Technologies for Machine - Detector Interface magnets

M. Koratzinos

5th PBC technology mini workshop: Superconductivity Technologies

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Introduction

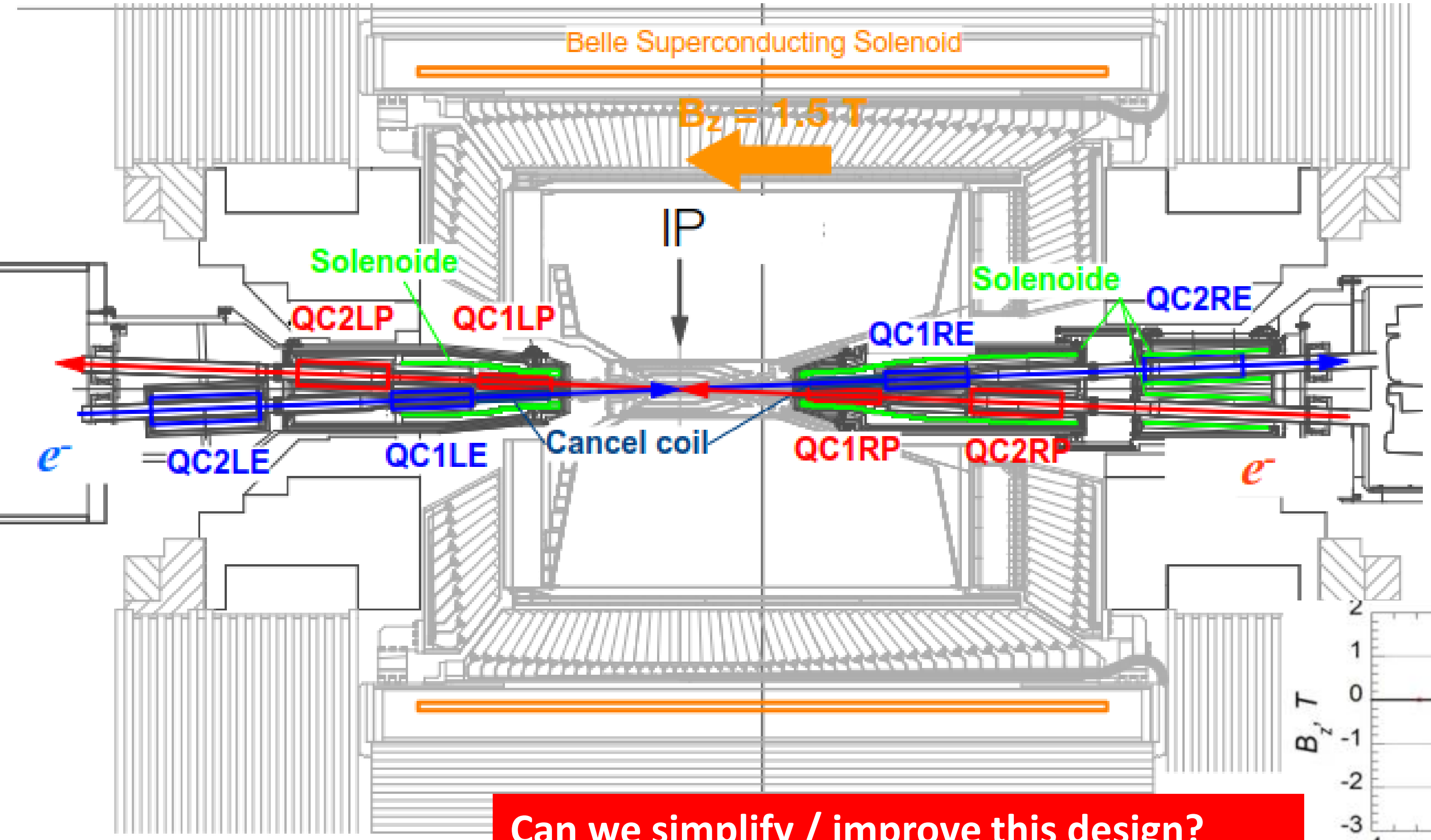
- Modern e+e- colliders(like FCC-ee, SuperKEKb, etc.) all have a very critical and very complex system of magnets very close to the interaction region, usually called the Machine-detector interface (MDI) region
- The performance of these colliders essentially depends on the performance of the design in this region – in the case of FCC-ee these ~5m around the IP define the performance of the 90-km accelerator

The MDI constraints

- In this MDI area the accelerator designer needs to achieve the highest possible performance
- This means two things:
  - that the final focus quadrupoles need to be as close to the IR as possible
  - That the two beams collide at an angle (30mrad in the case of FCC)
- The colliding angle is needed so that the two beams interact (and disrupt) each other only when absolutely necessary
- The colliding angle, in combination with the necessary detector magnetic field, disrupts the orbit of the colliding bunches (see further) and mitigation is necessary
- Final focus quadrupoles need to be as close to the IP but cannot overlap, so a slim design is preferable
- This in turn means that there is no space for iron to shield the magnetic fields, so a big potential problem is crosstalk

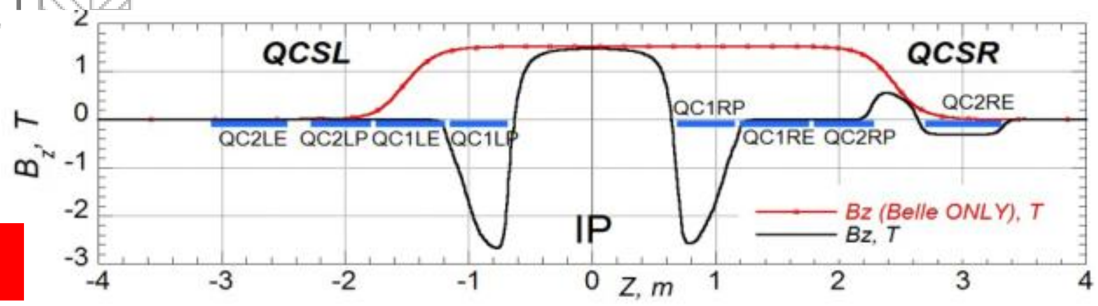
What was done before: SuperKEKb

Belle II and QCS



55 individually powered magnetic elements!

- 4 FF quadrupoles per beam line
- 35 corrector coils
- 8 cancel coils
- 4 compensation solenoids
- Detector solenoid 1.5T



Can we simplify / improve this design?

Many corrector magnets

IR status for Phase-2 commissioning

Construction of superconducting corrector magnets

- The corrector magnets were constructed by BNL under the research collaboration
  - BNL special technique: direct winding method
  - The SC coils were wound directly on the helium inner vessel, and they are multi-layered.
  - Types of corrector magnets:
    - Normal and skew dipoles: correction of the quadrupole center magnetically
    - Skew quadrupole: correction of the quadrupole mid-plane angle
    - Normal and skew sextupoles: cancelling the sextupole fields induced by the assembly errors of the quadrupoles
    - Normal octupole: tuning the dynamic apertures
    - QC1P leak field cancel magnets (sextupole, octupole, decapole, dodecapole): cancelling the leak field from QC1P to HER beam line. QC1P is the magnet without magnetic yokes.

QC1P octupole leak field cancel magnet

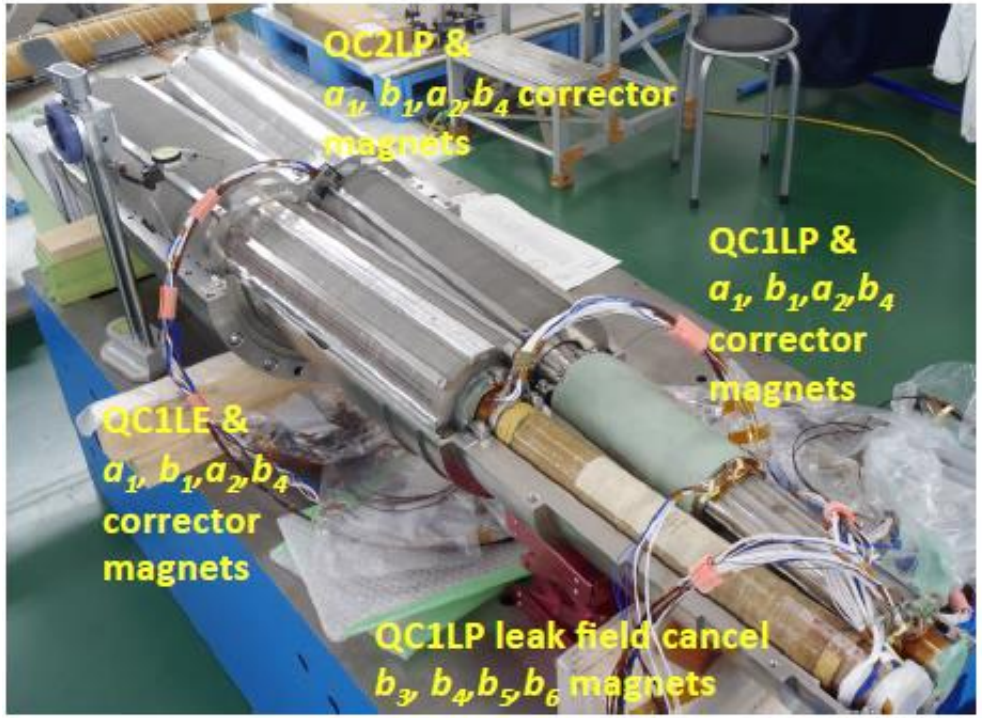
N. Ohuchi

Many corrector magnets

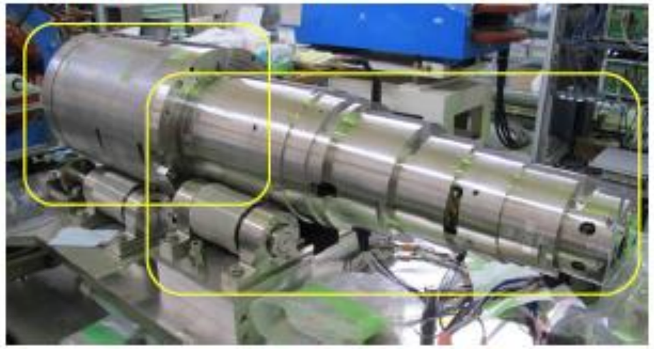
IR status for Phase-2 commissioning

Construction of QCS superconducting magnets

- SC quadrupole magnets and corrector magnets
  - Three quadrupole magnets (QC1LP, QC1LE, QC2LP) and the corrector magnets were assembled in the support block to keep the precise position between magnets.



Iron block   Stainless steel block



The magnets are covered with the stainless steel block and the iron block.

N. Ohuchi

This makes the design very complex

From SuperKEKB to FCC

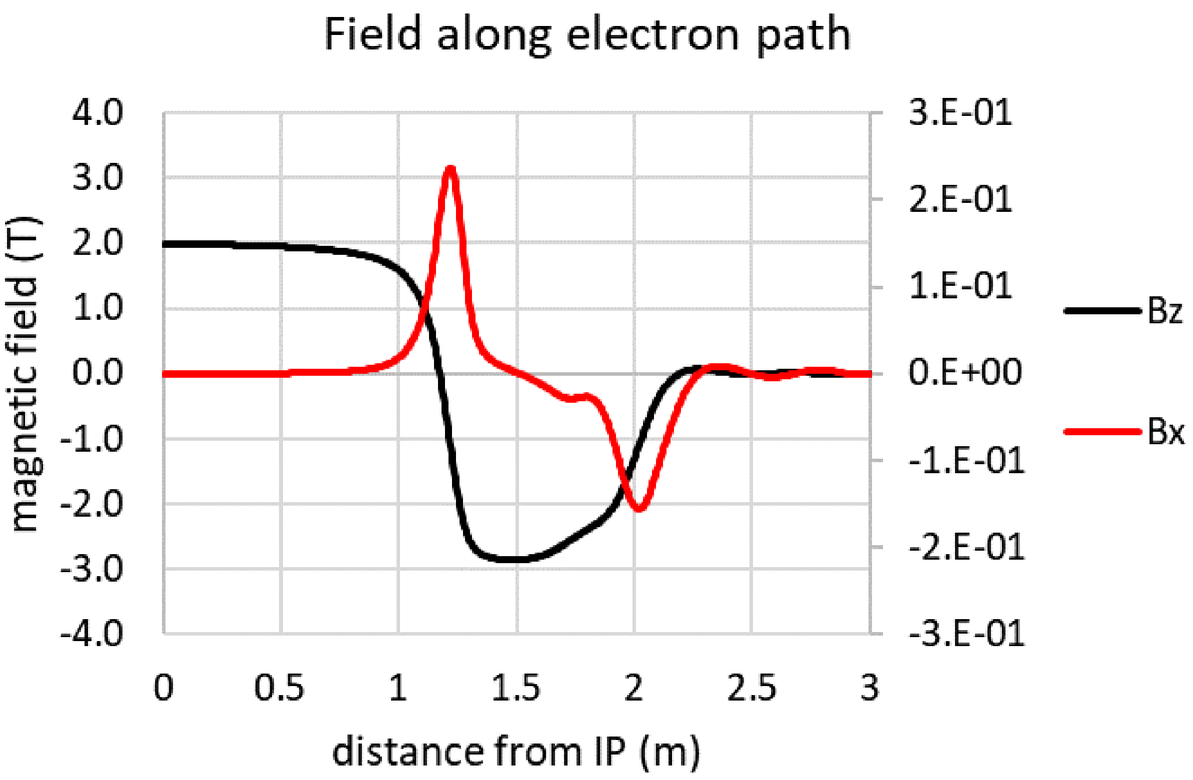
- Can we improve on the SuperKEKB design?
- The answer is YES. FCC has one considerable advantage: (almost) identical energies for the two beams
- This simplifies the design
- Instead of “cancel coils” and “correction coils” we incorporate the correction inside the quadrupoles
- We also make sure that the FF quads sit in a zero magnetic field

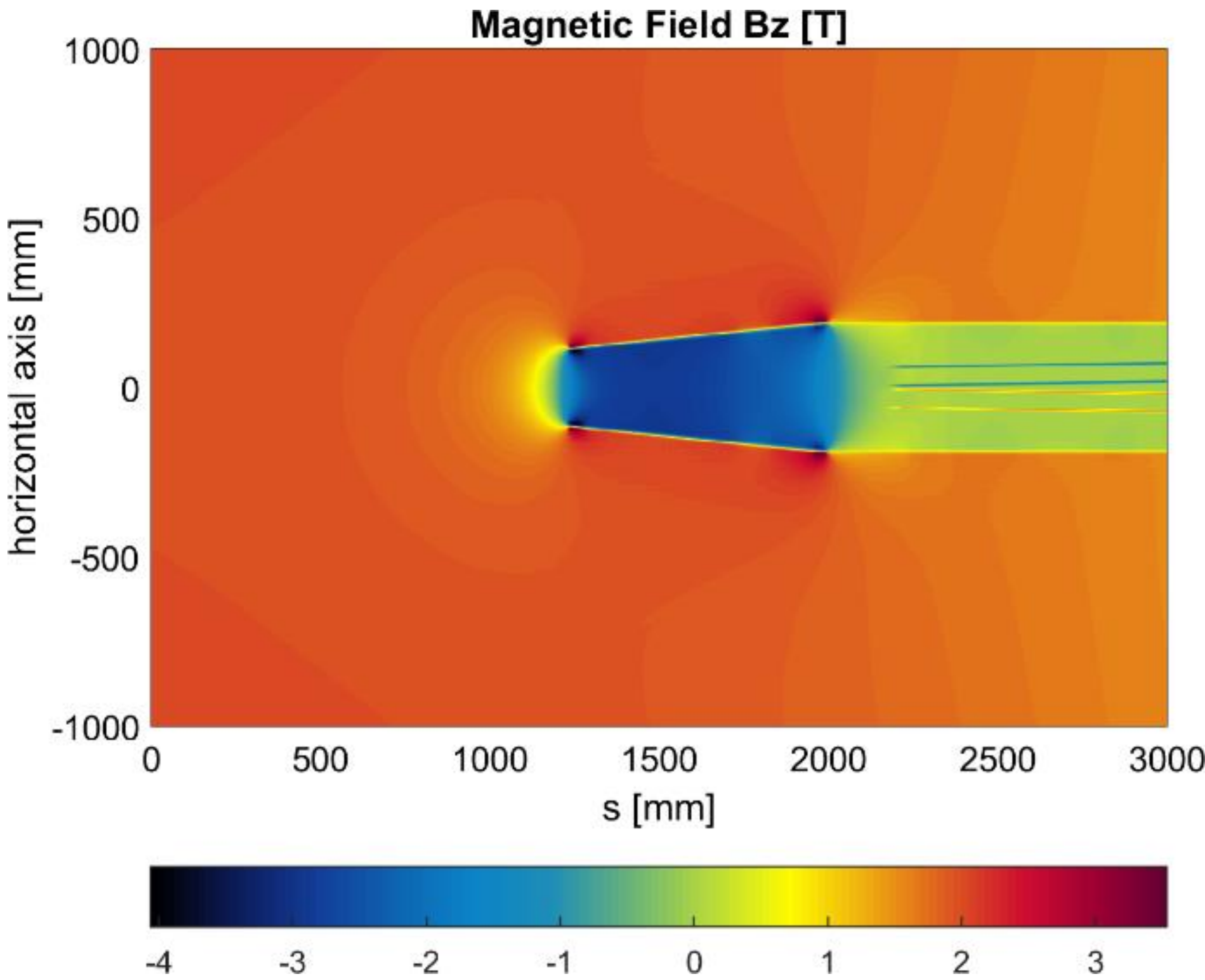
SuperKEKB	**FCC-ee**
4 FF quads per beam line	6 FF quads per beam line
35 corrector coils	12 corrector coils
8 cancel coils	0 cancel coils
4 compensation solenoids	4 compensation solenoids
Detector solenoid at 1.5t	Detector solenoid at 2T

Compensation scheme

- For good performance the vertical emittance blow up in the interaction region should be minimized
- This means that the magnetic field integrals seen by the beam are very close to zero *and* field derivatives are as gentle as possible.
- Also, the final focus quadrupoles should sit in a zero magnetic field environment
- The problem is best solved with the introduction of two magnetic systems:
  - The screening solenoid, that cancels out the detector magnetic field
  - The compensating solenoid, that un-does the effect of the magnetic field of the detector solenoid

Compensation scheme example: FCC-ee





Screening solenoid: length 3m, strength 2T
Sompensating solenoid: length 70cm, strength 5T

FCC-ee compensation scheme

- For details, please refer to our paper “The magnetic compensation scheme of the FCC-ee detectors”, M. Koratzinos and K. Oide, https://doi.org/10.18429/JACoW-IPAC2021-THPAB012
- Scheme with two magnetic elements (solenoids) per side [the minimum possible]
- These elements need to be superconducting.
- By the time of FCC construction, I believe that HTS conductors will be the conductor of choice.

Simulated performance

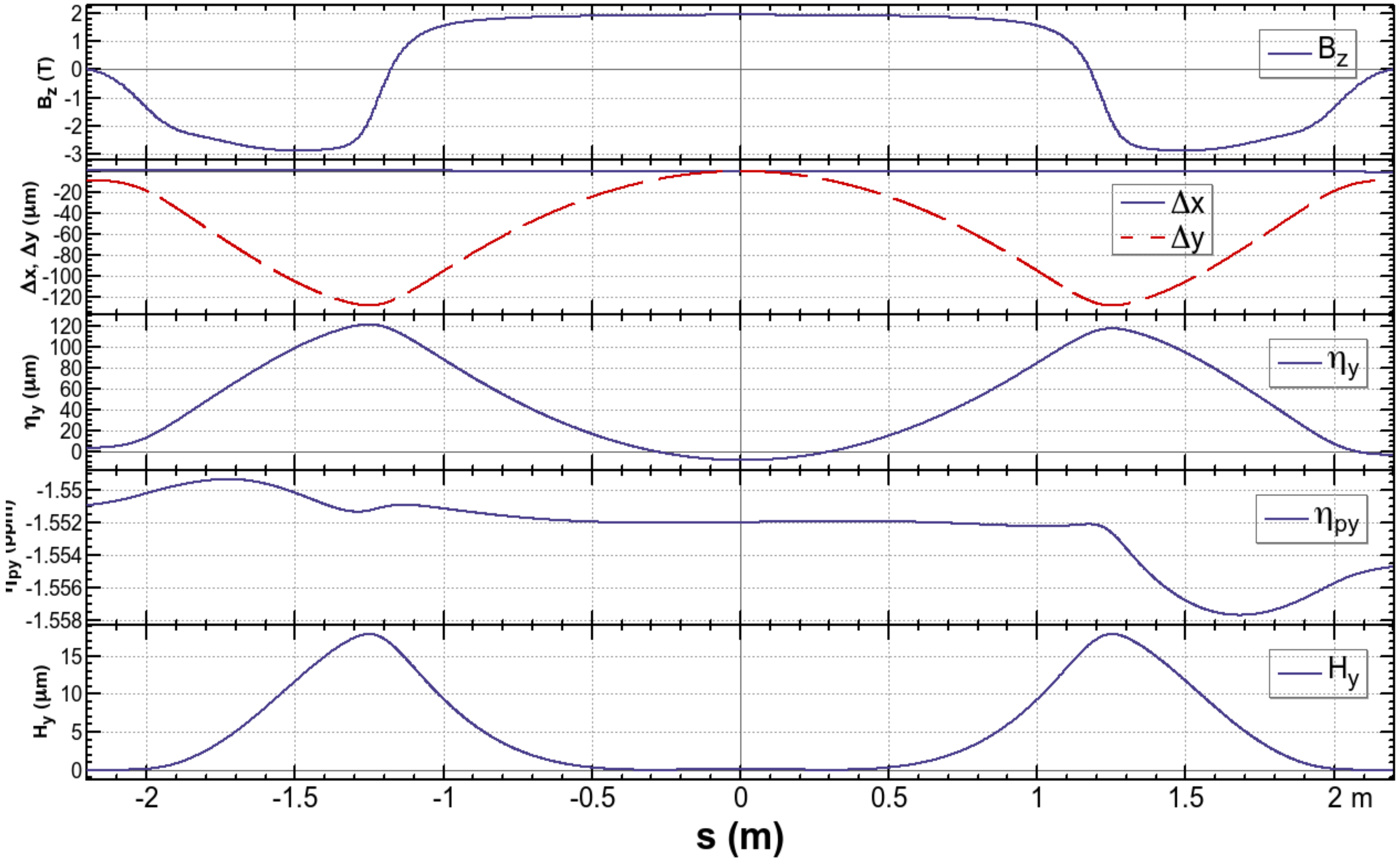


Figure 4: Optics functions in the area ±2m from the IP. From top to bottom: longitudinal magnetic field, closed orbit deviation from the tilted straight line going through the IP, vertical dispersion, vertical momentum dispersion, $\mathcal{H}_y$(vertical emittance generation function).

The emittance blow up **is 0.24 pm at a beam energy of 45.6 GeV for 2IPs.**

Integral fields are:

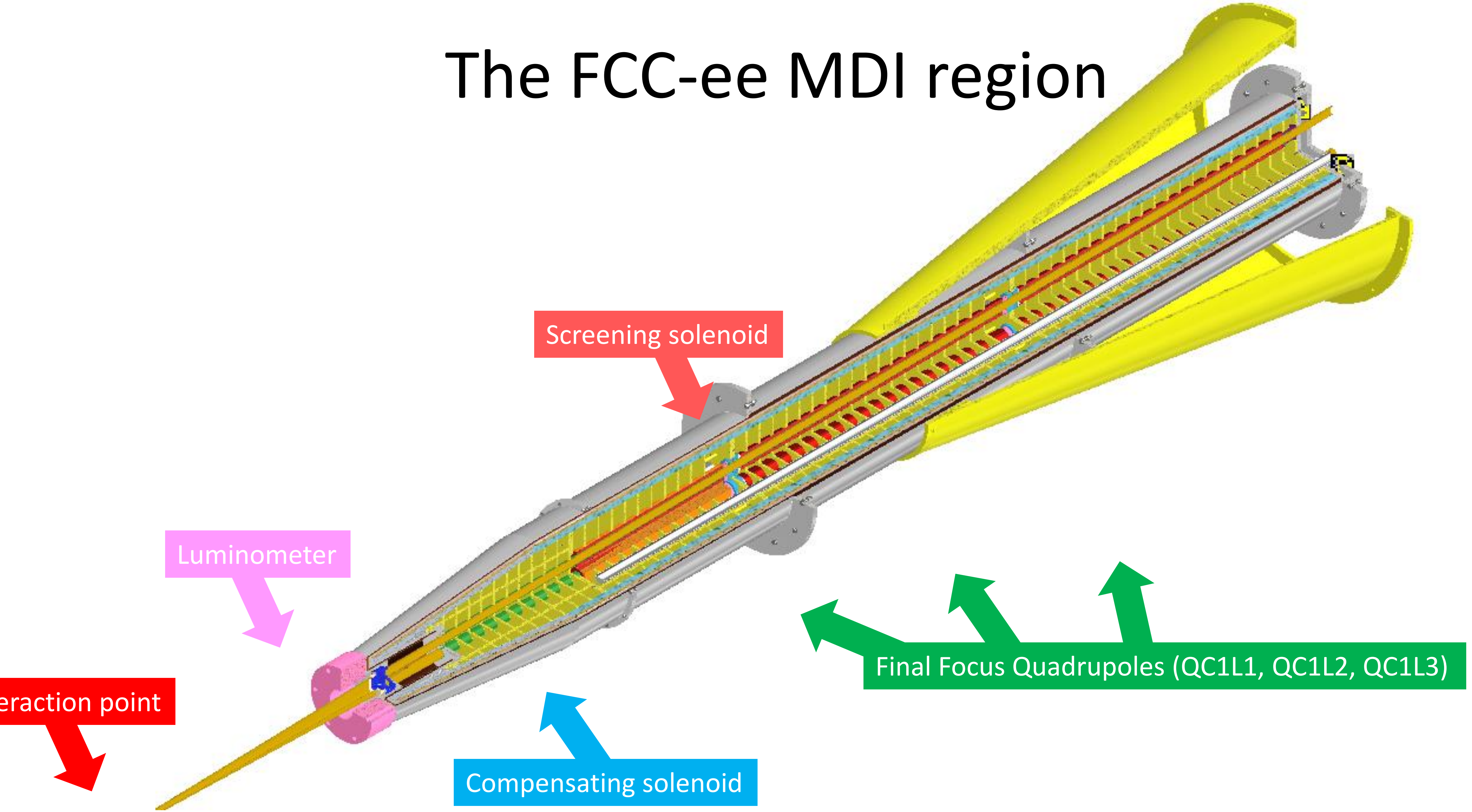
- $\int B_x ds = 2.4 \times 10^{-5}$ Tm
- $\int B_z ds = 5.8 \times 10^{-2}$ Tm and
- $\int_{2.2}^{3.6} B_z ds = 6.2 \times 10^{-3}$ Tm.

The relatively large $\int B_z ds$ value is due to the uncertainty in the design of the end yoke of the detector magnet; when this is finalized, the compensation can be tuned to keep this value arbitrarily small.

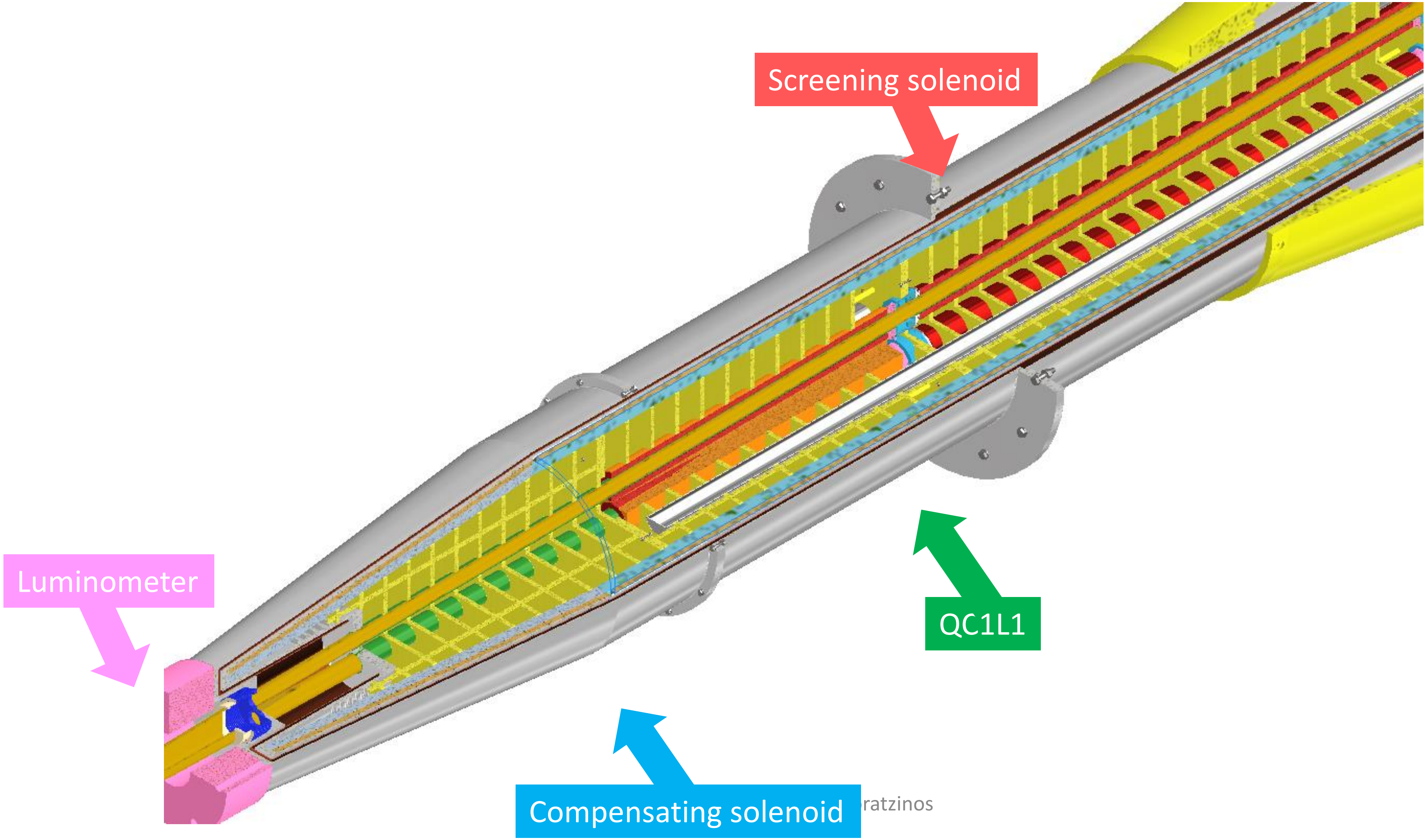
Overview of the FCC-ee design

- Cantilevered, 4.3m long
- Connected rigidly on one side (away from the IP)
- Some mechanical coupling (cables)also close to the center of gravity
- QC1 magnets mechanically coupled with each other and to a strong skeleton
- Skeleton also holds in place the two solenoids
- BPMs linked to the beampipe with laser position monitoring
- Thin Helium vessel (welded together)
- Thin and non-structural cryostat for insulation vacuum

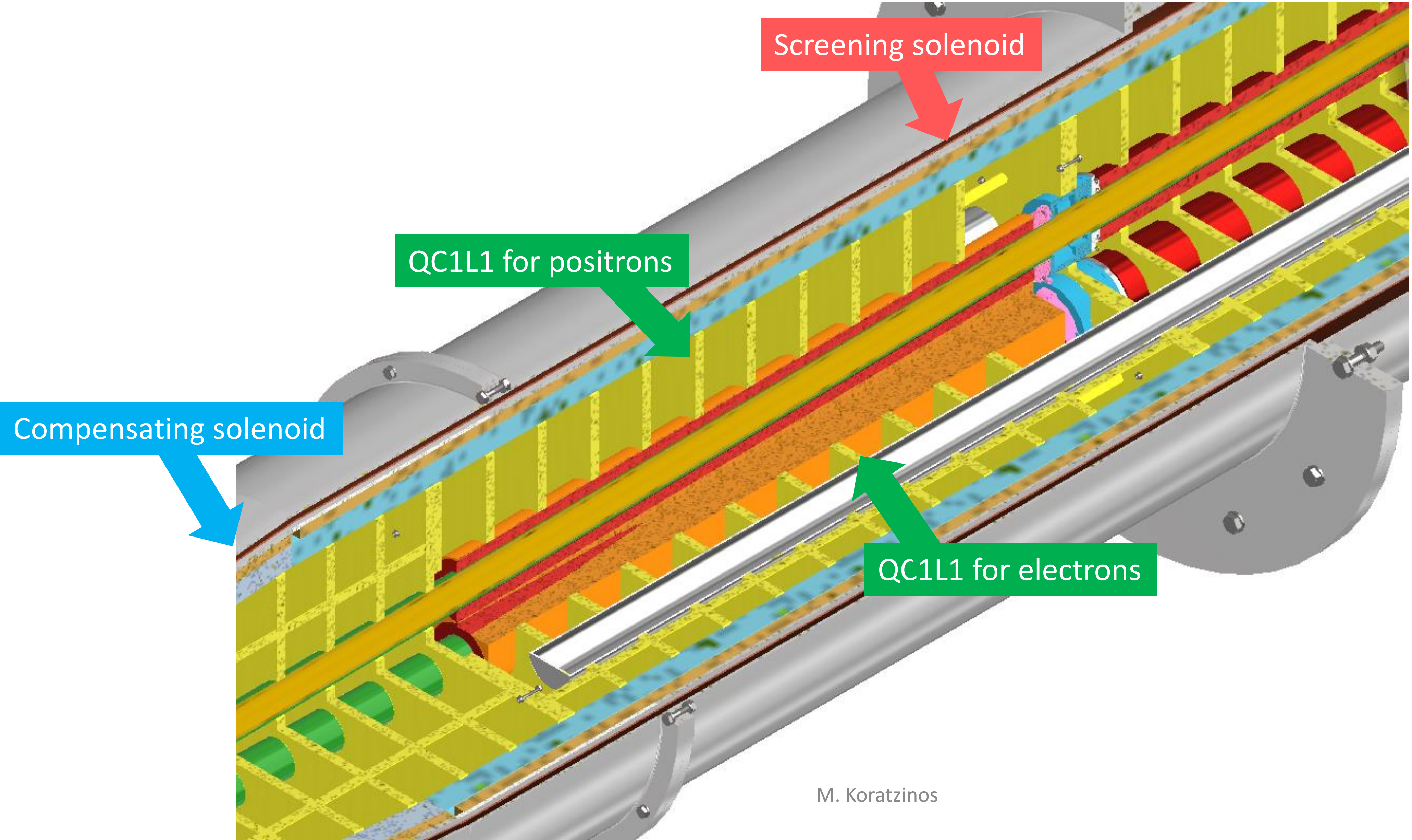
The FCC-ee MDI region



The FCC-ee MDI region



The FCC-ee MDI region



Final focus quadrupoles

- Two main units on each side of the IP and for each beam, e^+ (P)and e^-(E): QC1LE, QC2LE, QC1RE,QC2RE, QC1LP, QC2LP, QC1RP,QC2RP
- QC1 is inside the detector and itself comprises three units per side per beam: QC1L1P, QC1L2P,QC1L3P, QC1L1P, QC1L2P,QC1L3P, QC1L1E, QC1L2E,QC1L3E, QC1L1E, QC1L2E,QC1L3E
- There are 5X2X2=20 single aperture units in total

	Start position (m)	Length (m)	B' @Z (T/m)	B' @W (T/m)	B' @ H (T/m)	B' @ tt (T/m)
QC2L2	-8.44	1.25	25.05	43.82	61.30	69.50
QC2L1	-7.11	1.25	-0.18	0.00	7.32	56.85
QC1L3	-5.56	1.25	-19.35	-34.38	-53.08	-99.98
QC1L2	-4.23	1.25	-18.57	-32.94	-53.07	-99.98
QC1L1.1	-2.9	0.7	-40.95	-70.00	-99.71	-95.39
QC1L1.2	2.2	0.7	-40.95	-70.00	-99.71	-95.39
QC1R2	2.98	1.25	-25.44	-37.25	-51.94	-100.00
QC1R3	4.31	1.25	-19.54	-39.51	-53.65	-91.87
QC2R1	5.86	1.25	14.64	16.85	-2.65	37.19
QC2R2	7.19	1.25	19.50	44.32	67.52	94.43

- Optics design is such that E and P quads have the same strength
- Maximum strength is 100T/m

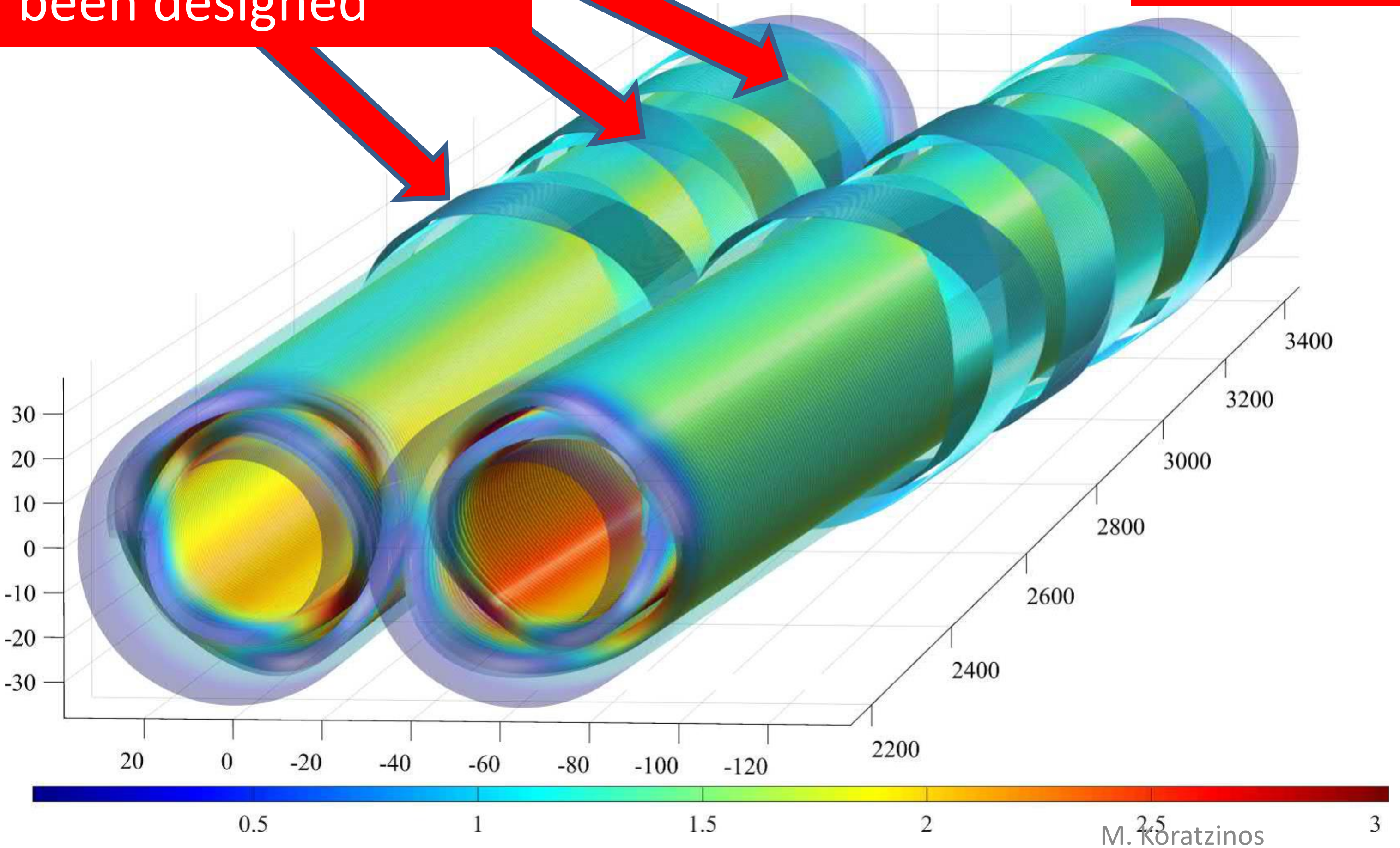
- The most difficult element is QC1L1, the closest to the beam and where the E and P quads are closer together

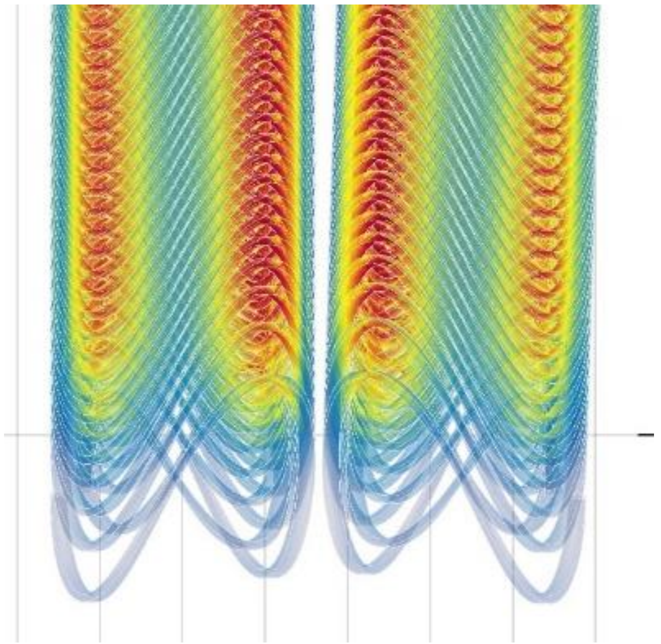
QC1L1

QC1L1 is the first and most demanding pair of quadrupoles of the final focus system of FCC-ee

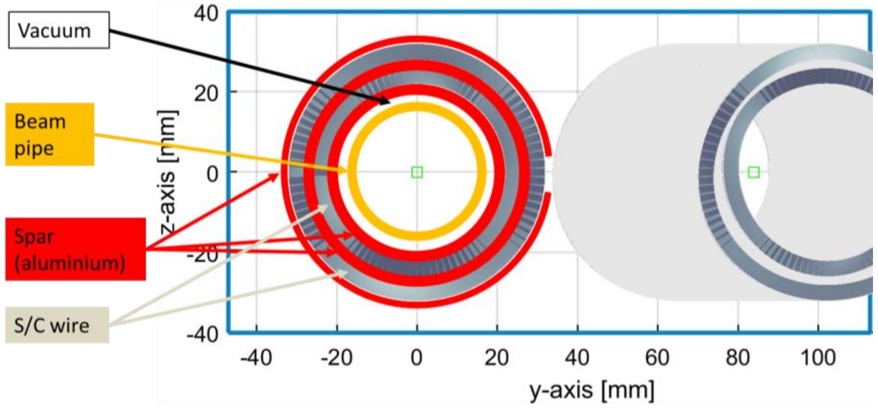
Correctors have also been designed

Iron-free design





Inner bore: 40mm (diameter)
Fits outside the warm water-cooled beam pipe of inner diameter 30mm



Main challenges for QC1L1

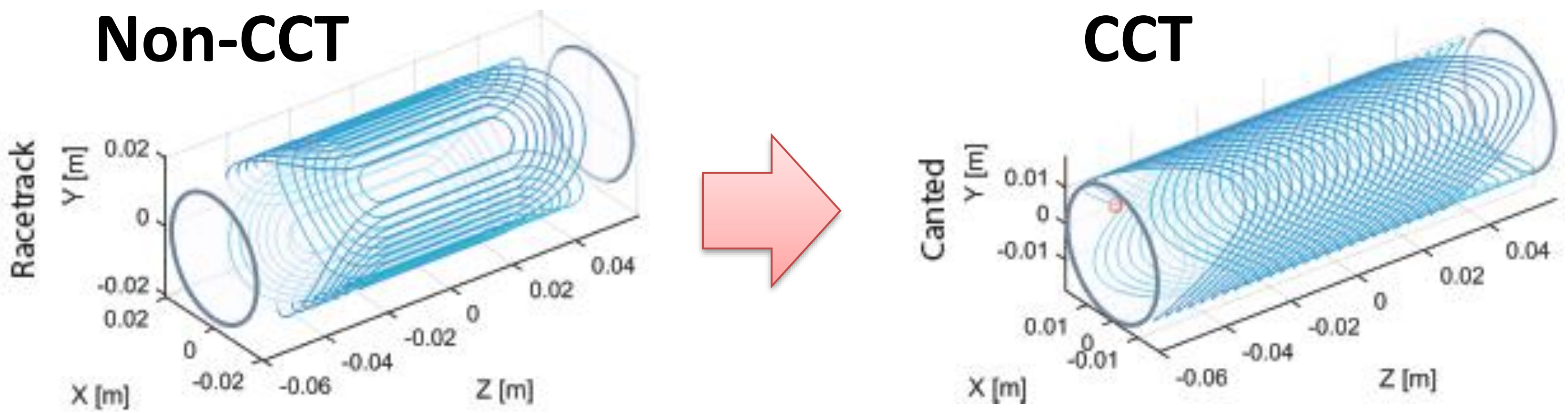
- Lack of space: 66mm between the two beams at QC1L1. Quads are at an angle so crosstalk varies along the length
- Required field quality: better than 10^{-4} and of $O(10^{-5})$
- Need to eliminate crosstalk between the two quadrupoles
  - The beam pipe inner diameter is 30mm
  - The beam pipe is warm, so we need vacuum insulation and cooling/heating for the beam pipe
  - The minimum size of the thickness of the double layer beam-pipe with the cooling liquid flowing in-between is 3mm
  - We are then leaving 2mm for vacuum and a heat shield
  - ➔ **aperture of FF quads is 40mm**
  - ➔ **space left for former, conductor, yoke = 13mm**
  - ➔ **it would be impossible to fit an iron yoke with reasonable thickness to eliminate crosstalk**

Choice of technology for QC1L1

- There is only one technology we have identified that can tackle those challenges: a CCT iron-free design
- A CCT design can compensate for the crosstalk between quadrupoles even in the case that crosstalk changes every centimetre: see M. Koratzinos et al.[1709.08444](https://arxiv.org/abs/1709.08444) [physics.acc-ph] Published in: *IEEE Trans.Appl.Supercond.* 28 (2018) 3, 4007305
- A CCT design can also compensate for edge effects ensuring excellent field quality locally at every point of the magnet. This is important since the optics functions vary wildly close to the IP
- Original idea Paoloni et al, SuperB final focus quadrupole*

*S.Farinon et al., DOI: 10.1109/TASC.2021.3053346

CCT magnets



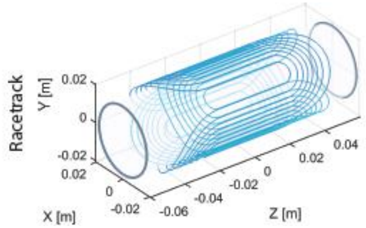
…are very simple objects

- They comprise two coils on two concentric cylinders
- Each coil produces a solenoid field plus an arbitrary multipole field (dipole, quad, sextupole…)
- The two solenoid fields from the two coils exactly cancel
- Grooves are precisely defined for winding the cable on a substrate which is usually metal (aluminium)

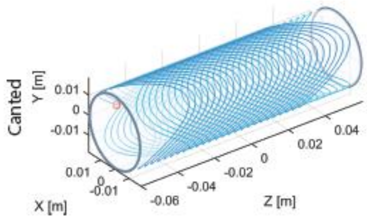
CCT advantages

- A CCT (Canted Cosine Theta) is a type of accelerator magnet where the multipole mix is a *local* attribute of a magnet. (One can trivially design a magnet which is a dipole on one side and a quadrupole in the other.)
- Other important advantages of CCTs:
  - Cheap to make – from the magnet design program to CAD to CNC machine with no manual interventions
  - Easy to make – no pre-stress! Stress management is trivial in CCTs
  - Fast to make – few steps, no expensive equipment
  - Excellent field quality

Conventional



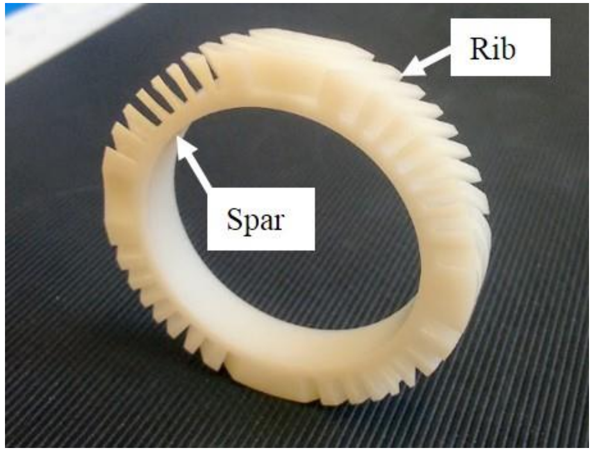
CCT



The CCT formula

Two layers are needed: The position of the center of the groove is described by the following equations:

$$x = R\cos\theta\;;$$
$$y = R\sin\theta\;;$$
$$z = \sum_{n_B}\left[\frac{R\sin(n_B\theta)}{n_B\tan\alpha_{n_B}}\right] + \sum_{n_A}\left[\frac{R\cos(n_A\theta)}{n_A\tan\alpha_{n_A}}\right] + \frac{\omega\theta}{2\pi}$$



- R is the radius of the layer
- n_B, n_A is the multipole order (B for normal, A for skew) [1 = dipole, 2=quadrupole, etc]
- α is the “skew angle”, the strength of the multipole
- θ runs from 0 to $2\pi n_t$ where n_t is the number of turns
- ω is the pitch per winding

For the second layer, R is slightly increased (depending on the thickness of the spar and the cable) and the skew angle and current flow has the opposite sign.

The CCT formula - quadrupole

In the case of a pure quadrupole, the formula simply becomes:

$$x = R\cos\theta\ ;$$

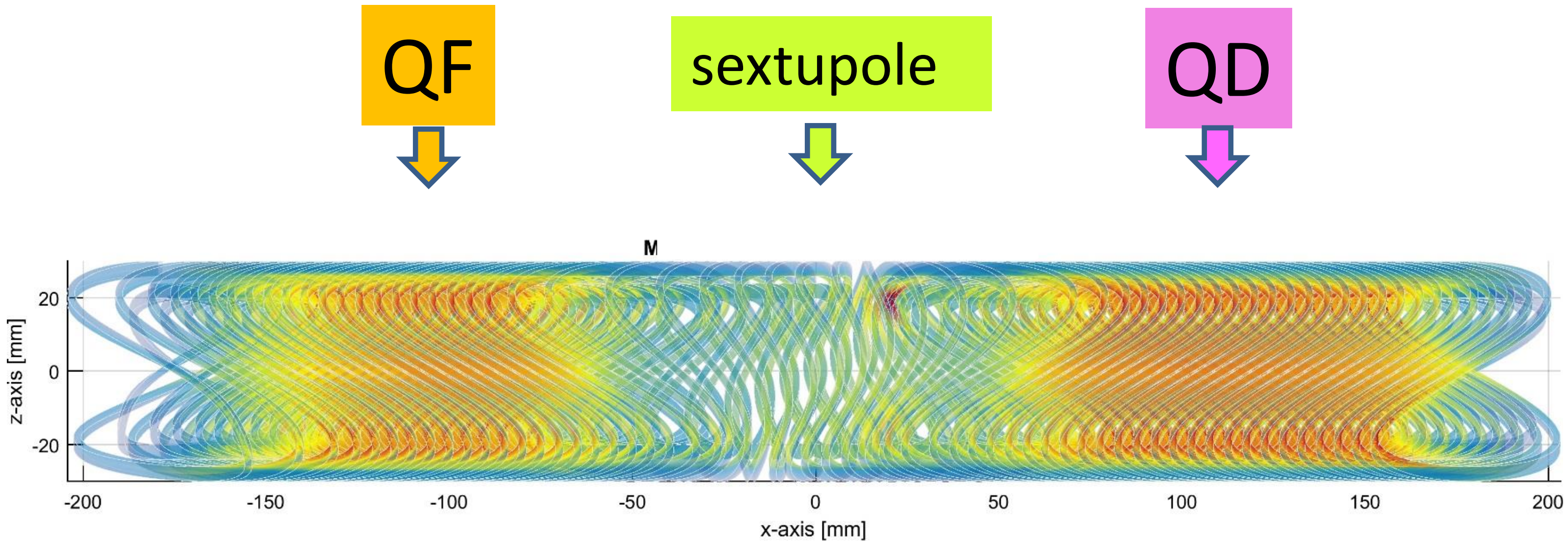
$$y = R\sin\theta\ ;$$

$$z = \frac{R\sin(2\theta)}{2\tan\alpha_2} + \frac{\omega\theta}{2\pi}$$

- R is the radius of the layer
- α_2 is the quadrupole skew angle
- θ runs from 0 to $2\pi n_t$ where n_t is the number of turns
- ω is the pitch per winding

An illustration: an example of a combined function CCT magnet

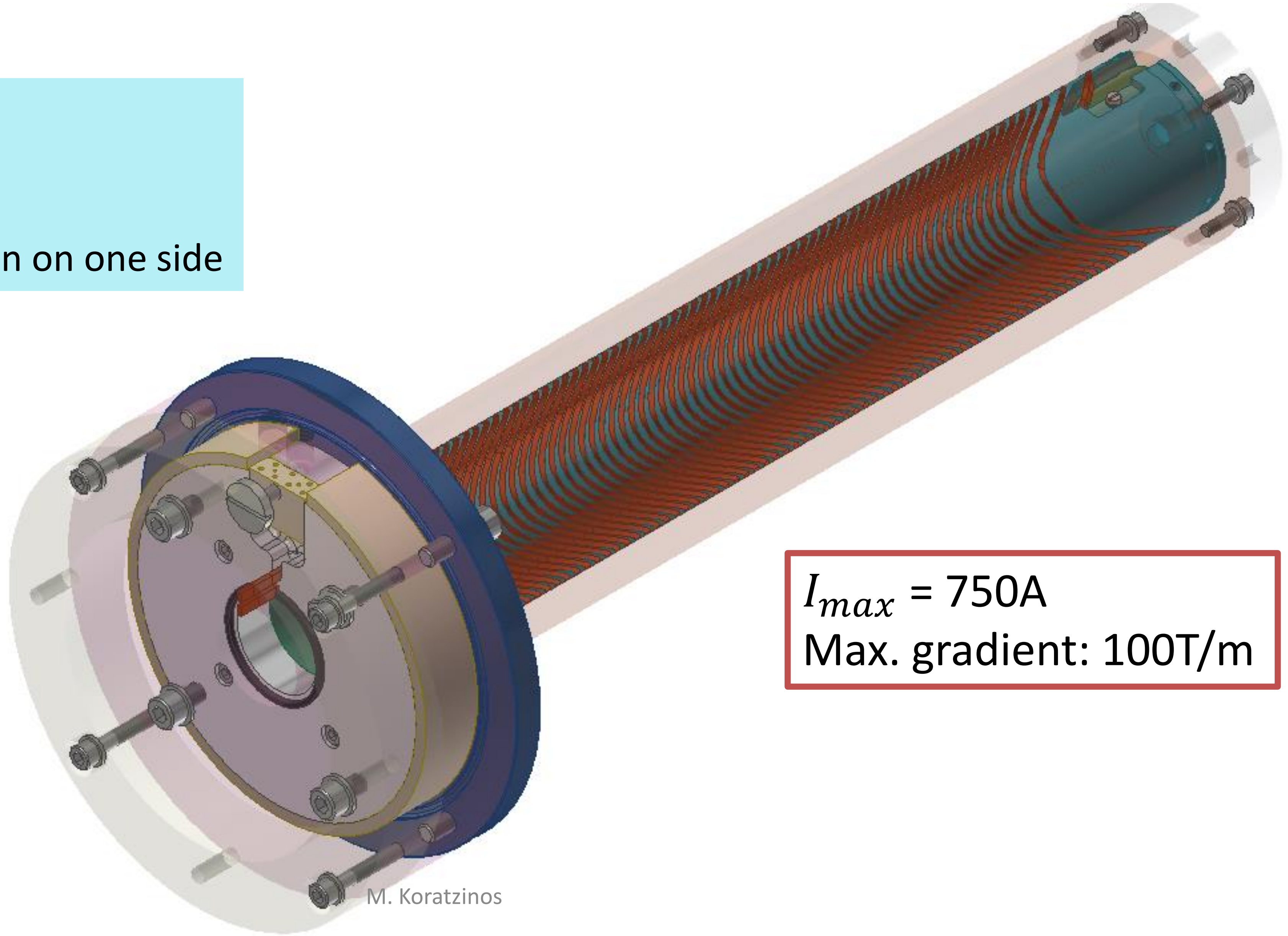
- CCT coils can be customised with any multipole ingredients that can change every turn of the coils, allowing limitless customization…
- (useless) example: QF/QD in one unit (with a sextupole in between)



In reality, multipole components needed to eliminate crosstalk are so small that the extra wiggles are not visible to the untrained eye

The FCC-ee Final Focus Quadrupole prototype

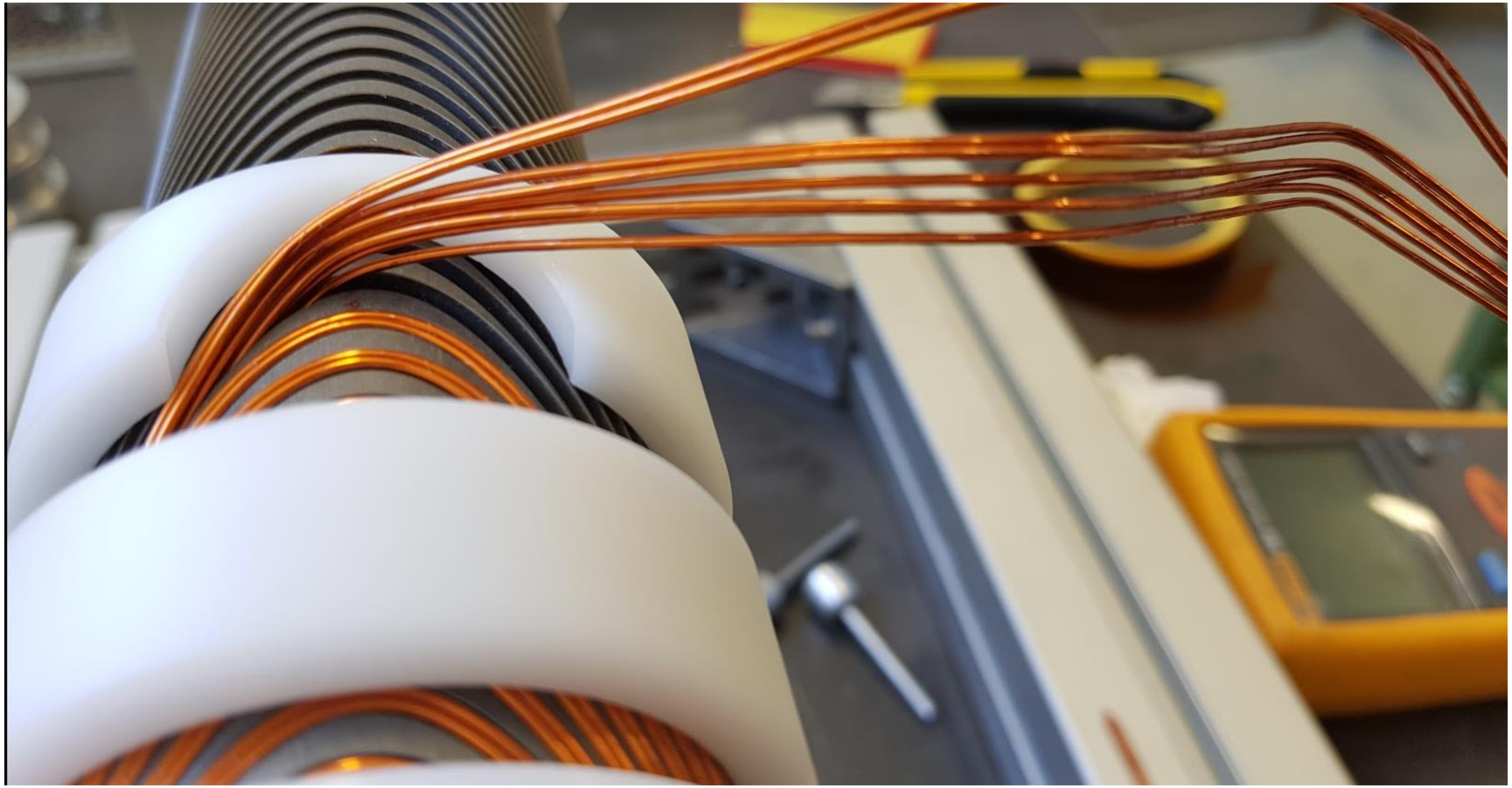
- NbTi conductor
- Single aperture
- 43cm long
- With edge correction on one side



I_{max} = 750A
Max. gradient: 100T/m

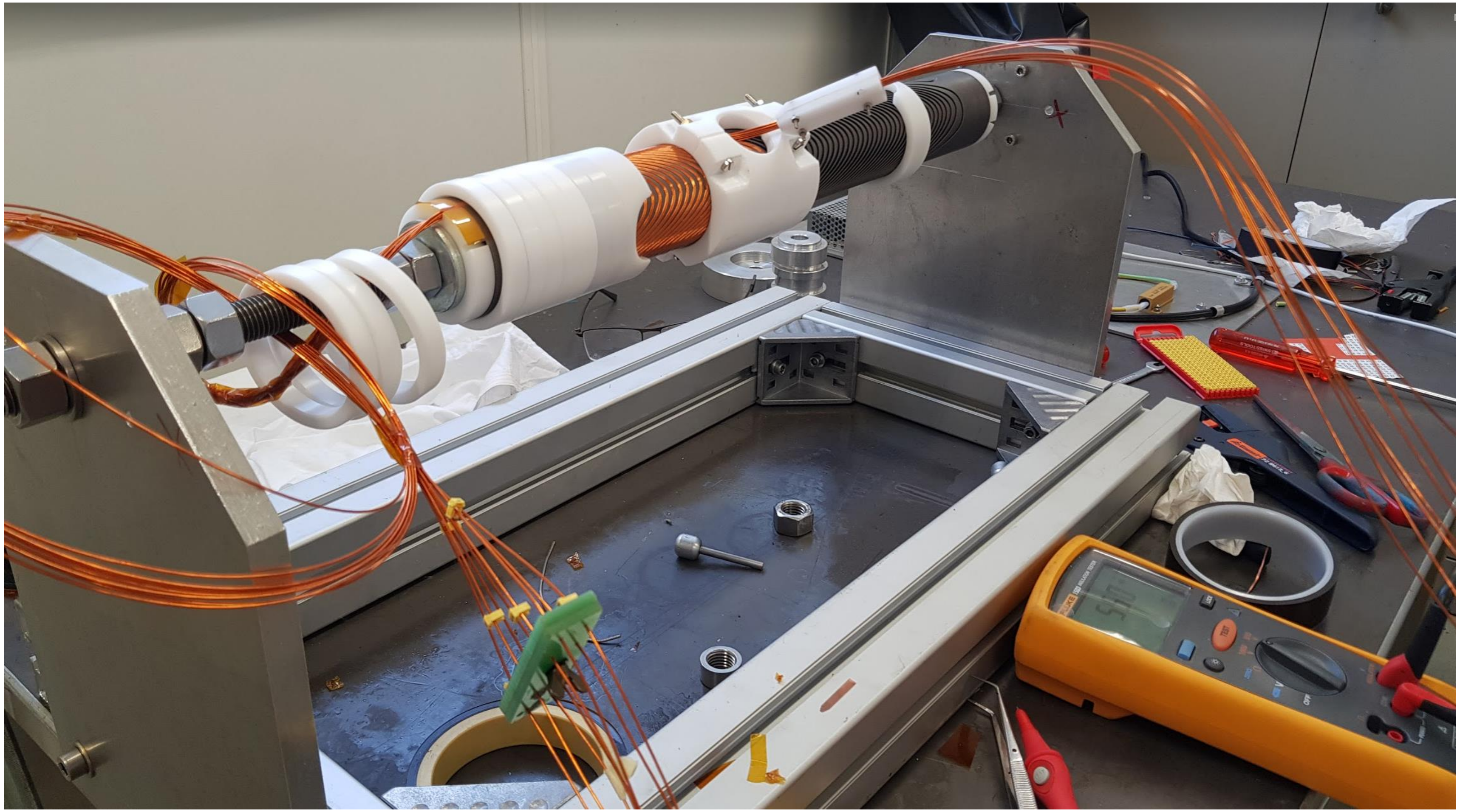
Example of a CCT manufacturing and winding process

Winding process

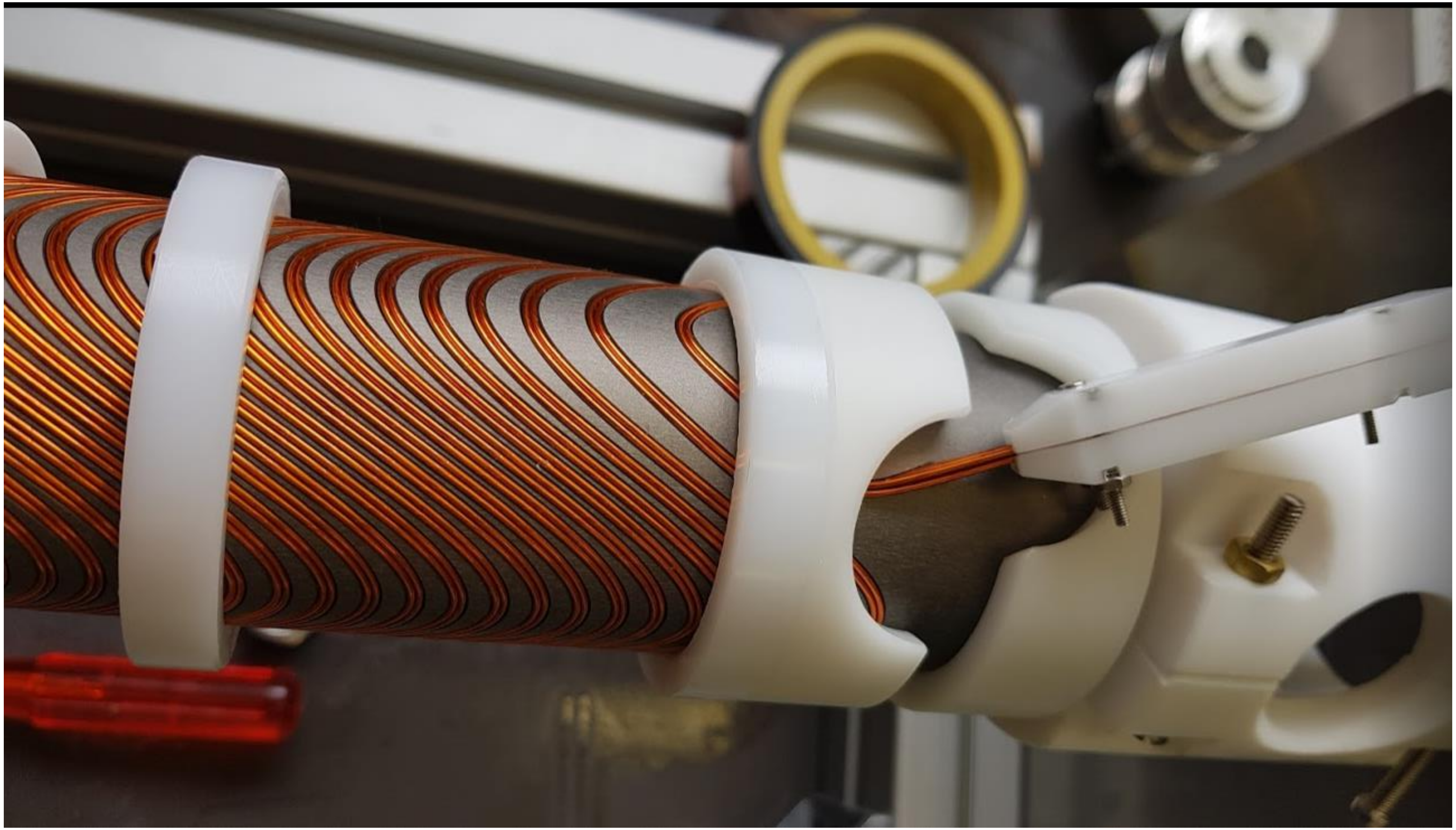


Inner layer started

Inner layer half way

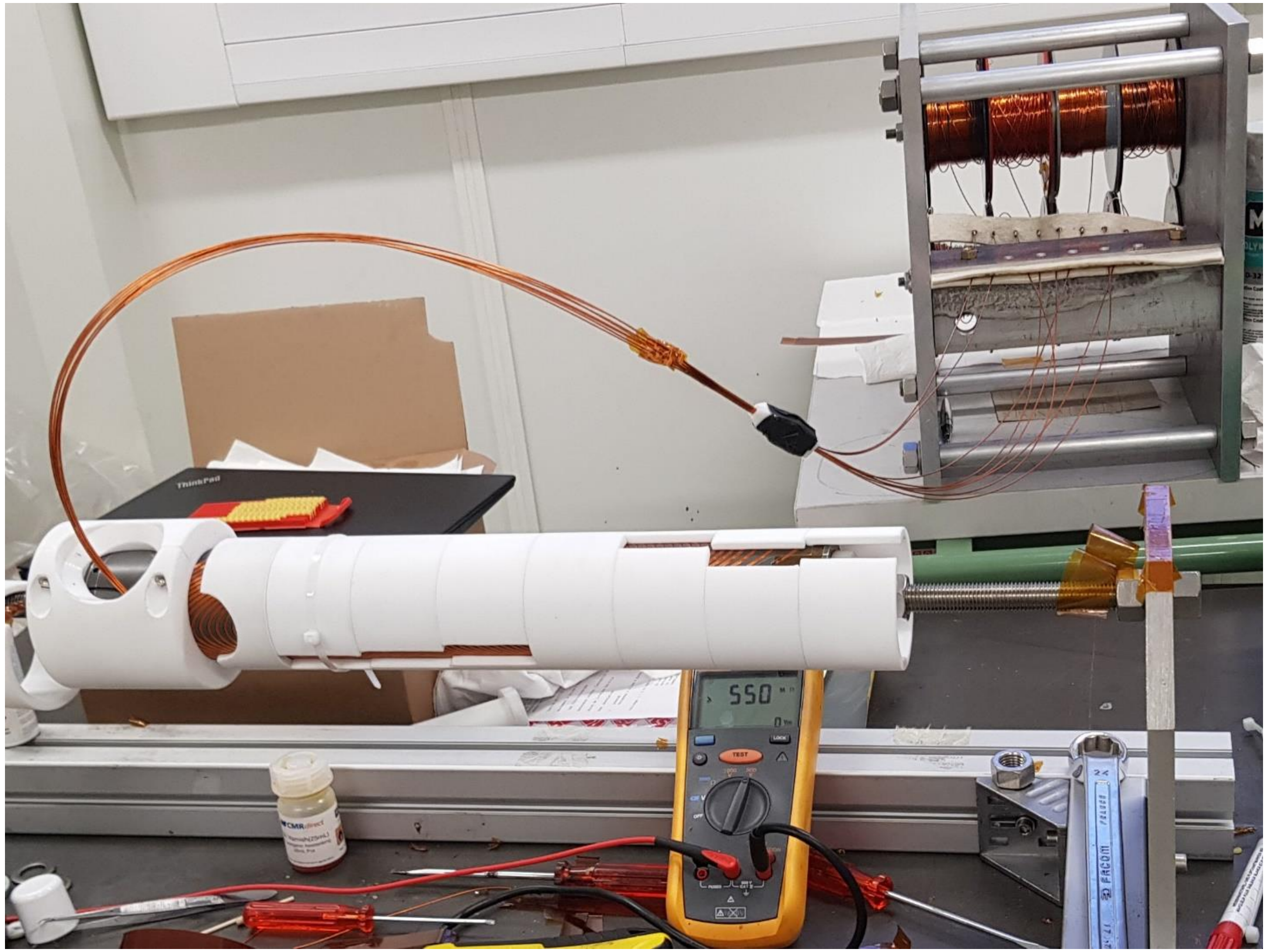


Inner layer done

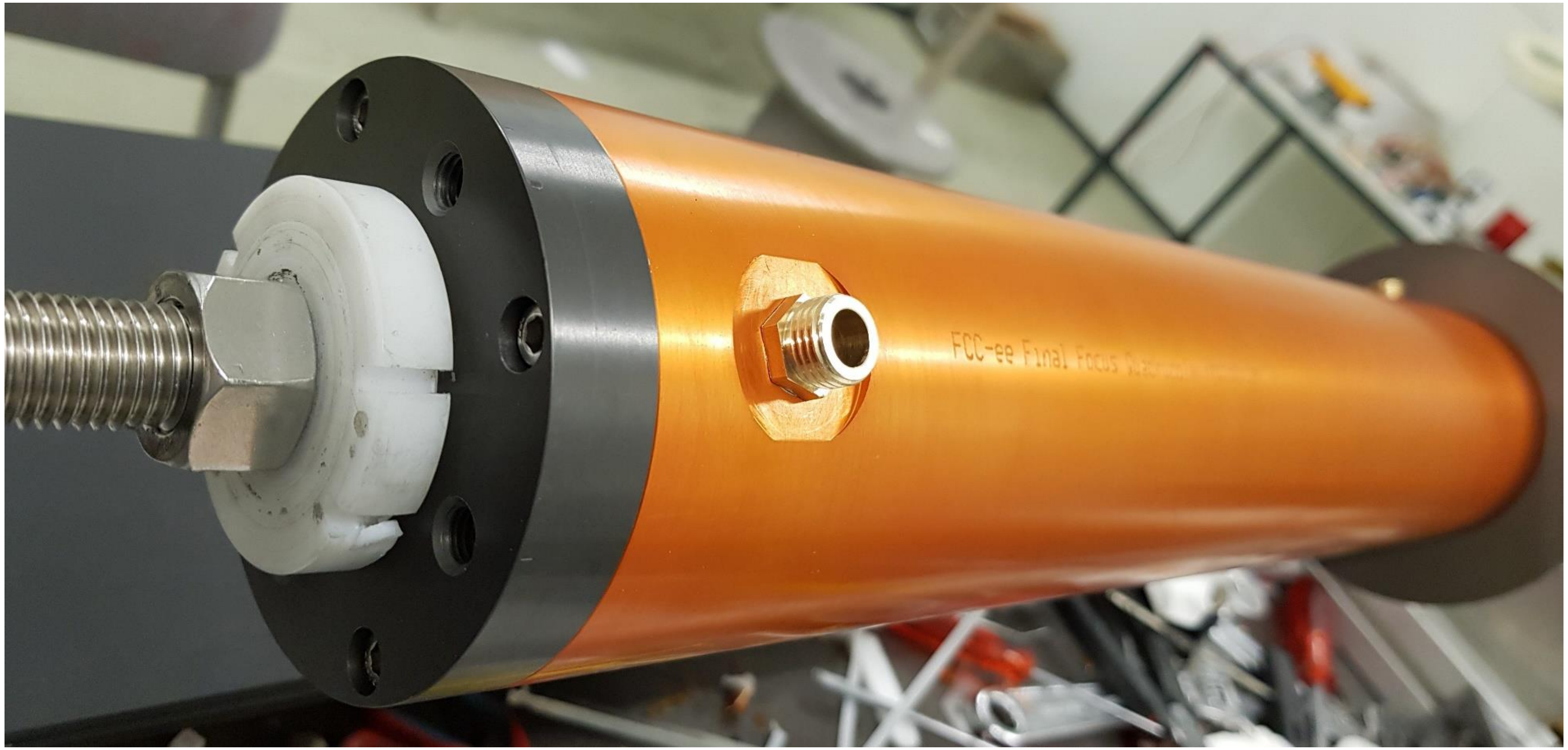


Outer layer half way

Outer layer done



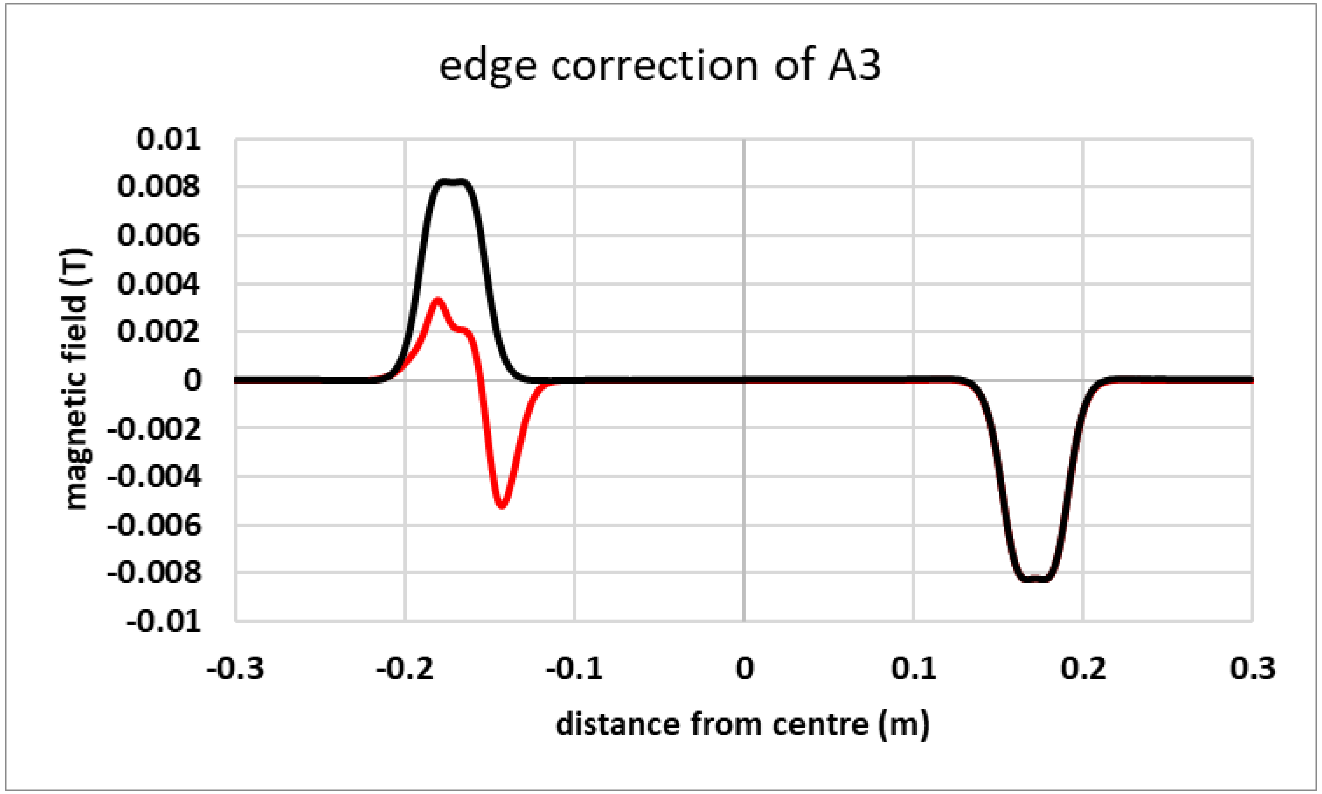
With sleeve and end plates



Local edge correction

- By design, a CCT magnet has all integral multipoles vanish (with the exception of the main one).
- However, the skew (A) components of the magnetic field compensate only because they have opposite signs at the entry and exit of the magnet.
- QC1L1 sits in an area of rapidly-changing optics functions: the change of beam size between the entry and exit of the magnet is a factor of ~2. ➔ a local correction is needed

Example: correction of A3 component, one side only. In red: corrected; in black: uncorrected



M. Koratzinos et al.[1709.08444](https://arxiv.org/abs/1709.08444)[physics.acc-ph]

IPAC21 paper

MAGNETIC MEASUREMENTS AT WARM OF THE FIRST FCC-EE FINAL FOCUS QUADRUPOLE PROTOTYPE

M. Koratzinos[1], MIT, G. Kirby, C. Petrone and M. Liebsch, CERN

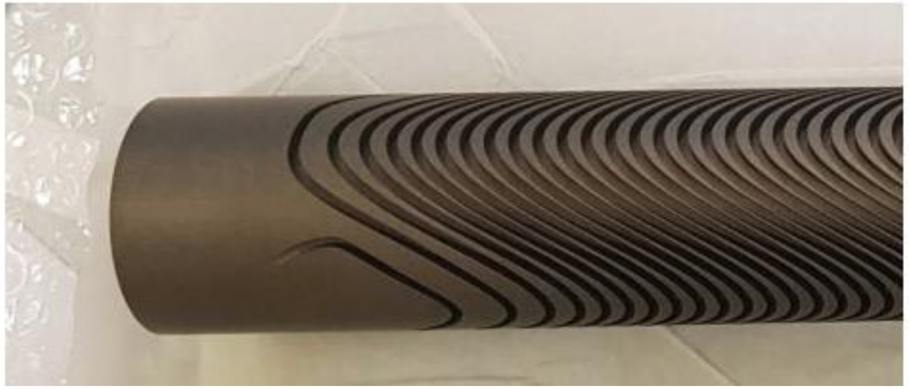
Abstract

The first FCC-ee final focus quadrupole prototype has been designed, manufactured, assembled and tested at warm. The prototype is a single aperture quadrupole magnet of the CCT type. One edge of the magnet was designed with local multipole cancellation, whereas the other was left with the conventional design. An optimized rotating induction-coil sensor was used. A technique was developed to take into account field distortions due to the environment of the test and distinguish them from magnet effects, demonstrating an excellent field quality for the prototype.

INTRODUCTION

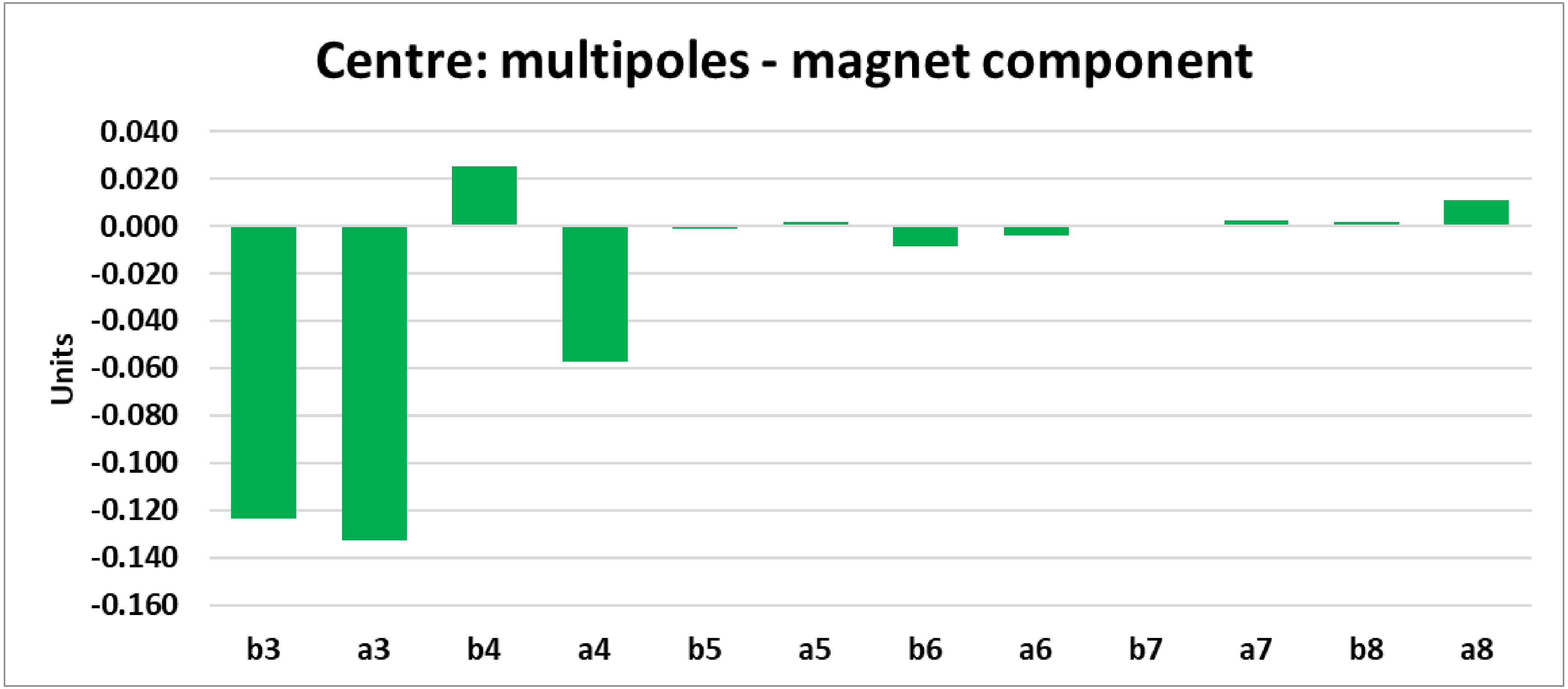
The FCC project aims to deliver a high-luminosity e^+e^- storage ring with a range of energies from 45 to 182.5 GeV per beam (FCC-ee) [1] [2]. It incorporates a "crab waist"

other. The idea behind the edge correction is this: a CCT magnet has non-zero multipole components at the edges, which exactly integrate to zero when integrating over the whole magnet. However, this magnet will be placed in an area of rapidly changing optics functions, and therefore global compensation is not sufficient. Instead, all multipoles vanish locally at the edge of the magnet using the technique described in [3]. *Figure 1* shows the inner magnet former on the corrected edge.



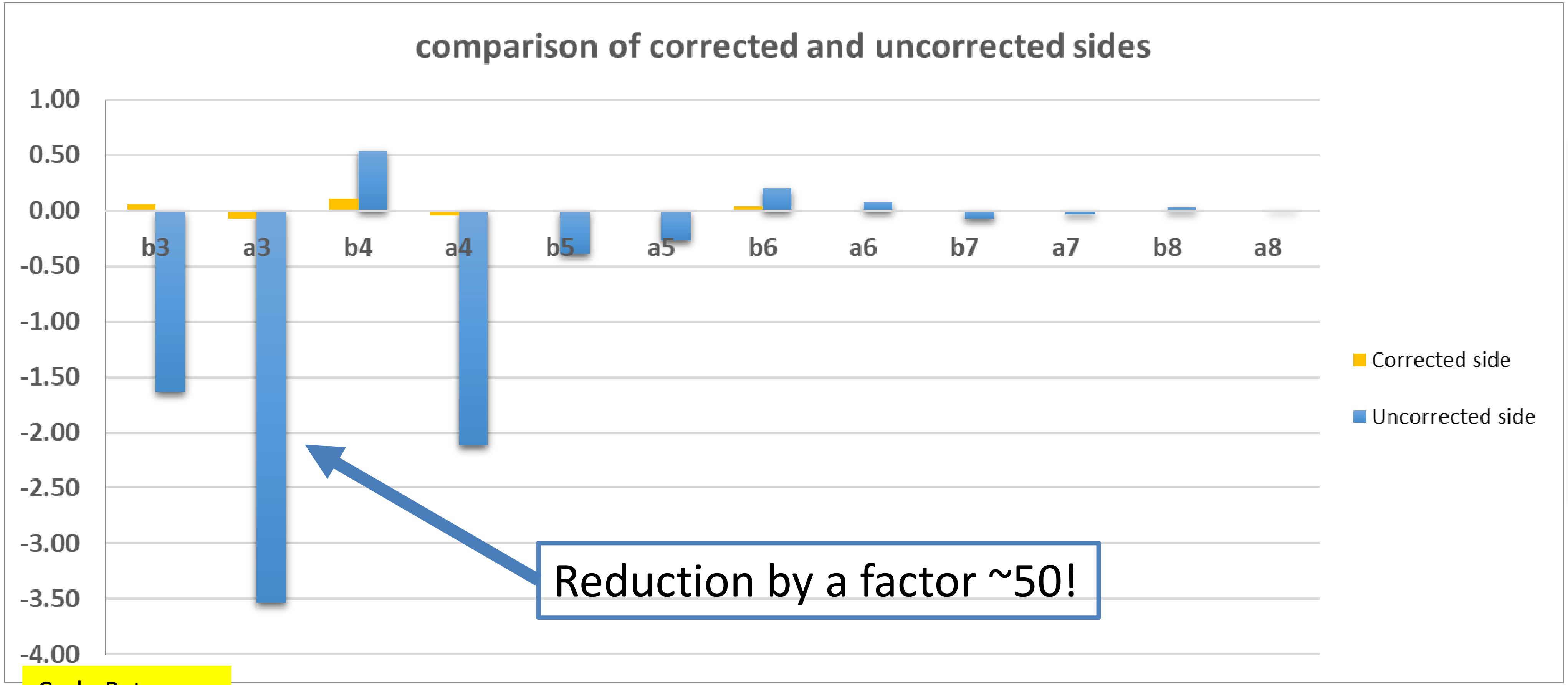
arXiv:2105.13230 **[physics.acc-ph]**

Results - centre



All multipoles are below 0.15 units and only b3, a3 is above 0.10 units. (this is barely above the sensitivity of the method)

Field quality at the edge, comparison



Carlo Petrone

Corrected side has edge effects that are 0.1 units or less

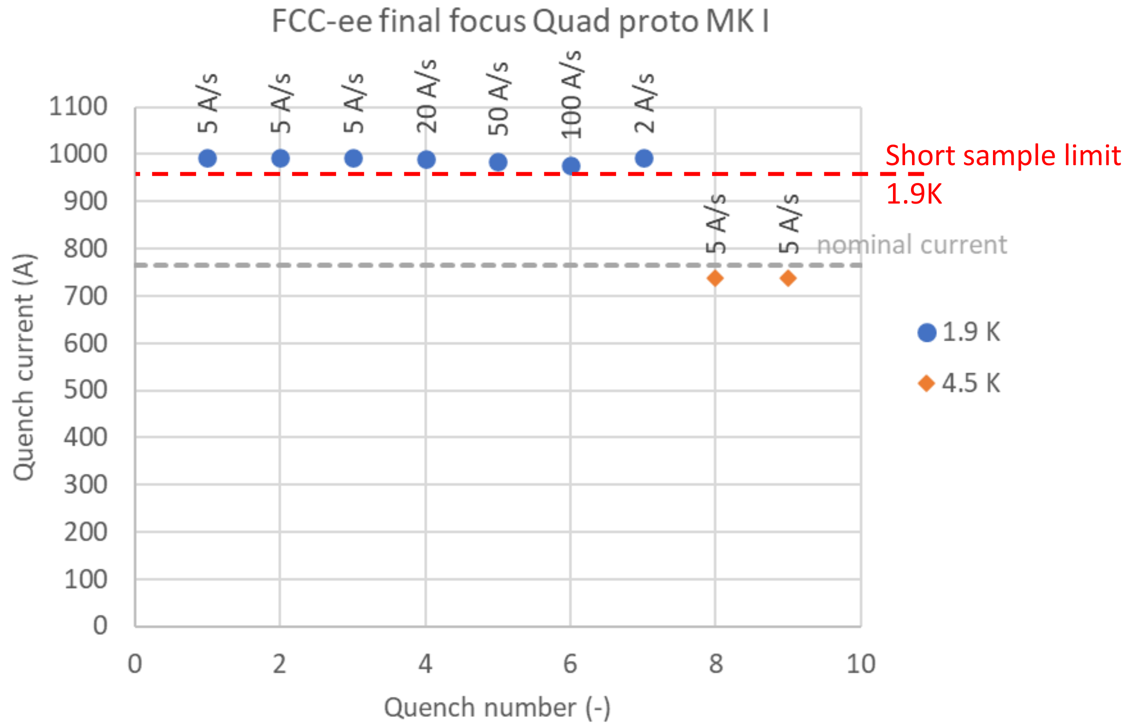
For both plots, the normalization is to the full length of QC1L1 (1200mm)

Edge correction really works!

The test at SM18

- Cryostat supporting 1.9K superfluid helium
- Training campaign
- Measurement of splice resistance
- Measurement of quenchback
- Measurement of RRR

SM18 Test results Oct 27-31 - Training

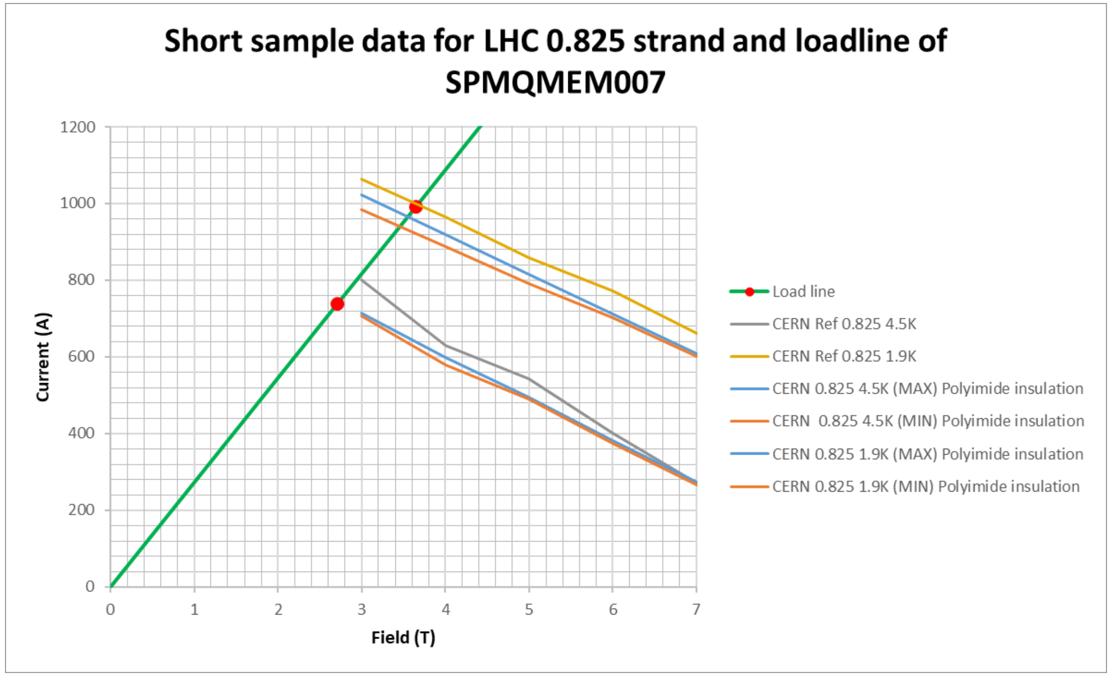


No training quenches were seen up to short sample limit

No degradation was seen for quenches at short sample limit

1.9 K: reached 991 A, peak field on conductor is 3.65 T

4.5 K: reached 738 A, peak field on conductor is 2.71 T



Gradients achieved:
- (Nominal): 100T/m
- Maximum at 1.9K: 130T/m
- Maximum at 4.5T: 96T/m

#	T(K)	RR (A/s)	Iquench(A)	Quench location
1	1.9	5	992	Coil 2
2	1.9	5	992	Coil 2
3	1.9	5	992	Coil 2
4	1.9	20	991	Coil 2
5	1.9	50	985	Coil 2
6	1.9	100	977	Coil 2
7	1.9	2	992	Coil 2
8	4.5	5	738	Coil 1
9	4.5	5	737	Coil 1

Test report EDMS https://edms.cern.ch/document/2976492/1
Gerard Willering, Jerome Feuvrier for TE-MSC-TM

Measured field quality table at cold

Units of 10^{-4} at a reference radius of 10mm (2/3 aperture)

n	Center section	Non-corrected section	Corrected section	Extrapolated total
b_3	0.19	-7.02	0.12	0.31
b_4	0.31	3.02	0.59	0.87
b_5	-0.11	-1.60	-0.05	-0.16
b_6	0.48	0.90	0.21	0.68
b_7	0.01	-0.32	-0.01	0.00
b_8	0.00	0.14	0.00	0.00
a_3	0.07	-12.56	-0.14	-0.06
a_4	0.48	-8.19	-0.25	0.24
a_5	-0.04	-0.90	0.03	-0.01
a_6	-0.04	0.39	-0.02	-0.06
a_7	-0.01	-0.20	0.00	0.00
a_8	-0.01	0.08	-0.01	-0.02

M. Koratzinos

Multipole field errors in units of 10^{-4} normalized to the full prototype (magnetic length 332mm). Last column extrapolates to the full length QC1L1 (magnetic length 700mm) by using 2.83 center sections and twice the corrected section

Upgrade to HTS

- Changing the technology from NbTi to HTS would mean that we can operate at 30K instead of 2K.
- BUT, HTS comes in form of tapes, not trivial to design a quadrupole with crosstalk compensation.
- I am happy to report that I think I have solved all these technical problems.
- Possible collaboration with LAPP Annecy for building a prototype

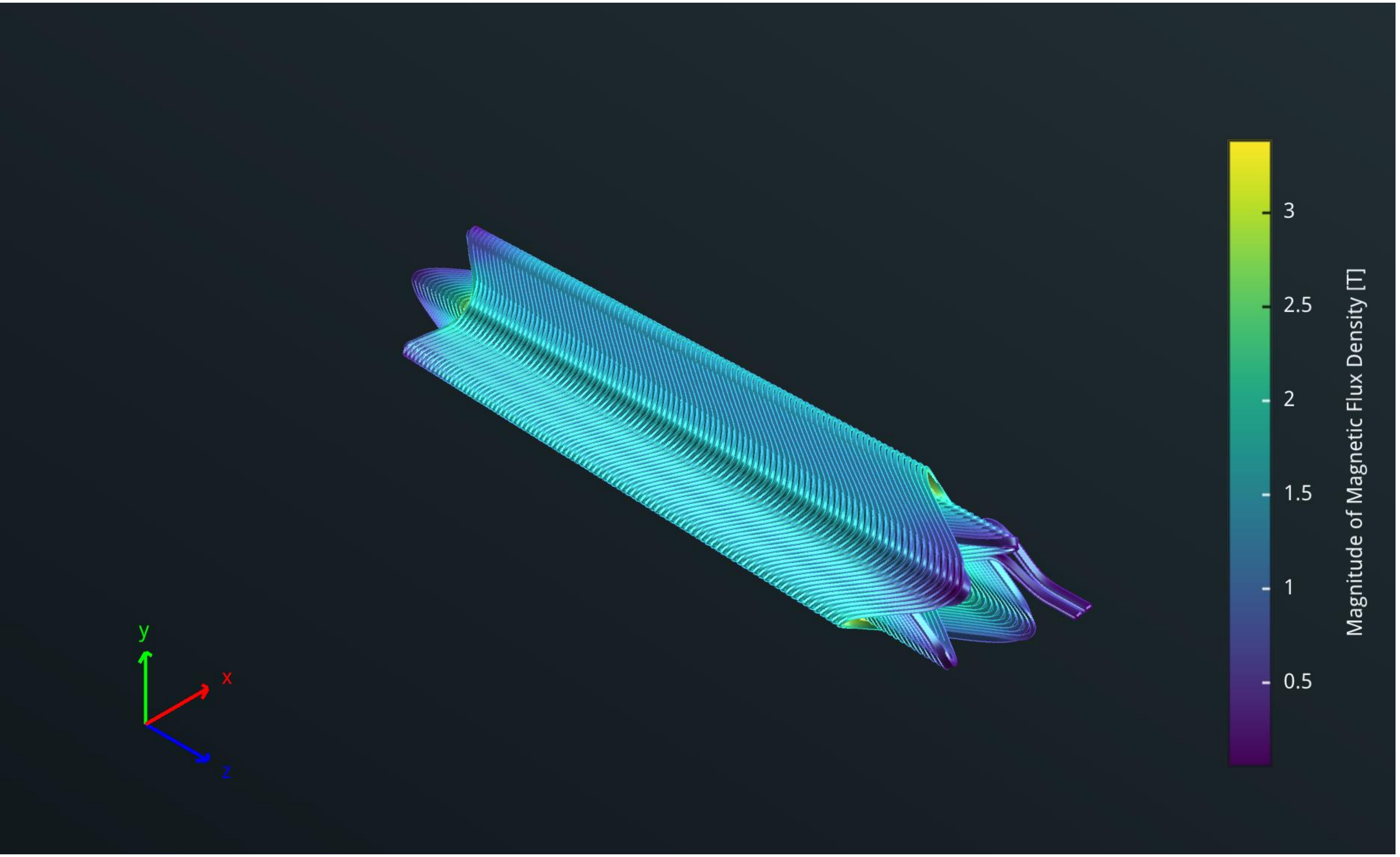
Can HTS tape be wound in a CCT?

- The CCT formula needs to be modified slightly
- The modified profile now is not a circle but a rounded square
- This is patented technology [patent WO2023111601 owned by MTG solutions Sarl – info at mtg_solutions@protonmail.ch]
- Same technology is used for the HTS4 project of CHART (the development of HTS main magnets for FCC-ee)

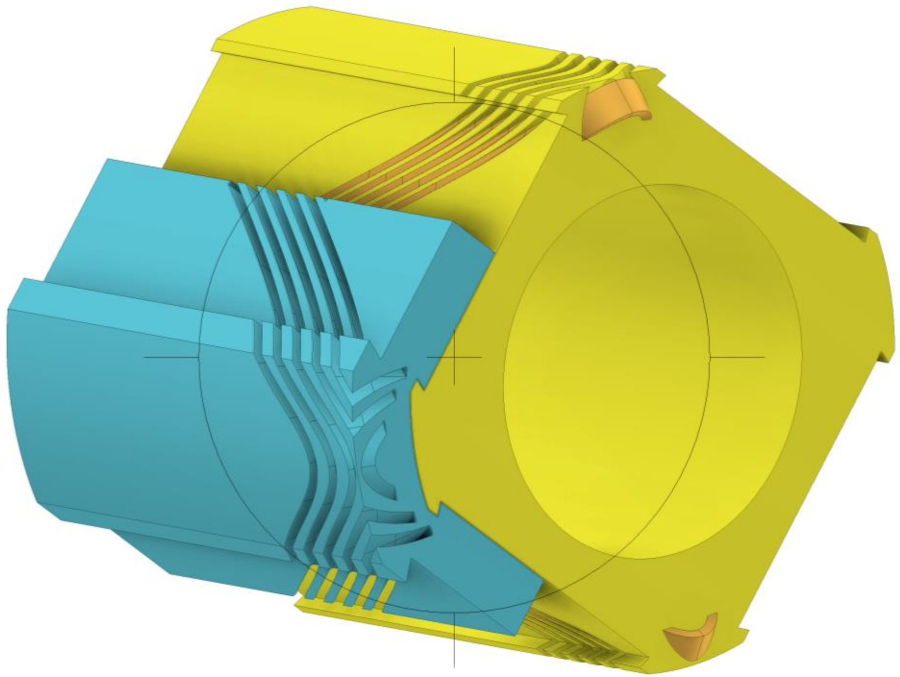
The HTS4 project

- Has designed and constructed a sextupole demonstrator
- Design gradient: 1000T/m2
- Current: 200A
- Operating temperature: 40K
- To be impregnated and tested

Magnetic and mechanical design of an HTS quadrupole prototype

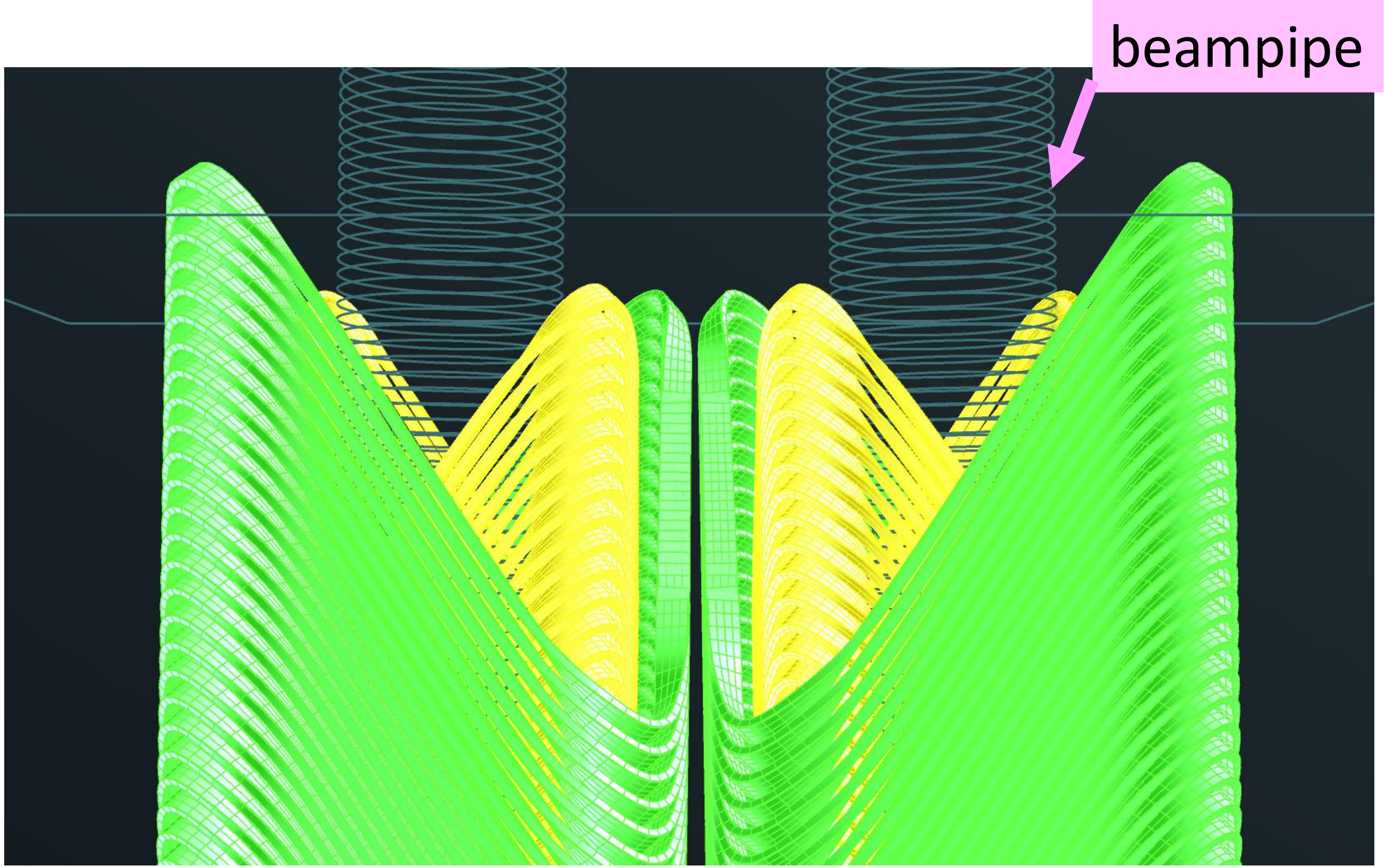


Similar in size to NbTi prototype



M. Koratzinos

Detail at 2200mm from the IP



Summary

- The MDI region is complex and of paramount importance to modern colliders
- Final focus magnets need to incorporate crosstalk compensation
- A CCT technology is an excellent solution to this problem
- A CCT prototype has been built and tested with excellent results
- An HTS version is under design and construction

THANK YOU