IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2016.
Invited presentation 4OrCC_01 given at MT-24, Seoul, Korea, October 18-23, 2015.

International Conference on Magnet Technology

Seoul, 18 – 23 October 2015

Magnets for the ESRF diffraction limited light source project

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ESRF | The European Synchrotron

OUTLINE

I. Introduction

- The ESRF light source
- Lattice and magnets

II. Magnet designs and prototyping

- Dipole-quadrupoles
- High gradient quadrupoles
- Permanent dipoles with longitudinal gradient
- Tolerances

III. Magnetic measurements

- ESRF stretched-wire benches
- Measurement methods

IV. Conclusion

INTRODUCTION

ESRF – The European Synchrotron

- Light source built in the 1990's
- Located in Grenoble, France
- 6 GeV machine
- 200 mA current
- 840 m long storage ring

INTRODUCTION

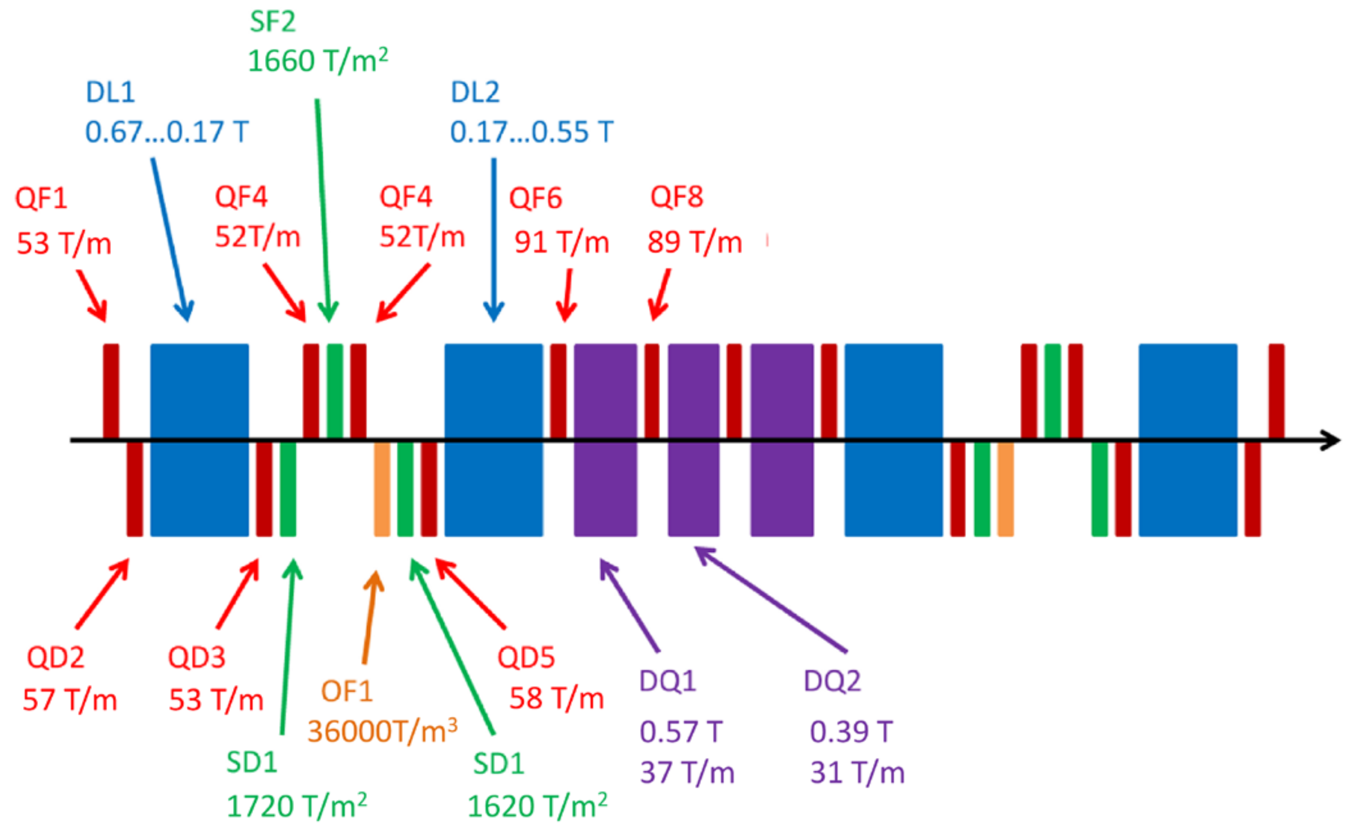
ESRF–EBS project

- Increased brightness
- Horizontal emittance: 4 nm·rad→ 135 pm·rad
- New storage ring
- Same insertion devices source points
- Increased number of bending magnets
- Reduced power consumption
- Installation in 2019

More details about ESRF upgrade in
[Farvacque , IPAC 2013]

INTRODUCTION

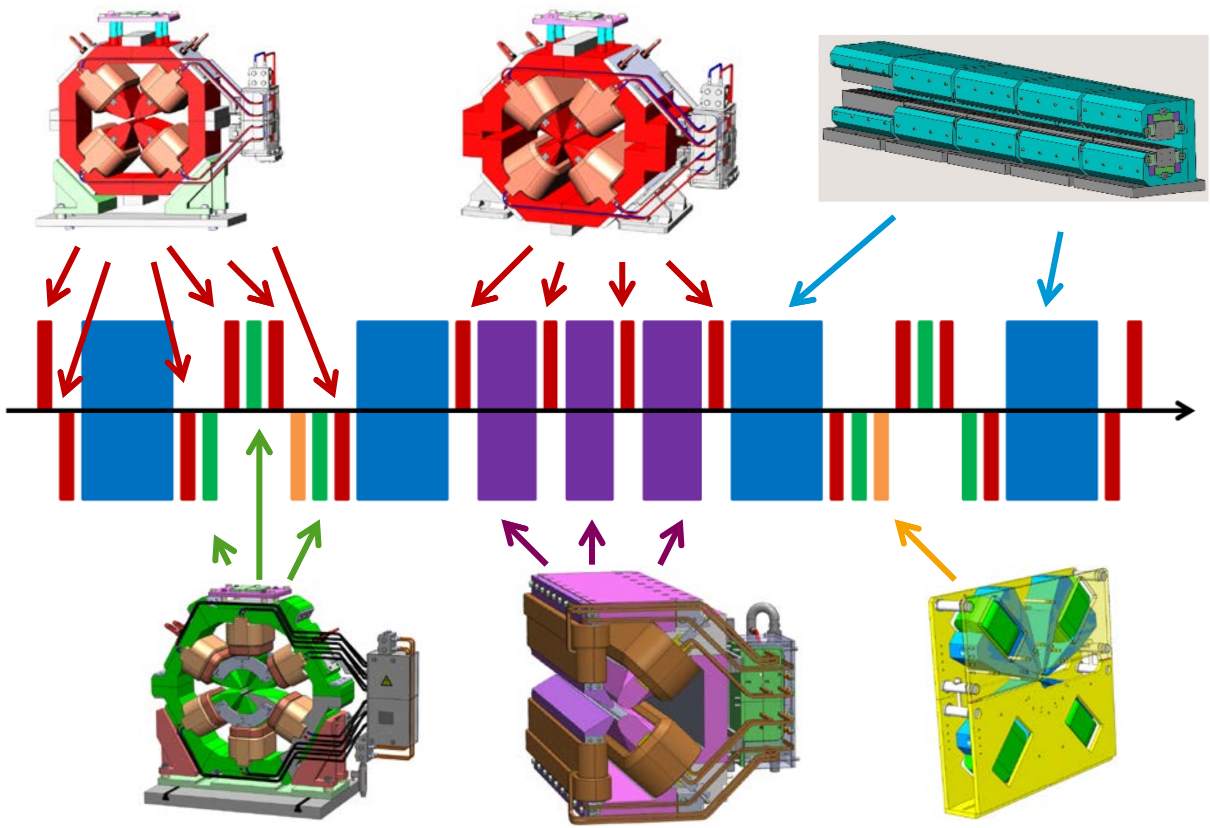
ESRF upgraded storage ring magnets: one cell



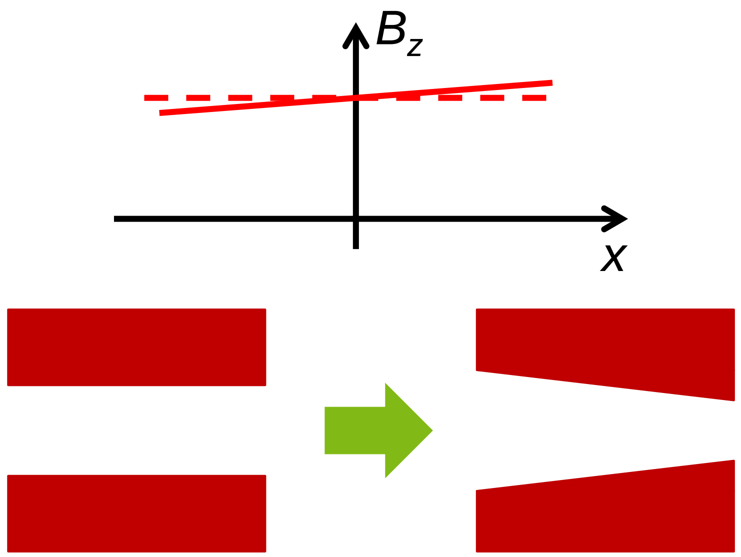
32 cells
~1000 magnets
(without correctors)

INTRODUCTION

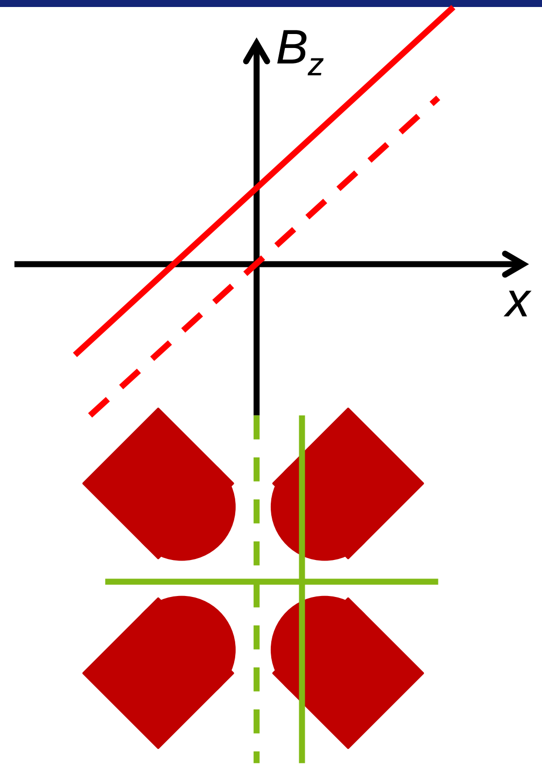
ESRF upgraded storage ring magnets: one cell



COMBINED DIPOLE-QUADRUPOLES (DQ)



Tapered dipole
High field, low gradient

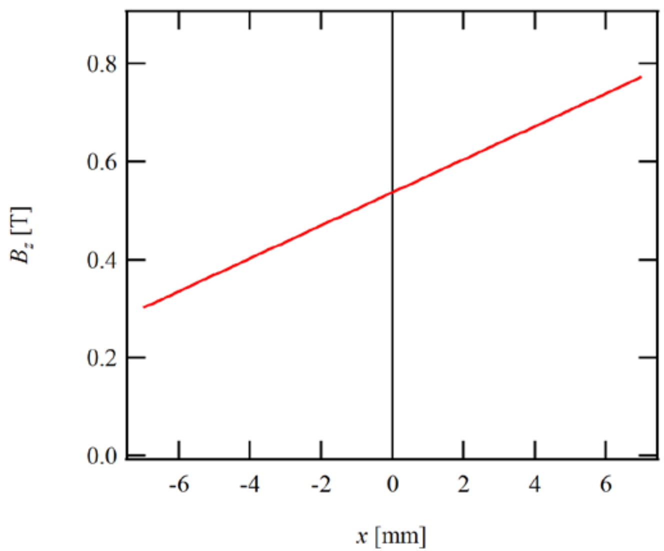


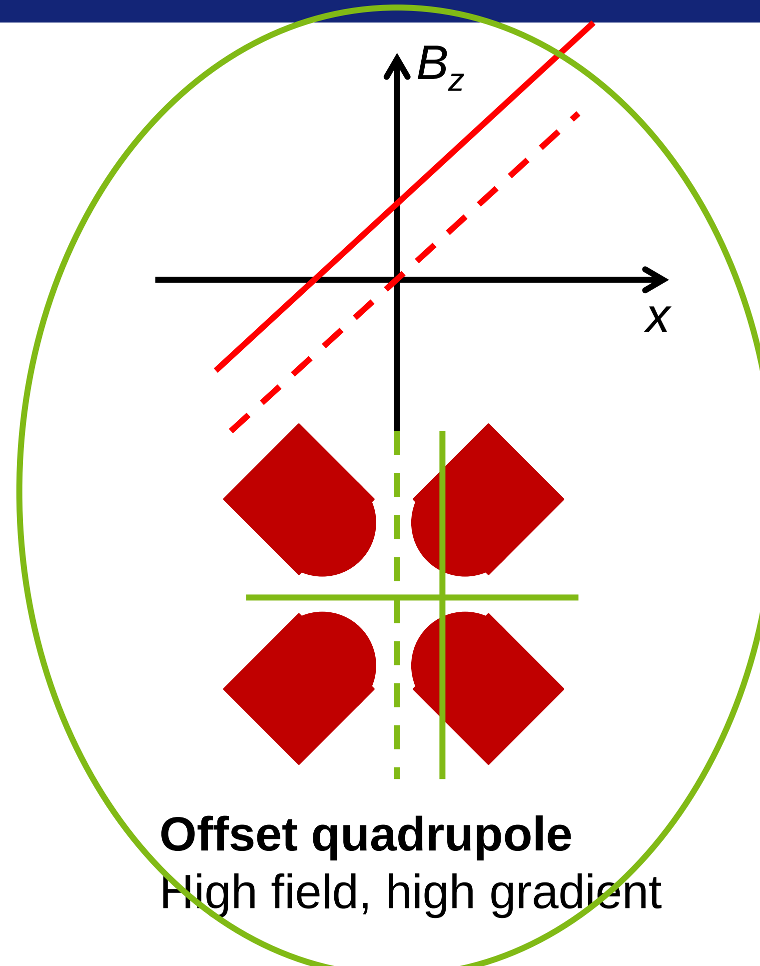
Offset quadrupole
High field, high gradient

COMBINED DIPOLE-QUADRUPOLES (DQ)

Magnetic specifications

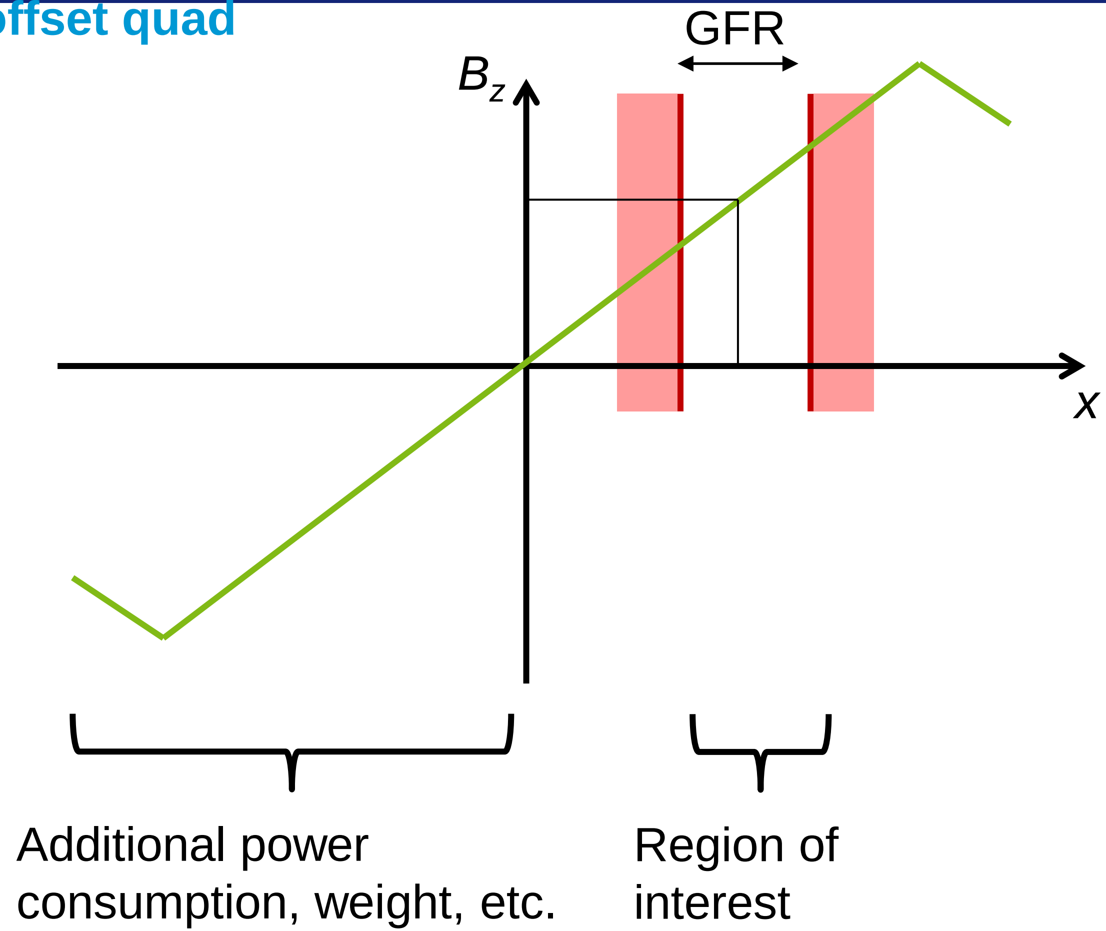
- DQ1: B = 0.57 T, G = 37 T/m
- DQ2: B = 0.39 T, G = 31 T/m.





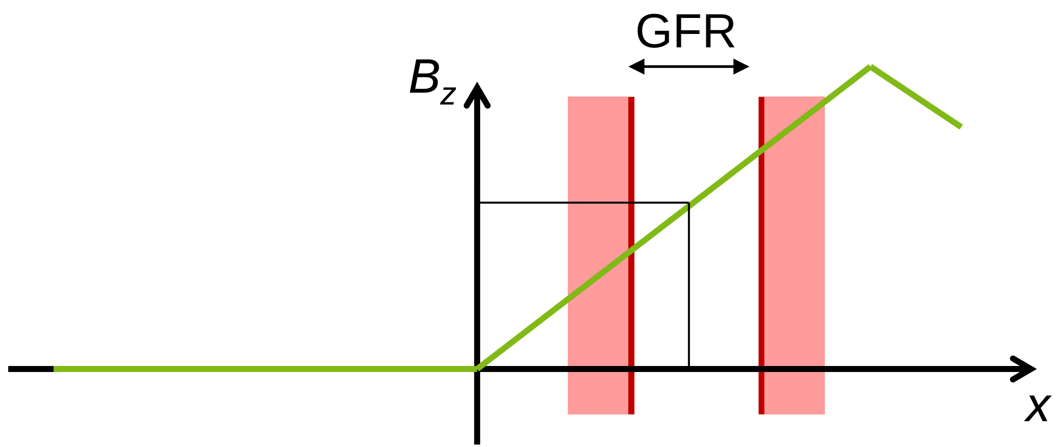
COMBINED DIPOLE-QUADRUPOLES (DQ)

Field of an offset quad



COMBINED DIPOLE-QUADRUPOLES (DQ)

A new target for DQ field



Pro

- Lower power consumption and weight
- Easy access on one side (vacuum chamber, magnetic measurements)

Cons

- Design and construction are more complex

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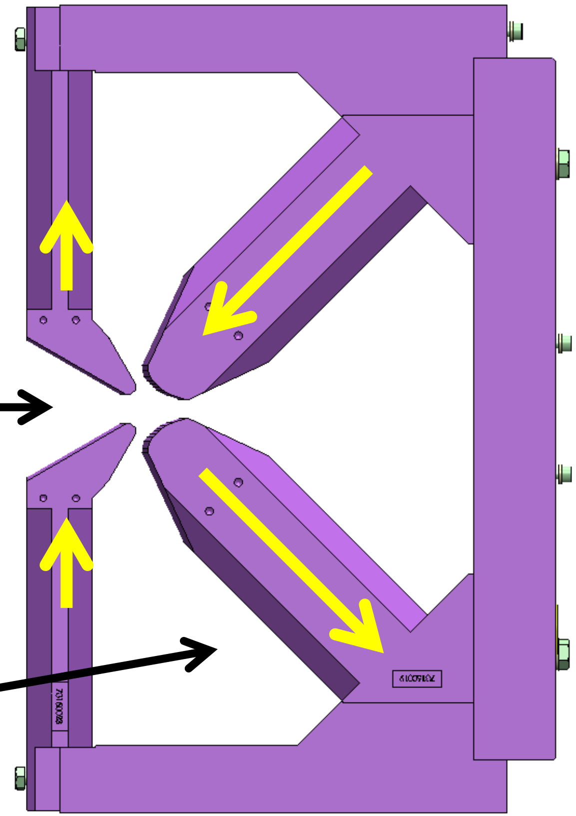
COMBINED DIPOLE-QUADRUPOLES (DQ)

Auxiliary pole

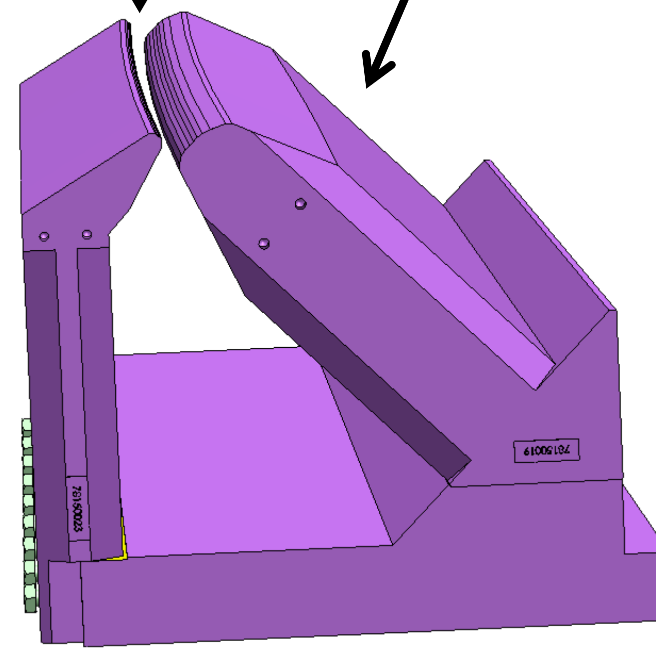
Gap
Vacuum chamber
Magnetic meas.

Main pole



Curved & shaped poles

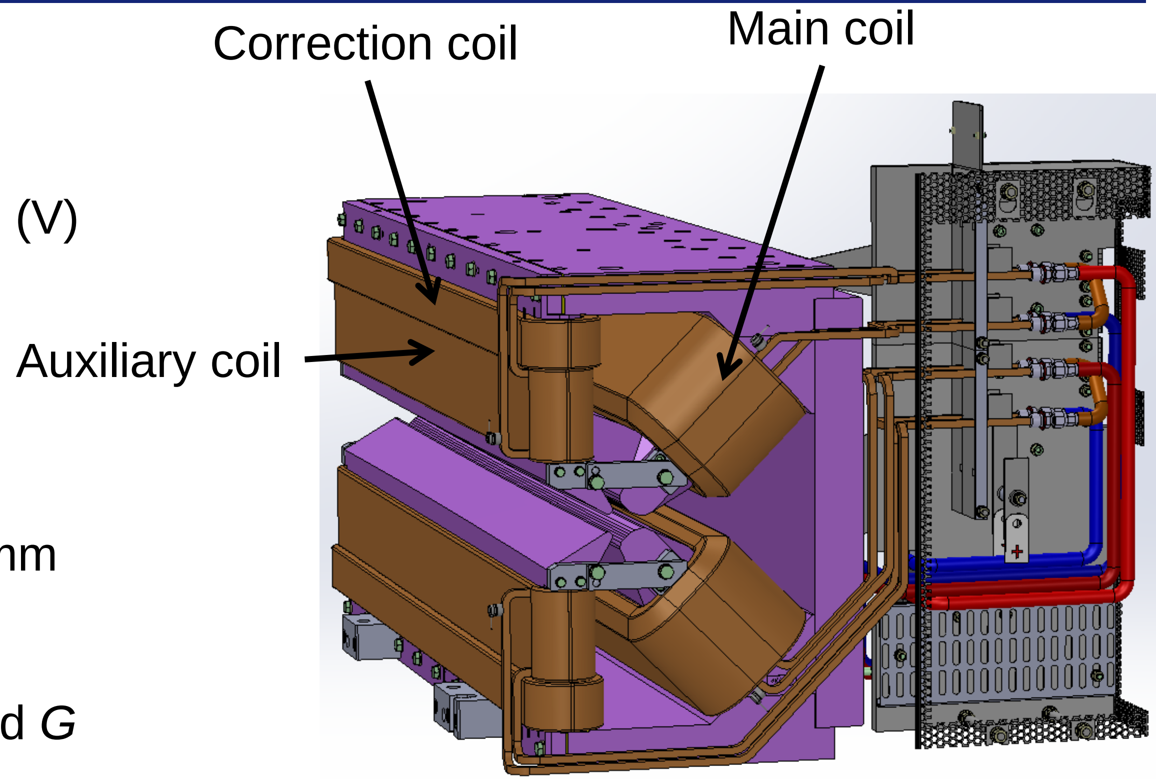
Straight yoke



COMBINED DIPOLE-QUADRUPOLES (DQ)

Main parameters

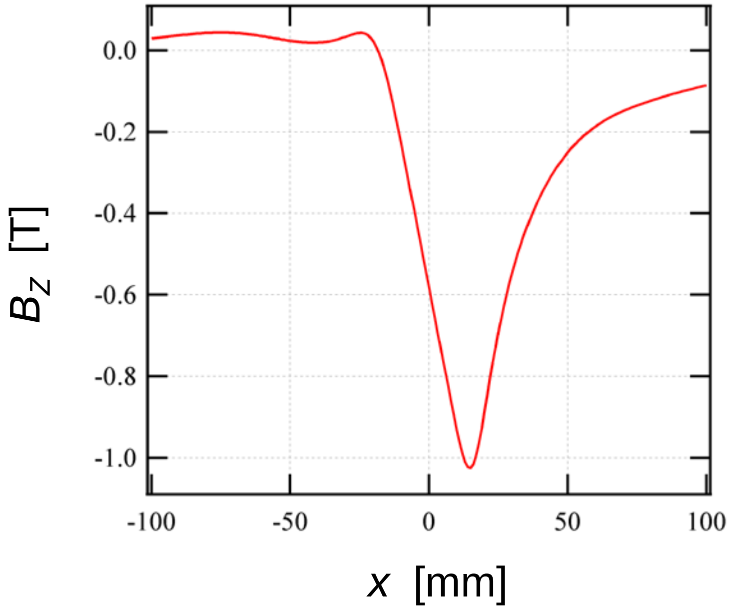
- 0.56 T, 37 T/m
- GFR radii: 7 mm (H), 5 mm (V)
- 1028 mm iron length
- 85 A nominal current
- 1.5 kW total power
- Vertical gaps: 18 mm / 12 mm
- Mass ~ 1ton
- Independent tuning of *B* and *G*
- ±2.5 % at fixed *B* and ±2 A in correction coils



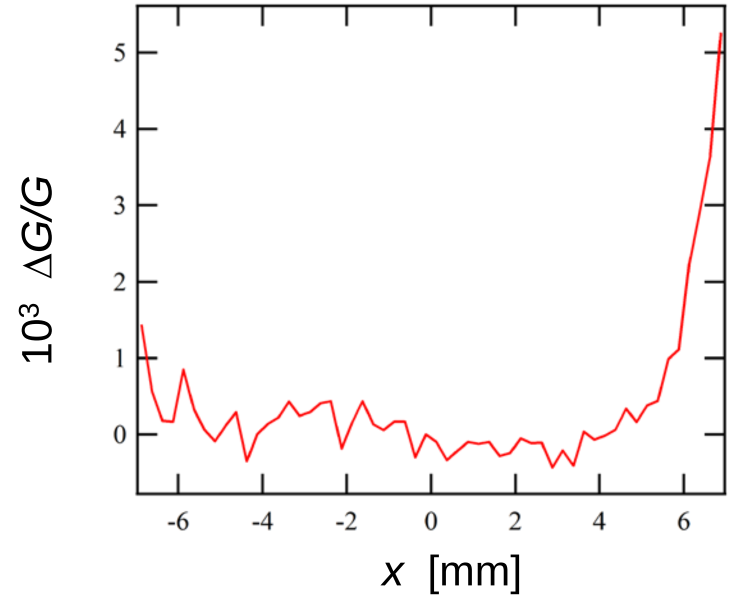
Design view of a DQ magnet (engineering design F. Villar et al.)

COMBINED DIPOLE-QUADRUPOLES (DQ)

Magnetic characteristics



Vertical field vs. transverse position
No field on one side of the magnet



Gradient errors vs. transverse position
Specifications: $\Delta G/G<1\%$ in GFR

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QUADRUPOLES

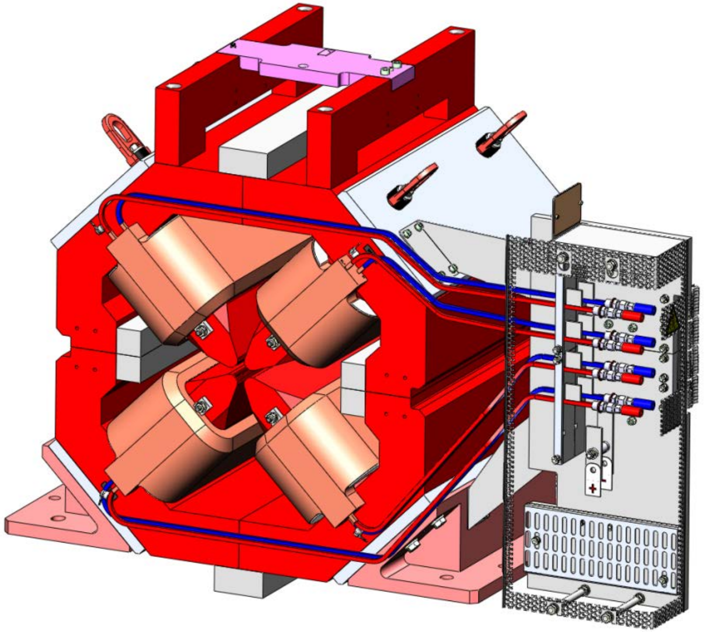
Main quadrupole magnet parameters

High gradients

- 90 T/m gradient, 388 – 484 mm length
- 12.6 mm bore radius, 11 mm vertical gap
- 1.8 – 2.1 kW power consumption

Moderate gradient

- Up to 58 T/m gradient, 162– 295 mm length
- 16.4 mm bore radius, 11 mm vertical gap
- 0.7 – 1.1 kW power consumption



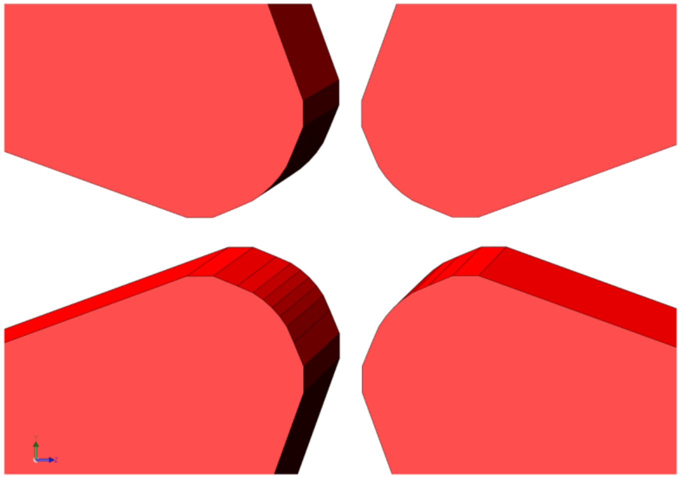
Design view of a high gradient quad (engineering design F. Villar et al.)

QUADRUPOLES – DESIGN

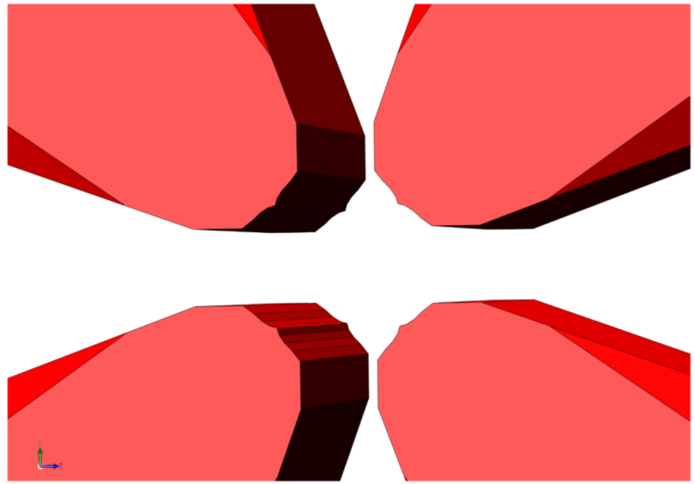
Pole shape optimization

[Le Bec, IPAC 14]

Results



Moderate gradient quadrupole
G = 58 T/m
R_0 = 16.4 mm
Gap = 11.2 mm



High gradient quadrupole
G = 90 T/m
R_0 = 12.6 mm
Gap = 11.2 mm

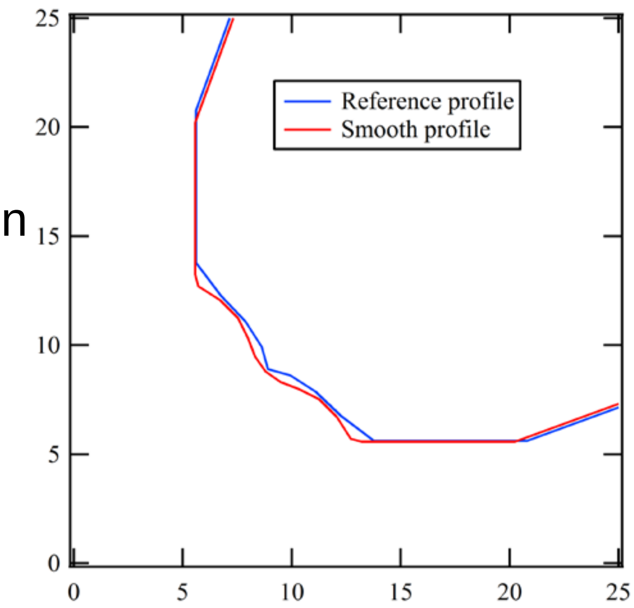
QUADRUPOLES – DESIGN

Comparison of two pole shapes

•Sharp pole shape (reference)

•Smoother shape obtained with different optimization parameters

•The "smooth shape" also shows sharp angles, but not at the same position.



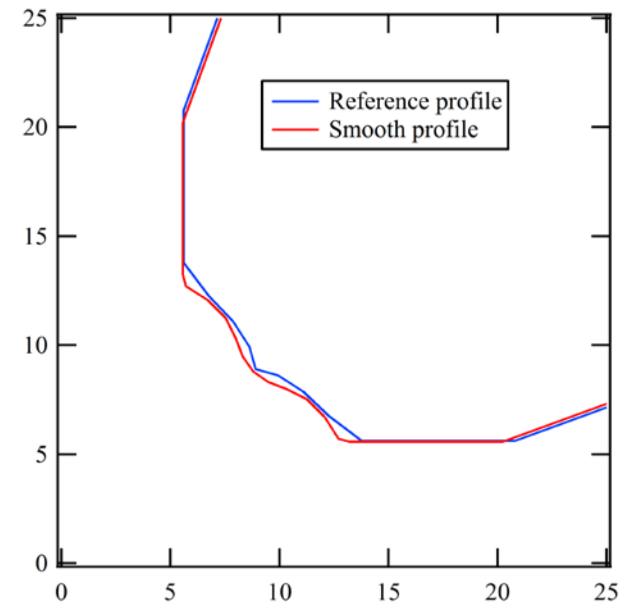
Multipole content @ 7 mm

n	b_n reference	b_n smooth
6	$-0.02\ 10^{-4}$	$-0.48\ 10^{-4}$
10	$0.51\ 10^{-4}$	$0.80\ 10^{-4}$
14	$-0.51\ 10^{-4}$	$-0.80\ 10^{-4}$
18	$0.05\ 10^{-4}$	$0.07\ 10^{-4}$
22	$0.00\ 10^{-4}$	$0.00\ 10^{-4}$

QUADRUPOLES – DESIGN

Sensitivity to pole shape errors

- ± 0.020 mm for pole shapes
- ± 0.020 mm for pole locations
- ± 0.040 mm global pole tolerances



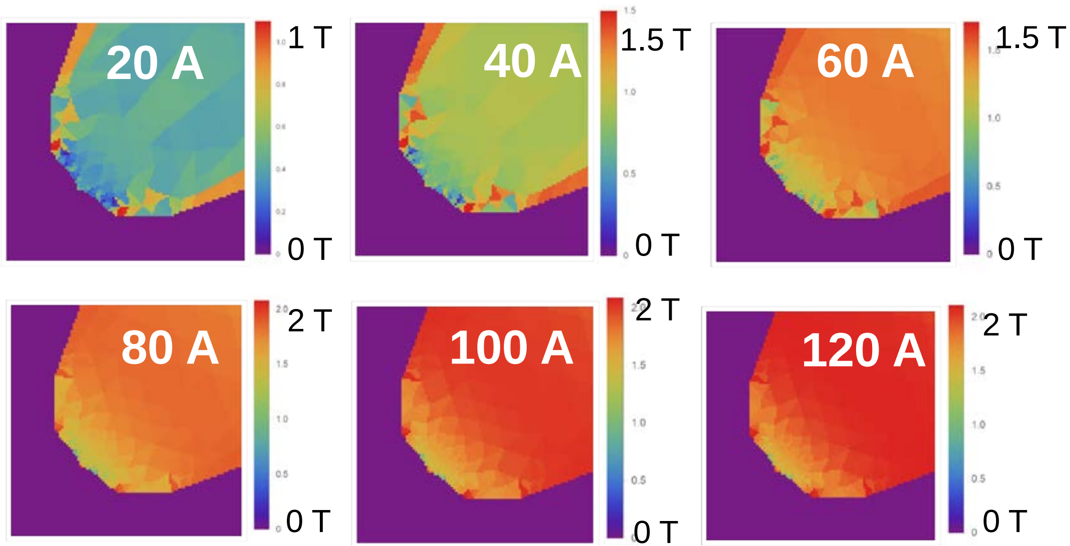
n	σb_n reference	σb_n smooth
3	$5.2\ 10^{-4}$	$5.2\ 10^{-4}$
4	$2.6\ 10^{-4}$	$2.1\ 10^{-4}$
5	$1.3\ 10^{-4}$	$1.1\ 10^{-4}$
6	$0.7\ 10^{-4}$	$0.6\ 10^{-4}$

➔ Sensitivity to profile errors is almost the same

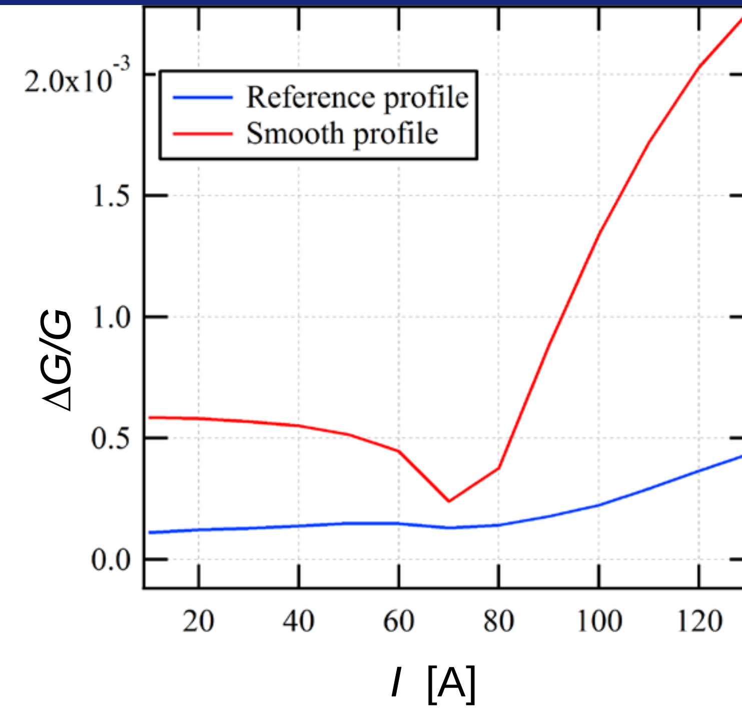
QUADRUPOLES – DESIGN

ΔG/G vs. excitation current

- The sharp profile has a better behavior for a large range of excitation current



Magnetization $\mu_0 M$ [T]. The central part of the profile saturates early due to its sharp profile. This "compensates" for the saturation of the edges and decreases the b_6 variation.



Gradient errors vs. excitation current

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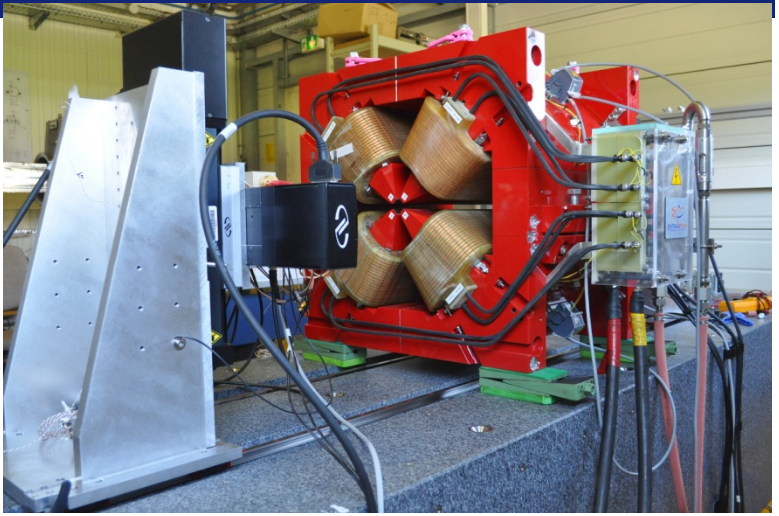
QUADRUPOLES – HIGH GRADIENT PROTOTYPE

Prototype built

- Designed in May 2014
- Delivered in March 2015
- Solid iron magnet (AISI 1010 material)
- Magnetic measurements done
- ±0.020 mm tolerances on the assembled prototype
- 86 T/m, 484 mm iron length

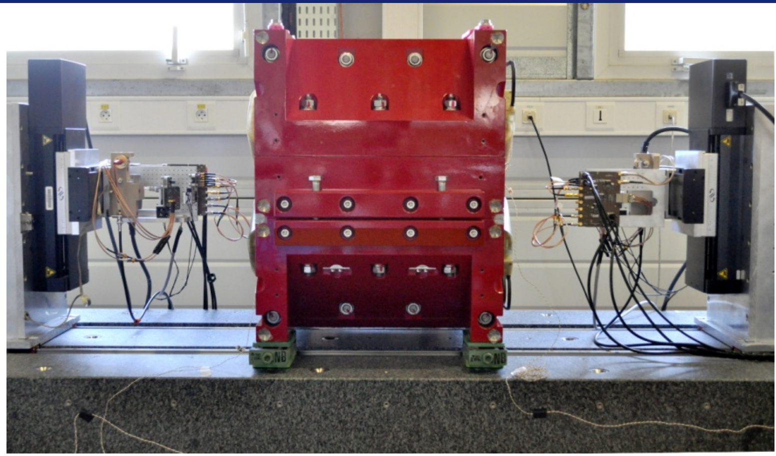


High gradient prototype installed on a stretched wire measurement bench

QUADRUPOLES – HIGH GRADIENT PROTOTYPE

Measurement bench

- ESRF stretched-wire bench

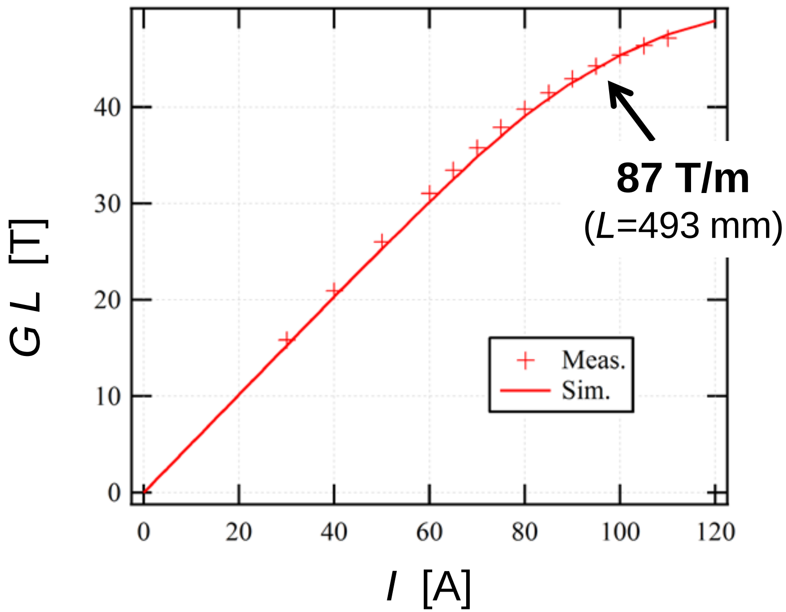


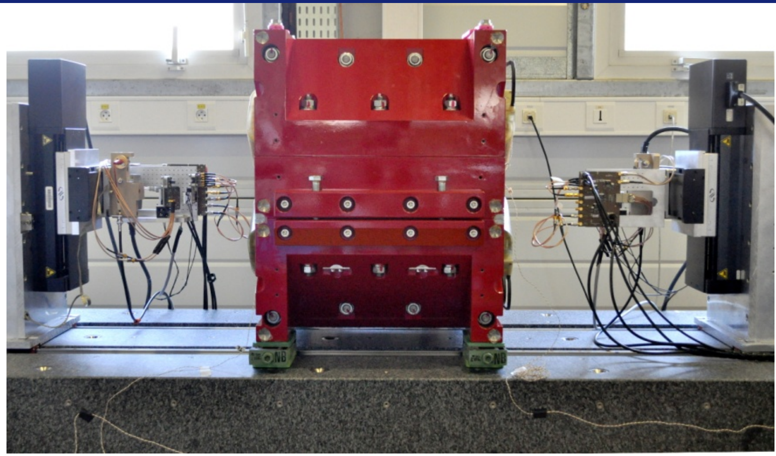
Magnet strength

- Nominal current: 89 A
- Iron length: 484 mm
- Power consumption: 2.2 kW
- Meas. Int. gradient: 42.29 T at first magnetization, 42.96 T after cycling
- Sim. Int. gradient: 42.29 T
- **Measured gradient: 87.1 T/m, assuming 493 mm magnetic length**

QUADRUPOLES – HIGH GRADIENT PROTOTYPE

Excitation curve



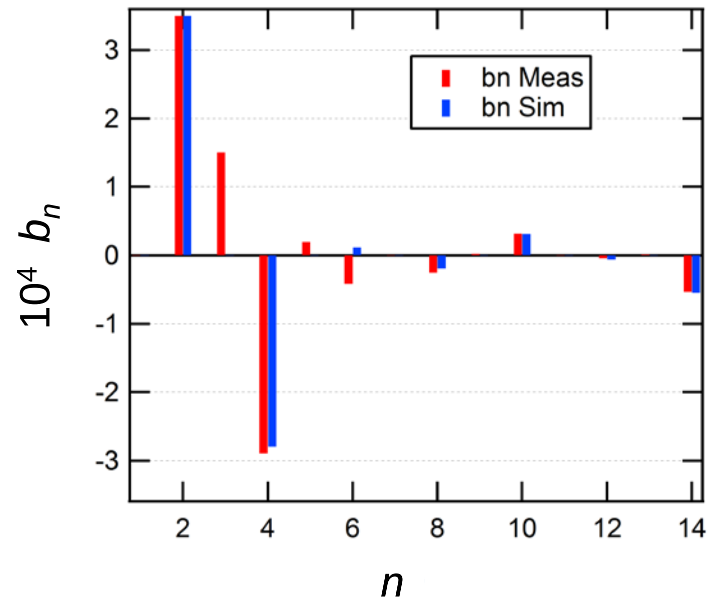


Measured and simulated excitation curves.

QUADRUPOLES – HIGH GRADIENT PROTOTYPE

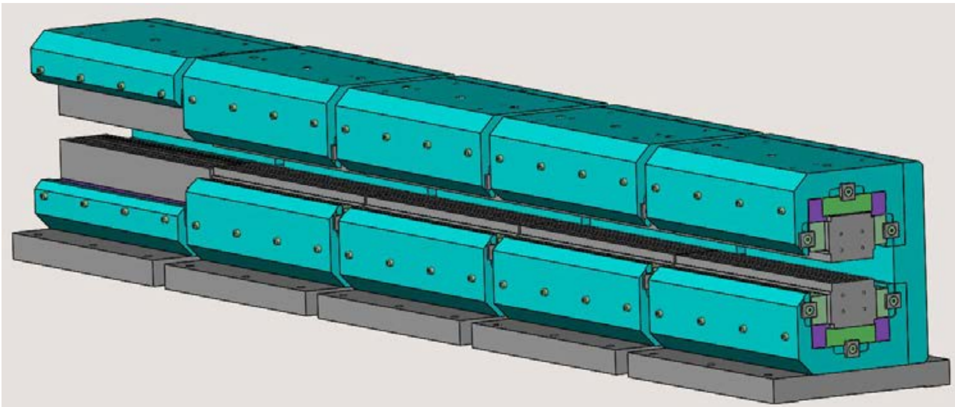
Field quality measurements

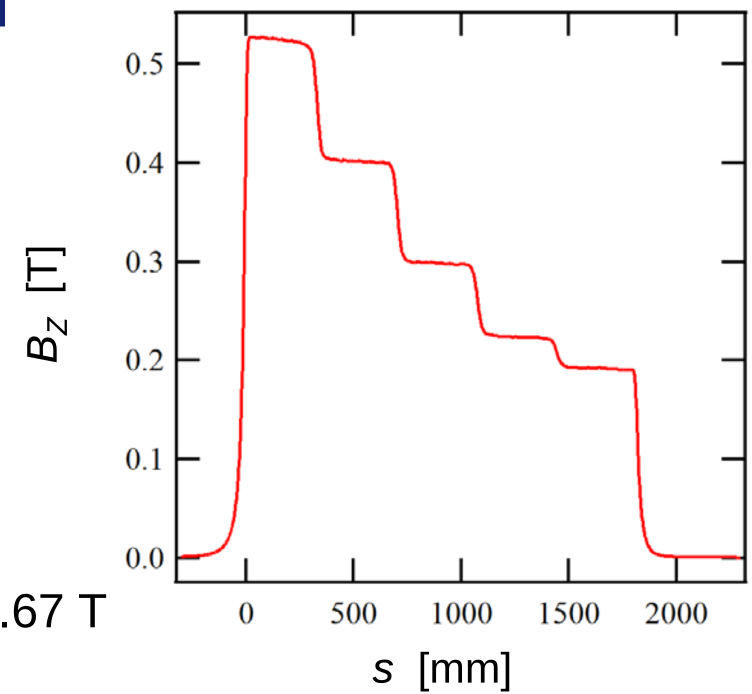
- Measured with ESRF stretched wire bench
- 3 units octupole at GFR radius
- Fits with simulations



Normal multipoles simulated and measured multipoles, expressed at the GFR radius (7 mm). The simulation includes measured pole location errors. b_2: quadrupole (vertical axis is truncated to 3.5 10^{-4}), b_3: sextupole, etc.

PERMANENT MAGNET DIPOLES WITH LONGITUDINAL GRADIENT (DL)





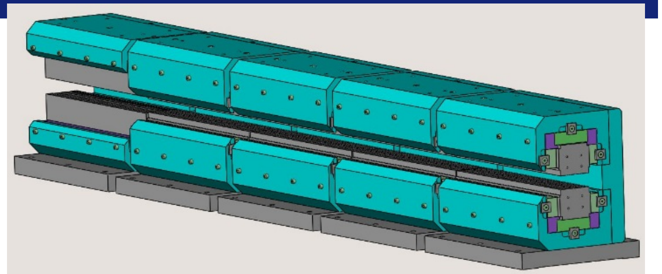
Vertical field vs. longitudinal position

- Field ranging from 0.17 T up to 0.55 or 0.67 T
- Total length: 1.85 m
- Gap: 25 mm
- Magnet mass: 400 kg
- PM Mass: 45 kg of Sm_2Co_{17} material

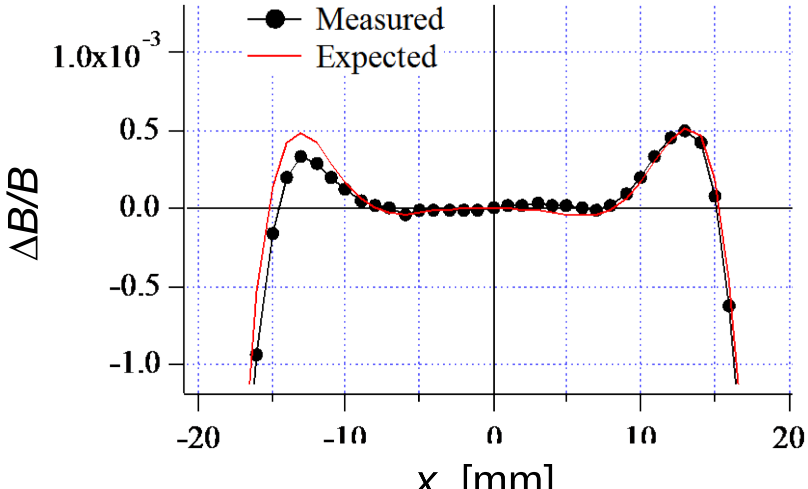
(Design and measurements of the DL magnet: J. Chavanne)

PERMANENT MAGNET DIPOLES WITH LONGITUDINAL GRADIENT (DL)

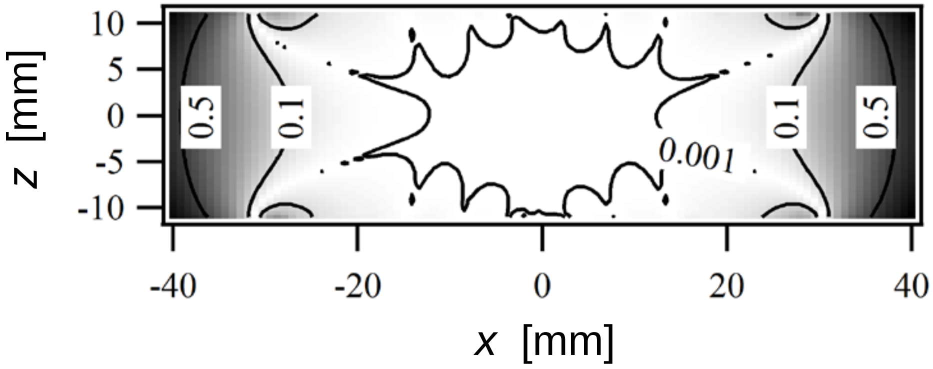
Field homogeneity



- Quality dominated by pole faces parallelism
- Easy and fast mechanical correction (shimming)
- Tolerance: $\Delta B/B < 10^{-3}$ @13 mm



Field homogeneity (Hall probe measurement)



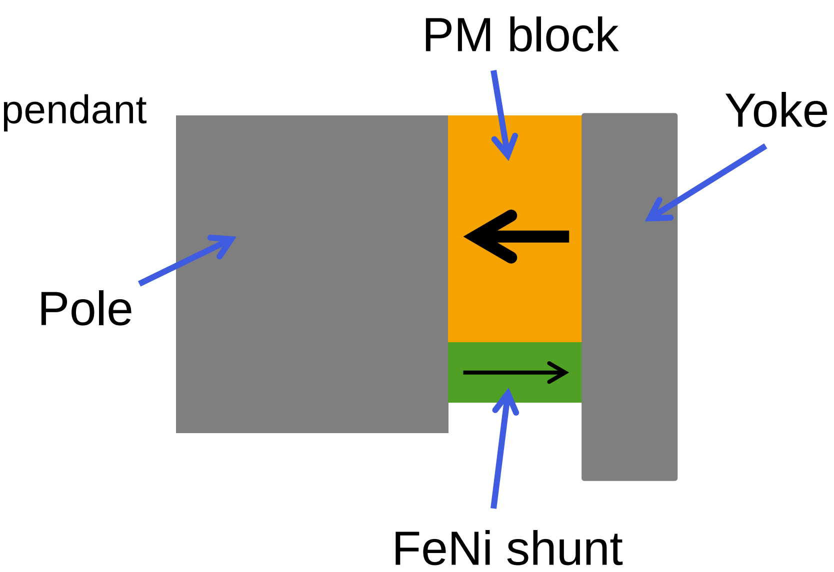
Integrated field homogeneity for 2 modules (Stretched-wire measurement)

PERMANENT MAGNET DIPOLES WITH LONGITUDINAL GRADIENT (DL)

Thermal stability

- Dominated by PM material temperature coefficient
- Can be compensated by passive FeNi shunts
  - The FeNi shunts are saturated
  - The saturated magnetization is temperature dependant

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

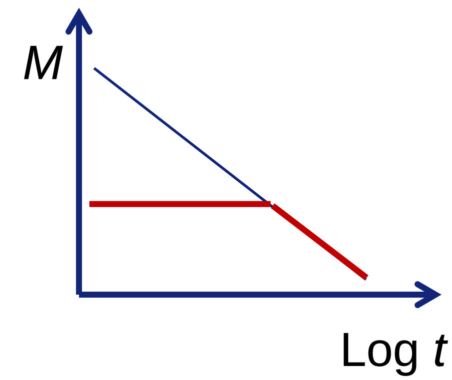


Passive thermal compensation of PM material

PERMANENT MAGNET DIPOLES WITH LONGITUDINAL GRADIENT (DL)

Long term stability

- Small demagnetization vs. time due to thermal excitation
- Can be stabilized before installation by thermal process



PM magnetization vs. time

Radiation damage

- Experiences with in-vacuum undulators
- Sm_2Co_{17} material has the highest resistance to radiation damage
- Resistance to radiation damage governed by coercivity

[Chavanne, IPAC14]

ERRORS AND TOLERANCES

Assembly errors

Multipolar error at the bore radius → $$\Delta B_N(\rho_0) \propto \frac{\Delta_{x,y}}{\rho_0}$$

Mechanical error → $\Delta_{x,y}$

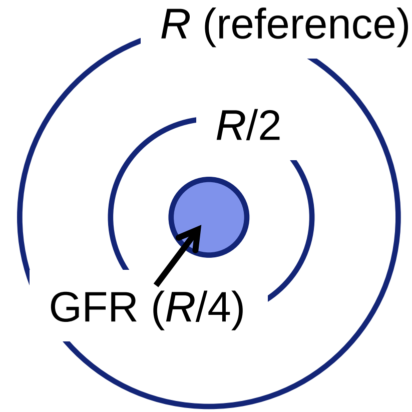
Bore radius → ρ_0

Errors at the GFR boundary

$$\Delta B_N(\rho) = \left(\frac{\rho}{\rho_0}\right)^{N-1} \Delta B_N(\rho_0)$$

(GFR radius = ρ)

Error @ $\rho=R/4$	$\rho_0=R$	$\rho_0=R/2$
Quadrupolar	ε_2	$4\varepsilon_2$
Sextupolar	ε_3	$8\varepsilon_3$
Octupolar	ε_4	$16\varepsilon_4$



Small apertures → Tigh mechanical tolerances

ERRORS AND TOLERANCES

Tolerances computations

- Large number of samples with pole profile errors and pole location errors
- Field quality computations (multipoles)
- Standard deviations of multipoles for different mechanical tolerances
- Lifetime and dynamic acceptance computations [Liuzzo, IPAC 2015]

Impact of quadrupole tolerances on electron beam lifetime and dynamic aperture (S. Liuzzo)

Global tolerance (Shape +Assembly) [mm]	Lifetime [h]	Dynamic aperture [mm]
± 0.020	22.5 ± 1.9	8.6 ± 0.8
± 0.040	22.3 ± 2.2	8.1 ± 0.5

ERRORS AND TOLERANCES

Tolerances computations

- Large number of samples with pole profile errors and pole location errors
- Field quality computations (multipoles)
- Standard deviations of multipoles for different mechanical tolerances
- Lifetime and dynamic acceptance computations [Liuzzo, IPAC 2015]

Global tolerances (including pole shapes & locations)
± 0.040 mm for most of the magnets
± 0.050 mm for dipole-quadrupoles (long magnets)

STRETCHED WIRE MAGNETIC MEASUREMENT BENCH

Multipole strength

- Linear and circular measurements

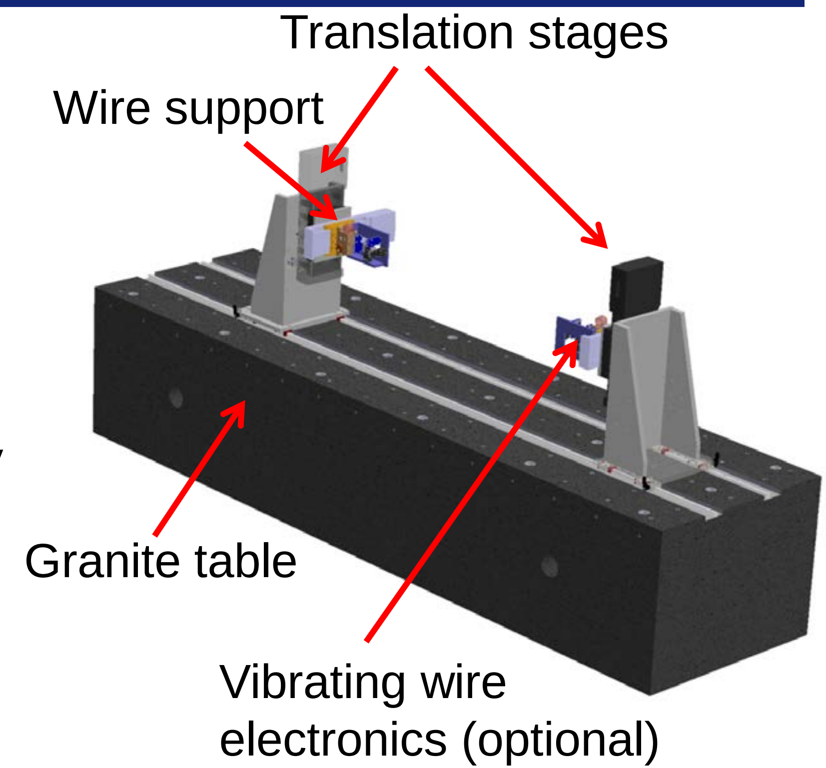
Field quality

- Circular measurements
- Multipole analysis
- < 1 “unit” (10^{-4} of main multipole) accuracy
- Analysis of complex wire trajectories is possible
- Calibration bench being manufactured

Alignment & fiducialization

•Error budget $\sigma_x \approx \sigma_Y \approx \sigma_Z \approx 28$ µm

(assuming $\sigma = 20$ µm for laser tracker)

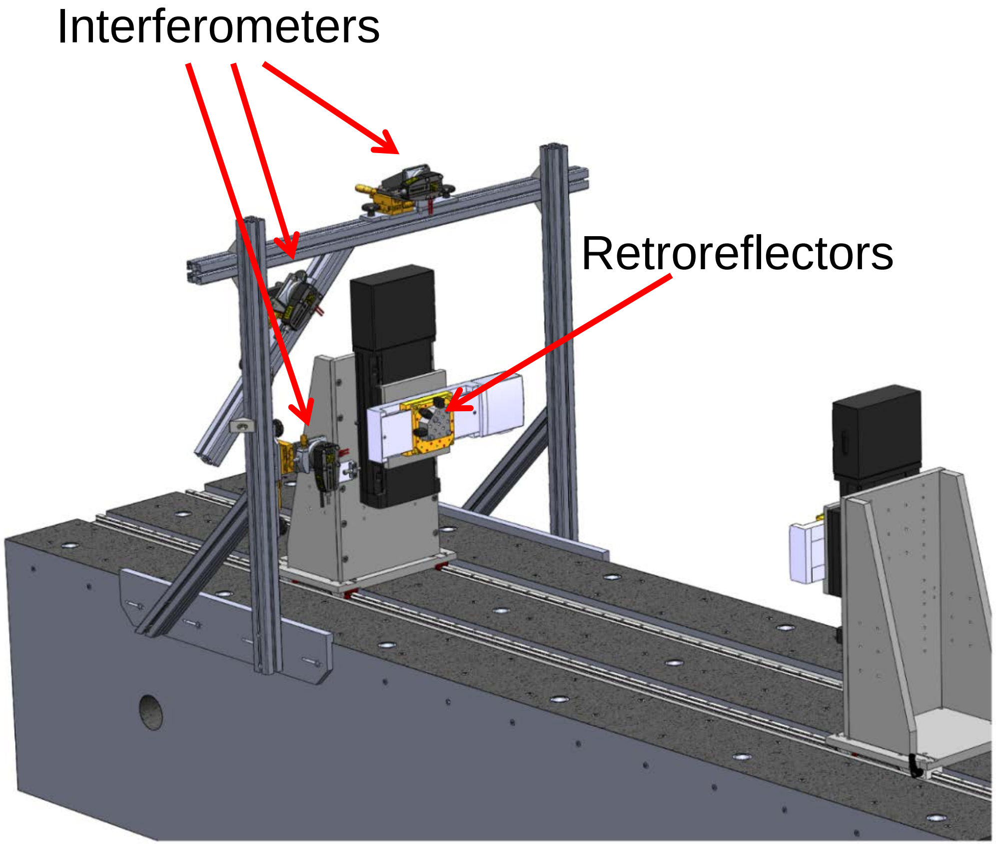


[Le Bec, PRSTAB 12]

STRETCHED WIRE MAGNETIC MEASUREMENT BENCH

Calibration bench

- Easy to install and to transport
- Fast calibration
- Based on 3 interferometers
- Measurements of scale errors
- Measurement of stage angles
- Implementation of correction tables
- Position errors ~0.001 mm after calibration



MEASUREMENT METHODS – MULTIPOLES

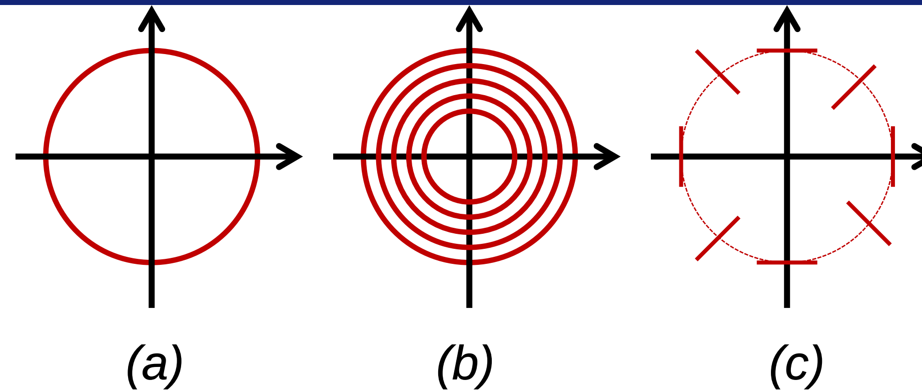
Multipole measurements

$$\mathbf{B}_{\mathbf{MEAS}} = \mathbf{MC}$$

where **C** are the multipoles and

$$M_{mn} = f\left(z_m, \theta_m, n\right)$$

➔ *Matrix inversion*



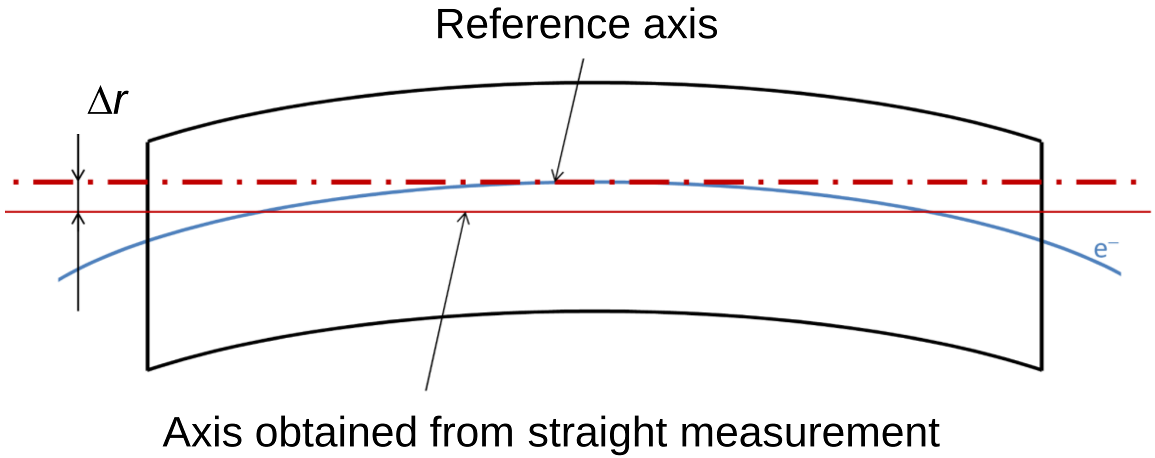
(a): Single radius circular measurement (good repeatability).
(b): Multiple radii circular measurements (improved accuracy).
(c): Compensation of the quadrupole term.

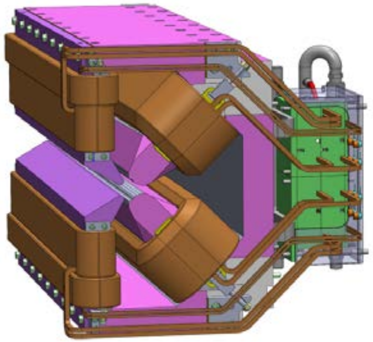
Advantages

- Flexibility
- Suitable for arbitrary wire trajectory
- Correction of wire position errors
- Cancellation of arbitrary multipoles

MEASUREMENT METHODS – DQ MAGNETS

DQ Stretched wire measurements





SWM to be used for

- Fiducialization
- Calibration of the bending angle
- Field quality control

MEASUREMENT METHODS – DQ MAGNETS

First approximation

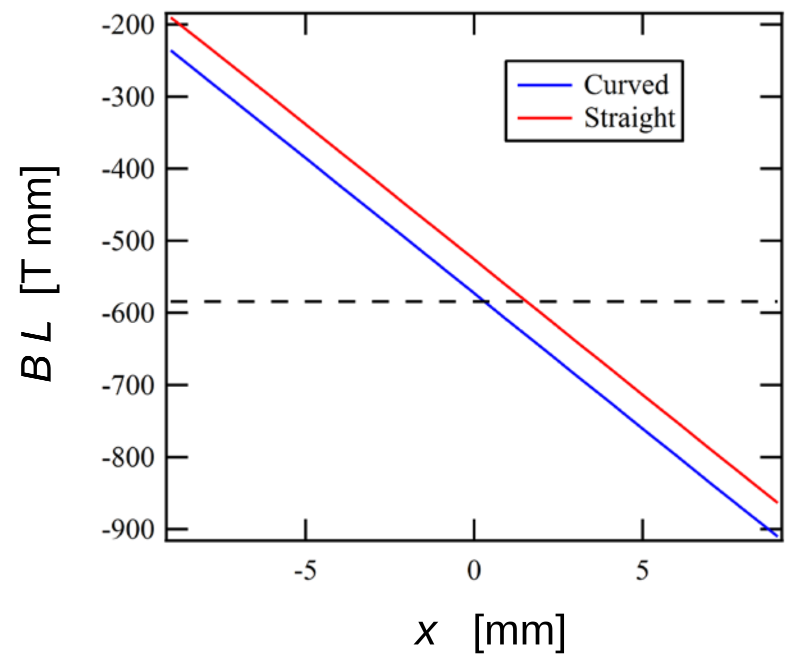
- Higher order multipoles neglected
- Same gradient for curved and straight integrated field
- Transverse offset ~ sag / 3

(Results from [A. Jain, DLSR 2014])

Simulation results for DQ1

- $(G_C - G_S)/G_C = 6\ 10^{-4}$
- $\Delta r - sag/3 = 3\ \mu m$

What about higher order terms?



MEASUREMENT METHODS – DQ MAGNETS

Effect of higher order multipoles

$$I_S(z) = I_2 \sum_{n=1}^{N} (b_n + i a_n) \left(\frac{z}{\rho} \right)^{n-1} = B_S L$$

Integral along a curved path, series development, …

$$I_C(z) \approx I_2 \sum_{n=1}^{N} (\beta_n + i \alpha_n) \left(\frac{z}{\rho} \right)^{n-1}$$

with $(\beta_1 + i\alpha_1, \ldots, \beta_N + i\alpha_N)^T \approx \mathbf{A} (b_1 + i a_1, \ldots, b_N + i a_N)^T$

and $A_{mn} = \dfrac{(n-1)!}{(m-1)!(n-m)!(2(n-m)+1)8^{n-m}} \left(\dfrac{L}{R_0 \rho} \right)^{n-m}$

With some limits: I_S is analytic and I_C is not.

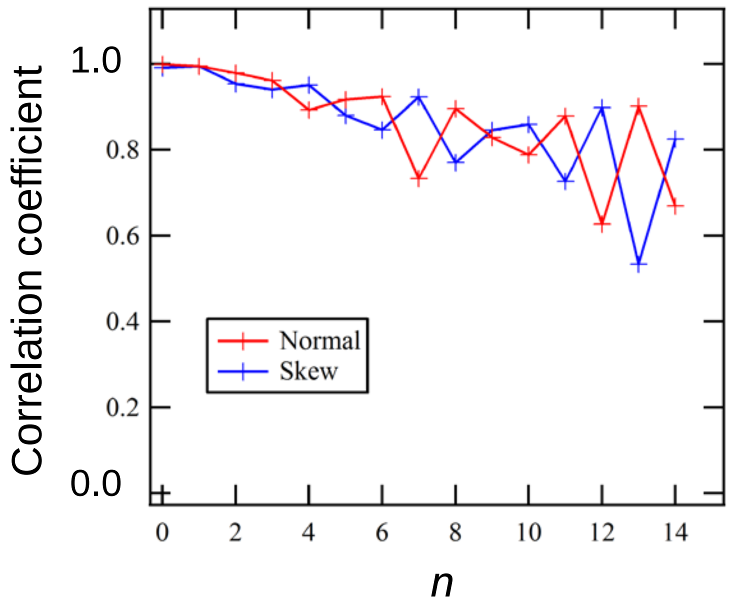
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2016.
Invited presentation 4OrCC_01 given at MT-24, Seoul, Korea, October 18-23, 2015.

MEASUREMENT METHODS – DQ MAGNETS

n	Curved multipoles	Straight multipoles	Straight multipoles + correction
1	21792.0	20006.2	21792.9
2	10000	9995.3	10000.5
3	17.03	13.73	14.51
4	-4.22	4.39	1.75
5	5.93	-7.99	-4.03
6	19.79	-0.99	0.95

MEASUREMENT METHODS – DQ MAGNETS

Correlation coefficient between curved and straight measurements



➔ *Stretched wire measurements are good indicators for field quality*

CONCLUSION

ESRF – EBS

- 6 GeV synchrotron light source with 135 pm·rad horizontal emittance
- Installation in 2019
- More than 1000 magnets, procurement started

Magnet design

- New single-sided dipole-quadrupole concept (DQ)
- High gradient (90 T/m) quadrupole, prototype measured
- Permanent magnet dipoles with longitudinal gradient (DL)

Magnetic measurements

- Stretched wire benches developed in house
- Suitable for strength meas., field quality and alignment (including DLs and DQs)

MANY THANKS FOR YOUR ATTENTION