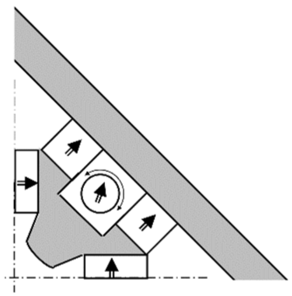
Gradients up to 120 T/m

Moderate field (can probably be increased)

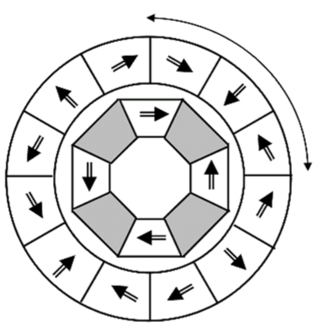
[Volk 01, Iwashita 06, Bondarchuk 06, Shepherd 14]



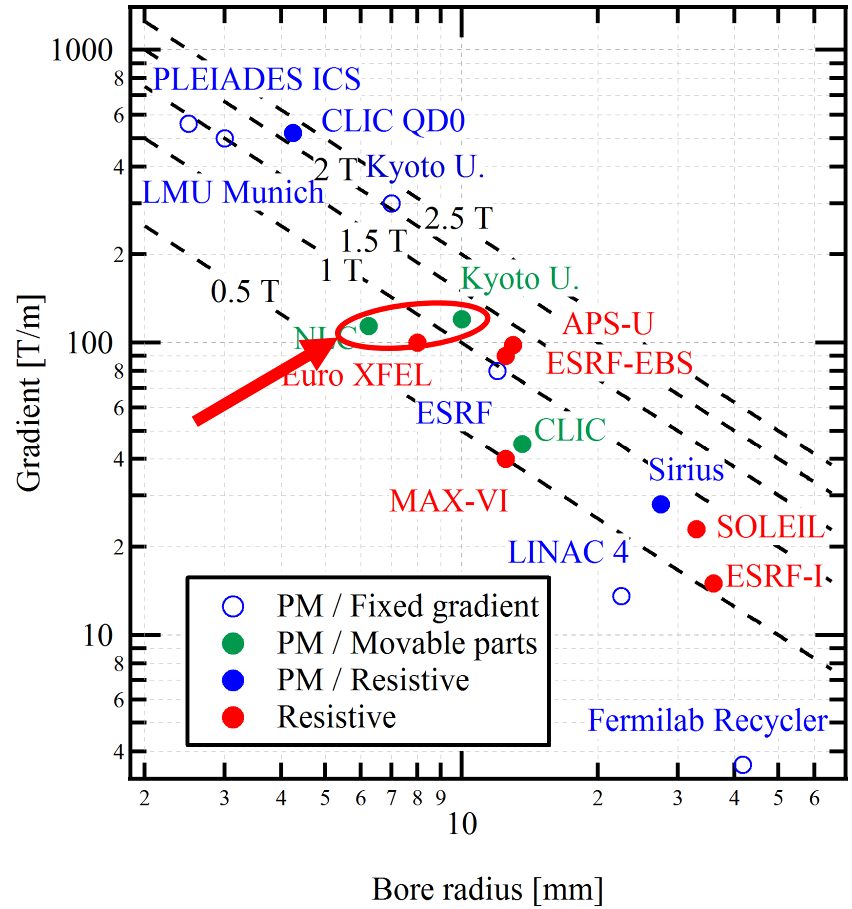
Tunable PMQ
Movable parts



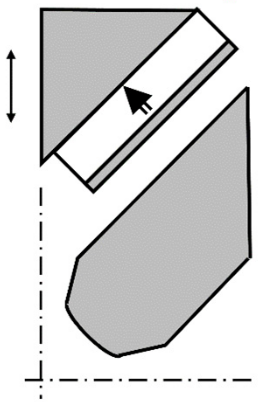
Rotated PM rods
89 T/m < *G* < 115 T/m
Centre shift ± 20 µm
[Volk 01]

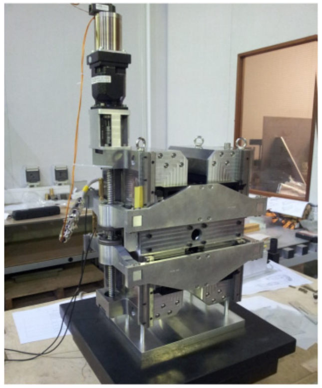


Rotation of outer magnets
17 T/m < *G* < 120 T/m
Centre shift ± 10 µm
[Iwashita 06]



Tunable PMQ
Movable parts





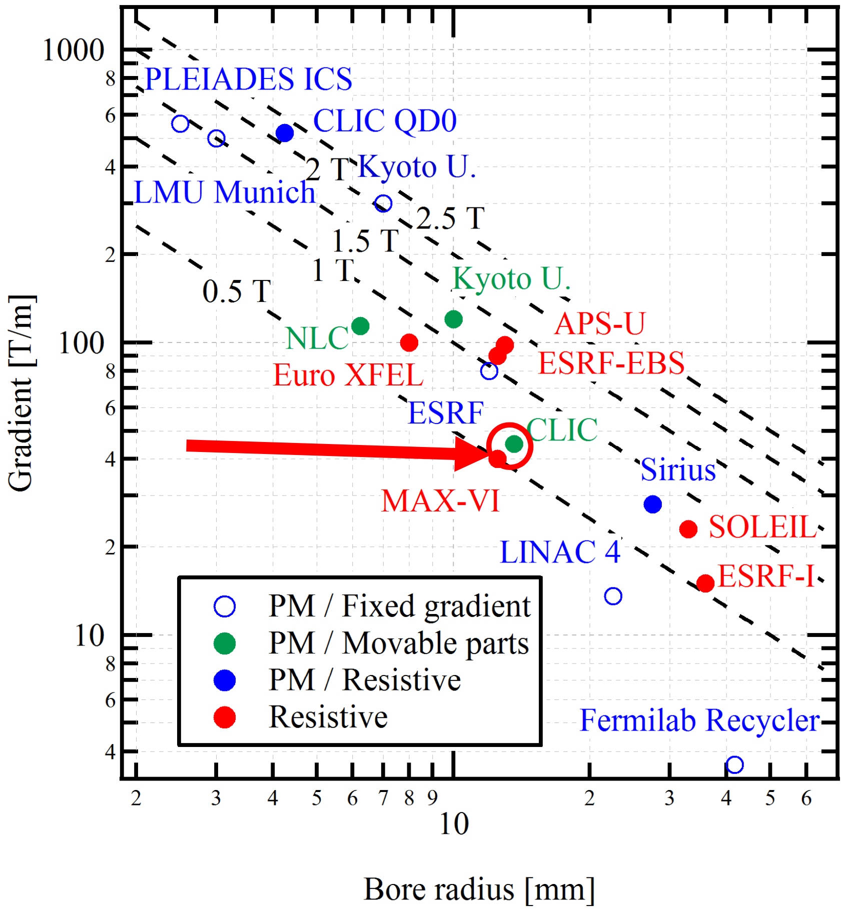
(Courtesy B. Shepherd)

Displacement of PM blocks and upper yoke

3 T/m < *G* < 44 T/m

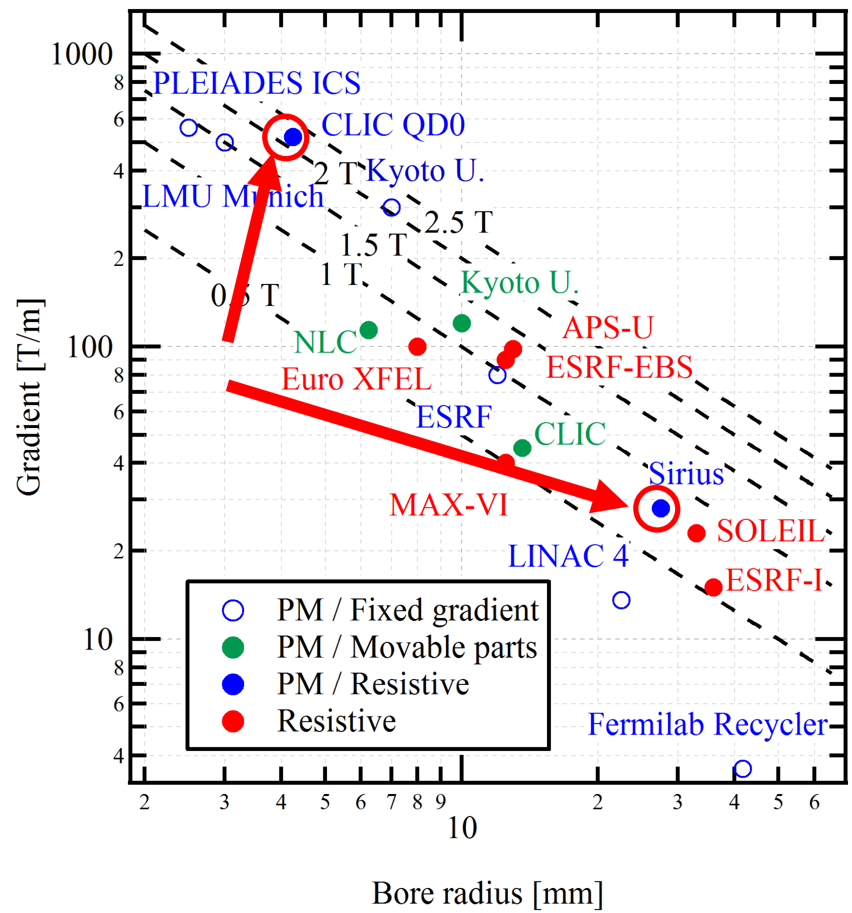
Centre shift ± 50 µm

[Shephred 14]



STATE OF THE ART

Tunable PMQ
PM / Resistive hybrid magnets

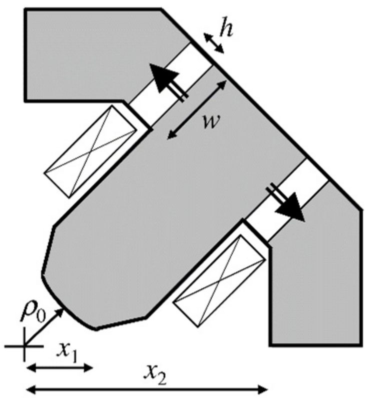


[Modena 12, Tosin 12]

STATE OF THE ART

Tunable PMQ
PM / Resistive hybrid magnets

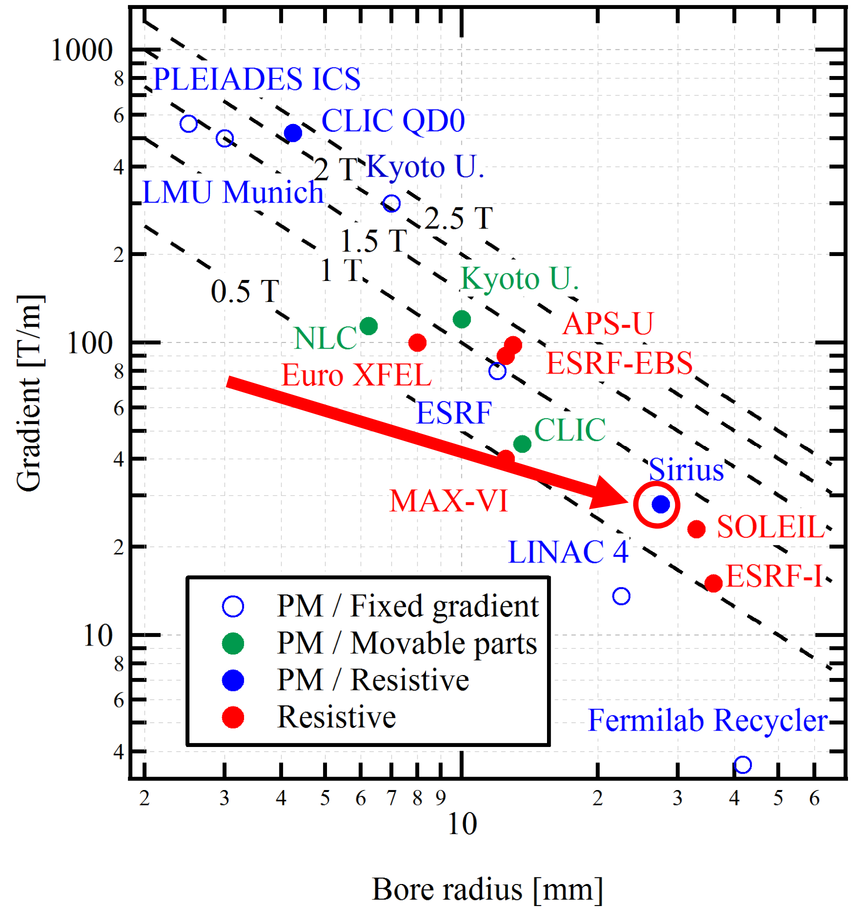
Iron dominated magnet



G ≈ 28 T/m

Tuning 70−100%

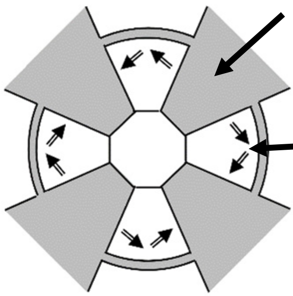
[Tosin 12]

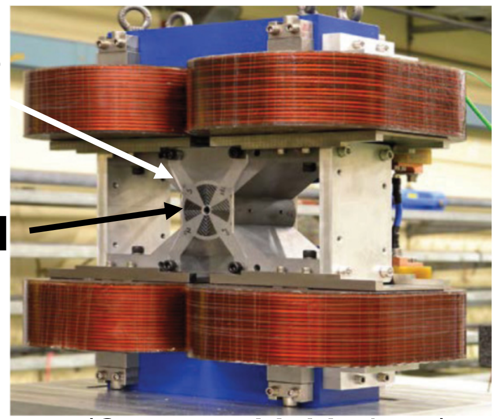


STATE OF THE ART

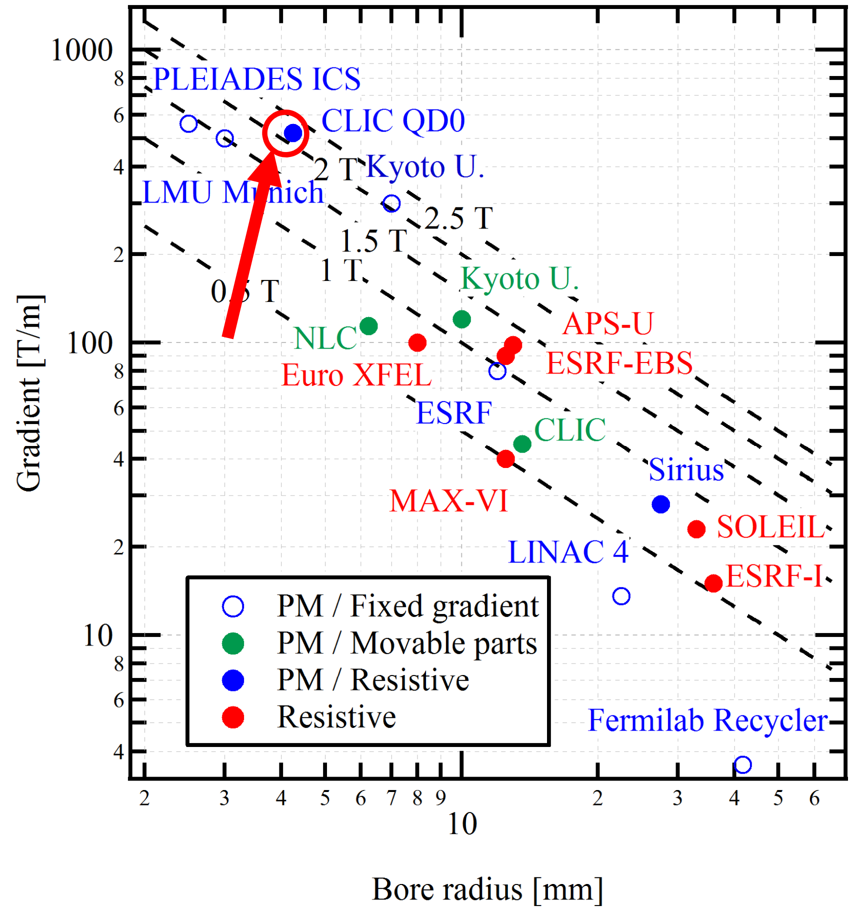
Tunable PMQ

PM / Resistive hybrid magnets





(Courtesy M. Modena)



$G \approx 520$ T/m and $r_0 = 4.12$ mm

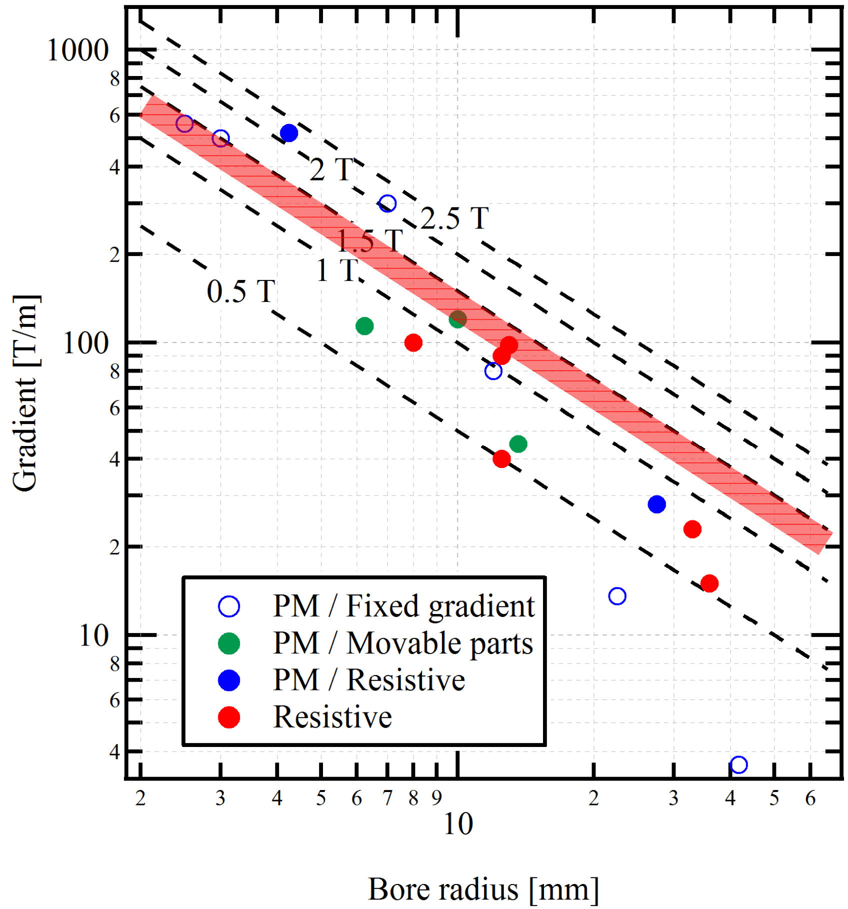
Tuning 30−100%

[Modena 12]

HIGH GRADIENT QUADRUPOLES – GRADIENT AND APERTURE

Gradient, aperture and field

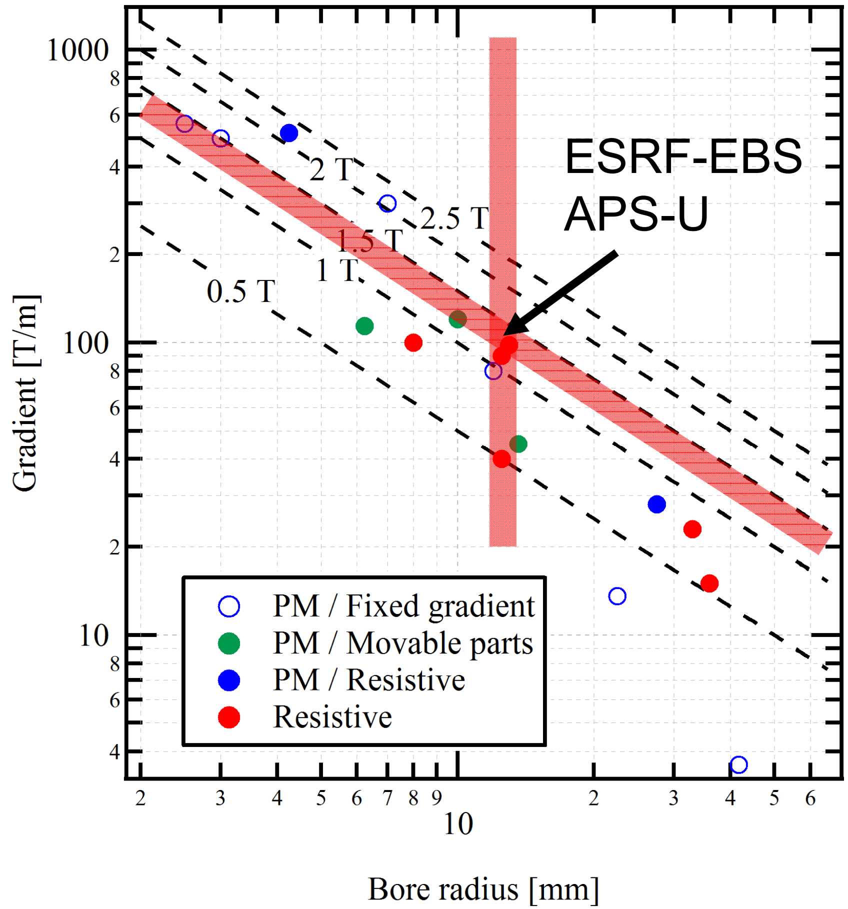
- Fields $G\ r_0$ < 1.5 T may be reached with resistive magnets with FeCo poles



HIGH GRADIENT QUADRUPOLES – GRADIENT AND APERTURE

Gradient, aperture and field

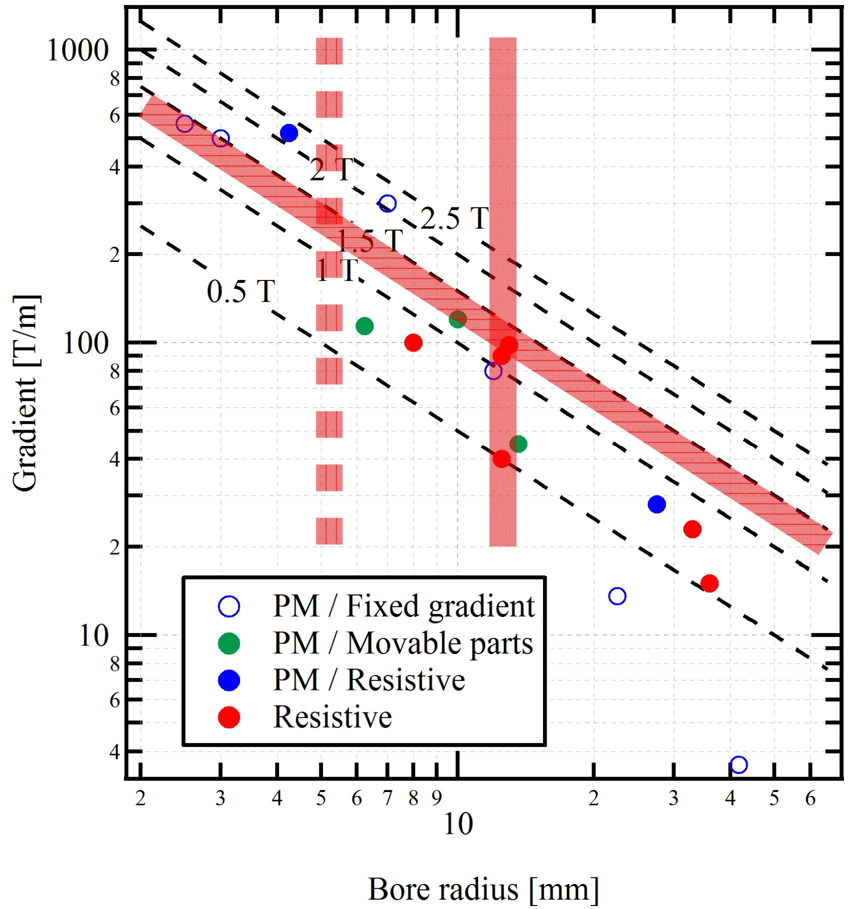
- Fields $G\ r_0 < 1.5$ T may be reached with resistive magnets with FeCo poles
- 12.5−13 mm radius for ESRF-EBS and APS-U high gradient magnets



HIGH GRADIENT QUADRUPOLES – GRADIENT AND APERTURE

Gradient, aperture and field

- Fields $G\,r_0 < 1.5$ T may be reached with resistive magnets with FeCo poles
- 12.5−13 mm radius for ESRF-EBS and APS-U high gradient magnets
- Minimum aperture not clearly defined



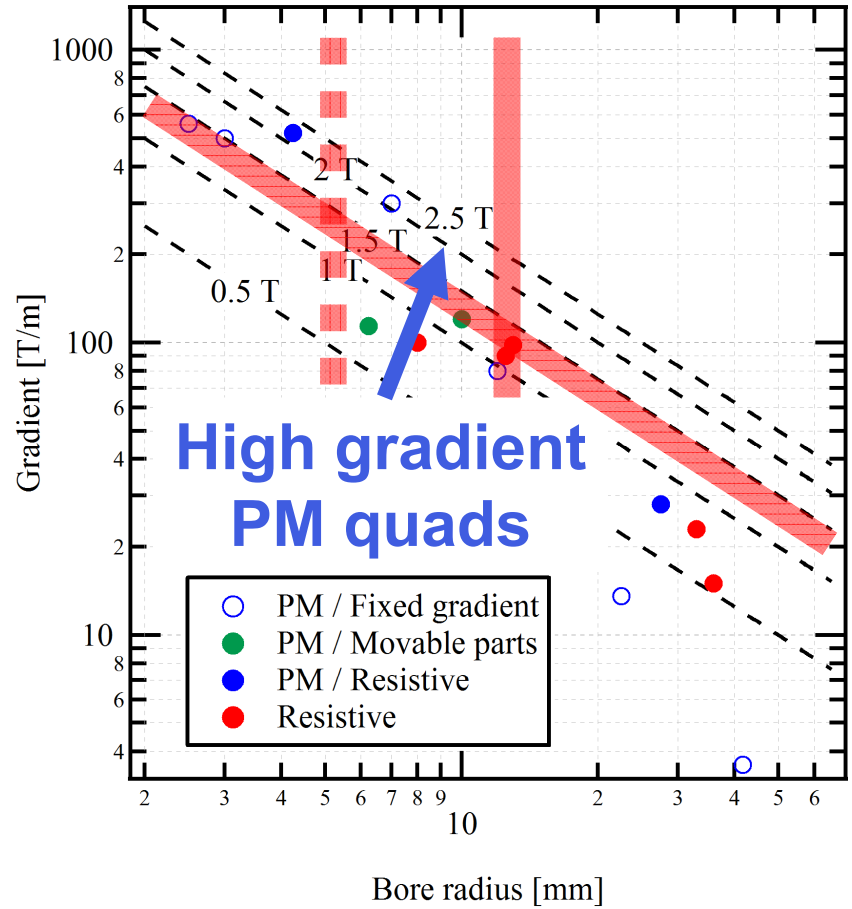
HIGH GRADIENT QUADRUPOLES – GRADIENT AND APERTURE

Gradient, aperture and field

- $G\ r_0 > 1.5$ T
- 5 mm < r_0 < 10 mm
- $G \geq 200$ T/m seems achievable with PM quads

(Does not mean that lower gradient PM quads have no interest!

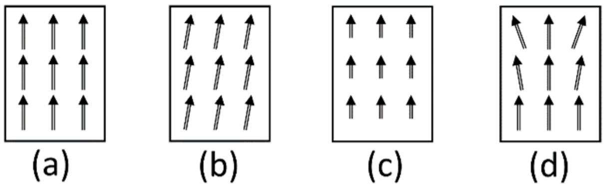
Moderate gradient PM quads are compact, low/zero power and reliable)



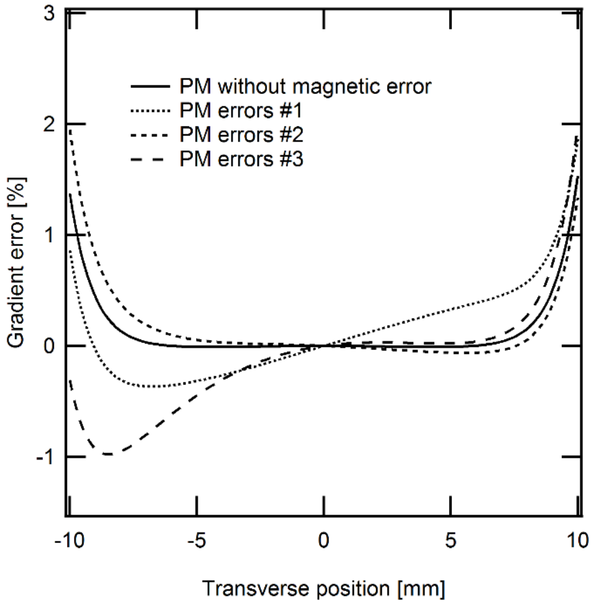
HIGH GRADIENT QUADRUPOLES – HOMOGENEITY

PM blocks flaws

- Magnetization axis and strength errors
- Magnetization inhomogeneities



Typical PM errors



Gradient of a Halbach type magnet with σ_M = 0.01 M, σ_{Axis} = 0.8°, σ_{Pos} = 35 µm, and 15 mm inner radius.

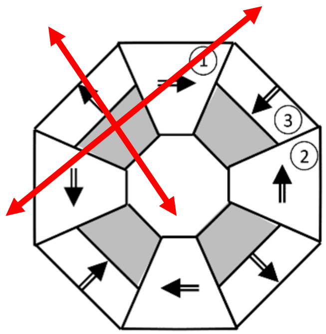
HIGH GRADIENT QUADRUPOLES – HOMOGENEITY

PM blocks flaws

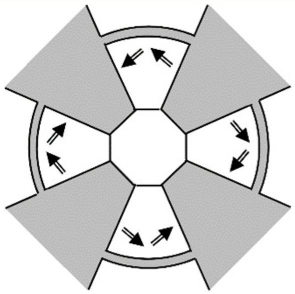
- Magnetization axis and strength errors
- Magnetization inhomogeneities

Position of the poles

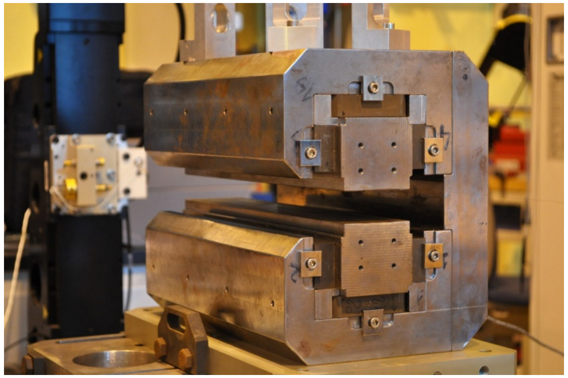
- Poles are independent to each other



Pole displacements



Four poles as a single part [Modena 15]



Positioning of dipole poles at the ESRF

HIGH GRADIENT QUADRUPOLES – HOMOGENEITY

PM blocks flaws

- Magnetization axis and strength
- Magnetization inhomogeneities

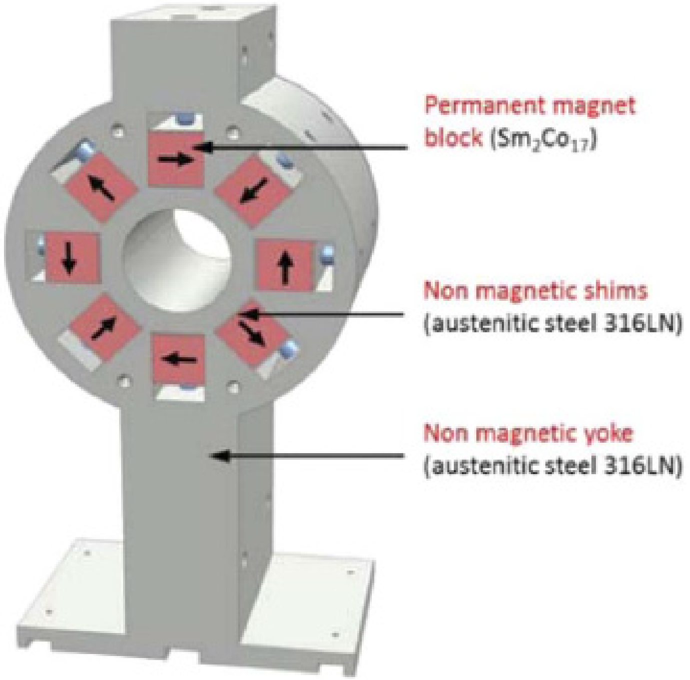
Position of the poles

- Poles are independent to each other

Gradient shimming

- Pole/magnet displacements

[Becker 09, Thonet 16]



Magnet displacements
(Courtersy P. Thonet, [Thonet 16])

HIGH GRADIENT QUADRUPOLES – HOMOGENEITY

PM blocks flaws

- Magnetization axis and strength
- Magnetization inhomogeneities

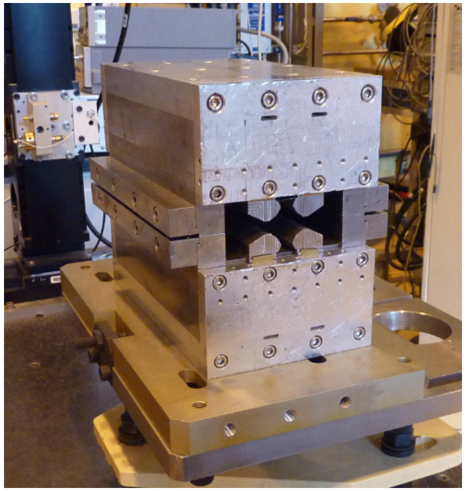
Position of the poles

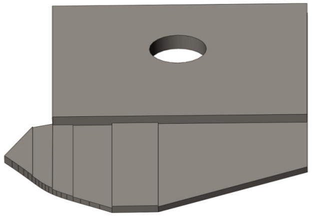
- Poles are independent to each other

Gradient shimming

- Pole/magnet displacements
- Iron parts, machining, etc.

[N'gotta 15]





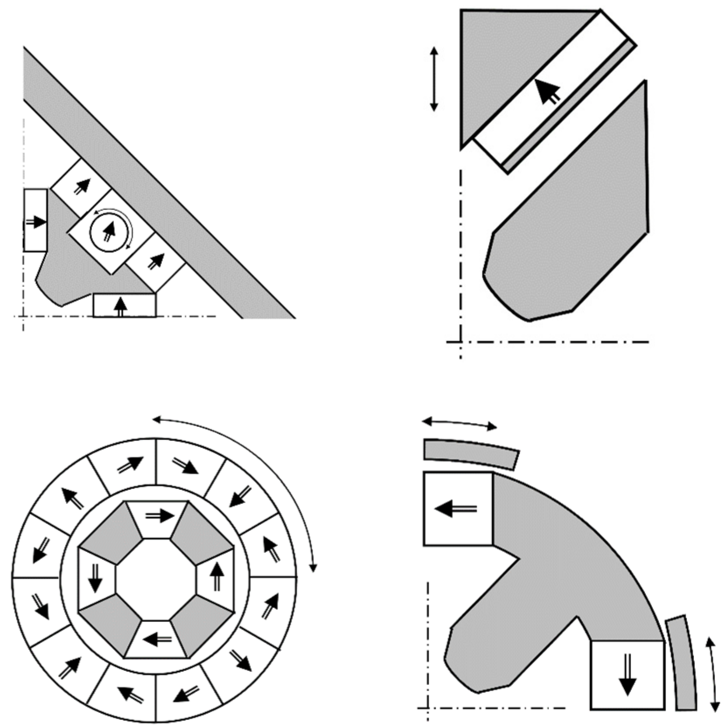
Machined iron shim
(Courtersy P. N'gotta, [N'gotta 15])

HIGH GRADIENT QUADRUPOLES – TUNING THE GRADIENT

Gradient tuning

Mechanical tuners

- Wide tuning range, almost 0−100%
- Almost zero power consumption
- Centre shift observed (± 10 µm to ± 50 µm, depending on the design)
- Reliability of encoders, drivers, etc.?
- PMQs are compact, but this may not be the case for mechanical tuners
- Developments are still in progress



Mechanical tuners [Volk 01, Shepherd 14, Iwashita 06, Bundarchuk 06]

HIGH GRADIENT QUADRUPOLES – TUNING THE GRADIENT

Gradient tuning

Trimming coils

At optimal magnet dimensions:

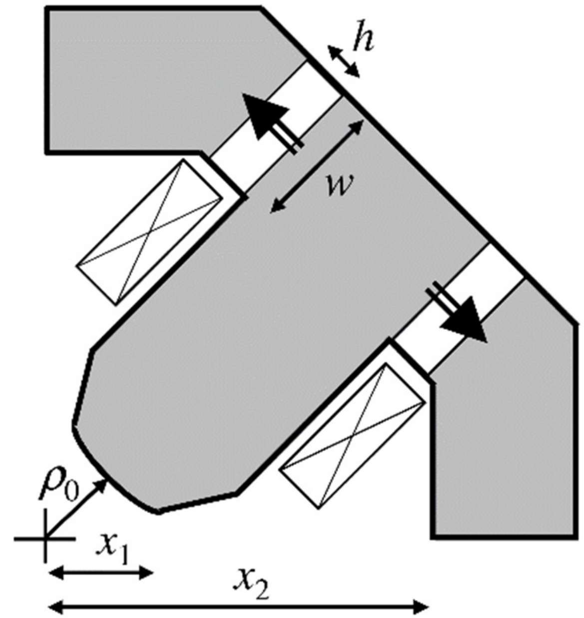
$G = G_{PM} + \mu_0 NI / r_0^2$ (1)

➔ Current efficiency divided by 2!

(Not valid for saturated magnets, which is the case of high gradient PMQ)

Suitable for small tuning ranges

±5% obtained with ±10% of the current without PM

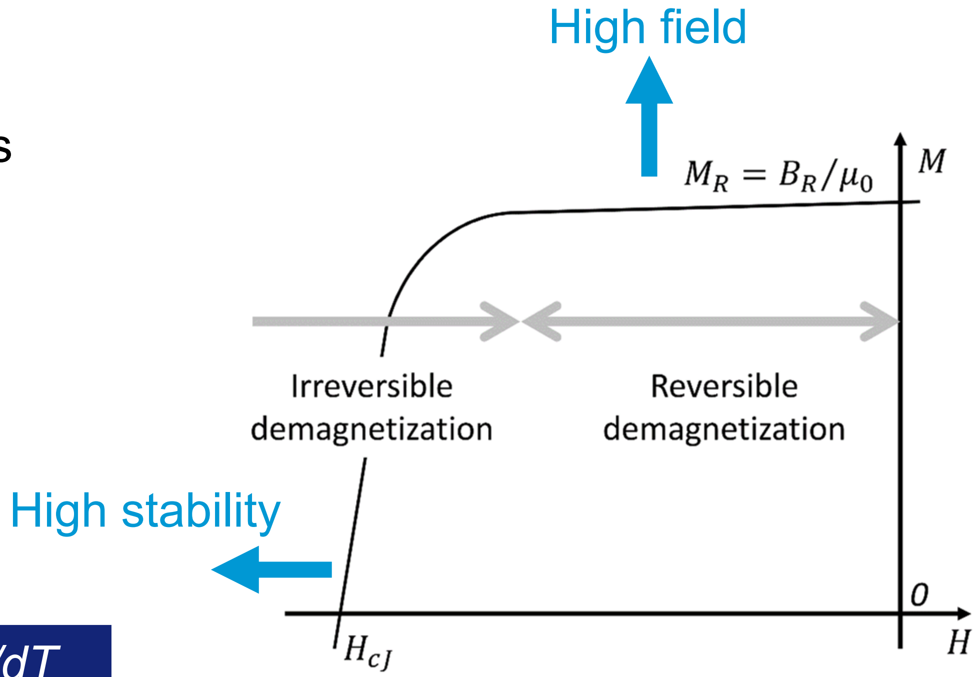


Hybrid quadrupole [Tosin 12]

(1) see proceedings

Warm PM materials

- Rare-Earth / transition metal alloys
- $Nd_2Fe_{14}B$ and Sm_2Co_{17}
- Higher energy product for NdFeB
- Higher resistance to radiation damage for SmCo



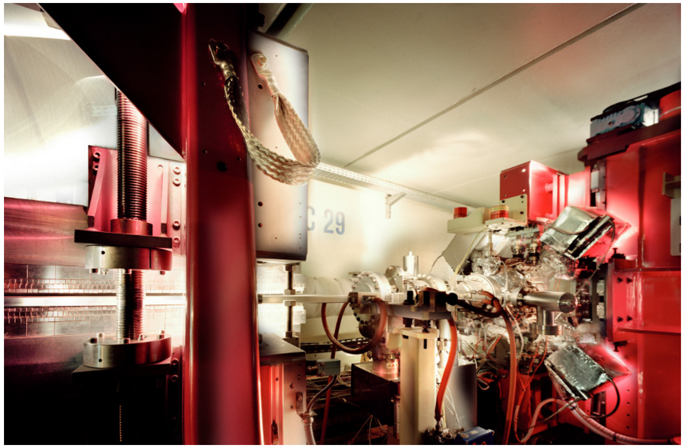
Demagnetization curve

Material	B_R [T]	H_{cJ} [MA/m]	dB_R/dT [10^{-3}/K]
Sm_2Co_{17}	1.05−1.15	0.8−2.1	−0.3
$Nd_2Fe_{14}B$	1.08−1.43	0.8−3	−1

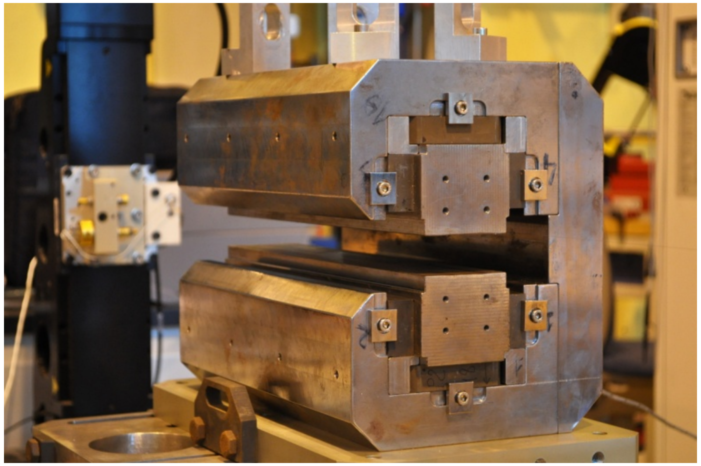
HIGH GRADIENT QUADRUPOLES – PM MATERIALS

Warm PM materials at the ESRF

- NdFeB used in in-air insertion devices
- SmCo used in most in-vacuum undulators
- SmCo+thermal compensation used in the EBS dipoles



Insertion Devices at the ESRF
(Courtesy P. Ginter/ESRF)



PM dipole module

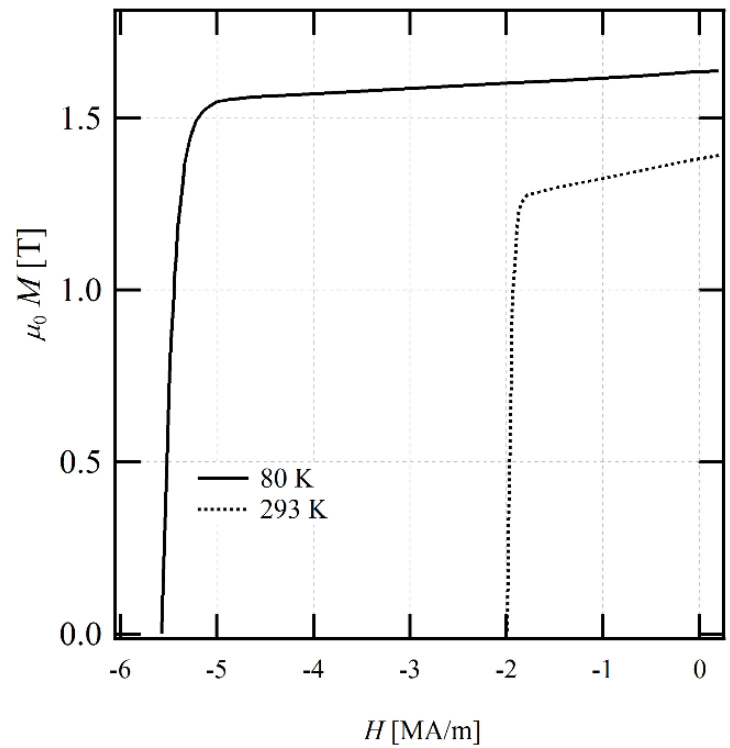
HIGH GRADIENT QUADRUPOLES – PM MATERIALS

Cold PM materials

- NdFeB properties improved at low temperature
- Spin Reorientation Transition at 135 K
  ➔ Optimal temperature ≈150K
- Pr/NdFeB alloys can be used at 80K
- B_R≈1.6 T at 80 K
- H_{cJ}≈−5.6 MA/m ($\mu_0 H_{cJ}$≈ 7 T) at 80 K
- H_{cJ} at 300 K sufficient to avoid demagnetization during assembly

High field, high resistance to radiation damage

[Hara 04]



M(H) curve of a $Pr(0.8)_2Nd(0.2)_2Fe_{14}B$ alloy

HIGH GRADIENT QUADRUPOLES – PM MATERIALS

Cold PM materials

- Cryogenic PM Undulators (CPMUs) installed in a few light sources
- 3 CPMUs at the ESRF: 2 NdFeB + 1 Pr/NdFeB

Characteristics of the last CPMU installed

- 2 m long
- Operated at 80 K
- 5 mm gap
- 15 mm period
- 1 T magnetic field

HIGH GRADIENT QUADRUPOLES – PM MATERIALS

Towards Cryogenic PM quadrupoles?

For Halbach type magnets:

- $G\ r_0 \approx$ 1.5 T (B_R = 1.1 T NdFeB @ 300 K)➔ $G\ r_0 \approx$2 T (Pr/NddFeB @ 80 K)
- $G \approx$ 250 T/m if r_0 = 8 mm (Pr/NdFeB @ 80 K)

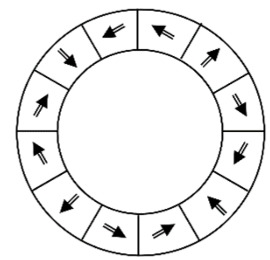
Challenges

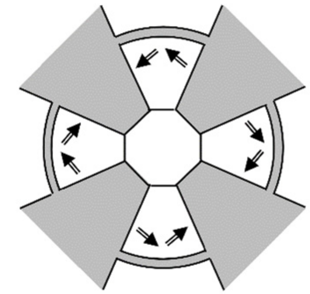
- Vacuum & cryogenics
- Field quality and shimming at low temperature
- Measurement & alignment
- Gradient tuning

PERSPECTIVES

High gradient high field quadrupoles

- Gradient $G \geq 200$ T/m seems achievable at radius $r_0 > 1.5/G$



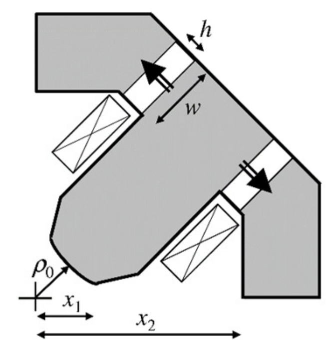


Gradient homogeneity

- Development of shimming methods
- Should be compatible with series production

Gradient tuning

- Trimming coils seems suitable for lightsource applications with reduced tuning range
- Strongly non linear devices due at high gradients and fields



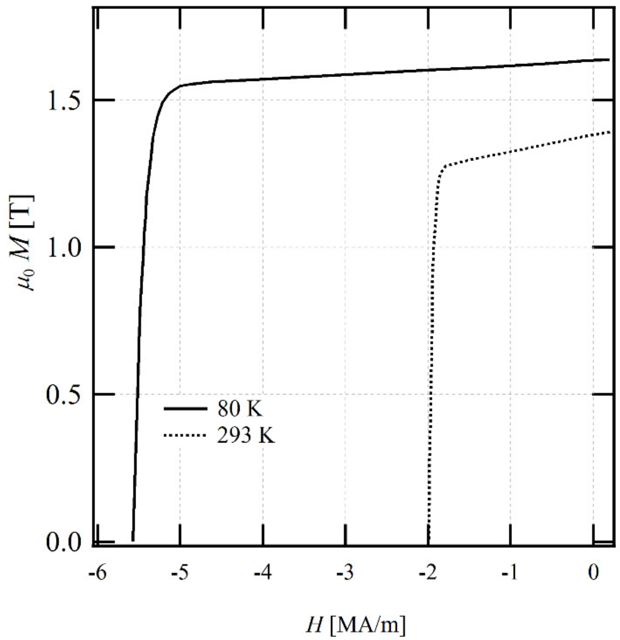
PERSPECTIVES

Cryogenic PM Quadrupoles

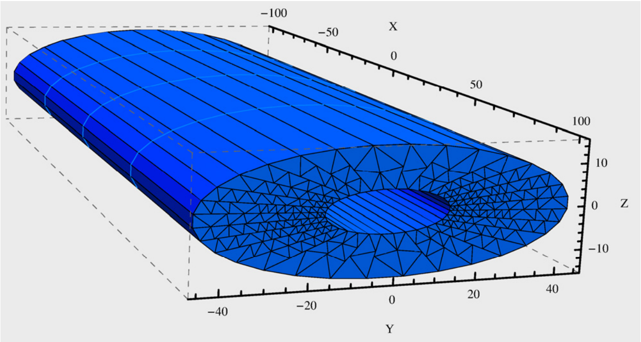
- Higher remanent field
- Higher resistance to radiation damage
- Technologically challenging

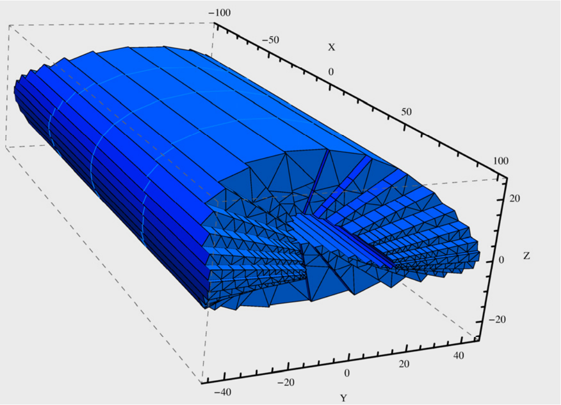
Shape optimization

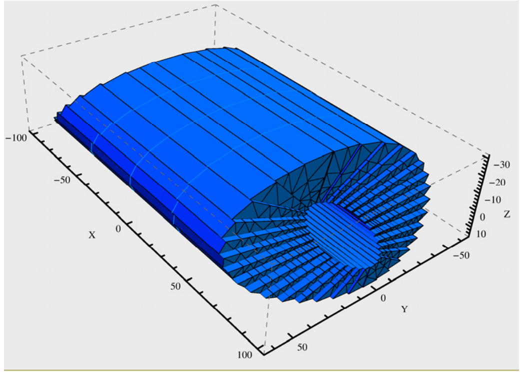
- New PMQ shapes?
- Topologic optimization applied to PMQ



THANK YOU FOR YOUR ATTENTION

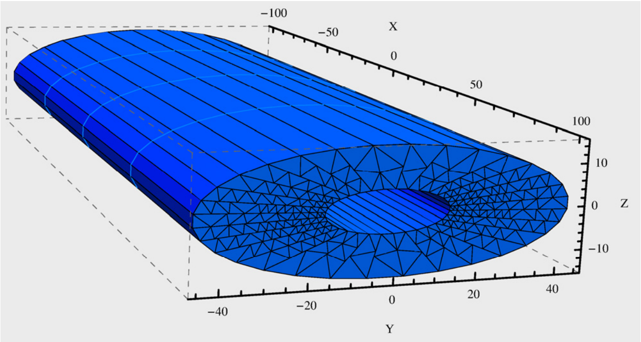


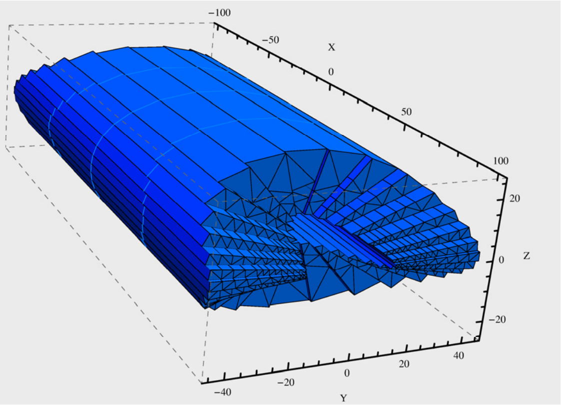


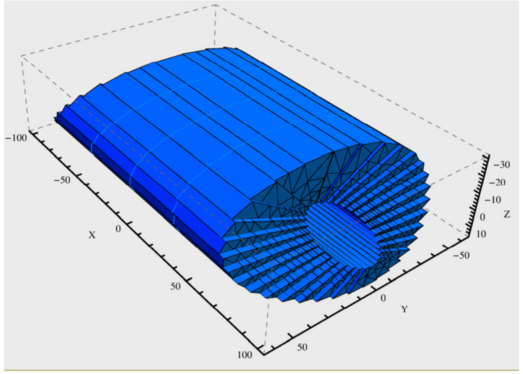


All these magnets are good quadrupoles

THANK YOU FOR YOUR ATTENTION







All these magnets are good quadrupoles at least in simulations…

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