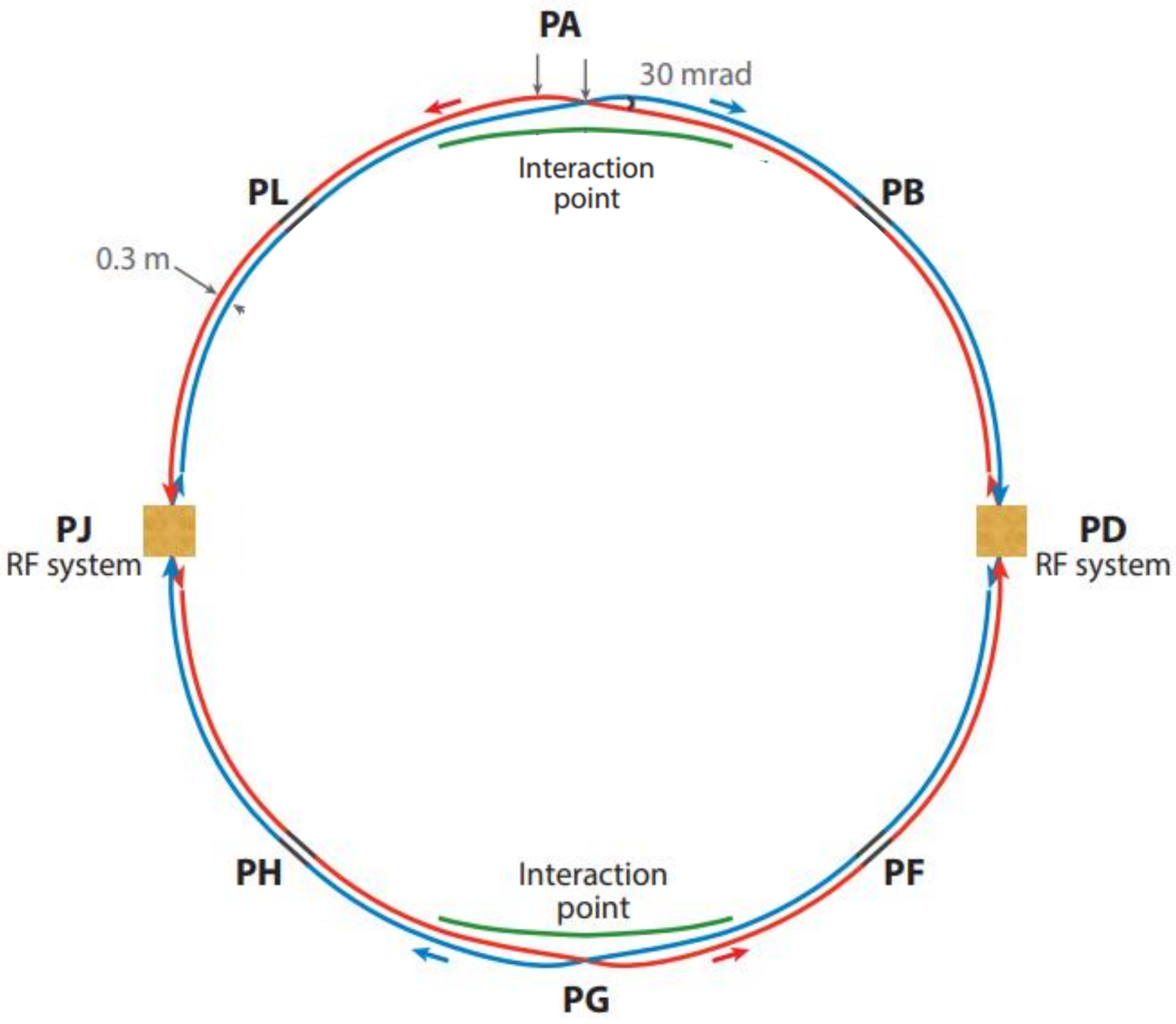
Magnetic Measurements of the First Short Models of Twin-Aperture Magnets for FCC-ee

A. Milanese J. Bauche C. Petrone

Resistive magnets for the lepton collider arcs (FCC-ee)



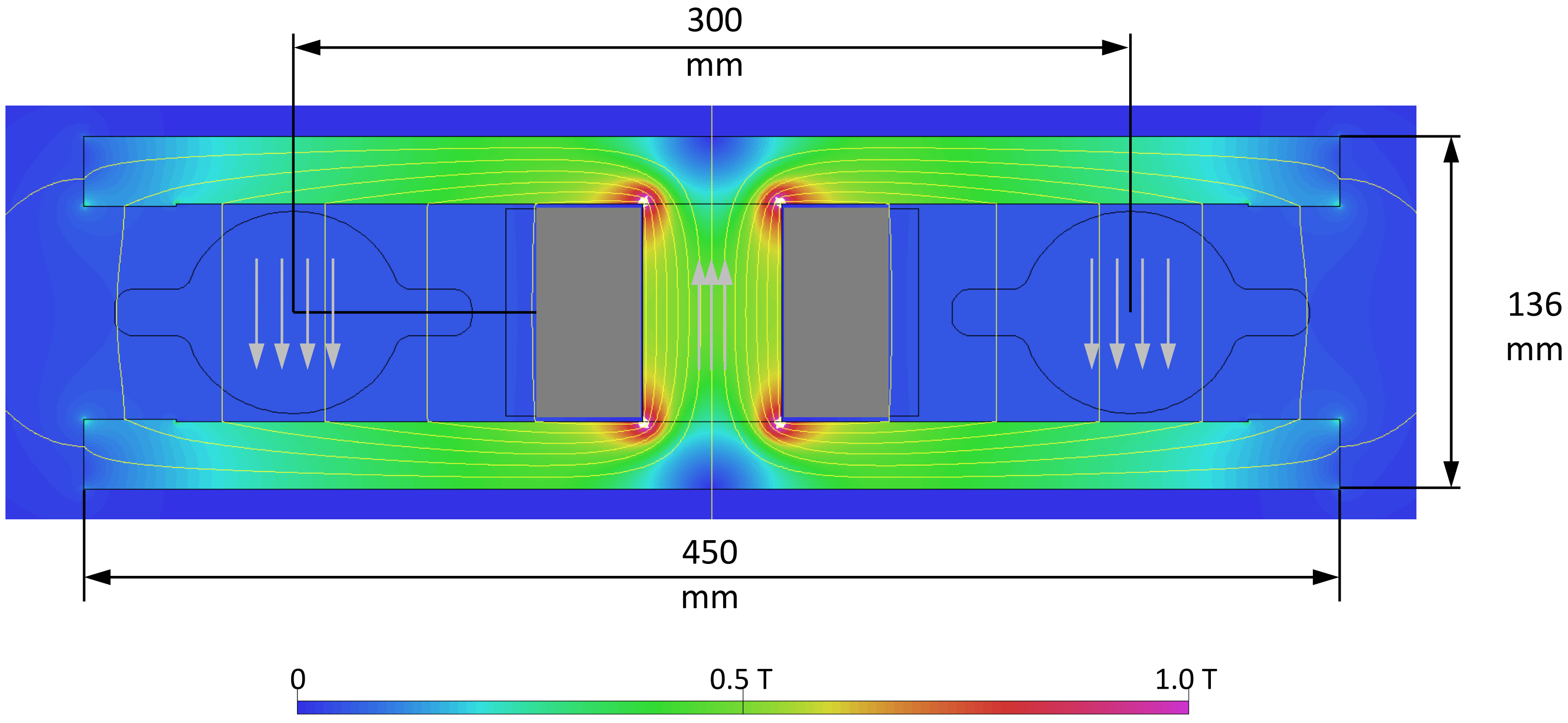
Double ring collider:

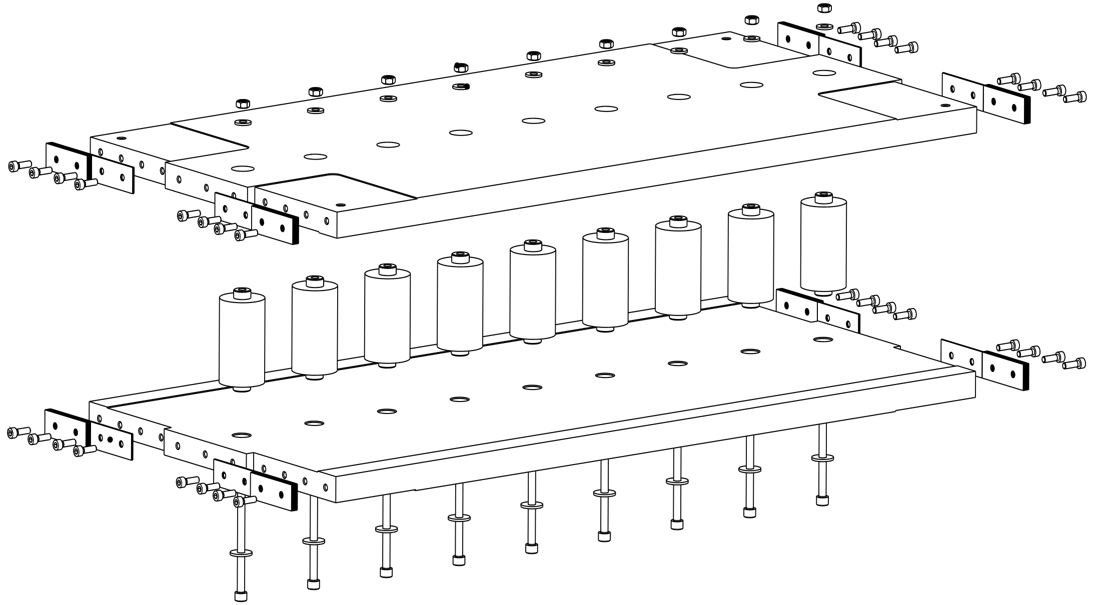
- Circumference (km) **97.756**
- Beam energy (GeV) **45.6 80 120 175 182.5**
- Packing factor of 81.8% (**~ 80 km**)
- **8700** double-aperture dipoles
- **2900** double-aperture quadrupoles

M. Benedikt *et al.*, "Future Circular Collider Conceptual Design Report, vol. 2: the Lepton Collider (FCC-ee)," Eur. Phys. J. ST. 228, no. 2 (2019)

Dipole Bending Magnets

Dipole short models: design





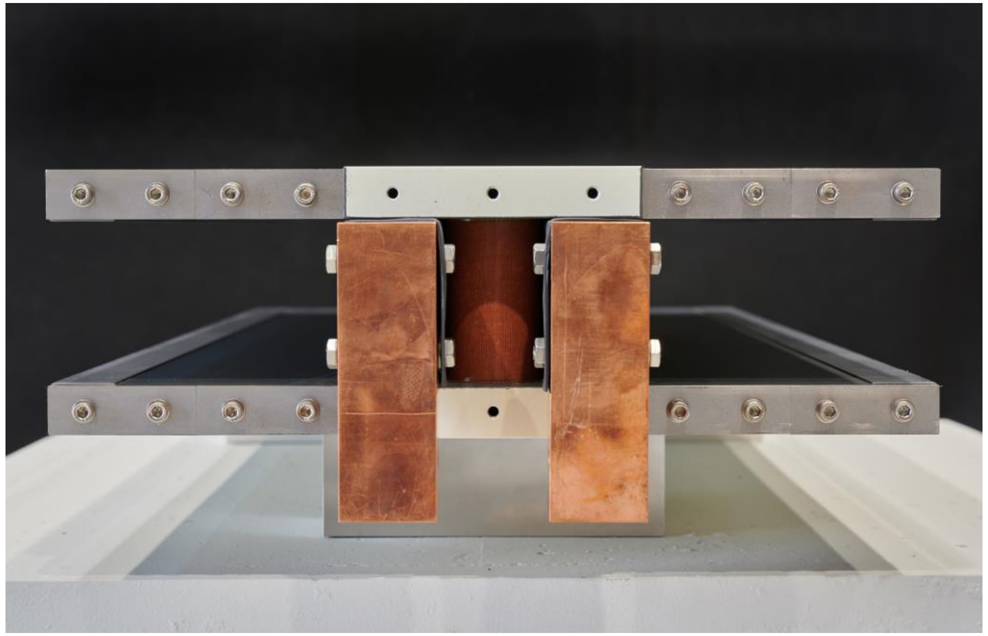
Parameter (dipoles)	Value	Units
Field strength (45.6 GeV–182.5 GeV)	14.1–56.6	mT
Aperture (horizontal × vertical)	130 × 84	mm
Good Field Region (Diameter)	20	mm
Field quality in GFR (not counting quad.)	$10^{-4} \approx 1$	unit

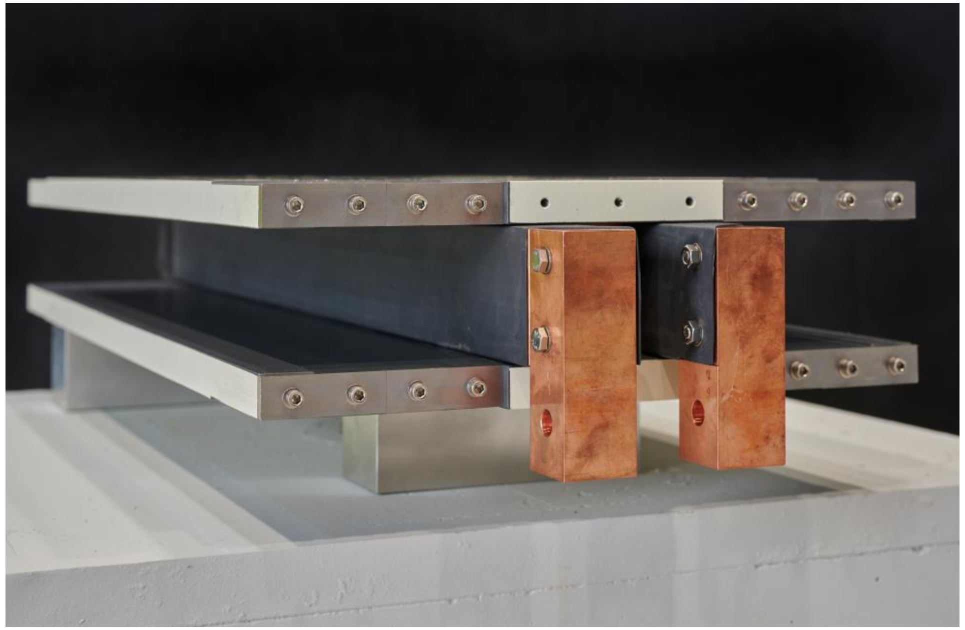
Double aperture magnet

- Twin apertures design: compactness
  - ✓ Two aluminum busbars (one coil)
  - ✓ Low current density 1 A/mm^2
  - ✓ Energy-efficient (total 16 MW)
- Vacuum pipe defines the aperture

A. Milanese, "**Efficient Twin Aperture Magnets for the Future Circular e$^+$/e$^-$ Collider**," Phys. Rev. ST Accel. Beams

Dipole magnets: short models





To understand the **performance** and **industrialization** needs - > **two models produced**:

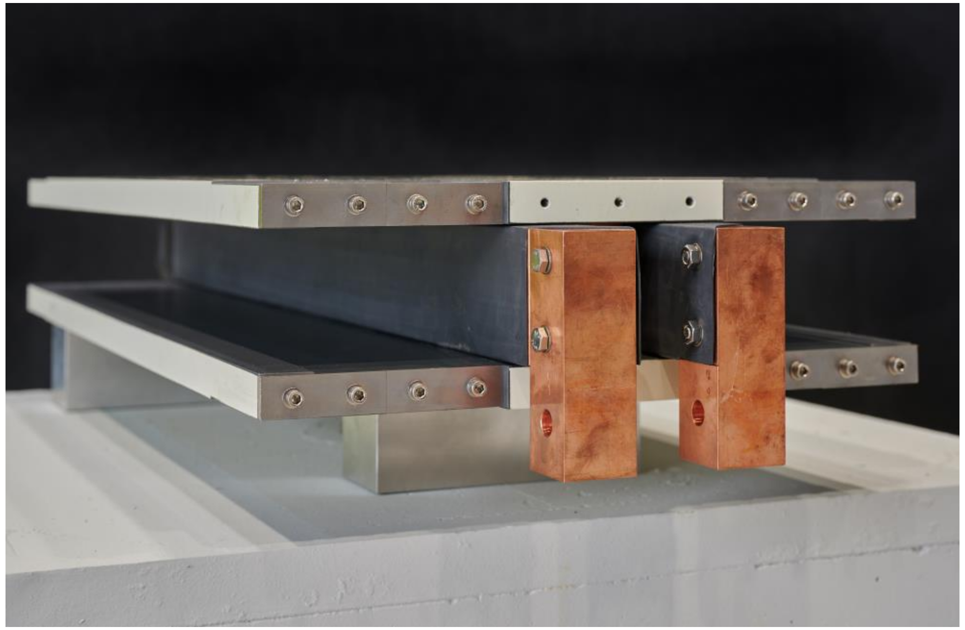
1. **ARMCO** pure iron (Fe = 99.85%), solid yoke
2. **S355** construction steel, solid yoke.

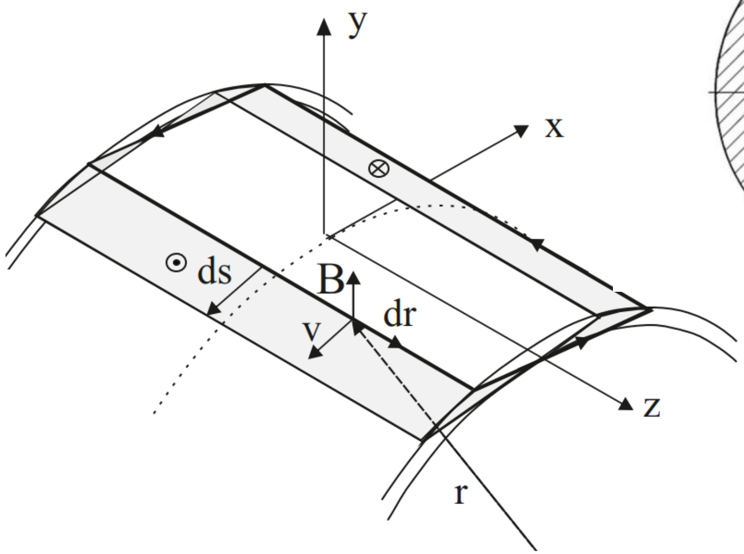
Copper coil, air cooled, 0.9 m in length

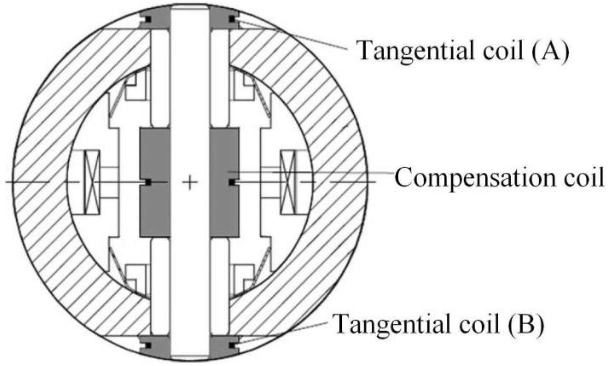
Study apertures symmetry

- Field quality
- Hysteresis
- Transfer function (Field vs Current)

Magnetic measurement method: rotating induction coils



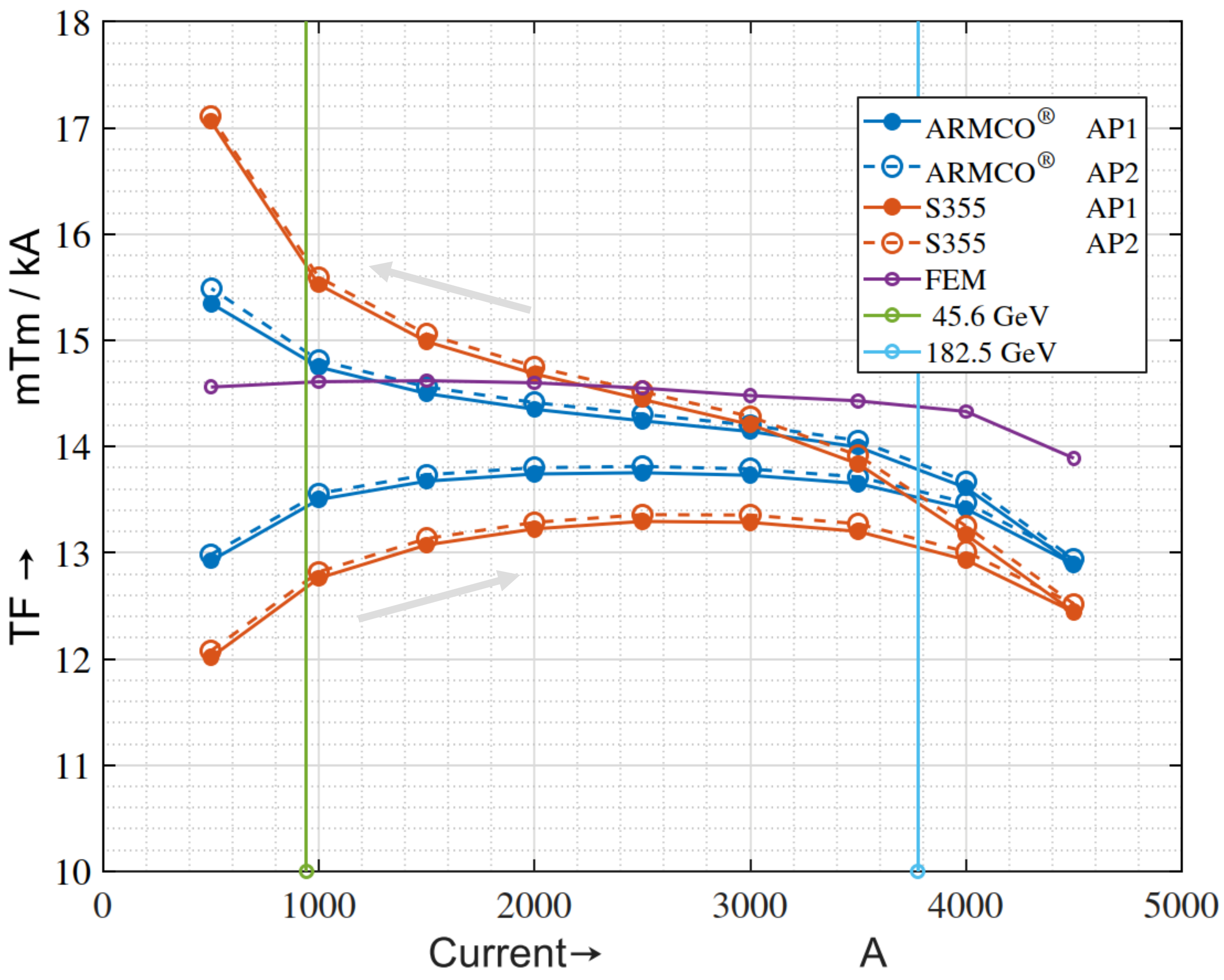


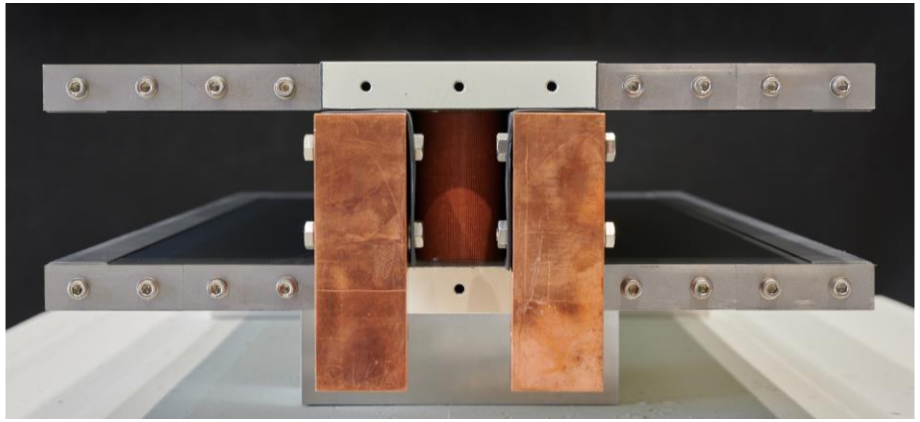


- Incremental flux linkage
- Coil surface moves on a circular trajectory
- Surfaces adaptable to the field level by design
- Compensation improves multipoles sensitivity
- Used an available shaft (L=1.2 m, r=30 mm)

C. Petrone, "**Magnetic measurements of the FCC-ee dipole models PXMBHAACAC-CR000001/2**," CERN EDMS 2050314

Magnetic Measurements: dipole transfer functions

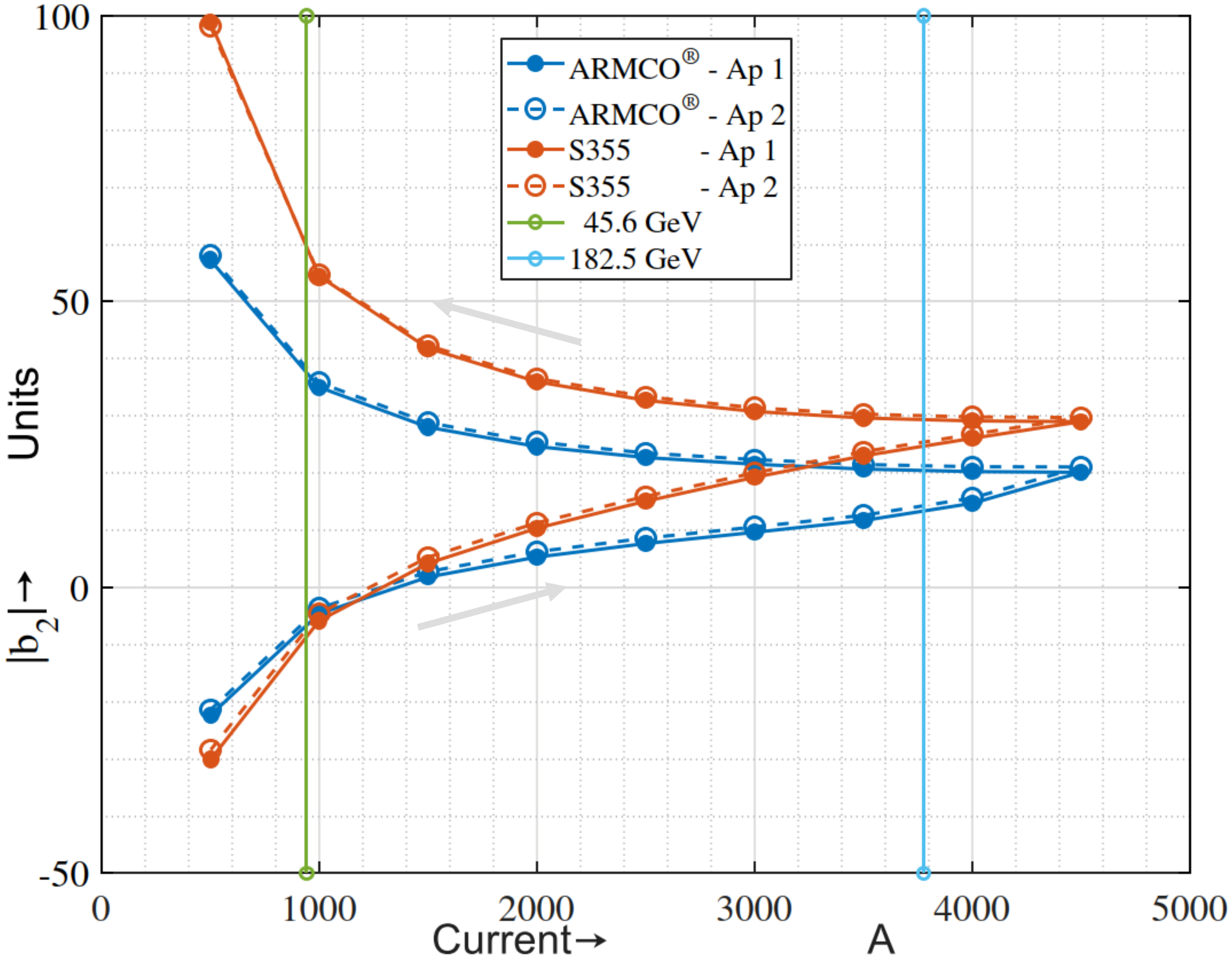




Ap 1 Ap 2

- Simulation do not consider hysteresis
- Two apertures differ <2‰ in both materials
- Larger hysteresis effect for the S355

Magnetic Measurements: multipoles @ 10 mm reference radius



Aperture 1 @ 4500 A

	ARMCO		*S355*	
n	b_n	a_n	b_n	a_n
3	-0.48	0.70	-0.06	0.52
4	0.49	0.05	0.48	0.10
5	-0.07	0.02	-0.07	-0.01
6	0.03	0.00	0.03	0.00

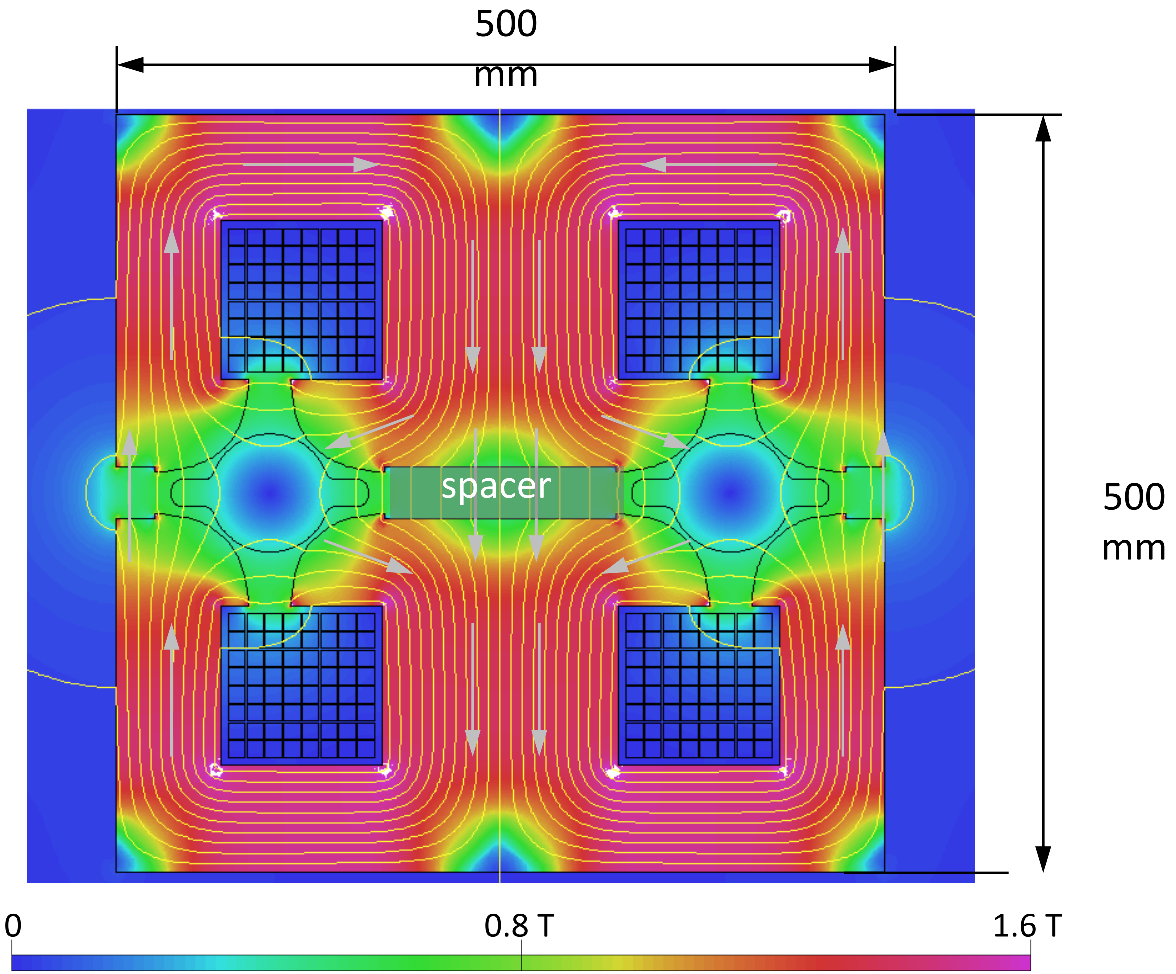
Both apertures follow nicely for both materials

The largest multipole b_2 has two effects:

- Geometric effect can be adjusted
- Hysteresis effect, more complex to correct

Quadrupole Magnets

Quadrupole magnets: design



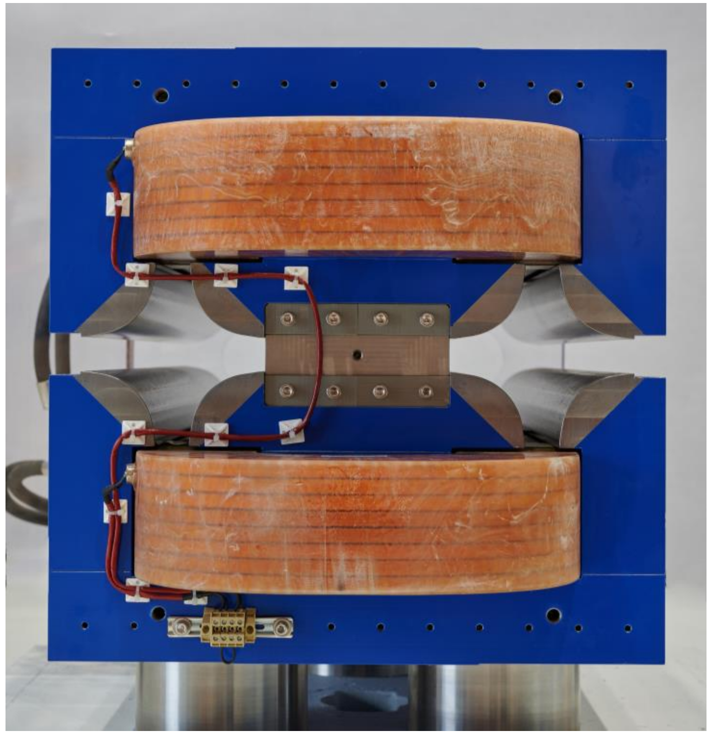
Parameter (quadrupoles)	Value	Units
Maximum gradient	9.9	T/m
Aperture (Diameter)	84	mm
Good Field Region (Diameter)	20	mm
Field quality in GFR (not counting dip.)	$10^{-4} \approx 1$	unit

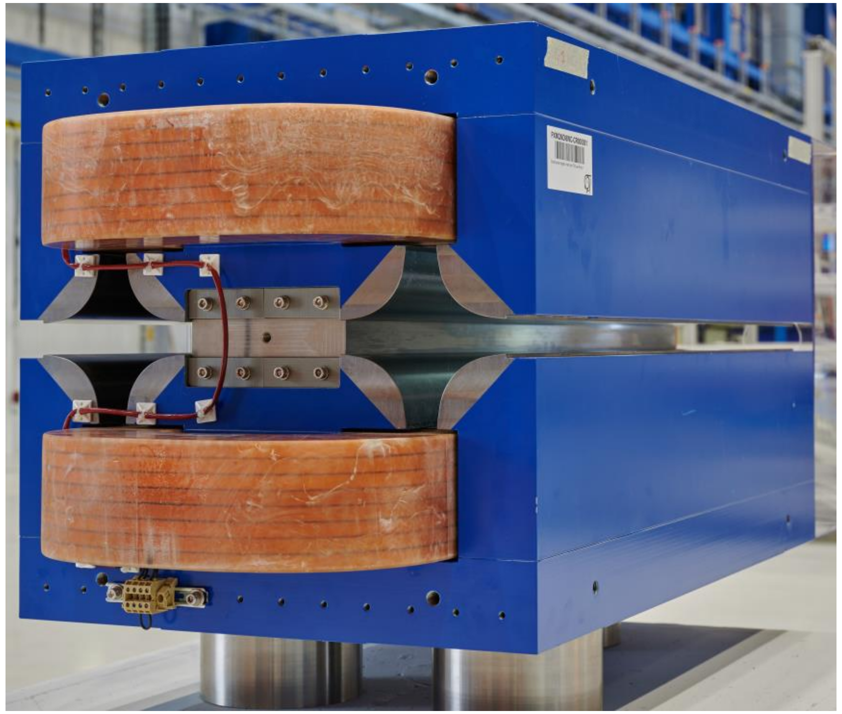
Double aperture magnet

- Twin apertures design:
  - ✓ 30-turn copper coils (two coils)
  - ✓ Energy-efficient (total 23 MW)
- Dipole defines the aperture distance

A. Milanese, M. Bohdanowicz, "**Twin aperture bending magnets and quadrupoles for FCC-ee**" IEEE Trans. Appl. Supercond.(2018)

Quadrupoles magnet: short models





To understand the **performance** and **industrialization** needs - > 0.9 m in length

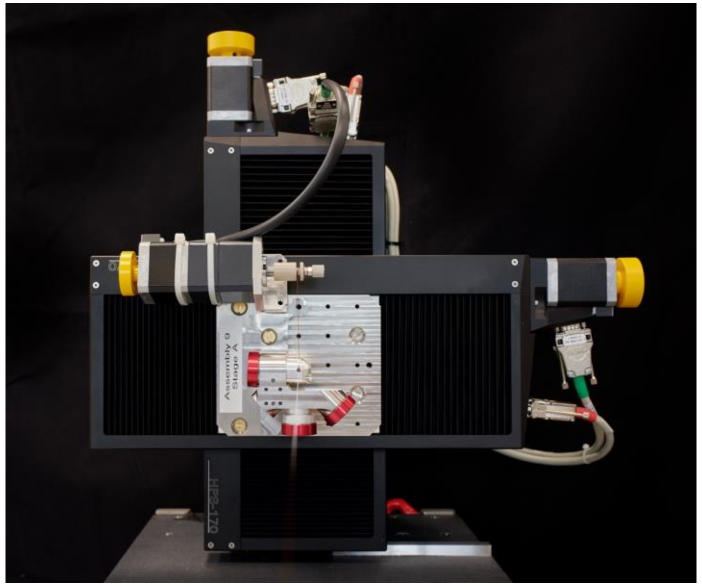
Only two copper coils, water cooled

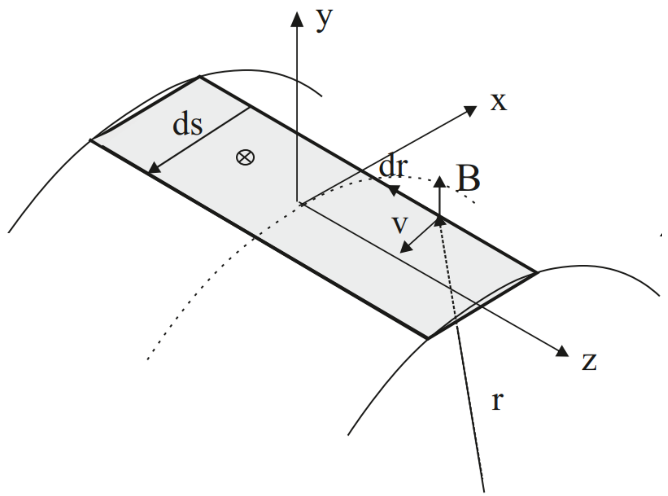
1. ARMCO pure iron, solid yoke

Study apertures symmetry

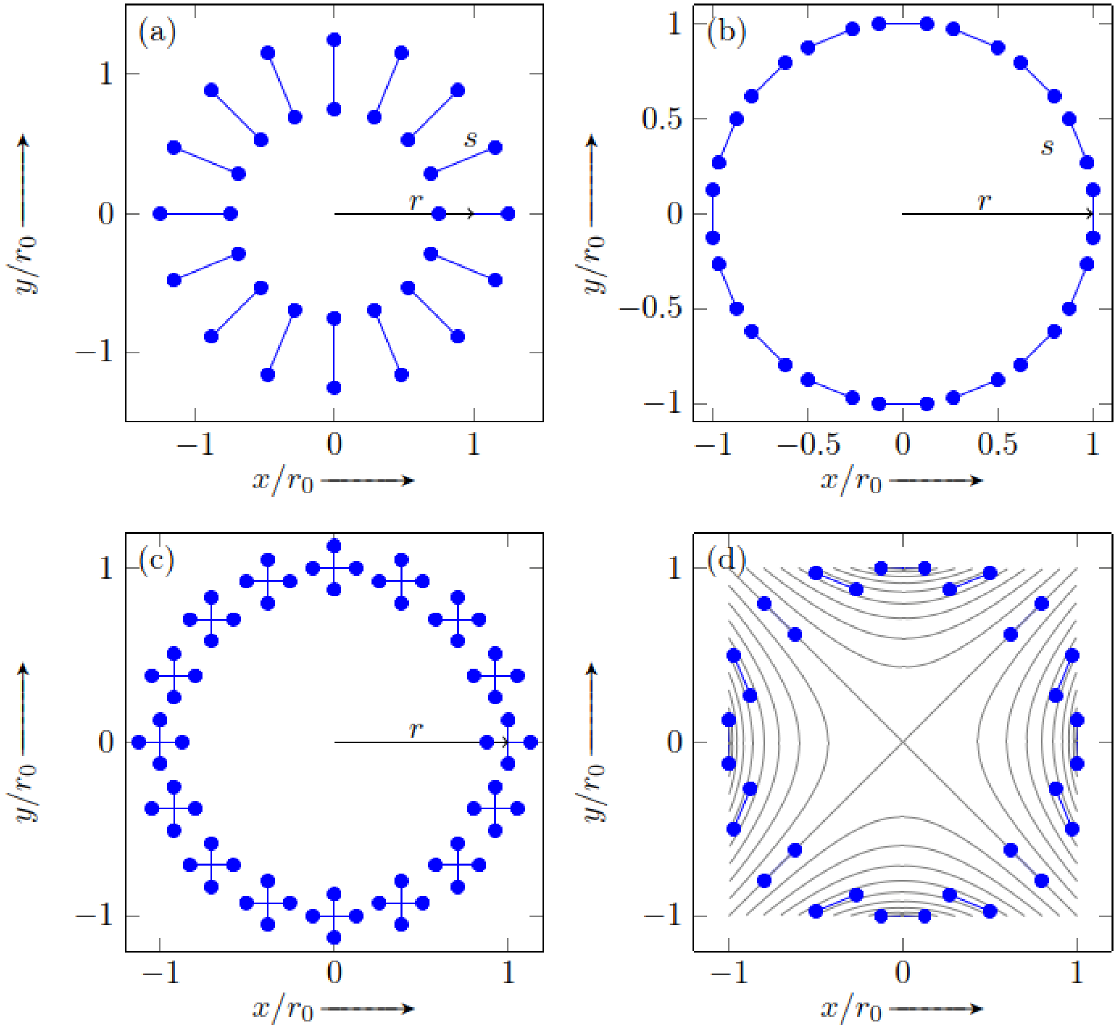
- Field quality
- Hysteresis
- Transfer function (Field vs Current)
- **Magnetic axis location**

The stretched-wire sampling technique





Wire displacements along the circular trajectory

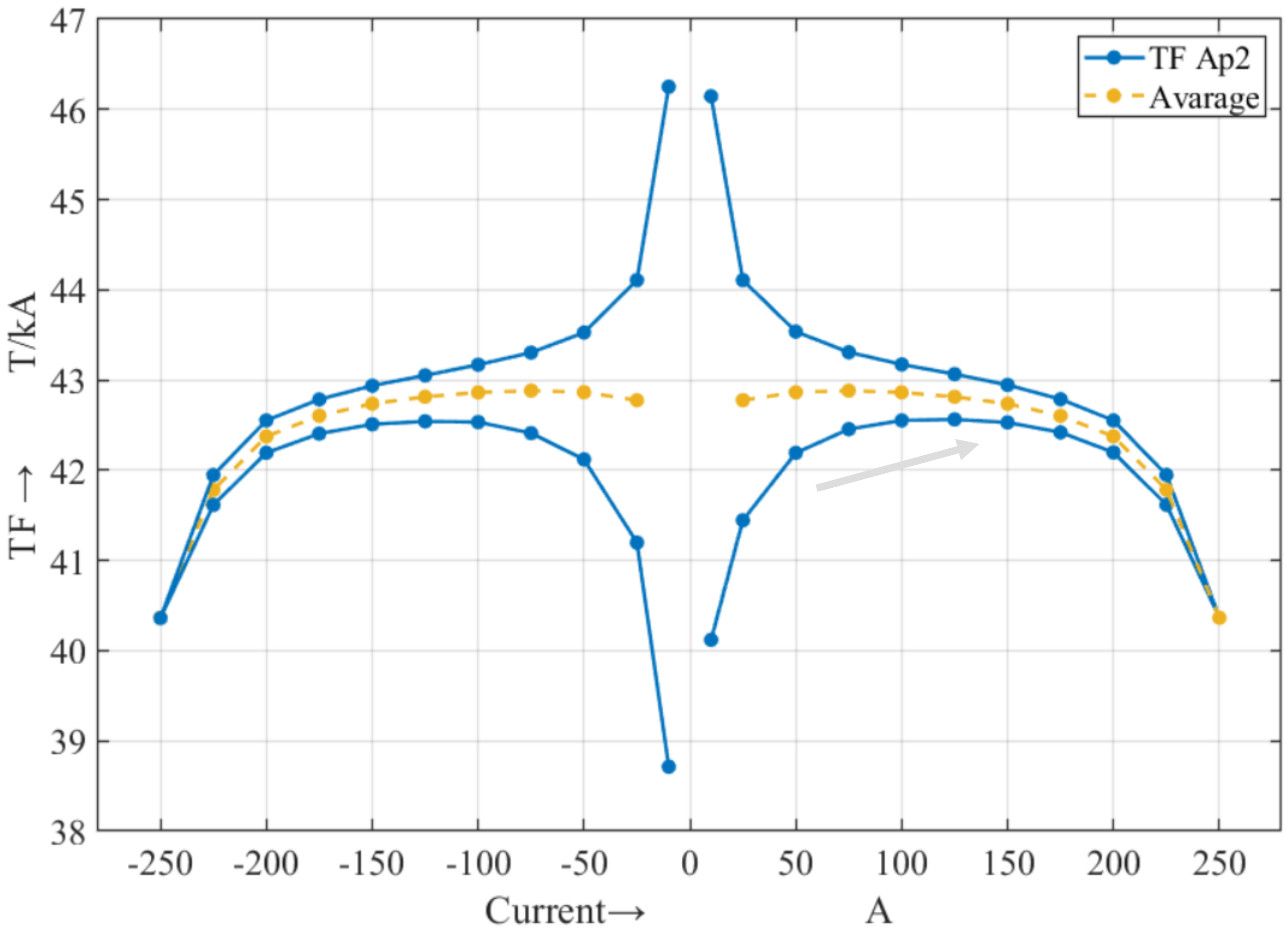


$$\Phi\Big|_{z_i}^{z_f} = L\,\mathrm{Re}\left\{\sum_{n=1}^{N}\frac{(B_n+\mathrm{i}A_n)}{n r_0^{n-1}}\left(z_f^n - z_i^n\right)\right\}$$

$$\begin{pmatrix}\Phi\Big|_{z_{i,1}}^{z_{f,1}}\\ \vdots \\ \Phi\Big|_{z_{i,P}}^{z_{f,P}}\end{pmatrix} = L\,\mathrm{Re}\left\{\begin{pmatrix}(z_{f,1}-z_{i,1}) & \cdots & \frac{1}{N r_0^{N-1}}\left(z_{f,1}^N - z_{i,1}^N\right)\\ \vdots & \ddots & \vdots \\ (z_{f,P}-z_{i,P}) & \cdots & \frac{1}{N r_0^{N-1}}\left(z_{f,P}^N - z_{i,P}^N\right)\end{pmatrix}\begin{pmatrix}B_1+\mathrm{i}A_1\\ \vdots \\ B_N+\mathrm{i}A_N\end{pmatrix}\right\}$$

Developments for measuring multipoles by the stretched-wire technique

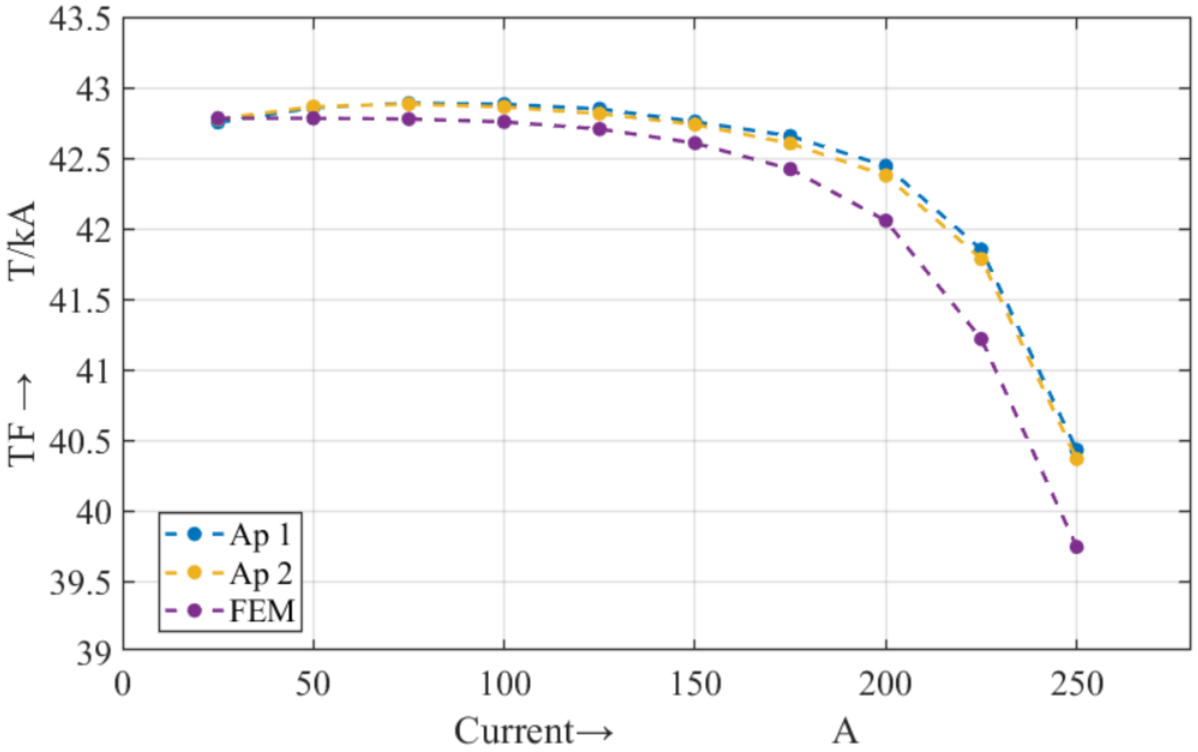
Magnetic Measurements: quadrupole transfer function



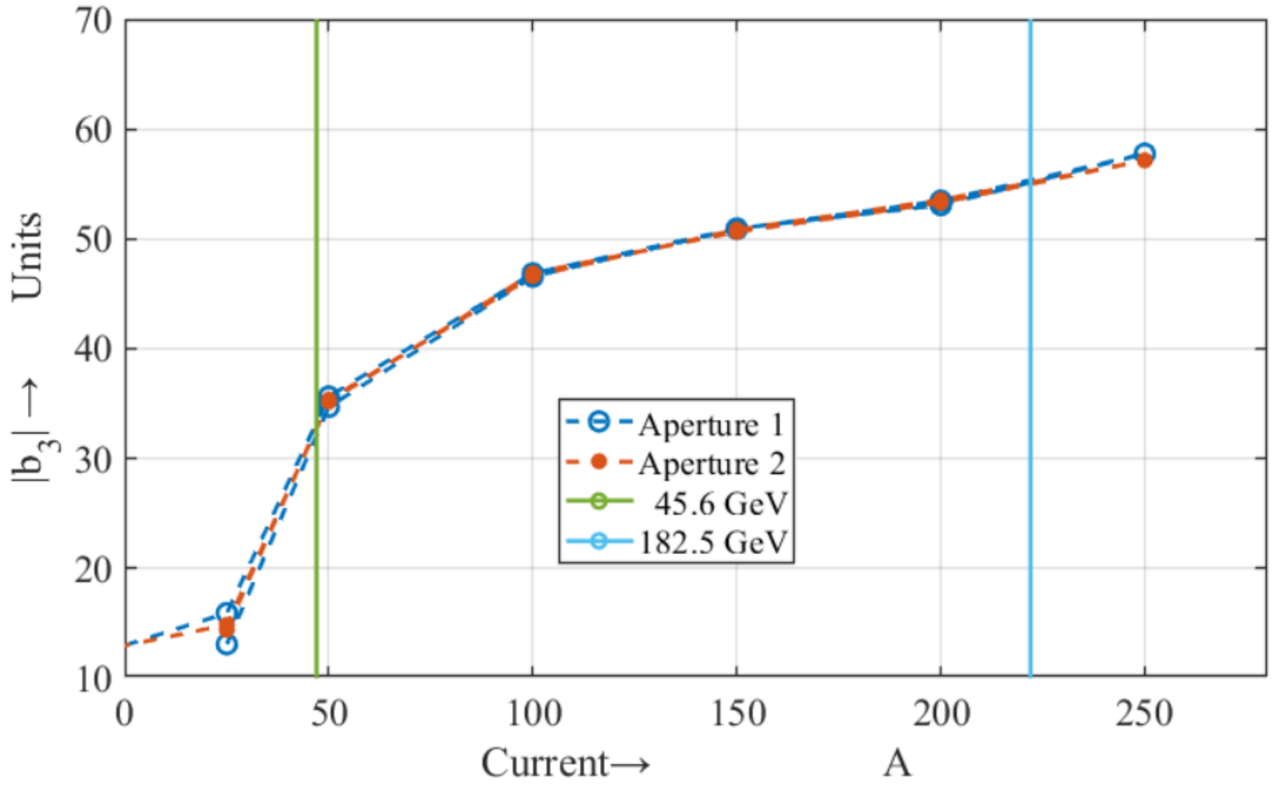
Two apertures are similar (1.6‰)

- ✓ Very good mechanical assembly

Agreement with the simulation on the order of 1%



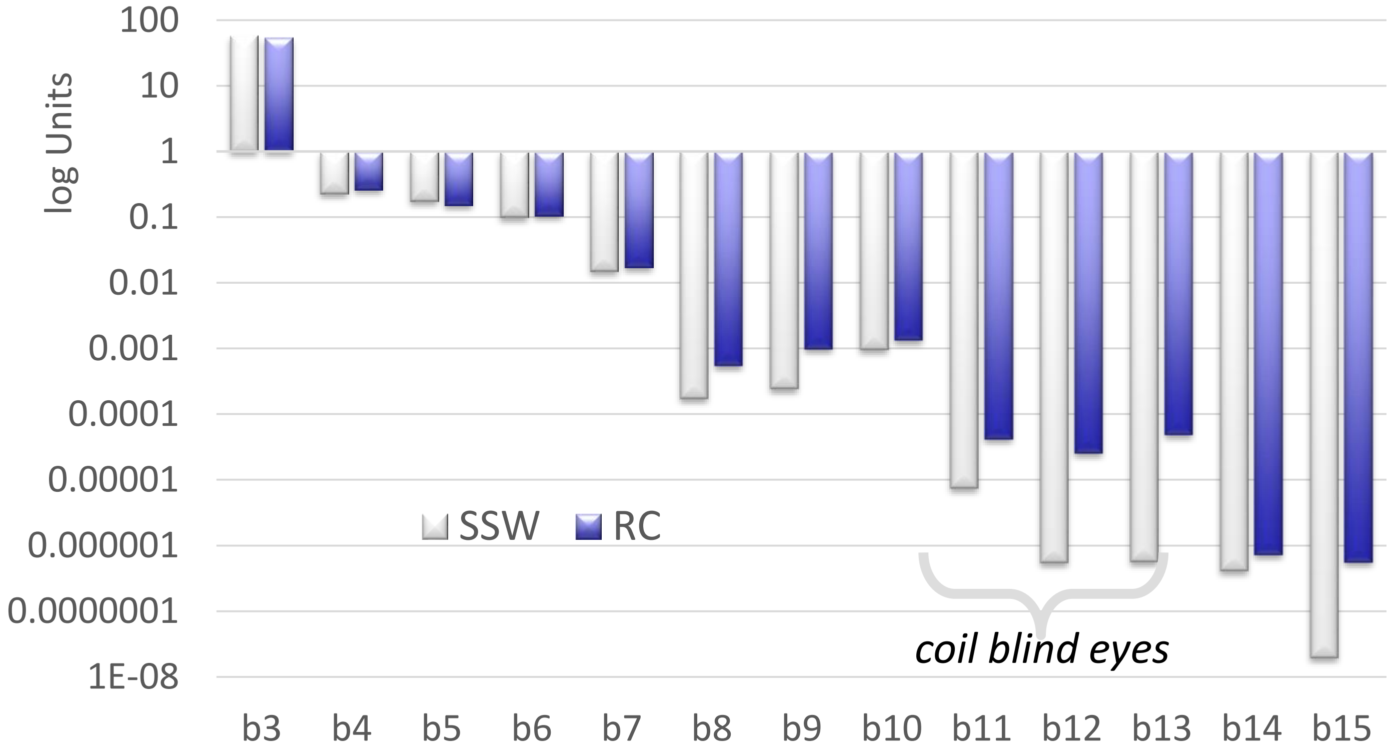
Magnetic Measurements: multipoles @ 10 mm reference radius



- The two apertures follow each other
- Good agreement with rotating coil measurements
- Measurements at 30 mm radius

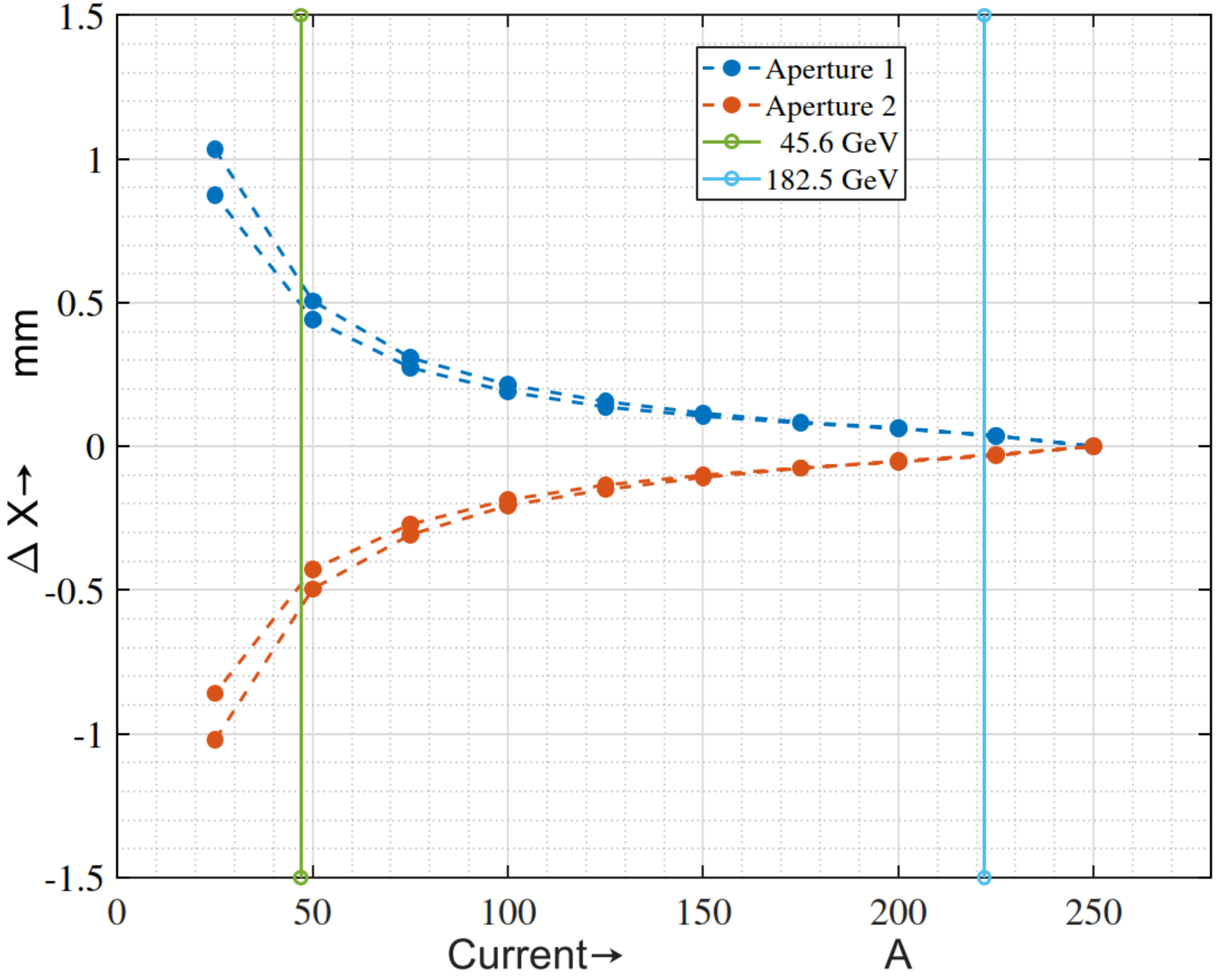
Aperture 1 @ 250 A

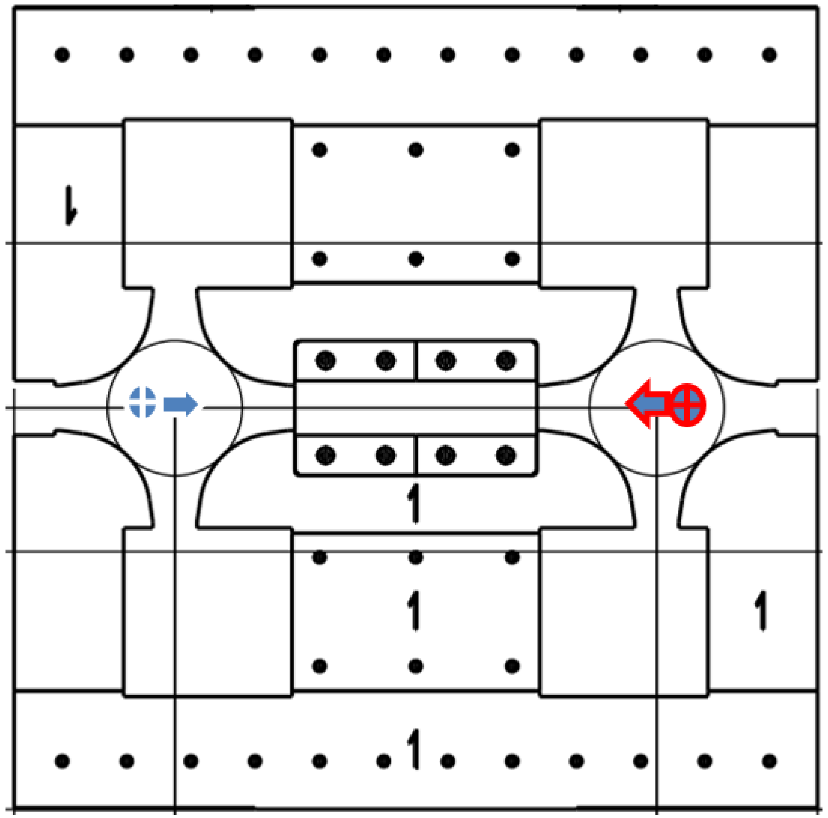
n	b_n	a_n
4	-0.227	0.093
5	0.175	-0.034
6	0.100	-0.007
7	-0.015	0.003



MT 26 International Conference on Magnet Technology Vancouver, Canada | 2019

Magnetic axis shifts by 0.4 mm in the energy range





Conclusions

Dipole

- The design of the **twin-aperture** dipole using only one coil (busbars) is validated
- The cost-effective design of the **dipoles** using construction steel for the yoke is possible
- For both materials, **pre-cycling** may be required and **compatible** with the machine operation

Quadrupole

- The design of the **twin-aperture** quadrupole using only two coils is feasible
- The shift of the **magnetic axis** needs further studies or **considered** in the beam optic
- The stretched-wire **scanning technique** for measuring multipole has been validated

Thank you