8th International Particle Accelerator Conference

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Review of Permanent Magnet Technology for Accelerators

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ESRF | The European Synchrotron

SOLEIL SYNCHROTRON

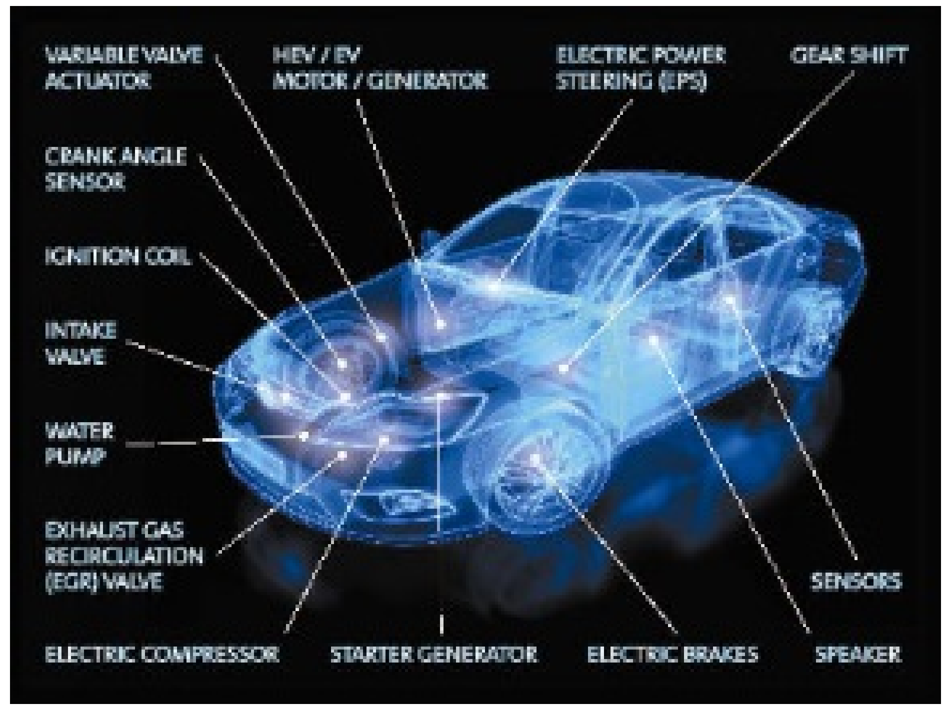
OUTLINE

- **Introduction**
- **Principal characteristics of permanent magnets (PM)**
  - Magnetic performance
  - Material temperature stability
  - Radiation damage
- **Recent PM development in accelerators**
  - High gradient PM Quadrupoles
  - Longitudinal Gradient PM Dipoles for low emittance storage rings (DLSR)
- **Conclusion and perspectives**

INTRODUCTION

Permanent magnets are widely used in our daily life

Consumer electronic industry



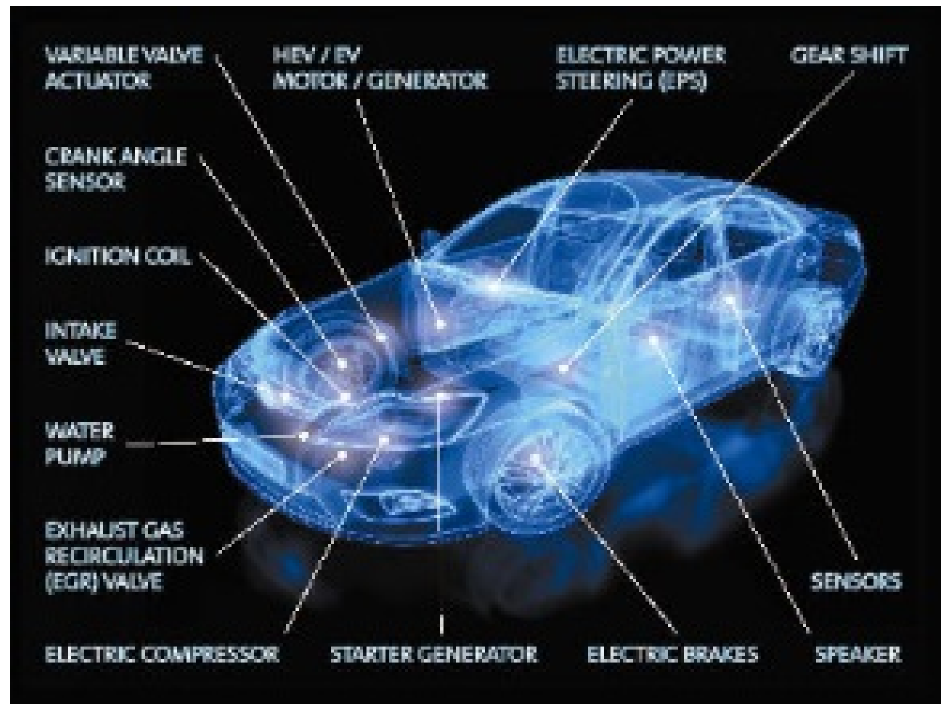
Automotive industry

renewable energy industry

Health industry

Permanent magnets are widely used in our daily life

Consumer electronic industry



Automotive industry

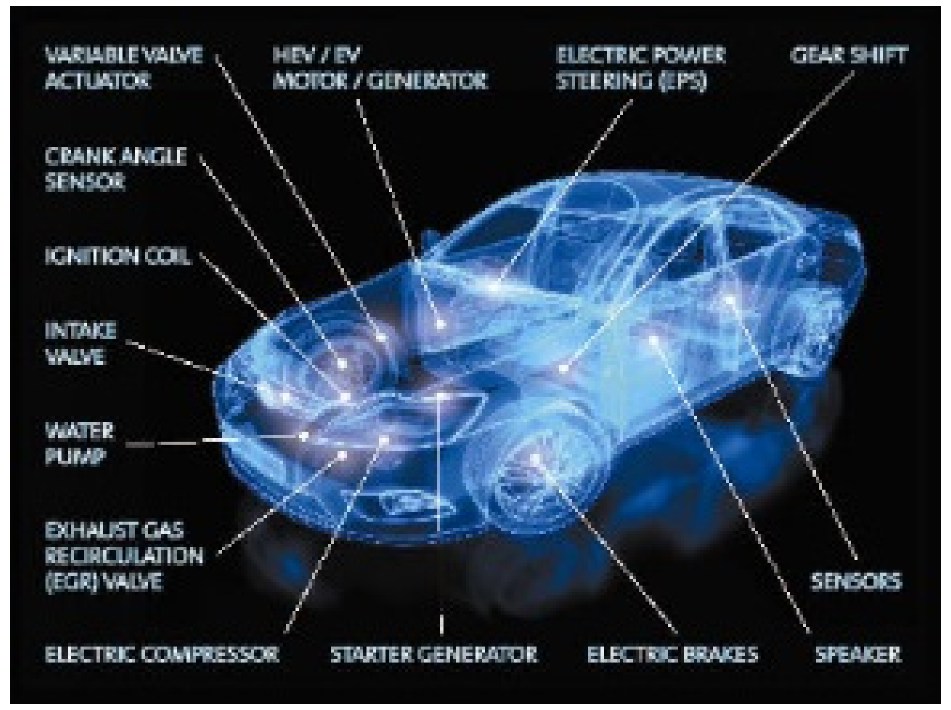
renewable energy industry

Health industry

PM Family	Discovered
Alnico	30's
Ferrites	50's
SmCo	60's
NdFeB	80's

Permanent magnets are widely used in our daily life

Consumer electronic industry



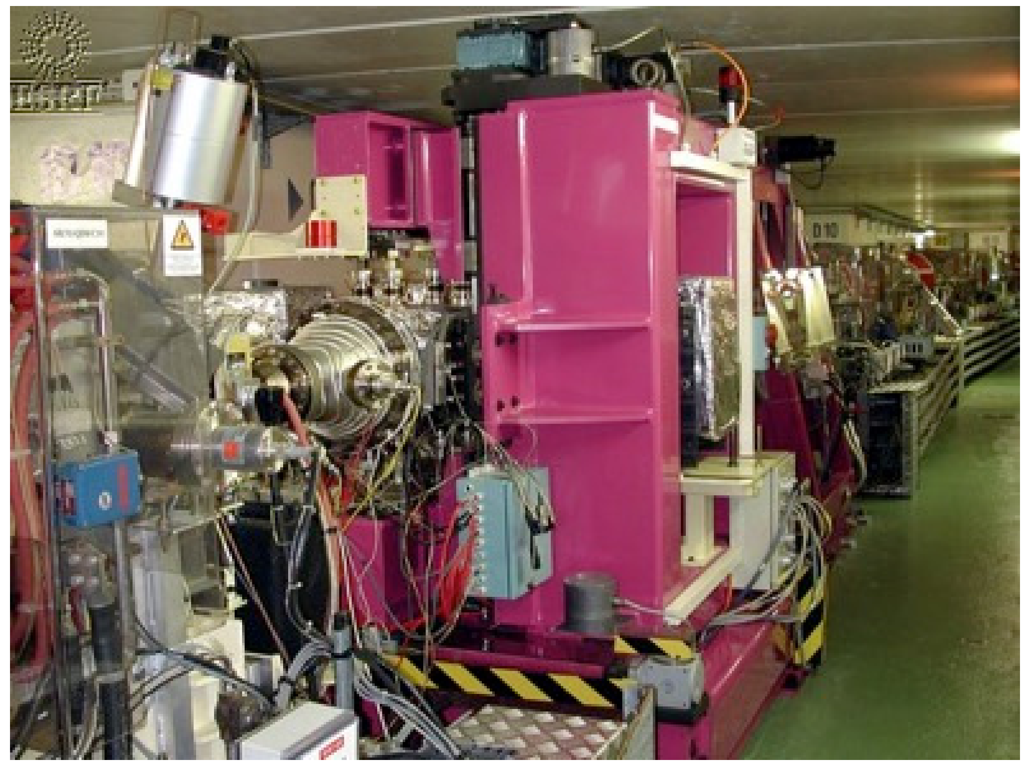
Automotive industry

renewable energy industry

Health industry

PM Family	Discovered
Alnico	30’s
Ferrites	50’s
SmCo	60’s
NdFeB	80’s

Permanent magnets are used in accelerators mainly for insertion devices and for some dedicated devices



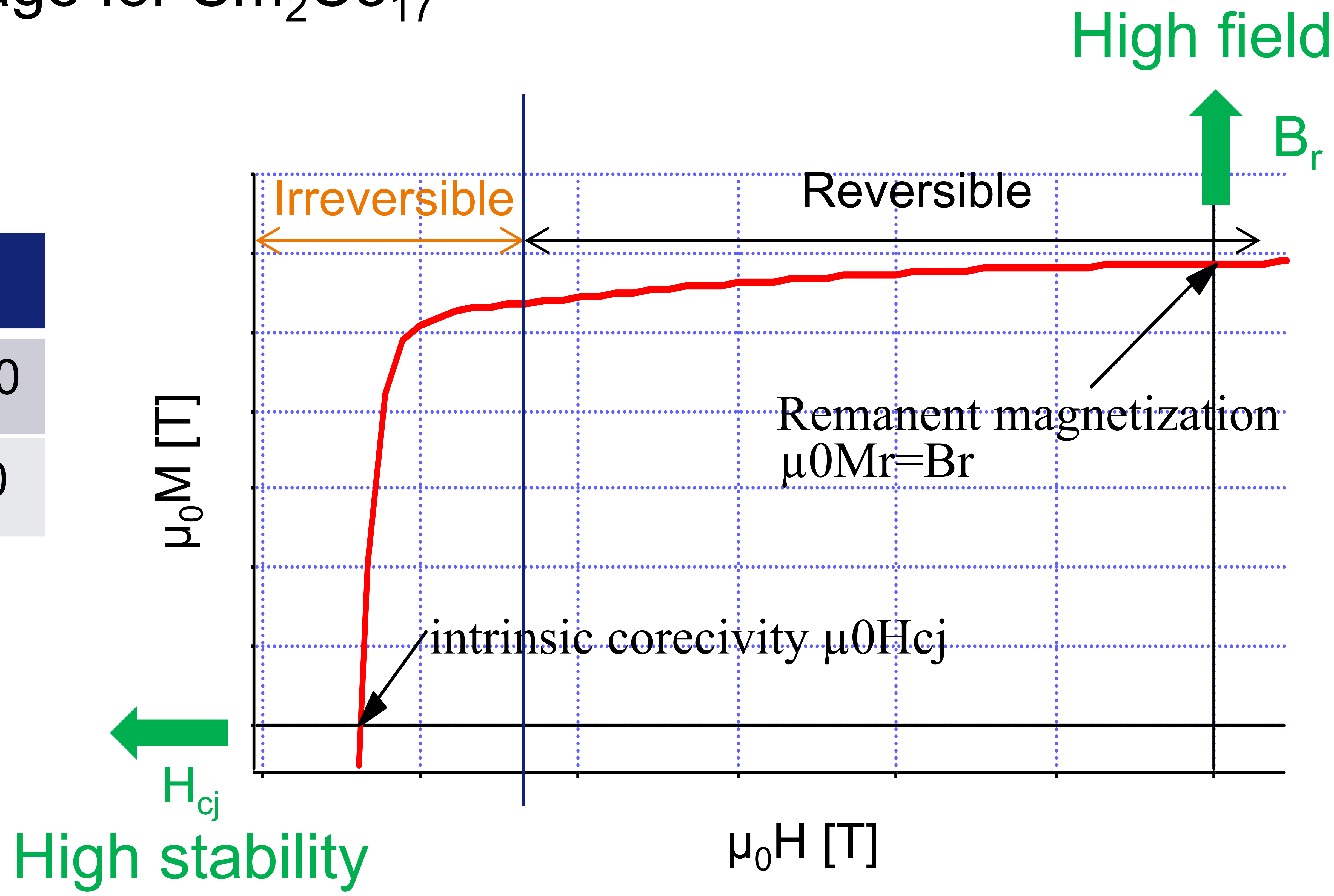
ESRF

SOLEIL

Magnetic performance

- Sm_2Co_{17} and $Nd_2Fe_{14}B$ used for Accelerator devices
- High remnant magnetization for $Nd_2Fe_{14}B$
- High resistance to radiation damage for Sm_2Co_{17}

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

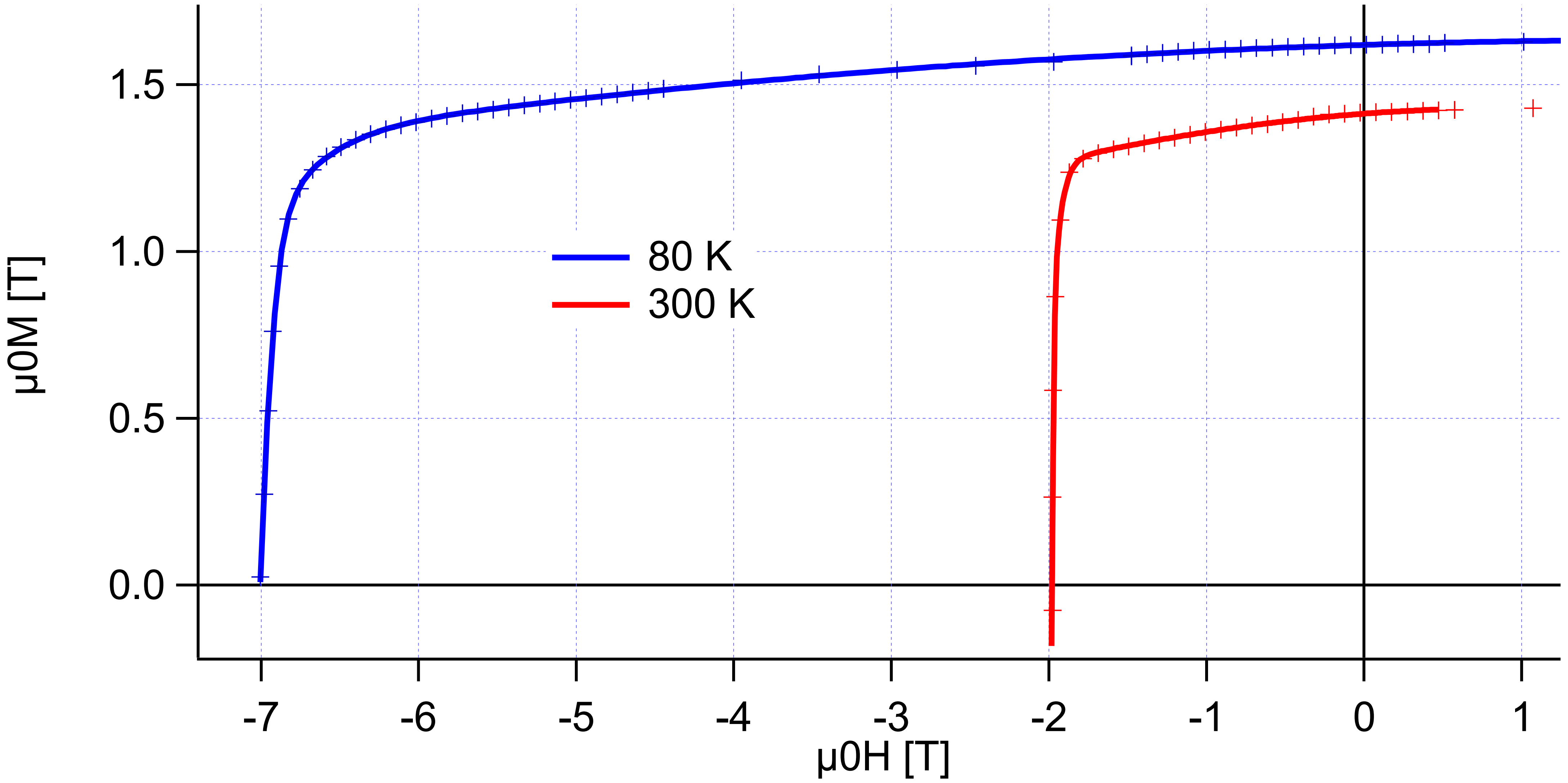


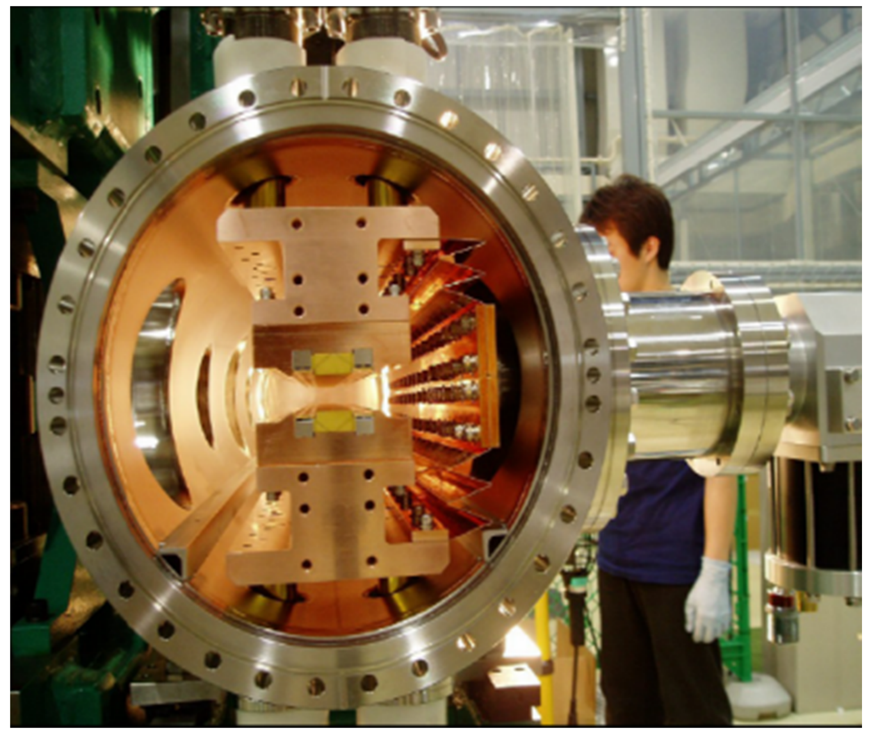
PRINCIPAL CHARACTERISTICS OF PERMANENT MAGNETS

Magnetic performance at low temperature

- Higher performance (B_r and H_{cj}) at cryogenic temperature
- $Nd_2Fe_{14}B$ and $Pr_2Fe_{14}B$ used at cryogenic temperature
- $Nd_2Fe_{14}B$ performance (B_r) limited by the Spin Reorientation Transition around 135 K
- $Pr_2Fe_{14}B$ performance (B_r) not limited by the SRT and can be cooled to 77 K

Type	B_r (%/C)	H_{cj} (%/C)
Sm_2Co_{17}	- 0.03	- 0.2
$Nd_2Fe_{14}B$	- 0.1	- 0.6
$Pr_2Fe_{14}B$	- 0.1	- 0.6





Cryogenic Permanent Magnet Undulator (CPMU)

Br : 1.41 T 300K, 1.62 T @ 80 K
µ0Hc: 2 T @ 300 K, 7 T @ 80 K

Samples provided by Konit (China)

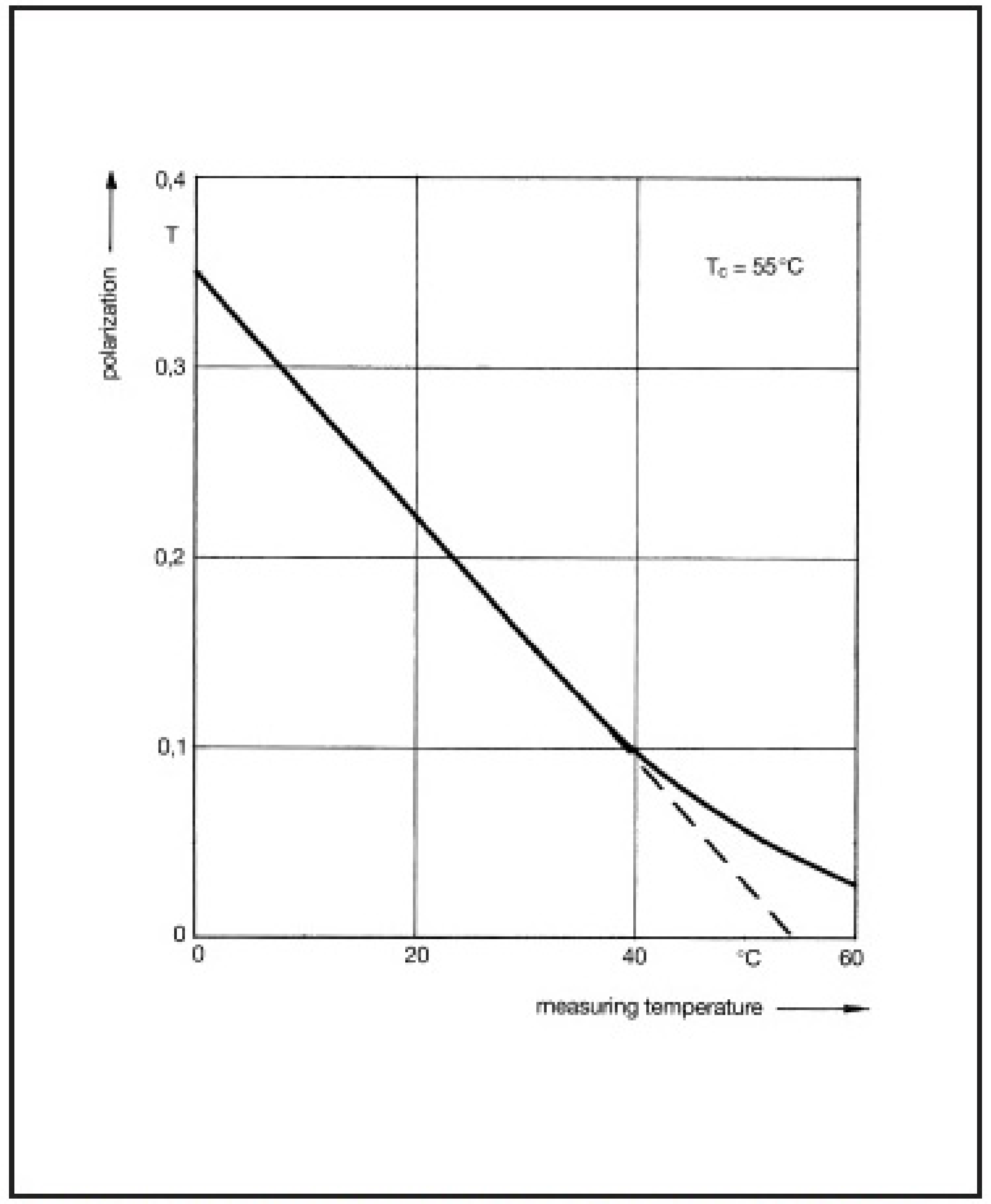
T. Hara et al., *PRSTAB, 7, 050702 (2004)*

PRINCIPAL CHARACTERISTICS OF PERMANENT MAGNETS

Material temperature stability

- PM performance are temperature dependent
- PM devices with fixed field should be compensated
- Use of passive correction with Fe-Ni allow
- dB/B < 10^{-5}/C after compensation

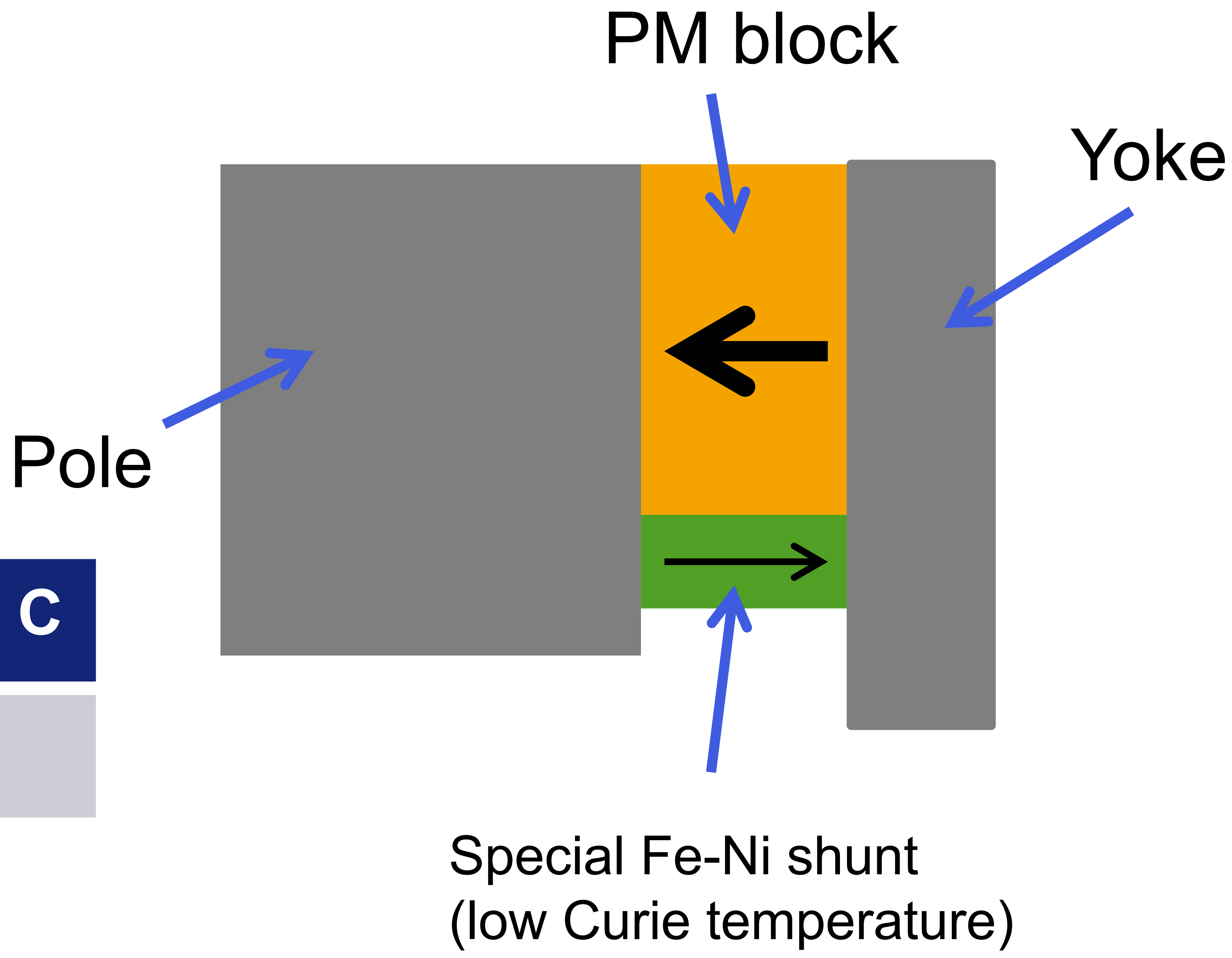
Material	dB/dT
Sm_2Co_{17}	– 3.3 10^{-4}
$Nd_2Fe_{14}B$	– 10^{-3}



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

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

THERMOFLUX (VACUUMSCHMELZE)



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

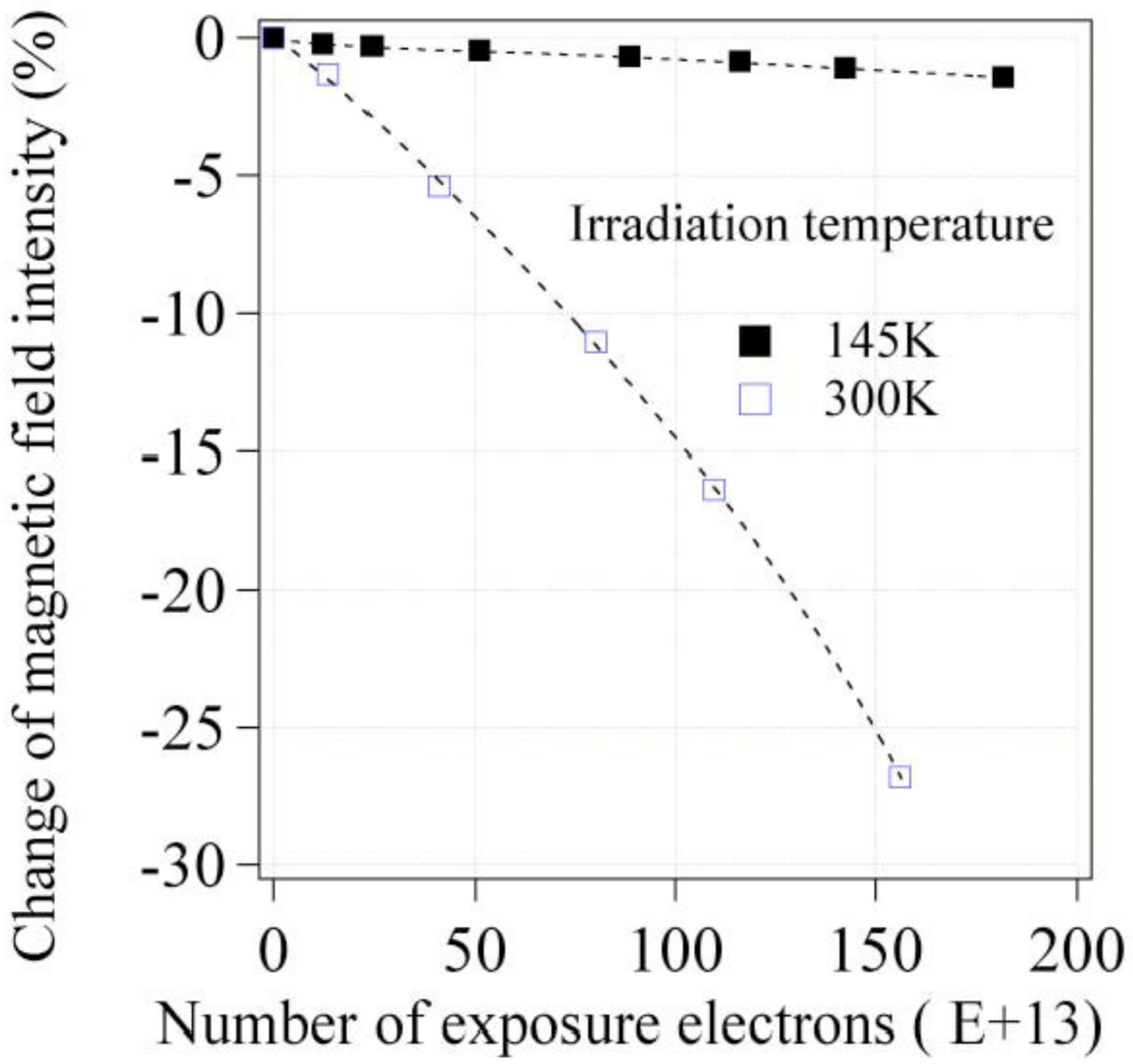
PRINCIPAL CHARACTERISTICS OF PERMANENT MAGNETS

Radiation damage

- Radiation exposure leads to demagnetization of permanent magnet
  - Sm_2Co_{17} has a higher resistance to radiation damage (high coercivity H_{cj})
  - Demagnetization depends on magnet shape and working point in the magnet

- Effect similar to that of a thermal partial demagnetization

- Undulator damaged by radiation in several facilities (ESRF, APS, PETRA III)
- The radiation damage risk has increased with the development of small gap devices (in-vacuum IDs)
- CPMUs Have better resistance to radiation damage risks (very high coercivity H_{cj})



$Nd_2Fe_{14}B$ (NEOMAX BH50)

T. Bizen, *ERL 2011, Tsukuba, Japan, p. 121-126, (2011)*

T. Bizen, *NIMA, 467-468, p. 185-189, (2001)*

HIGH GRADIENT PM QUADRUPOLES

High gradient quadrupoles are of great interest for

- Colliders
- Free Electron Lasers
- Low emittance storage rings

HIGH GRADIENT PM QUADRUPOLES

High gradient quadrupoles are of great interest for

- Colliders
- Free Electron Lasers
- Low emittance storage rings

Permanent magnets are a good candidate for this type of device

⬇

Small surfaces with high magnetisation
No power consumption and no water cooling

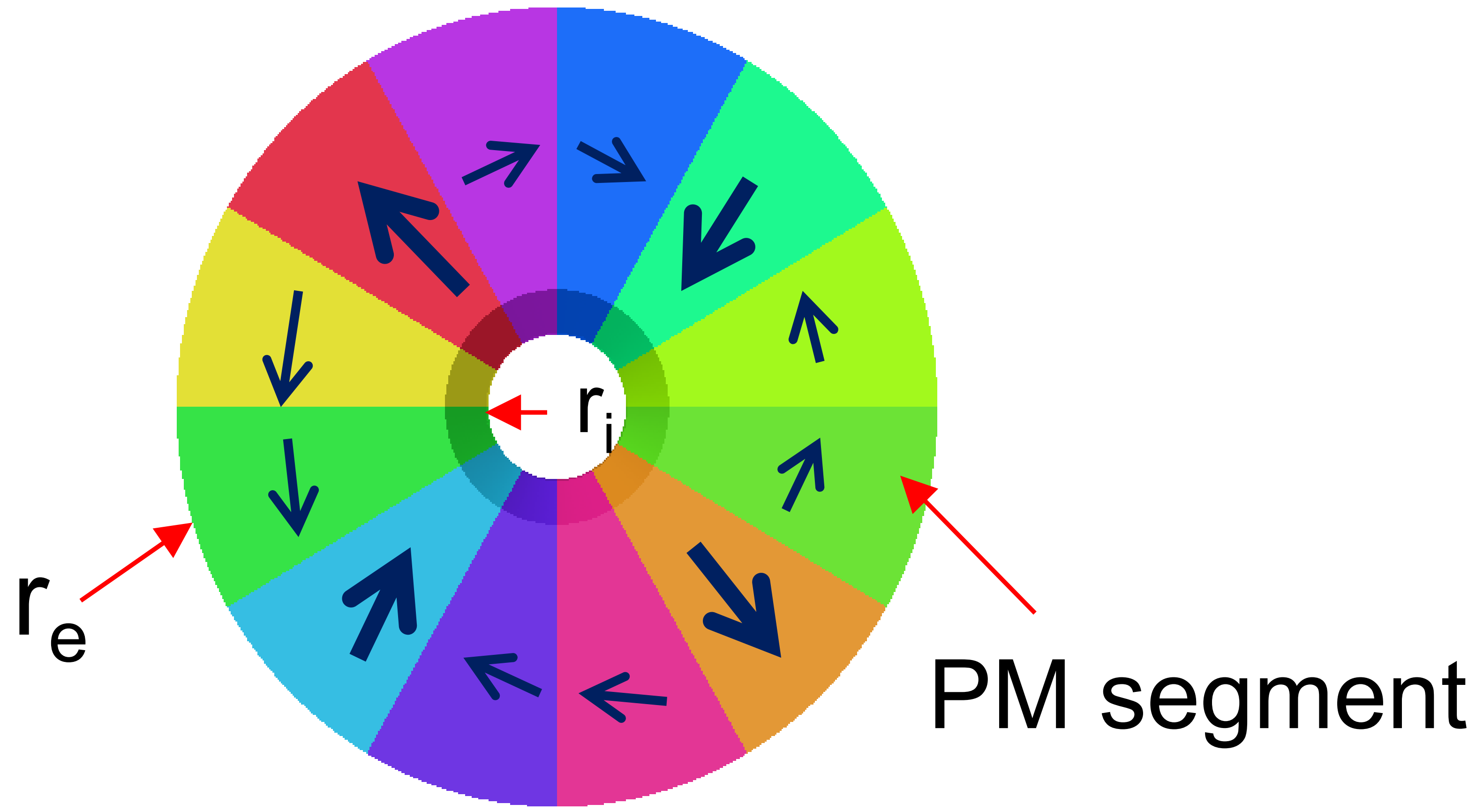
HIGH GRADIENT PM QUADRUPOLES

Fixed gradient PM quadrupoles

- Ultra high gradient
- Very compact devices
- Homogeneity very sensitive to PM quality
  - Remnant magnetization variation
  - Magnetization angle variation
  - Mechanical assembly
- No Tunability

Halbach permanent magnet quadrupole

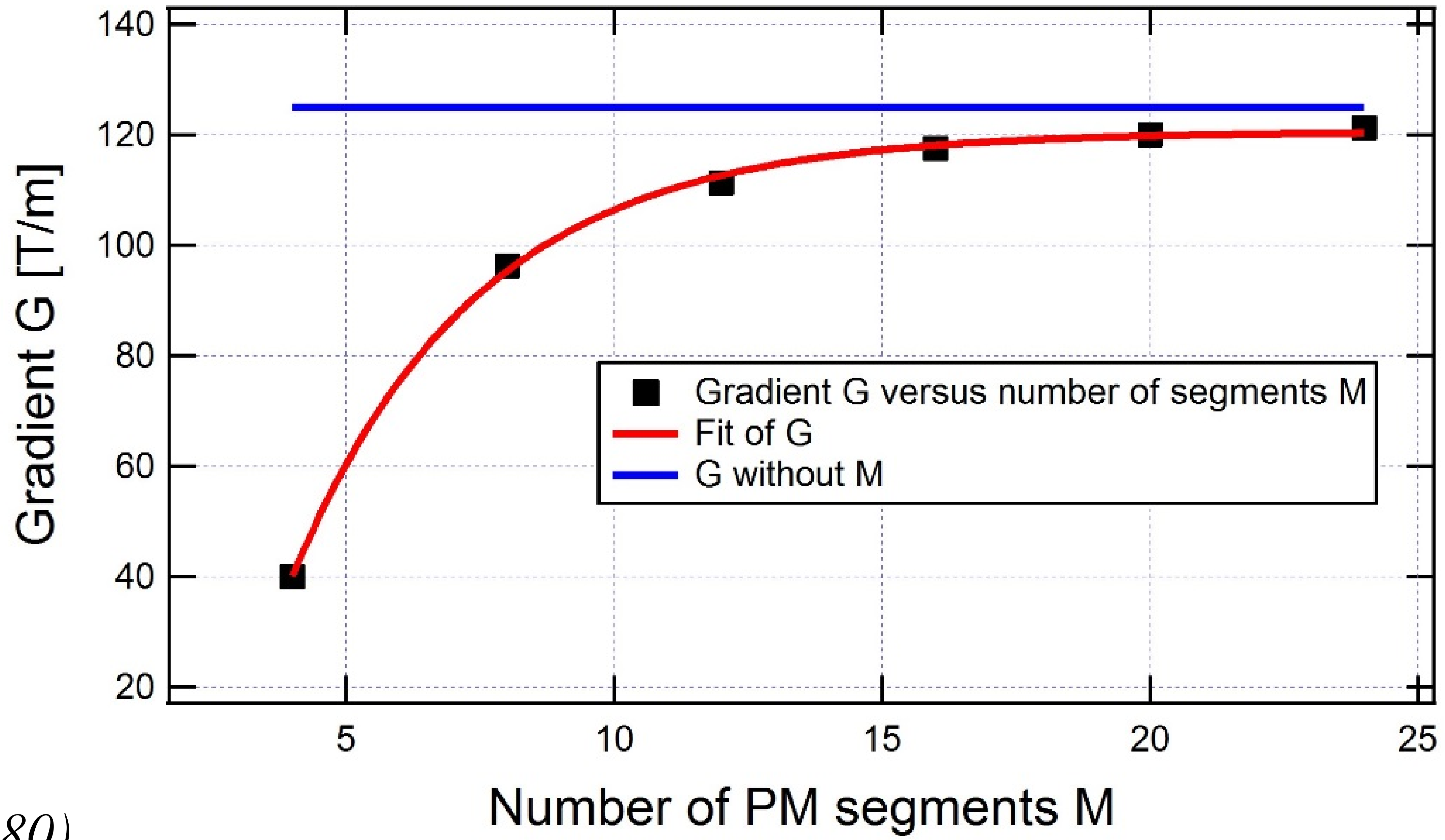
$$G = 2Br\left(\frac{1}{r_i} - \frac{1}{r_e}\right)K$$



K depends on the number of segments M

M	4	8	12	16	20	24
K	0.32	0.77	0.89	0.94	0.96	0.97

r_i = 10 mm
r_e = 20 mm
B_r = 1.25 T
G = 125 T/m

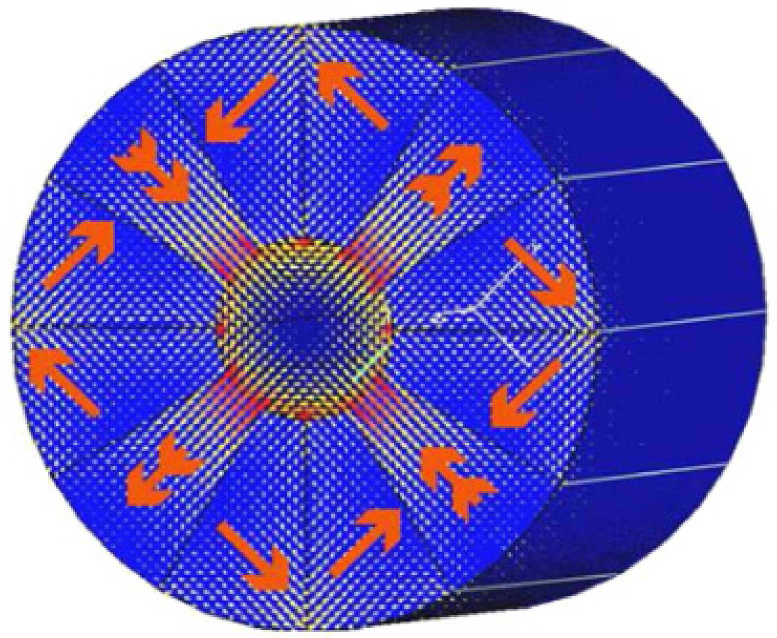


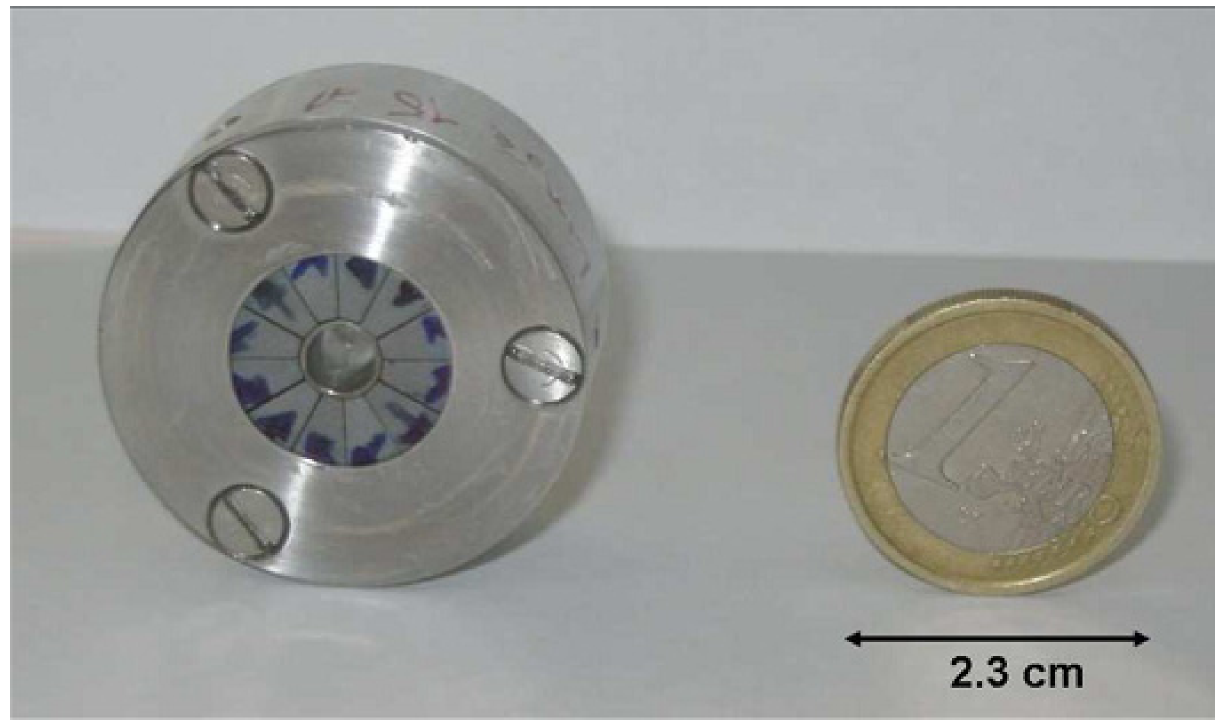
K. Halbach, *NIM 169, p. 1-10, (1980)*

Fixed gradient PM quadrupoles

PPM Halbach PMQ

Gradient	500 T/m
Bore radius	3 mm
Tunability	No



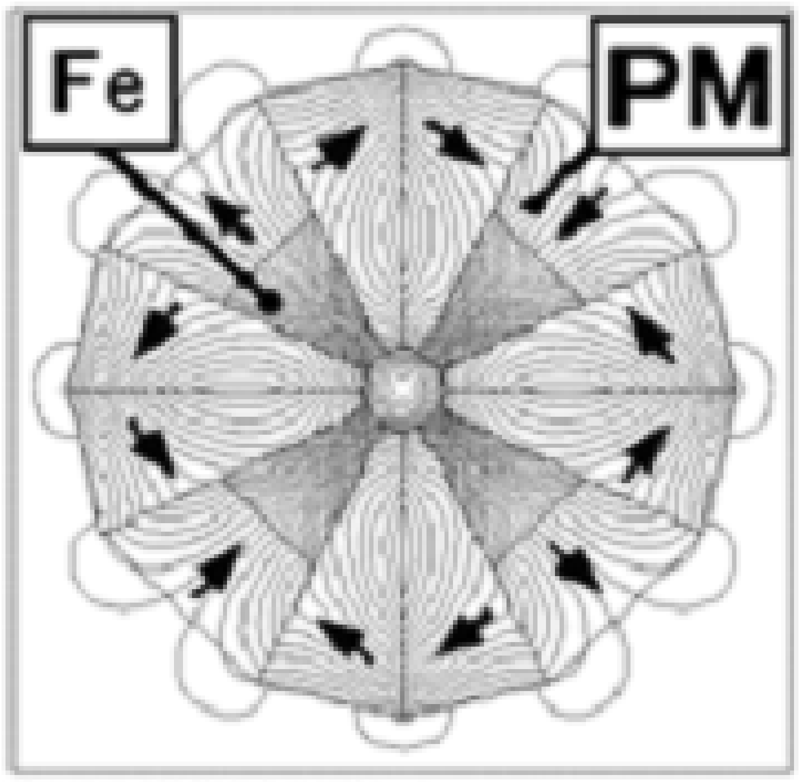


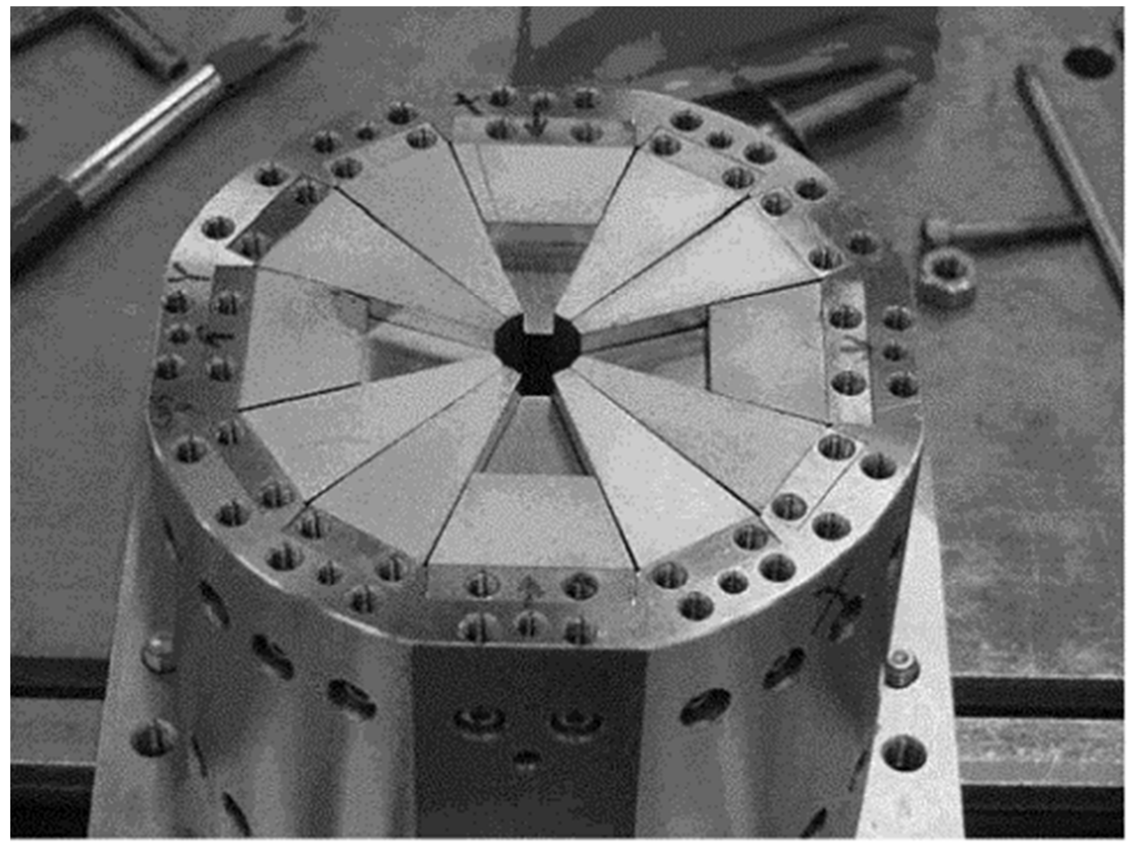
T. Eichner et al., *PRST, 10, 082401 (2007)*

J.K. Lim et al., *PRST, 8, 072401 (2005)*

Hybrid Halbach PMQ

Gradient	115 T/m
Bore radius	7 mm
Tunability	No



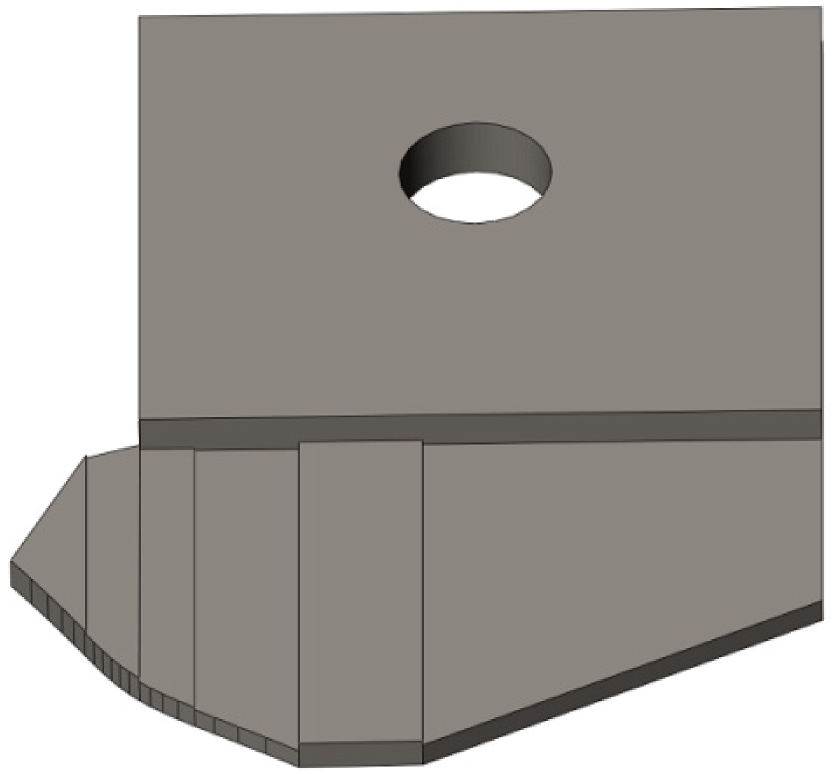


T. Mihara et al., *SLAC – PUB – 10248, February 2004*

Fixed gradient PM quadrupoles

- Dominated Iron quadrupole
- Good field homogeneity
- Moderate gradient field
- No Tunability

Gradient	80 T/m
Bore radius	12.5 mm
Tunability	No



Field correction shim

r = 7 mm,

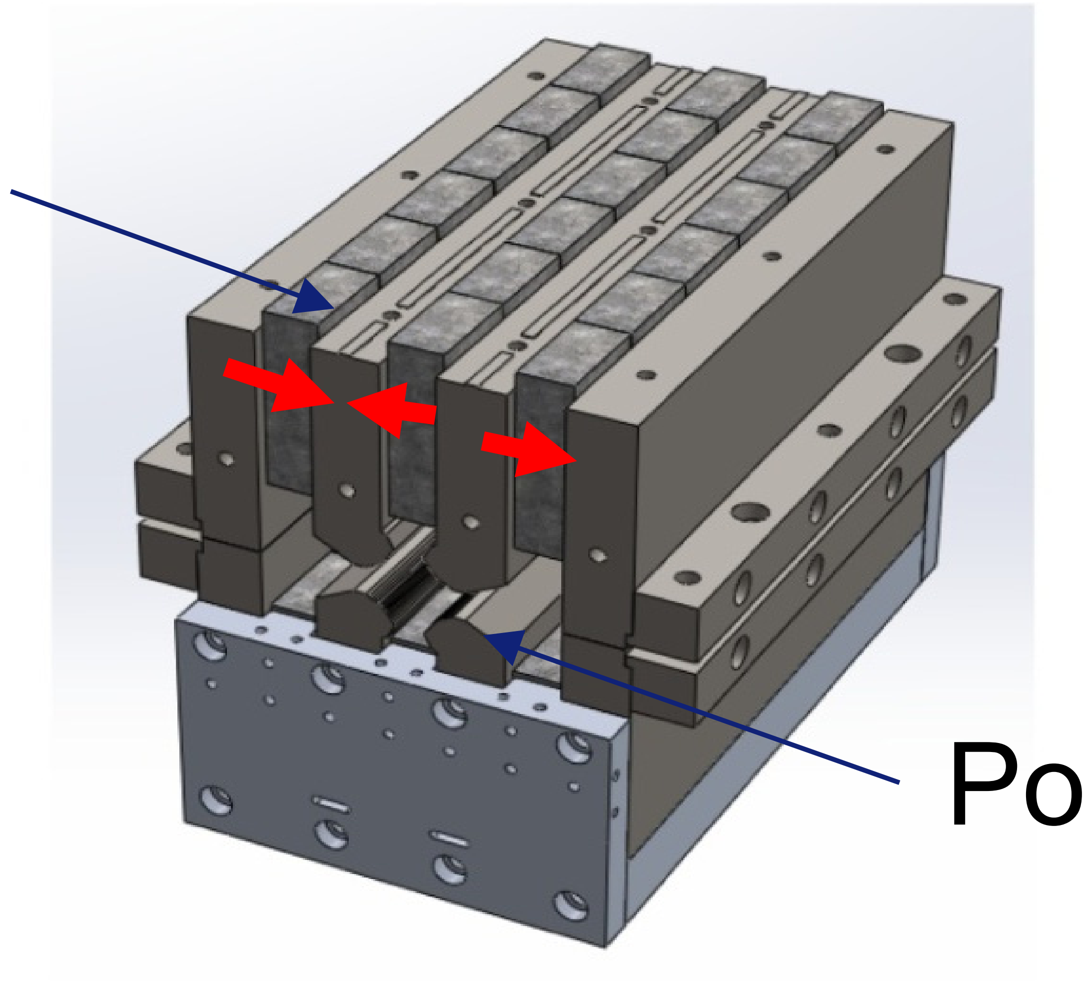
$(b_n / b_2) \cdot 10\,000$

$b_3 = -1.3$

$b_4 = 3$

$b_6 = -8.4$

$b_{10} = -7$



P. N'gotta et al., *PRAB, 19, 122401 (2016)*

HIGH GRADIENT PM QUADRUPOLES

Variable gradient PM quadrupoles

- Hybrid or dominated iron devices
- High and variable gradient
- Different type of gradient tunability
  - Displacement parts
  - Rotation parts
  - Additional coils

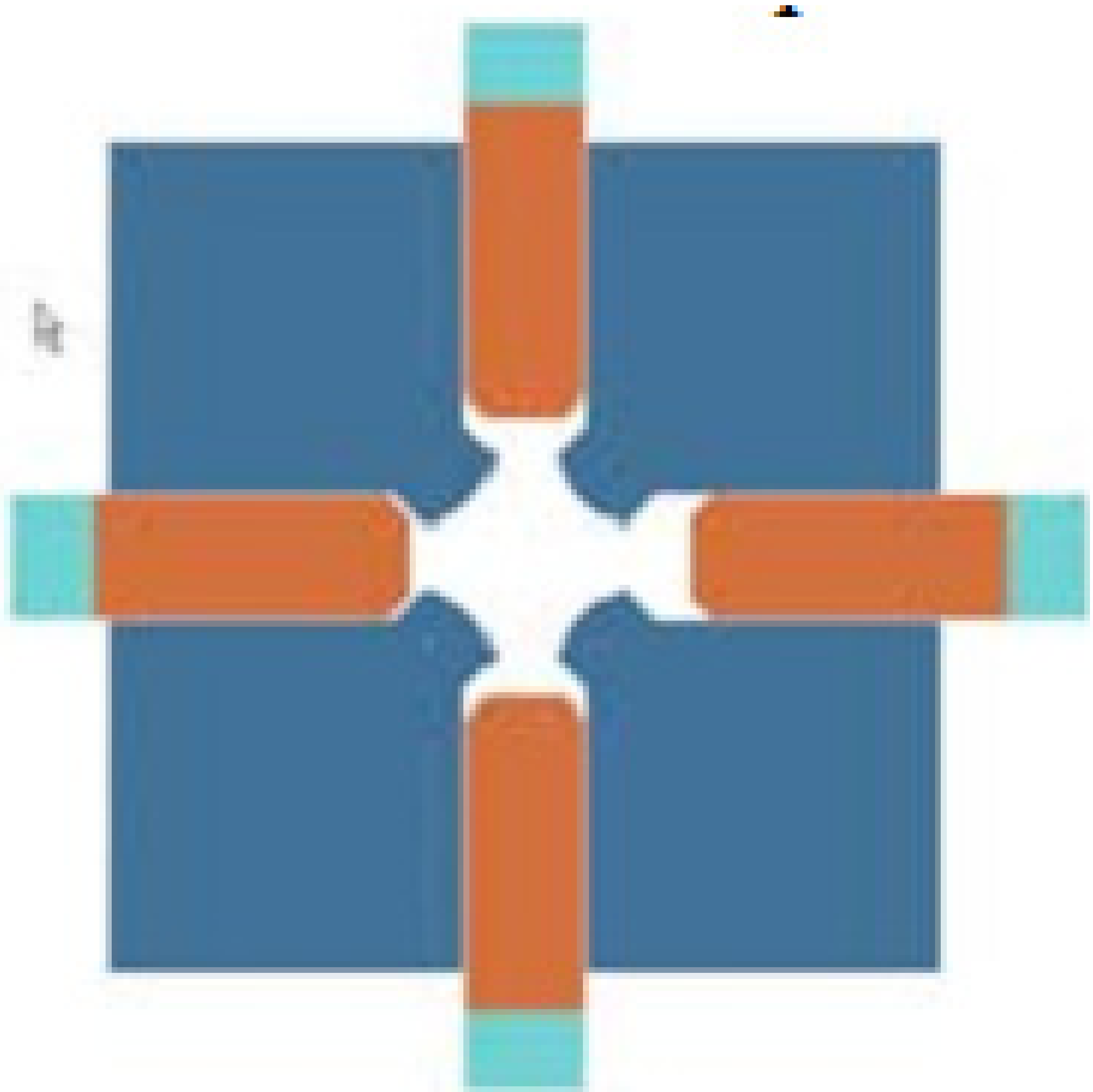
- Precision and reliability depends on motors and encoders
- Magnetic center shift with gradient variation

HIGH GRADIENT PM QUADRUPOLES

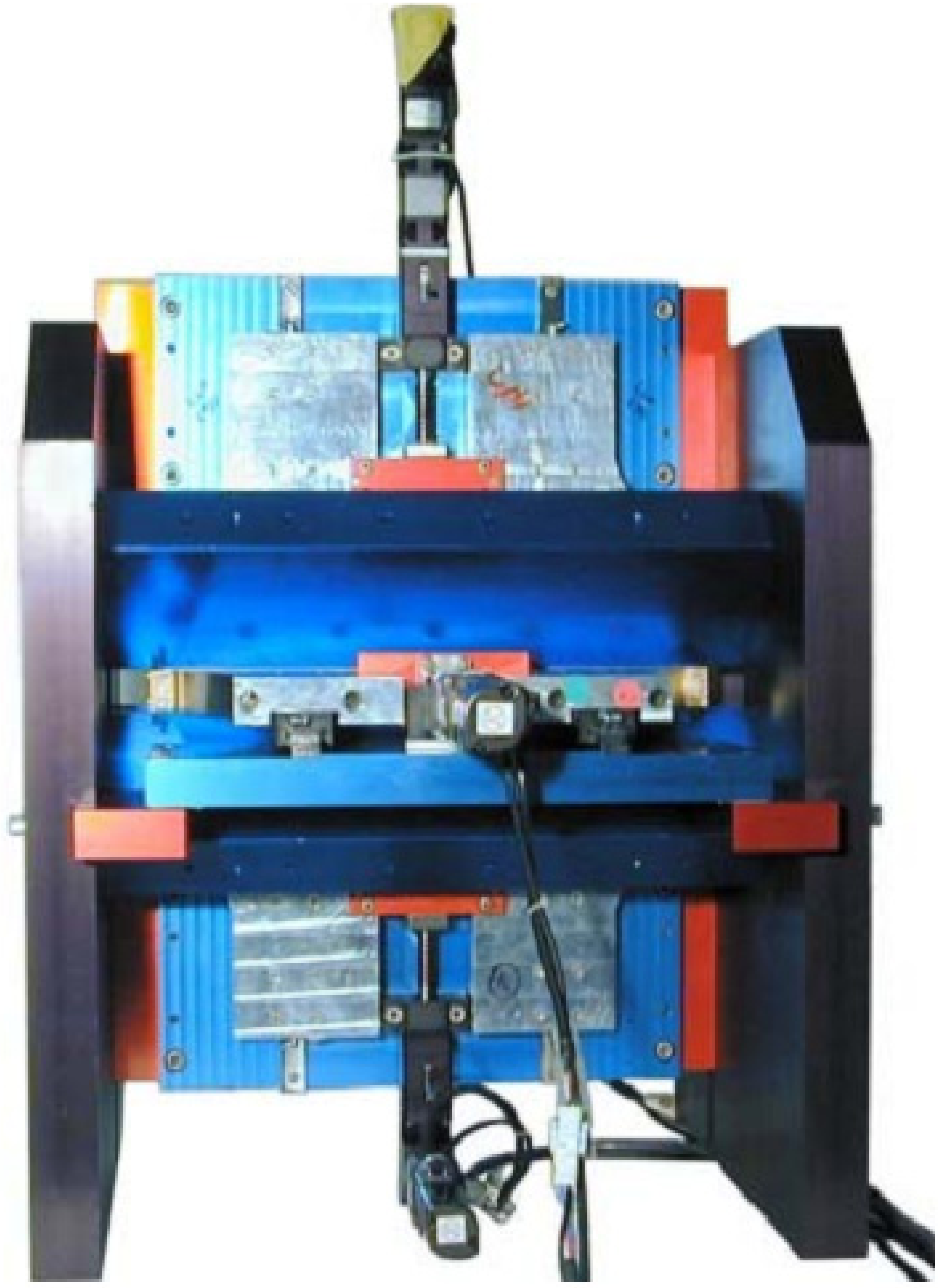
Variable gradient PM quadrupoles

- Dominated iron quadrupole
- Fixed poles and yoke, displacement of all PMs
- Moderate and variable gradient
- A motor for the displacement of each PM
- Magnetic center shift calibrated using PM position

Bore radius	6.5 mm
Max Gradient	115 T/m
Min Gradient	13 T/m
Magnetic center shift	2.5 µm



PMs linear retraction



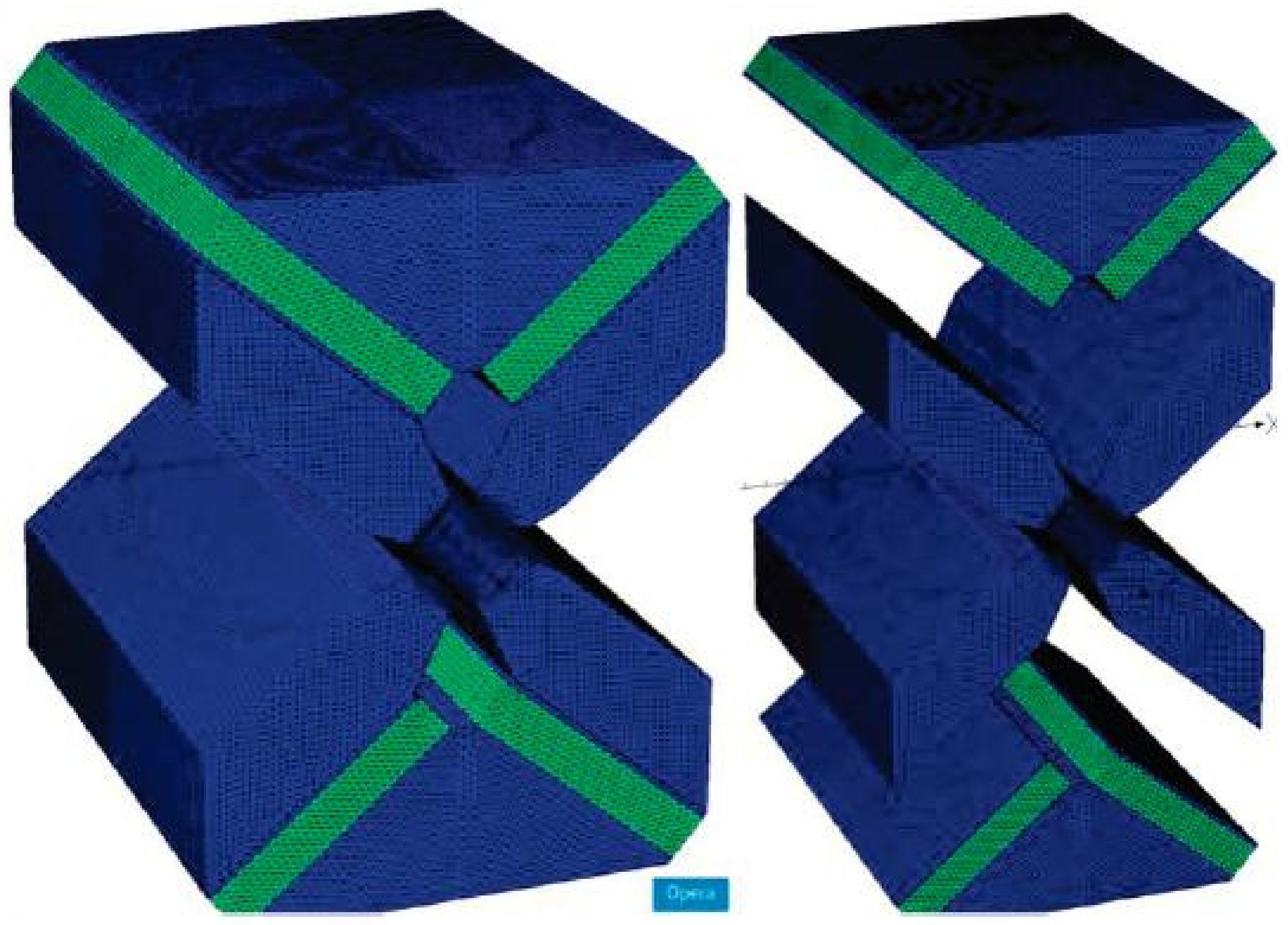
***S. C. Gottschalk** et al., PAC05, Knoxville, USA, 2005*

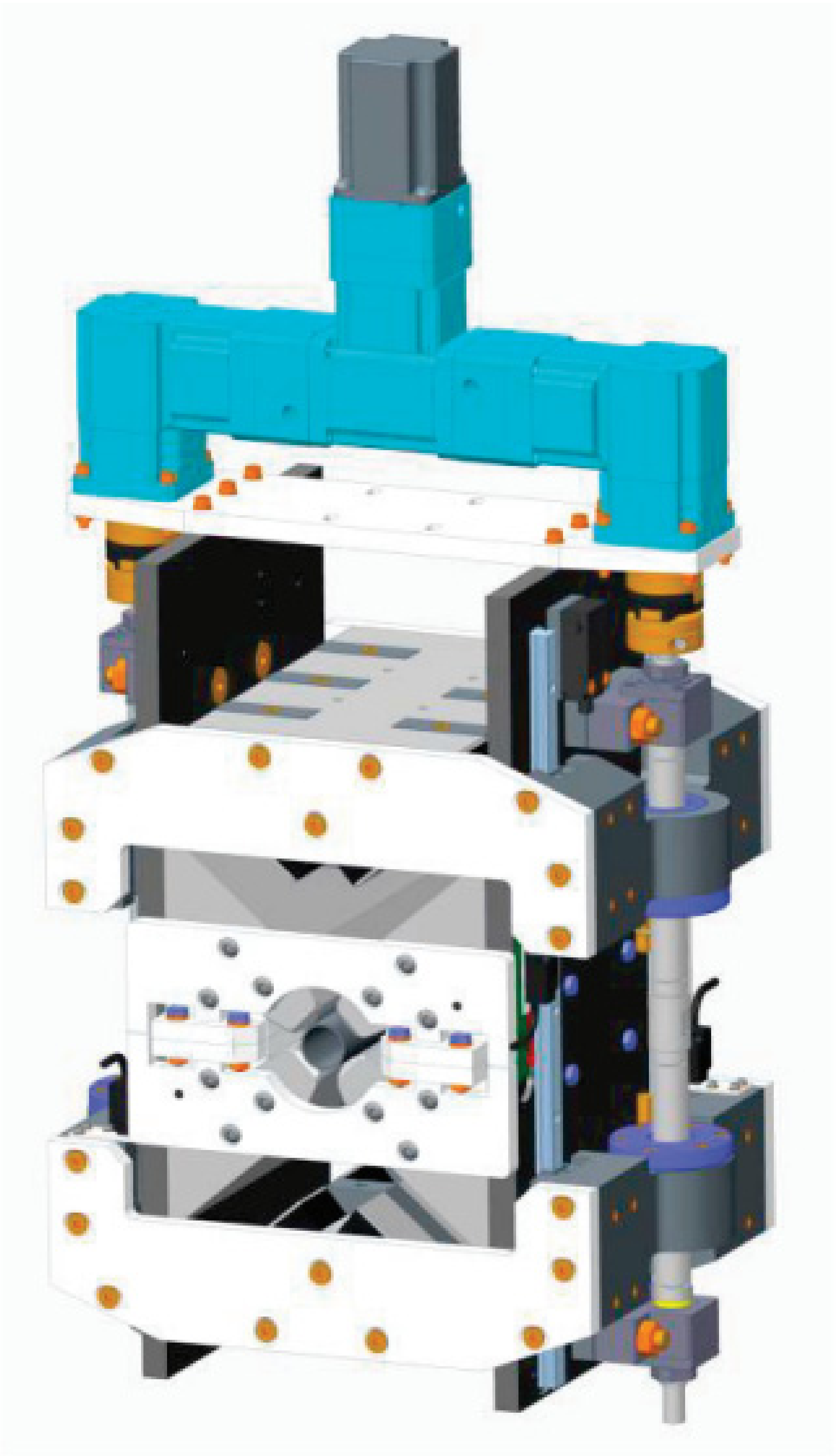
Variable gradient PM quadrupoles

Displacement parts (PMs and yoke)

- Dominated iron quadrupole
- Fixed poles and vertical displacement of PMs and yoke
- Moderate and variable gradient
- High Magnetic center shift
- One motor and gearboxes for the displacement of both parts

Bore radius	13.6 mm
Max Gradient	60 T/m
Min Gradient	15 T/m
Magnetic center shift	100 µm





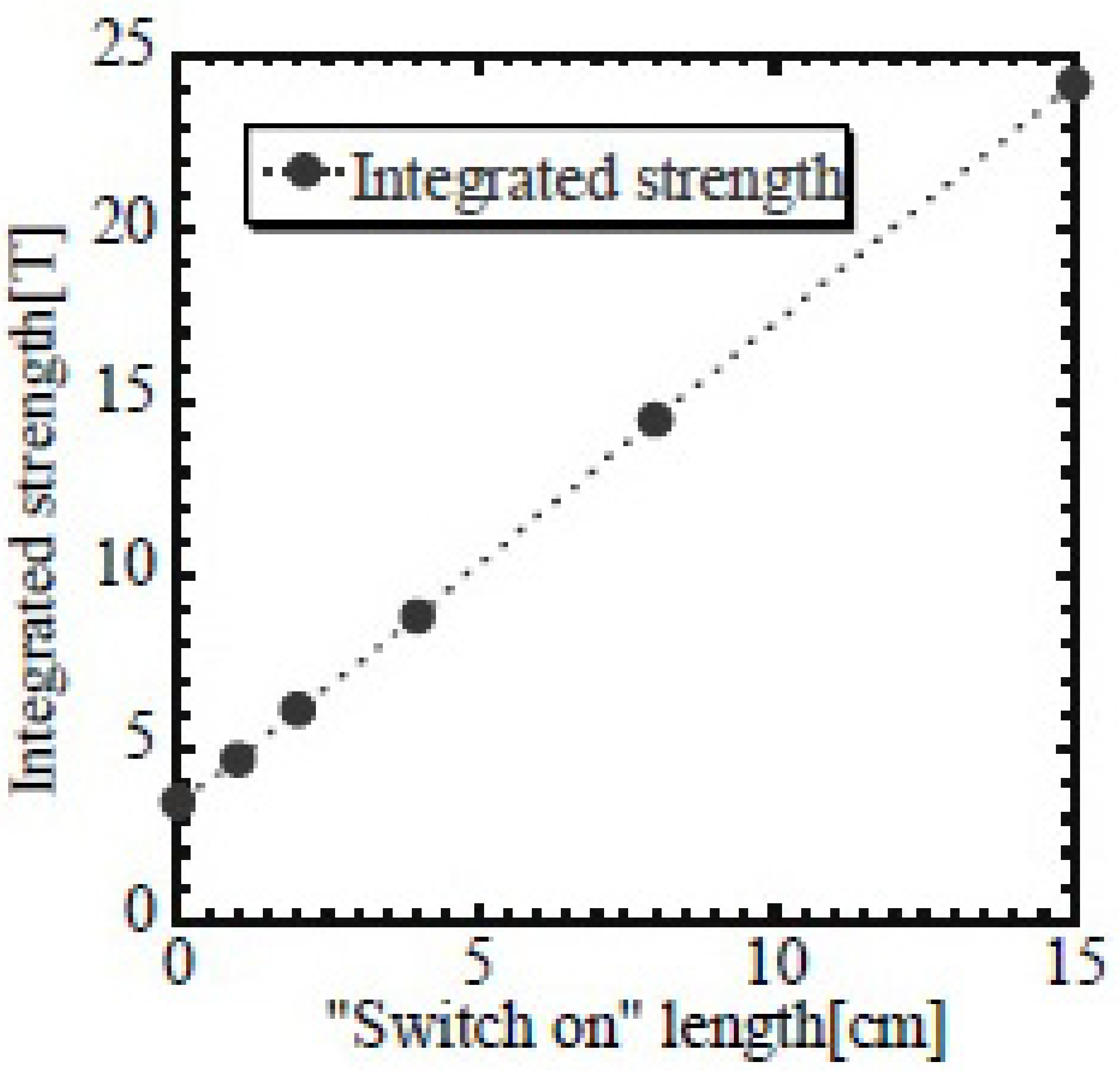
***B.J.A. Shepherd** et al., IPAC13, Shanghai, China, 2013*

Variable gradient PM quadrupoles

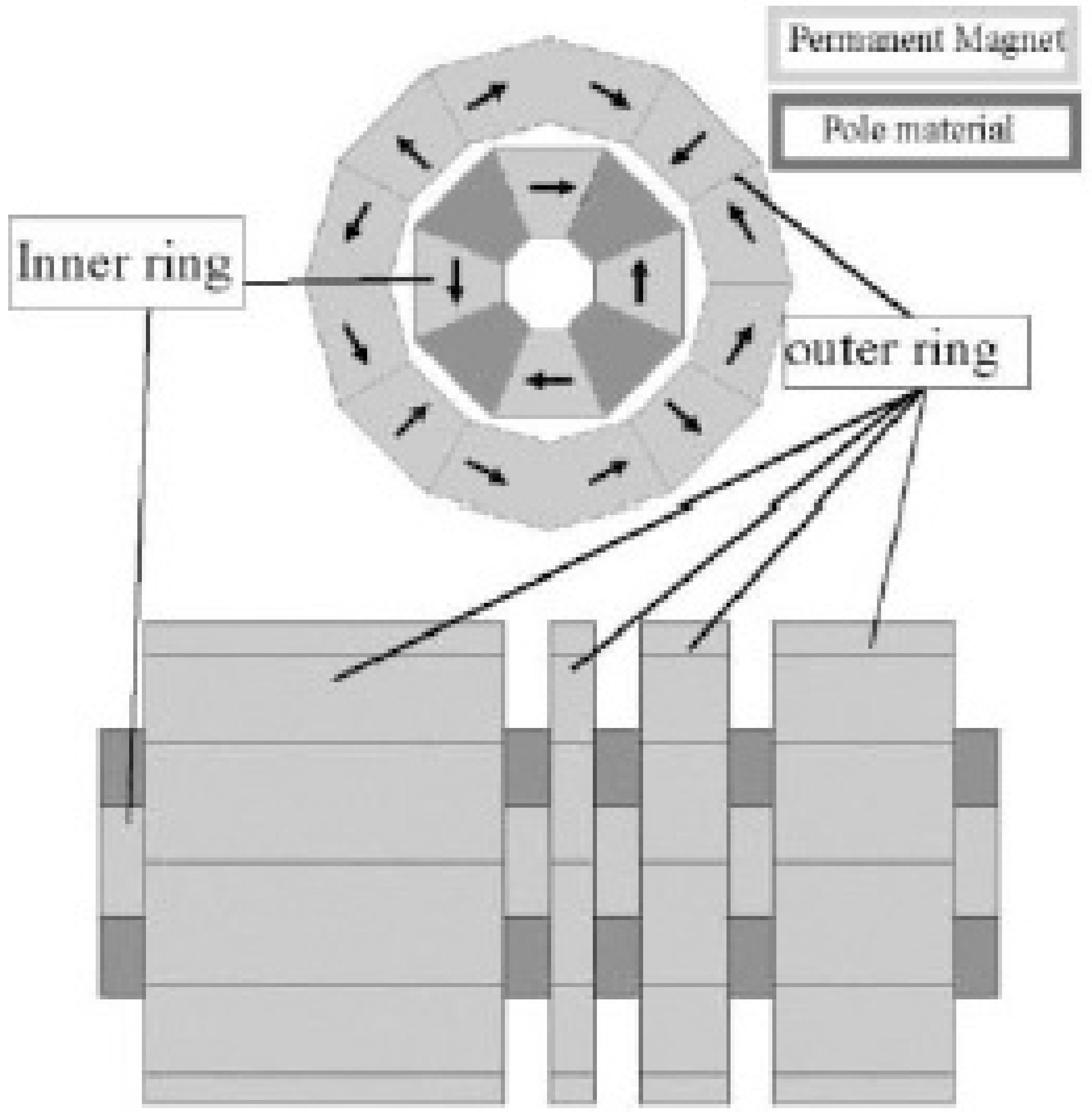
- Hybrid quadrupole
- Halbach rings, 1 fixed Hybrid ring and 4 rotated PPM rings
- High and variable gradient
- Magnetic center shift corrected by shimming outer rings

Rotation outer ring

Bore radius	10 mm
Max Gradient	120 T/m
Min Gradient	17 T/m
Step	7 T/m
Magnetic center shift	20 µm



Contribution of each outer ring

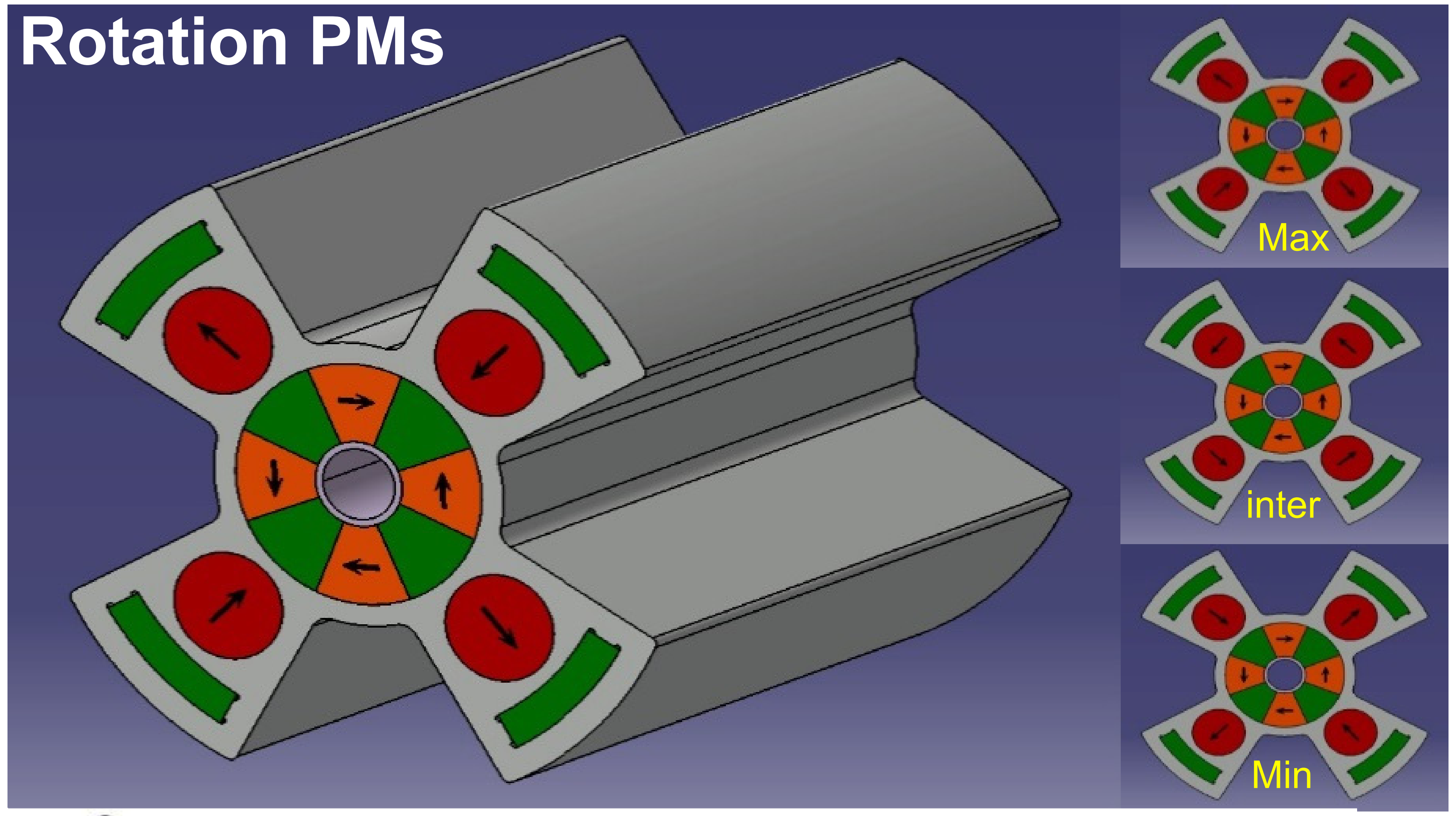


Y. Iwashita et al., EPAC06, Edinburgh, Scotland, 2006

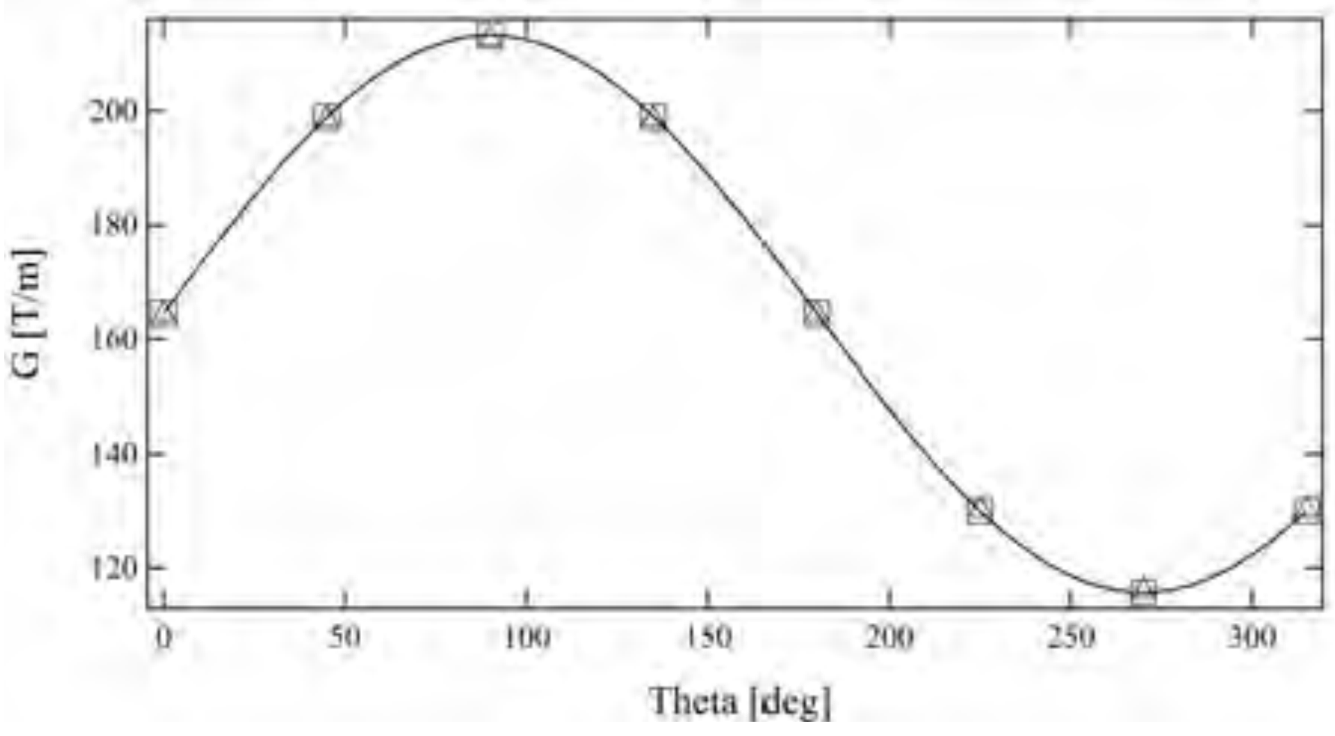
HIGH GRADIENT PM QUADRUPOLES

Variable gradient PM quadrupoles

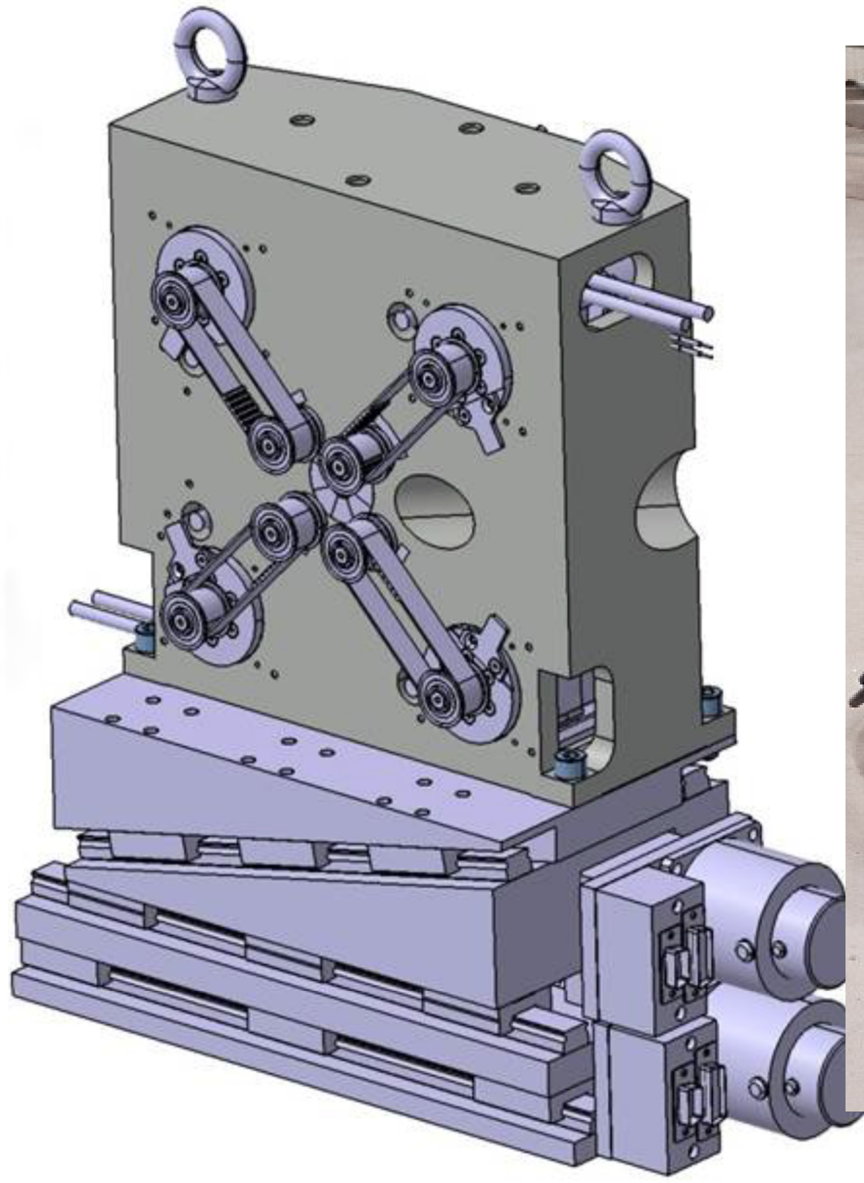
- Hybrid compact quadrupole
- Fixed Hybrid ring and 4 rotated PM cylinders
- High and variable gradient
- Magnetic center shift corrected by translation stages
- Magnetic measurement with different methods
- 7 quadrupoles with lengths from 26 mm to 100 mm

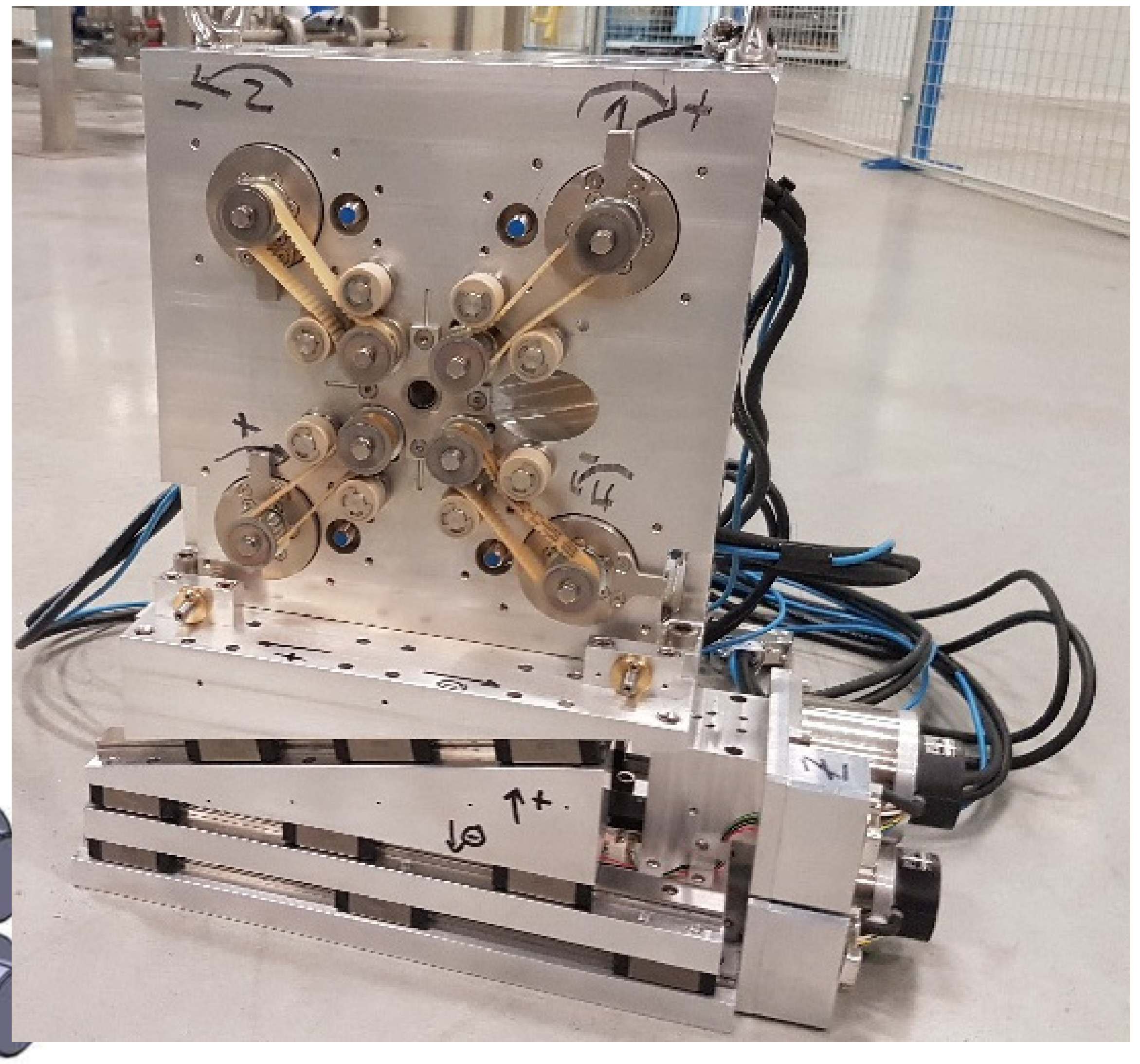


Bore radius	6 mm
Max Gradient	210 T/m
Min Gradient	110 T/m
Magnetic center shift	20 µm



Gradient versus tuning magnets angle with (Δ) TOSCA and (□) RADIA. (Line) sinus t.





F. **Marteau** et al., *APL, submitted (2017)*

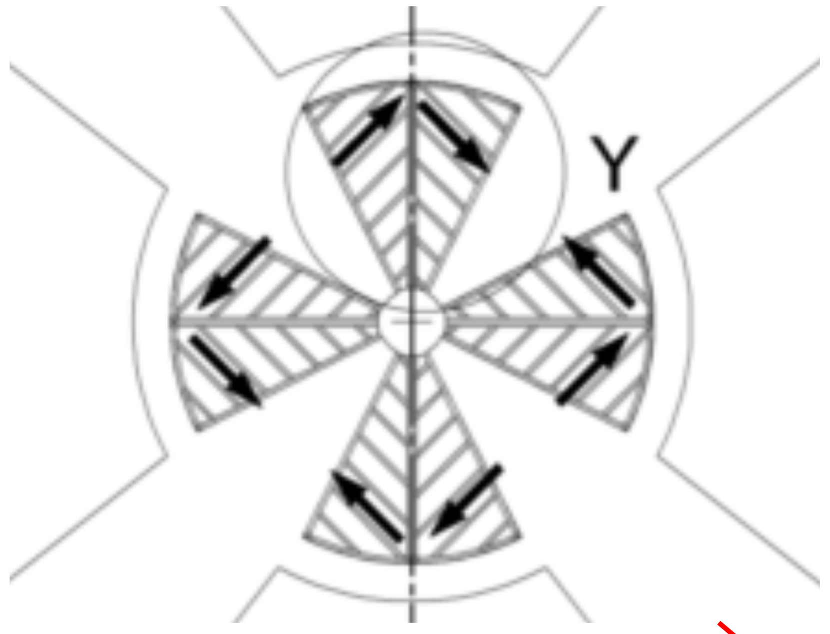
J.T. ***Volk*** *et al., PAC01, Chicago, USA, 2001*

Variable gradient PM quadrupoles

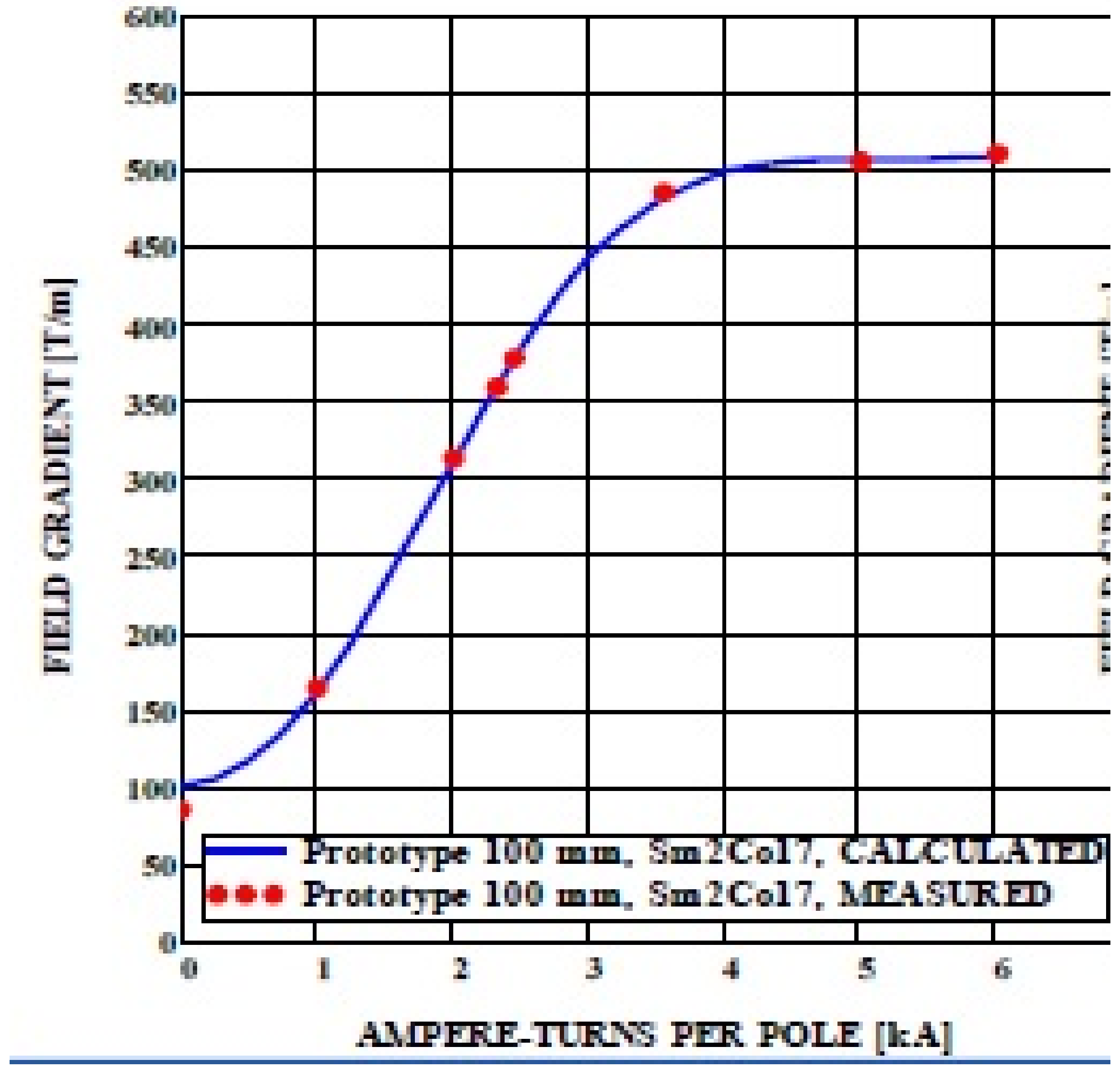
- Dominated iron quadrupole
- Combined fixed PMs and coils
- Ultra high and variable gradient
- Good field quality < 0.1 % in 1 mm GFR

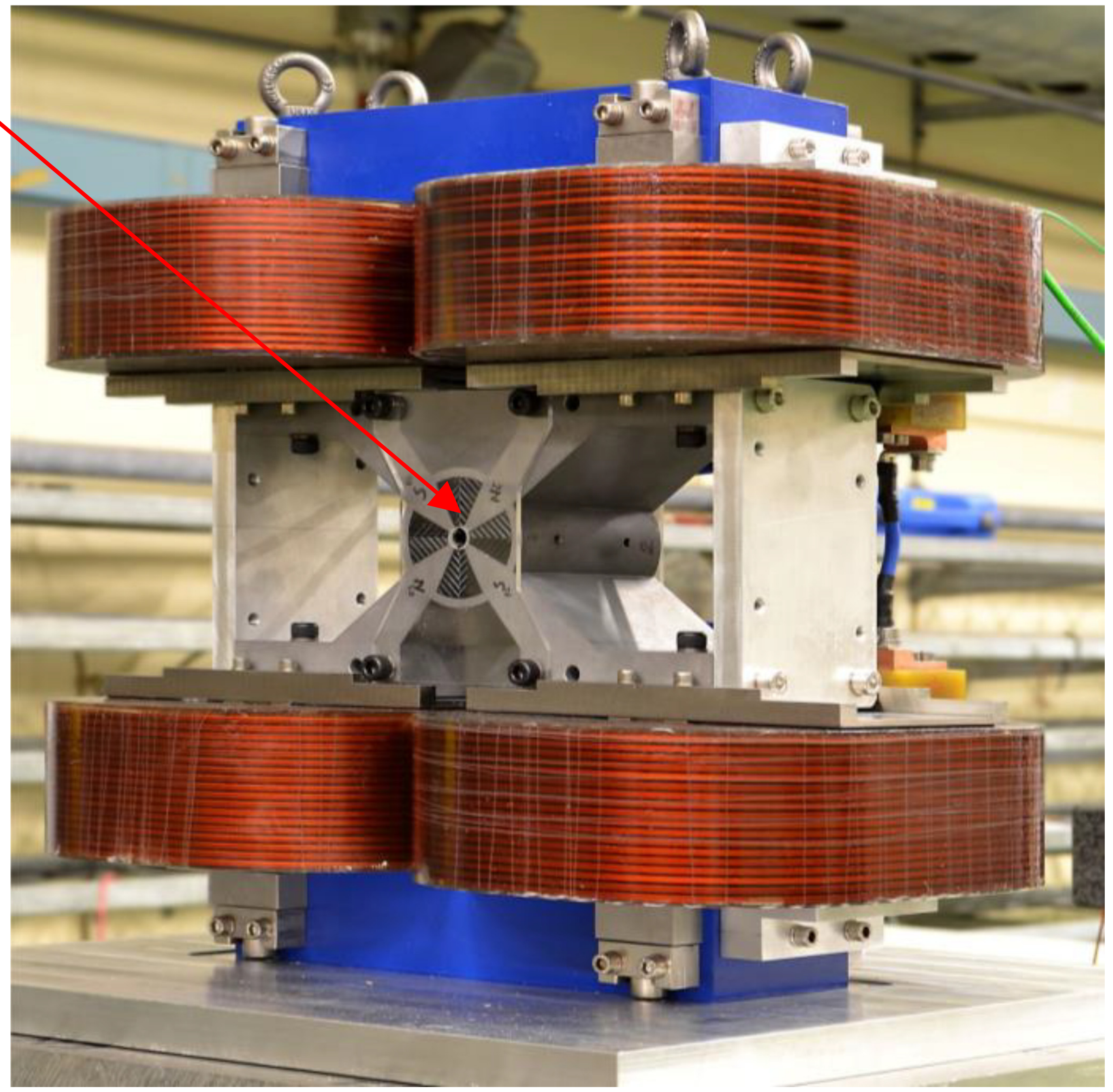
- Less compact device with coils
- Power consumption

Bore radius	4.12 mm
Max Gradient	> 500 T/m
Min Gradient	100 T/m



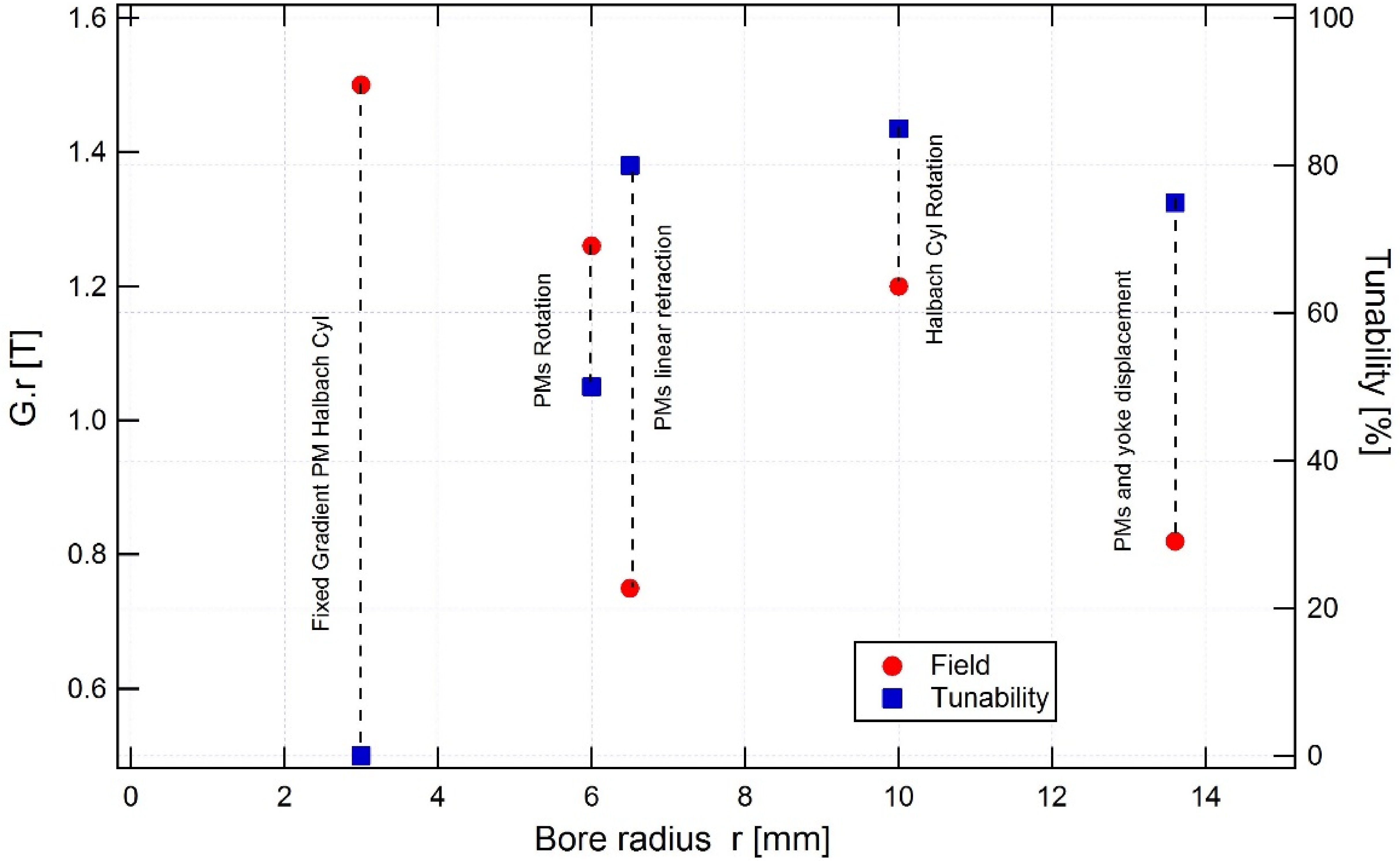
PMs and coils





M. Modena et al., IPAC12, New Orleans, USA, 2012
M. Modena, Workshop at CERN, Geneva, Switzerland, 2014

HIGH GRADIENT PM QUADRUPOLES



- Rotation systems are more efficient and more compact
- Dominated iron with linear displacement have better field quality
- Magnetic center shift depends on the gradient variation systems

High gradient PM quadrupoles are still dedicated devices

The trend is towards Low Emittance Storage Rings

New facilities

MAX IV in Sweden – 330 pm.rad
Commissioning done

Sirius in Brazil – 250 pm.rad
Construction in progress

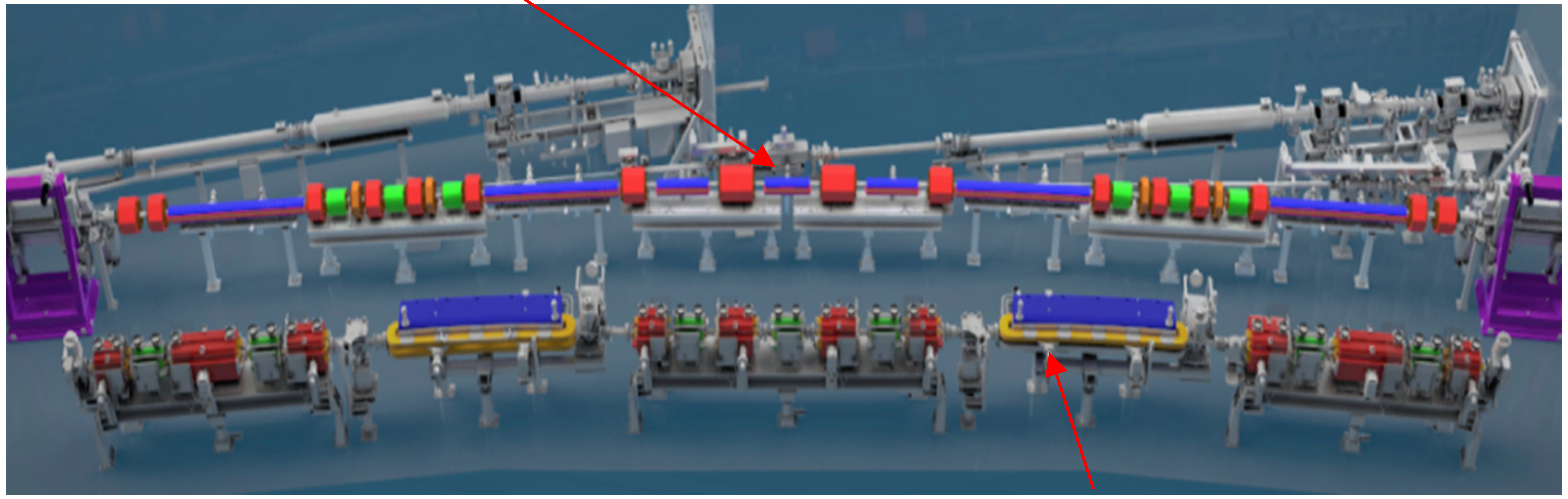
Upgrade facilities using the existing building

ESRF-EBS in France – 140 pm.rad
Commissioning expected in 2020

APS-U in USA – 70 pm.rad
Commissioning expected in 2023

SPring-8-II in Japan – 149 pm.rad
Upgrade studies on progress

ESRF-EBS will be 7BA 6 GeV lattice



ESRF today has DBA 6 GeV lattice

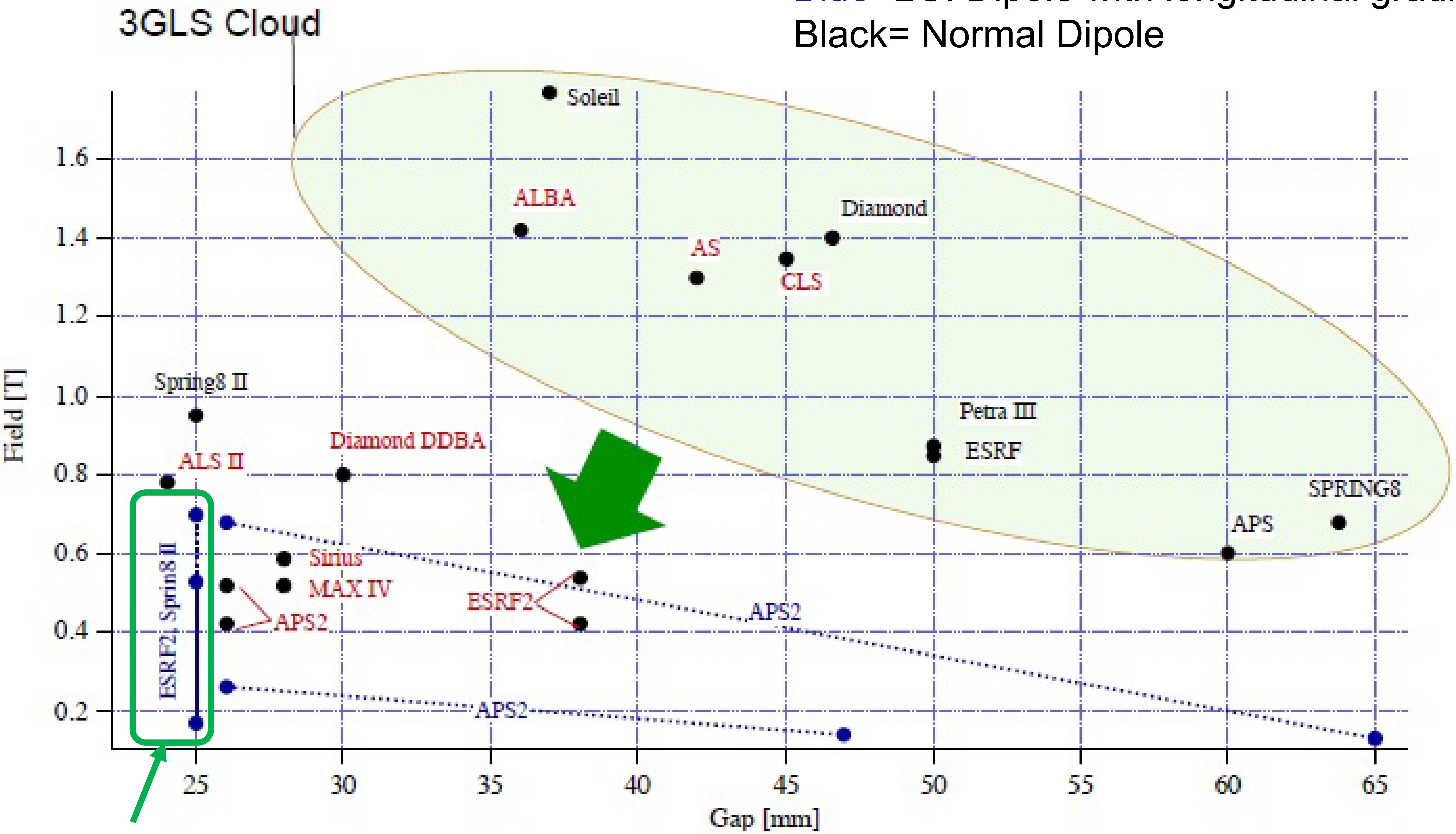
Emittance $\propto 1/(N\ \text{dipoles})^3$

↓

Increase number of dipoles

LG PM DIPOLES FOR LOW EMITTANCE STORAGE RINGS

Red=DQ: Combined dipole quadrupole
Blue=LG: Dipole with longitudinal gradient
Black= Normal Dipole



PM Dipoles with Longitudinal Gradient

Compact electromagnets at MAX IV

LG PM DIPOLES FOR LOW EMITTANCE STORAGE RINGS

PM dipole have advantages over electromagnet one

- Compact devices
- No power supply and no cooling systems
- Better reliability (no water and power supply failures)
- Less control systems, cables and noise
- Important reduction in operation cost

ESRF	Spring-8
410 k€	720 k€

Estimation of electric power cost for dipoles in 2016

Challenges for permanent magnet Dipoles

- Magnetic field design
- Magnetic field tuning and shimming
- Temperature dependence
- Demagnetization risks
- Series production

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Challenges for permanent magnet Dipoles

- Magnetic field design
- Magnetic field tuning and shimming
- Temperature dependence
- Demagnetization risks
- Series production

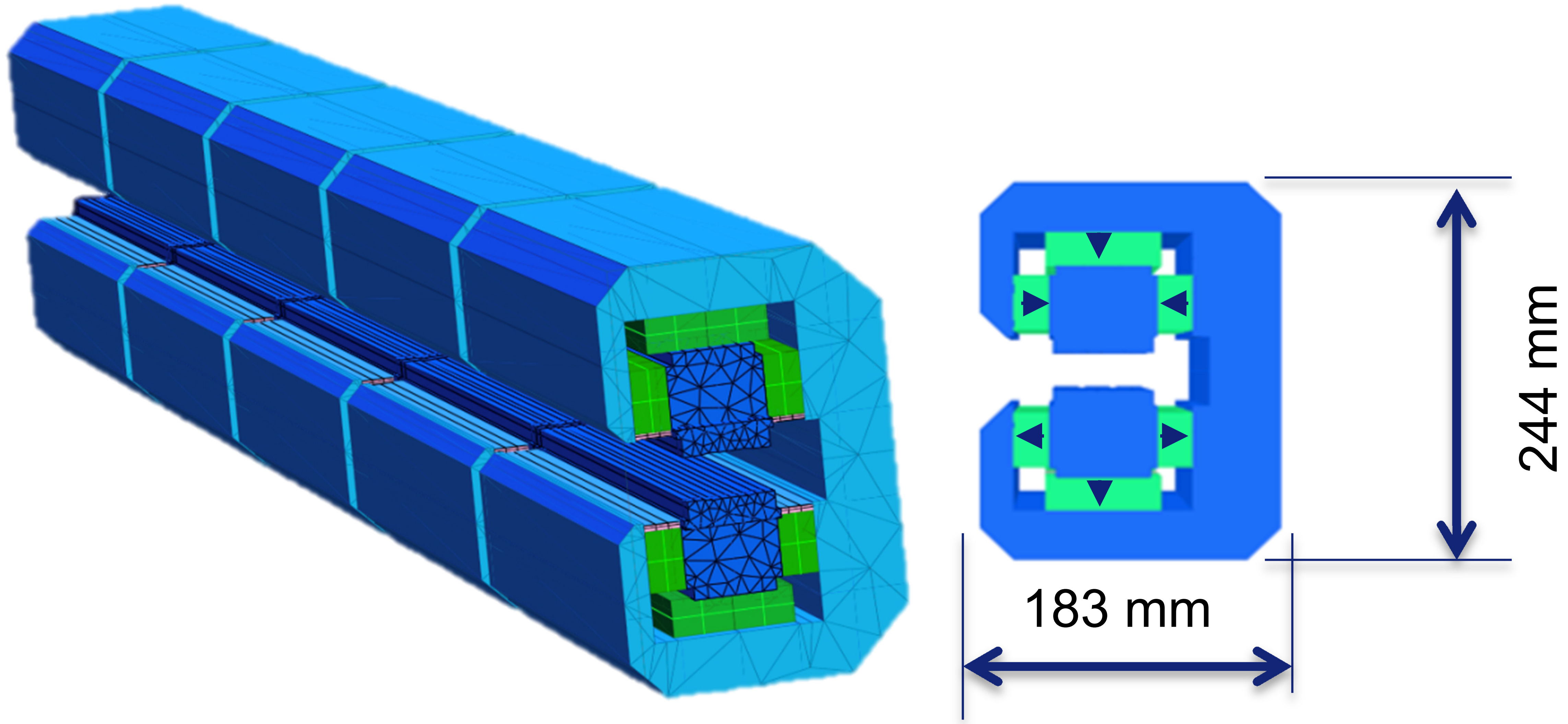
There are almost no PM devices used as standard magnets in accelerator lattices, the only exception being the Fermilab recycler

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

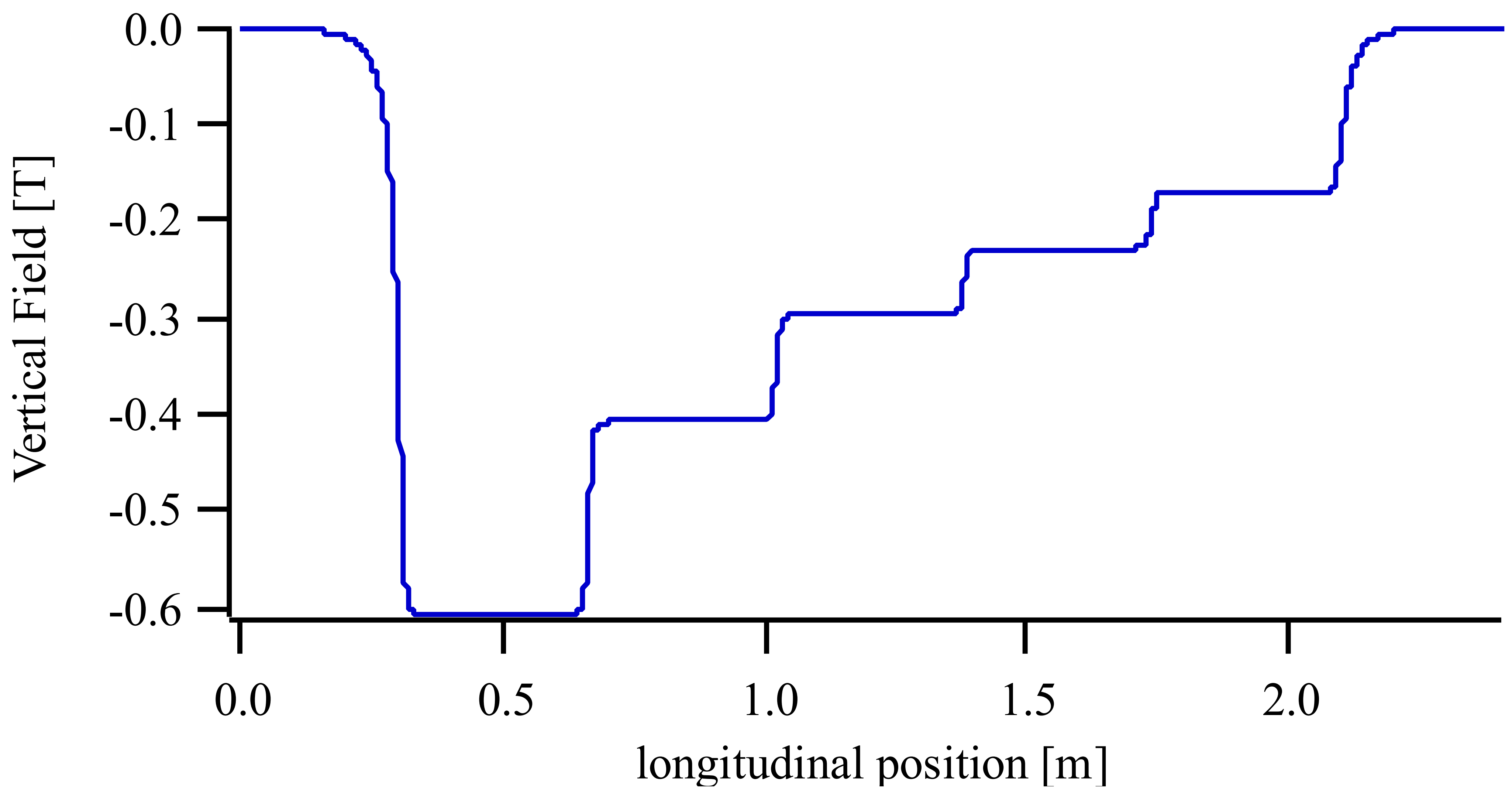
LG PM DIPOLES FOR LOW EMITTANCE STORAGE RINGS

Dipole		
Gap	mm	25.5 – 30.5
Iron length	mm	1788
Permanent magnet		Sm_2Co_{17}
Iron		Pure iron
Number of dipoles		128

		DL1	DL2
Strength	T	0.67 – 0.17	0.54 – 0.17



Dipole constituted by 5 modules



Vertical field vs. longitudinal position

ESRF-EBS LG Dipole

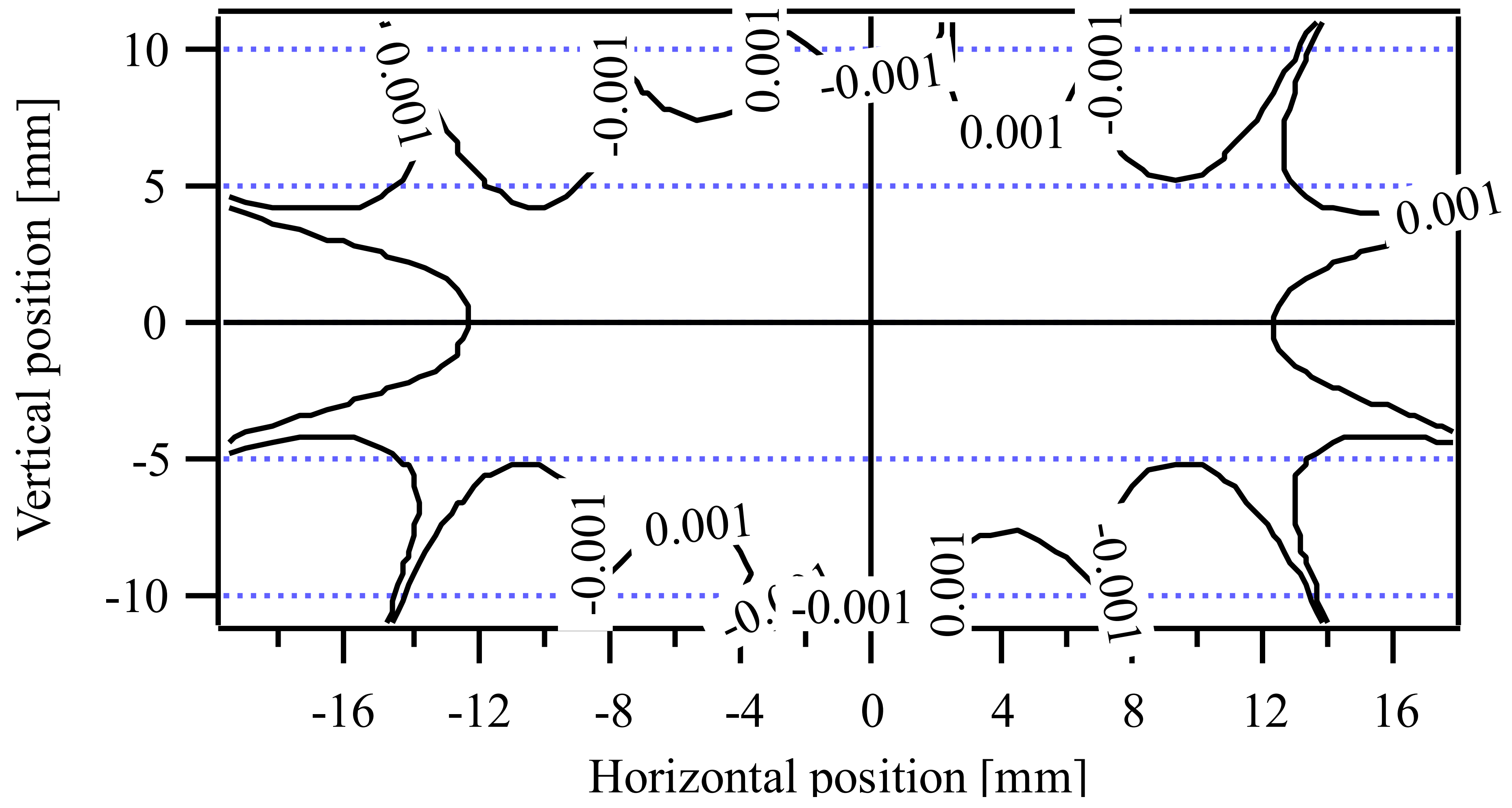
Prototypes to confirm calculated performance and to define the series production process

- Permanent magnet assembly
- Magnetic field strength and quality
- Longitudinal field integral fringe
- Temperature compensation

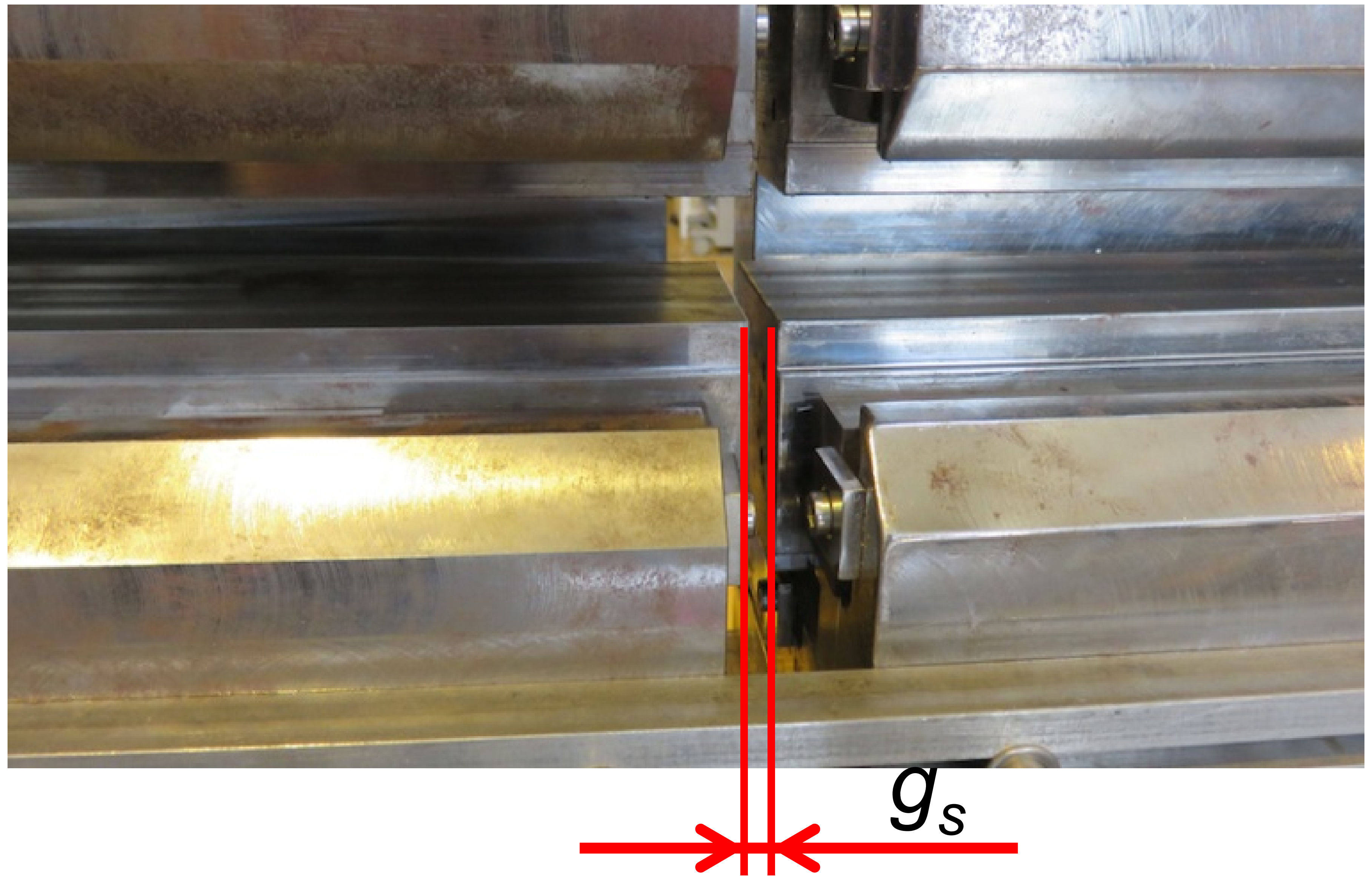
Two modules with 0.62 T and 0.41 T

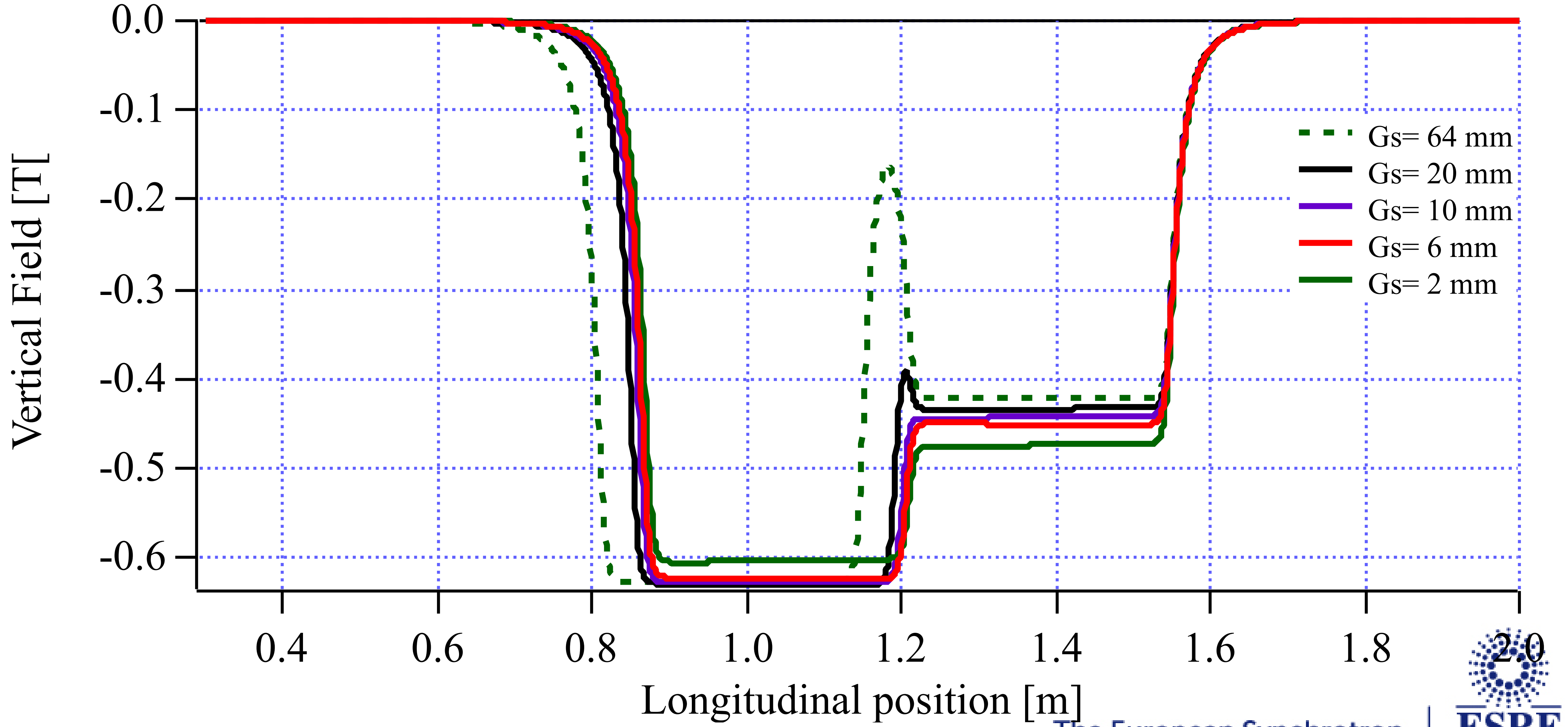
LG PM DIPOLES FOR LOW EMITTANCE STORAGE RINGS

- PM assembly needs special tools
- Field quality depends on pole parallelism
- Shimming required to reach targeted field
- Longitudinal gap to be defined for flat field



Tolerance: $\Delta B/B < 10^{-3}$ @13 mm

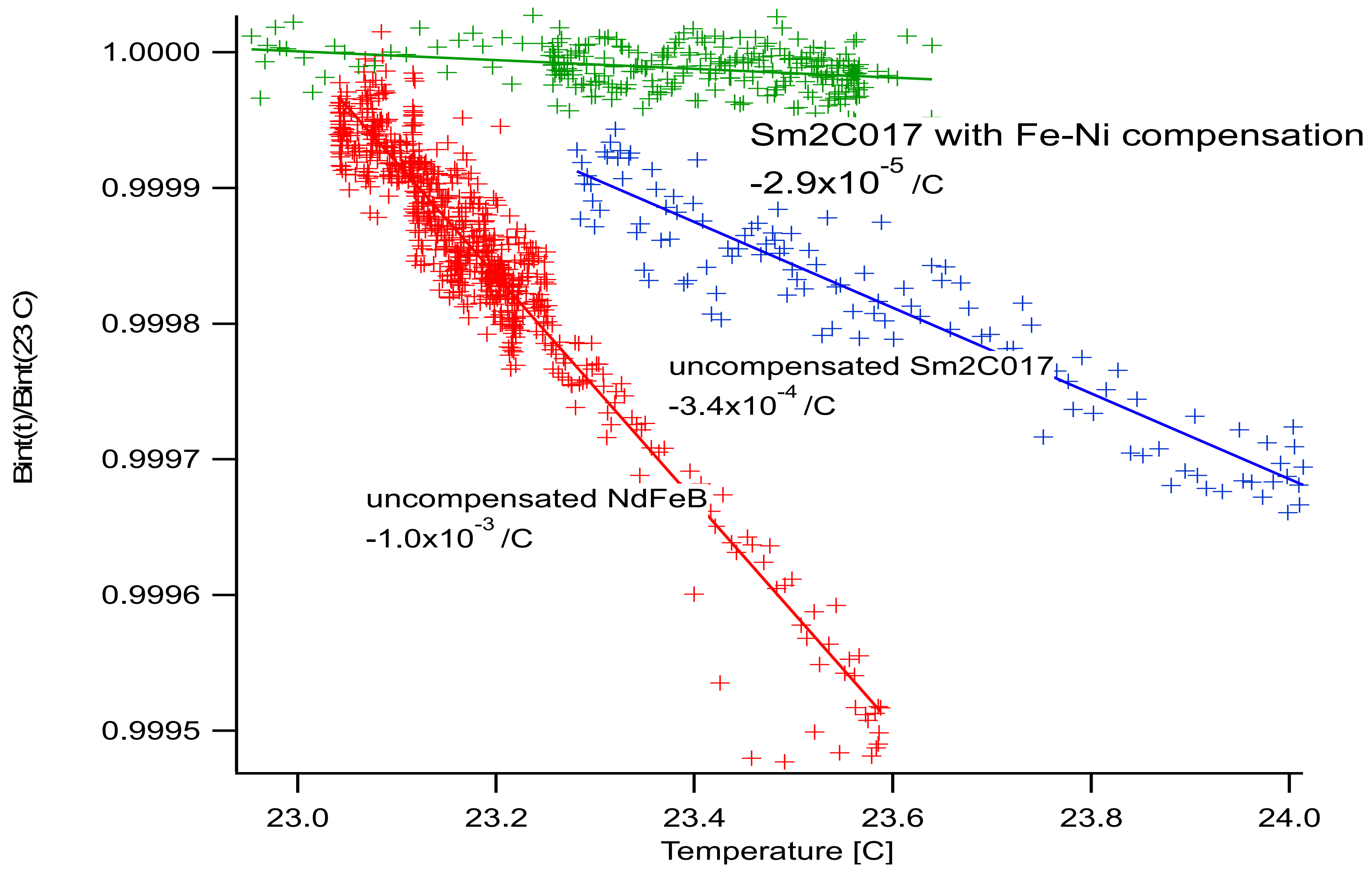




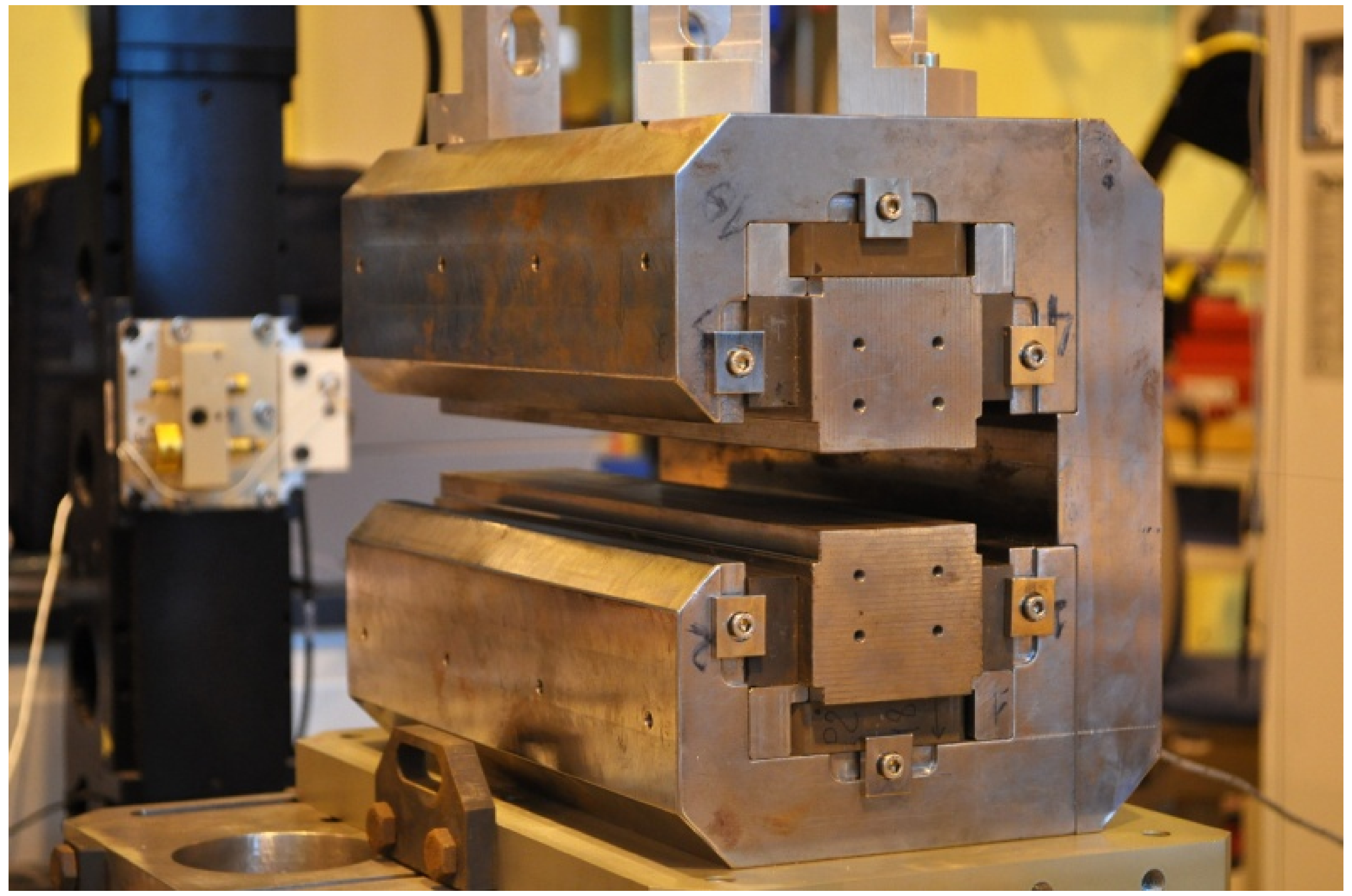
Flat field at longitudinal gap g_s = 5 mm

LG PM DIPOLES FOR LOW EMITTANCE STORAGE RINGS

- Dominated by PM material temperature coefficient
- Compensated by passive Fe-Ni shunts
  - The Fe-Ni shunts are ~ saturated
  - The magnetization in Fe-Ni has large temperature dependence



Field integral measurements on PM DL modules
NdFeB PM, Sm_2C0_{17} PM



ESRF Dipole module

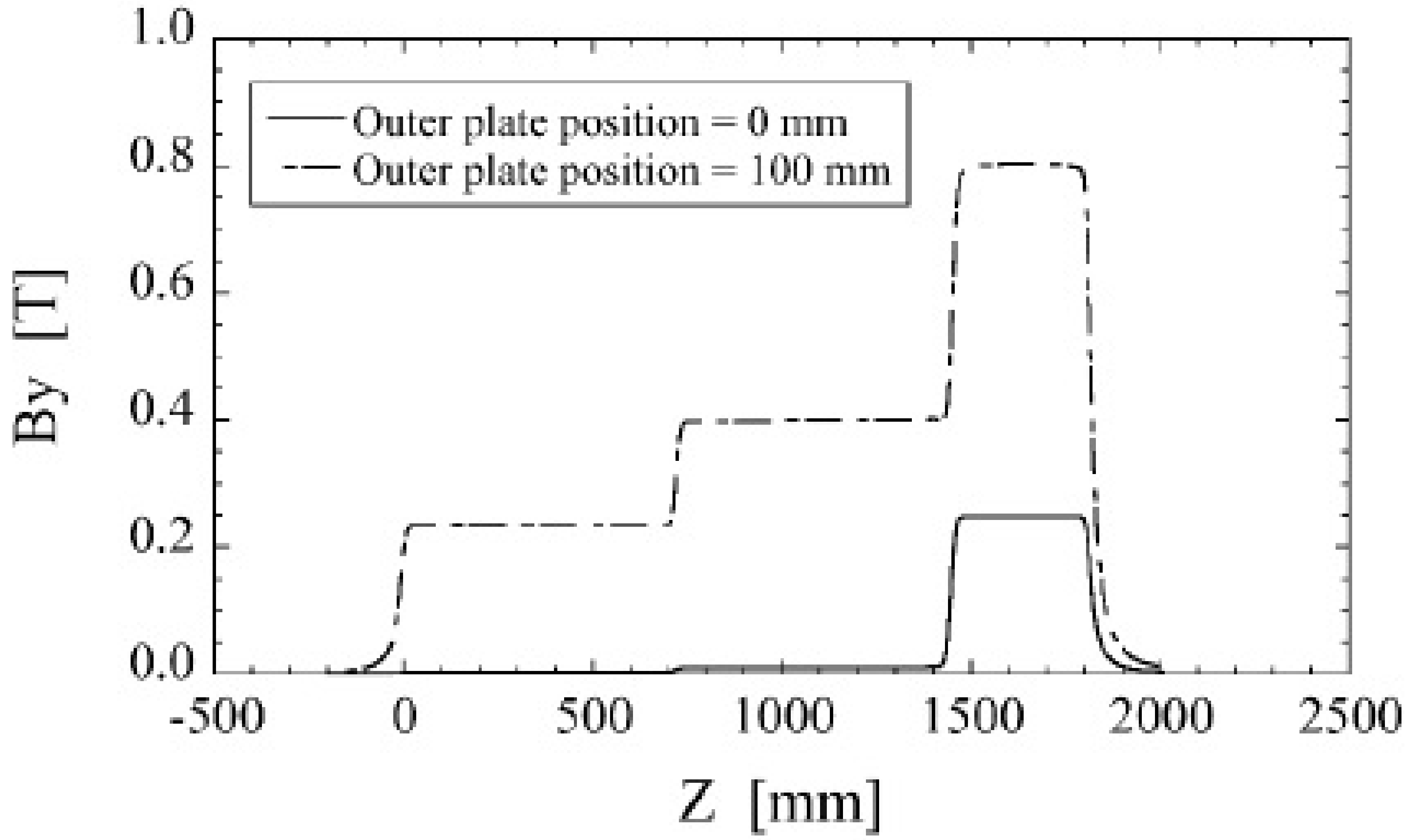
dB/B/dT after compensation:**< 40 ppm/C**

LG PM DIPOLES FOR LOW EMITTANCE STORAGE RINGS

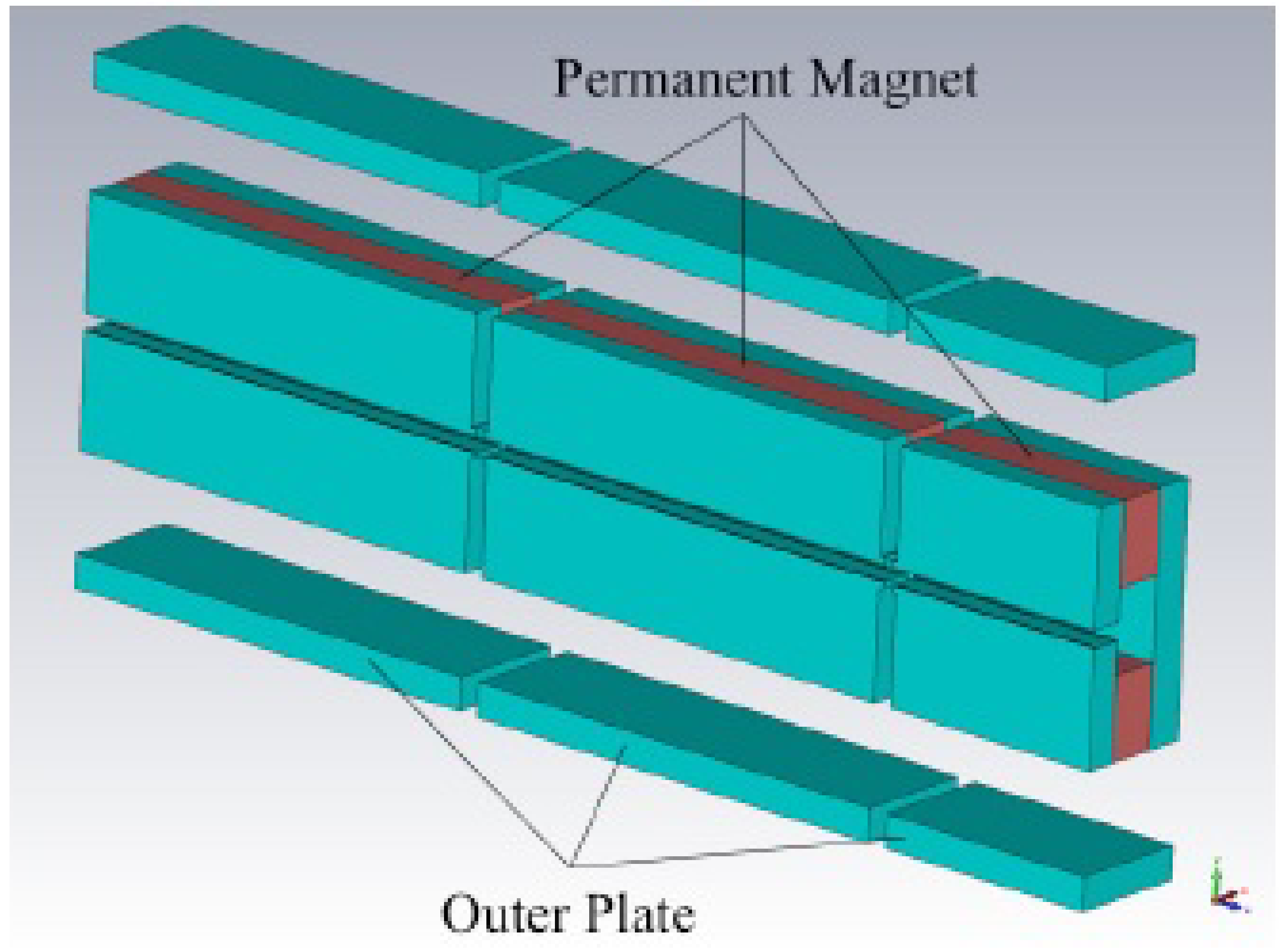
Dipole		
Gap	mm	25
Iron length	mm	1750
Permanent magnet		Sm_2Co_{17}
Iron		Pure iron
Number of dipoles		176

		LGB1	LGB2
Strength	T	0.54 – 0.19	0.79 – 0.26

Vertical field vs. longitudinal position



The LGB designs are now being modified.



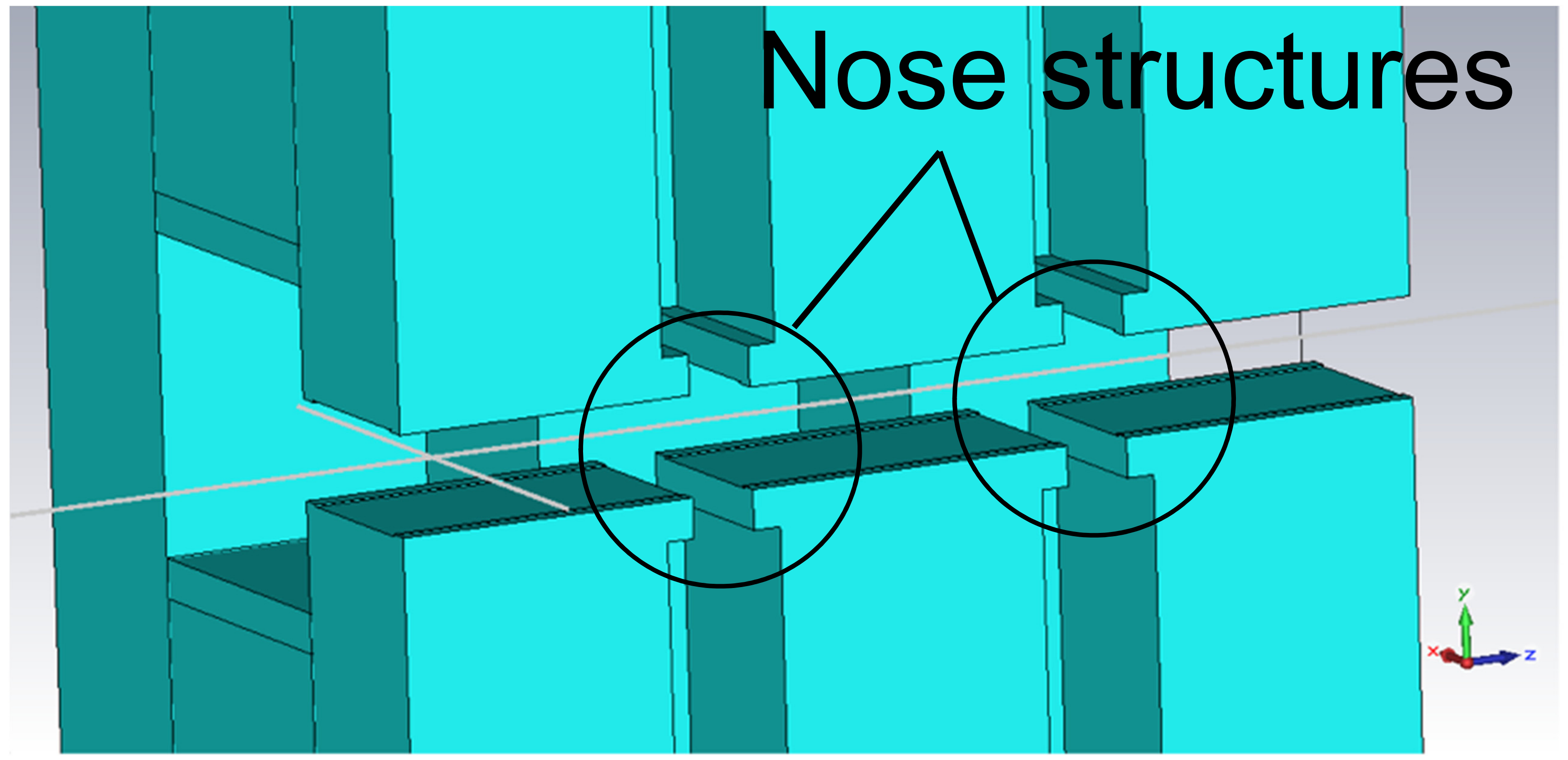
Dipole constituted of 3 modules

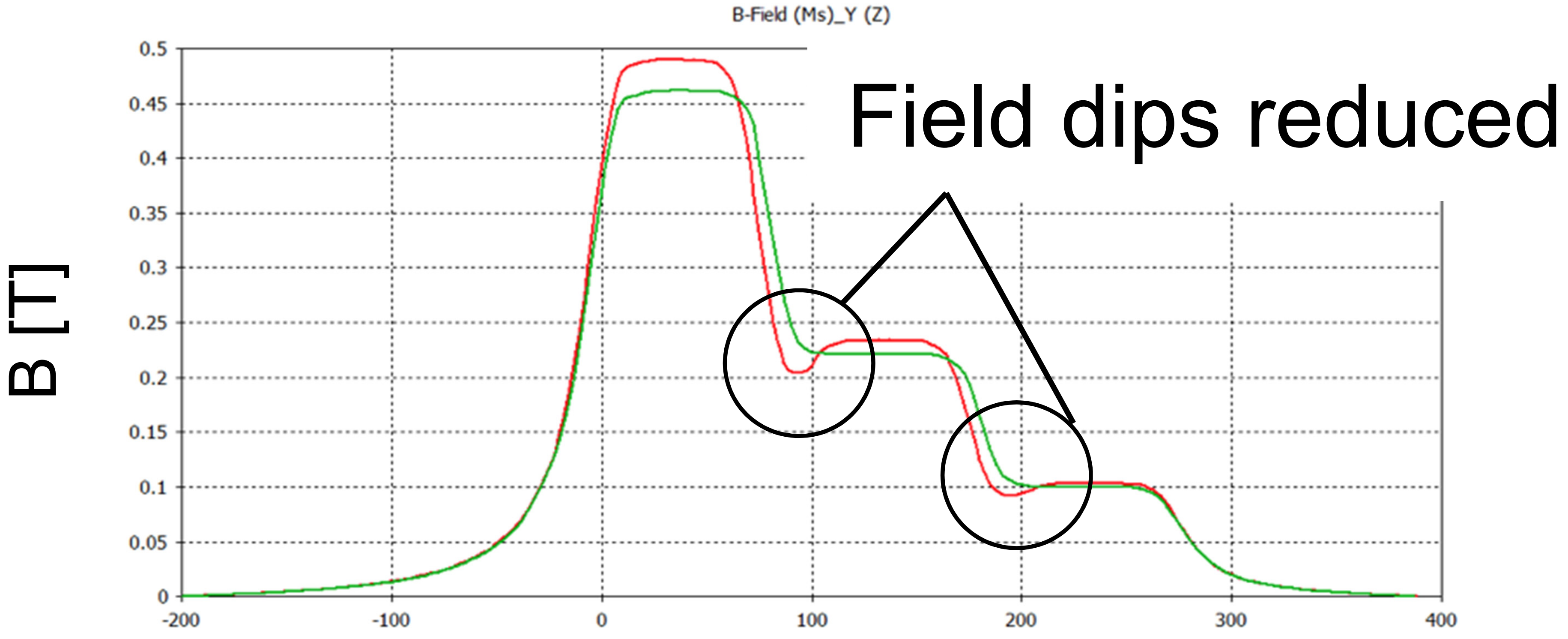
Spring-8-II LG Dipole

Courtesy of T. Watanabe

LG PM DIPOLES FOR LOW EMITTANCE STORAGE RINGS

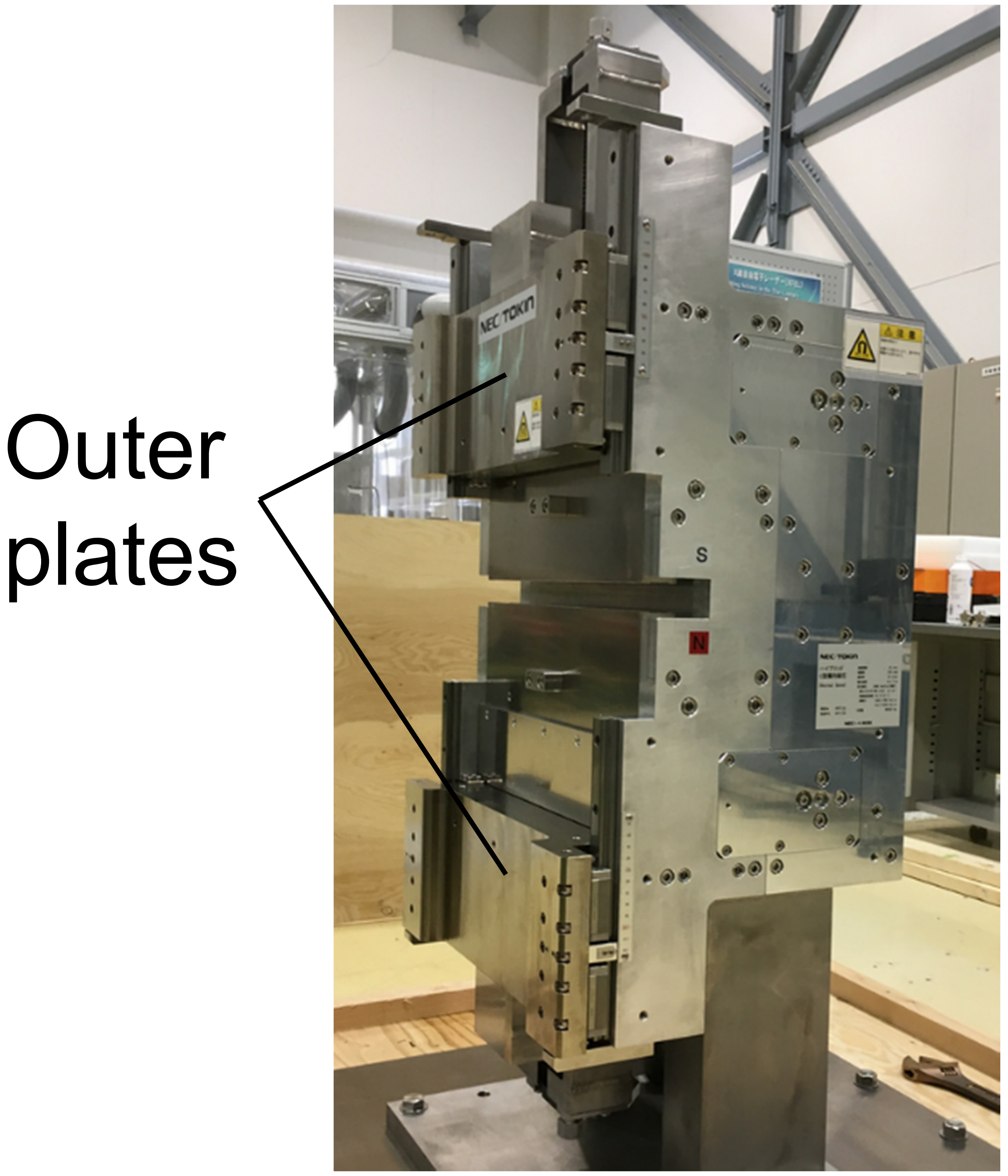
- Outer plates for B-field tuning
- "Nose structures" for smooth B-field transition between modules
- Temperature compensation

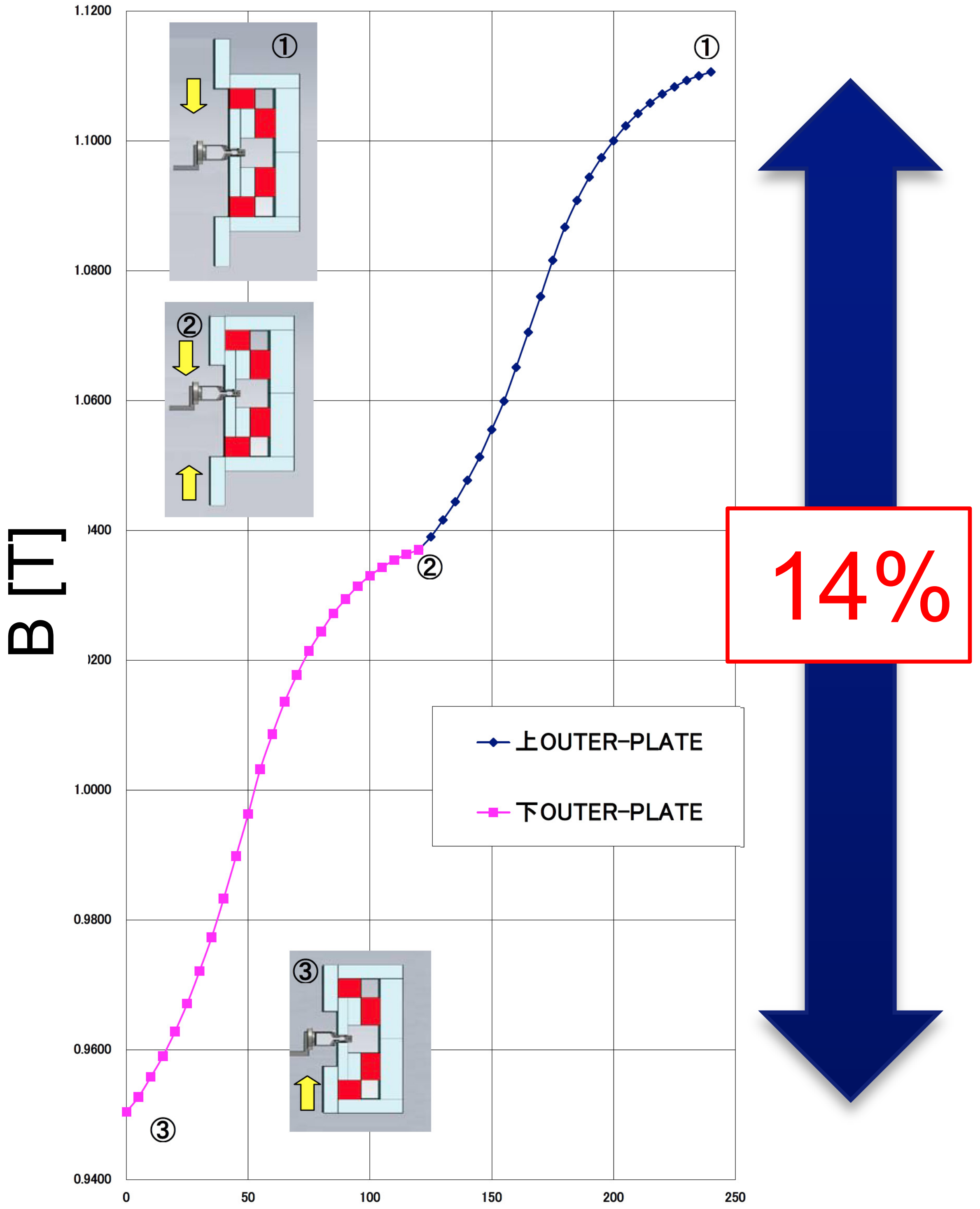




Longitudinal axis [mm]

Prototype for SPring-8-II dipole magnets (14 % B-field tuning by outer plates.)





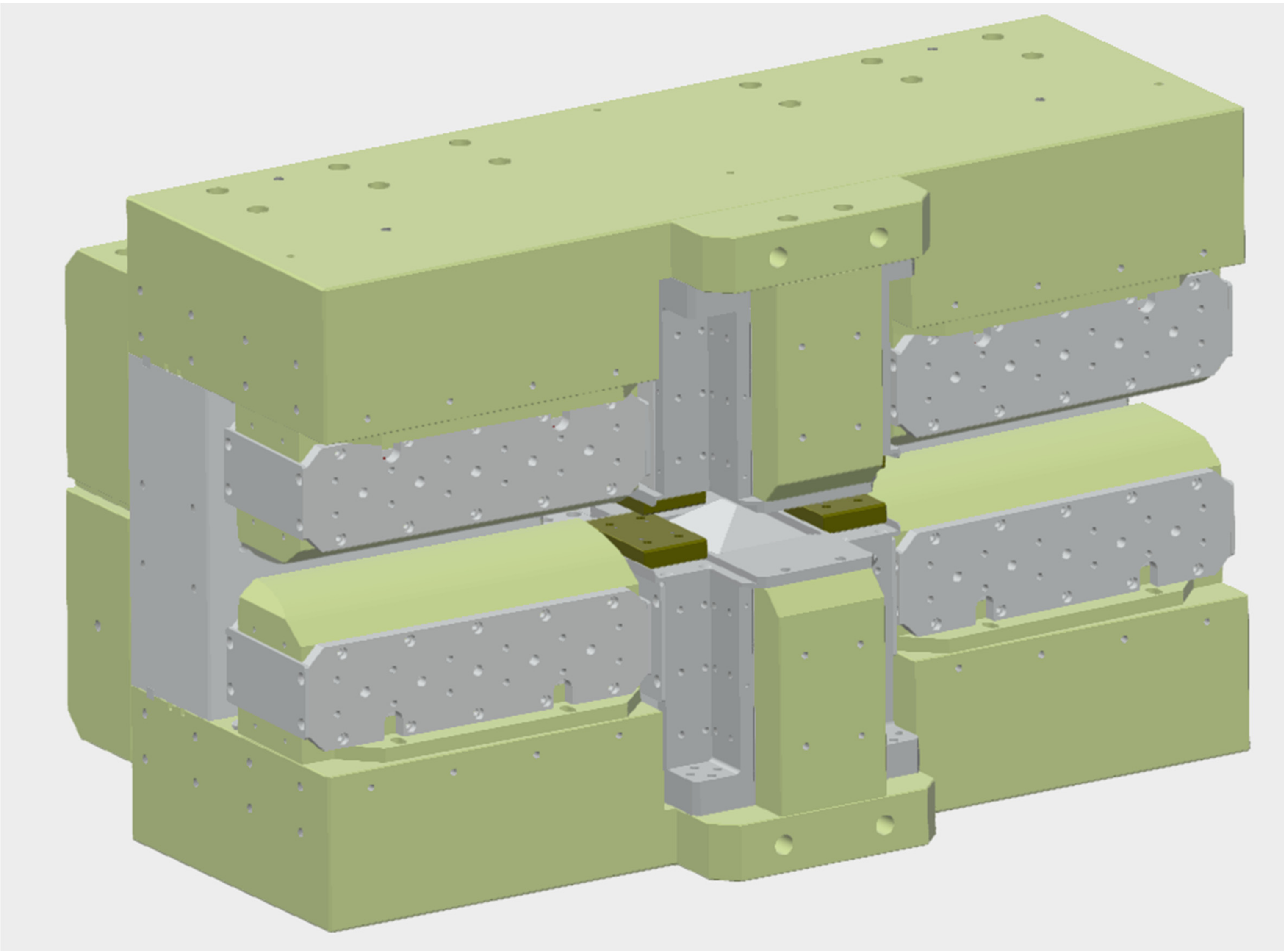
Outer plate position

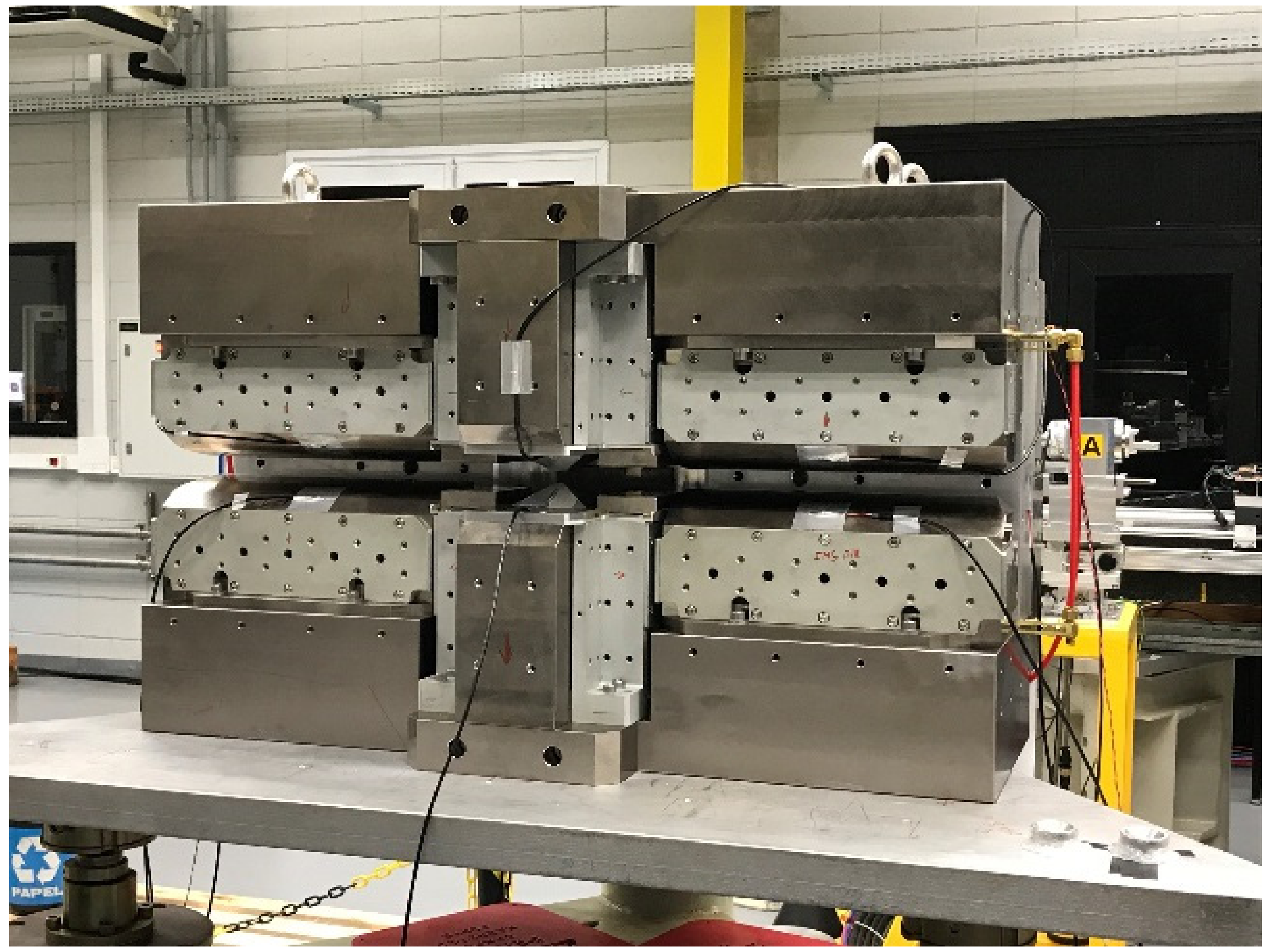
Courtesy of T. Watanabe

LG PM DIPOLES FOR LOW EMITTANCE STORAGE RINGS

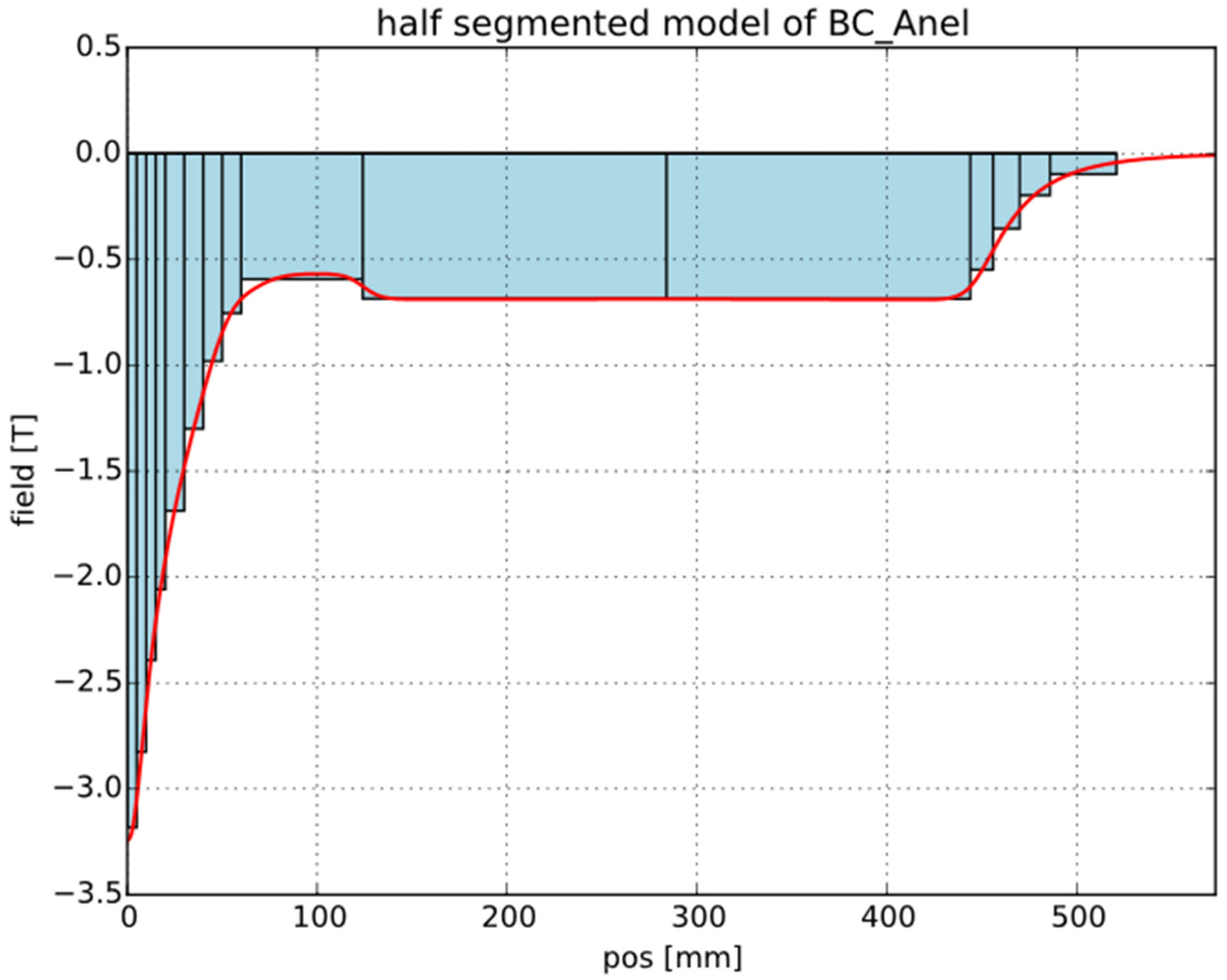
Dipole		
Gap	mm	26 - 11
Iron length	mm	828
Permanent magnet		$Nd_2Fe_{14}B$
Iron		Pure iron
Number of dipoles		20

		BC
Strength	T	3.2 – 0.58





SIRIUS BC Dipole



Vertical field vs. longitudinal position

Courtesy of Lin Liu

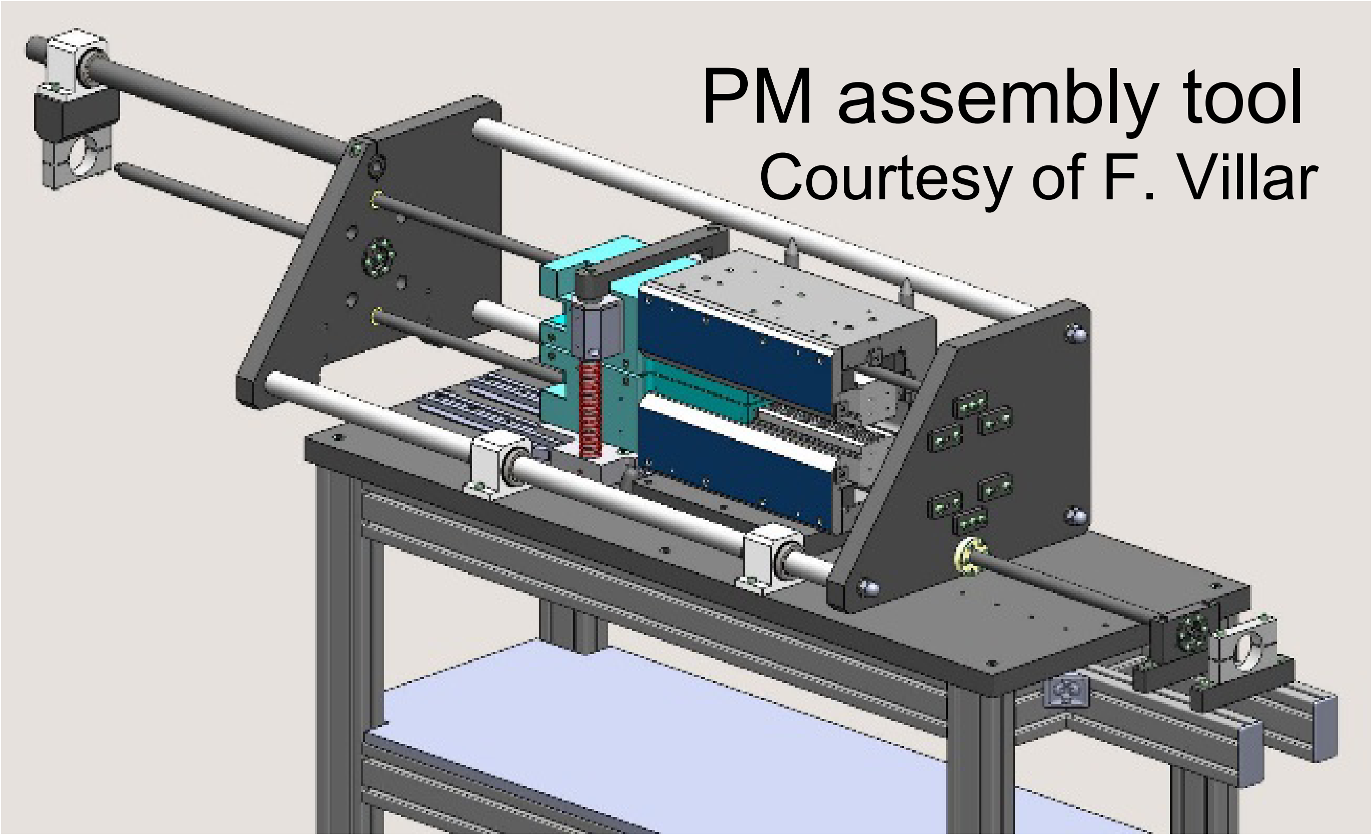
LG PM DIPOLES FOR LOW EMITTANCE STORAGE RINGS

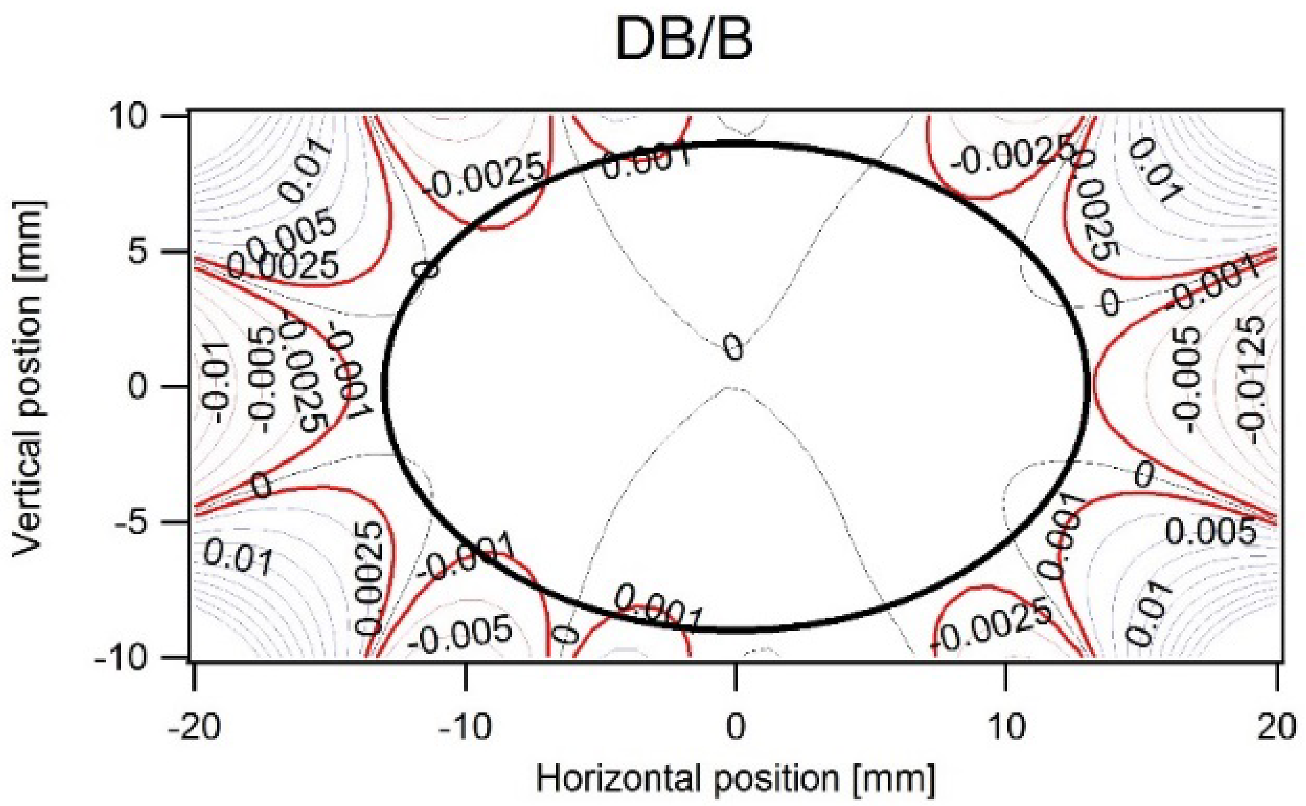
Series production in progress

ESRF PM dipoles assembly area

LG PM DIPOLES FOR LOW EMITTANCE STORAGE RINGS

- Procurement of different parts
  - 6 tons of PM material (>15000 blocks)
  - 660 Mechanical parts (poles and yokes)
- Development and test of PM assembly tools
  - Easy to use tooling
  - Management of PM forces
  - Robustness for long term use
- PM assembly and thermal compensation
  - Assembly of PMs on each module
  - Fe-Ni amount depends on module type
  - Adjustment of the position of the poles
- Magnetic measurement and shimming
  - Measurement and shimming of each model to reach targeted field
  - Measurement and shimming of PM dipole to reach final performances
  - Fiducialisation of the dipole





ESRF stretched wire magnetic bench

PM Dipole ready for use

47 dipoles out of 128 are assembled

CONCLUSION AND PERSPECTIVES

- Dedicated high gradient and compact PM quadrupoles have been developed
  - Lack of space
  - Limitation of electromagnet quadrupole
- Energy saving could be an important criteria
  - Quadrupoles for low heat to air facilities
  - Accelerators with a large number of quadrupoles
- PM LG Dipoles development is in progress
- lattice PM multipole magnets R&D for Low emittance storage rings
  - Dominated iron quadrupole with precise pole shape
  - Improve the magnetic center shift with gradient tunability
  - Limited tenability quadrupoles with low consumption air coils
  - Sextupole and octupole magnets require large tunability

CONCLUSION AND PERSPECTIVES

- Resistive magnet close to limit (quadrupoles)
- Complicated vacuum chamber technology with small magnet aperture

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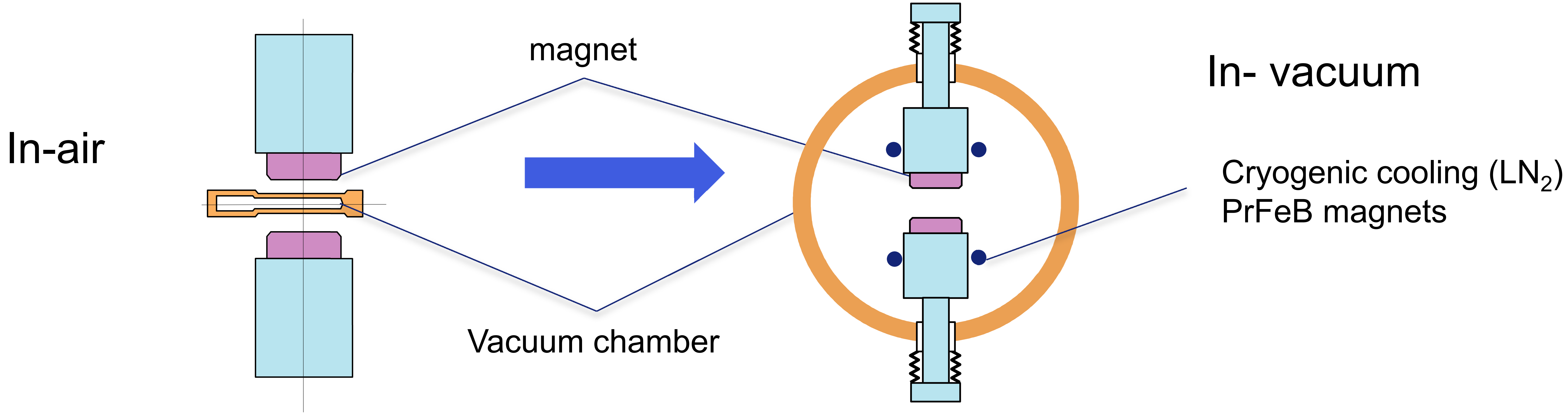
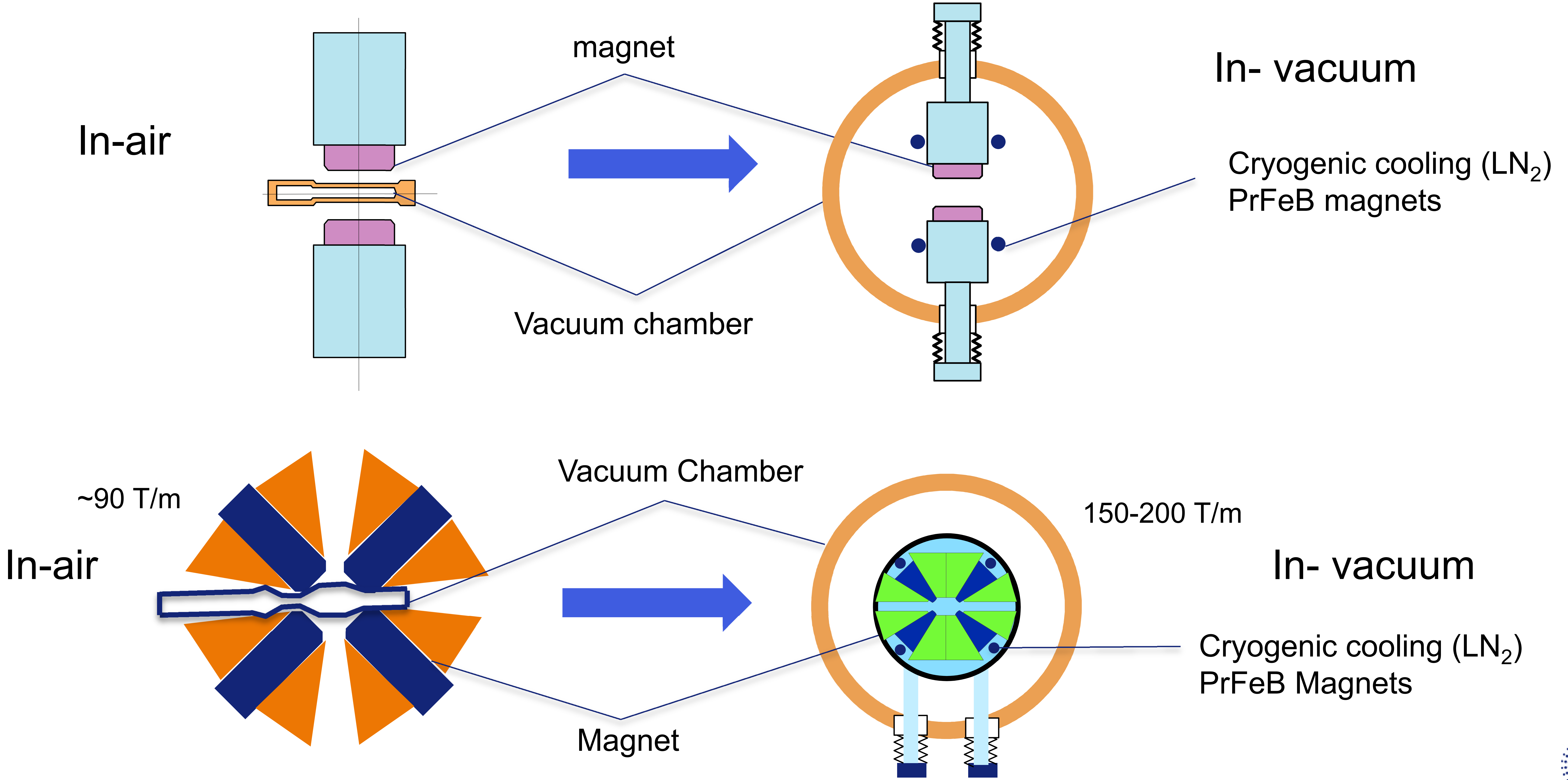


CONCLUSION AND PERSPECTIVES

- Resistive magnet close to limit (quadrupoles)
- Complicated vacuum chamber technology with small magnet aperture



MANY THANKS FOR YOUR ATTENTION