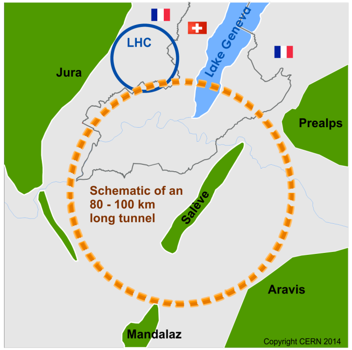
Machine Detector Interface for the e^+e^- Future Circular Collider

M. Boscolo (LNF-INFN)

for the FCC-ee MDI Group



Outline

- FCC-ee
- 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

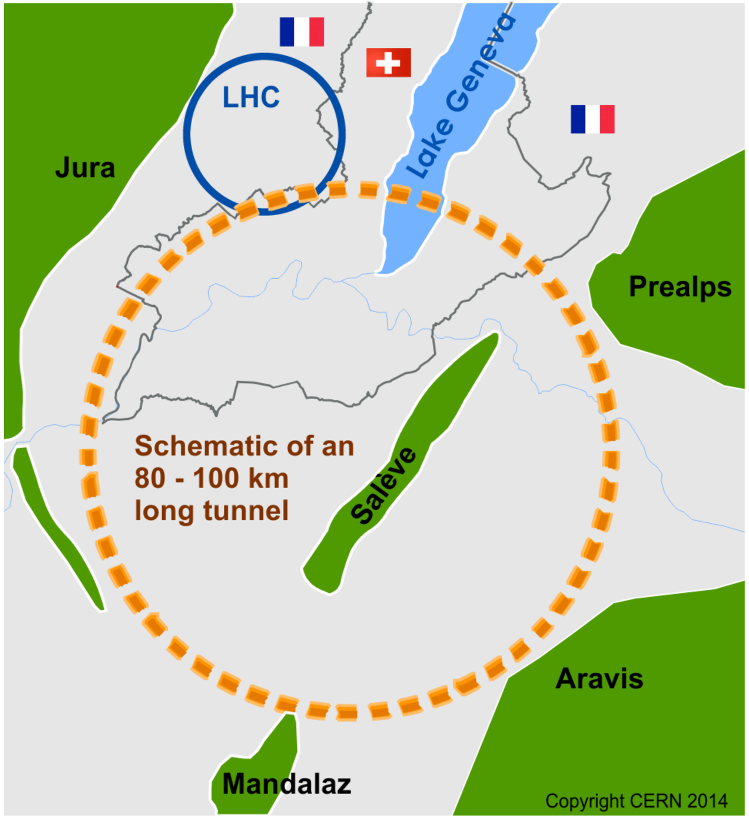
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2018)

International FCC collaboration (CERN as host lab) to study:

- ***pp-collider (FCC-hh)***
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

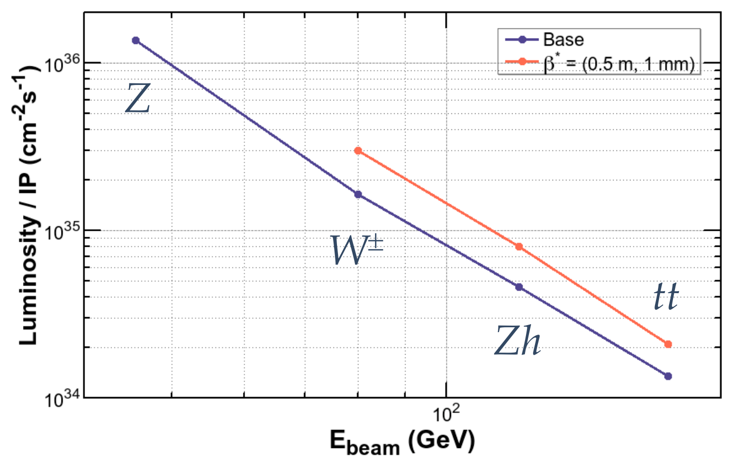
- **80-100 km infrastructure in Geneva area**
- ***e^+e^- collider (FCC-ee) as potential intermediate step / as a possible first step***
- *p-e (FCC-he) option, HE-LHC …*



Parameters 2017 (Preliminary)

Design		2017			
Circumference	[km]	97.750			
Arc quadrupole scheme		**twin aperture**			
Bend. rad. of arc dipoles	[km]	10.747			
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	80	120	175
SR energy loss/turn	[GeV]	0.036	0.34	1.72	7.80
Long. damping time	[ms]	414	76.8	22.9	7.49
Current/beam	[mA]	1390	147	29.0	6.4
Bunches/ring		70760	7280 (4540)	826 (614)	64 (50)
Particles/bunch	[10^{10}]	4.0	4.1 (6.6)	7.1 (9.6)	20.4 (26.0)
Arc cell		60°/60°	90°/90°		
Mom. compaction α_p	[10^{-6}]	**14.79**	7.31		
β-tron tunes ν_x / ν_y		269.14 /267.22	389.08 / 389.18		
Arc sext. families		208	292		
★ Horizontal emittance ε_x	[nm]	**0.267**	0.28	0.63	1.34
★ $\varepsilon_y/\varepsilon_x$ at collision	[%]	0.38	0.36	0.2	0.2
★ β_x^* / β_y^*	[m / mm]	**0.15 / 1**	1 / 2 (0.5 / 1)		
Energy spread by SR	[%]	0.038	0.066	0.099	0.147
Energy spread SR+BS	[%]	0.073	0.072 (0.091)	0.106 (0.122)	0.193 (0.212)
Hor. beam-beam ξ_x		0.008	0.080 (0.046)	0.081 (0.053)	0.082 (0.049)
Ver. beam-beam ξ_y		0.106	0.141 (0.141)	0.140 (0.140)	0.140 (0.138)
RF Voltage	[MV]	**255**	696	2620	9500
Bunch length by SR	[mm]	2.1	2.1	2.0	2.4
Bunch length SR+BS	[mm]	4.1	2.3 (2.9)	2.2 (2.5)	2.9 (3.5)
Synchrotron tune ν_z		−0.0413	−0.0340	−0.0499	−0.0684
RF bucket height	[%]	3.8	3.7	2.2	10.3
Luminosity/IP	[10^{34}/cm^{2}s]	**137**	16.4 (30.0)	4.6 (8.0)	1.35 (2.09)

★ parameters mostly MDI/IR related



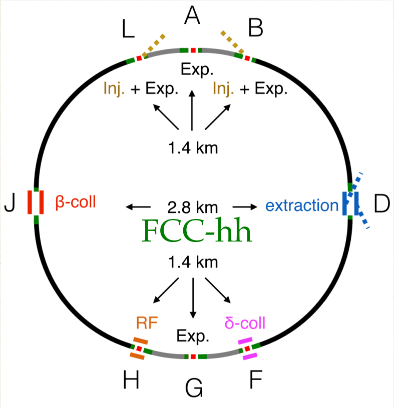
- The numbers in () correspond to "high-lumi" option.
- The luminosities are geometrical ones, no dynamics involved.

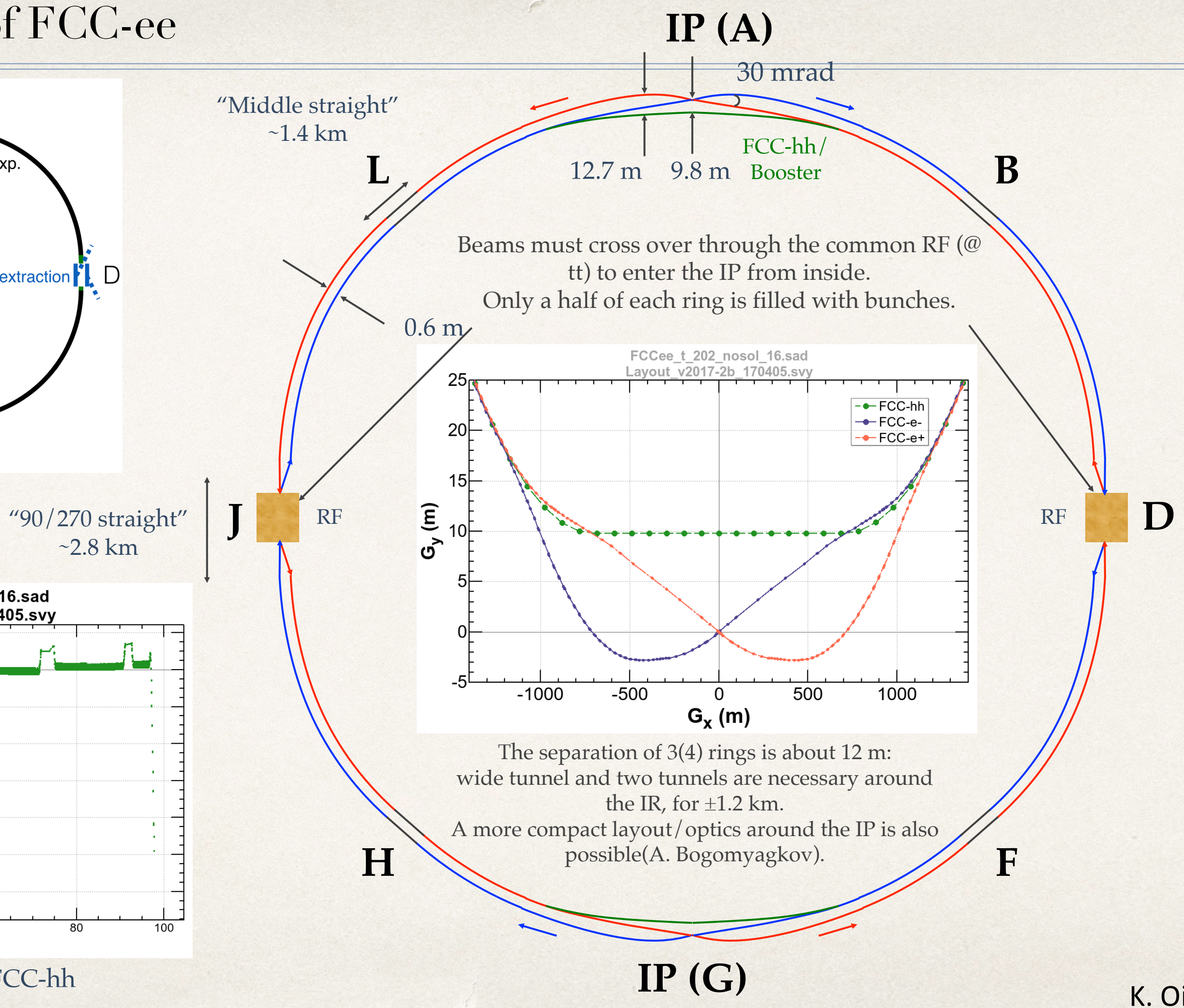
K. Oide, FCC WEEK17

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 absolute measurement of $\approx 10^{-4}$ (at the Z).
- Luminosity and beam induced **background sources** into the detector are being considered for the different running energies together with masks, shieldings and collimators. G-4 detector modeling follows IR design.

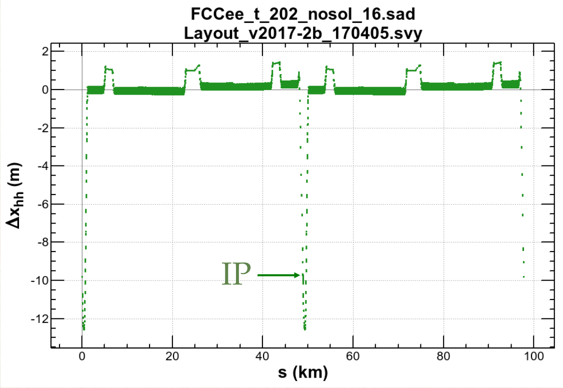
Layout of FCC-ee





Beams must cross over through the common RF (@ tt) to enter the IP from inside.
Only a half of each ring is filled with bunches.

The separation of 3(4) rings is about 12 m: wide tunnel and two tunnels are necessary around the IR, for ±1.2 km.
A more compact layout/optics around the IP is also possible(A. Bogomyagkov).

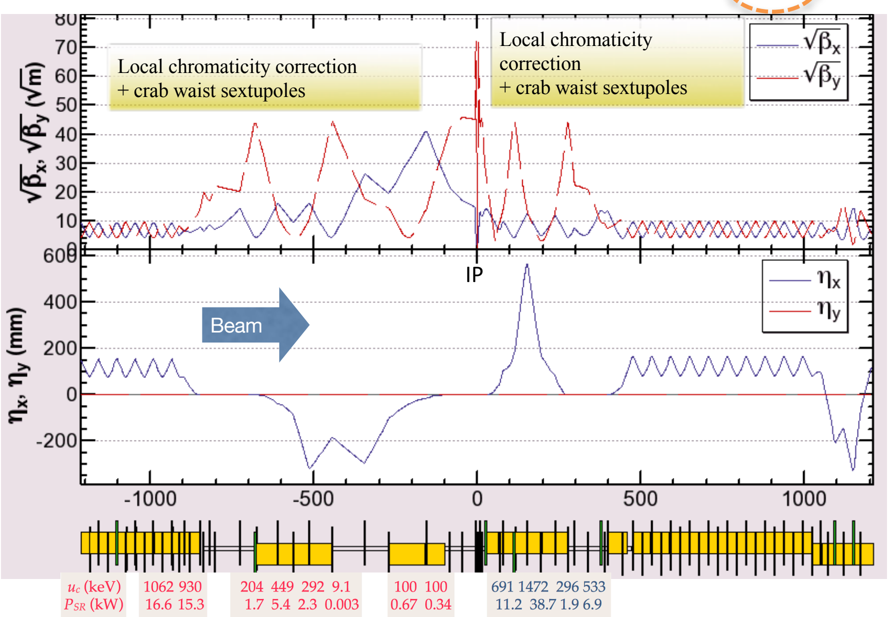


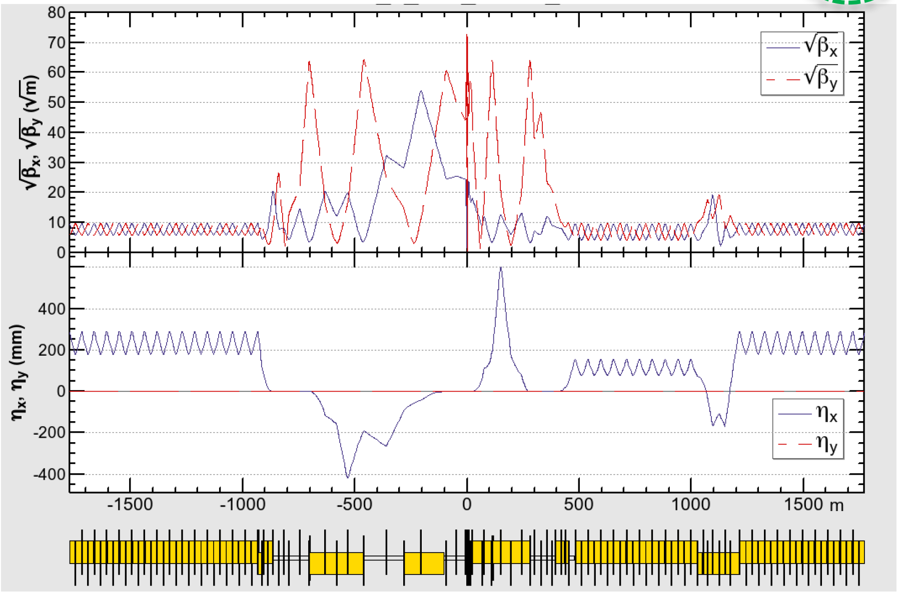
Relative distance to FCC-hh

Asymmetric IR optics

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

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

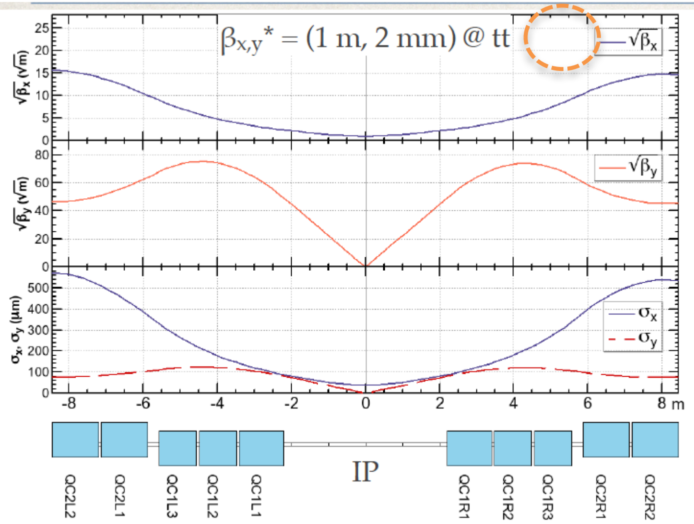


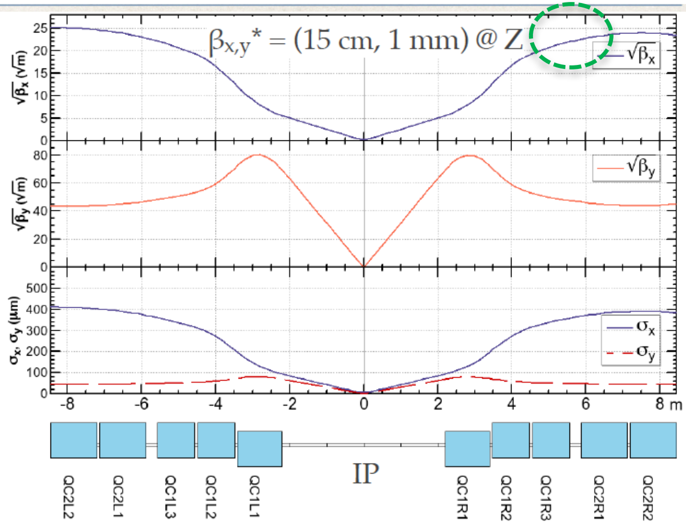


- **Synchrotron radiation from the upstream last dipoles is limited to 100 keV (E_{cr}) up to 450 m from the IP**
- Local chromaticity correction sections needed for the energy acceptance requirement of 2%

K. Oide

IR Optics





- 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

βx^* reduction from 50 cm to 15 cm at Z

(motivation: to mitigate the coherent beam-beam instability at Z)

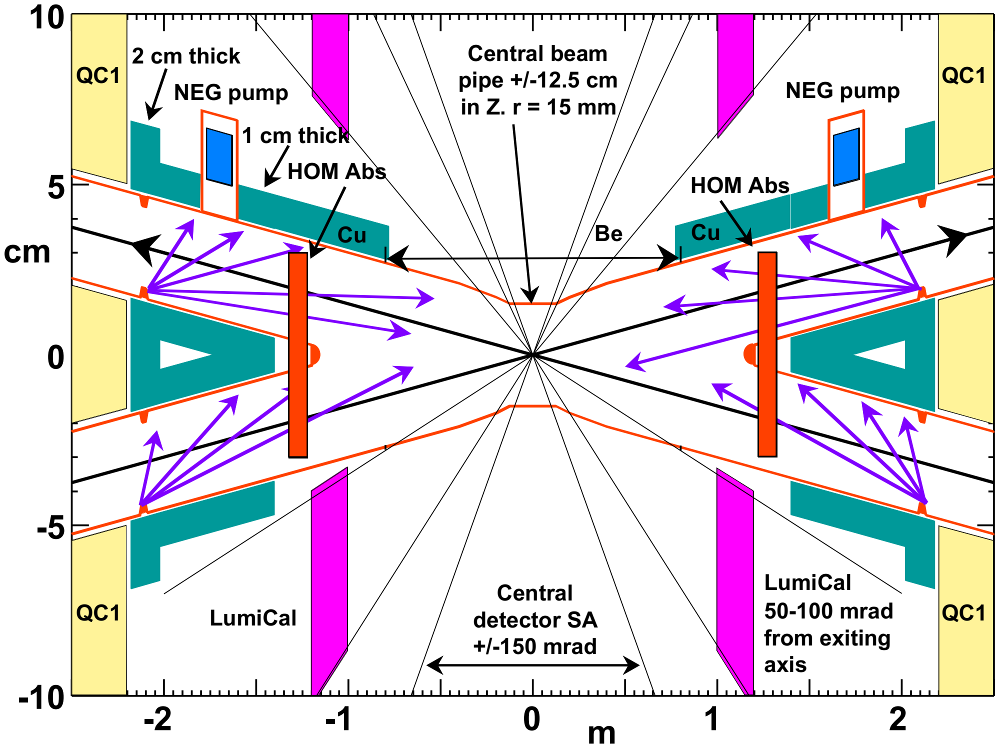
K. Oide

Some details on the Main Features of the **FCC-ee MDI** design

- Present baseline **optics** works well for all beam energies, **L*=2.2 m** fulfills the requirements.
- **Symmetric beam pipes** in the FF.
- Detector **Lumical** from 1.0 m to 1.2 m from the IP.
- **Compensating solenoid** in present design starts at 1.25 m.
- **Warm beam pipe, water cooled** .

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

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

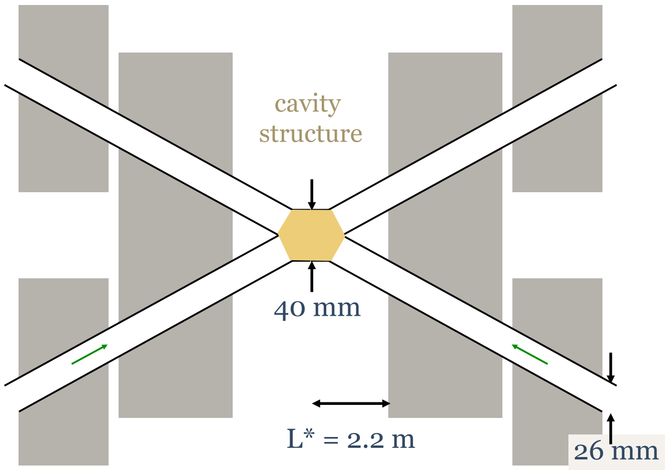


M. Sullivan

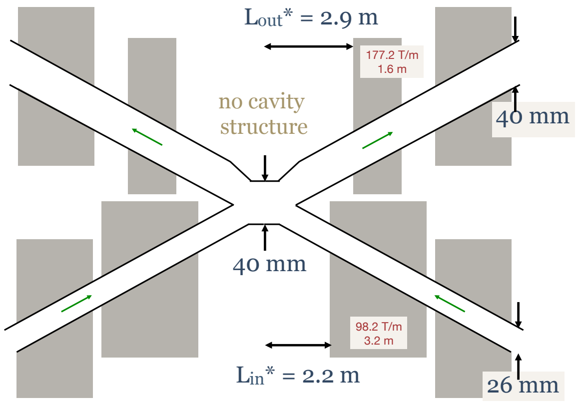
Symmetric Final Focus design

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

HOM trapping by the cavity structure at IP



Asymmetric L*: larger outgoing beam pipe & thinner final quads



HOM can escape through the outgoing pipe

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

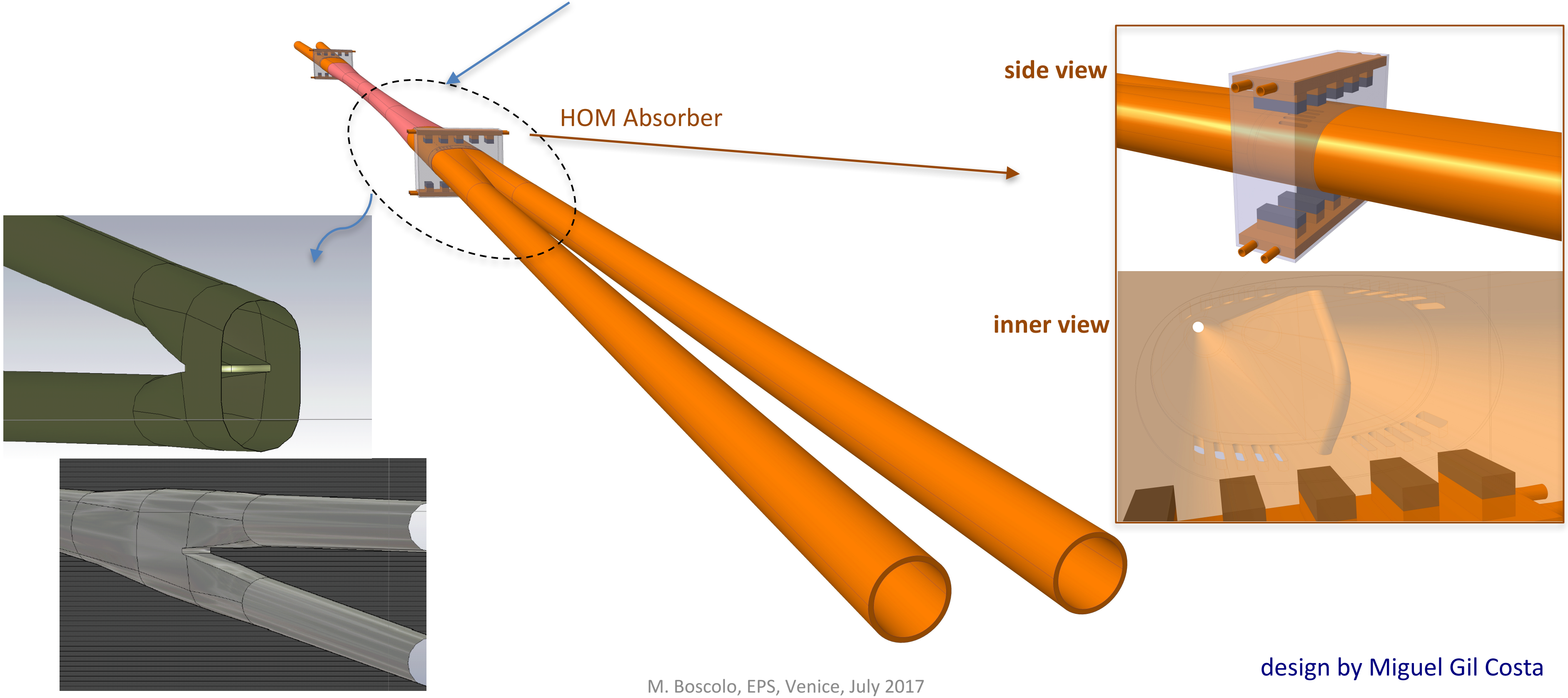
IR Beam pipe design
for wake field calculations

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

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)

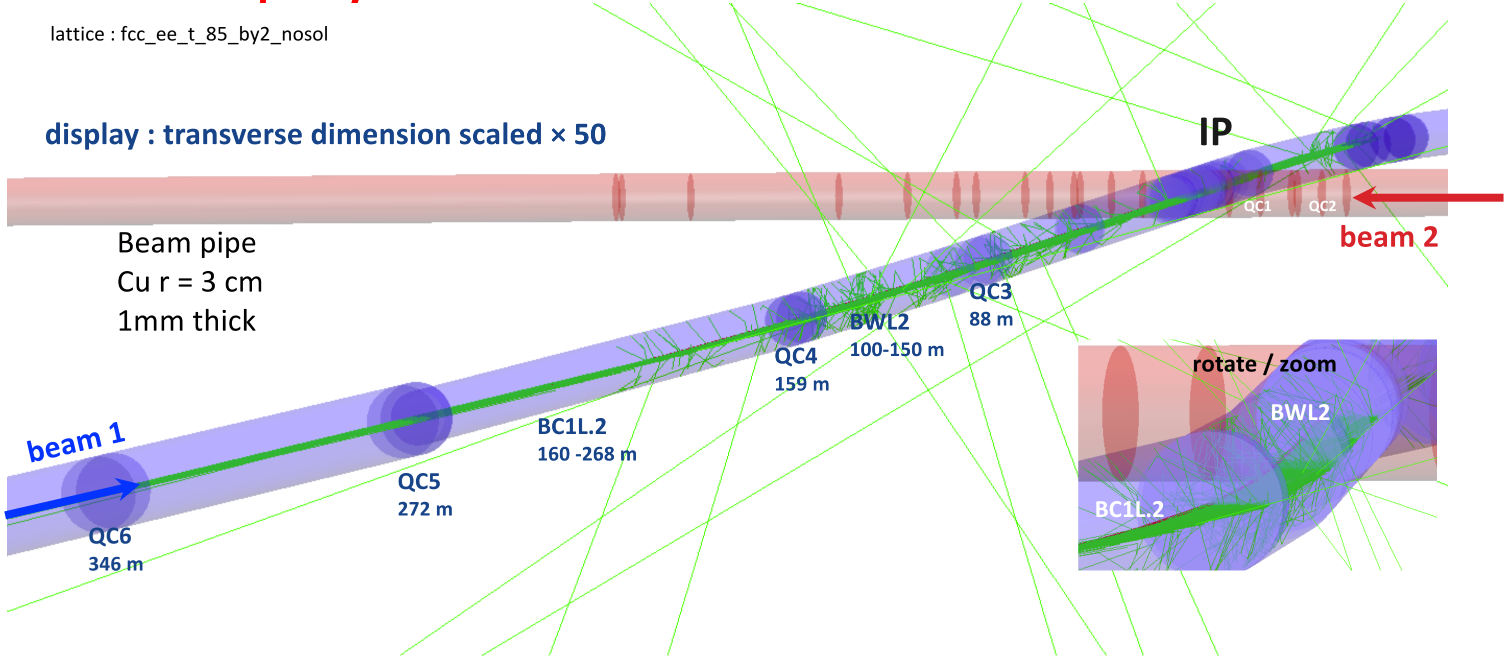
Various lattice options have been studied in detail with different approaches*

- **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

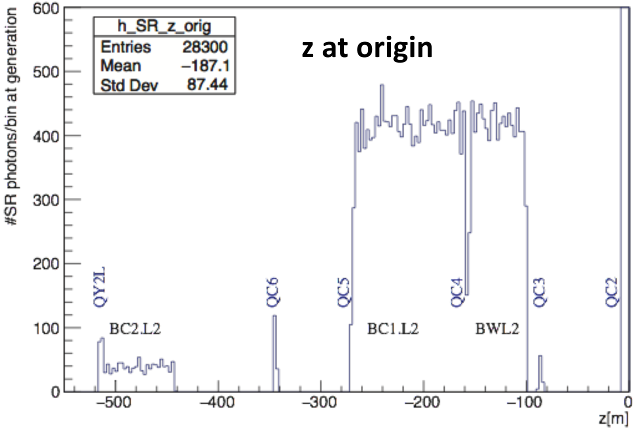
28300 SR γ's generated, first 1000 γ's shown here

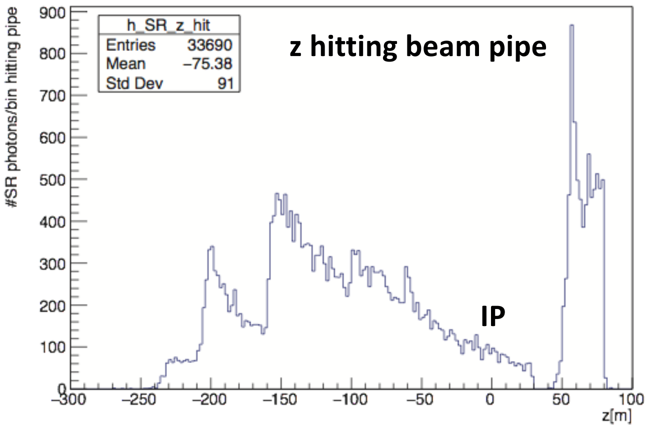
rather fast, < 1 min (MacMini i7)

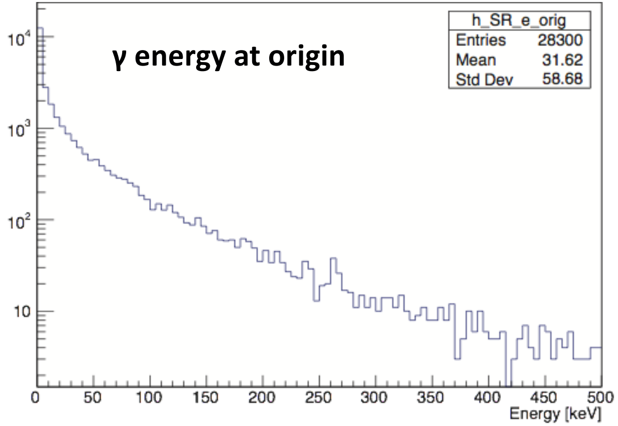
multiply with
2.3e+11/5000 = 4.6e7
to get statistics of 1 bunch
1.3e12 SR γ's

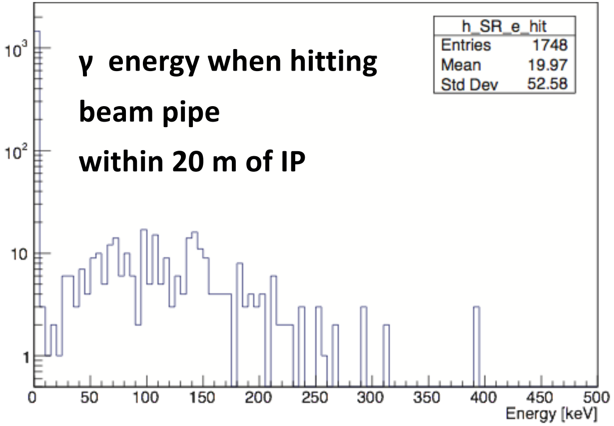
H. Burkhardt

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)

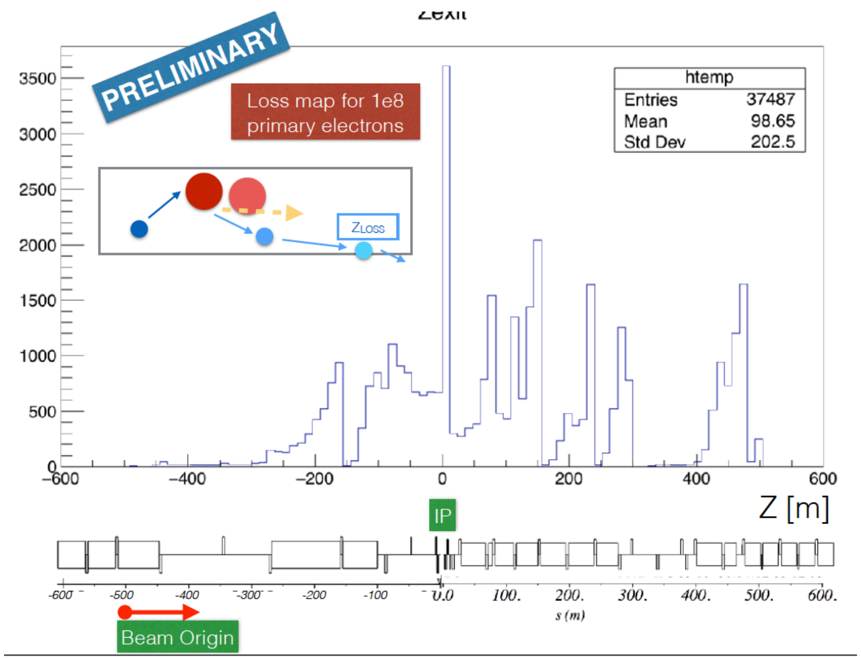
with **SR generation in bends + quads + beam profile generation**

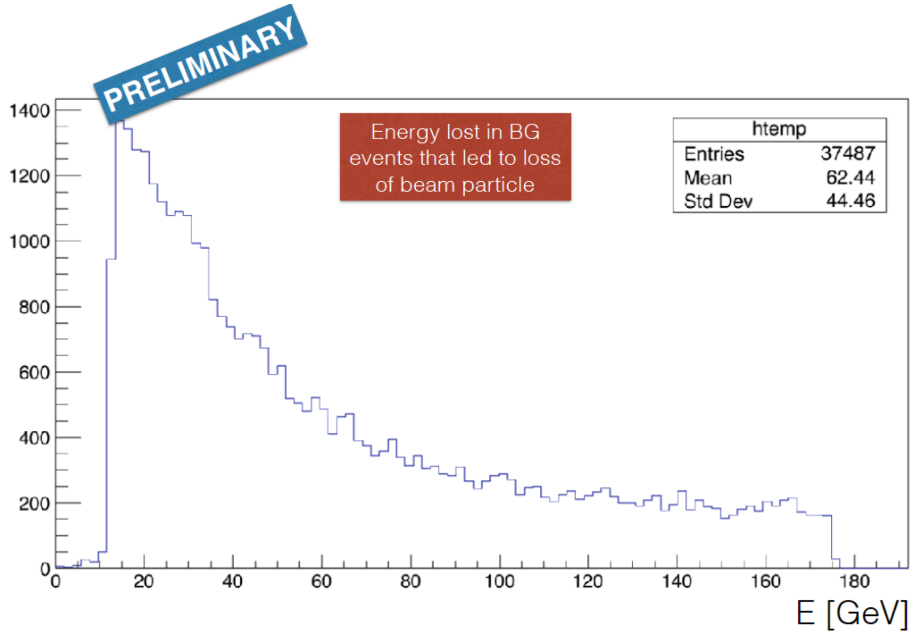
- **Same principle also works for beam gas**

- 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

Preliminary G4 beam-gas simulation

- inelastic beam-gas +/-500m from IP
- 175 GeV
- vacuum density increased by 10 orders of magnitude ($5x10^{-9}$mbar -> 50mbar)





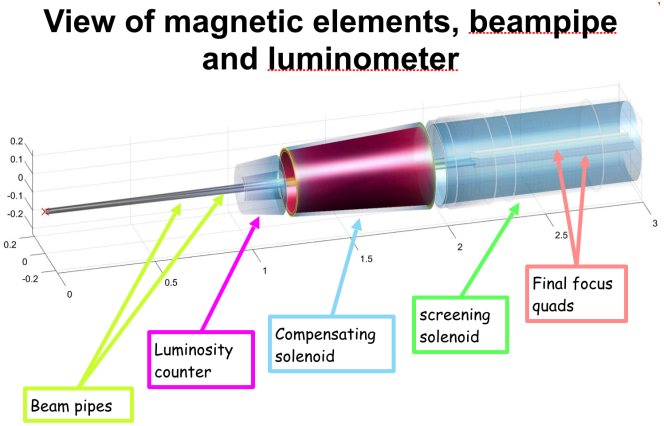
Solenoid Compensation Scheme

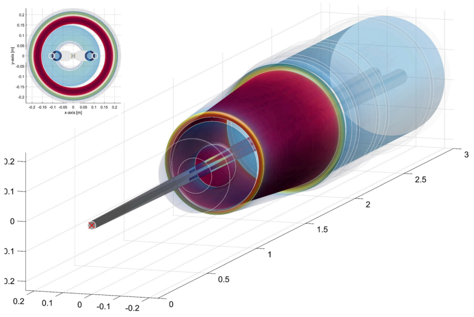
Constraints:

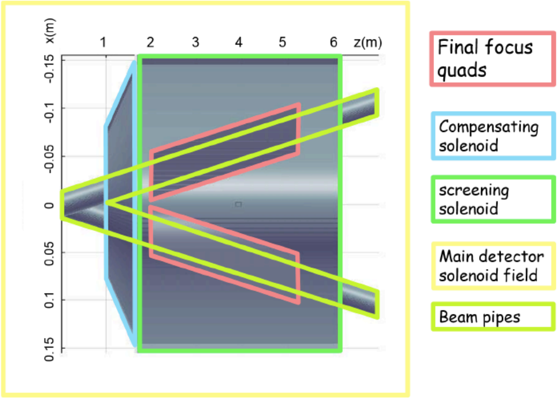
- **2T** detector field
- **L*=2.2m**
- Space (i.e. only 6.6 cm distance at the tip closest to IP for QD0)
- must be inside the lumical acceptance
- final focus quads inside the detector (low βy^* and large crossing angle)
- leave space for **luminosity detector** at small angle
- field quality at each 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.

Solenoid Compensation Scheme







M. Koratzinos

Two solenoids are introduced in the IR:

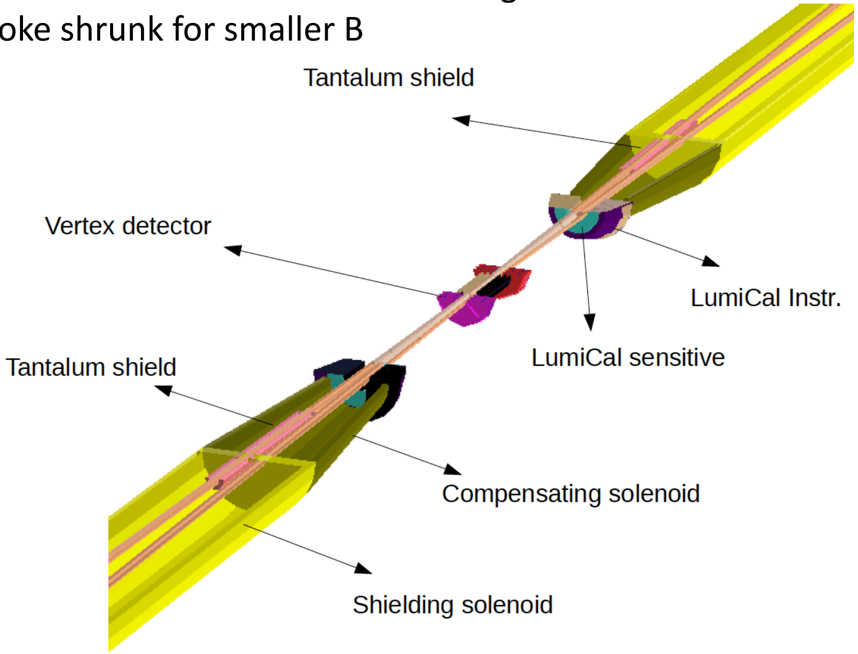
- **screening solenoid** that shields the detector field inside the quads (in the quad net solenoidal field=0)
- **compensating solenoid** in front of the first quad, as close as possible, to reduce the ε_y blow-up (integral BL~0)

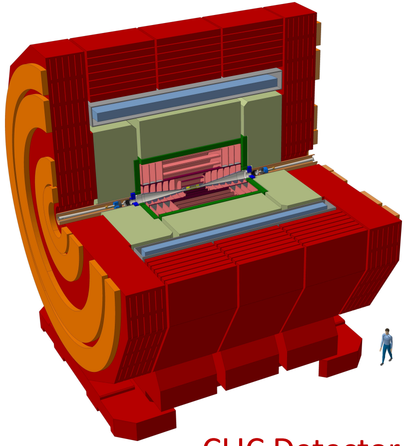
0.3 pm is the overall ε_y blow-up for 2IPs @Z with this compensation design

Geant4 detector and IR modeling

modified CLIC detector model with 2T magnet and FCC-ee IR design:

- vertex layers closer to beamline
- extended tracker to compensate for lower B
- HCAL shrunk to 5.5 interaction lengths
- Yoke shrunk for smaller B





CLIC Detector

Backgrounds simulations in the detector

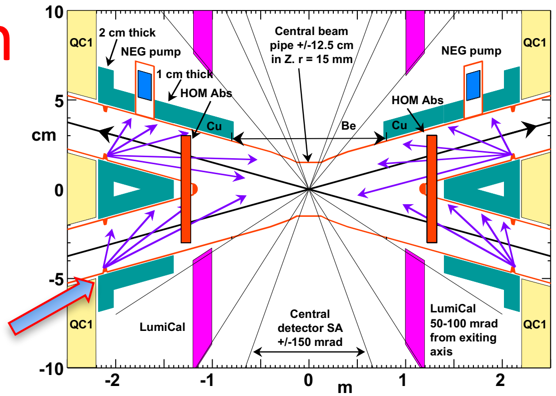
- We have performed full simulation studies of effects of various backgrounds mostly on the **Vertex and Tracker** (more recently also on the **luminosity monitor**) part of the modified CLIC detector, estimating **hit density/ occupancy/ deposited energy**.

- Focus on $\mathbf{E_{cm} = 350}$ **GeV** (tt) as worst case scenario for most of the considered backgrounds.

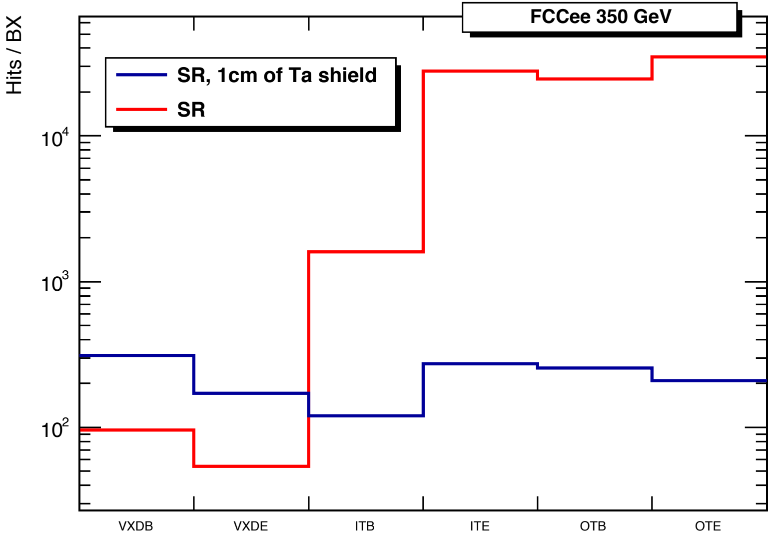
- Studied:
  - **Synchrotron radiation**
  - $\mathbf{e^+e^-}$ **pair production**
  - **γγ to hadrons**

Synchrotron Radiation

- **Dominant source of primary background in detector**
- Study at top energy (175 GeV)
- Full simulation of the last bend photons scattered from the tip of the mask



- expected ~5x10^6 scattered photons/beam
- **proper shielding (1cm Ta) is effective in intercepting the photons**



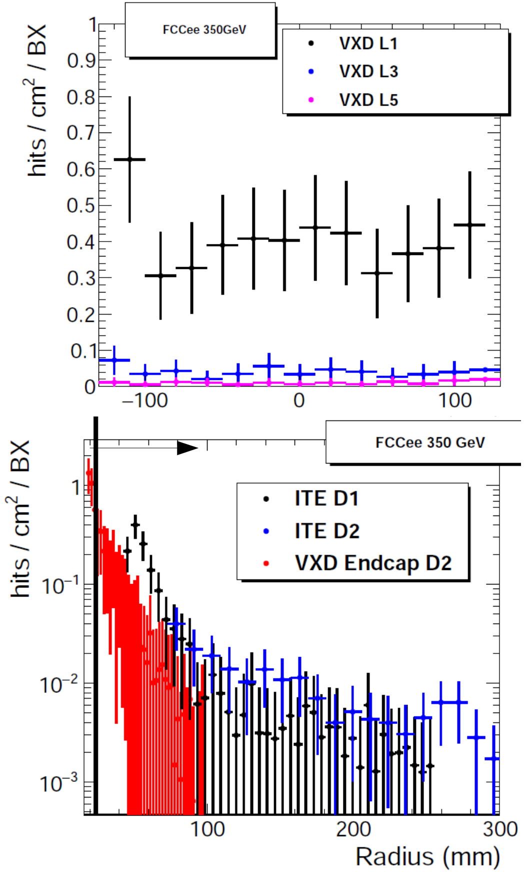
Pairs production

Pairs generation with Guinea Pig

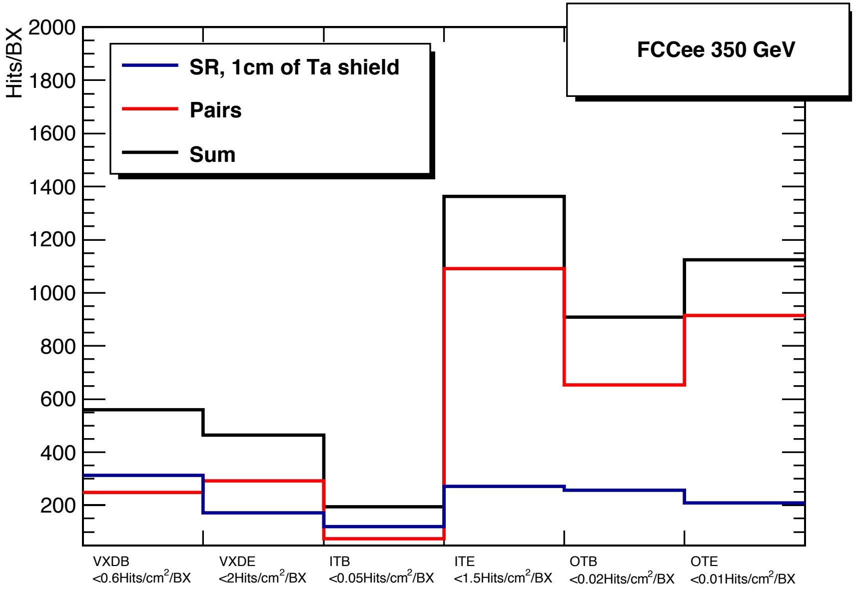
Full simulation studies using DD4hep ILCSoft (geant4 based simulation) / ILCSoft

Assuming a pixel pitch of 20μm and an average cluster size of 5

- Occupancy/BX ~ 10^{-5} for the hottest areas (~10^{-2}/BX @ILD-VD)
- For E_{cm} 91.2 GeV
  - Maximum occupancy ~ $2x10^{-6}$ observed in VXD Endcaps
  - However note the very short bunch spacing of ~ 3ns
  - For example: a sensor with readout time of 3μs would integrate over 1000 BX
  - Occupancy / r.o. time ~ $2x10^{-3}$



Combined effect of SR and pairs background

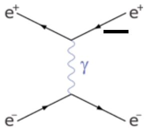


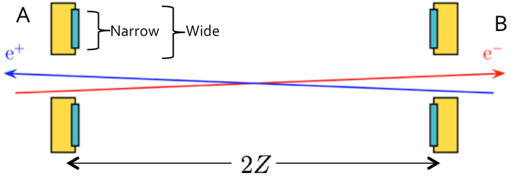
Maximum hit density in the hottest are of each subdetector per bunch crossing

Detector Luminosity Monitor

Luminosity monitoring:

- **Absolute** – target precision $\mathbf{10^{-4}}$
- **Relative** for Z lineshape measurement – need a relative precision of $\mathbf{2\text{-}5 \times 10^{-5}}$
  - 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

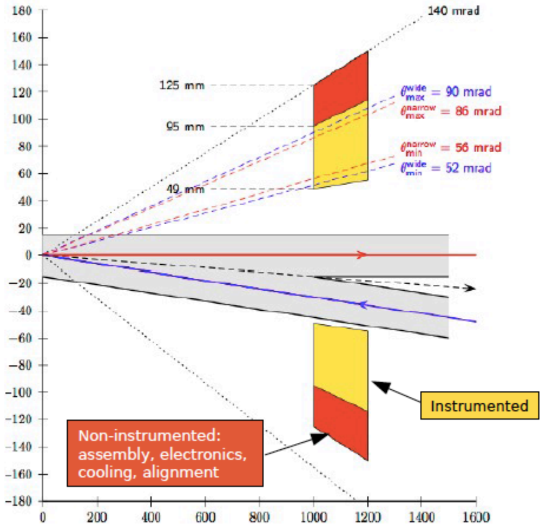




Two counting rates:
- SideA = NarrowA + WideB
- SideB = NarrowB + WideA

- Average over SideA and SideB rates: Only dependent to second order on beam parameters: $\frac{\delta \bar{R}}{\bar{R}} = 3\left(\frac{\delta z}{Z}\right)^2$ $\frac{\delta \bar{R}}{\bar{R}} = 2\left(\frac{\delta x}{r_{\min}}\right)^2$

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

Still a big challenge given the available space in the IR

M.DAM

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 at 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

Conclusion and Future Steps

- **IR Layout** baseline defined
- 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

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

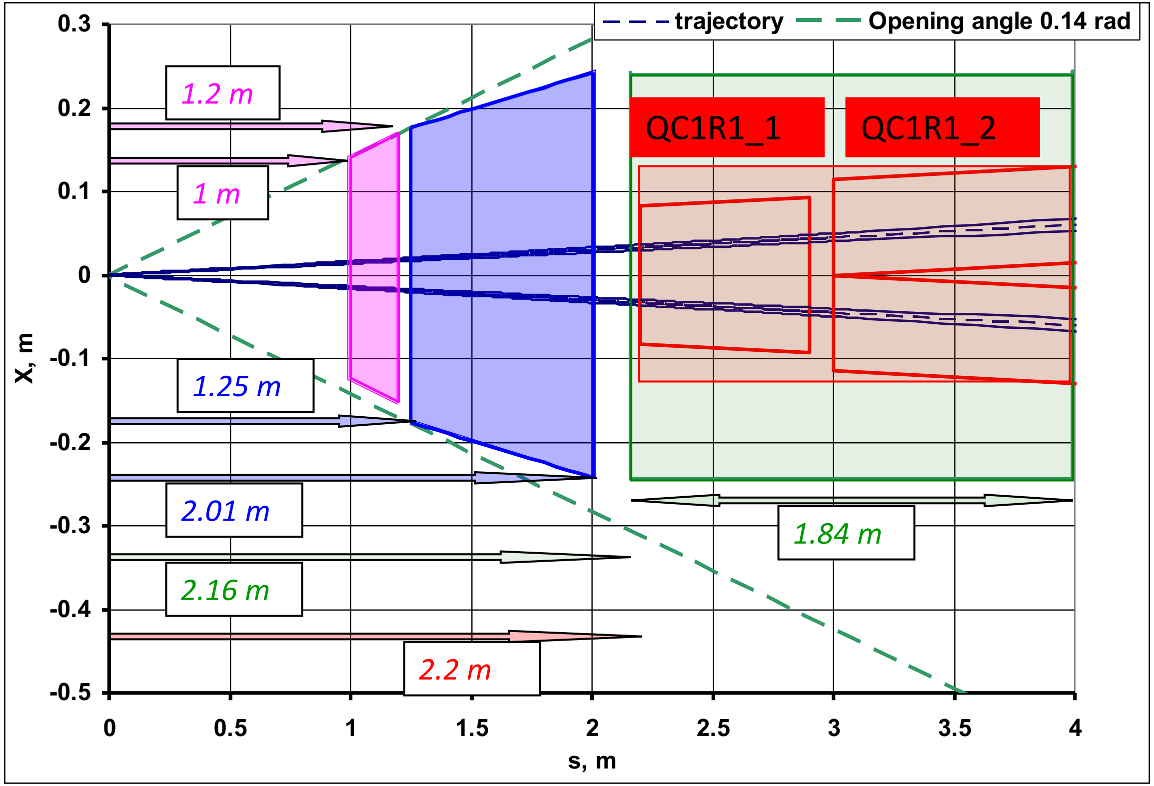
Summary of LumiCal Geometry

- 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



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