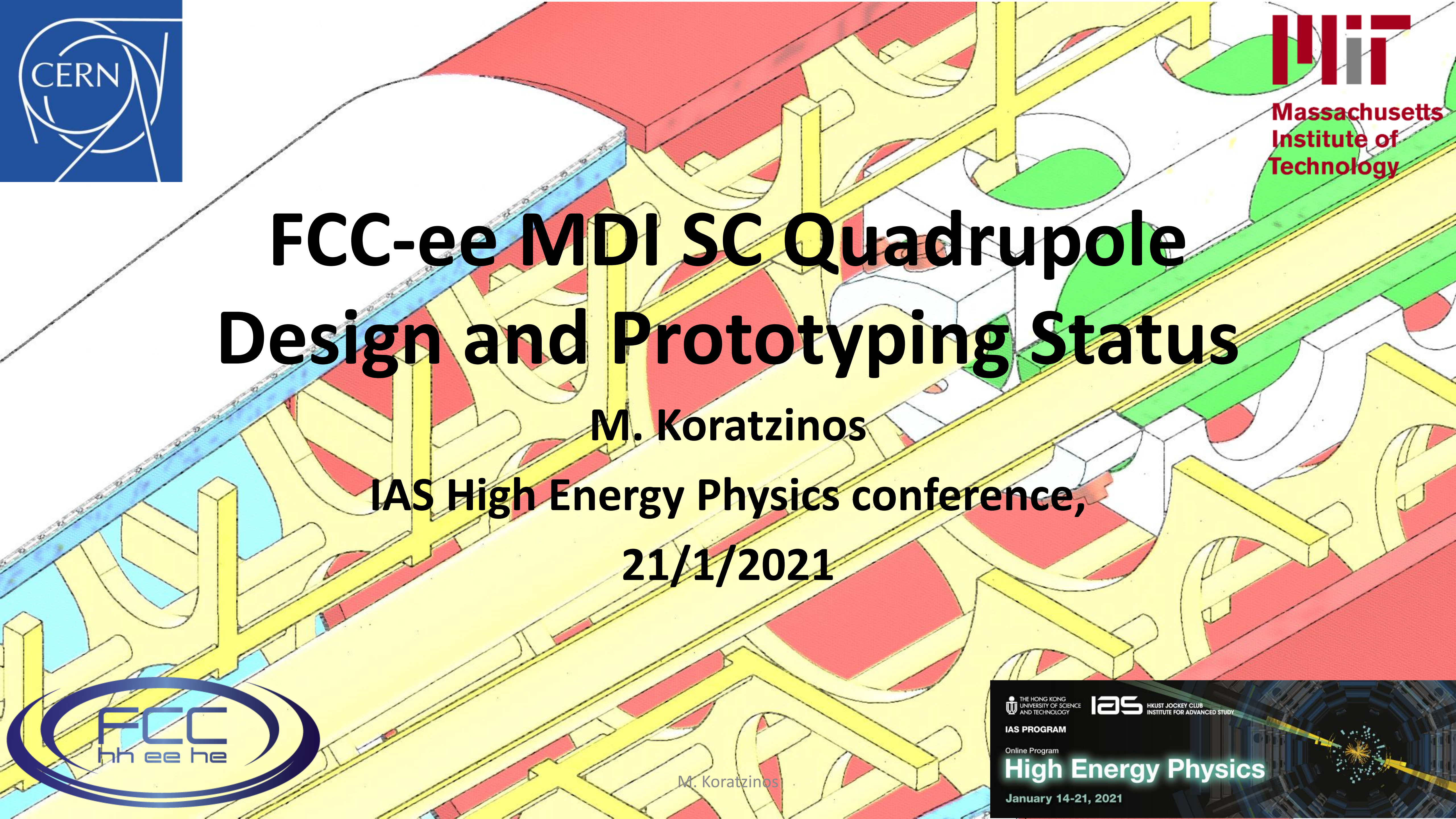

Massachusetts Institute of Technology

FCC-ee MDI SC Quadrupole Design and Prototyping Status

M. Koratzinos

IAS High Energy Physics conference,

21/1/2021

THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY
IAS HKUST JOCKEY CLUB INSTITUTE FOR ADVANCED STUDY
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High Energy Physics
January 14-21, 2021

Acknowledgements

- For the design: Glyn Kirby, Jeroen van Nugteren (author of Field)
- Manufacturing: the CERN main workshop, Karol Scibor
- Bits and pieces: the B927 boys, Pierre-Antoine Contat, Jacky Mazet
- Winding and assembly: Herman ten Kate’s team in B180, Tim Mulder
- Special tools manufacturing: the CMS workshop in P5, Maf Alidra
- Warm testing: the B311 boys Carlo Petrone, Melvin Liebsch, Dmitry Akhmedyanov, Stefano Sorti
- This work would not have been possible without the support of many people. I would like to especially thank Austin Ball, Katsunobu Oide, Frank Zimmermann, Guenther Dissertori, Michael Benedikt

Preamble

The main considerations when designing a final focus quadrupole system are:

- L* value: this is the distance from the IP of the final focus quadrupole closest to the IP
  - The smaller the value, the better the focusing of the beams
- Beam pipe size
  - The smaller the beam pipe, the easier it is to accommodate the quads, but beam heating increases and physical aperture decreases.
- Quadrupole field strengths
  - Are dictated by the optics and ultimately the luminosity performance. They need to be within the reach of technology and not induce too much synchrotron radiation

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

From the FCC CDR update 13/12/2019, Katsunobu Oide

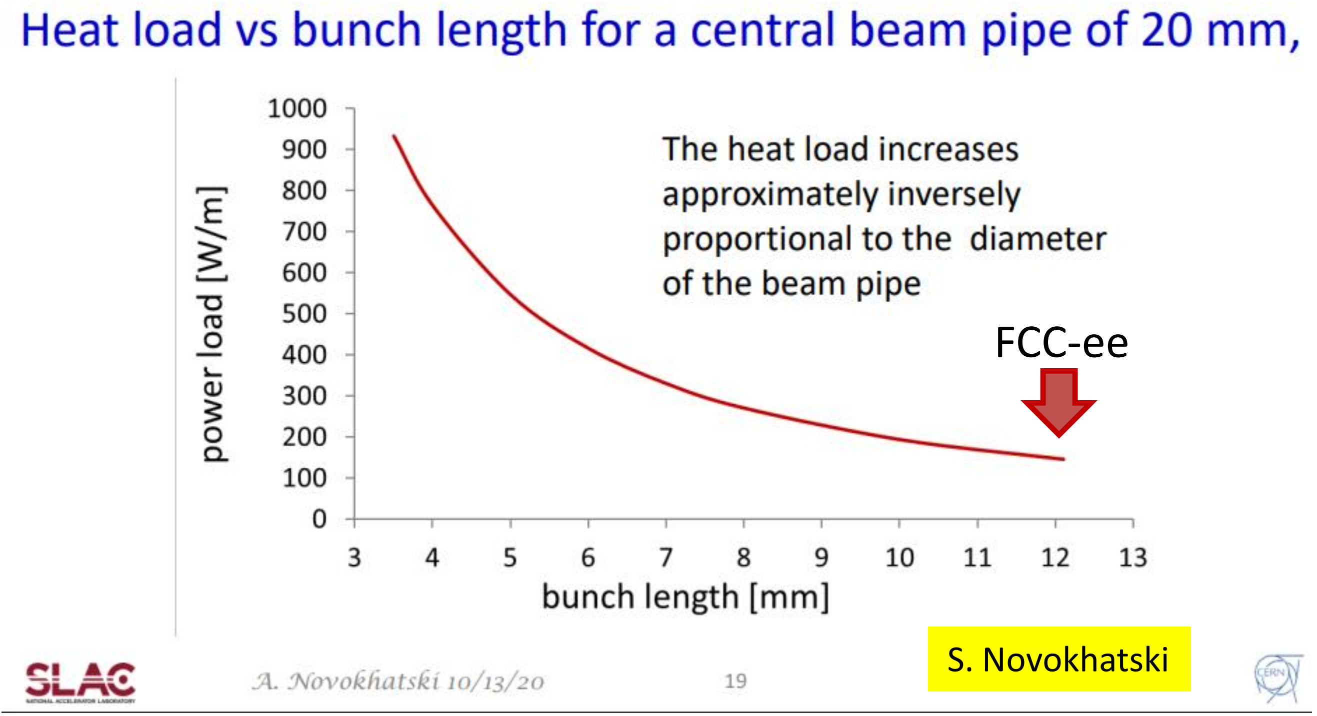
	Start position (m)	Length (m)	B' @Z (T/m)	B' @W (T/m)	B' @ H (T/m)	B' @ tt (T/m)
QC2L2	-8.44	1.25	25.05	43.82	61.30	69.50
QC2L1	-7.11	1.25	-0.18	0.00	7.32	56.85
QC1L3	-5.56	1.25	-19.35	-34.38	-53.08	-99.98
QC1L2	-4.23	1.25	-18.57	-32.94	-53.07	-99.98
QC1L1.1	-2.9	0.7	-40.95	-70.00	-99.71	-95.39
QC1L1.2	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

The updated parameters are rather different for QC1L1: its length is now 70cm from 120cm

Beam pipe size

- Since space is at a premium, the smaller the beam pipe the easier to accommodate the final focus quads and the easier to shield the E from the P type
- The beam-stay-clear for FCC in the vicinity of the IP is ±12 mm
- We have decided to have a beam pipe with inner radius of 15mm (b-s-c plus margin)
- Beam resistive heating is inversely proportional to beam pipe diameter (important for the Z running)



Heat load vs bunch length for a central beam pipe of 20 mm,

The heat load increases approximately inversely proportional to the diameter of the beam pipe

S. Novokhatski

A. Novokhatski 10/13/20 19

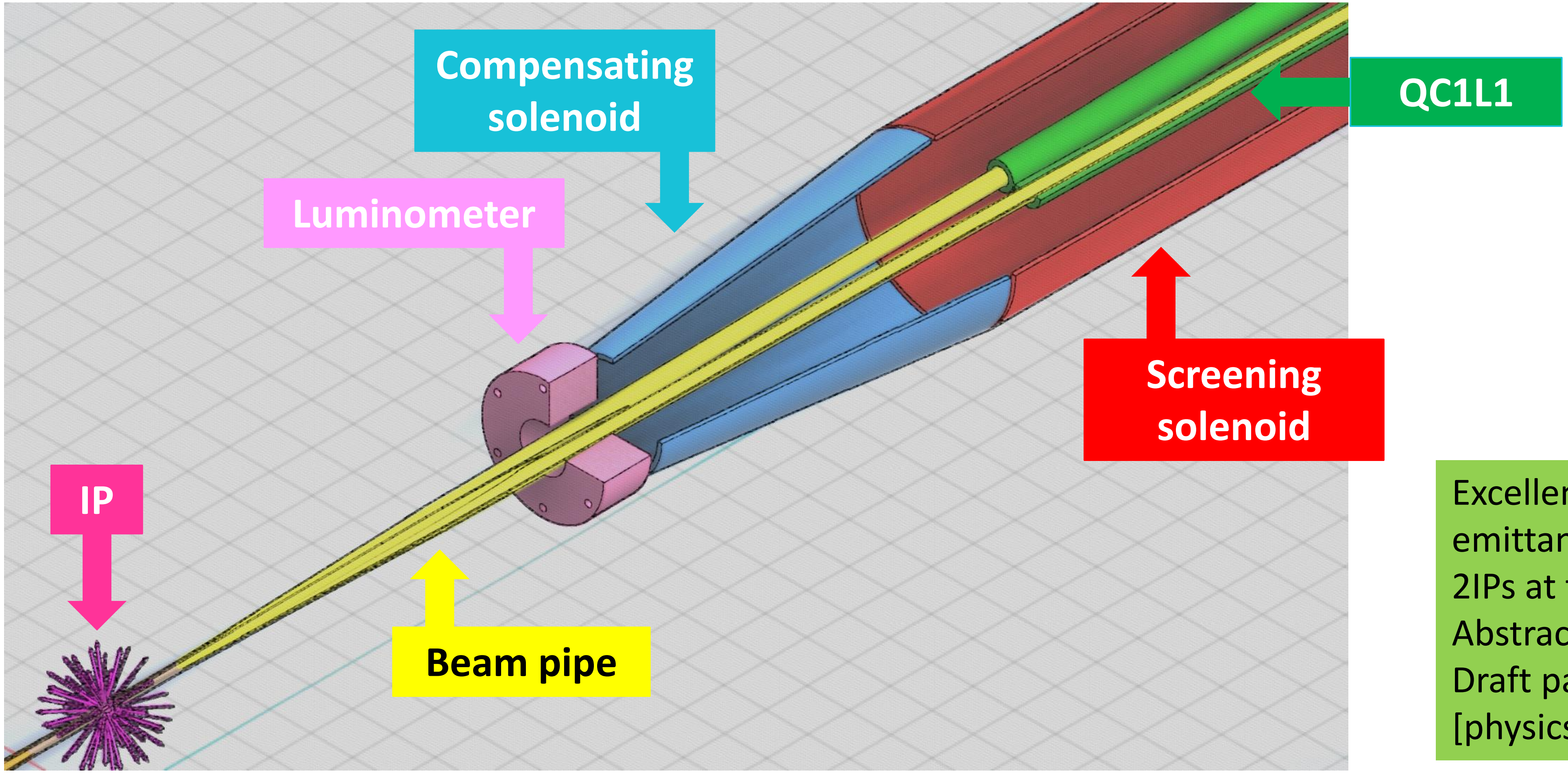
FCC-ee @Z : ~100W/m for a beam pipe inner diameter of 30mm
[cf CEPC with a beam pipe inner diameter of 17mm and a bunch length of 9.6mm: ~200W/m for an equivalent beam current]

➔FCC-ee approach: try and design the FF quads with the constrain of a beam pipe inner diameter of 30mm

Choice of L*

- (L* is the position of the front face of the final focus quadrupole. The shorter it is, the easier it is to focus the beams to a narrower spot.)
- However, the final focus quad is only one of the main components that needs to fit in the proximity of the IP, inside the detector: the compensation system must also work, and this takes space
- This system comprises:
  - Empty space, to allow for the vertex detector and Luminosity counter
  - A compensation solenoid to undo the twisting of the beam due to the detector solenoid
  - A screening solenoid, as the final focus quadrupoles should reside ina field-free region
- In the case of FCC, L* was chosen to be **2.2m** which leads to excellent performance as published in our CDR and will be presented in IPAC2021.

The FCC-ee compensation scheme



Excellent performance: vertical emittance blow-up = **0.24pm** for 2IPs at the Z for an L*=2.2 m. Abstract submitted to IPAC 2021. Draft paper: arXiv:2101.05704 [physics.acc-ph]

Choice of technology for QC1L1

- The pivotal requirement for the design is the close proximity of the QC1L1 quads, only 66 mm at the front tip. Moreover, the two quads are at an angle
- There should be no crosstalk between the quads, otherwise performance will be affected.
- There is not enough space to shield the two quads using an iron yoke
- All requirements are fulfilled with a CCT iron-free design

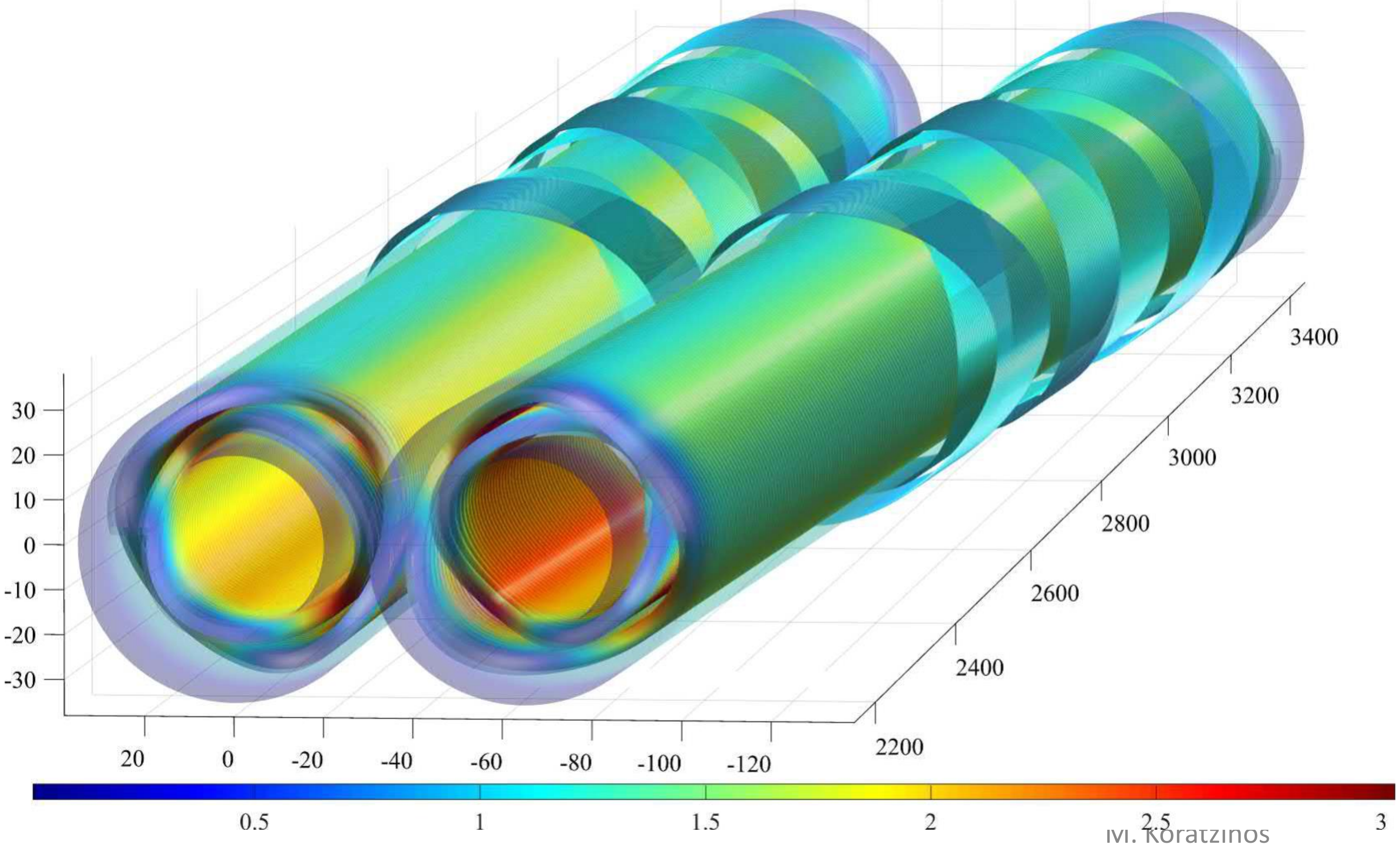
CCT accelerator magnets

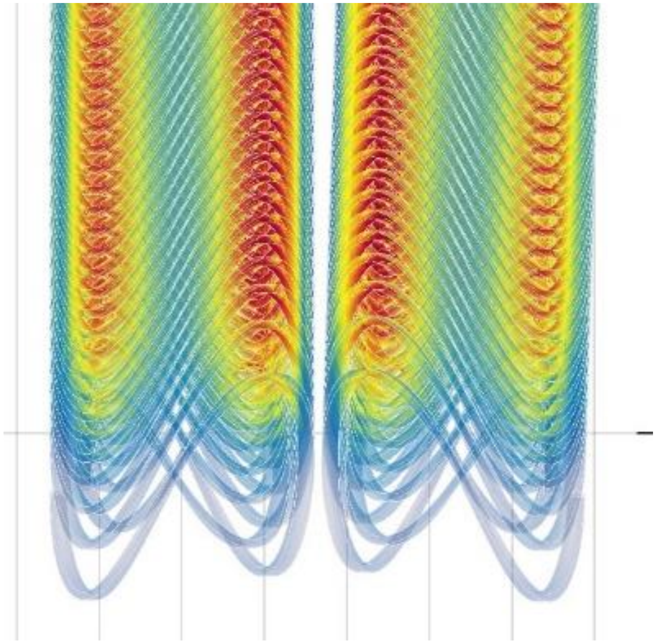
- A CCT (Canted Cosine Theta) is a type of accelerator magnet where the multipole mix is a *local* attribute of a magnet. (One can trivially design a magnet which is a dipole on one side and a quadrupole in the other.)
- The QC1L1 magnets are NOT quadrupoles. They are quads minus the field due to the other aperture. But together they make two nearly perfect quadrupoles
- 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 – please see further

QC1L1

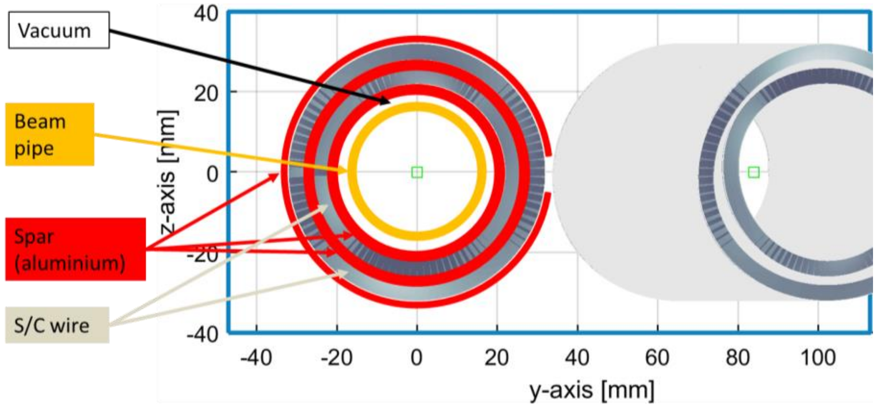
QC1L1 is the first and most demanding pair of quadrupoles of the final focus system of FCC-ee

Iron-free design





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



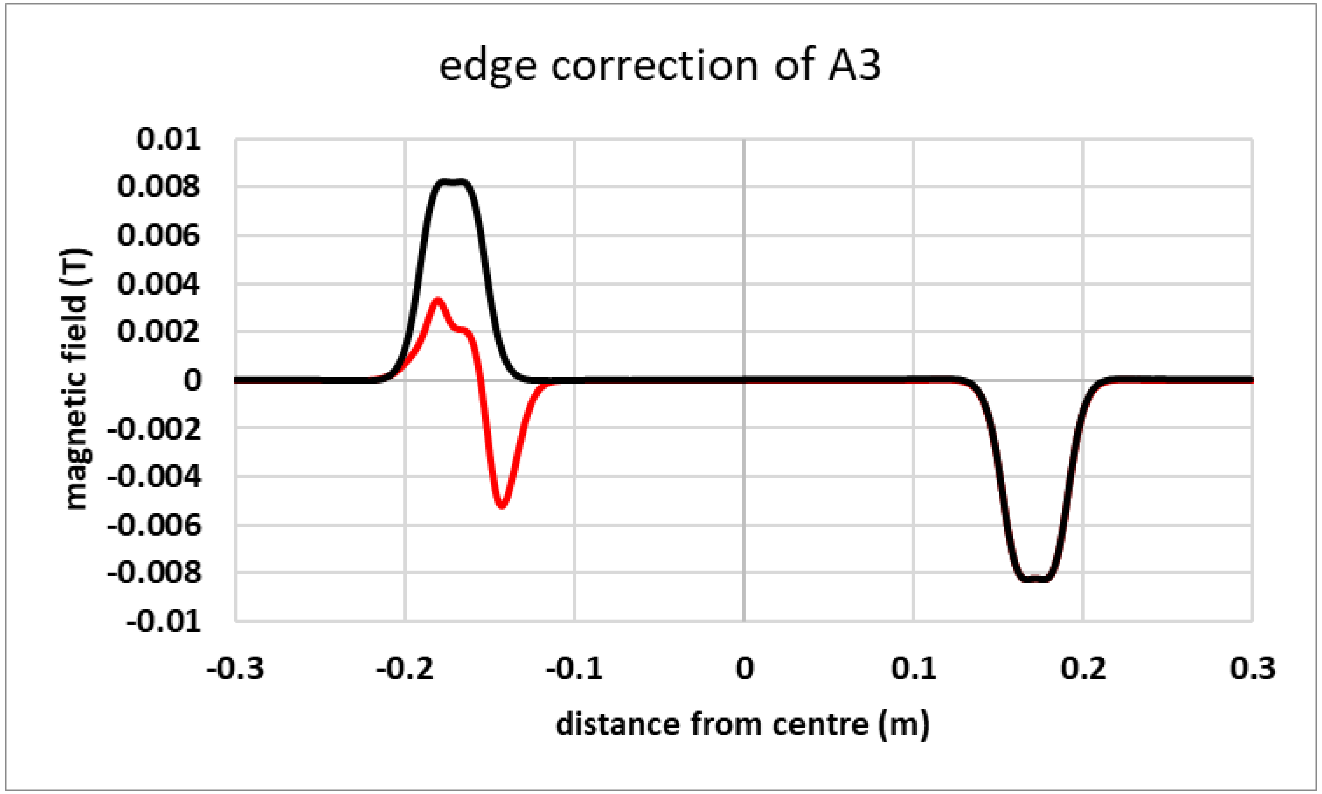
Why prototype?

- Although it works very well on paper, we need to test it in practice
- The first prototype is a single aperture magnet. So how can we test the crosstalk performance?
- The specific prototype employs a technique similar to the crosstalk compensation: edge correction
- One end of the magnet is corrected for local multipoles, which are present on every accelerator magnet design
- Exactly the same technique and tools are used for the crosstalk compensation of a double aperture design. ➔ If the edge correction works as expected, so will the crosstalk compensation

Local edge correction

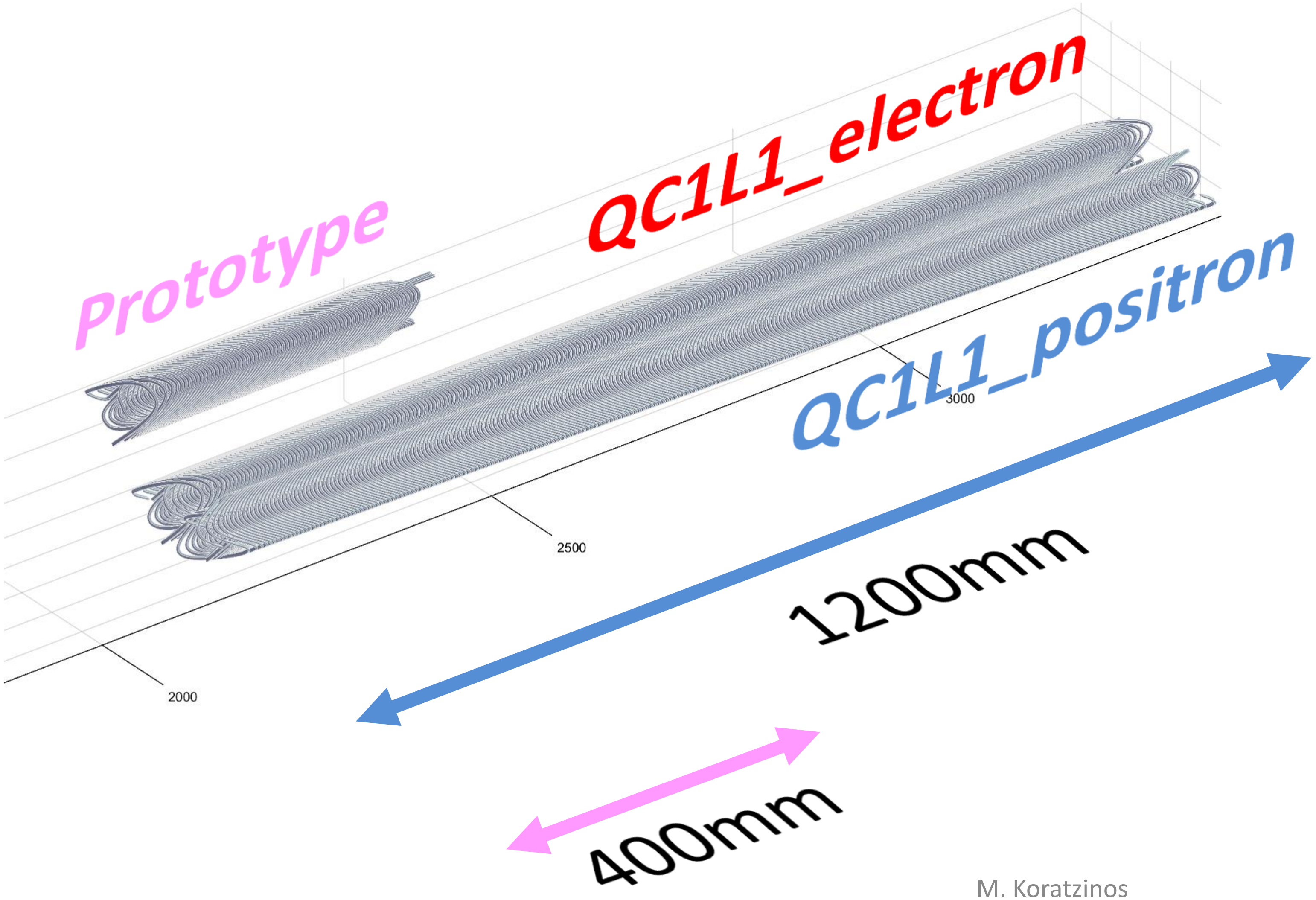
- By design, a CCT magnet has all integral multipoles vanish (with the exception of the main one).
- However, the skew (A) components of the magnetic field compensate only because they have opposite signs at the entry and exit of the magnet.
- QC1L1 sits in an area of rapidly-changing optics functions: 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 [physics.acc-ph]

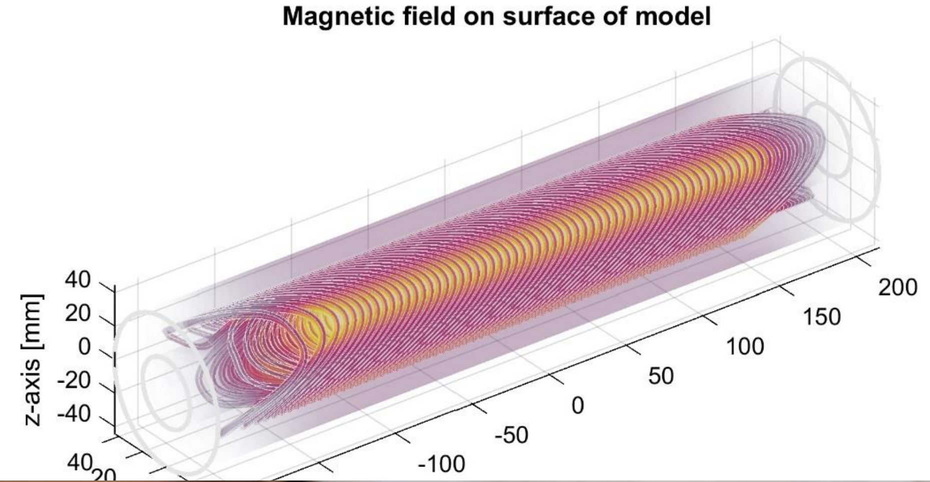
QC1L1 and the prototype

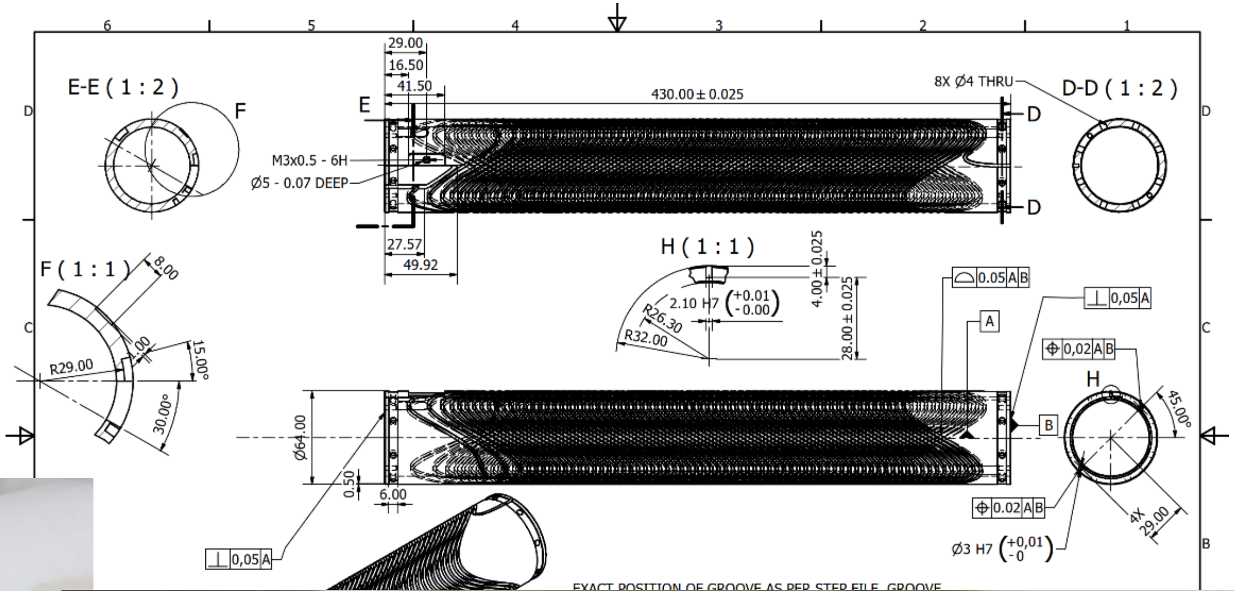


The first FCC-ee Final Focus prototype is a single-aperture version of QC1L1, with identical aperture (40mm) but one-third of the length (26% of the quadrupole strength).
It has asymmetric edges

I_{max} = 725A
Max. gradient: 100T/m

Design, manufacture and winding

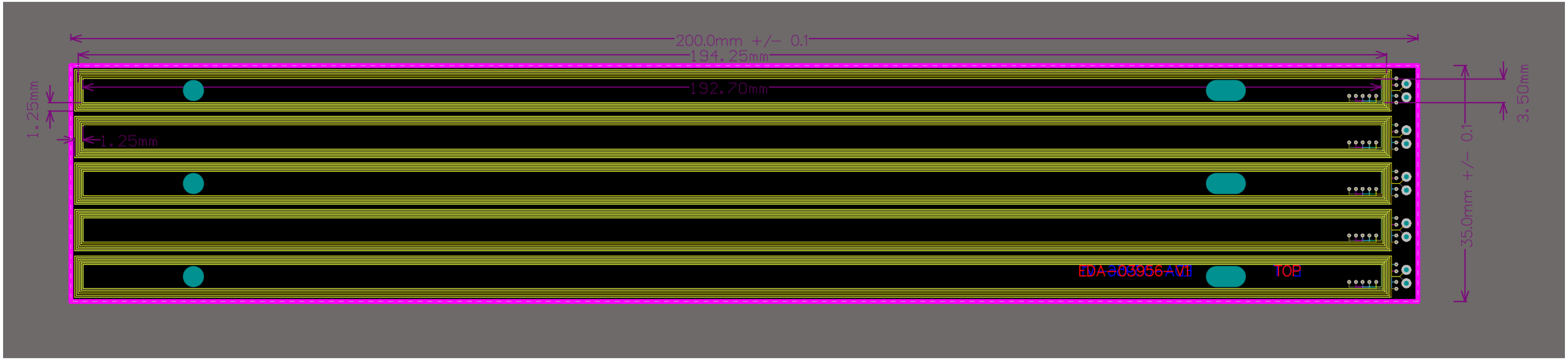




Testing at warm

- The first magnetic quality tests were performed at warm
- A rotating coil arrangement was used:
  - The magnet is powered with a current of 5 A (0.7% of maximum current) at room temperature
  - We measure the magnetic flux as the coil is rotated.
  - Each measurement is averaged over 100 revolutions
  - Then the data is post-processed to calculate the first 15 multipoles.
  - Then current is reversed and another (100-revolution) measurement is taken
  - The final numbers are the average over the two polarities – This eliminates the contribution due to the earth's magnetic field and any other static fields.
- All measurements made at a radius of 10mm
- Rotating coil length: 200mm (194mm active), width 35mm
- The rotating coil can be moved to measure the (integrated) field at different areas of the magnet: the middle, the corrected side and the uncorrected side

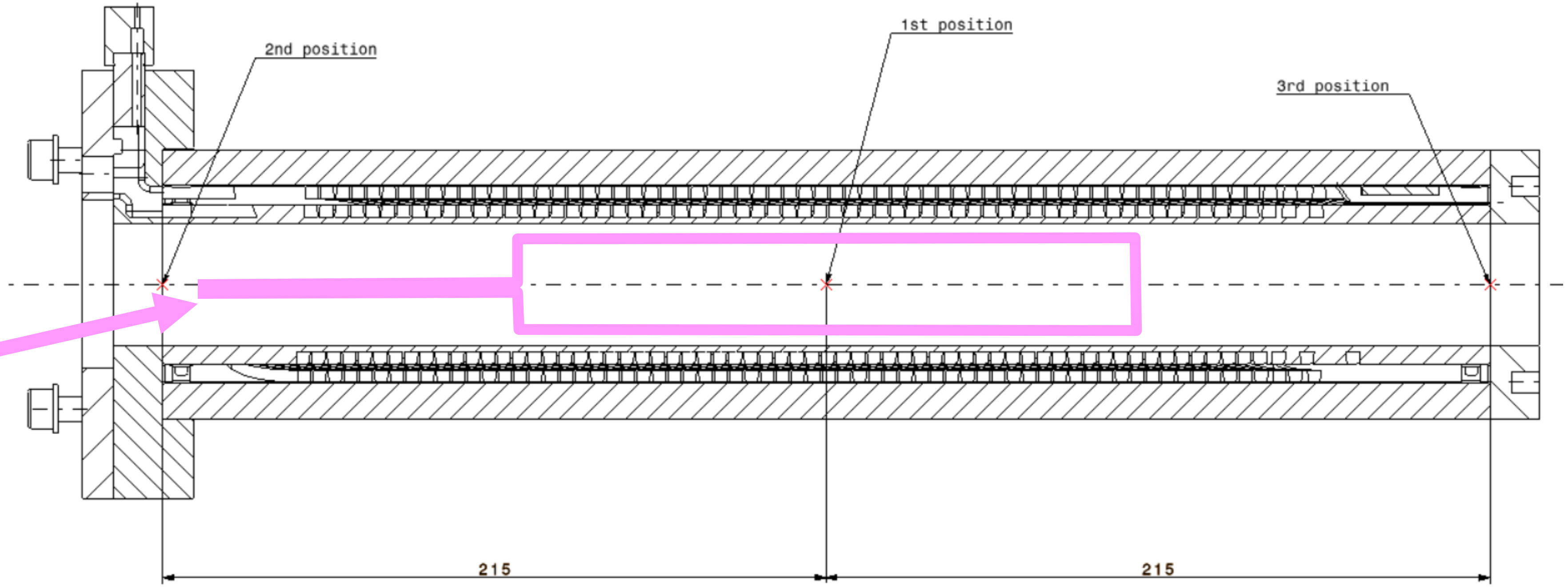
The rotating coil



Length is 200mm nominal, 194.25 mm active, width is 35mm, split in five individual coils

- For the quadrupole magnet, the individual coils are combined in such a way, that the coil is immune to the B2 field component, which is the dominant one, to be able to see errors in higher multipoles
- For the transfer function measurement, the coil is combined linearly

Testing arrangement



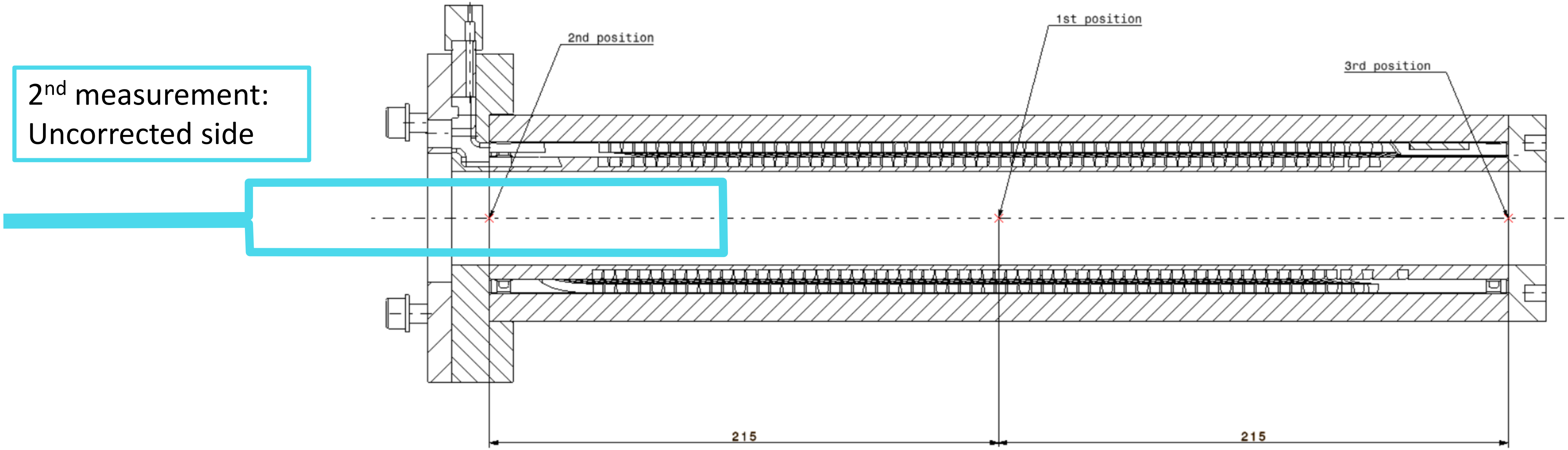
1st measurement:
Centre

Rotating probe

Three rotating coil measurements at the **middle**, at the **uncorrected edge** and at the **corrected edge**

Testing arrangement

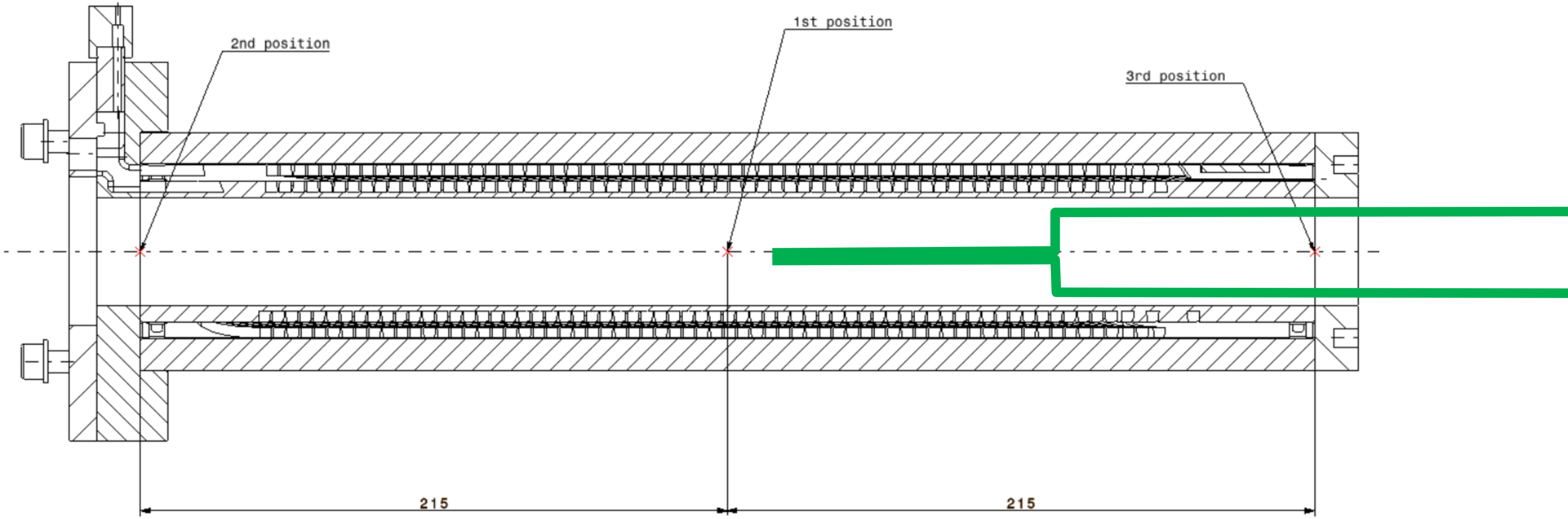
2nd measurement:
Uncorrected side



Three rotating coil measurements at the middle, at the **uncorrected edge** and at the **corrected edge**

Testing arrangement

3rd measurement:
Corrected side



Three rotating coil measurements at the middle, at the uncorrected edge and at the **corrected edge**

Measurement video

Nomenclature

Magnetic field of accelerator magnet: $B_z = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{Z}{R}\right)^{n-1}, z = x + iy = re^{i\theta}$

The way that results are traditionally presented is as follows:

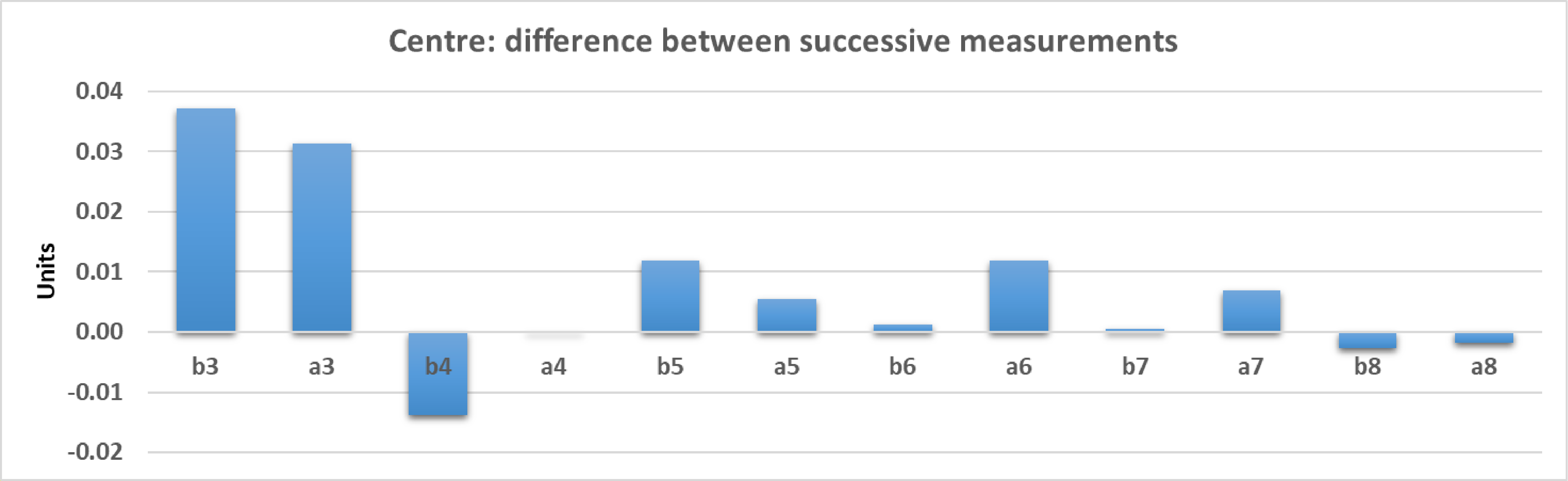
- a_n, b_n are the multipoles of order n ($n = 1 : dipole; n = 2 : quadrupole; n = 3 : sextupole, etc.$) they are measured in units of 10^{-4}
- a_n are the skew components, b_n the normal components
- Definitions:
  - $b_n = \frac{B_n}{B_2} \times 10{,}000\ @\ R = 10mm$ where B_2 is the dominant, quadrupole component
  - Same for the skew components: $a_n = \frac{A_n}{B_2} \times 10{,}000\ @\ R = 10mm$
- Traditionally R is chosen as 2/3^{rds} aperture. Our beam pipe is 15mm radius, so we measure at 10mm

Repeatability of measurements

The first test is the (short-term) reproducibility of measurements: The plot shows two successive measurements. Repeatability is excellent, within 0.04 units or better

➔ The sensitivity of the method is at the ~0.02 unit level

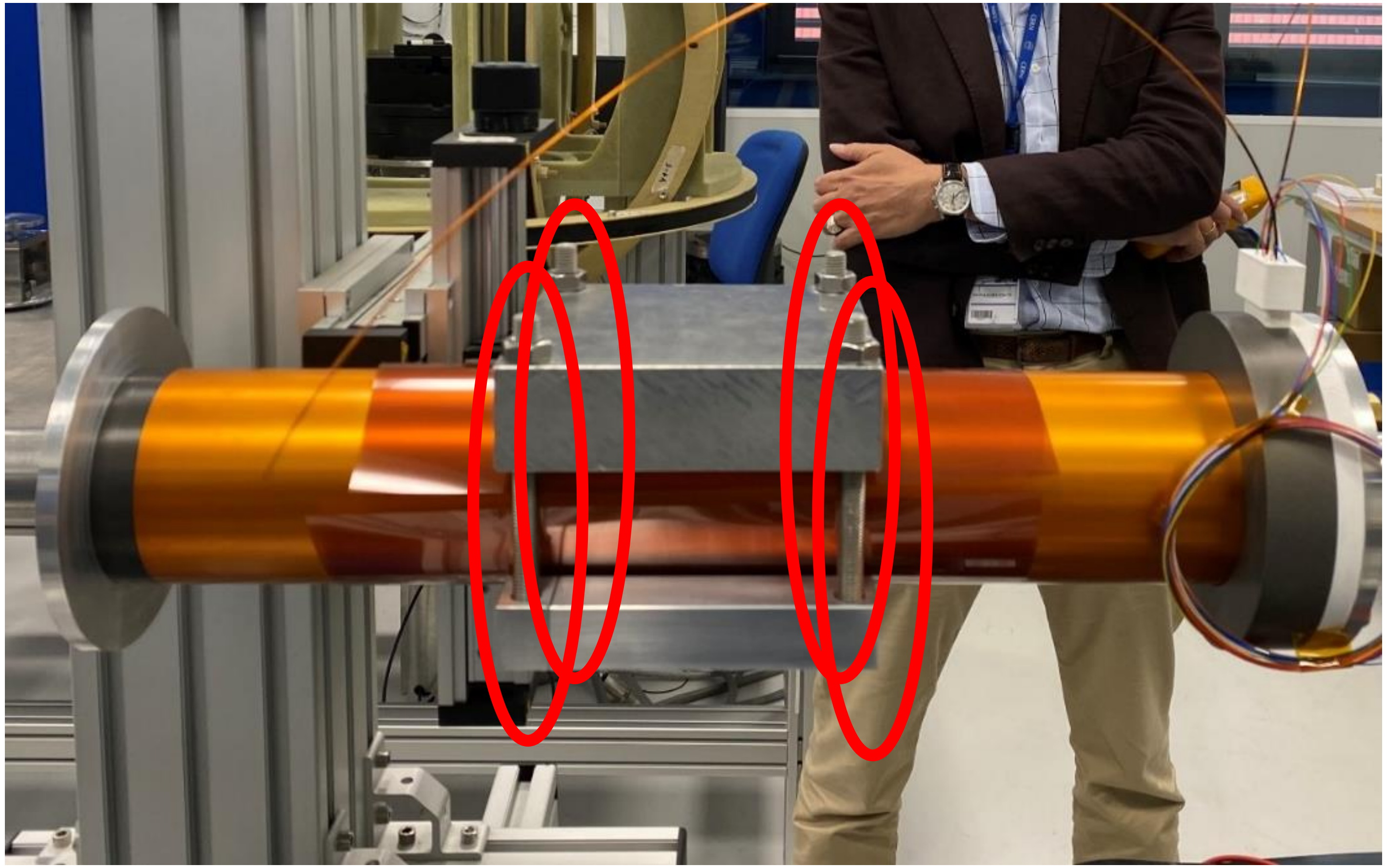
preliminary



Carlo Petrone

Centre measurement

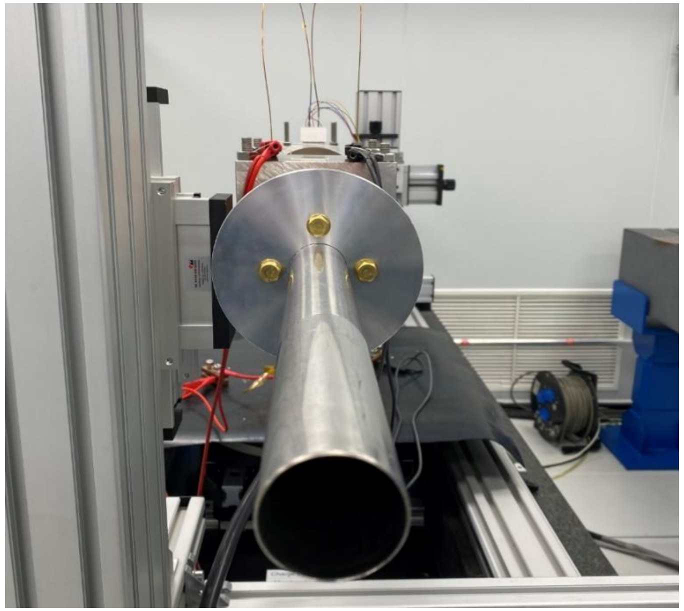
- We need to make sure that whatever we measure is due to the magnet and not its environment
- Although the mechanical clamping of the magnet is with aluminium claws, we have also used stainless steel high-strength bolts
- At this level of precision, we need to guard against these bolts distorting the field and therefore introducing multipoles
- Do not forget that we are dealing with 10^{-5} effects



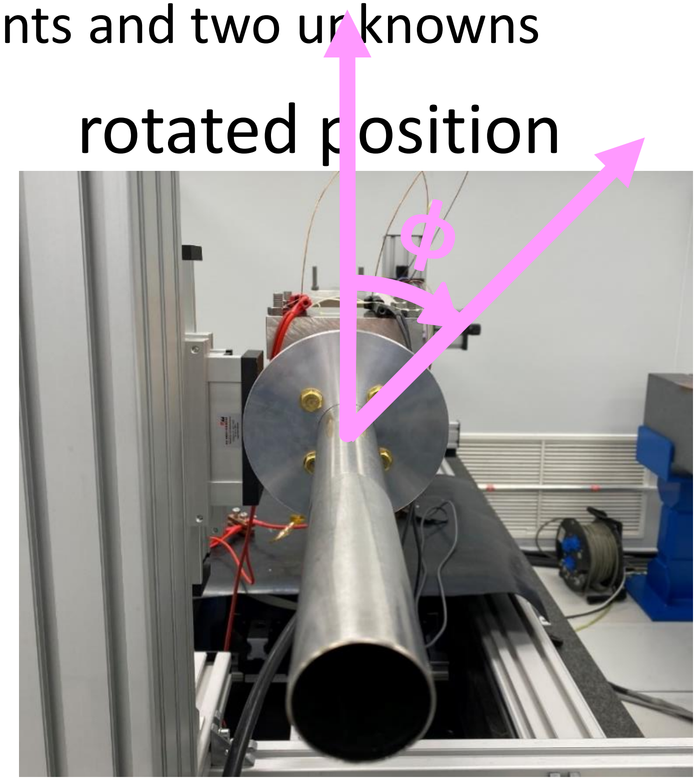
A strategy for measuring the pure magnet components

- We decided to take two measurements: one with the magnet in its proper position and the second where the magnet is rotated by ~45 degrees. (suggested by Glyn Kirby, CERN)
- The multipole errors due to the magnet should rotate with the magnet, but the errors due to the environment should not
- We then have two measurements and two unknowns

Original position



rotated position



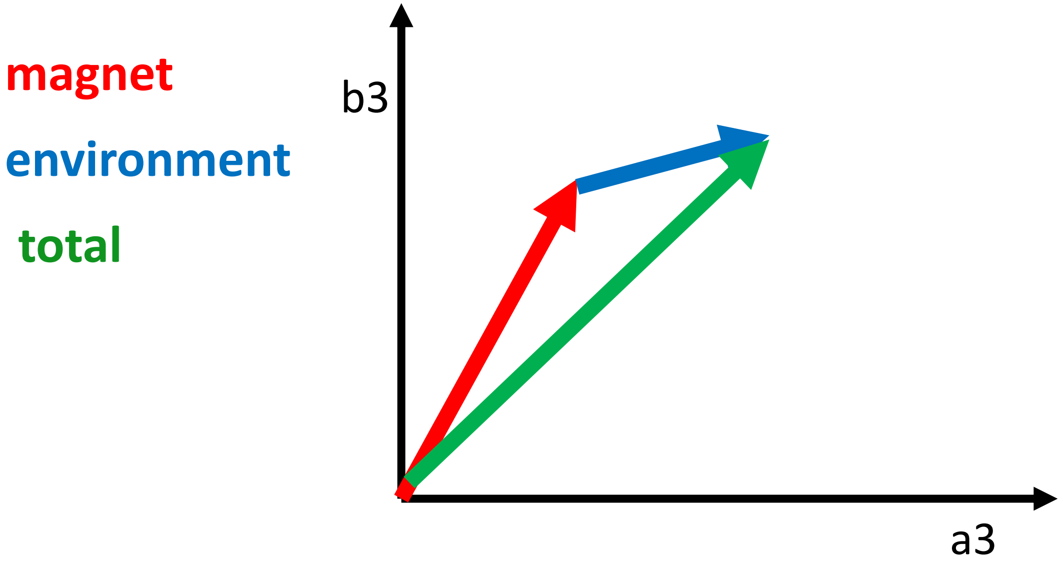
In our case, ϕ was measured to be 41.87 degrees

Rotated/original measurements

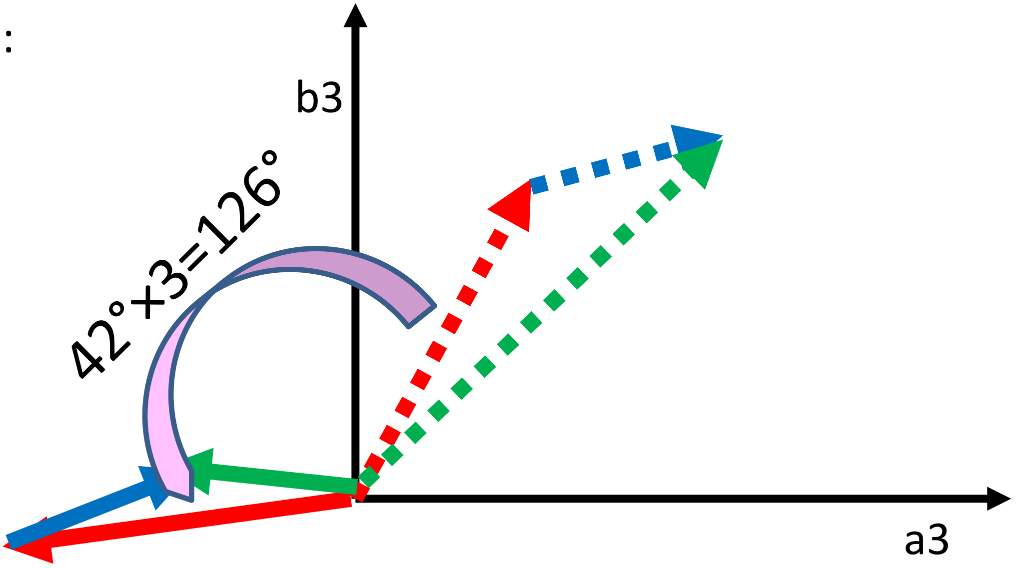
	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8
Original data (units)	-0.24	0.30	0.54	0.54	-0.17	-0.03	0.64	-0.12	0.03	-0.01	0.00	-0.03
Rotated data (units)	0.08	0.43	0.49	0.66	-0.16	-0.03	0.65	-0.11	0.03	0.00	0.00	-0.03

If a multipole component comes from the magnet and not from the environment, it is expected to change under this rotation.

Example:



Rotate by 42 degrees:

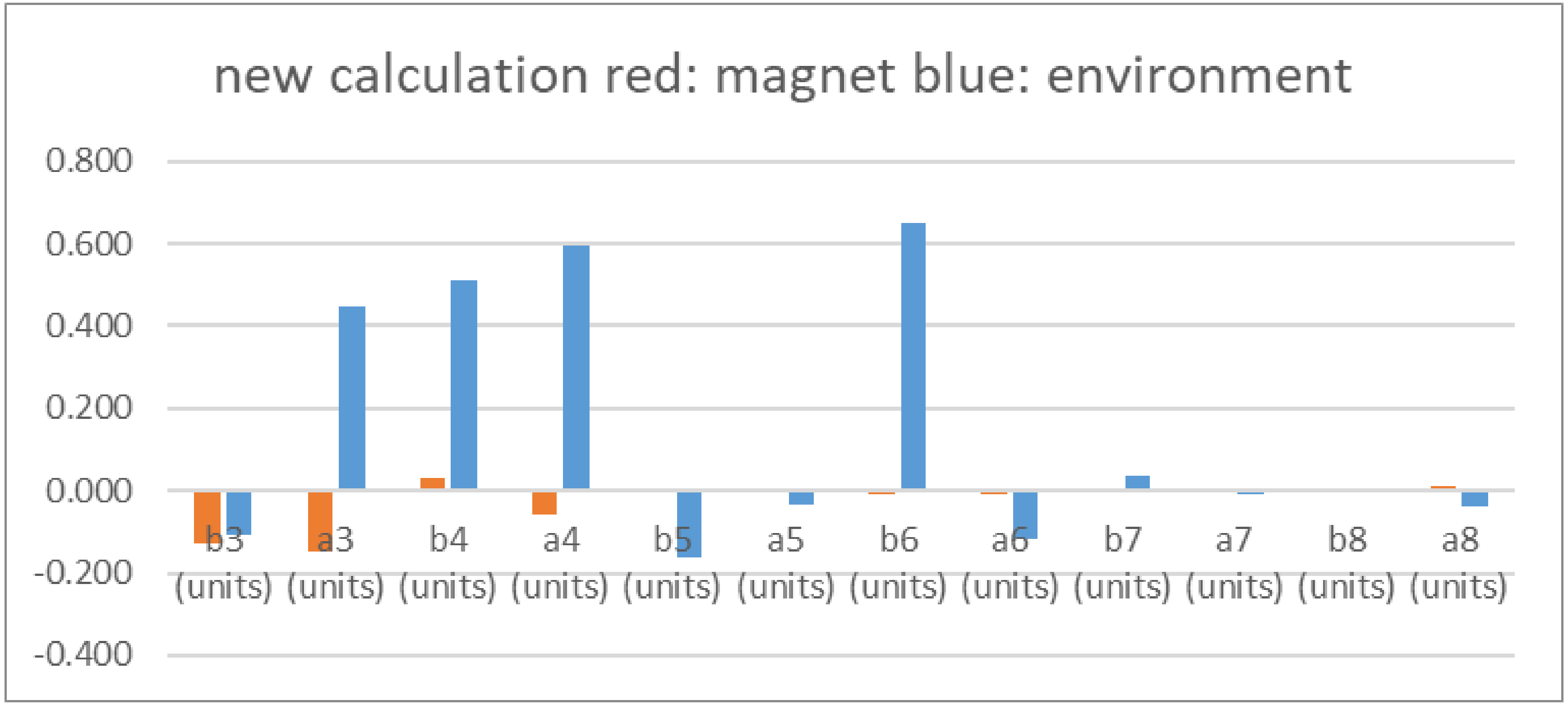


Vector rotates by (rotation angle) × n

Results

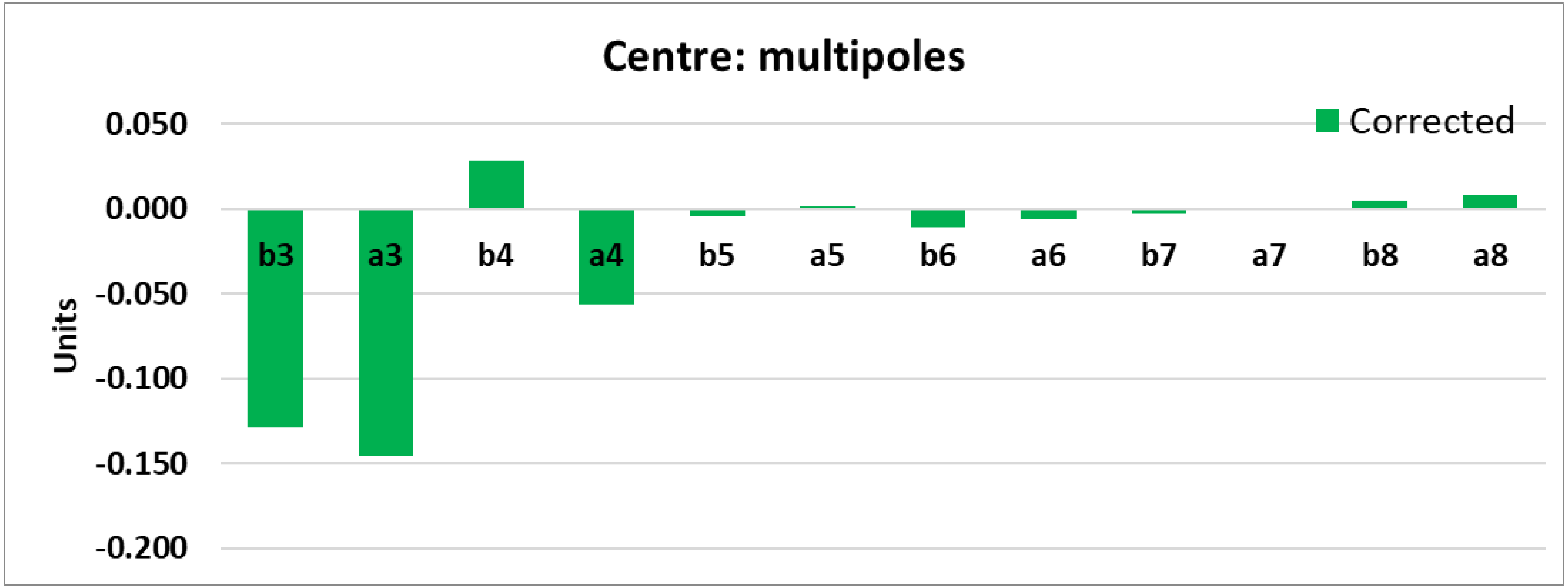
preliminary

	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8
Original data	-0.24	0.30	0.54	0.54	-0.17	-0.03	0.64	-0.12	0.03	-0.01	0.00	-0.03
Rotated data	0.08	0.43	0.49	0.66	-0.16	-0.03	0.65	-0.11	0.03	0.00	0.00	-0.03
Magnet component	**-0.129**	**-0.146**	**0.029**	**-0.057**	**-0.004**	**0.001**	**-0.011**	**-0.006**	**-0.003**	**0.001**	**0.004**	**0.009**
Environment component	-0.110	0.447	0.510	0.595	-0.163	-0.035	0.652	-0.118	0.033	-0.008	-0.005	-0.036



A big chunk of the measured multipoles can be attributed to the environment

Results - centre



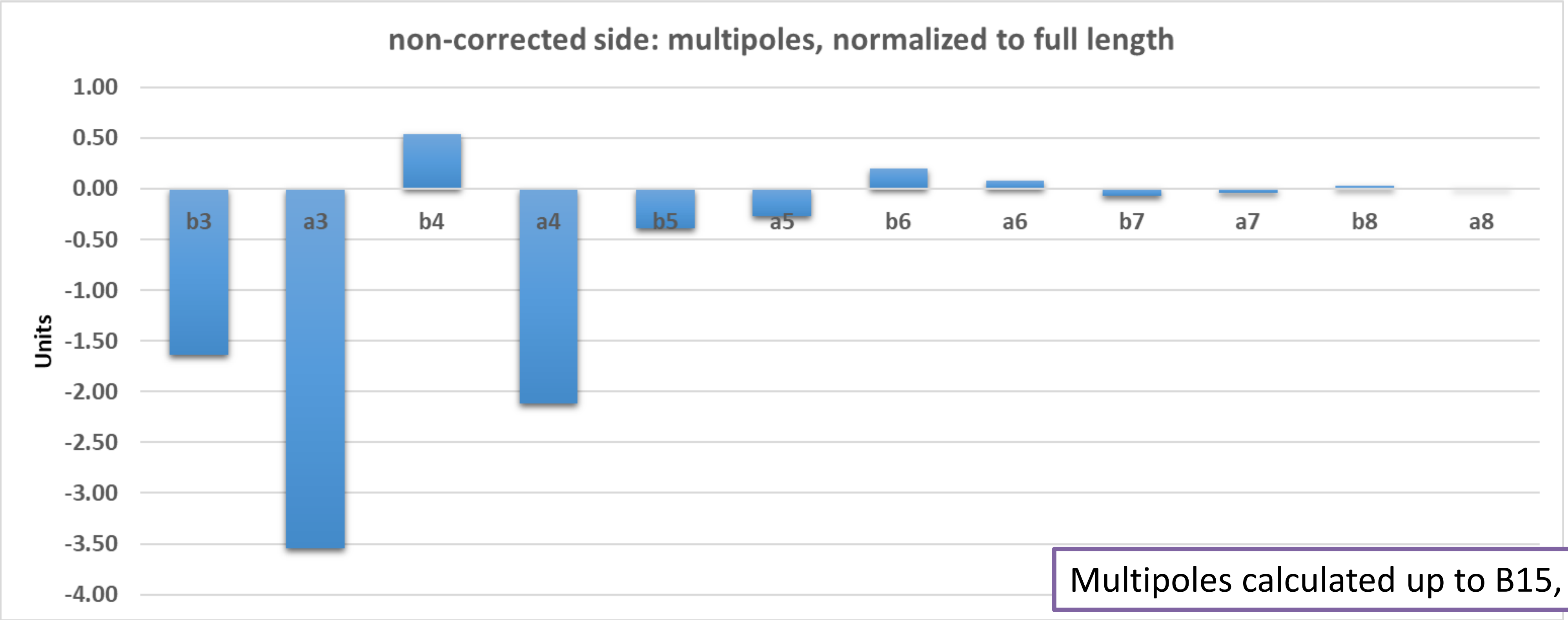
preliminary

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, without correction

@10mm radius

preliminary



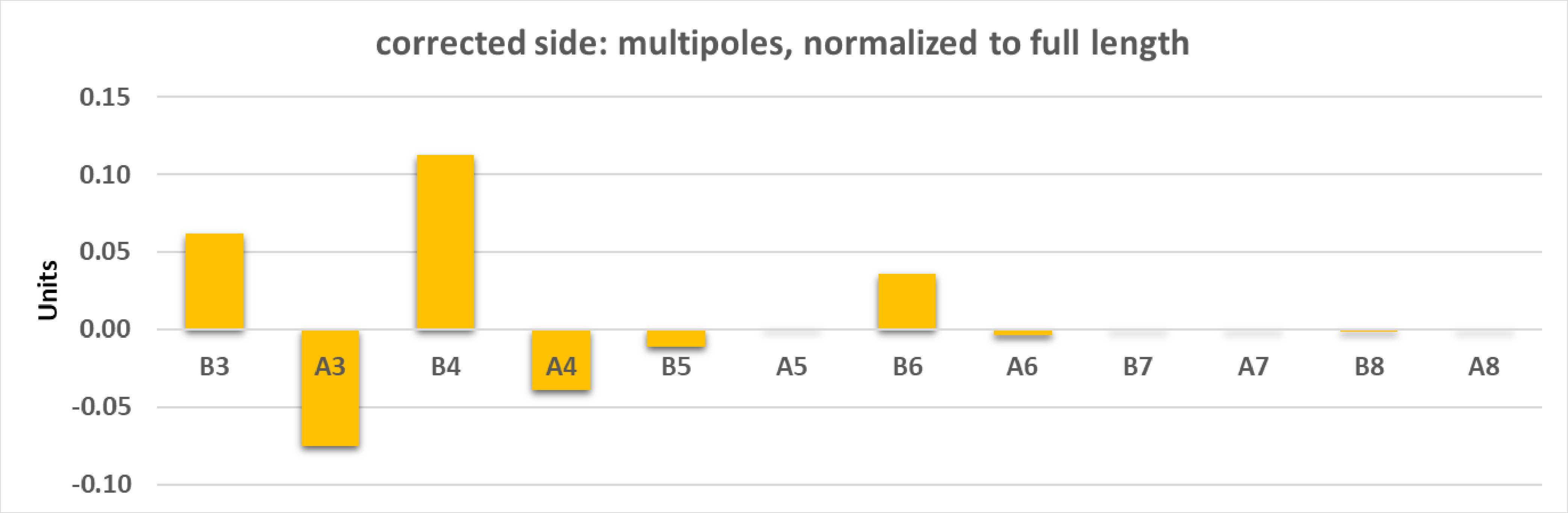
For this measurement we do not have rotated data

Multipoles calculated up to B15, A15, but are all zero

Carlo Petrone

3.5 units in A3, 2 units in A4

Field quality at the edge, with correction



@10mm radius

preliminary

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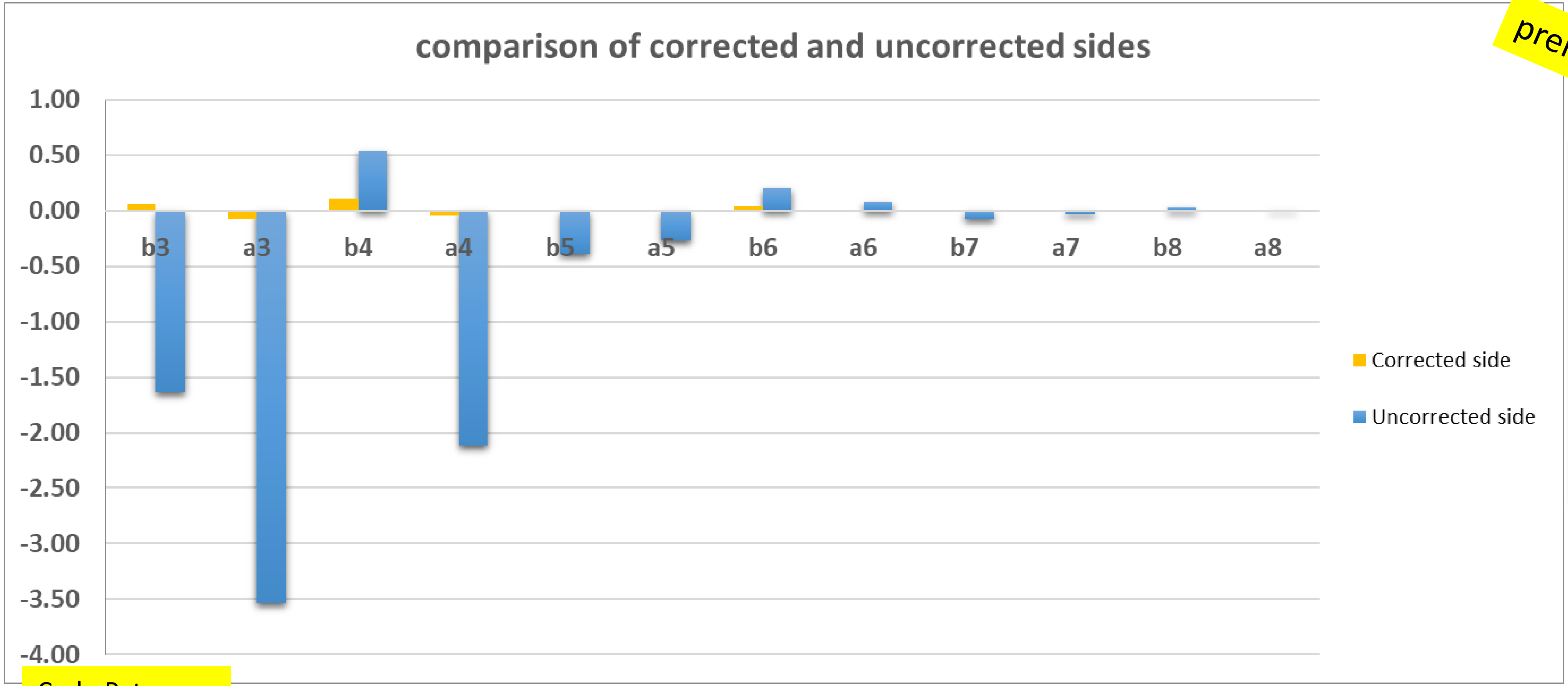
For this measurement we do not have rotated data, real magnet errors might be smaller

0.1 units maximum. An excellent result.

Multipoles calculated up to B15, A15, but are all zero

Field quality at the edge, comparison



preliminary

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!

Conclusions

- The first FCC-ee final focus prototype has been designed, manufactured and the first tests at warm are available (results are preliminary).
- Field quality is excellent.
- All multipoles in the middle of the magnet are 0.15 units or less, approaching the accuracy of the method. These are real measurements, not simulation!
- The novel technique of locally correcting each edge for edge effects is working beautifully → this gives us confidence that the crosstalk compensation will also work.
- All multipoles of the corrected edge contribute 0.1 units or less. ➔ this is a “perfect edge” magnet.
- The CCT technique is very well suited for the final focus quadrupoles of FCC-ee (and also CEPC…).