IR magnets and envelopes

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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 (Field)
- 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)
- FF quad manufacturing courtesy CERN main workshop (K. Schibor)
- FF quad winding curtesy Herman Ten Kate and Tim Mulder
- Quad prototype measurement campaign: Carlo Petrone

Contents

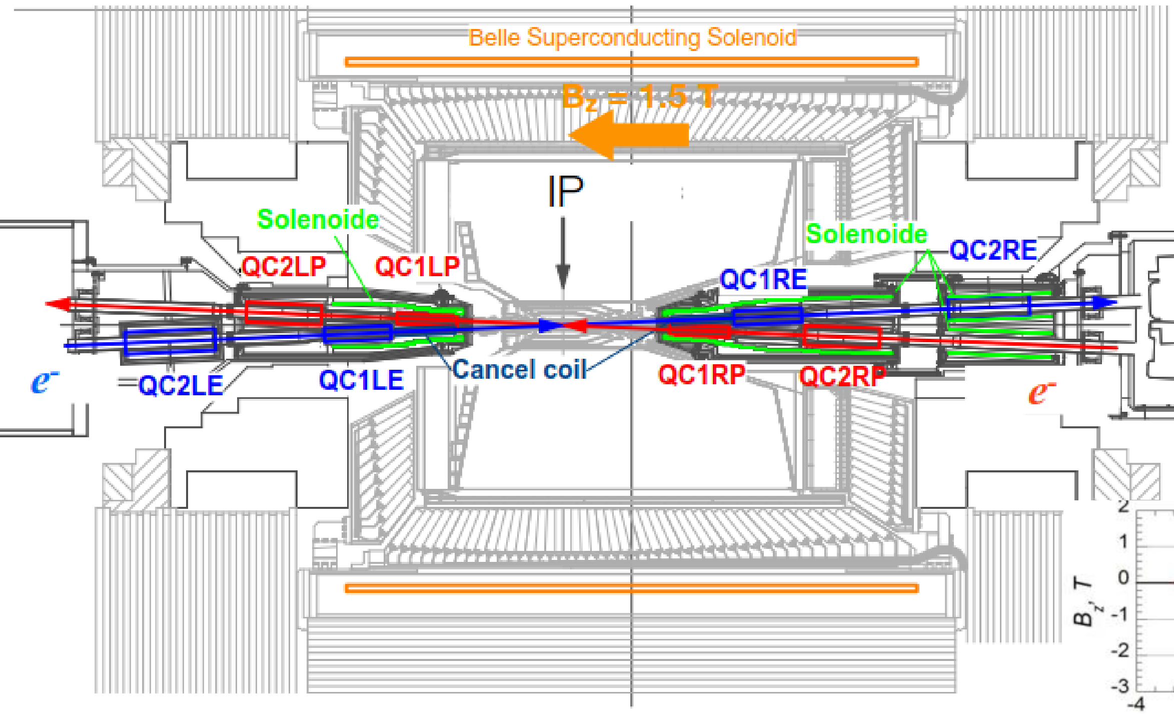
- The IR magnets
  - The compensation scheme
  - FF quadrupoles
- How does it all fit?
  - 100 mrad cone
- News
  - FF quadrupole project
  - Mechanical design
  - Thin cryostat

The stage

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

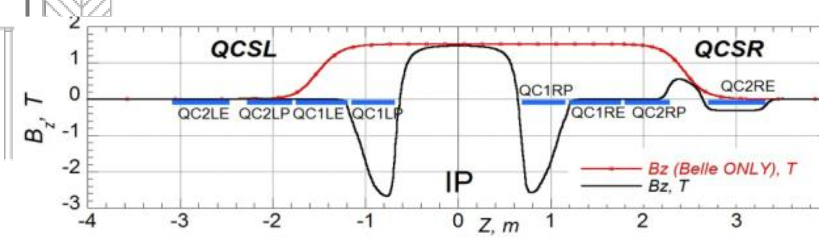
Prior art

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



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Note that first FF quad sits in high magnetic field

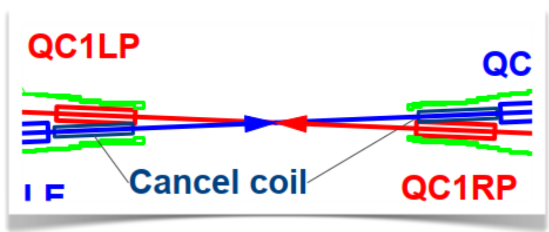
Prior art – Belle II cancel coils

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.

Satisfying all requirements

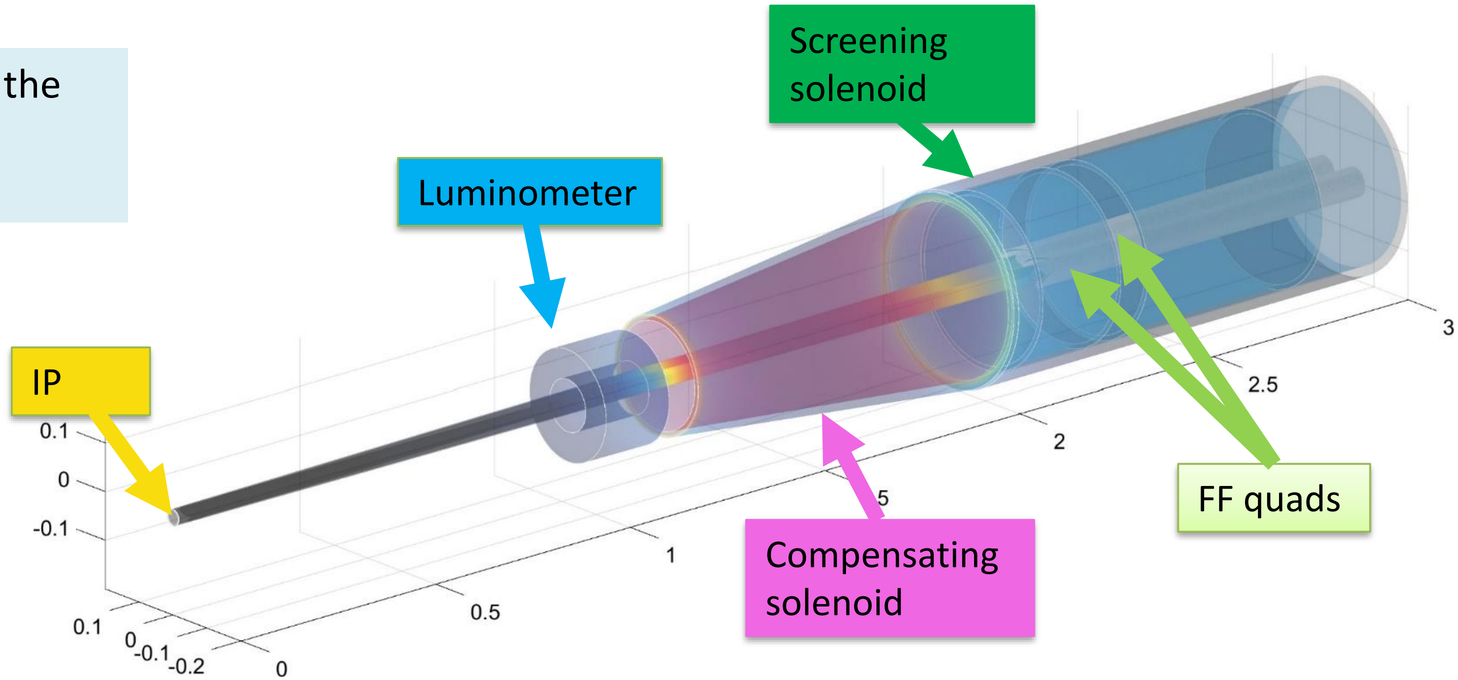
- Requirement 4 (Zero field @ quads) means that screening solenoids are needed.
- Requirement 3 (emittance blow up) necessitates the use of a compensating solenoid.
- We have managed to fit the compensating solenoids in the region upstream of the screening solenoids, whereas the area of ±1.23 m from 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

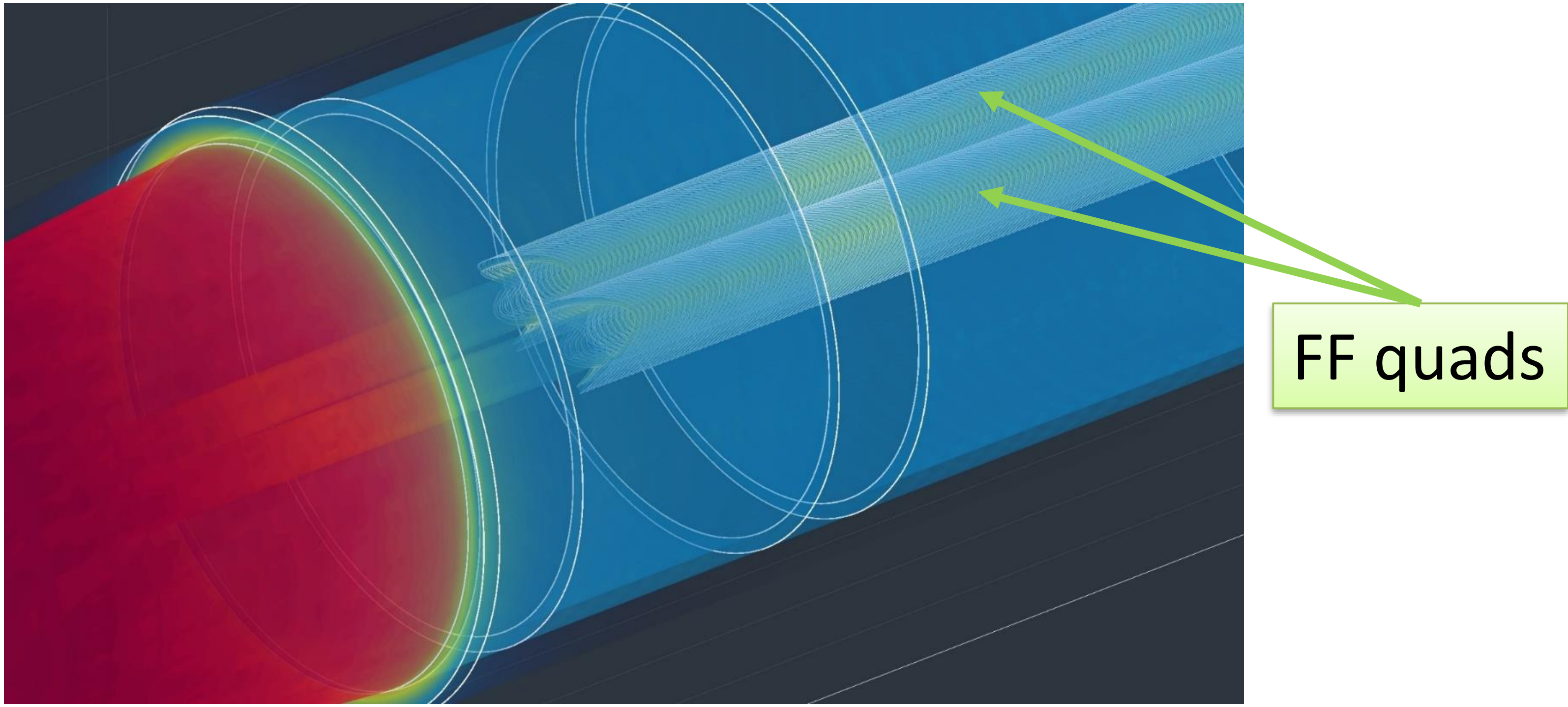
- L* = 2.2m; 30mrad opening angle between beamlines
- Luminometer needs to fit in front of magnetic elements and as far back as possible to have a decent rate
- FF quads sit in a zero longitudinal field region (integral of solenoid field <50mTm) encompassed by a screening solenoid which needs to extend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



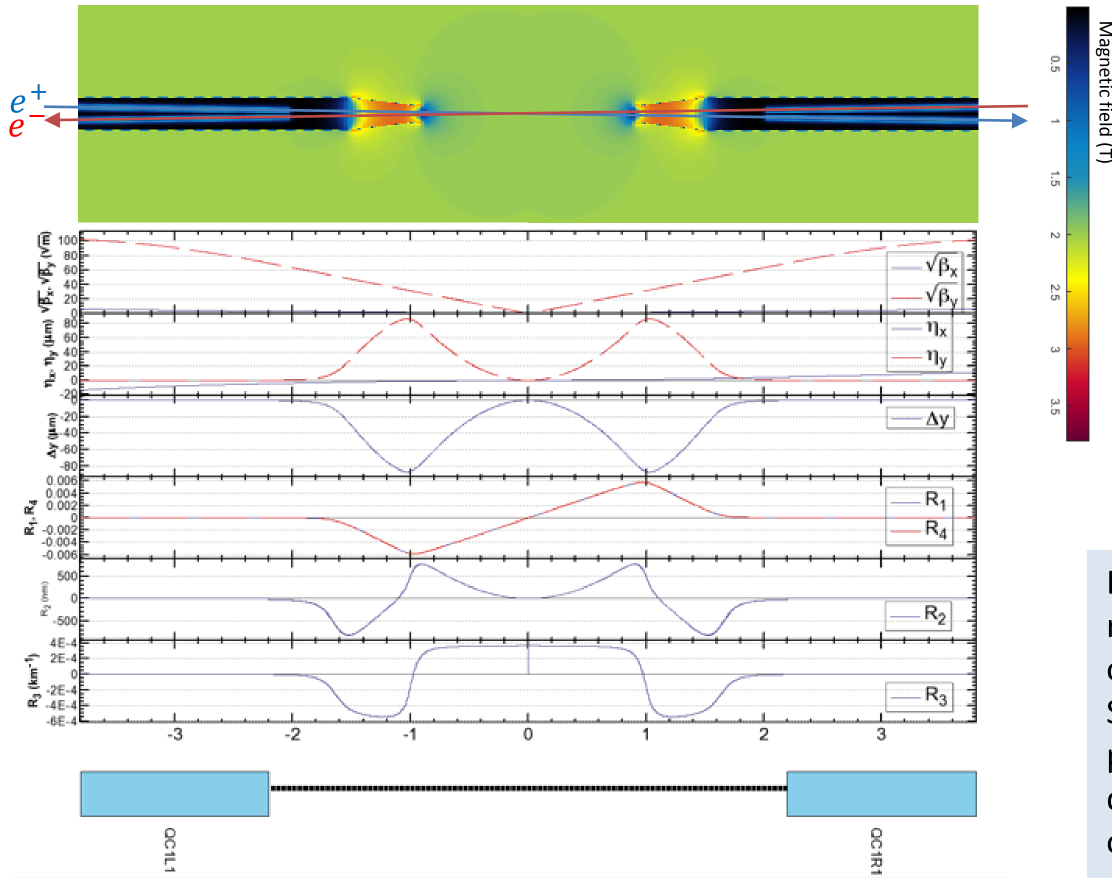
Zoom at 2.2m from the IP



The compensation scheme

View from top

Optics functions SAD



Vertical emittance blow-up <0.4pm for two IPs
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.

Satisfying 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. (but not the cryostats!)
- 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 of better than 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.

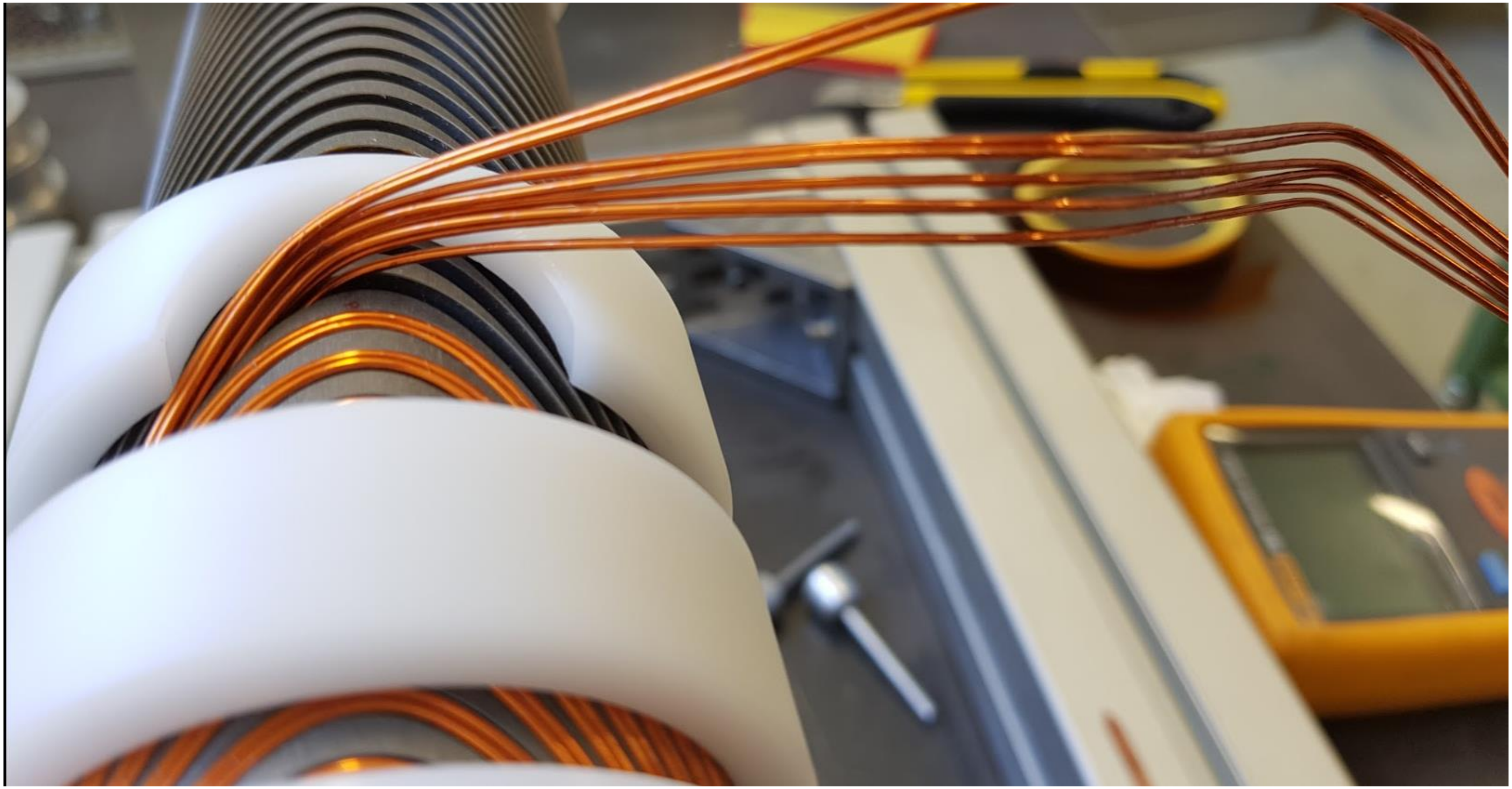
FF prototype news

- Since Brussels:
  - (manufacturing, winding table, with stepper motor completed)
  - 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

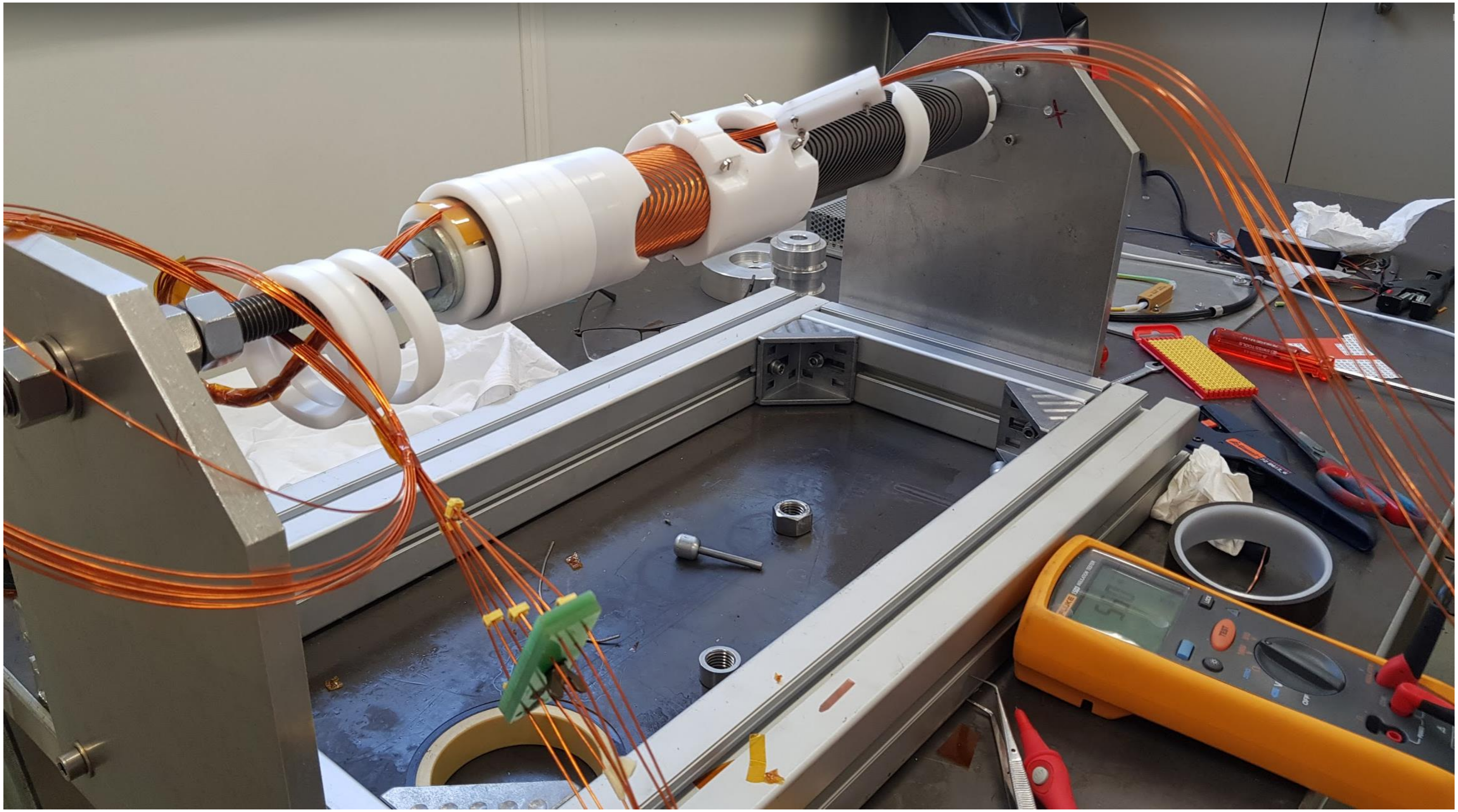
Arrival of machined parts

Winding process

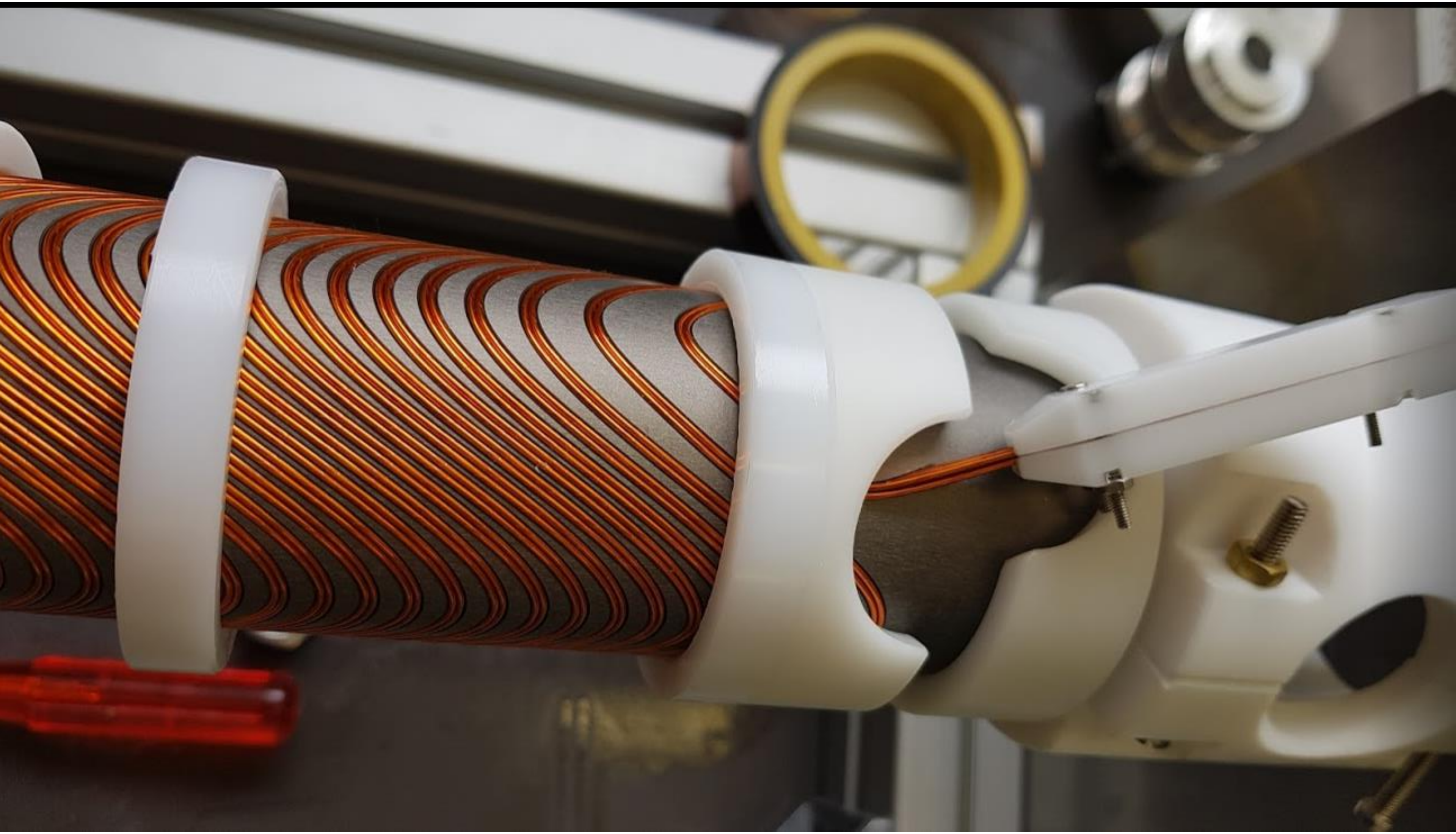


Inner layer started

Inner layer half way

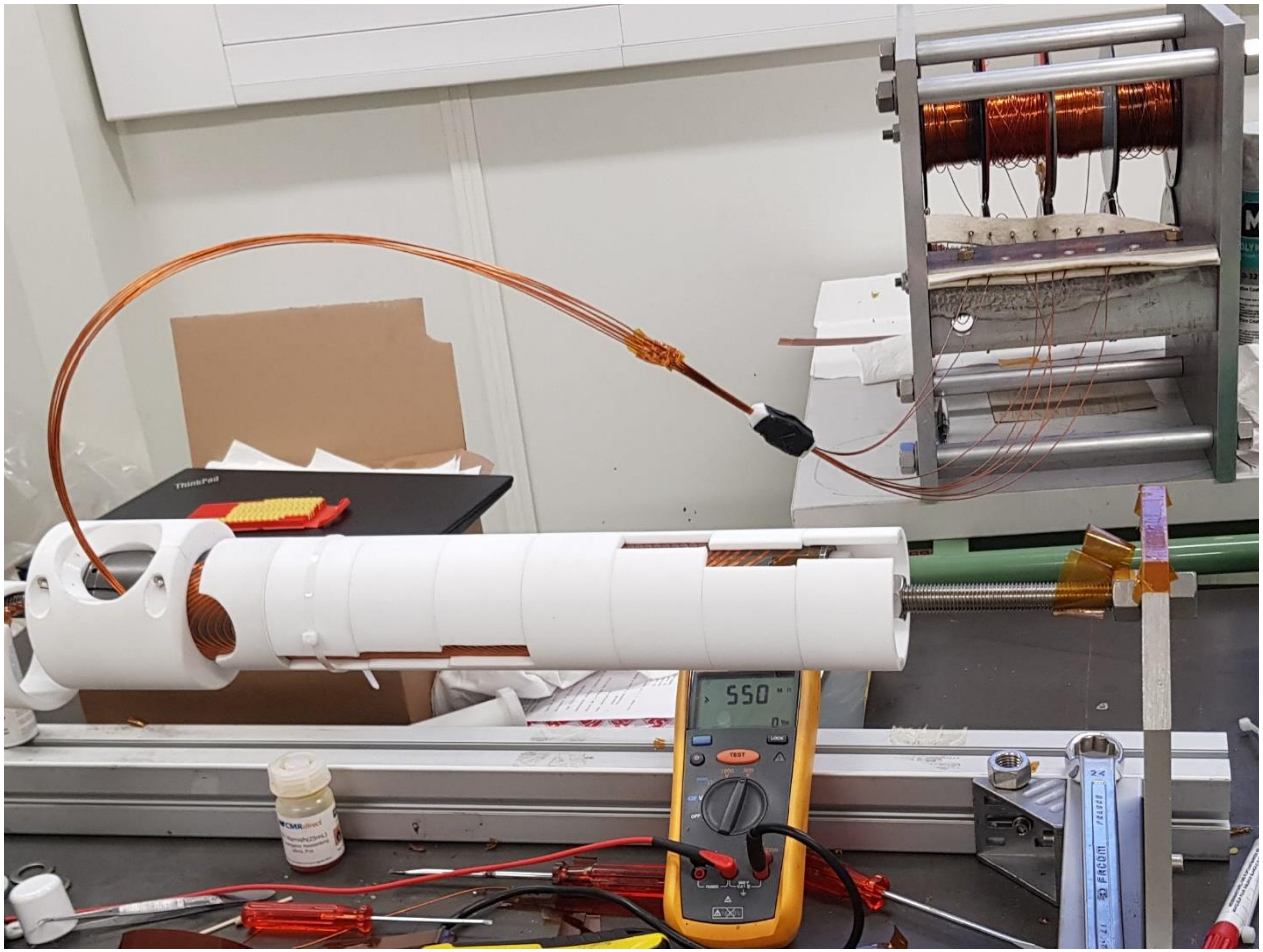


Inner layer done

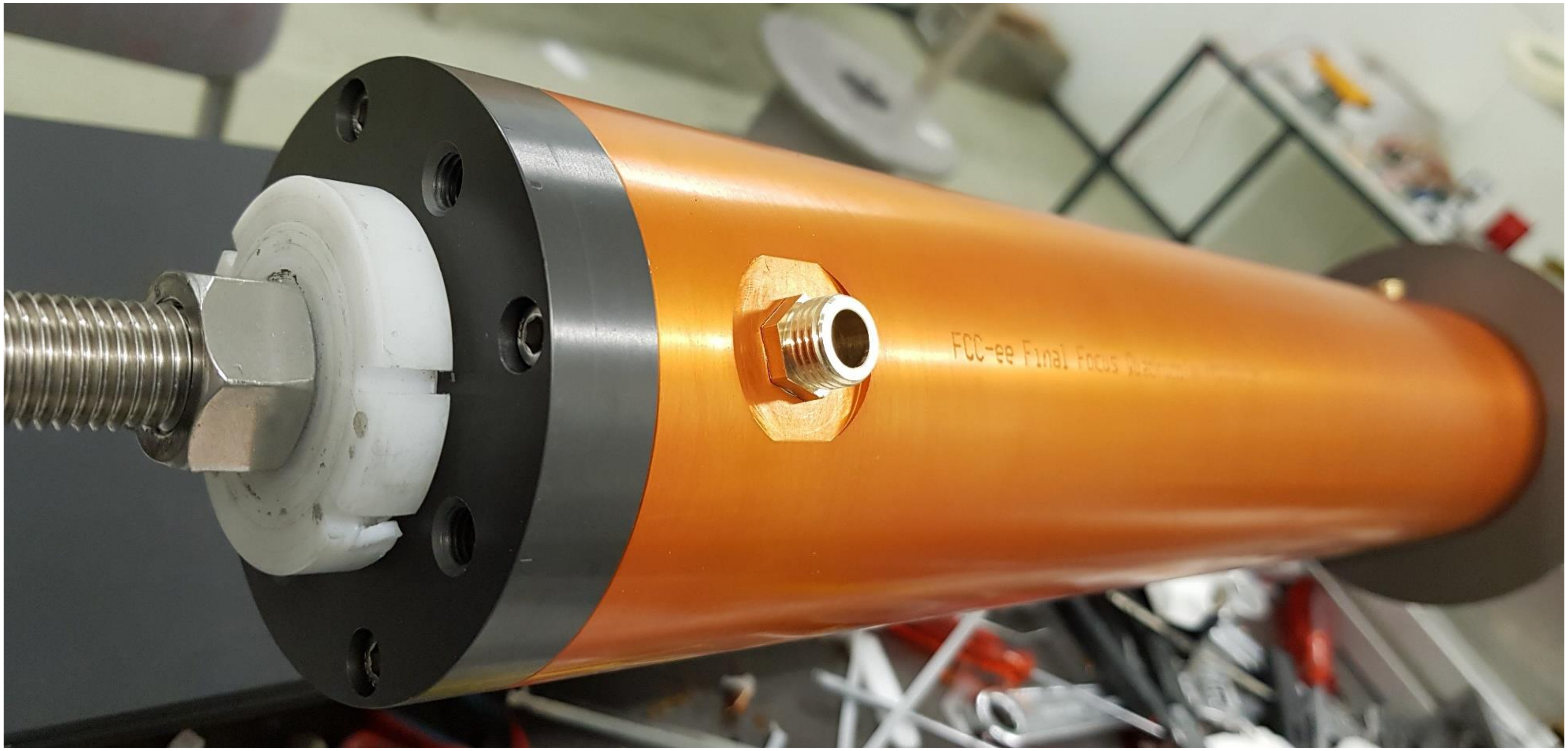


Outer layer half way

Outer layer done



With sleeve and end plates

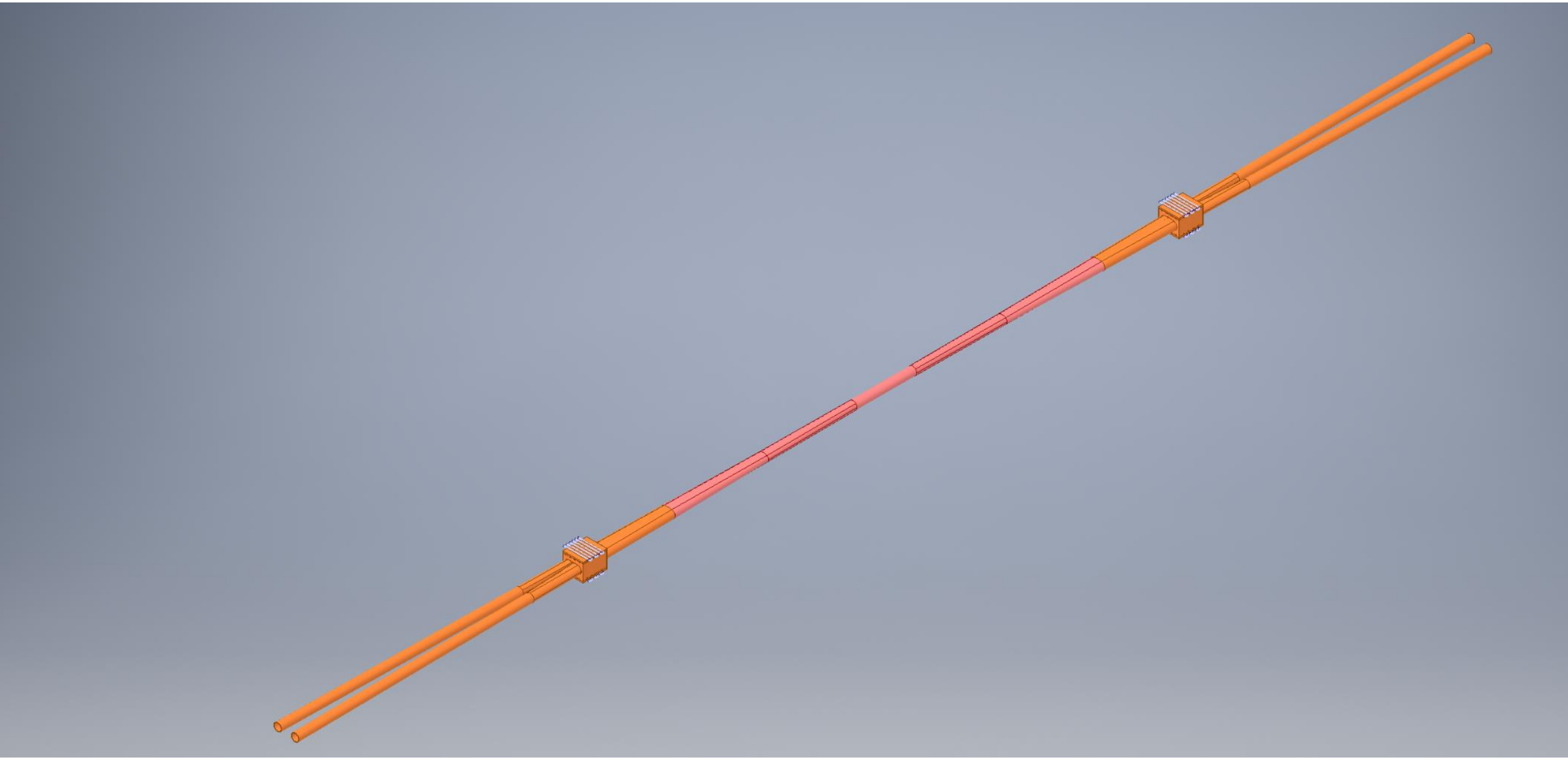


…just in time for Christmas!

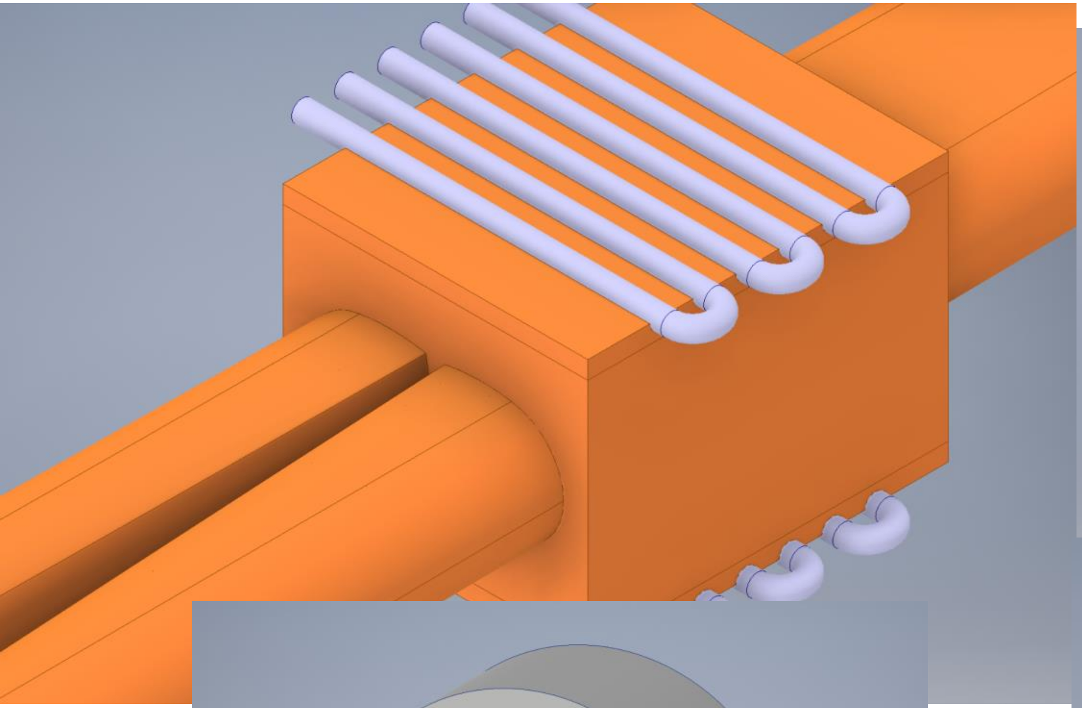
Mechanical design

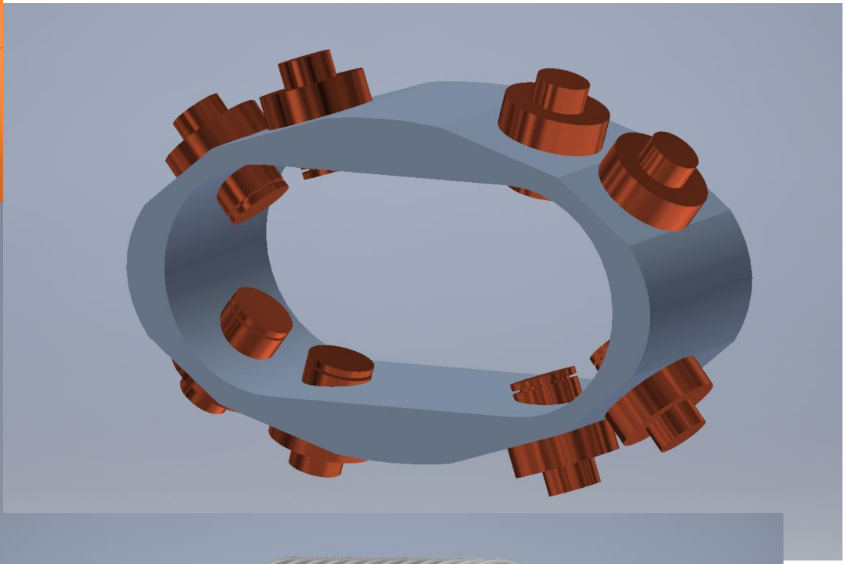
- Going towards a TDR, we need a mechanical design study, at least at the conceptual level
  - can the system be built?
  - Can it ne assembled?
  - Can it be cooled?
  - How about vibrations? Will they kill luminosity?

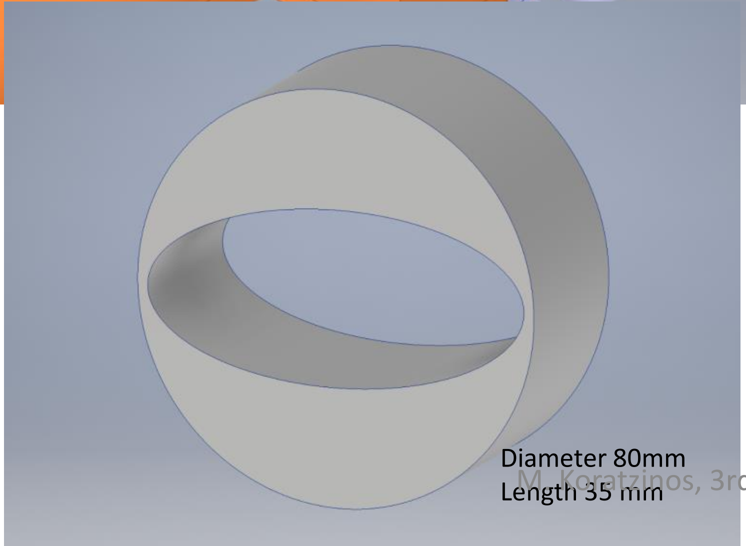
Beam pipe and HOM absorbers

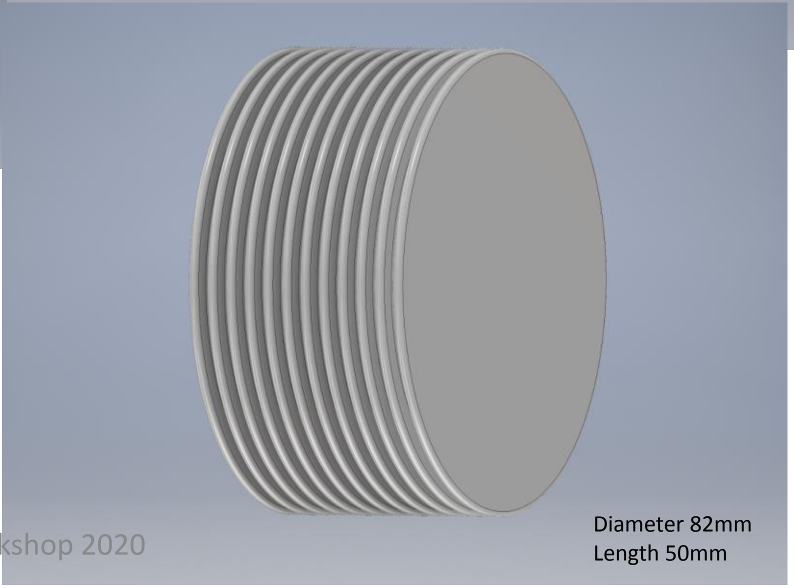


HOM absorber, BPM, remote flange, bellows

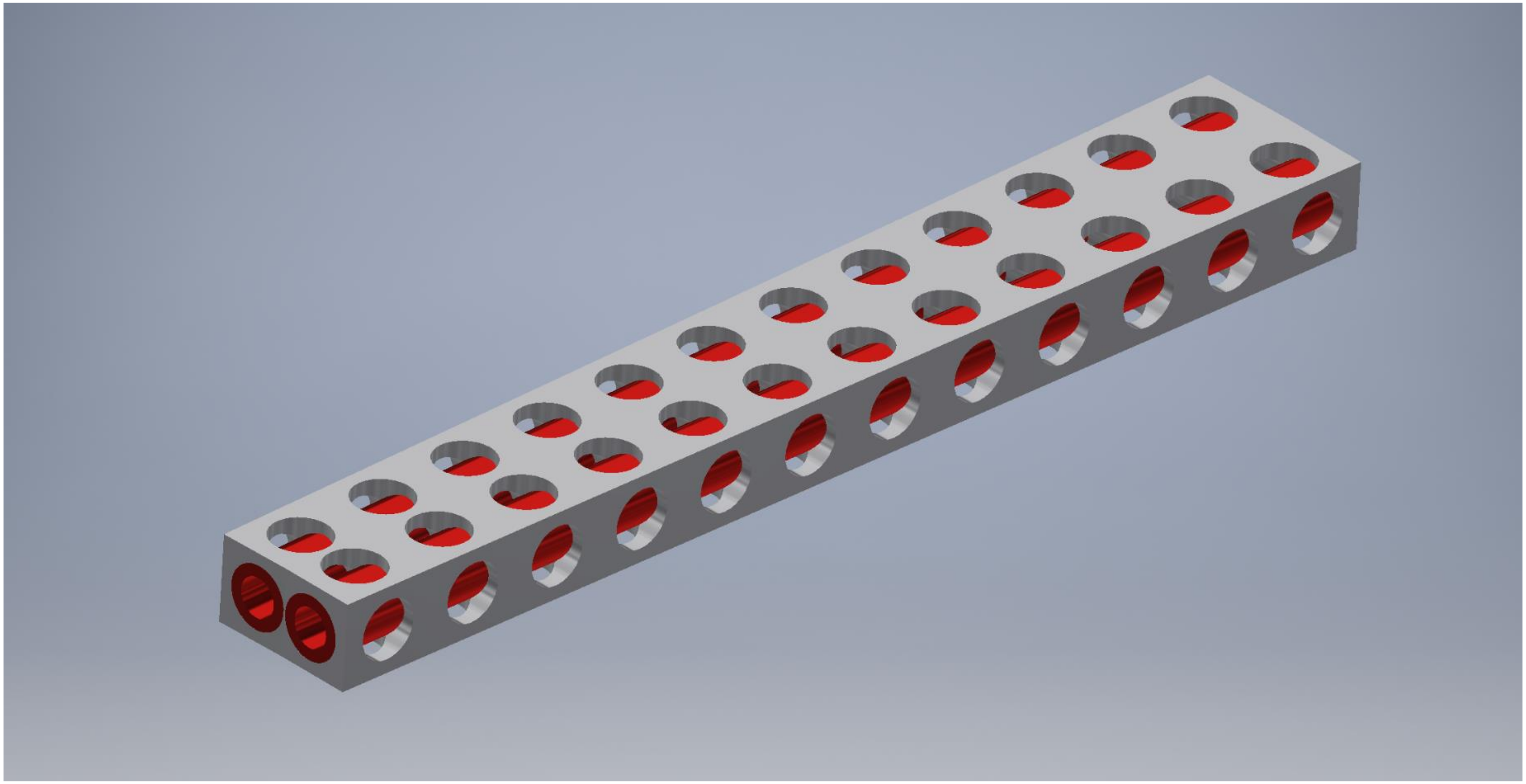




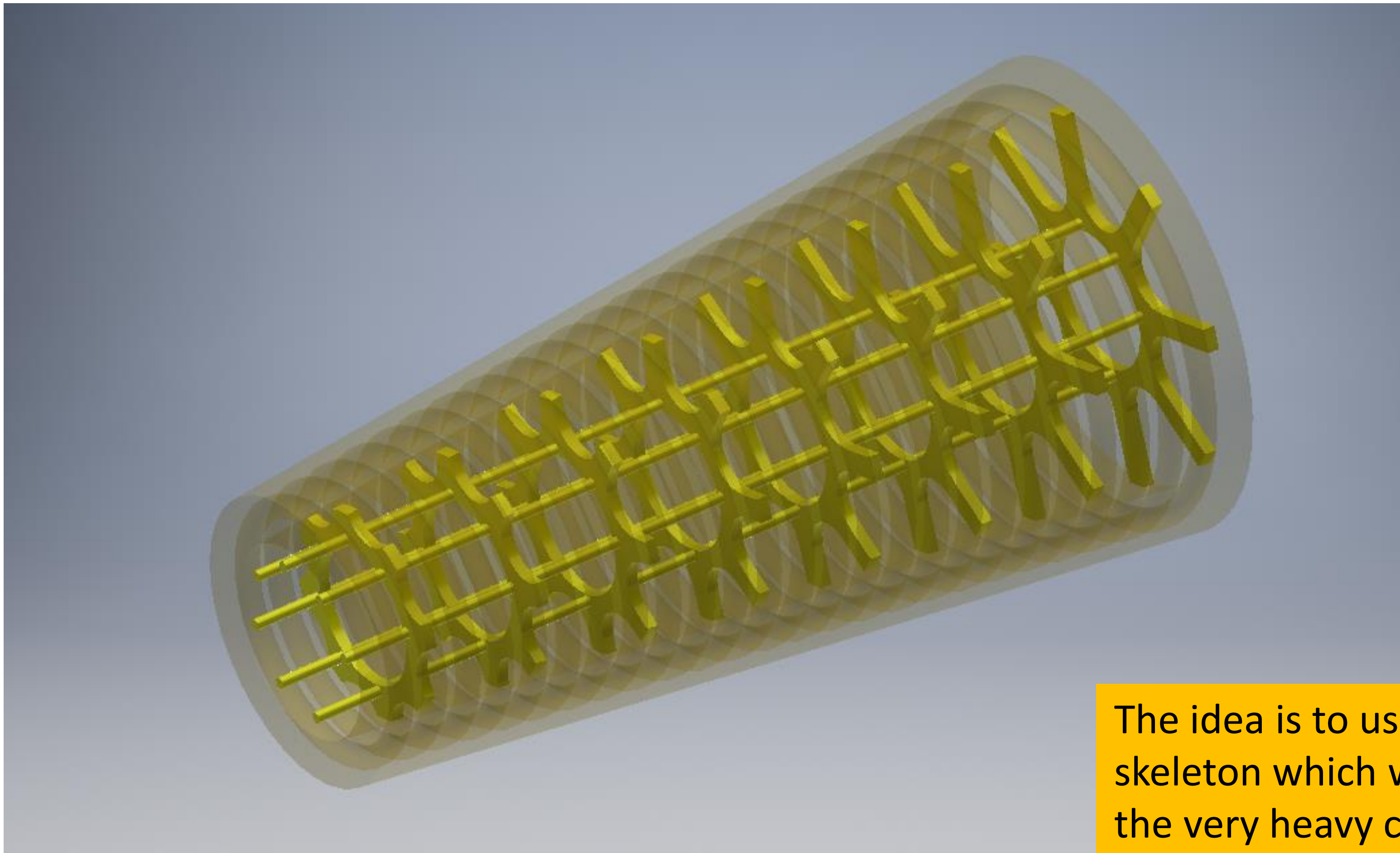




FF quad assembly

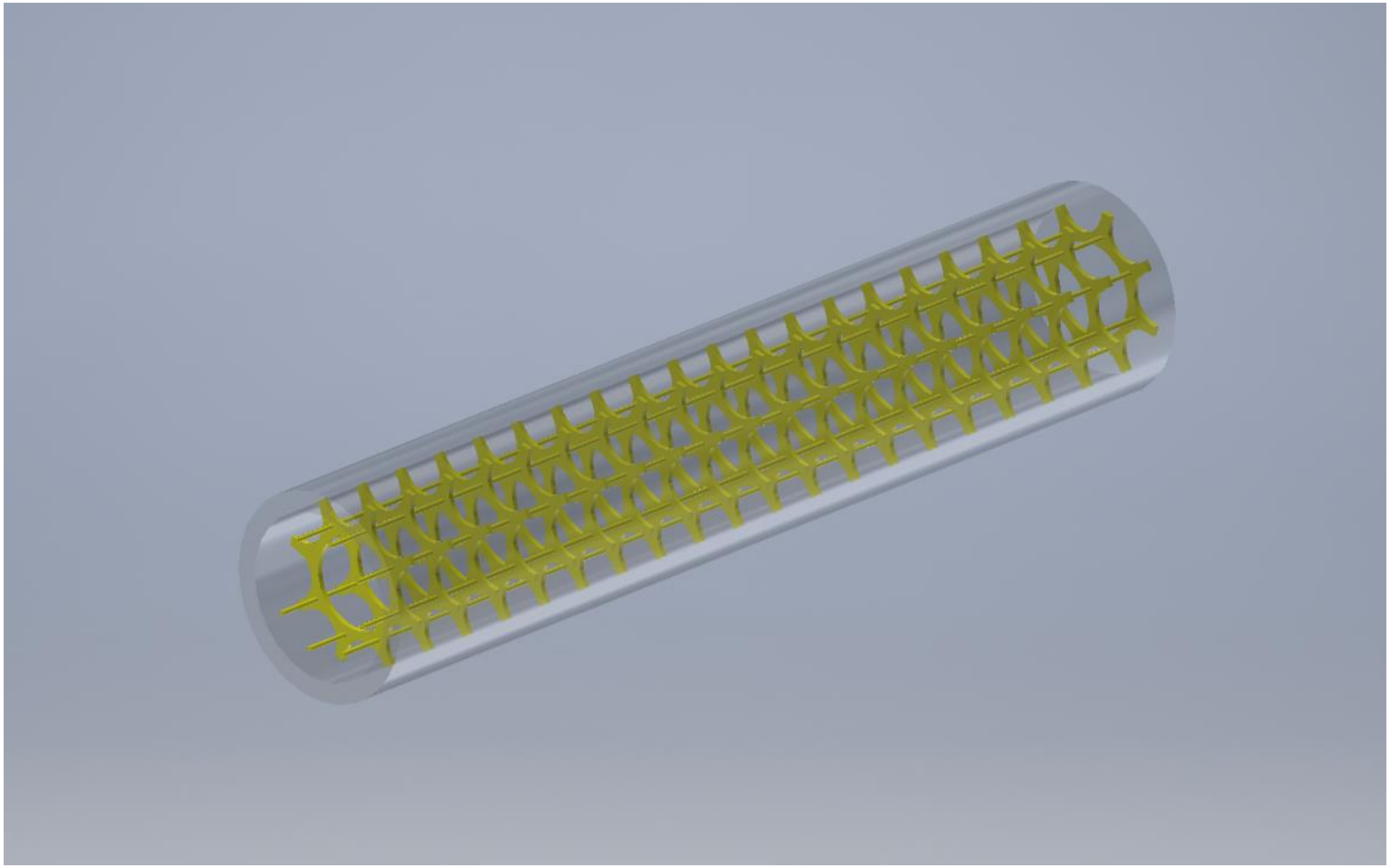


Mechanical design: compensating solenoid with skeleton

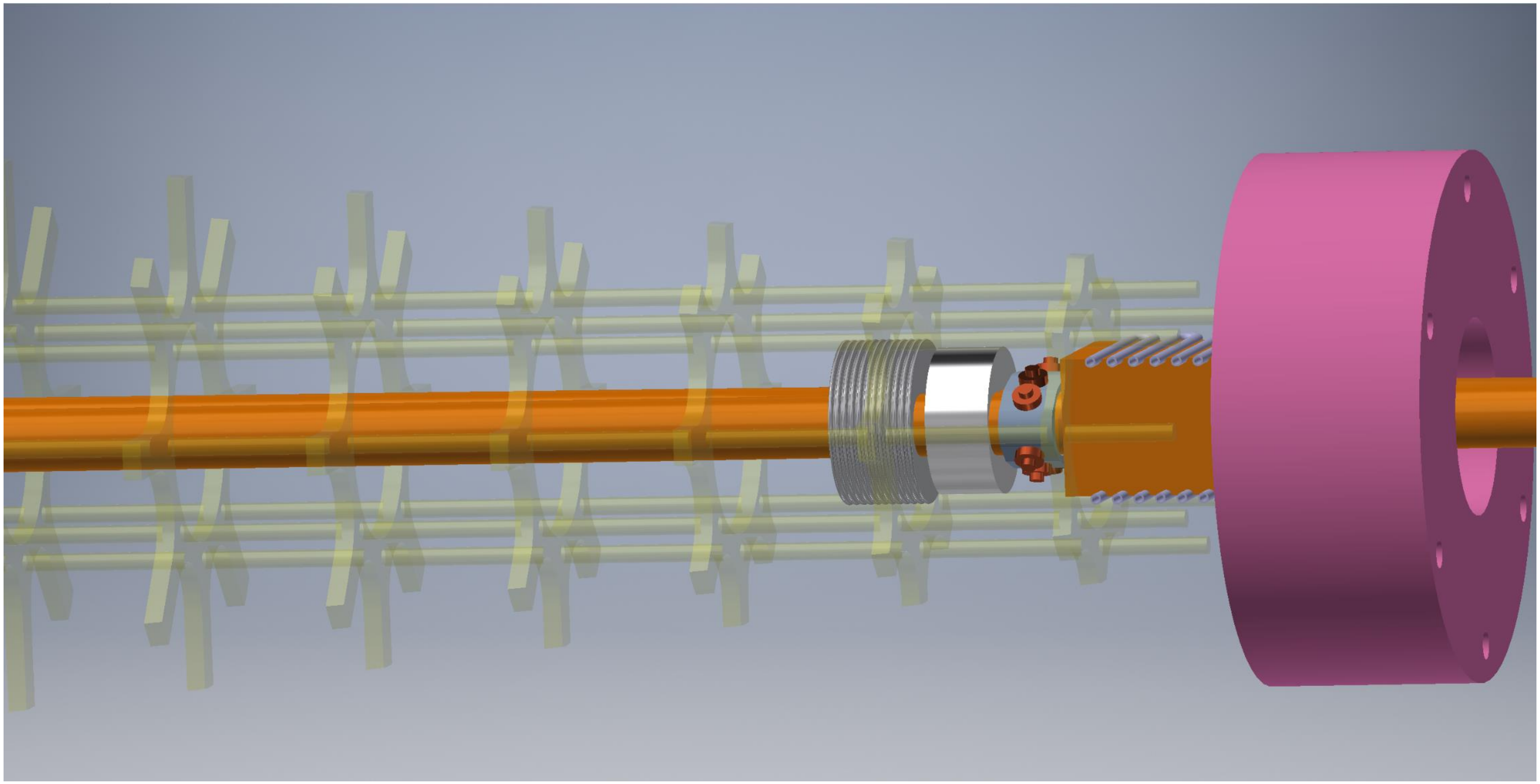


The idea is to use a stiff skeleton which will replace the very heavy cryostat. All load bearing capability will rely on this skeleton

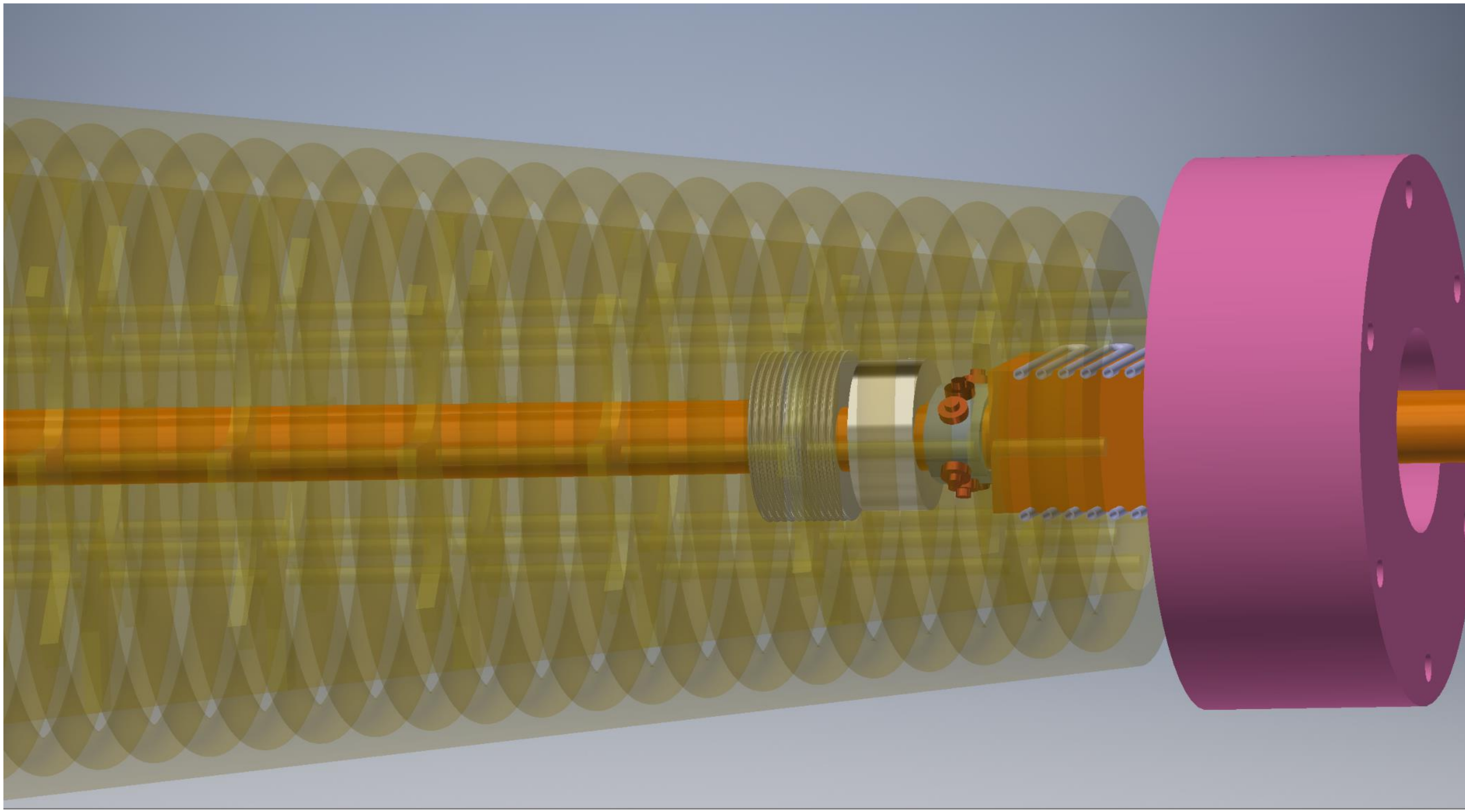
Screening solenoid with skeleton



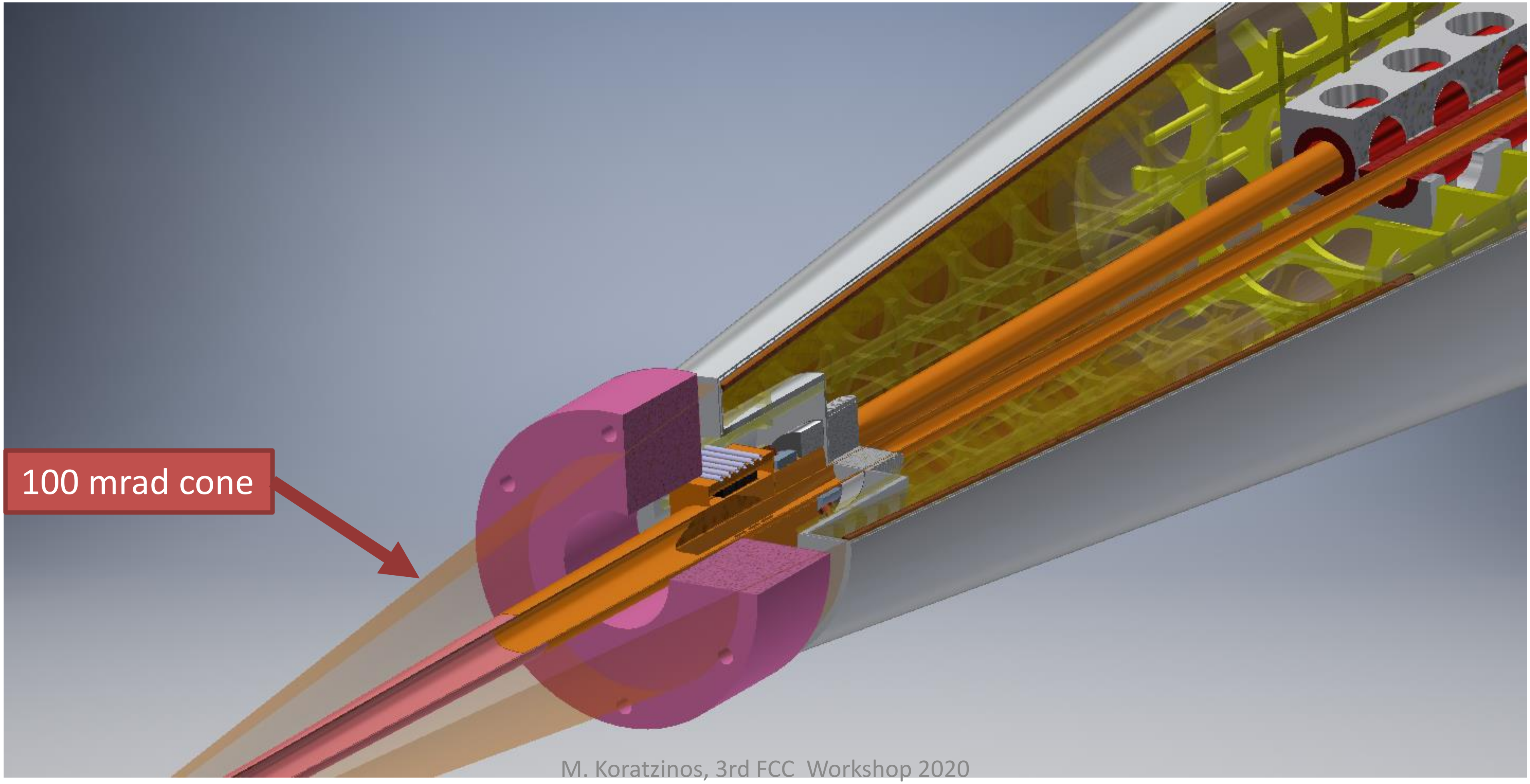
Assembly: beam pipe, HOM abs., BPM, flange, bellows



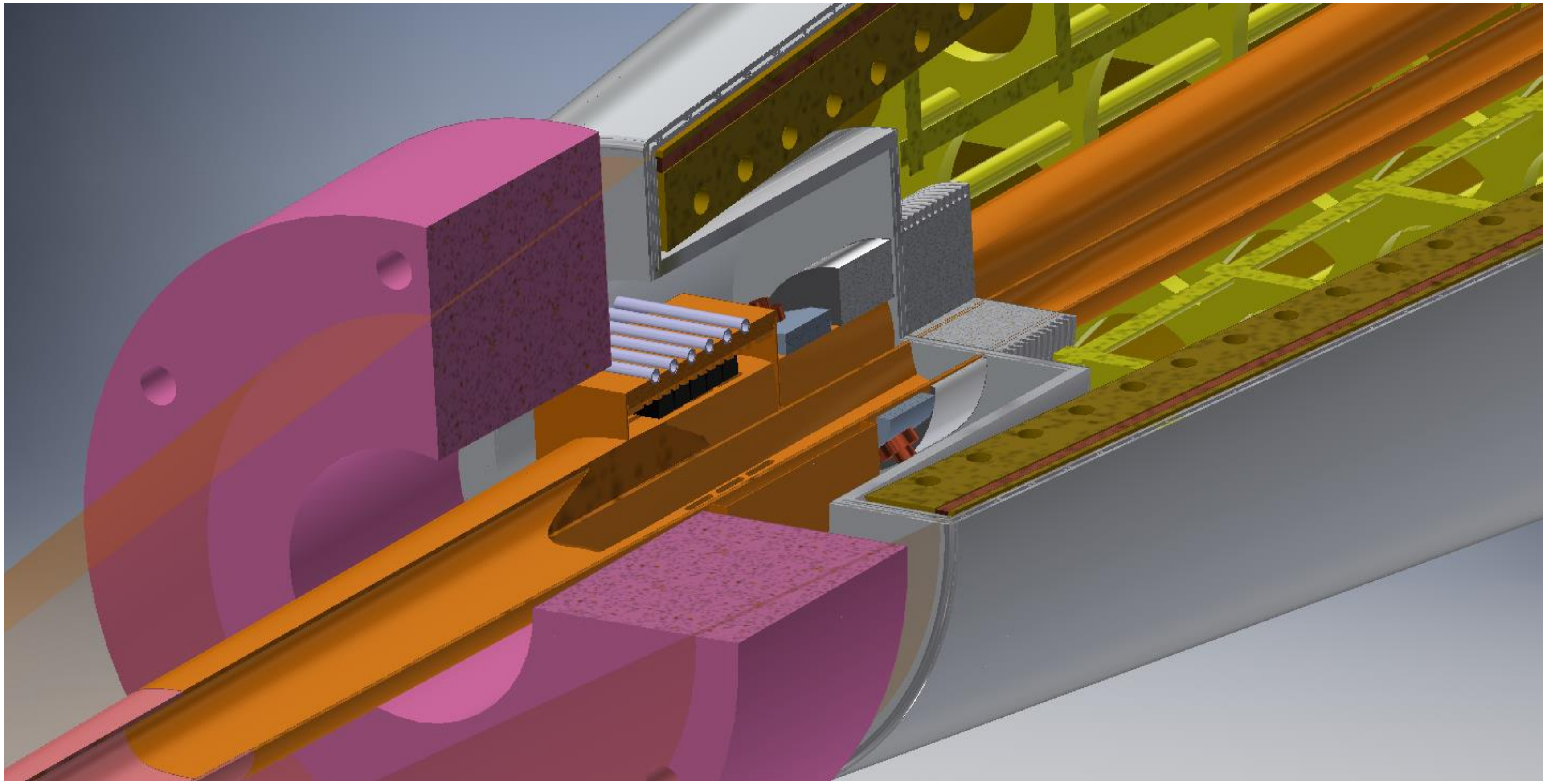
Assembly: beam pipe, HOM abs., BPM, flange, bellows



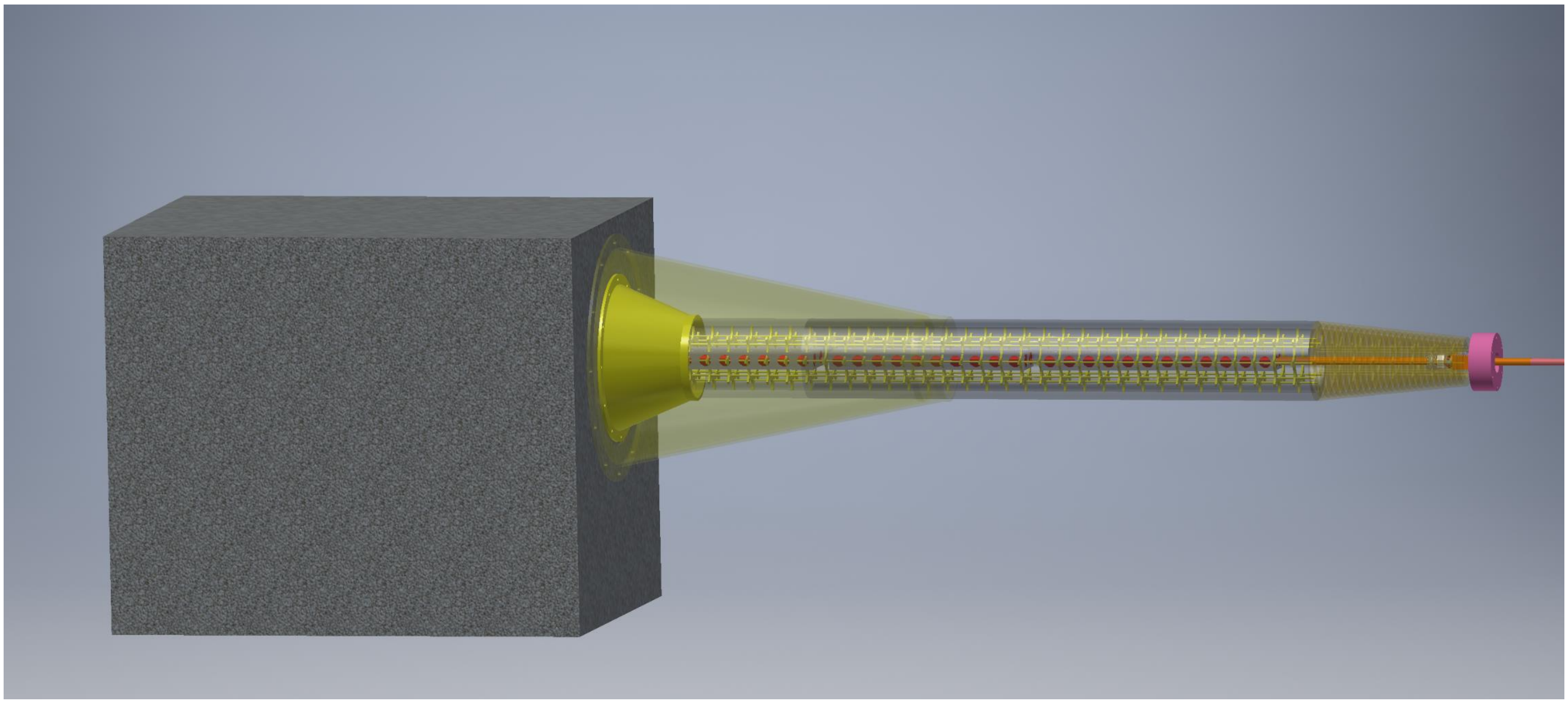
All elements, including cryostat



Zoom on front of cryostat



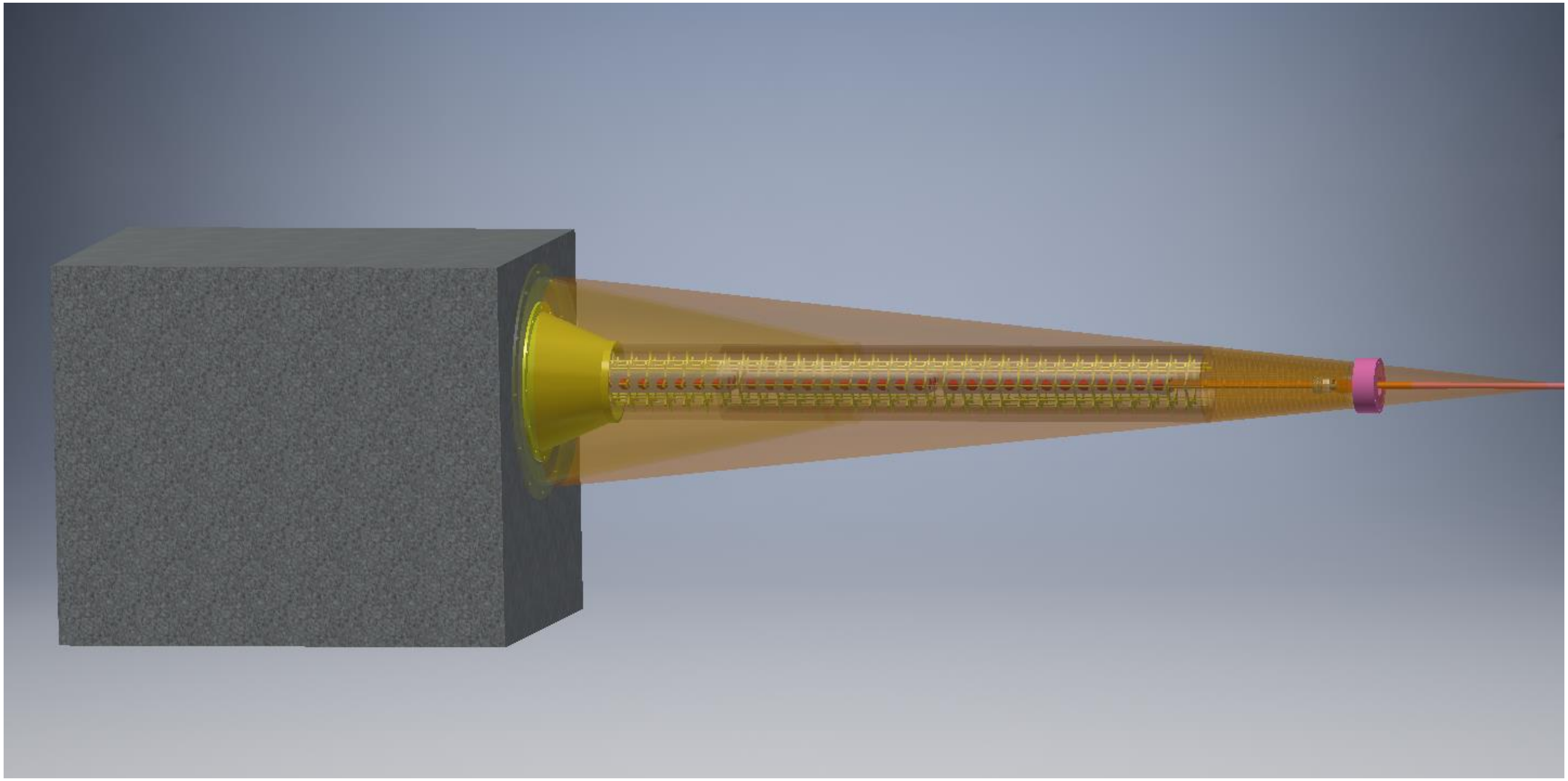
Cantilever assembly



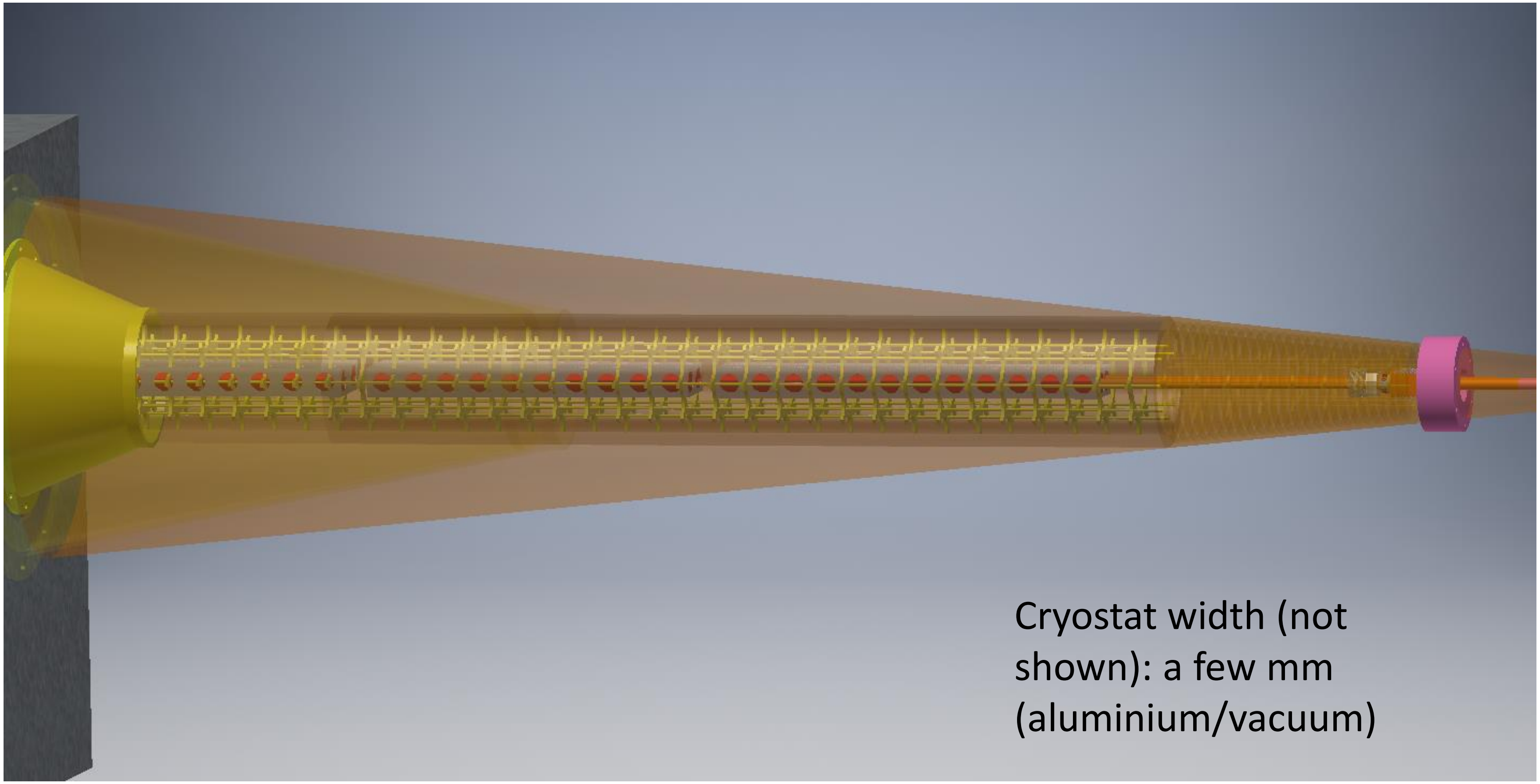
From support to tip of compensating solenoid

4370 mm

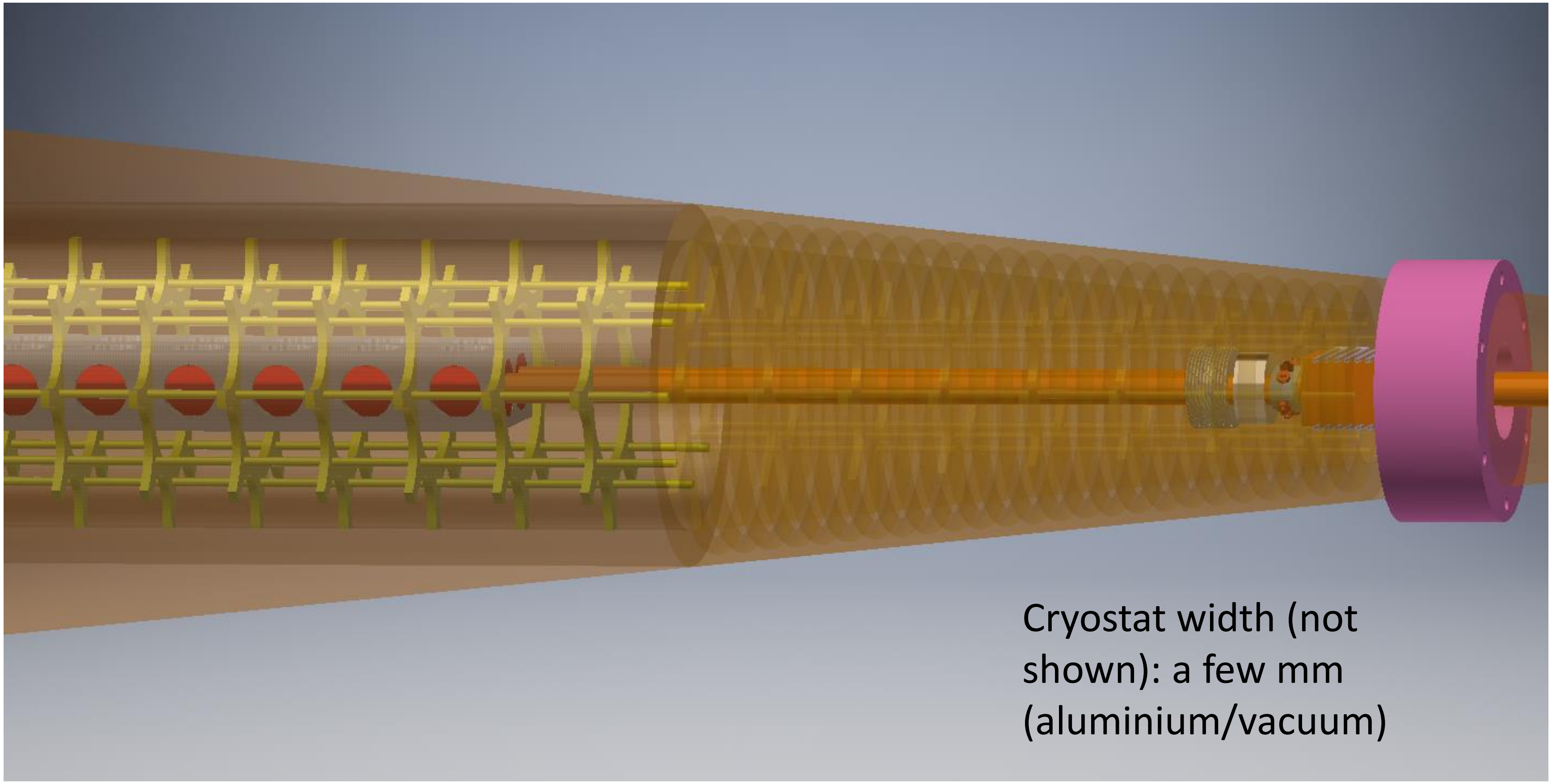
With 100 mrad cone



Zoom – all heavy elements inside the 100mrad cone, but no cryostat



Zoom – all heavy elements inside the 100mrad cone, but no cryostat



Forces and stress analysis calculation

- Presented on the optics meeting 4/10/2019
- Details as additional slides at the end of this presentation
- Forces: 300 kN on compensating solenoid, 80 kN on screening solenoid
- Torque: 1000 Nm on screening solenoid
- Misalignment: (10mm on both solenoids, plus 100mrad twist of compensating solenoid): 1300 Nm on screening solenoid
- Stress analysis: no showstoppers with 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
- direct SR heating: zero (I assume that masks will take all direct SR)

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.

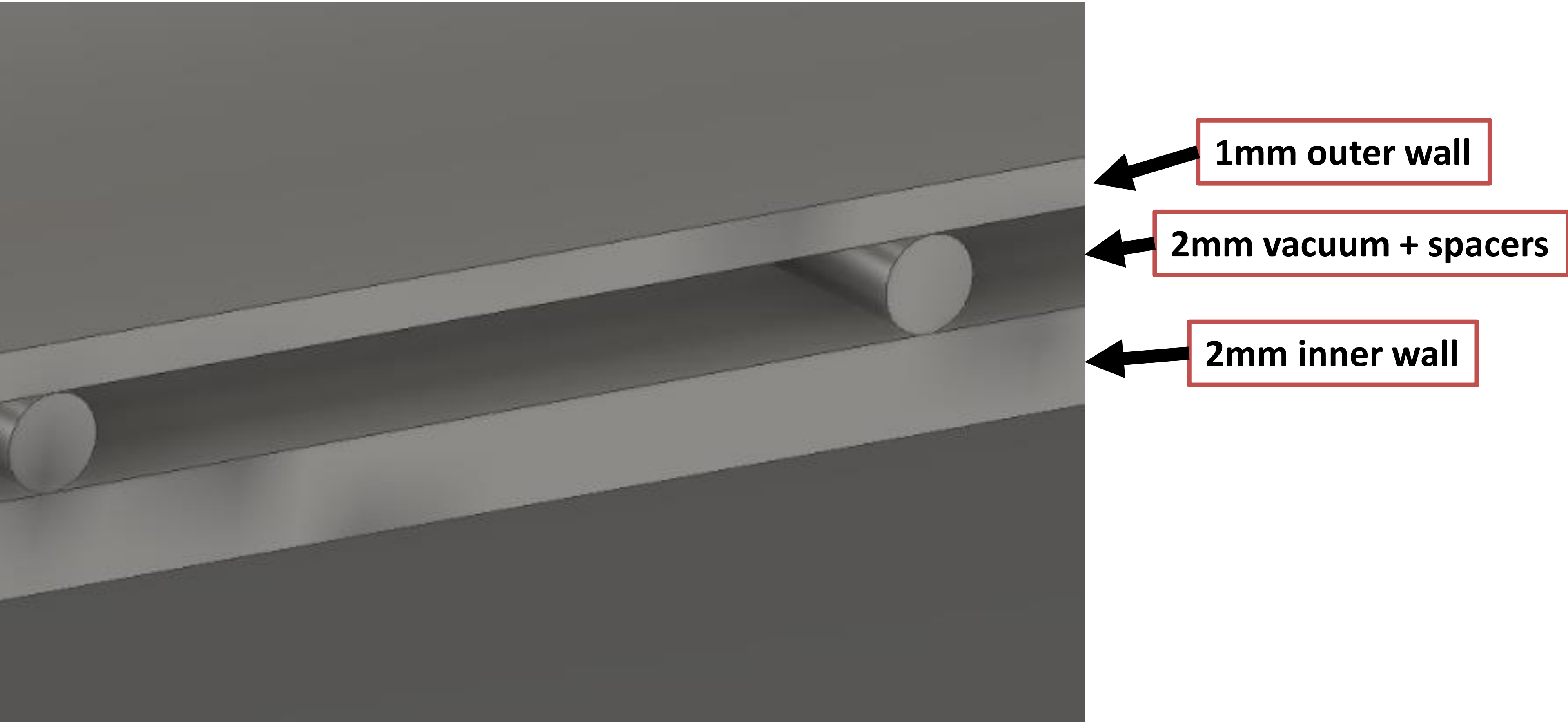
Calculation of heat loads to the cooling system

- Our beam pipe is warm and our magnets cold
- BB radiation at 300 K is 500 W/m^2
- For emissivity of 0.08 the radiation is 40 W/m^2 (emissivity of polished copper is 0.02 to 0.05)
- Beam pipe circumference is ~35mm*3.14 = 0.11m
- So, the heat load on the cryogenics is **4W per meter**
- (By comparison: LHC arc dipole 0.2W/m, triplet 7-9W/m)
- Outer diameter of cryostat: ~25cm; for emissivity of 0.08 heat load is 30W/m – here we need radiation shields

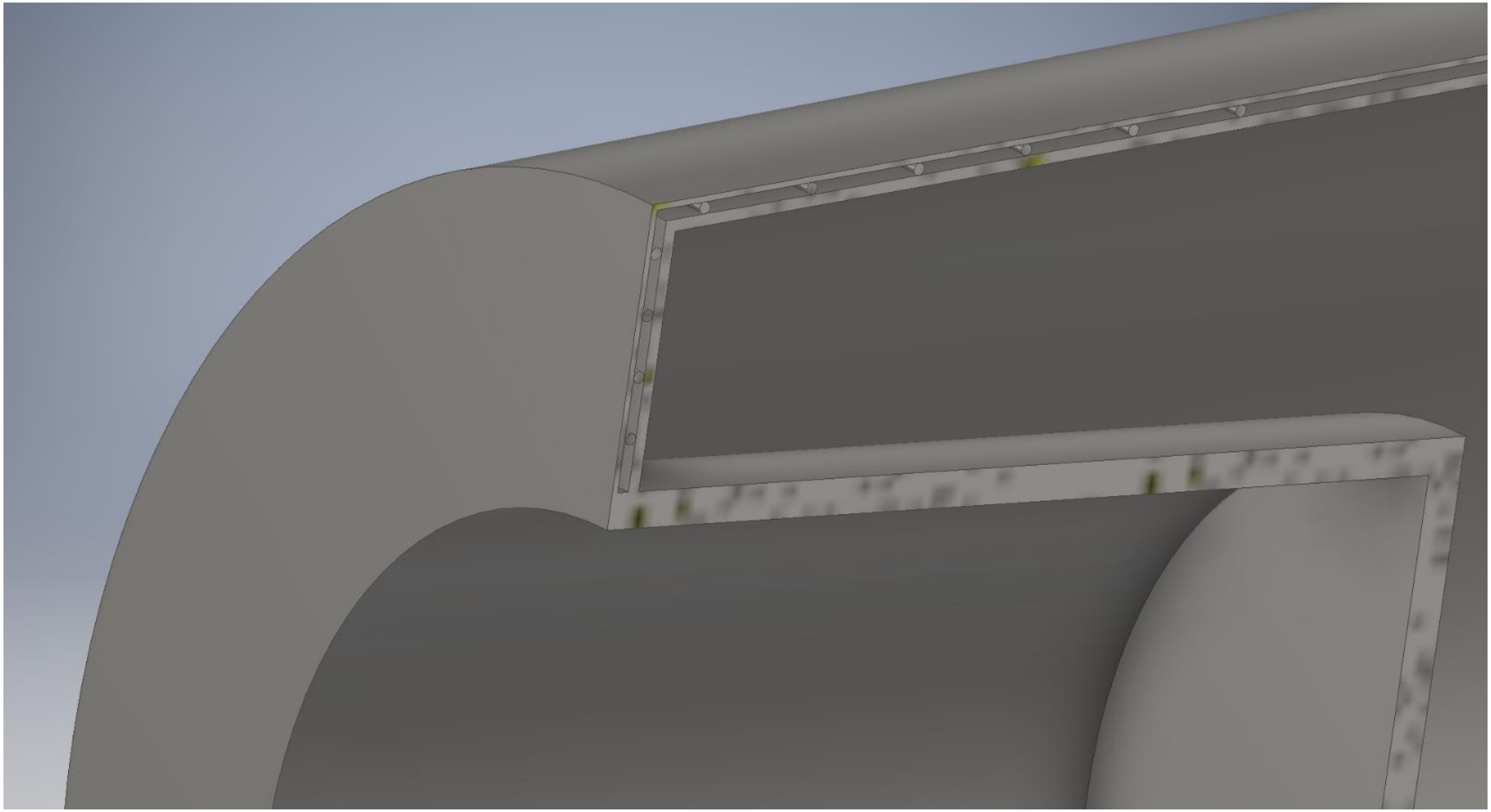
Thin cryostat

- According to Vittorio Parma (CERN cryostat expert) 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!)
- I have made a conceptual design of a cryostat which is 5 mm thick

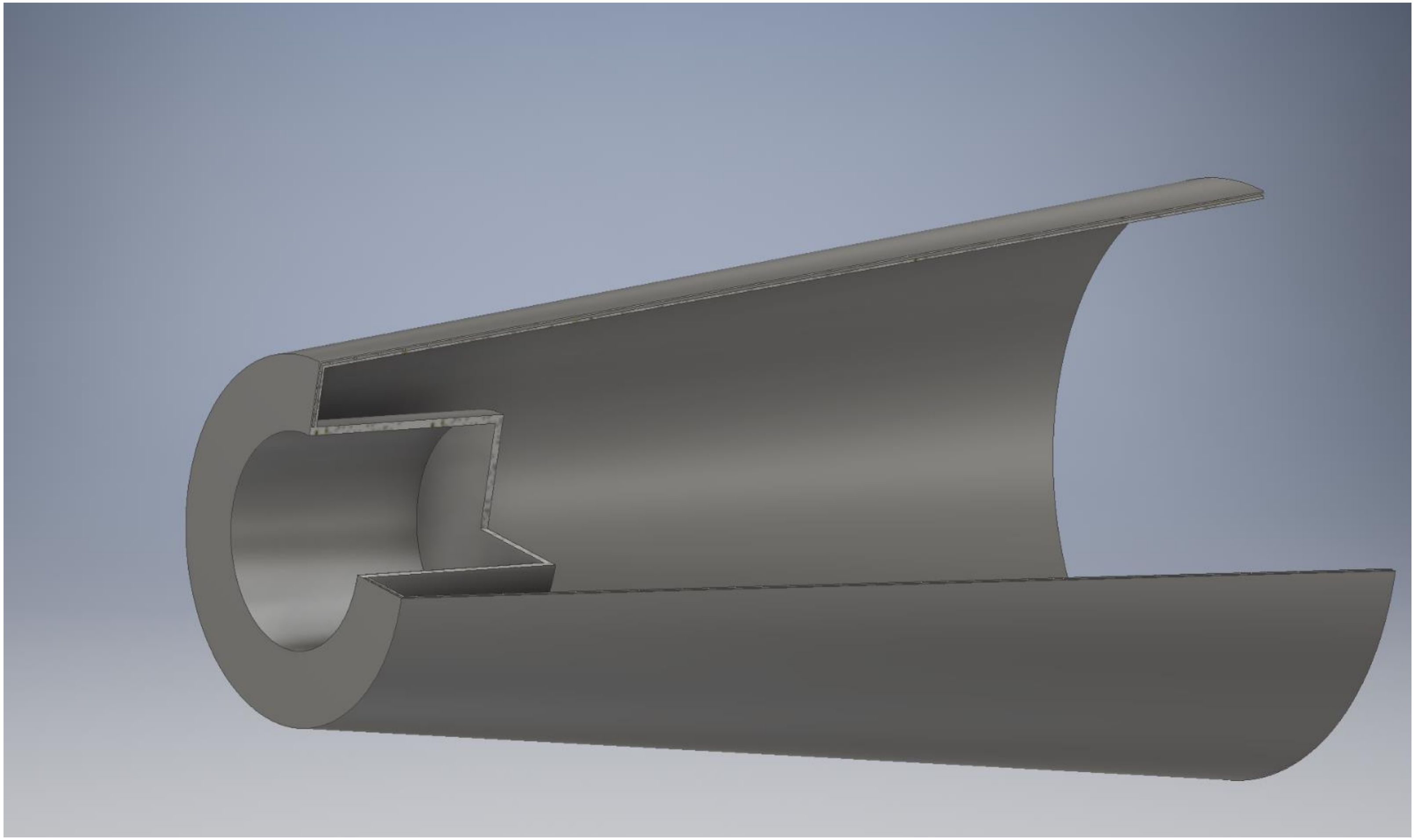
Thin cryostat



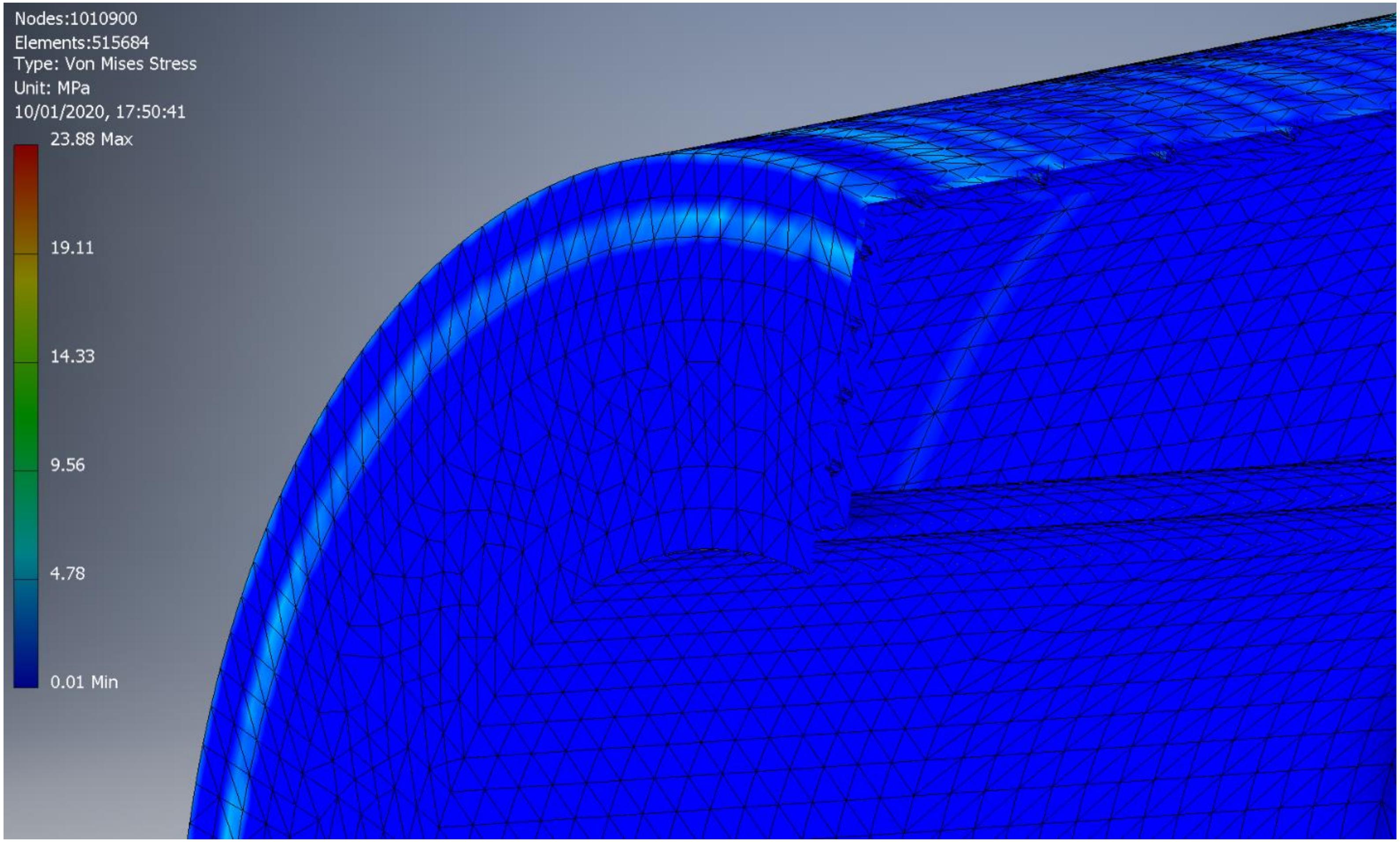
Thin cryostat



Thin cryostat



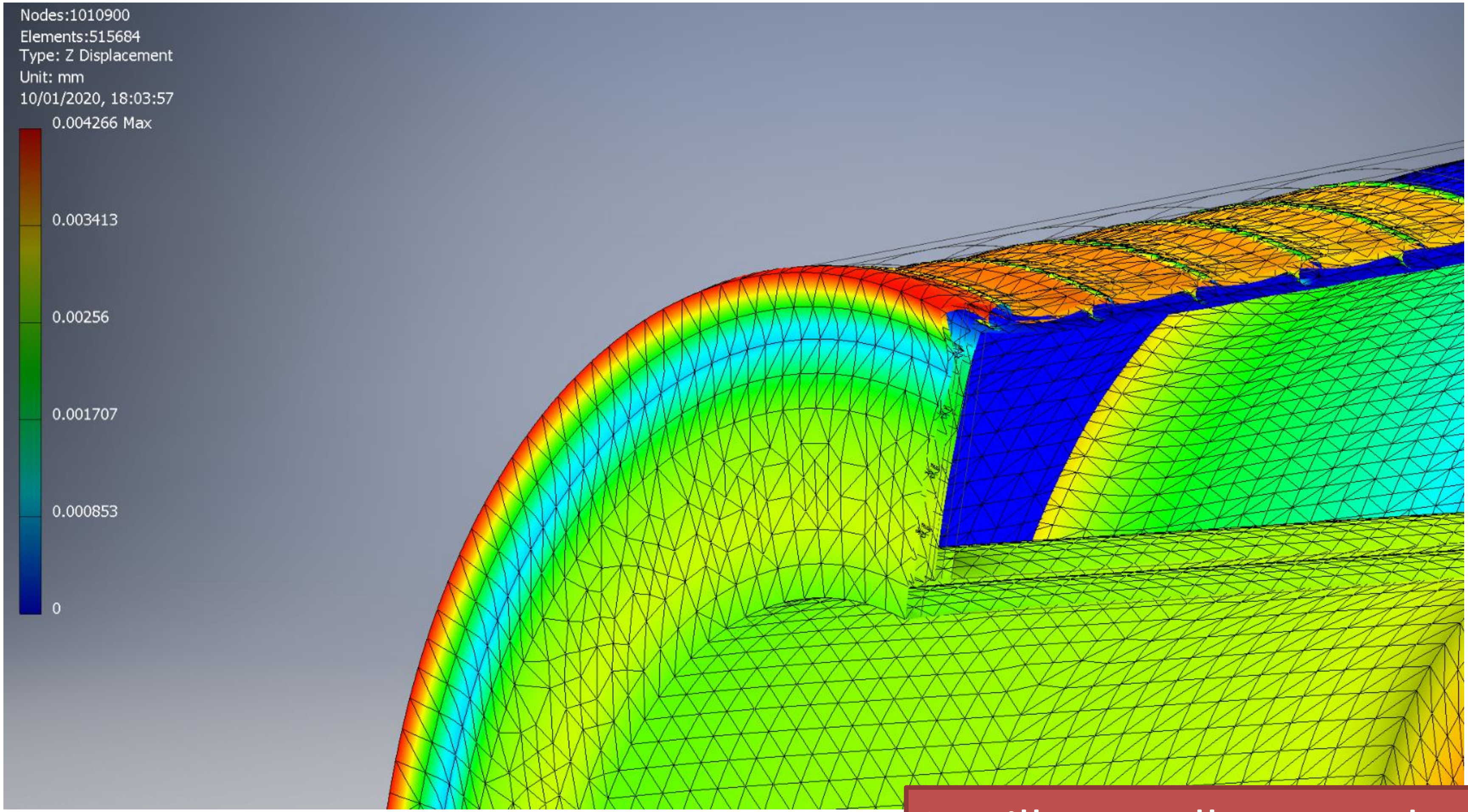
Von Mises Stress



Safety factor: 10.5 minimum

This is overengineered

deformation



It will not collapse under vacuum safety factor is 10

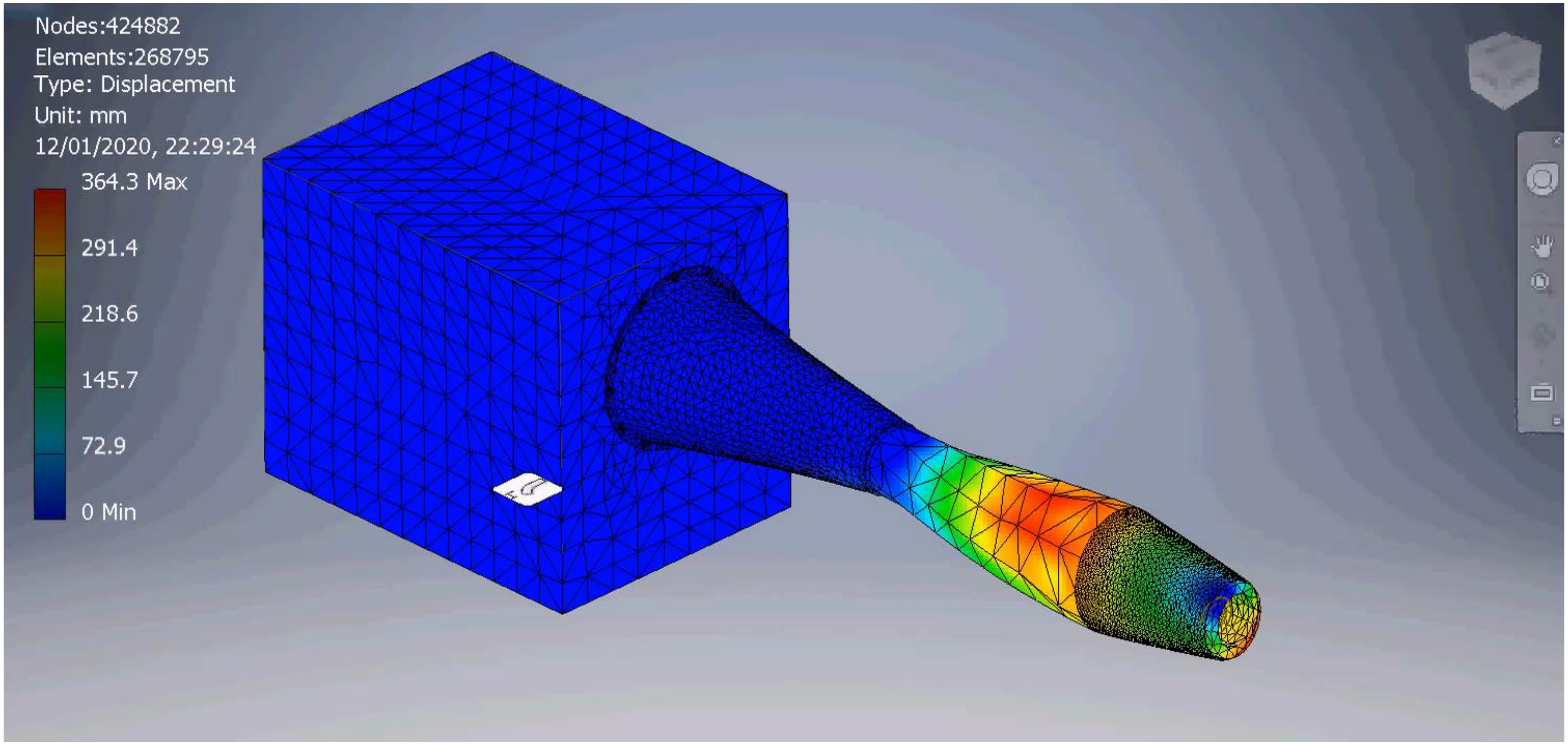
Conclusion thin cryostat

- A thin cryostat is not out of the question! Indeed, it looks plausible
- If a thin cryostat can work, we can satisfy the 100mrad requirement! To within a few millimetres, we are there.

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

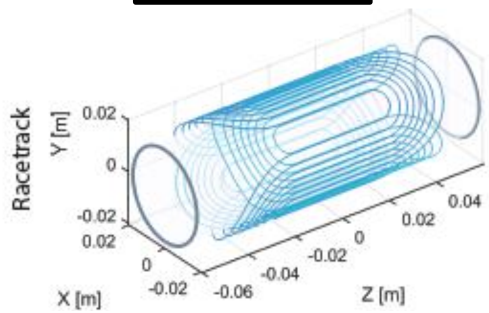
Conclusions

- 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

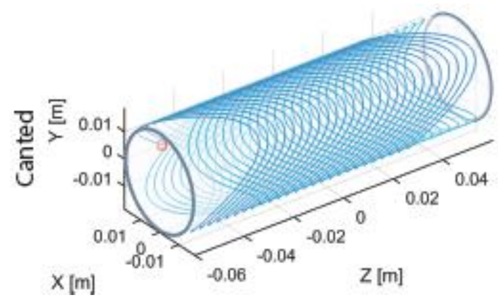
Extra slides

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

Conventional



CCT (Double Helix)



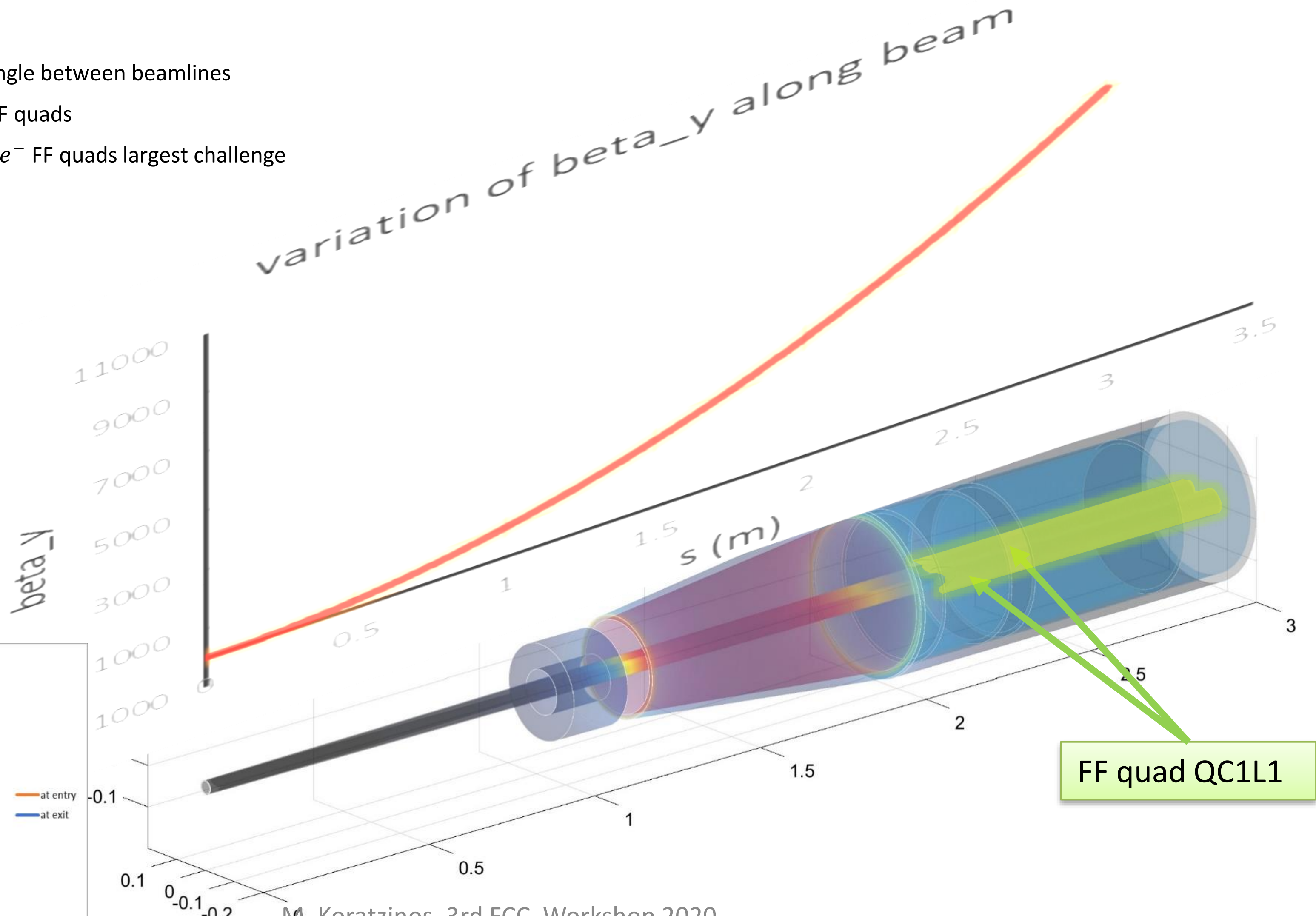
- Novel idea (discovered in the 70ies, but gained momentum recently with the advent of CNC manufacturing and 3D printing)
  - Excellent field quality
  - Engineering simplicity: no pre-stress; fast prototyping
  - Simpler and cheaper than conventional designs
  - But: more conductor for same field compared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

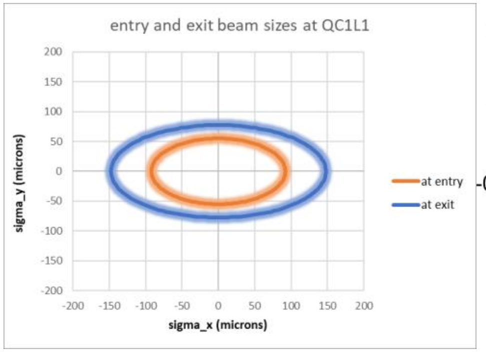
Local compensation

L* = 2.2m; 30mrad opening angle between beamlines

⇒ very little space between FF quads

⇒ crosstalk between e^+ and e^- FF quads largest challenge





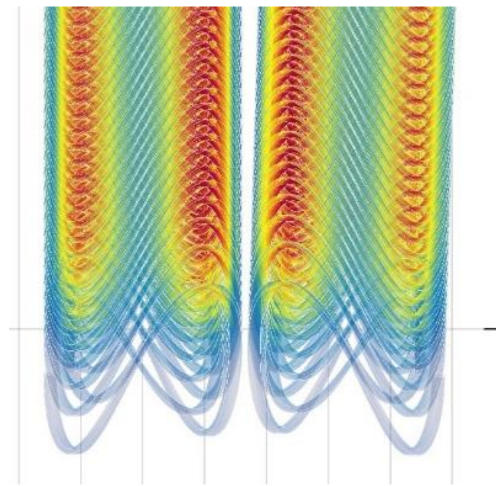
Iron-free design

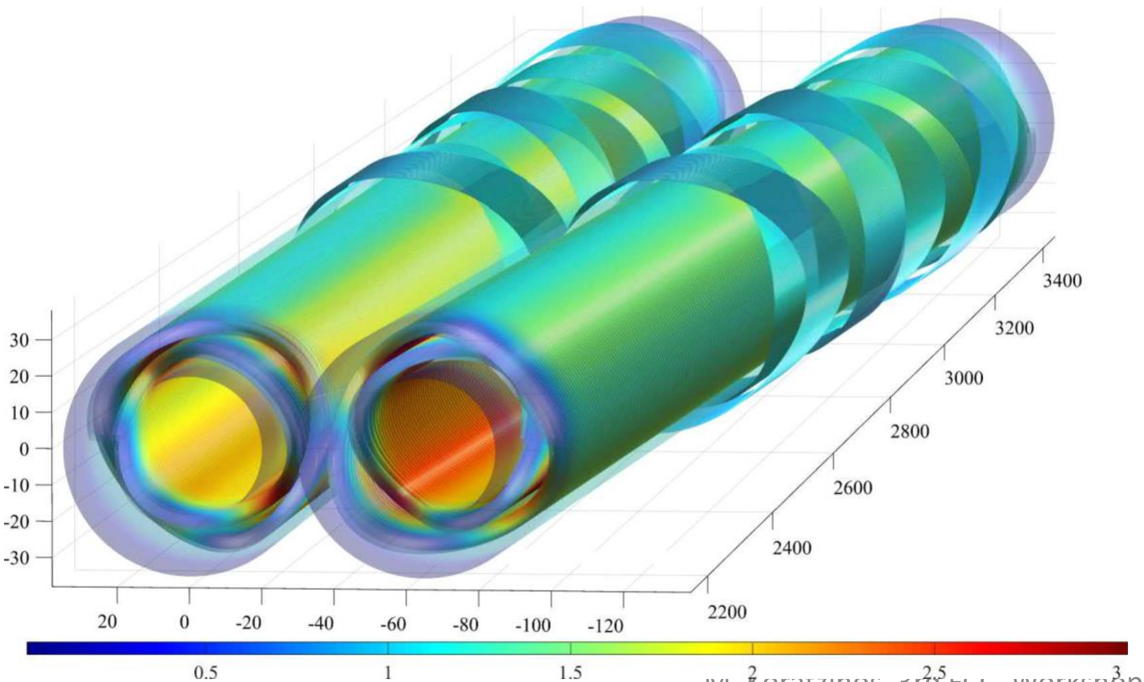
- Iron cannot provide the elimination of cross-talk, since there is very little space between magnets
- Therefore, the compensation must be embedded in the quadrupole design
- This can be trivially done in a CCT design
- Keep in mind that iron-free also means that everything is linear

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

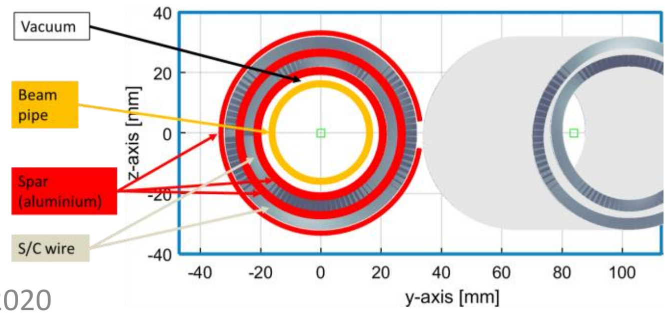
QC1L1

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

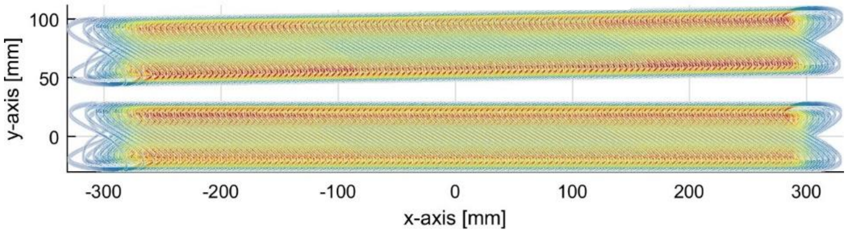




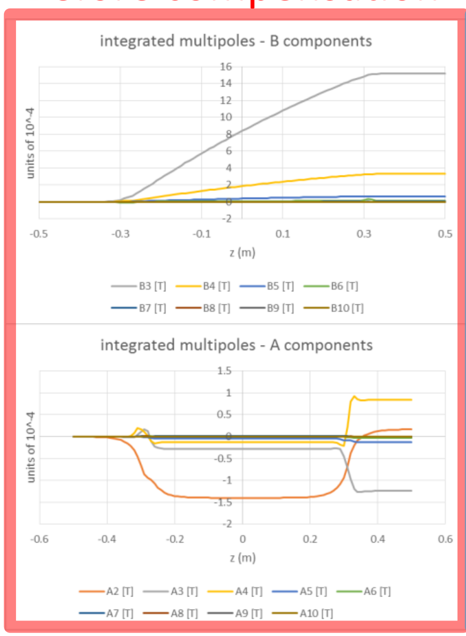
Inner bore: 40mm (diameter)
Fits outside the warm water-cooled beam pipe of inner diameter 30mm



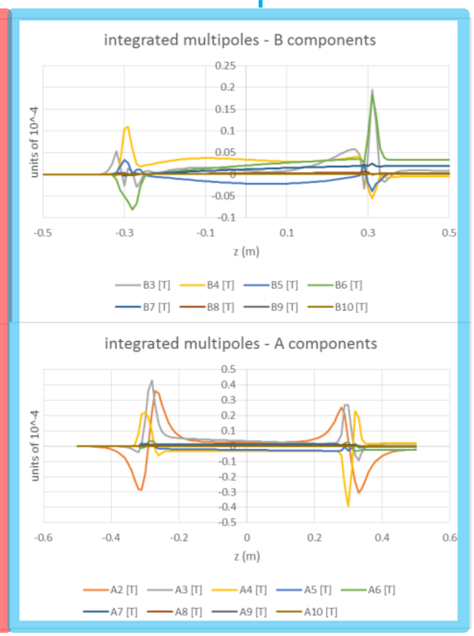
Crosstalk compensation



Before compensation



After compensation



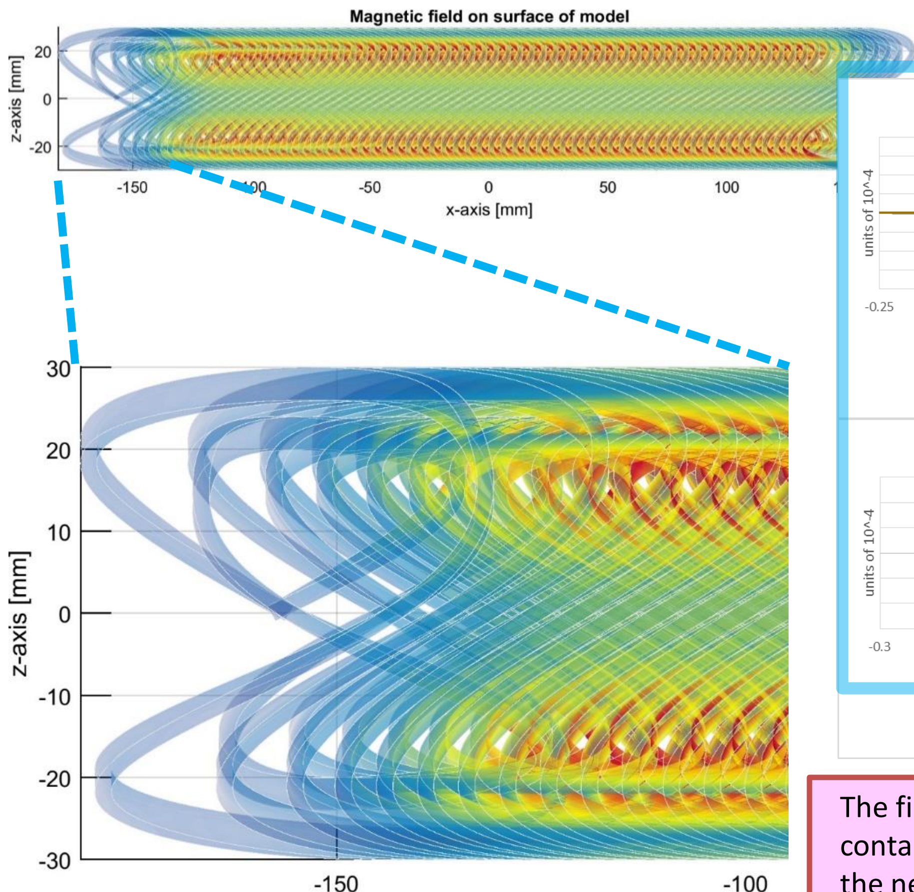
QC1L1 quadrupole:
length = 1200mm
Aperture: 40mm
distance at tip: 66mm
angle 30mrad
powered together

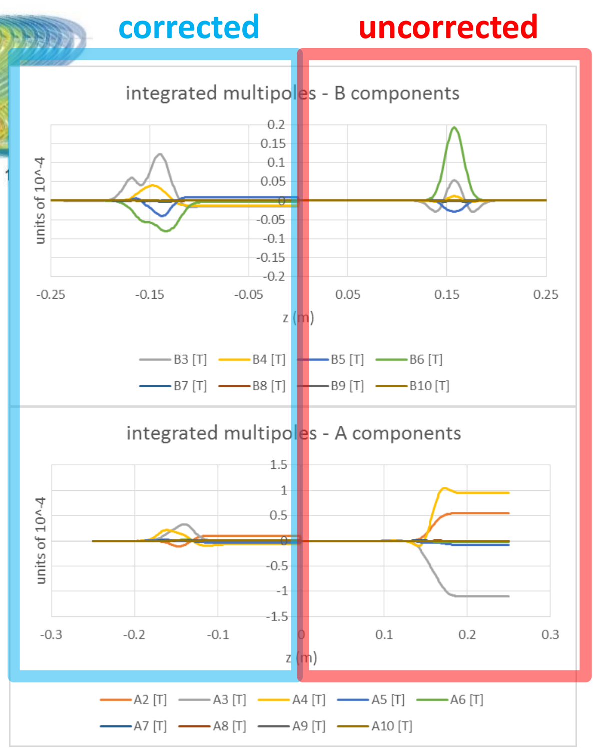
After compensation:
all multipoles are
under 0.1 units
(limited by
alignment errors,
not included here)

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



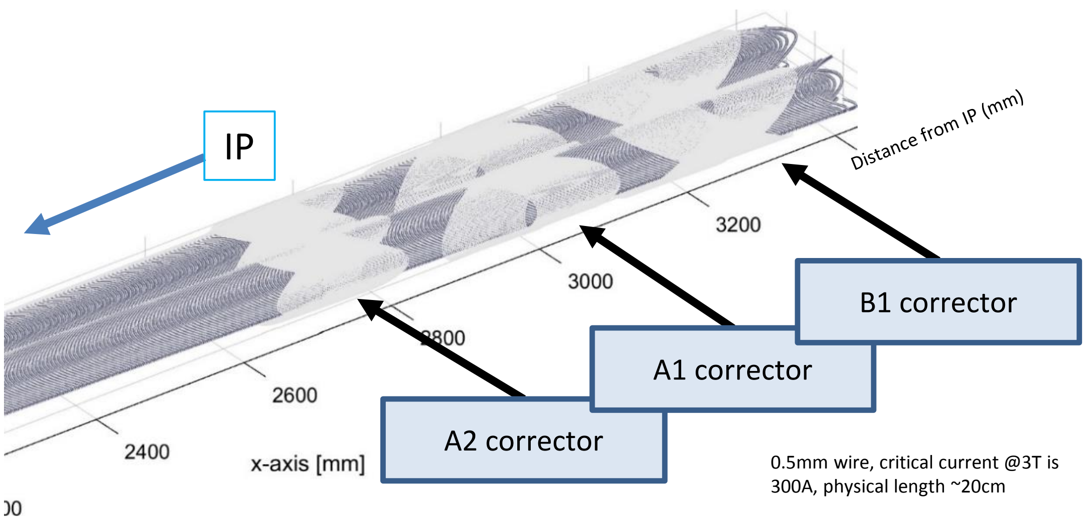


The first two turns of the quadrupole contain, apart from the B2 component, all the necessary components to nullify the edge effects.

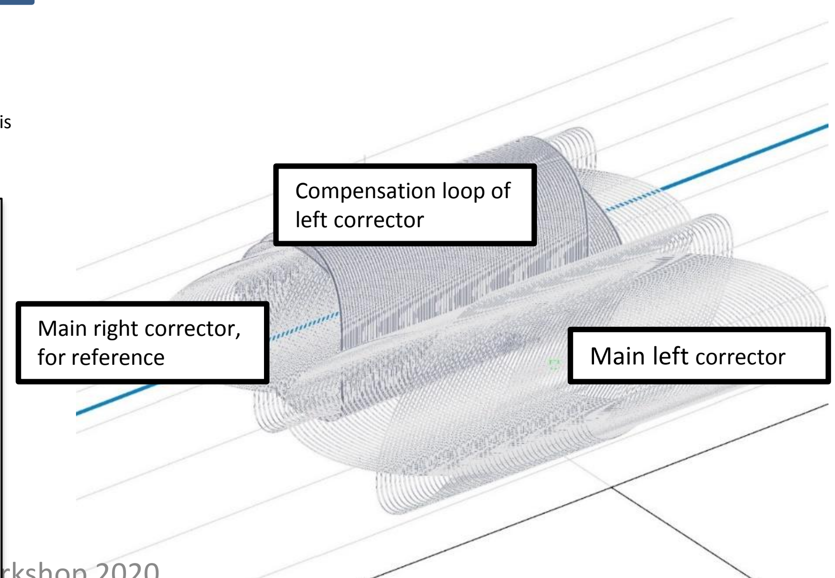
Packaging advantages

- 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 space in the design.
- Each corrector comes with its own compensating coil in the other aperture to compensate for the (small) crosstalk

Correctors



Correctors can be packaged very efficiently



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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

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!

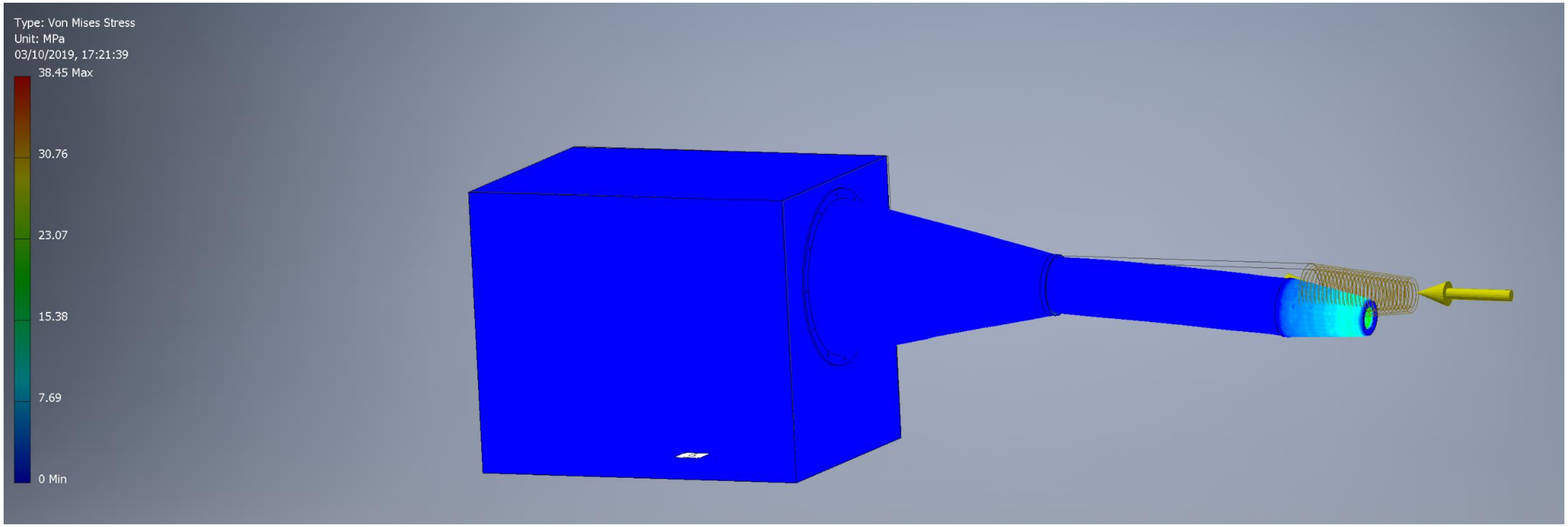
K. Oide, Wednesday 26/6/2019

- 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

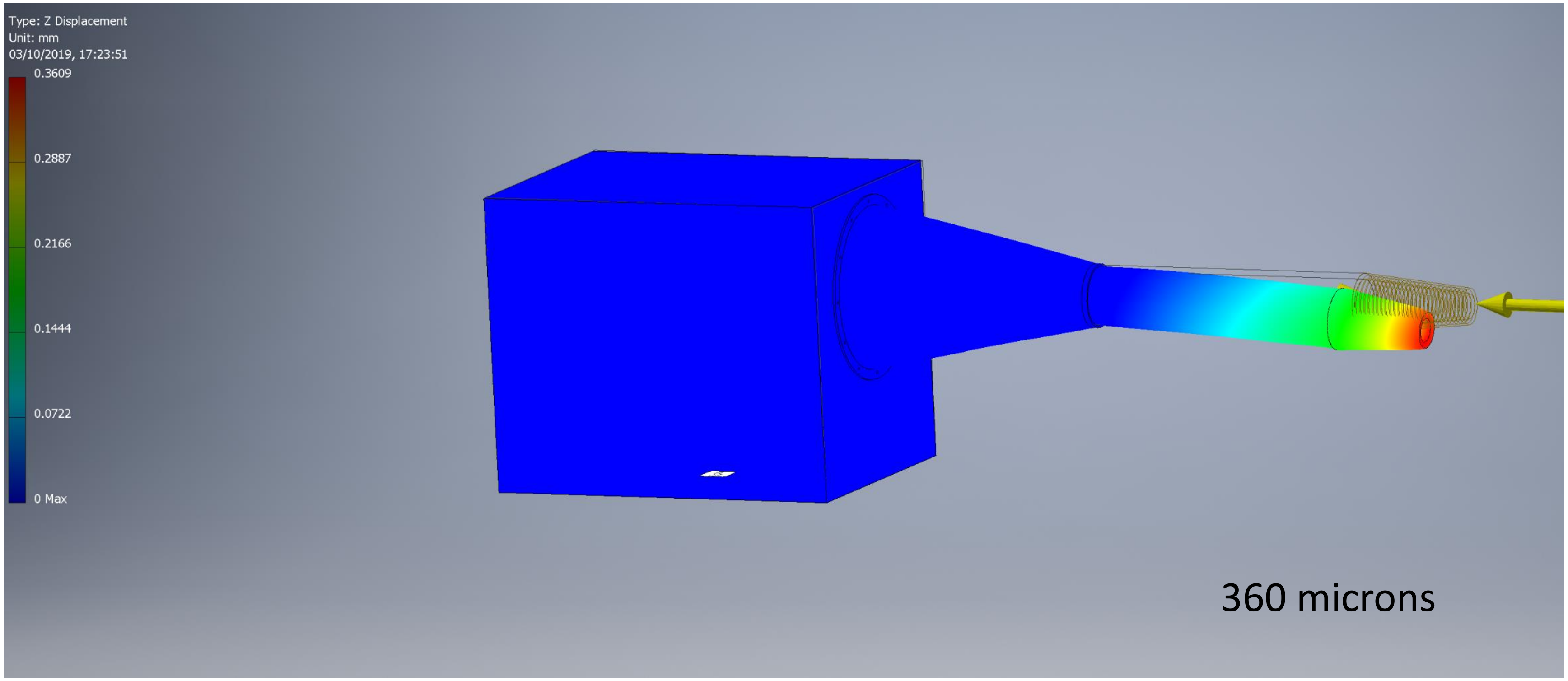
Stress analysis – very preliminary

- Use a simplified version of the CAD model **without** the skeleton.
- The coil former is already 4cm thick, sufficient to support the weight and the EM forces
- The reasoning is the following: since we cannot fight all vibration modes, it is easier to have a simple structure with the lowest frequency
- Static stress analysis with gravity and electromagnetic forces

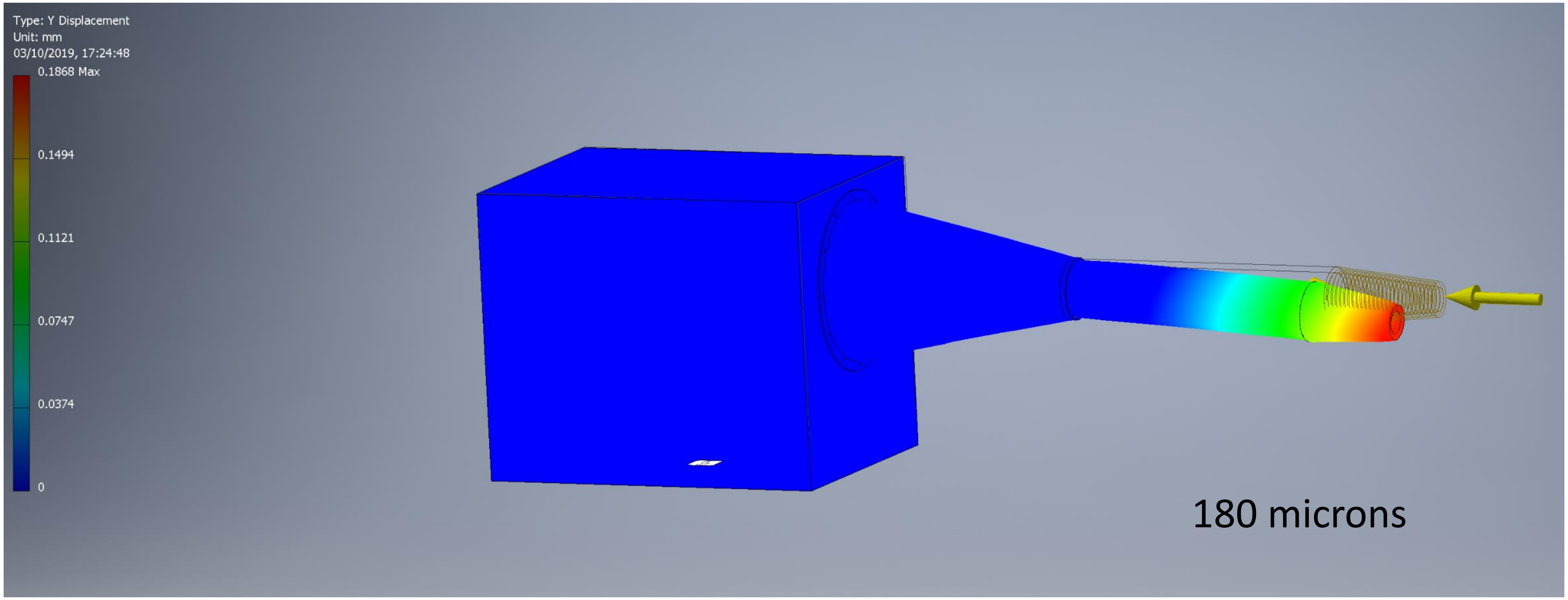
Static analysis – von Mises stress max 40MPa



Z displacement



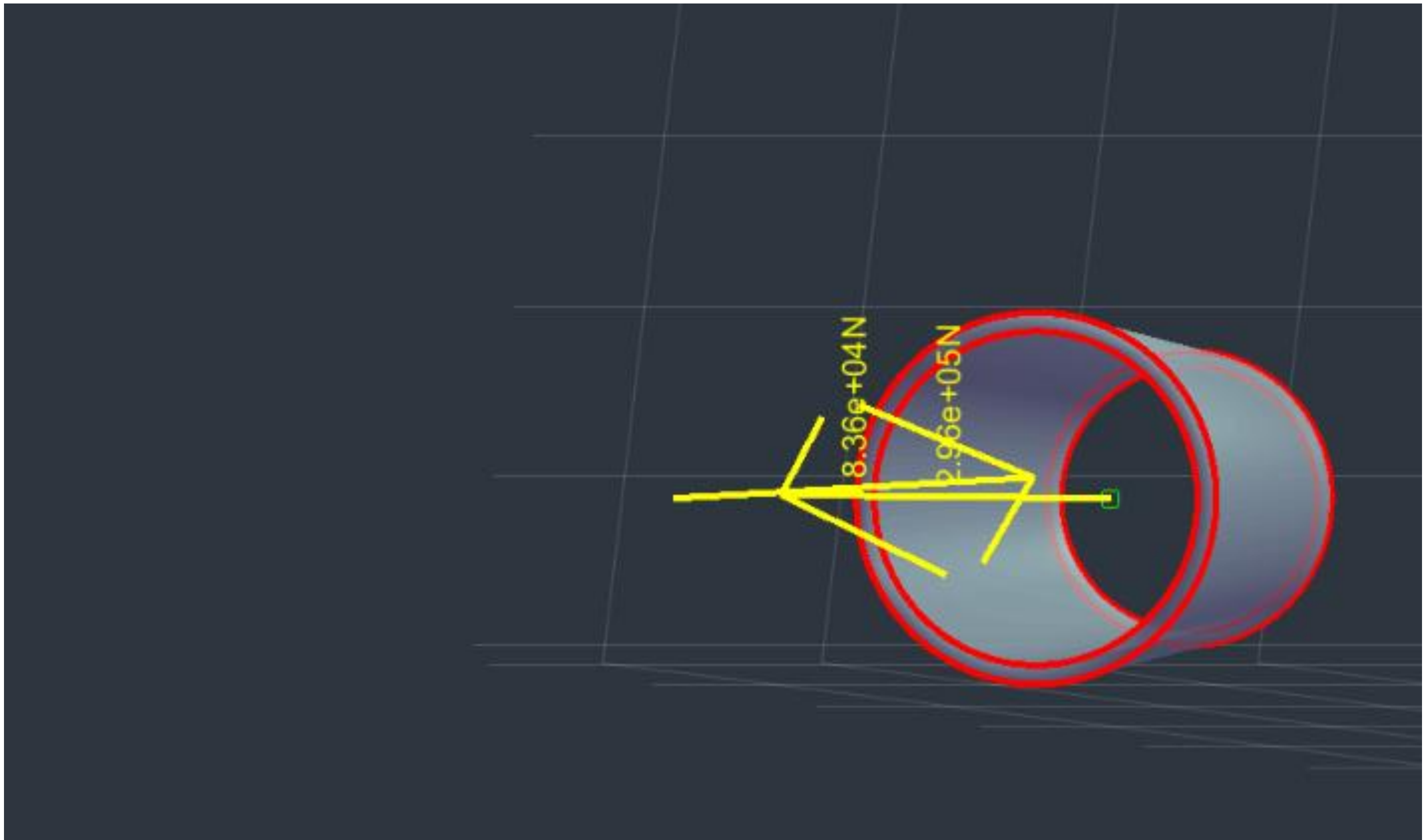
Y displacement



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: -8t towards the IP
- Comp. solenoid: +30t, towards the endcap

Forces and torques

Name	x [m]	y [m]	z [m]	Fx [N]	Fy [N]	Fz [N]	Fmag [N]	Tx [N.m]	Ty [N.m]	Tz [N.m]	Tmag [N.m]
main detector solenoid	0	0	0	721854.6	721898.9	2422.292	1020891	-2296.81	2296.886	0.05287	3248.237
anti_solenoid	0	0	3.6	1475.536	1522.768	-83548.6	83575.48	554.4594	-536.366	-10708.6	10736.38
anti_sol_4T	0	0	1.6	888.7587	912.7048	295704.3	295707.1	65.42666	-65.2918	2550.376	2552.05
anti_solenoid_right	0	0	-3.6	1475.392	1522.619	83548.87	83575.77	-554.419	536.3337	-10708.6	10736.38
anti_sol_4T_right	0	0	-1.6	888.2166	912.1454	-295705	295707.8	-65.7677	65.63288	2550.415	2552.107

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	721854.62	721898.9	2422.2915	1020891	-2296.814	2296.886	0.05287	3248.237
anti_solenoid	1475.536	1522.768	-83548.58	83575.48	554.45939	-536.366	-10708.6	10736.38
anti_sol_4T	888.75868	912.7048	295704.35	295707.1	65.426663	-65.2918	2550.376	2552.05
anti_solenoid_right	1475.3919	1522.619	83548.871	83575.77	-554.4193	536.3337	-10708.6	10736.38
anti_sol_4T_right	888.21662	912.1454	-295705	295707.8	-65.76765	65.63288	2550.415	2552.107

Misalignment analysis

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
anti_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
anti_sol_4T	8.9E+02	9.1E+02	**3.0E+05**	3.0E+05	6.5E+01	-6.5E+01	2.6E+03	2.6E+03
anti_solenoid_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
anti_sol_4T_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								
anti_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
anti_sol_4T	1.0E+04	1.1E+03	**3.0E+05**	3.0E+05	2.8E+01	2.5E+03	2.5E+03	3.6E+03
anti_solenoid_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
anti_sol_4T_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								
anti_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
anti_sol_4T	7.1E+02	8.7E+02	**3.0E+05**	3.0E+05	6.0E+01	-3.4E+02	2.6E+03	2.6E+03
anti_solenoid_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
anti_sol_4T_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								
anti_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
anti_sol_4T	-2.7E+04	2.7E+02	**2.9E+05**	2.9E+05	1.5E+03	**5.1E+04**	2.5E+03	5.1E+04
anti_solenoid_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
anti_sol_4T_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

Recap forces and twists

- Forces: 30 tons on compensating solenoid, 8 tons on screening solenoid
- Torque: 1000 Nm on screening solenoid
- Misalignment: 10mm on both solenoids, plus 100mrad twist of compensating solenoid: 1300 Nm on screening solenoid