Massachusetts Institute of Technology

Overview of MDI at FCC-ee

M. Koratzinos

IAS High Energy Physics conference,

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THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

HKUST JOCKEY CLUB INSTITUTE FOR ADVANCED STUDY

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

The FCC MDI team is (authors of our recent paper from eeFACT18: http://accelconf.web.cern.ch/AccelConf/eefact2018/papers/wexba02.pdf)

N. Bacchetta, E. Belli, M. Benedikt, A. Blondel, O. Blanco, A. Bogomyagkov, H.Burkhardt, F. Collamati, M. Gil Costa, M. Dam, K. Elsener, H. Ten Kate, D. El-Khechen, A. Kolano, A. Krasnov, P. Janot, R. Kersevan, M. Koratzinos, E. Leogrande, E. Levichev, M. Lückhof, M. Migliorati, A. Novokhatski, K. Oide, E. Perez, S. Pivoravov, S. Sinyatkin, M. Sullivan, N. A. Teherani, G. Voutsinas, O. Viazlo, G. Voutsinas, J. Wenninger, F. Zimmermann

…and growing!

Contents

- The requirements
- The IR magnets
  - The compensation scheme
  - FF quadrupoles
- The luminometer
- Backgrounds and collimation
- Mechanical design considerations

See also in this series:

Mini-Workshop: Accelerator - Machine Detector Interface for Future Colliders, 16-17 January 2020, IAS

- M. Koratzinos, Overview of MDI at FCC-ee
- Helmut Burkhardt, Lessons Learned from LEP and Their Application to FCC/CEPC

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

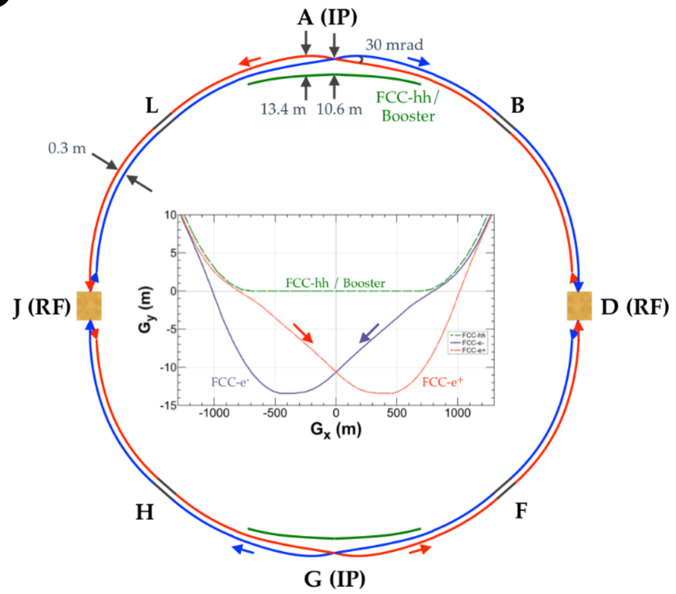
Why is MDI important?

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 $\boldsymbol{\beta_y^*}$ (from 0.8 to 1.6mm) 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)

Key parameters for MDI design

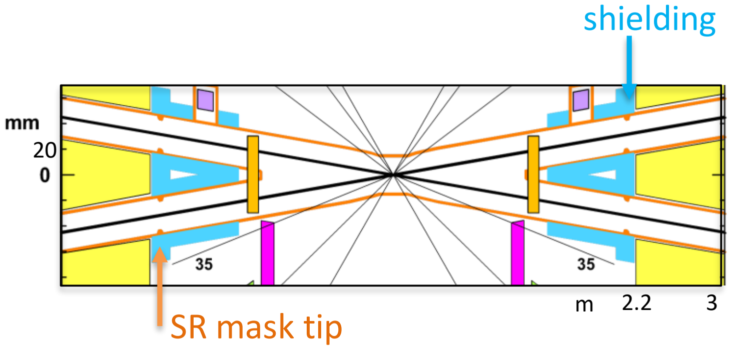
- **Asymmetric IR optics**
- **crab-waist scheme ➔** large horizontal crossing angle: **30 mrad**
- **Flexible optics design: common lattice for all energies,** except for a small rearrangement in the RF section
- **Large energy acceptance (>2.8 %)** at high energy, due to strong beamstrahlung that limits beam lifetimes



- **Synchrotron radiation** at FCC-ee is one of the main drivers for the MDI design
- Self-imposed limit: **$E_{critical}$ < 100 keV** for incoming beam to IP from 500 m
    - Very soft bends 500m upstream the IP
    - Last dipole is ~100m upstream from the IP and is very long (~200m) and very weak (~30Gauss @Z)

countermeasures:

- ✓ SR mask tips to intercept SR photon fans
- ✓ high-Z shielding (W) outside vacuum chamber
- ✓ sawtooth ridged chamber inside FF quad being considered
- ✓ absorbers and/or SR collimators



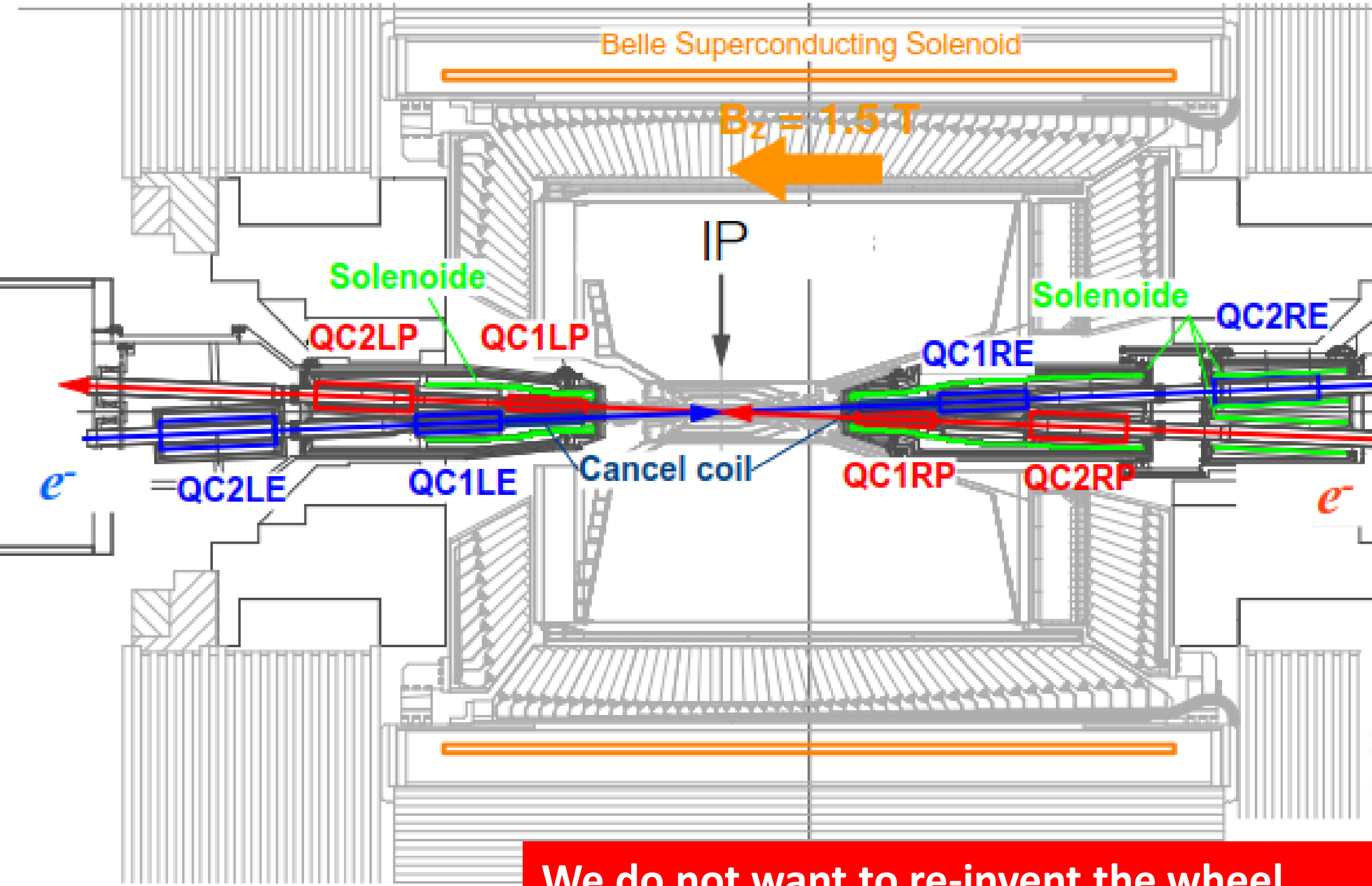
M. Boscolo

M.Boscolo, 3rd FCC workshop, CERN, 13-17 Jan. 2020

MAGNETIC ELEMENT DESIGN

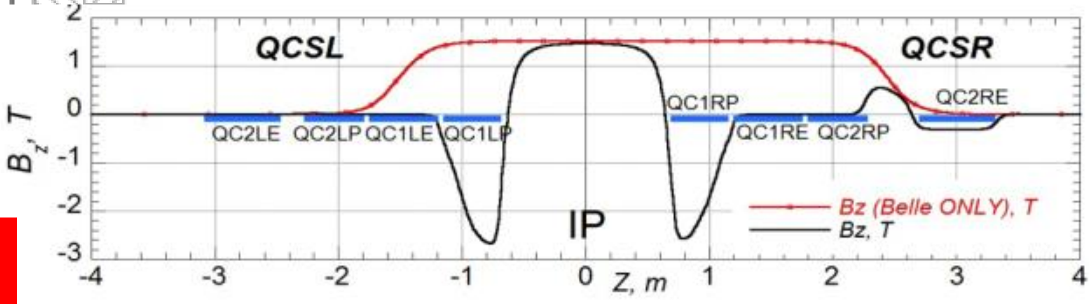
Prior art

Belle II and QCS



55 individually powered magnetic elements!

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



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

Note that first FF quad sits in high magnetic field

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

1. Adequate space for the detectors: magnetic elements reach angles of up to 100 mrad. The luminosity counter sits unobstructed in front of all magnetic elements.
2. In order to minimise emittance blow-up due to coupling between transverse planes, the integrated field 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.

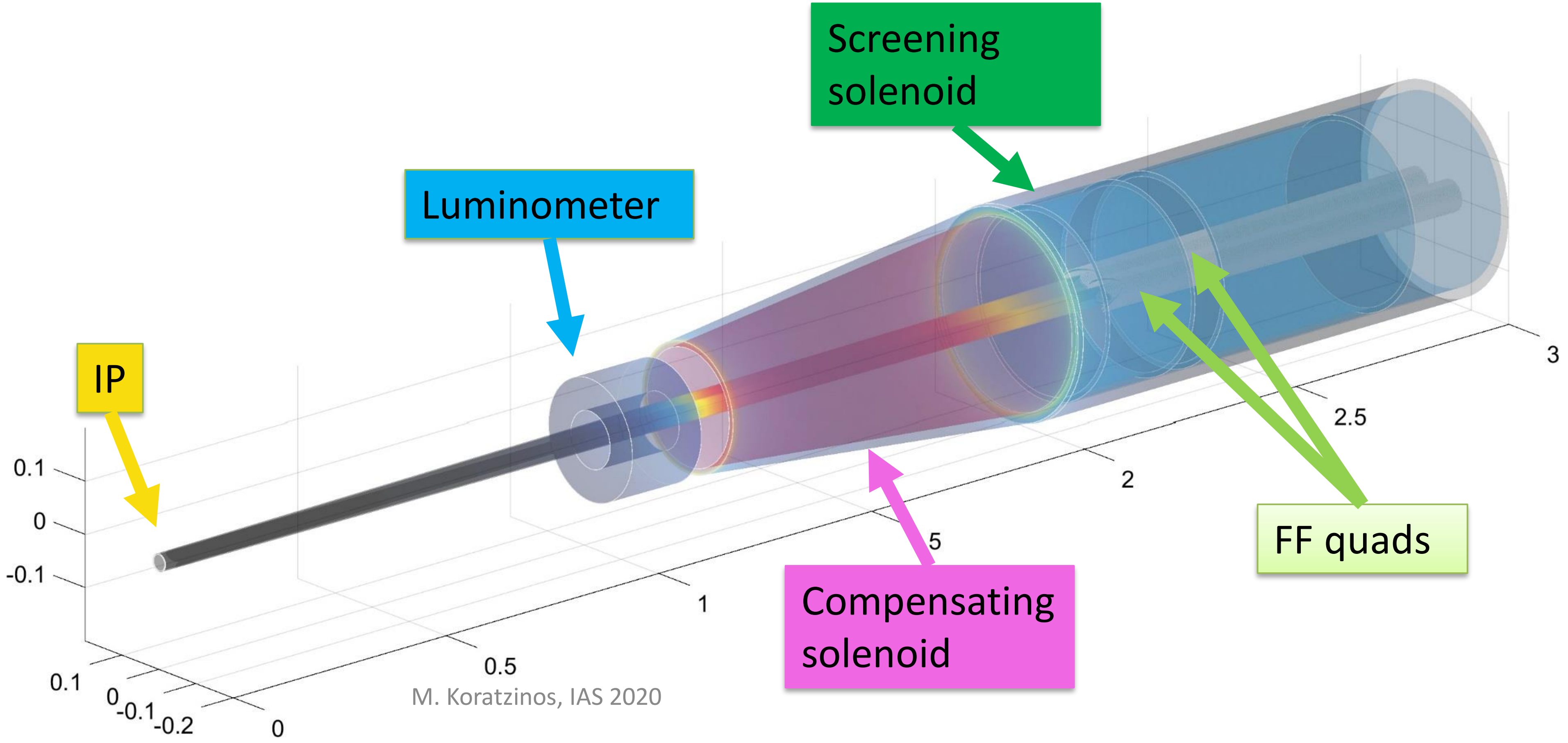
Design considerations to satisfy all requirements

- 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.



Screening solenoid

Luminometer

IP

Compensating solenoid

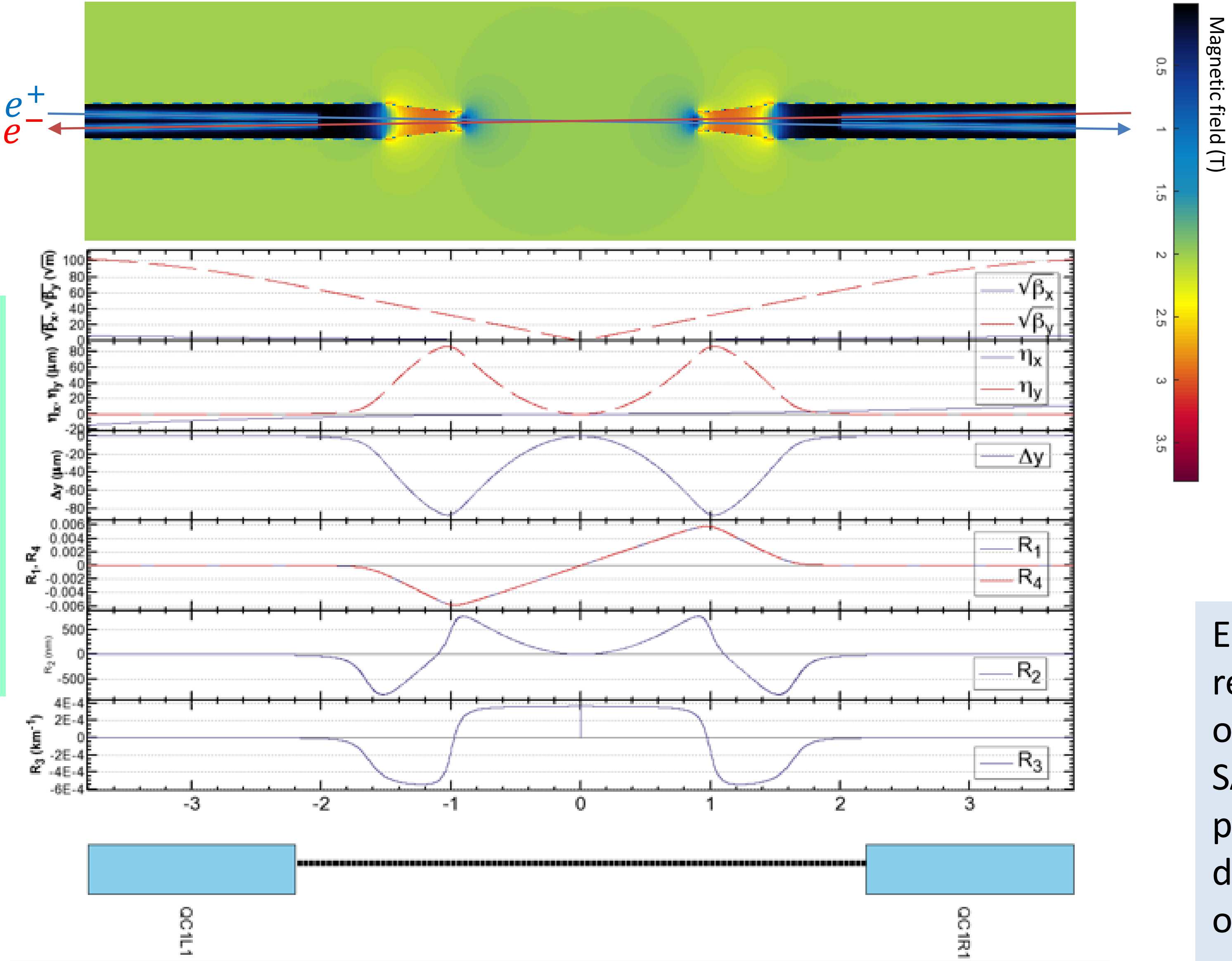
FF quads

M. Koratzinos, IAS 2020

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 (requirement 3)

The integrated solenoid field inside the quadrupoles of less than 10 mTm (satisfying requirement 4)

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

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

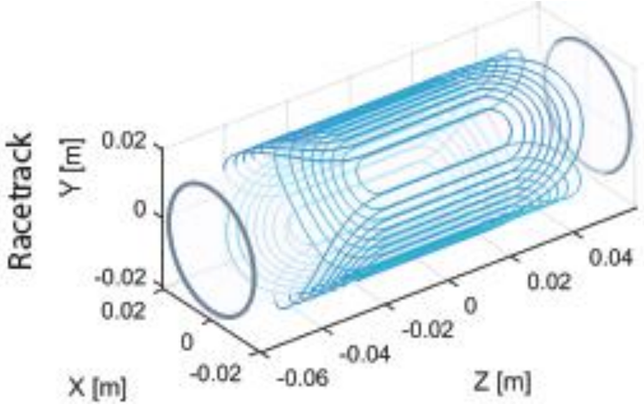
- Going from 2T to 3T this factor is 7.6
- If the emittance blow up from 2 IPs is 0.4pm at 2T, at 3T it is 3pm
- This emittance will completely dominate the total emittance (budget is 1pm)
- Luminosity will be reduced by $\sqrt{3}$ (=1.7) and for the same statistical accuracy one needs to run 1.7 times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

Final focus quadrupole design

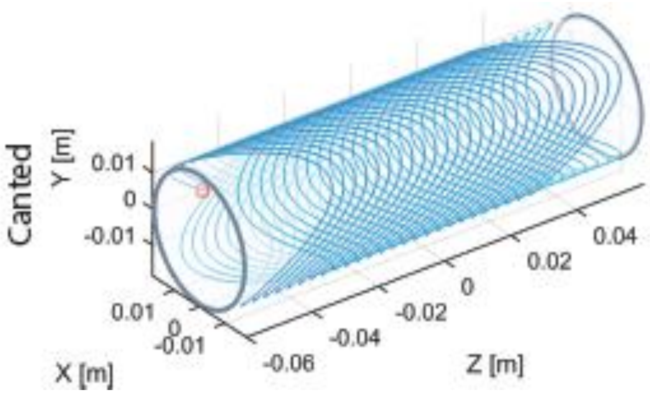
- The stringent requirements of the final focus quadrupoles are satisfied by using a canted-cosine theta design. The proposed design features iron-free coils with crosstalk and edge effect compensation, with a field quality (from simulation!) of around 0.1 units for all multipoles (requirement 5).
- 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

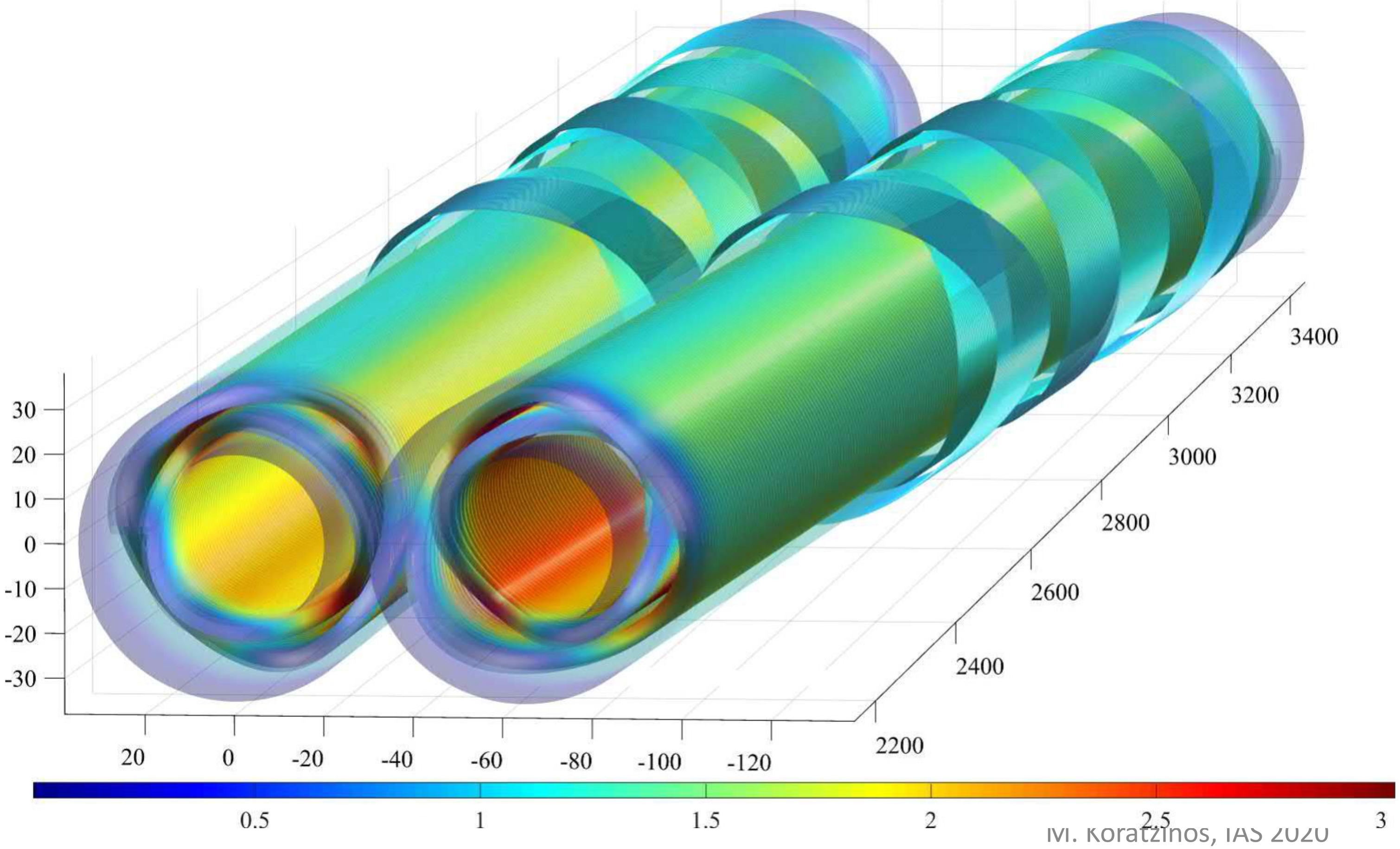
The CCT advantages and disadvantages

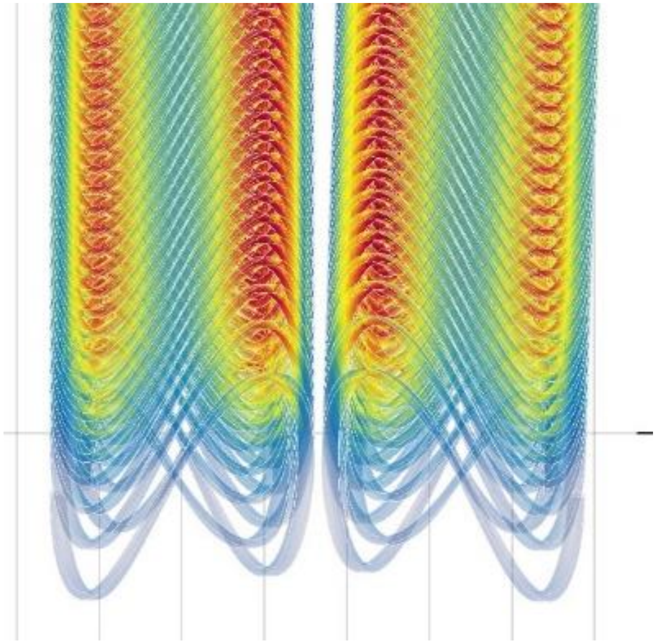
- **Disadvantages**:
  - Each layer produces a field of the chosen multipole plus an (unwanted) solenoid field
  - The solenoid fields of the two layers exactly cancel out, but the multipole fields add up
  - Due to this cancellation, more conductor (~30% more) is needed to deliver the same field as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

QC1L1

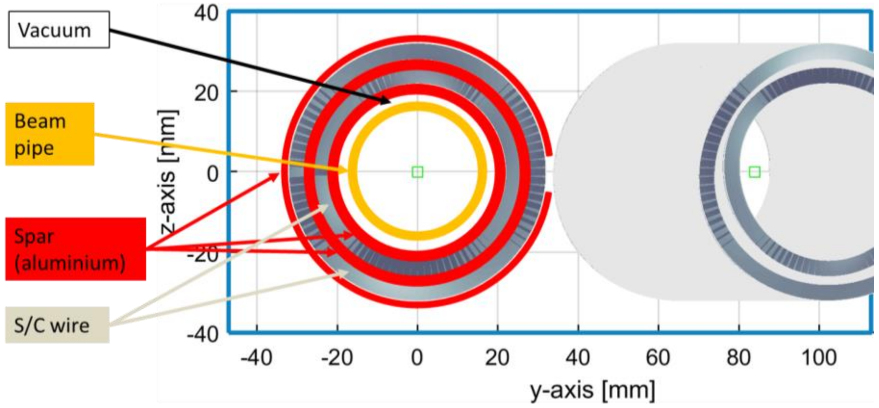
QC1L1 is the first and most demanding pair of quadrupoles of the final focus system of FCC-ee

Iron-free design

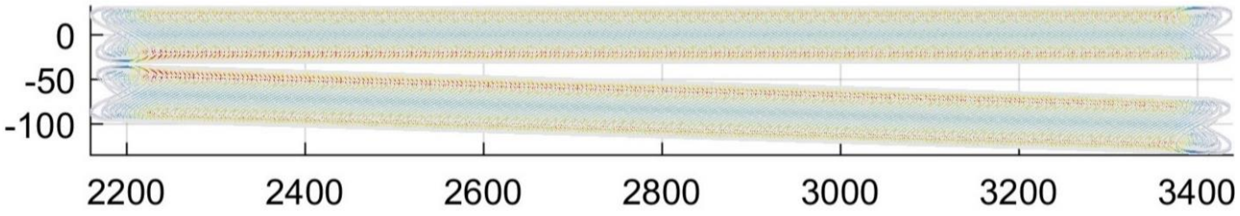




Inner bore: 40mm (diameter)
Fits outside the warm water-cooled beam pipe of inner diameter 30mm

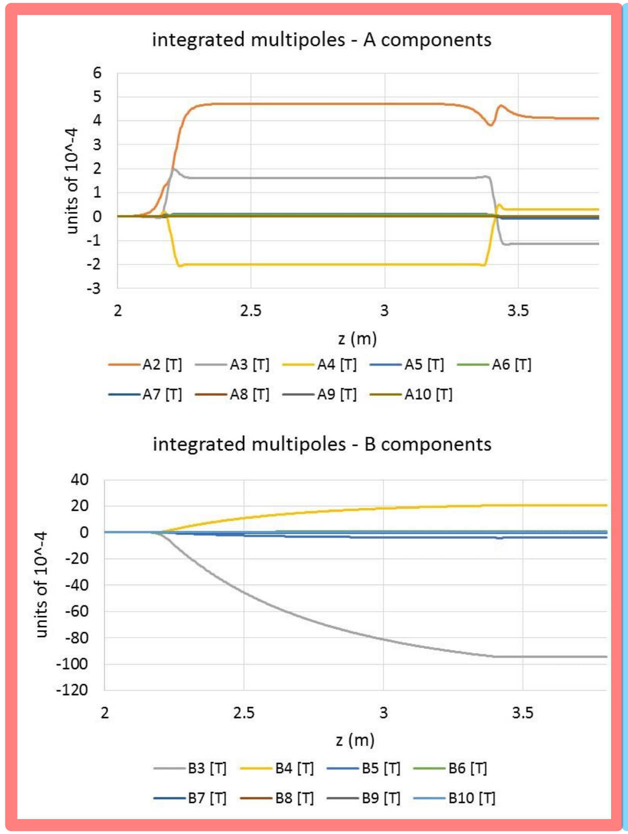


Crosstalk compensation

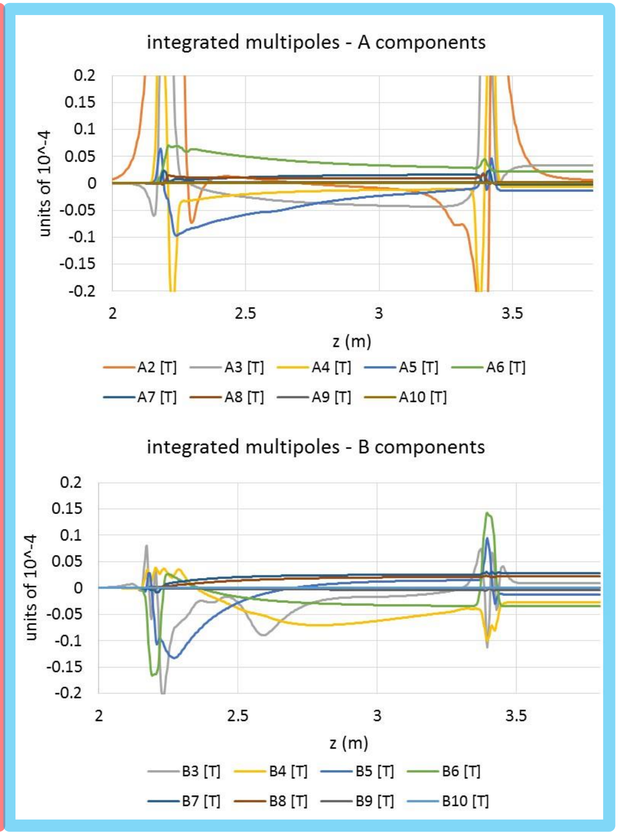


QC1L1 quadrupole:
length = 1200mm
Aperture: 40mm
distance at tip: 66mm
angle 30mrad
powered together

Before compensation

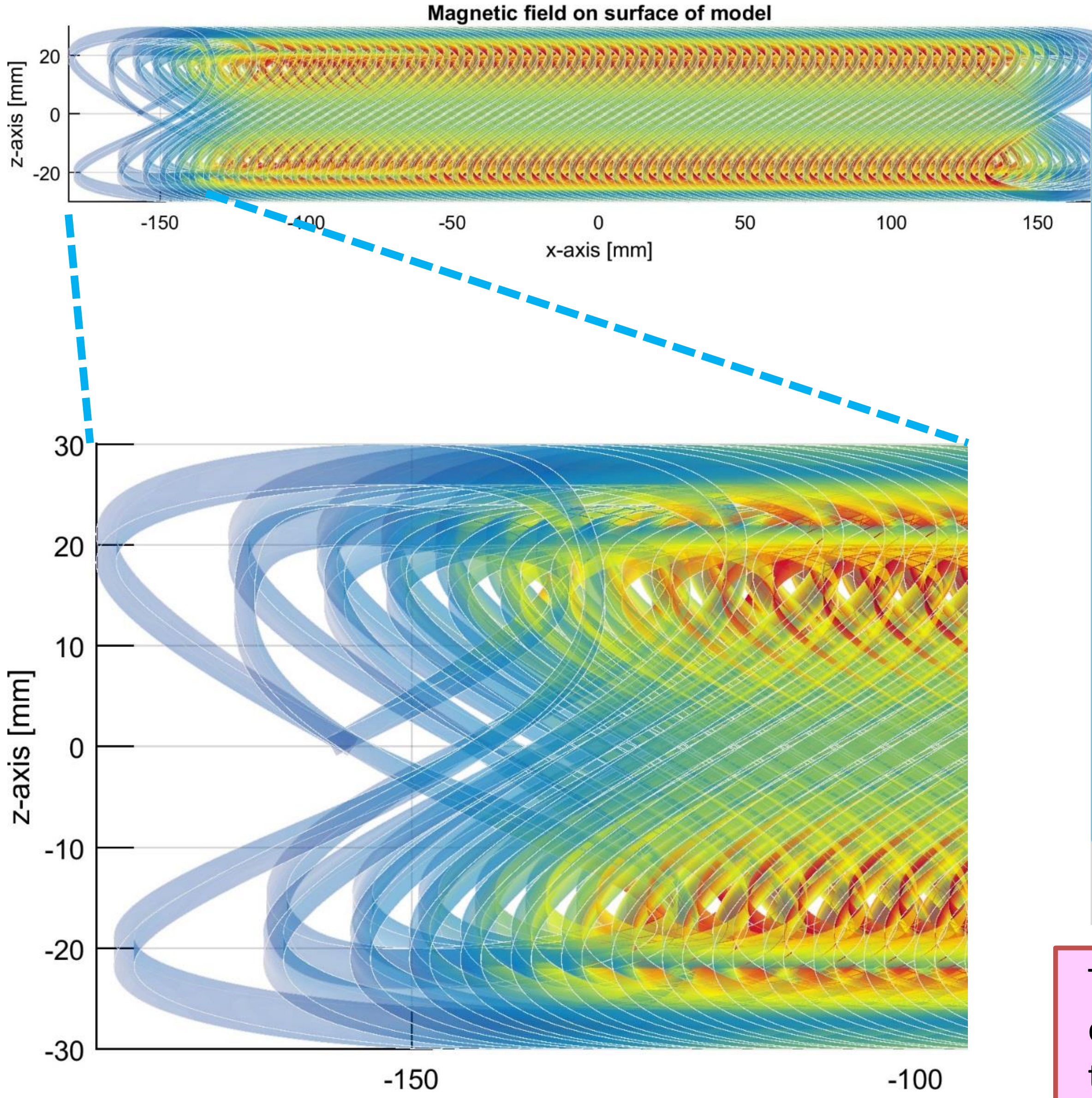


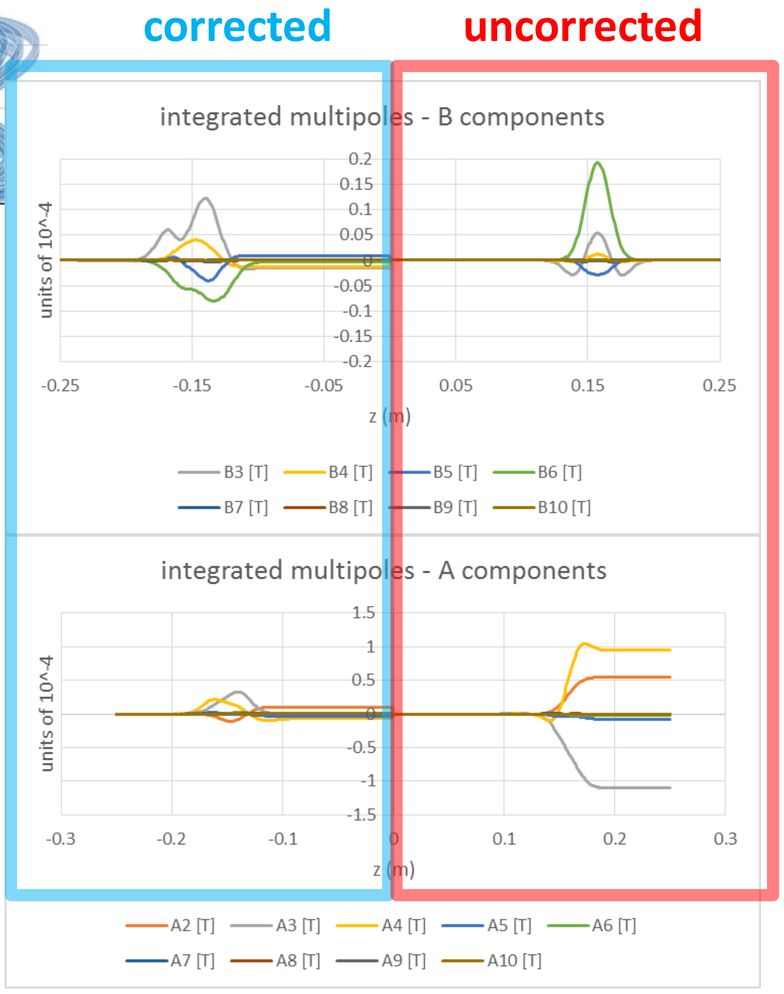
After compensation



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

The FF quadrupole – local edge compensation





Local edge correction important due to rapidly changing beta function:

$\boldsymbol{\beta_y}$ @2.2m = 6km;

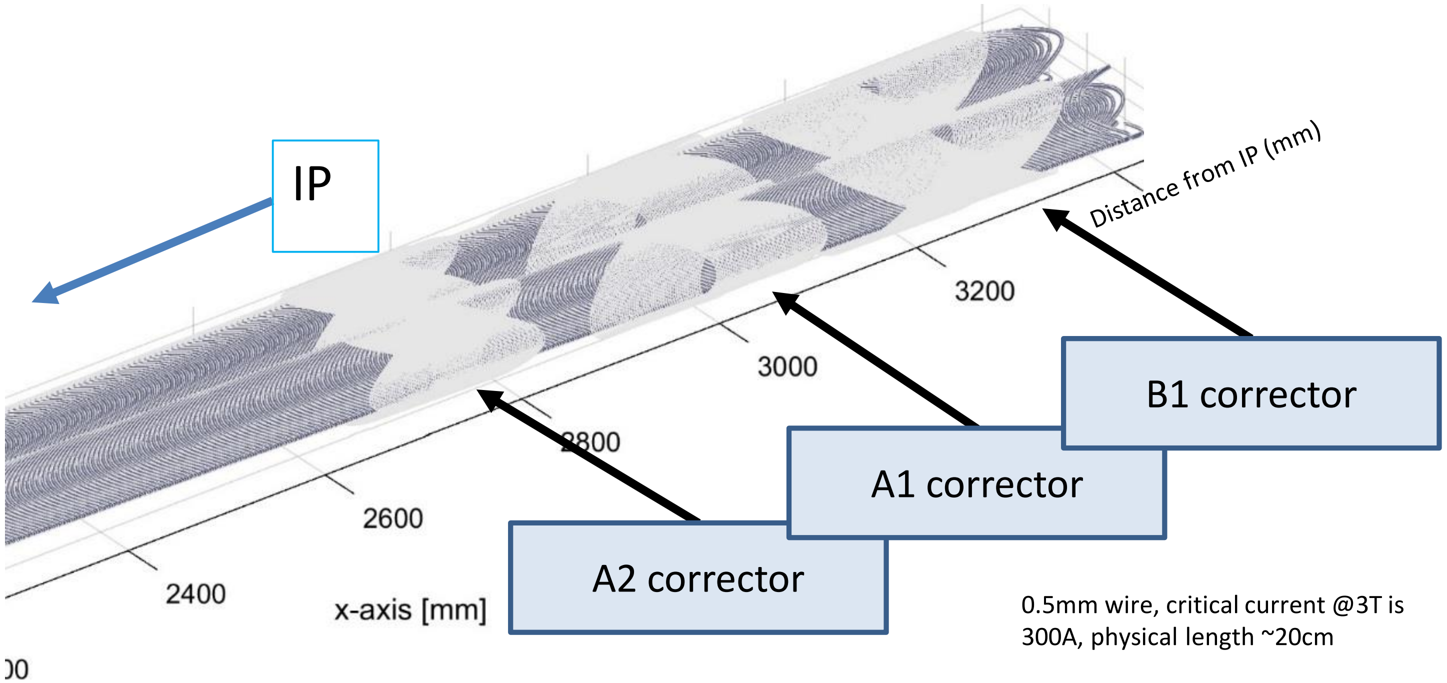
$\boldsymbol{\beta_y}$ at 3.4m = 14km

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

Magnet field quality is excellent throughout

Correctors

Correctors can be packaged very efficiently



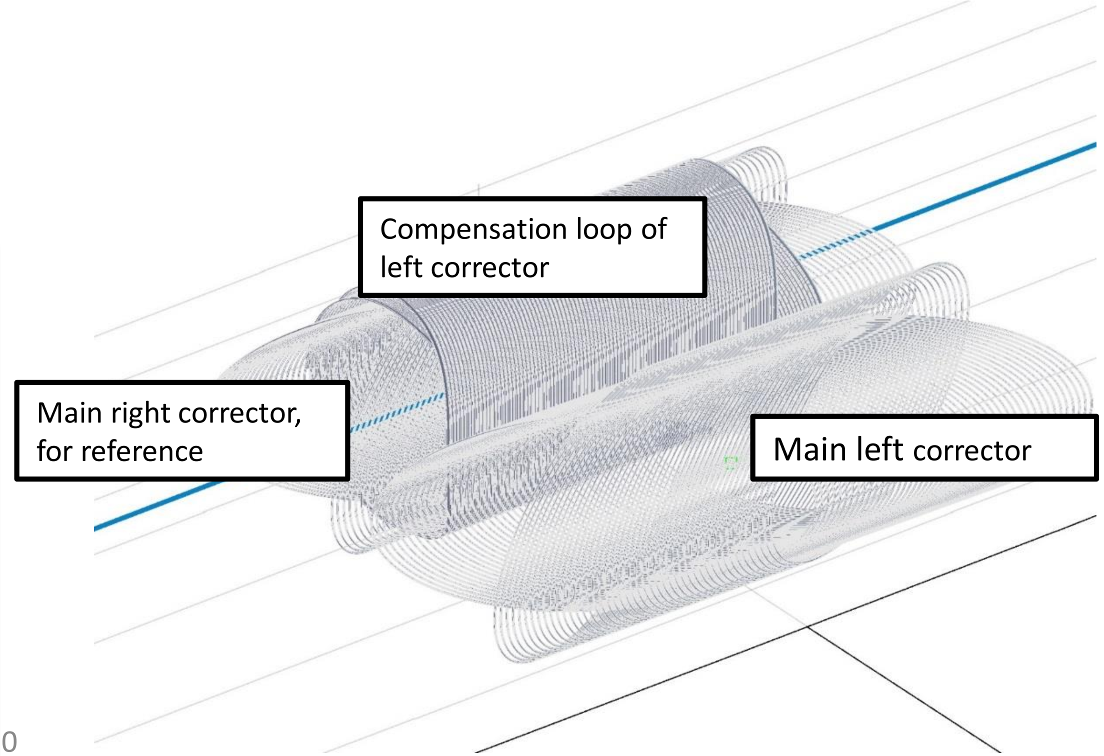
B1 corrector

A1 corrector

A2 corrector

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

- Optics requirements are that a number of correctors is 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

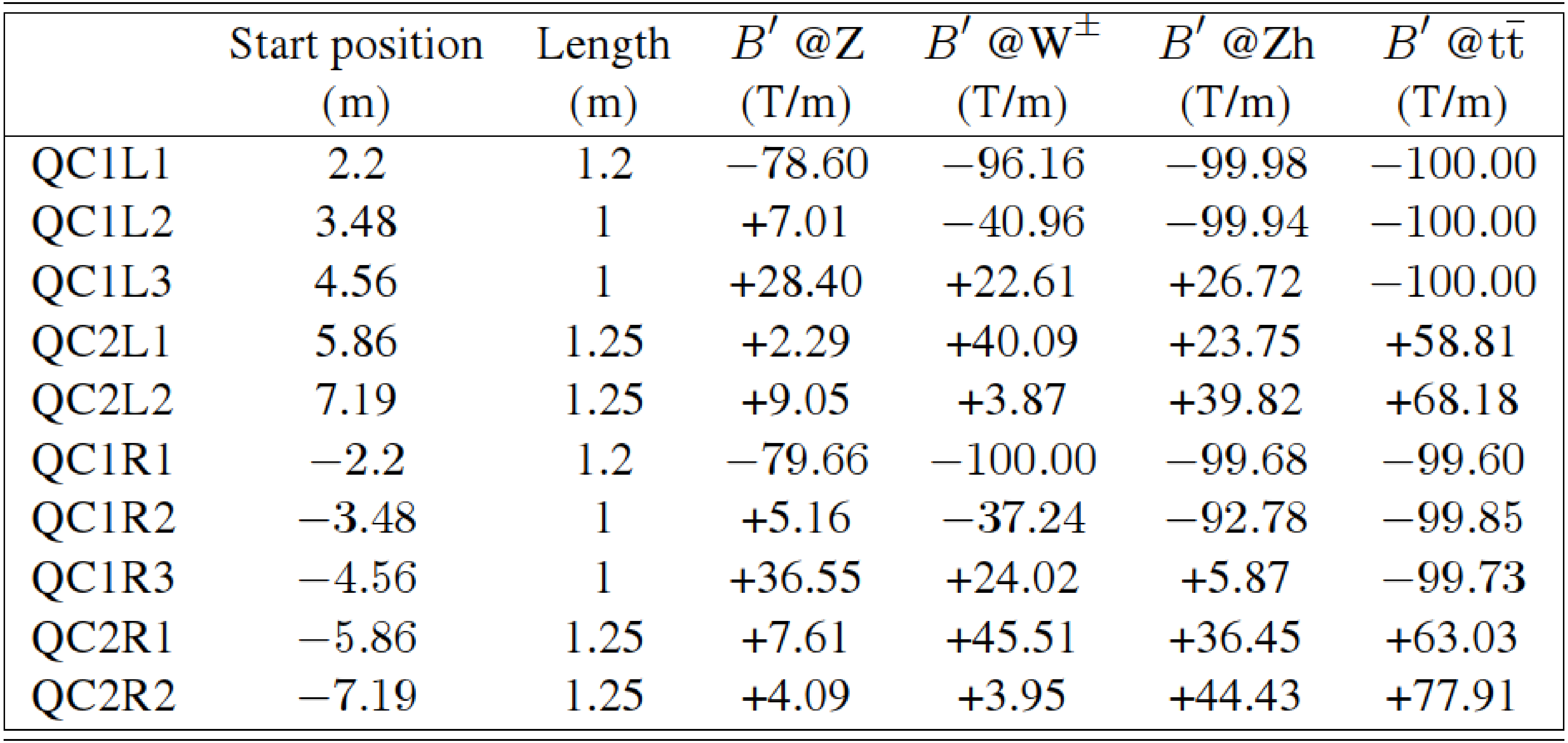


Compensation loop of left corrector

Main right corrector, for reference

Main left corrector

The FCC-ee Final Focus magnets

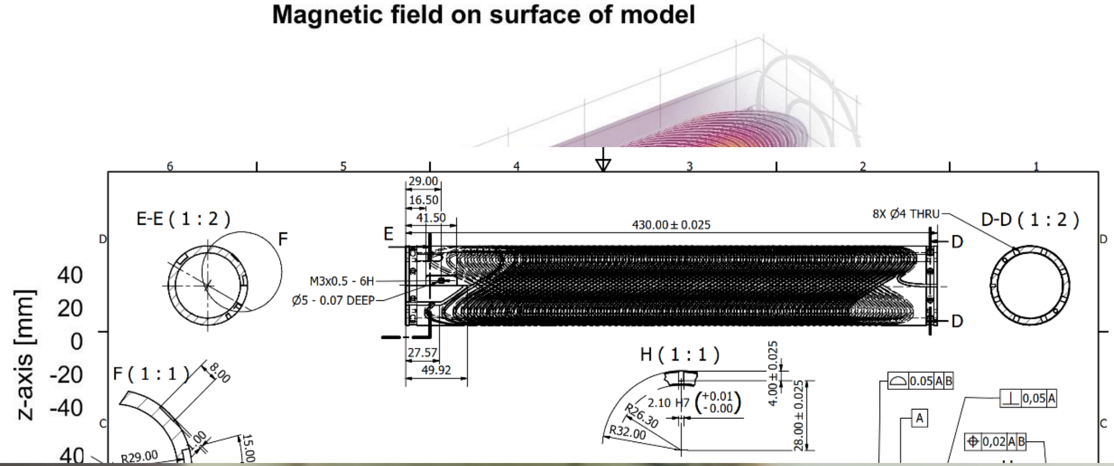


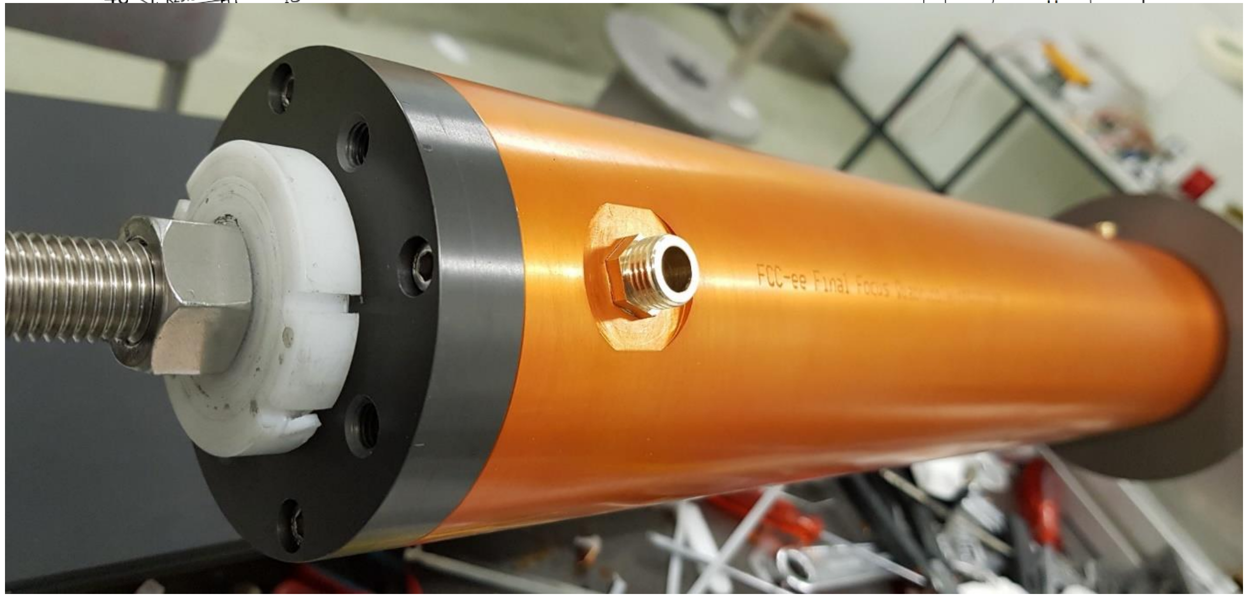
	Start position (m)	Length (m)	B' @Z (T/m)	B' @$W^{\pm}$ (T/m)	B' @Zh (T/m)	B' @$t\bar{t}$ (T/m)
QC1L1	2.2	1.2	−78.60	−96.16	−99.98	−100.00
QC1L2	3.48	1	+7.01	−40.96	−99.94	−100.00
QC1L3	4.56	1	+28.40	+22.61	+26.72	−100.00
QC2L1	5.86	1.25	+2.29	+40.09	+23.75	+58.81
QC2L2	7.19	1.25	+9.05	+3.87	+39.82	+68.18
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

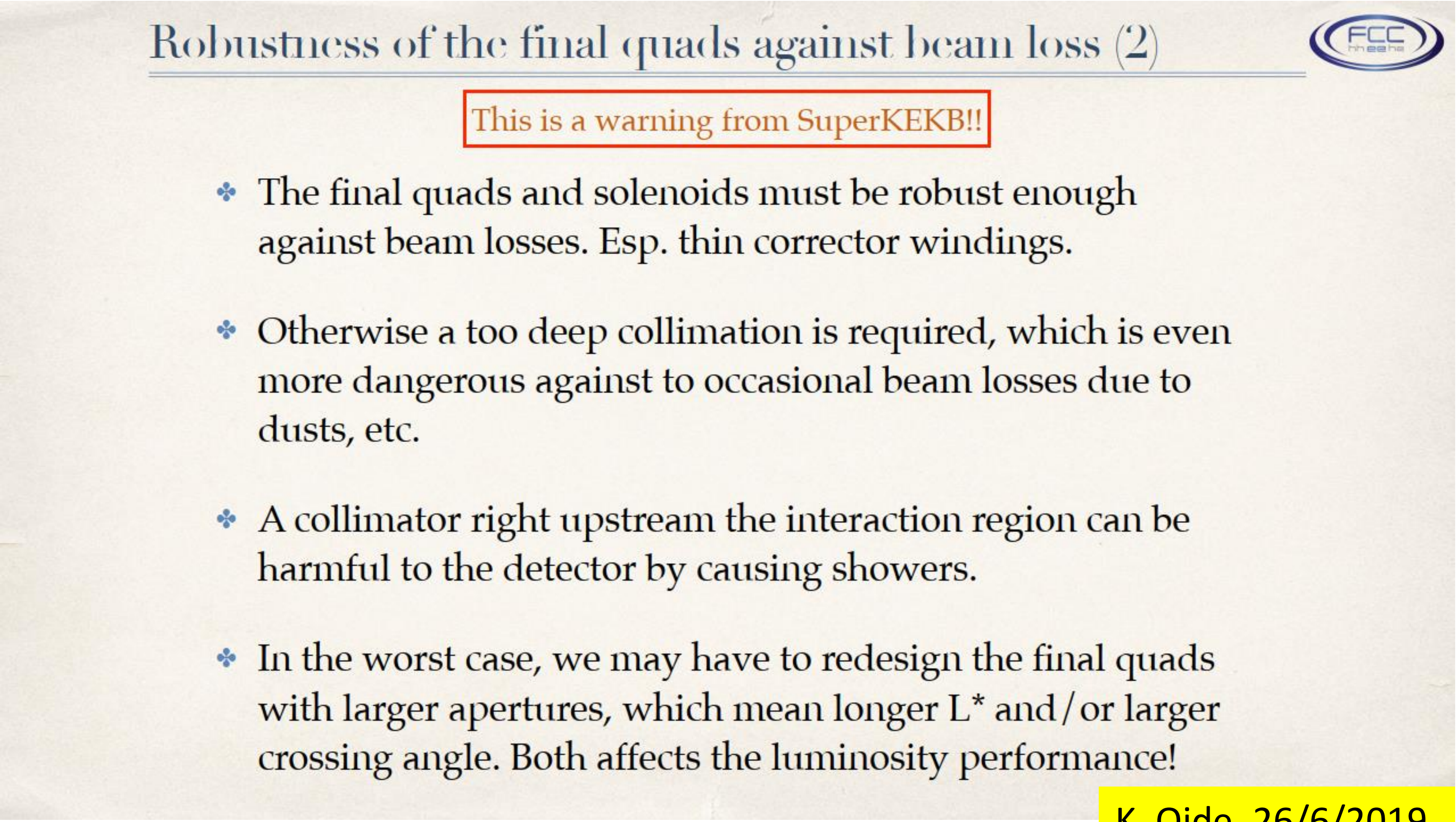
- CCT is a relatively new idea in magnet design, and never one has been built with compensation. It is therefore imperative that a prototype is build and tested
- ➔ the FCC FF quad prototype project was born
- Steps completed:
  - Full magnetic analysis
  - Full mechanical design
  - Manufacturing of all parts and tools
  - winding table, with stepper motor
  - Winding completed
  - Outer sleeve and endplates installed.
  - Mechanical assembly completed

- Rotating probe (C. Petrone)
  - Sensing coils (special to quadrupoles) completed
  - Design of rotating shaft under way
  - Warm testing: Q1 of 2020
  - Cold testing: Q2 of 2020


Magnetic field on surface of model



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

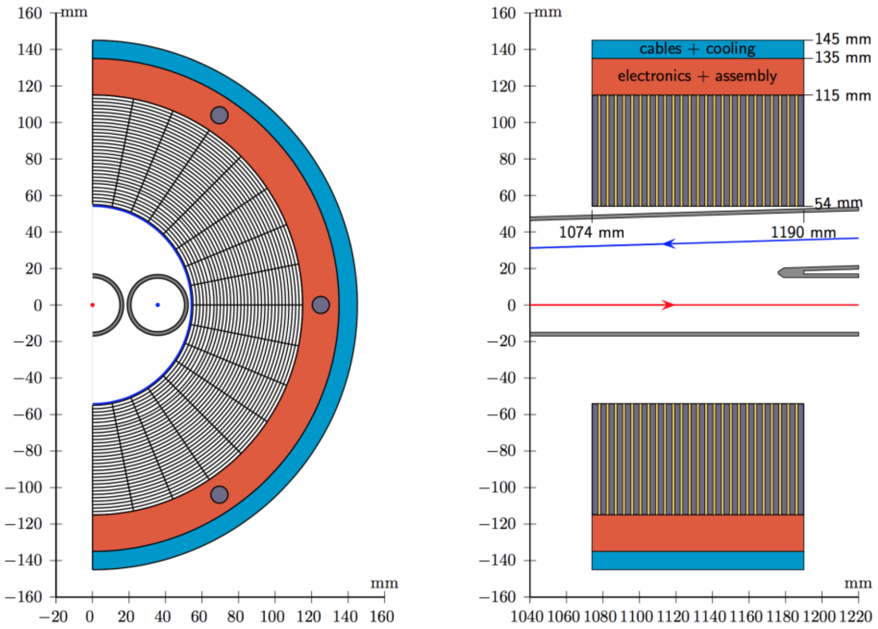
- Although NbTi conductor is adequate for the FF quads and correctors, we should consider HTS conductors because of the extra margin we will get against quenches.
- This is a technology that can be tested today
- We can be sure that in 20 years HTS conductors will be cheaper and better

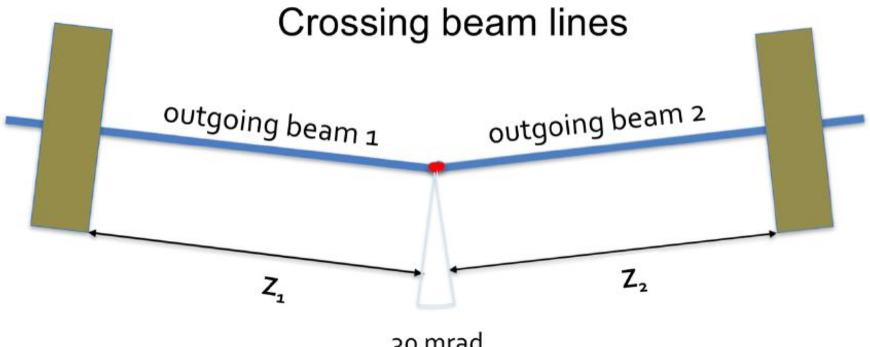
LUMINOSITY COUNTER

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 precision of 1 µm

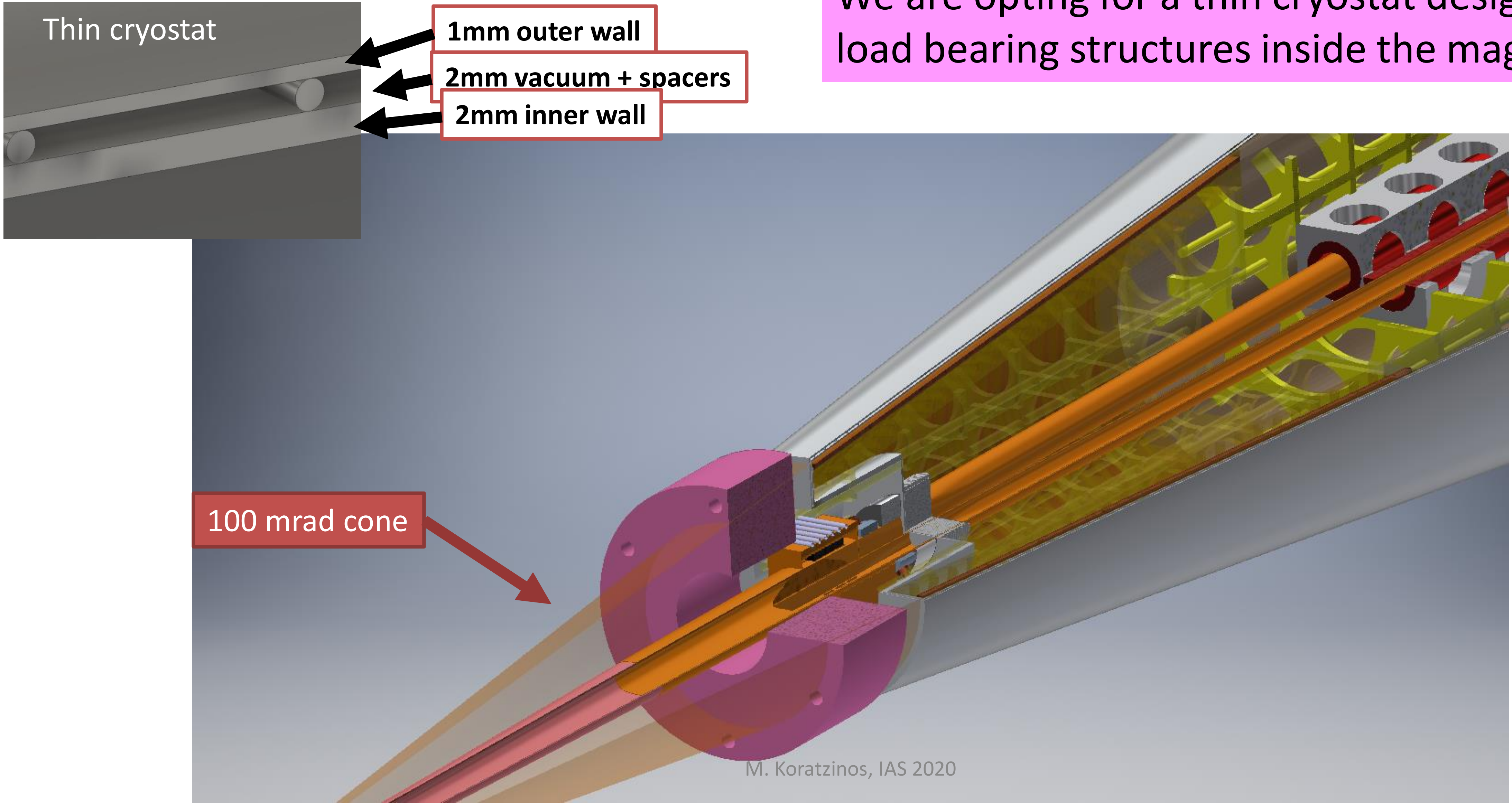
MECHANICAL DESIGN AND INTEGRATION

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

Mechanical design

We are opting for a thin cryostat design with all load bearing structures inside the magnet coils



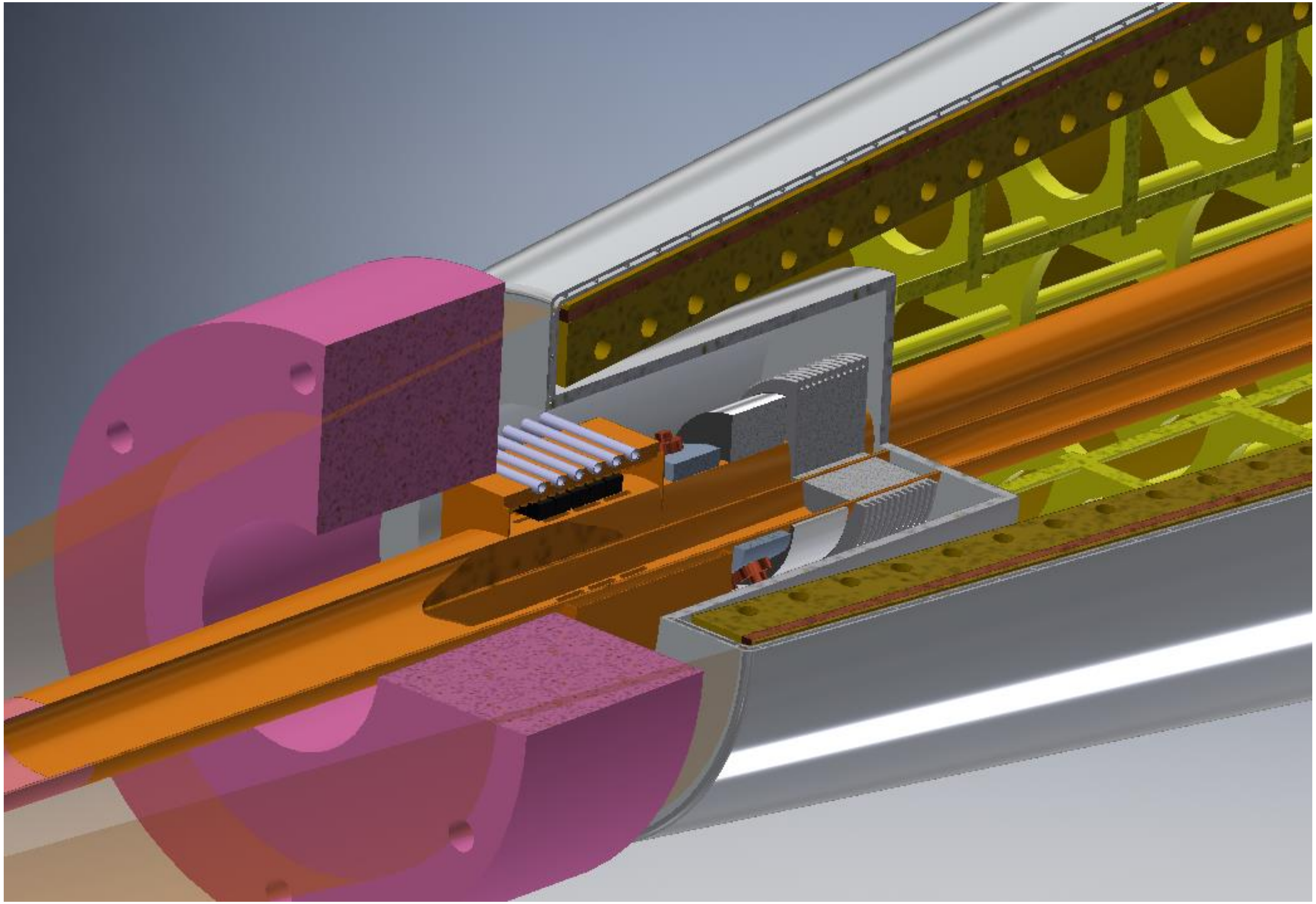
1mm outer wall

2mm vacuum + spacers

2mm inner wall

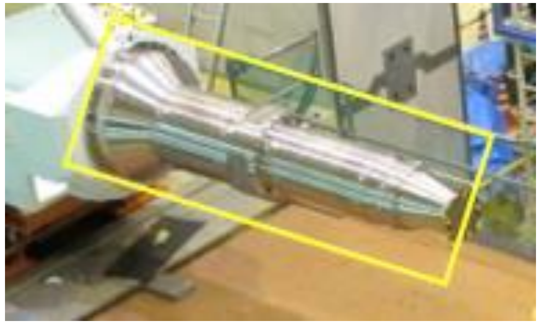
100 mrad cone

Zoom on front face of cryostat

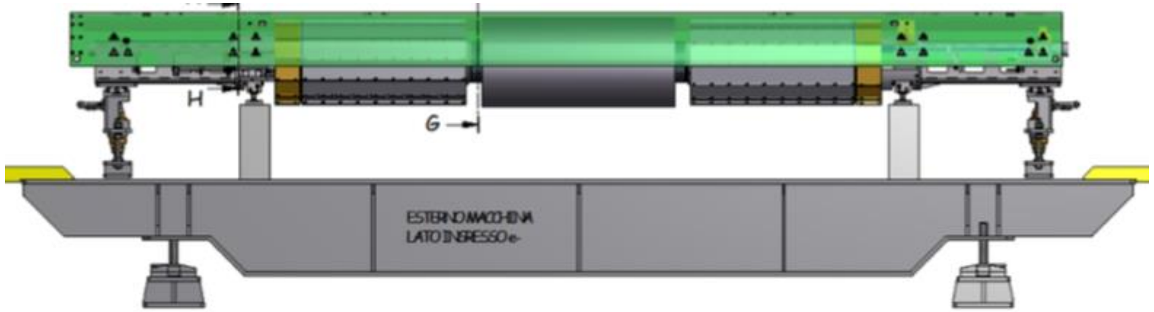


Integration and assembly

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



  - One piece insert like DAFNE

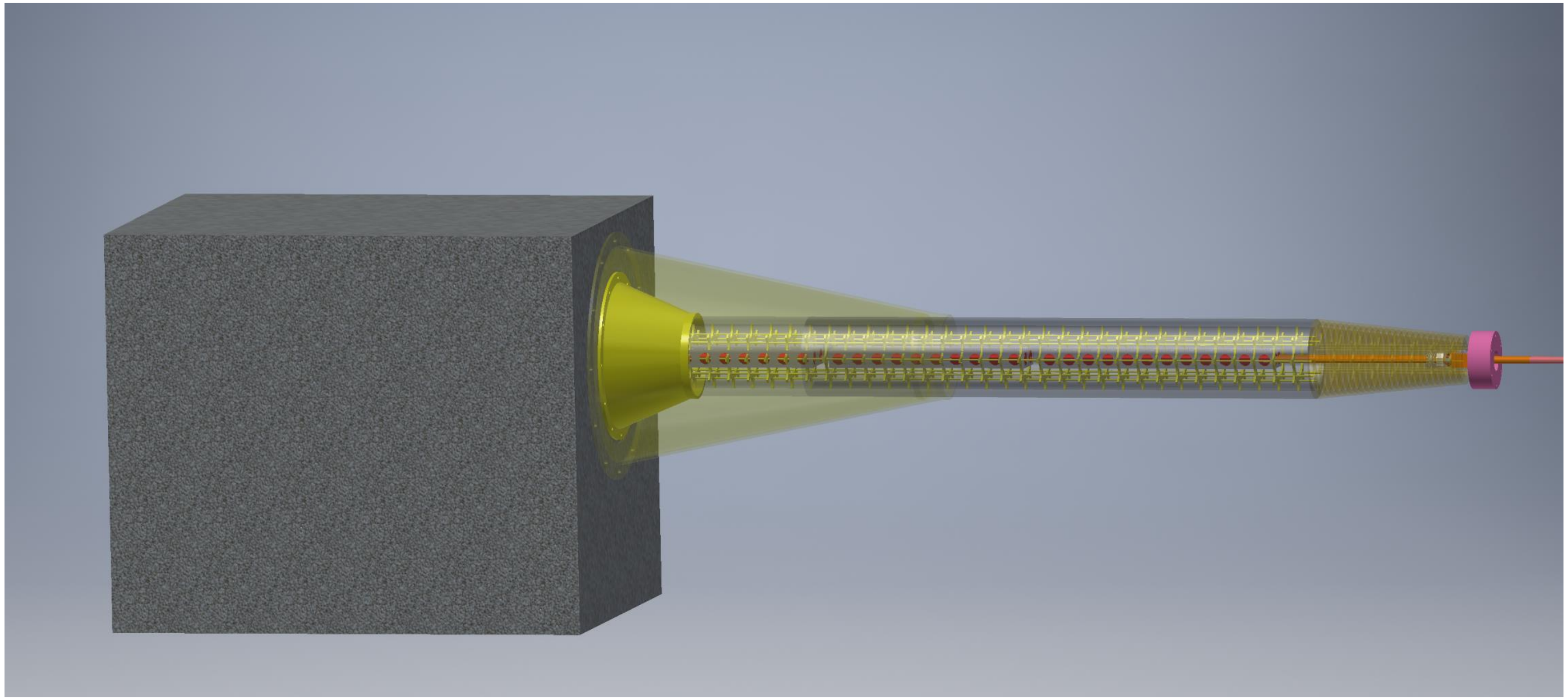


A cantilever design
- needs a remotely operated flange
- The two sides are decoupled

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

Cantilever assembly

Conceptual design



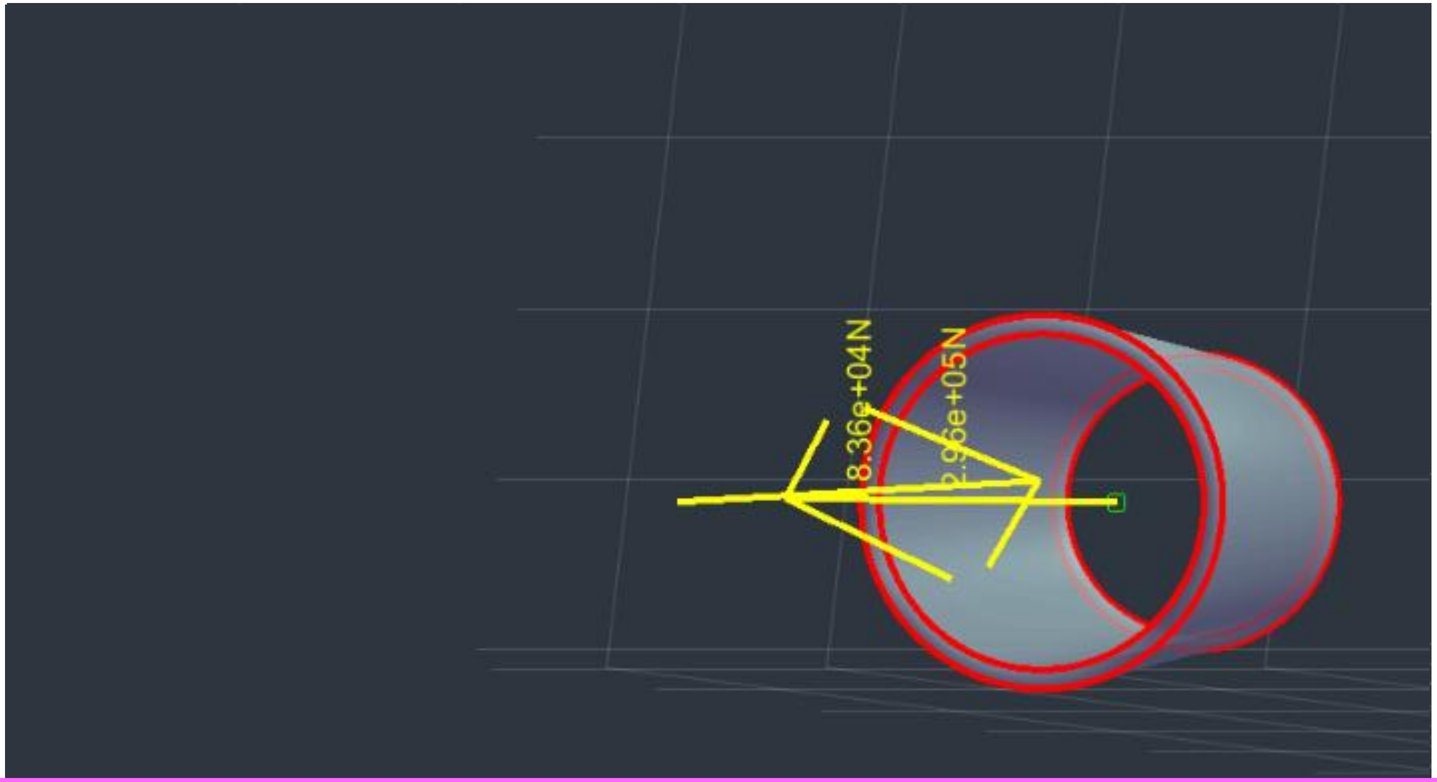
From support to tip of
compensating solenoid

4370 mm

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



Forces and torques with misalignment have also been computed

For both sides:

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

BACKGROUND STUDIES

Backgrounds

- An essential part of the study and very resource demanding
- We need to
  - generate this background,
  - track it to the detector and
  - estimate its effect
- A variety of generation, tracking and physics codes need to work together
- Two broad categories
  - **IP backgrounds**: due to colliding beams
  - **Single beam backgrounds**: present even in the absence of collisions

Generators and tools

IP

Background source	Generator	Tracking code for loss map
Beamstrahlung	GuineaPig , BBWS	SAD, MADX
Radiative Bhabha	GuineaPig, BBBrem	SAD, MADX
Pair production (incoherent dominant)	GuineaPig	Geant4
γγ to hadrons	combination of GuineaPig and Phythia	Geant4
Synchrotron Radiation	*Geant4, SYNRAD+, BKG_SYNC*	*MDISim / G4*
Thermal photons	*MC by H. Burkhardt*	*MADX*
Beam-Gas Bremstrahlung (BGBrem)	*Geant4*	*MDISim (G4/ROOT/MADX)*
Beam-Gas Coulomb (BGCoul)	*MC by A. Ciarma & M.B. (in progress)*	*interface with PTC_MADX*
Touschek	*MC by A. Ciarma & M.B. (planned)*	*interface with PTC_MADX*

Single beam

Studied, small effect

Beamstrahlung

- Beamstrahlung is Synchrotron Radiation in field of opposing beam, estimated at the Z with **Guinea-Pig**
- The IR will generate **a very significant flux and power of hard X-rays, lost mostly in the first downstream bend** (49-55 m from IP)

Classical SR and Guinea-Pig	<Nγ>	<Eγ> keV	Power KW
IP magnets (quad, solenoid)	1.3	24	43 kW
Beamstrahlung	0.15	2000	**417 kW**

(also without collisions)

photon energies extend into the GDR region

- **~460 kW hitting in a narrow ~5 m wide region** 49-55 m downstream from IP
- We need to dissipate order 100 kW/m

H. Burkhardt

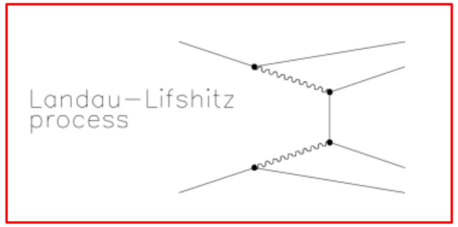
As well as a few MW / IP with spectrum extending into tenths of MeV
(strongly varying with bb-parameters and residual separation)

Radiative Bhabha

- BBBrem has been implemented in **SAD**
- Beam loss due to radiative Bhabha for FCC-ee at the Z:
    - **4 kW** in the region up to **400 m downstream** the **IP**
    - **150 W** within the first quad **QC1**
- The effect of beam-beam adds another 20% on the loss at QC1.
- The result is neither sensitive to the misalignment of aperture at QC1, nor to the IP solenoid field.
- The tolerance of the final focus quadrupole for such amount of beam loss must be examined.
- Cross check with other methods is necessary and in progress.
- Z peak : losses all happen well before reaching the second IP
- 182.5 GeV: a few losses in the vicinity of the second IR. Tracking into the detector (CLD) was done and checked that this background is negligible.

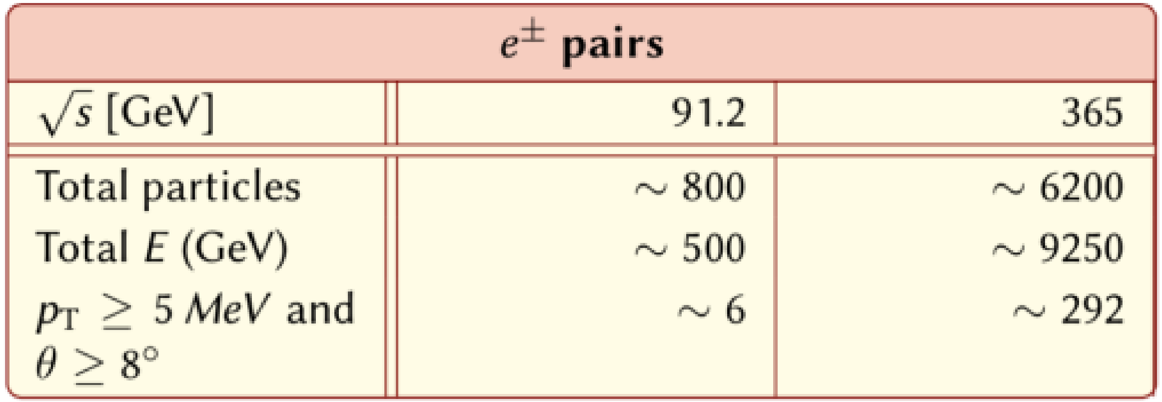
K. Oide

Pair production



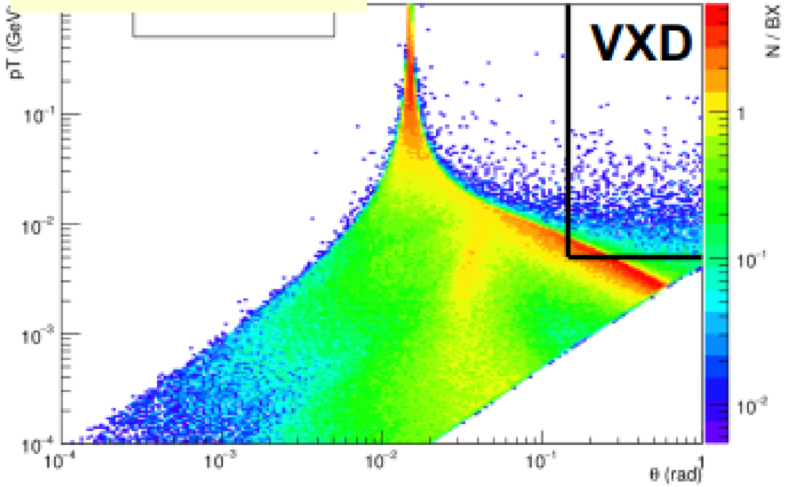
- At FCC : about 80% of the pairs created (and of the energy they carry) come from the LL process. Beamstrahlung photons contribute to the remaining 20%.
- FCC dominated by incoherent pair production (IPC) : $\gamma\gamma \rightarrow e^+e^-$

Per BX :



$e^{\pm}$ pairs		
$\sqrt{s}$ [GeV]	91.2	365
Total particles	~ 800	~ 6200
Total E (GeV)	~ 500	~ 9250
$p_T \geq 5\ MeV$ and $\theta \geq 8°$	~ 6	~ 292

√s = 365 GeV

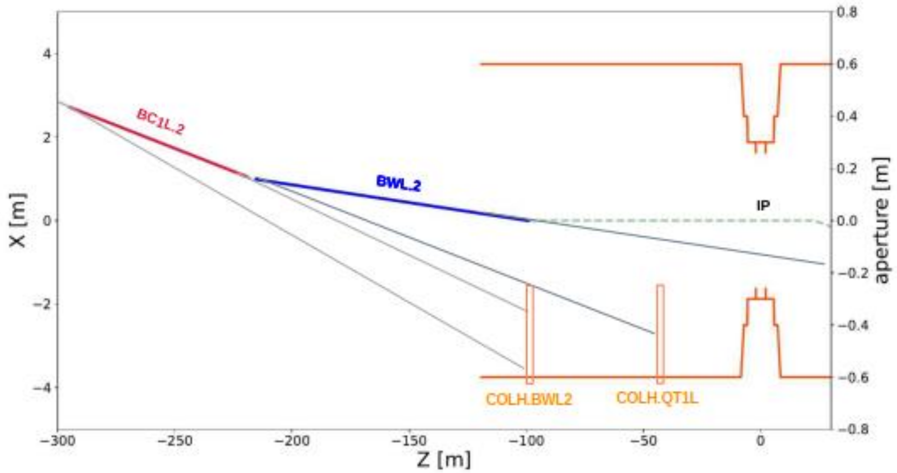


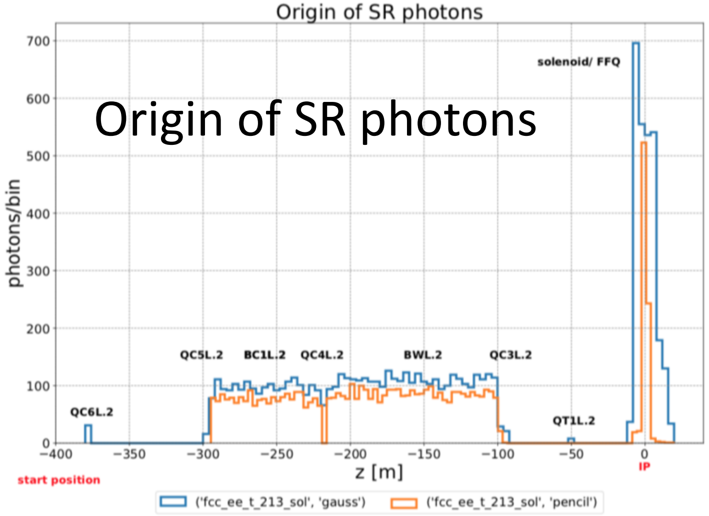
E. Perez

Large # of particles is created, that carry (collectively) up to 9 TeV. But few particles reach the detector, even at the highest energy.

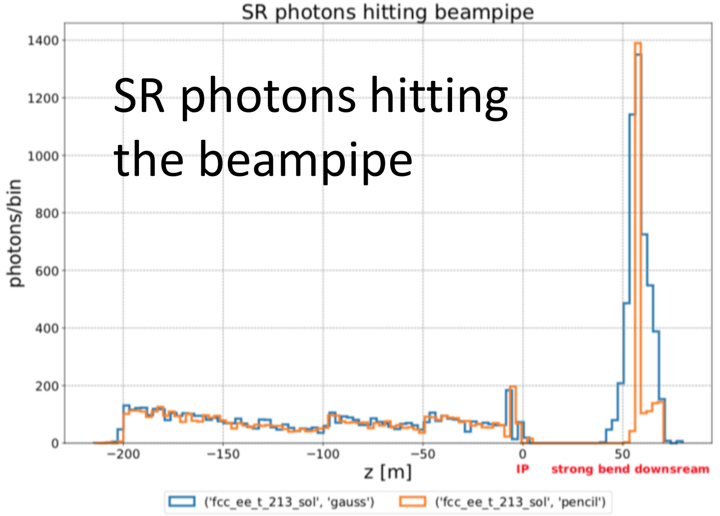
Synchrotron Radiation

IR collimators and SR cones

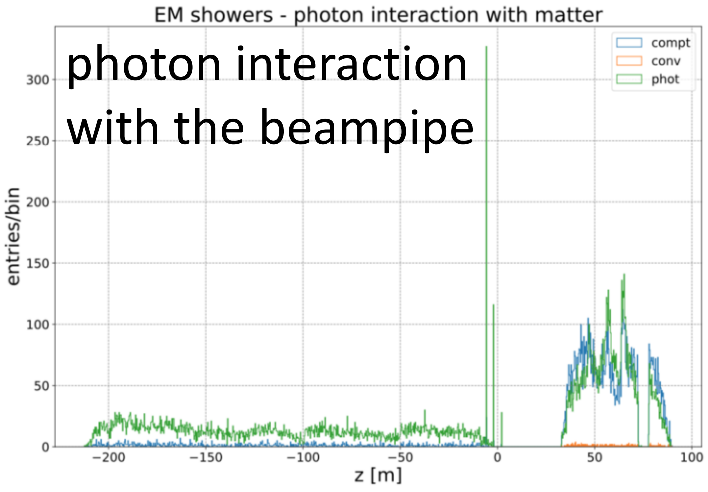




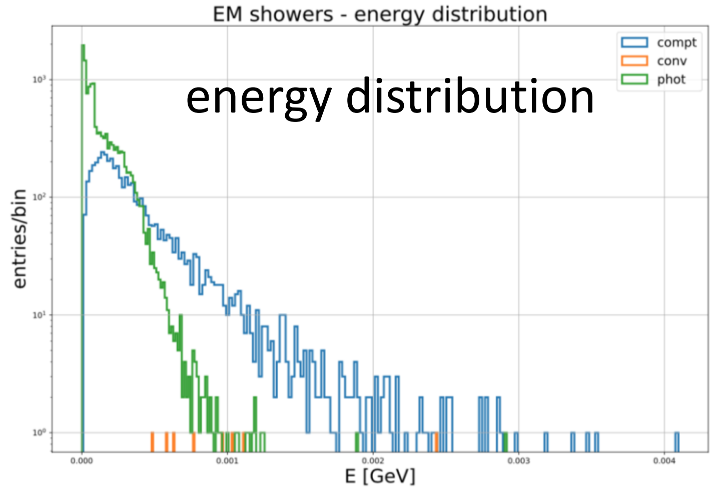
Origin of SR photons



SR photons hitting the beampipe



photon interaction with the beampipe



energy distribution

MDISim: Powerful simulation tool for very detailed analysis
Interfaces
MADX/ROOT/GEANT4

→ Collimator strategy

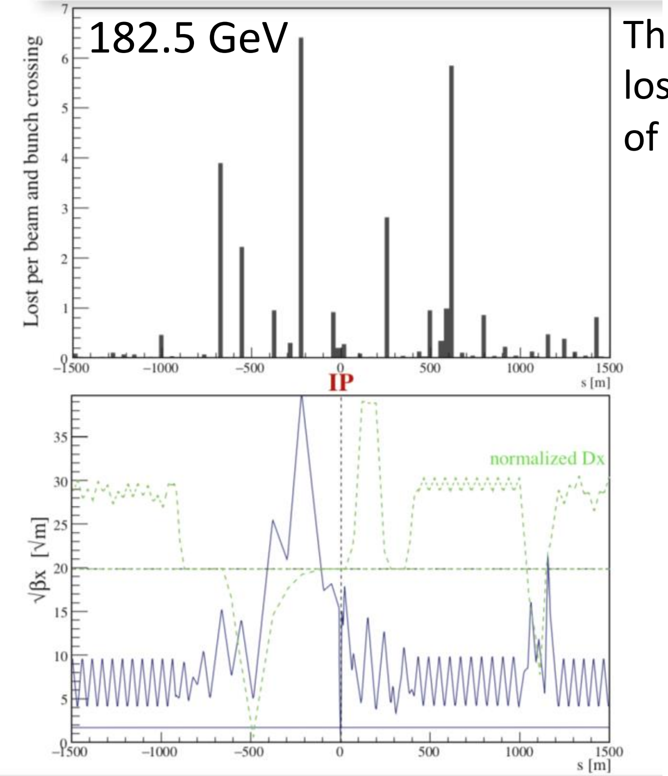
M. Luckhof

Thermal photon scattering

First described in 1987 by V. Telnov, it was the main single beam lifetime limitation in LEP. Well measured and simulated using the algorithm described in SL/Note 93-73

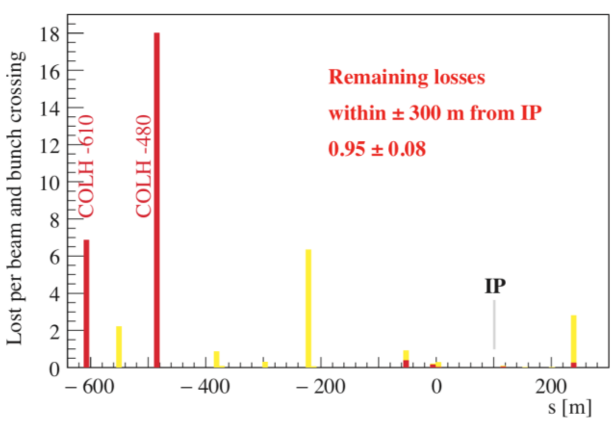
Today simulation is done using C++ with multithreading, 10^9 events in few min

Normalized loss distribution +/- 1.5 km around IP



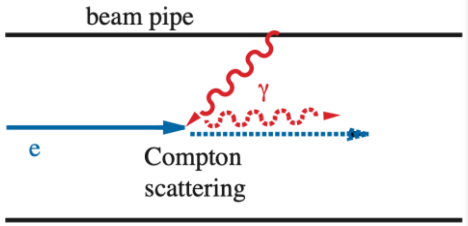
Thermal γ 31.2 ± 0.5 |s|<1.5 km from IP
lost/beam/crossing
of which 11.1 ± 0.3 |s|< 300 m

Losses now concentrated at these collimators



photon density

$\rho_\gamma = 5.3\times10^{14}$ m^{-3}



very roughly

0.07 eV thermal photons

boosted by γ^2 to GeV

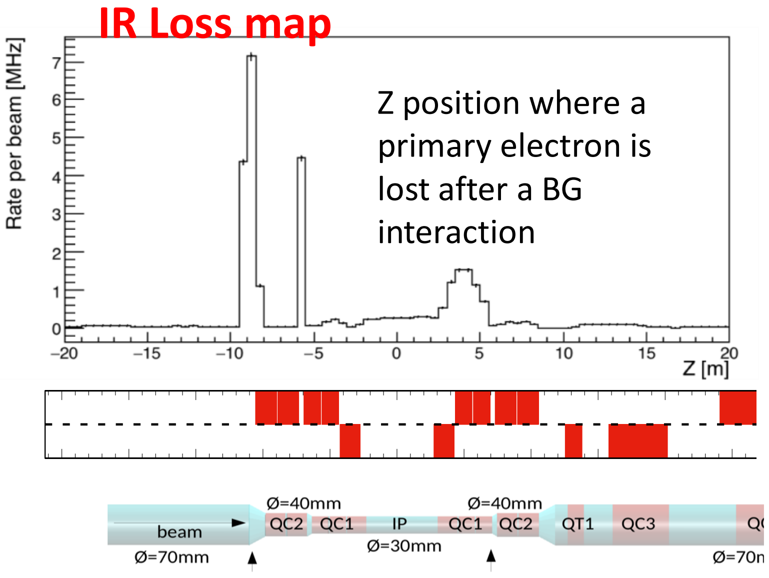
energy loss from beam

mitigation by off-momentum collimators

H. Burkhardt

Beam – gas scattering

Inelastic

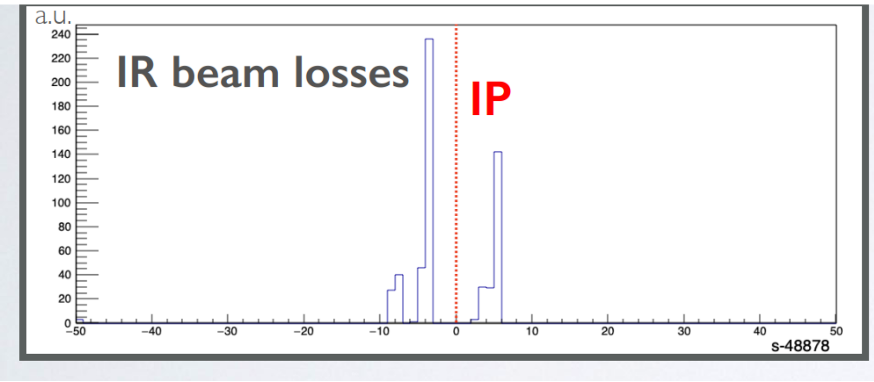

IR Loss map

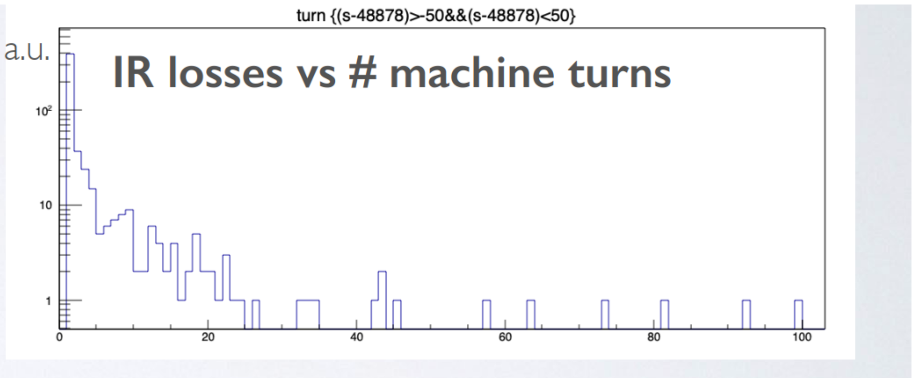
Z position where a primary electron is lost after a BG interaction

FCC-ee energy	Loss rate [-800;+200] m from IP [MHz]	Loss Rate [-20;+20] m from IP [MHz]
Z	147	29
W	16	3
H	3	0.5
t	0.5	0.1

tracked only into lumical showing negligible backgrounds rates

Elastic

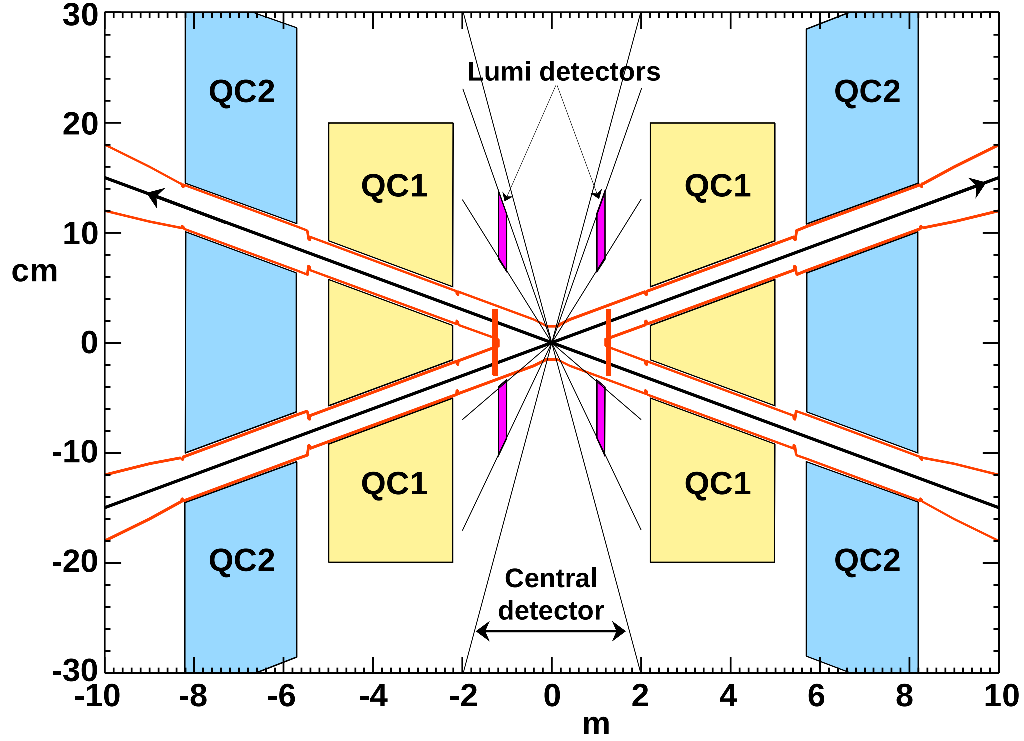




- Most of the **particles are lost close to the IR final focus quadrupoles**, where the physical aperture gets smaller
- Most of particles are lost at the first turn

SIZE OF THE BEAM PIPE

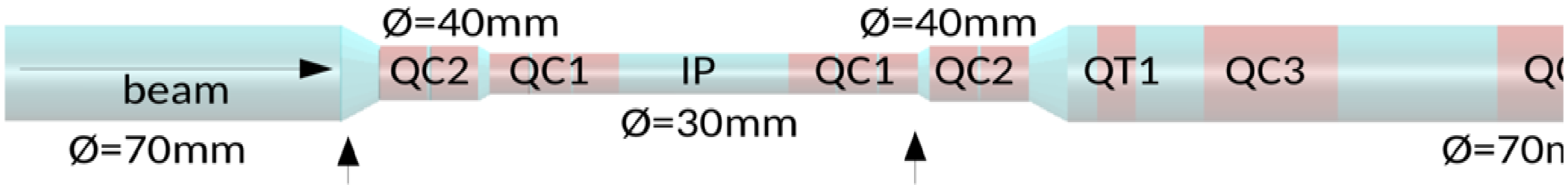
Beam pipe design around the IP



M. Boscolo

What defines the beam pipe dimensions is:

- SR hitting the detector area
- Beam sizes
- Heating due to impedance
- For physics, we want this as small as possible
- A series of masks and shielding protect from SR

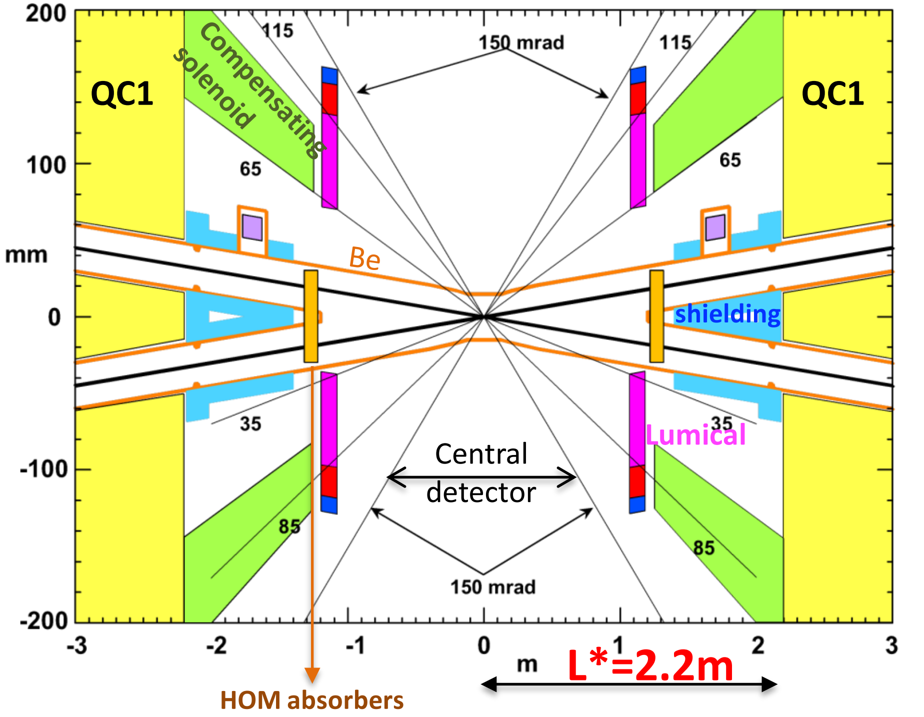


Can it be made smaller?

We have opted for a 30mm dimeter beam pipe close to the IP.

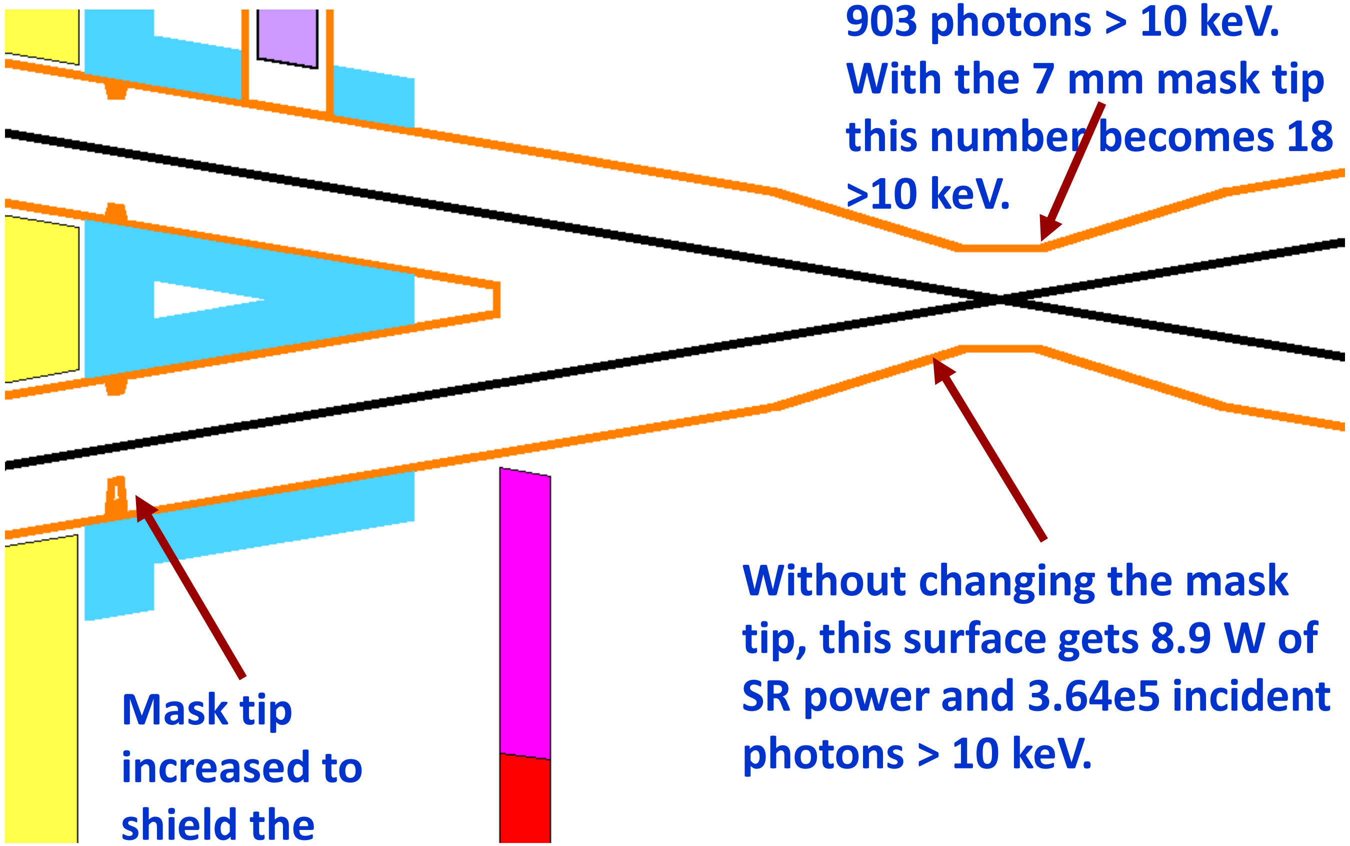
- Central region +-12.5cm is water cooled beryllium (5um of gold, 1.5mm beryllium, 1mm of water)
- Beam pipe around the FF quadrupoles (QC1L1, QC1L2, QC1L3) is 30mm diameter

Moving from 15 to 10mm radius


2D-top view with expanded x-coordinate

- The SR fan from the last bend magnet misses the central chamber
- The mask at -2.1 m shadows the central chamber
- No SR direct hits in the central region

Close up



FF SR strikes here with 903 photons > 10 keV. With the 7 mm mask tip this number becomes 18 >10 keV.

Without changing the mask tip, this surface gets 8.9 W of SR power and 3.64e5 incident photons > 10 keV.

With the mask tip at 7 mm this number goes to 0.2 photons >10 keV.

Mask tip increased to shield the tapered section

Now central beam pipe is +-9cm with diameter 20mm, then a taper of 31cm on each side

M. Sullivan

Central beam pipe: 30mm vs 20mm

- Work in progress!
- Two aspects: SR background and resistive heating

- **The 10mm radius beam pipe needs a deeper mask (standard design: 10mm from the central beam line, new design: 7mm or even 5mm mask)**
- **The 10mm radius beam pipe (even though shorter) intercepts FF quadrupole radiation even with a 5 mm radius mask**
- **For the 45GeV case a 7mm mask is fine (even 10 mm mask is OK?)**
- **For the 120GeV case a 5 mm mask is needed**
- **(SR from the quads is difficult to estimate since it depends on beam tails)**

Beam pipe diameter [mm]	Heat load @45GeV [W/m]	Max Temp. [K] without cooling
30	97	88
20	145	198

- The heat load critically depends on the bunch length – here assumed to be 12mm – non-colliding beams heat more

A. Novokhatski

Work in progress to study trapped modes with an improved beam pipe model

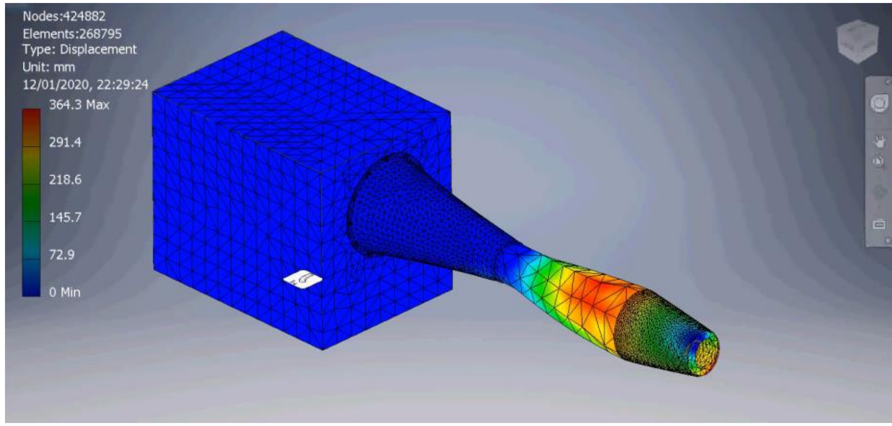
Going to a 10mm radius central beam pipe does not seem to be out of the question!
Work is continuing

Vibration management and feedback

Work only starting

- Here the situation is considerably simpler than (single pass) linear colliders
- The FF quads for the e+ and e- beams sit is close proximity (O(10cm))
- Any coherent motion of the e+ and e- FF quads per side creates the same orbit deviation for both beams (i.e. no effect) up to the revolution frequency of the machine (3000Hz)
- The above is not true for the main arc quadrupoles as the beta functions for a twin quad are not the same for e+ and e-. To be studied
- Any incoherent motion (that will have a much smaller amplitude than coherent motion) needs to be looked at.
- Based on the above, an orbit feedback looking at the beam-beam deflection will probably be sufficient. The response time will be very fast if we apply something similar to the ILC's intra-train feedback, which is below microsecond. A more usual system can handle up to 1/10 of revolution freq., thus 300 Hz, where external vibration is already very small. The beam-beam deflection method has been well established with beam at B-factories and SLC for many years

K. Oide



Example of twist mode in our cantilevered design (F9, 306Hz)

CRAB WAIST SEXTUPLES

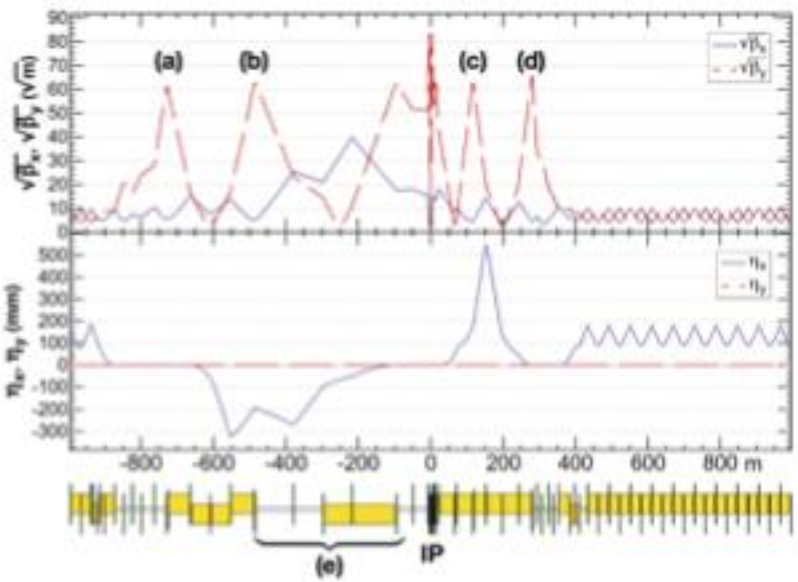
Grab waist sextupoles

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

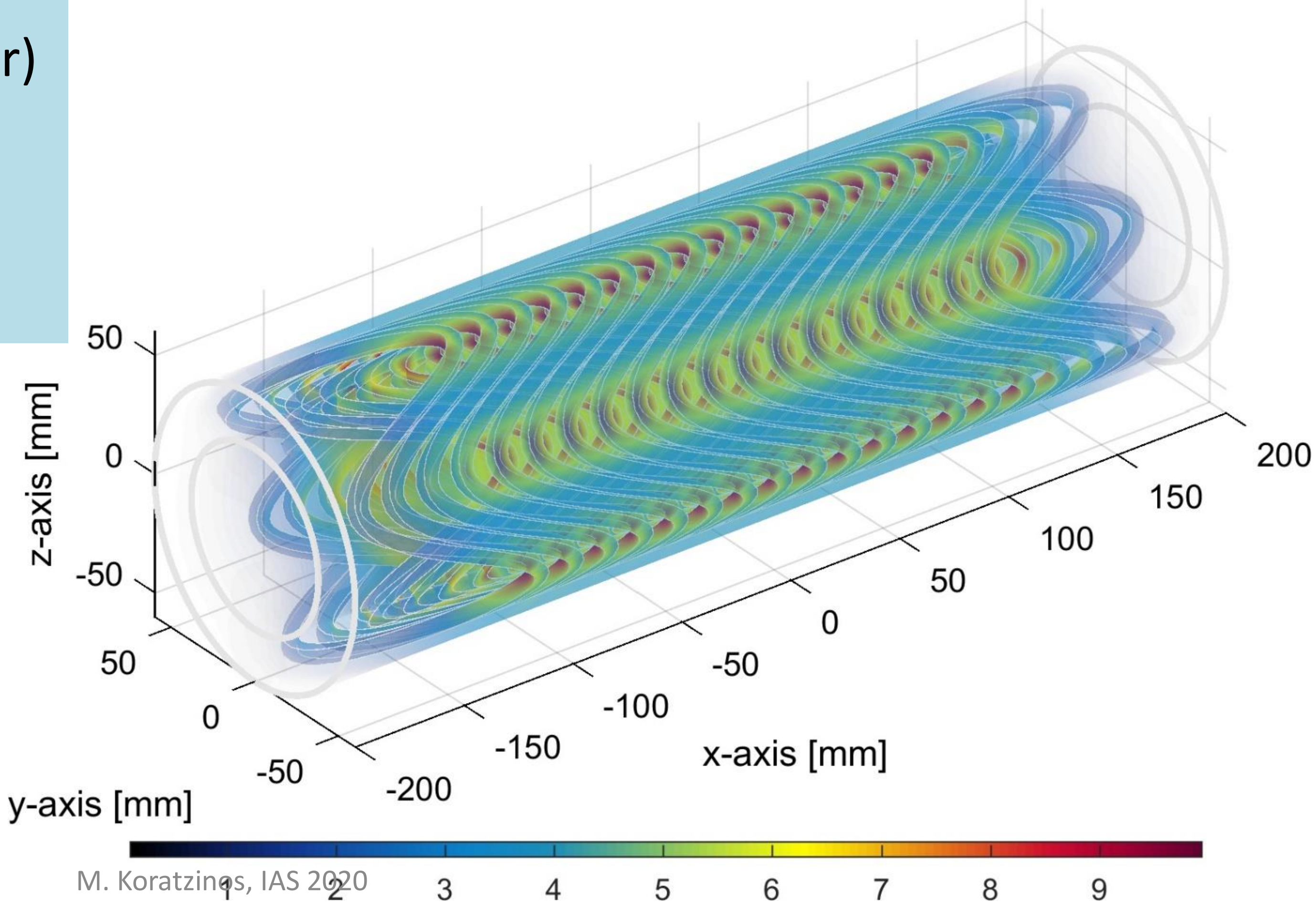
Unique to FCC-ee, is a set of four strong sextupoles in the vicinity of the IP (a, b, c, d below, strength is B'' : 7350 T/m^2)

- 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



Magnetic field on surface of model



Conclusions

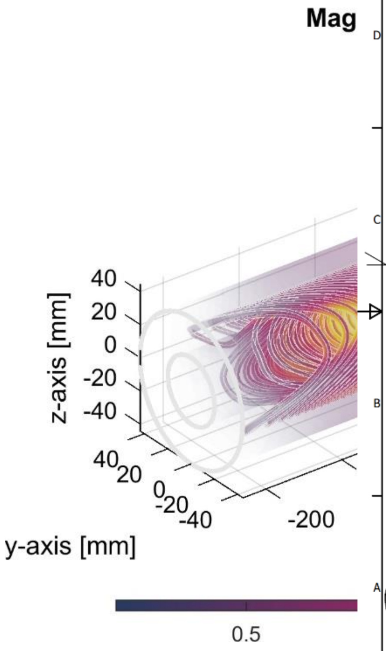
- The IR magnets
  - The compensation scheme is the simplest possible and fulfils all our requirements
  - FF quadrupoles are challenging but CCT design ideally suited for our application
  - FF quadrupole prototype built and awaits testing
- Smaller beam pipe for the area around the vertex detector considered
  - Not out of the question
- Mechanical integration has started
- Backgrounds
  - Complex work, many different codes should work together, well under way, no showstoppers

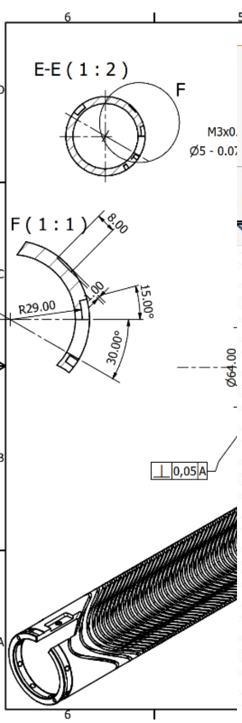
Extra slides

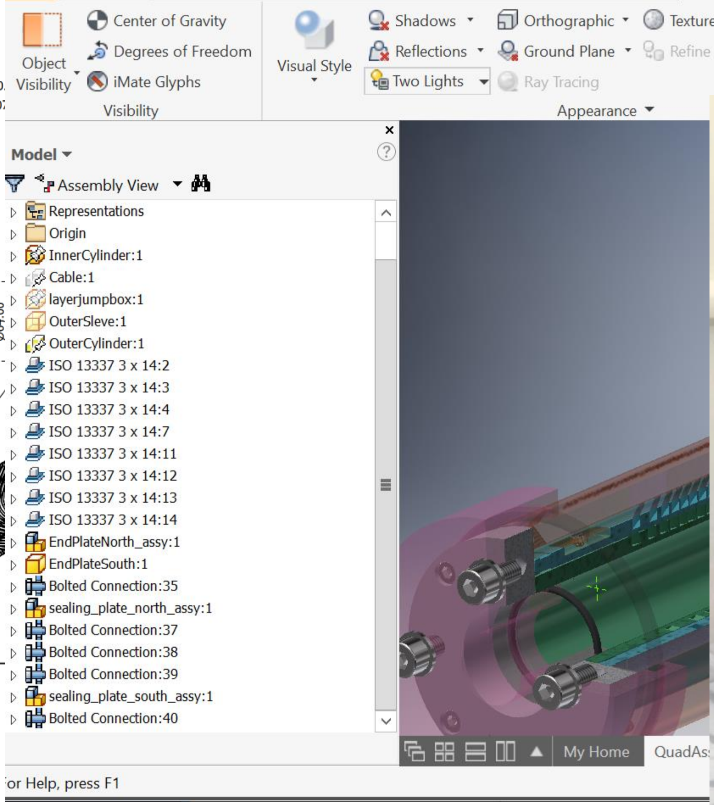
Misalignment analysis

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

The FCC-ee FF quadrupole prototype – magnetic design, mechanical design, manufacturing







Representations
Origin
InnerCylinder:1
Cable:1
layerjumpbox:1
OuterSleve:1
OuterCylinder:1
ISO 13337 3 x 14:2
ISO 13337 3 x 14:3
ISO 13337 3 x 14:4
ISO 13337 3 x 14:7
ISO 13337 3 x 14:11
ISO 13337 3 x 14:12
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

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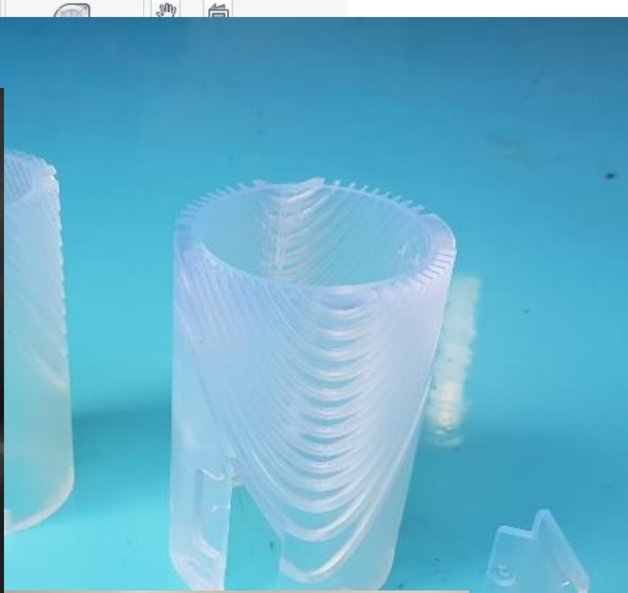

Assembly