Final Focus Magnets

FCC November week 2020

4th FCC physics and experiments workshop

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11/11/2020

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This talk

This talk will be split in two parts:

- Part I: The compensation scheme: improved version since the CDR
- Part II: The prototype FF quad first results: test at warm

Part I:
The FCC-ee compensation scheme: consolidation

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Introduction

- Moving towards the TDR, we need to consolidate (update and improve) the compensation scheme as presented in our CDR
- One major challenge is to find an extra 5mm of space for the cryostat. That means that the compensating solenoid needs to be made 5% smaller…
- …increasing the emittance blow-up…
- So, I then tried to re-optimise to gain what was lost (or even a bit more)

Many thanks to Katsunobu for patiently helping me in my debugging sessions, for checking my results and providing valuable feedback

Role of compensation

- According to our CDR, the role of the compensation scheme is to satisfy (amongst others) the following conditions:
  1. Total integral of Bdl seen by the beam should be close to zero (*)
  2. Field in the vicinity of QC1L1 < ±50mT (**)
  3. Emittance blow up should be as small as possible

(*) tunable by changing the current of the compensating solenoid: I stop iterations if better than 10^{-3} Tm. CDR states that emittance blows up by 0.1pm for a 10^{-3} Tm mismatch in compensation

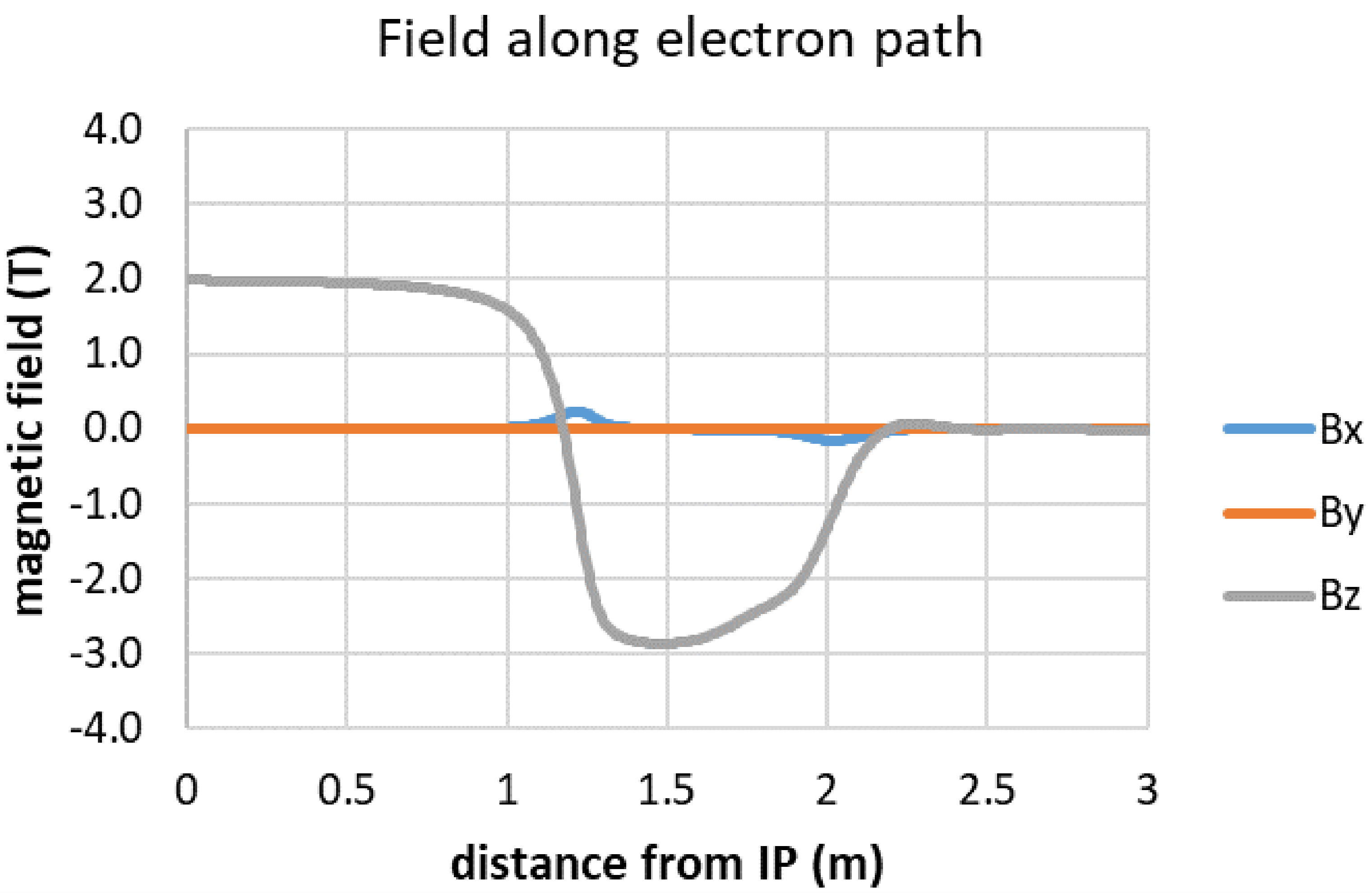
(**) this is not investigated at depth. Could be too stringent

Emittance blow-up only important for the Z running

Improvements over CDR

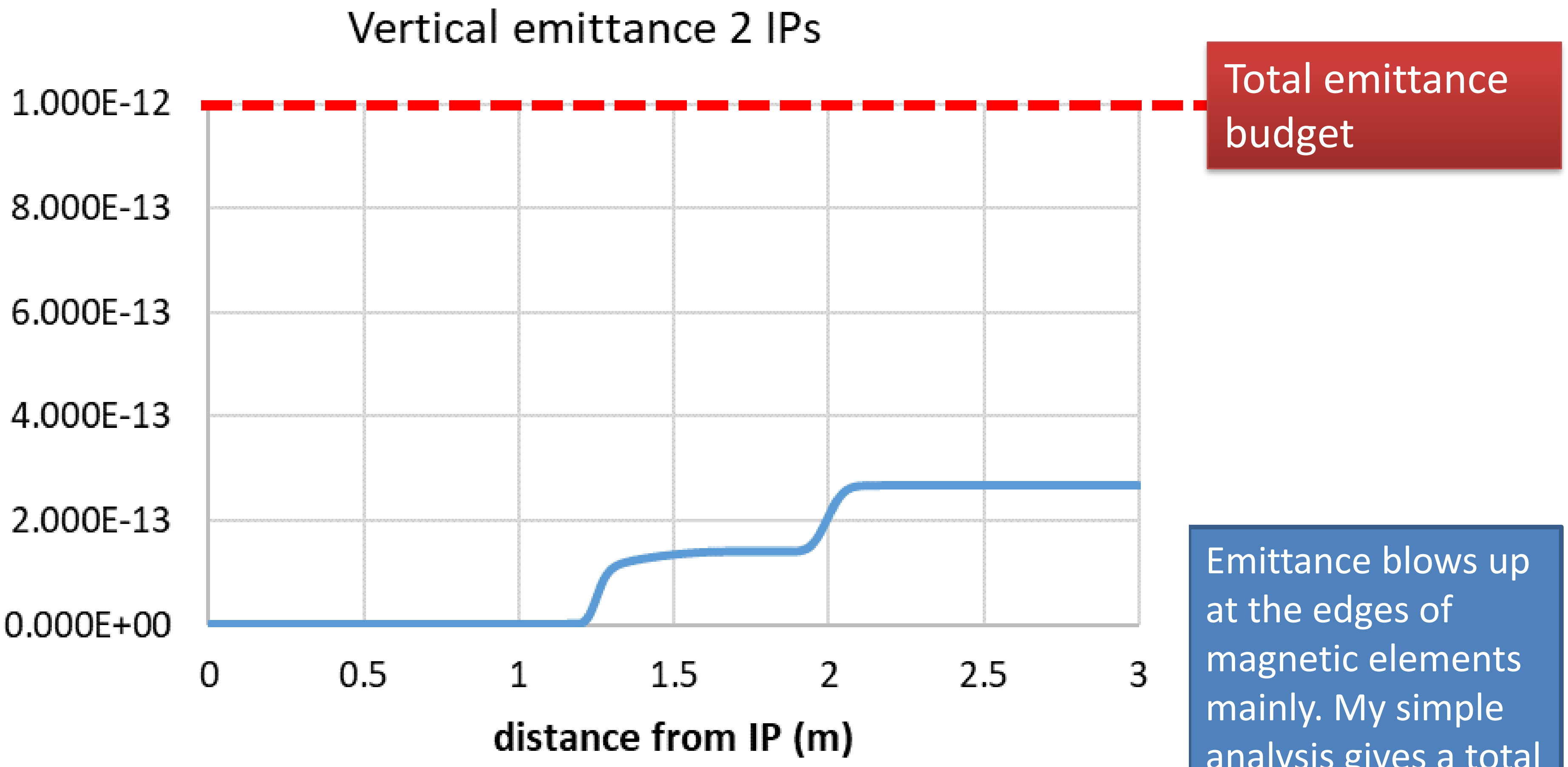
- The outer radius of the coils has been reduced so as to leave 5mm for the cryostat
- the compensating solenoid starts 5mm further downstream
- The screening solenoid and compensating solenoid are 5mm apart
- Now both coils have variable pitch ➔ great for optimising
- The exact shape of the coil is now exported directly from the magnet optimization program. Before, the coil was a cylindrical envelope.
- Reminder: CDR number for the emittance blow-up for 2IPs at the Z: **0.4pm**

Field profile



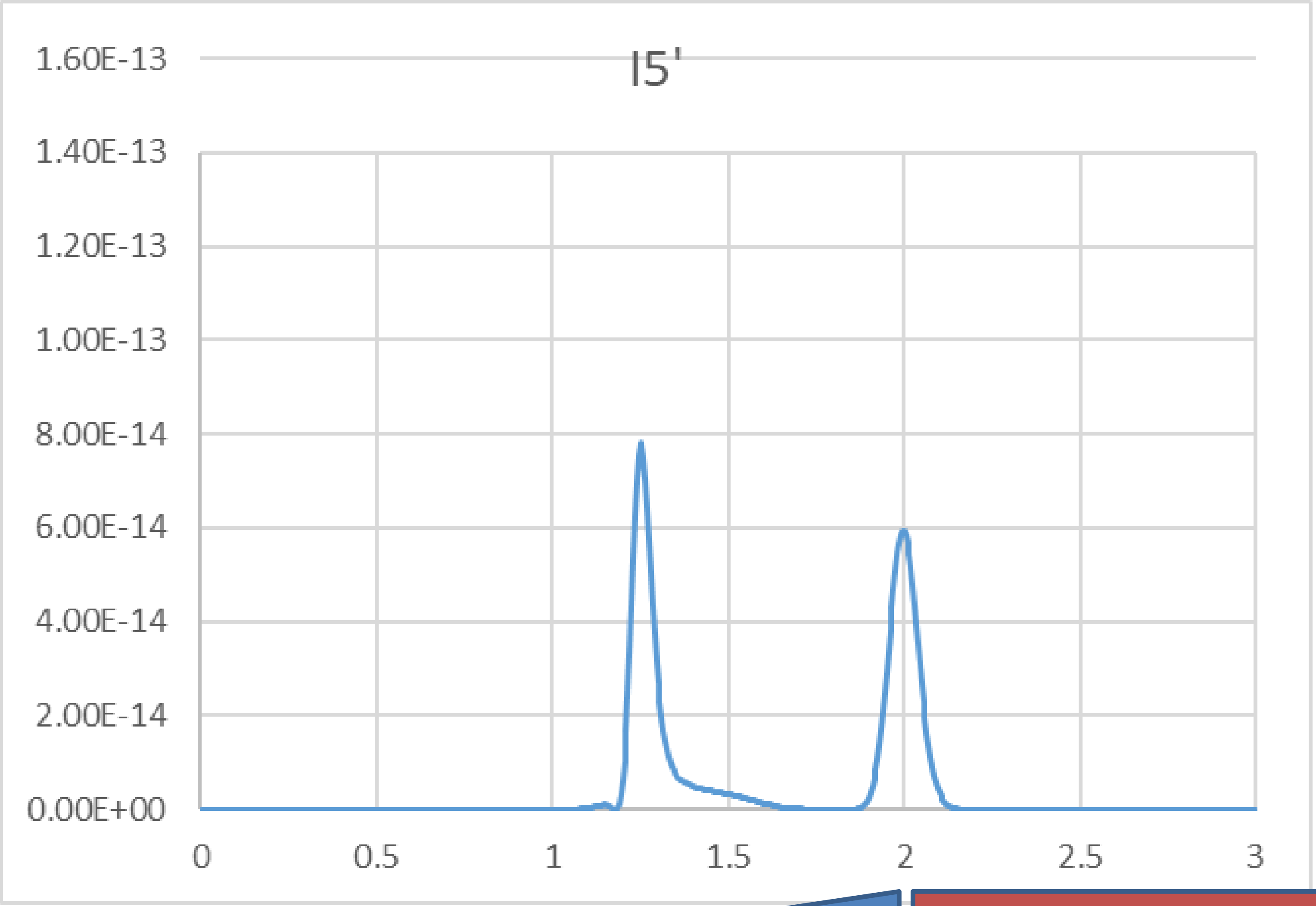
Note that I have concentrated in the region ± 3m from the IP. The zero field region actually extends to ±5m, but I do not have the return yoke design. For this analysis it is safe to assume that the field after ± 3 m is zero.

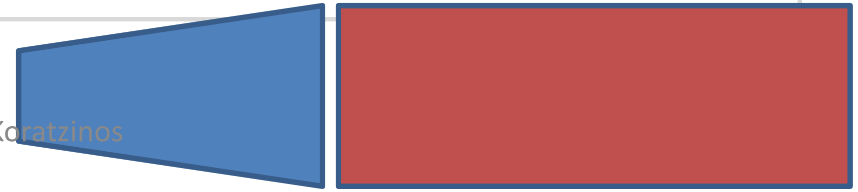
Vertical emittance blow up at the Z



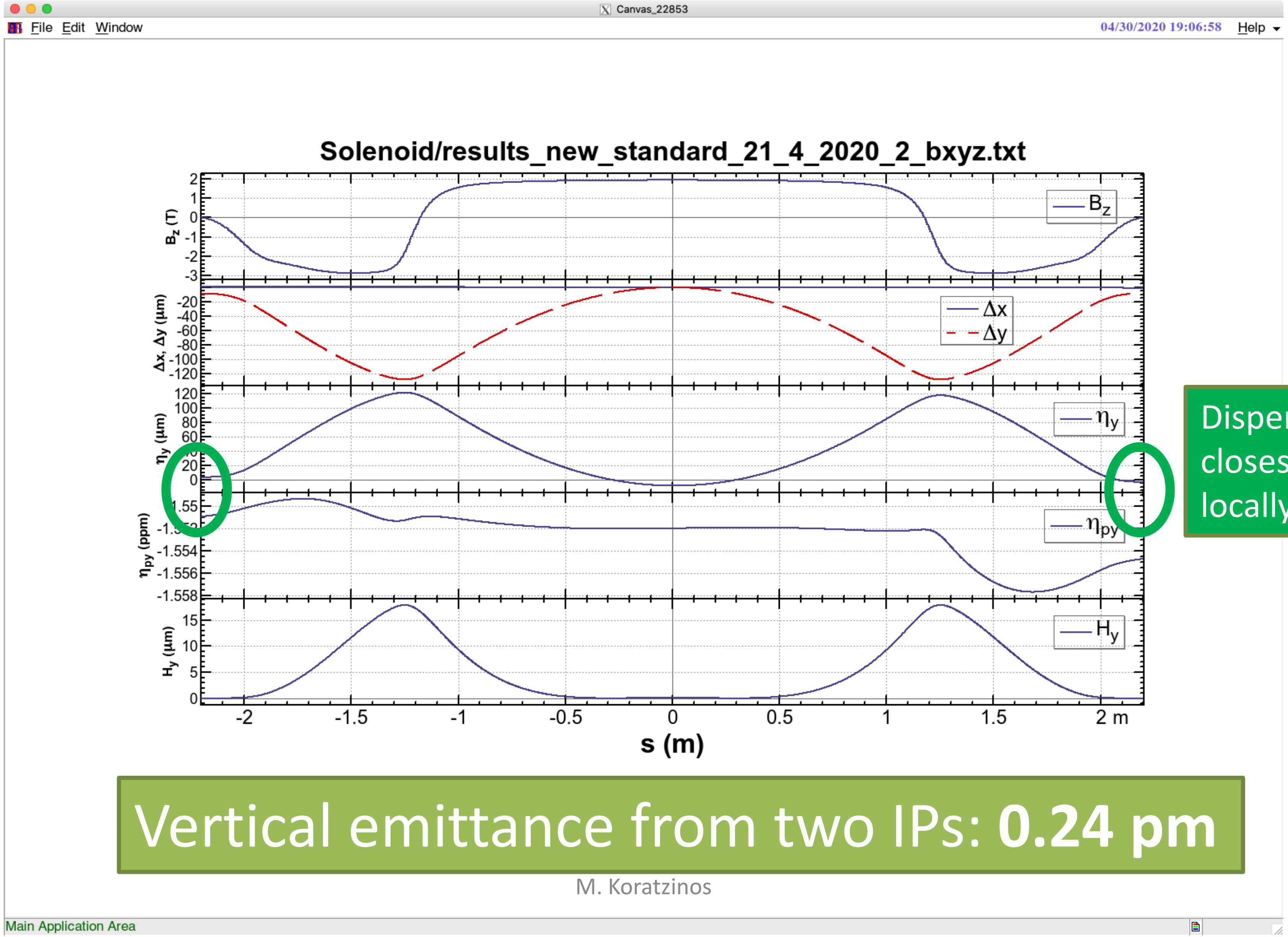
Emittance blows up at the edges of magnetic elements mainly. My simple analysis gives a total of **0.27 pm** for 2 IPs

where emittance grows





SAD results



Dispersion closes locally

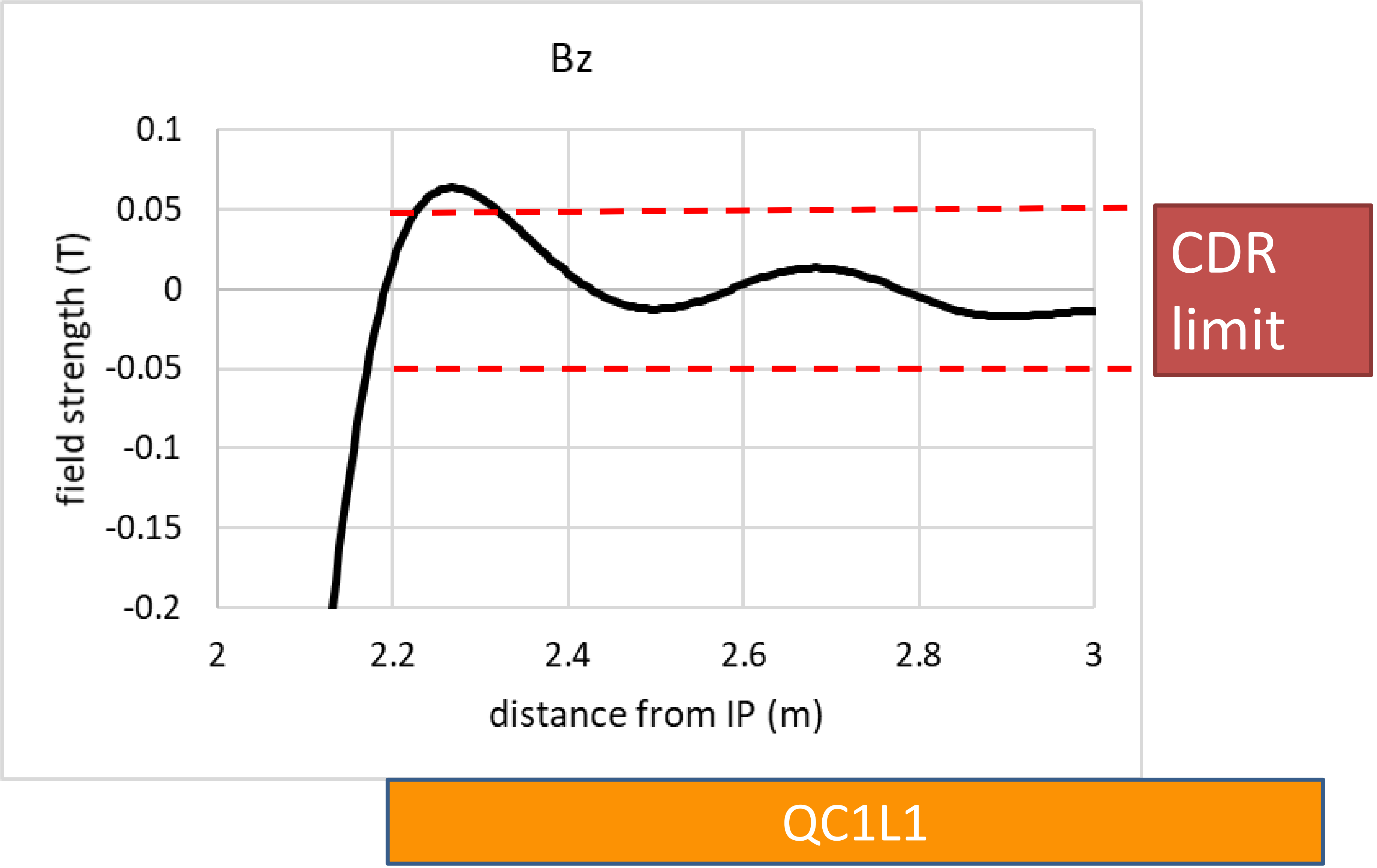
Vertical emittance from two IPs: **0.24 pm**

M. Koratzinos

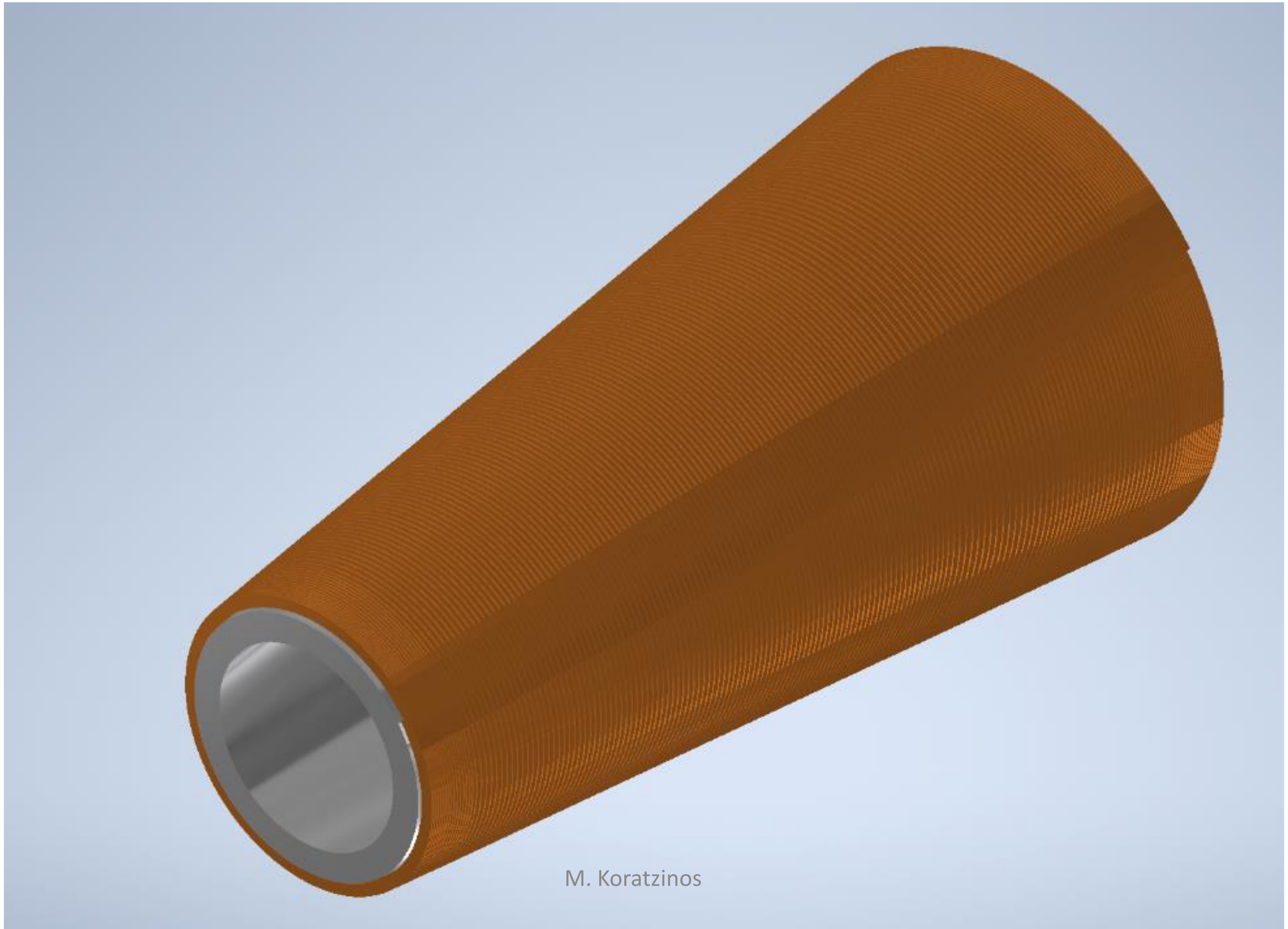
A note on dispersion leak

- Our initial CDR conditions are insufficient to ensure that no dispersion leaks out
- We need the extra condition that $\int B_x ds = 0$ on top of the condition of $\int B_z ds = 0$.
- Since I have two degrees of freedom (the current in the compensation solenoid and the current in the screening solenoid) I can actually make both integrals arbitrary close to zero in principle (I have not mathematically proven this!)
- In practice, I have managed a $\int B_x ds = (few) \times 10^{-5}$ and $\int B_z ds = (few) \times 10^{-3}$ (which is easy to improve further if needed)

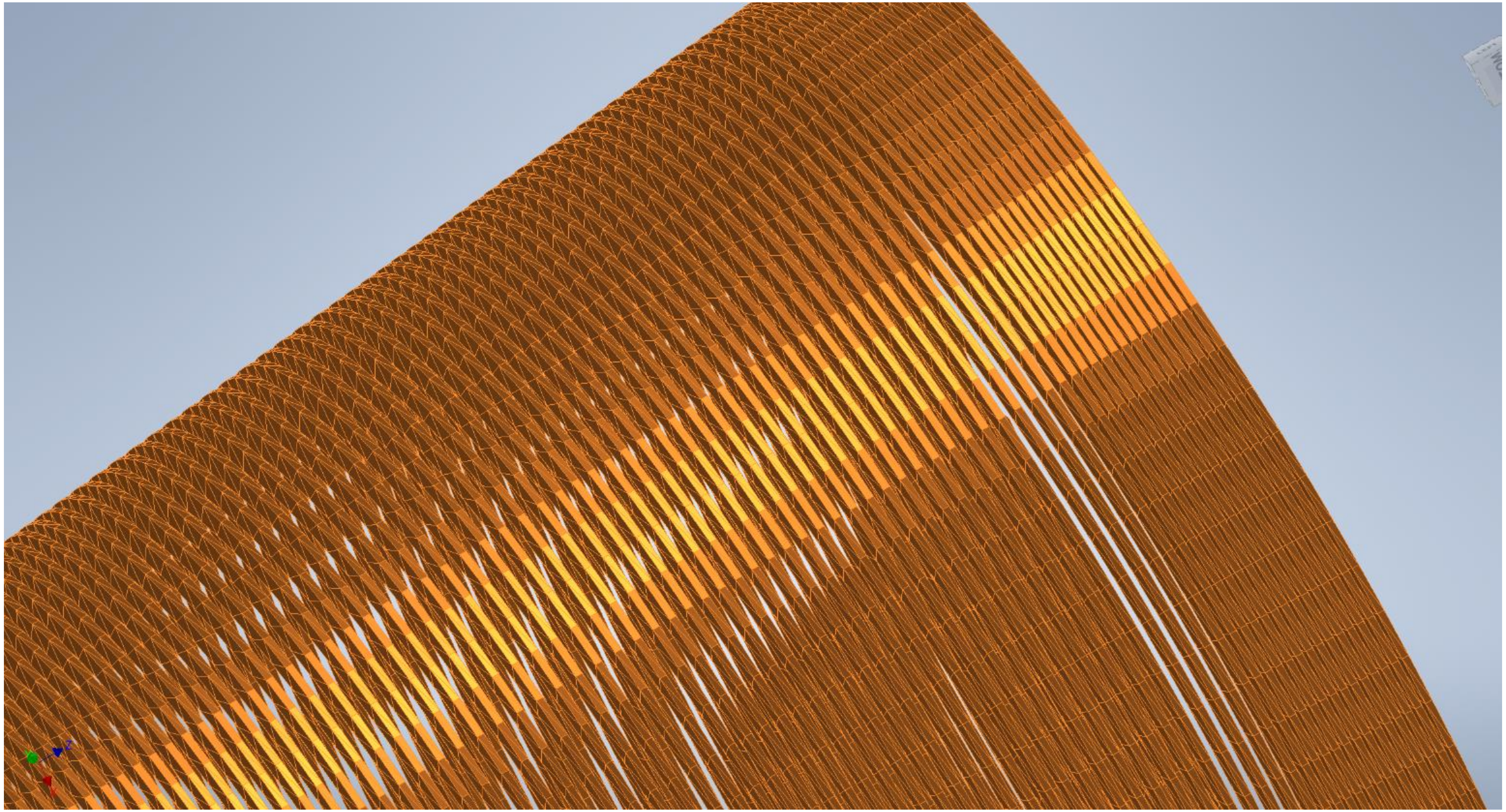
Field in the vicinity of QC1L1



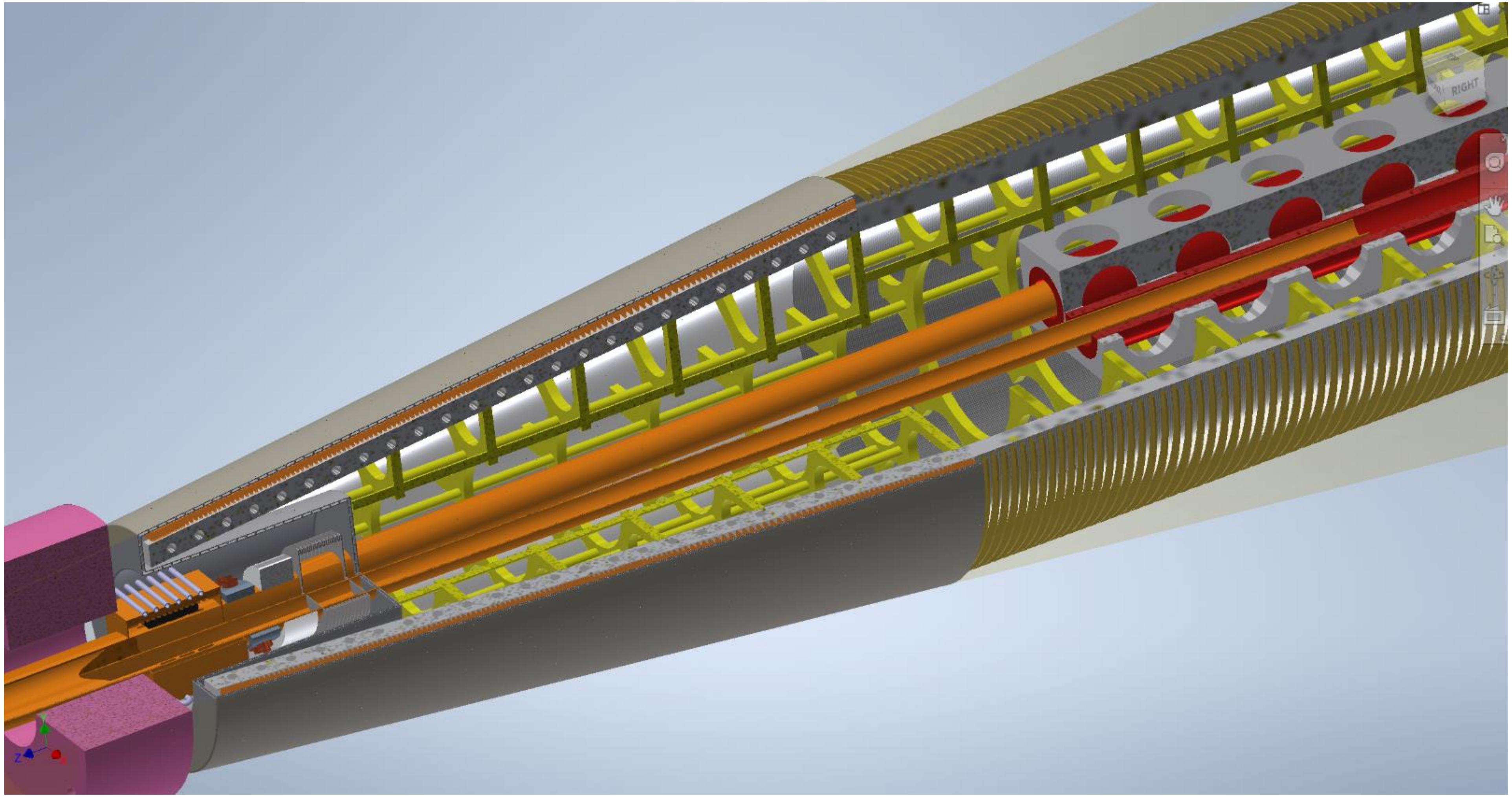
Export to CAD – compensating solenoid wire



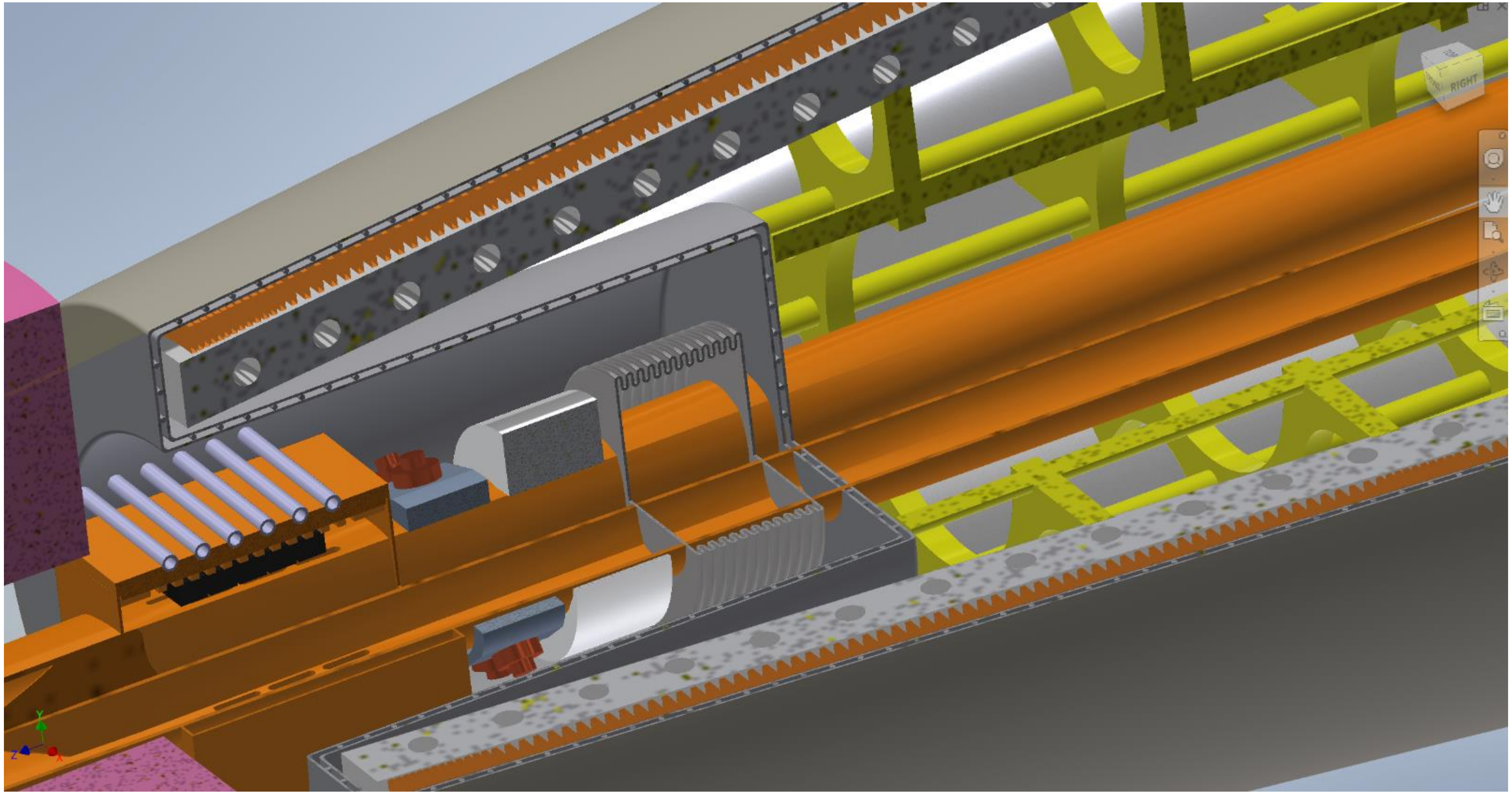
Individual wire is exported



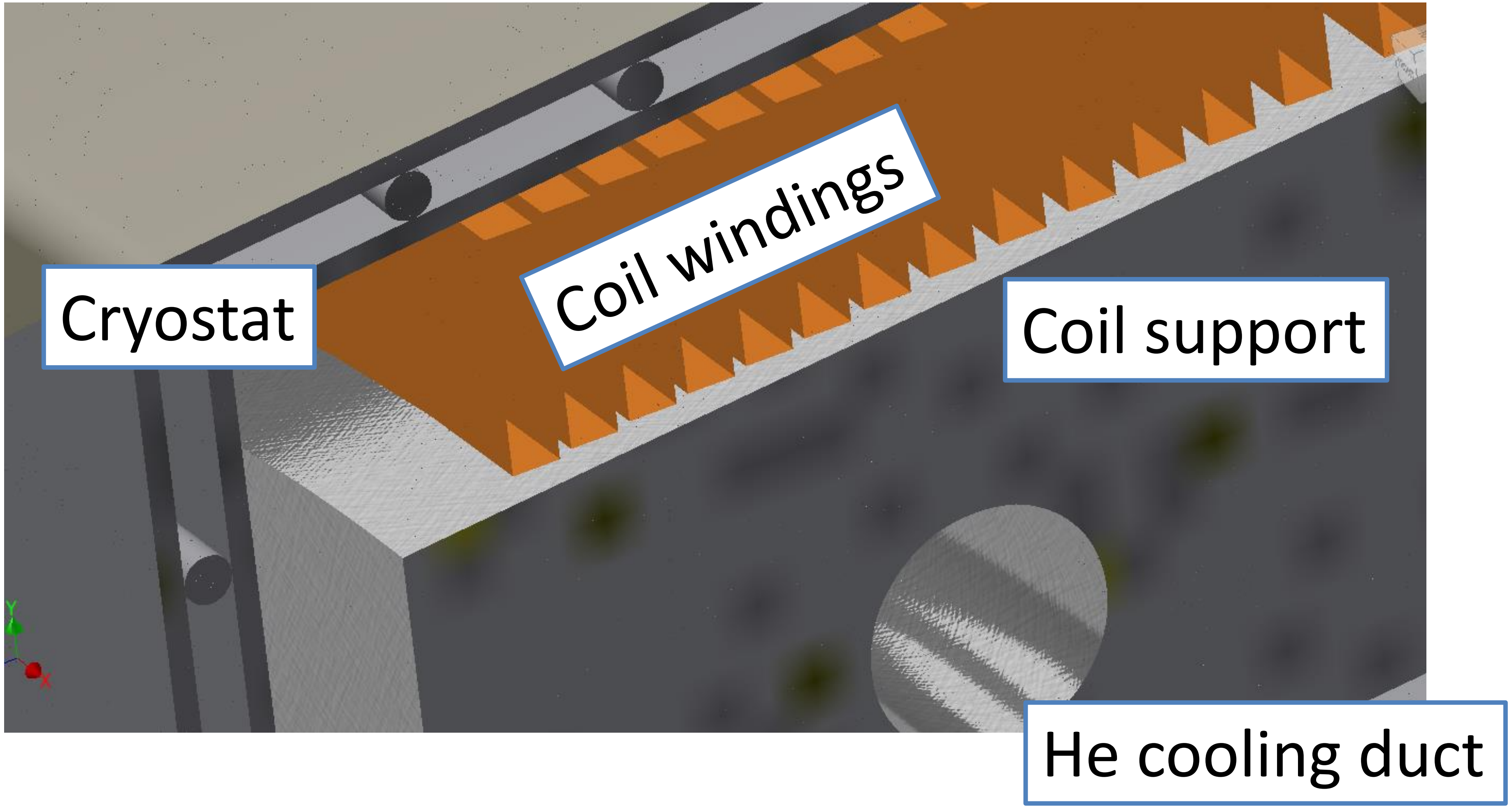
The full assembly



Front of the compensating solenoid



Front of the compensating solenoid



Summary - compensation

- The FCC-ee compensation scheme is an elegant two-element solution with a compensating solenoid and a screening solenoid.
- A new optimization of the compensation scheme has been performed
- Now everything fits inside the 100mrad cone, including the cryostat
- Emittance blow up from two IPs according to the optics analysis: **0.24pm** at the Z (compared to 0.4pm quoted in our CDR) therefore, ** this will not be a bottleneck if we need to go to 4IPs! **
- Realistic representation of the solenoids, down to the individual cable
- This is a complex analysis, I probably could not have done it if not for COVID19…

Part II: FCC-ee prototype FF quad Mk I: test at warm

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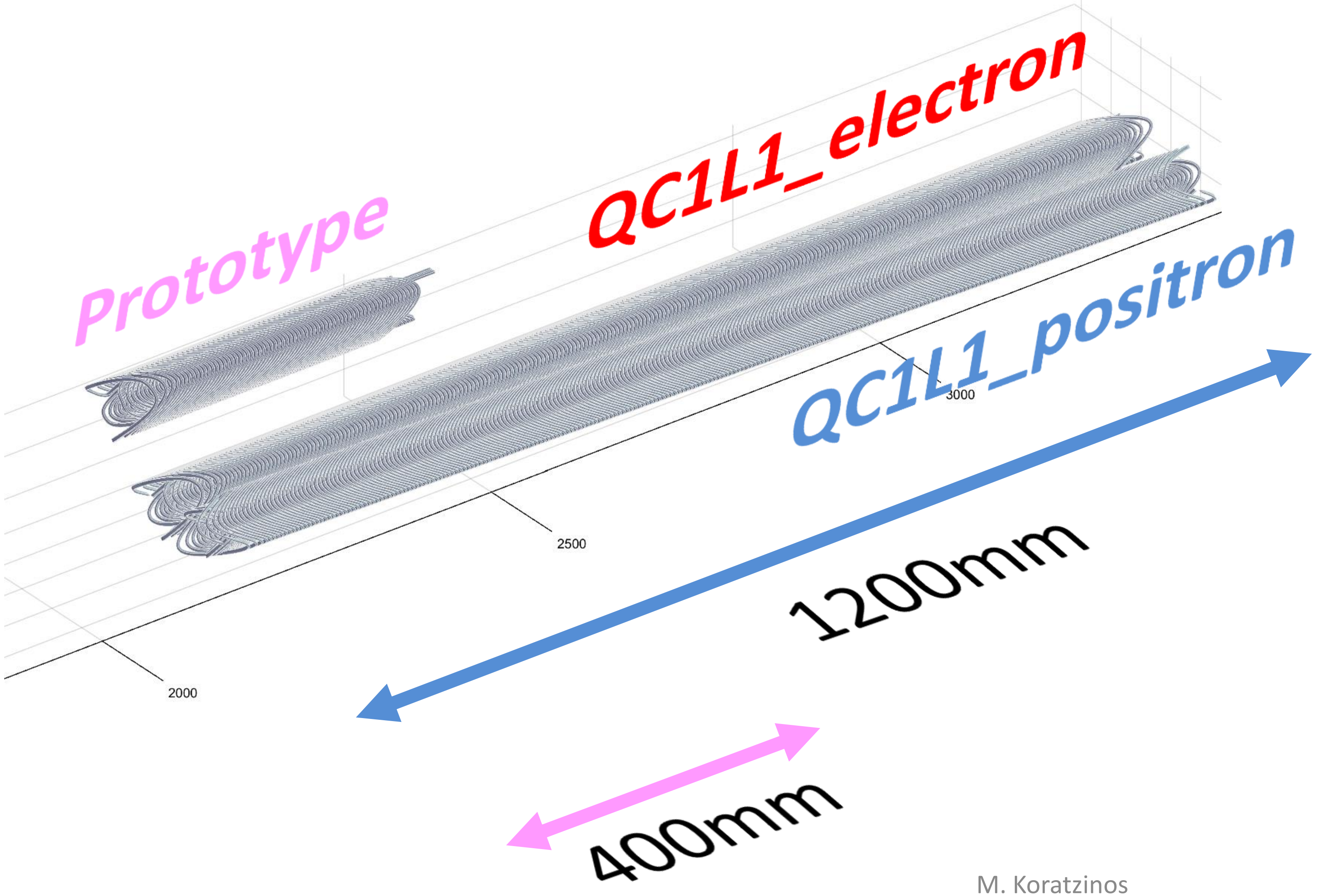
Acknowledgements

- 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

QC1L1 and the prototype



FCC-ee has opted for the CCT technique for the final focus quads with no iron and with compensation

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

The first FCC-ee Final Focus prototype is a single-aperture version of QC1L1, with identical aperture but one-third of the length.

Features of the prototype

- It has the same aperture as QC1L1 (40 mm)
- It has asymmetric edges: one edge with no intervention the other edge using a novel idea for edge correction (https://ieeexplore.ieee.org/document/8292834)
- What we hope to learn:
  - Field quality for the bulk of the magnet (not the edges)
  - Field quality of the unmodified edge
  - Field quality of the modified edge
  - Performance at cold (max. gradient, quench performance, etc.)
- If the modified edge works as expected, we are on a good path to apply compensation due to the close proximity of the two magnets

Previous episodes

- The prototype has already gone through the following stages:
  - Magnetic design using the Field program, including the "perfect edge" correction "***A Method for Greatly Reduced Edge Effects and Crosstalk in CCT Magnets***": https://ieeexplore.ieee.org/document/8292834
  - Mechanical design in Autodesk Inventor
  - Manufacturing in the CERN main workshops
  - Assembly and winding in B180
  - **Warn testing in B311** ← this episode

Programme of testing and future

- Warm tests (started 6/11/2020) **All results are preliminary**
- Cold tests (to be scheduled)
- Next steps:
  - Second prototype with lessons learned – still single aperture
  - Third prototype which will be double aperture.

Testing arrangement

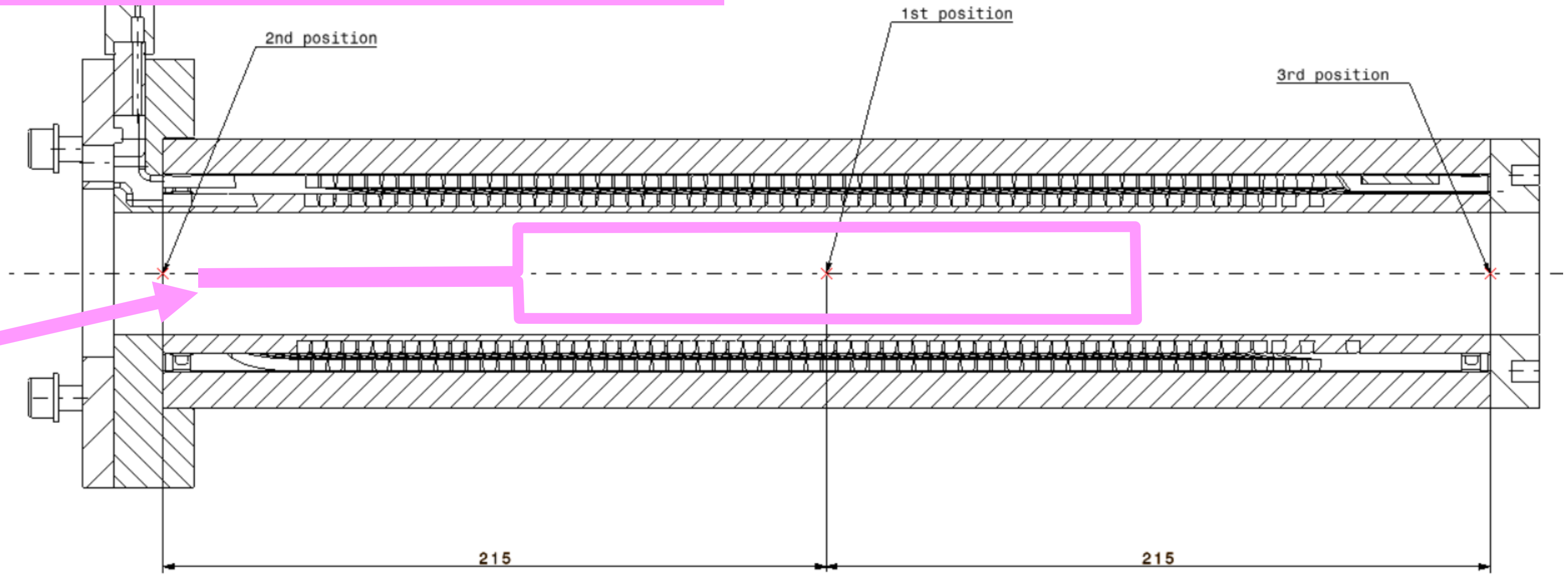
Rotating coil measurement:

- The flux as the coil rotates is measured. Then the data is post-processed to calculate the first 15 multipoles.
- Each measurement is the average over 100 turns
- Then current is reversed and another measurement taken

All measurements at 2/3rds aperture: since our beam pipe is 15mm radius, the measurements are made at 10mm radius
Rotating coil length: ~200mm; current: 5A

1st measurement: Centre

Rotating probe



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

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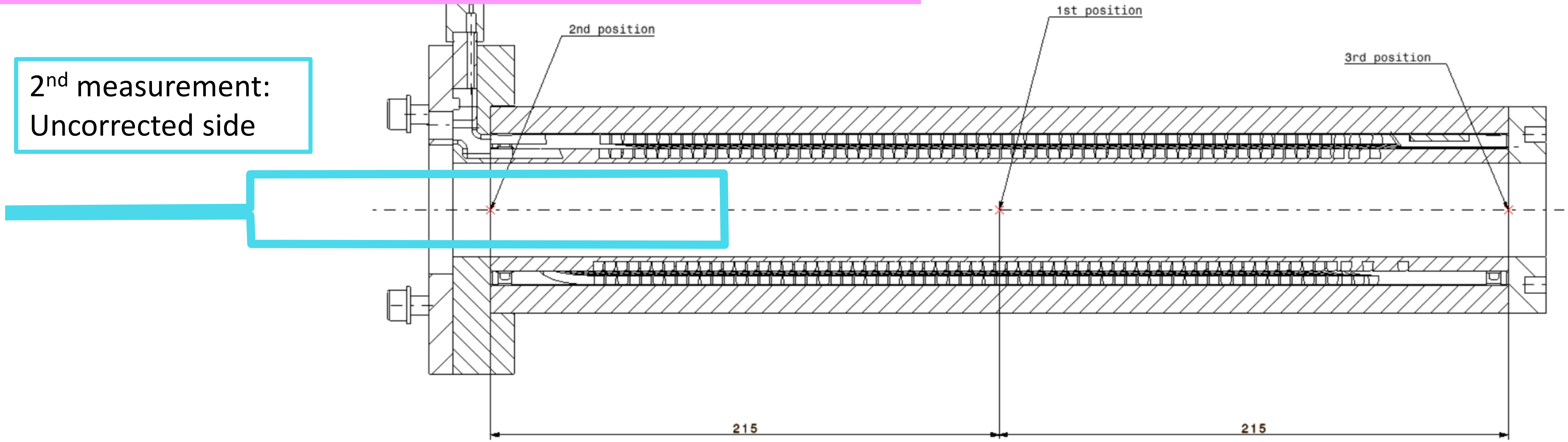
2nd measurement:
Uncorrected side



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

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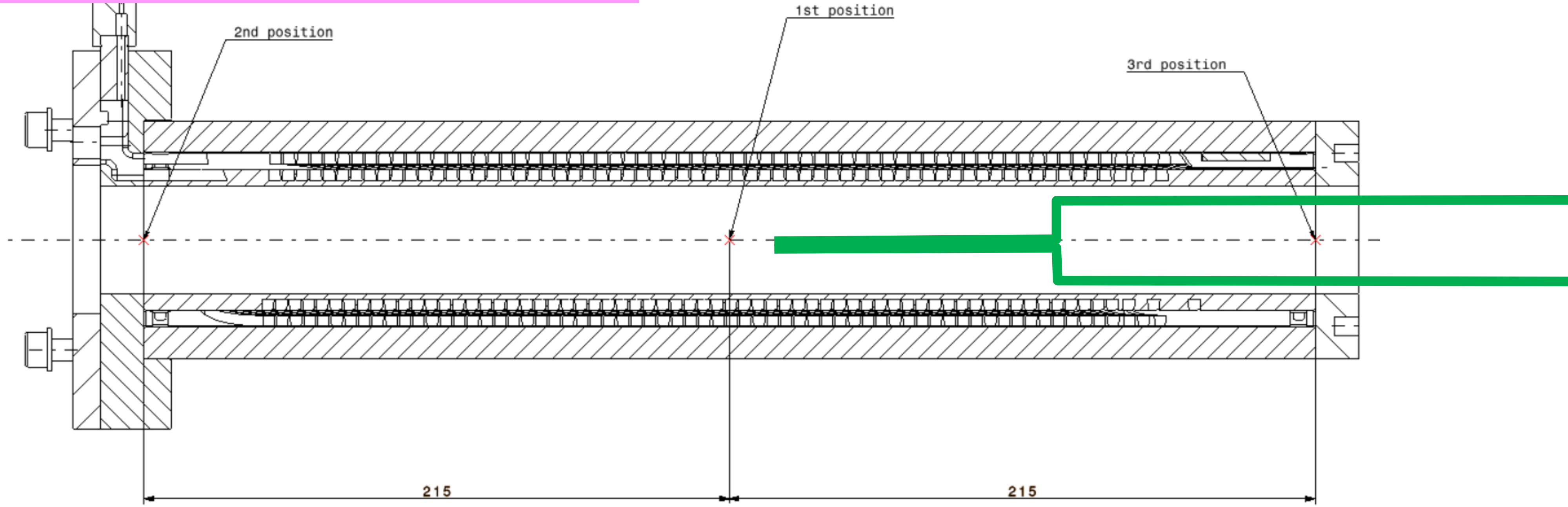
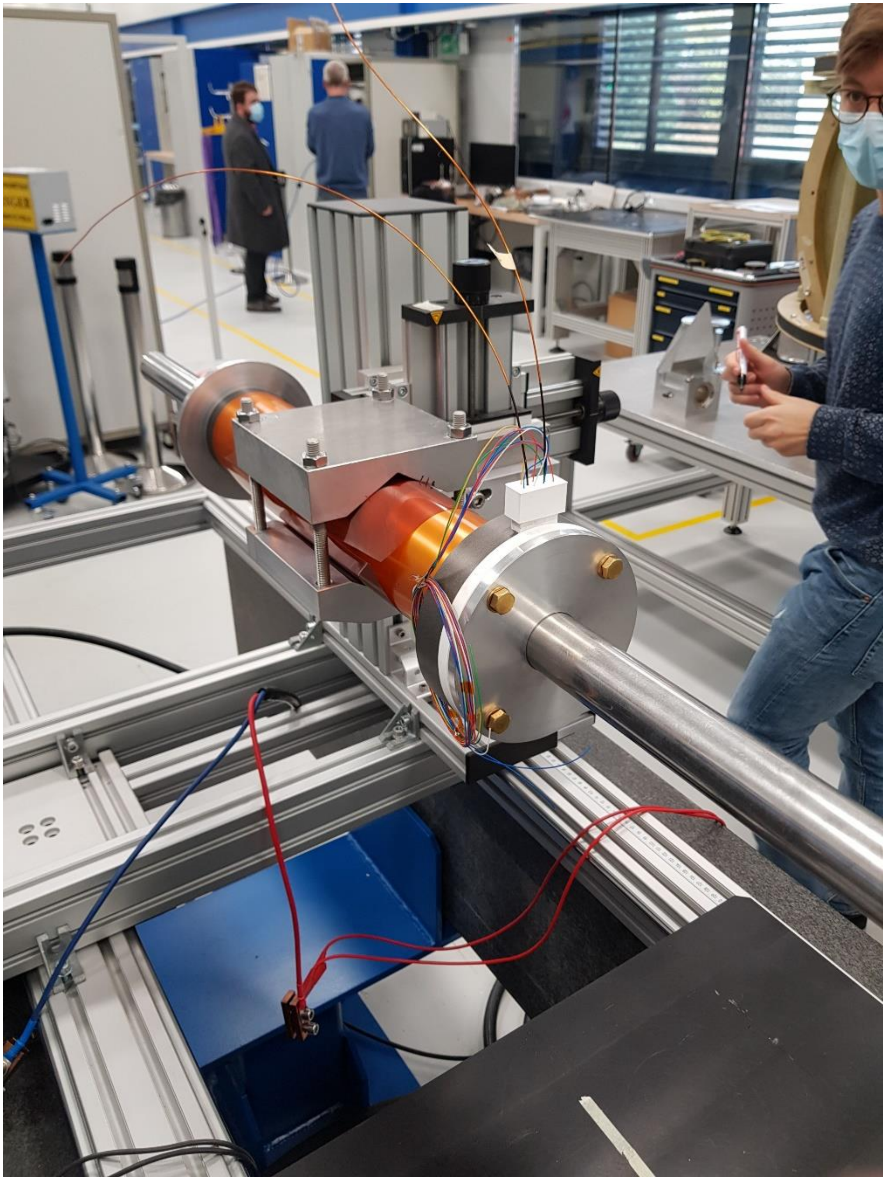
3rd measurement:
Corrected side



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

Measurement setup in b311



FCC-ee FF quad prototype warm test

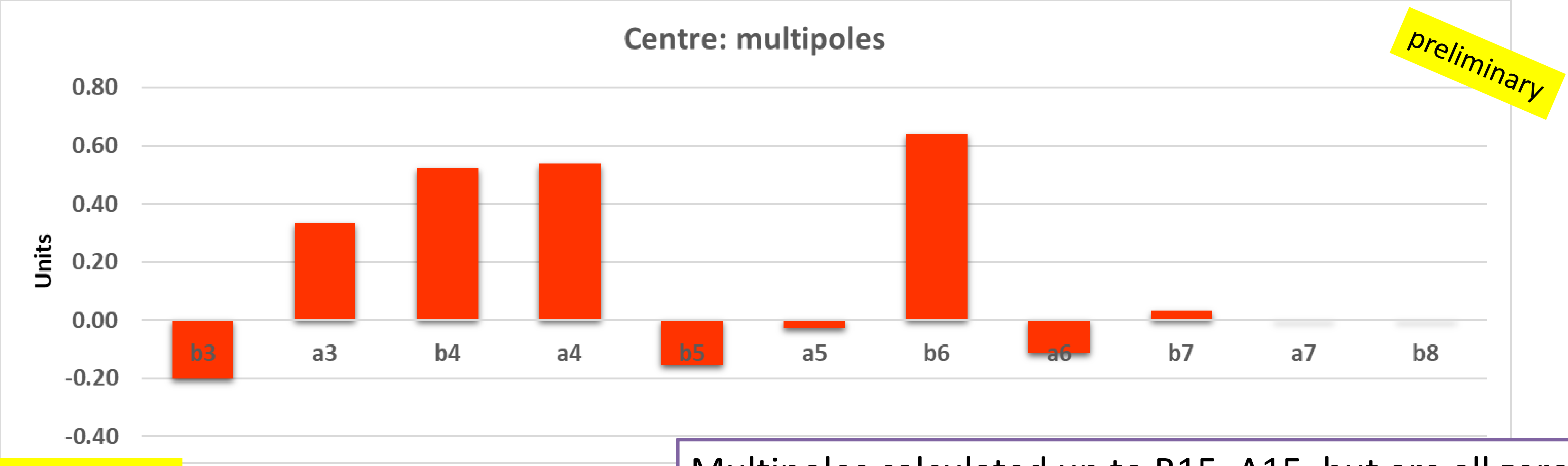
Magnet in place on the testing jig

The team: Thank you

Measurement video

Field quality at the centre of the magnet

@10mm radius

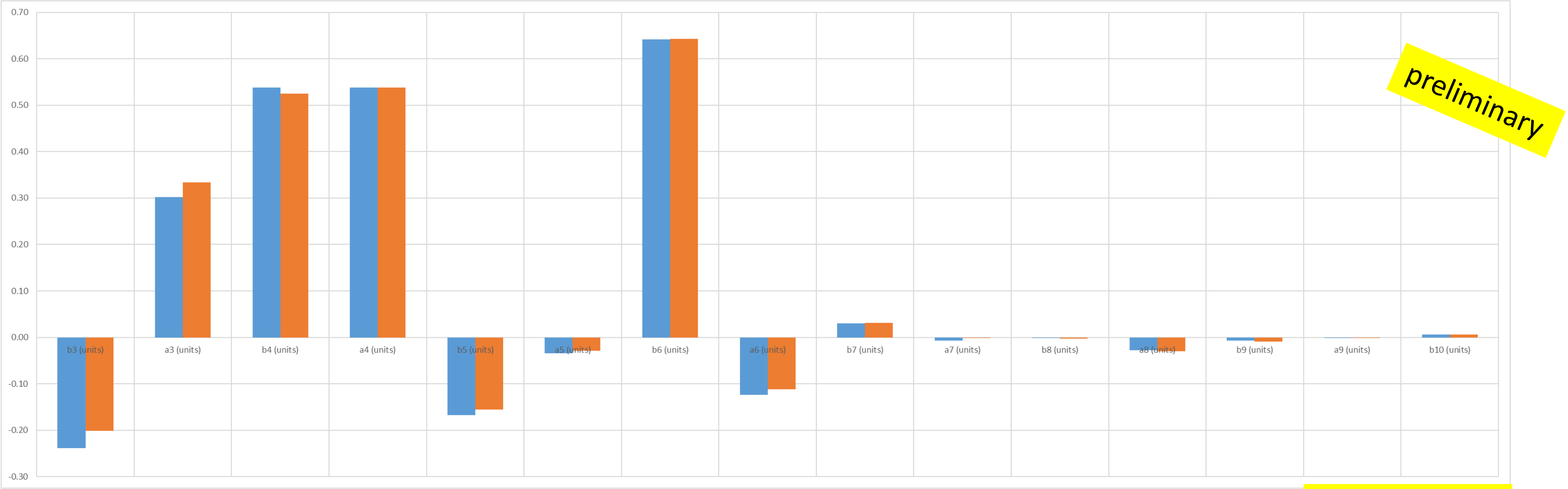


Carlo Petrone

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

About 0.5 units deviation. Note, that this can be corrected if needed using the same technique discussed later for correcting edge effects.

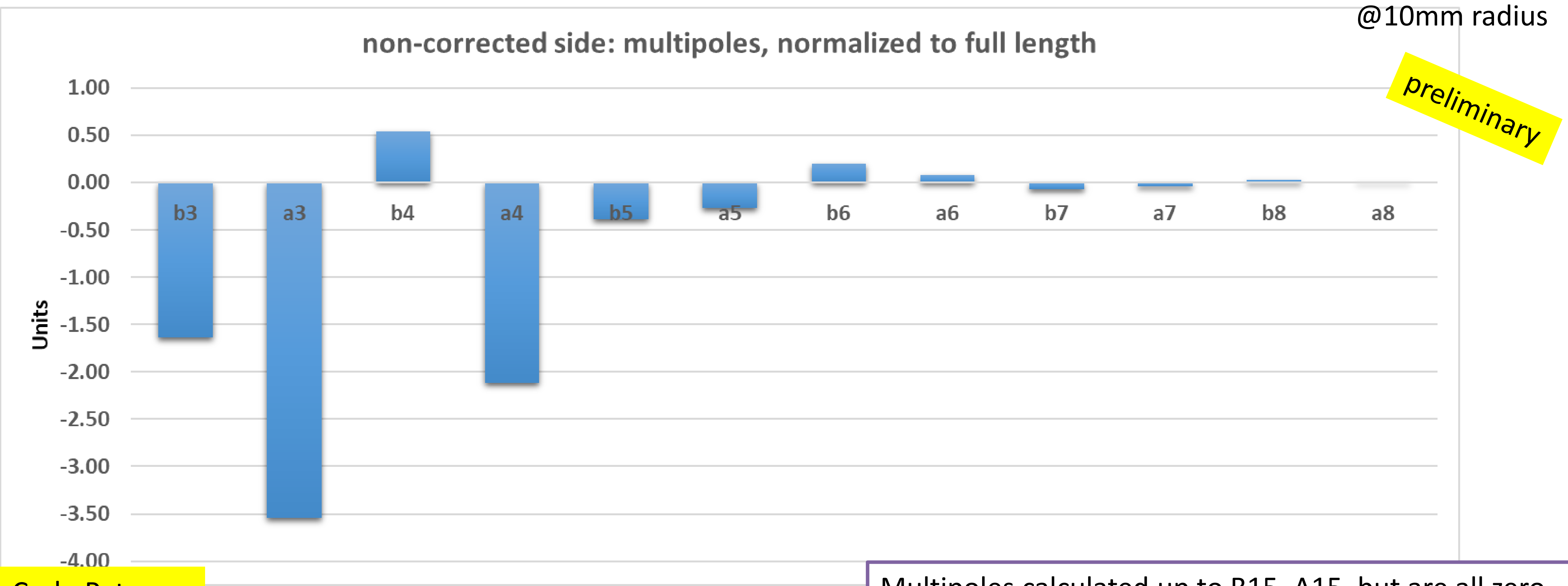
Repeatability of measurements



Carlo Petrone

The plot shows two successive measurements. Repeatability is excellent, within 0.04 units or better

Field quality at the edge, without correction

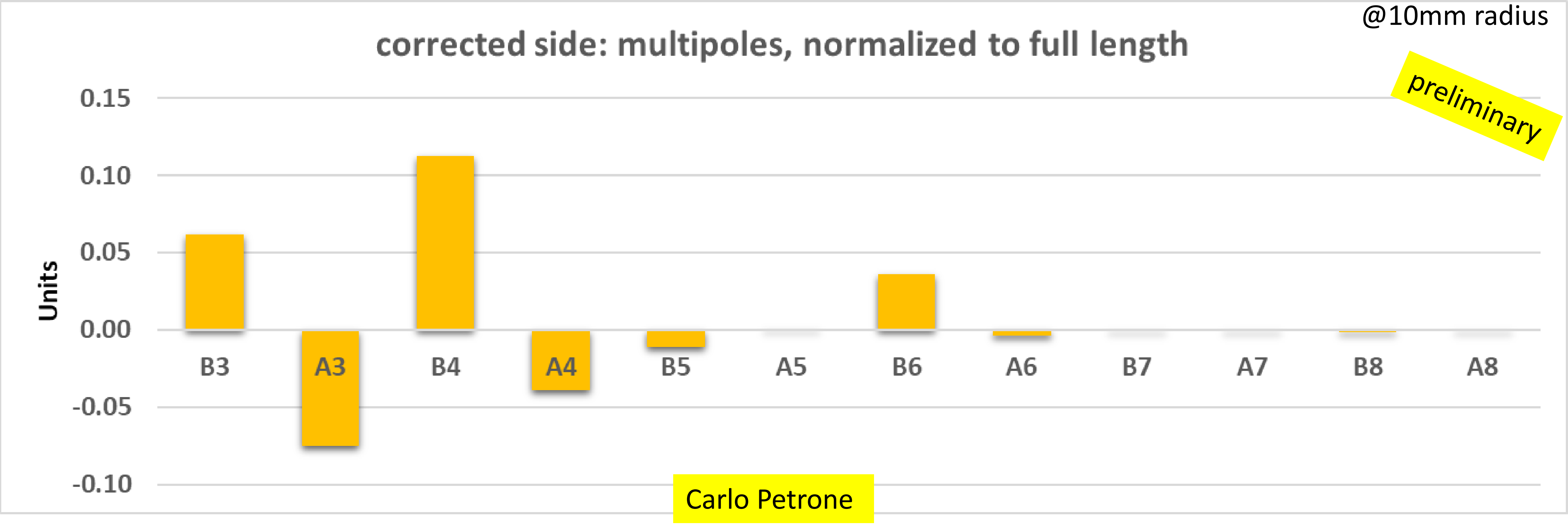


Carlo Petrone

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

3.5 units in A3, 2 units in A4, 1.5 units in B3… pretty good, but we can do better!

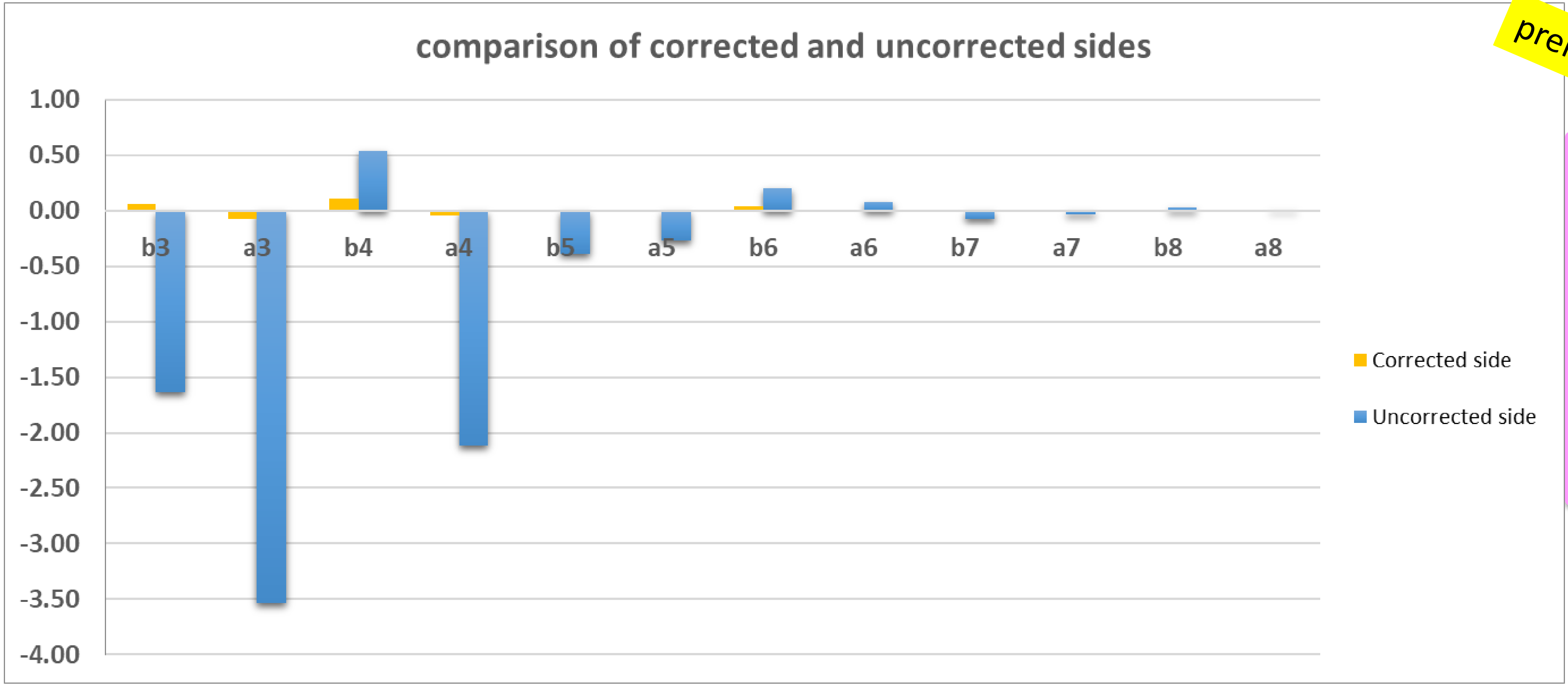
Field quality at the edge, with correction



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

0.1 units maximum. An excellent result.

Field quality at the edge, comparison



preliminary

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)

Carlo Petrone

Conclusions – warm test of FF prototype

- 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 0.6 units or less. And this is something that can be corrected, if needed.
- The novel technique of locally correcting each edge for edge effects is working beautifully
- All multipoles of the corrected edge contribute 0.1 units or less. ➔ this is a "perfect edge" magnet
- Looking forward to the rest of the tests and for prototype no 2, 3, etc.