INFN LNF
Istituto Nazionale di Fisica Nucleare

FUTURE CIRCULAR COLLIDER
Innovation Study

FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

MACHINE DETECTOR INTERFACE REQUIREMENTS AND CONSTRAINTS

Manuela Boscolo (INFN-LNF)

MAPS detectors technologies for the FCC-ee vertex detector
CERN, 1-2 July 2024

Outline

- Introduction
- Crab-waist scheme
- Beam parameters for the 4 energy runs
- Injection filling scheme & top-up injection
- Mechanical layout of the beam pipe and of the interaction region
- Backgrounds & Radiation levels
- Next steps

Introduction - Boundary Conditions

Ideal case:

- High luminosity
- Full (4π) detector acceptance
- Low background conditions

Real life: see talk by H. Burkhardt

- Achievable Luminosity
  high enough as required by physics program
- Good detector acceptance
  in forward/rear direction
- Tolerable background rates

Luminosity and acceptance requirements depend very much on the physics program

extra-constraints: injection, crossing angle, synchrotron radiation

Introduction -Detector Constraints for the accelerator design

- Physics acceptance from the nominal beam axis
- Smallest possible beam pipe radius
- Thinnest possible beam pipe wall
- Solenoidal detector
- Separation scheme
- L* (free distance between the IP and the first final focus quad)

	Mitigation Remedies:
• Low SR backgrounds	first bends far from IP, to minimize SR from FF quads: orbit at centre of quads
• Low Beam-gas backgrounds	good pumping
• Low radiative Bhabha backgrounds	proper shielding

FCC-ee layout

Double ring e+e- collider with 91 km circ.

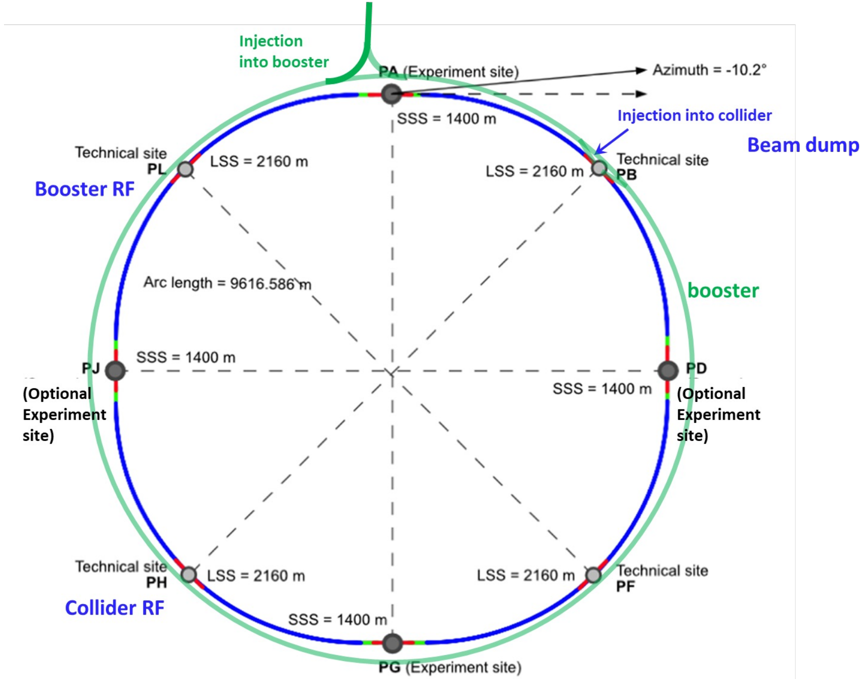
Common footprint with FCC-hh, except around IPs

Perfect 4-fold super-periodicity allowing 2 or 4 IPs; large horizontal crossing angle 30 mrad, crab-waist collision optics

Synchrotron radiation power 50 MW/beam at all beam energies

Top-up injection scheme for high luminosity

Requires booster synchrotron in collider tunnel and 20 GeV e+/e- source and linac



Accelerator Design

Well developed layout that will deliver (extremely) high luminosity Z → t-tbar

Design benefits from LEP, LHC, DAFNE, and B-factory experience as well as LC, EIC and CEPC development

Have detailed lattices for collider rings and booster
Full simulations of beam-beam effects
Working on alignment and correction strategies

The accelerator has highly repetitive Arcs with challenging IRs
- → Develop prototype of half arc-cell
- → Develop IR mock-up

Most R&D is focused on optimizing systems for power efficiency & cost

High-level Requirements for the IR and MDI region -1

- **One common IR for all energies, flexible design** with a constant detector field of **2 T**
  - This has been a requirement since the CDR: we have the same IR and MDI for all energies and all of the four IPs.

- **At Z pole a Luminosity of ~ 10^{36} $cm^{-2}s^{-1}$ is required**
  - This luminosity can be obtained with the **crab-waist scheme** (nano-beams & large crossing angle).
  - **Continuous top-up injection** is required **with few percent of current drop** to keep a constant luminosity, lifetime is ~15 min (as defined to decrease the beam intensity by 1/e, without any injection).

- **Cone angle of 100 mrad between accelerator/detector** required from the physics
  - **Presently not realistic:** first look at the cryostat dimension with thermal shielding thickness show larger angles necessary.
- **Solenoid coupling compensation**
  - The integral $\int B_z ds = 0$ to avoid vertical emittance blow-up.
  - Baseline: Two compensating solenoids in front of the first final focus quad, all inside the detector
    - B=2 T detector solenoid field required.
  - Alternative: Compensating solenoids outside the detector at ~20 m from the IP
    - Higher detector solenoid field opportunity (next MDI meeting, 8/7/24)

High-level Requirements for the IR and MDI region -2

- **Luminosity monitor** @Z: absolute measurement to 10^{-4} with low angle Bhabhas
  Acceptance of the lumical sets constraints to the central vacuum chamber design and material budget

- **Minimization of the Synchrotron Radiation impacting on the IR**
  Optics design constraint: weak bends upstream the IR (and strong ones downstream, to produce the horizontal crossing angle), having an asymmetric optics wrt IP
  Critical energy below 100 keV produced by the last bending magnets upstream the IR: required from the LEP2 experience (see talk by H. Burkhardt)

Critical energy: $E_c = \frac{3}{2}\hbar c\frac{\gamma^3}{\rho}$

Half of the synchrotron radiation is radiated below, and the other half above the critical frequency.

The mean photon energy is about 30% of the critical energy $<E_\gamma>= \frac{8}{15\sqrt{3}}E_c = \frac{4}{5\sqrt{3}}\hbar c\frac{\gamma^3}{\rho}$

FCC-ee Interaction Region rationale: crab-waist

Crab-waist scheme, based on two ingredients:

- concept of **nano-beam scheme:**
  - vertical squeeze of the beam at IP and large horizontal crossing angle
  - large ratio σ_z/σ_x reducing the instantanous overlap area, allowing for a lower β_y*
- concept of **crab-waist sextupoles:**
  - placed at a proper phase advance they suppress the hourglass effect by inducing a constant β_y along the larger coordinate of the beams overlap.

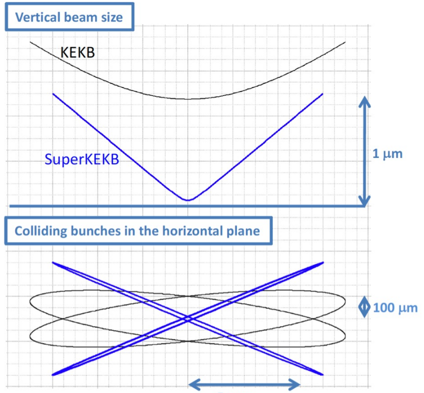
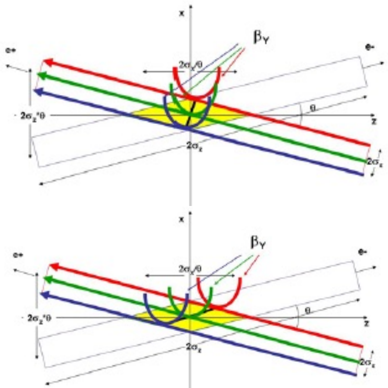


Figure 2: Schematic view of the nanobeam collision scheme.

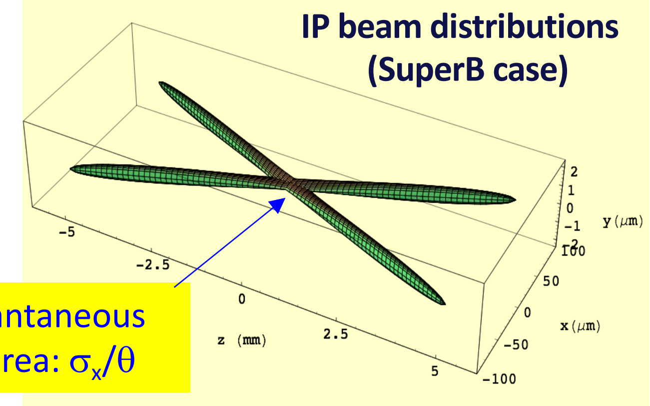
SuperKEKB https://arxiv.org/pdf/1809.01958.pdf



crab sextupoles off

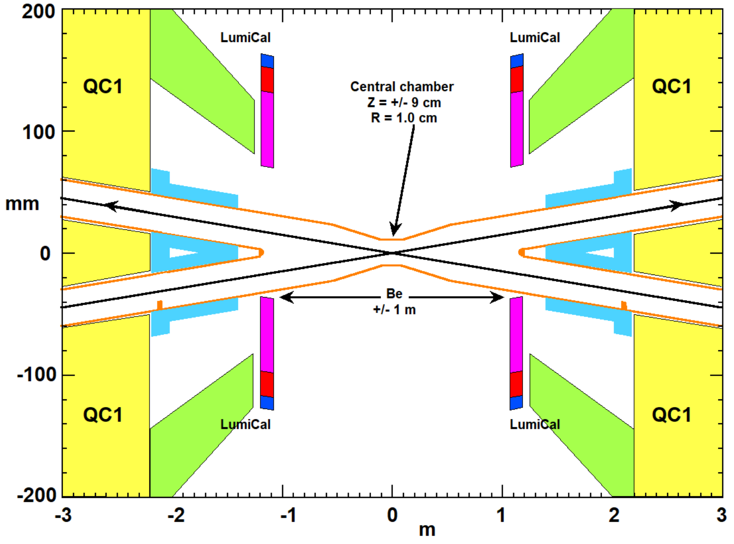
crab sextupoles on

DAFNE, PRL 104, 174801 (2010)



Small instantaneous collision area: σ_x/θ

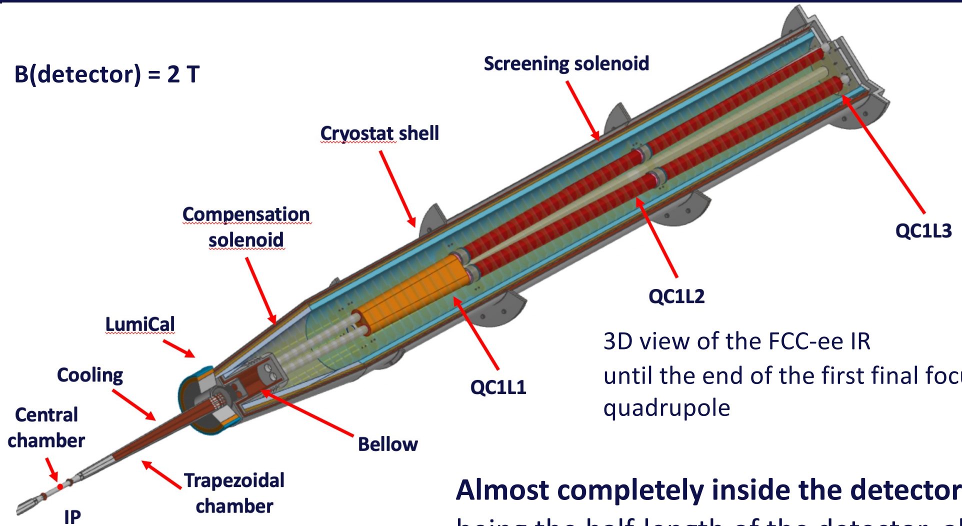
FCC-ee Interaction Region



FCC-ee IR layout.

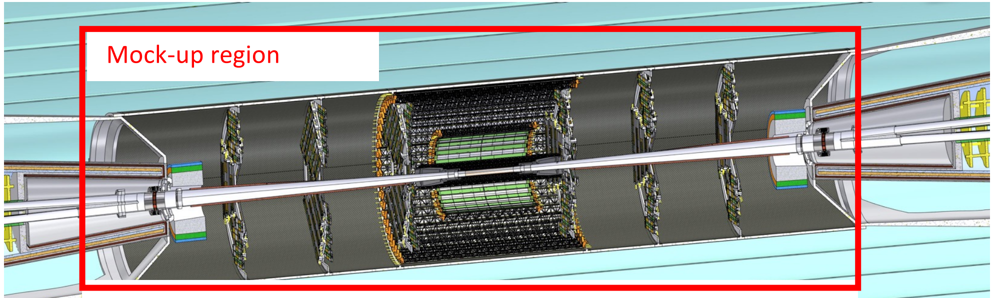
L*, is 2.2 m. The 10 mm central radius is foreseen for ± 9 cm from the IP, and the two symmetric beam pipes with radius of 15 mm are merged at 1.2 m from the IP.

B(detector) = 2 T



3D view of the FCC-ee IR until the end of the first final focus quadrupole

Almost completely inside the detector, being the half-length of the detector about 5.2 m and the end of QC1L3 at about 5.6 m.



3D view of FCC-ee IR including the rigid support tube, vertex detector and outer trackers.

FCC-ee main machine parameters

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Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* **[m]**	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	≥5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11

	Z	WW	H (ZH)	ttbar
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

Design and parameters dominated by the choice to allow for 50 MW synchrotron radiation per beam.

FCC-ee main machine parameters

horizontal crossing angle 30 mrad = 1.7 deg

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50 ps rms

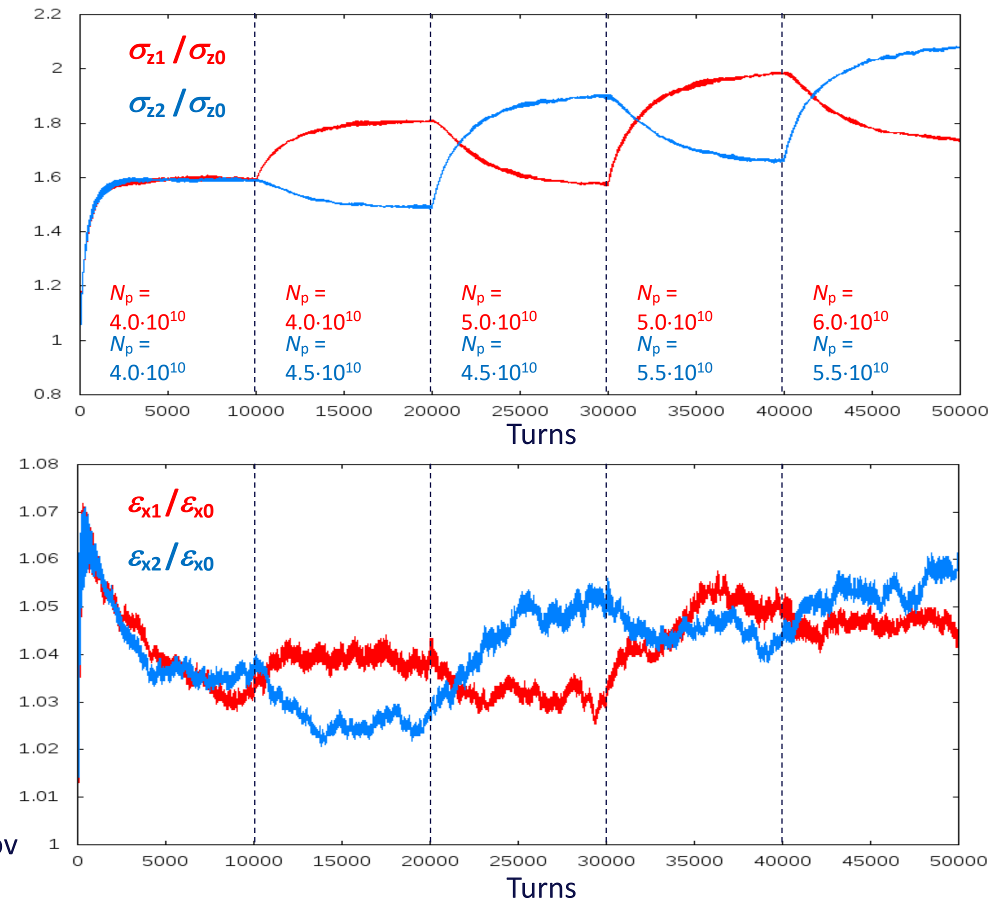
Design and parameters dominated by the choice to allow for 50 MW synchrotron radiation per beam.

C = 90.7 km

Bunch spacing 20 ns

Filling Scheme motivation-Bootstrapping

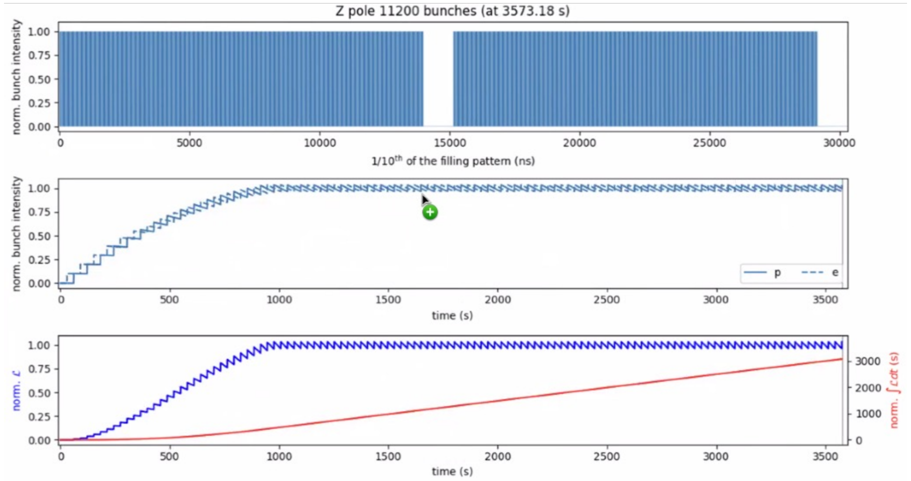
- With the nominal bunch population required for high luminosity, σ_z increases ~3.5 times because of beamstrahlung.
- If we bring into collision so large currents with the “initial” σ_z (energy spread created only by SR), the beam-beam parameters will be far above the limits.
- The beams will be blown up and killed on the transverse aperture, before they are stabilized by the beamstrahlung.
- To avoid this, we must gradually increase the bunch population during collision, so we come to *bootstrapping*.



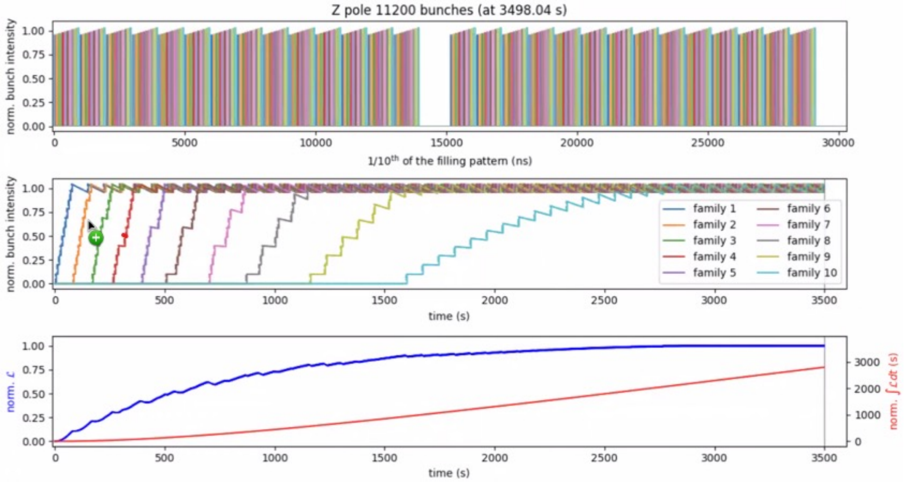
Courtesy Dmitry Shatilov

Revised Filling Scheme to control electron cloud

“CDR scheme”



“Carli-Bartosik scheme”



only 1/10 of intensity per booster cycle
- vacuum pressure-tolerant

only 1/10 of collider bunches at intermediate intensity
- anti e-cloud build up

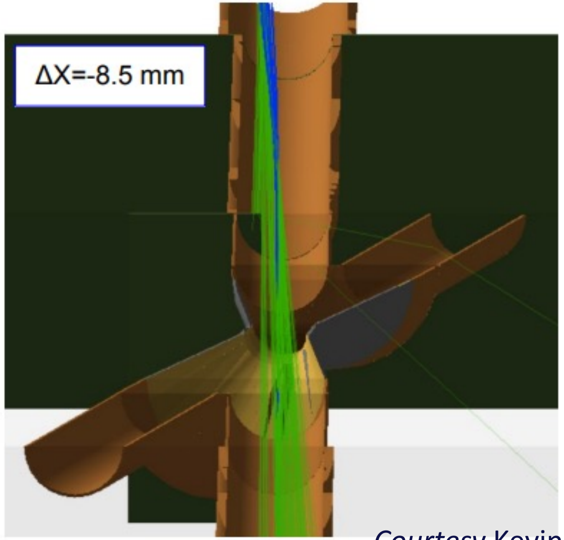
yet same integrated luminosity as for CDR scheme !

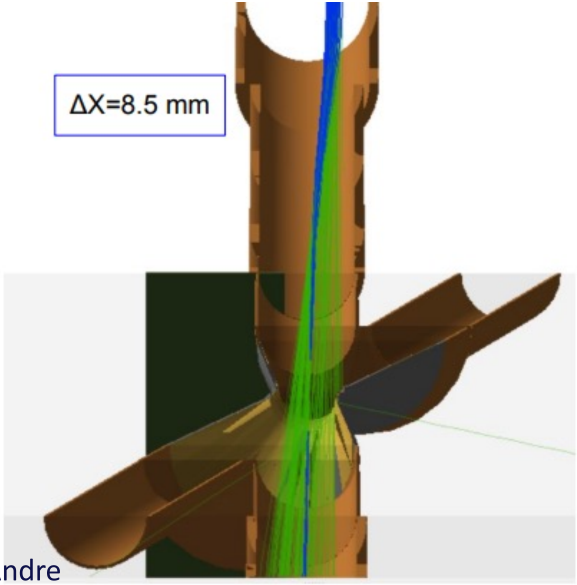
H. Bartosik, C. Carli, L. Mether, F. Zimmermann

Top-up injection

Required **with few percent of current drop** to keep a constant luminosity (lifetime is ~15 min).

Off-axis top-up injection challenging at Z due to large orbit excursion and slow damping.
SR intercepted by the last mask ∼0.2mJ/Xing compared ∼0.8μJ/Xing from colliding beam





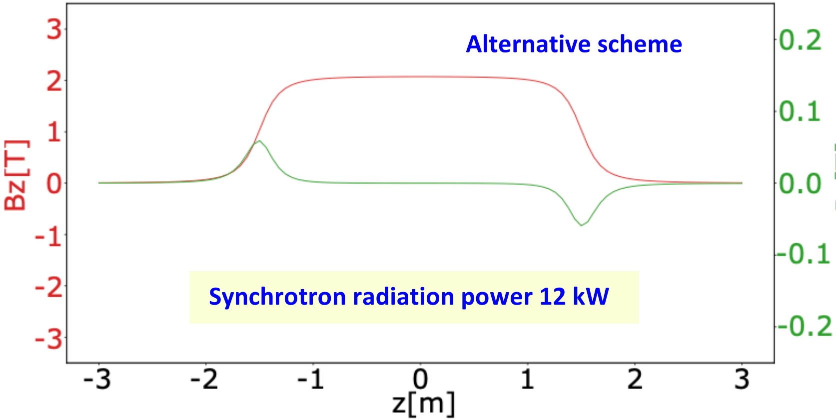
Courtesy Kevin Andre

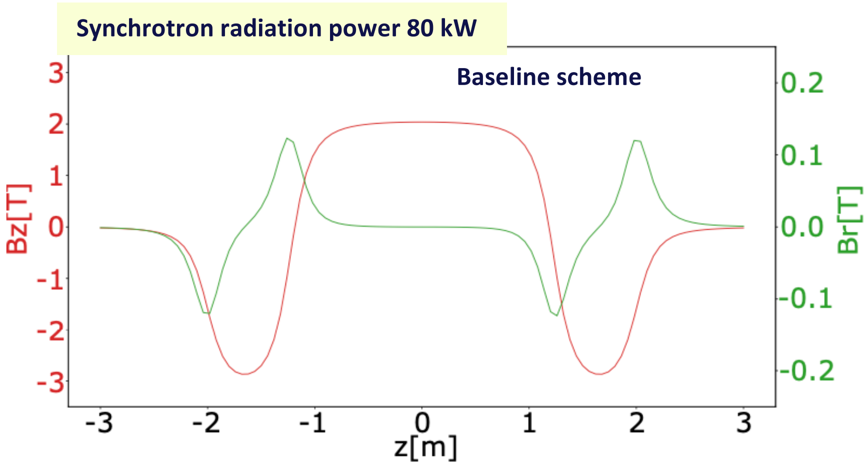
preference for longitudinal injection

https://doi.org/10.18429/JACoW-IPAC2024-TUPC68

Solenoid Coupling Compensation Scheme

Longitudinal and radial magnetic fields along the 15 mrad axis





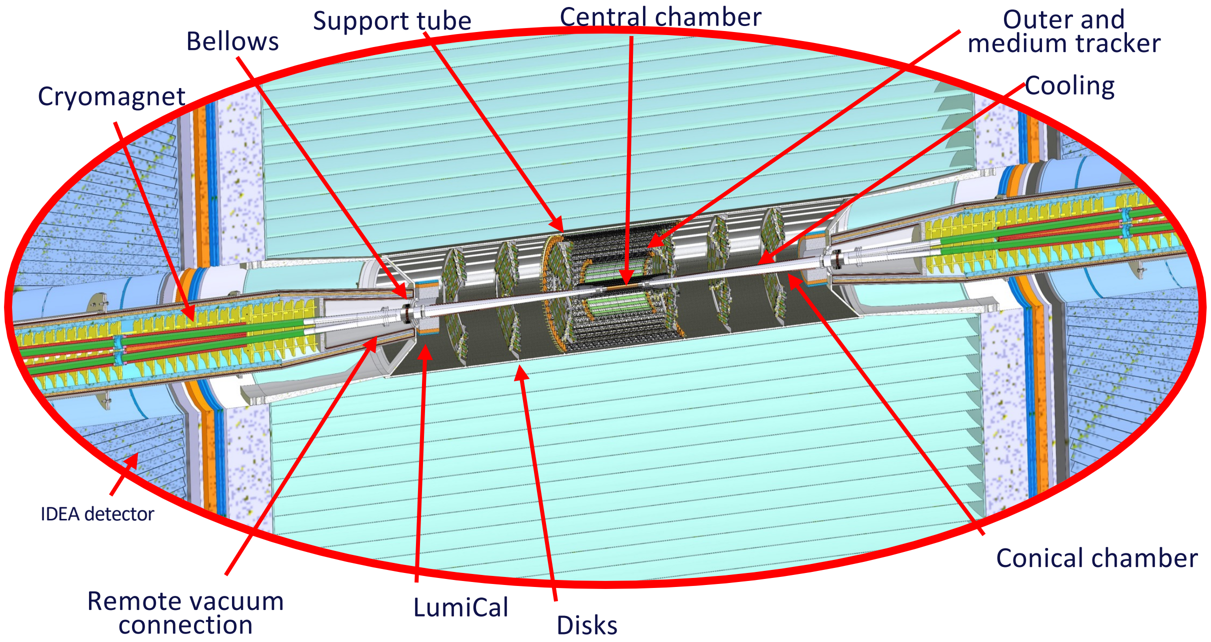
Skew quadrupolar components in the FFQs align the magnet axis to the rotated reference frame of the beam

Correctors right after the beam pipe separation and around the FFQs compensate the orbit distortion generated by the horizontal crossing angle in the detector field

Alternative scheme:

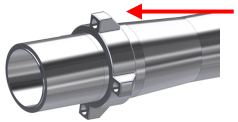
- Vertical emittance increase is only 0.2% of the nominal value of 1 pm.
- Chromatic behavior of the vertical emittance increase small in the range of dE/E = ±4%.

FCC-ee engineered Interaction Region



Design in continuous optimization:

- vacuum chamber copper cooling manifolds replaced by AlBeMet to minimize showers in the LumiCal

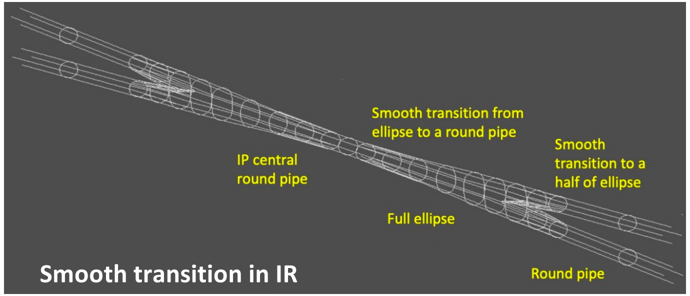


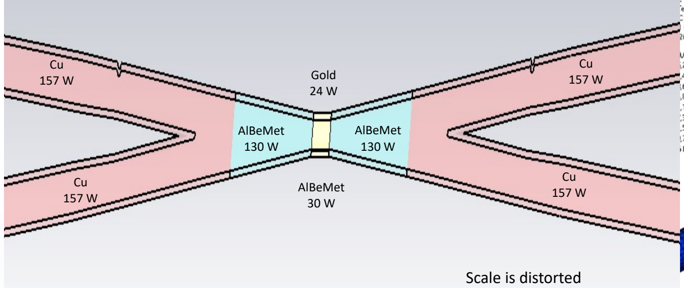
Inlet/outlet paraffin cooling for central chamber

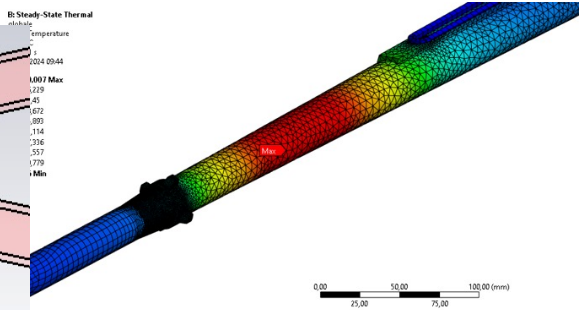
- More advanced and detailed studies on vertex detector integration
- IR magnet system to be integrated
- Remote vacuum connection to be designed
- Crucial area: a full-scale mockup assembly has started

Ref: M B , F. Palla, et al., *Mechanical model for the FCC-ee MDI,* EPJ+ Techn. and Instr., https://doi.org/10.1140/epjti/s40485-023-00103-7
M. B. et al., Progress in the design of the future circular collider FCC-ee interaction region, IPAC24, 18-25 May 2024, Nashville, USA, DOI: 10.18429/JACoW-IPAC2024-TUPC67

Low-impedance IR vacuum chamber







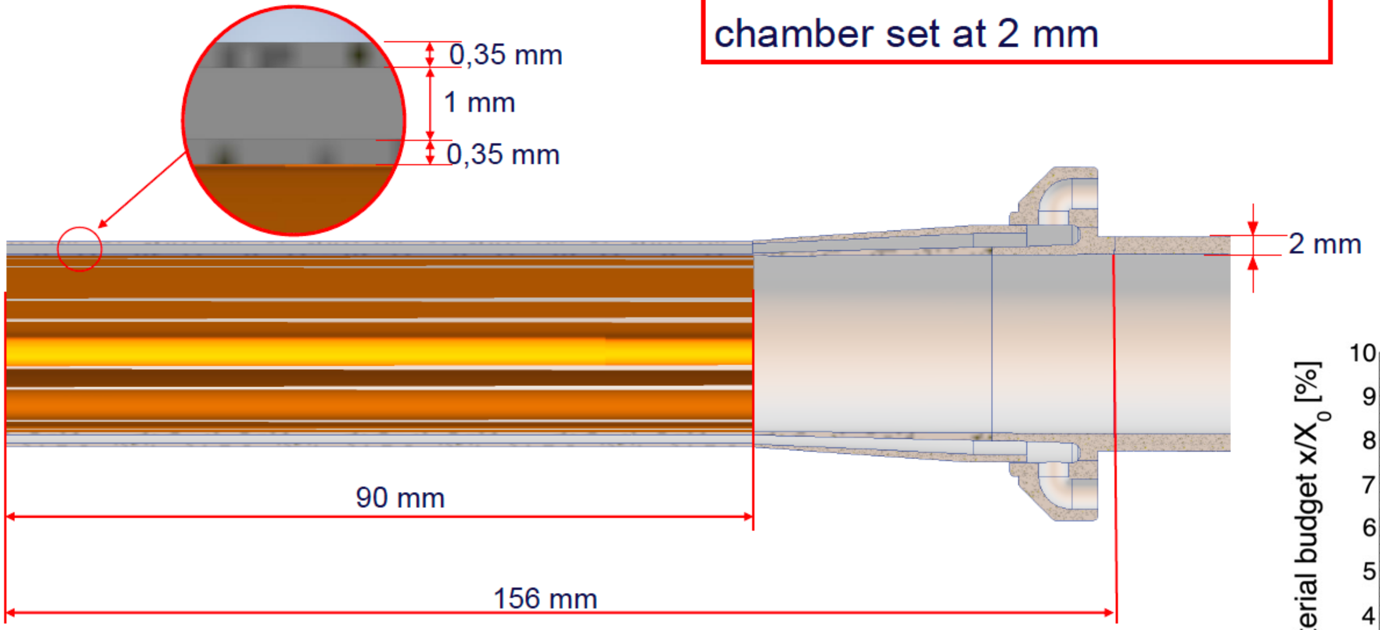
beam energy [GeV]	45
beam current [mA]	1280
number bunches/beam	1000
rms bunch length with SR / BS [mm]	4.38 / 14.5
bunch spacing [ns]	32

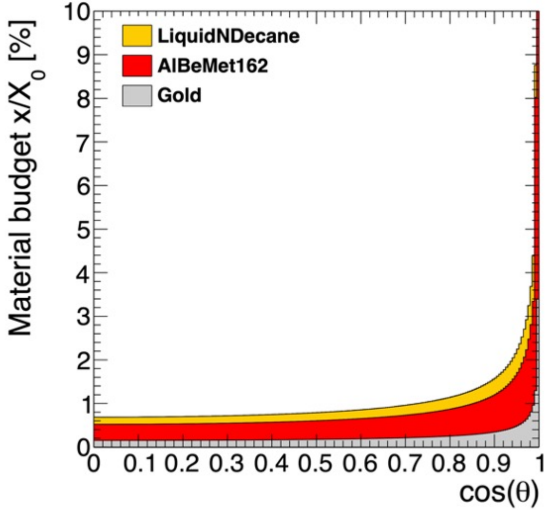
	conical chamber	central chamber
coolant	water	paraffin
T_{max} (chamber)	50°C	29°C
T_{max}(coolant)	18 °C	20 °C

Study and optimization of the material budget for the beam pipe has been performed and is in progress. LumiCal requirements and material budget minimization considered, also comparing Be with AlbeMet.

Thickness of the chamber

Uniform thickness of the conical chamber set at 2 mm



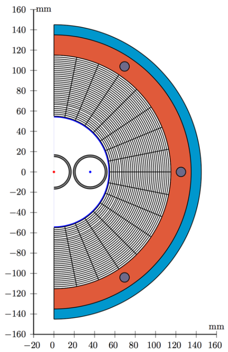


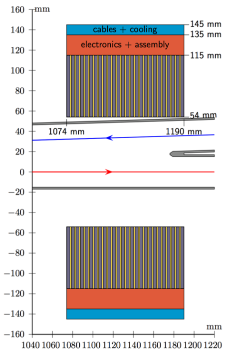
LumiCal constraints & requirements

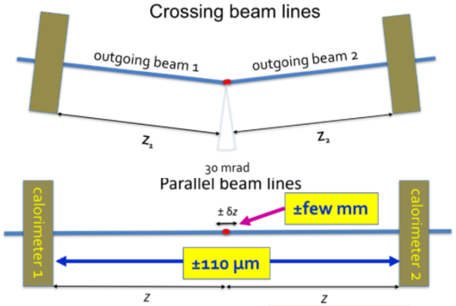
Goal: absolute luminosity measurement 10^{-4} at the Z

Standard process Bhabha scattering

- Bhabha cross section 12 nb at Z-pole with acceptance **62-88 mrad** wrt the outgoing pipe
- Requires **50-120 mrad clearance to avoid spoiling the measurement**
- The LumiCals are centered on the outgoing beamlines with their faces perpendicular to the beamlines
- Requirements for alignment
  - few hundred µm in radial direction
  - few mm in longitudinal direction



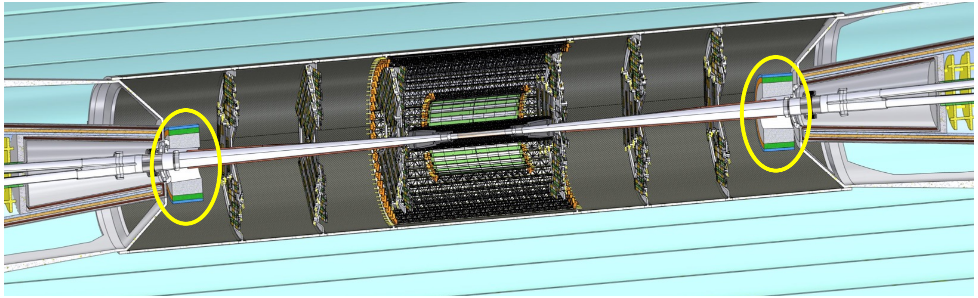




M. Dam

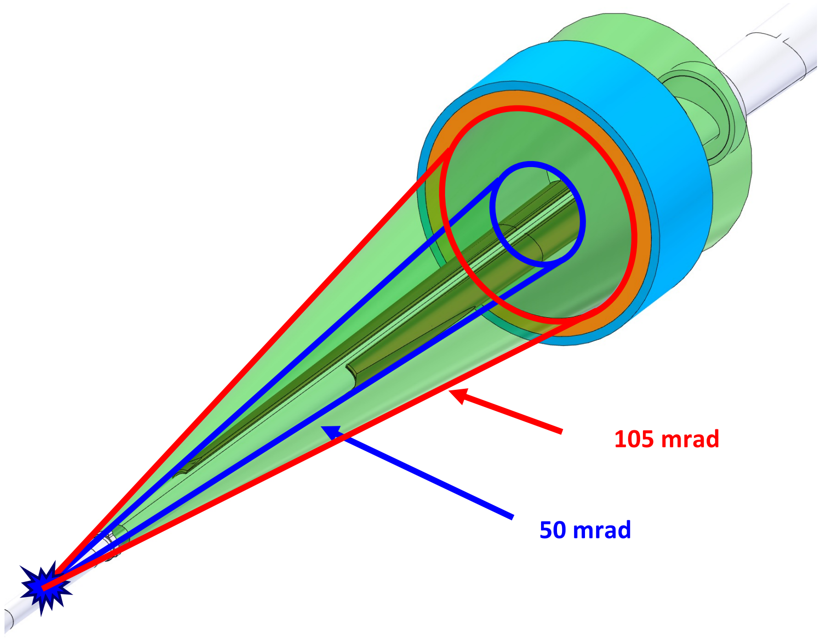
Lumical integration:

- **Asymmetrical cooling system** in conical pipe to provide angular acceptance to lumical
- **LumiCal held by a mechanical support structure**

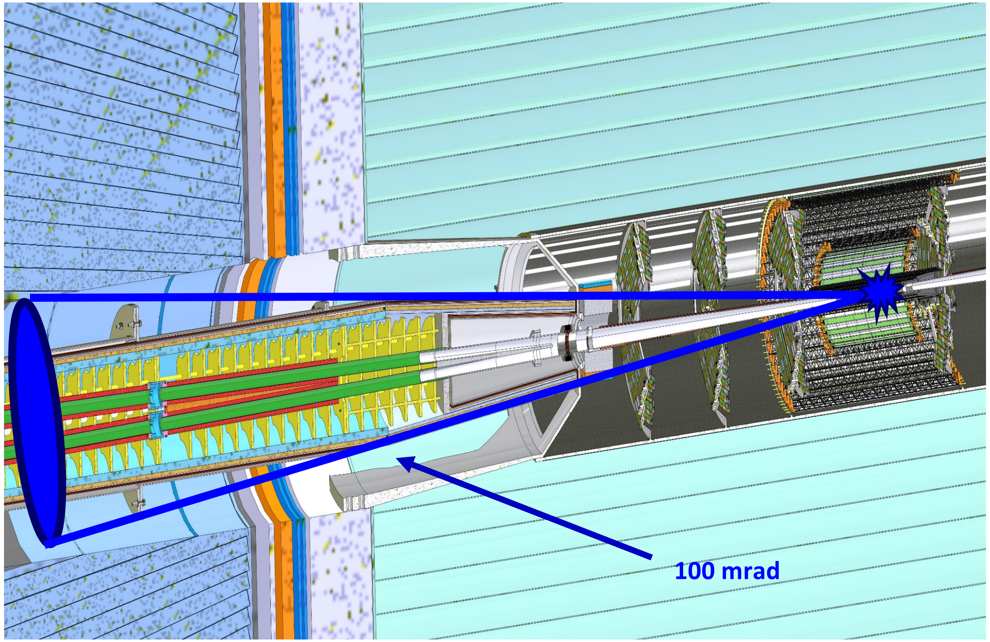


Spatial constraints

To achieve the required performance, it is necessary to have **low material budget** within the LumiCal acceptance (between **50 mrad** and **105 mrad** centered on the outgoing beam pipe).



Every component of the MDI must stay inside the **100 mrad detector acceptance** cone.



Status of Beam Backgrounds studies

First studies due to luminosity backgrounds (IPC) on detector hit occupancies have been evaluated.

Synchrotron radiation in the IR simulated in detail up to the internal beam pipe.
First evaluation of beam-gas losses up to the internal beam pipe.

Next steps necessitates to track those particles

- up to suitable surface before the detector to allow detector hit occupancies
- evaluate energy deposits in the machine components

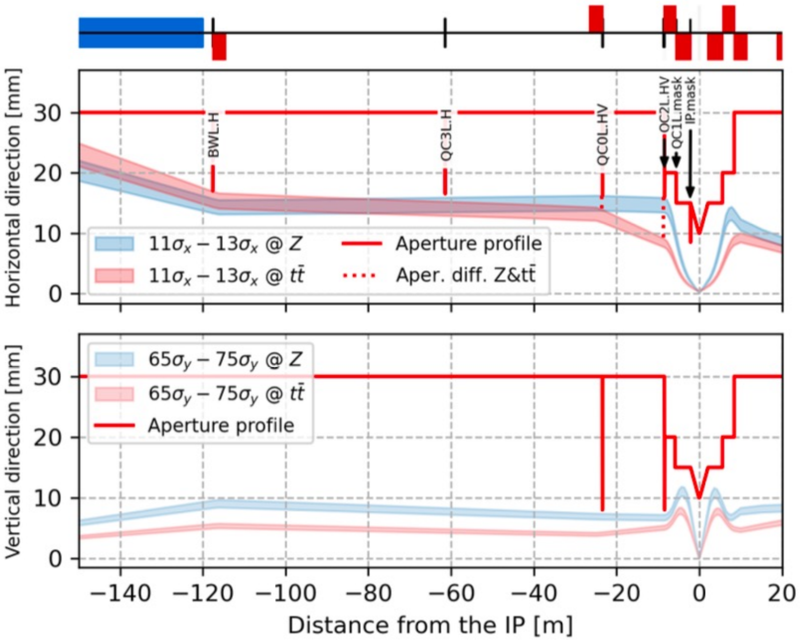
Synchrotron Radiation backgrounds

Simulations with **BDSIM** (GEANT4 toolkit), featuring SR from Gaussian beam core and transverse halo.

Characterisation of the SR produced for **all beam energies**.

SR produced upstream the IP:

- by the **last dipoles and quadrupoles upstream the IR** can be a background source, to be collimated and masked
- by the **IR quads and solenoids** collinear with the beam and will hit the beam pipe at the first dipole after the IP.



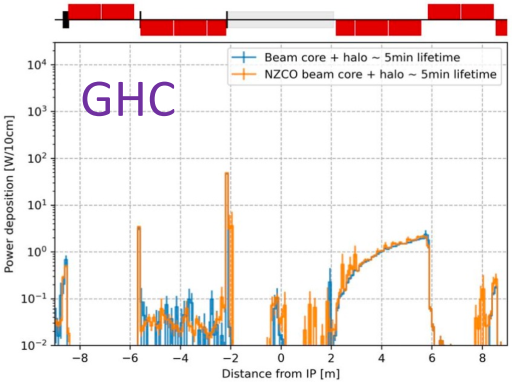
Courtesy Kevin Andrè

Synchrotron Radiation background

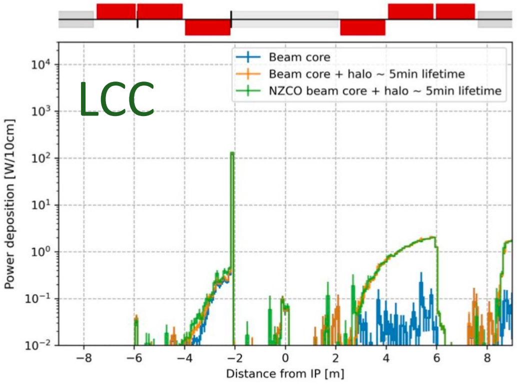
Courtesy Kevin Andrè

BDSIM (Geant4 based) simulation with comparison of **GHC and LCC optics at Z and ttbar: similar power deposited** near the IP was founded.

Results at Z energy



GHC - SR power deposition summary
1% of the particles in the tails, with beam lifetime equivalent to 5 min, and 100 um X&Y and 6 urad PX&PY applied to the NZCO beam core.



LCC - SR power deposition summary
1% of the particles in the tails, with beam lifetime equivalent to 5 min, and 100 um X&Y and 6 urad PX&PY applied to the NZCO beam core.

Power deposition ± 8 m from IP

Power deposition on the vacuum chamber from SR evaluated for

- tilted beams
- beam tails
- injected beams
- various optics versions

SR collimators and masks defined

Next steps

- Include X-ray in the simulation
- SR during filling and top-up injection
- Track these photons in subdetectors

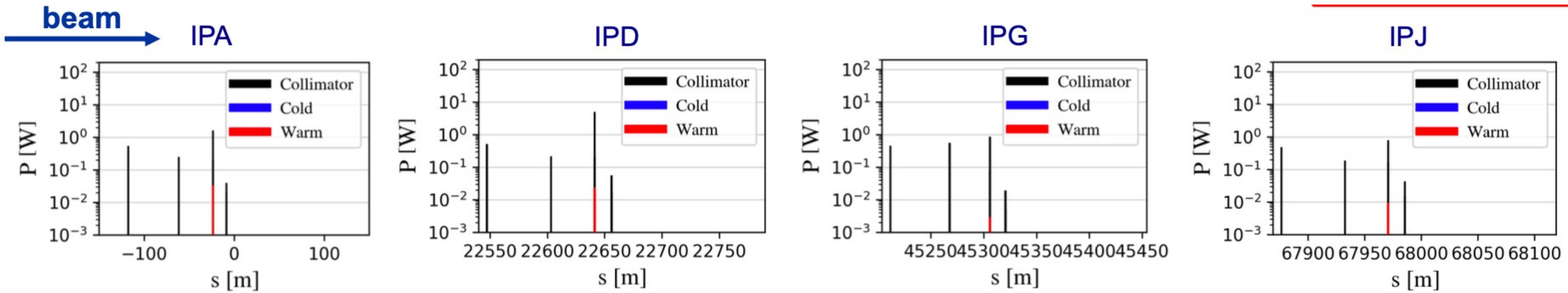
Beam-gas beam losses and MDI collimators

Courtesy Giacomo Broggi

Beam-residual gas interactions implemented in the **Xsuite-BDSIM** simulation tool

First estimated beam-gas lifetime (dominated by bremsstrahlung):

$\tau_{eBrem} \sim 3h\ 20min$



- SR collimators intercept the vast majority of beam-gas beam losses in the IRs

Next steps

- Consolidate results
- Other beam operation modes
- Impact on detector backgrounds

MDI Vacuum

- Pressure profiles for the ~600 m upstream and ~500 m downstream of the IP have been computed: it has been found that adopting a fully NEG-coated vacuum chamber with additional lumped NEG pumps at strategic locations (near SR absorbers) would allow obtaining a pressure in the **10^{-10} mbar range after ~100 Ah of integrated beam dose (for the Z-machine)**. **Starting the FCC-ee at higher energies (e.g. H) would therefore need a longer time to condition**, since the beam current is much lower compared to the Z case (~50x lower). **The final solution cannot be given until the MDI optics is not finalized.**
- In order to make a more precise vacuum commissioning scenario **it is important to use the real beam energy commissioning scenario**, the ideal case being starting at the Z energy since it has a much higher SR photon flux, and therefore accelerated decrease of the dynamic pressure.
- MDI-specific vacuum issues, e.g. gold- and **NEG-coating** of the IP chambers will be tackled soon.

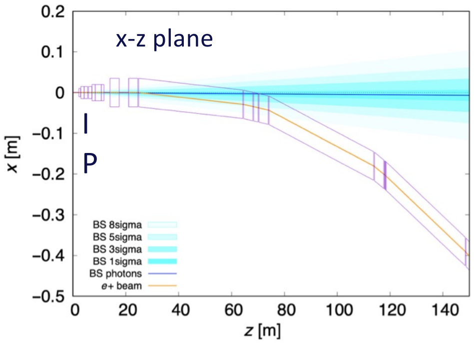
↓

Bake-out

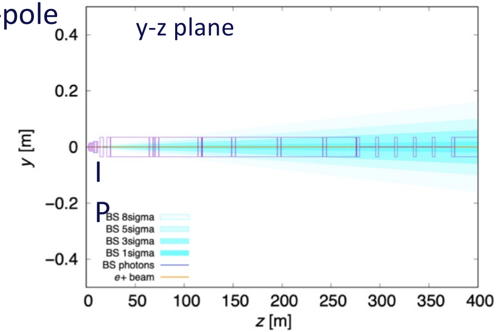
Courtesy from R. Kersevan

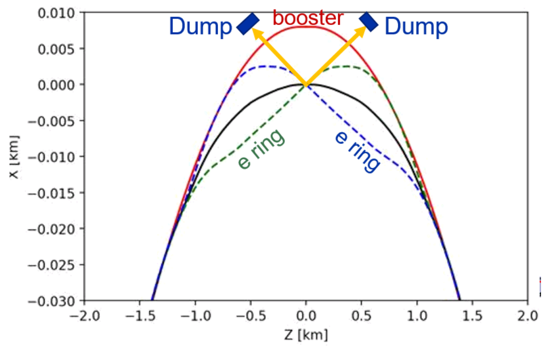
Beamstrahlung Radiation

Radiation from the colliding beams is very intense 400 kW at Z



Z-pole





Dump placed 500 m from IP in order to have enough separation from booster / collider (space for shielding)

MB and A. Ciarma, "Characterisation of the Beamstrahlung radiation at FCC-ee", PRAB 26, 111002 (2023), link

High-power beam dump needed to dispose of these BS photons **+ all the radiation from IR**: FLUKA simulation ongoing

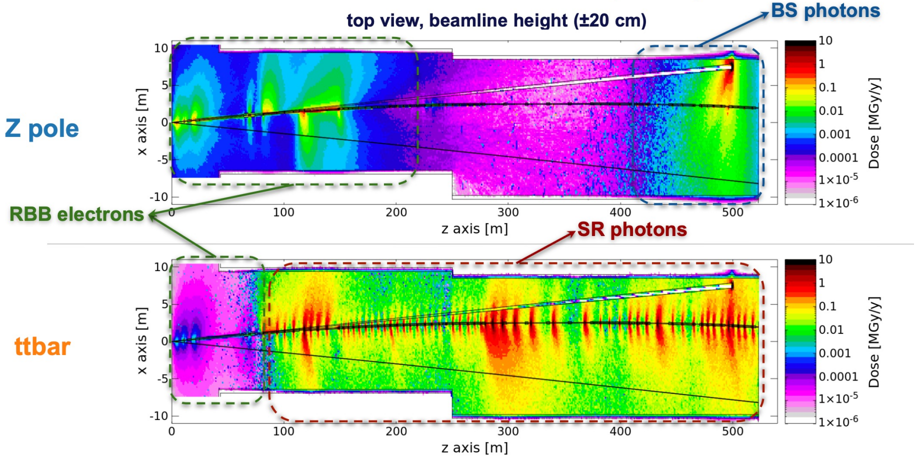
- Different targets as dump absorber material are under investigation
- Shielding needed for equipment and personnel protection for radiation environment

Radiation dose from Fluka simulation in the MDI area

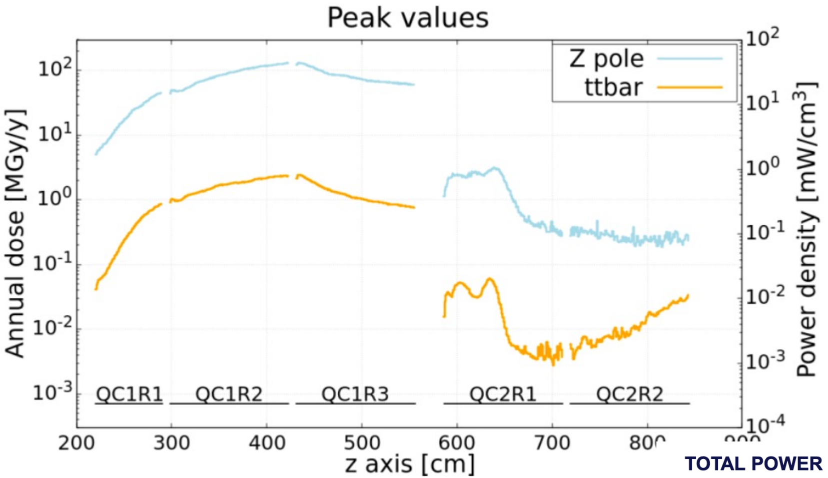
Courtesy Alessandro Frasca

Beamstrahlung dump

Annual TID in the tunnel from BS, SR, and RBB



Power deposition in FFQs SC coils from radiative Bhabhas



5 mm of tungsten ensures
- peak dose: 3 MGy/y
- peak power density deposition: 1 mW/cm³

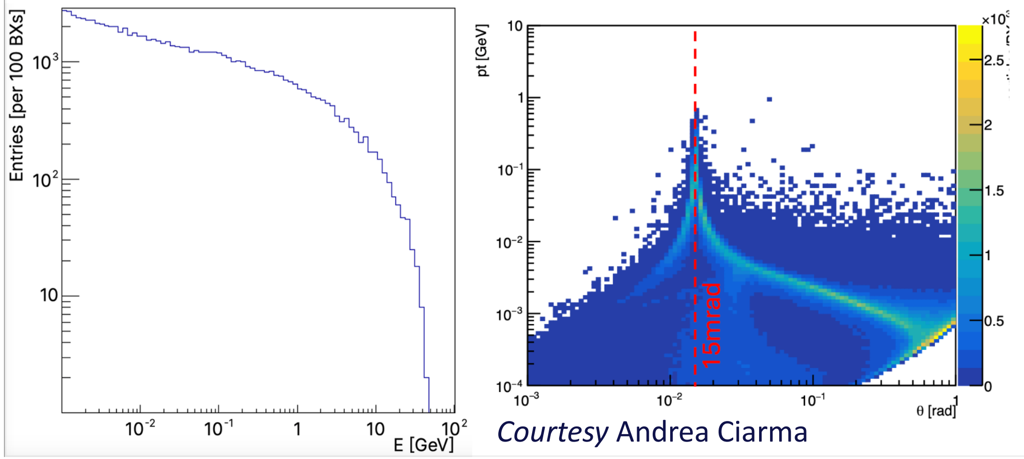
TOTAL POWER DEPOSITED

	Z pole	ttbar
QC1R1	0.30 W	3.4 mW
QC1R2	1.54 W	20.4 mW
QC1R3	2.00 W	29.7 mW
QC2R1	0.20 W	1.9 mW
QC2R2	0.04 W	1.8 mW

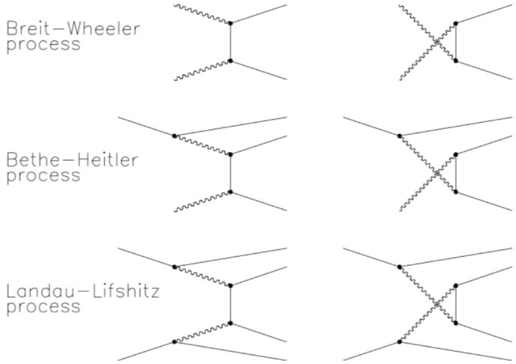
Incoherent Pairs Creation (IPC)

Secondary e+e- pairs produced during bunch crossing via the interaction of beamstrahlung photons with real or virtual photons.

Z pole, V23 optics, GuineaPig++



Courtesy Andrea Ciarma



see talk by A. Ilg

- Cluster size of 5, safety factor of 3, 25 μm pitch pixels
- Cut at 1.8 keV of deposited energy (500 e-)

First occupancy and hit rates calculations in the vertex detector

	FCC-ee	ALICE ITS3
Occupancy	$\sim 20\times10^{-6}$	$\sim 30\times10^{-6}$
Hit rate	$170\ MHz/cm^2$	$250\ MHz/cm^2$

Next steps

- ❑ Study the integration of the services and add other components (i.e. bellows, bpm,…)

- ❑ Beam induced backgrounds
  - Activity on the software and MDI model level, great effort done, to be continued in the next months.
    - Halo beam collimators implemented.
    - IP backgrounds evaluated.
    - Single beam effects (e.g. beam-gas, thermal photons, Touschek) being implemented in Xsuite.
    - SR backgrounds studied in different conditions and baseline/LCCO optics was compared.
    - Injection backgrounds
    - Study of IR radiation level & fluences started (Fluka)
  - Results to be used by the detectors to estimate their backgrounds, and feedbacks to MDI to optimize shieldings, masks and collimators.
  - Beamstrahlung dump with radiation levels

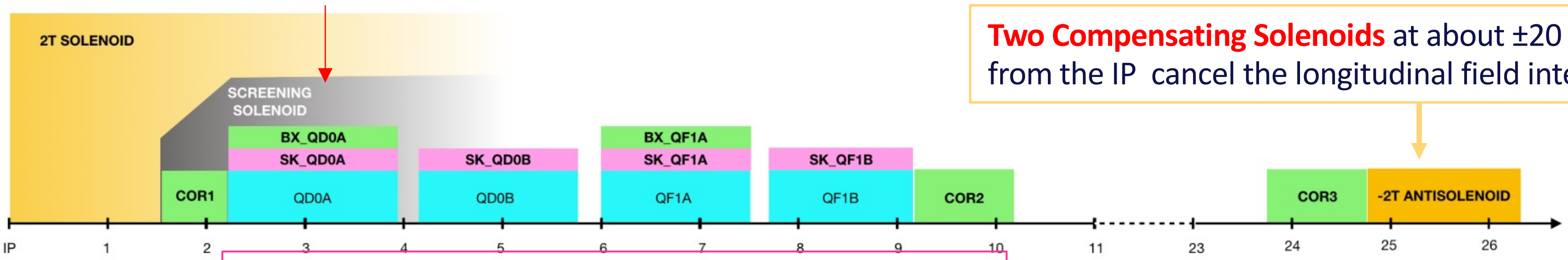
And thanks to many people for inputs!

Alternative Solenoid Compensation Scheme

Details in: IPAC2024- TUPC68, "Alternative Solenoid Compensation Scheme for the FCC-ee Interaction region", A. Ciarma, M.B., H. Burkhardt, P. Raimondi: link

A **Screening Solenoid** shields the Final Focus Quads

Two Compensating Solenoids at about ±20 m from the IP cancel the longitudinal field integral



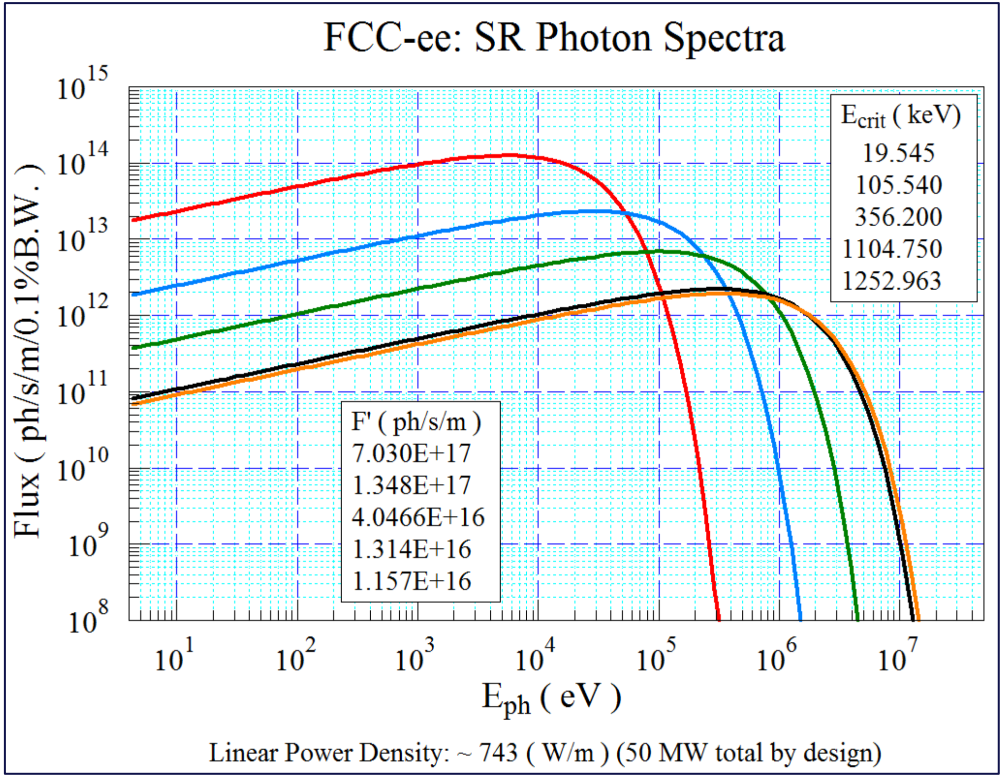
skew quadrupolar components in the FFQs align the magnet axis to the rotated reference frame of the beam

correctors right after the beam pipe separation and around the FFQs compensate the orbit distortion generated by the horizontal crossing angle in the detector field

- **This solution is optics independent.**
- **The tuning knobs -correctors and skews- are needed for orbit and coupling correction for all optics.**

SR spectra in the arcs – not in the IR!

- **Z-Pole: very high photon flux (→ large outgassing load);**
- **t-pole (182.5): extremely large and penetrating radiation, critical energy 1.25 MeV;**
- **t-pole (and also W and H): needs design which minimizes activation of tunnel and machine components;**
- **W, H-pole: intermediate between Z and T; still E_{crit} > Compton edge (~100 keV)**



Courtesy by R. Kersevan