CHALLENGES OF MDI FOR FUTURE HIGGS FACTORIES

Manuela Boscolo (INFN-LNF)

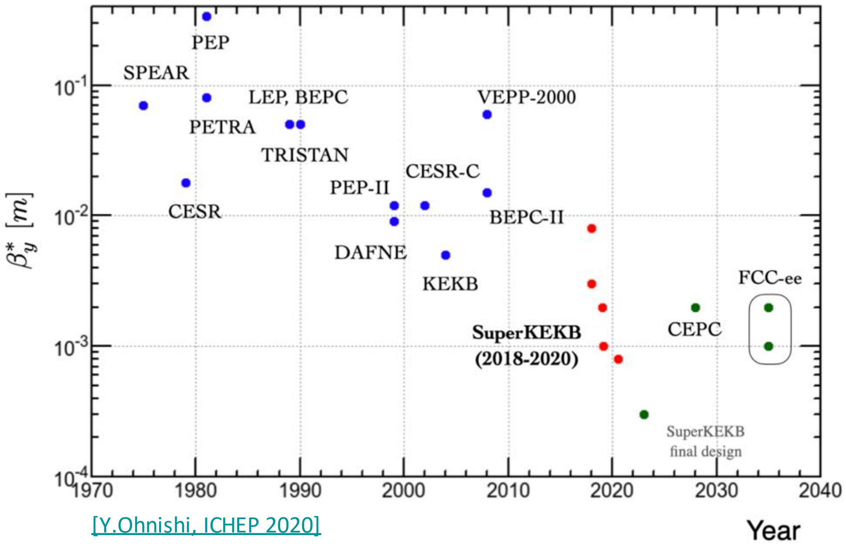
The 2025 International Workshop on the High Energy Circular Electron Positron Collider
Guandzhou 4-10 November 2025

Context

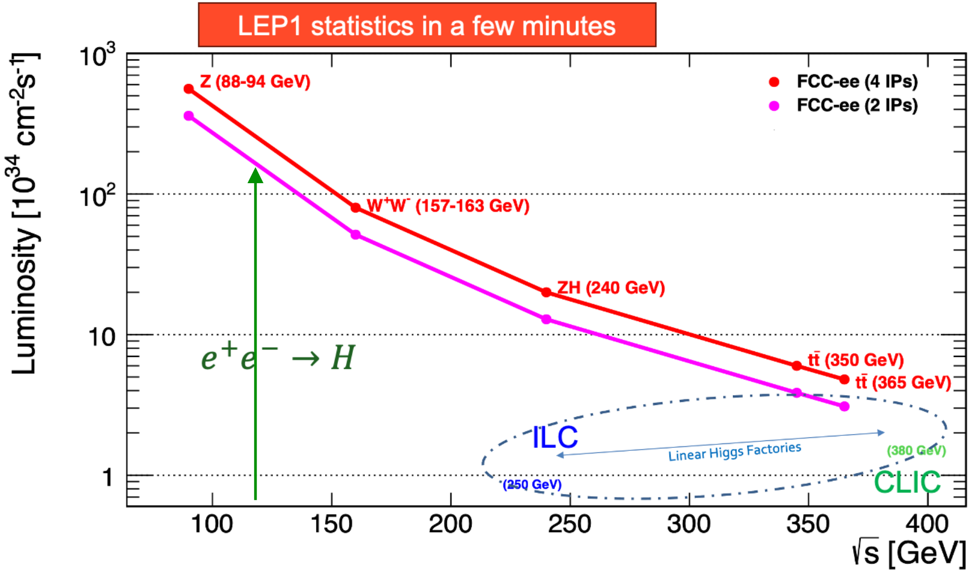
- The proposed designs for e^+/e^- colliders Higgs Factories (FCC-ee, CEPC, CLIC, LCF, LEP3) show a similar level of complexity and challenges, in particular for what concerns the Machine Detector Interface (MDI).
- Circular colliders offer more flexibility for the operation at different energies at high luminosity.
- SuperKEKB provides experience for FCC-ee/CEPC/LEP3 in further understanding and addressing potential limitations and devising solutions.

Future e+e- Colliders Performance

e+e- circular: vertical squeeze at IP



[Y.Ohnishi, ICHEP 2020]



Challenges on MDI design

Hardware

- **Small L* → QD0 inside detector**
  - trade-off between detector hermeticity and cryostat clearances
- **Integration**
  - Minimise impact of services on detector
- **Beam pipe**
  - material budget
  - Y-pipe very close to the IP and inside the detector
  - Active cooling for circular colliders
- **Alignment**
  - Stringent requirements of FFQs and LumiCal
- **Vibrations** suppression at the IR and vertex detector
- **Beamstrahlung and SR dump (~ hundreds of kW)**
  - dedicated alcove, radiation, target at dump

Performance

- **High Luminosity**
- Robustness against **beam-induced and IP backgrounds**
  - IPC dominant especially for LC
  - SR backgrounds
- **Collimation**
- **Radiation** environment, and occupancy and spurious hits

Challenges on MDI design

Hardware

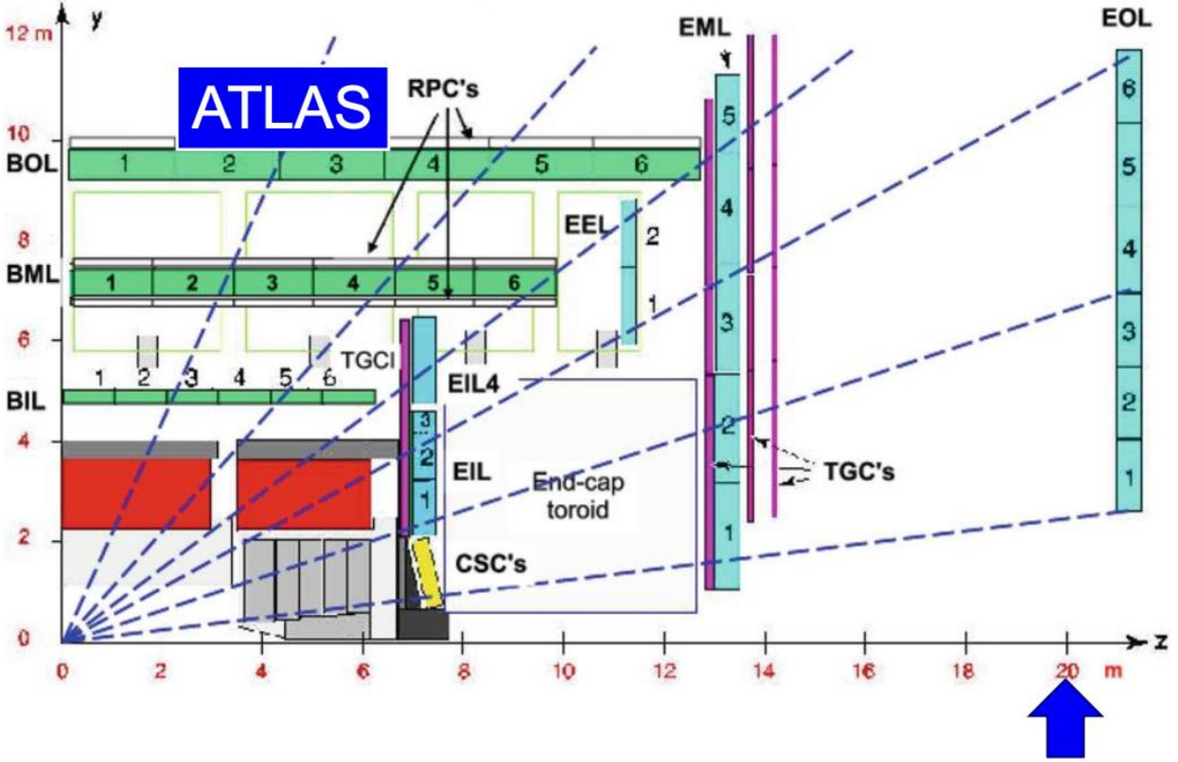
- **Small L* → QD0 inside detector**
  - trade-off between detector hermeticity and cryostat clearances
- **Integration**
  - Minimise impact of services on detector
- **Beam pipe**
  - material budget
  - Y-pipe very close to the IP and inside the detector
  - Active cooling for circular colliders
- **Alignment**
  - Stringent requirements of FFQs and LumiCal
- **Vibrations** suppression at the IR and vertex detector
- **Beamstrahlung and SR dump (~ hundreds of kW)**
  - dedicated alcove, radiation, target at dump

Performance

- **High Luminosity**
- Robustness against **beam-induced and IP backgrounds**
  - IPC dominant especially for LC
  - SR backgrounds
- **Collimation**
- **Radiation** environment, and occupancy and spurious hits

→ **part of the ECFA-DRD8-WP1 Collaboration on Mechanics & Integration (FCC-ee, CEPC)**

Comparison between LHC and FCC-ee MDI



Last accel. element 2.2 m

Last accel. element 20 m

IR Overview of future Higgs factories

e^+e^- Circular

- uniform luminosity distribution in time (CW), top-up injection
- new concept of nano-beams to increase luminosity, very far from LEP2 rates and step forward also from flavour factories, go toward LC,
- compact IR (L*↓)
- tight mechanical space constraints, including FF quads and IR correctors
- high crossing angle
- High beam energy → SR
- High intensity → heating, vacuum
- Beamstrahlung relevant like for LC, incoherent pairs

e^+e^- Linear

- high instantaneous luminosity within bunch train (low O(10Hz) rep rate)
- higher occupancy at the same ave Luminosity
- very low-β demands for the ultimate final focus quads design
- smallest beam size ever demands for tightest alignment specs, and fast feeback for beam steering
- IP bkgs, incoherent pairs, radiative Bhabha

Interaction Region rationale

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* (because β_y* must be constant along the overlap area to avoid hourglass effect)
- 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.

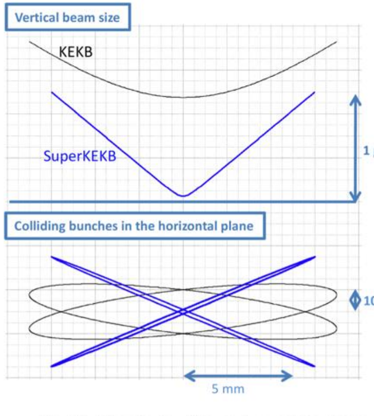
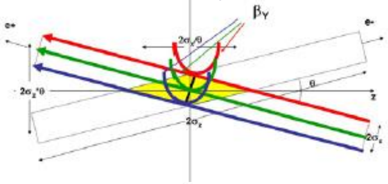
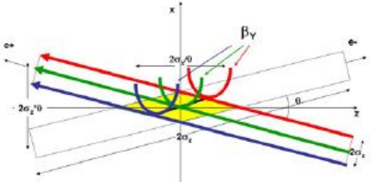


Figure 2: Schematic view of the nanobeam collision scheme.

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



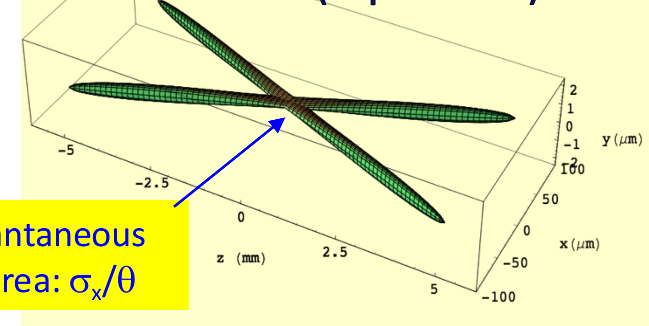
crab sextupoles off



crab sextupoles on

DAFNE, PRL 104, 174801 (2010)

IP beam distributions (SuperB case)



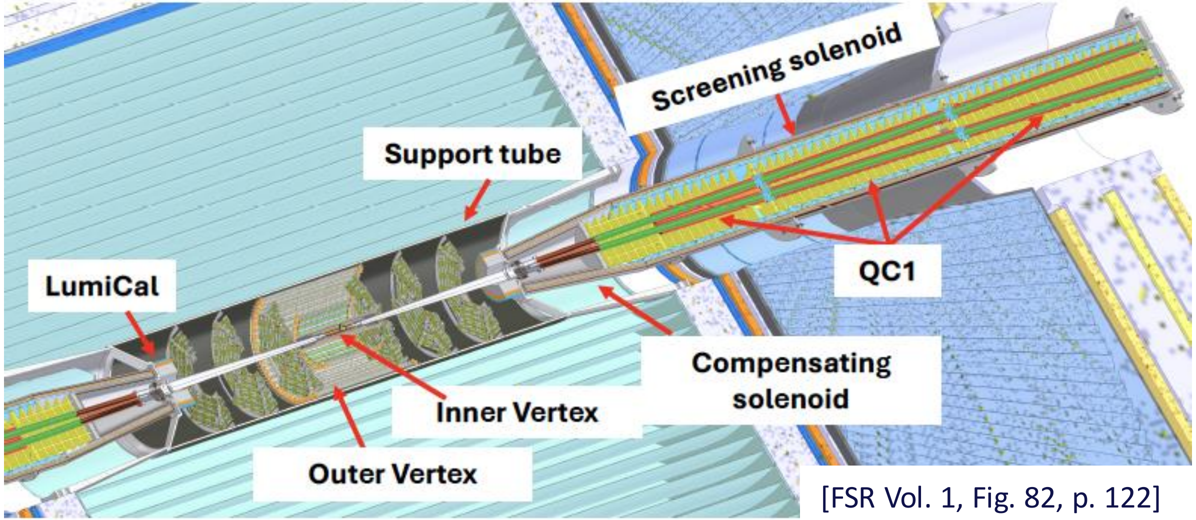
Small instantaneous collision area: σ_x/θ

FCC-ee MDI layout

IR magnet system inside the detector and is all cryogenic

- Compensating solenoid
- Final focus quadrupole QC1
- Screening solenoid

Space budget is difficult, especially for the first segment of QC1, due to the close proximity of the exterior of the two beam pipes because of their size and crossing angle.



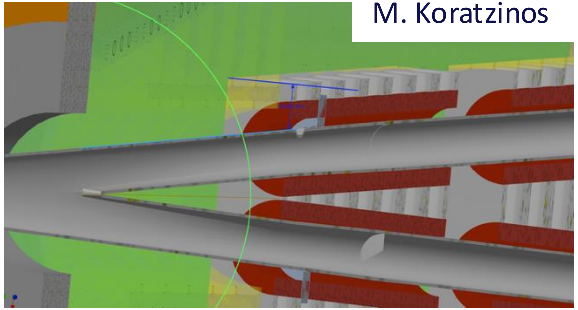
[FSR Vol. 1, Fig. 82, p. 122]

EPJ Techn Instrum (2025) 12:4 https://doi.org/10.1140/epjti/s40485-025-00117-3

Challenges on the FCC-ee final quadrupole

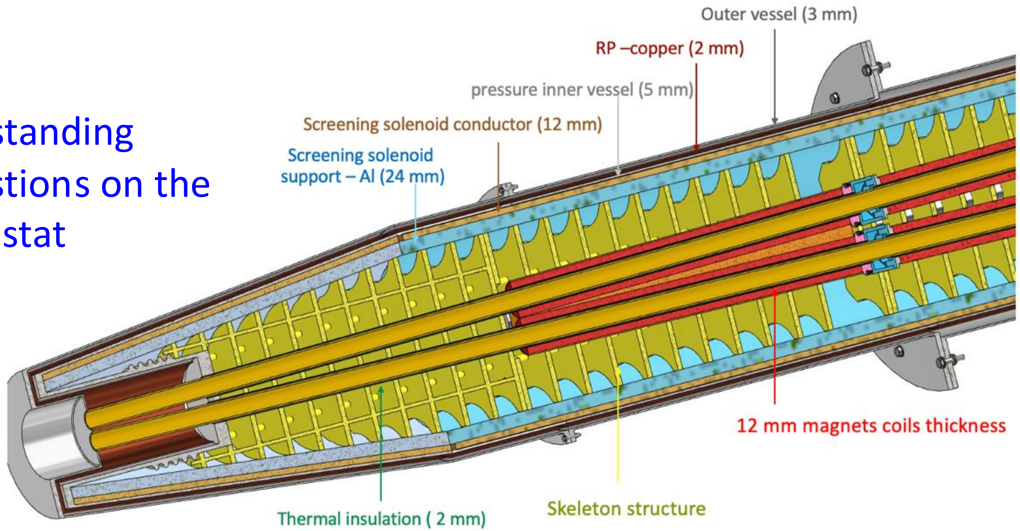
- Small distance of coils at first segment of QC1L1
- Need space for skew correctors winding to be added around QC1
- Need to allow few per cents of different strength of the FFQ
- Cryostat has to fit in the crowded MDI region

M. Koratzinos

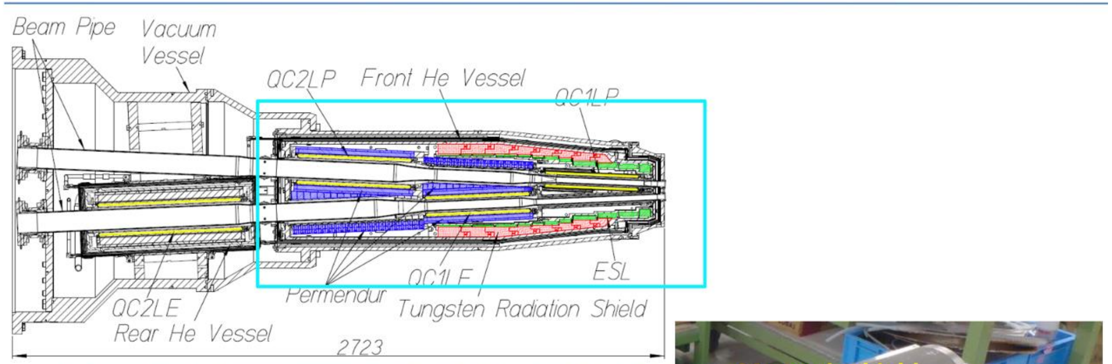


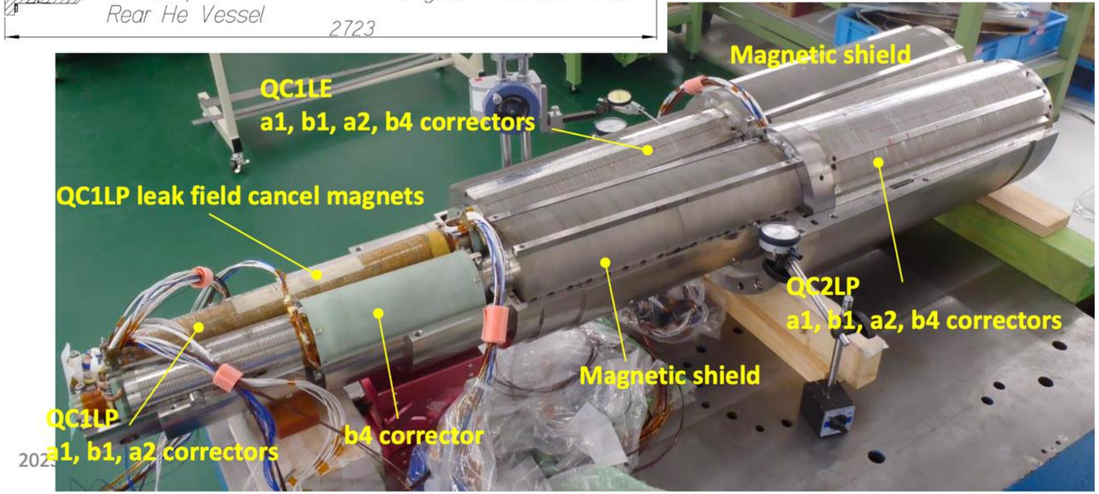
minimum distance between the magnetic centers of e+/e- for QC1L1 is (only) 66 mm

Outstanding questions on the Cryostat



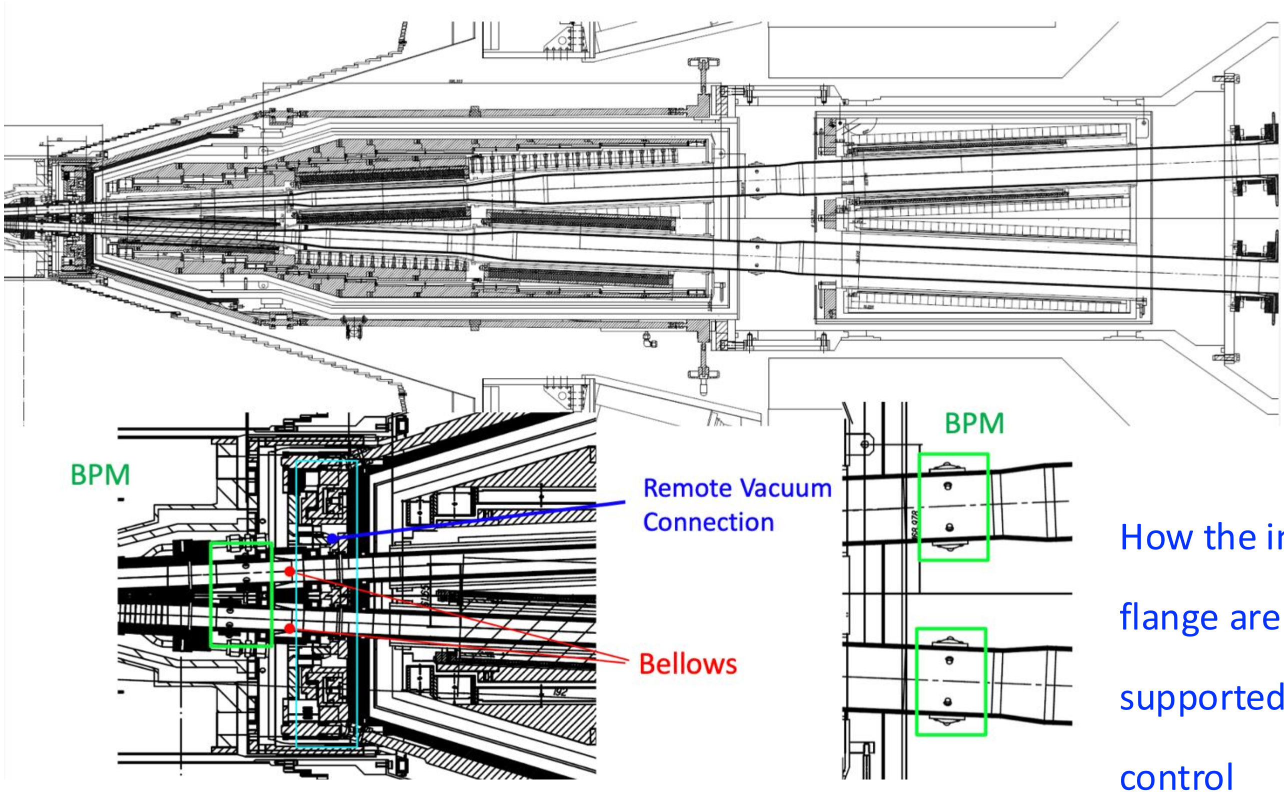
Challenge of SuperKEKB IR magnet integration





Courtesy N. Ohuchi

Challenge of SuperKEKB IR magnet integration

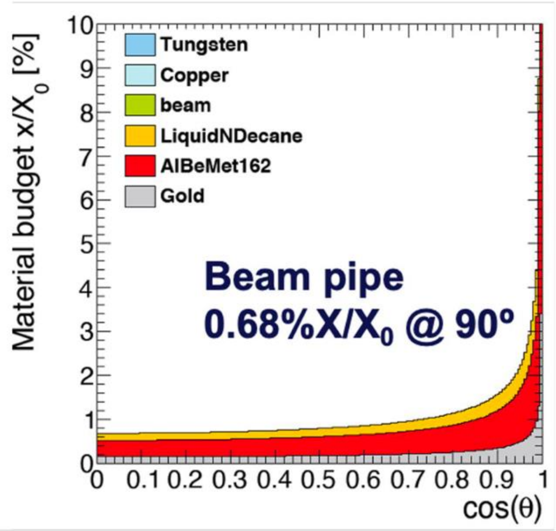


How the in-board BPM, bellows and magic flange are positioned and supported, overall alignment, vibration control

Courtesy N. Ohuchi

Challenges on the FCC-ee beam pipe

- **Beam pipes in AlBeMet (62% Be, 38% Al) up to LumiCal**
- **Central beam pipe 1 cm internal radius**
  - Internally 5 µm gold coated to reduce impedance and shield of sync. rad. photons.
- **Actively cooled due to impedance heat load**
  - Liquid paraffin for the central one (~60 W) and water for the lateral ones (~130 W).
- **Minimised material budget**
  - Central beam pipe double wall AlBeMet, paraffin and Au (0.68% X_0)
  - Lateral beam pipes minimised within LumiCal acceptance: (mostly 7% X_0, few regions up to 50% of X_0). Shaped to minimise showers off manifolds



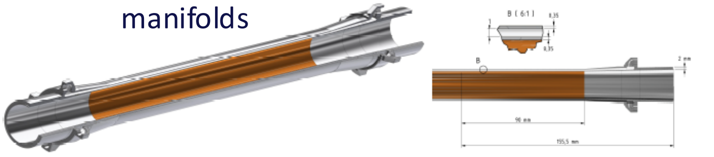


Fig. 48: Central chamber in AlBeMet162 including cooling inlets and outlets (left); cross-section view and zoom of the structure of the cooling channel for the paraffin flow.

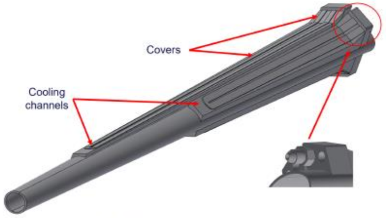
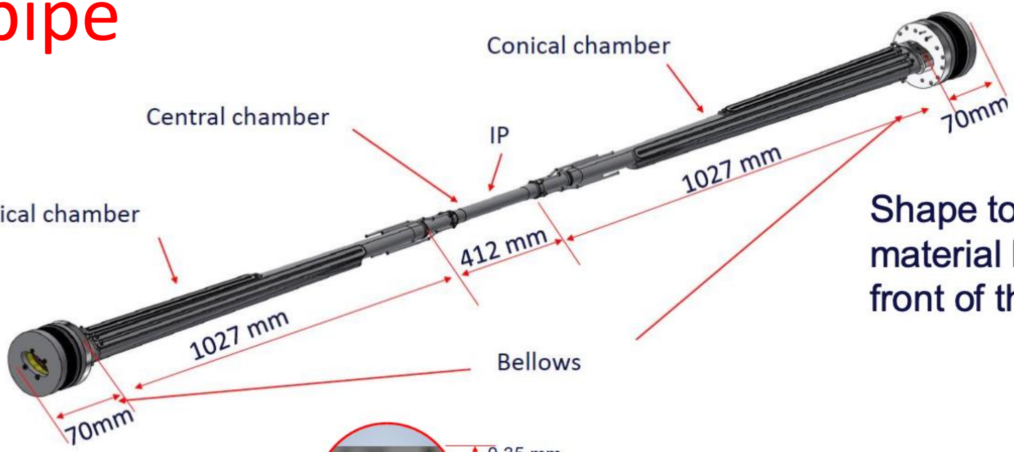


Fig. 49: Ellipto-conical vacuum chamber.

FCC-ee beam pipe

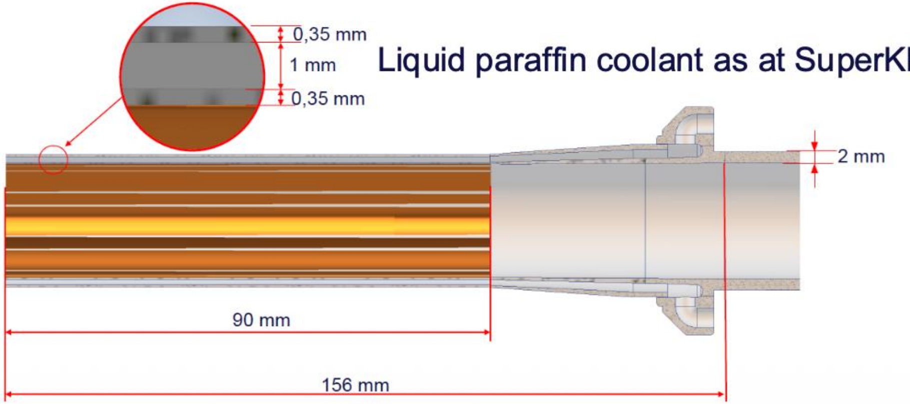
2 cm diameter at the IP
18 cm long
350 μm thick
AlBeMet (38% Al 62% Be)

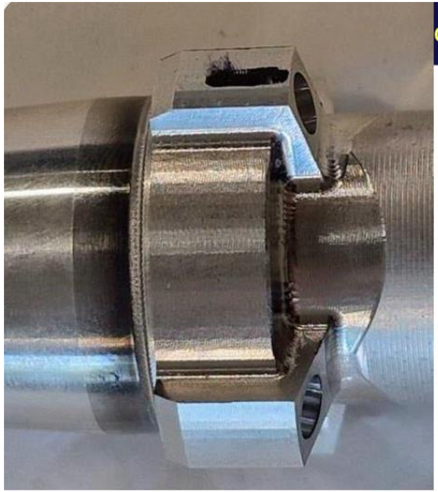


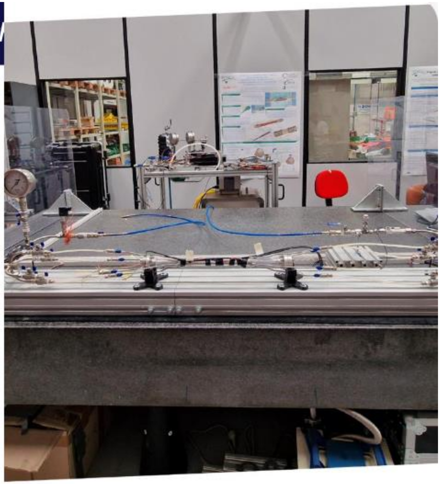
Shape to minimise material budget in front of the LumiCal

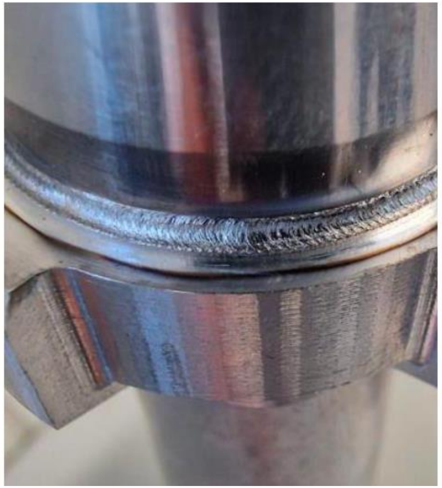
Internal 5 μm gold coating

Liquid paraffin coolant as at SuperKEKB





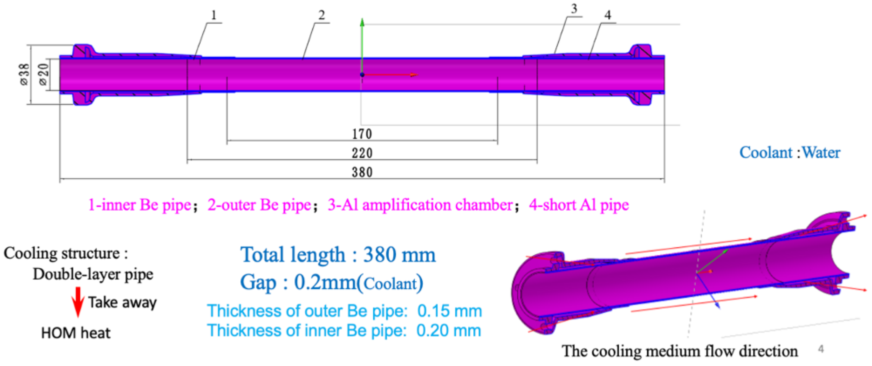


FCC-ee interaction region mockup (INFN Frascati)

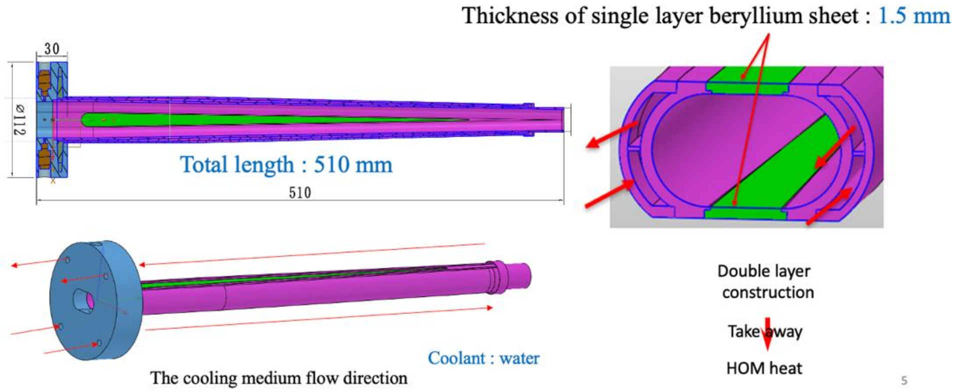
- Thin Al beampipes (2 cm diameter and 450 μm thick)
- Liquid paraffin (central) and water (lateral) cooled
- Manufactured at Comeb s.r.l. (IT)
- Electron-beam welded at Ravenscourt Eng. Ltd (UK)
- Next steps:
  - bellows and CF composite support tube fabrication
  - Integration of LumiCal and Vertex detectors mockup
  - Integration of hardware alignment system

Similar challenges and R&D on CEPC beam pipe

The Central Be pipe

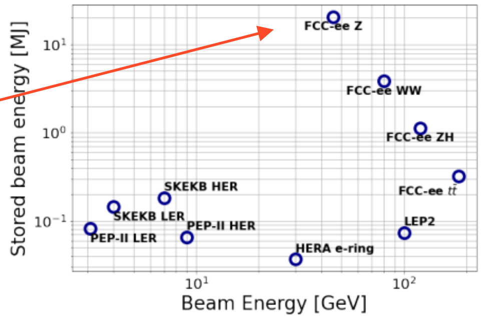


The extending Al pipe --- Gradient runway type



A different solution wrt FCC-ee

FCC-ee collimation overview



FCC-ee presents **unique challenges**:

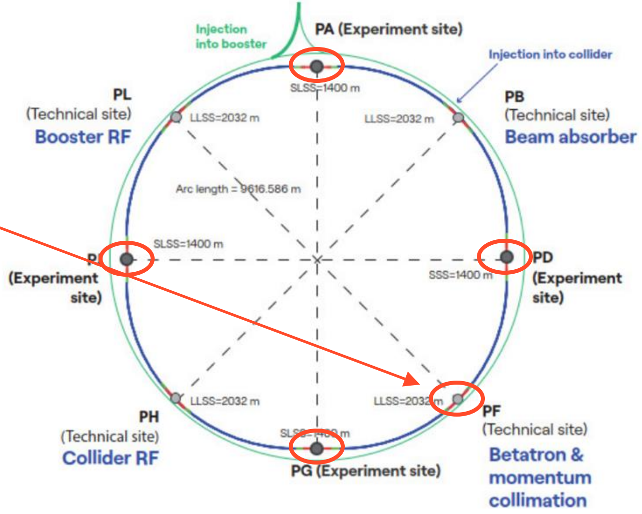
- At Z pole 17.5 MJ of stored beam energy (two orders of magnitude bigger than any other lepton collider)
- Beams are highly destructive

Collimation system must:

- Protect the machine and the detectors from unavoidable beam losses
- **Minimize background for the experiments**

Collimation set-up:

- Global system in **PF**: 2 stage betatron + momentum
- **Experimental IRs**: SR collimators and mask + robust tertiary collimator
- Local protection for injection, extraction
- **Secondary particle shower absorber**



Beam-induced Backgrounds

Luminosity backgrounds

Synchronous with the interaction, can be discriminated at trigger level

Beamstrahlung: photons and spent beam

- Incoherent e^+e^- Pair Creation (**IPC**) ← **dominant** – **Use GuineaPig**
- Coherent e^+e^- Pair Creation
- $\gamma\gamma$ to hadrons

Radiative Bhabha - $e^+e^- \rightarrow e^+e^-\gamma$. Use BBBrem (benchmarked with LEP data)

Single Beam effects

Mostly can be mitigated with collimators & shielding, except for those produced just in the IR.

- Synchrotron Radiation
- Beam-gas
- Thermal photons
- Touschek
- Injection backgrounds
- Beam halo losses

A collimation insertion intercepts most the beam losses. Tertiary collimators upstream MDI area protect the experiments. Residual losses produce BIB and need to be tracked into detectors for occupancy and data rates.

FCC-ee Beam-gas interaction contribution to detector

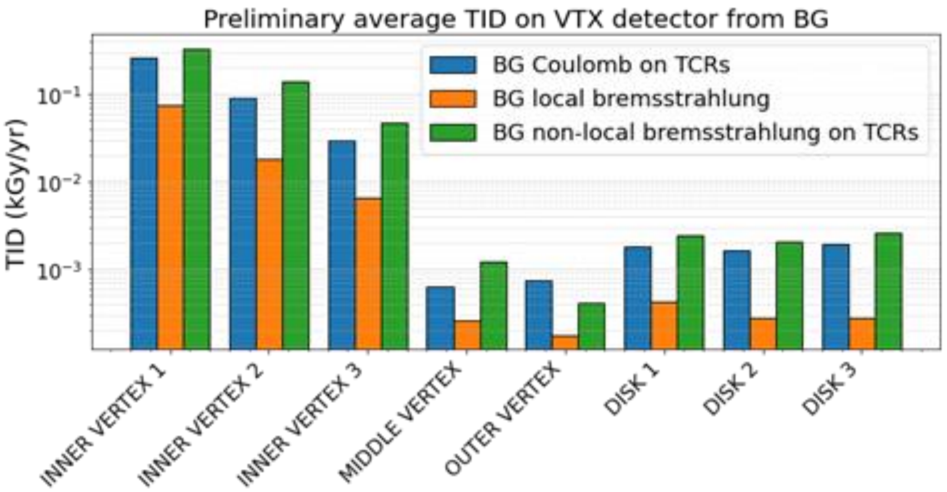
Beam-gas bremsstrahlung

- contribution from TCTs negligible
- contribution from hits on TCRs non-local, higher than local BG bremsstrahlung

Beam-gas Coulomb scattering

- contribution from TCTH negligible
- contribution from hits on TCRs comparable to BG bremsstrahlung hits
- contribution from TCTV difficult to estimate

local: upstream the MDI, single pass
non-local: generated far from IP and multiturn

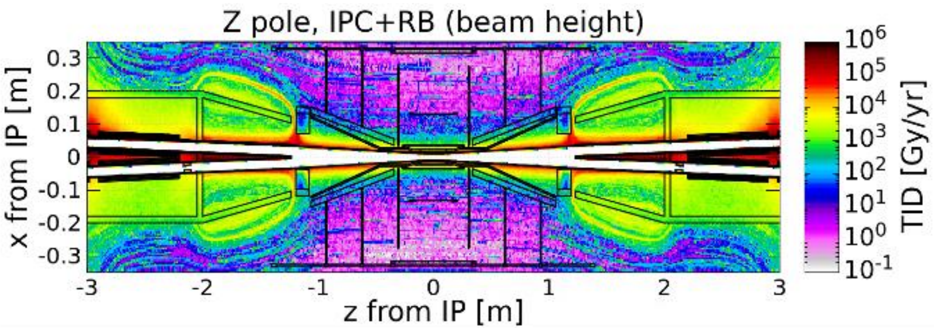


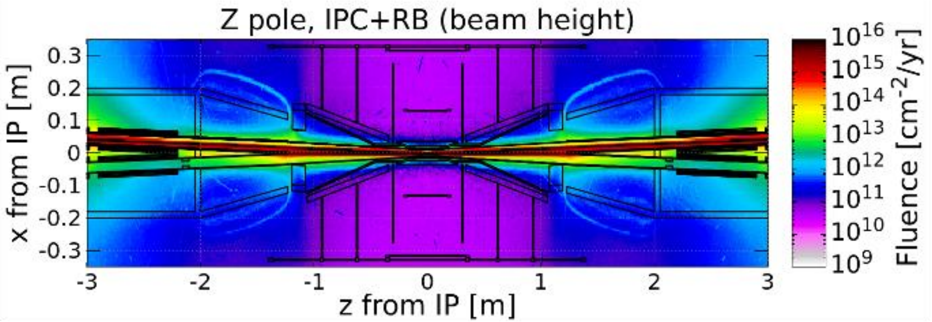
Doses are proportional to backgrounds, subleading wrt IPC

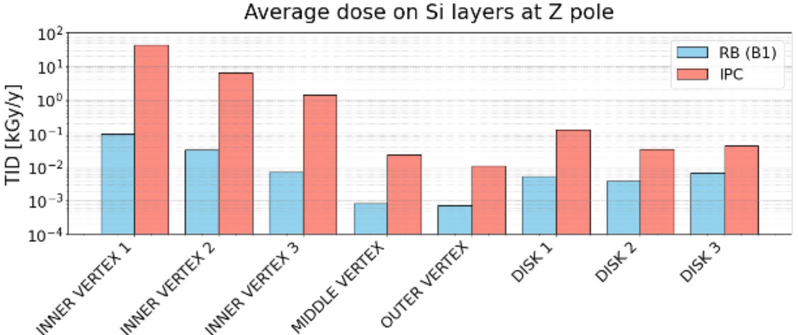
FCC-ee Vertex detector radiation levels

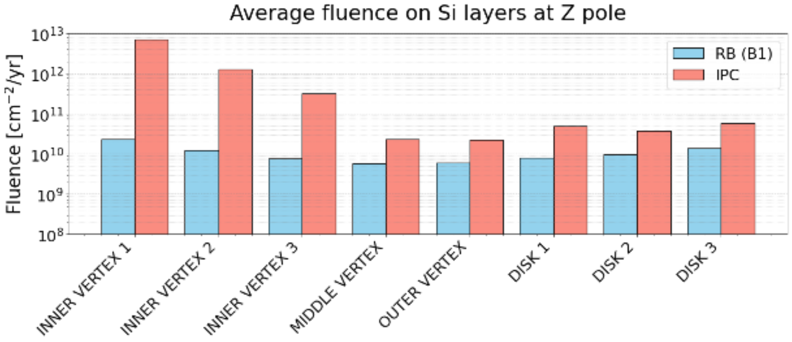
IPC dominant source

- Innermost layer (at ~1.3 cm) TID and fluence are one order of magnitude higher than second layer.
- Current MAPS technologies are OK
  - At 15 cm distance, dose and fluence are about 3 orders of magnitude smaller than innermost layer



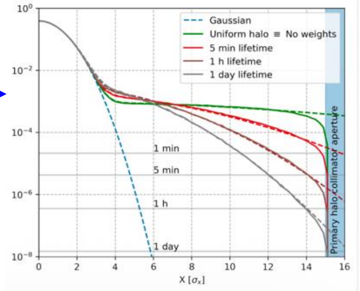




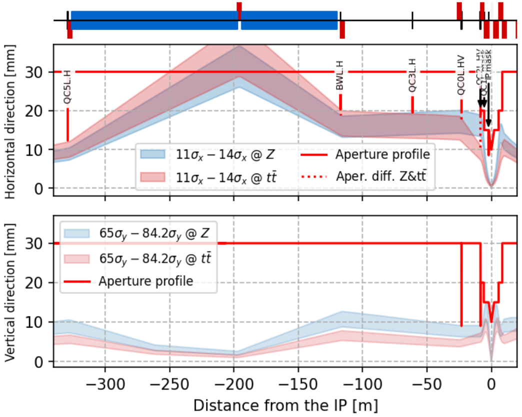


FCC-ee Synchrotron Radiation (SR) backgrounds

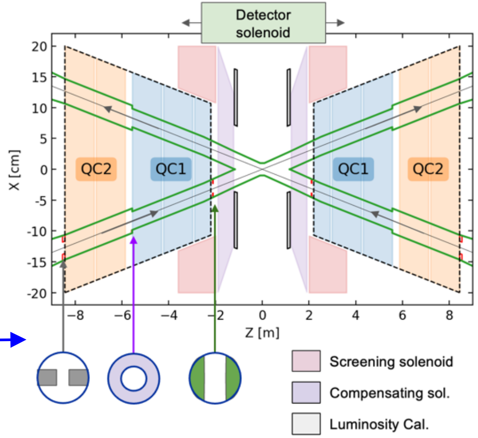
- Simulations with BDSIM (GEANT4 toolkit)
- SR evaluated for
  - **beam core** with non-zero closed orbits for considering optics imperfections
  - **transverse beam tails,** pessimistic weighted halo model used:



bulk of SR produced upstream the IR is stopped by collimators



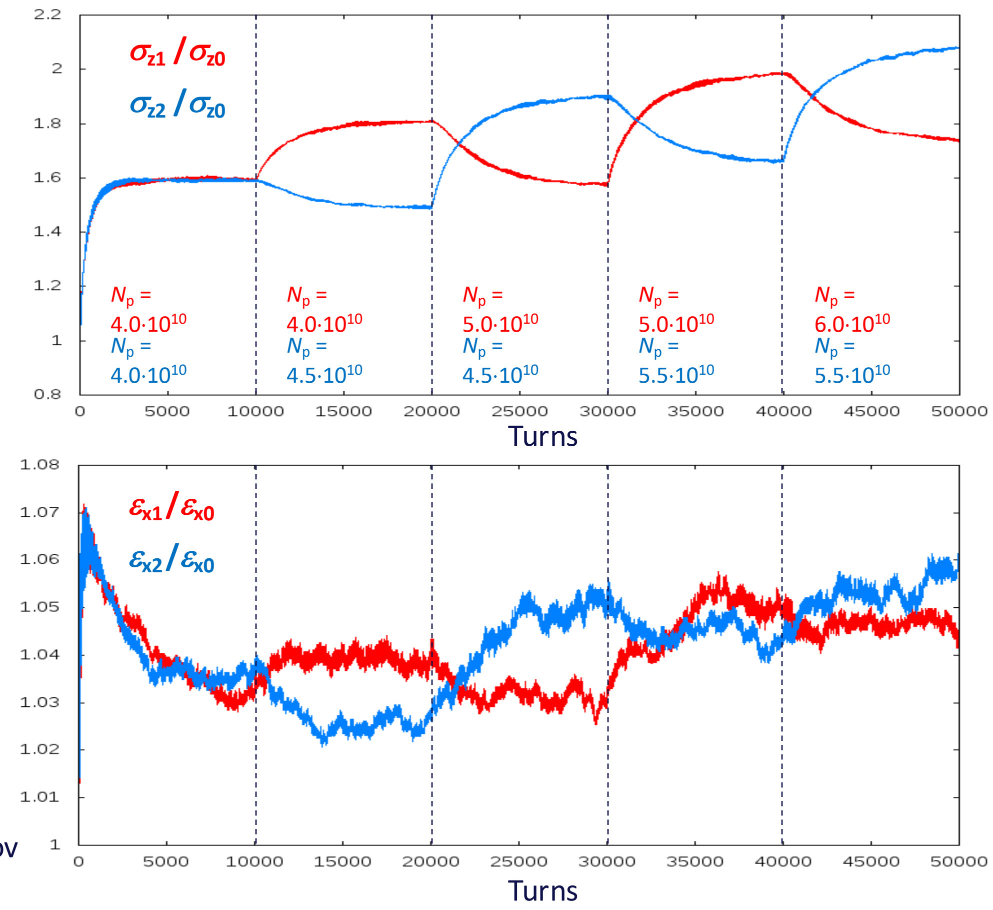
- **SR produced in the IR** by **IR quads and solenoids:**
  - bulk of SR is collinear with the beam and will hit the beam pipe at the first dipole after the IP → no direct hits in the detectors
  - Transverse tails in the fringing field of the final quads produce SR that may hit the detector: **masks at the exit of QC1 and QC2**



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*.

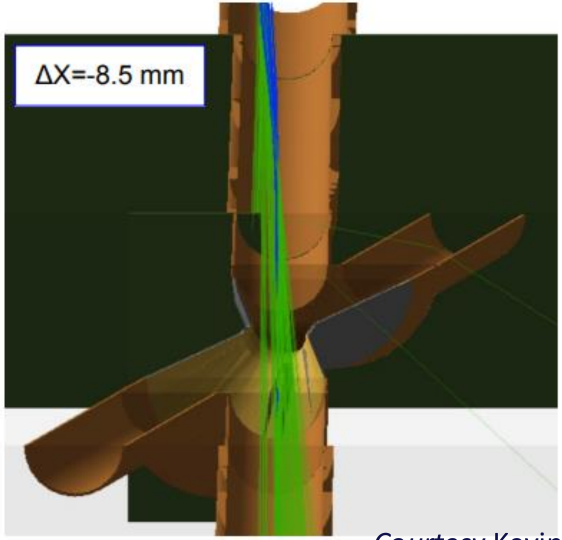
Courtesy Dmitry Shatilov

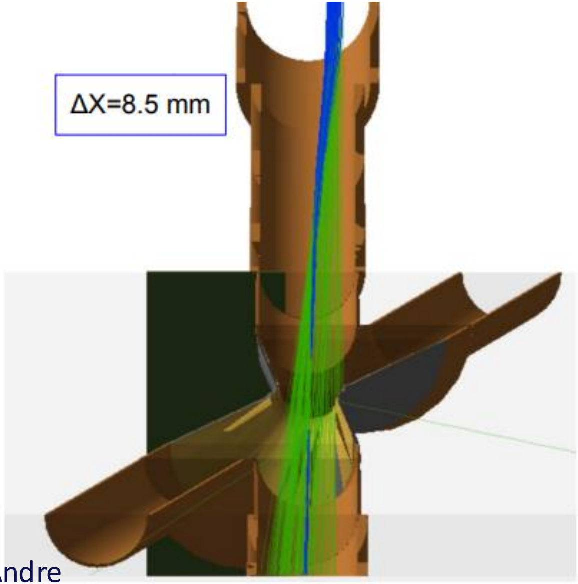


Top-up injection

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



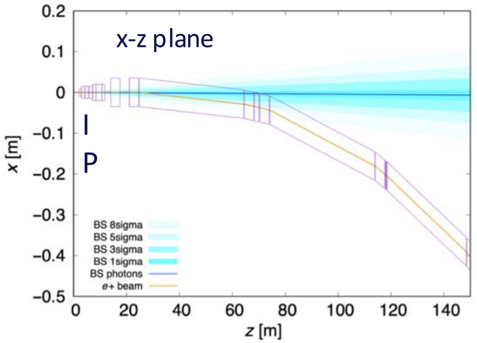


Courtesy Kevin Andre

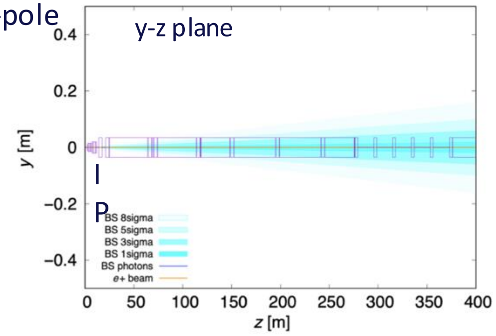
preference for longitudinal injection

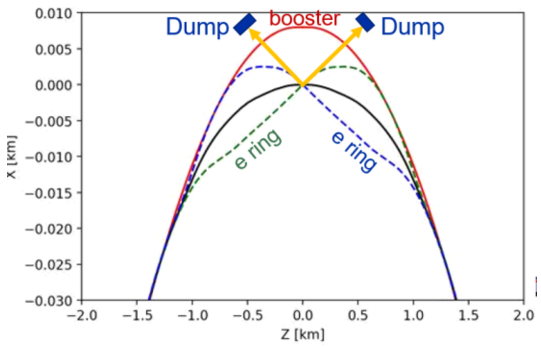
FCC-ee Beamstrahlung Radiation

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



Z-pole





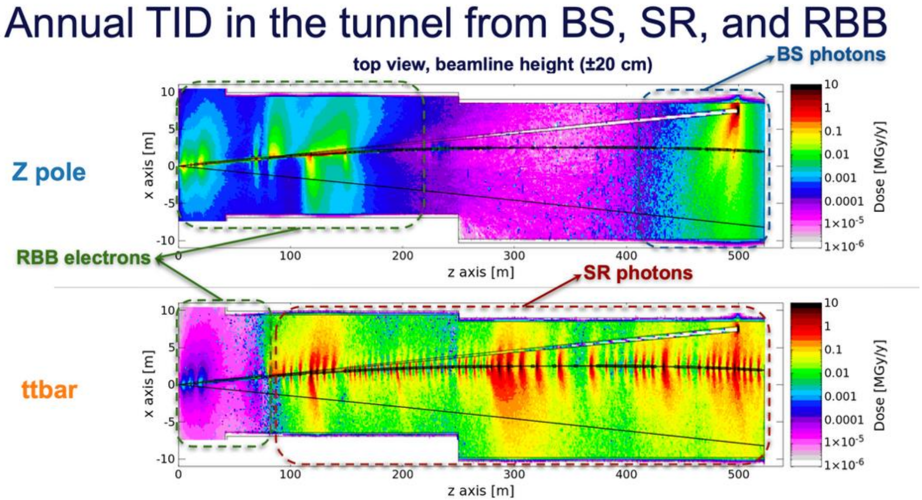
Dump placed 500 m from IP in order to have enough separation from booster / collider (space for shielding)

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

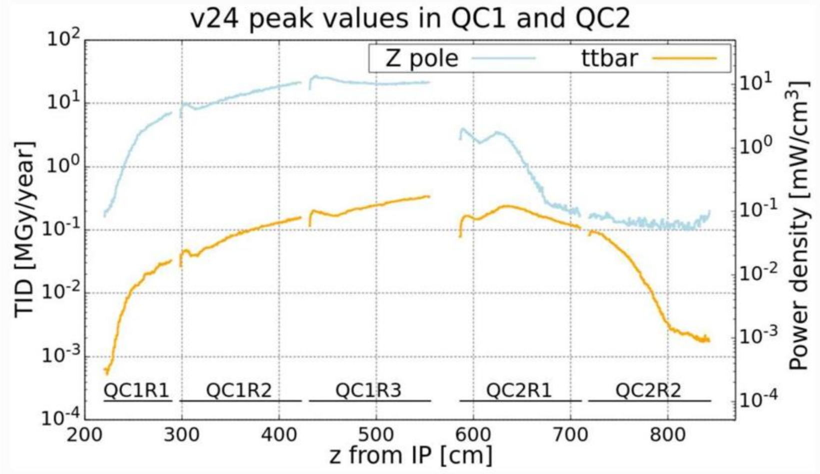
High-power beam dump needed to dispose of these BS photons **+ all the radiation from IR**: FLUKA simulation ongoing

- 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 FCC-ee MDI area



Power deposition in FFQs SC coils from radiative Bhabhas



2 mm of tungsten are needed

Power at Z pole [mW]	QC1R1	QC1R2	QC1R3
W shielding	84	587	1037
Al layer 1	4	27	48
Coil layer 1	11	74	131
Al layer 2	2	15	26
Coil layer 2	6	42	76
Total (magnet)	23	158	281

Courtesy Alessandro Frasca

IR and MDI for e^+e^- Linear Colliders

Squeezed beams at the IP: requires extreme final focus quads gradient

Extreme mechanical precision mandatory to reach goal luminosity, two necessary ingredients:

- **active and passive alignment system**, R&D
- **fast feedback** (beam steering at nm precision level)

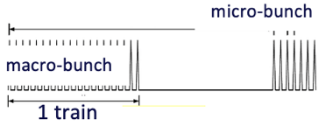
Beam-induced backgrounds -> constraints on beam pipe radius and geometry, vertex detector radius ($\gamma\gamma$ -> hadrons)

Challenge on MDI mechanics, electronics, services, minimal tolerances

Low mass tracker supports with integrated cooling –R&D performed through past years

The very different bunch structure between LC (bunch trains) and circular (uniform fill) leads to very different detector solutions:

- **In-time pile-up of hadronic backgrounds, sufficient granularity for topological rejection**
- **At CLIC: ns-level timing in many detectors systems (0.5 ns micro-bunch spacing, 312 bunches)**
- **Power pulsing of front-end electronics, reduced power consumption**



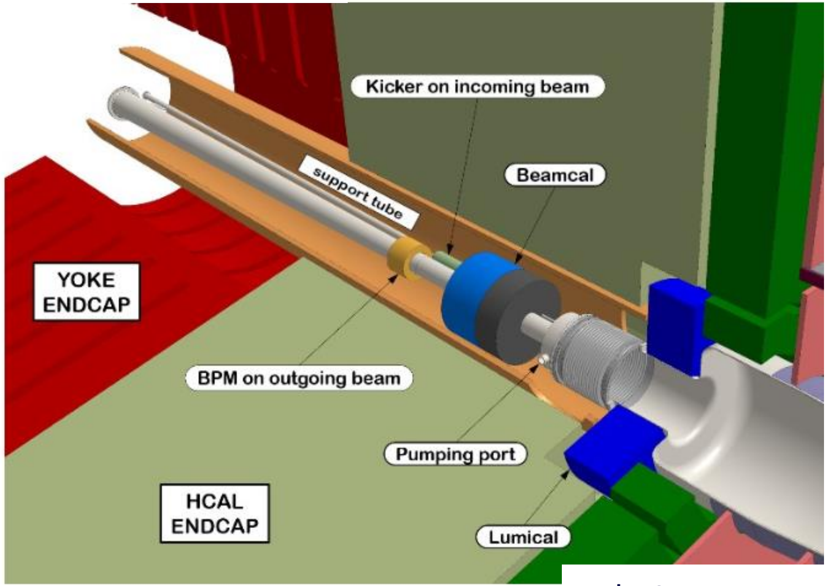
LC bunch structure

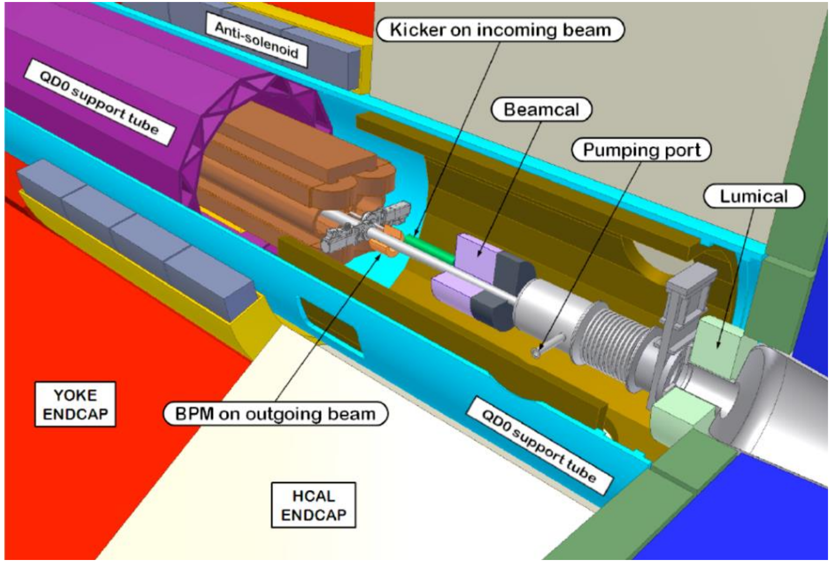
CLIC MDI

ArXiv:1903.08655 (2018)

simpler design

ArXiv:1202.6511 (2011)





σ_x^*= 0.144 μm
σ_y^*= 2.97 nm @380 GeV

L* = 6 m both 380 GeV and 3 TeV

QD0 outside the detector at 380 GeV and 3 TeV

QD0 mounted on the tunnel floor (much smaller vibrations)

no pre-absorber, no cantilever support for QD0

divided in three segments, much smaller gradient (25 T/m), larger aperture radius (25 mm)

no anti-solenoid needed

L* = 4.3 m at 500GeV

L* = 3.5 m at 3TeV

ILC IR and MDI

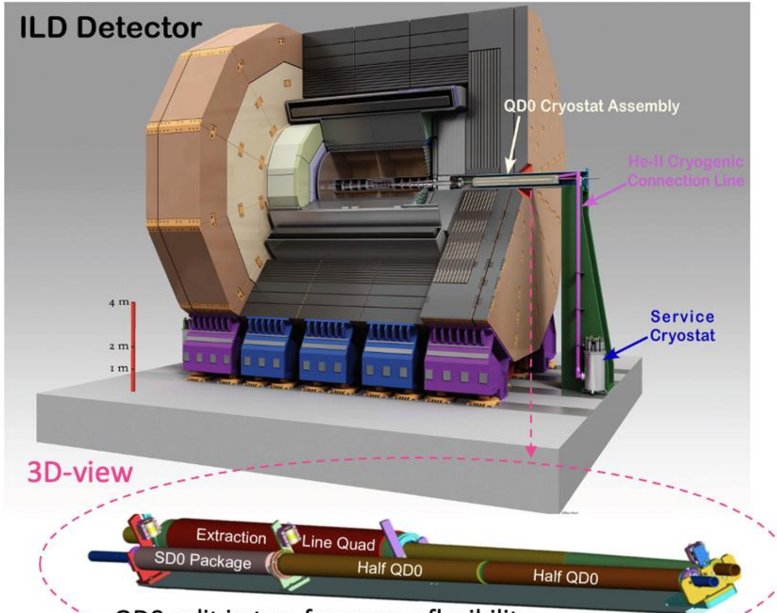
	FCC-ee	ILC	CLIC
Transv. rms emittance (pm)	H: 270, 630, 1340 V: 1, 1, 3	H: 20, 10 V: 0.14, 0.07	H: 2.4, 0.22 V: 0.8, 0.01

Very small beams at IP - determine a challenging MDI design

σ_x^*= 0.52 μm
σ_y^*= 7.7 nm

squeezed beams can be obtained with strong FF quads

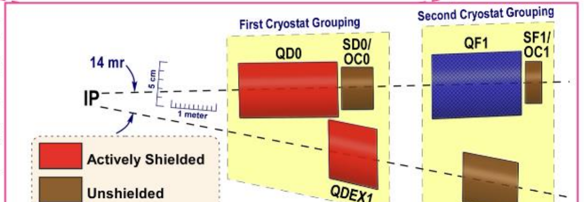
[Arxiv_2019]	[TDR (2013)]
L* = 4.1 m	L* 4.5 m (ILD) 3.51m (SiD)



QD0 split in two for energy flexibility

- Strong SC **QD0**, as compact as possible, inside the detector, shielded coils, correctors needed (BNL direct-wind technology) **R&D** [see B. Parker, LCWS2021]
- **alignment** system : vertical position of the centre of the incoming-beam-line quadrupole field O(50 nm) challenging
- **Overall integration with push-pull system** in less than 24hrs
- Stable luminosity with **train-by train** and **intra-train feedbacks** **-> BPMs at μm/ sub-μm level**
- **Luminosity feedback**
- **Luminosity measurement:** precision of $\approx 10^{-3}$,
- Lumical: Bhabha rate in the 30-90mrad polar angle region in front the FF quads @500Ecm 10 bhabhas/bunch train; 1.5k pairs/BX for

Two independent cryostats, with **QD0 cryostat almost entirely into the detector.** Only the QD0 cryostat is moved together with detector during push-pull operation.



140 A Linear Collider Vision for the Future of Particle Physics Jenny List

ILC BDS

CLIC BDS

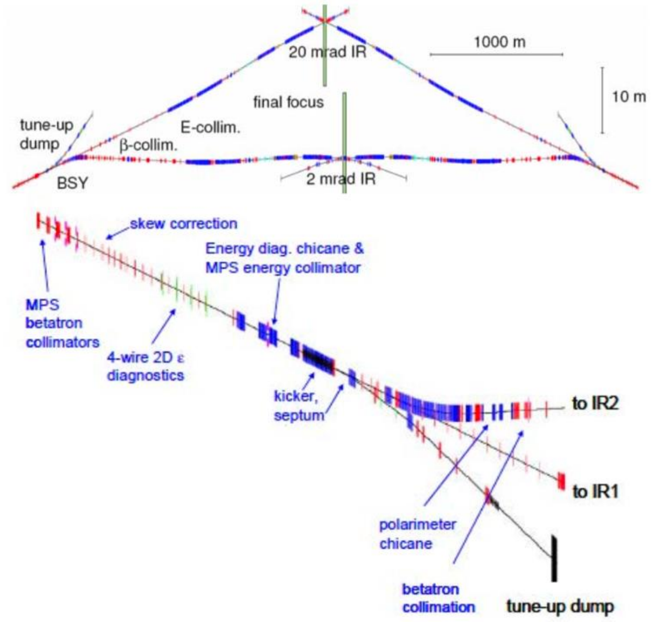


Figure 52: ILC BDS optics design with 2 IPs. Top: Layout of the two IRs with 20 and 2 mrad crossing angle; Bottom: Layout of the BDS section after the Main Linac and the FF section.

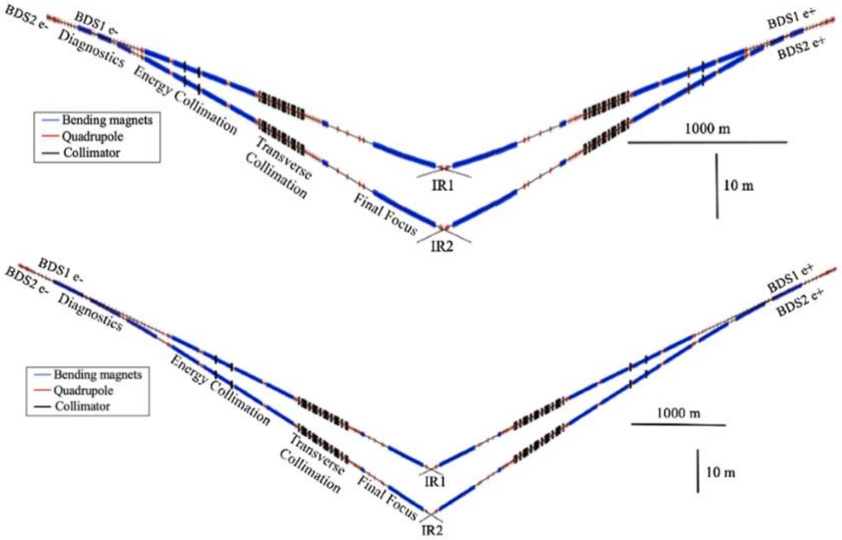


Figure 53: CLIC BDS optics design with 2 IPs. Top: Layout of the two IRs at 380 GeV with 16.5 and 20 mrad crossing angle; Bottom: Layout of the two IRs at 3 TeV with 20 and 25.5 mrad crossing angle

Summary

MDI can be the key for success/unsuccess for any collider → it is really mandatory to dedicate the proper R&D and effort in the optimization of its design.

Some of the main challenges and R&D presented are

- strong SC magnets, magnets integration with detector
- experience in synchrotron radiation mitigation, including vacuum chambers technology
- low impedance vacuum chamber, material and thickness optimization, radius (great impact on vertex detector!)
- vacuum chamber cooling due to heat load
- alignment systems inside the detector
- BEAM INDUCED BACKGROUNDS & SYNCHROTRON RADIATION BKG: correct and reliable modeling essential for a successful MDI design, R&D not easy, experience on present (and past) colliders really important.

And thanks to many people for inputs!

Spare slides

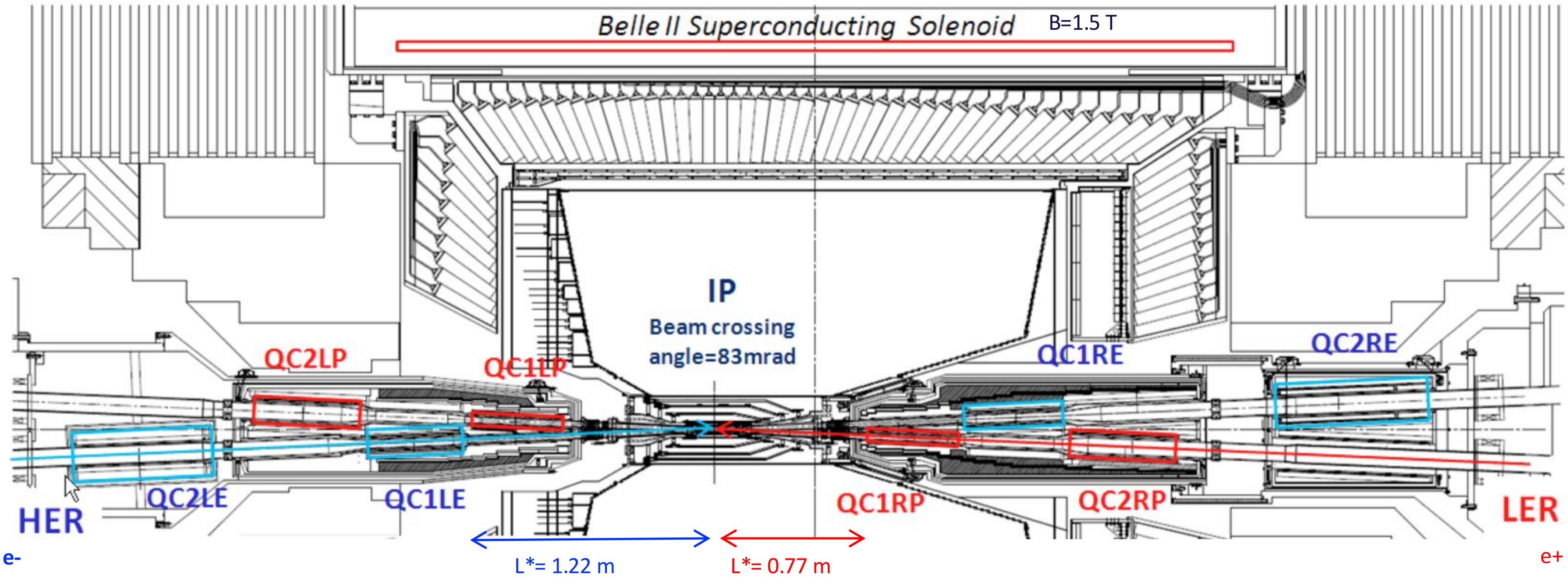
IR future colliders Parameter Table

particle		e^+e^-			
type		circular		linear	
collider name		SuperkekB	FCC-ee	ILC	CLIC
Beam Energy	GeV	LER (e+) 4 HER (e-) 7	45.6, 120,182.5	125, 250	190 / 1500
$\mathcal{L}$ (peak)	$10^{34}cm^{-2}s^{-1}$	80	230, 8.5, 1.6	1.4, 1.8	1.5, 6
crossing angle	mrad	83	30	14	16.5, 20
Bunch spacing	ns	4	20	554, 5Hz train	0.5, 50Hz 312 train
L* (free region)	m	L 0.77 H 1.22	2.2	4.1	6
β_x*	cm	L 3.2 H 2.5	15,30, 100	1.3, 2.2	80 / 70
β_y*	mm	L 0.27 H 0.3	0.8, 1, 1.6	0.41, 0.8	0.1 / 0.12
Normalised emittance x	µm	L 25 H 63	24, 148, 479	5, 10	0.95/ 0.66
Normalised emittance y	nm	L 68 H 177	89, 235, 1000	35, 35	30/20
B_{det}	T	1.5	2	5 (SiD)	3.5-5
central pipe radius	cm	1	1 (1.5 CDR)	1	3

SuperKEKB FF magnets and detector

$\sigma_x^* = 10.7\ \mu m$
$\sigma_y^* = 62\ nm$

$\sigma_x^* = 10.1\ \mu m$
$\sigma_y^* = 48\ nm$



CLIC QD0 Prototype

https://arxiv.org/pdf/1202.5952.pdf

QD0 requirements (**2009**) **L*=3.5, 4.3 m, inside detector**
The magnetic requirements for the QD0 are quite severe: the extremely high gradient needed, the small aperture of the magnet bore, the length of the magnet, the required tunability.

- Distance between post collision line beam pipe and beam axis ~35 mm
- **Active stabilisazion of the quadrupole**: sufficient rigidity and with a well known dynamic behaviour (vibration eigenmodes, no source of vibration (ex. coil coolant flux)

Parameter	Value
Nominal field gradient	575 T/m
Nominal integrated field gradient	1570 T
Magnetic length	2.73 m
Magnet bore diameter	8.25 mm
Good field region(GFR) radius	1 mm
Integrated field gradient error inside GFR	< 0.1%
Adjustment	+0 to -20%

Table 1: Magnetic and geometric requirements for the QD0 quadrupole

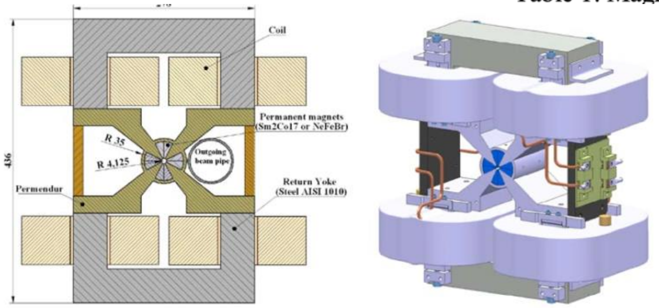


Figure 2-3: Conceptual design of the QD0 cross section and full assembly

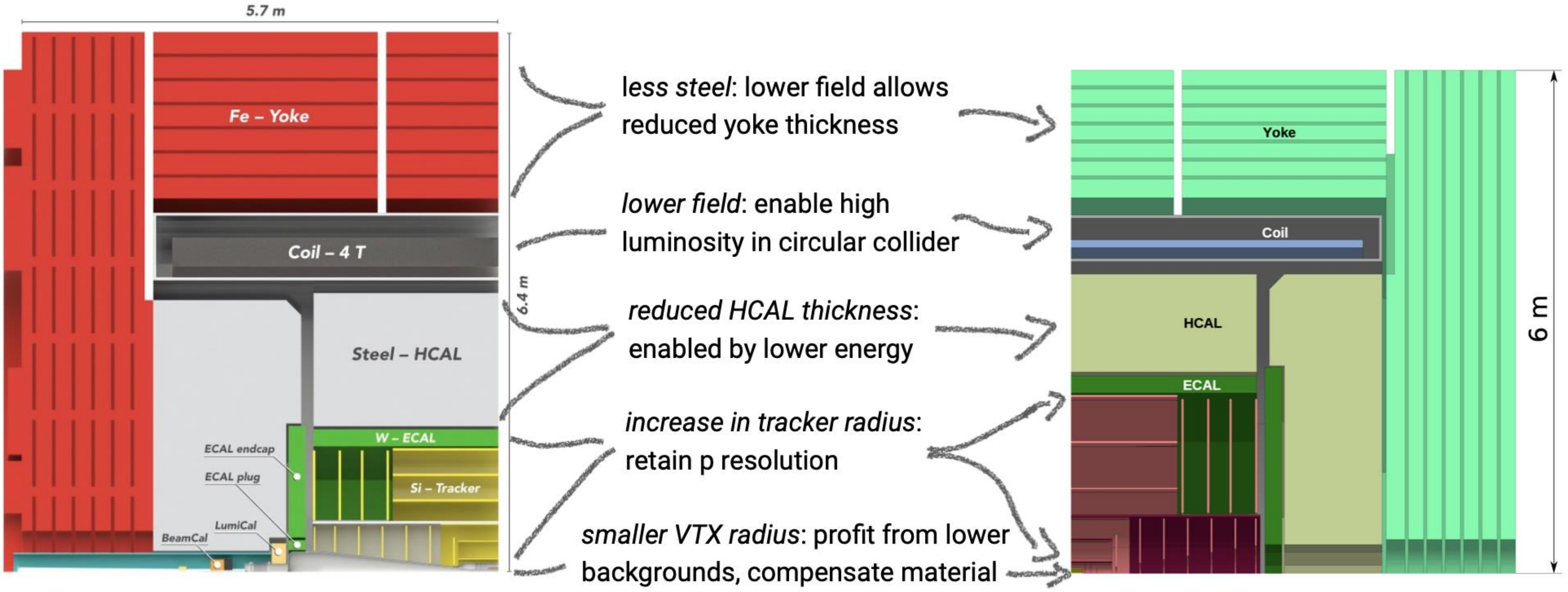
CLIC QD0 Main Parameters		100mm prototype	Real magnet 2.7m
Yoke			
Yoke length	[m]	0.1	2.7
Coil			
Conductor size	[mm]	4×4	4×4
Number of turns per coil		18×18=324	18×18=324
Average turn length	[m]	0.586	5.786
Total conductor length/magnet	[m]	0.586×324×4=760	5.786×324×4=7500
Total conductor mass/magnet	[kg]	26.8×4=107.2	265.2×4=1060.8
Electrical parameters			
Ampere turns per pole	[A]	5000	5000
Current	[A]	15.432	15.432
Current density	[A/mm^2]	1	1
Total resistance	[mOhm]	896	8836
Voltage	[V]	13.8	136.4
Power	[kW]	0.213	2.1

Table 2: Magnetic and geometric parameters for the QD0 "Short Prototype" and "Full Size" magnet.

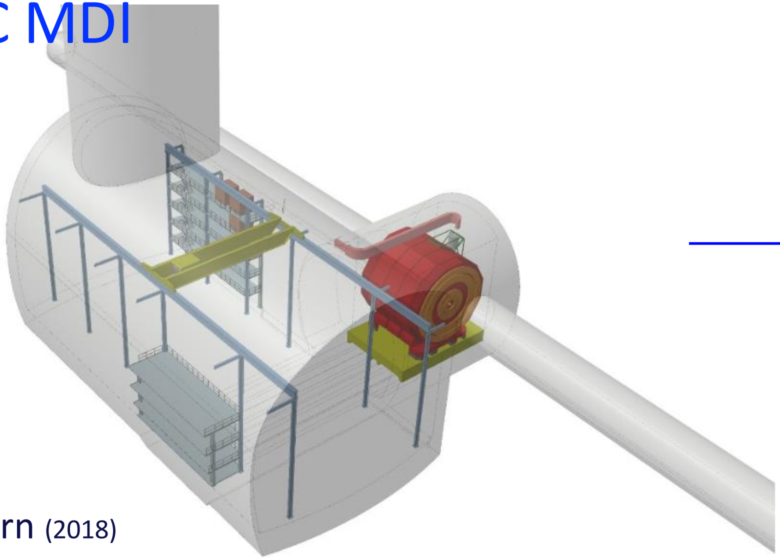
From LCs to FCCee

From CLICdet to CLD

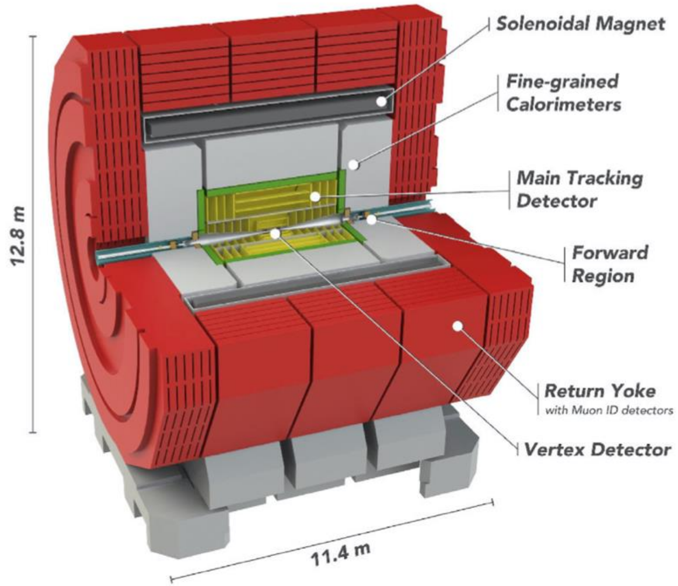
- A LC-inspired FCCee detector concept - retaining key performance parameters
  Evolving from CLIC to CLD



CLIC MDI



cavern (2018)



(Most of the detector elements unchanged)

Key issues:

- Minimization of radiation:

  Collimators and masking to suppress bkg from beam-beam and beam dumps

  - Background suppression and radiation shielding

  NIM A 983 (2020) 164522 link

Lower backgrounds from incoherent pairs at 380 GeV allow for a **smaller central vacuum chamber**, and thus a **smaller radius of the innermost vertex detector layer**

Radiation effects and beam-beam at 3 TeV determine the design constraints