FCC-ee interaction region concepts

M. Koratzinos, C. Ormond

FCC week

02/06/2022

Introduction

- We do have (and we are happy with) a conceptual design for all elements of the interaction region
- We are now proceeding to a more detailed engineering design
- We need to make sure no important detail is overlooked
- The following is an ad-hoc mixture of established facts and "my vision" on how I see engineering solutions
- All engineering drawings I will show here exist in our CAD design area

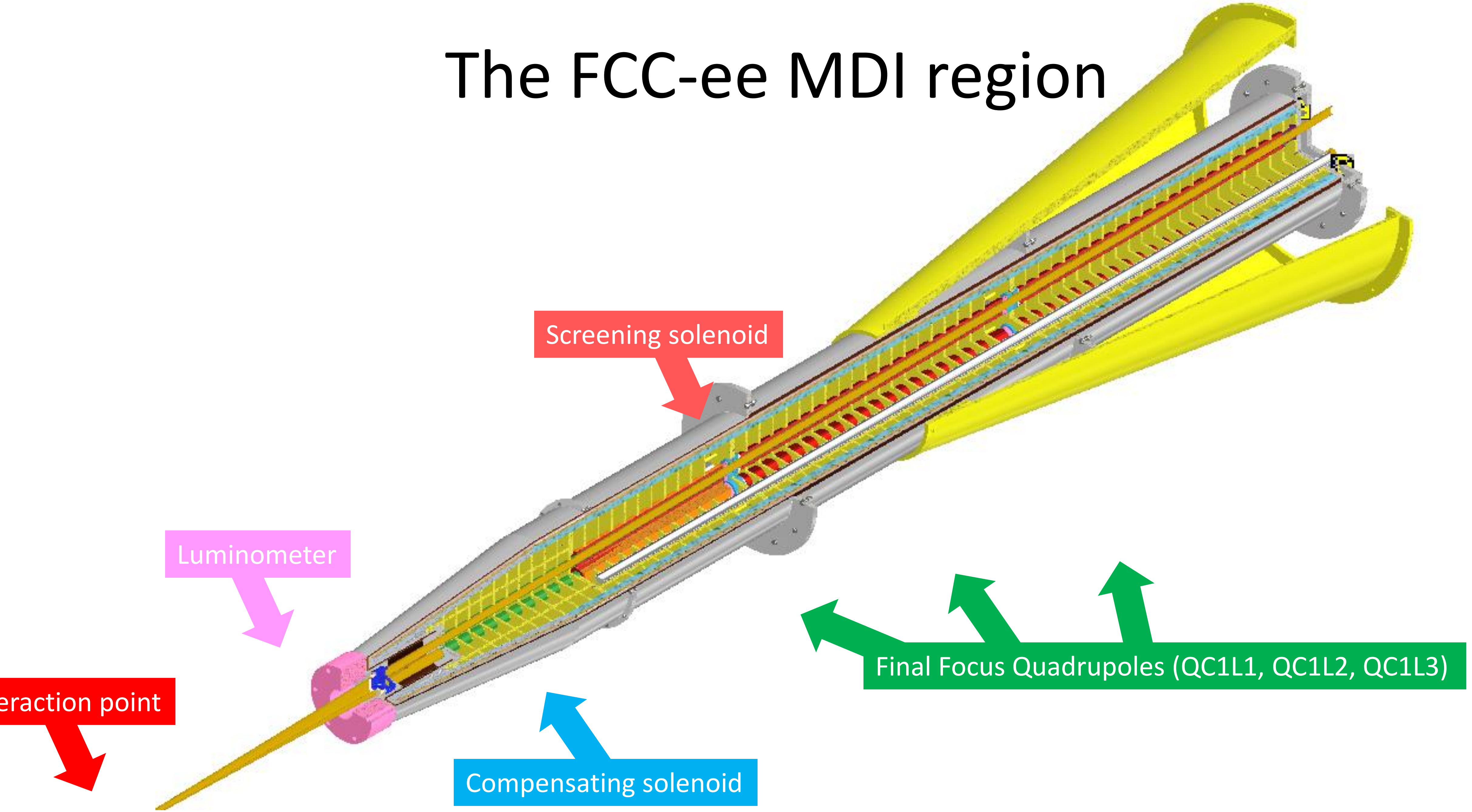
The systems

- Final focus quadrupoles: QC1L1, QC1L2, QC1L3
- Final focus correctors
- Beam instrumentation (BPMs)
- Compensation scheme solenoids (shielding solenoid, compensation solenoid)
- (Luminometer) – will not talk about it today
- Cryostat
- The mechanical structure
- Beam pipe
- Alignment system
- Assembly scheme

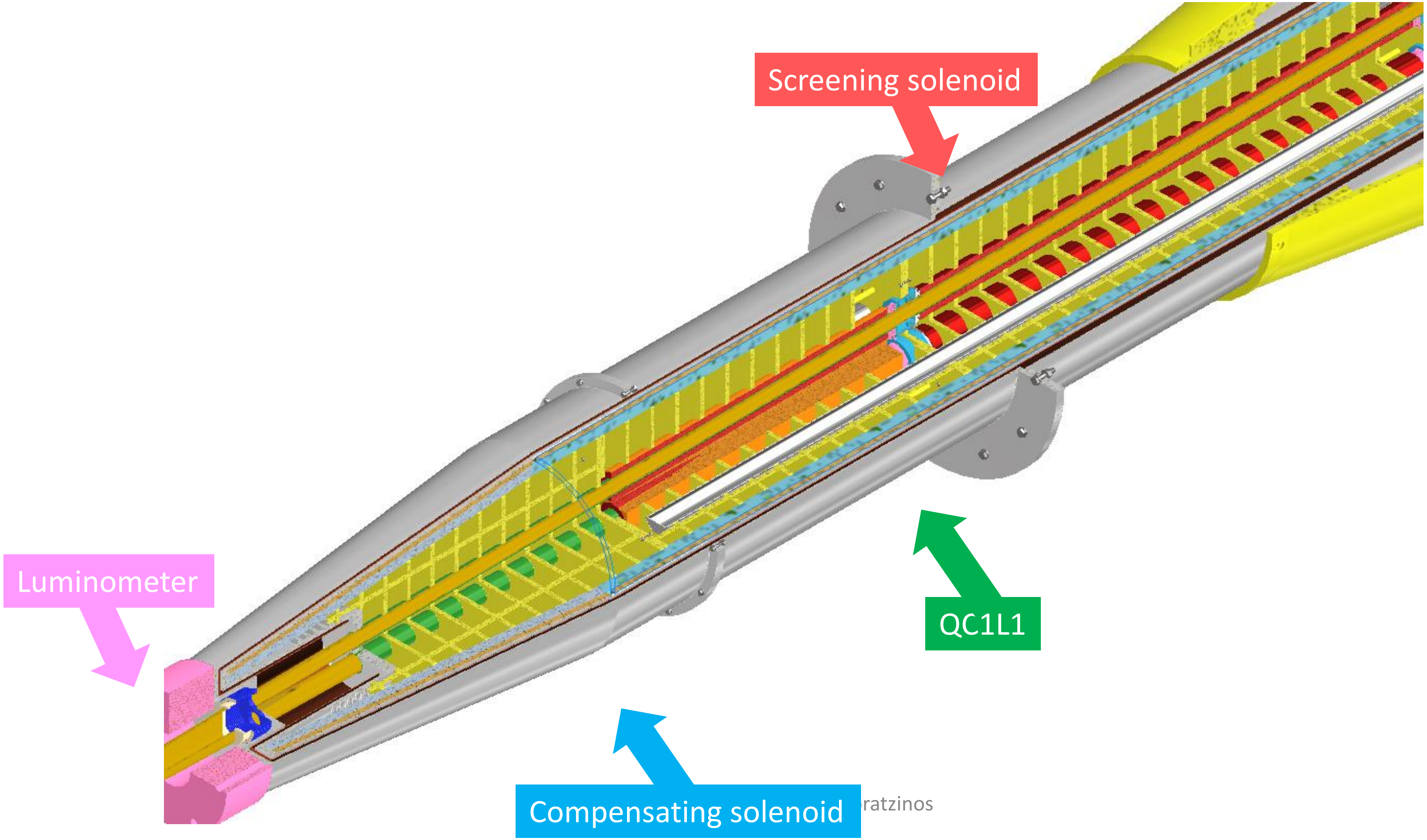
Overview of conceptual design

- Cantilevered, 4.3m long
- Connected rigidly on one side (away from the IP)
- Some mechanical coupling also close to the center of gravity
- QC1 magnets 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
- There is an extra, thin, Helium vessel (welded together)
- Thin and non-structural cryostat for insulation vacuum

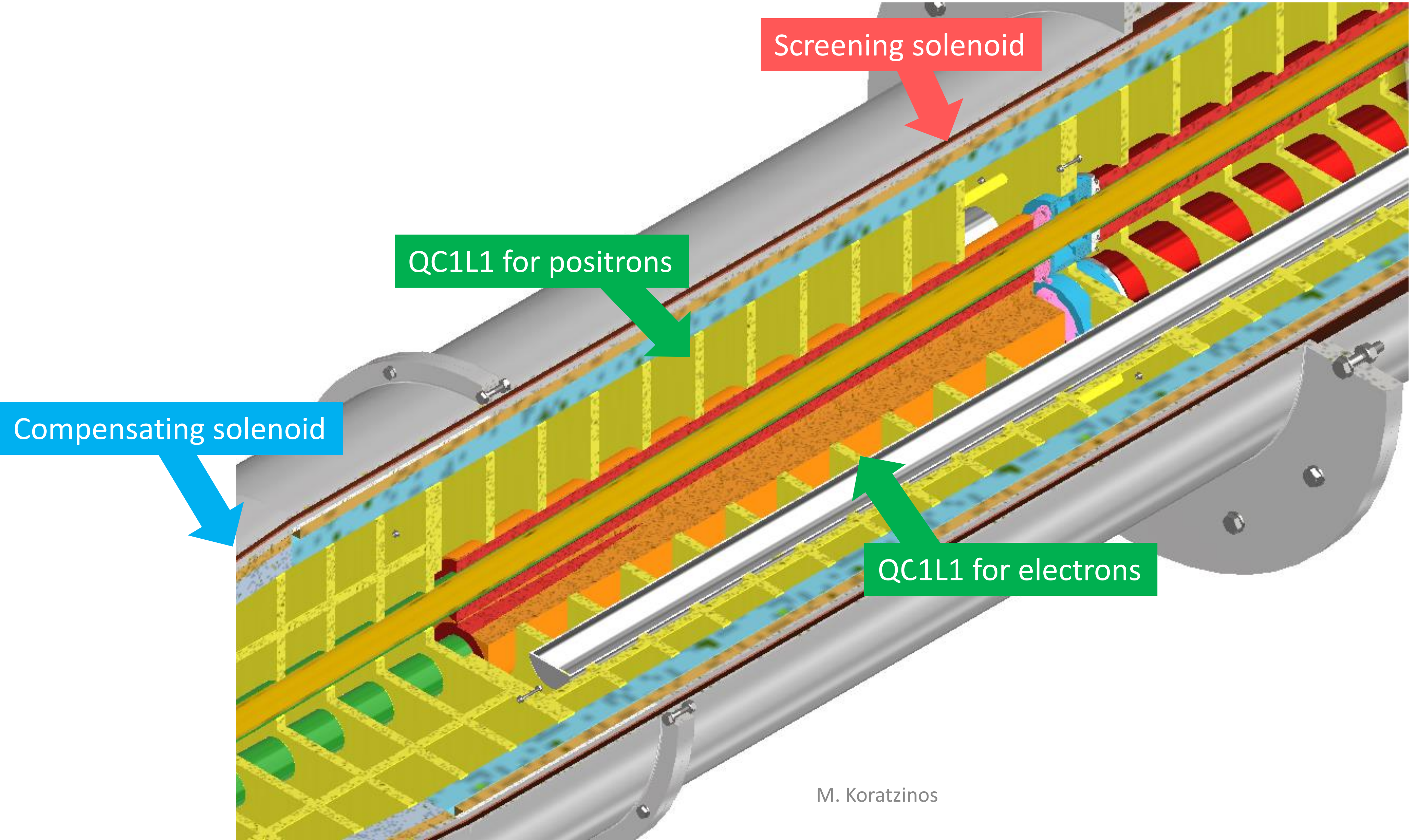
The FCC-ee MDI region



The FCC-ee MDI region



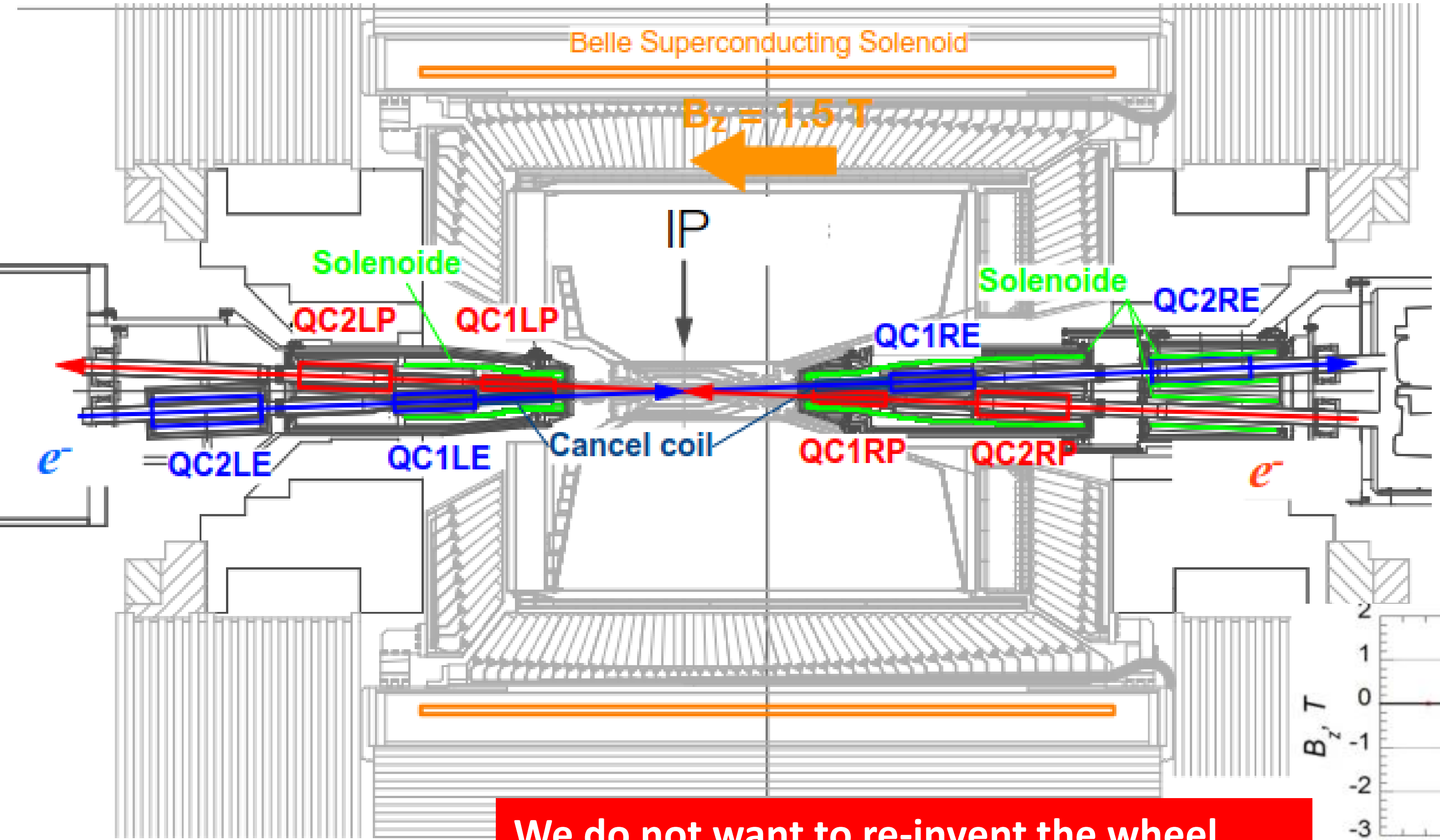
The FCC-ee MDI region



MAGNETIC ELEMENT DESIGN

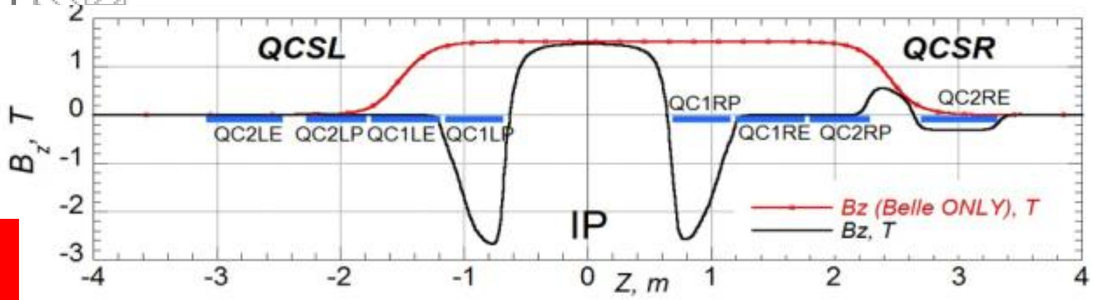
Prior art

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



We do not want to re-invent the wheel, but can we simplify / improve?

Note that first FF quad sits in a high magnetic field

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 considerably
- 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

FCC-ee: six requirements at the IP related to magnet design

1. Adequate space for the detectors: magnetic elements reach angles of up to 100 mrad. The luminosity counter sits unobstructed in front of all magnetic elements.
2. In order to minimise emittance blow-up due to coupling between transverse planes, the integrated field $\int B_z ds$ seen by the electrons crossing the IP should be zero. Compensation off by 0.1% results in a vertical emittance blow-up of 0.1 pm per IP – the effect is quadratic.
3. The integral $\int B_x ds$ should also be zero, so that any vertical dispersion would not leak to the rest of the ring.
4. Vertical emittance blow-up due to unavoidable fringe fields in the vicinity of the IP should be smaller than the nominal emittance budget of 1pm. Problem worse at the Z.
5. The final focus quadrupoles should reside in a zero-field region to avoid transverse beam coupling; $\int B_z ds$ in the vicinity of final focus quads should be much less than 3×10^{-2} Tm.
6. The field quality of the FF quadrupoles should be better than 1×10^{-4} for all multipoles.

Design considerations to satisfy all requirements

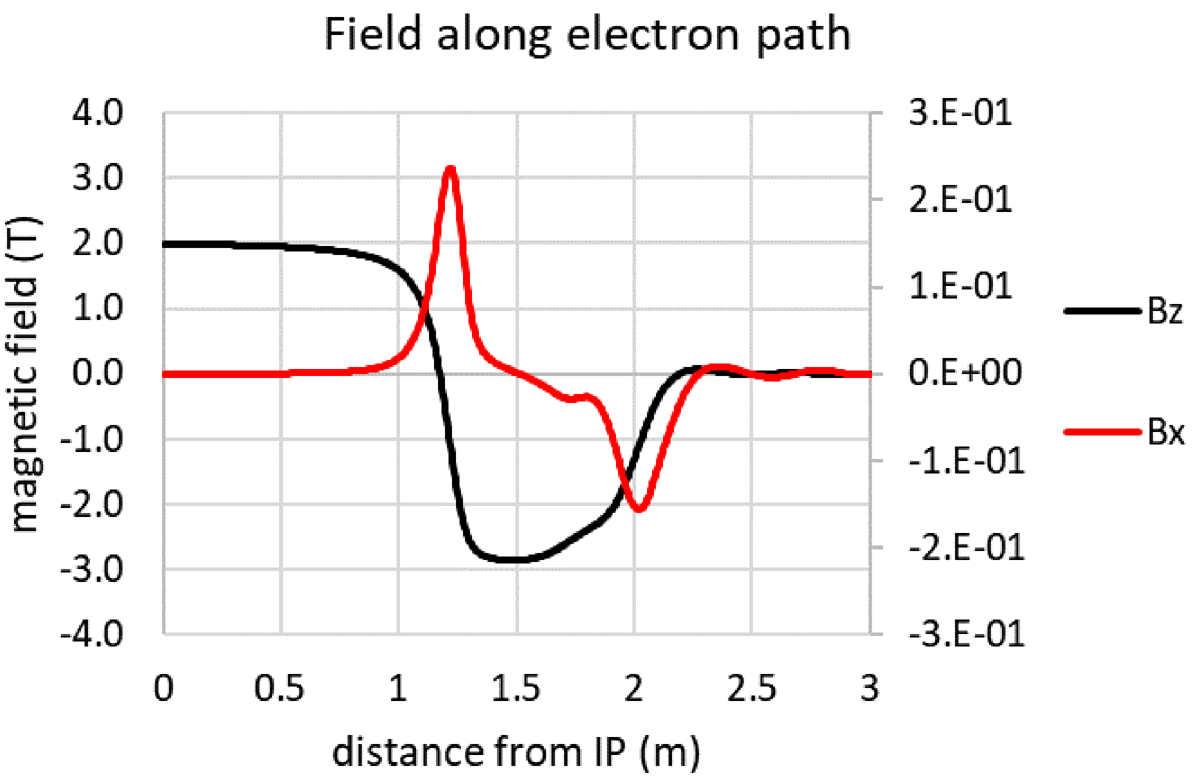
- Requirement 4 (Zero field @ quads) means that screening solenoids are needed.
- Requirement 3 (emittance blow up) necessitates the use of a compensating solenoid.
- We have managed to fit the compensating solenoids in the region upstream of the screening solenoids, whereas the area of ±1.23 m from the IP is completely free of magnetic elements, and therefore the luminometer and other technical elements can reside.
- Requirement 5 (field quality) is demanding due to the close proximity of the two final focus quadrupoles for the two beams.
- Finally, requirements 2 and 3 (integrated fields zero) can be approximately satisfied by tuning the overall design (not trivial)

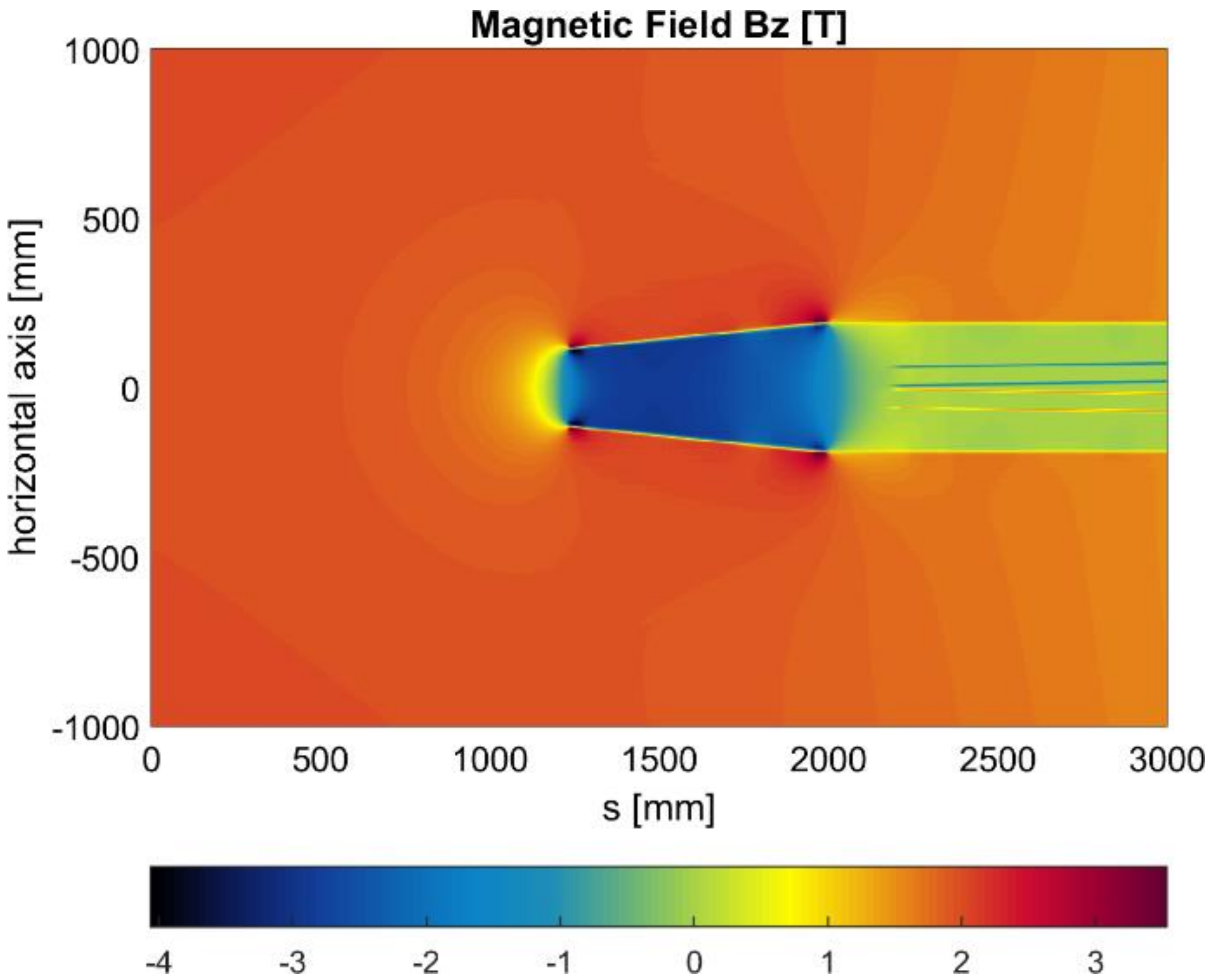
COMPENSATION SCHEME

Compensation scheme design

- 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]
- Use of LHC-technology: LHC Rutherford cable, super-fluid Helium operation.
- By the time of FCC construction, HTS conductors might be a viable alternative

Field profiles





Results

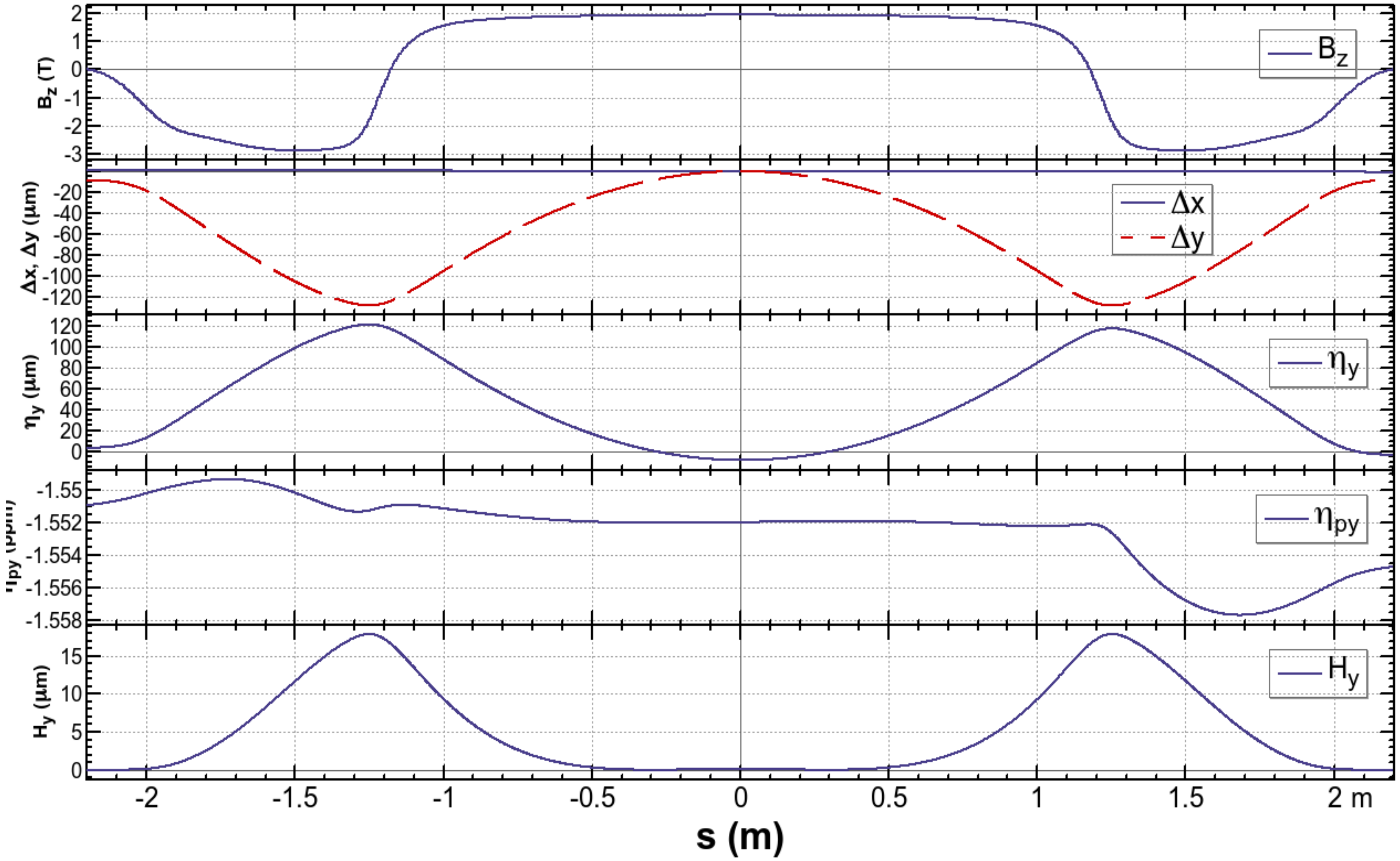


Figure 4: Optics functions in the area ±2m from the IP. From top to bottom: longitudinal magnetic field, closed orbit deviation from the tilted straight line going through the IP, vertical dispersion, vertical momentum dispersion, $\mathcal{H}_y$(vertical emittance generation function).

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.

FF QUADS AND PROTOTYPE

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

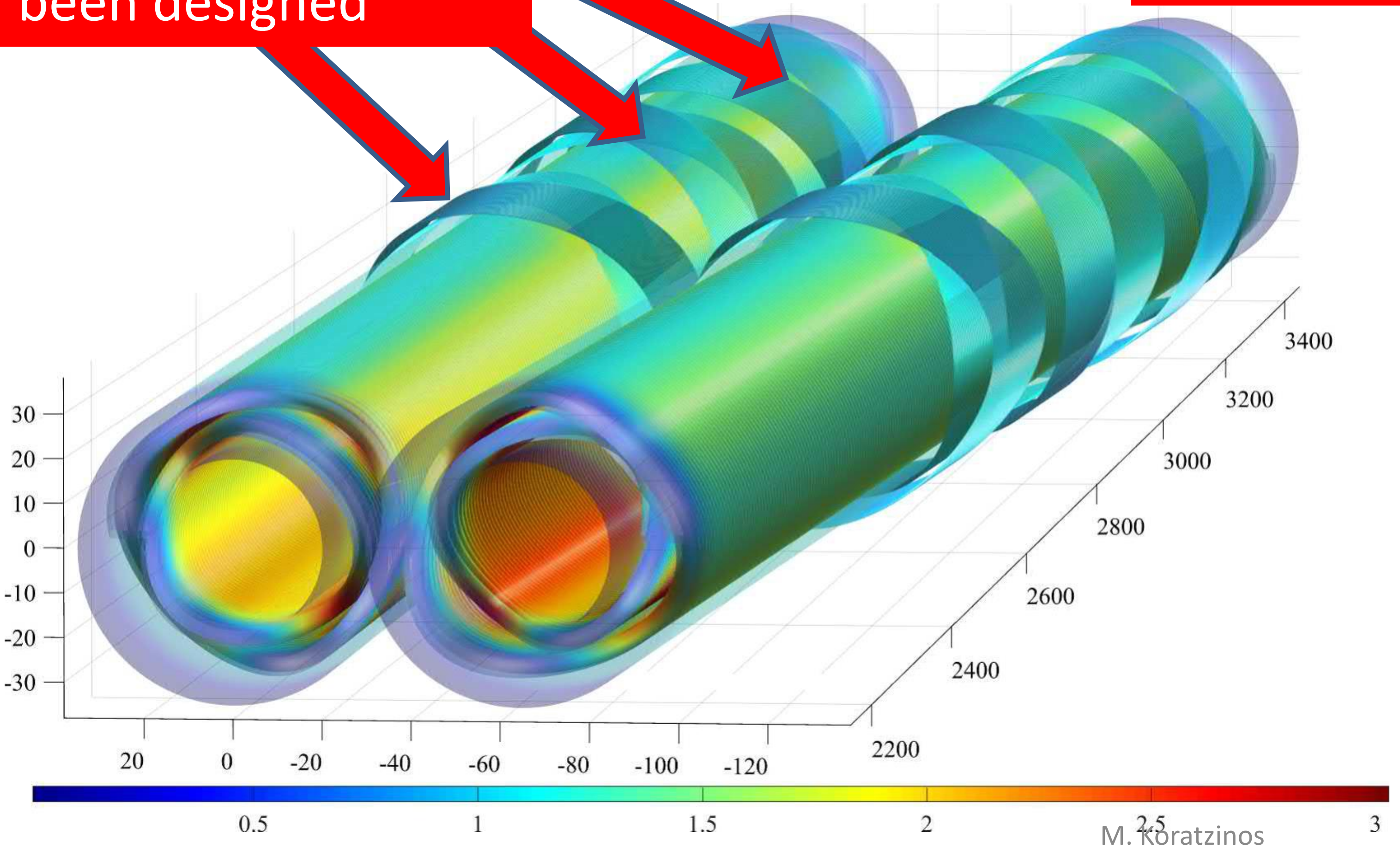
The updated parameters are rather different for QC1L1: its length is now 70cm from 120cm

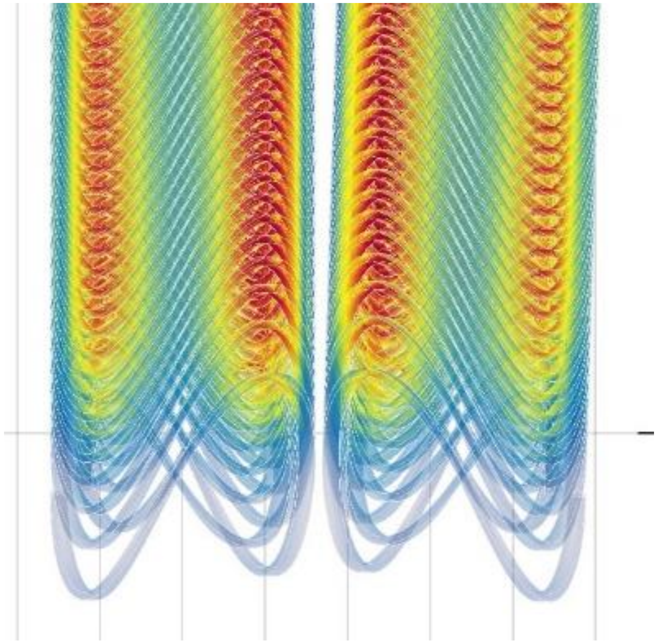
QC1L1

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

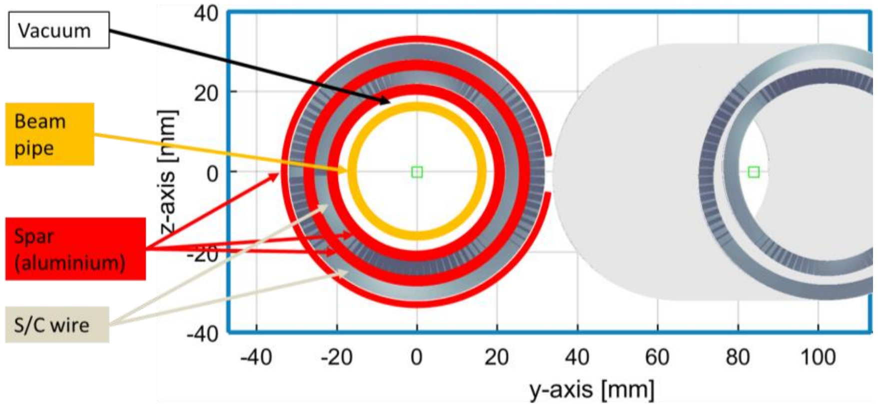
Correctors have also been designed

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 very difficult to fit an iron yoke with reasonable thickness to eliminate crosstalk**

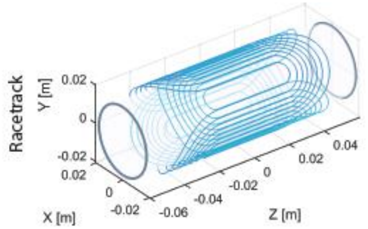
Choice of technology for QC1L1

- 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 [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

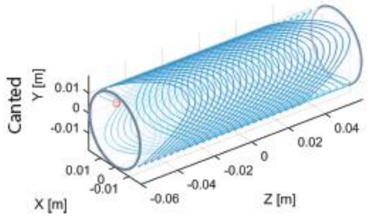
CCT accelerator magnets

- 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

Conventional

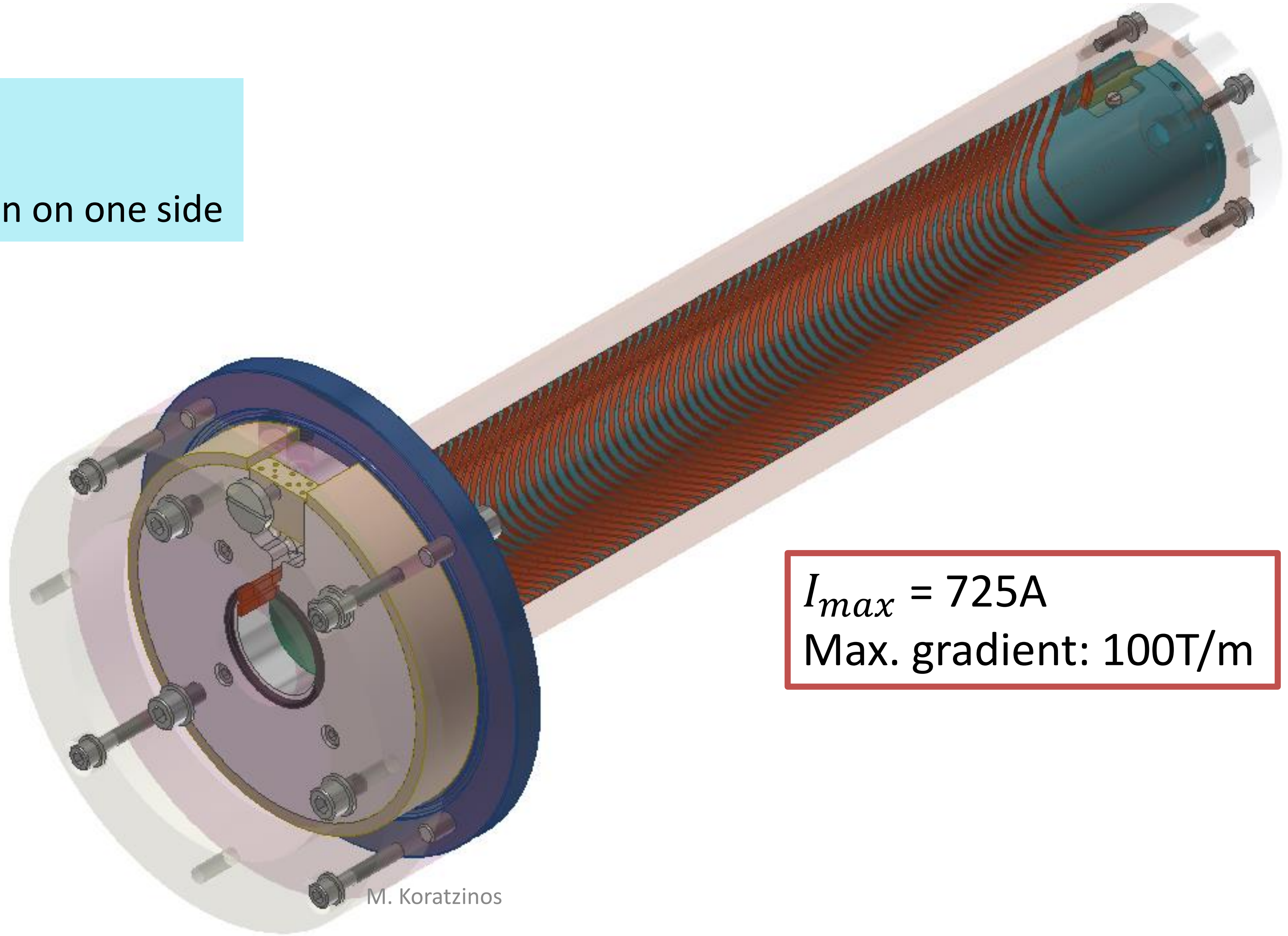


CCT



The FCC-ee Final Focus Quadrupole prototype

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

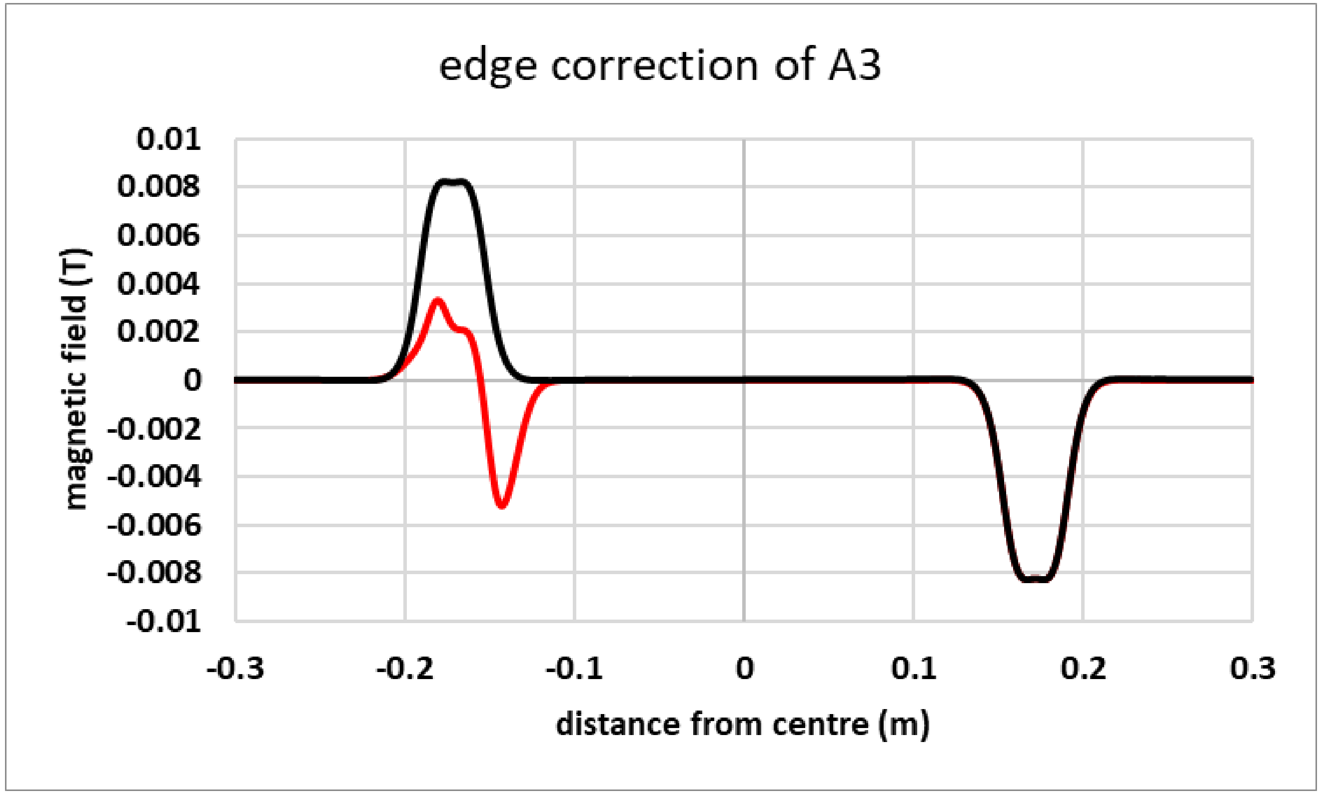


I_{max} = 725A
Max. gradient: 100T/m

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]

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

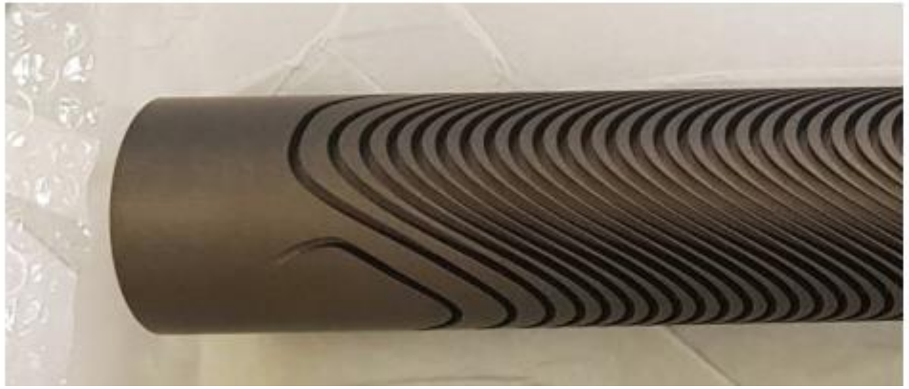
Abstract

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

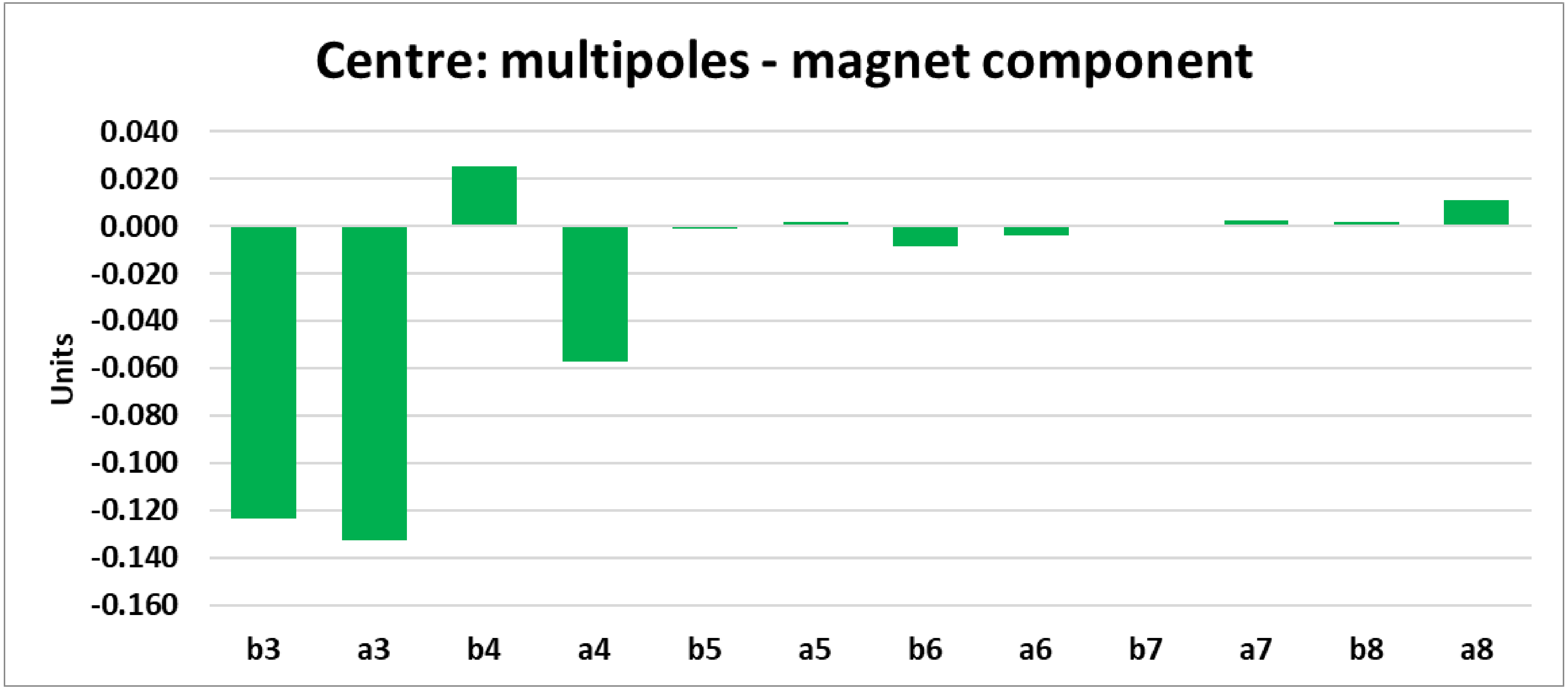
The FCC project aims to deliver a high-luminosity e^+e^- storage ring with a range of energies from 45 to 182.5 GeV per beam (FCC-ee) [1] [2]. It incorporates a "crab waist"

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.



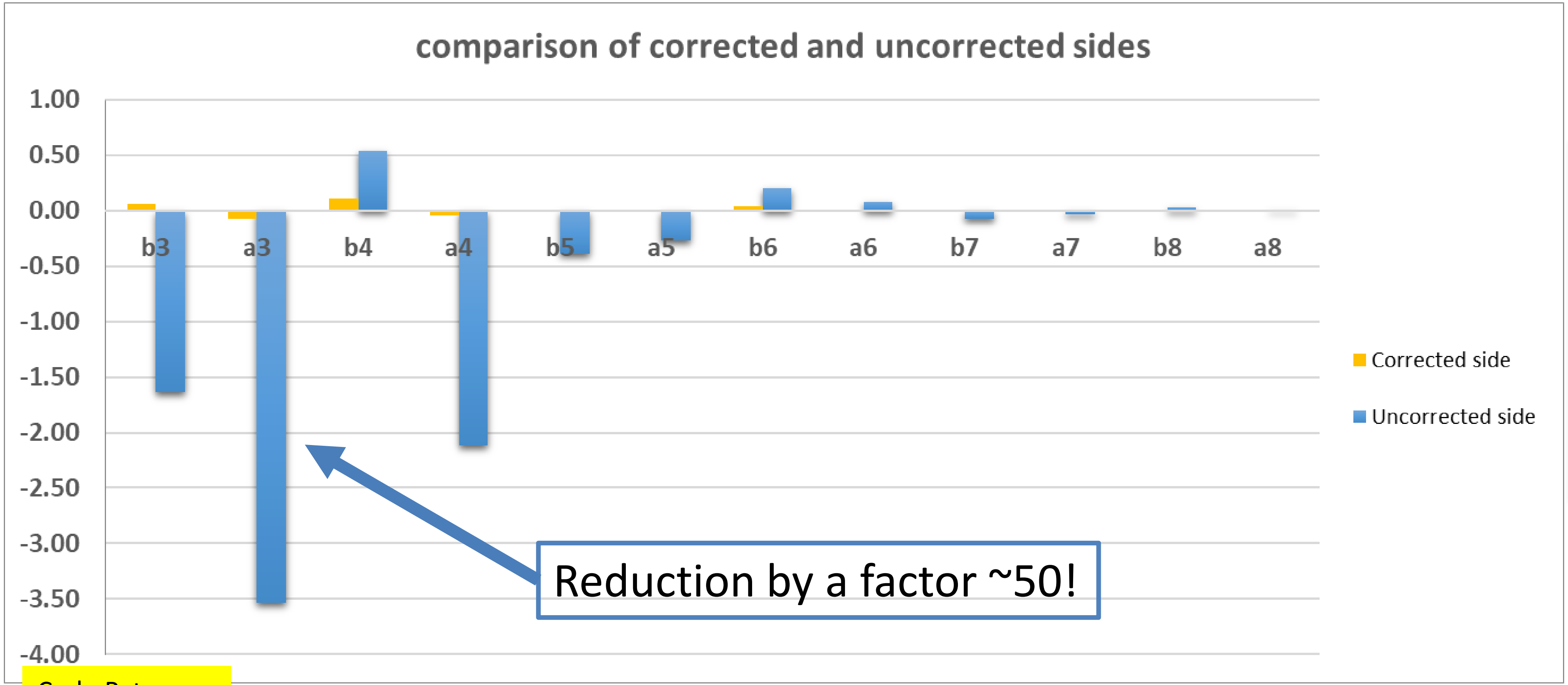
arXiv:2105.13230 **[physics.acc-ph]**

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!

Conclusions FF quad prototype

- The first FCC-ee final focus prototype has been designed, manufactured and the first tests at warm are available (IPAC paper arXiv:2105.13230).
- 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…).
- Hope to be able to test the magnet at cold also

ENGINEERING CONCEPTS

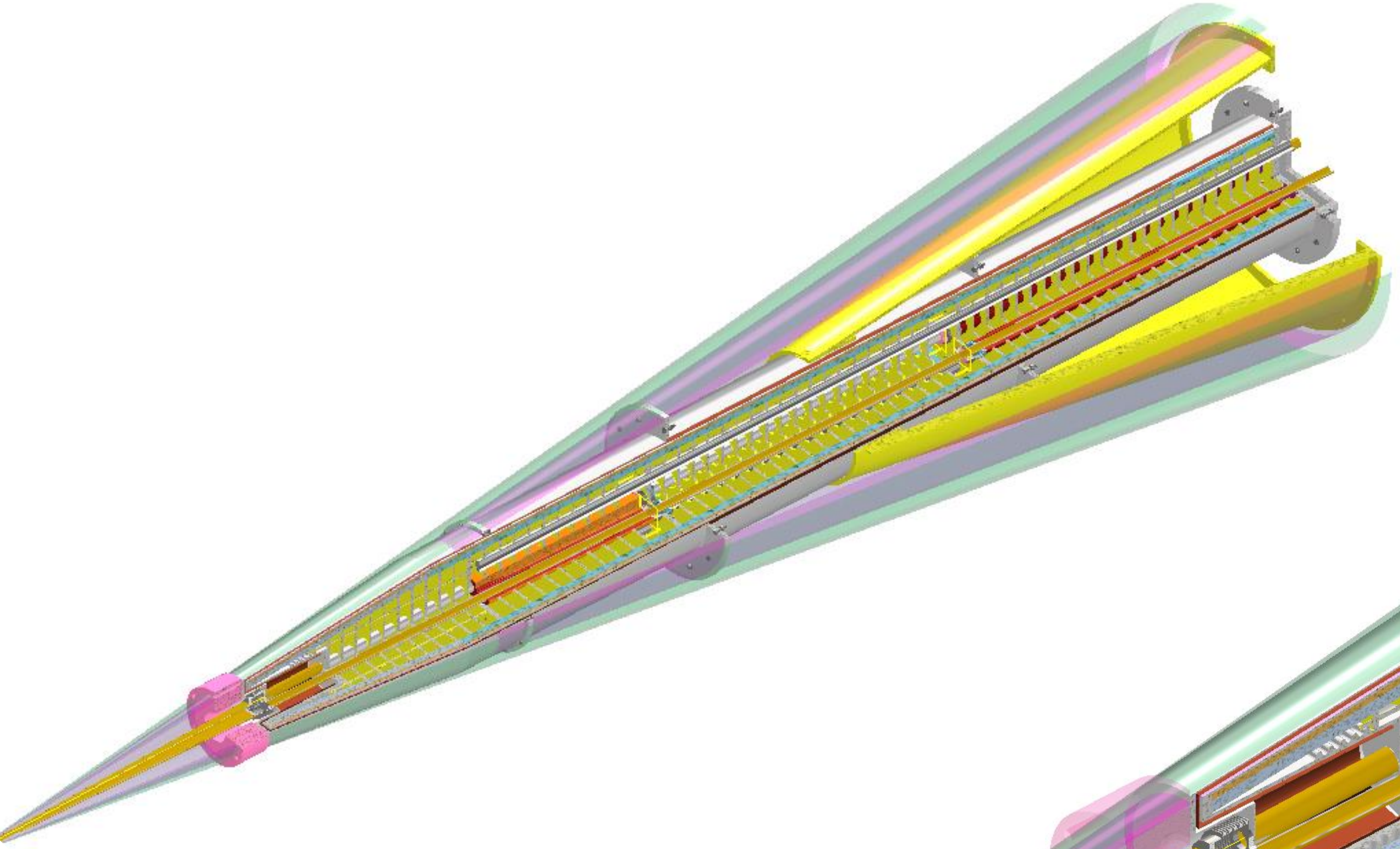
Engineering concepts

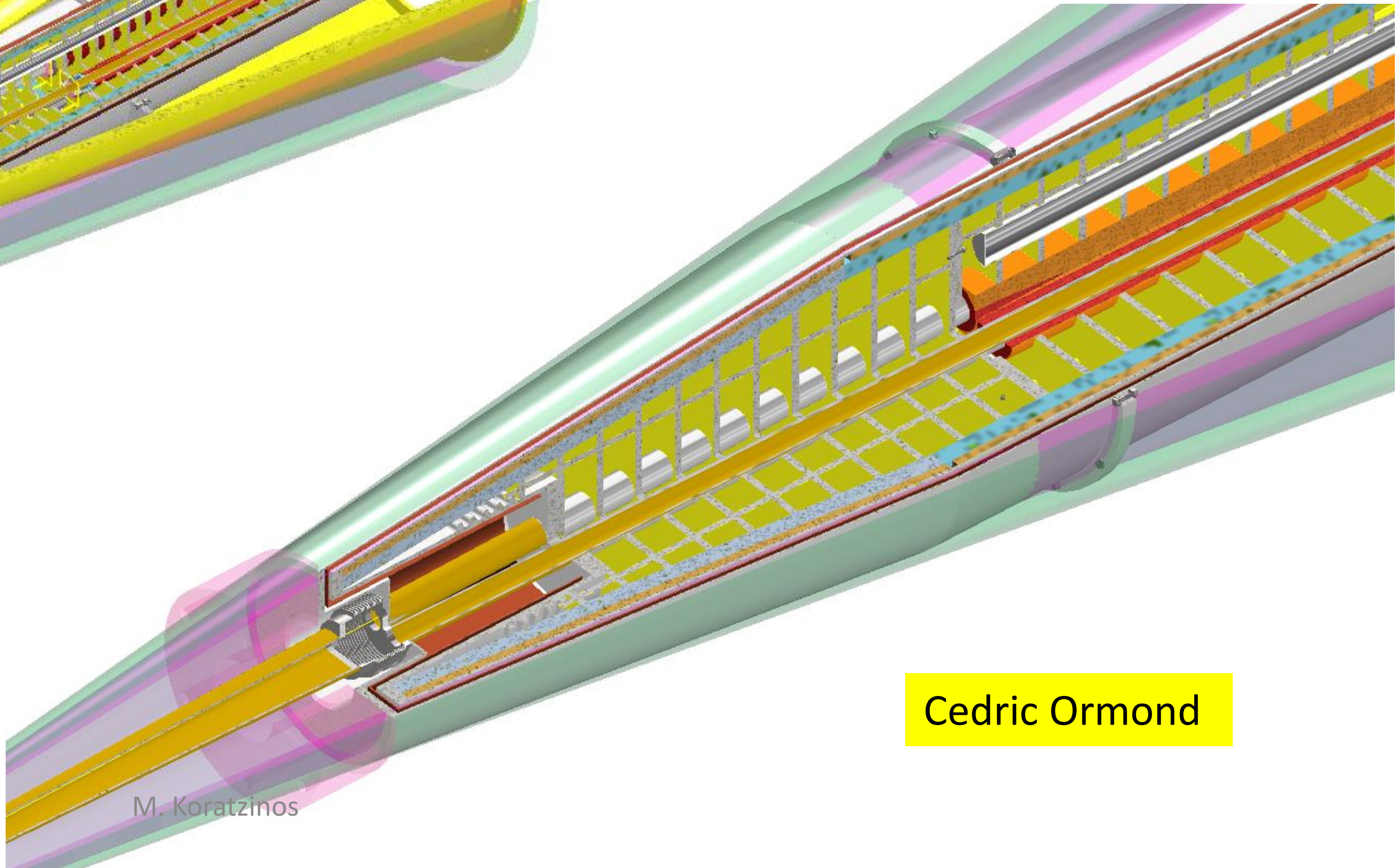
- We will now talk about the most important engineering concepts of the cantilevered assembly and the solutions we envisage
- Cedric Ormond has done most of the detailed CAD design
- **This is arguably the most complicated and expensive part of the machine: space is very tight, there are conflicting requirements and the assembly procedure is very complex.**

Progress since last presentation

- We have now moved towards an engineering design of all elements:
  - Mechanical coupling between magnets to ensure alignment
  - Mechanical structure (skeleton)
  - Helium vessel (welded)
  - Insulation vacuum vessel
  - Thermal screen (new element)
- We have failed to keep the 100mrad cone. We now are at 113mrad. We prefer to press on with the design, then find ways to improve.

New, more complete, design



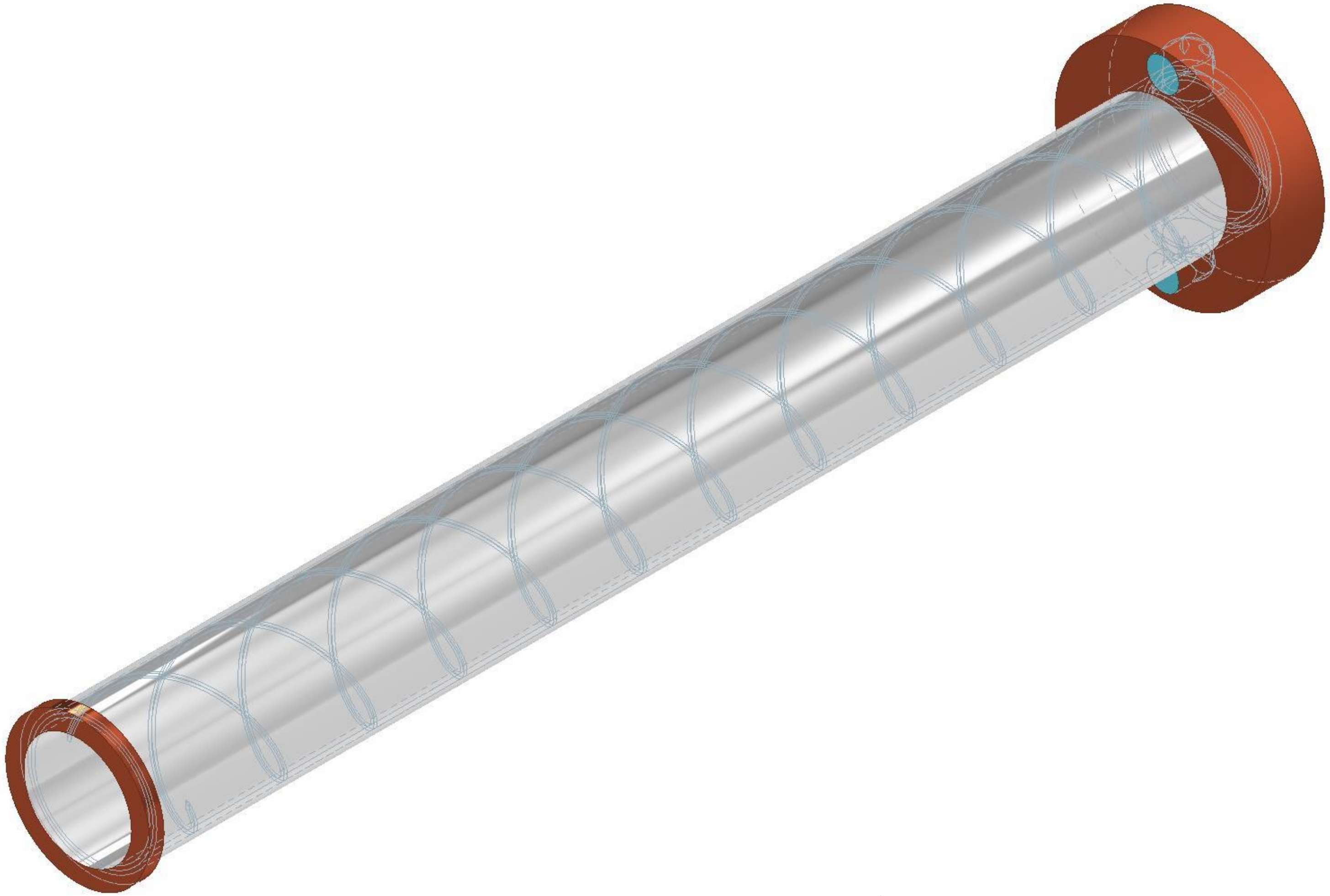


Pink: 100mrad cone
Green: 113mrad cone

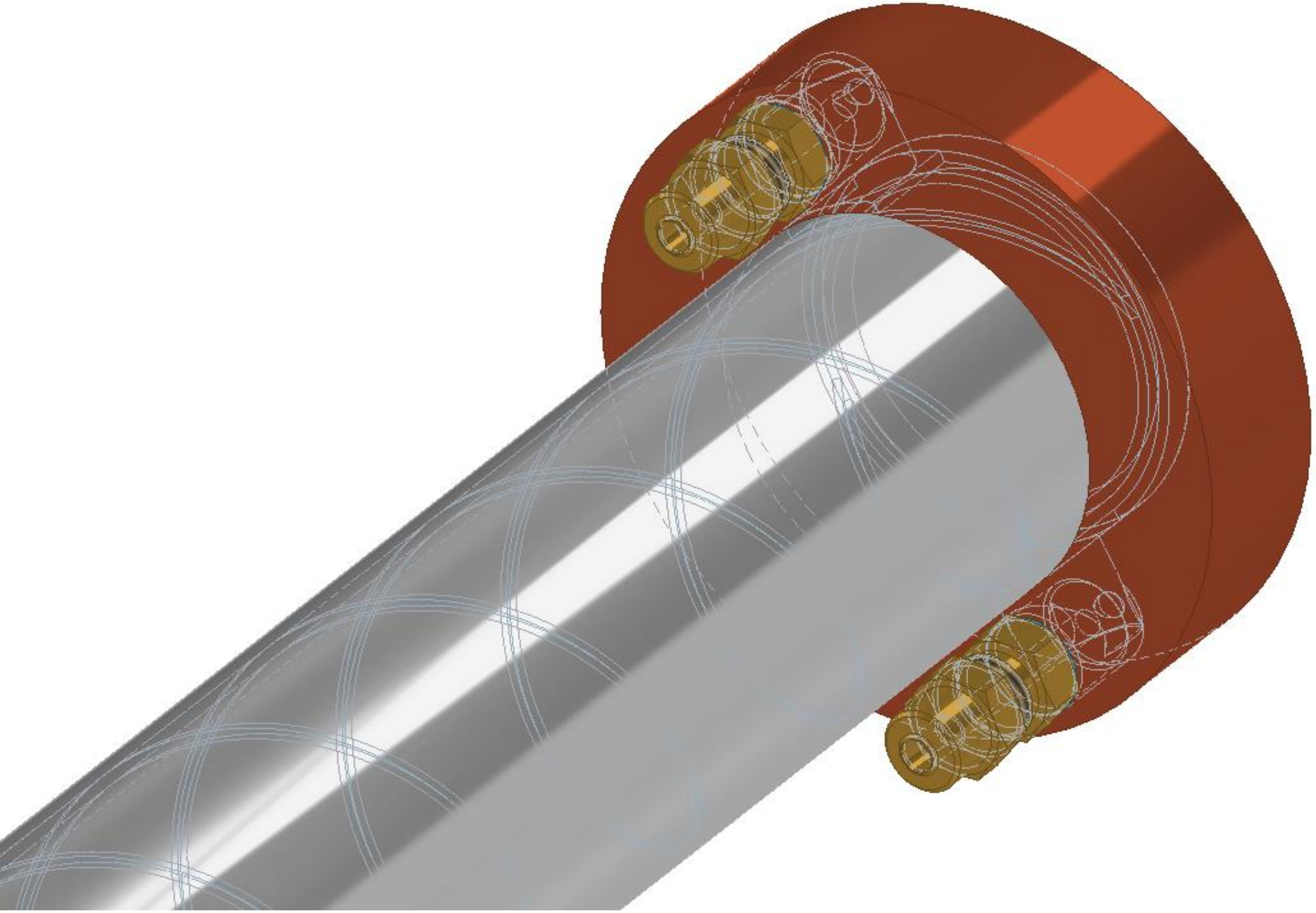
Cedric Ormond

BEAM PIPE

Water-cooled beam pipe



Water-cooled beam pipe



- Two-skin design
- Spiral spacer that channels water
- Inlet/outlet on the same side
- Water xsection in the beampipe: inlet: 50mm2, outlet 50mm2
- Length: 4300mm
- Heat: 140W/m or 600W per pipe
- Water inlet/outlet tubes: 8mm
- For a water flow rate of 0.5m/sec ➔ Delta_theta = 6K
- This is not challenging

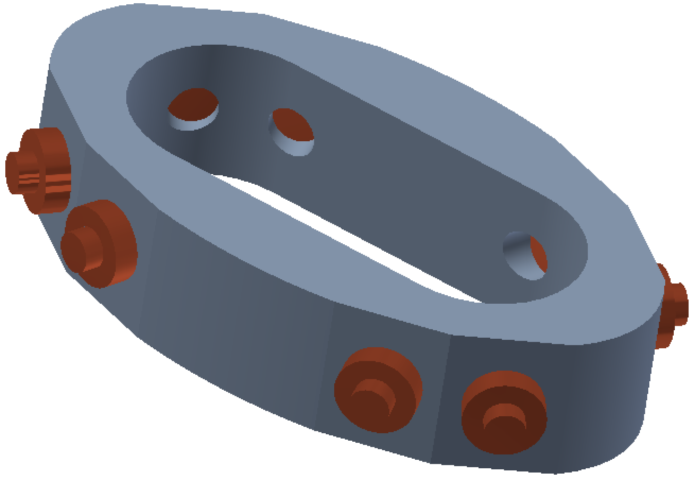
Excellent R&D topic

BEAM POSITION MONITORS

BPM design

- Ideally, BPMs need to be mechanically coupled to the magnets, but the beam pipe is in the way. One could envisage a system with flanges and bellows for the BPMs, but this will not work in our case.
- Our solution: BPMs are rigidly connected to the beam pipe, which is free to move inside the magnet aperture.
- There is a laser system that continuously monitors the position of the beam pipe with respect to the (final focus) magnets

Old design

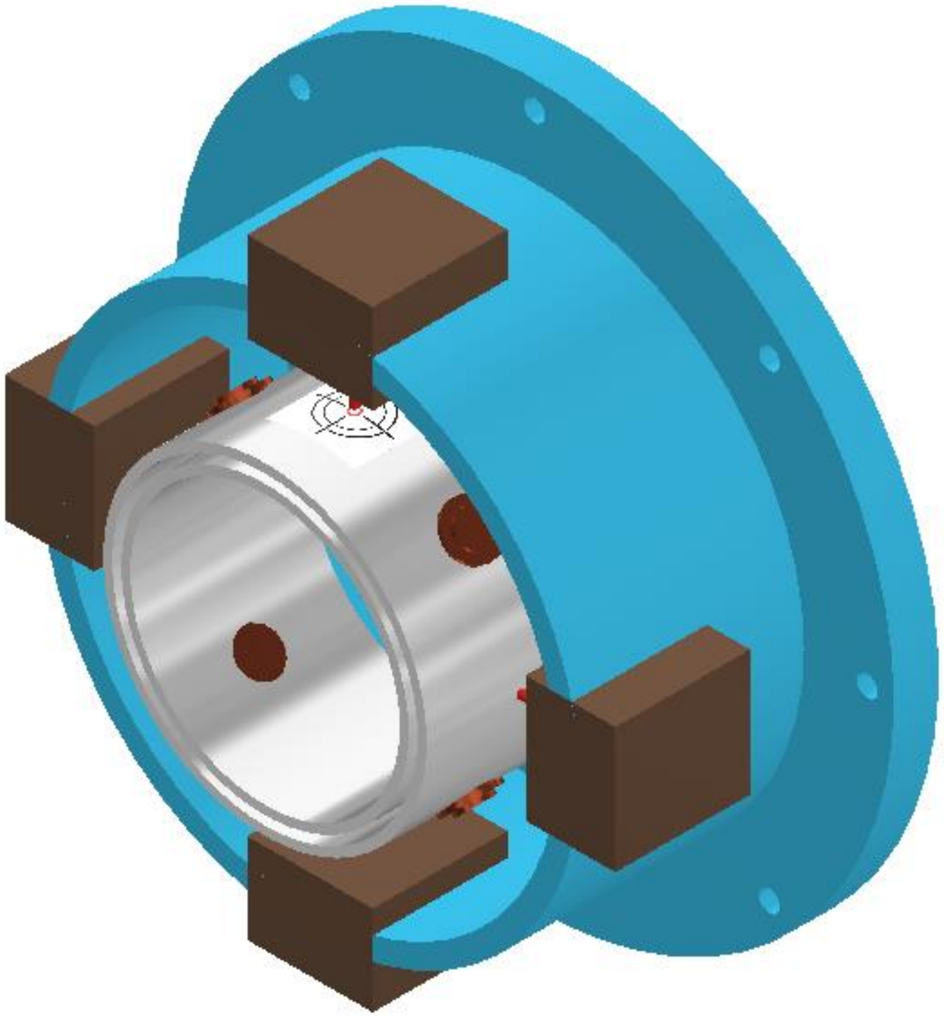


we need one BPM per QC1 quad

New design

Cedric Ormond

Beampipe alignment using a (cold) laser system



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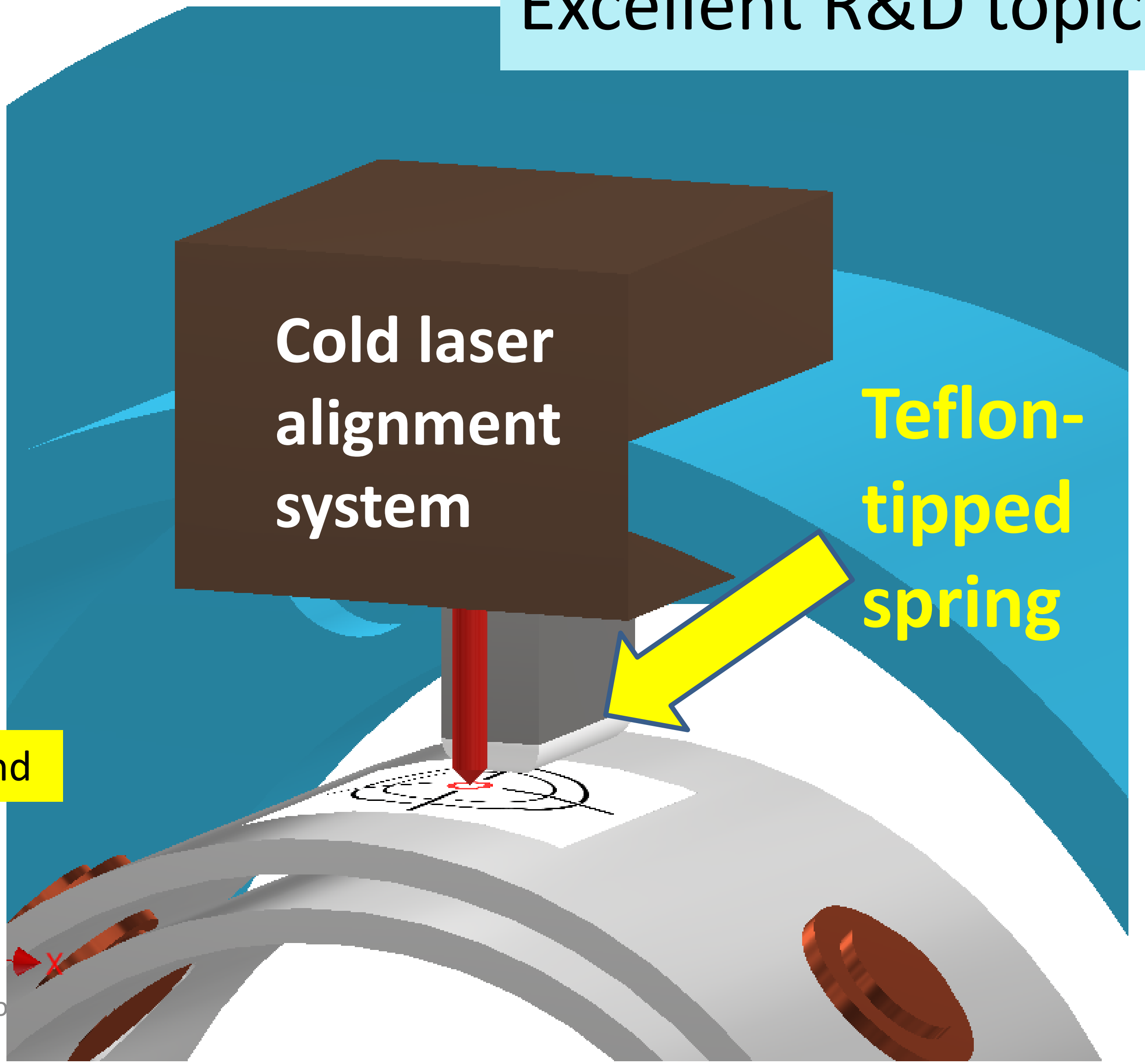


Excellent R&D topic

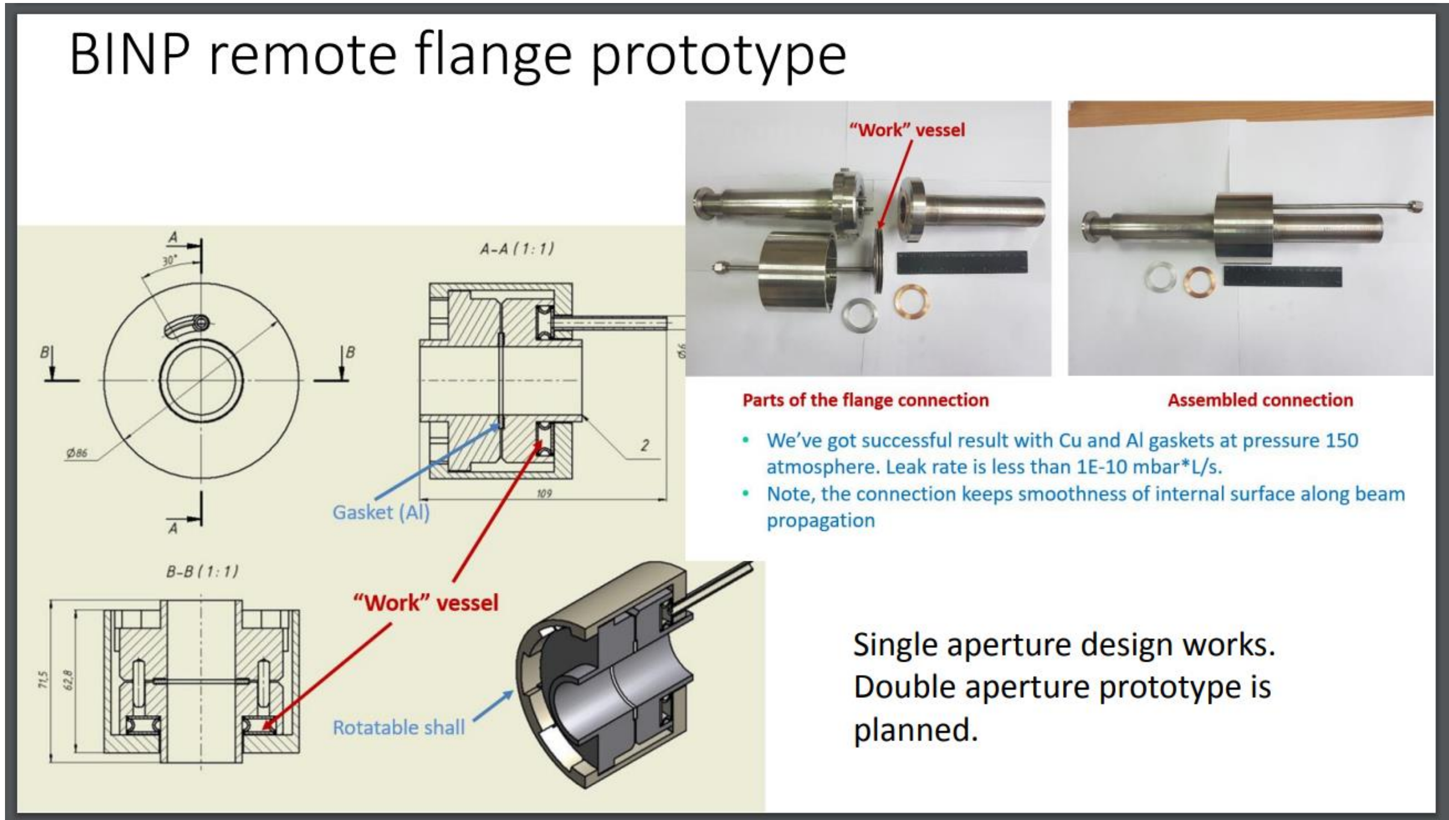
Added complication: insulation vacuum

REMOTE FLANGE

Remote flange

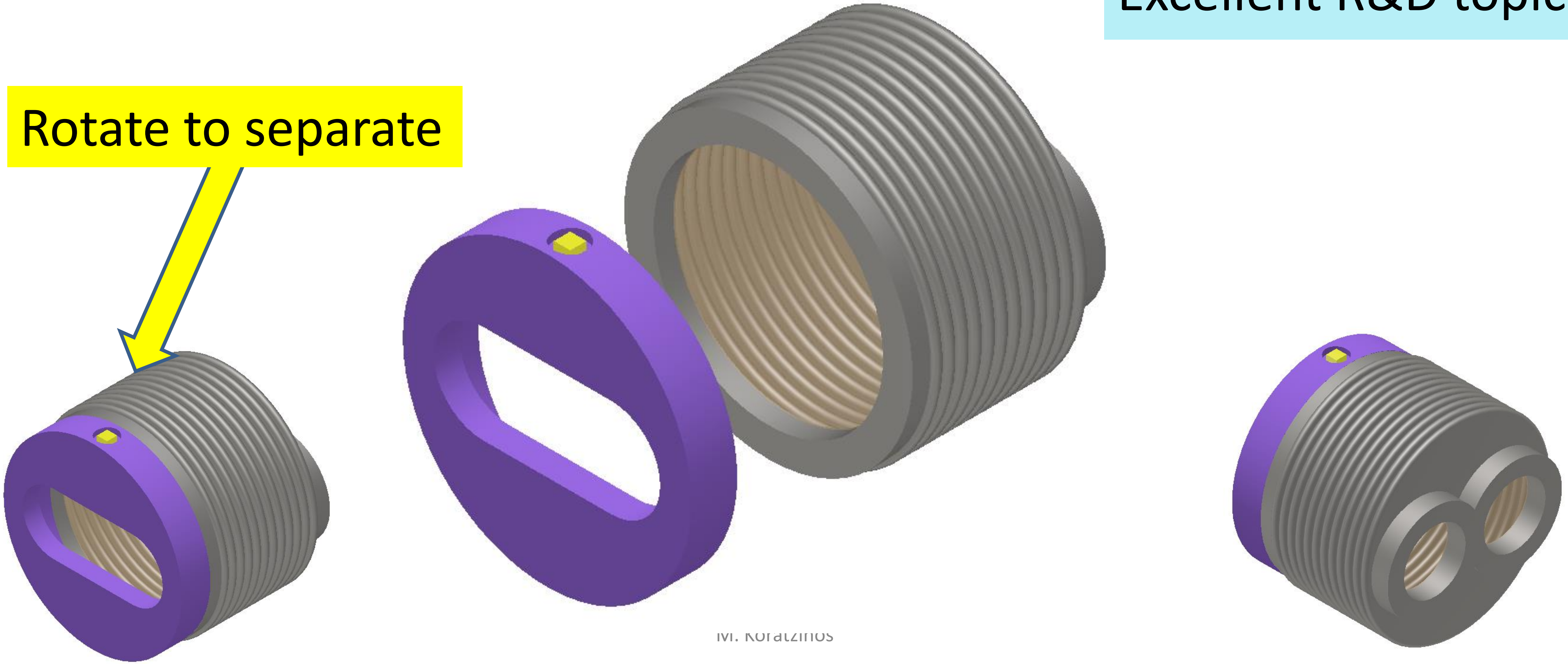
- To be able to assemble/disassemble the structure, we need a disassembly flange.
- This flange sits at the intersection of the trapezoidal pipe to the two separate pipes, close to the luminometer
- Due to space requirements, this flange needs to be remotely operated: once to lock the beam vacuum at the end of assembly, and once to unlock after a run for disassembly.

Already discussed by our BINP colleagues in 2019



Remote flange – functional description

Excellent R&D topic



HEAT MANAGEMENT

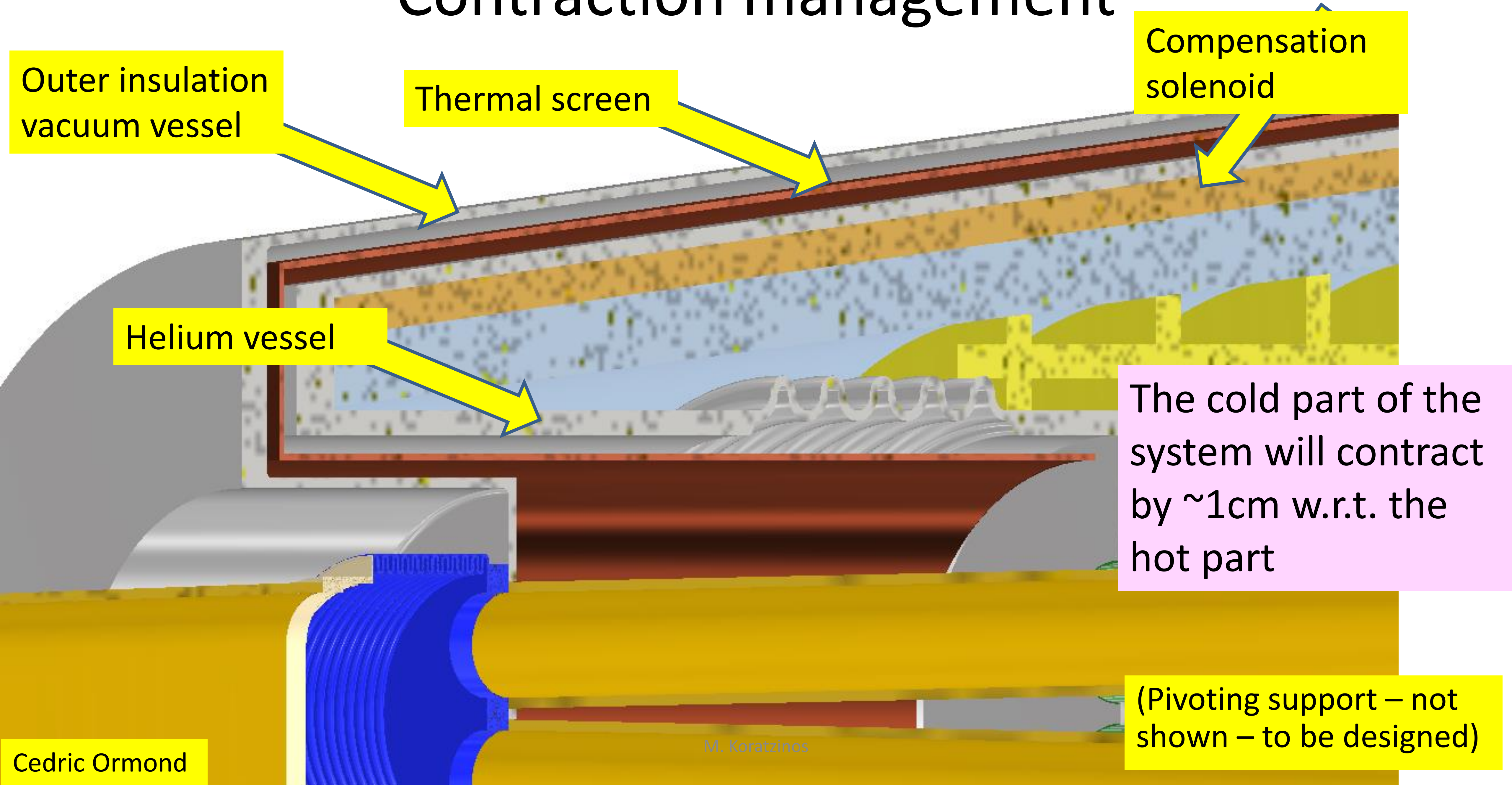
Heat management- superfluid He

- The current design uses super-fluid helium for cooling (like the LHC main magnets)
- Superfluid helium has excellent heat removing properties…
- …but also there are points of extra caution:
- Superfluid helium has zero viscosity, so will find the smallest of holes to seep out.
- This necessitate the use of a welded (and inspected) helium vessel, which could be thin

Heat management – black body radiation

- Even in the presence of adequate thermal insulation vacuum, heat radiates following the black body radiation law
$$P_{radiated} = \varepsilon\sigma(T_1^4 - T_2^4) \quad where \quad \sigma = 5.67\,W/m^2K^4$$
- Even using the lowest emissivity materials (ε = 0.02- polished silver coating), there is substantial amount of radiated energy ($9W/m^2$)
- For the area next to the beam pipe, there is no space for extra radiation shielding, but the area is small ($0.9m^2$ for both beam pipes). Radiated power is ~8W
- For the external surface (~$6m^2$) , we plan to have a radiation shield at some intermediate temperature (say 100K) and that reduces the heat load from ~60W to ~1W

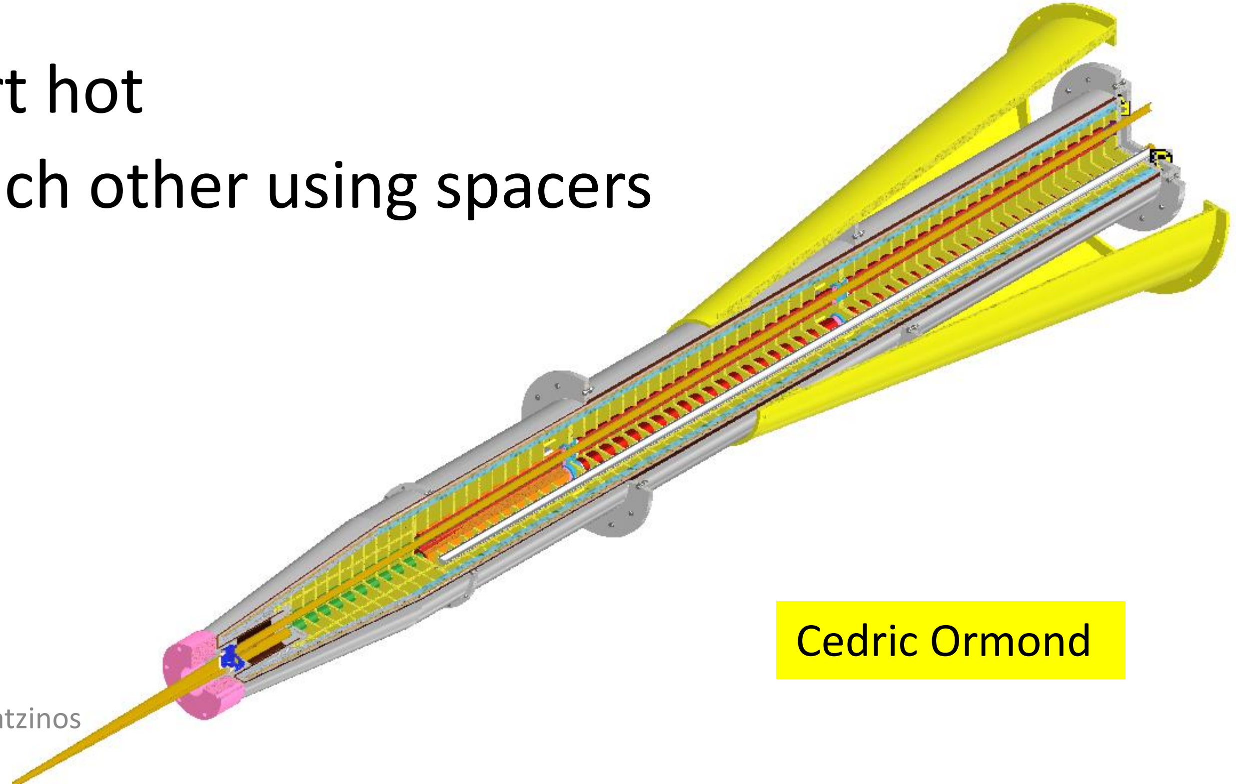
Contraction management



MECHANICAL STRUCTURE

Mechanical structure – towards an engineering design

- We have started work to go from the conceptual to a more engineering design
- The mechanical support is a (stainless steel) backbone skeleton, cantilevered,
  - from l=1220mm to l=5600mm
  - **length=4380mm**
  - Weight ~1700 kg per side
- Part of the design is cold, the other part hot
- Magnets are aligned with respect to each other using spacers

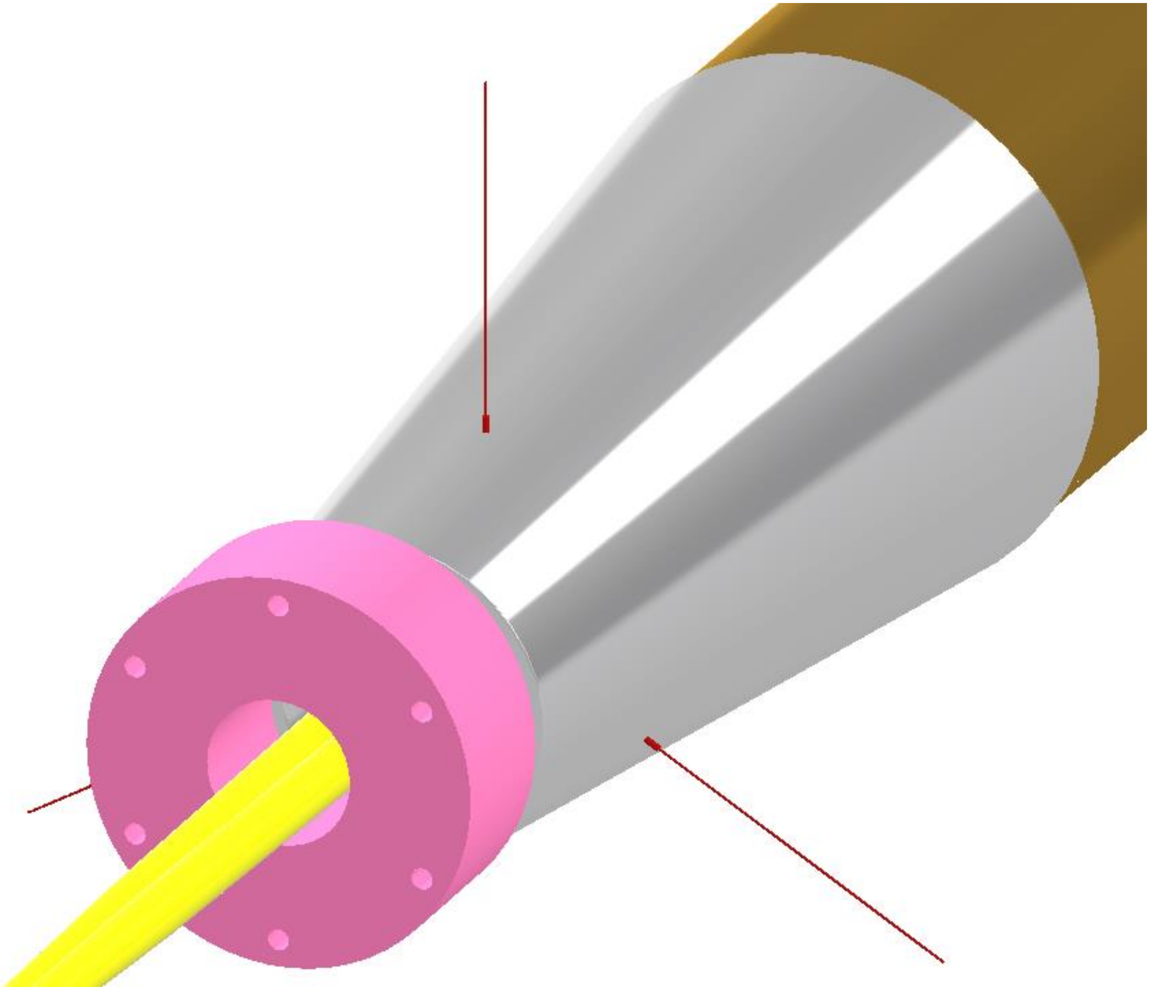


Cedric Ormond

Mechanical support of the cantilever structure

- This is a very complex system.
- Mechanical support will rely on supporting the bulk of the cantilever design at the point far away from the IP. This is because space is not an issue there, and we can use longer and stronger supports to reduce heat creeping in the cryostat.
- The secondary supports close to the centre of gravity of the system need to have a pivot design due to the shrinkage of the system at low temperatures.
- Vibration control

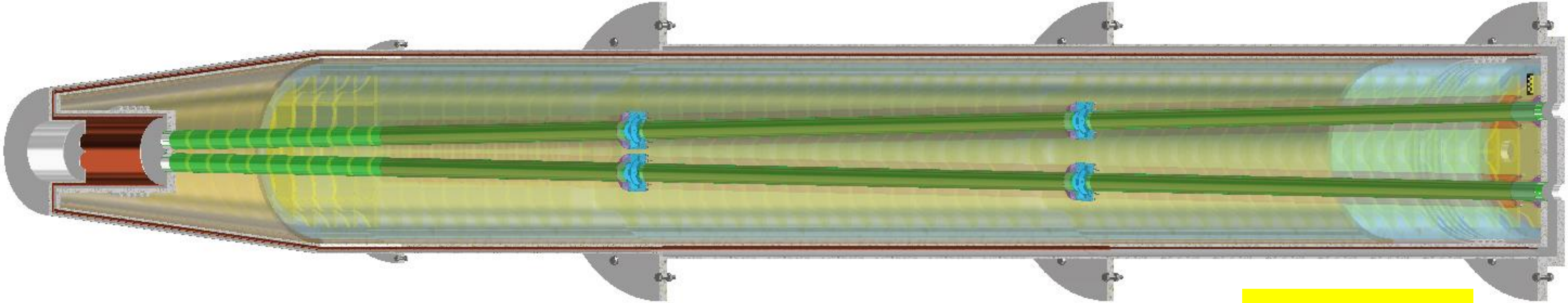
Extra support



- If needed we can also have a “Mercedes star” (left, in red) structure at the front of the structure with piano wires going through the detector (if the detector people allow us!
- This can help primarily for the vibration mitigation

Helium vessel

- Helium II operation necessitates the use of a dedicated helium vessel (which can be thin) which is welded together.
- Below we can see the helium vessel (in green) between the insulation vacuum and the magnet aperture
- On the outside the helium vessel is a bit thicker.
- A big relief valve is envisaged to make sure that helium gas has an escape route in case of a quench



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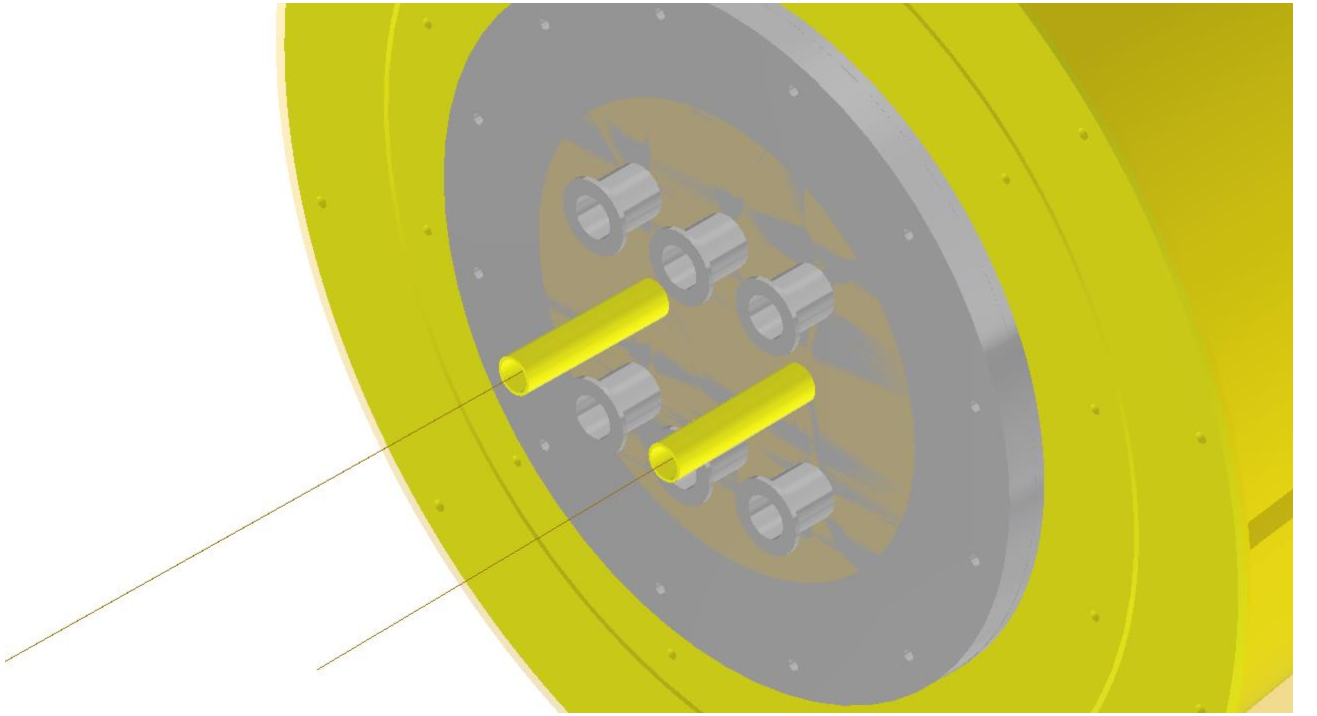
Services

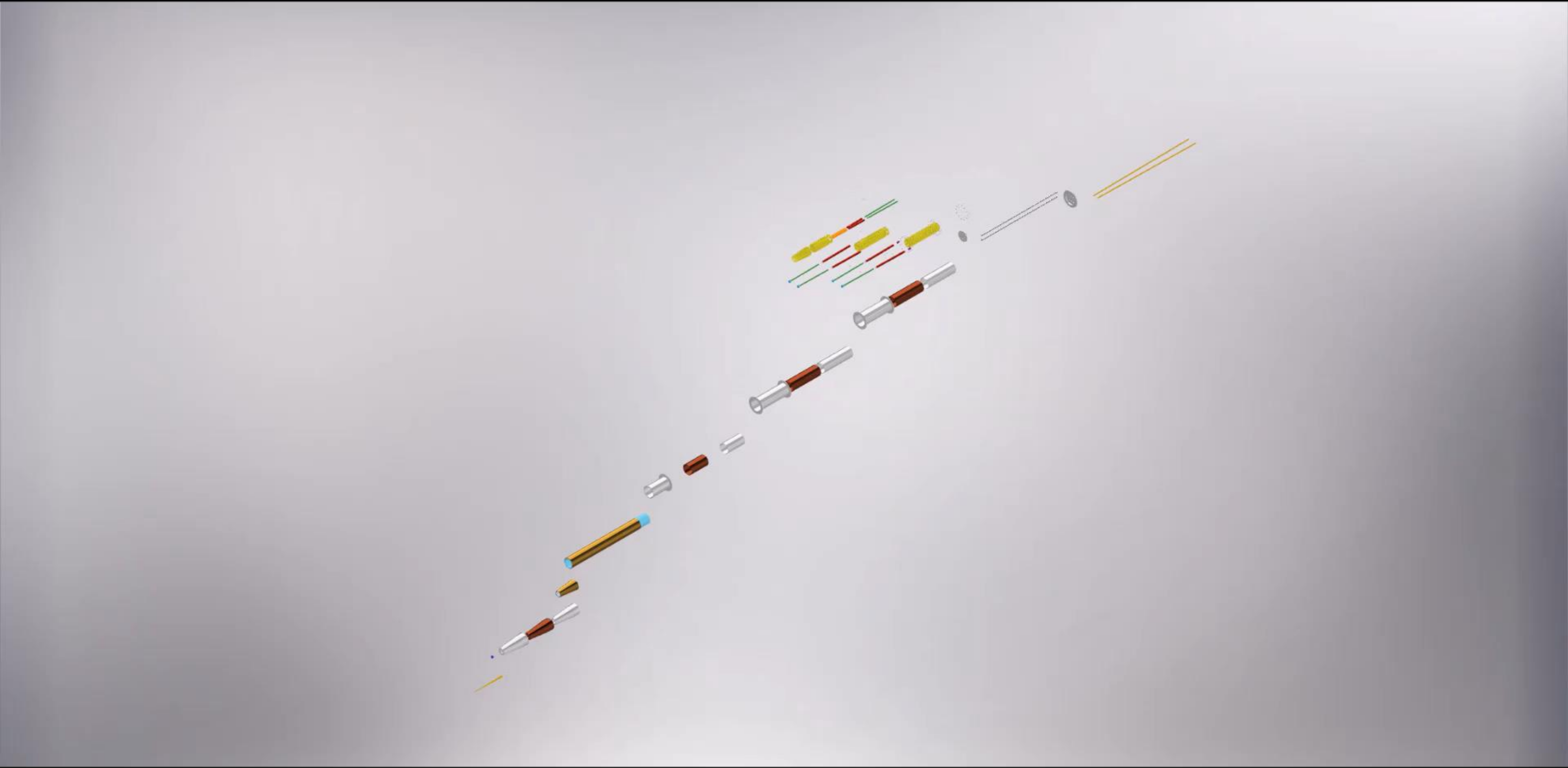
- The system will need a number of services:
- Liquid helium
- Low-pressure helium line for the heat exchanger (two lines)
- Insulation vacuum pumps
- Beam vacuum pumps
- He gas relief valve
- High current systems:
  - Compensation solenoid
  - Screening solenoid
  - QC1L1
  - QC1L2
  - QC1L3
- Medium current systems:
  - Correctors (dipole x, dipole y, skew quadrupole per beam per side)



ASSEMBLY

Assembly

- Assembly is not straightforward, but we think we have a working assumption.
- Assembly starts from the end away from the IP
- The beam pipes are some of the final elements to be assembled
- Still a lot of work to be done here
- A video is the best way to explain this



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Final word

- This is an exciting project!
- Since this system is (arguably) the most complicated of the whole FCC-ee machine, let’s make it truly state-of-the-art

THANK YOU

Extra slides

Discussion on s/c choices

- This system has been designed using NbTi as conductor and superfluid helium as coolant.
- The reasoning was that the alternative, HTS, was largely unproven when we started the project, especially regarding field quality of the final focus quadrupoles.
- However, HTS has performance advantages over LTS NbTi.
- The uncertainty about HTS should change by the time we need to construct FCC (2040+)
- We need a roadmap on this possible transition to HTS