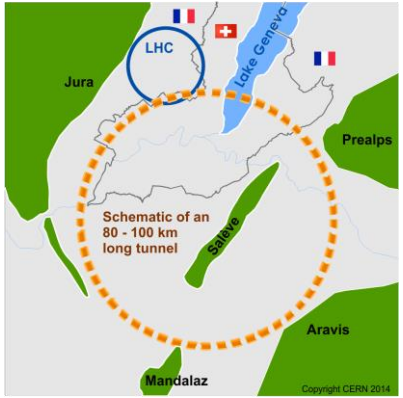


MDI status and overview

M. Boscolo (INFN-LNF)

N. Bacchetta, E. Belli, M. Benedikt, A. Blondel, A. Bogomyagkov, H.Burkhardt, F. Collamati, M. Dam, H. Ten Kate, D. El-Khechen, A. Kolano, P. Janot, R. Kersevan, M. Koratzinos, E. Levichev, M. Lückhof, A. Novokhatski, K. Oide, E. Perez, S. Sinyatkin, M. Sullivan, P. Vobly, G. Voutsinas, J. Wenninger, D.Zhou, F. Zimmermann

Third Annual Meeting of the **F**uture **C**ircular **C**ollider Study

Berlin, 31st May 2017

Introduction: MDI Group

- Our WG was formed officially on January 2016 with
- monthly meetings: http://indico.cern.ch/category/5665/
- MDI WG Mandate:
  - IR design, Synchrotron Radiation and Masking, Other accelerator backgrounds, Magnetic integration, luminosity measurements, …
- FCC-ee accelerator design review last October
  - outcome from the committee: strongly suggest, **before converging to an IR baseline**, to **revisit several important and entangled MDI issues,** such as **beam-pipe dimension and masking, choice of l*, final magnet parameters, trapped mode analysis, space and location of luminosity monitors, magnet integration, overall detector layout, etc..**
  - These MDI issues have been addressed in a **two weeks MDI workshop** last **January** at CERN assembling the main system experts (http://indico.cern.ch/event/596695)

Outline

- IR Optics
- IR layout
- Vacuum chamber design for trapped modes analysis
- Solenoid Compensation scheme
- Luminosity monitor
- Background studies
  - **Synchrotron radiation** -> main issue especially at top energy, beam-gas, ...
  - **IP backgrounds:** Beamstrahlung, radiative Bhabha, pairs, $\gamma\gamma$-> hadrons
- Conclusion and future steps

Specific topics covered by dedicated talks

Optics: main requirements with an impact to MDI

- **Crab waist scheme**
  - ✓ large crossing angle
- **2 IPs**
- **β^*_x / β^*_y = 1m / 2mm (175 GeV)**
  - ✓ 0.15m / 1mm (45.6 GeV)
- **Vertical emittance ≈ pm**
  - ✓ very good solenoid compensation scheme needed
- **Horizontal emittance ≈ 0.2-1.3 nm**
- **Energy acceptance 2% (at top energy)**
  - ✓ for acceptable beamstrahlung lifetime
- **$E_{critical}$ < 100 keV for incoming beam to IP from 500 m**
  - ✓ based on LEP experience
- **As close as possible to the FCC-hh beam line**

MDI design

Different studies performed by the MDI group to determine the best design:

- large crossing angle together with $\varepsilon_y \approx$pm requires good **solenoid compensation scheme and influences L* choice**
- Position, size and optimal coverage of **the luminosity detector** influences the request on L*
- **Synchrotron radiation** heavily influences the design: simulation with different approaches and check its detector sustainability
- Possible **HOM** in the IR being studied with proposed symmetric and asymmetric IR beam pipes.
- **Infrastructure** studies to fit with FCC-hh constraints.

Challenge of the FCC-ee IR

- The FCC-ee collider is a challenging machine, with unprecedented high e^+e^- c.m. energy, luminosity and circumference.
- We have a flexible **IR layout**, **common for all energies**.
- The **crab-waist** collision scheme has been chosen for the IR design.
- **Synchrotron Radiation** needs special care especially at the top energy and also due to the large crossing angle (total 30 mrad). This topic is a **main driver of the IR layout**.
- The large crossing angle with the request of $\varepsilon_y \approx$ **pm** scale requires a dedicated **solenoid compensation scheme**.
- **Luminosity monitor** aims at a precision measurement of $\approx 10^{-4}$ (at the Z energy).
- Luminosity and beam induced **background sources** into the detector are being considered for the different running energies together with masks, shieldings and collimators. Detector modeling follows IR design.

Main Features of the MDI design

- Present baseline **optics** works well for all beam energies.
- **L*=2.2 m** fulfills the requirements.
- **Symmetric beam pipes** in the FF are our baseline option.
- Detector **Lumical** is placed from 1.0 m to 1.2 m from the IP.
- **Compensating solenoid** in present design starts at 1.25 m. The corresponding ε_y blow-up is ≈0.3 pm.
- **Central chamber** is **30 mm diameter** as well as **inside the QC1.**
- The diameter of the beam pipe in **QC2** is larger, **40 mm**.
- **Warm beam pipe, water cooled** .
- **CAD design** of the **IR vacuum chamber** has been used to study **wake fields** in IR.

IR Optics

more details in talk by K. Oide

Baseline optics* established in **2016**

In **2017**:

- **smaller β_x***
- **60°/60° arc cell at Z**

Motivations for these changes:

- to mitigate the coherent beam-beam instability at Z,
- to adopt the Twin Aperture Quadrupole scheme for arc quads,
- to fit the footprint to a new FCC-hh layout

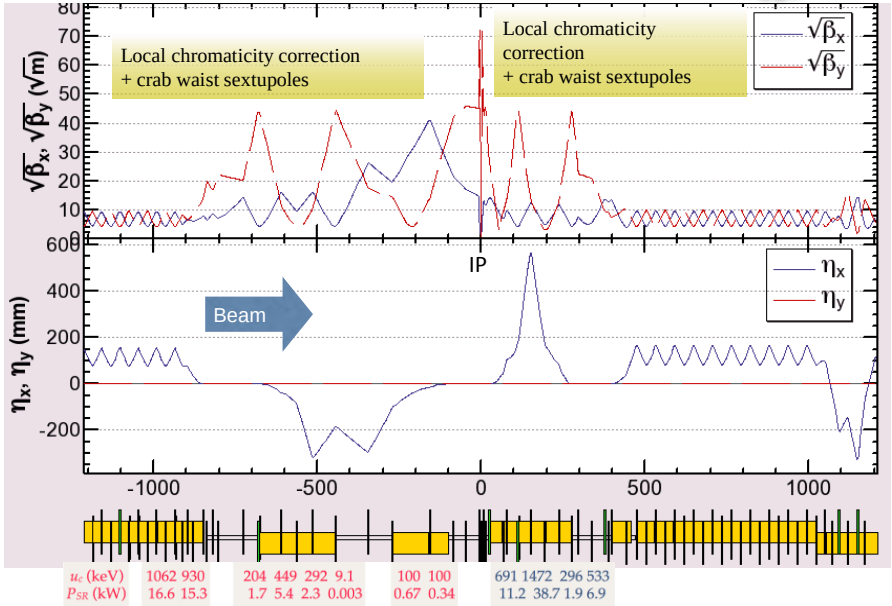
Design		2017		2016	
Circumference	[km]	97.750		99.984	
Arc quadrupole scheme		**twin aperture**		single aperture	
Bend. radius of arc dipole	[km]	10.747		11.190	
Number of IPs / ring		2			
Crossing angle at IP	[mrad]	30			
Solenoid field at IP	[T]	±2			
ℓ^*	[m]	2.2			
Local chrom. correction		y-plane with crab-sext. effect			
RF frequency	[MHz]	400			
Total SR power	[MW]	100			
Beam energy	[GeV]	45.6	175	45.6	175
SR energy loss/turn	[GeV]	0.0360	7.80	0.0346	7.47
Long. damping time	[ms]	414	7.49	440	8.0
Polarization time	[s]	9.2×10^5	1080	9.2×10^5	1080
Current/beam	[mA]	1390	6.4	1450	6.6
Bunches/ring		70760	62	30180(91500)	81
Particles/bunch	[10^{10}]	4.0	21.1	10 (3.3)	17.0
Arc cell		60°/60°	90°/90°	90°/90°	
Mom. compaction α_p	[10^{-6}]	**14.79**	7.31	6.99	
Horizontal tune ν_x		269.14	389.08	387.08	
Vertical tune ν_y		267.22	389.18	387.14	
Arc sext. families		208	292	292	
Horizontal emittance ε_x	[nm]	**0.267**	1.34	0.086	1.26
$\varepsilon_y/\varepsilon_x$ at collision	[%]	0.38	0.2	1.2	0.2
β_x^*	[m]	**0.15**	1	0.5 (1)	1 (0.5)
β_y^*	[mm]	1	2	1 (2)	2 (1)
Energy spread by SR	[%]	0.038	0.144	0.038	0.141
RF Voltage	[MV]	**255**	9500	88	9040
Bunch length by SR	[mm]	2.1	2.4	2.6	2.4
Synchrotron tune ν_z		−0.0413	−0.0684	−0.0163	−0.0657
RF bucket height	[%]	3.8	10.3	2.3	11.6
Luminosity/IP	[10^{34}/cm^{2}s]	**121**	1.32	210 (90)	1.3 (1.5)

* PR-AB 19 (2016) 11, 111005

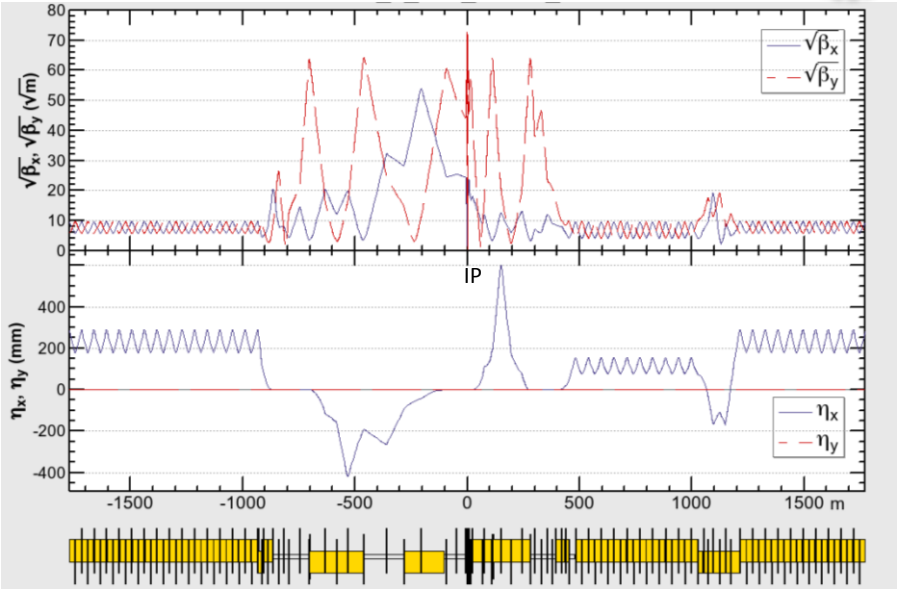
K. Oide

Asymmetric IR optics

90°, $\beta_{x,y}^*$ = (1 m, 2 mm) @*tt*



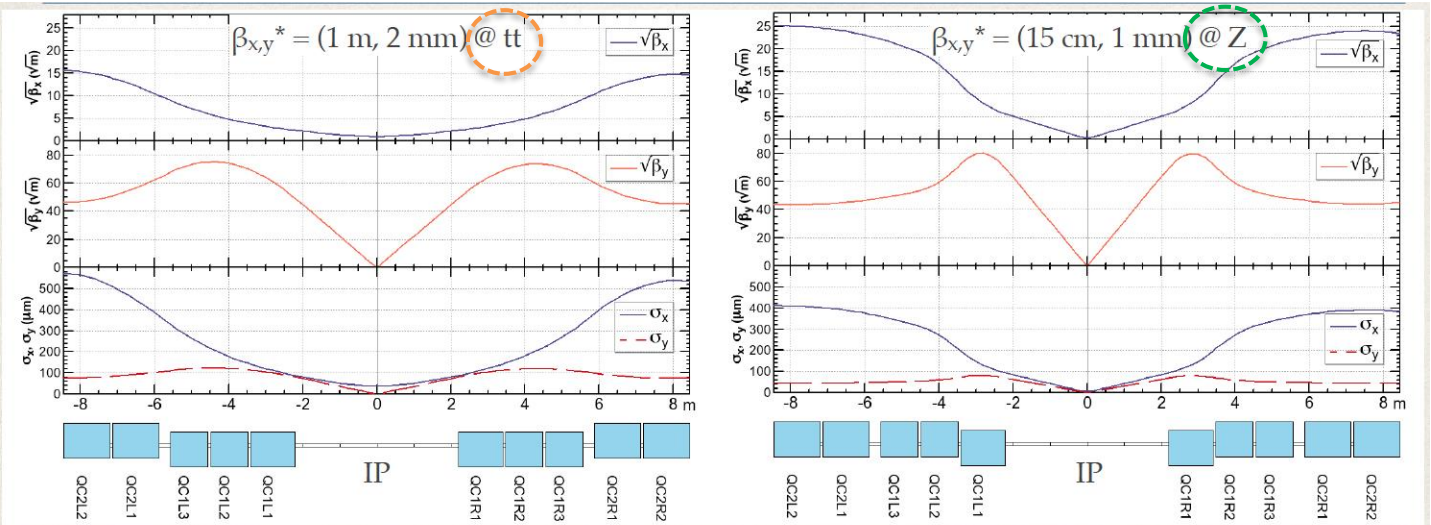
60°, $\beta_{x,y}^*$ = (15 cm, 1 mm) @ *Z*



- **Synchrotron radiation from the upstream last dipoles is limited to 100 keV (E_{cr}) up to 450 m from the IP.**
- Local chromaticity correction sections needed for the energy acceptance requirement of 2%

IR Optics

K. Oide



βx* reduction from 50 cm to 15 cm at Z-energy

- Divide QC1 into three independent pieces, reverse the polarity at Z.

	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

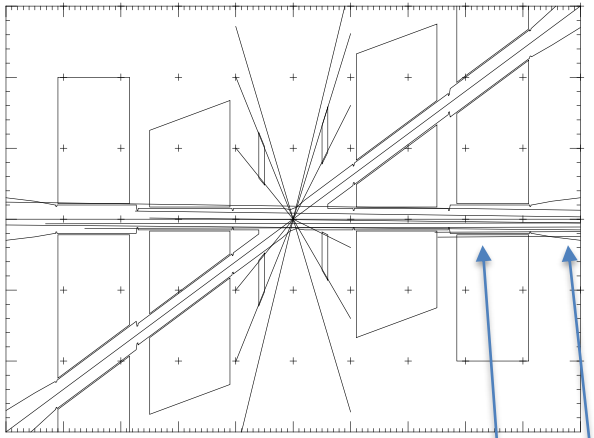
	L (m)	B′ @ tt (T/m)	B′ @ Z (T/m)
QC1R1	1.2	-99.9	-97.2
QC1R2	1	-99.9	+51.2
QC1R3	1	-99.9	+12.0
QC2R1	1.25	+78.6	+7.3
QC2R2	1.25	+76.2	+7.2

more details in talk by M. Sullivan

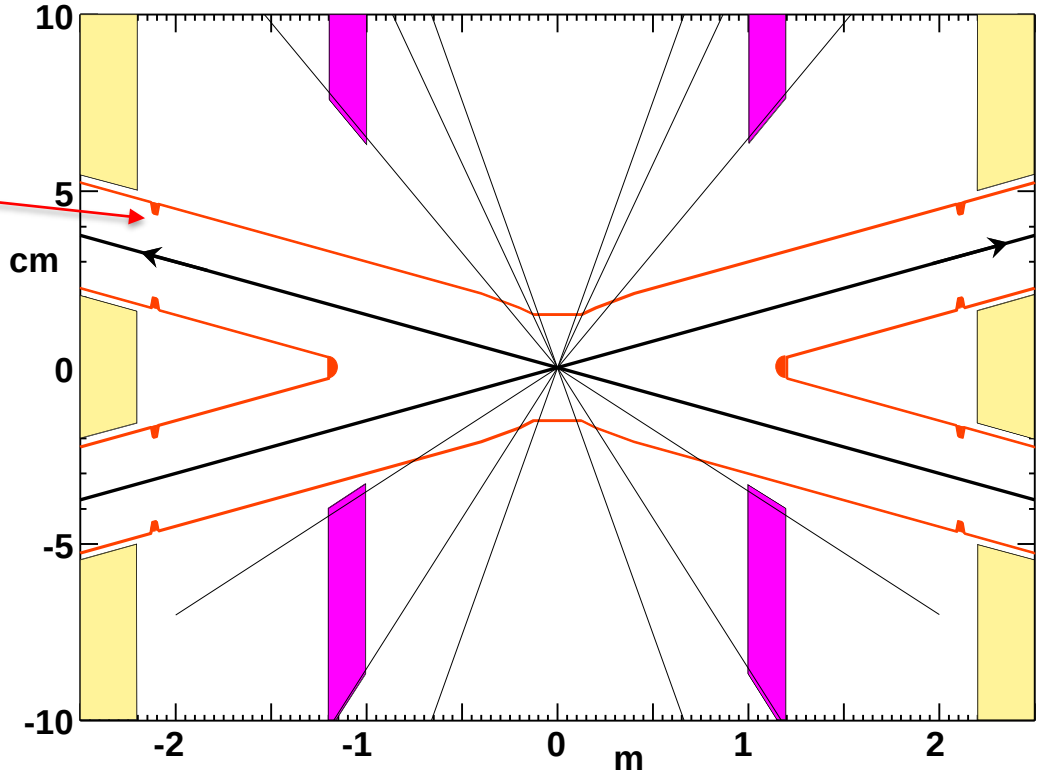
Interaction Region Layout

(diameter physical apertures)

central beam pipe = 30 mm
beam pipe aperture **in QD0** =**30 mm**
beam pipe aperture **masks tip**

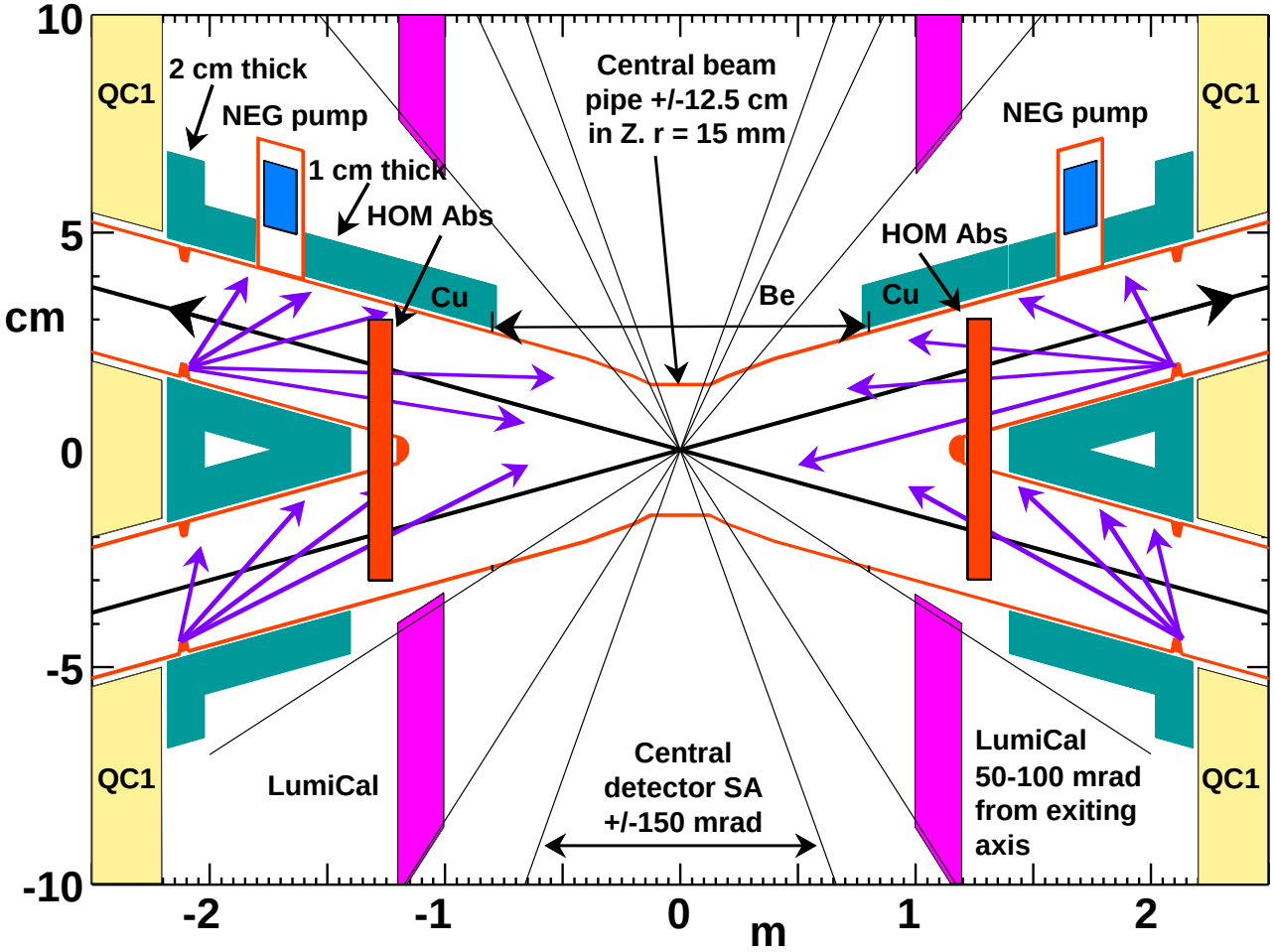


beam pipe aperture **in QF1** = **40 mm**
after QF1 = 60 mm



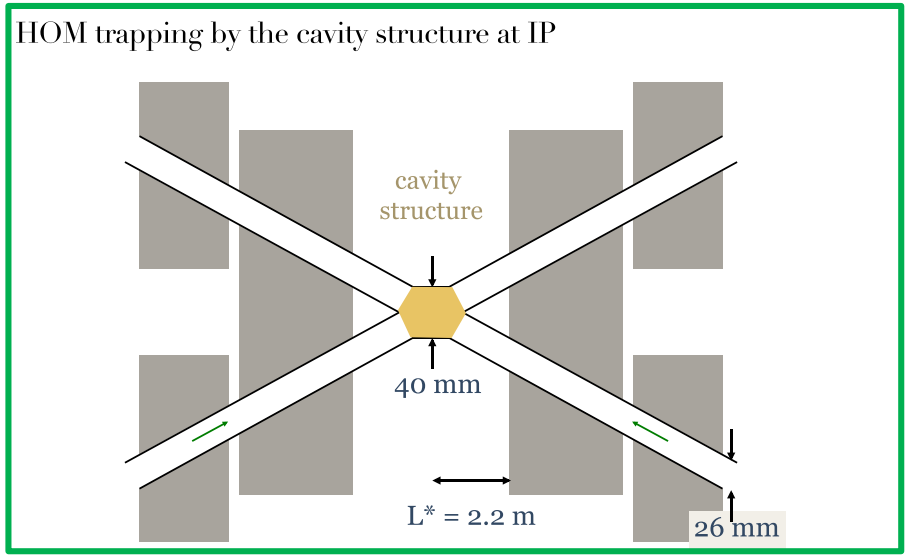
Interaction Region Layout

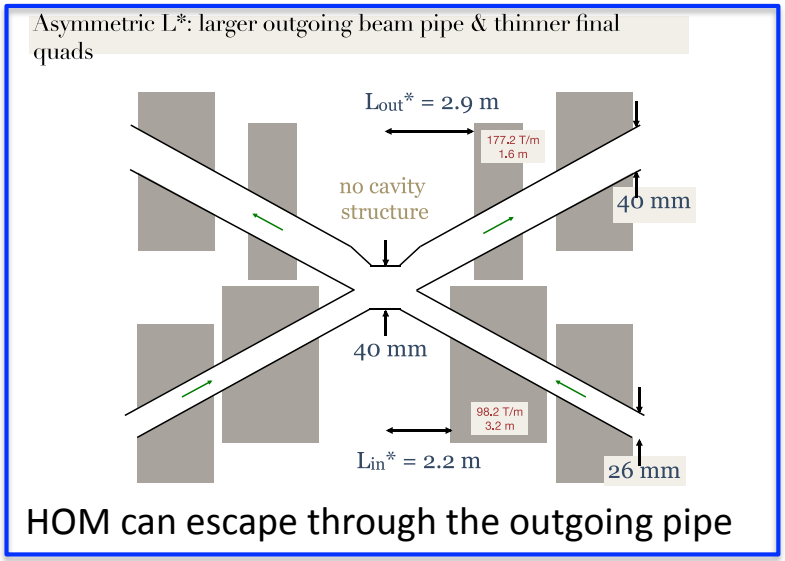
M. Sullivan



Symmetric Final Focus design

- We have **symmetric** final focus design with constant aperture from QD0 through the IP but also **asymmetric** beam pipes in the FF considered





These two possible solutions have been investigated, symmetric case is easier and no showstopper from HOM studies.

IR Beam pipe design for wake field calculations

details in next talk by A. Novokhatski

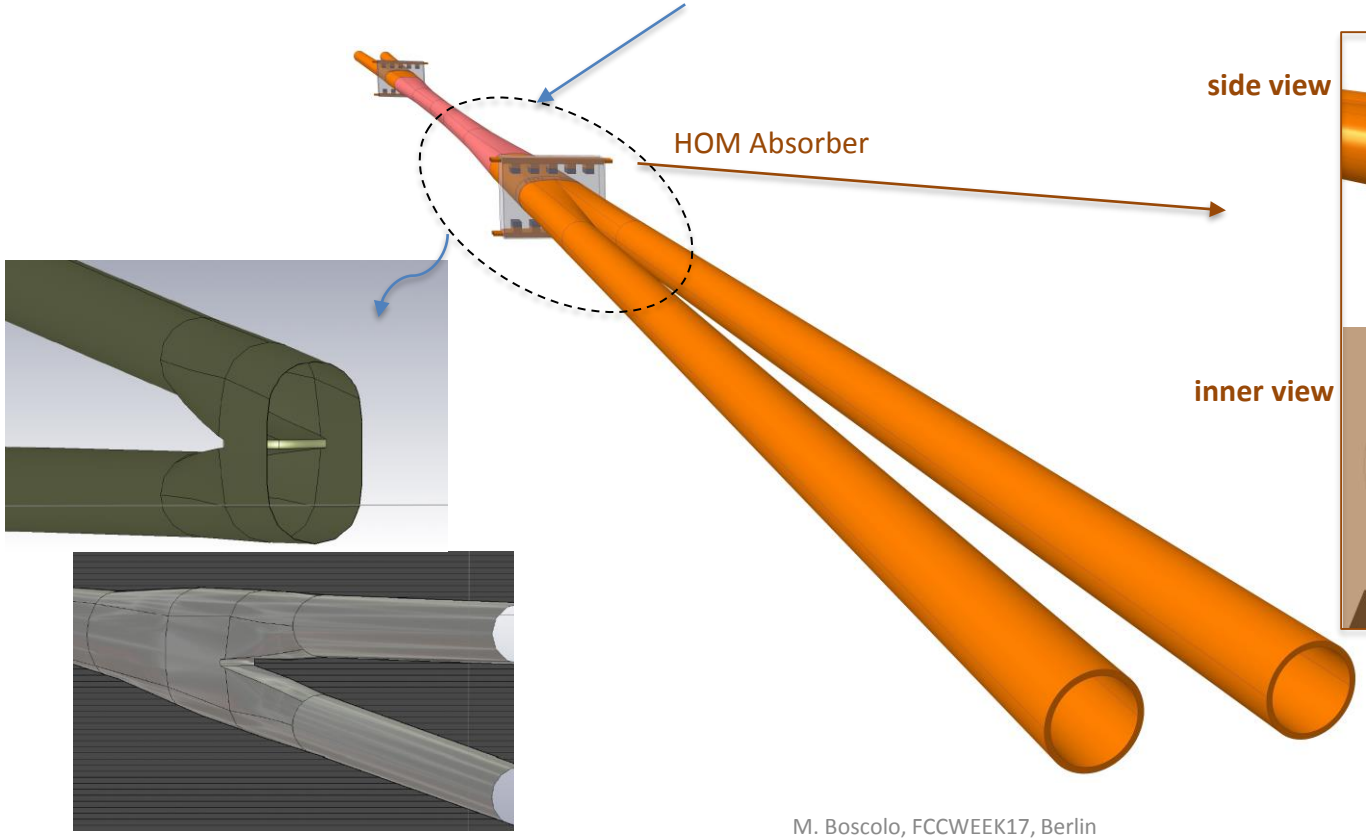
Two beam pipes are merged into one central pipe in the IR

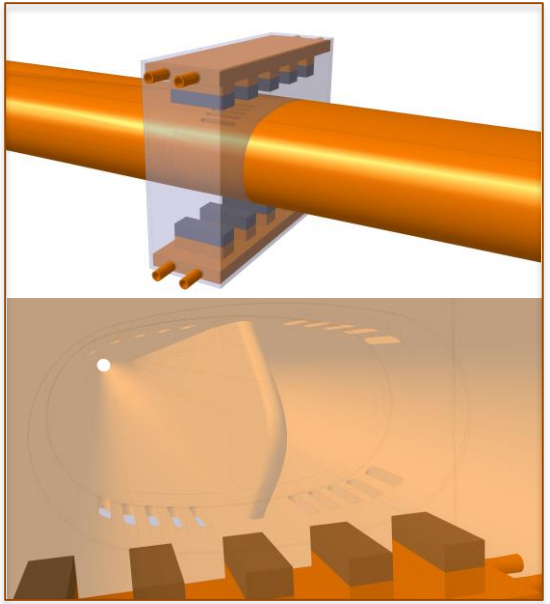
- **Professional CAD design** of the complicated **IR** geometry **done**, essential for
- **CST/HFSS numerical studies** for generated and/or absorbed e.m. fields, propagating or trapped in the IR
- **water cooling of the beam pipe needed** to avoid HOM heating in the IR chamber due to absorption of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

IR CAD design

details in next talk
by A. Novokhatski

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





design by Miguel Gil Costa

Synchrotron Radiation

Synchrotron Radiation is the main constraint for IR design and it drives the IR optics and layout

General requirement for the optics based on LEP experience:

1. Weak bends $E_{critical}$ < 100 keV (LEP2 was 72 keV)
2. Weak bends far from IP (LEP2 was 260 m from IP)
3. Keep Ecr $\lesssim$ 1 MeV in whole ring, to minimize n-production (LEP2 0.72 MeV)

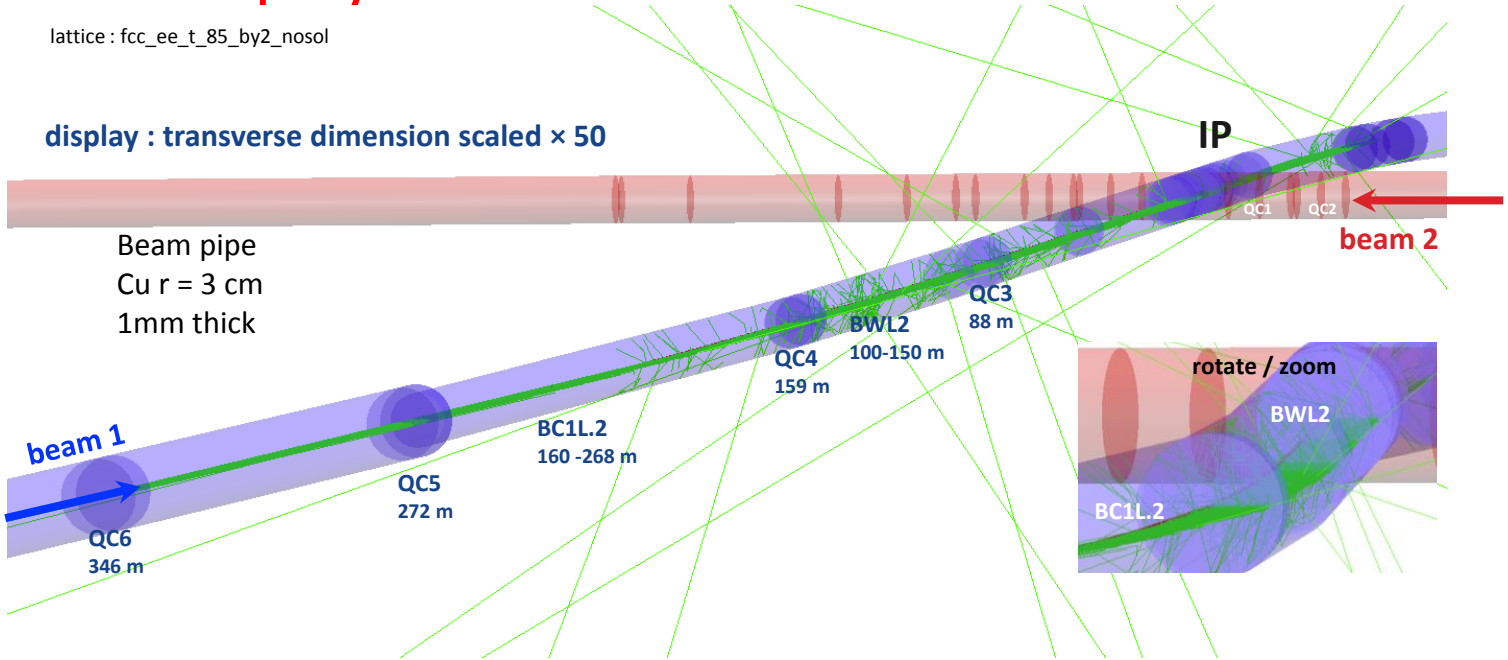
Various lattice options have been studied in detail with different approaches*

- **MDISim** (flexible software toolkit developed by H. Burkhardt et al.)
  - ROOT based machine detector interface toolbox described by MAD-X sequence
  - particle interactions in the IR/detector regions using GEANT4
- SYNC_BKG (modified version by M. Sullivan)
- SYNRAD+ (R. Kersevan)

* studies for FCC WEEK2016: PR-AB 19 (2017) 20, 011008

3d display - SR MDISim - Geant4 simulation

lattice : fcc_ee_t_85_by2_nosol



(Gaussian) beam 1, 5000 e+ 175 GeV

tracked 510 m to IP (just after BC3 to Q2)

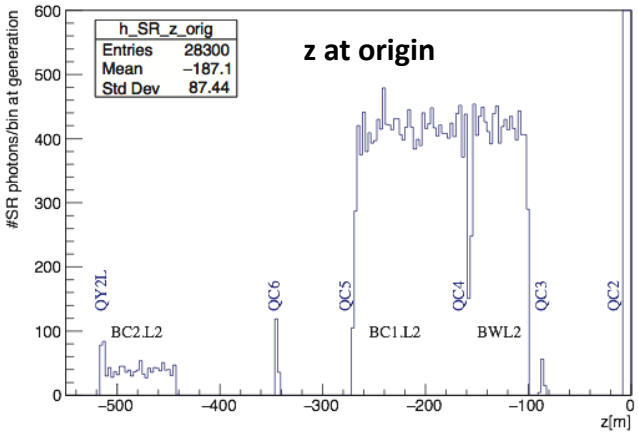
with SR and standard G4 em processes eIoni, eBrem, annihil, phot, compt, conv, Rayl

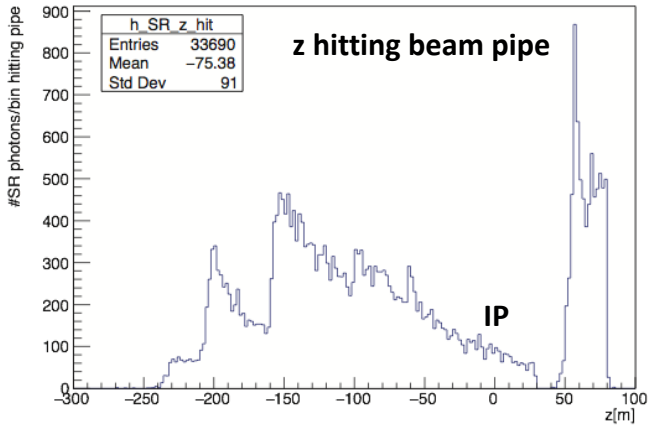
28300 SR γ's generated, first 1000 γ's shown here

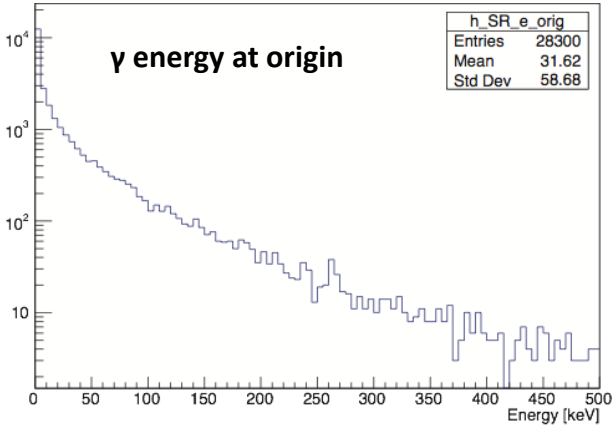
rather fast, < 1 min (MacMini i7)

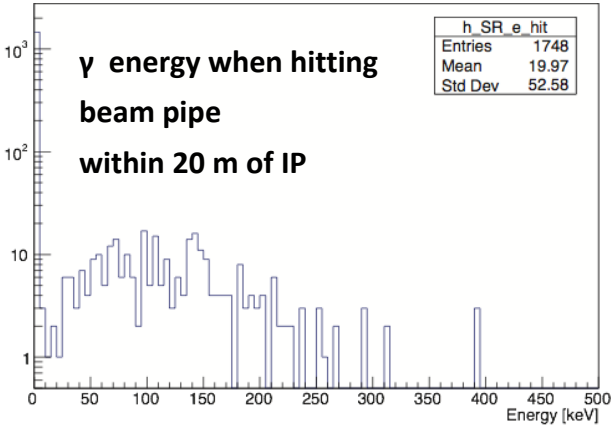
multiply with
2.3e+11/5000 = 4.6e7
to get statistics of 1 bunch
1.3e12 SR γ's

distributions of these photons









MDISim/Geant4 status and next steps

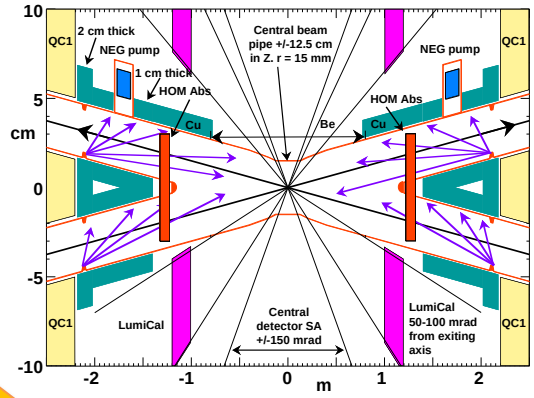
- **Automatic generation of geometry + fields - read by GEANT4**, followed by tracking in Euclidian coordinates works with sufficient precision
  (after improving Geant4 tracking - using new option /control/useDoublePrecision)
- with **SR generation in bends + quads + beam profile generation**
- **Same principle also works for beam gas** (check/improve single scattering model in G4)

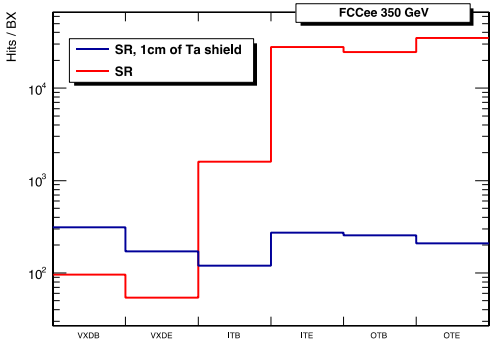
- Insert **collimator downstream** of **last bend** to intercept the incoming SR; optimize position
- **Combine** with **detailed IR geometry + detector simulation**
- **Implement solenoid**, still missing on MAD-X level -- could manually add field map on G4 level

see talk by M. Sullivan

Scatter rate normalization table

Beam energy (GeV)	Soft bend critical energy (keV)	Incident photon rate/xing (>1 keV)	Generated photons	Ratio Inc/Gen	Generated scattered photons	Actual scatter rate/xing
175	100	1.57×10^{9}	2×10^{8}	7.95	670120	5.3×10^{6}
125	35.0	1.87×10^{8}	2×10^{9}	0.094	868218	8.1×10^{4}
80	9.56	2.79×10^{7}	2×10^{10}	1.4×10^{-3}	799455	1119
45.6	1.77	2.26×10^{7}	5×10^{10}	4.5×10^{-4}	73685	33.3





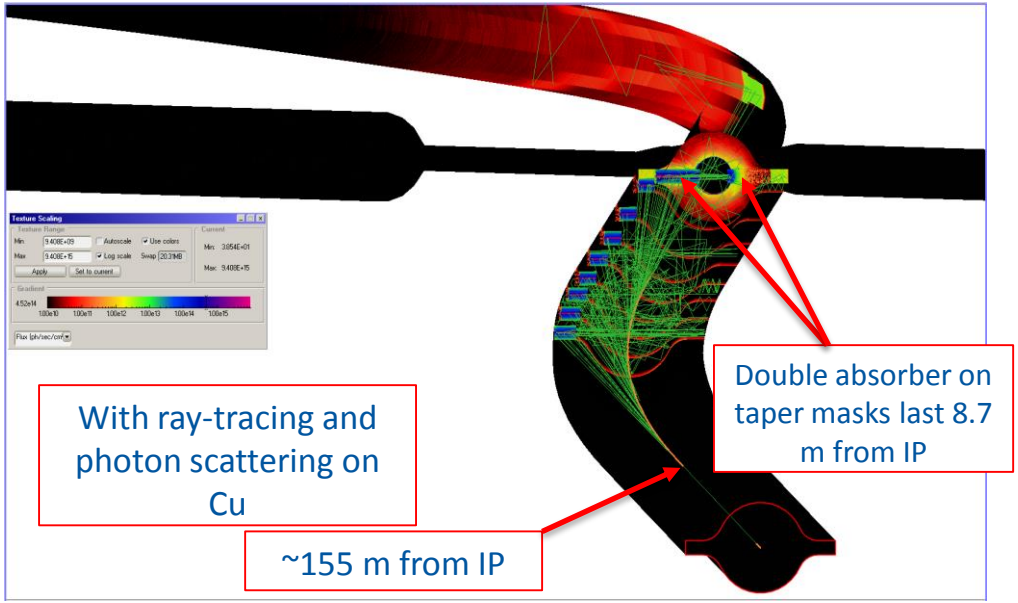
Proper shielding could substantially suppress the effect on detector

First results of full simulation study of the last bend photons scattered from the tip of the mask

SYNRAD+ studies in the IR and proposal of absorbers

see talk by R. Kersevan

SYRAD+ simulation studies indicate as a good solution to place lumped absorbers through the Cu vacuum chamber preventing SR to reach the IR and double absorbers before the IR



Solenoid Compensation Scheme

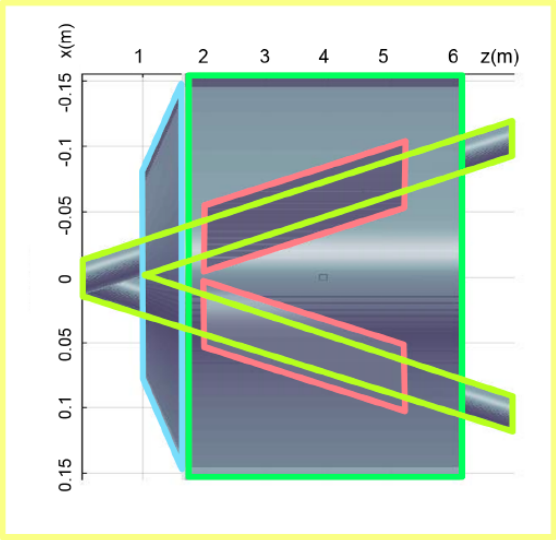
Constraints:

- **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.

see talk by E. Levichev

Solenoid Compensation Scheme



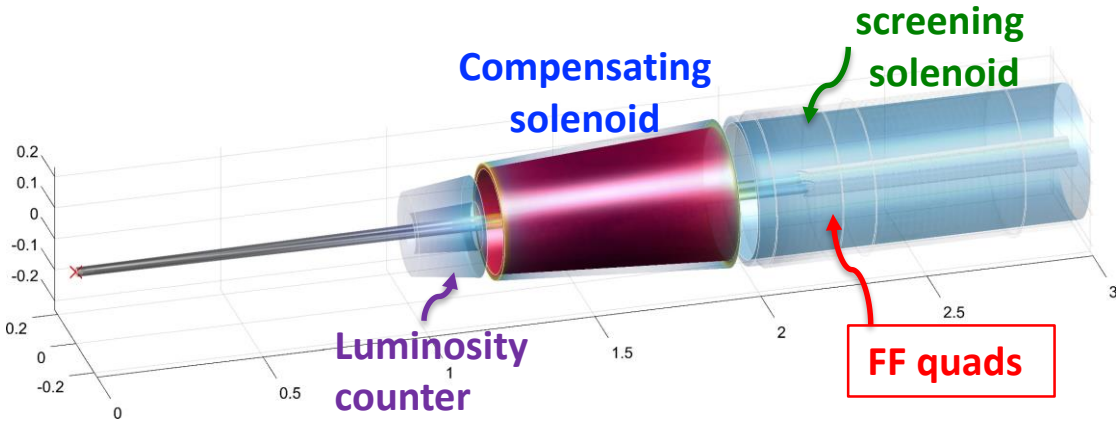
Final focus quads

Compensating solenoid

screening solenoid

Main detector solenoid field

Beam pipes



M. Koratzinos

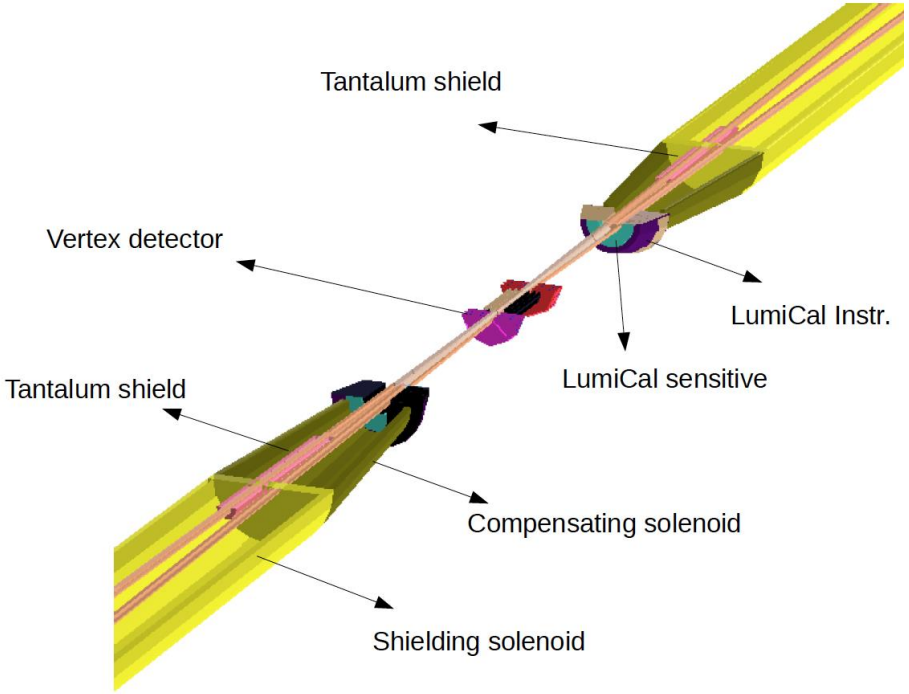
Two solenoids are introduced in the IR:

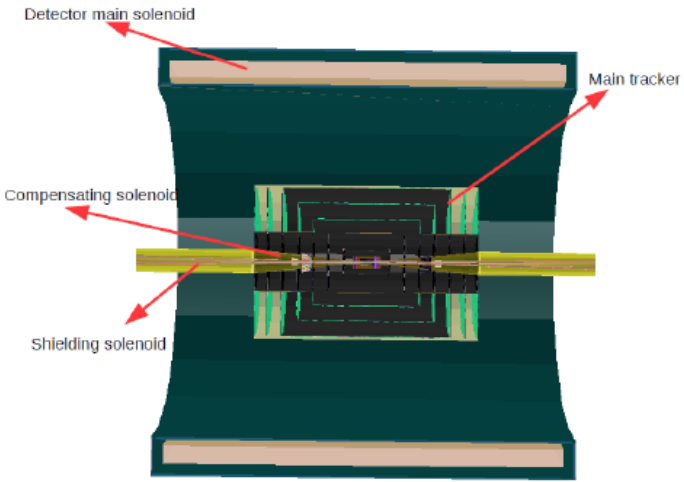
- **screening solenoid** that shields the detector field inside the quads (in the quad net solenoidal field=0)
- **compensating solenoid** in front of the first quad, as close as possible, to reduce the ε_y blow-up (integral BL~0)

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

see talk by G. Voutsinas

Geant4 detector modeling





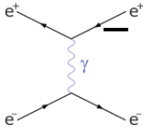
modified CLIC detector model with B=2T and FCC-ee IR design

see talk by G. Voutsinas

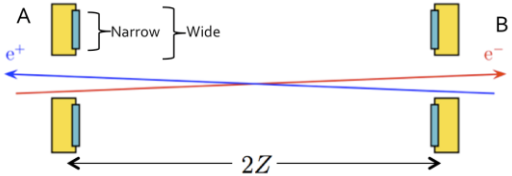
Detector Luminosity Monitor

Luminosity monitoring:

- **Absolute** – target precision **10^{-4}**
- **Relative** for Z lineshape measurement – need a relative precision of **$2\text{-}5 \times 10^{-5}$**
  - 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
  - Measured with set of two calorimeters; one at each side of the IP

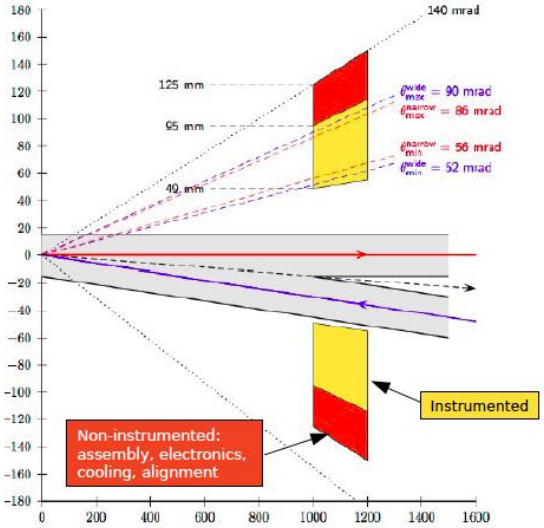


Two counting rates:
- SideA = NarrowA + WideB
- SideB = NarrowB + WideA

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

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

LumiCal Geometry



Cross section: σ = 23 nb
Geometric precision needed for absolute normalization to 10^{-4}

- δz = 50 μm
- δr_{min} = 1.6 μm
- δr_{max} = 5.8 μm

see talk by G. Voutsinas

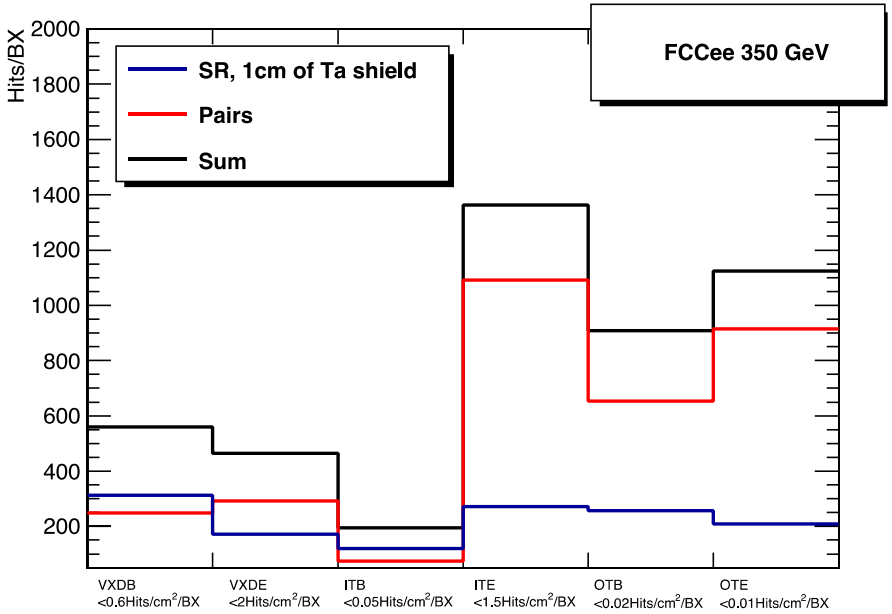
Challenges for LumiCal

- **Readout electronics**
  - Few ns beam crossing time:
    - To maintain backgrounds (off-momentum particles, etc) at a tolerable level, need **very fast readout** (one or few crossings)
  - Continous beam:
    - No power pulsing possible: heat dissipation, how to maintain mechanical stability
- **Control of geometry to few µm**
  - For increased acceptance in tight geometry suggest **conical layout** of monitors
    - Need detailed plan for mechanical assembly
  - Heat dissipation:
    - Need detailed plan for cooling
- **High integrated rate particularly ar low radii**
  - Possible need for radiation tolerant sensors and electronics

FCC-ee group (Copenhagen) invited to join ILC FCAL Collaboration for discussion of forward instrumentation issues

see talk by G. Voutsinas

SR and pairs background



Maximum hit density in the hottest are of each subdetector per bunch crossing

Conclusion and Future Steps

- **MDI for the FCC-ee is particularly challenging.**
- **Lots of progress since last October review, thanks to the combined effort of many people**
- **More is planned and remains to be done.**

- **IR Layout**
- Defined **beam pipe material, apertures, thickness**, shieldings
- **Synchrotron Radiation** in the IR evaluated at all beam energies, together with proper shielding, collimators and/or absorbers
- **G4 detector model** implemented to check backgrounds sustainability
- **Luminosity monitor feasible** design and position in IR defined
- **Solenoid compensation scheme** updated following baseline optics as discussed in January

Conclusion and Future Steps

- **Wake fields** calculations in IR in progress, also different chamber geometries under investigation
- **HOM absorber** in the central chamber needs further optimization
- **Vacuum Chamber heating** estimate and **water cooling** system
- Optimization of **SR masks, shielding, collimators, absorbers** also with full simulation
- **Solenoid Field maps** for more realistic studies (like SR from fringe solenoid fields, ..)
- Study of other **IR backgrounds** (off-momentum beam particles, beam-gas, radiative bhabha, complete $\gamma\gamma$-> hadrons)
- Full **G4 detector simulation** combined with the detailed IR geometry
- **QD0 design**: different proposals and design in progress
- **Injection backgrounds**
- Electron Cloud studies in the IR in progress, SEY<1.1 needed to avoid build-up
- More work will be needed for a more realistic and engineered design of the IR

Back-up

see talk by G. Voutsinas

Summary of LumiCal Geometry

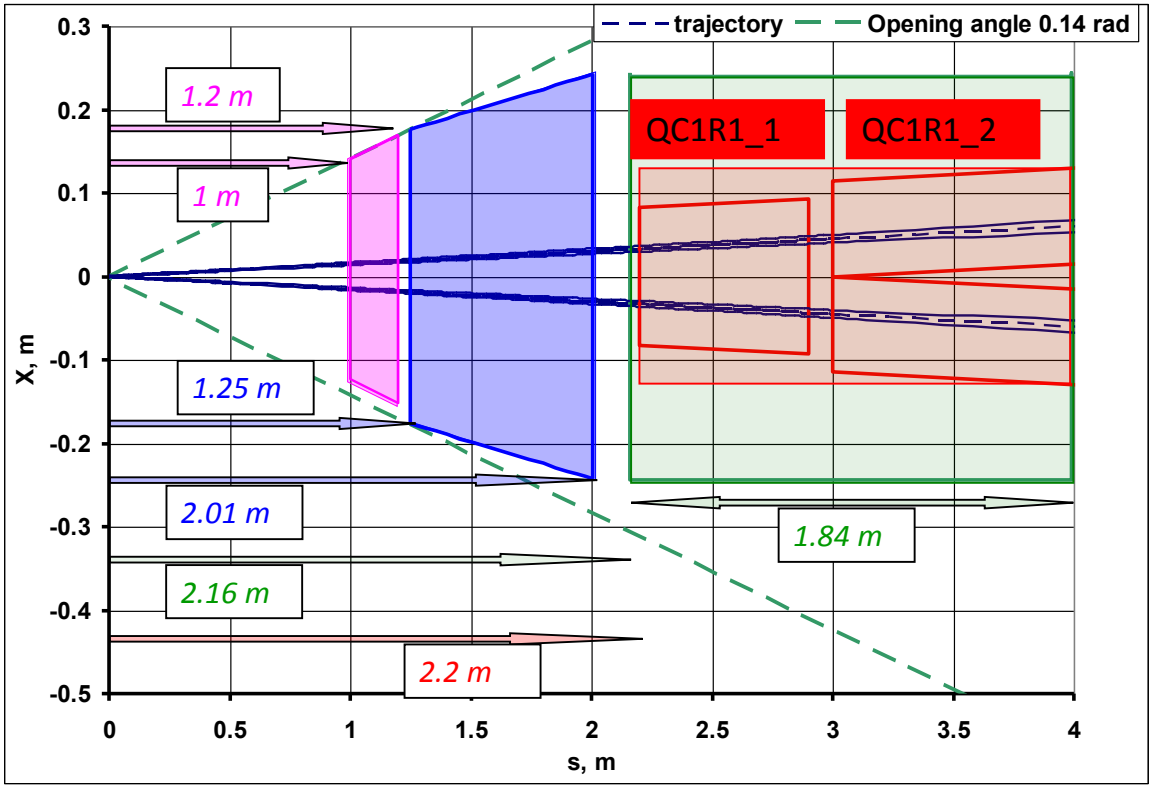
- Z position of calorimeter face: z_{face} = **1000 mm**
- Effective minimum scattering angle: θ_{min} = **55 mrad**
- Effective maximum scattering angle: θ_{max} = **115 mrad**
- Bhabha cross section: **30 nb**

Geometrical precision needed for $\delta L/L = 10^{-4}$:

- Distance between face of two calorimeters: $2\delta z_{face}$ = **100 µm**
- Inner radius of acceptance: δr_{min} = **2 µm**
- Outer radius of acceptance: δr_{max} = **18 µm**

Final Focus Magnets Layout

see talk by E. Levichev



Luminometer

Compensating Solenoid

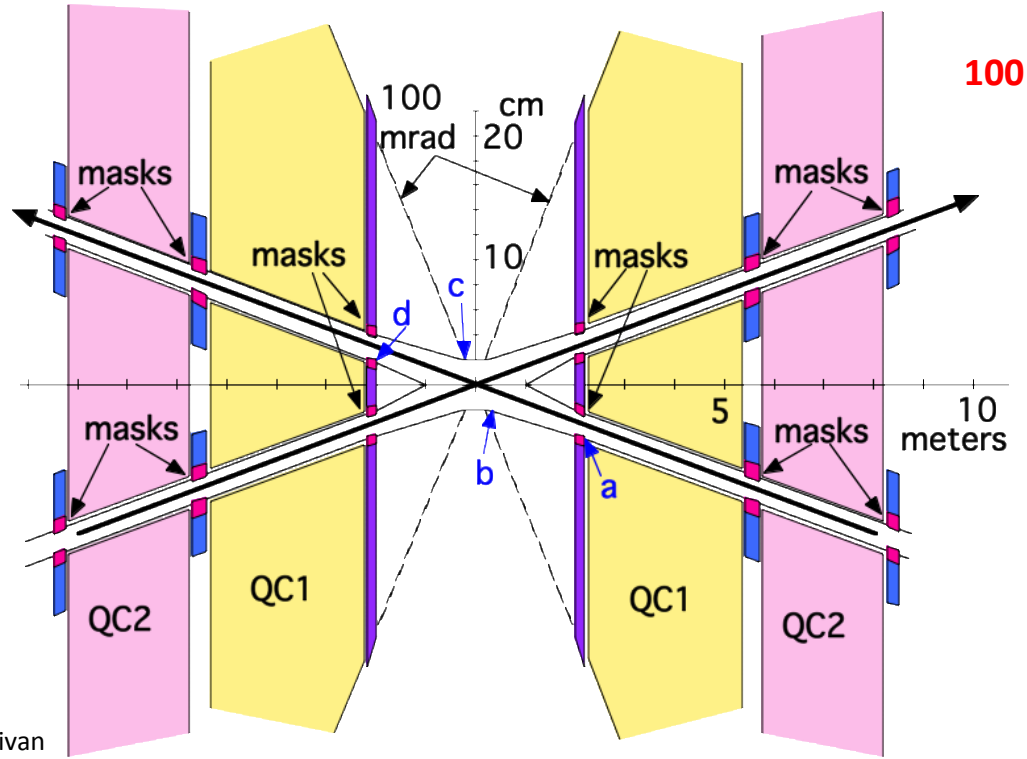
Screening Solenoid

Defocusing Quads

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

Before Jan. workshop: IR Layout with L*=2.2 m



M. Sullivan

beam pipe circular aperture in quads =24 mm (diameter)
beam pipe circular aperture masks =20 mm (diameter)

Before Jan. workshop: Zoom of IR Layout