FCC-ee MDI design
as outcome of the first week of MDI workshop and goal of this week workshop

M. Boscolo

Thanks to all participants for inputs and discussions
my slides are based on last weeks presentations, more details there

Workshop on the mechanical optimization of the FCC-ee MDI
January 30- February 9 2018, CERN

Goal

- We aim at a first **mechanical 3D design** that can be easily changed and updated
- We aim this week at discussing the **assembly concept** of our MDI design

Few iterations will be probably needed
(for example after impedance budget estimation)

example: CLIC MDI

arXiv:1202.6511

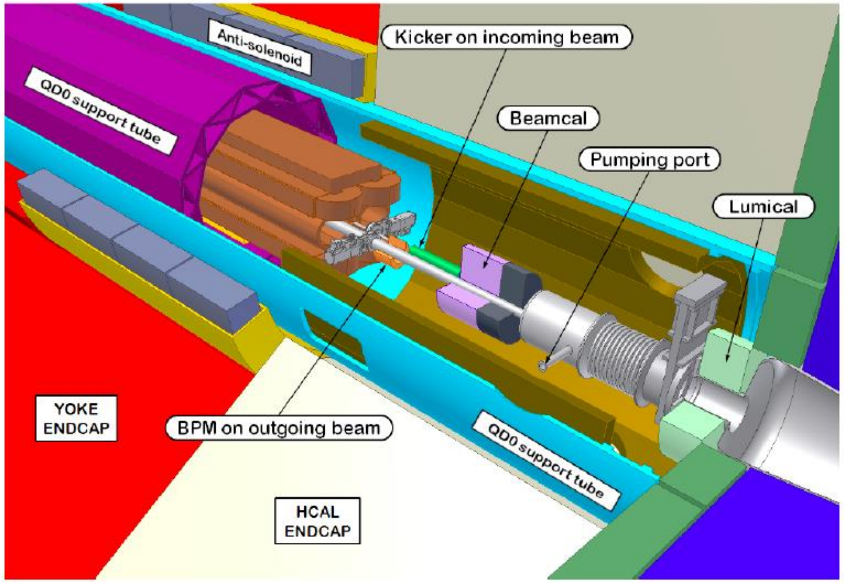
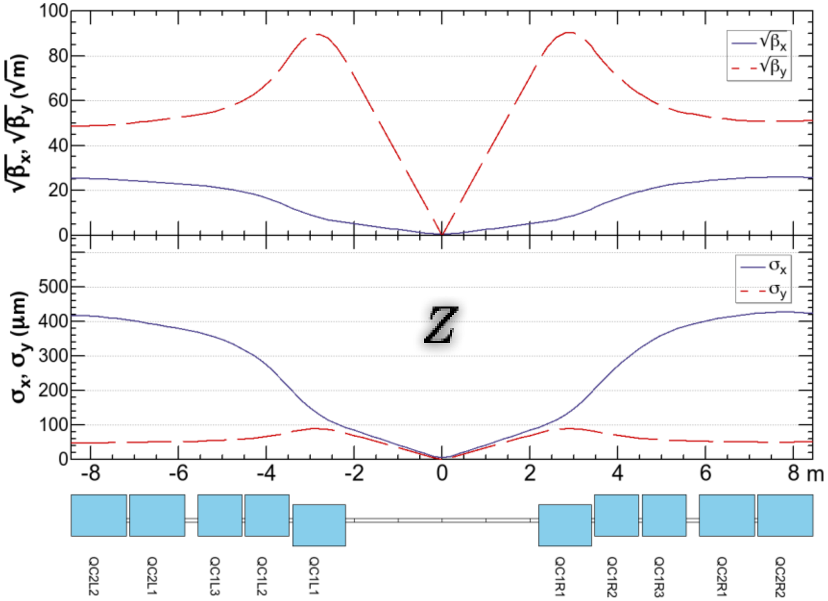


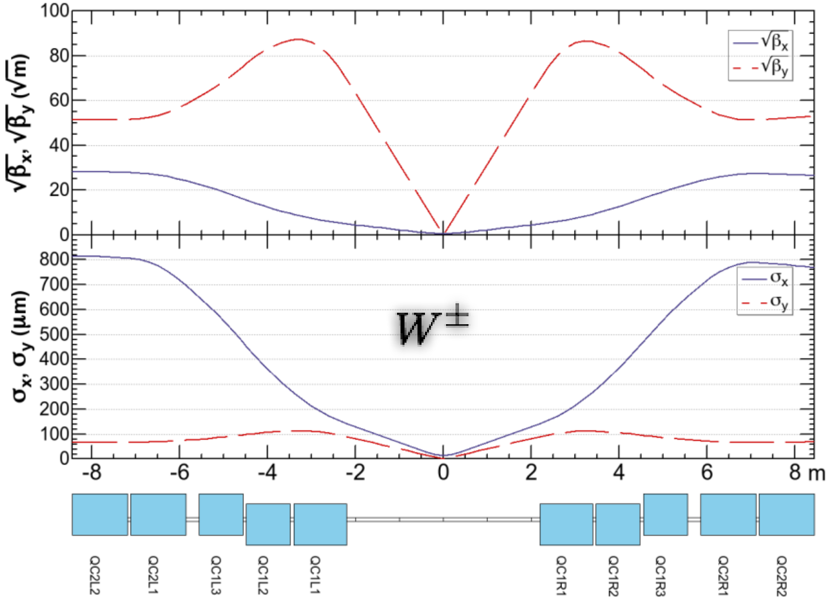
Figure 2: A schematic view of the CLIC Machine Detector Interface

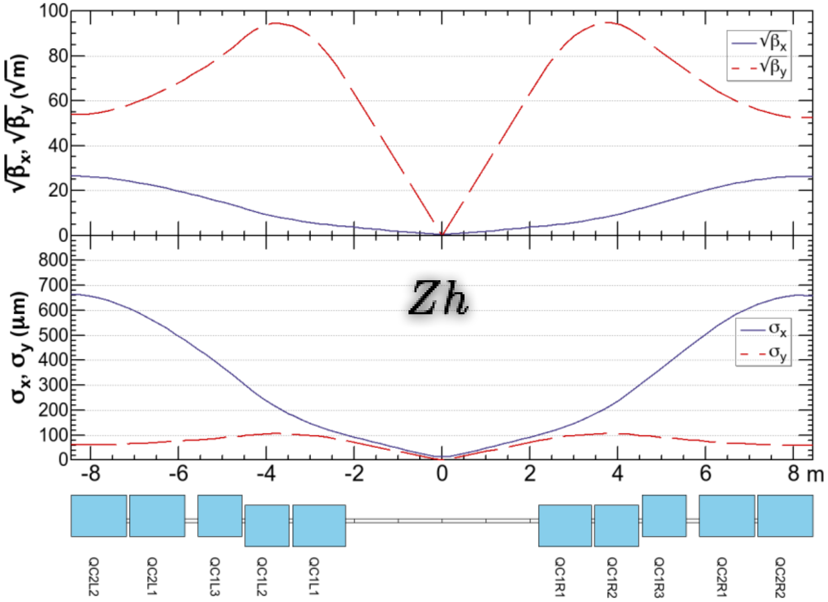
parameter	Z	W	H (ZH)	ttbar	
beam energy [GeV]	45.6	80	120	175	182.5
arc cell optics	60 / 60	60 / 60	90 / 90	90 / 90	
momentum compaction [10^{-5}]	1.48	1.48	0.73	0.73	
horizontal emittance [nm]	**0.27**	**0.84**	**0.63**	**1.34**	**1.46**
vertical emittance [pm]	1.0	1.7	1.3	2.7	2.9
horizontal beta* [m]	**0.15**	**0.2**	**0.3**	**1**	
vertical beta* [mm]	**0.8**	**1**	**1**	**1.6**	
length of interaction area [mm]	0.42	0.85	0.9	2.0	2.1
RF frequency [MHz]	400	400	400	400	400
tunes, half-ring (x, y, s)	(0.57, 0.61, 0.0125)	(0.562, 0.60, 0.0253)	(0.565, 0.60, 0.0179)	(0.554, 0.59, 0.0299)	(0.554, 0.59, 0.0311)
longitudinal damping time [ms]	415	77	23	7.5	6.6
SR energy loss / turn [GeV]	0.036	0.34	1.72	7.8	9.2
total RF voltage [GV]	0.10	0.75	2.0	8.8	10.3
RF acceptance [%]	1.9	3.5	2.3	3.5	3.5
energy acceptance [%]	±1.3	±1.3	±1.7	+2.4 / -2.8	+2.4 / -2.8
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.165	0.099 / 0.165	0.144 / 0.196	0.150 / 0.200
bunch length (SR / BS) [mm]	3.5 / 12.1	3.0 / 7.5	3.15 / 5.3	2.75 / 3.82	2.76 / 3.78
Piwinski angle (SR / BS)	8.2 / 28.5	3.5 / 8.7	3.4 / 5.8	1.1 / 1.6	1.1 / 1.5
Crab sextupoles [%]	97	92	80	50	50
bunch intensity [10^{11}]	1.7	2.3	1.8	3.2	3.35
number of bunches / beam	16640	1300	328	40	33
beam current [mA]	1390	147	29	6.4	5.4
luminosity [10^{34} cm^{-2}s^{-1}]	**230**	**34**	**8.5**	**1.9**	**1.7**
beam-beam parameter (x / y)	0.004 / 0.133	0.010 / 0.141	0.016 / 0.118	0.088 / 0.148	0.089 / 0.144
rad. Bhabha lifetime [min]	68	49	38	37	36
allowable asymmetry [%]	±5	±3	±3	±3	±3
required lifetime by BS [min]	29	16	11	12	12
actual lifetime (w) by BS [min]	> 200	24	18	24	25

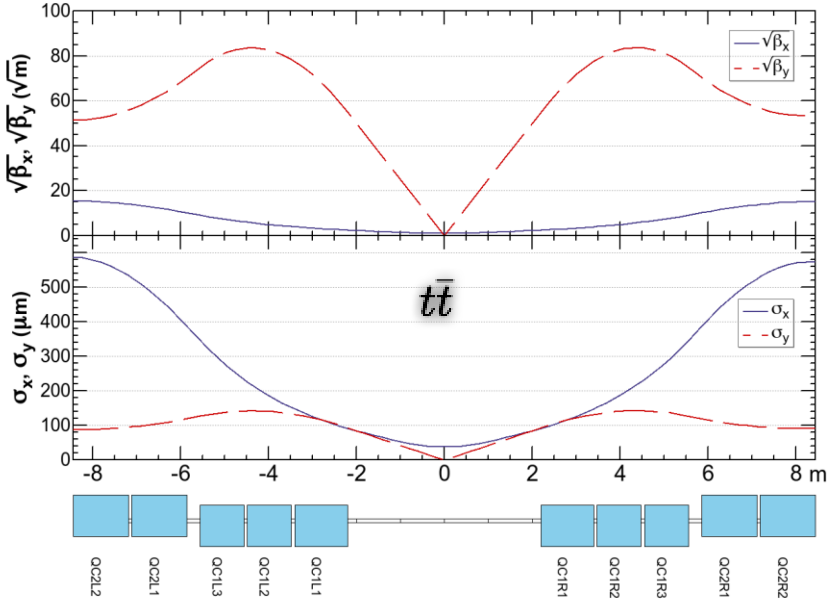
D. Shatilov, 19 Jan 2018

Optics & Beam Sizes Near IP

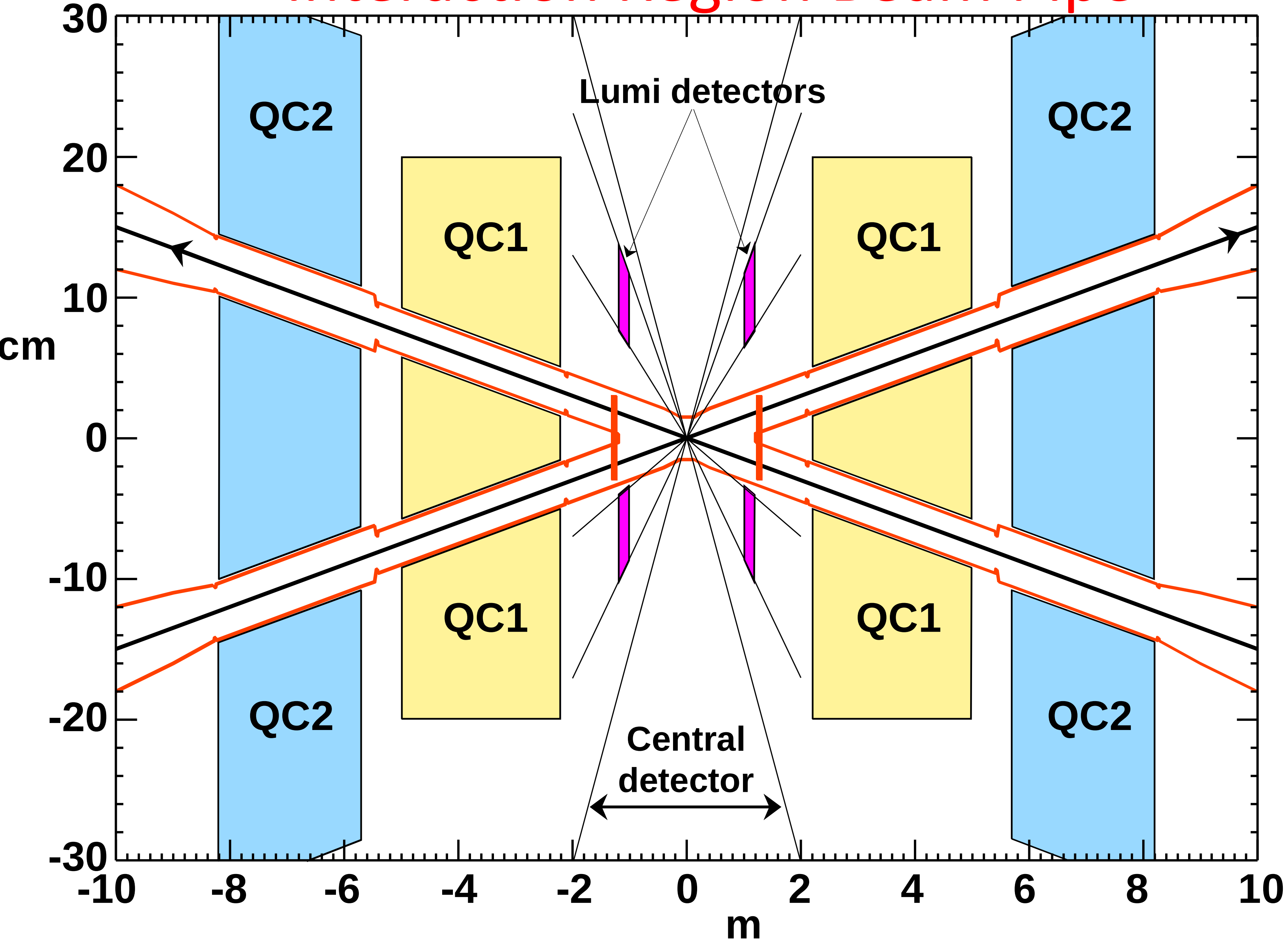




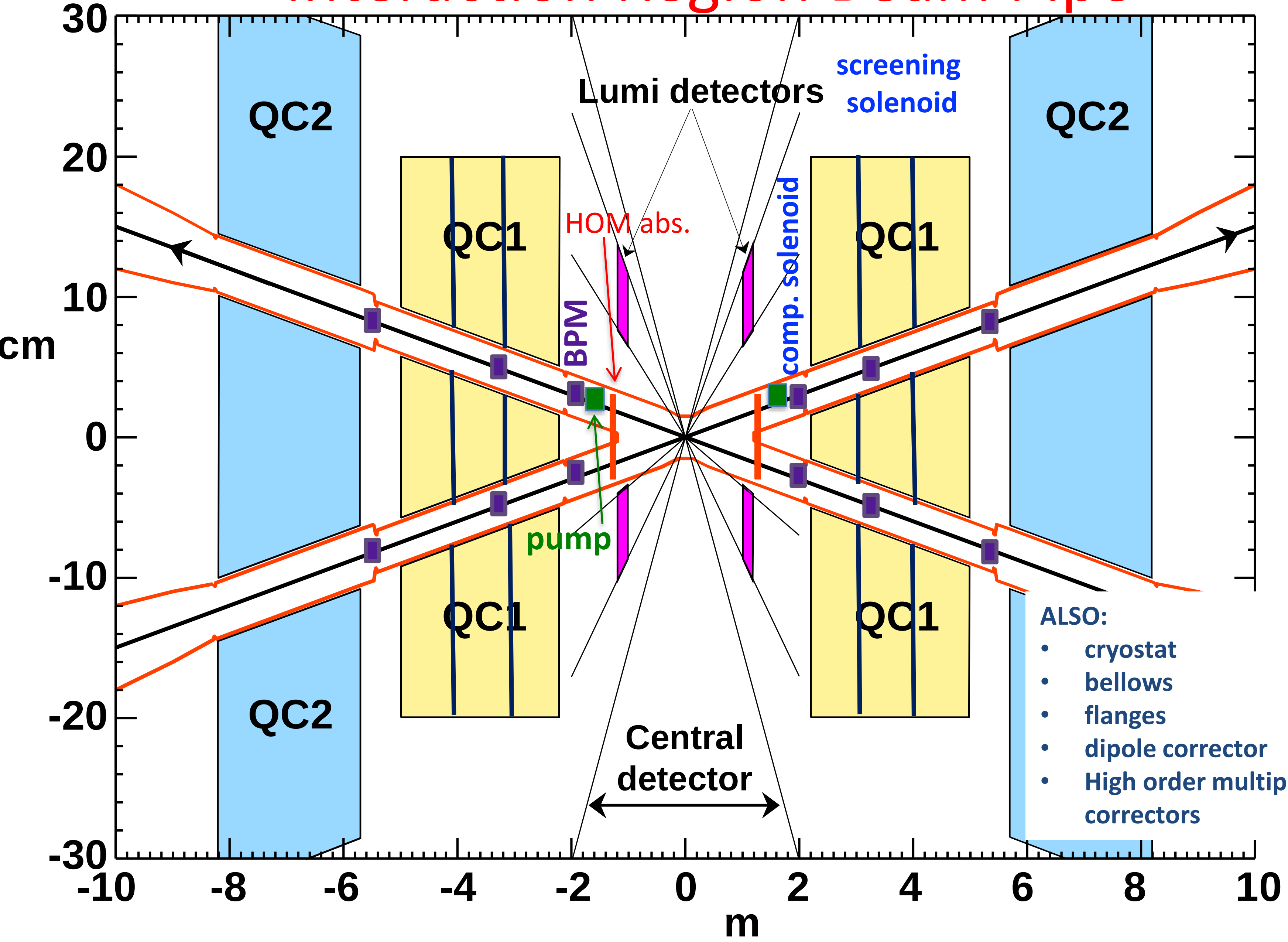




Interaction Region Beam Pipe

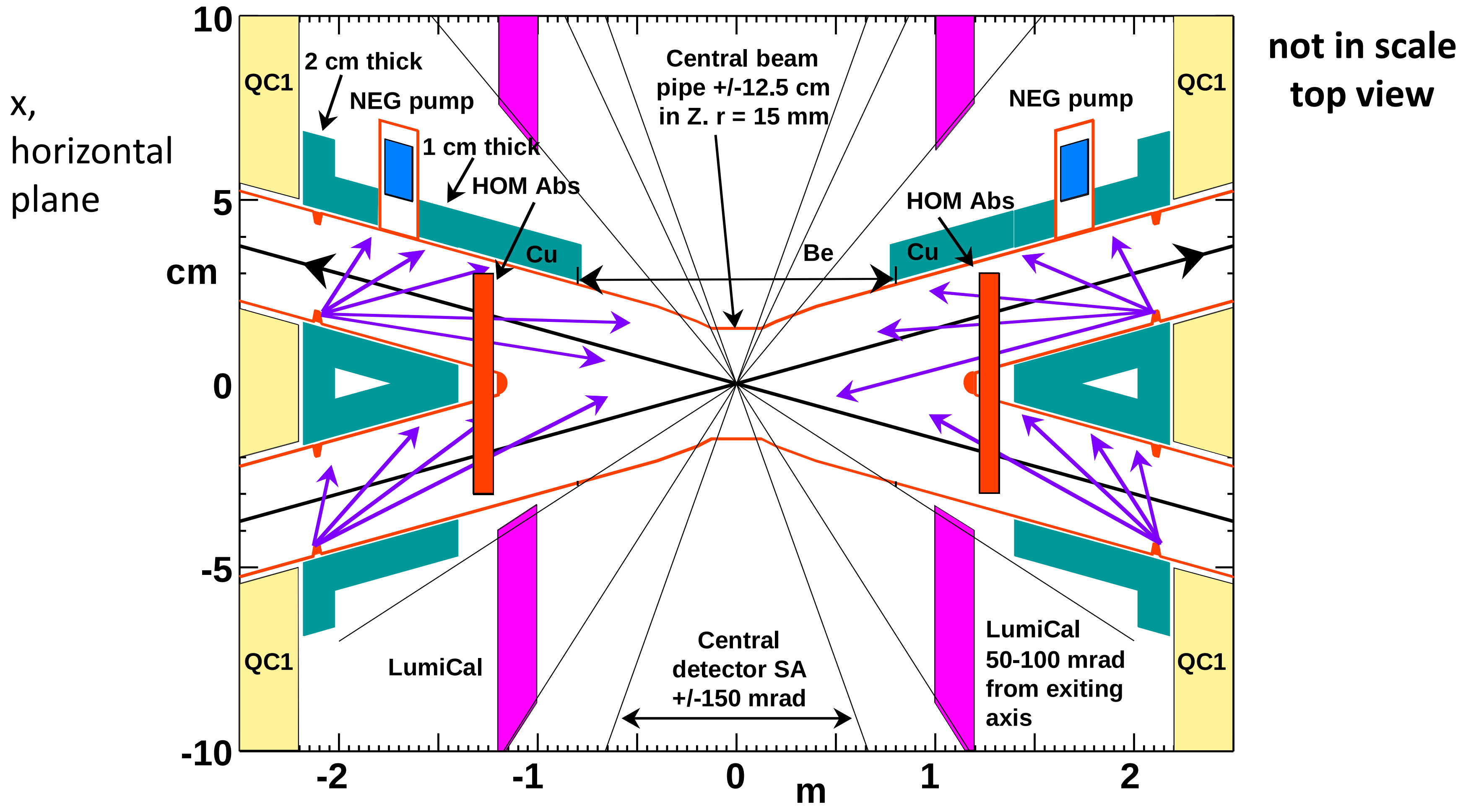


Interaction Region Beam Pipe



ALSO:
- cryostat
- bellows
- flanges
- dipole corrector
- High order multipoles correctors

Interaction Region Layout



not in scale
top view

Solenoid Compensation Scheme

comment on this number from last week [slide from FCCweek17]:

The 140mrad was the outcome of last year's MDI workshop, as best solution to minimize ε_y blow-up (0.3 pm out pf 1 pm nominal). Last week it was pointed out by detector group that angular acceptance for the machine (including compensating solenoid) should be 100 mrad.

M. Koratzinos are K. Oide are trying to find a good trade-off between 100 mrad requirement and acceptable ε_y blow-up. There will be a presentation this Wed.

Constraints:

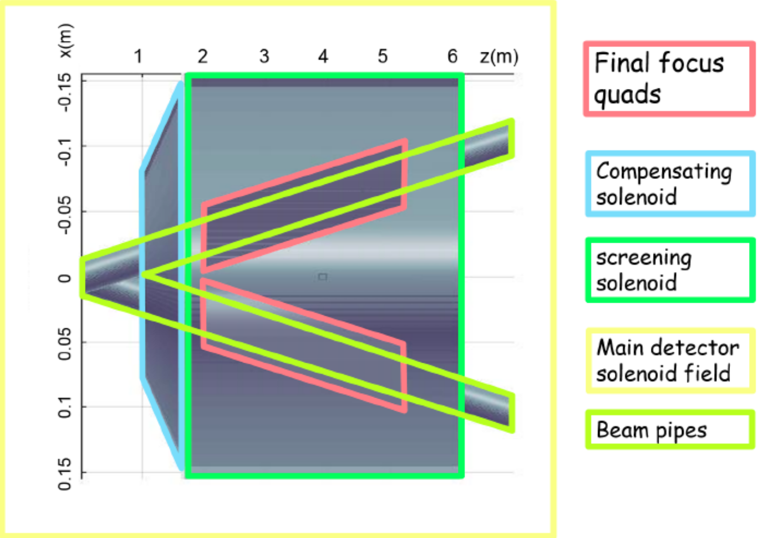
- **2T** detector field
- **L*=2.2m**
- Space (i.e. only 6.6 cm distance at the tip closest to IP for QD0)
- must be inside the lumical acceptance ~**140-170 mrad**
- final focus quads inside the detector (low βy^* and large crossing angle)
- leave space for **luminosity detector** at small angle
- field quality at each end and all along the FF quads $\lesssim 10^{-4}$ for all multipoles
- emittance blow-up much smaller than 1 pm

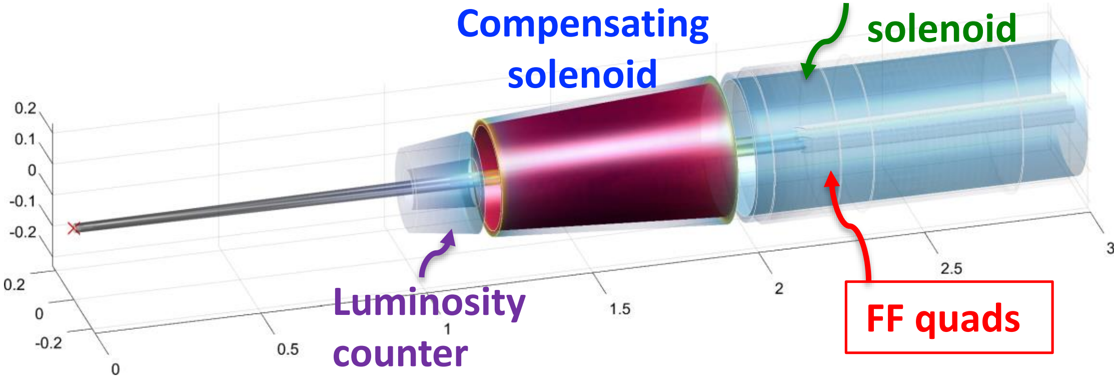
Particles on the beam axis are not on the detector axis, so they will experience vertical dispersion, that brings vertical emittance blow-up. Due to the low nominal ε_y~1 pm, this effect needs to be cured. A compensating and screening **solenoid scheme** has been designed.

[slide from FCCWEEK17]

see talk by E. Levichev

Solenoid Compensation Scheme





Compensating solenoid

screening solenoid

Luminosity counter

FF quads

M. Koratzinos

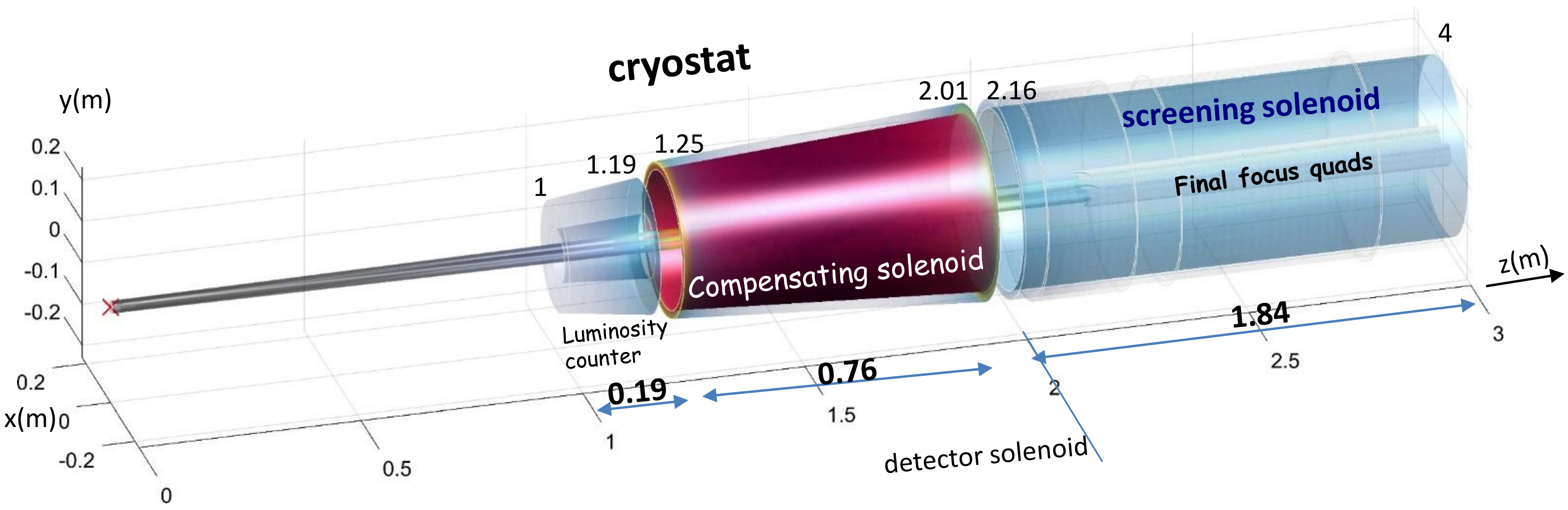
Two solenoids are introduced in the IR:

- **screening solenoid** that shields the detector field inside the quads (in the quad net solenoidal field=0)
- **compensating solenoid** in front of the first quad, as close as possible, to reduce the ε_y blow-up (integral BL~0)

0.3 pm is the overall ε_y blow-up for 2IPs @Z with this compensation design

[slide from FCCWEEK17]

The IR 3d view with magnets

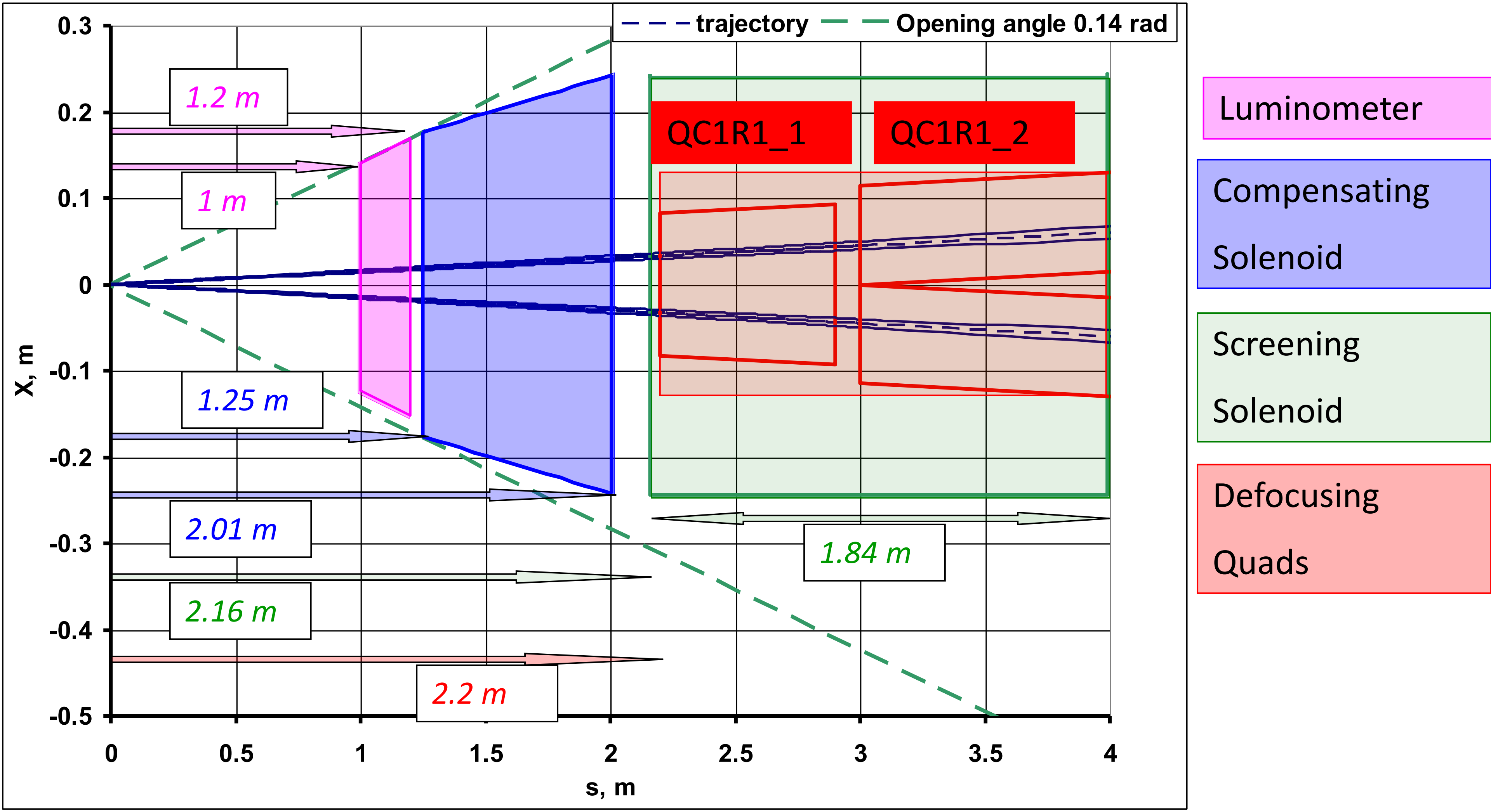


coordinates are from next slide

- opening angle 140 mrad (as from 2017 design)
- drift chamber at z=2m with 150 mrad opening angle
- detector solenoid dimensions 3.76m(inner radius) (outer radius 3.818m) × 4m (half-length)

Final Focus Magnets Layout

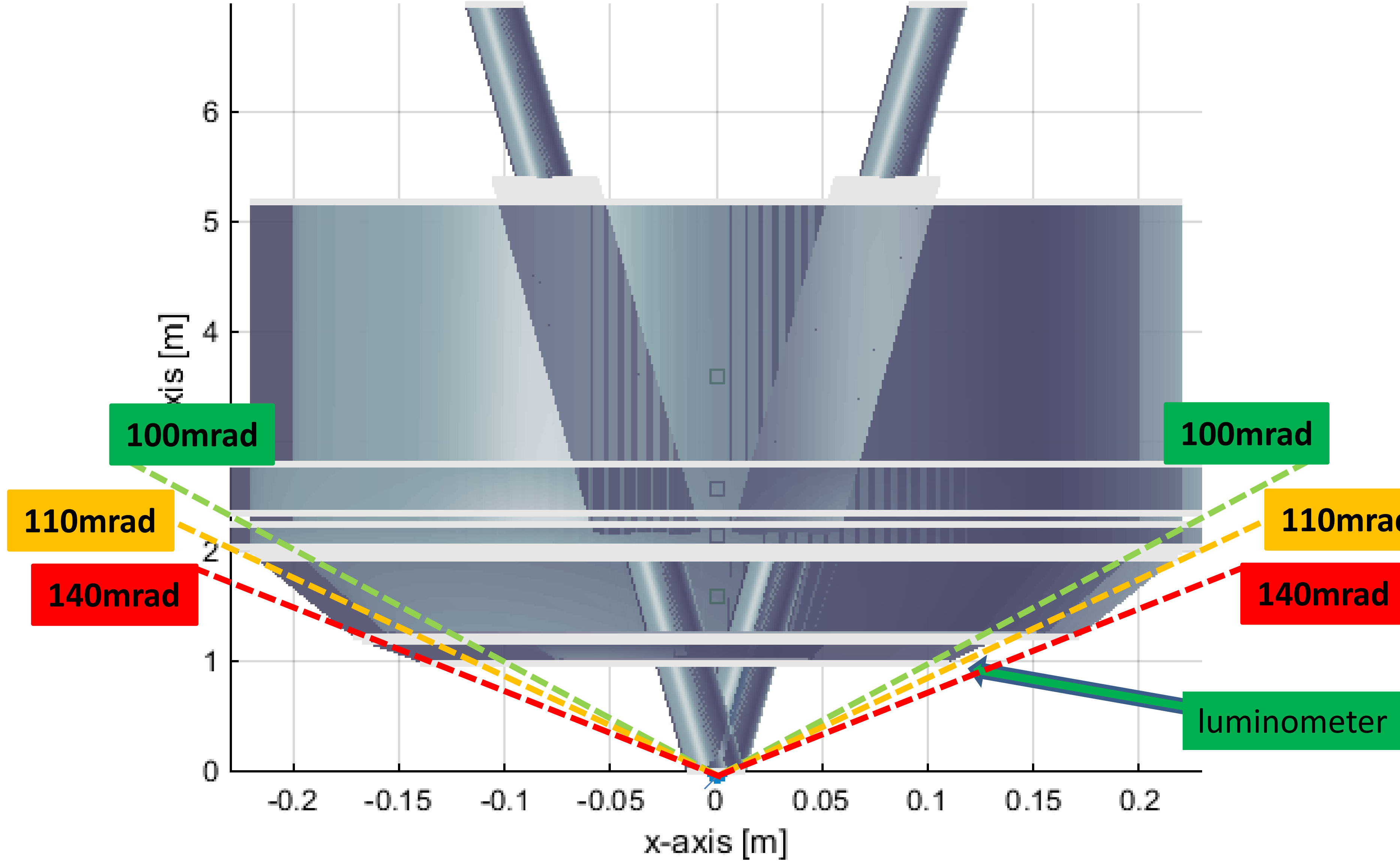
[S. Sinyatkin, summary talk MDI workshop Jan.17]



QC1R1_1:   L= 0.7 m,   K1=-75 / -75 T/m,   R = 0.015 m

QC1R1_2: L= 1.4 m,   K1=-173 / -166 T/m, R = 0.0175 m

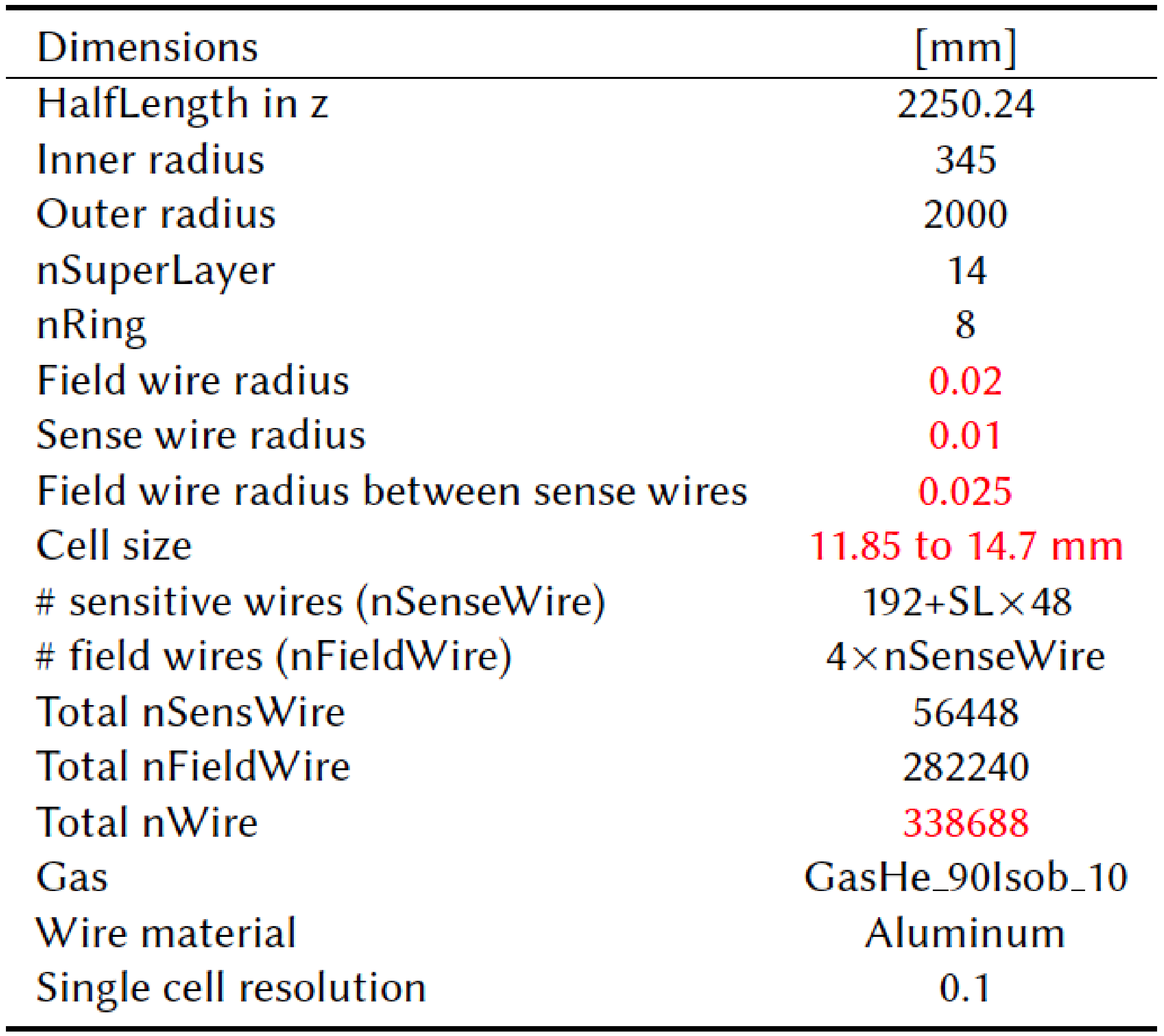
Latest layout



Drift chamber parameters

IDEA design

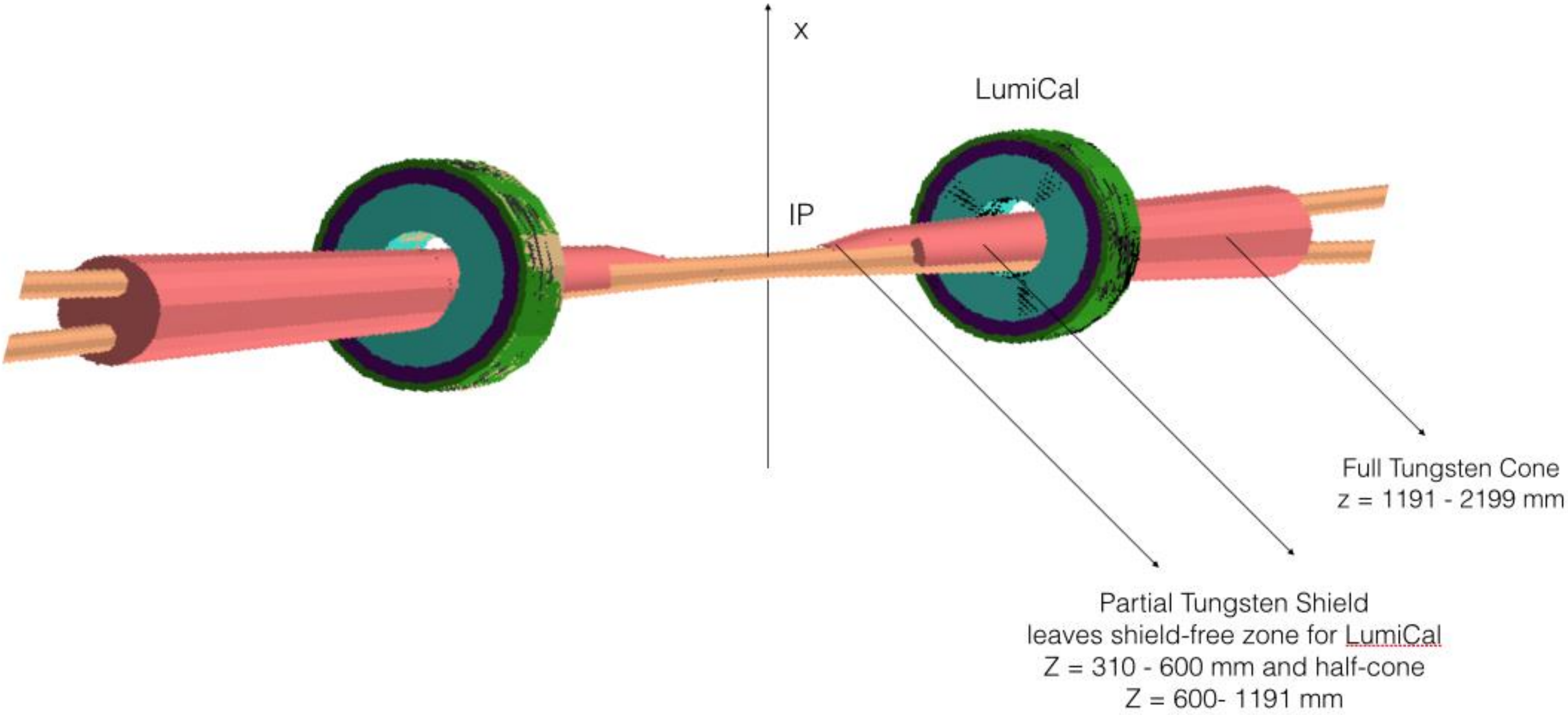
Length=4500 mm
Inner radius = 345 mm
Outer radius = 2000 mm



Dimensions	[mm]
HalfLength in z	2250.24
Inner radius	345
Outer radius	2000
nSuperLayer	14
nRing	8
Field wire radius	0.02
Sense wire radius	0.01
Field wire radius between sense wires	0.025
Cell size	11.85 to 14.7 mm
# sensitive wires (nSenseWire)	192+SL×48
# field wires (nFieldWire)	4×nSenseWire
Total nSensWire	56448
Total nFieldWire	282240
Total nWire	338688
Gas	GasHe_90Isob_10
Wire material	Aluminum
Single cell resolution	0.1

info from Niloufar Alipour Tehrani

Geant-4 IR model with the shield



Full Tungsten Cone
z = 1191 - 2199 mm

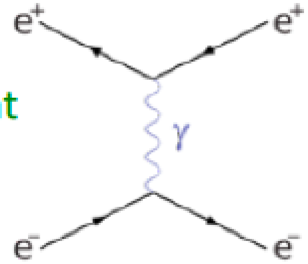
Partial Tungsten Shield
leaves shield-free zone for LumiCal
Z = 310 - 600 mm and half-cone
Z = 600- 1191 mm

thanks to Anna Kolano for providing this plot

Luminosity Monitoring with Bhabha scattering

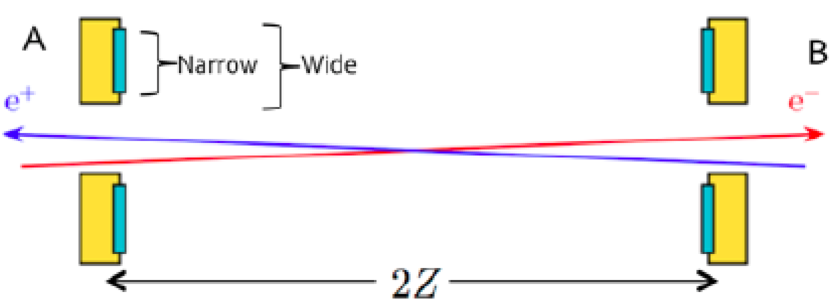
Luminosity monitoring:

- **Absolute** – target precision **10^{-4}**
  - May be best achieved through the process $e^+e^- \rightarrow \gamma\gamma$ (?)
- **Relative** for Z lineshape measurement – need a relative precision of **5×10^{-5}**
  - Need cross section comparable to Z production:, i.e. ≥ 15 nb
  - Can be achieved via **small angle Bhabha scattering $e^+e^- \rightarrow e^+e^-$**
    - Very strongly forward peaked – control of angular acceptance very important



$$\boxed{\sigma^{\mathrm{Bhabha}} = \frac{1040 \text{ nb GeV}^2}{s}\left(\frac{1}{\theta^2_{\min}} - \frac{1}{\theta^2_{\max}}\right)}$$

    - Measured with set of two calorimeters; one at each side of the IP

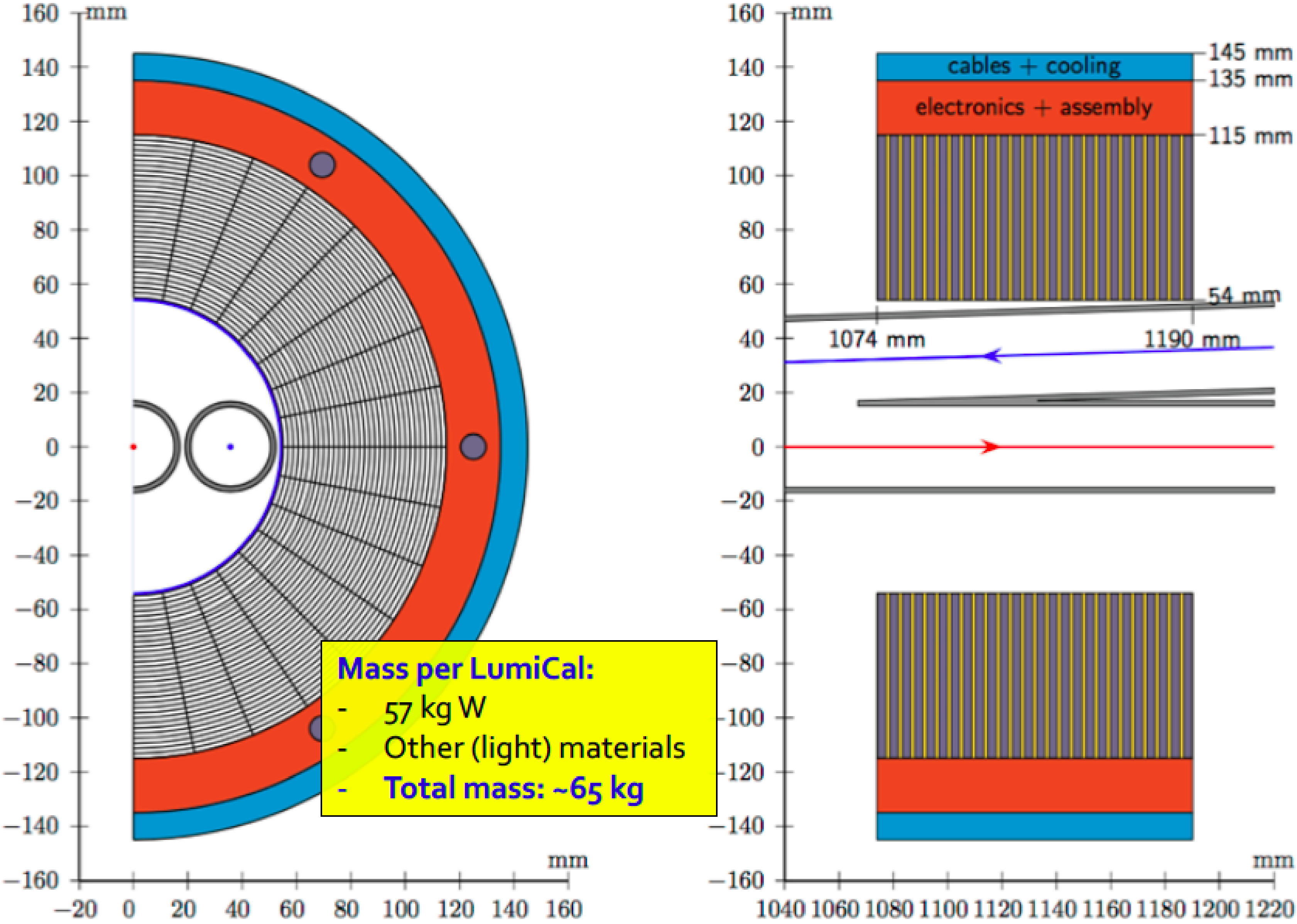


Two counting rates:
- SideA = NarrowA + WideB
- SideB = NarrowB + WideA

    - Average over SideA and SideB rates: Only dependent to second order on beam paramaters:

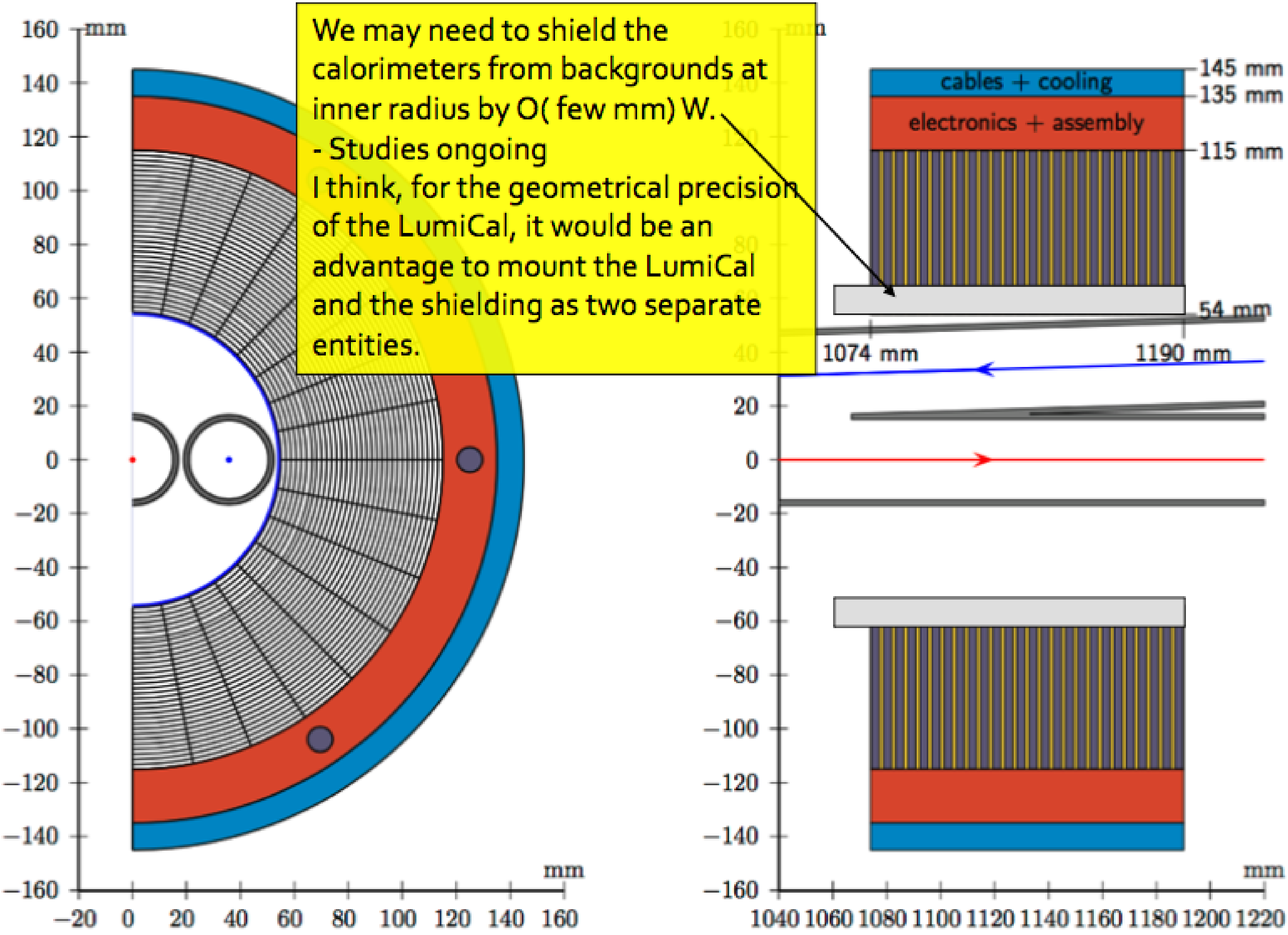
$$\frac{\delta \bar{R}}{\bar{R}} = 3\left(\frac{\delta z}{Z}\right)^2 \qquad \frac{\delta \bar{R}}{\bar{R}} = 2\left(\frac{\delta x}{r_{\min}}\right)^2$$

LumiCal Design



Mass per LumiCal:
- 57 kg W
- Other (light) materials
- **Total mass: ~65 kg**

Shielding towards beam pipe?

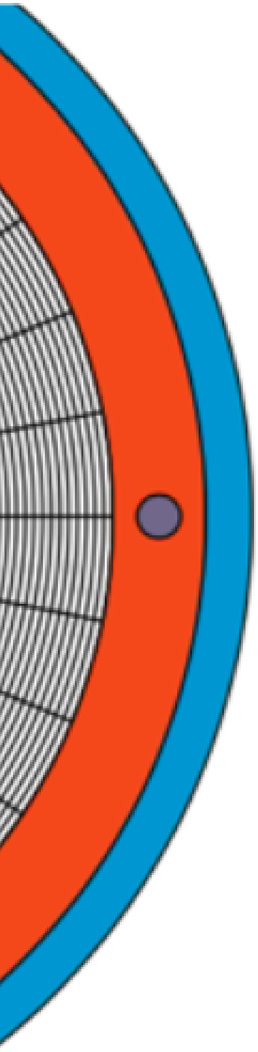


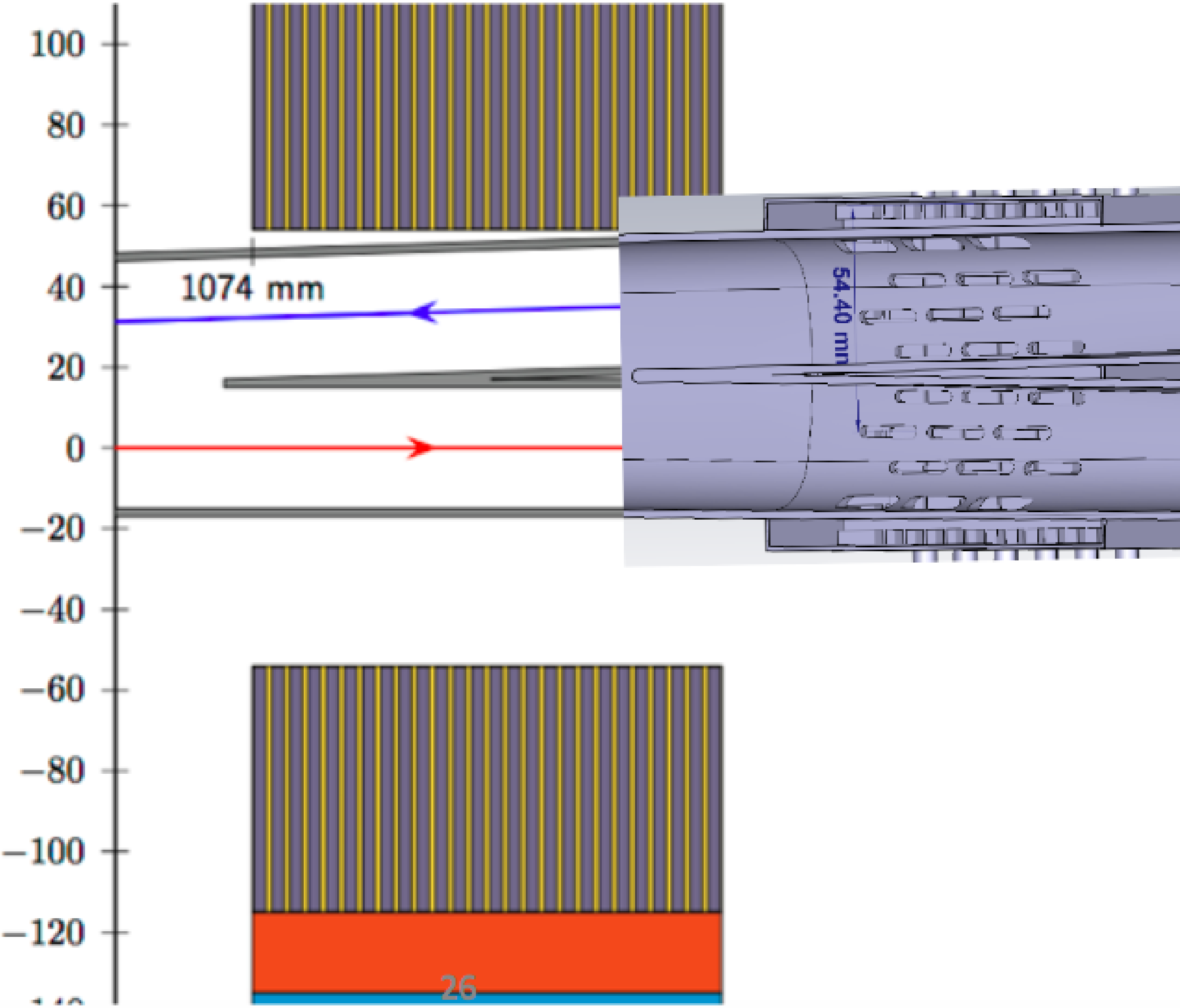
We may need to shield the calorimeters from backgrounds at inner radius by O(few mm) W.

- Studies ongoing

I think, for the geometrical precision of the LumiCal, it would be an advantage to mount the LumiCal and the shielding as two separate entities.

LumiCal and HOM absorber





A. Novokhatski 2/1/18

Mechanical Issues

- Internal to LumiCal
  - Assembly and meterology/alignment of Si readout pads to ~1.5 µm radial precision
  - Need cooling to remove ~100 W of heat per calorimeter
    - Stability to ±1 C° for geometrical precision
    - Cold and/or warm neighbours?
  - May need (thin – few mm) shielding towards beam pipe.
    - Supported from LumiCal or from beam pipe?

- External to LumiCal
  - How and from what is LumiCal supported?
    - Need very high precision: distance LumiCal/nominal IP to be controlled/measured to ~50 µm level
      - By how much will compensating magnets move when powered up?
  - And of course: Please no material in front of acceptance except (thin) beam pipe!

IR Beam pipe design for wake field calculations

details in next talk
by A. Novokhatski

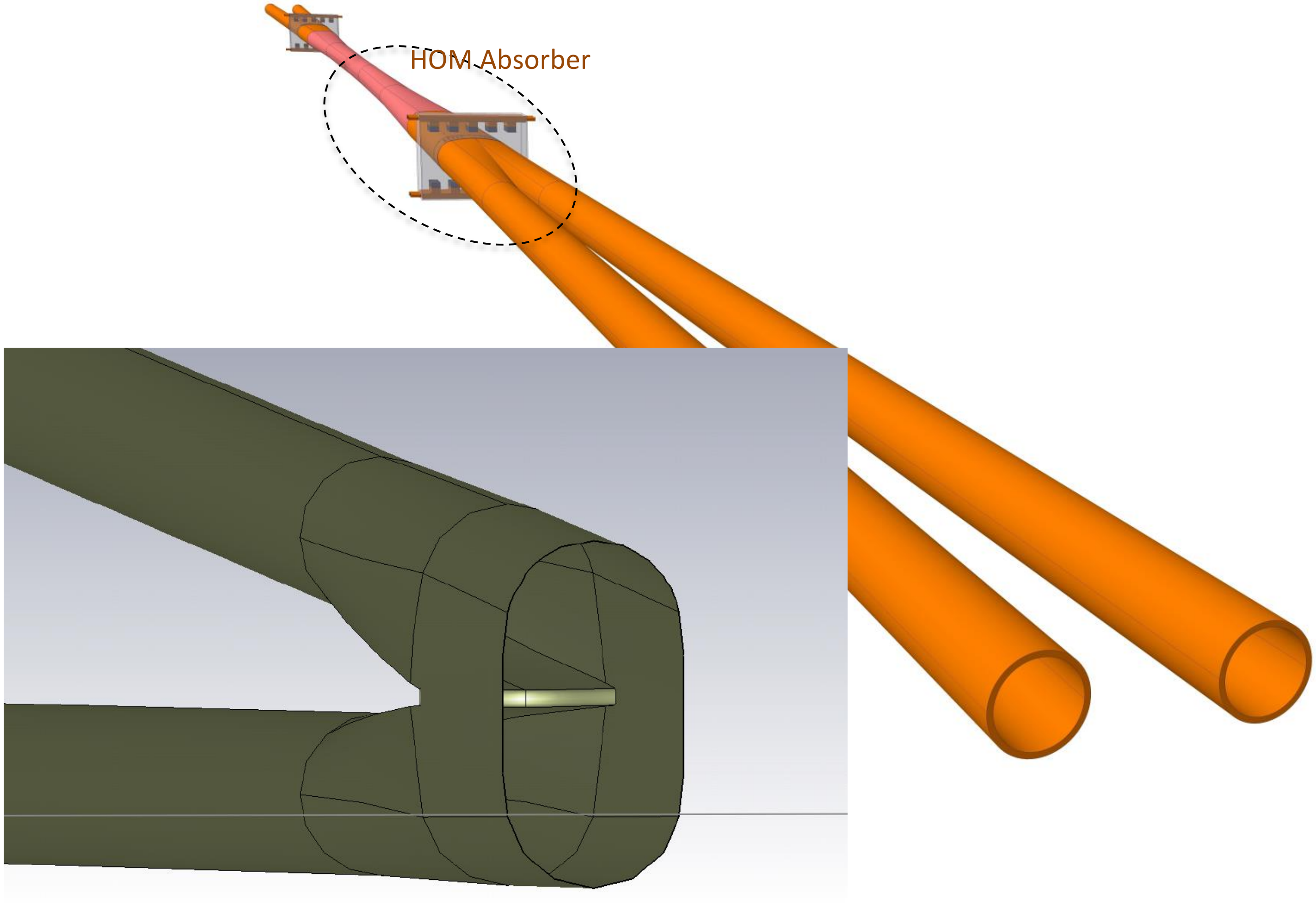
Two beam pipes are merged into one central pipe in the IR

- **Professional CAD design** of the complicated **IR** geometry **done**, essential for
- **CST/HFSS numerical studies** for generated and/or absorbed e.m. fields, propagating or trapped in the IR
- **water cooling of the beam pipe needed** to avoid HOM heating in the IR chamber due to absorption of e.m. fields
- **HOM absorber** design in progress in the central chamber, following the PEP-II experience.

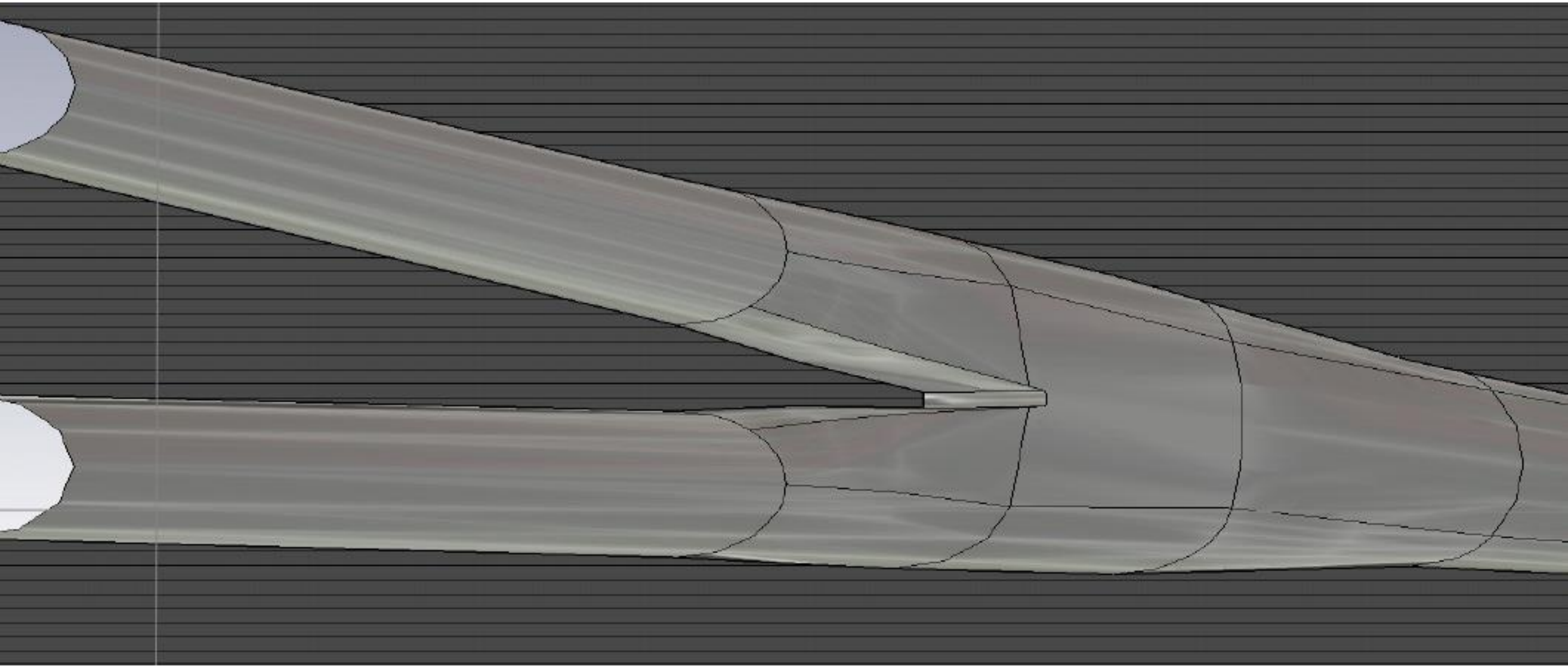
[slide from FCCWEEK17]

IR CAD design

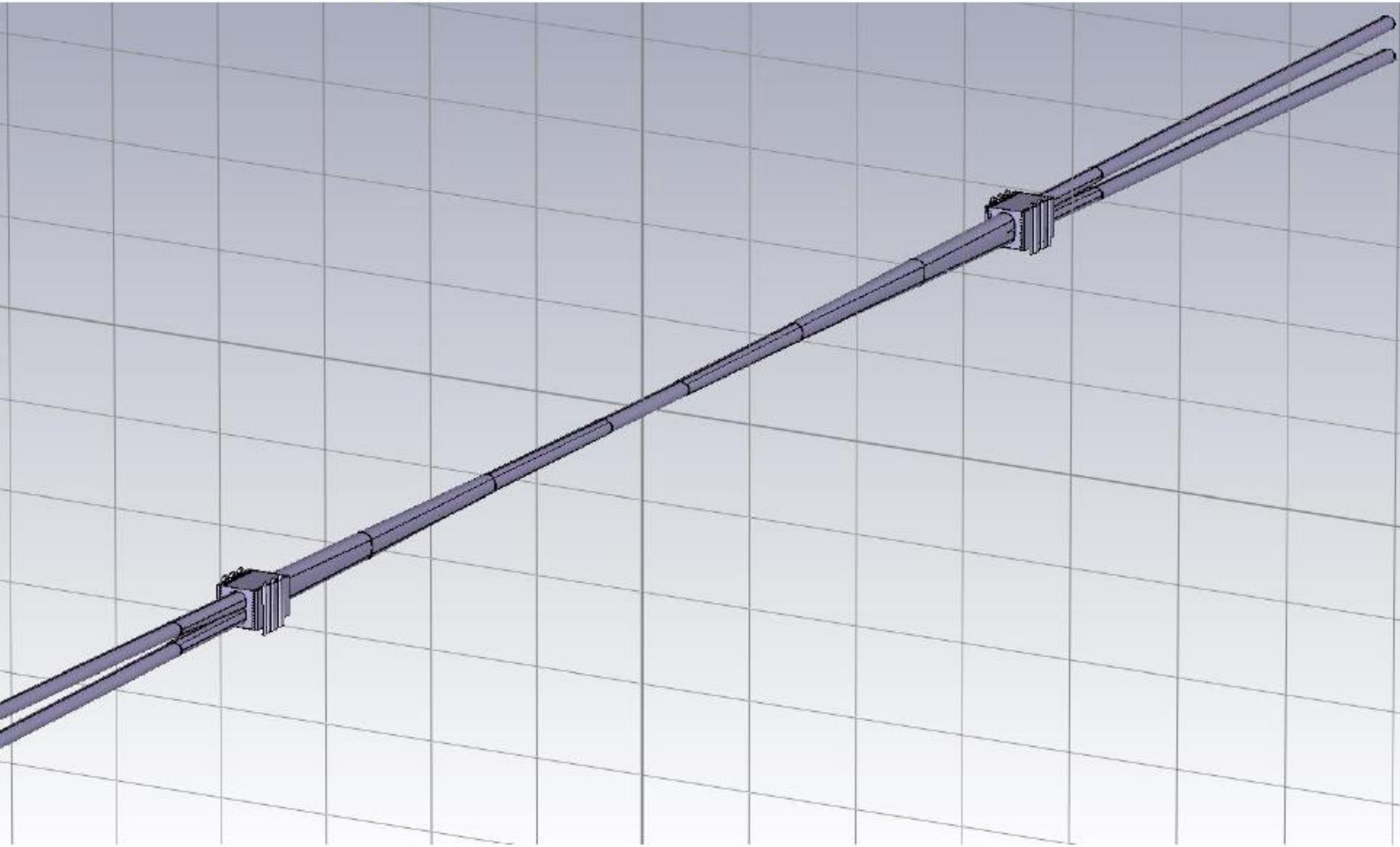
complicated geometry: the area where two beam pipes merge to one single pipe



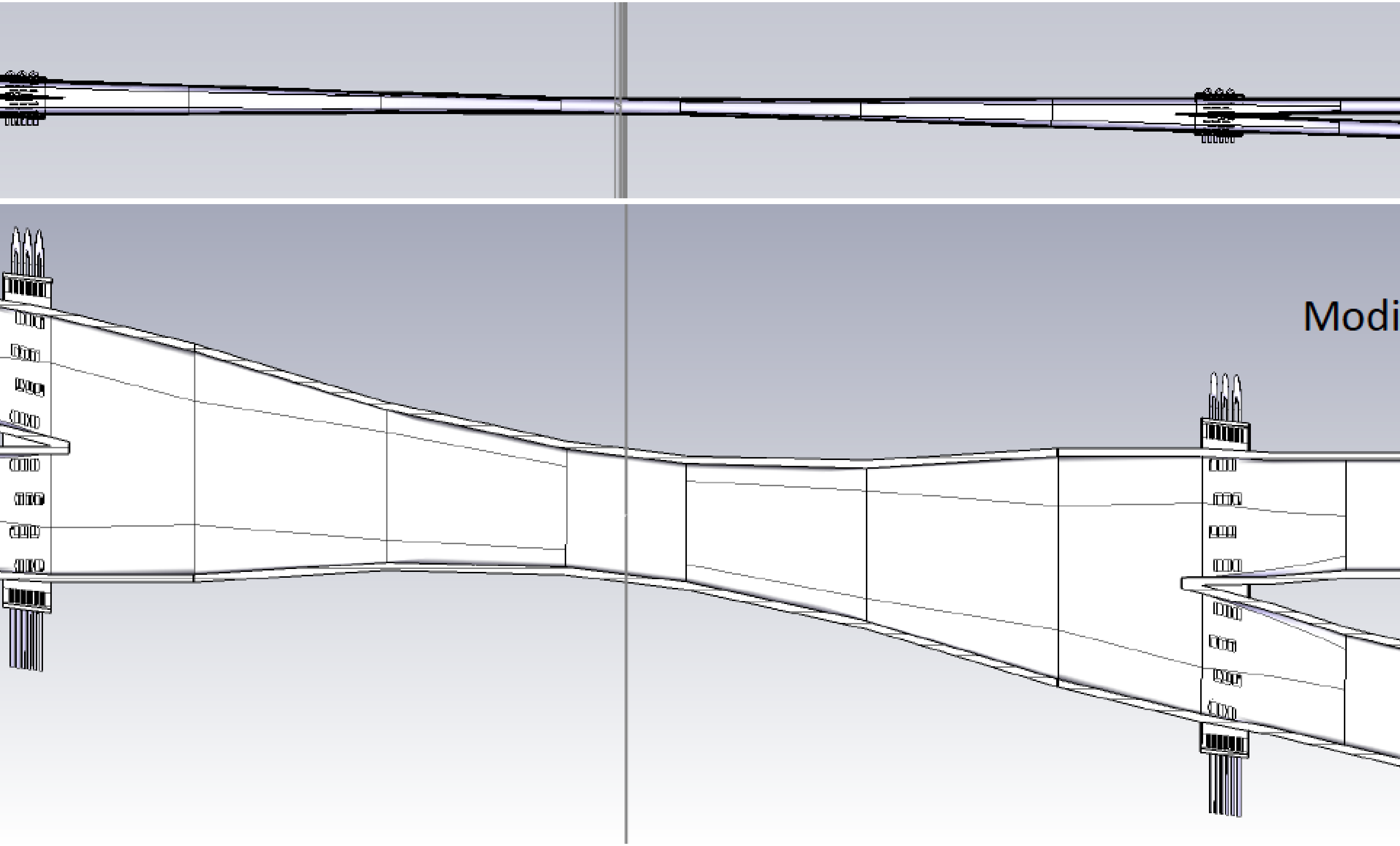
3d model of IR pipe



ee IR beam pipe with water-cooled HOM absor

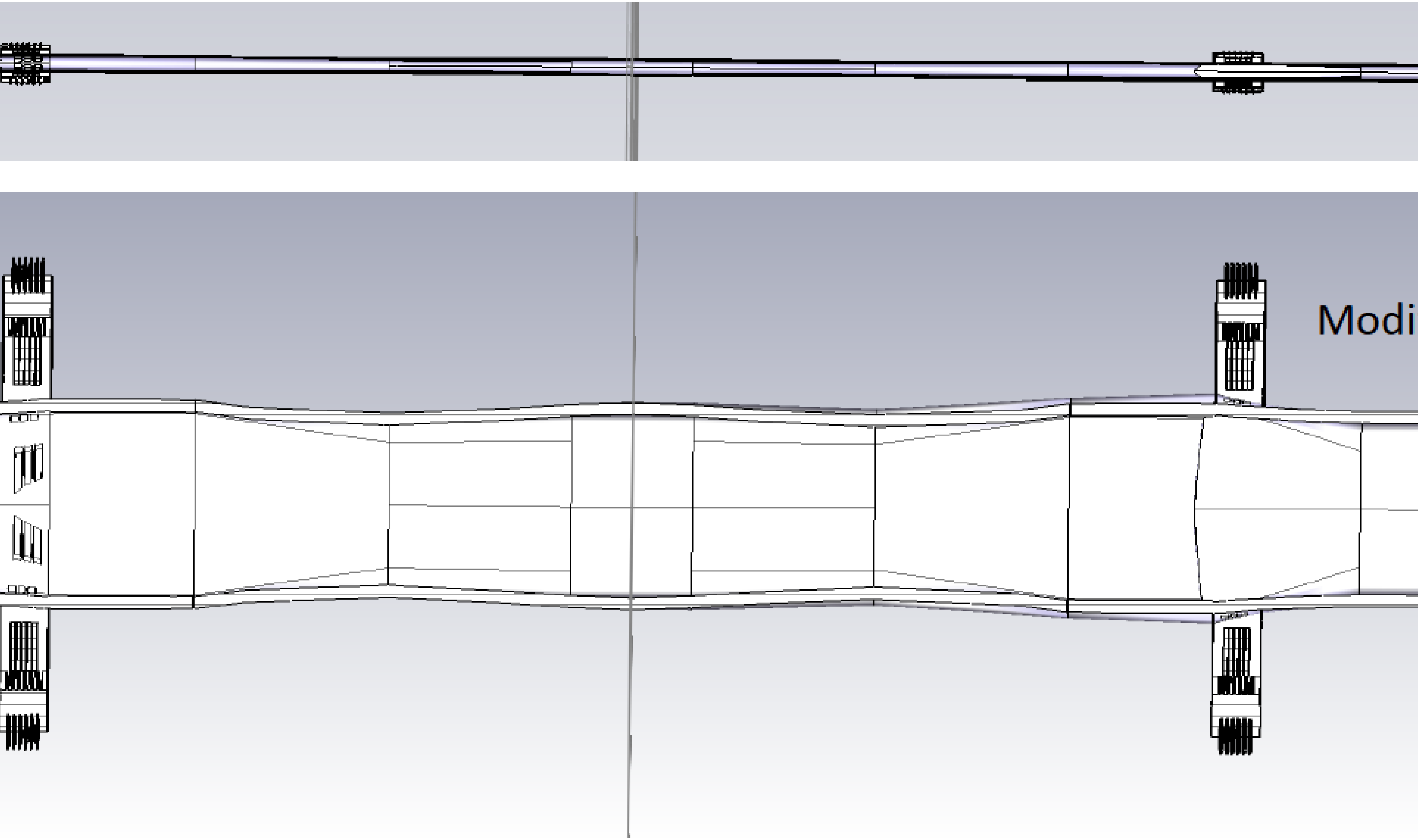


X-projection



Modi

Y-projection



Modi

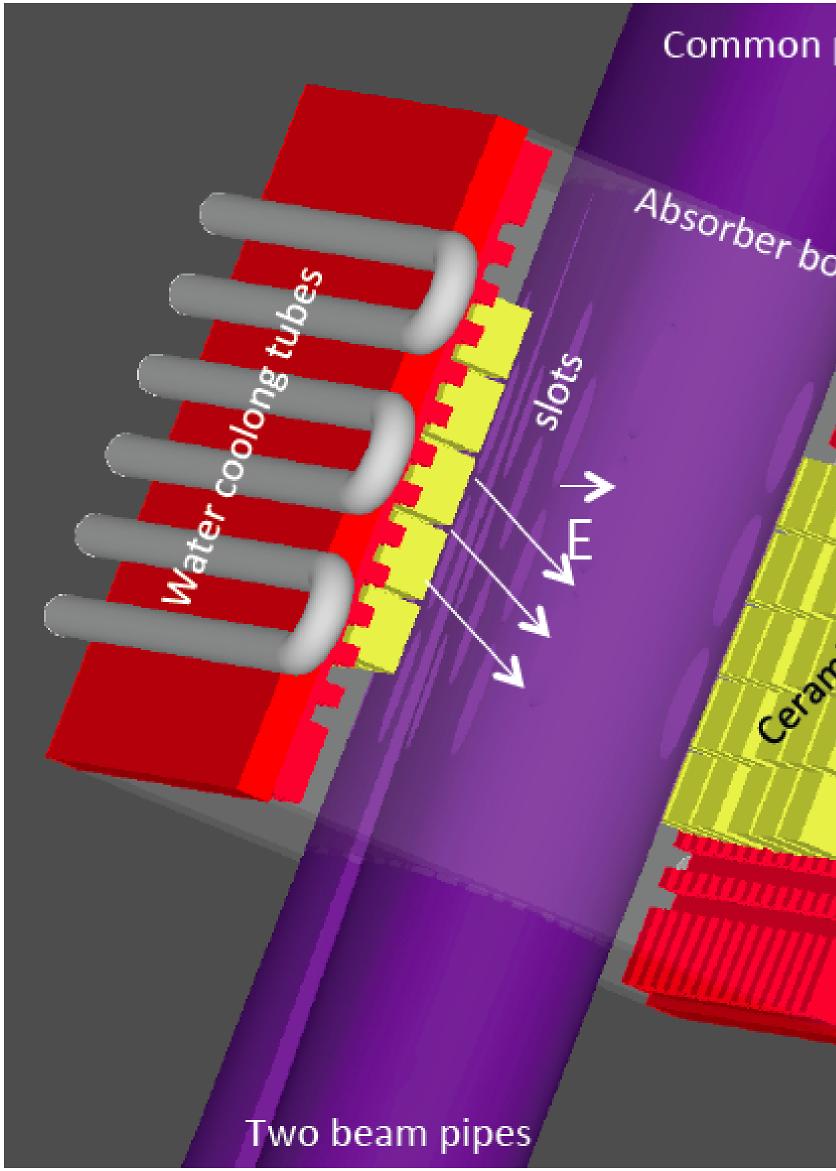
Primary concept of the HOM absorber

rber vacuum box is situated near (around)
connection. Inside the box we have ceramic
tiles and copper plates (walls). The beam
place have longitudinal slots, which connect
pipe and the absorber box. Outside the box
ainless steel water-cooling tubes, braised to
plates.

ds, which are generating by the beam in the
ransverse electrical component and can pass
e longitudinal slots in the beam pipe.

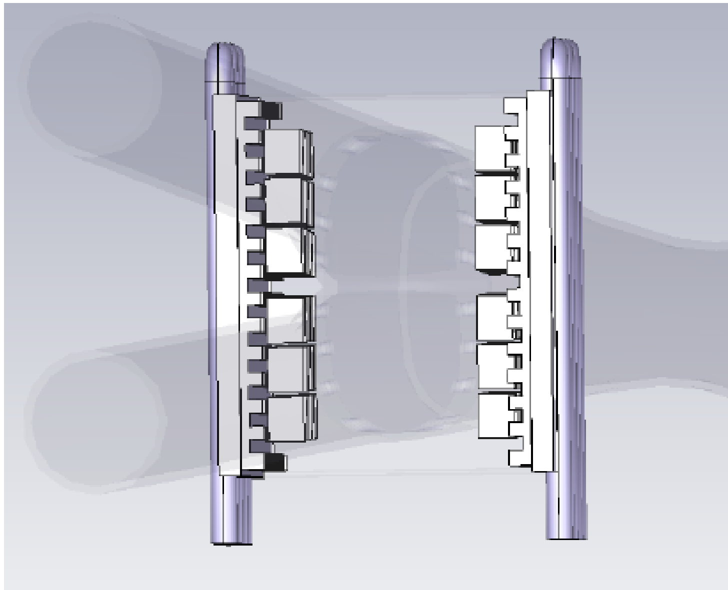
e absorber box these fields are absorbed by
es, which have high value of the loss tangent.

tiles are braised to copper plates with
he heat from ceramic tiles is transported
e copper plates to water cooling tubes.

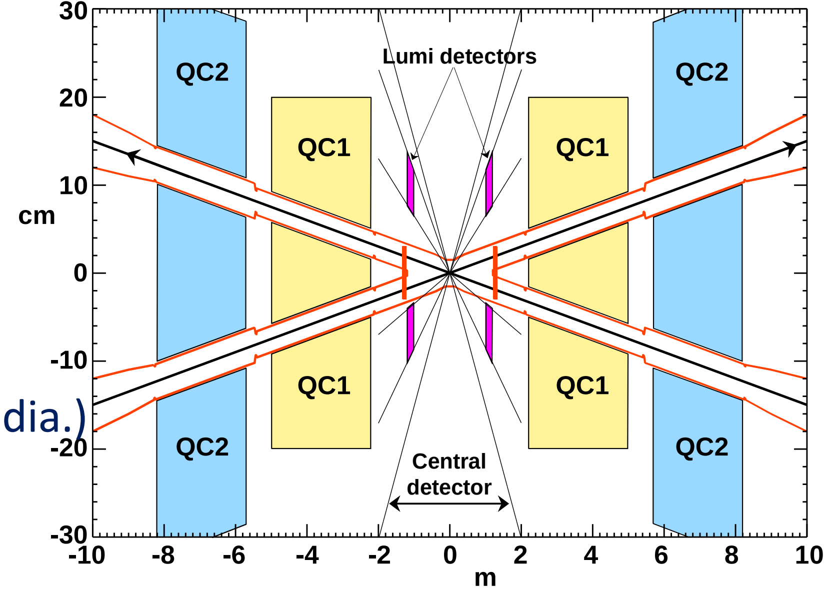


Next steps

- Optimization of the HOM absorber
  - Longitudinal slots
  - Number of tiles
  - Temperature raise in the absorber
- It may take several iterations to optimize the parameters of the absorber: CAD file -> calculations -> new CAD file => …
- Finally prepare a CAD file of the the more realistic IR geometry including BPS, bellows, flanges for the complete wake field calculations.



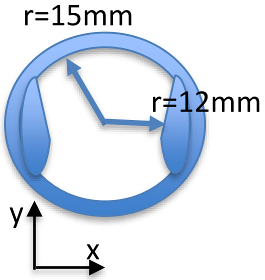
Beam pipe



DIMENSION

- Central beam pipe has 3 cm dia.
- Entering and exiting beam pipe through QC1 (3cm dia.)
- Pipe size increases to 4cm dia. in QC2
- Size outside QC2 is 7 cm dia. (but 6 cm in plot)

HORIZONTAL MASK TIPS



- +/-12 mm radius at Z= +/-2.1 m and +/-5.44 m
- +/-18 mm radius at Z= +/- 8.27 m
- Vert. 1cm; +/- 0.5 mm thickness

MATERIAL

- **Be** from about +/-80 cm to accommodate LumiCal
- **Cu** afterwards
- thickness of Neg coating under study, if also in the IR, on Be chamber
- 5 or 10 μm **Au** coating in the central Be chamber proposed
  (pros: useful at Z, conductivity of Be, image charge; cons: multiple scattering)?

Warm beam pipe, 2mm thickness above vacuum chamber needed for water cooling in QC1 and through the IR where 30mm dia. (if BSC elliptical, water copper tubes in the vertical plane)

QC1 design

- We have two designs

  more details needed

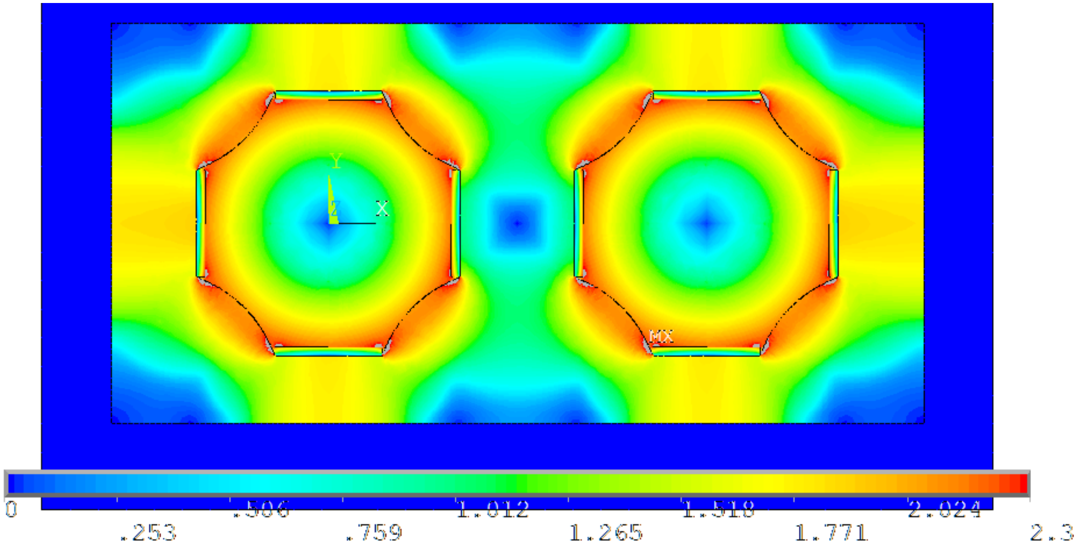
  - **BINP design**: iron yoke twin aperture (superconducting, needs cooling system)
  - **CCT design (**developed for Superb, crab-waist scheme)

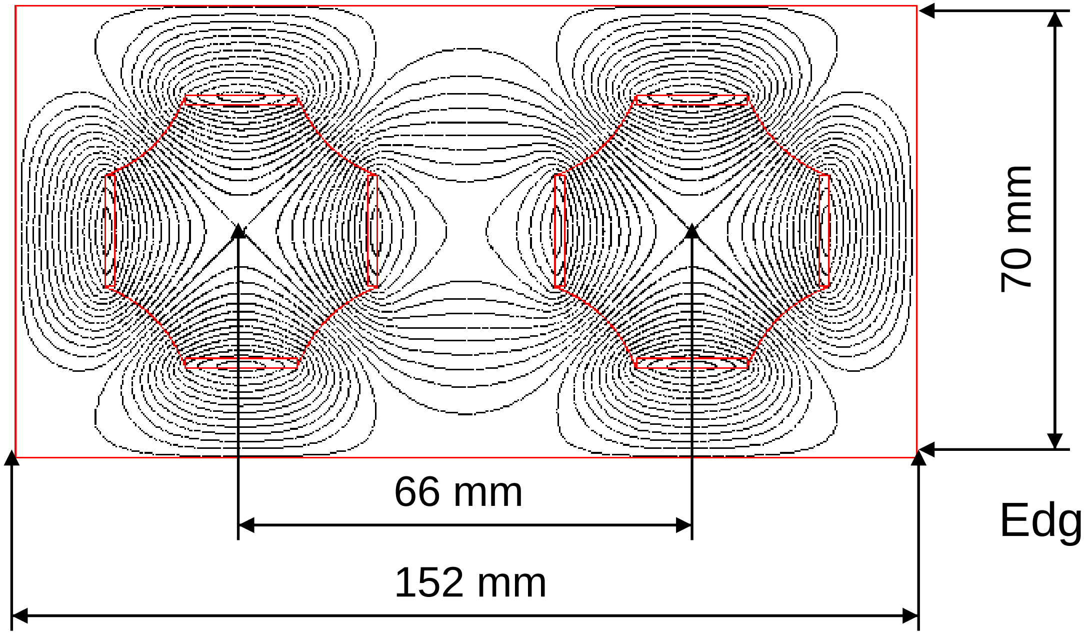
- More or less same space
- We plan to present both design in the CDR

Iron yoke twin-aperture quadrupole

2D model

BINP design





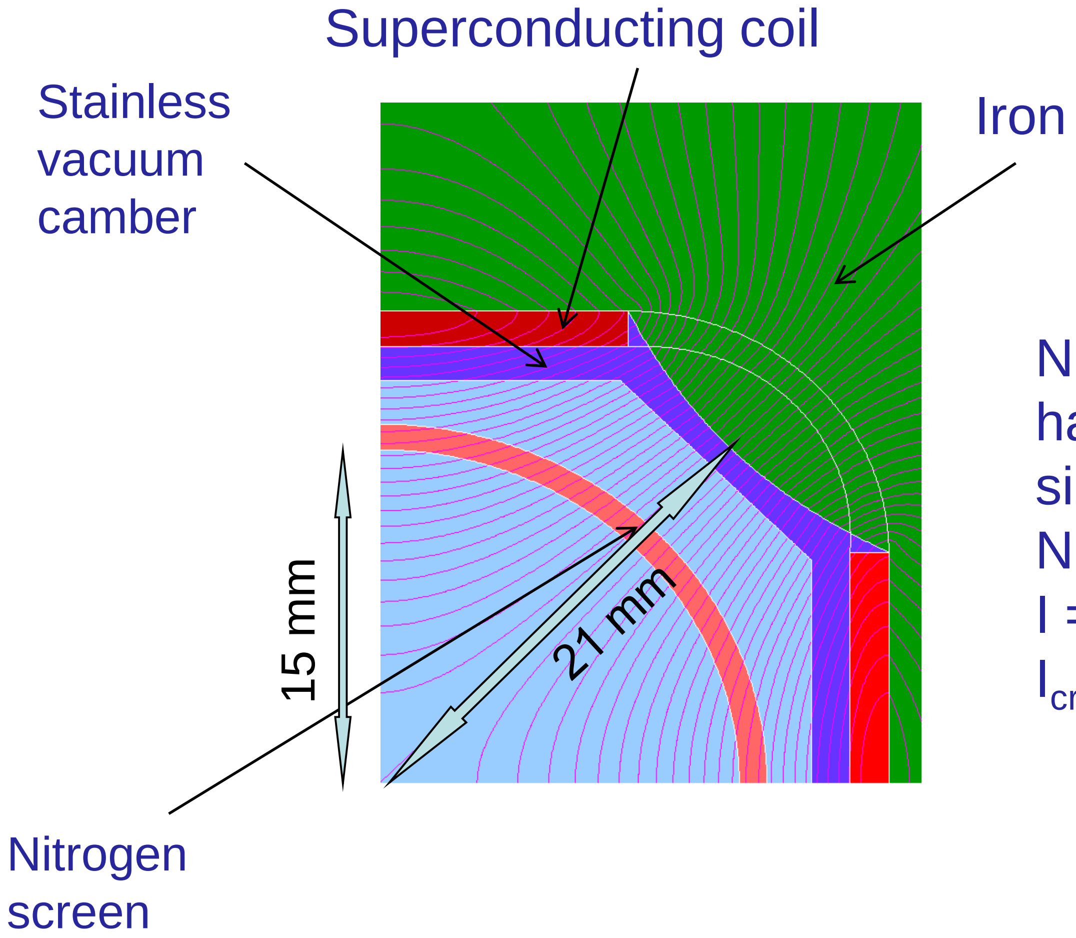
Edge of quad close to IP

Main parameters:

- Max.gradient 100 T/m Length 120 cm
- Aperture 4.2 cm
- Clear aperture 3 cm
- NbTi 1.4 x 0.8 mm^2 Saddle-type coils
- Permendure iron yoke

Design of final-focus magnets for FCC ee

BINP design



NbTi Superconducting cable has a rectangular shape, the size is 1.4 * 0.8 mm x mm

N=18

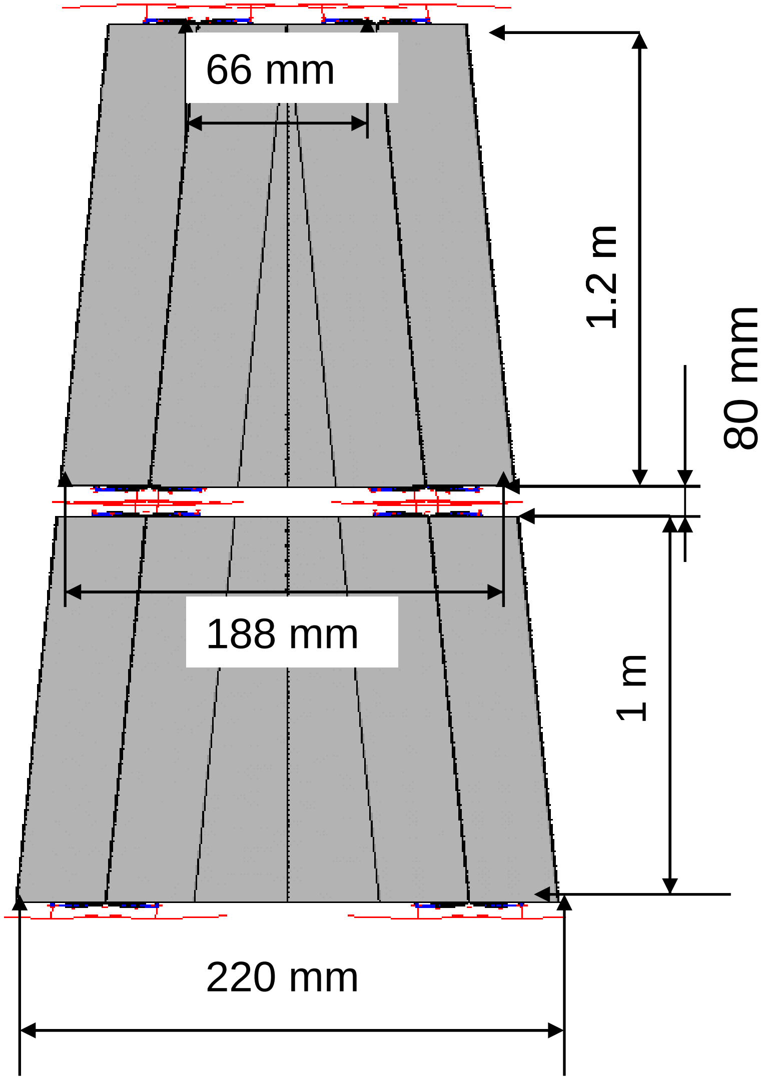
I = 961 A

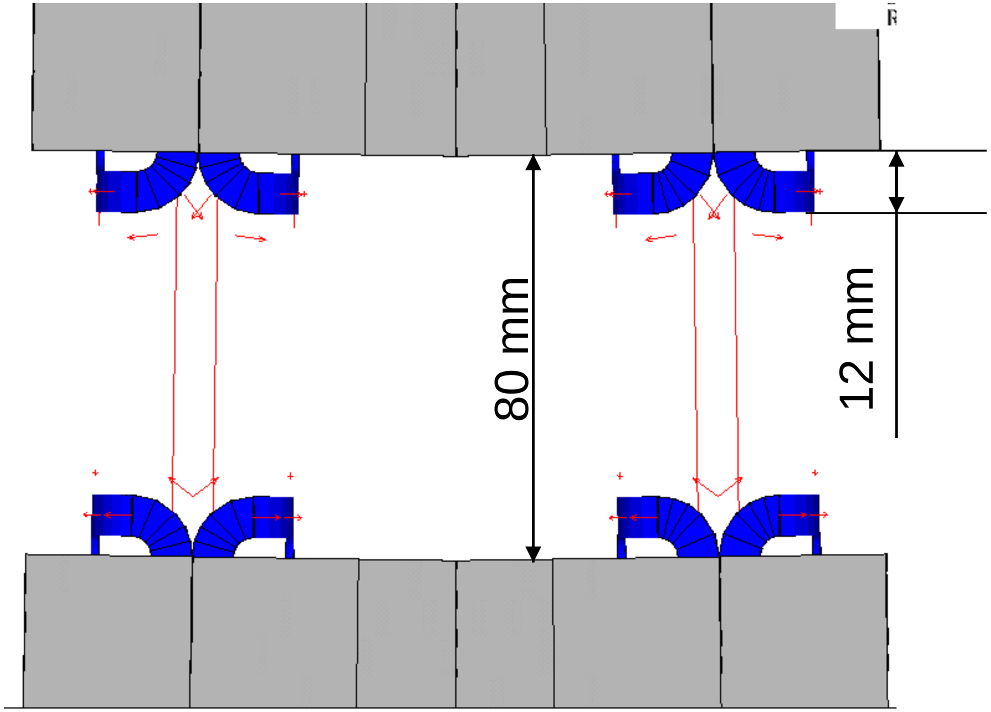
$I_{critical}$ (4.2 K; 4 T) = 2400 A

Iron yoke twin-aperture quadrupole

3D model

BINP design





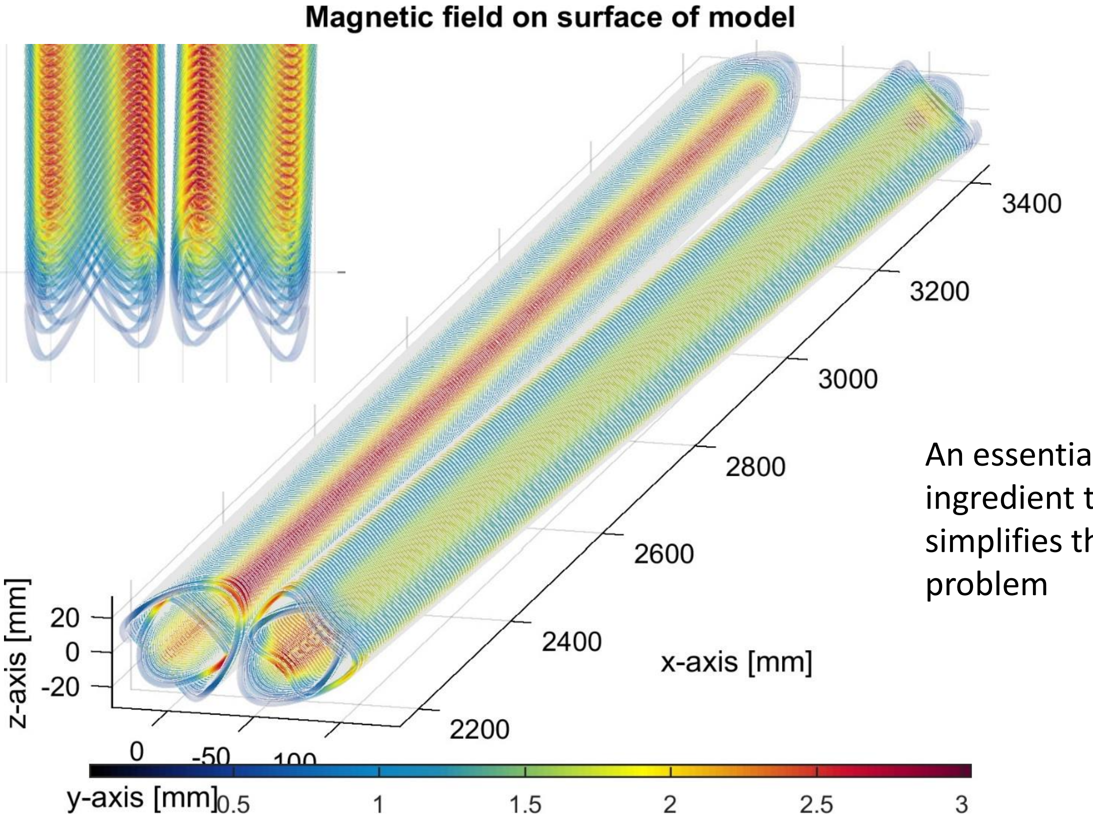
BINP design

Panofsky style quadrupole

- Pros:
  - Ordinary production of lenses.
  - Remaining solenoidal magnetic field in QC1 area is additionally screened by iron yoke of lenses.
  - No skew components of magnetic field created by lenses.
  - There is small crosstalk between apertures of lenses.

- Cons:
  - Saturation of iron yoke (nonlinearity) at large gradient.
  - High order multipole components at quadrupole edges.
  - No way to introduce high order multipole and skew components of magnetic field to compensate lattice nonlinearity.
  - Gradient is not large and limited by iron yoke saturation and critical current.

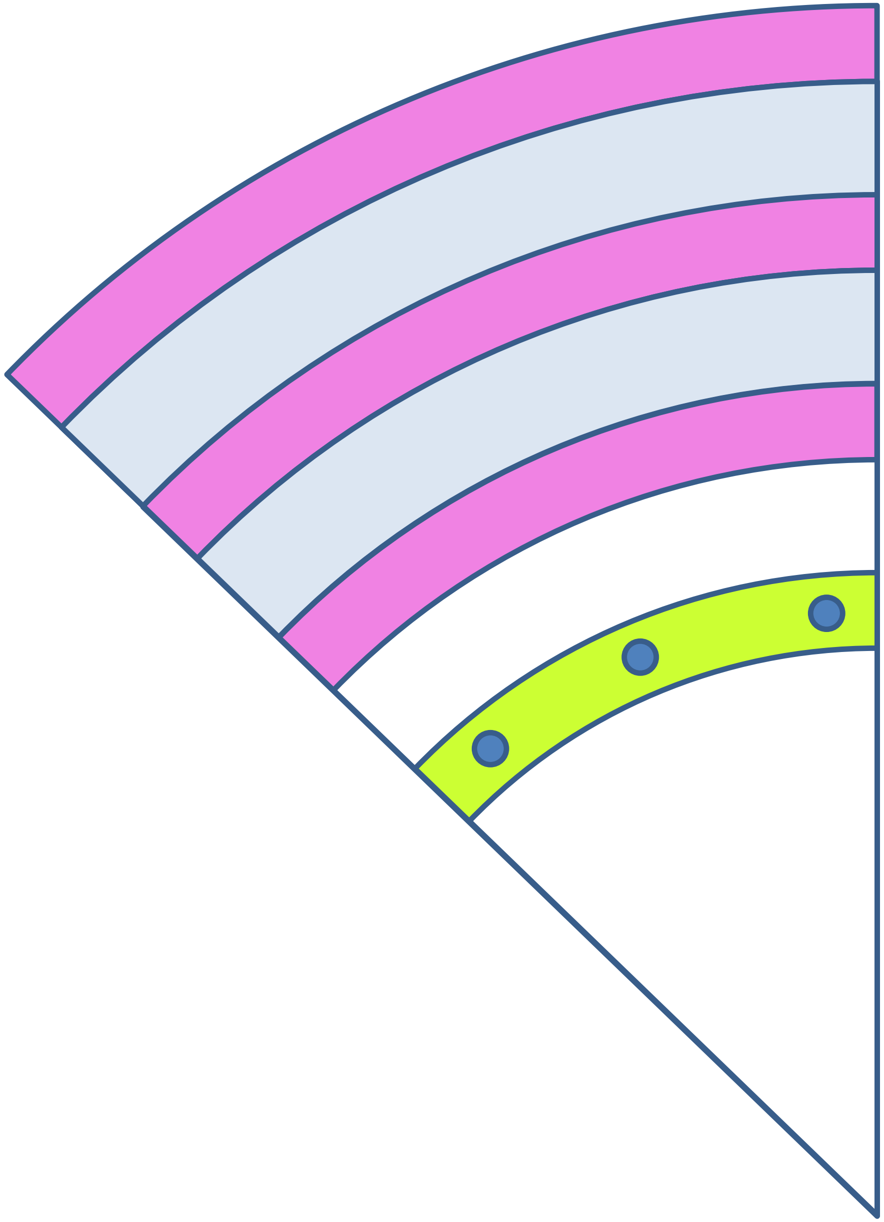
QC1 : CCT approach



An essential ingredient that simplifies the problem

Dimensions - radius

CCT design



32-34mm: outer spar

28-32mm: outer s/c cable

26-28mm: middle spar

22-26mm: inner s/c cable

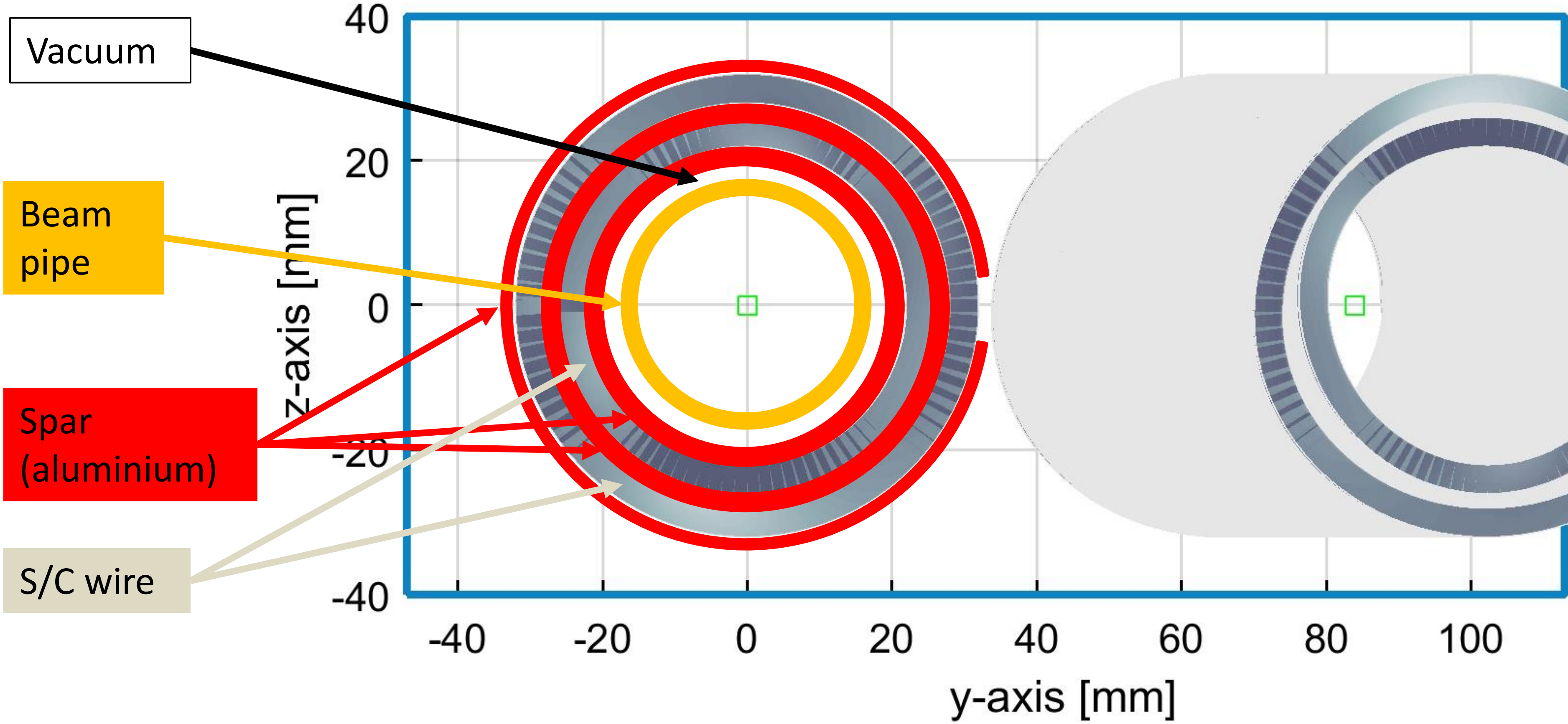
20-22mm: inner spar

17-20mm: vacuum + superinsulation

15-17mm: beam pipe

● Water cooling

Transverse dimensions



Vacuum

Beam pipe

Spar (aluminium)

S/C wire

Dimensions, specs

- The quads (QC1L1, QC2L2, QC2L3) follow the specs provided by Katsunobu
- I provide the multipole files at the correct magnetic lengths and approximate strengths separately for each magnet
- Katsunobu can change the strengths (linearly, as there is no iron) and combine magnets (again linearly, as there is no iron)

	L (m)	B’ @ tt (T/m)	B’ @ Z (T/m)
QC1L1	1.2	-94.4	-96.3
QC1L2	1	-92.6	+50.3
QC1L3	1	-96.7	+9.8
QC2L1	1.25	+45.8	+6.7
QC2L2	1.25	+74.0	+3.2

CCT design

Transverse dimensions

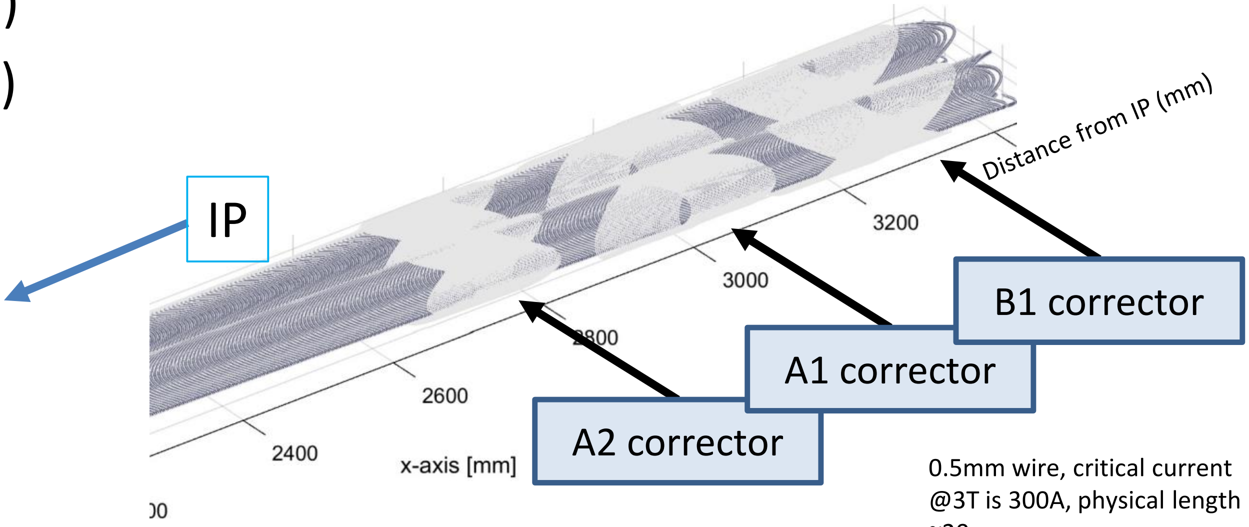
- Beam pipe is 30 mm diameter
- In the FF quads the first winding starts at 42mm
- The inner substrate starts at 40mm
- We are investigating if all the cooling needed can fit between 30 and 40mm.
- In this design there is a 2mm gap between the two FF quads at 2.2m
- The cable used has a cross section of 2×4=8mm^2. The critical current through this cross section permits gradients in excess of 150T/m. If we do not need this capability, we can reduce the size of the cable to 2×3mm. In this way we can reduce the overall radius of each quad by 2 mm (or increase the gap between them by 4mm)

Embedded correctors

- The design can have embedded correctors (x and y dipole correctors, skew quadrupole correctors, etc.)
- Each corrector is very thin and comprises four extra rings that go in the outside of the main quadrupole
- For excellent performance, each corrector has its compensating coil on the other aperture (powered in series)

All QC1L1 correctors – A1, B1 and A2

- Three correctors installed with single wire, 0.5mm, about 20cm long, current 200A (critical current @3K is 300A).
- Strength of correctors:
  - A1 25mT.m (210 units)
  - B1 17mT.m (145 units)
  - A2 35 units



0.5mm wire, critical current @3T is 300A, physical length ~20cm

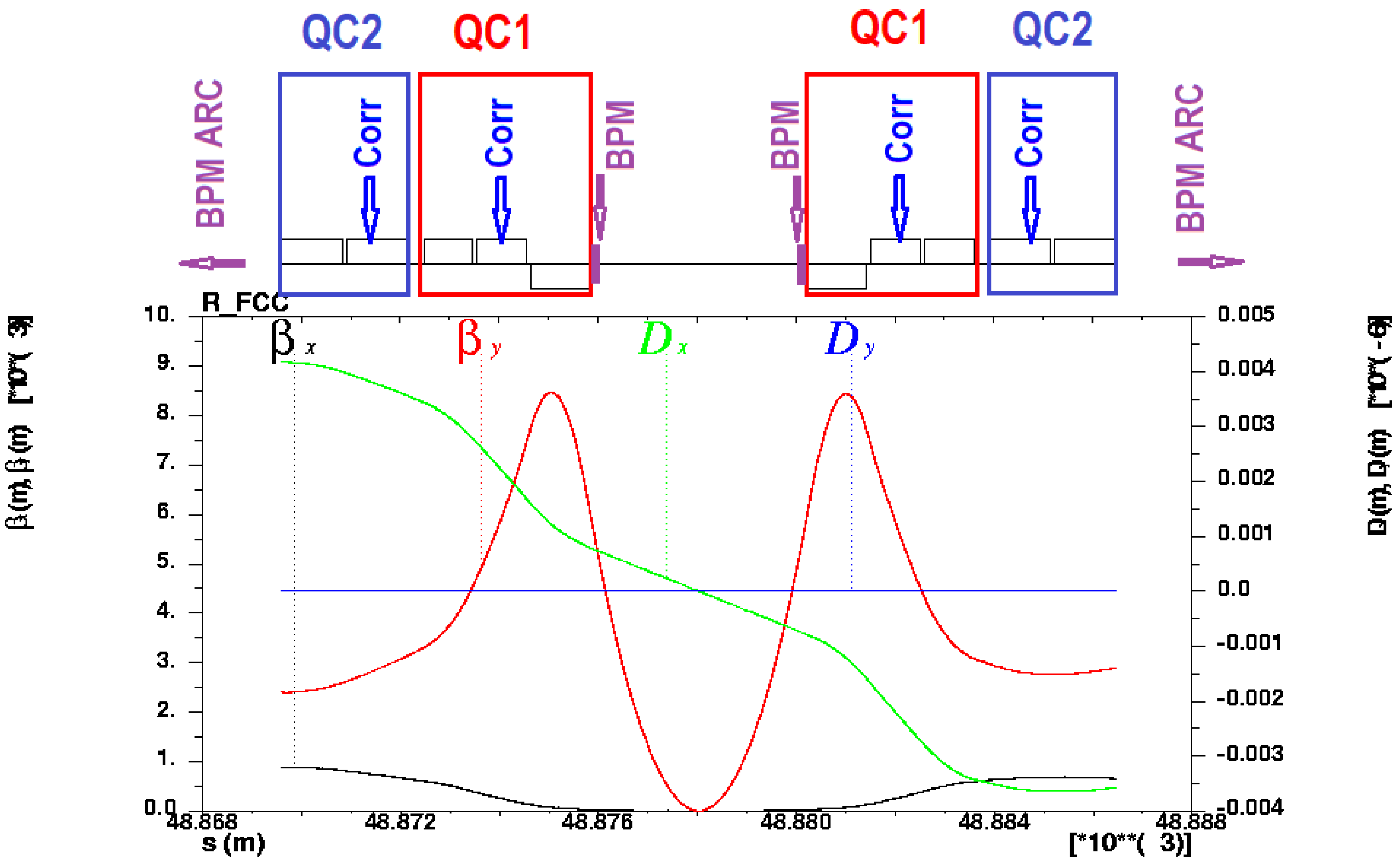
There is enough space for even five correctors, with no loss of packing factor

Conclusions on misalignment

- Internal misalignment should be better than 30um.
- Beam/detector misalignment of around 1mm has a negligible effect on field quality, due to the excellent field quality of the CCT design
- Ditto for 0.5mrad tilt
- The values of 1mm and 0.5mrad come from optics (Katsunobu) as expected typical values

Orbit errors at the FCC-ee due to the FF quadrupoles displacements (S. Sinyatkin)

COD excited by FF quads misalignments correction scheme



Heat load and cooling needs

2.5 ns bunch spacing, previous parameter list
updated results in progress

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**

IR Vacuum Concept (R. Kersevan)

Example: What average effective pumping speed would be necessary for the Z-pole machine in order to have an average pressure lower than 1.0E-9 mbar?

Photon flux: F (ph/s) = 8.08E+17 · E (GeV) · I (mA) = 5.34E+22 (ph/s)

If k=2.47E+19 (mol/mbar/liter), then the gas load Q is:

Q (mbar·l/s) = F (ph/s) / k(mol/mbar/l) · η(mol/ph)

with η= photodesorption yield.

→ Typically a machine is considered *vacuum conditioned* when η < 1.0E-6 (mol/ph):

Q' (mbar·l/s/m) = Q/ $2\pi\rho$ = 3.44E-8 (mbar·l/s/m) (in the arcs, ρ ~10 km)

P_{avg} (mbar) = Q' (mbar·l/s/m) / S_{eff} (l/s) · L(m)

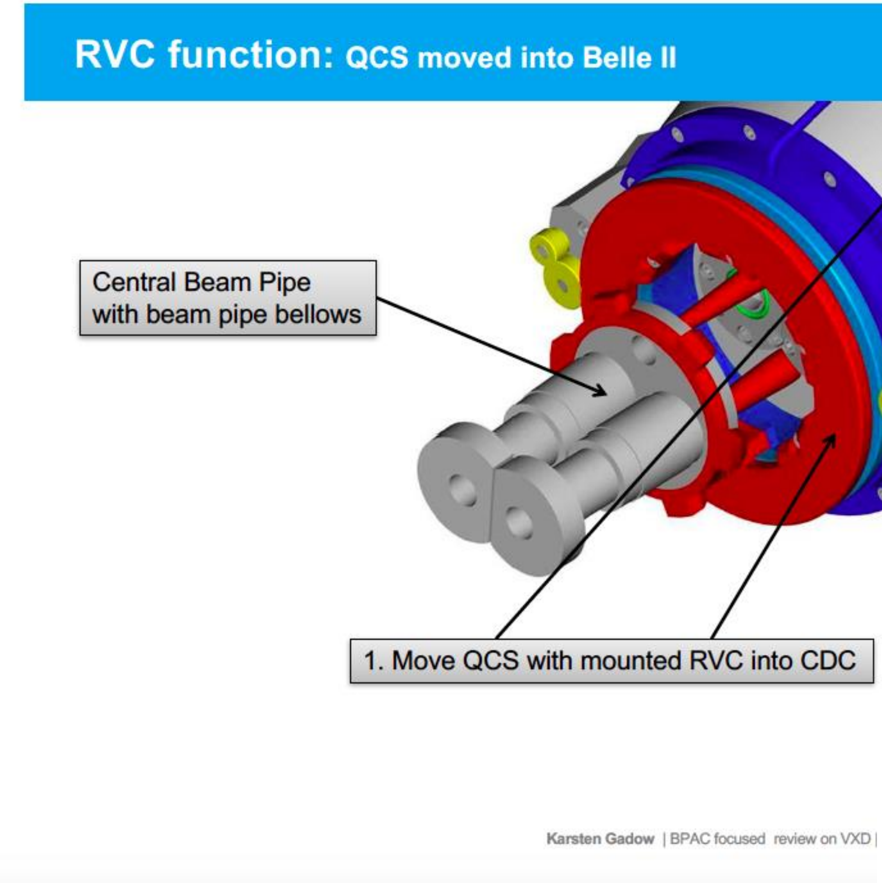
Solving for for S_{eff}, one gets: S_{eff} (l/s) = 34.42 · L(m) (dotted line at 45 deg on previous plot)

- This means that the Z-pole machine, due to its huge photon flux, would condition to P_{avg}<1.0E-9 only if 200 ÷ 500 l/s pumps are placed at a distance < 3 ÷ 4 m from each other;
- This, in turn, would mean that in the arcs one would need 19000 ÷ 25000 pumps/beam;
- Each lumped pump would in turn need pumping slots machined on the vacuum chamber: additional cost for machining, pumping plenum, flanges, cabling, etc...

RECAP AND PRESENT STATUS:

1. The “best” (read “*most efficient*”) **vacuum chamber cross-section** capable of intercepting ~ all of the primary dipole SR in the arcs has been identified (see FCC Week 2017 talk): it is a **SUPERKEKB-type one**, with smaller ID (70 mm) on the circular part and smaller “winglets” in the plane of the orbit (**only 11 mm height**);
2. **Many, short (~ 300 mm max) SR absorbers** are located at variable distance from each other (lattice position-dependent): **they absorb about 3~5 kW of primary SR power**;
3. Wherever possible, each absorber has a **pumping port installed in front of it**, connected via **~100 mm-long pumping slots** machined on the internal winglet (minimal geometrical impedance contribution);
4. **The same concept is envisaged/proposed for the MDI region**, where the two beams run in **separated and single-yoke magnets** (I have not see a design for these magnets yet: **NO CAD MODELS AVAILABLE!**);
5. The SUPERKEKB-type chamber profile ends immediately before the focusing doublet: It is connected to a **custom absorber which protects/masks the following chambers up to the IP** (see M. Sullivan’s presentation, this workshop);
6. The IP area chambers include the **“new” chamber with two integrated water-cooled HOM-absorbing ferrites** (as per A. Novokatski’s presentation, this workshop, based on M. Gil Costa’s CAD model);
7. Space for at least **one efficient NEG pump in the IP area is allocated** (see M. Sullivan’s pres.), but needs to be integrated in the existing CAD model; the area is crammed with detector components and cables (anti-solenoids, cryostats, remotely-operated flanges (like SUPERKEKB?), supports, alignment etc…), plus the necessary water-cooling circuit’s pipes; **NEEDS CAREFUL SCRUTINY!**
8. **See also M. Sullivan list of “Mechanical issues” at end of his presentation;**

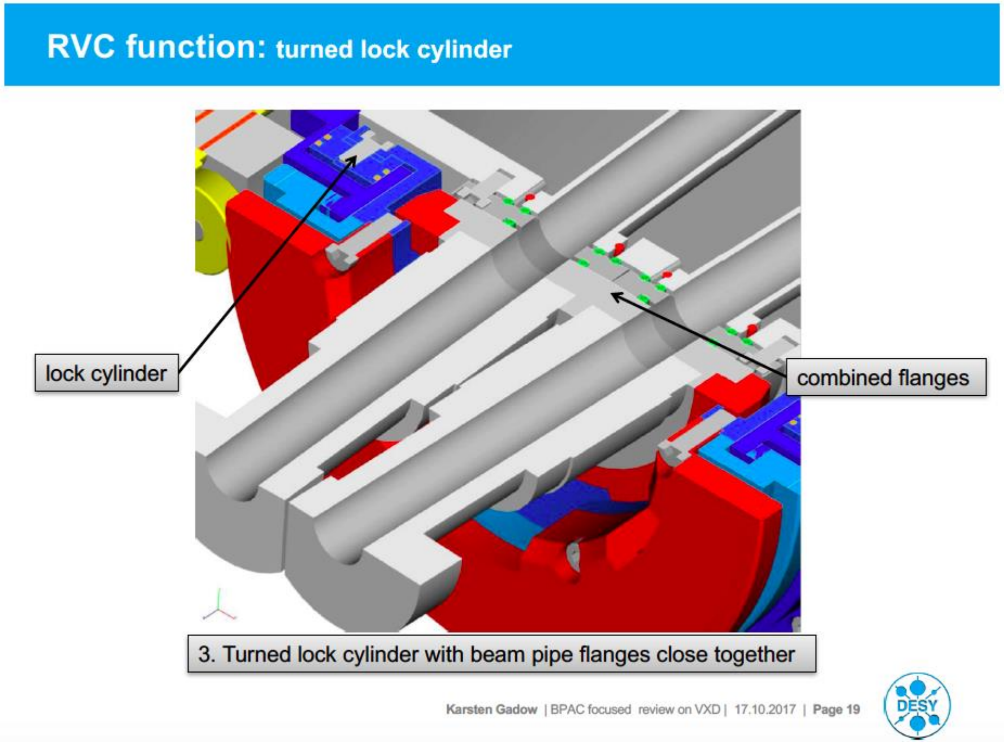
Remote vacuum connection at Superkekb (Karsten Gadow)



RVC function: QCS moved into Belle II

Central Beam Pipe with beam pipe bellows

1. Move QCS with mounted RVC into CDC



RVC function: turned lock cylinder

lock cylinder

combined flanges

3. Turned lock cylinder with beam pipe flanges close together

Concerns

- **Assembly**
  - Remote vacuum connection (ala Belle II)?
  - Bellows between Central chamber and cryostat chambers (at least 1-2 convolutions)
  - Central chamber support
  - Cable and cooling pipe space for central detectors
- **Vibration control**
- **Cryostat support**
- **Magnetic forces**
  - Anti-solenoids have strong expulsion forces?
  - Compensating solenoids have strong expulsion force near detector field edge
- **Overlapping Z space**
  - LumiCal
  - Cryostat
  - Remote vacuum assembly
  - NEG pump
  - HOM absorbers
  - Shielding

Summary

- The IR design has been relatively stable
- But now engineering concerns are coming into play
- These may force a reevaluation of the IR design
- We need space for bellows and vacuum connections and possibly supports
  - Move the FF quads back?
  - Shorten the anti-solenoid?
  - Move the Lumi-Cal forward?

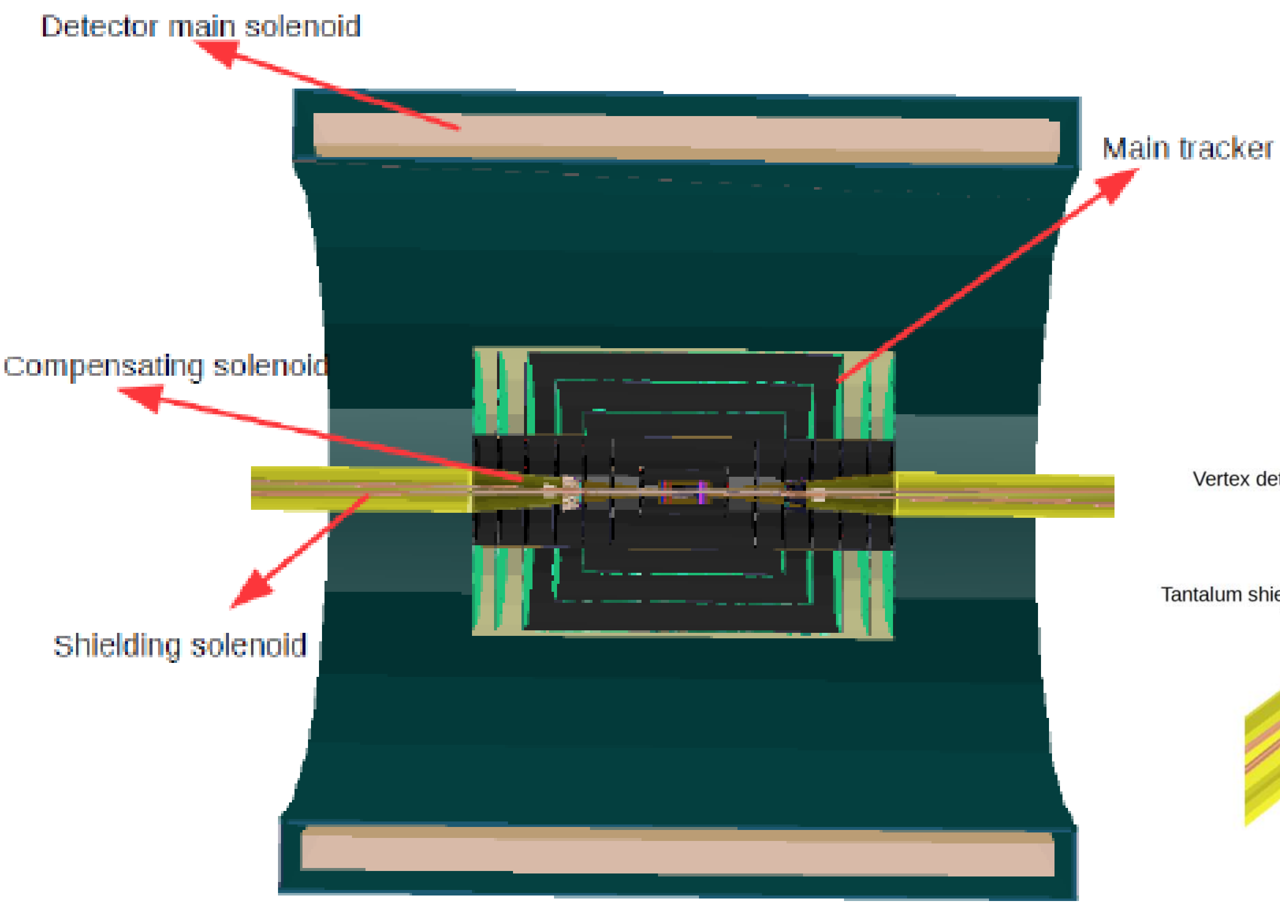
Conclusions and next steps

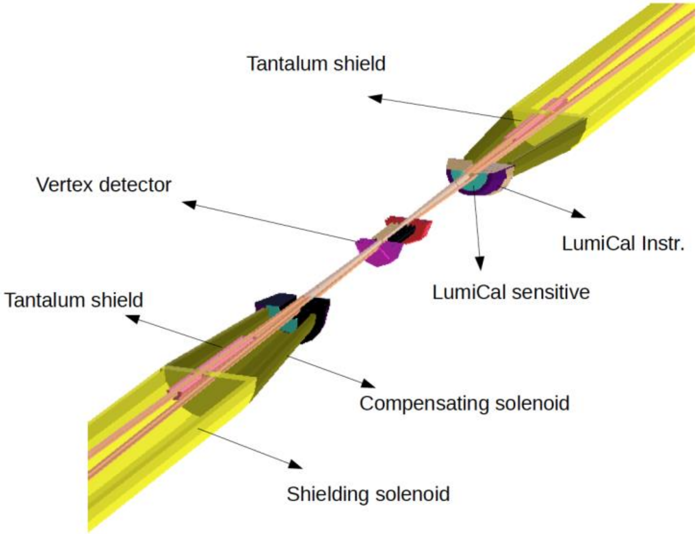
- **3d mechanical design, assembly concept**

- 3D simulation of the magnetic fields and magnetic forces in MDI area to optimize design.
- With a design that includes BPMs, bellows, flanges, a more realistic wake field calculation will be possible.
- Stabilisation issues are being addressed
- Alignments Alignment and mechanical tolerances

Back-up

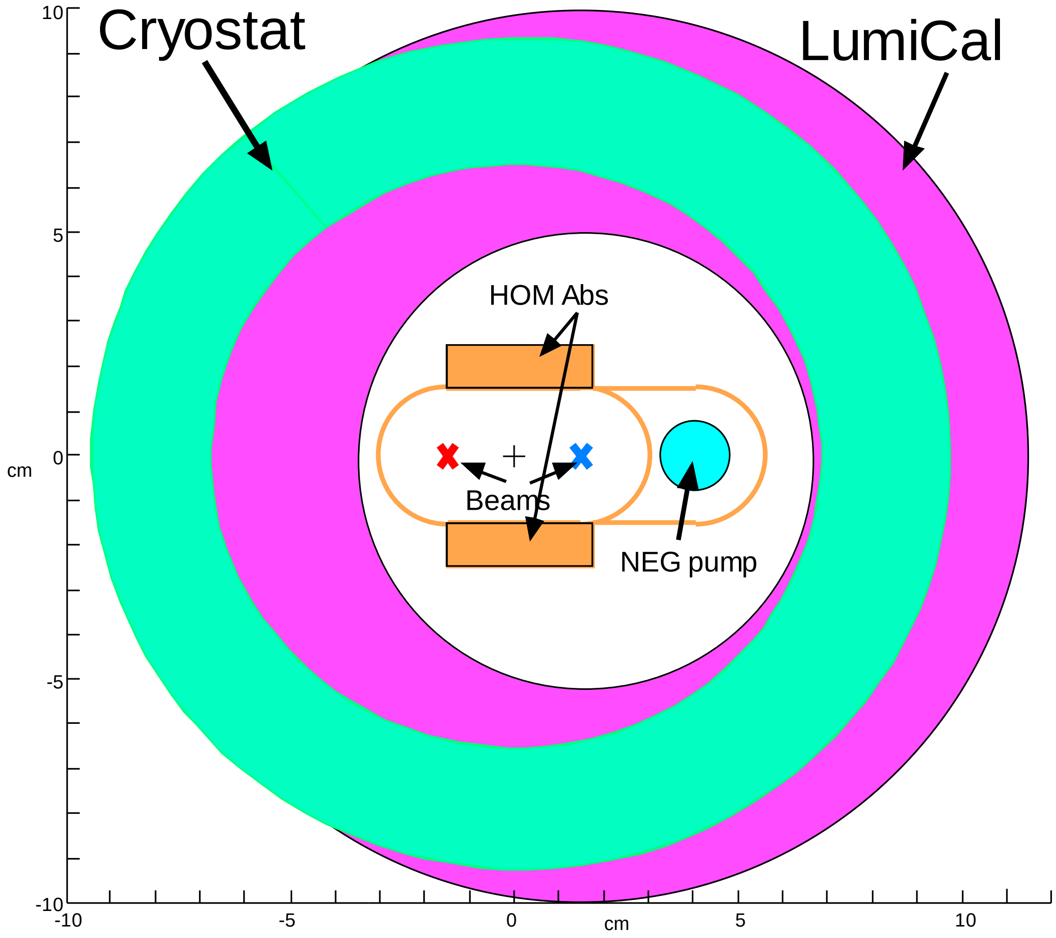
Geant4 detector modeling





modified CLIC detector model with B=2T and FCC-ee IR design

End view behind LumiCal



Shielding is not shown but we should be able to fit in at least 1 cm of a high Z material (Pb, W, Ta)

Features

- Central beam pipe has 3 cm dia.
- Entering and exiting beam pipe through Q1 (3cm dia.)
- Be from about +/-80 cm to accommodate LumiCal
- Pipe size increases to 4cm dia. in Q2
- Size outside Q2 is currently 6 cm dia.
- Mask tips +/-12 mm radius at +/-2.1 m and +/-5.44 m Horizontal plane only
- Mask tips +/-18 mm radius at +/- 8.27 m Horizontal plane only
  - Allows for possibility of cold bore magnets (shields quad beam pipes)
  - Need to remove 43 W of SR power between Q1 and Q2 on upstream side
  - Current IR design is for warm bores

Orbit errors at the FCC-ee due to the FF quadrupoles displacements (S. Sinyatkin)

Task

- FF Quads misalignments (QC1_1- QC1_3, QC2_1,QC2_2) :
  - Geodesy: transverse shift of FF quads with $\sigma_{x,y} = 25\ \mu\text{m}$.
  - Vibrations: transverse shift of FF quads with $\sigma_{x,y} = 0.1\ \mu\text{m}^*$.
- IR BPM misalignments:
  - Geodesy: transverse shift of BPMs with $\sigma_{x,y} = 25\ \mu\text{m}$.
  - Vibrations: errors of BPM readings with $\sigma_{x,y} = 0.1\ \mu\text{m}^*$.
- No misalignments of other elements.
- Shift of FF Quads distorts CO and dispersion.
- COD is corrected by IR steering magnets in the FF quadrupoles.
- FCCee_z_213_nosol_18.seq
- * THE MECHANICAL AND VIBRATION STUDIES OF THE FINAL FOCUS MAGNET-CRYOSTAT FOR SUPERKEKB. THPRI005 ProceedingsofIPAC2014,Dresden,Germany

Orbit errors at the FCC-ee due to the FF quadrupoles displacements (S. Sinyatkin)

Conclusion

- There is no closed orbit w/o correction for 25 µm shift of Q (a small amount). After correction, the required beam parameters are restored.
- The beams do not collide with 0.1 µm vibrations of FF Quads. Vertical emittance is blown up.
- Feedback is required to suppress influence of the FF quads vibrations.
- The beam parameters are destroyed after correction of 25 µm IR BPM misalignments. To optimize the parameters, a "golden" orbit is required.
- Due to vibrations, it is impossible to use the IR BPMs for the feedback system.
- It is necessary to measure Luminosity in the bandwidth 0-100 Hz. (Luminometer?)