FCC hh ee he

Massachusetts Institute of Technology

Overview of MDI at FCC-ee

M. Koratzinos

IAS High Energy Physics conference, 17/1/2020

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IAS PROGRAM

High Energy Physics

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Preface

What is presented is our baseline choice that is included in our FCC-ee CDR Volume 2 - The Lepton Collider (preprint submitted to Eur. Phys. J. ST 20 December 2018), plus any recent work

Acknowledgements

- Sergei Sinyatkin and the whole team at BINP for the original idea of the compensation scheme
- Eugenio Paoloni et al. from the SuperB project for the CCT idea for FF quads
- Glyn Kirby and Jeroen Van Nugteren of CERN/TE-MSC for fruitful discussions, guidance and the use of very useful tools (the Field program)
- Katsunobu Oide and Frank Zimmermann for helpful discussions
- The whole FFC collaboration for their support
- Rapid prototyping courtesy Idea*squared* at CERN (Markus Nordberg, Jani Kalasniemi, Hans Hagenes Boe
- FF quad manufacturing: the CERN main workshop (K. Schibor)
- Tool manufacturing courtesy the CMS experiment (A. Ball and M. Alidra and his team at point 5)
- FF quad winding curtesy Herman Ten Kate and Tim Mulder
- Quad prototype measurement campaign: Carlo Petrone

Contents

- The requirements
- The IR magnets
  - The compensation scheme
  - FF quadrupoles
- (The luminometer)
- (Backgrounds and collimation – see conference proper)
- Mechanical design considerations

What is MDI?

- MDI (Machine-Detector Interface) is a very loose term covering many different systems, all having in common that can be considered either a part of the machine or a part of the detector
- MDI covers the area close to the beam pipe and around the interaction point of each experiment. It includes
  - The beam pipe around the IP
  - Any final focus elements, if inside the detector
  - The detector solenoid compensation scheme
- Also has to deal with
  - The effects of passing and colliding beam (all types of backgrounds, SR radiation, impedance heating)
- …Without forgetting important engineering aspects
  - tolerances, mechanical vibration, force management, cryogenics
- At the same time, MDI elements should not impede detector quality
  - Hermeticity, adequate coverage for the luminometer, etc.
- Space is at a premium

Why is MDI important?

In a modern e+e- collider the MDI is arguably one of the most difficult aspects to design and operate

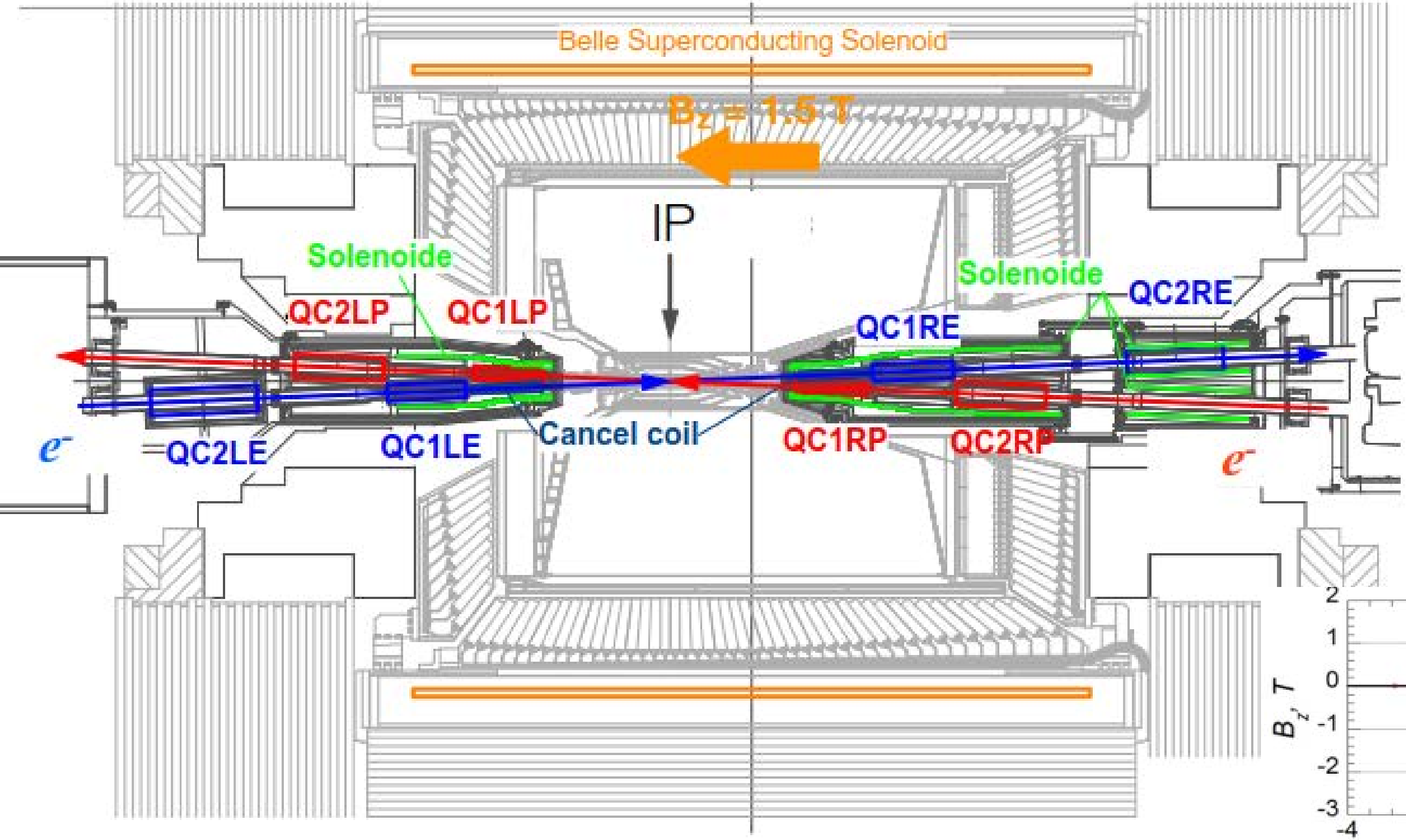
- MDI elements should only occupy a very small cone along the beam pipe – we are trying to fit everything to within 100mrad
- Small $\boldsymbol{\beta_y^*}$ requires the Final Focus quadrupoles to be inside the detector
- Very stringent optics requirements necessitate the use of a solenoid compensation scheme
  - Integral longitudinal field seen by the electrons needs to be zero
  - Vertical emittance blow up needs to be within budget (<0.5pm)
  - Any dispersion bumps need to close locally
  - The FF elements need to be at very low longitudinal field (total integral <50mTm)

The stage

- The magnetic elements required in the vicinity of the IP are the main detector solenoid and the final focus quadrupoles.
- Due to the very low $\boldsymbol{\beta_y^*}$ values required (0.8 to 1.6mm), $\mathcal{L}^*$ cannot be larger than 2.2m or loss in the luminosity performance will result.
- Crab waist requires an opening angle between electron and positron beams. 30mrad was chosen. This complicates the design considerably.

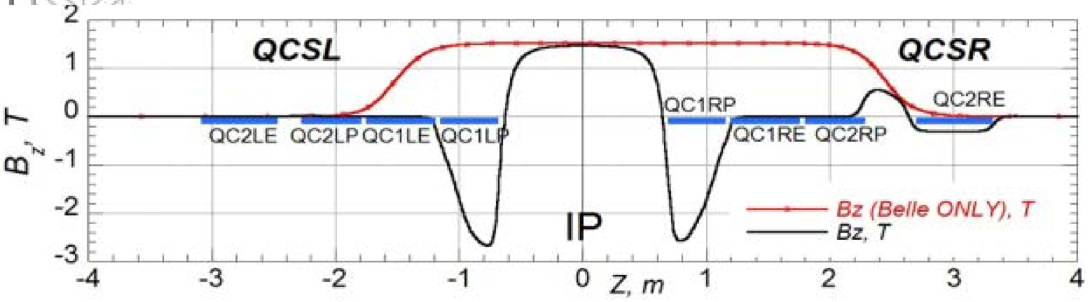
Prior art

Belle II and QCS



55 individually powered magnetic elements!

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



Note that first FF quad sits in high magnetic field

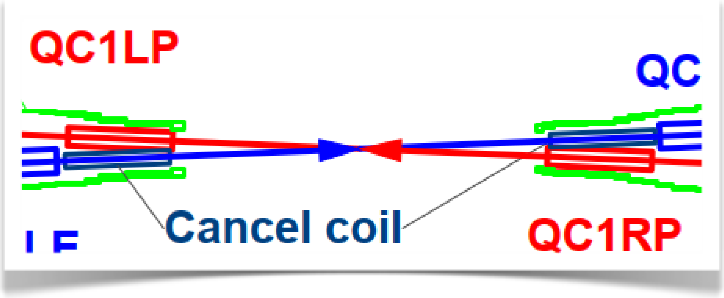
Prior art – Belle II cancel coils

Cancel magnets

Cancel magnets **cancel a leak field** from the main quadrupole magnet on the positron beam line to the electron beam line.

Cancel magnets consist of
- b3 magnet
- b4 magnet
- b5 magnet
- b6 magnet

on each (L/R) side.



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- Can we avoid the extra complication of "cancel magnets" to eliminate crosstalk between the electron and positron lines?
- At FCC-ee the situation is a bit simpler than superKEKb, since both beams have the same energy
- ➔ we have a design with the minimum amount of magnetic elements
  - Compensation scheme with two magnetic elements per side
  - FF quad with no cancel coils at all

FCC-ee: Requirements at the IP

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 seen by the electrons crossing the IP should be zero. If the compensation is off by 0.1% then the resulting vertical emittance blow up is 0.1 pm per IP – the effect is quadratic.
3. Vertical emittance blow-up due to fringe fields in the vicinity of the IP should be significantly smaller than the nominal emittance budget. Problem worse at the Z. We aim at a fraction of the nominal vertical emittance of 1 pm for two IPs.
4. The final focus quadrupoles should reside in a zero-field region to avoid transverse beam coupling; the maximum integrated solenoid field at the final focus quadrupoles should be less than 50 mTm at each side of the IP.
5. The field quality of the final focus quadrupoles should have errors smaller than 1×10^{-4} for all multipoles.

Design considerations to satisfy all requirements

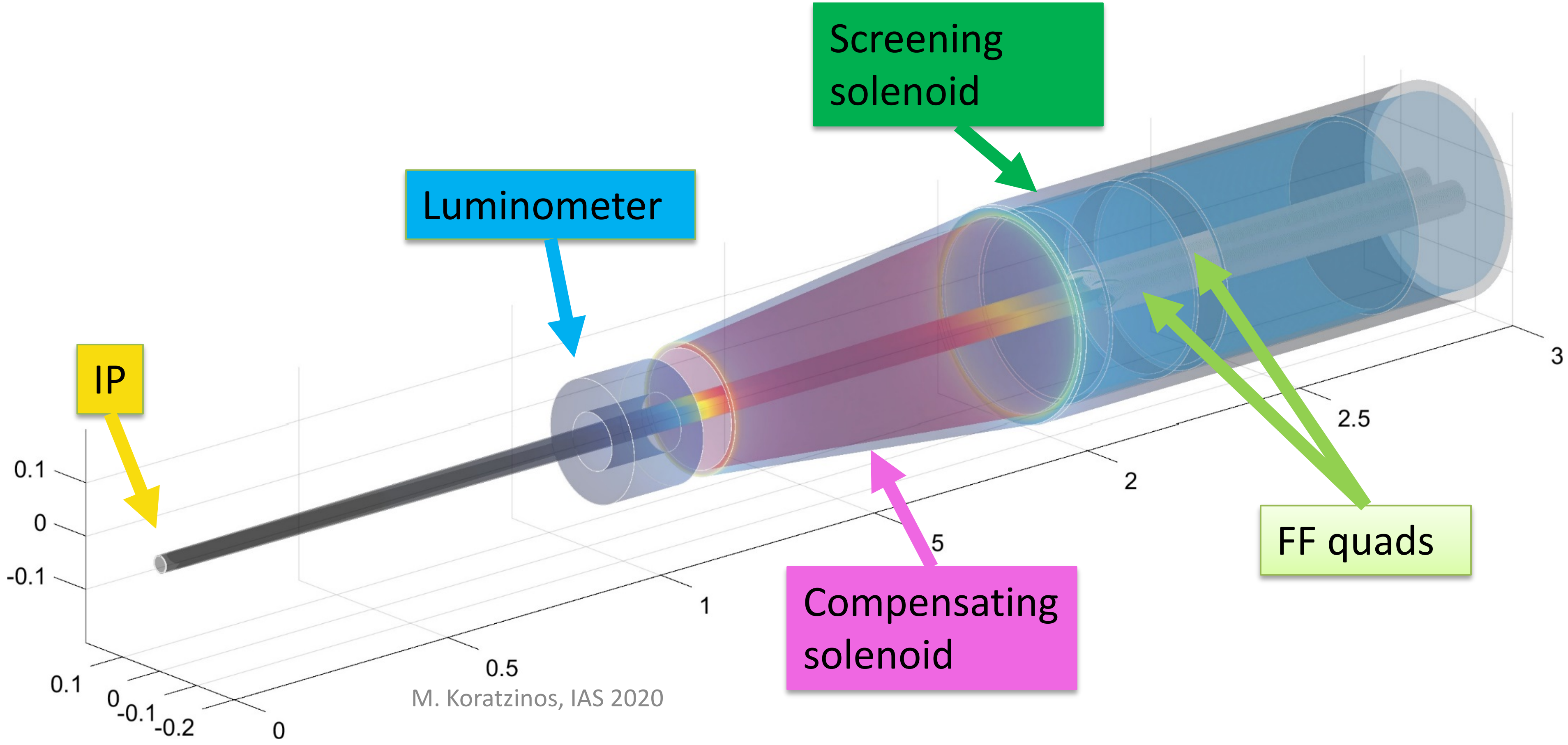
- Requirement 4 (Zero field @ quads) means that screening solenoids are needed.
- Requirement 3 (emittance blow up) necessitates the use of a compensating solenoid.
- We have managed to fit the compensating solenoids in the region upstream of the screening solenoids, whereas the area of ±1.23 m from 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, requirement 2 (integrated field zero) is the least stringent, as it can be satisfied by tuning the overall level of compensation; no specific design provision is needed.

The FCC-ee baseline solution

- L* = 2.2m; 30mrad opening angle between beamlines
- Luminometer needs to fit in front of magnetic elements and as far back as possible to have a decent rate
- FF quads sit in a zero longitudinal field region (integral of solenoid field <50mTm) encompassed by a screening solenoid which needs to extend to L* of 2.0m
- A compensating solenoid must sit between the screening solenoid and luminometer to ensure an integral field of zero

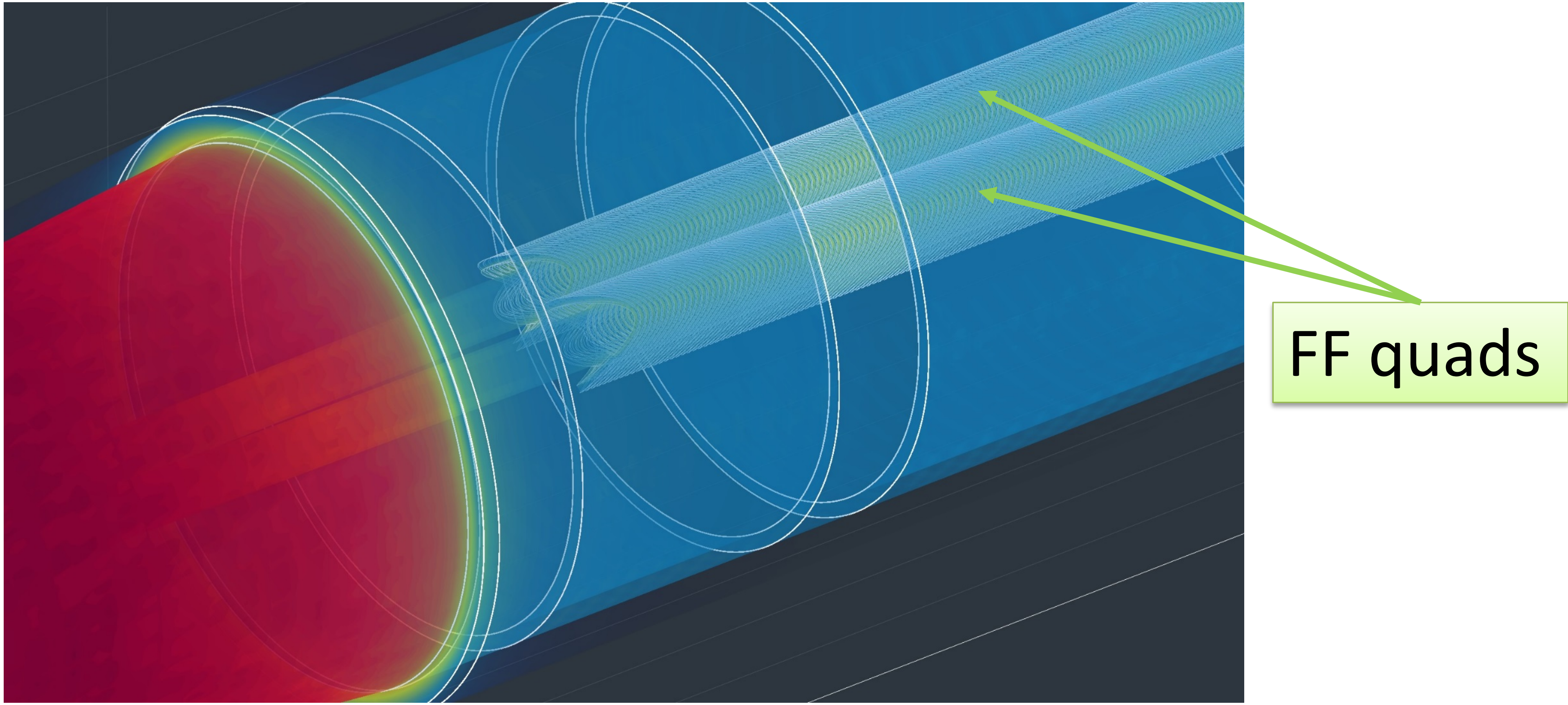
This is the design with the minimum number of magnetic elements.

Unlike linear colliders, we are facing the challenge of FF quads inside the detector!



M. Koratzinos, IAS 2020

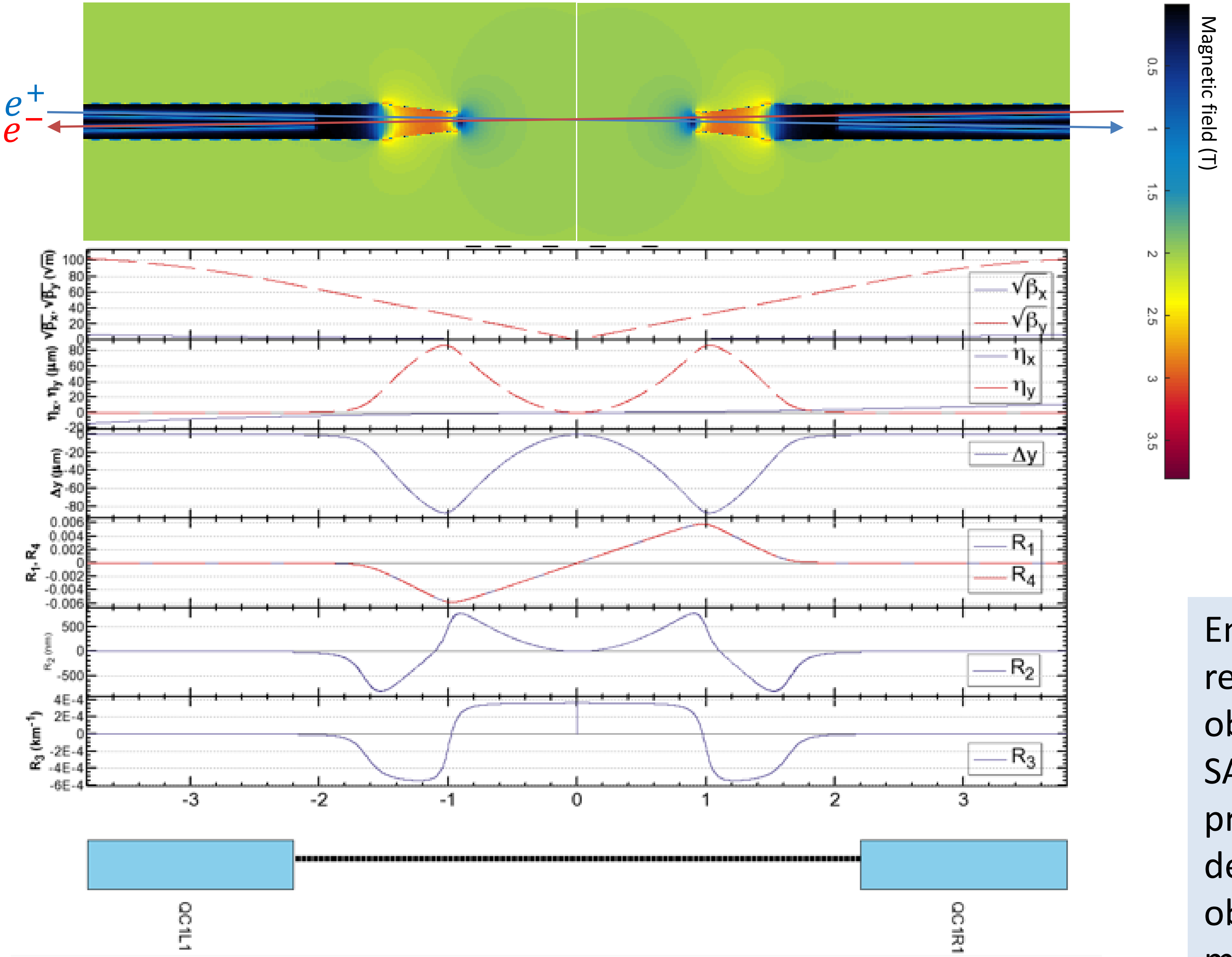
Zoom at 2.2m from the IP



The compensation scheme

View from top

Optics functions SAD



Vertical emittance blow-up 0.35 pm for two Ips @ the Z Dispersion closes completely locally

Emittance blow-up results have been obtained using the full SAD optics analysis program using as input detailed field maps obtained by the magnetic design.

Emittance blow up – 2T or 3T detector field?

- Emittance blow-up is a strong function of beam energy

$$\Delta\varepsilon_y \propto E_{beam}{}^3$$

- Going from 45GeV to 80 GeV the problem reduces by a factor 5.6 – becomes negligible
- Emittance blow-up is a strong function of detector solenoid field

$$\Delta\varepsilon_y \propto B_{detector}{}^5$$

- Going from 2T to 3T this factor is 7.6
- If the emittance blow up from 2 IPs is 0.4pm at 2T, at 3T it is 3pm
- This emittance will completely dominate the total emittance (budget is 1pm)
- Luminosity will be reduced by $\sqrt{3}$ (=1.7) and for the same statistical accuracy one needs to run 1.7 times longer

Does the design satisfy the requirements?

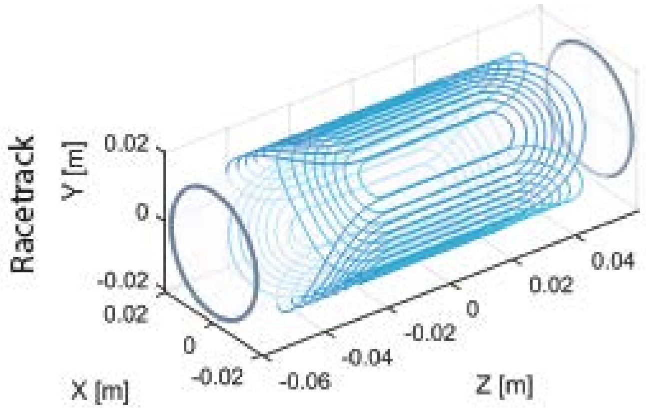
- This design results in an overall emittance blow-up at the Z energy of 0.4 pm for two IPs. This is within specification (requirement 3).
- The design fulfils requirement 1 in the sense that all magnet coils are at an angle of less than 100 mrad from the IP. (see further for the cryostat)
- Requirement 2 is met by trimming the total current of the screening and compensating solenoids until the integrated field seen by electrons is arbitrarily close to zero.
- The current design has an integrated solenoid field inside the quadrupoles of less than 10 mTm (satisfying requirement 4); this can be improved further if needed.

Final focus quadrupole design

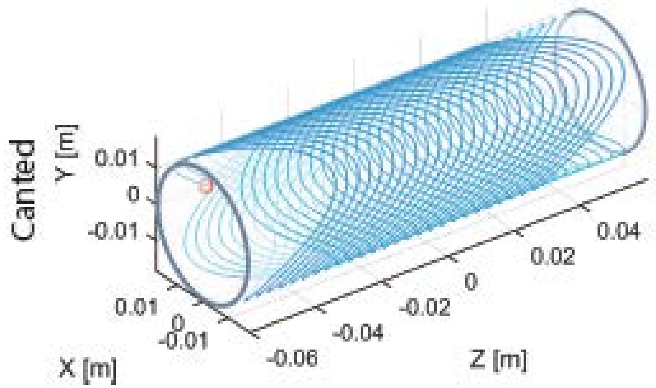
- The stringent requirements of the final focus quadrupoles are satisfied by using a canted-cosine theta design. The proposed design features iron-free coils with crosstalk and edge effect compensation, with a field quality (from simulation!) of around 0.1 units for all multipoles (requirement 5).
- Dipole and skew quadrupole correctors can be incorporated without increasing the length of the magnetic system
- A full magnetic analysis has been performed, including a misalignment analysis.

What is a CCT magnet (a.k.a. “double Helix”)?

Conventional



CCT (Double Helix)

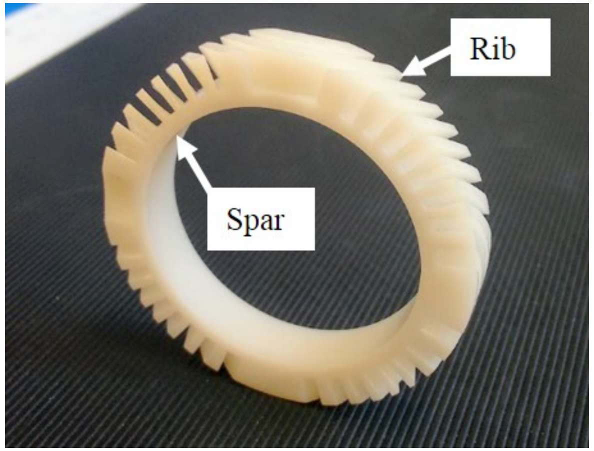


- Novel idea (discovered in the 70ies, but gained momentum recently with the advent of CNC manufacturing and 3D printing)
  - Excellent field quality
  - Engineering simplicity: no pre-stress; fast prototyping
  - Simpler and cheaper than conventional designs
  - But: more conductor for same field compared to conventional design

The CCT design in formulas

Tow layers are needed: The position of the centre of the groove is described by the following equations:

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



- 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 (90^o is zero strength, around 30^o gives maximum field)
- 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 disadvantage

- Each layer produces a field of the chosen multipole plus an (unwanted) solenoid field
- The solenoid fields of the two layers exactly cancel out, but the multipole fields add up
- Due to this cancellation, more conductor (~30% more) is needed to deliver the same field as a conventional design

The CCT advantage

- The field away from the edges has excellent homogeneity and purity, as it is produced by a perfect cosine(theta) current.
- Also, and most importantly for our application, the multipole mix is a *local* property of the magnet, which can vary along its length
- This is not possible with a traditional design.
- Stress management: highest stress where material is strongest; no need to pre-stress

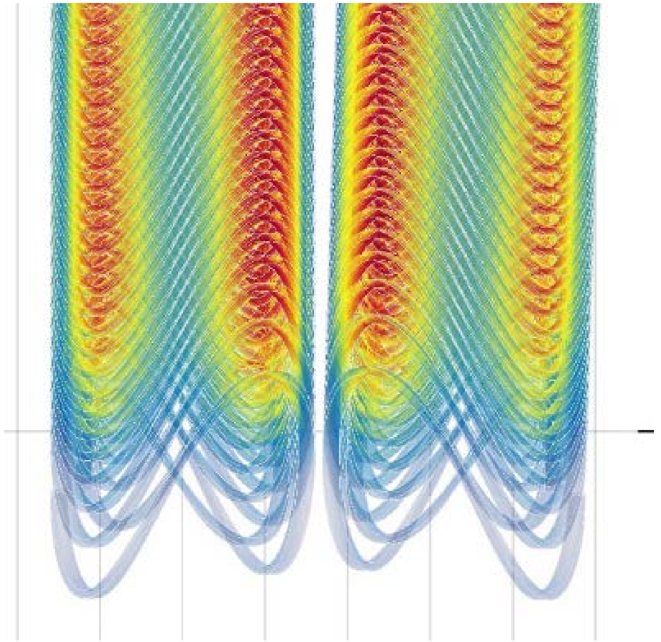
Iron-free design

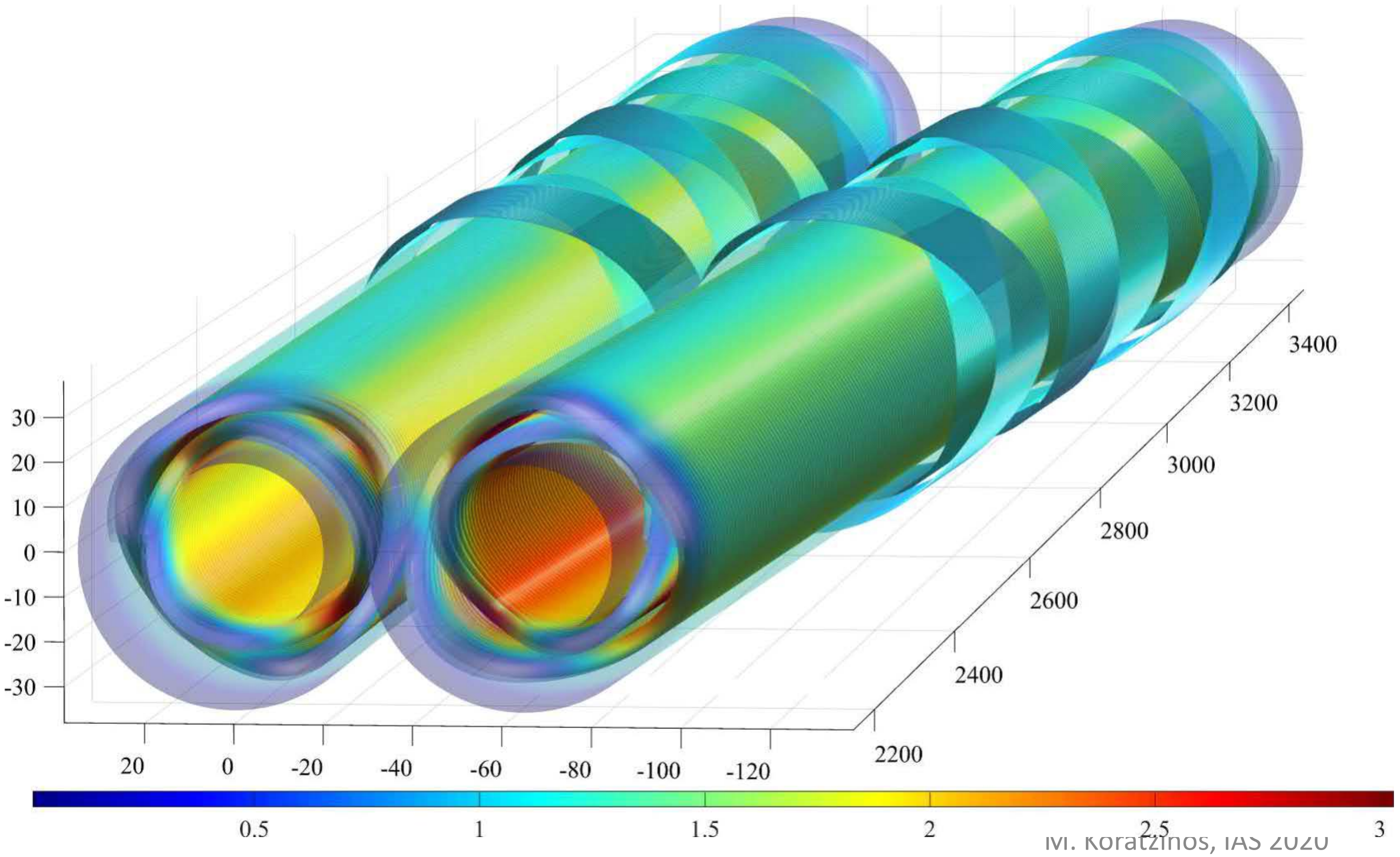
- Iron cannot provide the elimination of cross-talk, since there is very little space between magnets (~2mm between coils!)
- Therefore, the compensation must be embedded in the quadrupole design
- This can be trivially done in a CCT design
- Keep in mind that iron-free also means that everything is linear

First mention of a CCT approach for a similar application: Paoloni et al. for the SuperB project

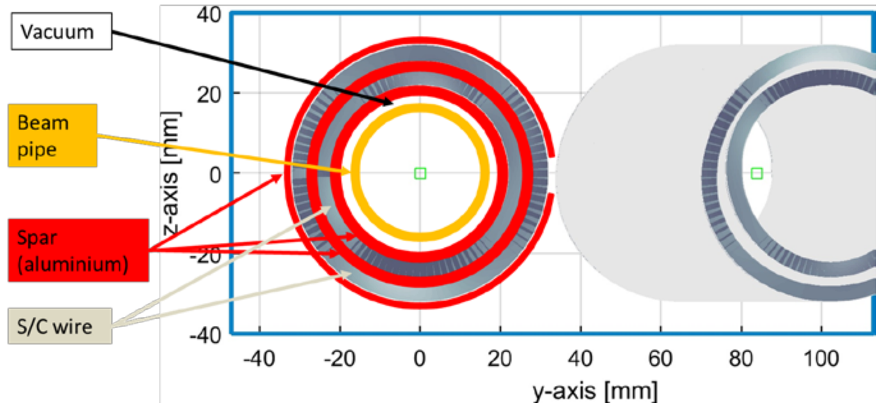
QC1L1

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

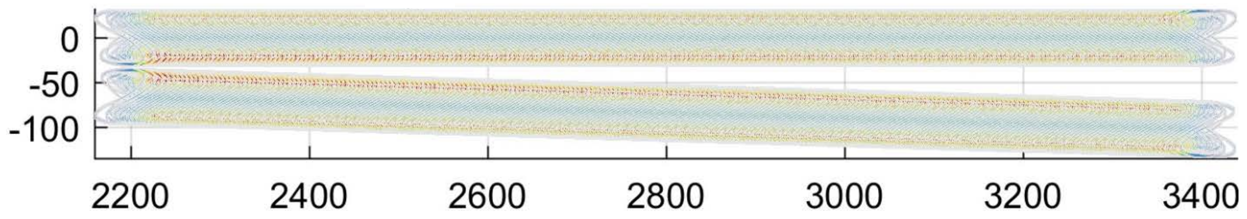




Inner bore: 40mm (diameter)
Fits outside the warm water-cooled beam pipe of inner diameter 30mm

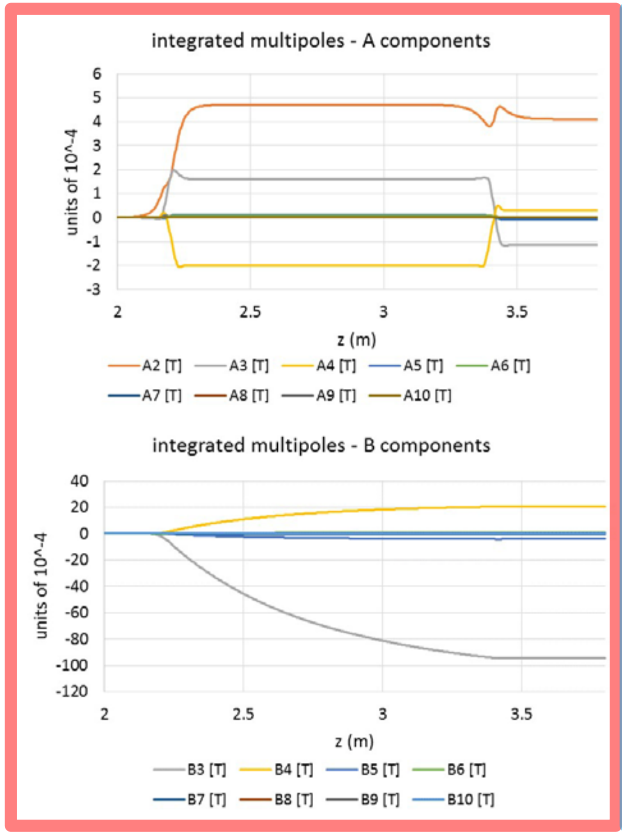


Crosstalk compensation

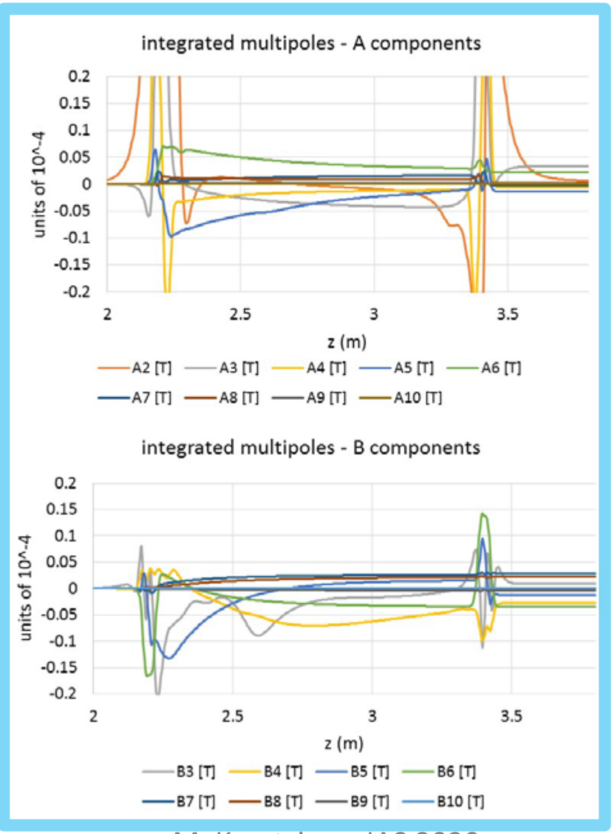


QC1L1 quadrupole:
length = 1200mm
Aperture: 40mm
distance at tip: 66mm
angle 30mrad
powered together

Before compensation



After compensation

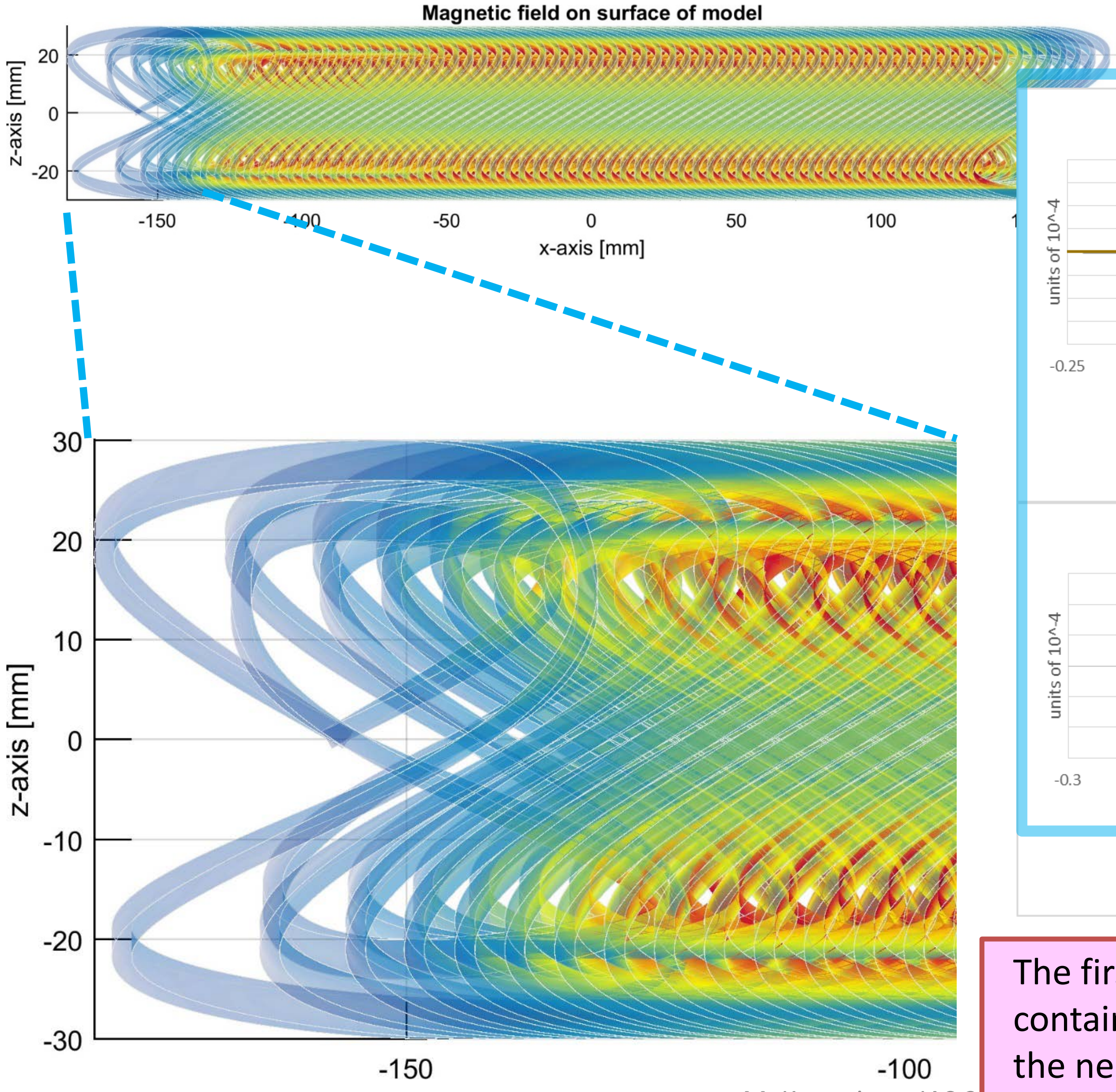


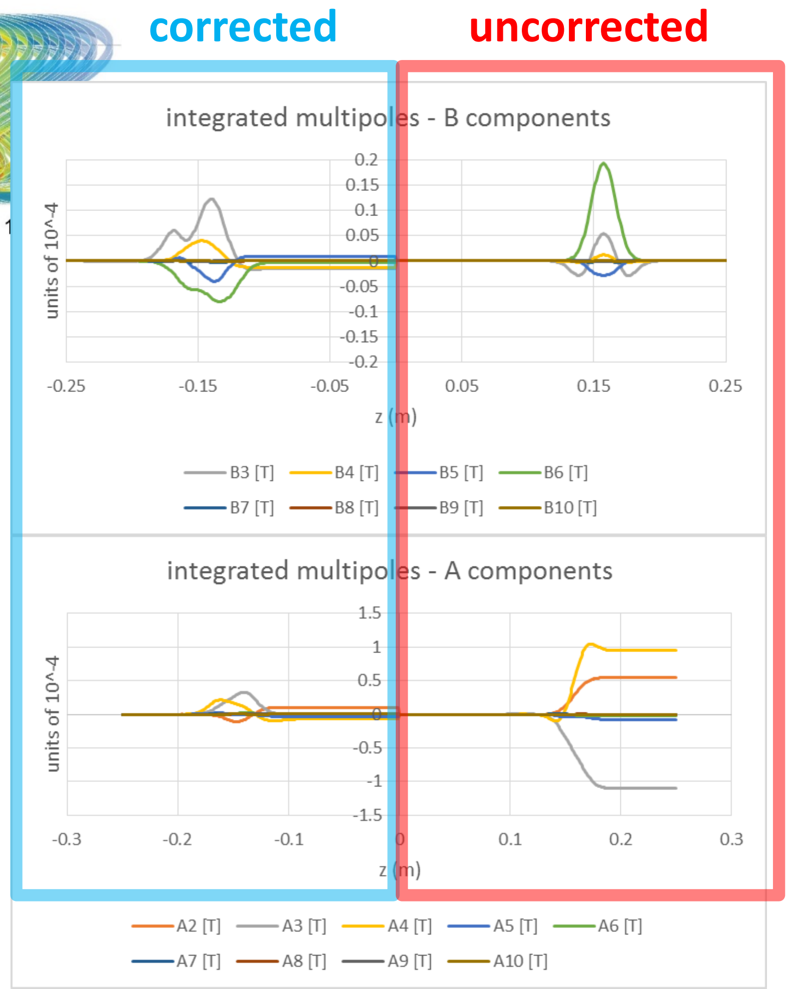
After compensation: all multipoles are under 0.1 units (limited by alignment errors, not included here)

A step further: local edges correction

- We now have a design with integrated multipoles of <0.1 units of 10^{-4}.
- There are, however, local field errors at the edges of the quadrupole. These integrate out when considering the whole length of the quadrupole.
- However, we are in a very demanding environment: field quality should be excellent even locally as we sit in an area of rapidly varying optics functions (the beam size at one and the other end of the quadrupole is different – beta_y @2.2m = 6km; beta_y at 3.4m = 14km

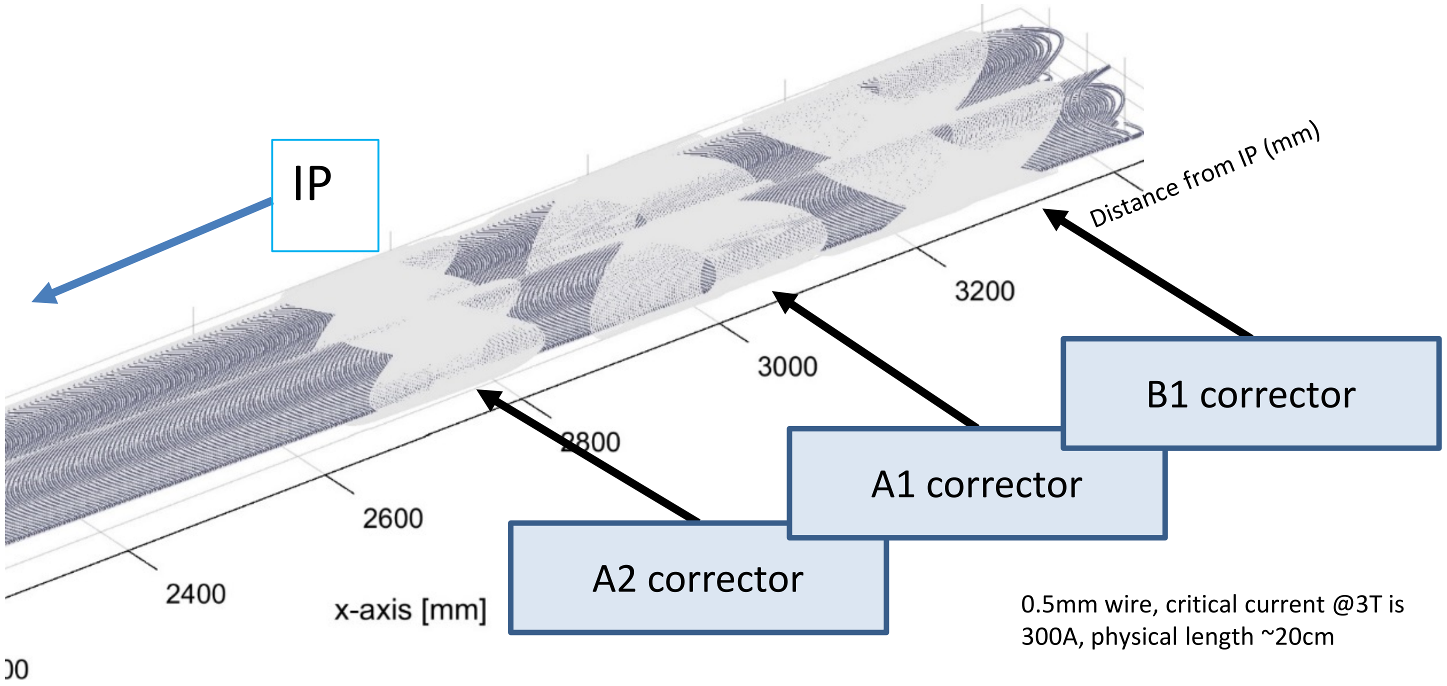
The FF quadrupole – local edge compensation





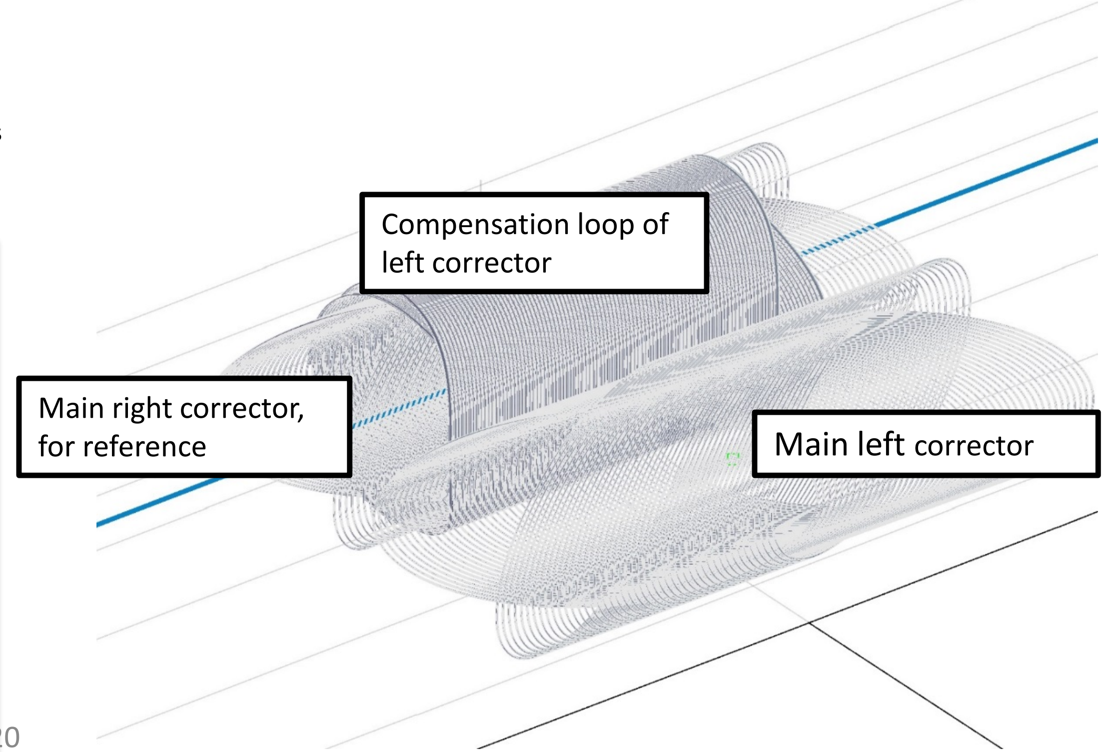
The first two turns of the quadrupole contain, apart from the B2 component, all the necessary components to nullify the edge effects.

Correctors



Correctors can be packaged very efficiently

- Optics requirements are that a number of correctors are needed as close to the IP as possible
- The absence of iron in this design makes it possible to include a number of correctors as extra rings on top of the quadrupole
- These correctors do not take extra (longitudinal) space in the design.
- Each corrector comes with its own compensating coil in the other aperture to compensate for the (small) crosstalk



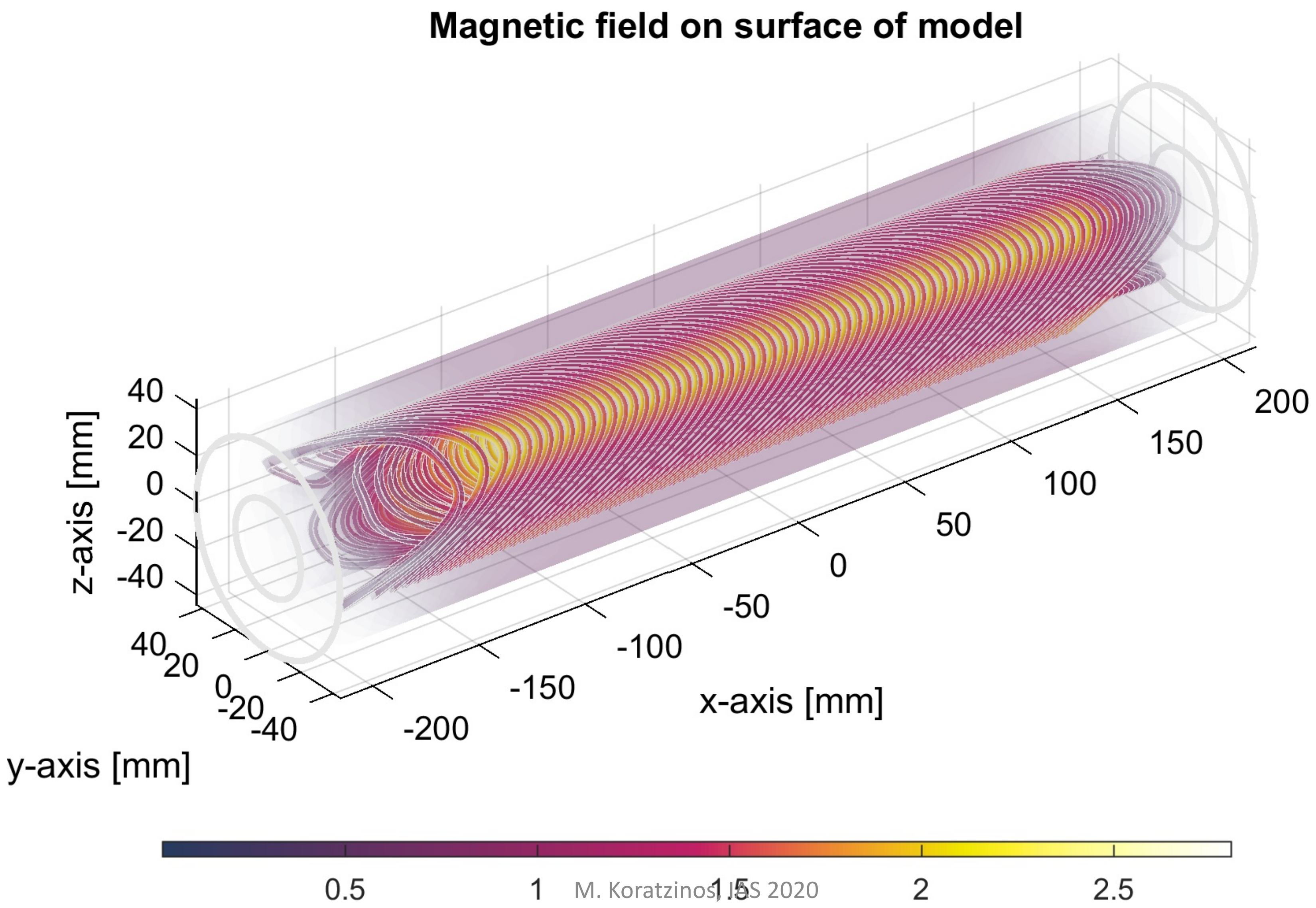
The FCC-ee Final Focus magnets

	Start position (m)	Length (m)	B' @Z (T/m)	B' @$W^{\pm}$ (T/m)	B' @Zh (T/m)	B' @$t\bar{t}$ (T/m)
QC1L1	2.2	1.2	−78.60	−96.16	−99.98	−100.00
QC1L2	3.48	1	+7.01	−40.96	−99.94	−100.00
QC1L3	4.56	1	+28.40	+22.61	+26.72	−100.00
QC2L1	5.86	1.25	+2.29	+40.09	+23.75	+58.81
QC2L2	7.19	1.25	+9.05	+3.87	+39.82	+68.18
QC1R1	−2.2	1.2	−79.66	−100.00	−99.68	−99.60
QC1R2	−3.48	1	+5.16	−37.24	−92.78	−99.85
QC1R3	−4.56	1	+36.55	+24.02	+5.87	−99.73
QC2R1	−5.86	1.25	+7.61	+45.51	+36.45	+63.03
QC2R2	−7.19	1.25	+4.09	+3.95	+44.43	+77.91

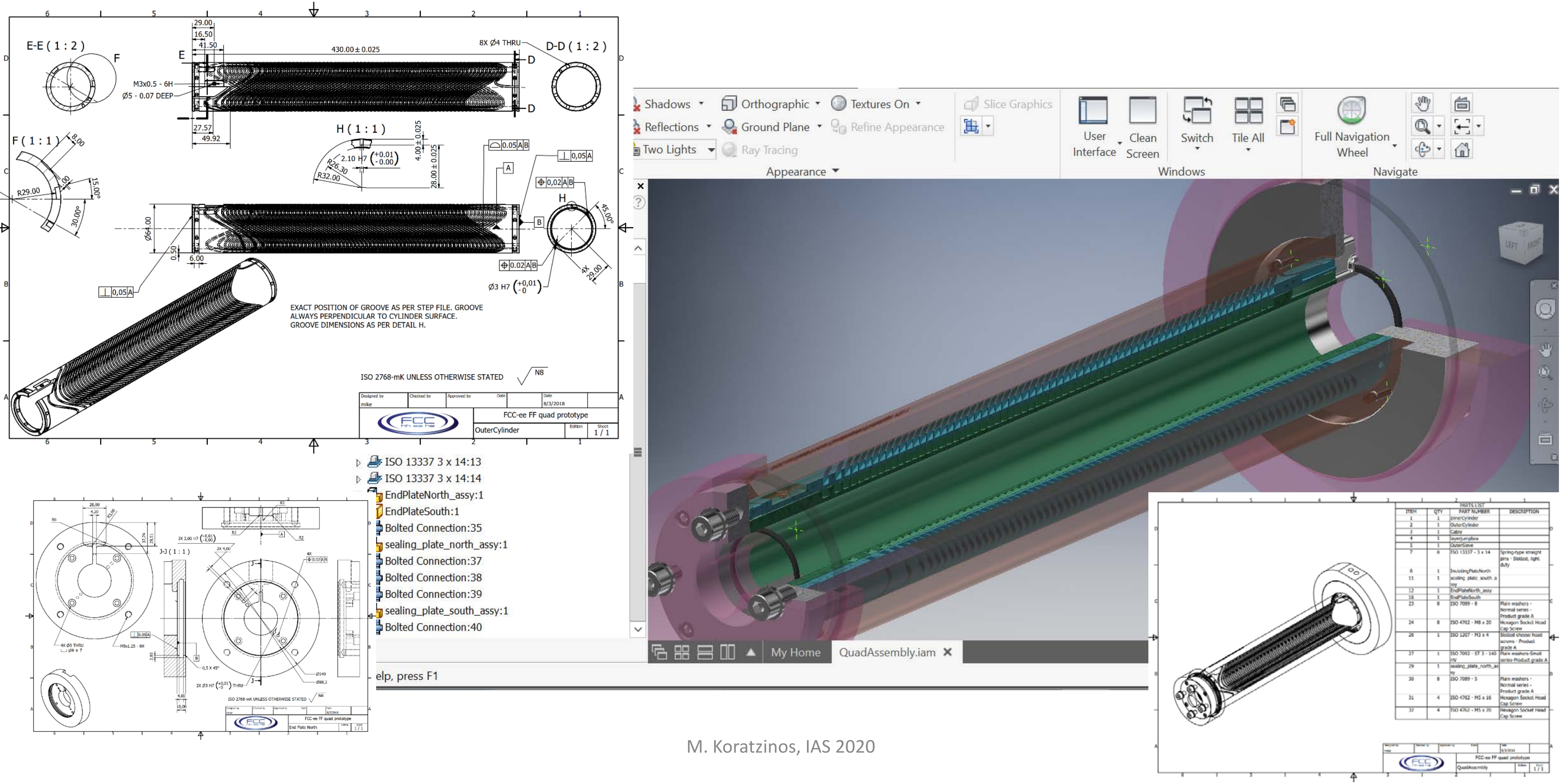
FF prototype news

- CCT is a relatively new idea in magnet design, and never one has been built with compensation. It is therefore imperative that a prototype is build and tested
- ➔ the FCC FF quad prototype project was born
- Steps completed:
  - Full magnetic analysis
  - Full mechanical design
  - Manufacturing of all parts and tools
  - winding table, with stepper motor
  - Winding completed
  - Outer sleeve and endplates installed.
  - Mechanical assembly completed
- Rotating probe (Carlo Petrone, CERN magnet group, Magnetic Measurement Section)
  - Sensing coils (special to quadrupoles) completed
  - Design of rotating shaft under way
  - Warm testing: Q1 of 2020
  - Cold testing: Q2 of 2020

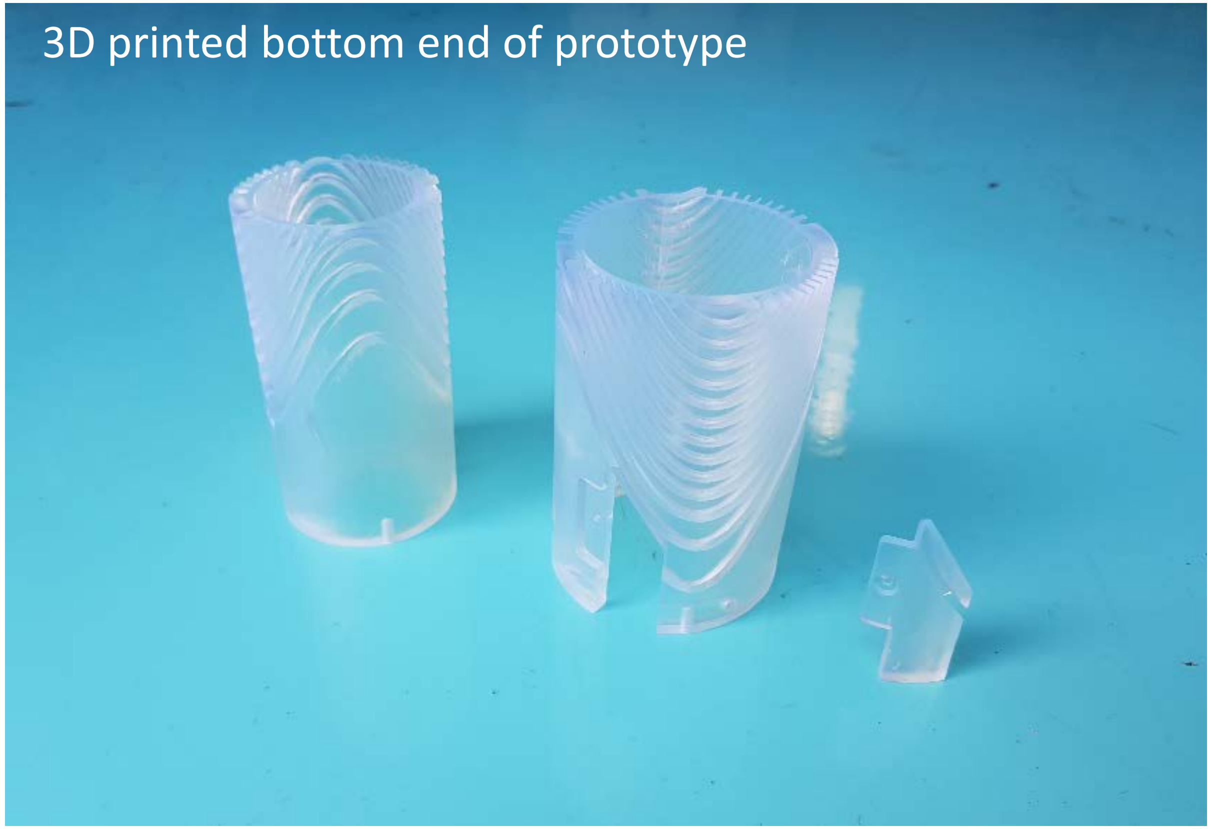
The FCC-ee FF quadrupole prototype – magnetic design



CAD design


E-E (1 : 2)
D-D (1 : 2)
F (1 : 1)
H (1 : 1)
430.00 ± 0.025
8X Ø4 THRU
M3x0.5 - 6H
Ø5 - 0.07 DEEP
EXACT POSITION OF GROOVE AS PER STEP FILE. GROOVE ALWAYS PERPENDICULAR TO CYLINDER SURFACE. GROOVE DIMENSIONS AS PER DETAIL H.
ISO 2768-mK UNLESS OTHERWISE STATED
FCC-ee FF quad prototype
OuterCylinder
Shadows
Orthographic
Textures On
Slice Graphics
Reflections
Ground Plane
Refine Appearance
Two Lights
Ray Tracing
Appearance
User Interface
Clean Screen
Switch
Tile All
Windows
Full Navigation Wheel
Navigate
ISO 13337 3 x 14:13
ISO 13337 3 x 14:14
EndPlateNorth_assy:1
EndPlateSouth:1
Bolted Connection:35
sealing_plate_north_assy:1
Bolted Connection:37
Bolted Connection:38
Bolted Connection:39
sealing_plate_south_assy:1
Bolted Connection:40
My Home
QuadAssembly.iam
elp, press F1
PARTS LIST

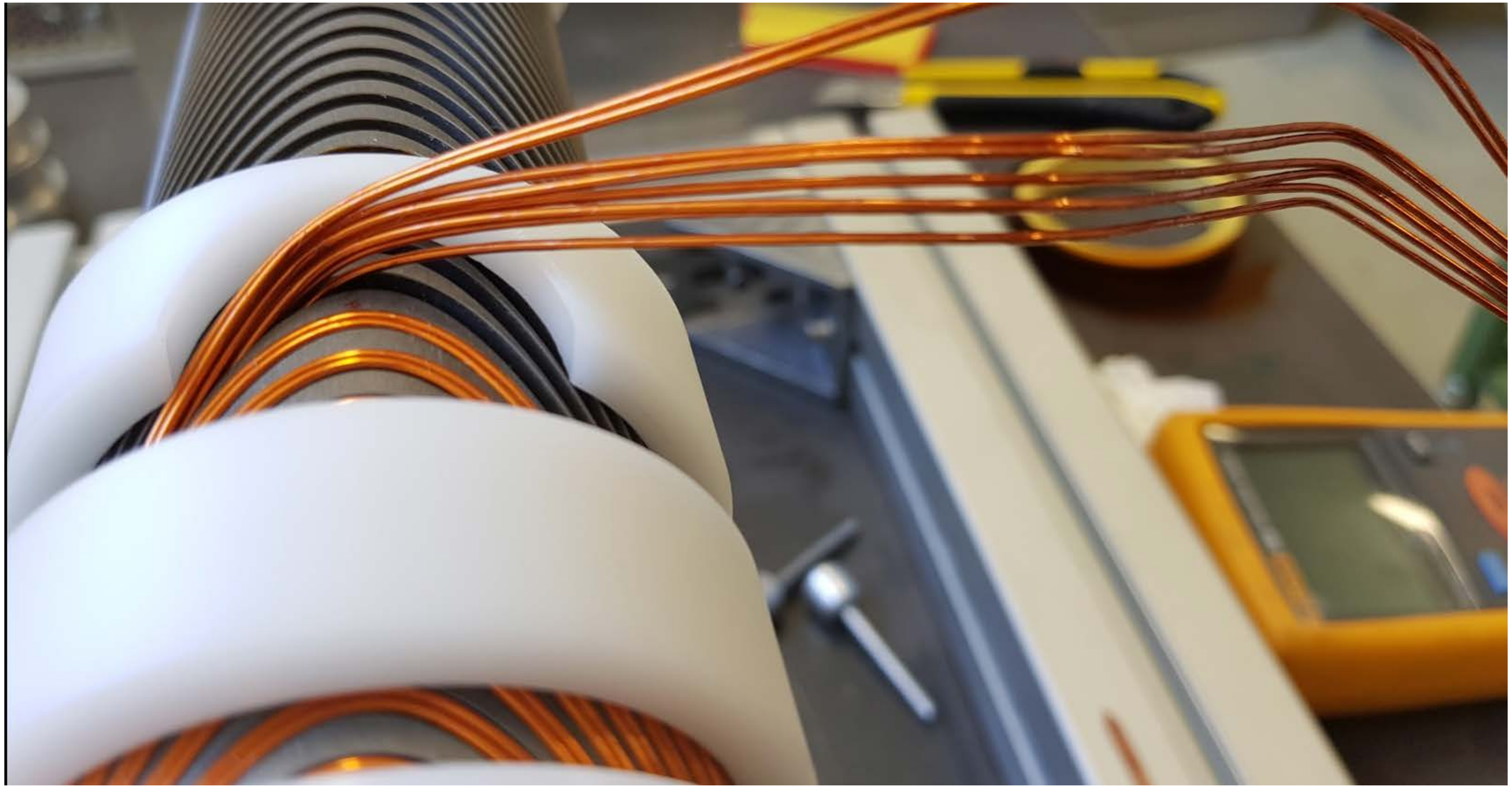
Quick prototyping and manufacturing



Precision: ±25 µm; new CNC machine can do < 10 µm

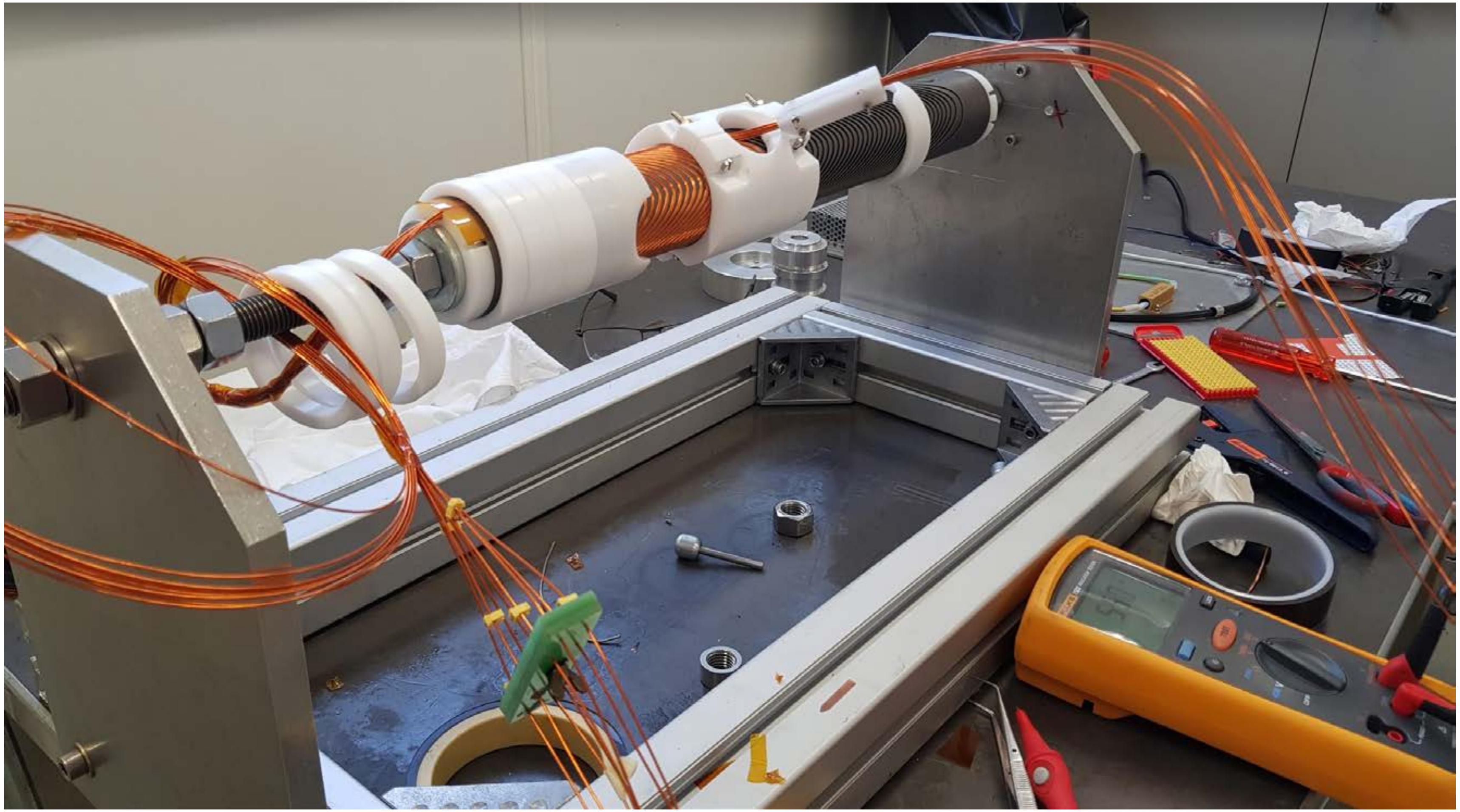
Arrival of machined parts

Winding process

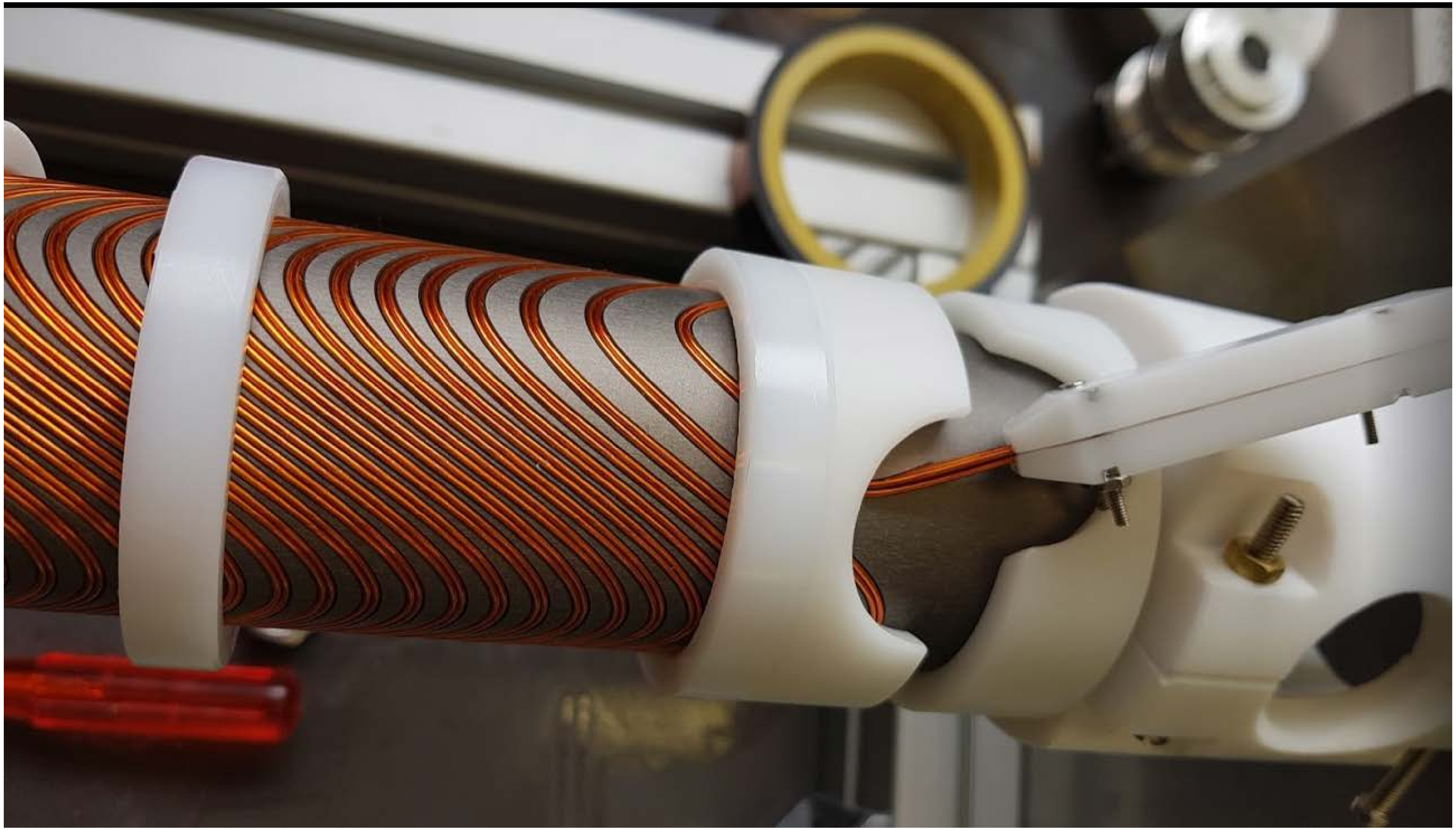


Inner layer started

Inner layer half way

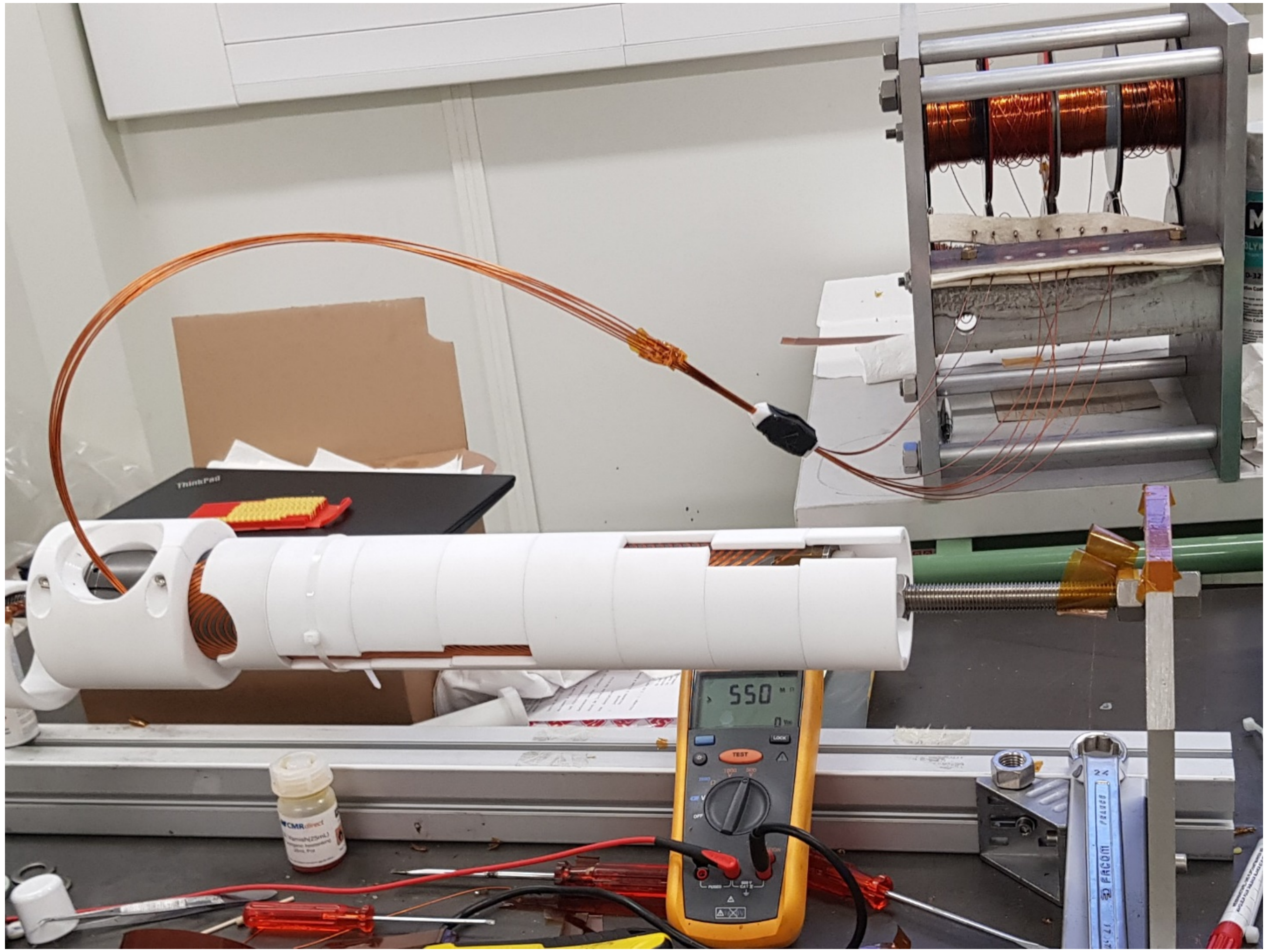


Inner layer done

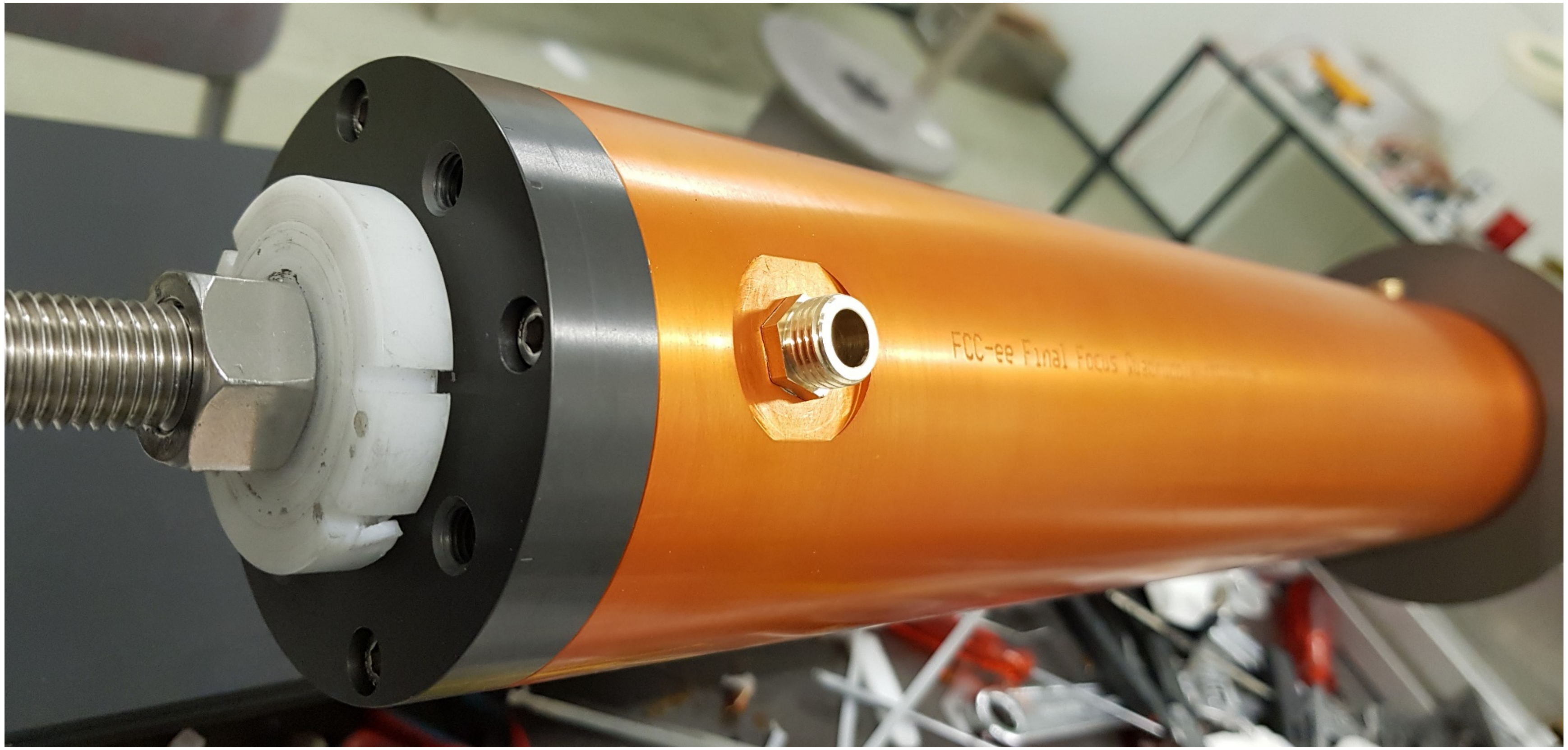


Outer layer half way

Outer layer done



With sleeve and end plates



…just in time for Christmas!

A warning from SuperKEKb

Robustness of the final quads against beam loss (2)

This is a warning from SuperKEKB!!

- The final quads and solenoids must be robust enough against beam losses. Esp. thin corrector windings.
- Otherwise a too deep collimation is required, which is even more dangerous against to occasional beam losses due to dusts, etc.
- A collimator right upstream the interaction region can be harmful to the detector by causing showers.
- In the worst case, we may have to redesign the final quads with larger apertures, which mean longer L* and/or larger crossing angle. Both affects the luminosity performance!

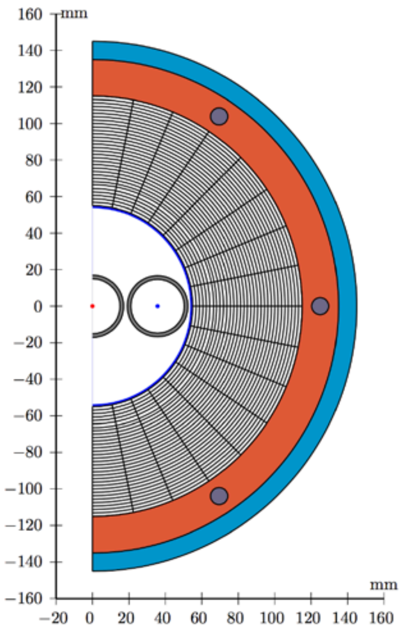
K. Oide, 26/6/2019

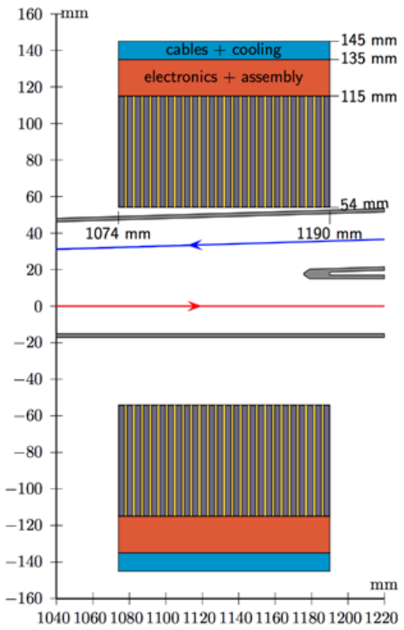
- Although NbTi conductor is adequate for the FF quads and correctors, we should consider HTS conductors because of the extra margin we will get against quenches.
- This is a technology that can be tested today
- We can be sure that in 20 years HTS conductors will be cheaper and better

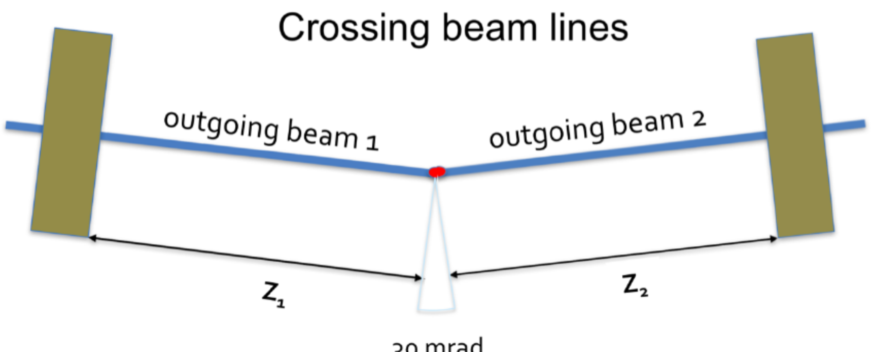
LumiCal

Goal: absolute luminosity measurement to 10^{-4} at the Z

- The luminosity calorimeter is a key device in the MDI area: tight space, alignment and background requirements.







Vital statistics:

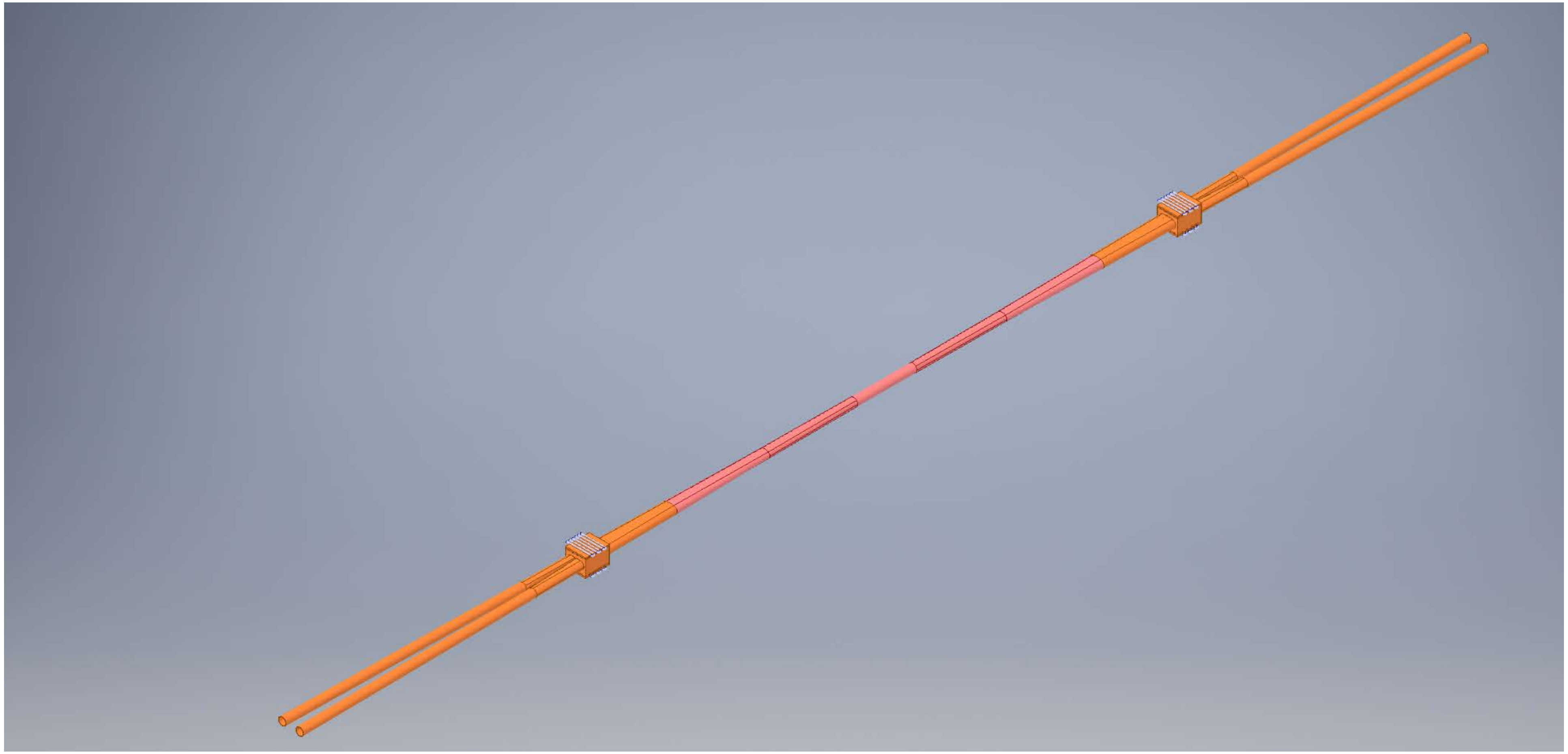
- W+Si sandwich: 3.5 mm W + Si sensors in 1 mm gaps
- 25 layers total: 25 X0
- Cylindrical detector dimensions:
  - Radius: 54 < r < 145 mm
  - Along outgoing beamline: 1074 < z < 1190 mm
- Sensitive region: 55 < r < 115 mm
- Detectors centred on and perpendicular to outgoing beamline
- Angular coverage(>1 Moliere radius from edge):
  - Wide acceptance: 62-88 mrad
  - Narrow acceptance: 64-86 mrad
  - Bhabha crosssection@ 91.2 GeV: 14 nb
- Region 115 < r < 145 mm reserved for services:
  - Red: Mechanical assembly, read-out electronics, cooling, equipment for alignment; Blue: Cabling of signals from front-end electronics to digitizers

Accuracy:
Aim for construction and metrology precisionof 1 μm

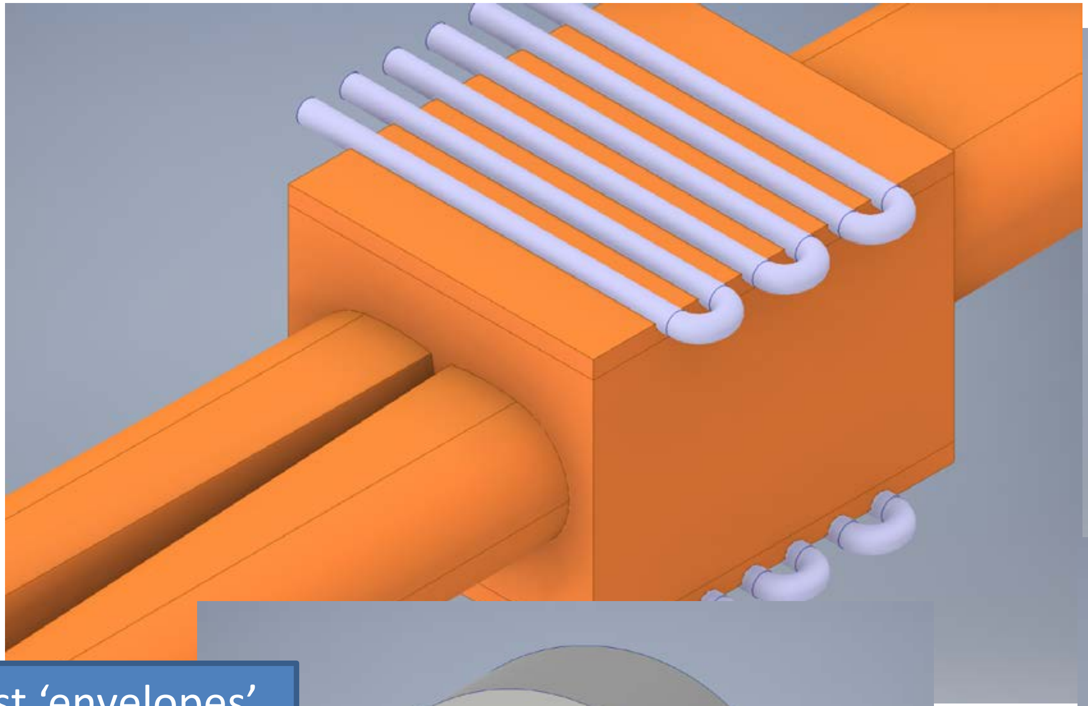
Mechanical design

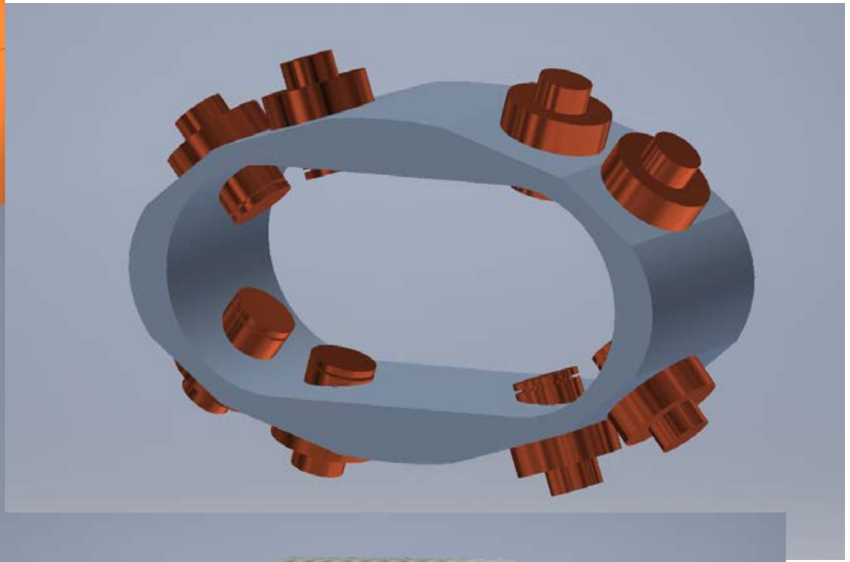
- Going towards a TDR, we need a mechanical design study, at least at the conceptual level
  - can the system be built?
  - Can it be assembled?
  - Can it be cooled?
  - Can we stay within the 100mrad cone?
  - How about vibrations? Will they kill luminosity?
- An effort for a conceptual mechanical design has just started
  - We are still not at the level of a real, detailed, mechanical design

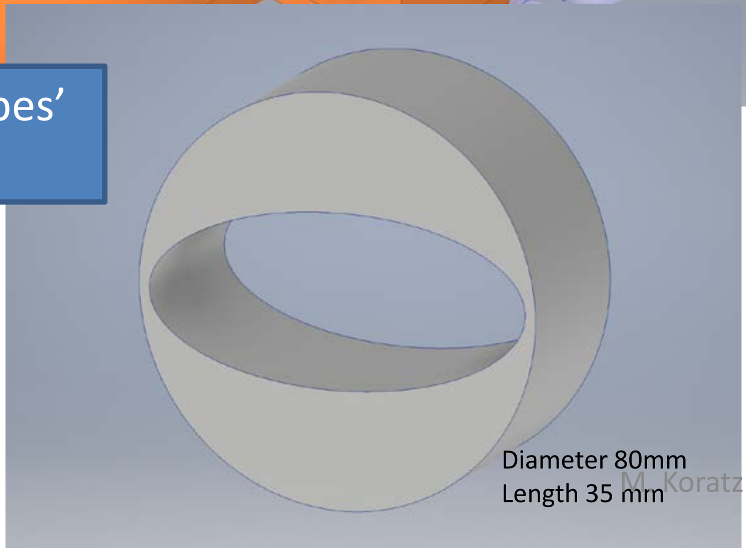
Beam pipe and HOM absorbers

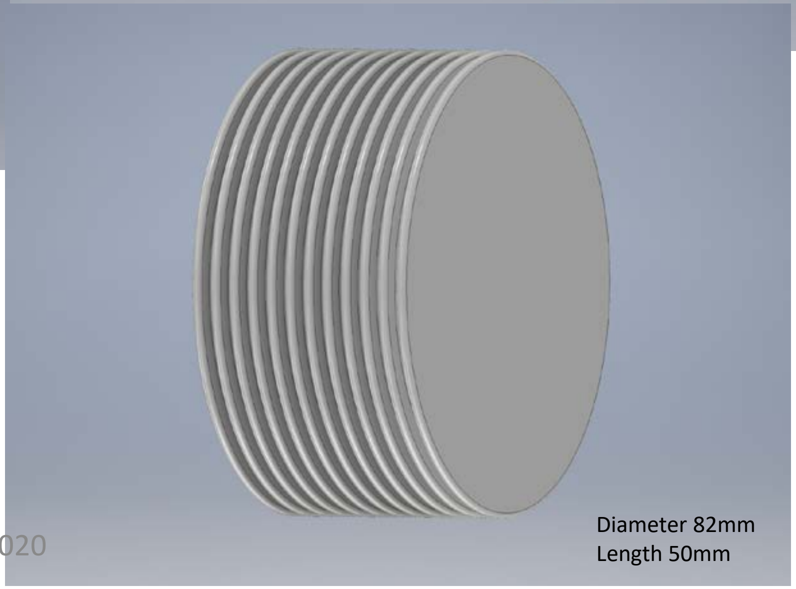


HOM absorber, BPM, remote flange, bellows



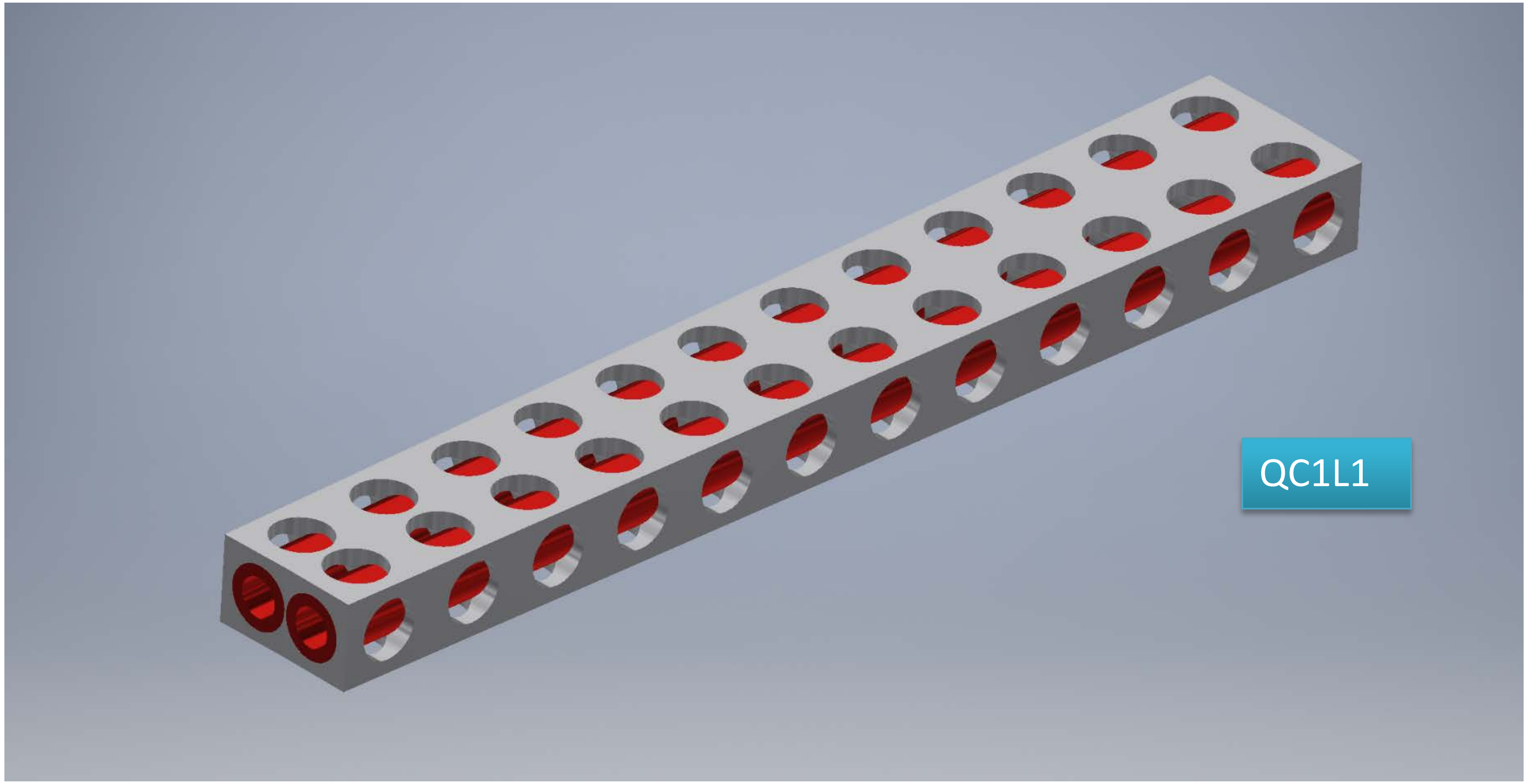




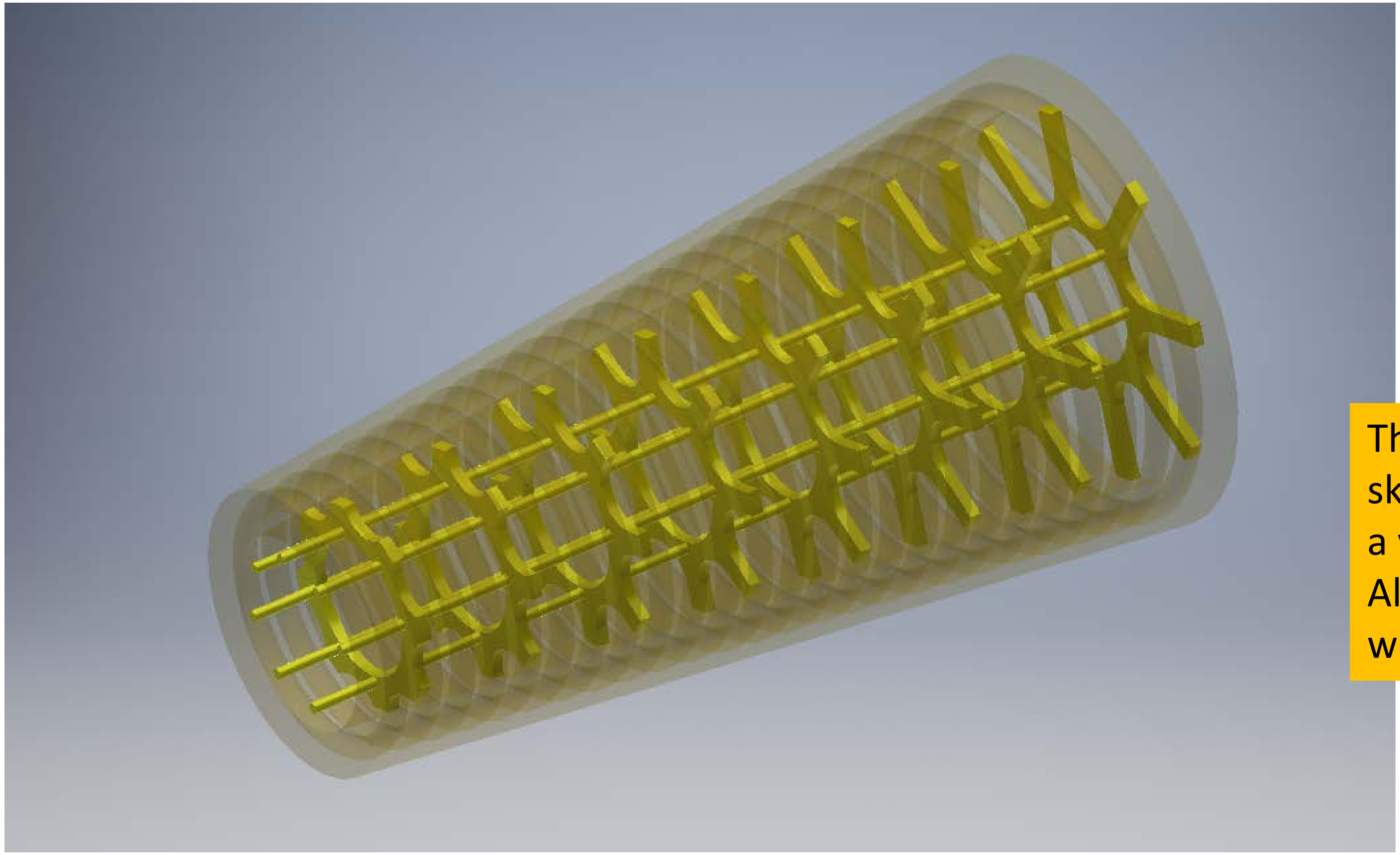


These are just 'envelopes' of the final parts!

FF quad assembly

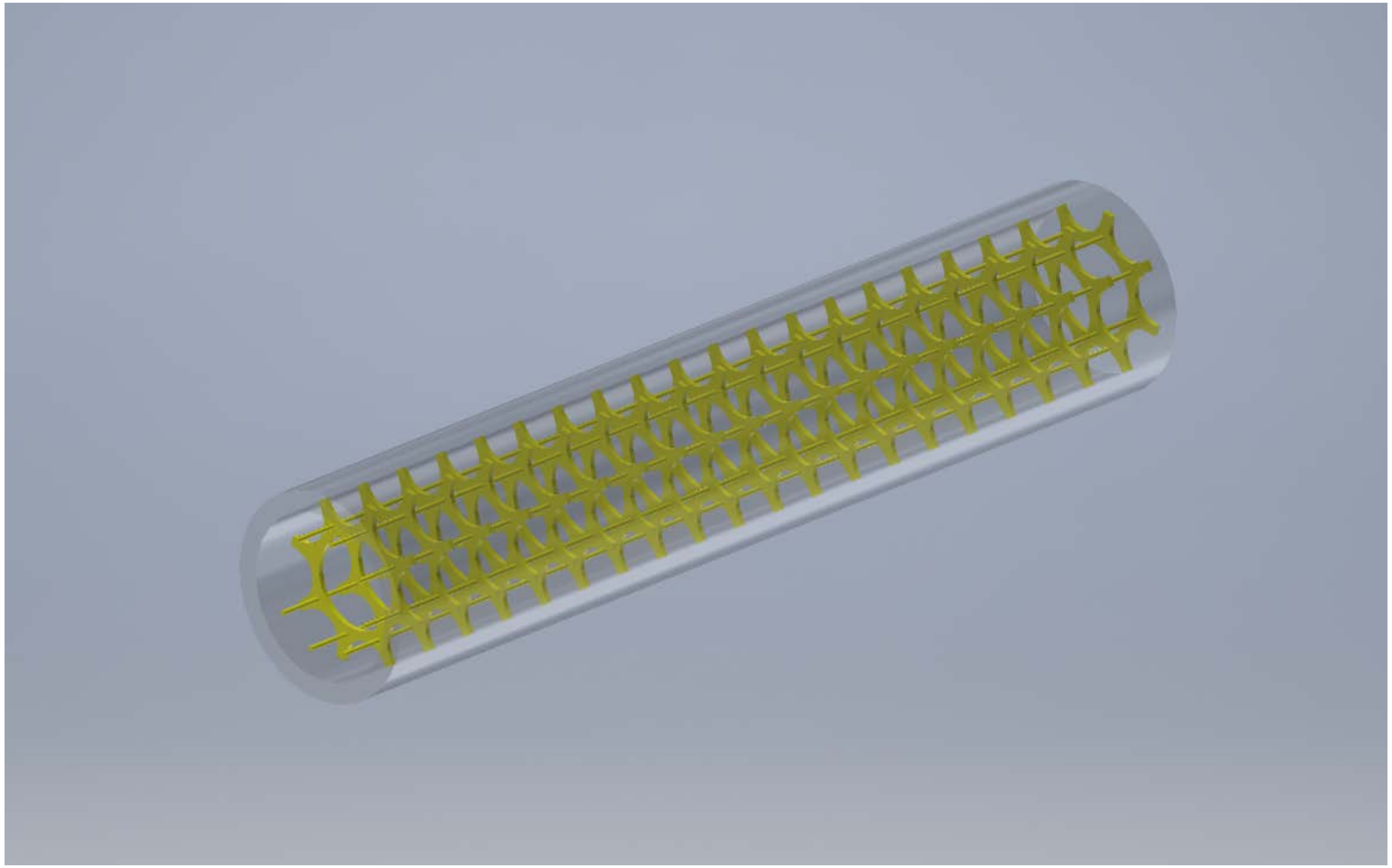


Mechanical design: compensating solenoid with skeleton



The idea is to use a stiff skeleton which will replace a very heavy cryostat.
All load bearing capability will rely on this skeleton

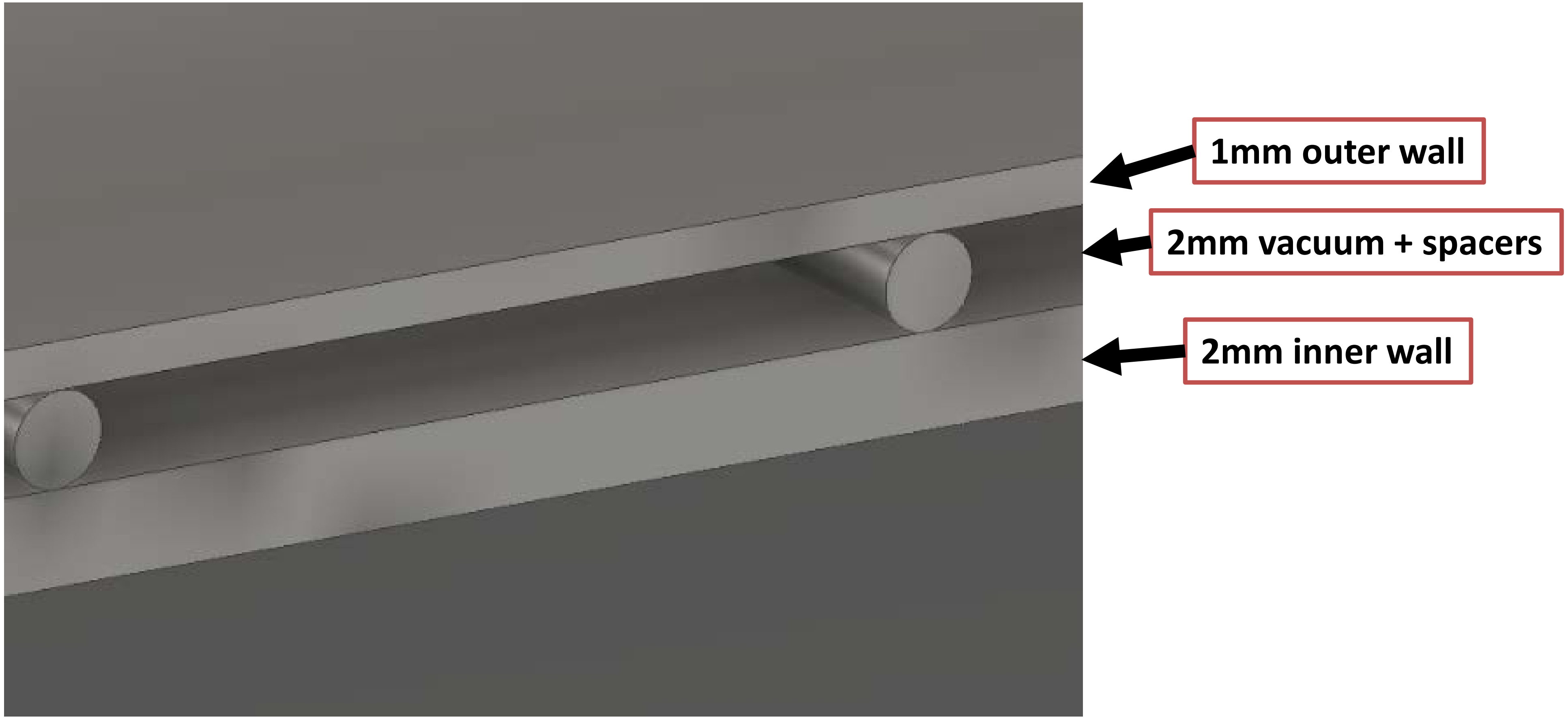
Screening solenoid with skeleton



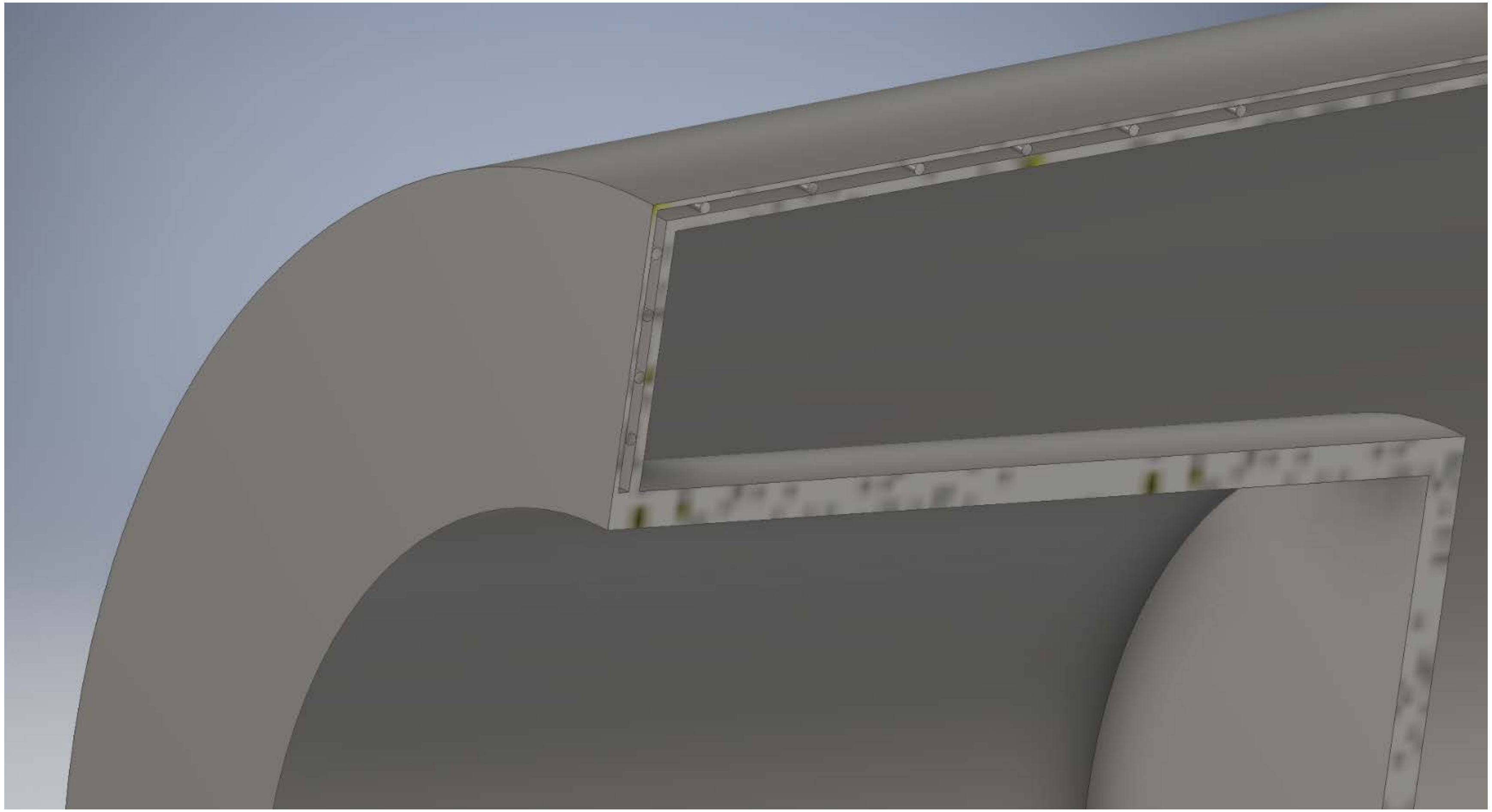
Thin cryostat

- The rule of thumb is that the cryostat adds an extra 2% to the dimensions of the system.
- (In our case, the screening solenoid radius near the IP is 123mm. Therefore, expect a cryostat about 2.5mm thick!)
- A very preliminary non-load bearing cryostat has been attempted with a thickness of 5mm.

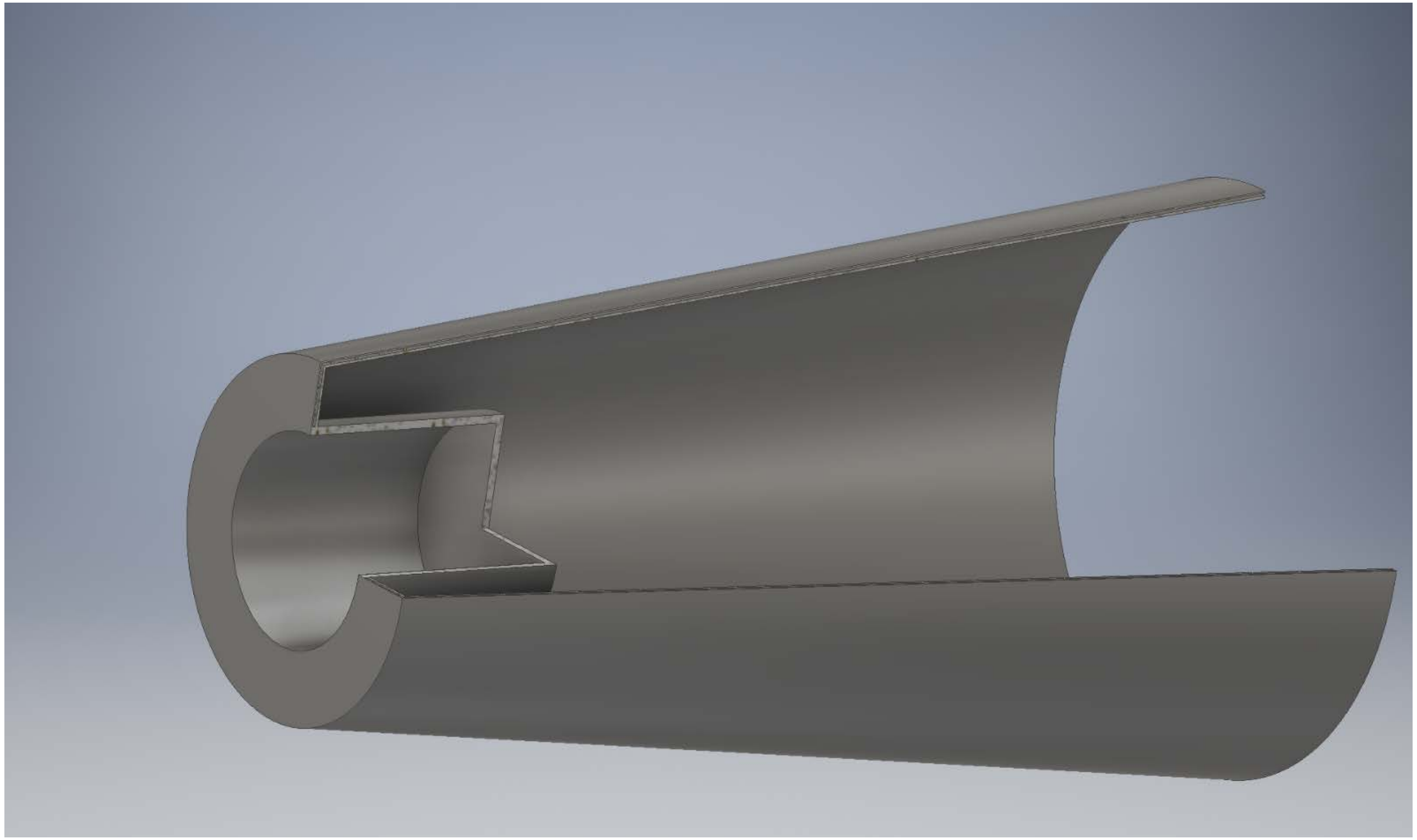
Thin cryostat



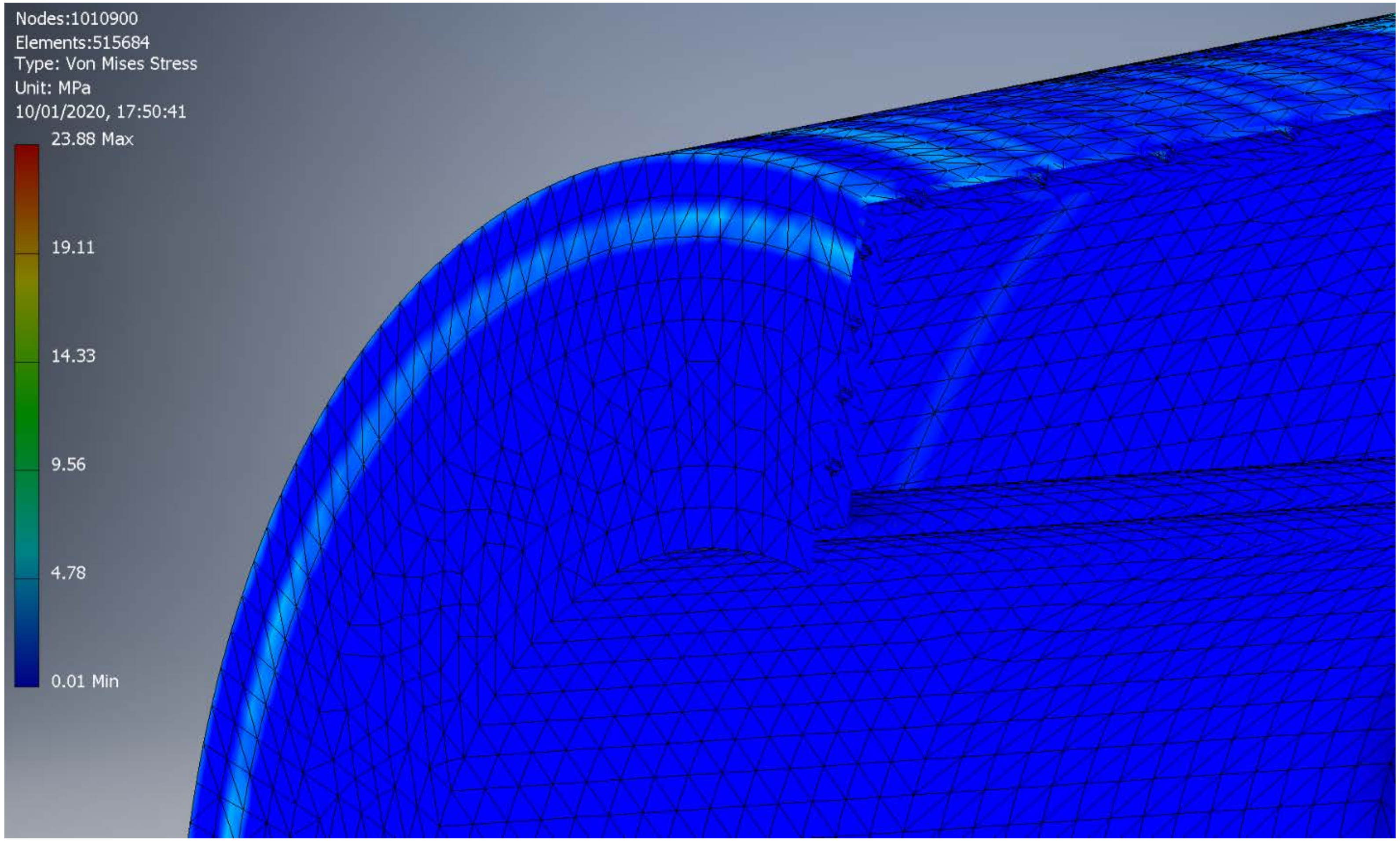
Thin cryostat



Thin cryostat



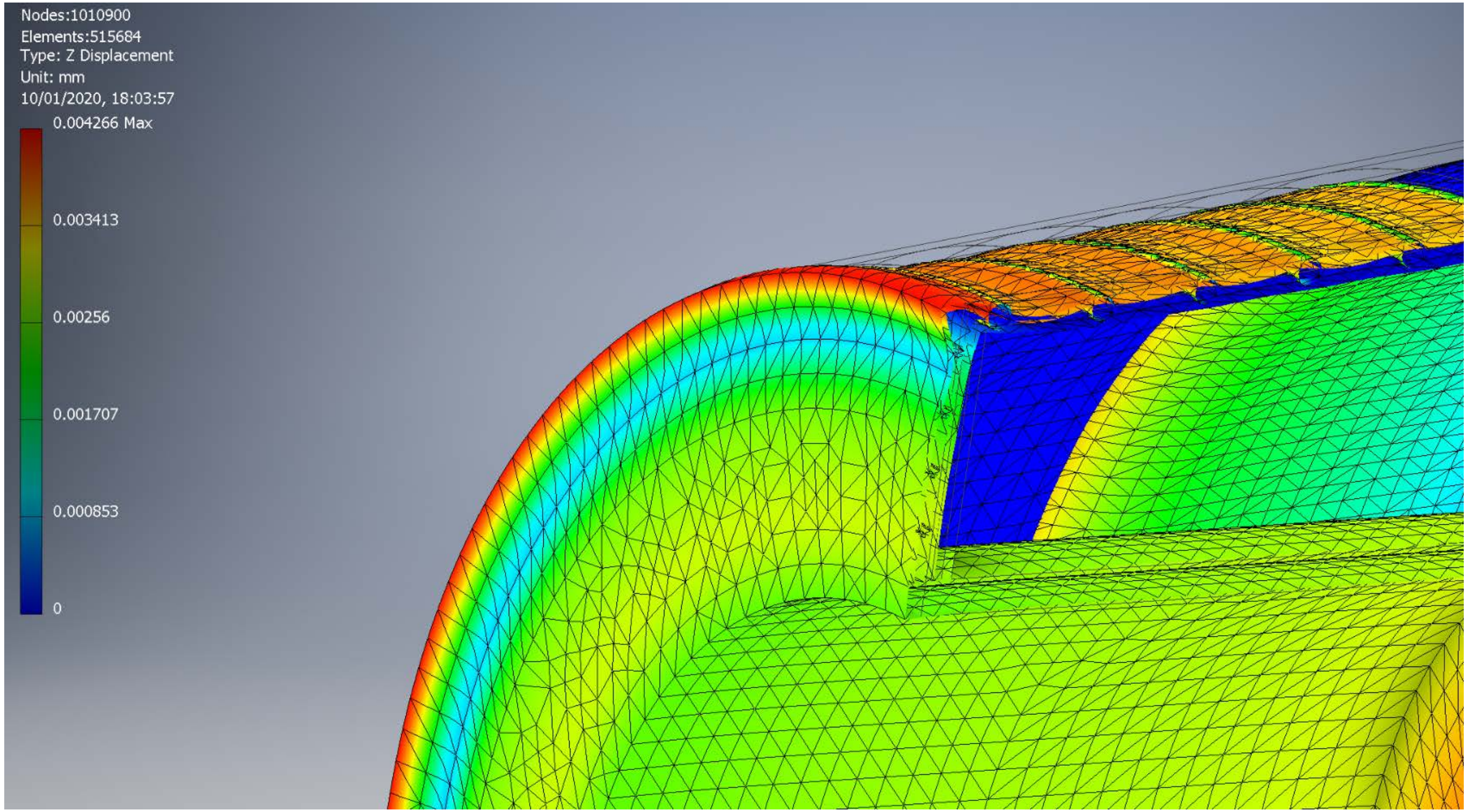
Von Mises Stress analysis



Safety factor: 10.5 minimum

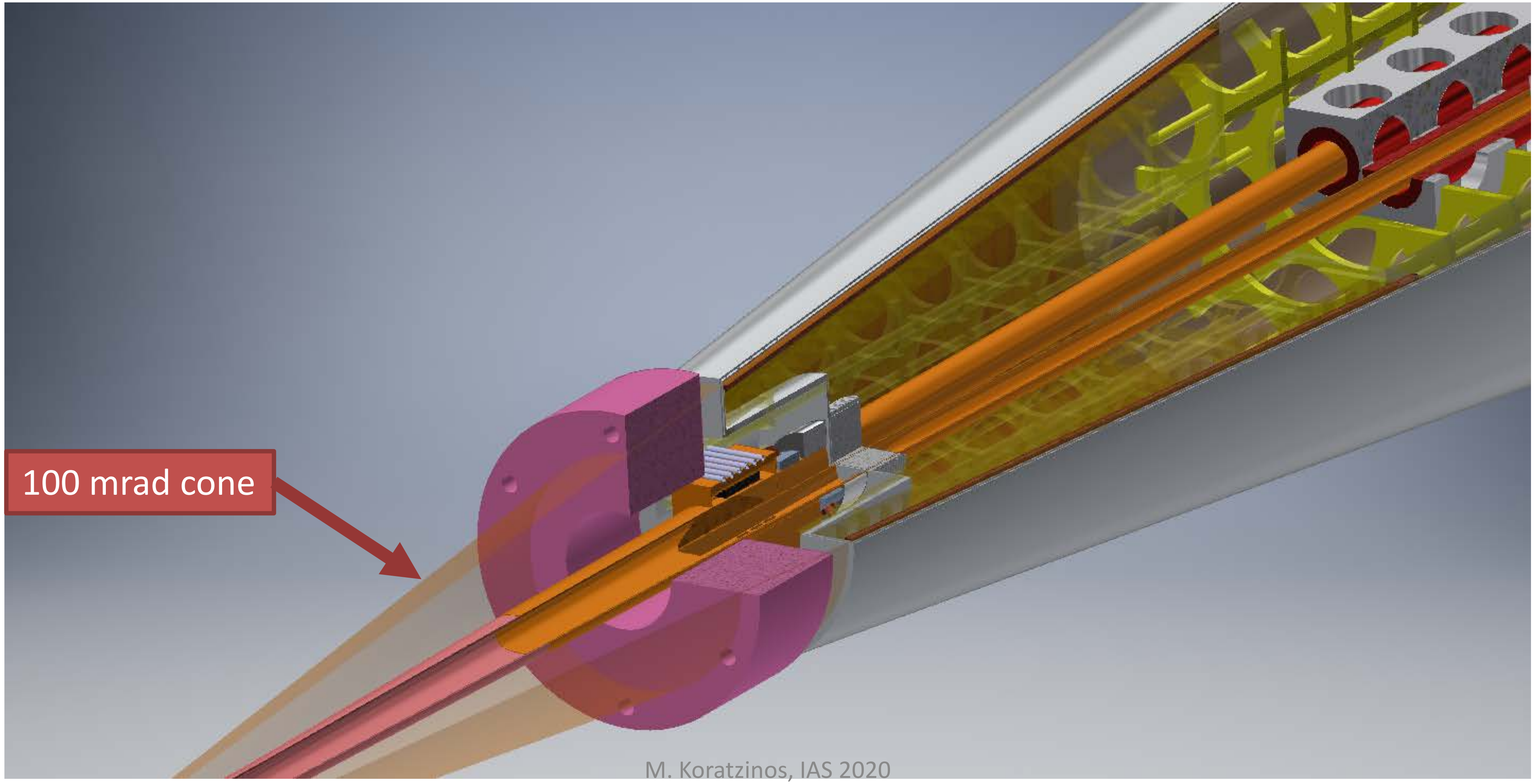
This is overengineered

deformation

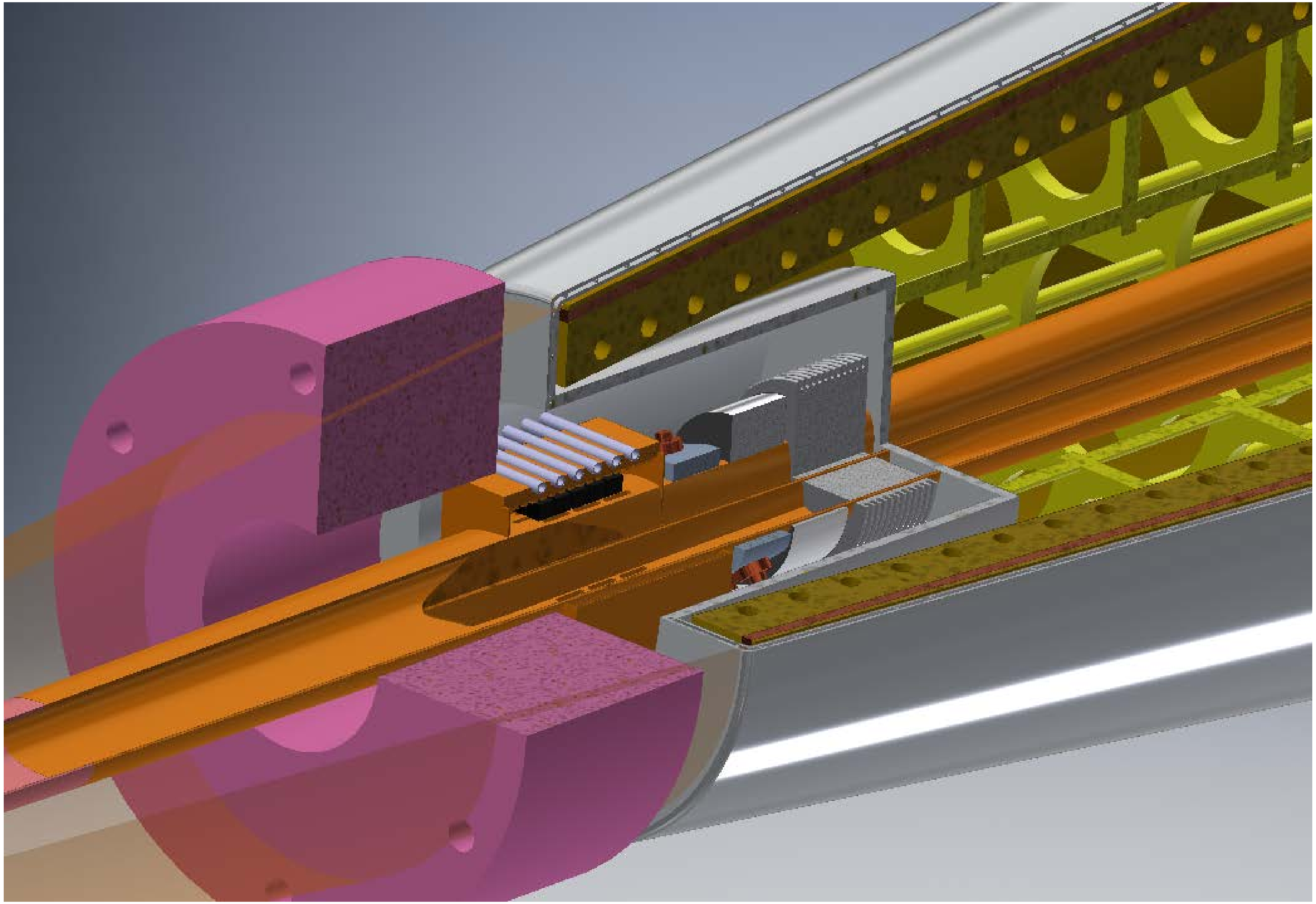


It will not collapse under vacuum safety factor is 10

All elements, including cryostat

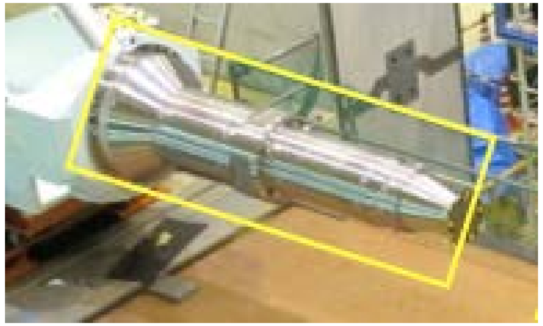


Zoom on front face of cryostat

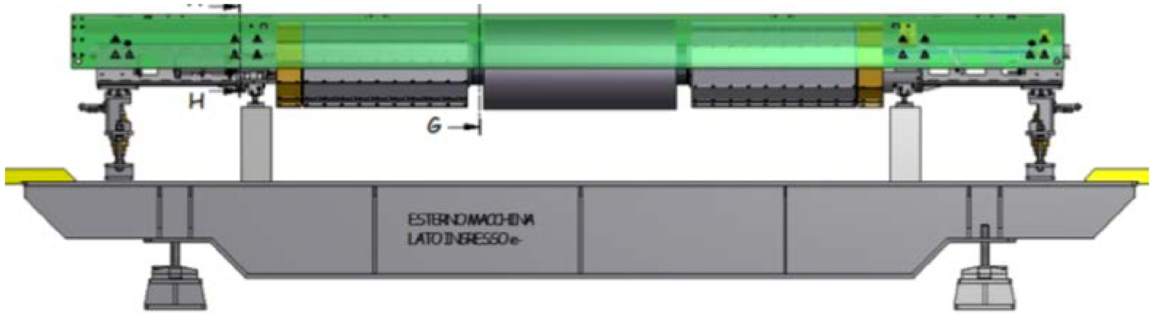


Integration and assembly

- We have two options for suspending the various MDI elements inside the detector
  - Cantilever design a-la SuperKEKb



  - One piece insert like DAFNE

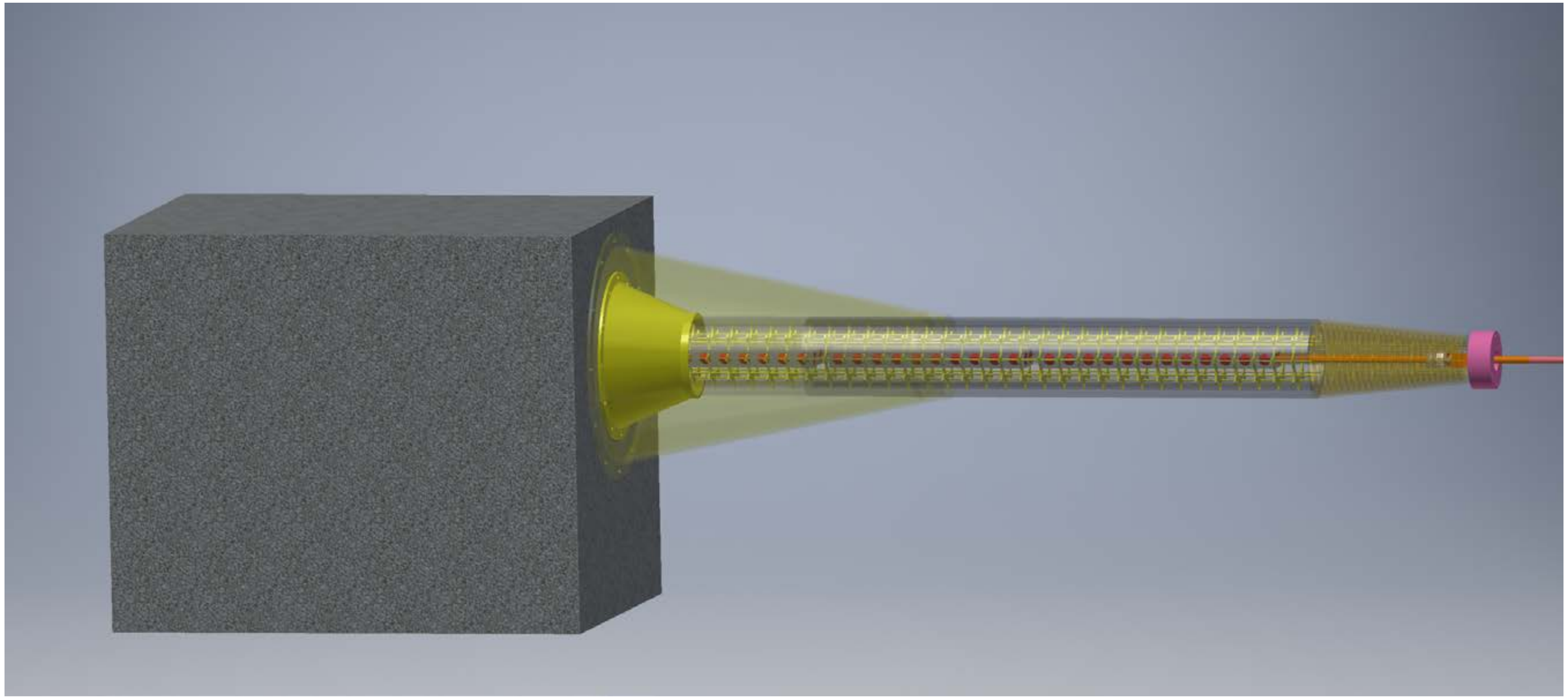


A cantilever design
- needs a remotely operated flange
- The two sides are decoupled

A one piece insert
- Needs a lot of space one one side of the detector
- The detector hole is defined by the largest cross section

My personal preference is on a cantilever design

Cantilever assembly



From support to tip of
compensating solenoid

4370 mm

Vibration studies

- Our beam size is only a few tens of nanometres!
- The cantilever design will vibrate with an amplitude orders of magnitude larger
- Good news: any vibration, even independent vibration right and left, common to the e+ and e- quads per side cancels out
- We are only left with torsional vibration (that has smaller amplitude and higher frequency)

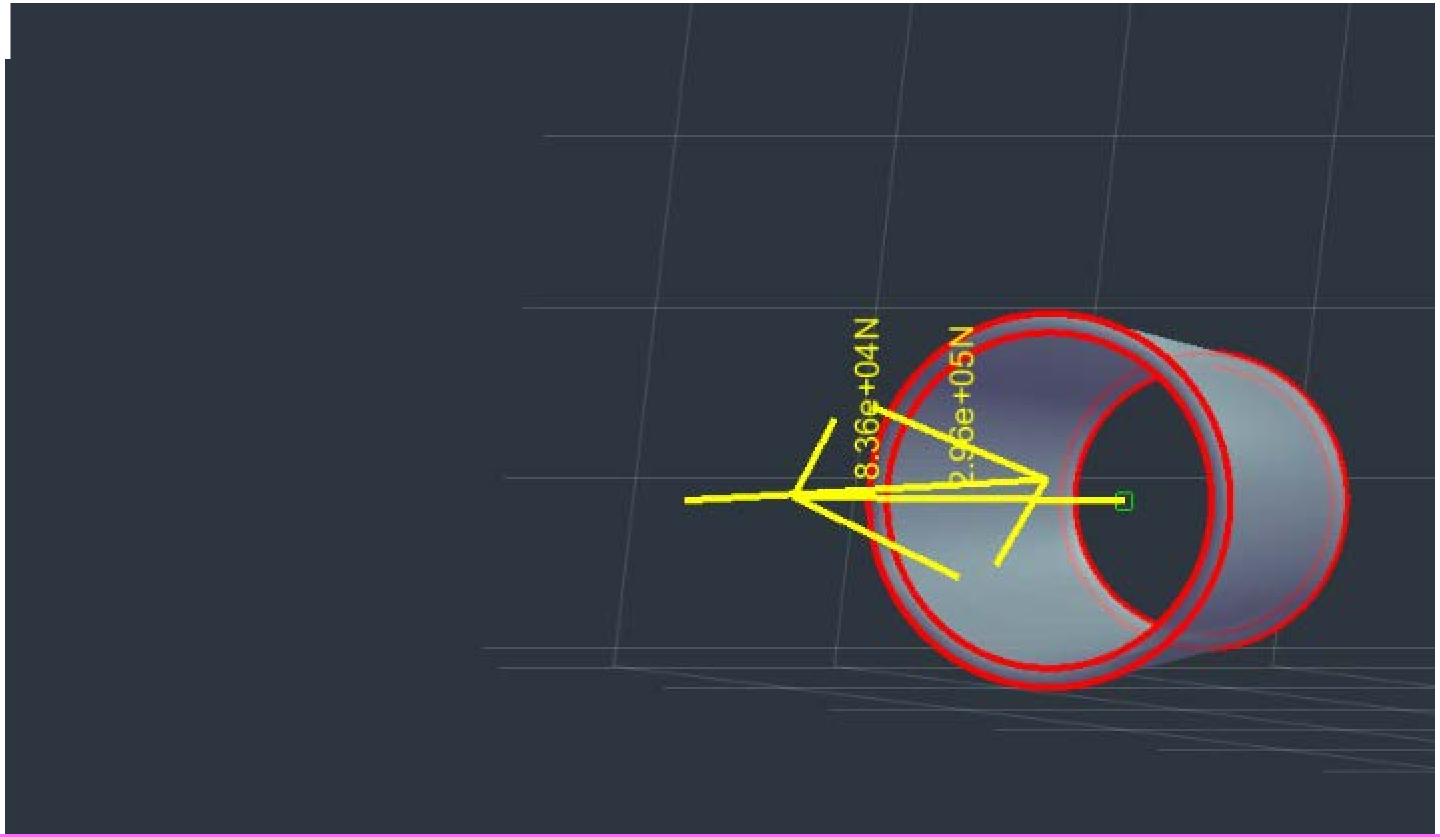
Modal analysis: F9, 306Hz

Here only one mode of vibration is shown (a twist mode). All modes should be studied to find the effect on the beam

Forces calculation

- Such a large magnet system is usually associated with substantial forces.
- I have made an initial calculation of the forces on each element (screening solenoid, compensating solenoid) for the benefit of the mechanics integration team
- The FF quads are sitting in zero field, so there is no force on them (but there is a force between them)
- A misalignment study is also performed

Perfect alignment: force on the solenoids, left side



For both sides:

- Screening solenoid: -80kN towards the IP
- Comp. solenoid: +300kN, towards the endcap

Misalignment analysis

Perfect alignment								
Name	Fx [N]	Fy [N]	Fz [N]	Fmag [N]	Tx [N.m]	Ty [N.m]	Tz [N.m]	Tmag [N.m]
main detector solenoid	7.2E+05	7.2E+05	2.4E+03	1.0E+06	-2.3E+03	2.3E+03	5.3E-02	3.2E+03
Screening solenoid	1.5E+03	1.5E+03	-8.4E+04	8.4E+04	5.5E+02	-5.4E+02	**-1.1E+04**	1.1E+04
Comp. solenoid	8.9E+02	9.1E+02	**3.0E+05**	3.0E+05	6.5E+01	-6.5E+01	2.6E+03	2.6E+03
Screening sol. right	1.5E+03	1.5E+03	8.4E+04	8.4E+04	-5.5E+02	5.4E+02	**-1.1E+04**	1.1E+04
Comp. solenoid right	8.9E+02	9.1E+02	**-3.0E+05**	3.0E+05	-6.6E+01	6.6E+01	2.6E+03	2.6E+03
Misalignment in x of screening solenoid only by 10mm								
Screening solenoid	-8.2E+03	1.3E+03	-8.3E+04	8.3E+04	3.0E+02	**1.3E+04**	**-1.1E+04**	1.7E+04
Comp. solenoid	1.0E+04	1.1E+03	**3.0E+05**	3.0E+05	2.8E+01	2.5E+03	2.5E+03	3.6E+03
Screening sol. right	1.5E+03	1.5E+03	8.4E+04	8.4E+04	-5.5E+02	5.4E+02	**-1.1E+04**	1.1E+04
Comp. solenoid right	8.9E+02	9.1E+02	**-3.0E+05**	3.0E+05	-6.6E+01	6.7E+01	2.6E+03	2.6E+03
Misalignment in x of screening solenoid by 10mm and comp. solenoid by 10mm								
Screening solenoid	1.4E+03	1.5E+03	-8.4E+04	8.4E+04	5.2E+02	-1.2E+03	**-1.1E+04**	1.1E+04
Comp. solenoid	7.1E+02	8.7E+02	**3.0E+05**	3.0E+05	6.0E+01	-3.4E+02	2.6E+03	2.6E+03
Screening sol. right	1.5E+03	1.5E+03	8.4E+04	8.4E+04	-5.5E+02	5.4E+02	**-1.1E+04**	1.1E+04
Comp. solenoid right	8.9E+02	9.1E+02	**-3.0E+05**	3.0E+05	-6.6E+01	7.0E+01	2.6E+03	2.6E+03
As above, plus 100mrad twist of comp. solenoid								
Screening solenoid	2.7E+04	2.1E+03	-7.8E+04	8.3E+04	1.5E+03	**-4.0E+04**	**-1.1E+04**	4.1E+04
Comp. solenoid	-2.7E+04	2.7E+02	**2.9E+05**	2.9E+05	1.5E+03	**5.1E+04**	2.5E+03	5.1E+04
Screening sol. right	1.5E+03	1.5E+03	8.4E+04	8.4E+04	-5.5E+02	5.2E+02	**-1.1E+04**	1.1E+04
Comp. solenoid right	8.6E+02	9.1E+02	**-3.0E+05**	3.0E+05	-6.5E+01	3.3E+01	2.6E+03	2.6E+03

Conclusions

- The IR magnets
  - The compensation scheme is the simplest possible and fulfils all our requirements
  - FF quadrupoles are challenging but CCT design ideally suited for our application
- How does it all fit?
  - We are only missing a few millimetres to fully adhere to the 100 mrad cone!
- Recent work
  - FF quadrupole project: assembly finished, awaiting testing
  - Mechanical design: conceptual design started
  - Thin cryostat: seems possible, no showstoppers

Extra slides

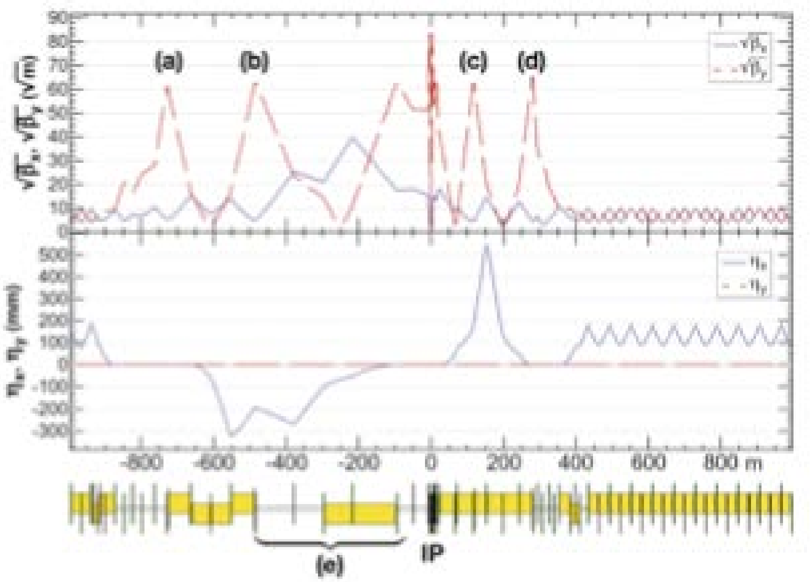
Grab waist sextupoles

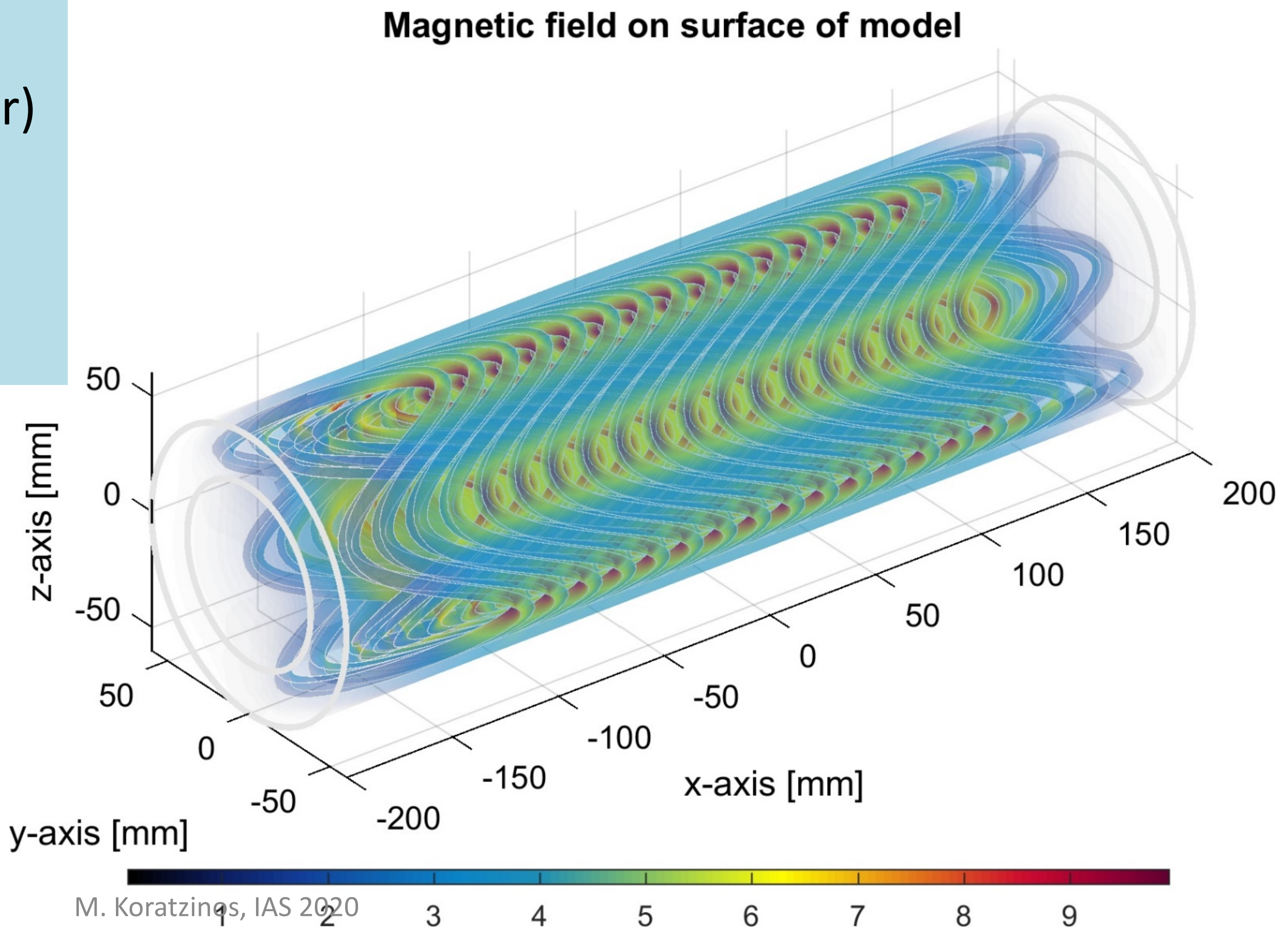
NbTi conductor is not suitable for this project. We should use HTS tape for it. Readily available from industry, although currently more expensive than NbTi

Unique to FCC-ee, is a set of four strong sextupoles in the vicinity of the IP (a, b, c, d below, strength is B'' : 7350 T/m^2)

- 78mm aperture, single aperture
- Very short (30cm)
- Very high field (10-11T on the conductor)
- CCT is ideally suited – correctors can go on top as extra rings saving space

Preliminary design





Heat load and cooling needs - reminder

According to E. Belli:

- For the most difficult case, QC1L1
- e-cloud: for SEY=1.1 ~20W/m, for SEY=1.2 ~200W/m
- resistive wall: for copper, ~100W/m
- Heating due to all backgrounds: ? (we are working on it)
- (I assume that masks will take the most part of backgrounds that would otherwise hit the detector)

From the above, the heat load appears to be **O(100)W/m**

Water flow needed for the beam pipe: for a 10 degree inlet-outlet difference, 1 lt of water per minute takes away 600W – not a challenge.

Notes on cooling

- Warm beam pipe with water cooling
  - Black body radiation at 300K is ~500W/m2
  - The beam pipe close to QC1L1 is 0.13m2
  - Emissivity of polished copper 0.023 to 0.052
  - Assume emissivity of 0.05 (we can do a factor 2 better)
  - Heating power due to radiation: 500X0.13X0.05= **3.2W**
  - With one radiation shield, we can cut this by half to 1.6W
  - For comparison:
    - LHC magnet, arc: 0.2W/m
    - LHC triplet: 7-9W/m
- Water flow needed: for a 10 degree inlet-outlet difference, 1 lt of water per minute: 4/60*4*10=0.6kW
- Or otherwise: for a rate of 1 lt/min and 100W load, water temperature rise is 1.5 degrees. – not challenging