FCC-ee MDI Layout

– Synchrotron Radiation Collimation in the FCC-ee MDI Area –

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The 2020 International Workshop on the High Energy Circular Electron Positron Collider
October 27, 2020

Outline

The FCC-ee
– An Overview –

FCC-ee – The Cornerstones

Baseline beam parameters

- machine for precision measurements:
  - 45.6 GeV: Z
  - 80 GeV: W
  - 120 GeV: Higgs (LEP)
  - 182.5 GeV: $t\bar{t}$
- **luminosity:** up to $2.3 \times 10^{36}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - high intensity (I_B of 1.4 A at Z)
  - nano-beam-scheme (nm or pm size)
  - 2 vs. 4 interaction points (IP)
- CDR for more details [3]
- **Synchrotron radiation power loss:** 50 MW/**beam**
- **critical energies** $\epsilon_c \geq 1\,\mathrm{MeV}$ **(around the ring)**
- arc bends vs. weak bends

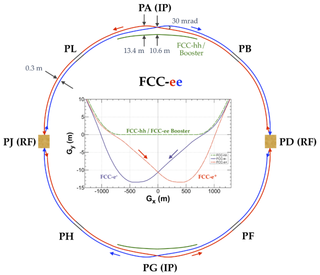


Figure: schematic 2 IP layout [8].

The FCC-ee
– Machine-Detector-Interface (MDI) –

SR as design constraint

- MDI: *accelerator meets detector*
- requires careful design
- different expectations/needs:
  - machine/detector protection
  - space for the detector
  - minimize background to physics
- if neglected:
  - machine won't reach design parameters
  - machine can't be operated
  - physics goal can't be reached
  - damage to machine/detector

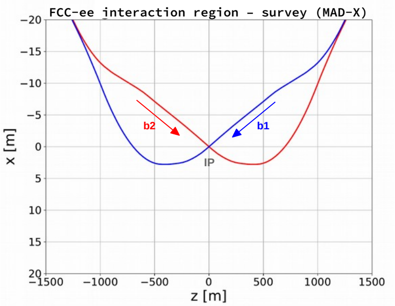
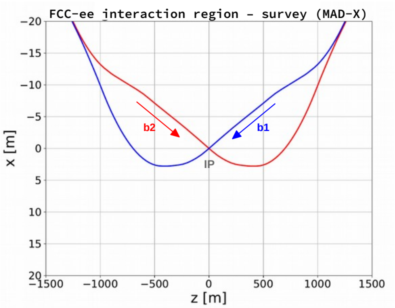


Figure: Asymmetric layout of the FCC-ee IR (top view).

SR & Machine Detector Interface (MDI)

IR design for FCC-ee

- asymmetric layout
- last bend at least a 100 m from IP
- crossing angle 30 mrad (no sep. dipoles)
- weak upstream bends ($\epsilon_c \downarrow$ with $\rho \uparrow$)
- fixed absorbers in the central IR (Z $\pm$10 m) $\Rightarrow$ Synchrotron Radiation masks
- located at 2.1 m and 5.6 m upstream of the IP
- 3rd mask (at about 8 m upstream) replaced by collimator



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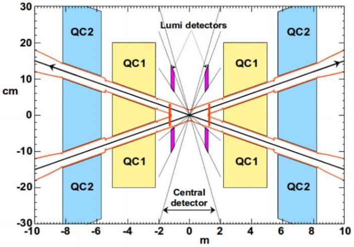


Figure: Illustration of the central IR (Z $\pm$10 m around IP, top view) [10].

SR & Machine Detector Interface (MDI)

IR design for FCC-ee

- 182.5 GeV: $\epsilon_c \leq 100$ keV (last upstream dipole)
- limit ϵ_c to 100 keV (last 450 m)
- limit ϵ_c to $\approx$1 MeV (whole machine)

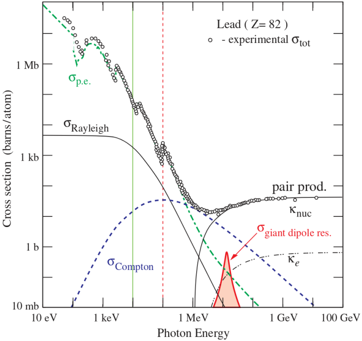


Figure: Photon interaction processes in lead [4].

Simulations I
– Introductory Example –

MDISim & FCC-ee - Introductory Example

Simulation procedure

- run MAD-X
- generate geometry
- detailed Monte Carlo (Geant4):
  1. start point & path length
  2. # primaries (bunch population)
  3. tracking
- 10^4 primaries $\leq 5\,\mathrm{min}$

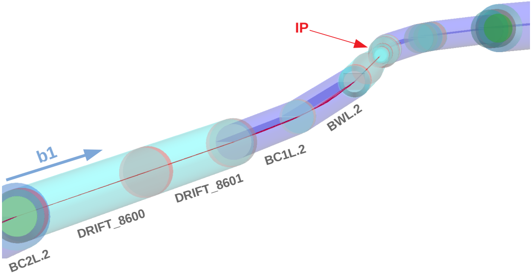


Figure: Perspective view in beam direction towards IP (Root display).

MDISim & FCC-ee - Introductory Example

Analysis

- location of origin
- distribution of hits
- number of generated photons
- energy distribution & heat-maps
- **all sensitive to:**
  - beam-type (pencil vs. Gaussian)
  - halo/tails

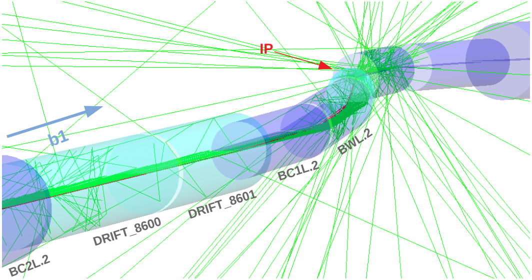


Figure: Same as before but with SR tracks in overlay (Root display).

Simulations II
– Characterization of the SR Background –

The Scenarios

Simulation Parameters

- top energy ($t\bar{t}$), 182.5 GeV
- horizontal emittance $\epsilon_x = 1.46$ nm
- vertical emittance $\epsilon_y = 2.9$ pm
- bunch population in the MC: N_{MC}
- particle distributions:
  - $N_{MC} = 10^4$ primaries
  - **default:** Gaussian bunch
  - **tails:** Ring-type distribution at $N\sigma_{x,y}$
    - **horizontal:** 15 σ_x, 1 σ_y
    - **vertical:** 50 σ_y, 1 σ_x
  - rather conservative
  - measurements at LEP (horizontal tails)
- starting point 300 m upstream (Group 1)

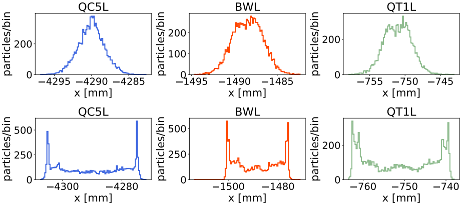


Figure: Initial particle distribution (horizontal plane) for a Gaussian (upper row) and horizontal tails (lower row).

Three Groups of Upstream Bends

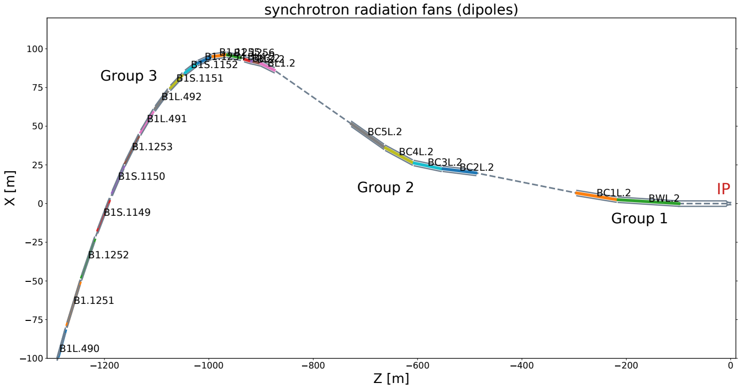


Figure: Top view (2D) on upstream bends, starting in the arc around 1300 m upstream.

Three Groups of Upstream Bends

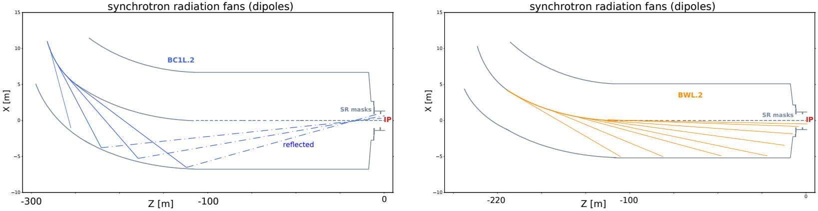
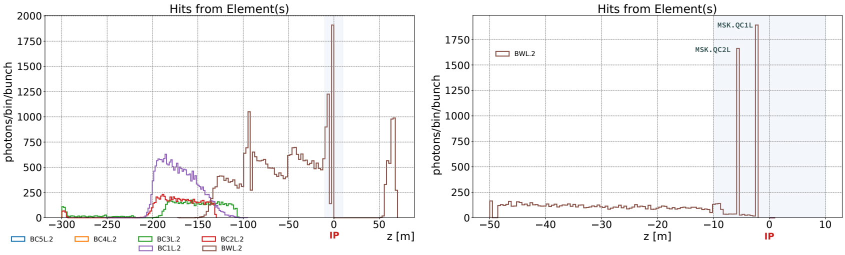


Figure: Sketch of Synchrotron Radiation fans from the last upstream bends BC1L.2 and BWL.2.

Radiation from Group I – Direct Hits



(a) (b)

Figure: Distribution of hits on the inner vacuum chamber wall, **sorted by elements of origin**. (a) from 300 m, (b) close-up of 50 m upstream.

Preliminary conclusion

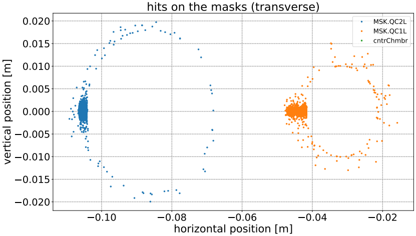
- 1st iteration: direct hits – **first generation photons**
- `BC1L.2` seems not relevant
- `BWL.2` exits directly towards straight section
  $\Rightarrow$ most significant contribution to photon background

Effects on Synchrotron Radiation Masks

Default Scenario

- 6675 hits on `MSK.QC2L` with $\langle\epsilon\rangle \approx 15.77\,\text{keV}$
- extrapolated on whole bunch: 1.54×10^{10}

- 1975 hits on `MSK.QC1L` with $\langle\epsilon\rangle \approx 26.44\,\text{keV}$
- extrapolated on whole bunch: 4.54×10^{9}



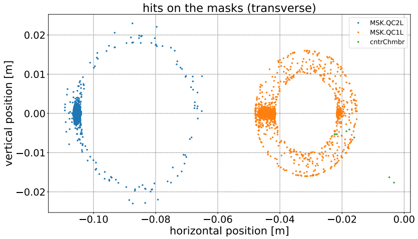
Effects on Synchrotron Radiation Masks

Horizontal Tails

- 6488 hits on `MSK.QC2L` with $\langle\epsilon\rangle \approx 17.75\,\text{keV}$
- extrapolated on whole bunch: 1.49×10^{10}

- 3515 hits on `MSK.QC1L` with $\langle\epsilon\rangle \approx 171.72\,\text{keV}$
- extrapolated on whole bunch: 8.08×10^{9}

- high energy tail on `MSK.QC1L`
- quads `QC3L.2` ($\approx$90 m) and `QT1L` ($\approx$50 m)
- about 2.8 % scatter off MSK.QC2L **back into beam-pipe**
- $\langle\epsilon\rangle \approx 115.34\,\text{keV}$



Effects on Synchrotron Radiation Masks

Additional mitigation beneficial:

- reduce photon rate at SR masks
- block high energy photons far upstream
- mitigate tails
- react to changes in orbit
- *every photon blocked early = one problem less for the MDI/detector*

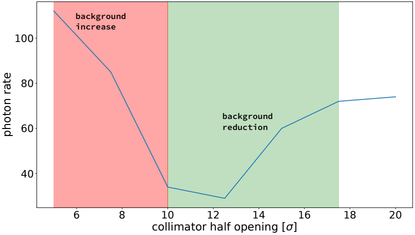


Figure: A collimator can reduce the background rate, depending on its aperture setting – too tight settings lead to background enhancement.

Simulations III
– Mitigation of the SR Background –

Updates on IR Geometry

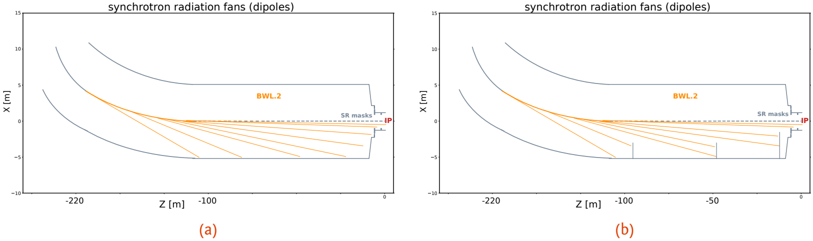


Figure: Sketch of Synchrotron Radiation fans. (a) last upstream bend. (b) collimators intercepting the radiation fans.

Table: Beam size at certain elements downstream of BWL.2.
Need to respect the dynamic aperture requirement (injection): 15 σ_x

Name	β_x [m]	σ_x [μm]	$15\sigma_x$ [mm]	$20\sigma_x$ [mm]
BWL.2	333.36	697.66	10.46	13.95
QC3L.2	303.68	665.87	9.99	13.32
QT1L.2	329.07	693.14	10.40	13.86
PQC2LE.2	237.60	588.99	8.83	11.78

Updates on IR Geometry

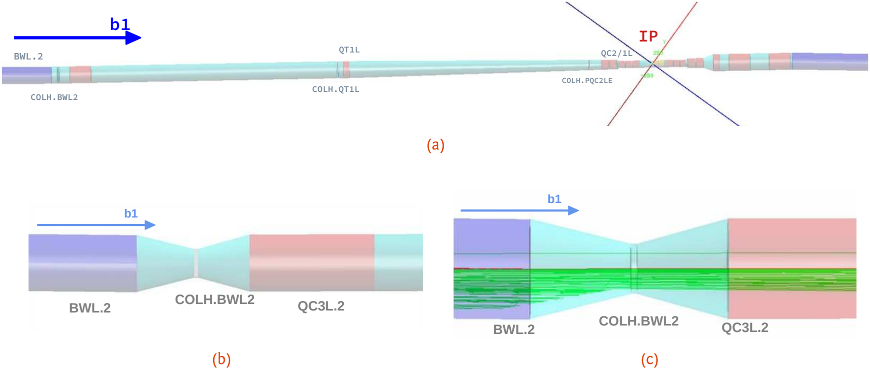
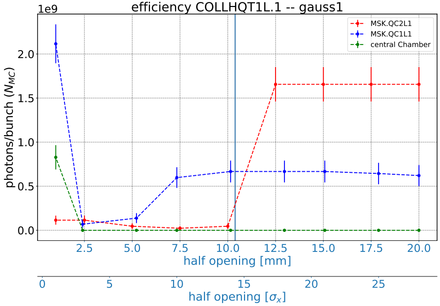
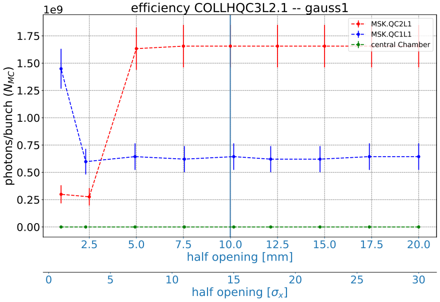


Figure: Collimators integrated in the MDISim geometry.

Far-out & Intermediate Collimator – Default Scenario

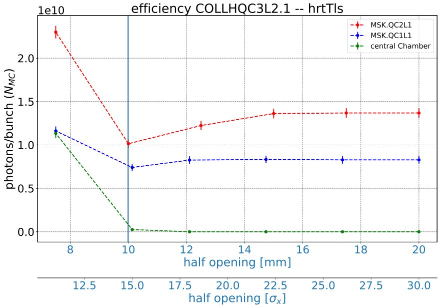


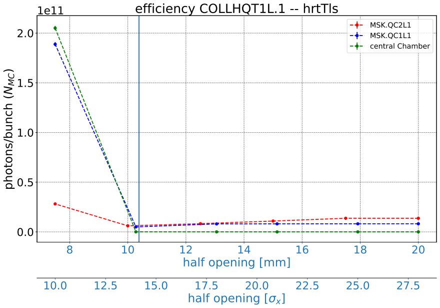


- outer mask: reduction between $\leq 20\,\sigma_x$ and $15\,\sigma_x$
- inner mask: no effect ($\geq 15\,\sigma_x$)
- central chamber: direct hits observed from $\leq 5\,\sigma_x$

- outer mask: no effect $\geq 15\,\sigma_x$
- inner mask: no effect $\geq 15\,\sigma_x$
- central chamber: no direct hits observed

Far-out & Intermediate Collimator – Horizontal Tails

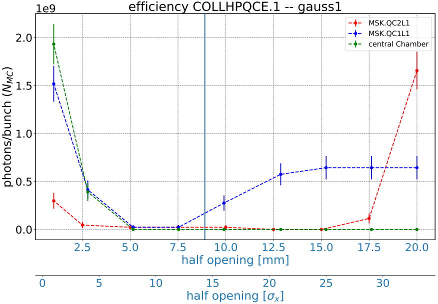


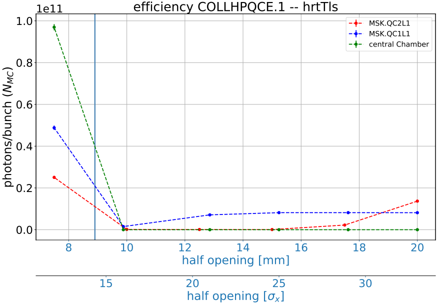


- outer mask: reduction between 22.5 σ_x to 15 σ_x
- inner mask: slight reduction between 17.5 σ_x to 15 σ_x
- central chamber: direct hits observed from $\leq$15 σ_x

- outer mask: reduction between 25 σ_x to 15 σ_x
- inner mask: reduction with 18 σ_x to 15 σ_x
- steep rise in the photon rate <15 σ_x
- central chamber: affected from 10 mm closure

Near Collimator – Default Scenario & Horizontal Tails





- outer mask: broad reduction between 35 σ_x to 15 σ_x
- inner mask: reduction with 25 σ_x to 15 σ_x
- minimum at both locations (partly above 15 σ_x)
- central chamber: affected from 10 σ_x closure

- outer mask: reduction between 35 σ_x to 17 σ_x
- inner mask: reduction with 22 σ_x to 17 σ_x
- central chamber: affected from $\leq$17 σ_x closure

Summary

The bottomline

- FCC-ee: large scale machine
- novel energy regime for $e^{\pm}$ collisions
- potentially serious photon background
- drives machine design and parameters
- collimation system currently studied:
  - additional mitigation measure
  - can relax condition in central IR
  - already assuming rather ideal conditions

The Codes

- MDISim as flexible software framework
- improvements wherever needed
- useful tool for background estimates
- first collimation proposal

On the Shelf

- X-ray reflections
- higher statistics (N_{MC})
- enhance the geometry model (CERN Vacuum Group)
- steps towards unification with detector simulations

Thank you for your attention.

References

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Backup slides

Synchrotron Radiation - Figures of Merit

Some Characteristics

- Energy loss/turn $U_0 \propto \frac{1}{E_0^3} \frac{E^4}{\rho_0}$
- Power $\langle P_{SR} \rangle = \frac{U_0}{T_0} \propto \frac{1}{E_0^3} \frac{E^4}{\rho_0 L}$
- countermeasure:
  - size of the ring (ρ)
  - restmass E_0
- electron vs. proton: $m_p/m_e \approx 1836$
- opening angle $\theta \propto 2/\gamma$
- typical frequency $\propto \gamma^3$ ($\gamma=E_B/E_0$)
- $\epsilon_c = \hbar\omega_c = \frac{2}{3}\hbar c \frac{\gamma^3}{\rho}$
- spectrum: 50 % above ϵ_c

In practical units ...

- $U_0[keV] = 88.46 \frac{E^4\ [GeV]}{\rho\ [m]}$
- $P_{SR}[kW] = 88.46 \frac{E^4\ [GeV]\ I[A]}{\rho\ [m]}$

- LEP (e, 45.6 GeV): U_0 = 126 MeV, P_{SR} = 1.06 MW
- HL-LHC (p, 7 TeV): U_0 = 5 keV, P_{SR} = 2.71 kW
- FCC (e, 182.5 GeV): U_0 = 9.12 GeV, P_{SR} = 49.25 MW

Considering FCC-ee ...

- ρ = 10.76 km
- $\gamma = \frac{E_B}{E_0} \approx 3.57 \times 10^5$ (182.5 GeV)
- $\epsilon_c \approx 556.94$ keV

X-Ray Reflection

- $\theta_{\text{in}} = \theta_{\text{out}}$
- dependent on incident angle
- Accelerator – critical angle [11]:

$$\theta_c[\text{mrad}] \approx \frac{33}{E_\gamma[\text{keV}]} \tag{1}$$

- nearly 100 % reflected, ***'mirror like surface'***
- even photons far upstream may reach the IR with enhanced probability
- typical angle (`BWL.2`, 100 keV): 0.33 mrad
- orbit deviations critical: 1 mm/100 m: μrad
- sudden background spikes; collimators indispensable (LEP, [11])

Experience from LEP

Some experience from LEP [11, 1, 2]:

- beam energy 45.6 GeV to 104.5 GeV
- **interaction region (IR):**
  - weak bends (dipole magnets)
  - long straight sections
- synchrotron radiation as serious background
- *"vacuum chamber, electronics, cables & beam instrumentation"*
- some locations: beam-pipe almost melted
- carefully designed collimation system
- ≈100 movable collimators
- 45.6 GeV: $\epsilon_c \approx 68$ keV (average arc dipole)

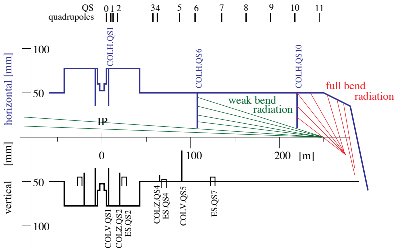

Figure: Example view of one LEP interaction region **(IR)** [11].

Machine Detector Interface Simulations - MDISim

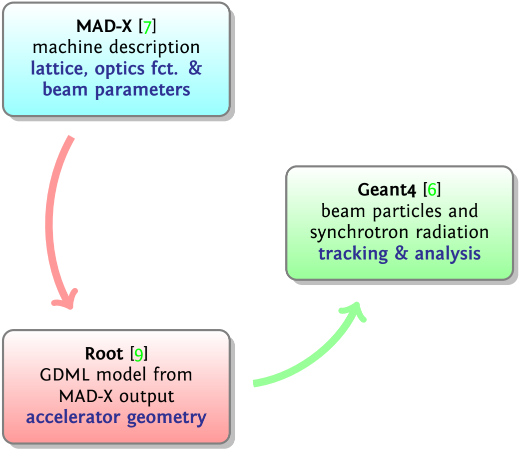

Figure: MDISim [5] combines three programs to study synchrotron radiation backgrounds.