ECFA

European Committee for Future Accelerators

Machine Detector Integration

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Task Force 8 Integration Symposium
ECFA Detector R&D Roadmap
Zoom, 31 March, 2021

INFN LNF Istituto Nazionale di Fisica Nucleare

CERN

Introduction

Key challenges for the machine detector integration of future colliders:

- e^+e^- circular: SuperKEKB (in operation), FCC-ee, CEPC
- e^+e^- linear: CLIC, ILC
- pp: FCC-hh
- e^- ion: EIC (approved), LHeC, FCC-eh
- $\mu^+\mu^-$ (still too early to be on the same foot)

Different projects are at **different level of maturity**, have different time scales, either under commissioning, approved or for the far future.

Rich field with mutual influence and interplay in accelerators design as well as in R&D on the various technologies and systems.

Future Colliders IR Overview

e^+e^- Linear

high instantaneous luminosity within bunch train (low O(10Hz rep rate)

higher occupancy at the same ave Luminosity

no hope to mitigate with a fast readout, cannot resolve within a bunch train

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, radiative beam-beam (beamstrahlung), pairs

e^+e^- Circular

uniform luminosity distribution in time (CW), top-up injection

lower rates than hh, but higher accuracy required

new concept for luminosity, very far from LEP2 rates and step forward also from flavor factories: nano-beams go toward LC,

compact IR (L*↓)

tight mechanical space constraints, including FF quads and correctors

high crossing angle

High energy -> SR

High intensity -> heating, vacuum

Beamstrahlung relevant like for LC (FCC-ee)

hh Circular

continuous beam, luminosities comparable to that of e+e-, higher cross-sections

cross-sections and beam size (and emittance) much larger ->

higher rates

luminosity and MDI driven by detector performance reach capability

large IR (L* ↑)

head-on

shielding and activation issues

beam halo

e^- ion Circular

e- beam like that of e+e- circular future colliders:
high current issues
SR

4π solid angle detectors,
very low angle is required for the physics (for e+e- 50-100 mrad typical physics cone)

enormous beam apertures required, FF quads and IR magnets very difficult

Future Colliders IR Overview

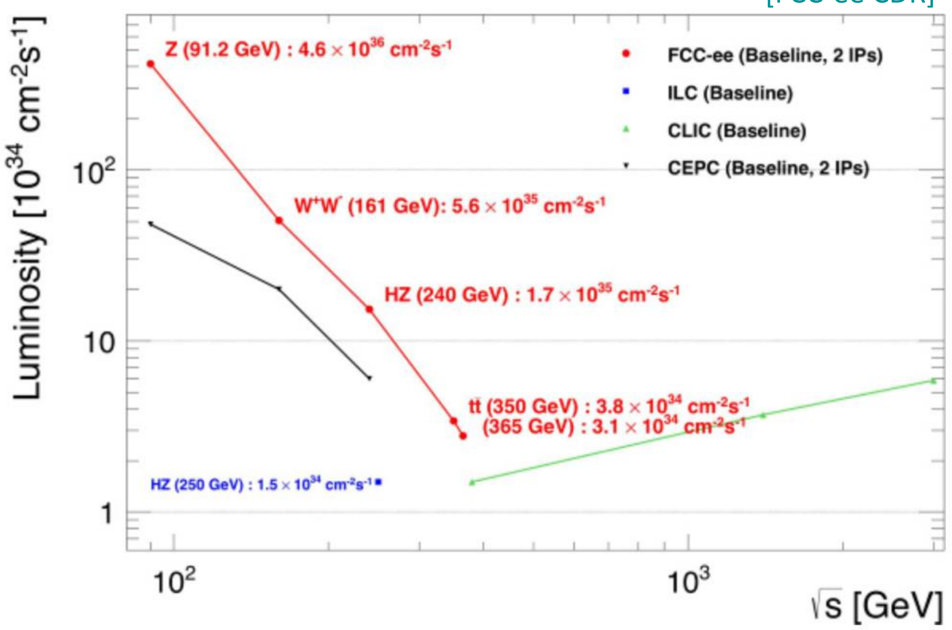
e^+e^- Linear	e^+e^- Circular	hh Circular	e^- ion Circular
SLC (1989) **ILC** **CLIC**	(AdA,1962) *long history* LEP *Factories* *(high current)* PEP-II KEKB DAFNE .. *Super factories* *(nanobeam concept)* SuperKEKB **FCC-ee** CEPC	ISR (1971) SPS Tevatron RHIC LHC →HL-LHC **FCC-hh** *(high field magnets)*	HERA (1992) EIC **LHeC** **FCC-eh**

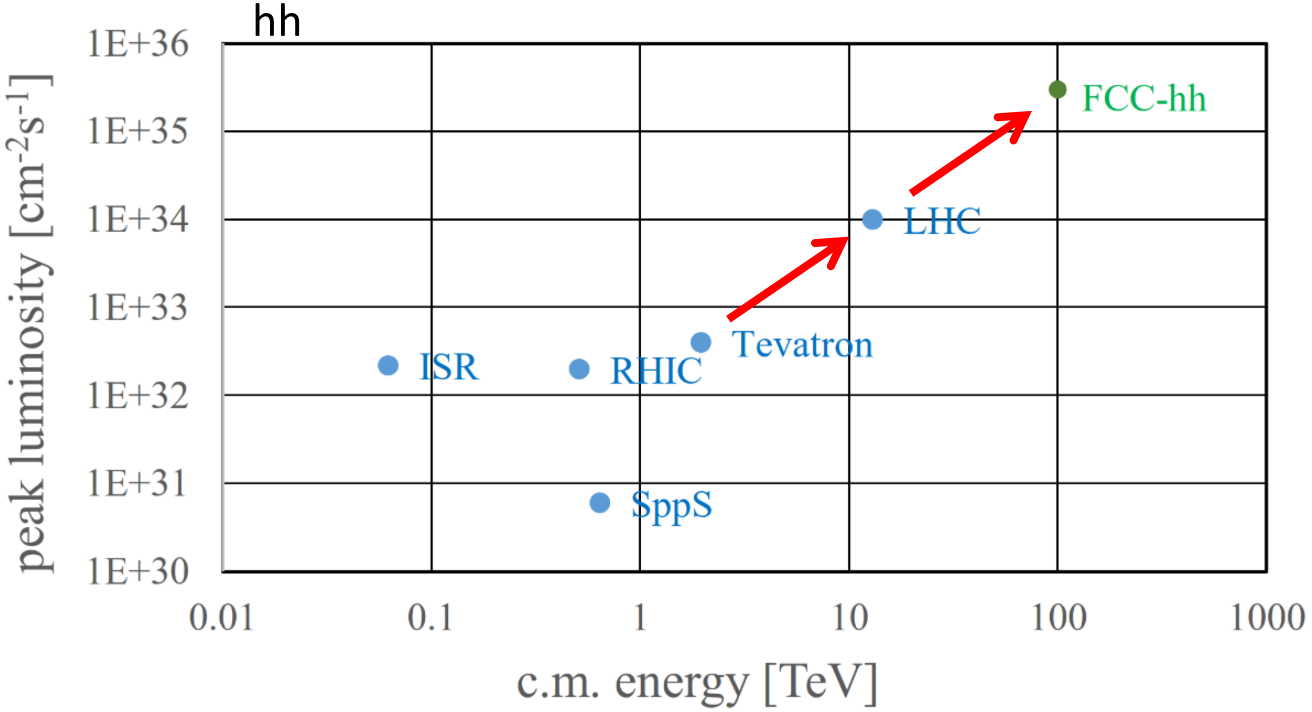
Please note:
Not exhaustive list

Future Colliders Performance

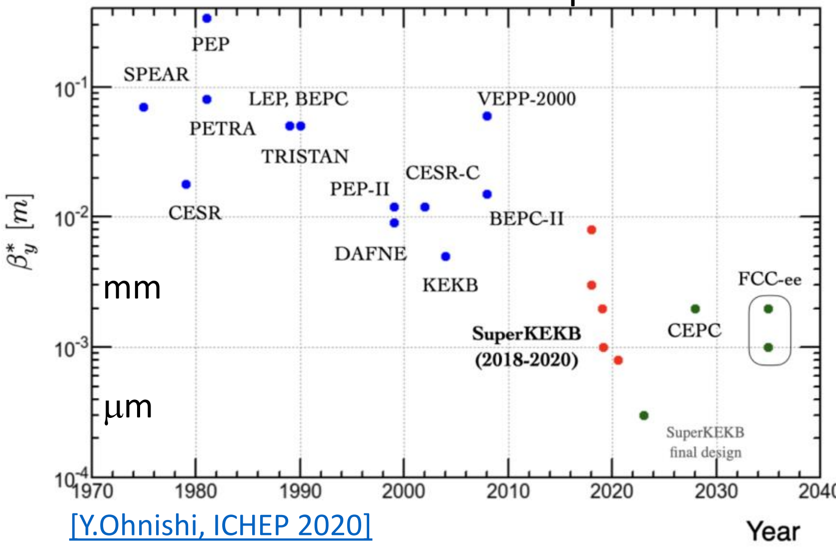
e+e-

[FCC-ee CDR]





e+e- circular: vertical squeeze at IP



[Y.Ohnishi, ICHEP 2020]

- **order of magnitude performance increase** in both **energy & luminosity**
- **100 TeV cm collision energy** (vs 14 TeV for LHC)
- **20 ab^{-1} per experiment collected over 25 years** of operation (vs 3 ab^{-1} for LHC)
- similar performance increase as from Tevatron to LHC
- **key technology: high-field magnets**

IR future colliders Parameter Table

particle		e+e-				pp			e- - ion	
type		circular		linear		circular			circular/ ERL	
collider name		SuperkekB	FCC-ee	ILC	CLIC	LHC	HL-LHC	FCC-hh	EIC	LHeC
Beam Energy	GeV	LER (e+) 4 HER (e-) 7	45.6, 120,182.5	125, 250	190 / 1500	7000	7000	50000	(e-) 10 (h) 275	(e-) 49.19 (p) 7000
$\mathcal{L}$ (peak)	$10^{34}cm^{-2}s^{-1}$	80	230, 8.5, 1.6	1.4, 1.8	1.5, 6	2.1	5	5-30	1	23
crossing angle	mrad	83	30	14	16.5, 20	0.26	0.5		25	0
Bunch spacing	ns	4	20	554, 5Hz train	0.5, 50Hz 312 train	25	25	25	10	50
L* (free region)	m	L 0.77 H 1.22	2.2	4.1	6	23	23	40	4.5	10
β_x*	cm	L 3.2 H 2.5	15,30, 100	1.3, 2.2	80 / 70	25	15	110-30	45 80	(e-) 6.45 (p) 10
β_y*	mm	L 0.27 H 0.3	0.8, 1, 1.6	0.41, 0.8	0.1 / 0.12	250	150	1100-300	56 72	(e-) 64.5 (p) 100
Normalised emittance x	μm	L 25 H 63	24, 148, 479	5, 10	0.95/ 0.66	3.5	2.5	2	(e-) 391 (h) 3.3	(e-) 50 (p) 2.5
Normalised emittance y	nm	L 68 H 177	89, 235, 1000	35, 35	30/20	3500	2500	2000	(e-) 25400 (h) 290	(e-) 50000 (p) 2500
B_{det}	T	1.5	2	5 (SiD)	3.5-5	Atlas 2T, CMS 4T			1.4	3.5
central pipe radius	cm	1	1.5 (1)	1	3	2.35 Atlas, 2.1 CMS	2.35 Atlas, 2.1 CMS	2.5	elliptical	elliptical

Some References

- FCC WEEK2020 and FCC-IS Kick-off meeting (2020)
- *FCC-ee: The Lepton Collider*, **Eur. Phys. J. Spec. Top. 228**, 261–623 (2019)
- *FCC-hh: The Hadron Collider*, **Eur. Phys. J. Spec. Top. 228**, 755-1107 (2019)
- K. Oide et al., **Phys. Rev. Accel. Beams 19**, 111005 (2016)
- Crab-waist collision scheme: ArXiv.070233

- The Compact Linear e+e- Collider (CLIC): Project Implementation Plan (2018), ArXiv:1903.08655
- The Compact Linear e+e- Collider (CLIC): Accelerator and detector, A. Robson (2018)
- CLIC MDI arXiv:1202.6511.pdf (2011)
- The International Linear Collider A global Project, ArXiv:1903.01629v3 (2019)
- ILC TDR

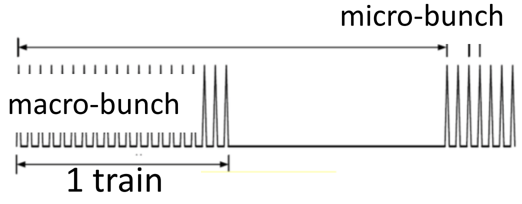
- EIC CDR, doi:10.2172/1765663 (2021)

- The LHeC at the HL-LHC, LHeC and FCC-eh study group, CERN-ACC-Note-2020-0002, ArXiv: 2007.14491 (2020)
- LHeC CDR, J. Phys. G: Nucl. Part. Phys. **39** 075001, arXiv:1206.2913 (2012)

- Muon collider design meetings: https://indico.cern.ch/category/12762/
- The future prospects of muon colliders and neutrino factories, RAST 10, 189 (2019), ArXiv:1808.01858 and Refs. therein

MDI for e^+e^- Linear Colliders

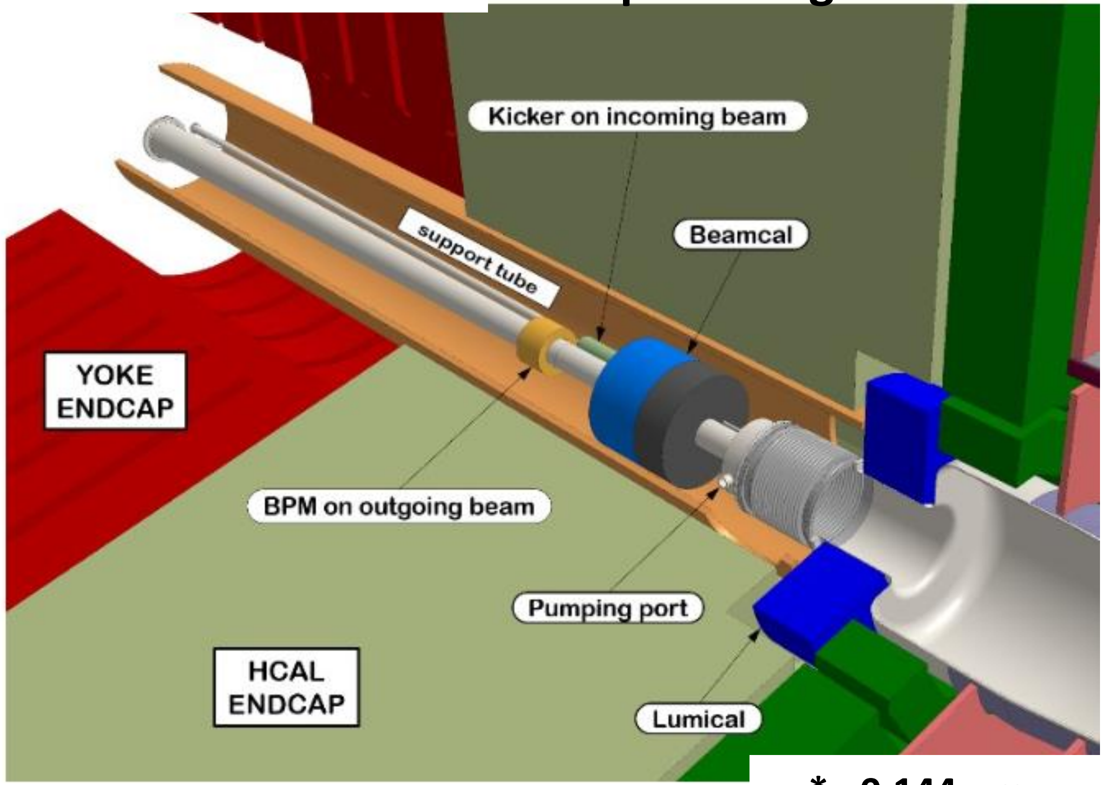
- **Very squeezed beams at the IP**
  - **Possible thanks to extreme final focus quads gradient, R&D** performed (first CLIC FF QD0 design aimed at values as high as 575 T/m)
  - **Extreme mechanical precision mandatory to reach goal luminosity**, two necessary ingredients:
    - **active and passive alignment system**, R&D activity
    - **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)** (even if ILC/CLIC are different wrt each other) **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**



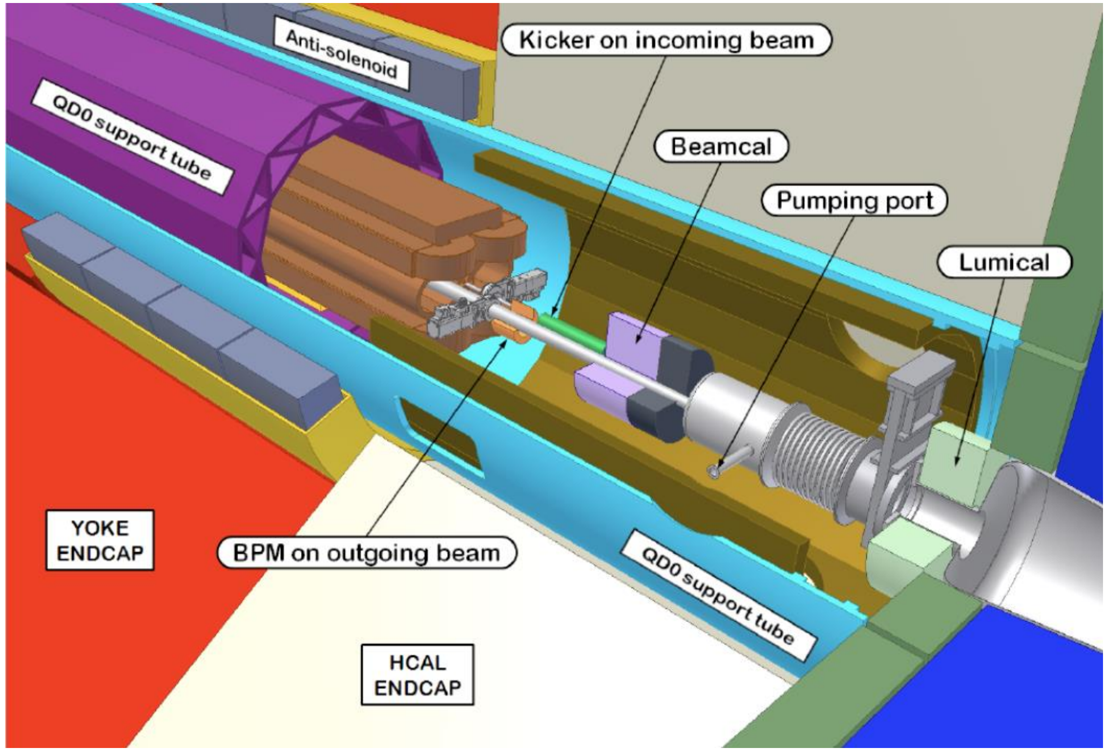
LC bunch structure

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

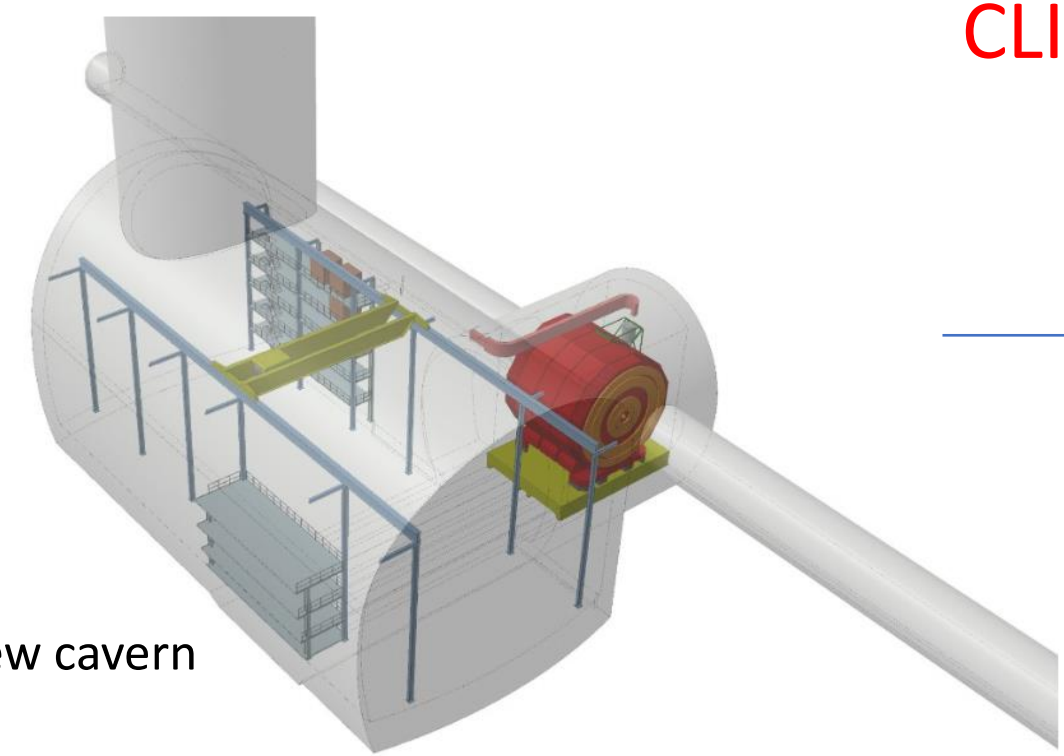
divided in three parts, much smaller gradient (25T/m), large aperture radius (25 mm)

no anti-solenoid needed

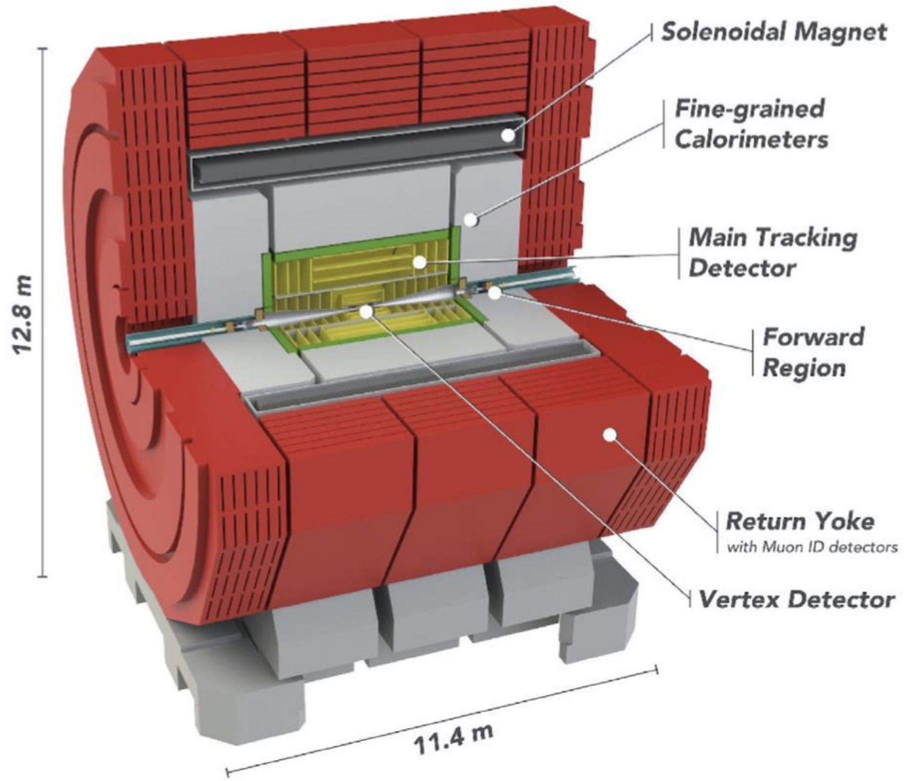
L* = 4.3 m at 500GeV

L* = 3.5 m at 3TeV

CLIC MDI



new cavern



(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

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.

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

- 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)

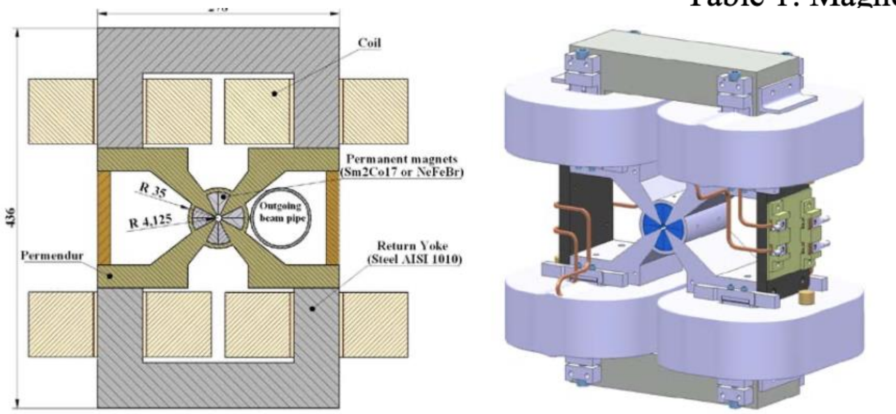


Figure 2-3: Conceptual design of the QD0 cross section and full assembly

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.

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

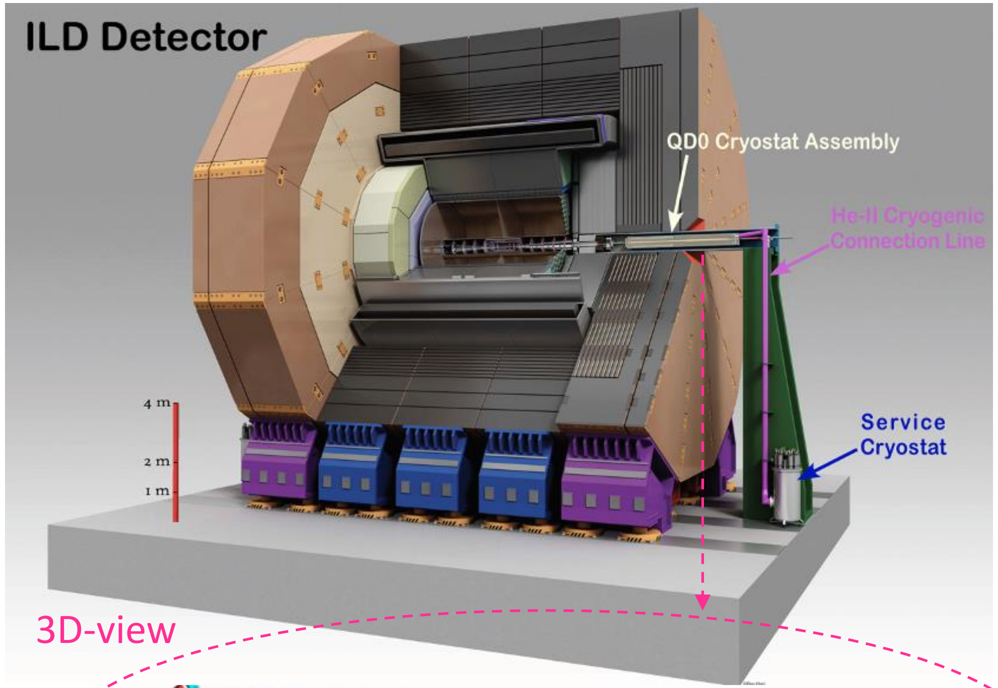
Very small beams at IP - determine a challenging MDI design

σ_x*= 0.52 μm
σ_y*= 7.7 nm

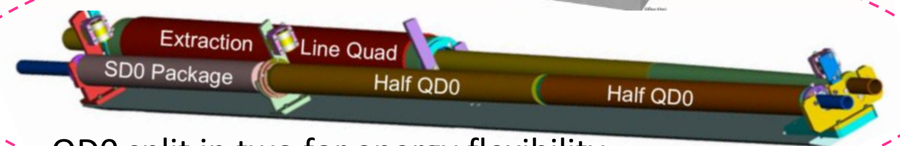
squeezed beams can be obtained with strong FF quads

[Arxiv_2019] [TDR (2013)]

L* = 4.1 m	L* 4.5 m (ILD) 3.51m (SiD)



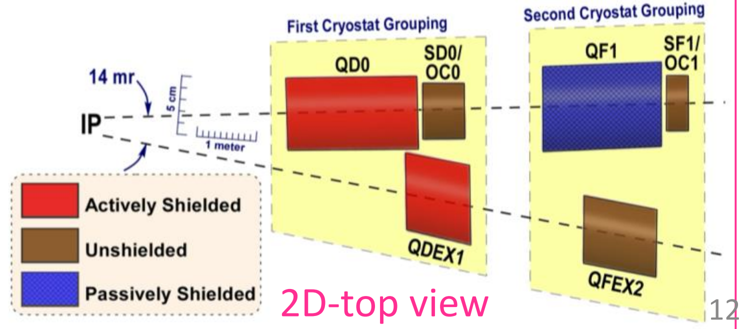
3D-view



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 fast lumi diagnostics at 5-30mrad

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



2D-top view

New collision scheme adopted by all future e^+e^- circular colliders

- **Crab-waist** based on two ingredients:
  - concept of **nano-beam scheme** (vertical squeeze of the beam at IP and horizontal crossing angle increased, reducing the instantanous overlap area, allowing for a lower β_y^*)
  - crab-waist sextupoles
- Smaller beams at IP → higher $\mathcal{L}$ & higher backgrounds
  (IP bkgs and beam losses in the FF quads due to the very high β-function)
- First Successful validation test performed at DAFNE (2008) link
- In summer 2020 SuperKEKB successfully implemented the FCC-ee *virtual* crab-waist, crab waist w/o new sextupoles (but reducing the strength of an existing FF sextupole) [K. Oide]

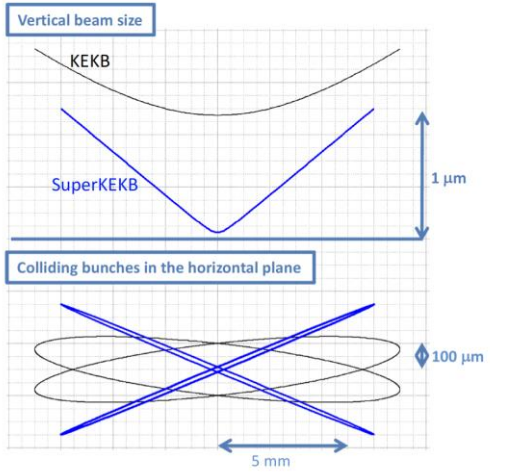


Figure 2: Schematic view of the nanobeam collision scheme.
https://arxiv.org/pdf/1809.01958.pdf

IMPACT on MDI design:

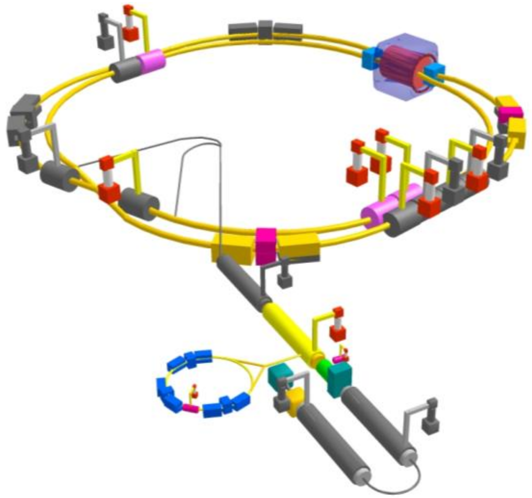
- Tight and packed interaction region → small L*, QD0 inside detector, mechanical constraints,
- Beam pipe design, as splitting in two pipes is very close to the IP
- Robustness against machine backgrounds (from IP and environment)
- Radiation damage and occupancy and fake hits
- Higher rate trigger, DAQ and computing

Commissioning of SuperKEKB is very precious experience for FCC-ee It allows experience on topics where R&D is not straightforword w/o beams, i.e. backgrounds modeling

KEKB and SuperKEKB IR relevant parameters

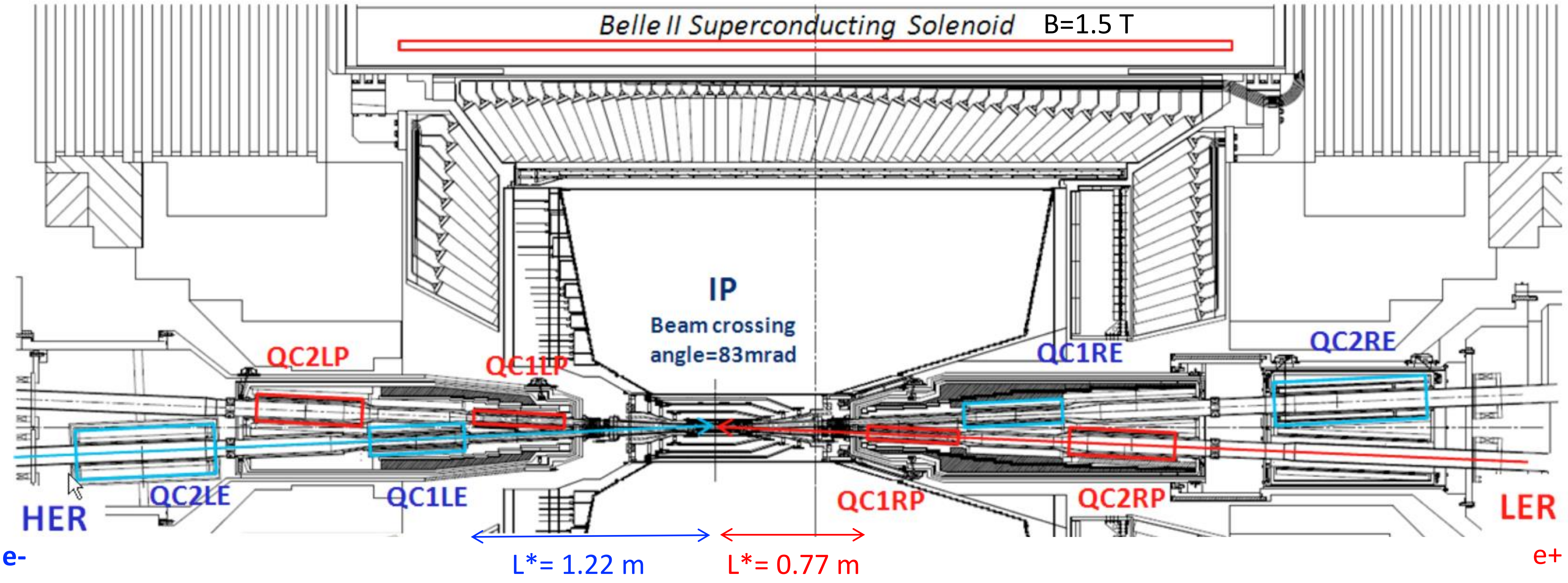
Parameters	unit	KEKB LER(e+)	KEKB HER(e-)	SuperKEKB LER(e+)	SuperKEKB HER(e-)
Luminosity	10^{34} $cm^{-2}s^{-1}$	2.11		**80**	
Circumference	m	3014		3014	
Energy	GeV	3.5	8.0	4	7.007
I (beam)	A	1.64	1.2	**3.6**	**2.6**
I (bunch)	mA	1.0	0.75	1.4	1.04
$\varepsilon_x / \varepsilon_y$ transv. rms	nm /pm	18 / 150	24 / 150	**3.2 / 8.64**	**4.6 / 12.9**
σ_x/σ_y(IP)	μm /nm	150 / 940	170 / 940	**10 / 48**	**11 / 62**

SuperKEKB is demonstrating FCC-ee key concepts

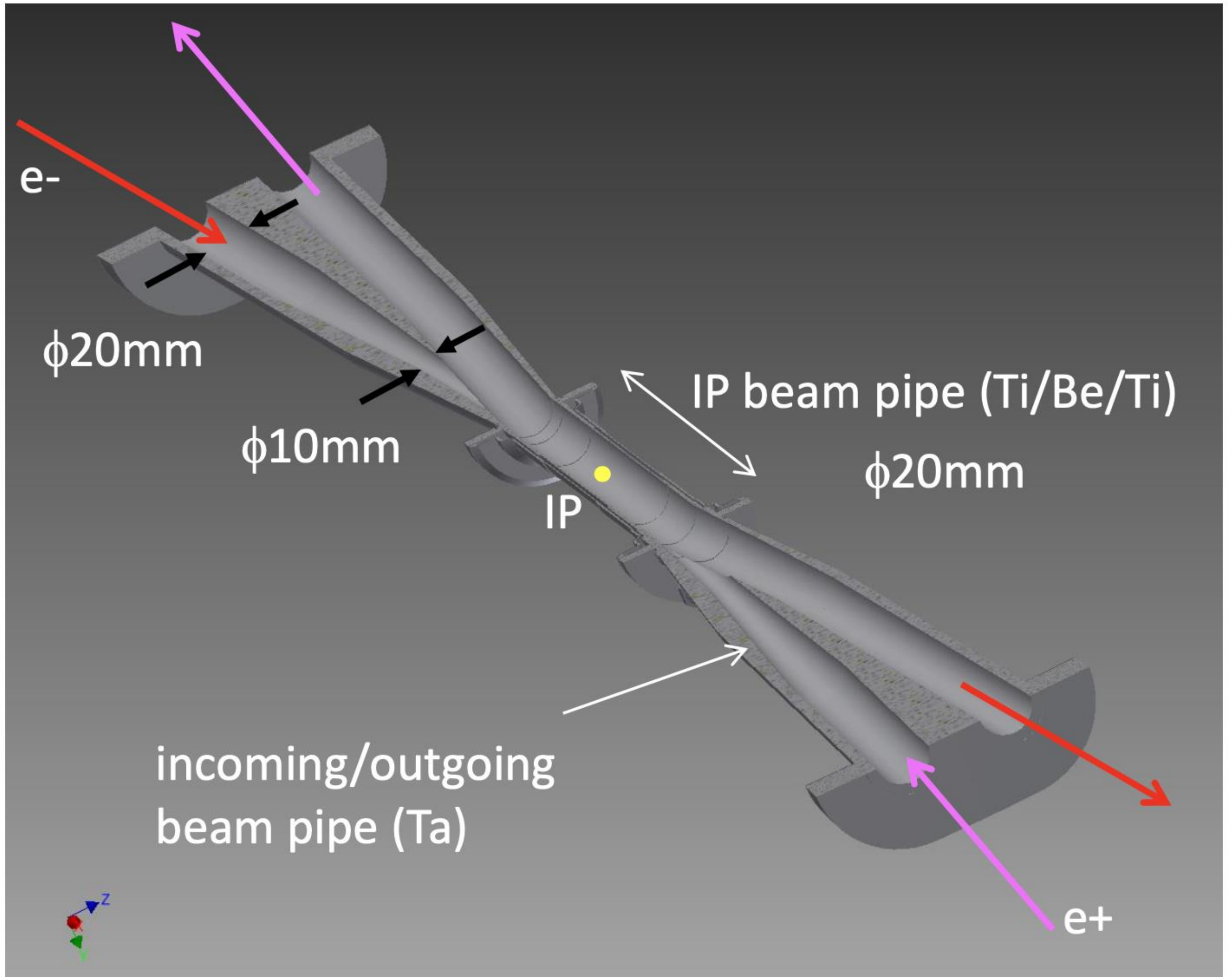


SuperKEKB FF magnets and detector

σ_x*= 10.7 μm σ_x*= 10.1 μm
σ_y*= 62 nm σ_y*= 48 nm



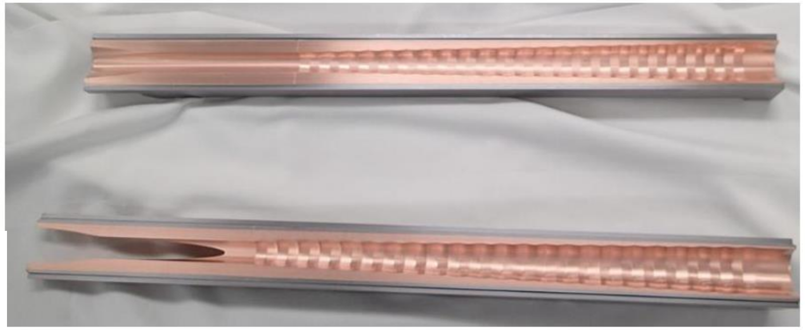
SuperKEKB beam pipe & synchrotron radiation



- ϕ20mm→ϕ10mm collimation on incoming beam pipes (no collimation on outgoing pipes, HOM can escape from outgoing beam pipe)

- Most of SR photons are stopped by the collimation on incoming pipe.
- Direct hits on IP beam pipe is negligible

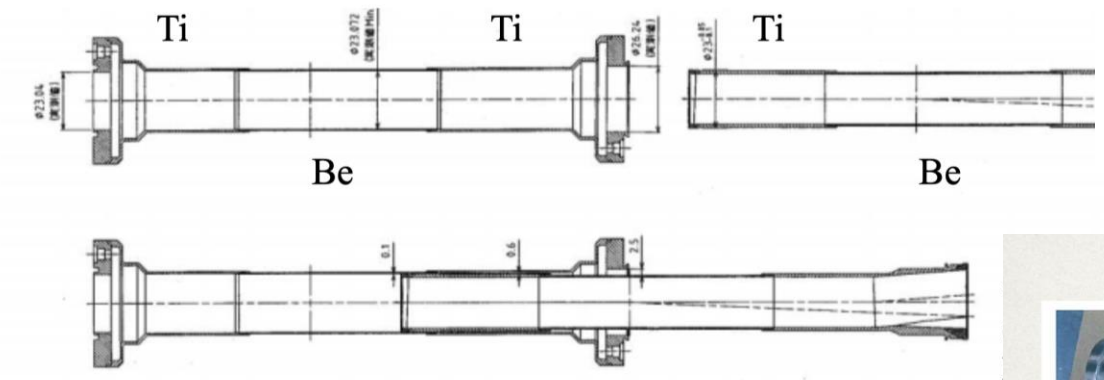
- To hide IP beam pipe from reflected SR, "ridge" structure on inner surface of collimation part.

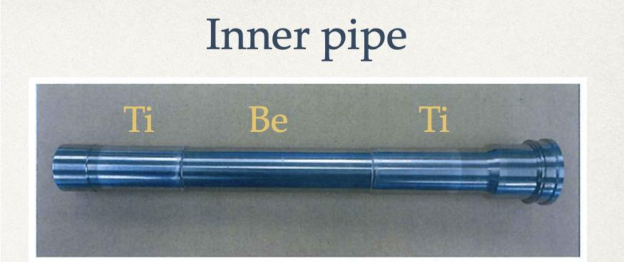


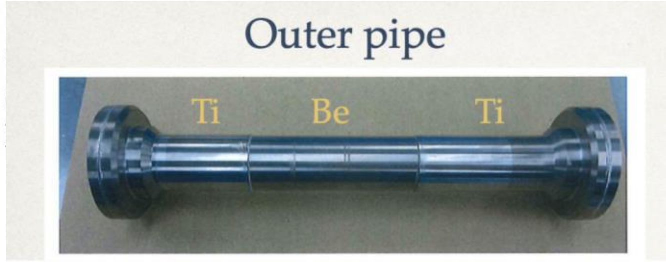
Inner surface of Be pipe are coated with **Au layer (10 μm)** to protect detectors from SR

SuperKEKB Be beam pipe at IP

- The beam pipe at the IP is a double pipe, each consists of middle (Be) and side (Ti) parts, brazed to each other.
- The inside of inner pipe is Au coated (10 μm thickness via 0.3 μmTi) by magnetonsputtering
- Paraffin runs between them



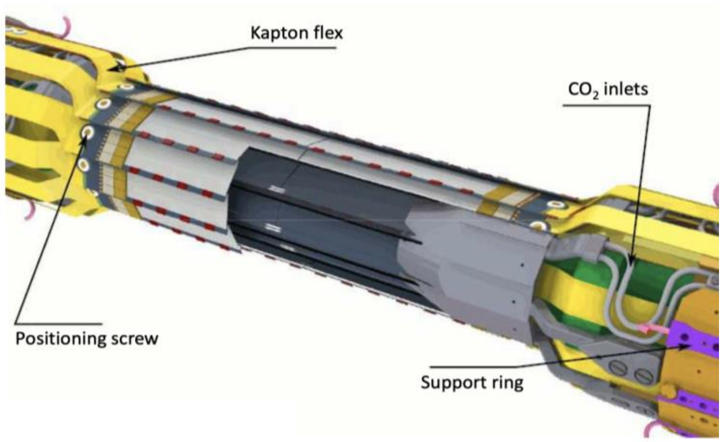




- Outer Be: 0.4 mm thick
- Inner Be: 0.6 mm thick
- Gap: 1 mm

K. Kanazawa

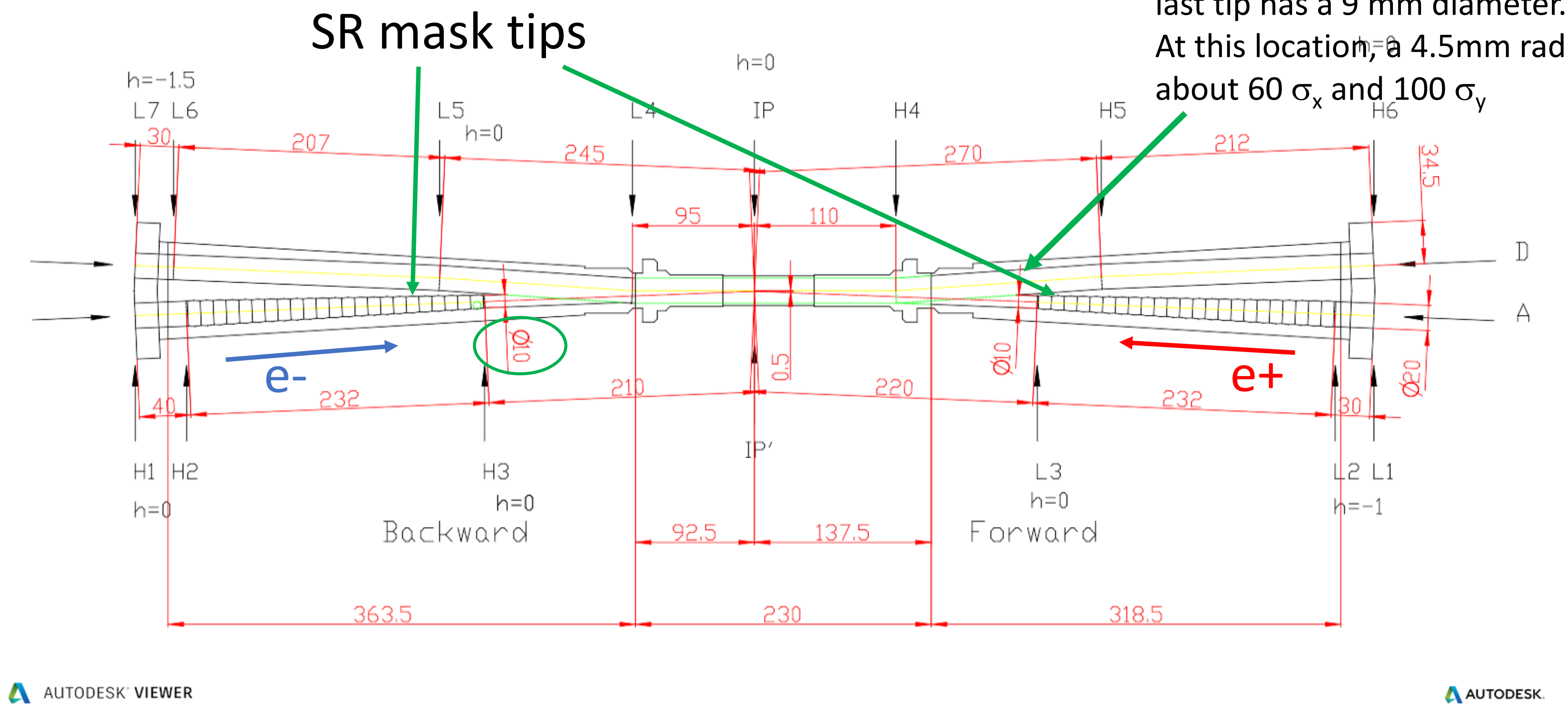
Light material (Be) inside detector acceptance
Paraffin ($C_{10}H_{22}$) flow to remove heat from image charge (~80 W)
Gold plating on inner wall protects detectors



- Low material budget cooling
  - Massive structures outside the acceptance to cool down the readout chips
  - The center of the ladder rely on cold air

IR beam pipe

The smallest aperture is about 20 cm from the IP and has a diameter of 10 mm. The last tip has a 9 mm diameter.
At this location, a 4.5mm radius equals about 60 σ_x and 100 σ_y



SuperKEKB backgrounds experience

- **Data/MC signals now within a factor of 2-3 with many down to the 20% level or better**

This includes detector background signals for large radius detector subsystems
i.e. calorimeter, TOP (Cherenkov particle ID), drift chamber,…

great job modeling the various backgrounds!

Vacuum scrubbing still major background source, Touschek is very important source for Belle II (highly dependent on the beam size, for them on the vertical size)

SR hit pattern on PXD forward: At the beginning of the run (2018) an unexpected background was found in the partially installed first layer of the vertex detector (PXD). It was explained as backscattered photons from downstream of the beam pipe that bounced back into the Be section producing hits in the pixel detector. This could be explained increasing the beam tails distribution in the model. (not critical, but under observation)

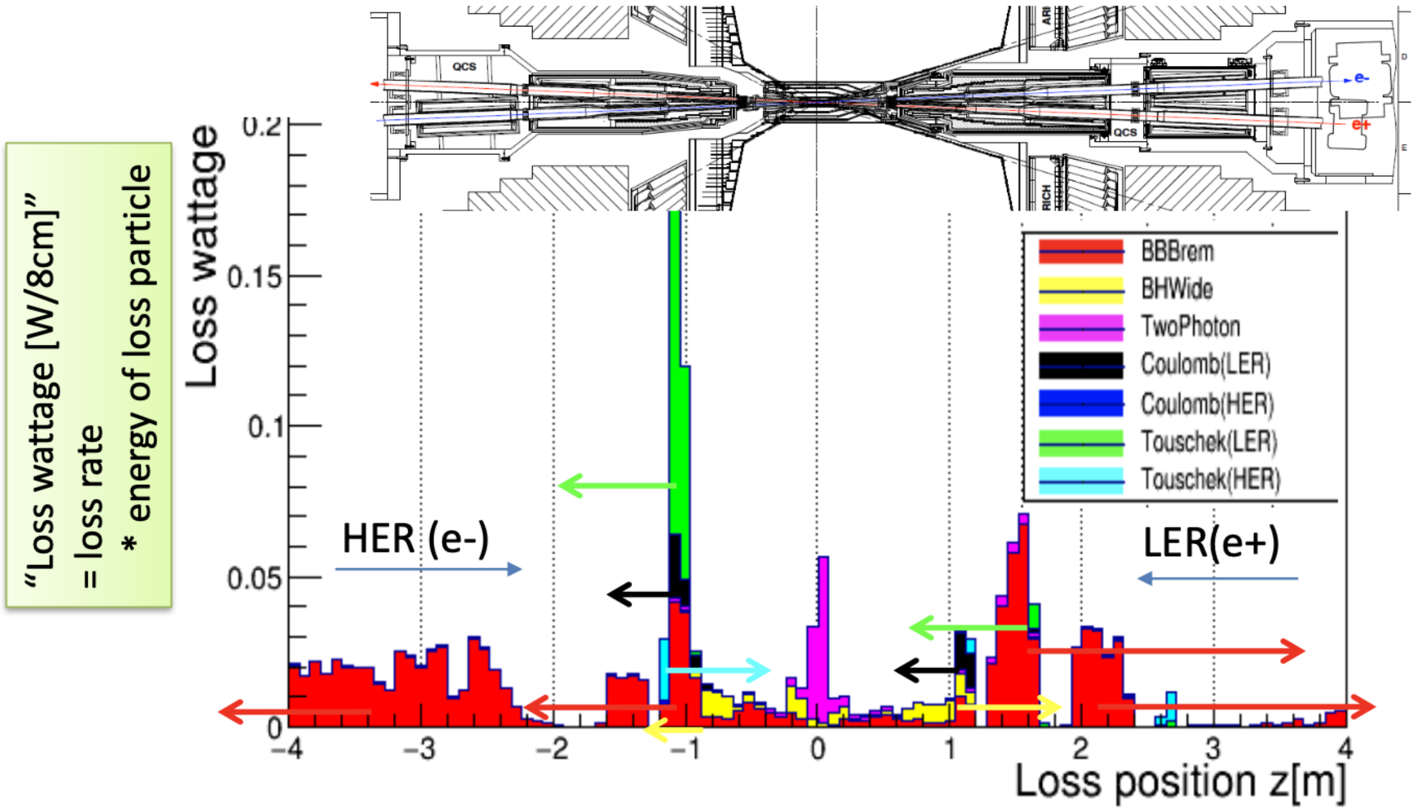
- **Injection background:** Belle II needs trigger veto after each injection, ~7-8% deadtime

Possible upgrades for backgrounds mitigation and reach full $\mathcal{L}$

- Collimators: add new ones and move some
- Additional shield around QCS bellow (2022)
- QCS modification,(2026?): wider beam pipe aperture -> less beam losses, less overlap of solenoid and quads
- > 2030 possible luminosity upgrades

Simulated IR beam loss distribution (design luminosity)

15th campaign (2017)

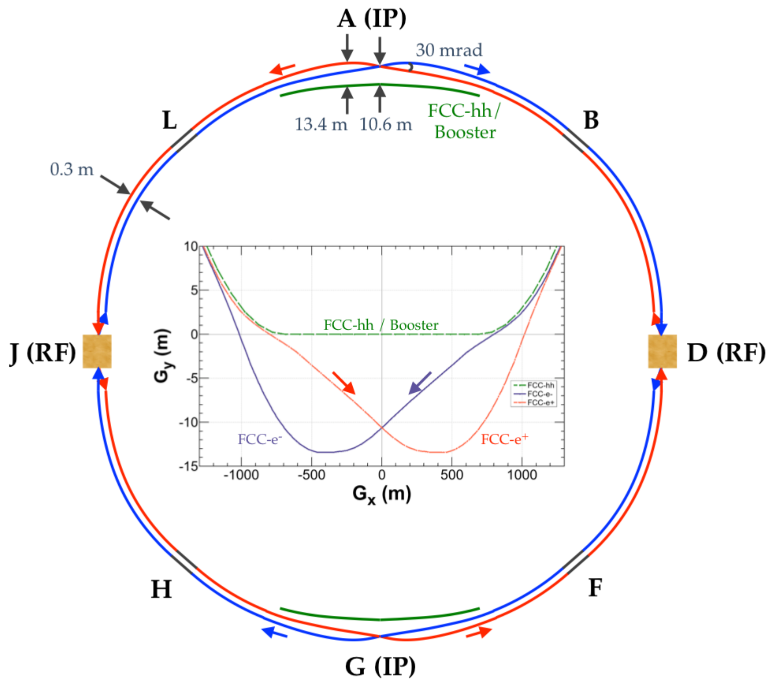


	LER (4GeV e+)	HER (7GeV e-)
Lumi-dependent BG	BBBrem: **1.08 W** (0.06 W in |z|<65cm) BHWide: 0.11 W (0.04 W), 2photon: 0.14 W(0.11W)	
Touschek	0.27 W (0.42GHz)	0.04 W (0.03GHz)
Coulomb	0.06 W (0. 10Hz)	0.00 W (0.002GHz)

measured IP bkgs consistent with prediction –will dominate at full luminosity

H. Nakayama

FCC-ee basic design choices



Determines the MDI layout

High $\mathcal{L}$ with the **crab-waist** scheme:

nanobeams with large horizontal crossing angle (30 mrad),

vertical squeezed and long bunches & virtual crab sextupoles

Small instantaneous overlap area, allowing for low β_y^* → $\mathcal{L}$ O(10^{36} $cm^{-2}s^{-1}$) @Z

Asymmetric IR optics suppresses synchrotron radiation towards the IP

$E_{critical}$ <100 keV from 450 m from the IP

Local chromaticity correction scheme for y-plane (a-d), incorporated with crab sextupoles (a,d) (energy acceptance up to 2.8%)

presently 2 IPs (alternative layouts with 3 or 4 IPs under study)

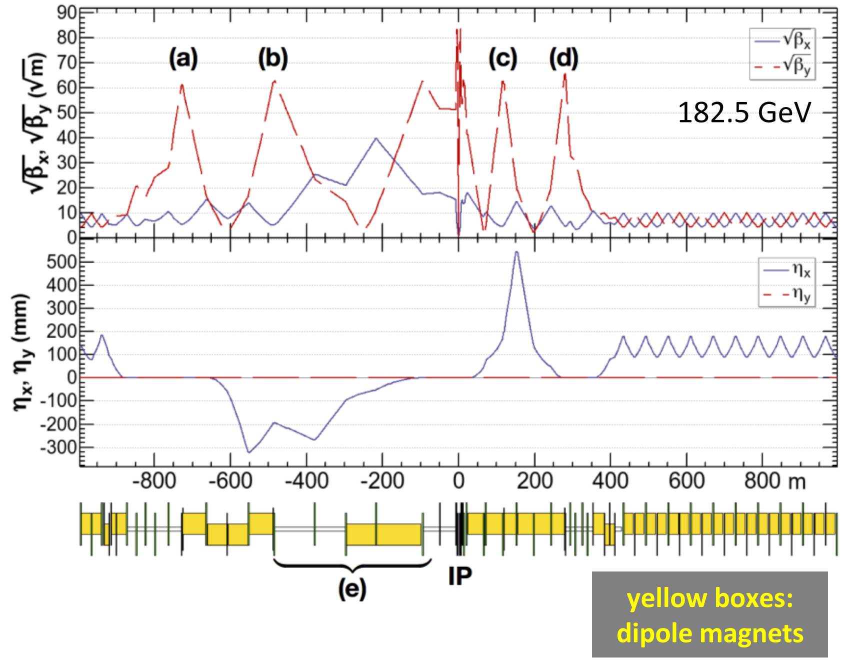
synchrotron radiation power 50 MW/beam at all beam energies; tapering of arc magnet strengths to match local energy

common RF for $t\bar{t}$ running

top-up injection requires **booster synchrotron in collider tunnel**

double ring e^+e^- collider ~100 km

follows footprint of FCC-hh, except around IPs



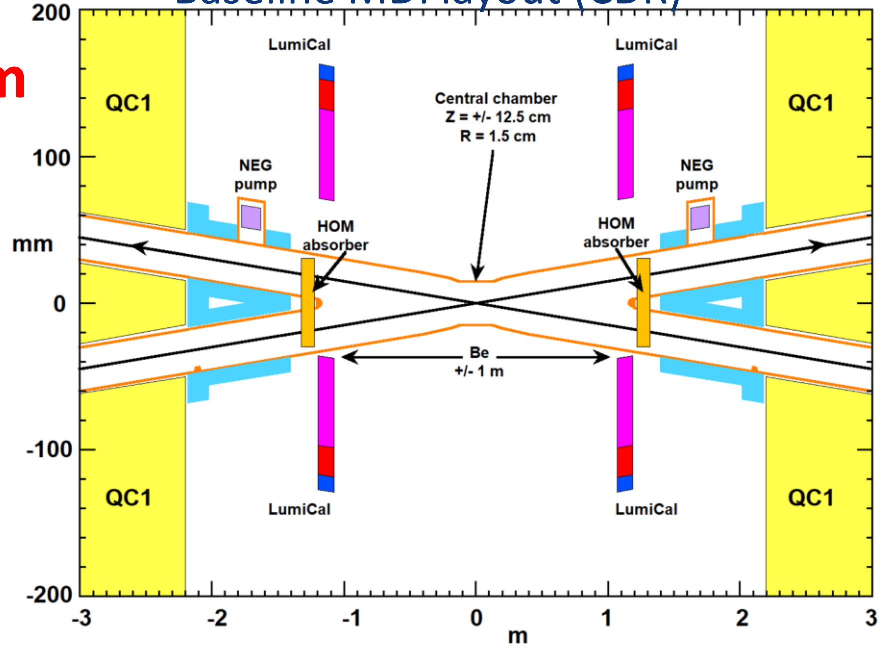
FCC-ee Interaction region & MDI – Integration challenge

- Requirement: **flexible** design, one IR at all energies
- **Very compact IR**, many magnets and devices inside detector
- **Very squeezed beams at IP** →
  - stringent quality of FF quads, and solenoid compensation
  - beam stabilization at IP: vibrations suppression, beam orbit and $\mathcal{L}$ feedback, tight alignment tolerances
- **High beam current at Z** (I=1.39 A) →
  - Heat load, cooling of beam pipe, HOM absorbers
  - Vacuum requirement, NEG coating, beam screens

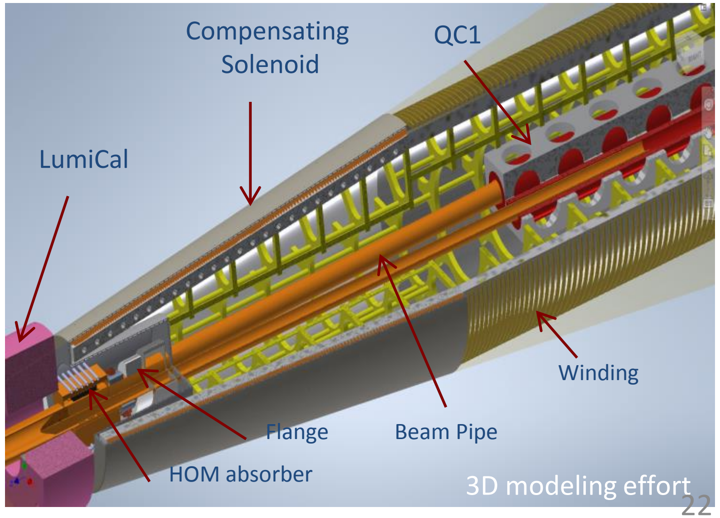
L*=2.2 m

B=2 T

Baseline MDI layout (CDR)



- **Solenoid compensation scheme** to preserve $\varepsilon_y \approx$ pm
- **Luminosity detector** @Z: absolute meas. to 10^{-4} (low angle Bhabha), acceptance to 1 μm level, tight requirements on alignement



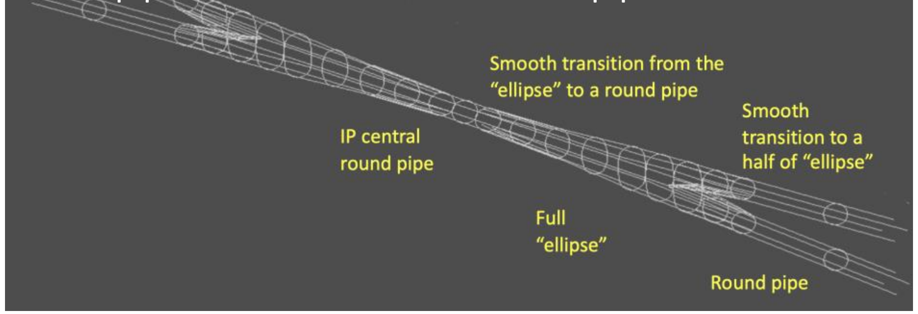
- **Synchrotron radiation**: detector sustainability top priority
- **Robustness against machine bkgs, occupancy**
- **Optimization of the central beam pipe design, material, thickness**
- Keep **low material budget**: minimise mass of electronics, cables, cooling

FCC-ee central beam pipe

Baseline design (CDR):

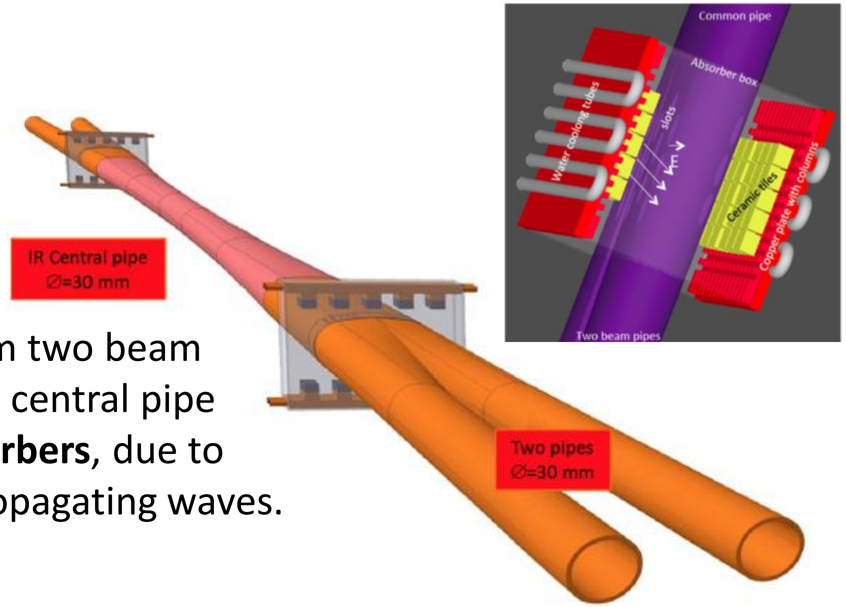
- **Warm pipe**
- Incoming and central beam pipes have a **constant diameter of 30 mm**
- Central part in Beryllium (in the lumical window acceptance)
- Shape determines low impedance
- Very good vacuum, low bkgs: SR masks, coating
- Remote vacuum connection (same concept as SuperKEKB)

General concept for minimizing the impedance of an IR beam pipe. Smooth transitions in the pipe connection.



HOM absorber
(from PEP-II experience)

[A. Novokhatski et al. PRAB 20, 111005 (2017)]



The transition from two beam pipes to a common central pipe requires **HOM absorbers**, due to trapped modes and propagating waves.

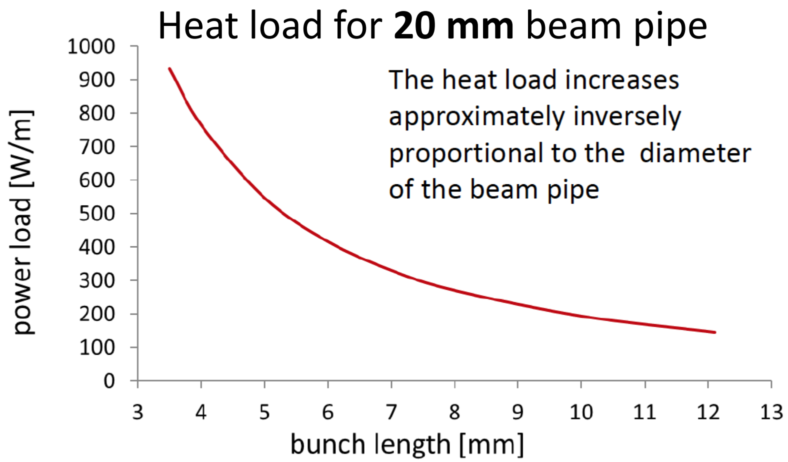
Liquid cooling needed due to the beam heat load, needed also in the central pipe (as for SuperKEKB).
few μm Au coating required in the central pipe (it can decrease the heat load by 30% but also for the low conductivity of Be)
-> one compromise to assure the best possible physics could be to foresee a different pipe for the Z and ttbar runs
(for SR shielding at ttbar, for heating from image currents at Z)

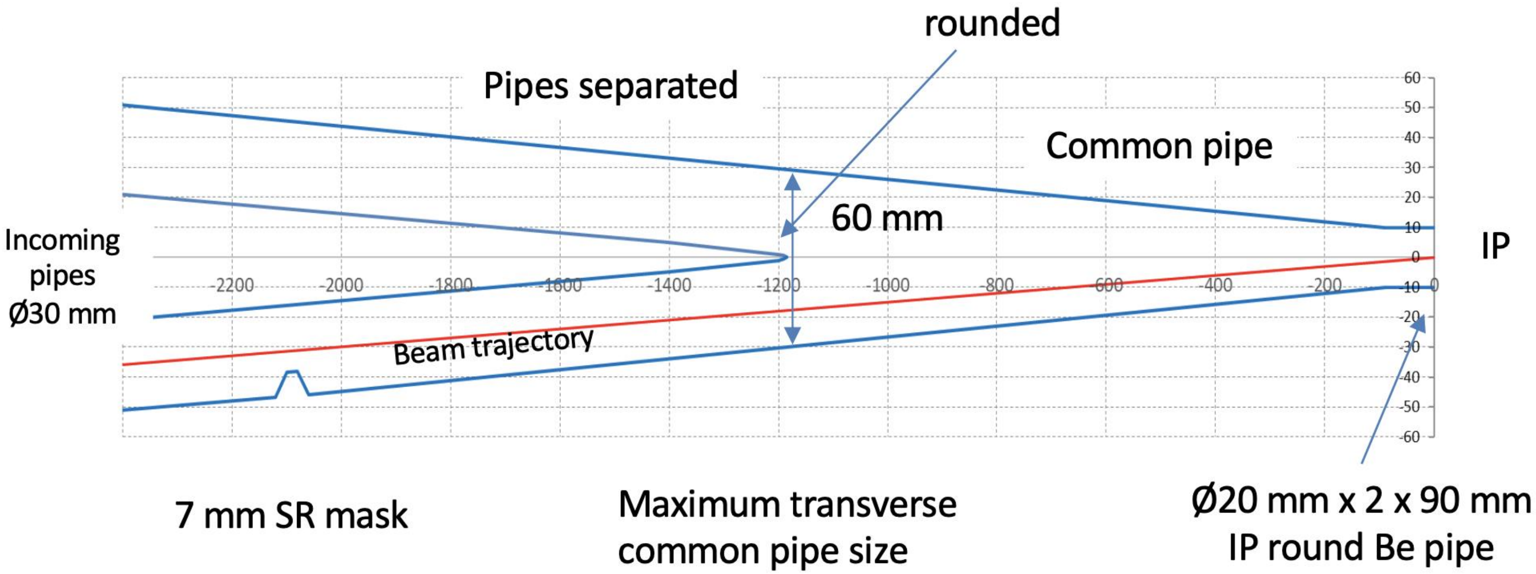
New FCC-ee central beam pipe with low impedance

Smaller central beam pipe 20 mm diameter

- Novel improved design with no need of HOM absorbers
- IR heat load unavoidable: em fields excited by the beams are due to the finite conductivity of the metal walls of the IR beam pipe
  Beryllium pipe takes 150 W/m from a 12 mm bunch

The heating power strongly increases with shortening the bunch length





We are considering AlBeMet instead of Be (~same X0)

A trade-off between better physics and worse backgrounds is needed (by simulation), given the relevance of the beam pipe choice, in terms of the success of the collider

Prototyping recommended

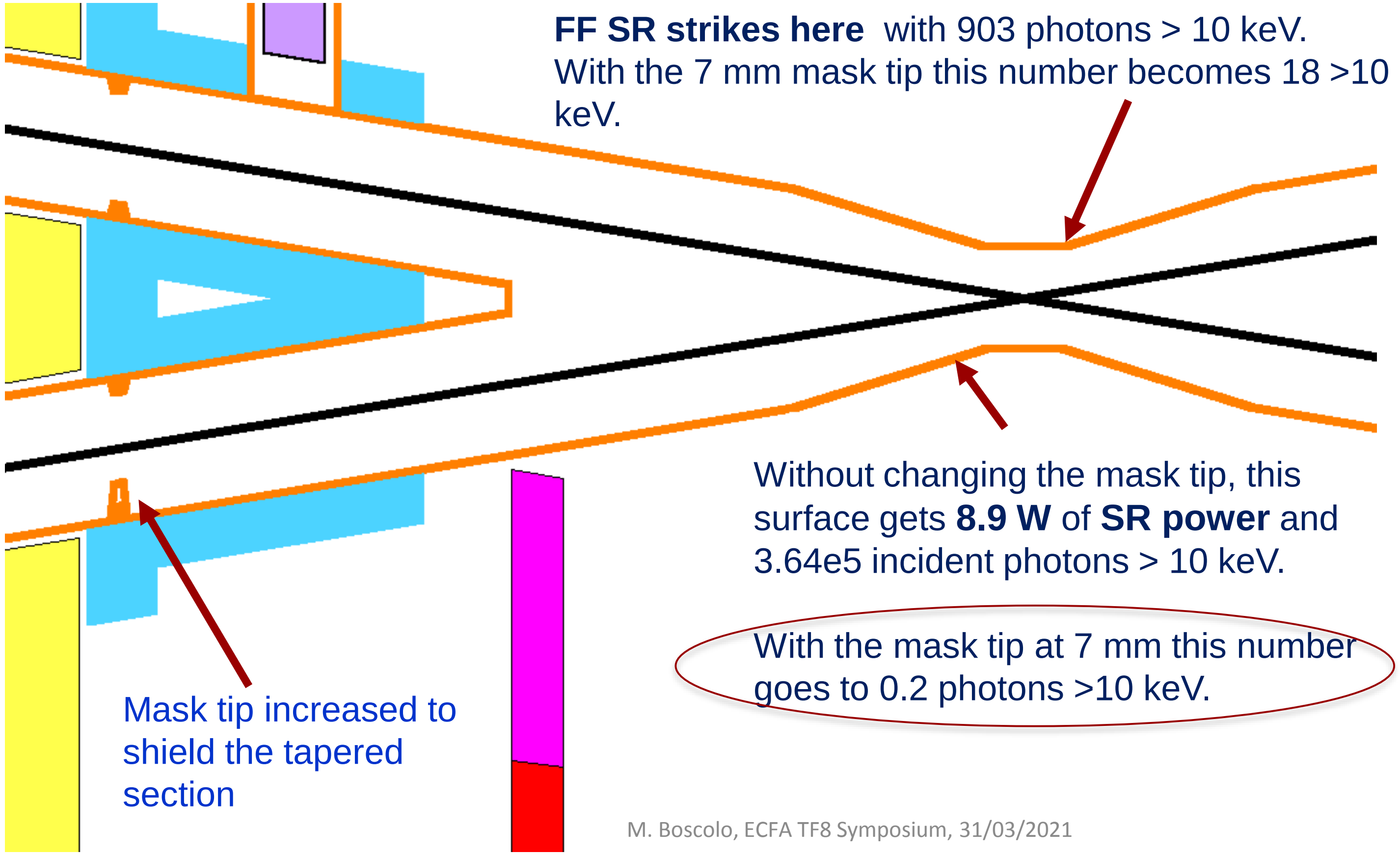
Synchrotron Radiation with smaller central beam pipe – Z case

M. Sullivan

Central pipe with 20 mm diameter and cylindrical length shorten from ±12.5cm to ±9cm

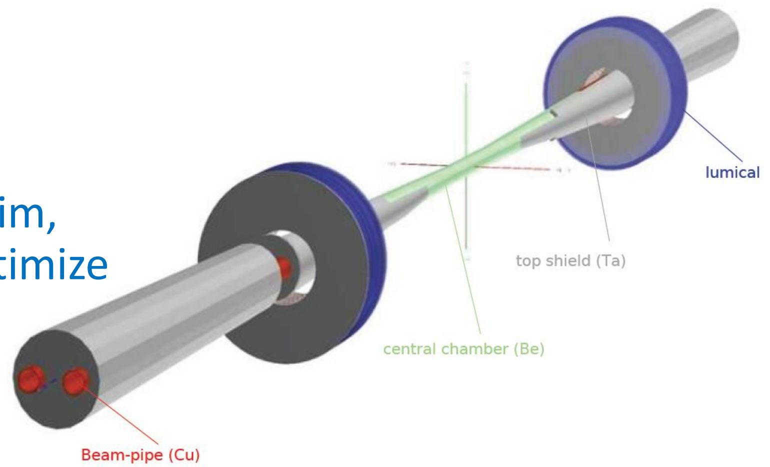
- The bend radiation can be masked away by reducing the mask radius at -2.1 m from 10 mm to 7 mm from the beam line.
- The quadrupole radiation cannot be totally masked away even with a 5 mm radius mask at -2.1 m

On-axis beam, non-Gaussian beam tails to 20 σ_x and 60σ_y



Smaller beam pipe:
impact on the vertex detector study on-going
also to optimize pipe thickness

FCC-ee Background studies



- **Synchrotron radiation background**
  - different codes used on the accelerator side for collimation and masking (MDISim, Synch_bkg, SynRad+) and impact on detector (Geant4) -> effort on-going to optimize beam pipe, masks, shielding
- **Generation of background sources**
  - IP backgrounds
  - Single beam backgrounds:
- **Tracking beam scattered particles**
  - **to produce IR loss map → and track into detectors** (CLD and IDEA)
  - **to produce loss maps around the ring → for collimation study**
  - Multiturn tracking for IP and single beam bkgs to be continued and strenghtened with more details, especially with non-ideal lattice (energy tapering with radiation, imperfections)
  - Collimation scheme
  - Beam tail

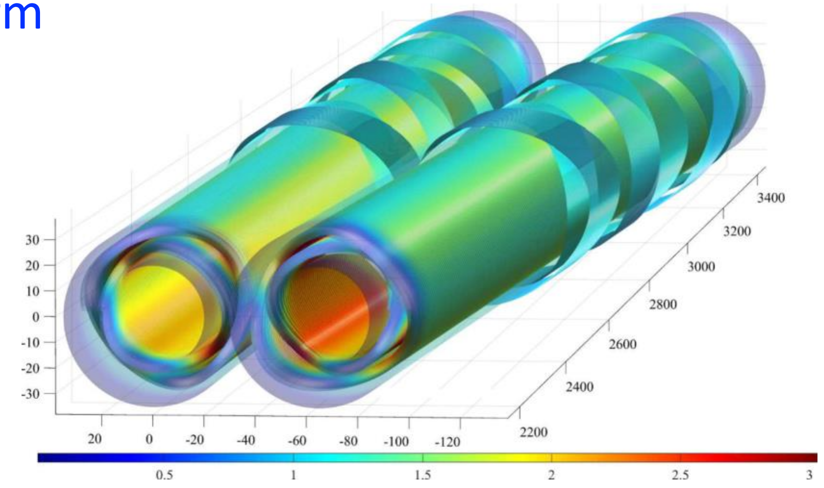
Backgrounds are found maneagable in detector
as documented in the CDR,
it is essential to continue and refine these studies
for more and more realistic simulations

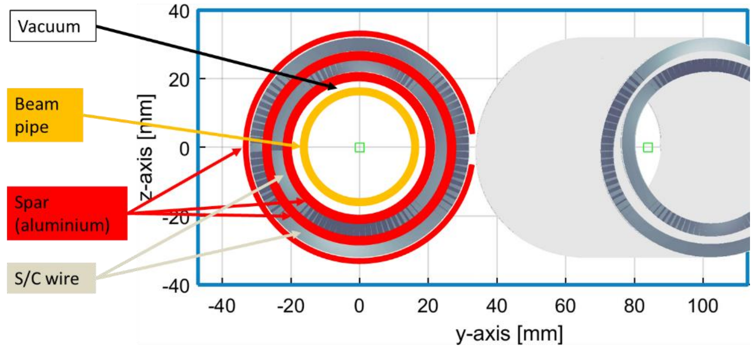
FCC-ee Final Focus quadrupole QD0 CCT design

- Final Focus quadrupoles CCT design, design with many advantages.
- The quadrupole is operated at **4.2 K, SC wires.**
- The maximum field gradient is 100 T/m.
- The inner diameter of the beam pipe in the vicinity of QC1 is 30 mm; around QC2 it is 40 mm. The FF quadrupoles have an inner diameter of 40 mm and an outer diameter of 68 mm (truncated to 66 mm for the first FF element, QC1L1).
- Study of proper shielding to avoid quench to be done

First study of a CCT approach for a similar application:
E. Paoloni, P. Fabbricatore *et al.* for the SuperB project

Prototyping and testing essential.
Small prototype was done, warm test recently performed.

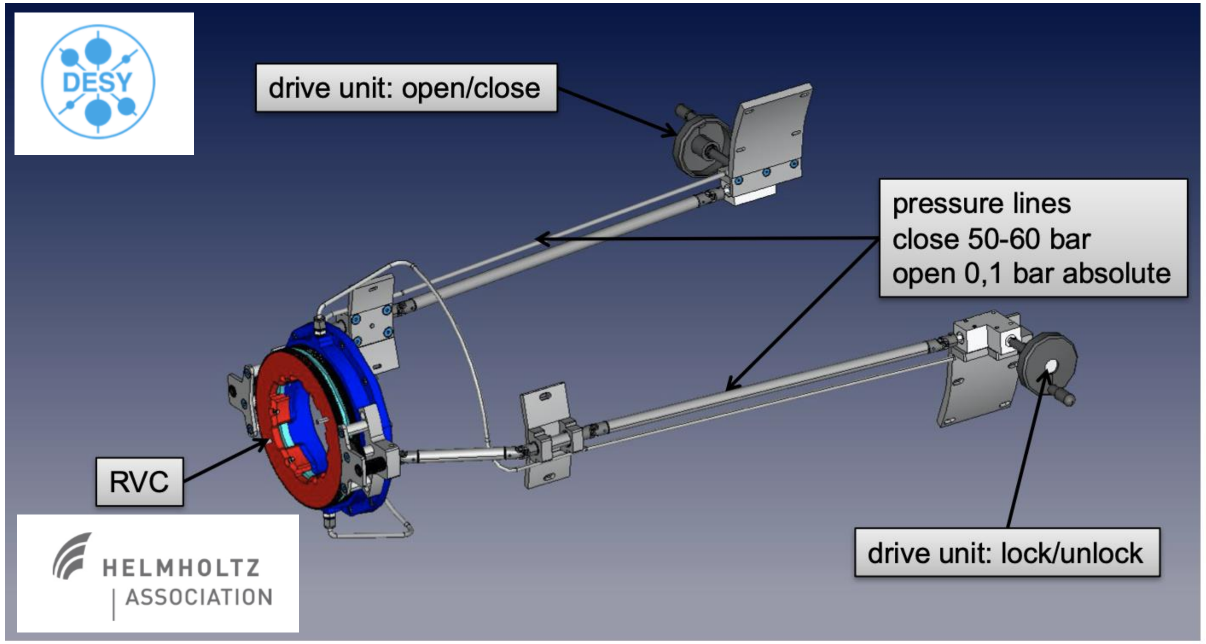


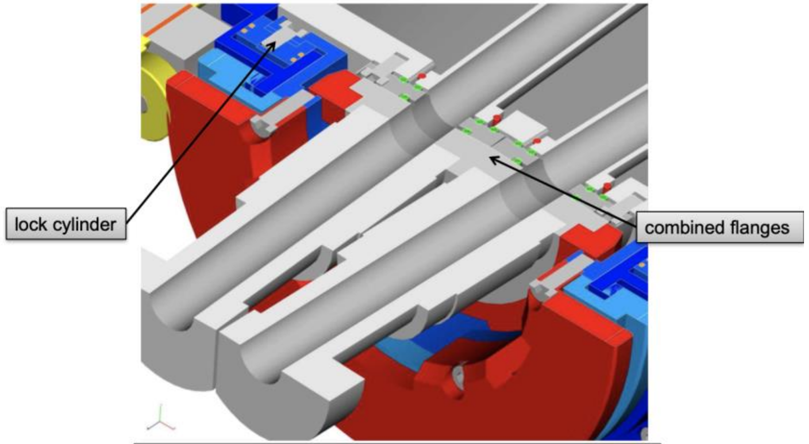


Remote Vacuum connection

- The foreseen strategy for the vacuum connection after installation follows the one developed for SuperKEKB proposed by DESY (Karsten Gadow)

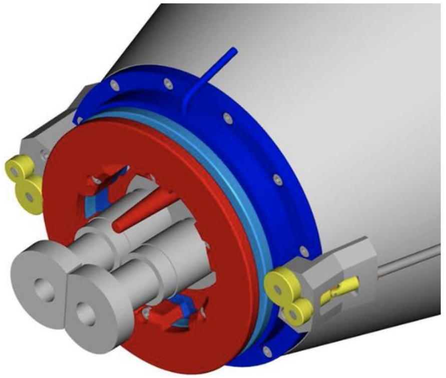
R&D advisable for FCC-ee





3. Turned lock cylinder with beam pipe flanges close together

Karsten Gadow | BPAC focused review on VXD | 17.10.2017 | Page 19



2. Move QCS with mounted RVC close to CBP to get flanges in contact

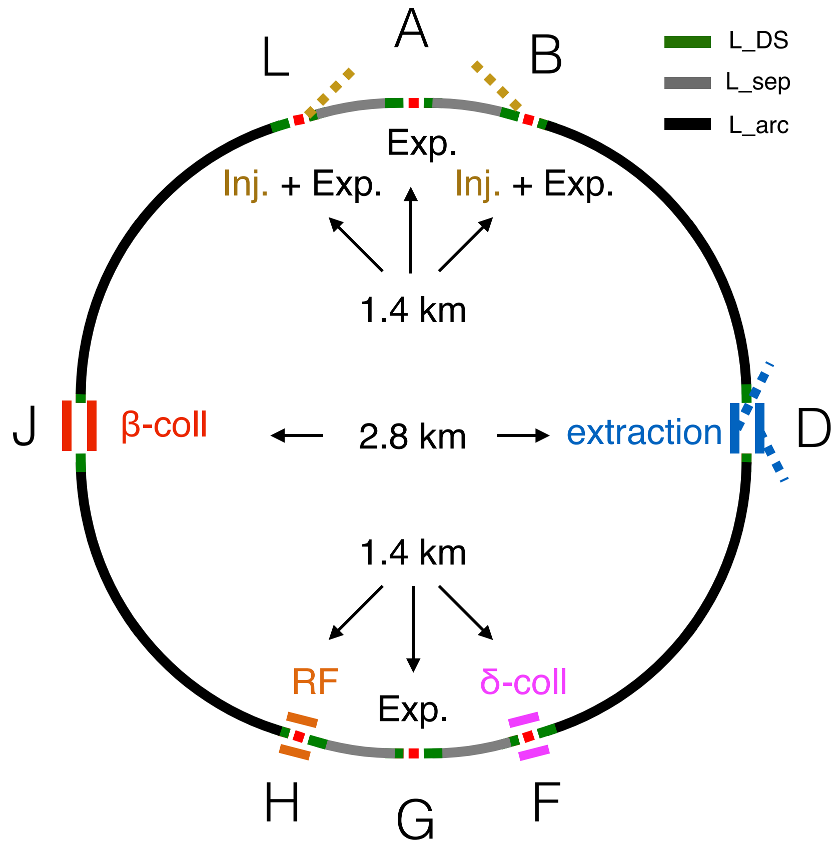
FCC-hh

	HL-LHC	FCC-hh
Cms energy [TeV]	14	100
Int. L., 2 det. [ab^{-1}]	6	30
Operation [years]	12	25
L [$10^{34}cm^{-2}s^{-1}$]	5	20-30
Circumference	26.7	97.75
Arc dipole field [T]	8	16
Bunch dist. [ns]	25	25
Backgr. events/bx	135	<1020
Bunch length [cm]	7.5	8
L* [m]	23	40

31 GHz of pp collisions

Pile-up 1000

4 THz of tracks



Two main IP's in A, G for both machines

Two High Luminosity IPs A/G

Two Lower Luminosity IPs L/B

Similar to layout at LHC

Unprecedented particle flux and radiation levels

10 GHz/cm2 charged particles

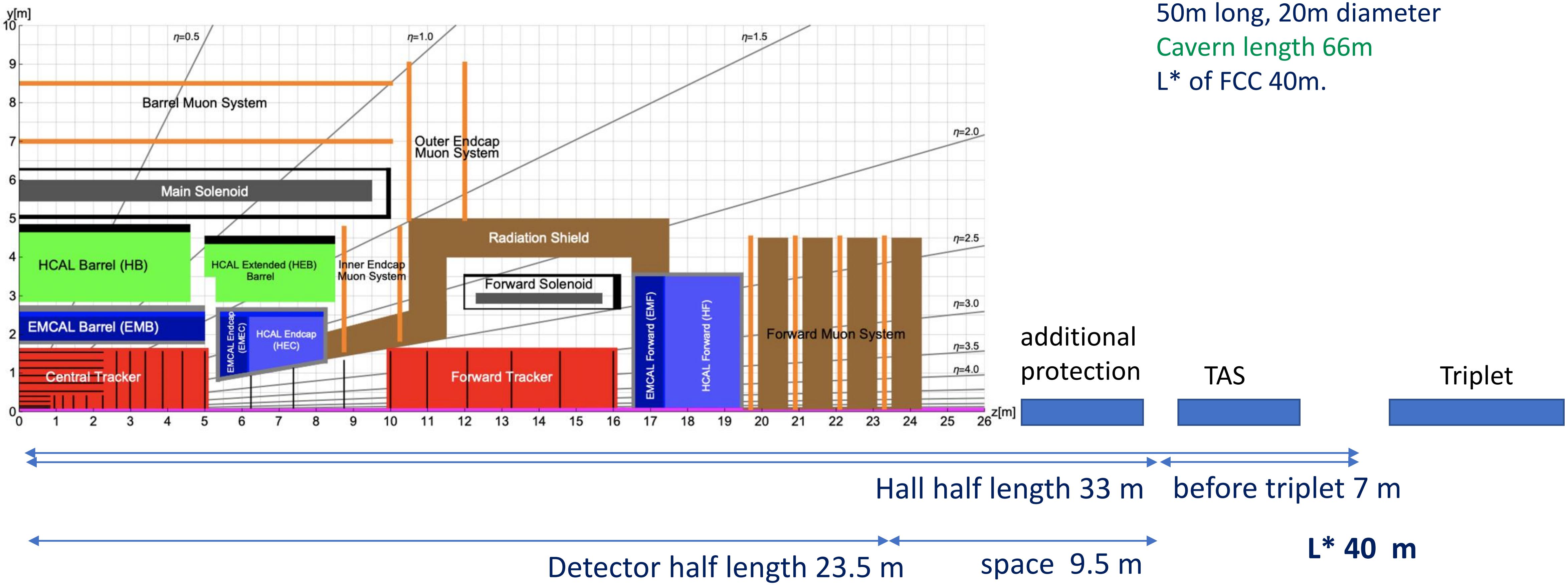
≈ 10^{18} cm^{-2} 1 MeV-n.eq. fluence for 30ab^{-1} (first tracker layer, fwd calo)

signal events from "Light" SM particles produced with increased forward boost

-> spreads out particles by 1-1.5 units of rapidity

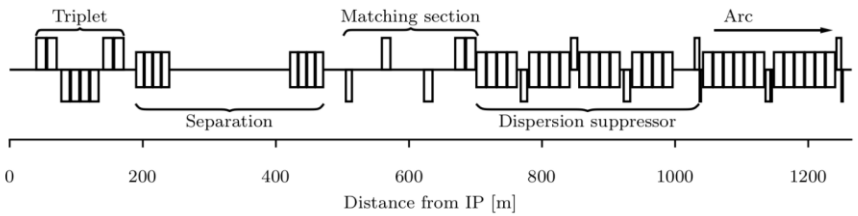
FCC-hh MDI

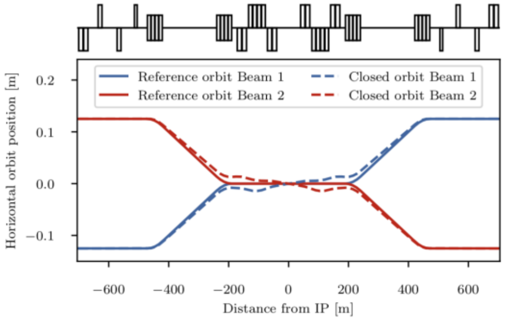
50m long, 20m diameter
Cavern length 66m
L* of FCC 40m.

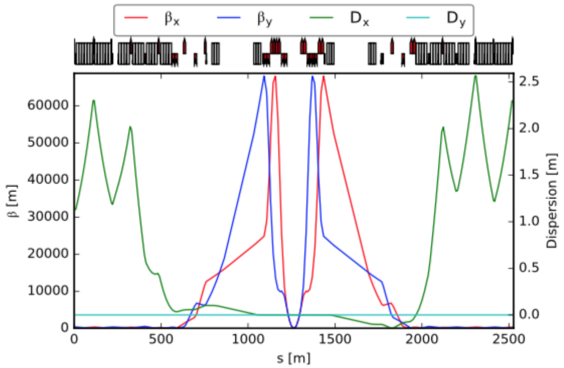


500 kW power into detector and accelerator (CNGS target!)
radiation in magnets requires some improvements of radiation hardness, considered feasible

FCC-hh IR optics



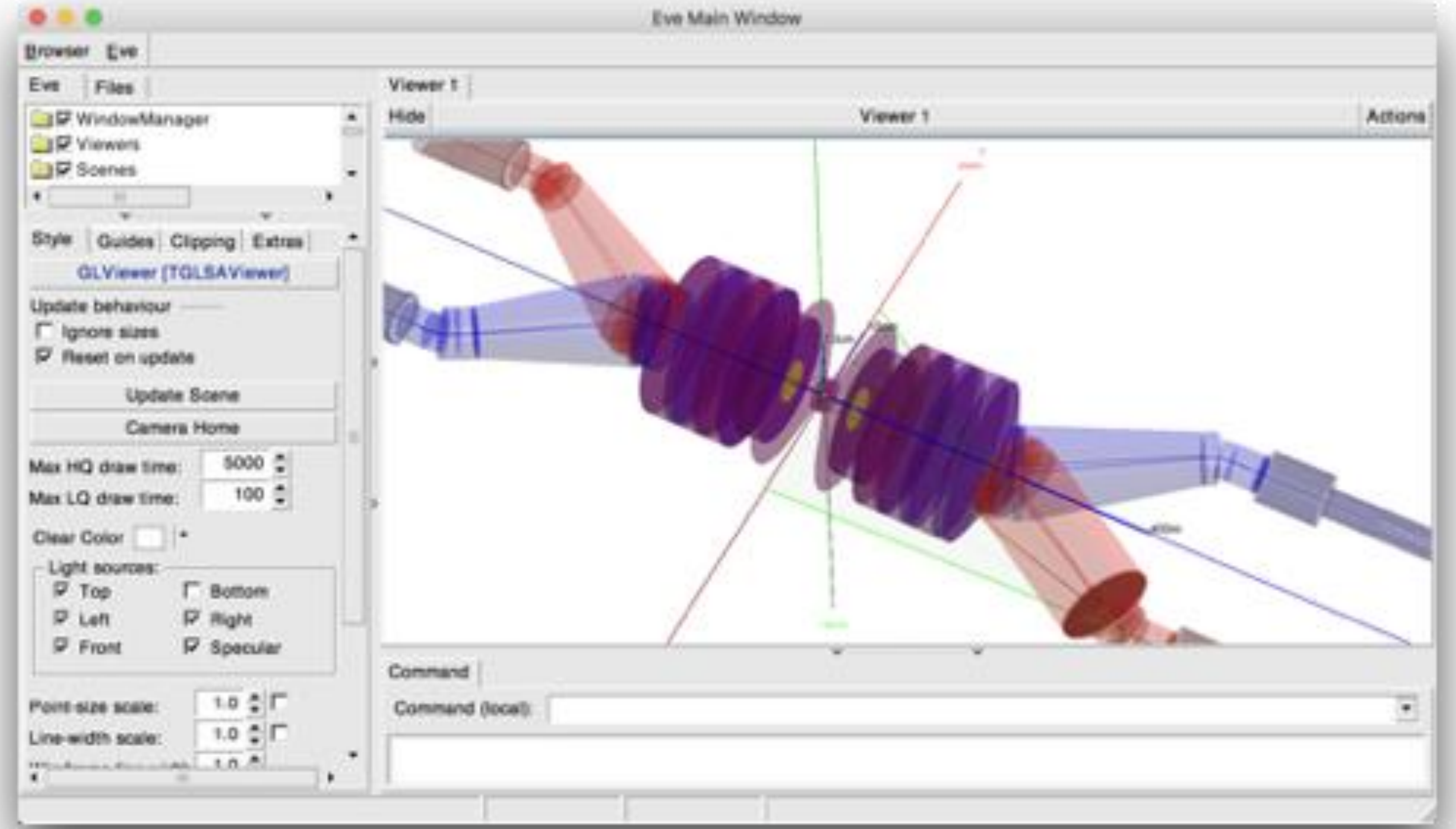




(a) Interaction region: LSS-PA-EXP & LSS-PG-EXP

- Design follows the structure of the LHC IR
- small β* at IP (∝1/√E): demanding IR optics design & large aperture in final focus triplet
- Challenge for magnet, protection design and collimation system (to intercept tail particles that could hit the triplet)
- 1.4 km required
- Final focus is a triplet (superconducting magnets) with a single aperture followed by normal conducting dipoles that separate the beams in individual aperture
- Design of the final focus system is driven by energy deposition from collision debris from the IP: short drift between IP and quad and large aperture in FF quads
- 20 m reserved for crab cavities

MDISim Toolkit



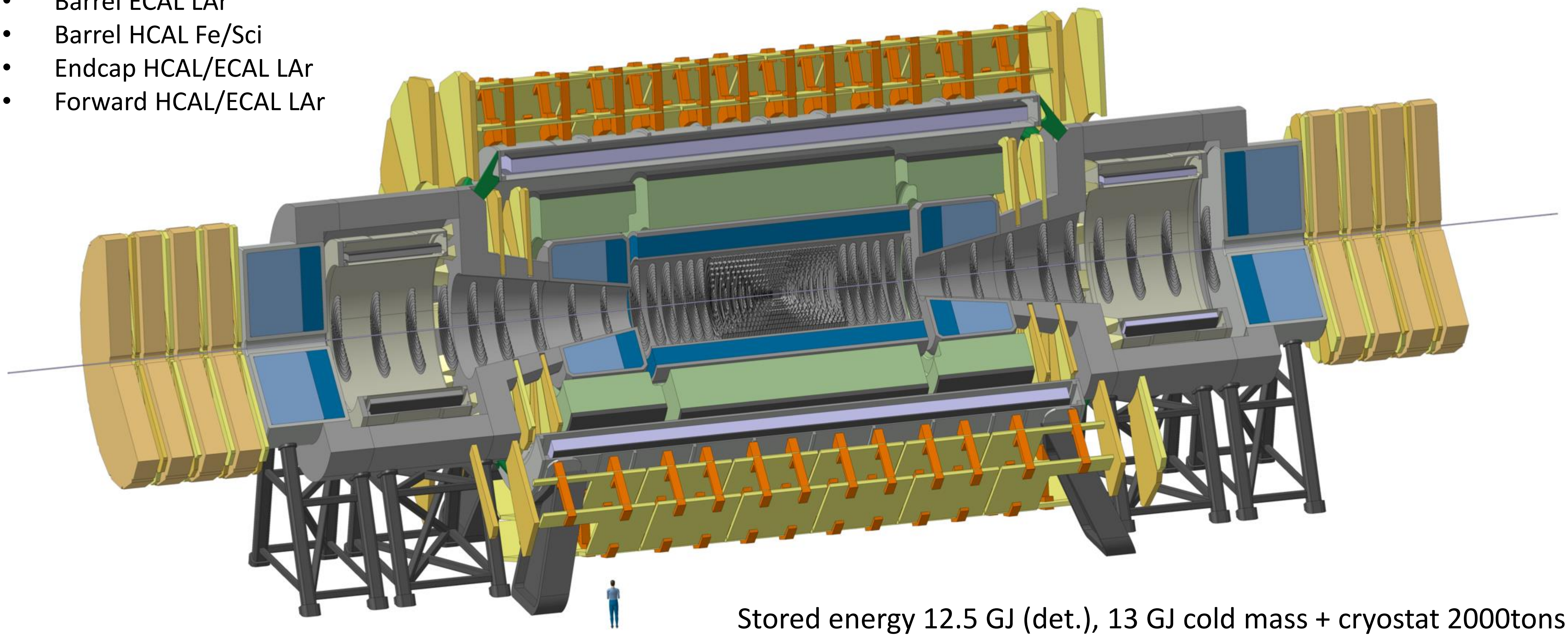
[Ref. MDISim]

Synchrotron Radiation from 50 TeV protons has been simulated into the MDI, finding a negligible contribution

FCC-hh Reference Detector

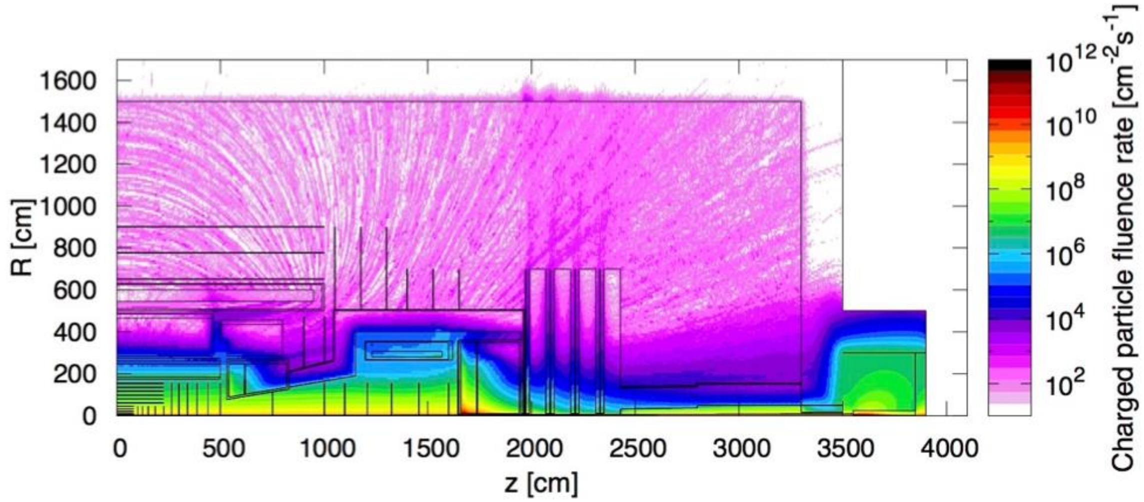
- 4T, 10m solenoid, unshielded
- Forward solenoids, unshielded
- Silicon tracker
- Barrel ECAL LAr
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

50m length, 20m diameter
similar to size of ATLAS



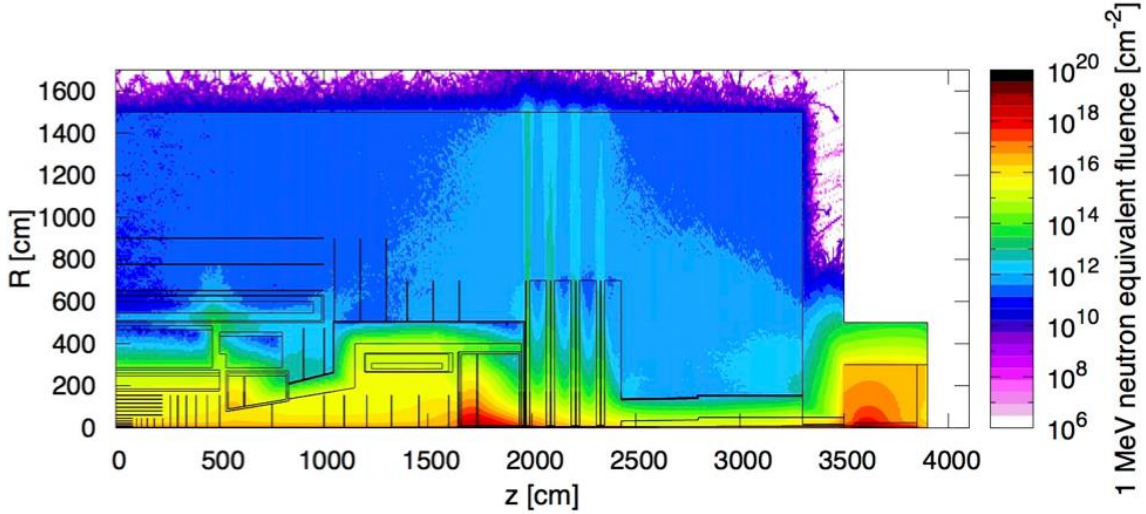
Stored energy 12.5 GJ (det.), 13 GJ cold mass + cryostat 2000tons

FCC-hh Radiation Studies for L=3x10^{35} cm^{-2}s^{-1} and 30ab^{-1}



Maximum of 10kHz/cm^2 of charged particle rate in the Barrel and Forward Muon System, similar to HL-LHC Muon Systems.

In the tracker volume the charged particle rate is just a function of distance from the beampipe with rather small dependence on z.

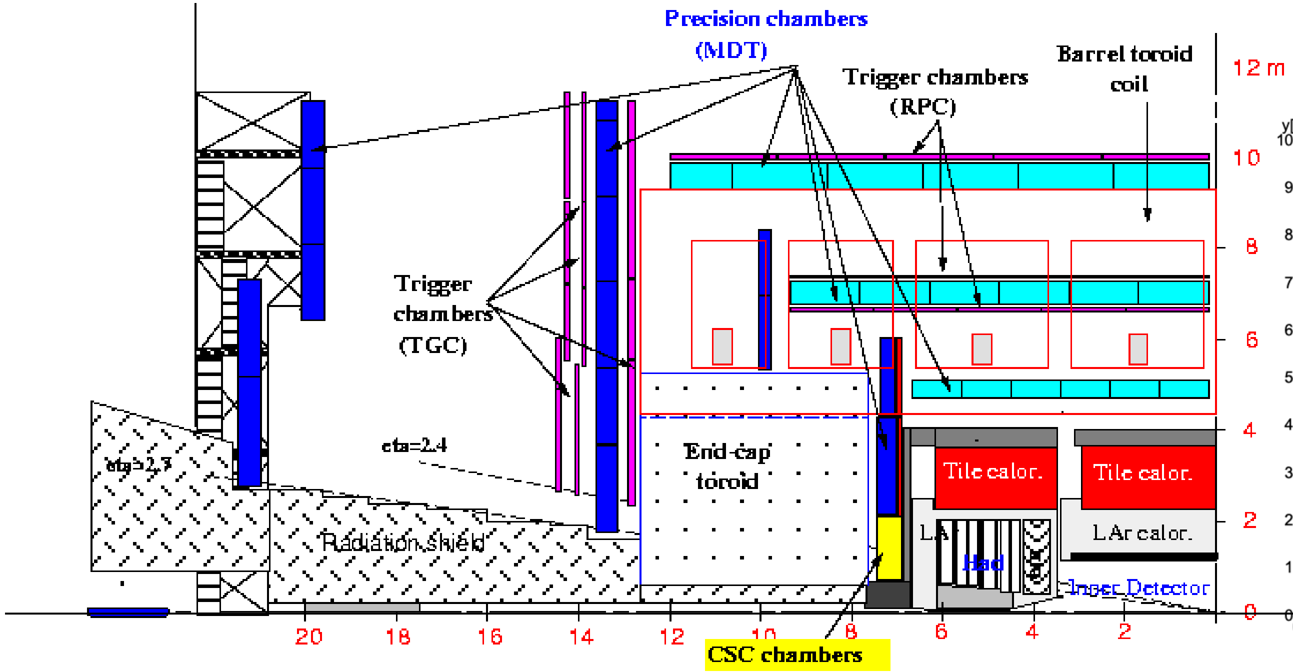


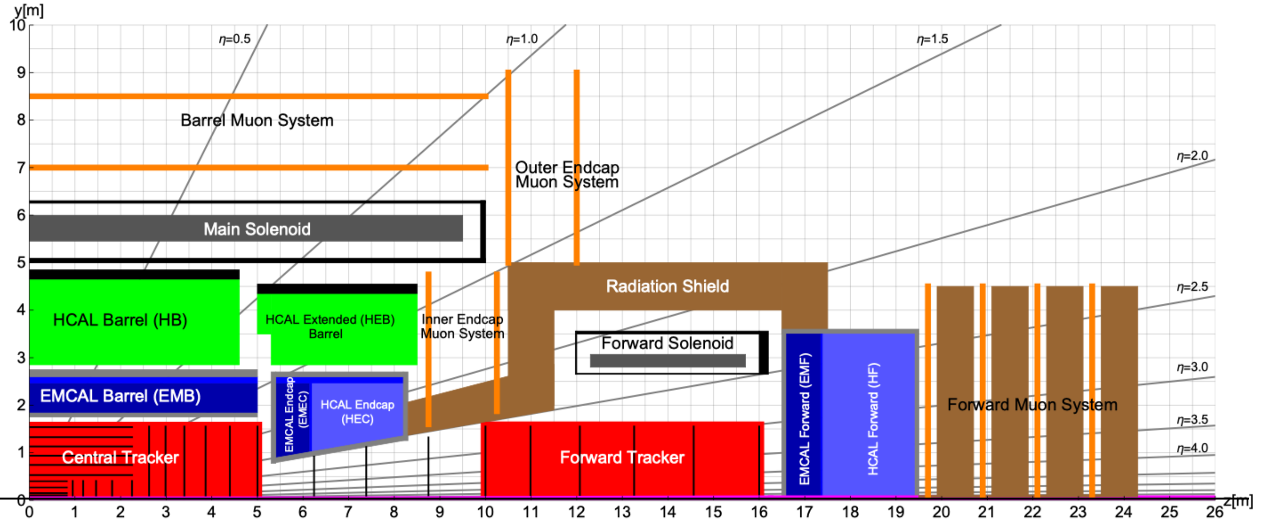
Hadron fluence in the order of 10^{18} /cm^2 close to the beampipe and 10^{15} -10^{16} /cm^2 (HL-LHC levels) for r>40cm.

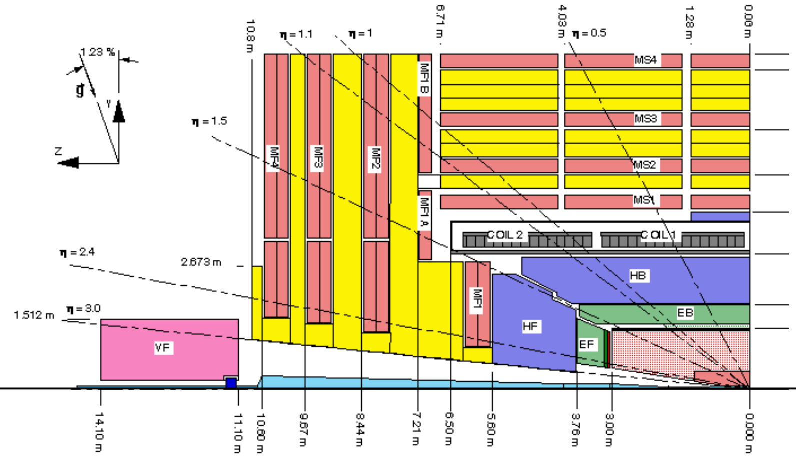
Extreme fluences in the forward calorimeter …

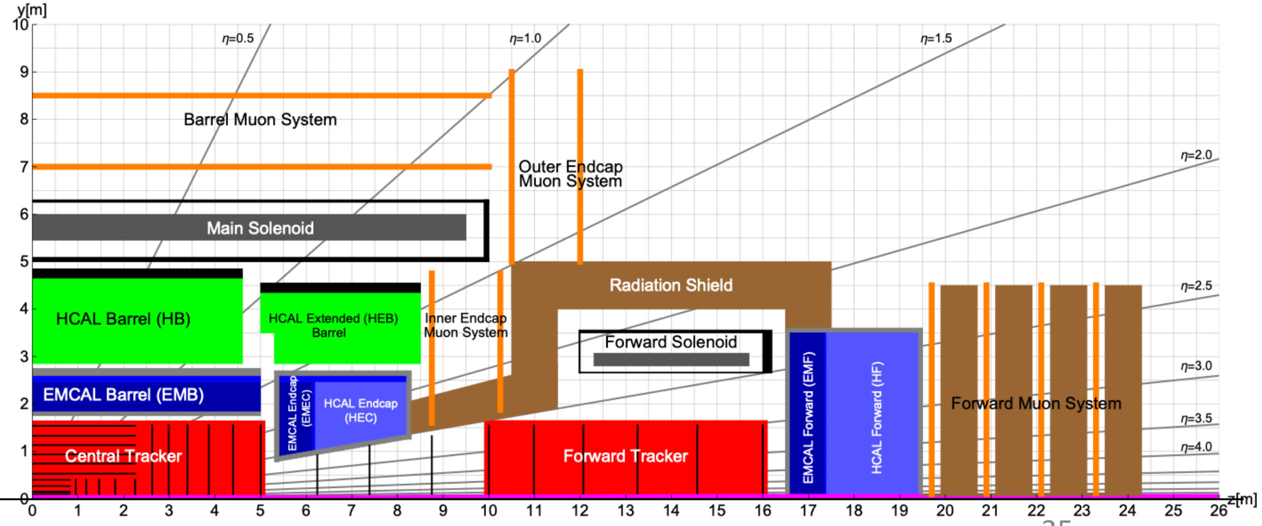
Triplet (z=40m), Triplet shielding TAS (z=35m) and related radiation are nicely 'buried' inside the tunnel.

Comparison to ATLAS & CMS



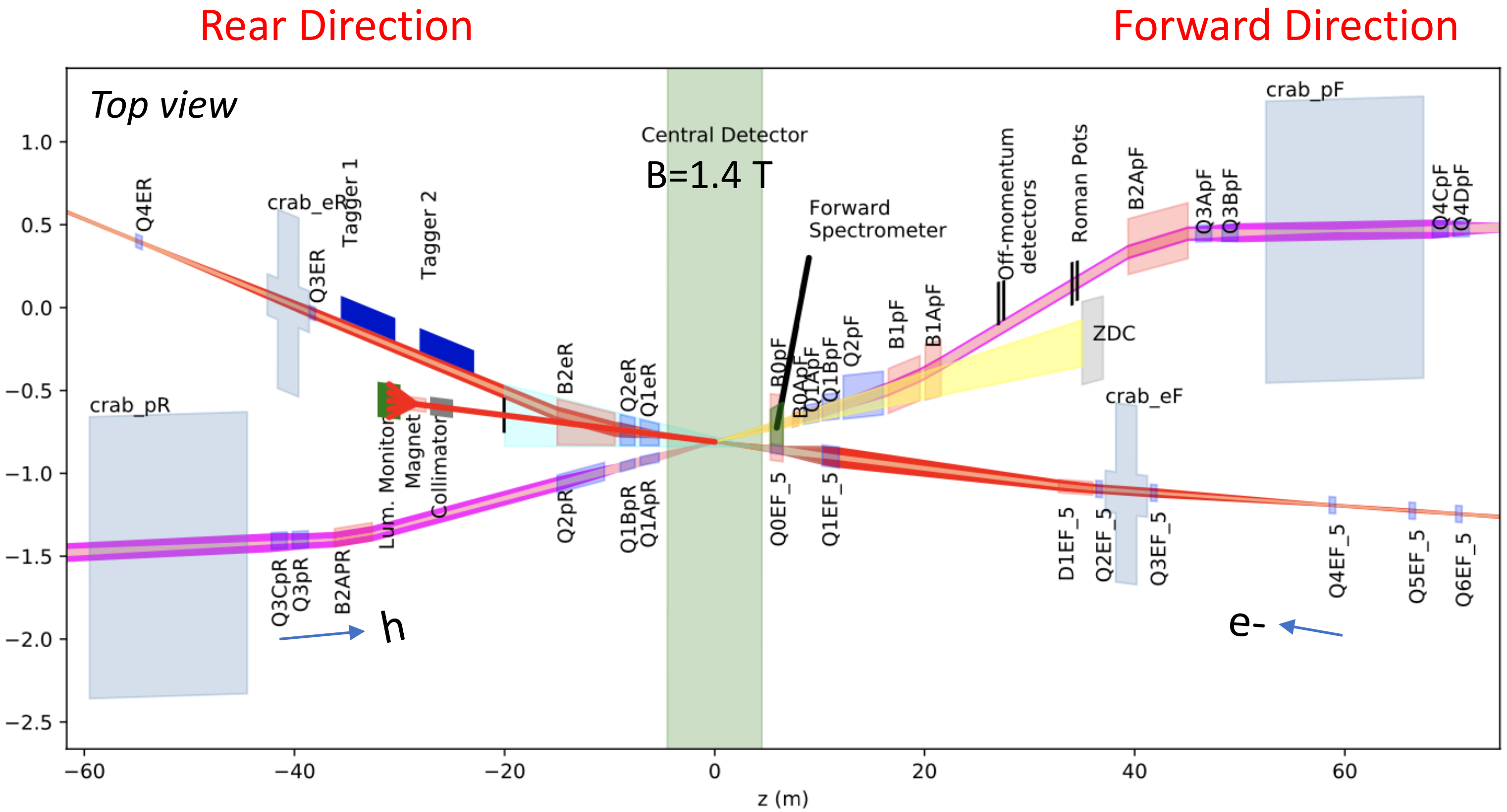






EIC IR & MDI

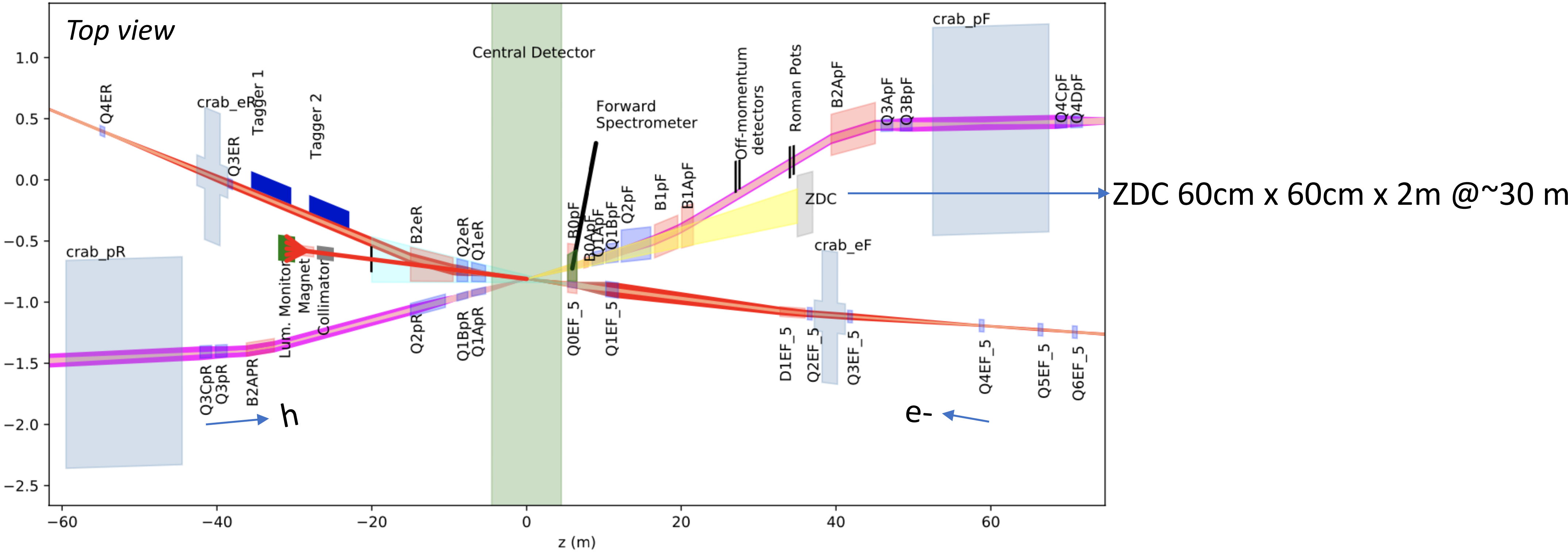
E_{cm}=104.9 GeV (h275/e-10)
$\mathcal{L}$ =10^{34} $cm^{-2}s^{-1}$
N [10^{10}]= 6.9 h/ 17.2 e-
L*= 4.5 m



IR Design integrates
- FF magnets
- luminosity and neutron detectors
- e- taggers
- spectrometer
- near-beam detectors (Roman pots for h)
- crab cavities
- spin rotators both beams

- **Squeezed beams**, esp. vertically, small βy* : small L* & strong FF quads (esp. hadron beam)
  Chromaticity needs to be compensated by nonlinear sextupoles which in turn reduce dynamic aperture
- **Large acceptance of protons scattered off the IP** required**: very large apertures** also for FF quads, scattered protons and neutrons are detected far downstream the IP
- **Near-beam-detectors,** placed **along the forward hadron beam pipe**
- **Crossing angle** (25 mrad): trade-off between the space for **neutron detector at zero degree (**forward direction) and **luminosity monitor** (e-exit) and **crab cavities (small voltage for beam dynamics issues)**

EIC IR & MDI



Synchrotron radiation background *(HERA experience)*

- No bending upstream for leptons (up to ~35m from IP)
- Rear lepton magnets: aperture dominated by sync fan

Lepton magnet aperture 15 σ beam size aperture (determined by the Syn. Rad cone)

Hadron magnets: 10σ beam size aperture

Requirements for hadron beam direction

- B0pF: Forward Spectrometer (6 - 20 mrad)
- Neutron Detector (+/-4 mrad)
- Roman pots (sensitive 1 to 5 mrad)

Mostly interleaved magnets

- Exception: B0 and Q1BpF/Q1eF

Large apertures of proton forward magnets

EIC

EIC CDR (2021)

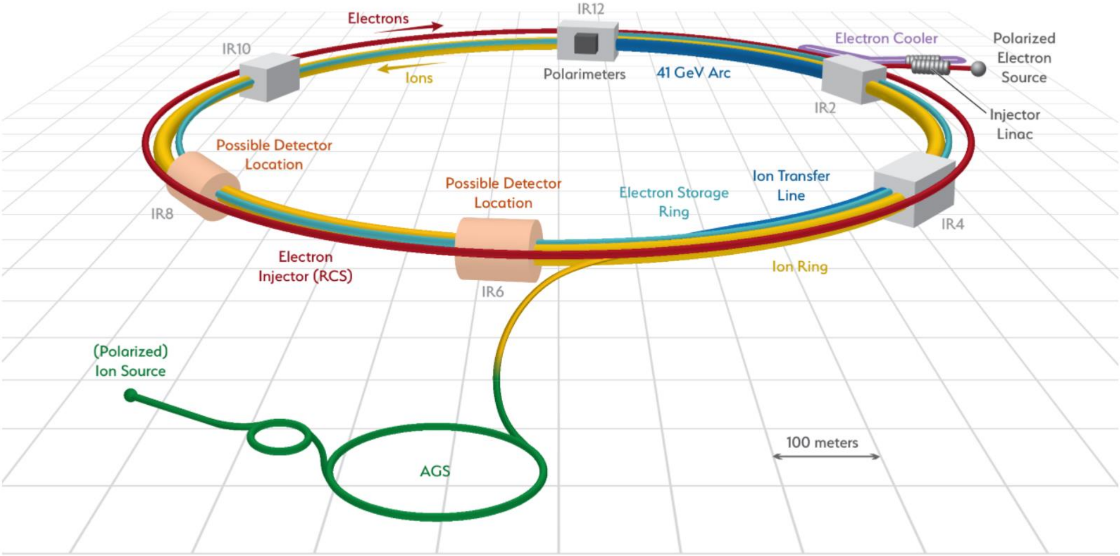
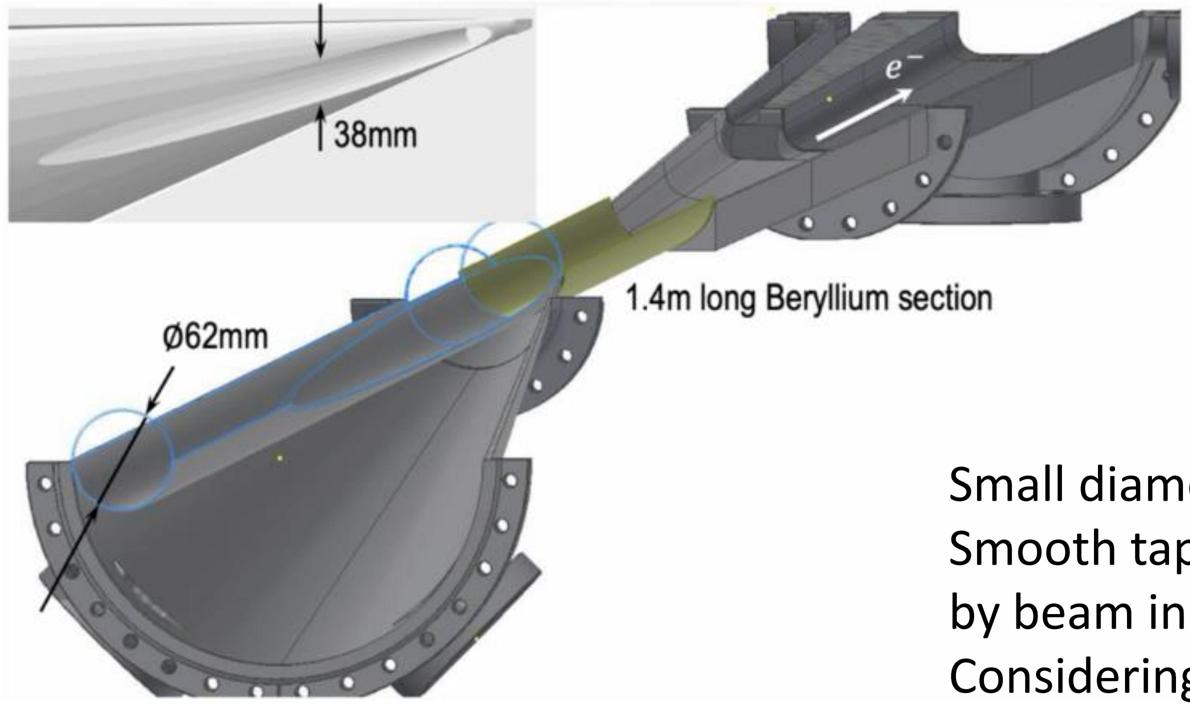


Table 1.1: Maximum luminosity parameters.

Parameter	hadron	electron
Center-of-mass energy [GeV]	104.9	
Energy [GeV]	275	10
Number of bunches	1160	
Particles per bunch [10^{10}]	6.9	17.2
Beam current [A]	1.0	2.5
Horizontal emittance [nm]	11.3	20.0
Vertical emittance [nm]	1.0	1.3
Horizontal β-function at IP β_x^* [cm]	80	45
Vertical β-function at IP β_y^* [cm]	7.2	5.6
Horizontal/Vertical fractional betatron tunes	0.228/0.210	0.08/0.06
Horizontal divergence at IP $\sigma_{x'}^*$ [mrad]	0.119	0.211
Vertical divergence at IP $\sigma_{y'}^*$ [mrad]	0.119	0.152
Horizontal beam-beam parameter ξ_x	0.012	0.072
Vertical beam-beam parameter ξ_y	0.012	0.1
IBS growth time longitudinal/horizontal [hr]	2.9/2.0	-
Synchrotron radiation power [MW]	-	9.0
Bunch length [cm]	6	0.7
Hourglass and crab reduction factor [17]	0.94	
Luminosity [$10^{34}\,cm^{-2}\,s^{-1}$]	1.0	

Central vacuum chamber

High electron beam current **2.5 A** -> (related issues: vacuum, photodesorption, heat load)



Small diameter, thin **walled Be in center region.**
Smooth tapers and transitions to limit energy deposited by beam in trapped modes (wakes).
Considering **HOM absorbers**

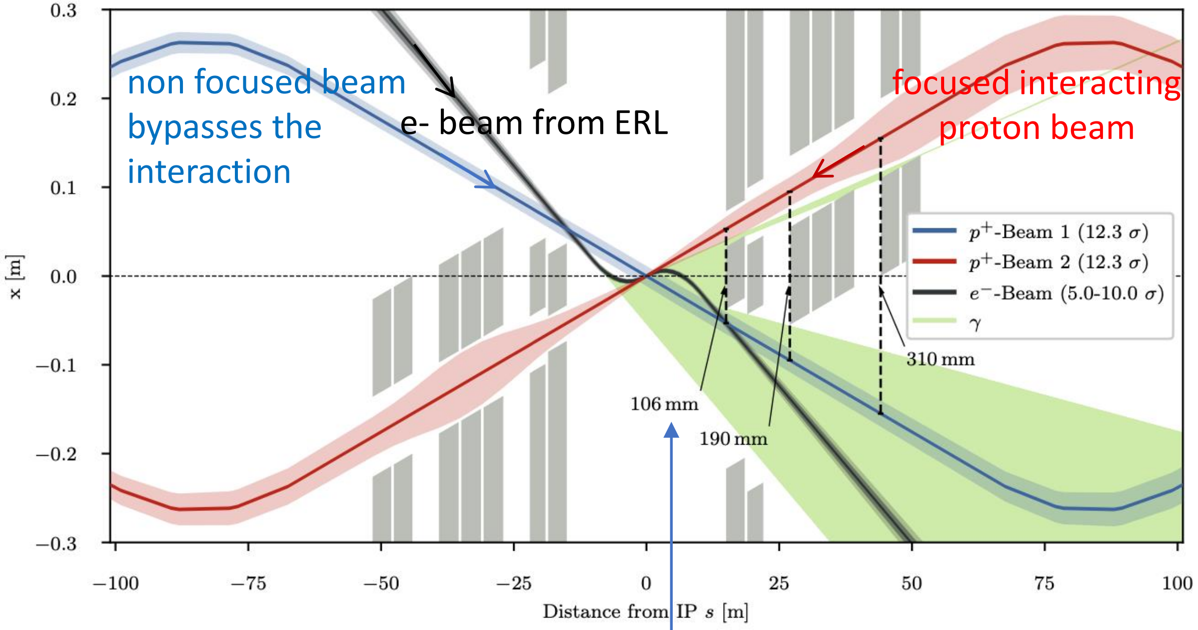
LHeC IR

ArXiv:2007.14491 (2020)

Head-on electron-proton collisions with dipoles in IR

On one side the beams should be fast separated, but this enhances the SR in the detector region, as a trade-off L* is increased and compromise for the β* values found (same achromatic telescopic squeezing implemented for HL)

Parameter	Unit	LHeC				FCC-eh	
		CDR	Run 5	Run 6	Dedicated	E_p=20 TeV	E_p=50 TeV
E_e	GeV	60	30	50	50	60	60
N_p	10^{11}	1.7	2.2	2.2	2.2	1	1
ϵ_p	μm	3.7	2.5	2.5	2.5	2.2	2.2
I_e	mA	6.4	15	20	50	20	20
N_e	10^9	1	2.3	3.1	7.8	3.1	3.1
β^*	cm	10	10	7	7	12	15
Luminosity	$10^{33}\,cm^{-2}s^{-1}$	1	5	9	23	8	15



- A dipole (B0) of 0.21 T separates e-/p at the entrance of the first quad
- Nb_3Sn CS for the proton triplet quads

To be incorporated in the HL-LHC lattice -> some constraints

L*(proton) = 15 m (was 10 m in CDR)

E(e-) = 49.19 GeV, I=20mA
P_{SR} = 38 kW
$E_{critical}$ =283 keV

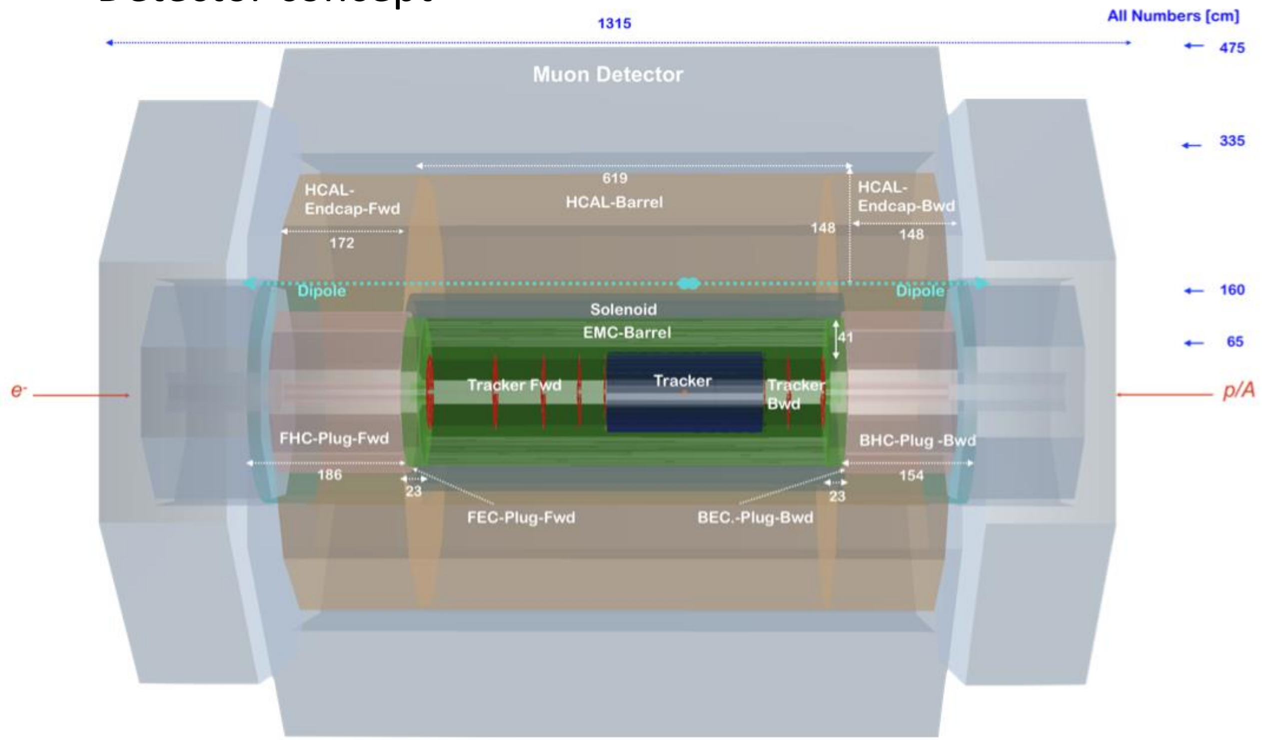
- Challenge from the SR in the IR is a bit relaxed with longer L*
- Challenge on beam current > 20 mA
- sub-μm level stability at IP required
- The beam pipe radius is an experimental challenge coping with strong SR and the forward tagging acceptance (similar to LHC challenges but there there is no pile-up in ep)

Intense e+ source would be needed for LHeC, R&D on e+ sources as joined effort for LC and LEMMA would be of interest

LHeC

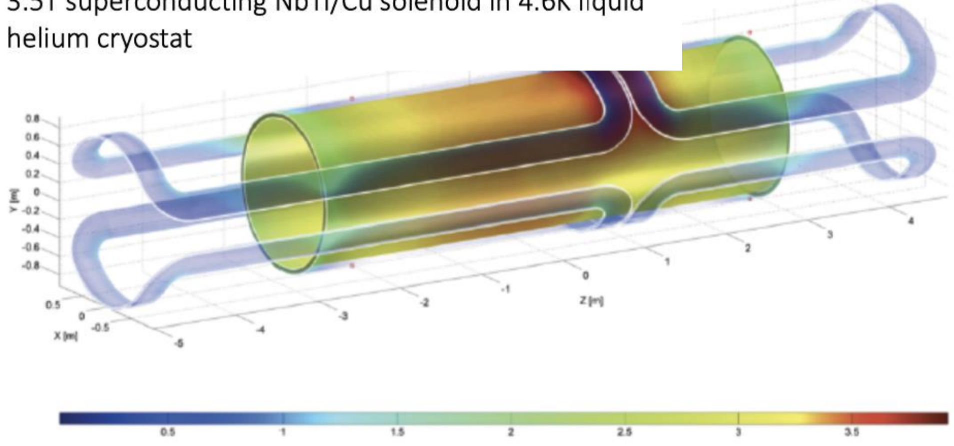
ArXiv:2007.14491 (2020)

Detector concept



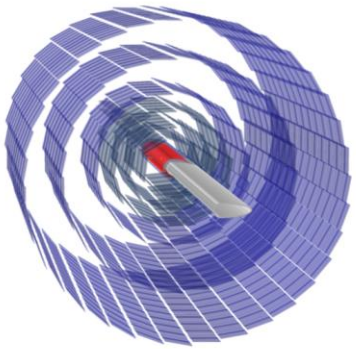
Complex magnet configuration

- Solenoid Detector Magnet (3.5T)
- Dual dipole magnets (0.15 – 0.3 T) throughout detector region (|z| < 14m)
  - to guide e-beam in and out
  - bend e-beam into head-on collision with p-beam
  - Safely extract the distorted e-beam
- 3.5T superconducting NbTi/Cu solenoid in 4.6K liquid helium cryostat



Solenoid and dipoles system housing in a common cryostat

free bore 1.8 m extending along the detector for 10 m



inner barrel tracker layers around the beam pipe

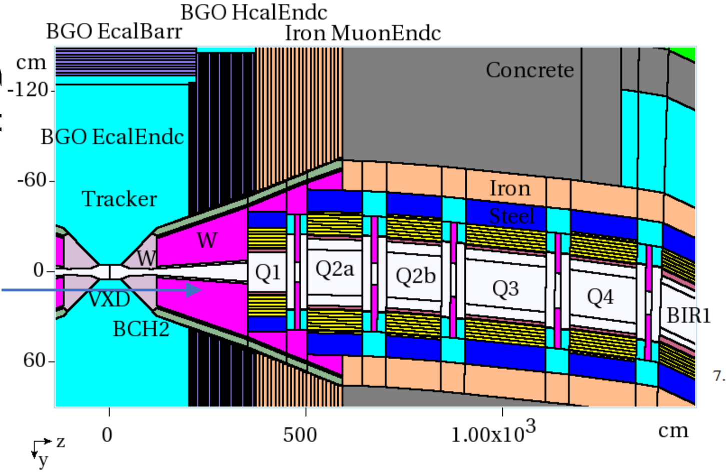
elliptical shape chosen for the beam pipe to allocate the three beams envelopes (15σ for p beam, 20σ for e- beam)

MDI challenge at Muon Colliders

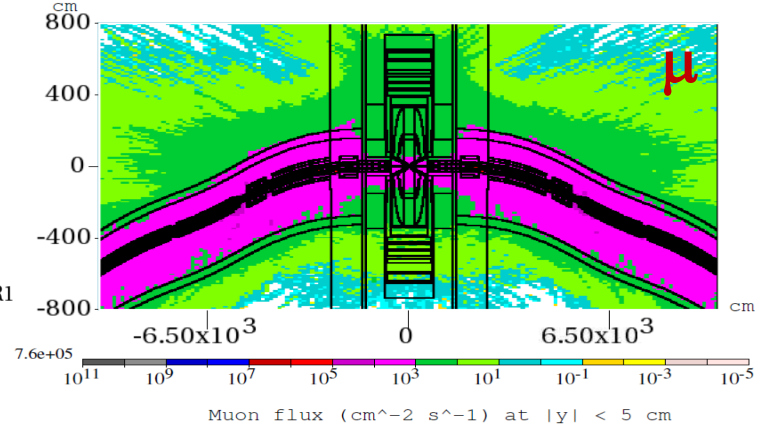
- **Far future** collider. MAP project: a design study was done, with experiment on cooling (MICE), proton target (MERIT)
- $\mathcal{L} \sim 10^{35} cm^{-2}s^{-1}$ obtained with $O(10^{12}\mu/bunch)$ inducing radiation hazard due to the neutrino production, fast muon decay. The MDI design is challenging.
- Dedicated backgrounds simulation were performed +/-200 m from the IP, Ecm@1.5 TeV

To protect SC magnets and detector, 10 and 20 cm W masks with $5\sigma_{x,y}$ elliptic openings are placed in the IR magnet interconnection regions and a sophisticated W cone inside the detector. (**nozzles** – crucial role)

[N. Mokhov]



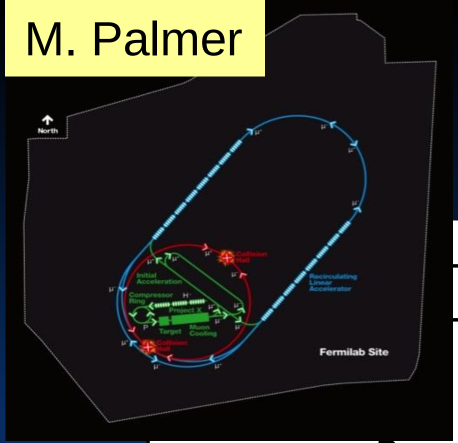
muon decay induced backgrounds



Recently these studies are being revisited by the International Muon Collider collaboration, forming after the EPPSU

- **Positron-driven** source MC would have the great advantage of aiming at high luminosity with low-emittance muon beams, allowing to reduce the muons/bunch, reducing the backgrounds, relaxing the challenge on the MDI (but the main challenge for high luminosity is on high e+ production rate)

M. Palmer



Muon Collider Parameters

Muon Collider Parameters					
		Higgs	**Multi-TeV**		
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
b*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, e_{TN}	p mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1.5	70	70	70
Bunch Length, s_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts
⇨ several × 10^{32} [Rubbia proposal: 5×10^{32}]

Fermilab

Conclusion

- **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.**

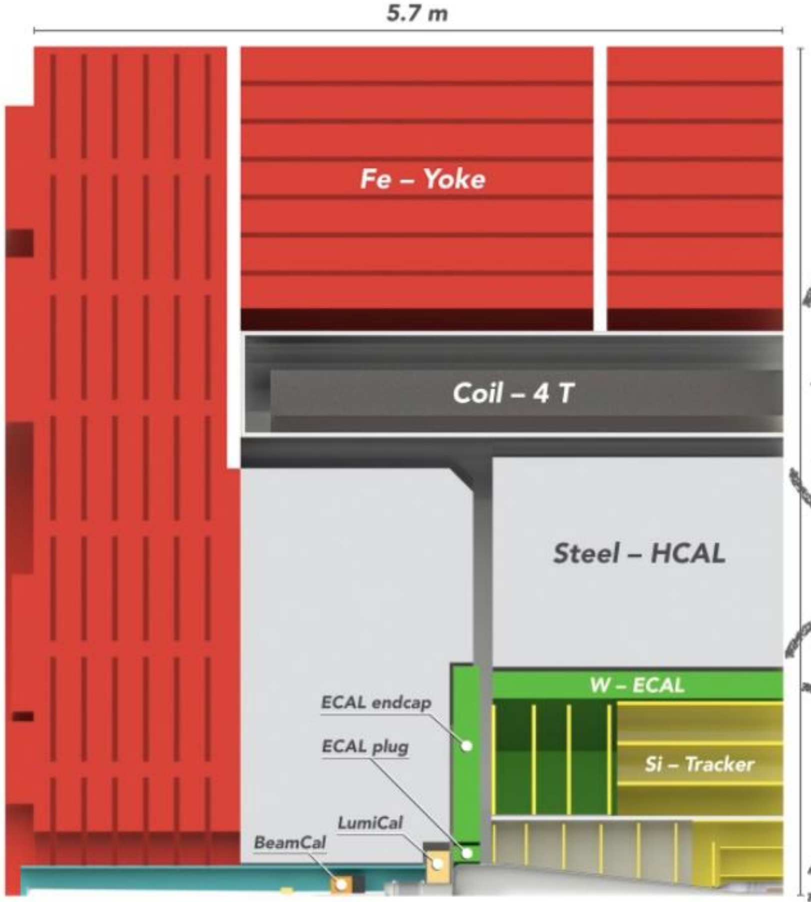
- Some of the main challenges and R&D discussed for different projects:
  - strong SC magnets, compact and high field magnets design
  - experience in synchrotron radiation mitigation, including vacuum chambers technology,
  - low impedance vacuum chamber, material and thickness optimization, radius (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.

Spare slides

From LCs to FCCee

From CLICdet to CLD

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



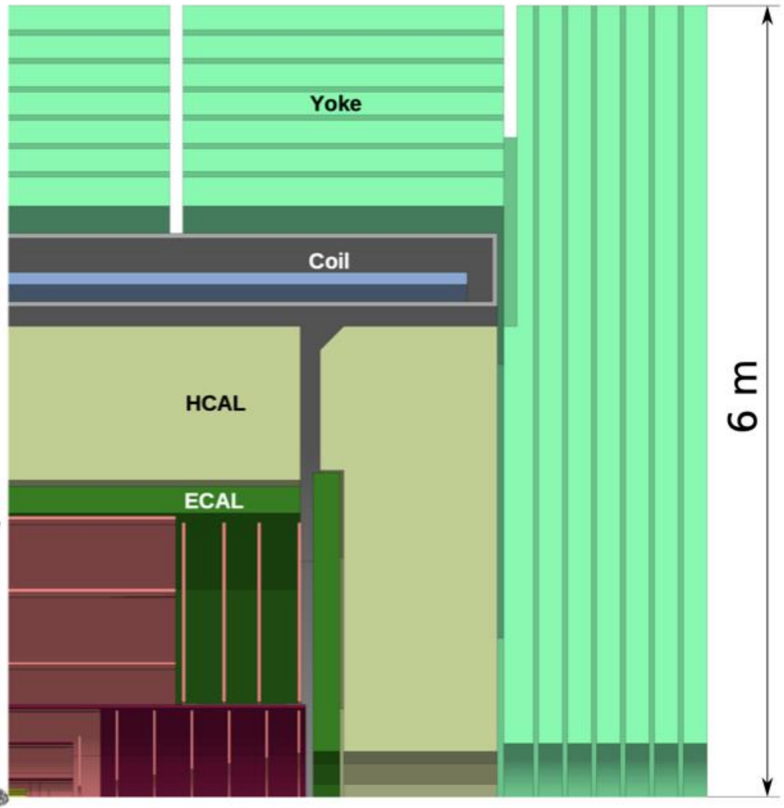
less steel: lower field allows reduced yoke thickness

lower field: enable high luminosity in circular collider

reduced HCAL thickness: enabled by lower energy

increase in tracker radius: retain p resolution

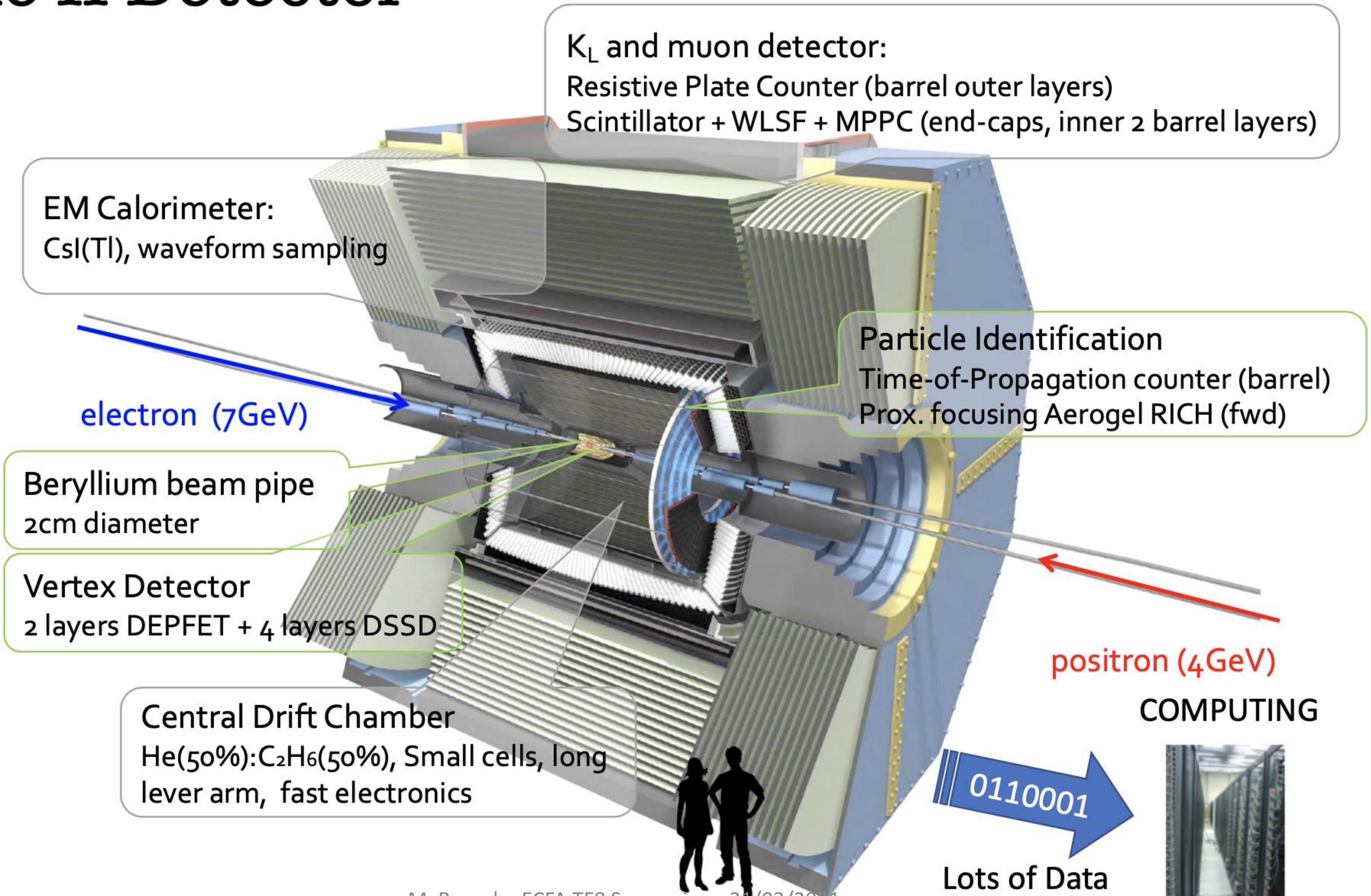
smaller VTX radius: profit from lower backgrounds, compensate material



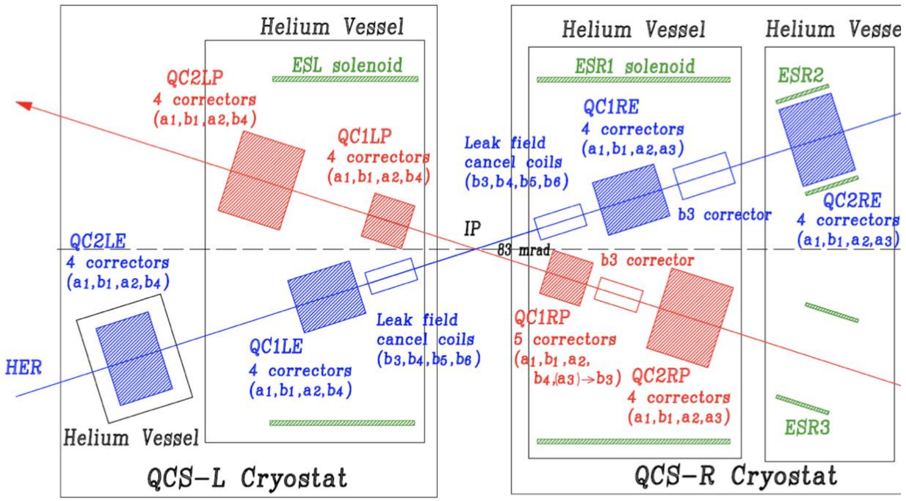
ILC collimators

- The collimation apertures required are approximately ~6–9σx in the x plane and ~40–60σy in the y plane. These correspond to typical half-gaps of the betatron spoiler of ~1 mm in the x plane and ~0.5 mm in the y plane.
- The spoilers are 0.5–1 X_0 (radiation length) thick, the absorbers are 30 X_0, and the protection collimators are 45 X_0.
- Electromagnetic showers created by primary beam particles in the collimators produce penetrating muons that can easily reach the collider hall. The muon flux through the detector is reduced by a 5 m-long magnetised iron shield 330 m upstream of the collision point that fills the cross-sectional area of the tunnel and extends 0.6 m beyond the ID of the tunnel ((with B= 1.5 T), also as radiation protection.

Belle II Detector



Superkekb FF quads



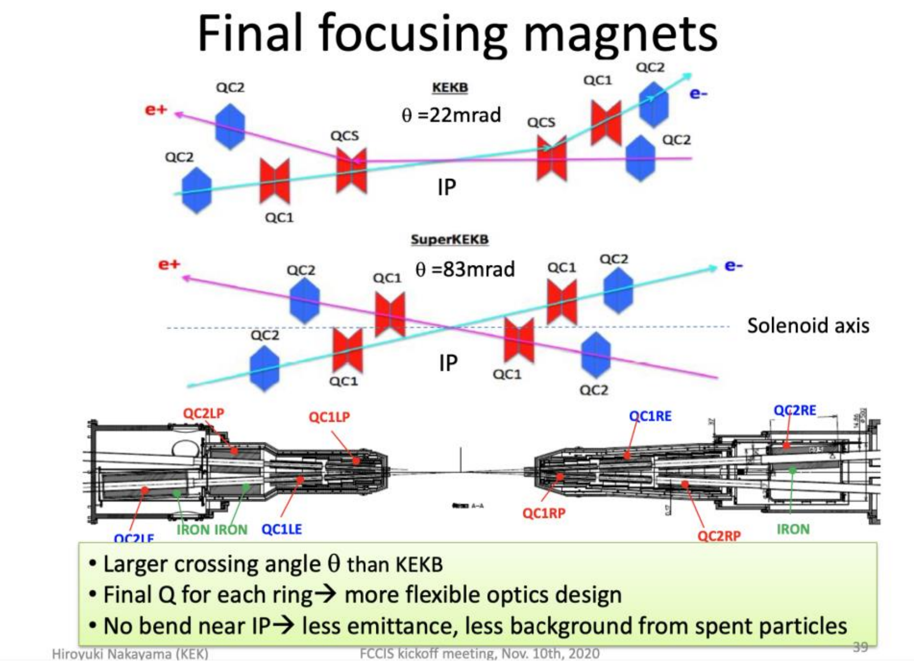


Figure 6: Four SC coils for QC1LP.

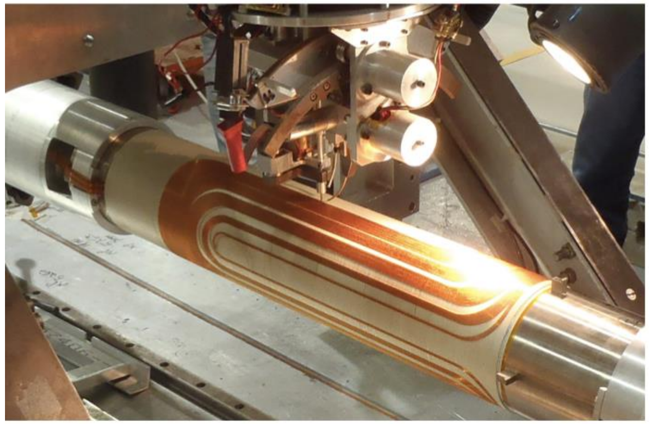


Figure 8: Winding process of corrector magnets in BNL.

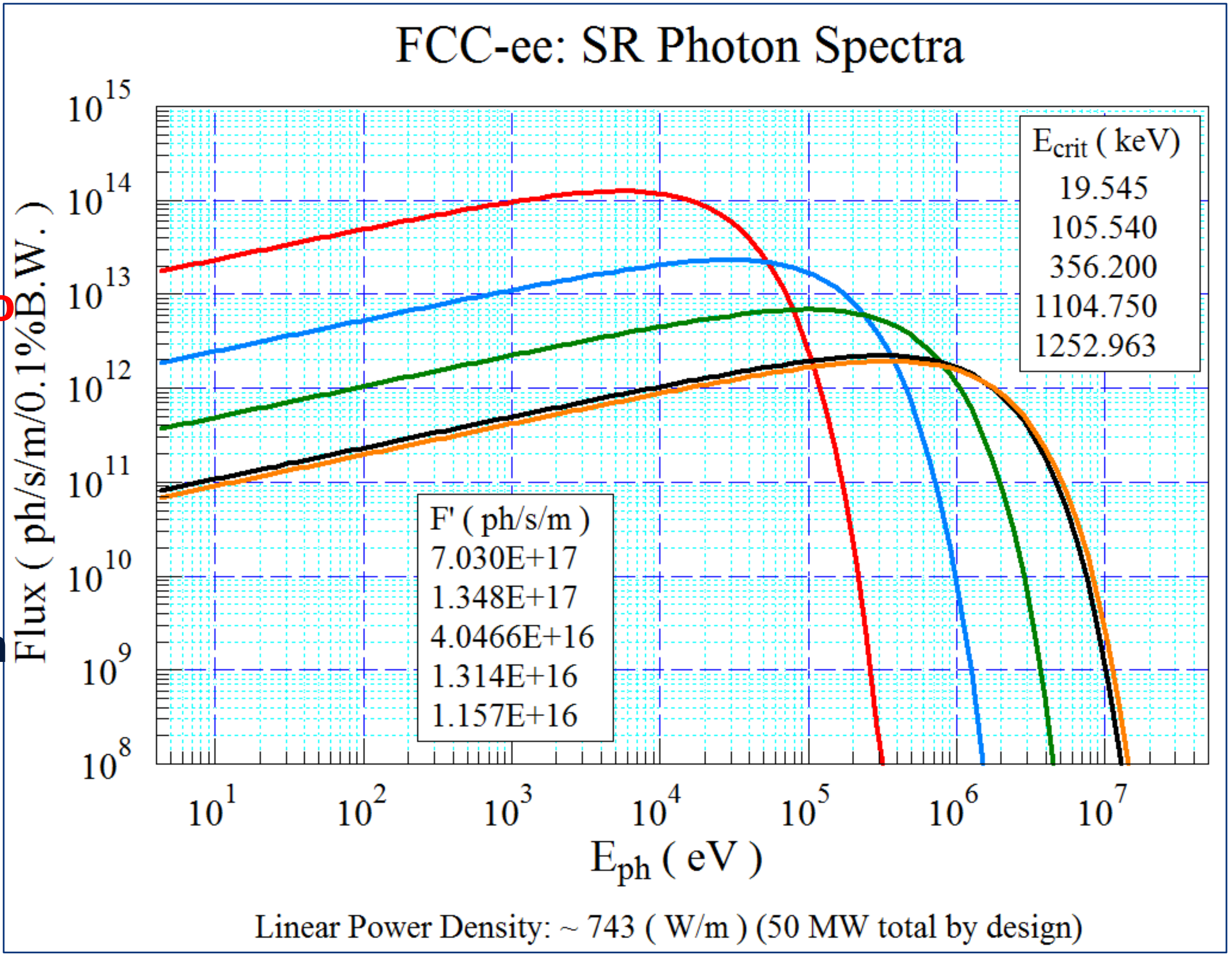
Parameter	QC1P	QC1E	QC2P	QC2E
G_D, T/m	76.37	91.57	31.97	36.39
I_D, A	1,800	2,000	1,000	1,250
B_P, T	4.56	3.5	2.43	2.63
LR, %	72.3	73.4	44	39
R_C, mm	25.0	33.0	53.8	59.3
R_{Yo}, mm	NA	70.0	93.0	115.0
L_{PM}, mm	409.3	455.4	495.5	618.9
L_{EM}, mm	333.6	373.1	409.9	537.0
Cable	NbTi	NbTi	NbTi	NbTi
θ_K, deg.	2.1	1.6	1.0	0.94

G_D: design field gradient at the magnet center, I_D: magnet design current, B_P: maximum field in the coil at I_D, LR: load line ratio to the critical point, R_C: SC coil inner radius, R_{Yo}: yoke outer radius, L_{PM}: magnet physical length, L_{EM}: effective magnetic length, θ_K: key stone angle of the SC cable

The SC quadrupole magnet consists of the two layer SC coils (double-pancake structure). For the coils, the Rutherford type NbTi cables were used. The cable consists of 10 strand wires of ϕ0.5 mm. SC corrector magnets had been developed from 2011 in BNL, and 43 corrector magnets were completed in February 2015. The winding of the SC coil was performed by the computer controlled winding robot, and the SC wire of ϕ0.35 mm was directly stuck on the outer surface of the sup- port bobbin as the helium inner vessel.

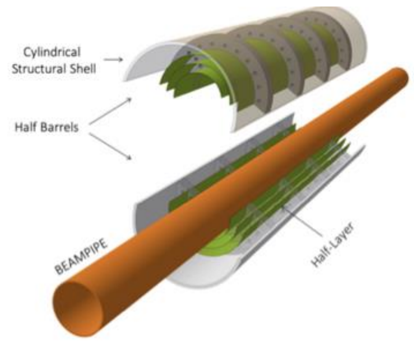
SR spectra and outgassing loads

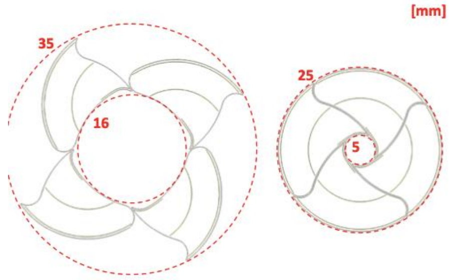
- **Z-Pole: very high photon flux (→ large outgassing load);**
- **Z-pole: compliance with scheduled operation (integrated luminosity first 2 years), requires quick commissioning to I_{NOM}=1.390 A;**
- **t-pole (182.5): extremely large and penetrating radiation, critical energy 1.25 MeV;**
- **t-pole (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)**



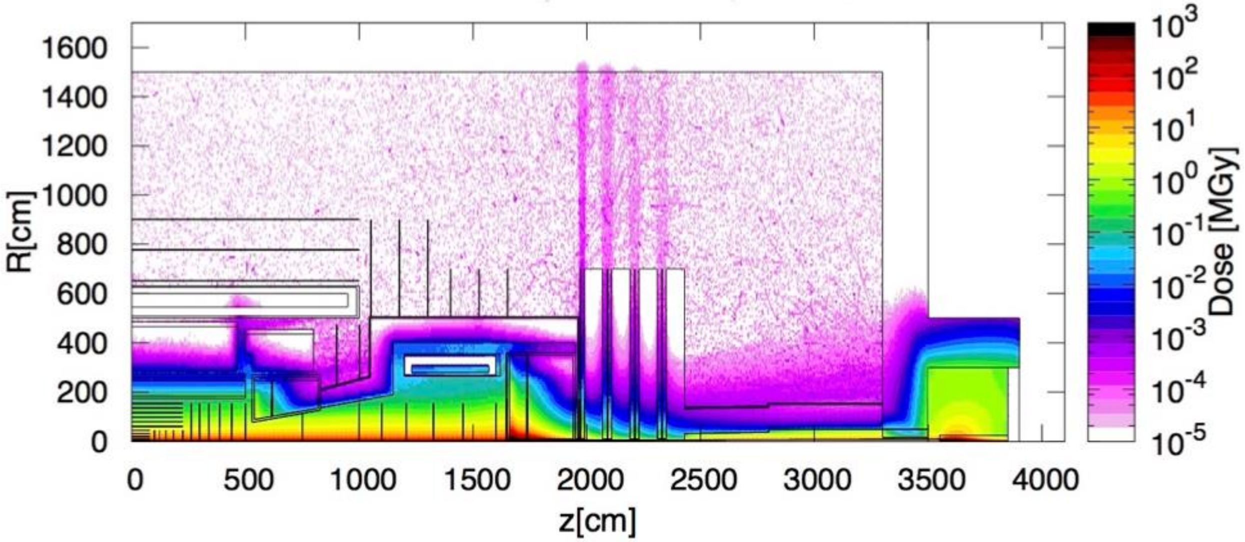
ALICE 3 – MDI R&D and Challenges

- Fast and ultra-thin detector with precise tracking and timing
- Fast -> for higher luminosity
- R&D on vertex layers
- Inner tracker
  - (futuristic) retractable detector for minimal distance from IP
  - ultra-thin layout MAPS sensors
  - small pixel pitch fro position resolution O(1 μm)
- Outer tracker
  - low material budget, lightweight mechanics, cooling and services
  - cost-effective sensors & modules
- Dedicated forward detector for soft photon, low p_T

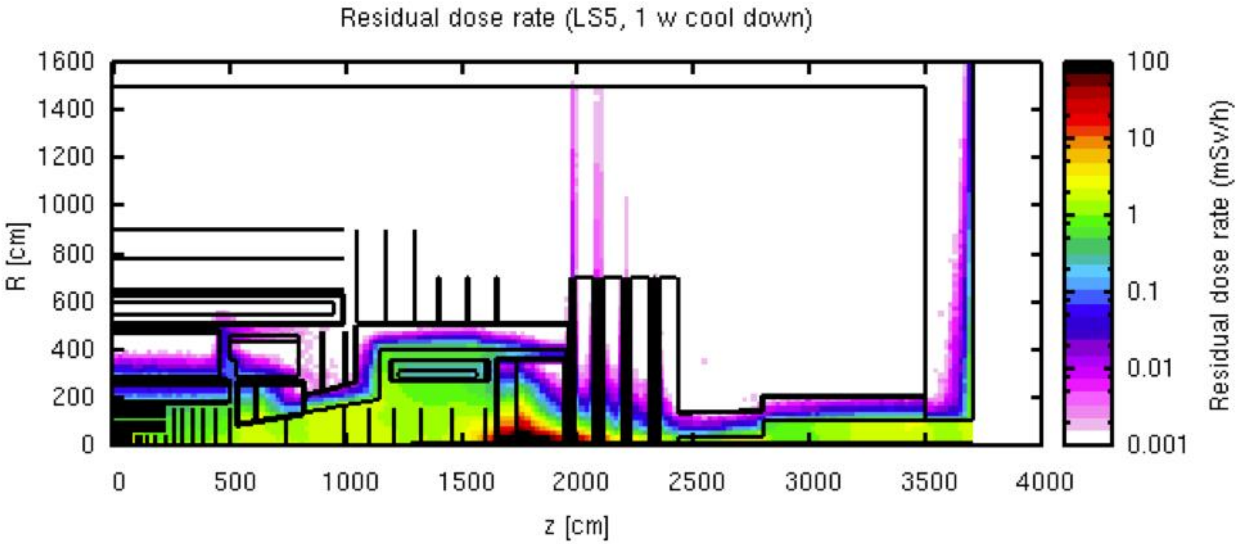




Radiation Studies for L=3x10^{35} cm^{-2}s^{-1} and 30ab^{-1}



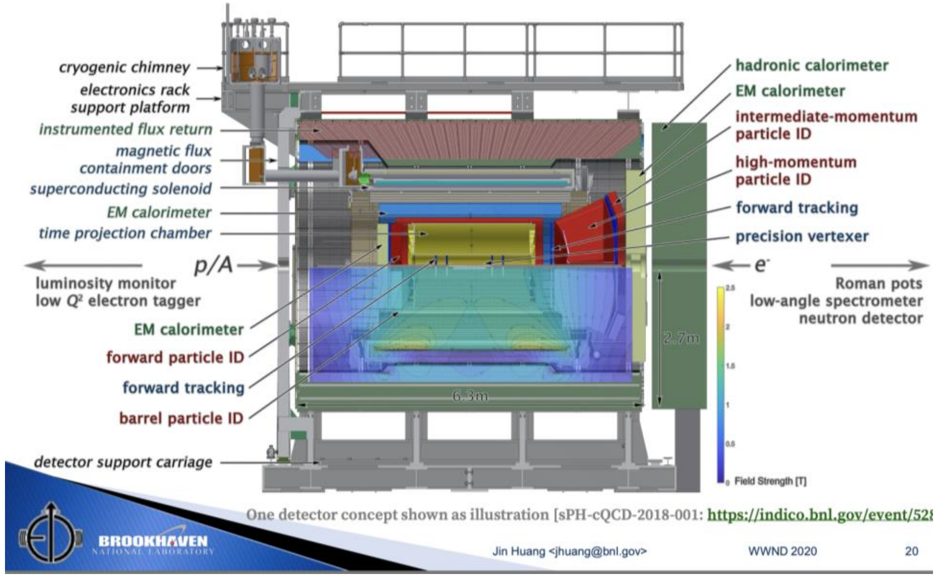
Dose of 300MGy in the first tracker layers.
<10kGy in HCAL barrel and extended barrel.



Dose from activation towards the end of FCC operation, 1 week of cooldown, so significant decrease for 1month, 1 year.

EIC MDI – IR Challenging Integration

- Requirements:
  - **Large rapidity** coverage, -4 < eta < 4 and behond especially in far-forward detectors
  - **small micro-vertex and large radius tracking**
  - Detector hermeticity

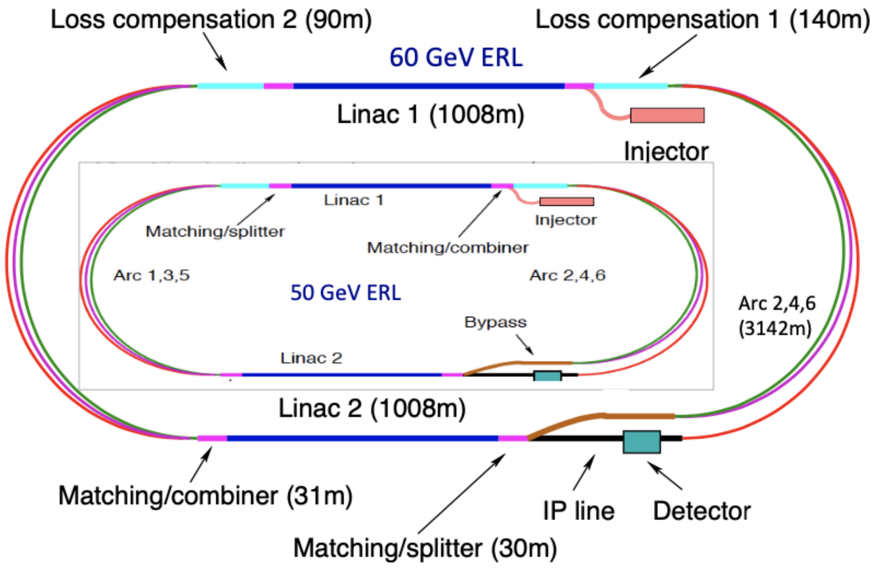


- **Challenge:** large acceptance for diffraction, tagging, neutrons from nuclear breakup ->
- **Integration challenge:** many ancillary detectors integrated in the beamline: low-Q2 tagger, Roman Pots, Zero-Degree Cal.,
- **Luminosity meas**.: hadron control of systematics, also for e- and hadron polarimetry

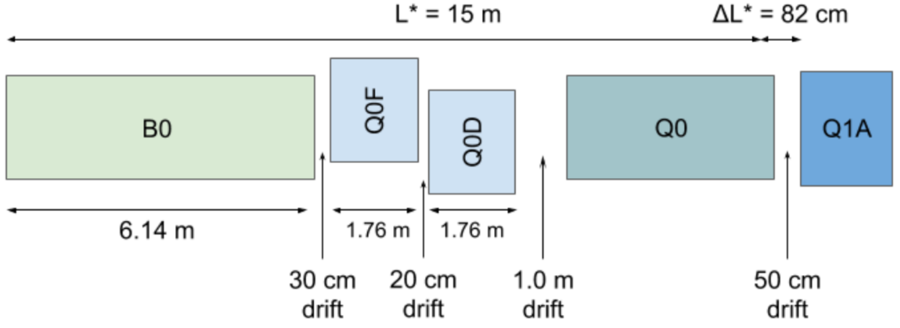
Vertex: small micro-vertex: MAPS, options: 6-layer barrel, 5+5 disks Si, option GEM for the most external. Hybrid option: SiV+TPC (barrel), 7 Si disks, opt1 TPC+ext.l.MPGD; opt2 coaxial layers of microRW. 20 mu m pitch (10 mu m considered)

LHeC

[ArXiv:2007.14491 (2020)]



IR



e-: doublet that optimises SR

Parameter	Unit	Q0F	Q0D
$\gamma\varepsilon_e$	mm·mrad	50	50
$\gamma\varepsilon_p$	mm·mrad	2.50	2.50
Gradient	T/m	36.2	26.1
Min. pole-tip radius	mm	28.9	38.1
Length	m	1.86	1.86

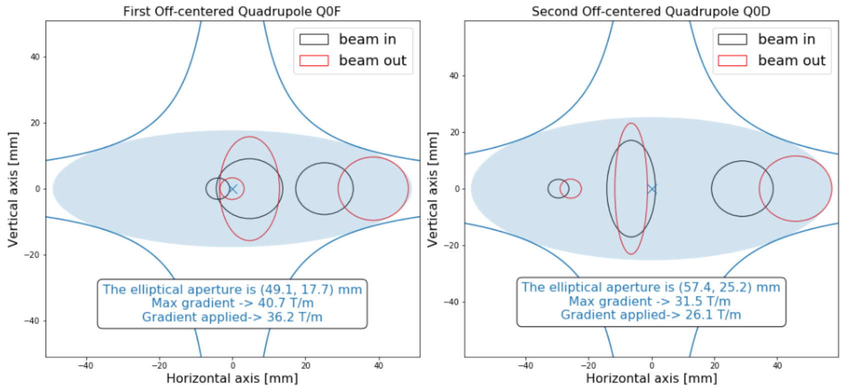


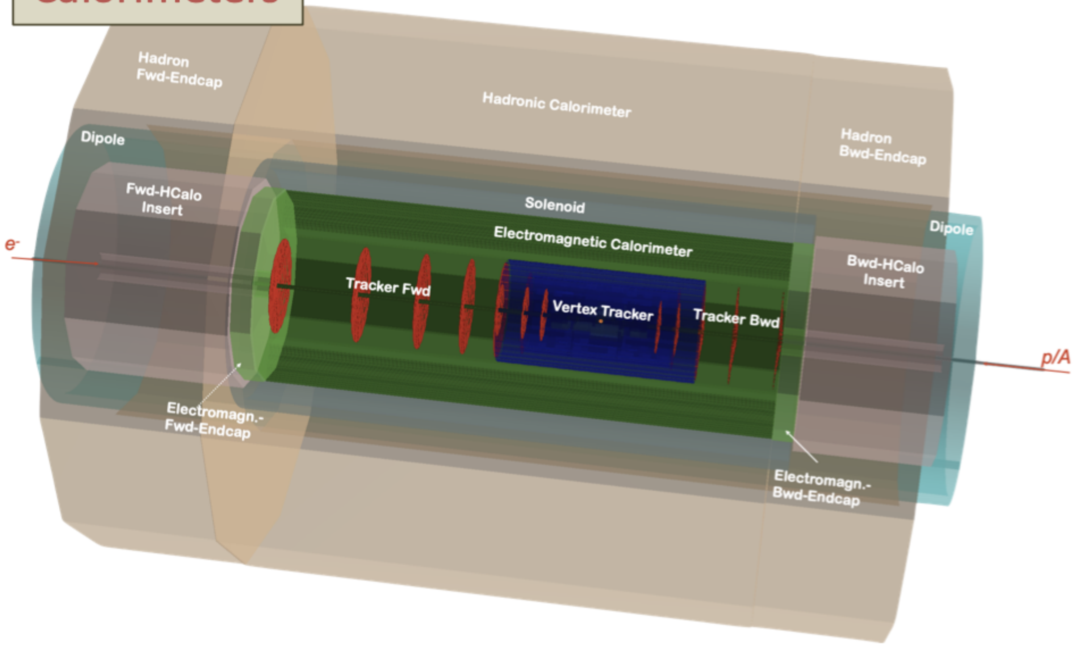
Figure 10.42: The position of the three beams at the entrance (black) and exit (red) of the electron doublet magnets. Following the internal convention, 15 σ plus 20 % beta beating plus 2 mm orbit tolerances beam envelopes are chosen for the proton beams. The beam size of the electrons refer to 20 σ. From left to right the three beams are respectively the non colliding proton beam (tiny circles), electron beam (squeezed ellipses) and the colliding proton beam.

Magnet	Gradient [T/m]	Length [m]	Free aperture radius [mm]
Q1A	252	3.5	20
Q1B	164	3.0	32
Q2 type	186	3.7	40
Q3 type	175	3.5	45

Table 10.21: Parameters of the final focus quadrupole septa. The parameters of Q1A/B and Q2 are compatible with the Nb_3Sn based designs from [845] assuming the inner protective layer of Q2 can be reduced to 5 mm thickness.

LHeC – The Large Hadron-Electron Collider at the HL-LHC

Calorimeters



- Complete coverage: $-5 < \eta < +5.5$
- Forward Region: dense, high density jets of few TeV
- Backward Region: in DIS only deposit of $E < E_e$
- Calorimeter depth
  - ECAL: 30 X_0 barrel & backward, ~ 50X_0 forward
  - HCAL: 7.1-9.3 Λ_I barrel & backward; 9.2-9.6 Λ_I forward
- Detector technologies (ala ATLAS):
  - ECal: Pb/LAr with accordeon geometry
  - HCAL: Pb/Scintillating tiles
  - Alternative: ECAL: Pb/Scintillator ⇨ eliminate cryogenics

Barrel Calorimeters

Calo (LHeC)		EMC	HCAL		
		Barrel	Ecap Fwd	Barrel	Ecap Bwd
Readout, Absorber		Sci,Pb	Sci,Fe	Sci,Fe	Sci,Fe
Layers		38	58	45	50
Integral Absorber Thickness [cm]		16.7	134.0	119.0	115.5
η_{max}, η_{min}		2.4, −1.9	1.9, 1.0	1.6, −1.1	−1.5, −0.6
$\sigma_E/E = a/\sqrt{E} \oplus b$	[%]	12.4/1.9	46.5/3.8	48.23/5.6	51.7/4.3
Λ_I / X_0		$X_0 = 30.2$	$\Lambda_I = 8.2$	$\Lambda_I = 8.3$	$\Lambda_I = 7.1$
Total area Sci	[m^2]	1174	1403	3853	1209

Forward/Backward Calorimeters

Calo (LHeC)		FHC	FEC	BEC	BHC
		Plug Fwd	Plug Fwd	Plug Bwd	Plug Bwd
Readout, Absorber		Si,W	Si,W	Si,Pb	Si,Cu
Layers		300	49	49	165
Integral Absorber Thickness [cm]		156.0	17.0	17.1	137.5
η_{max}, η_{min}		5.5, 1.9	5.1, 2.0	−1.4, −4.5	−1.4, −5.0
$\sigma_E/E = a/\sqrt{E} \oplus b$	[%]	51.8/5.4	17.8/1.4	14.4/2.8	49.5/7.9
Λ_I / X_0		$\Lambda_I = 9.6$	$X_0 = 48.8$	$X_0 = 30.9$	$\Lambda_I = 9.2$
Total area Si	[m^2]	1354	187	187	745

CDR-2020 (arXiv:2007:14491), tables 12.3 and 12.4

ILC BDS

Ref. TDR

The main subsystems of the BDS are (beam direction):

• a section containing emittance measurement and matching (correction) sections, trajectory feedback, polarimetry and energy diagnostics;

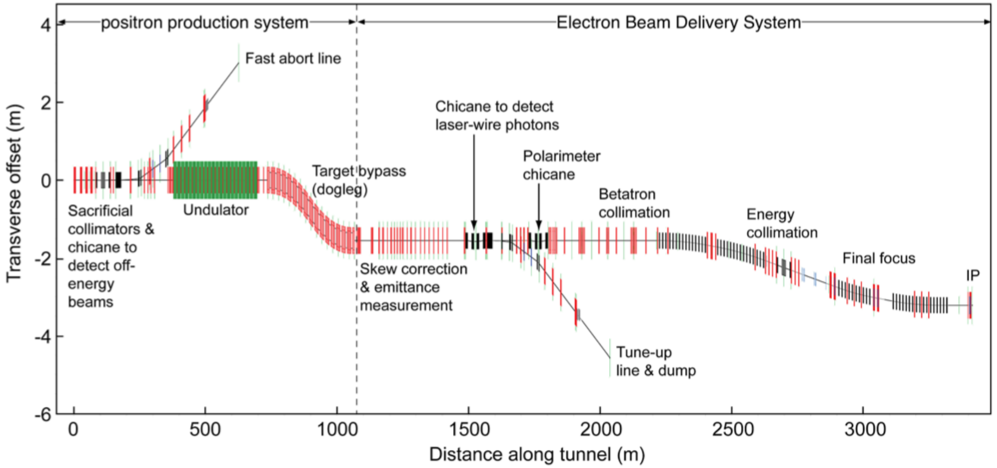
• a **collimation section** which removes beam-halo particles that would otherwise generate unacceptable background in the detector, and also contains magnetised iron shielding to deflect and/or absorb muons generated in the collimation process;

• the **final focus** (FF), which uses **strong compact superconducting quadrupoles** to focus the beam at the IP, with sextupoles providing local chromaticity correction;

• the interaction region, containing the experimental detectors. The final-focus quadrupoles closest to the IP are **integrated into the detector** to facilitate detector “push-pull”;

• the extraction line, which has a large enough bandwidth to transport the heavily disrupted beam cleanly to a high-powered water-cooled dump. The extraction line also contains important polarisation and energy diagnostics.

The beam-delivery optics provides demagnification factors of typically several hundreds in the beam size, resulting in very large beta functions (several thousand kilometres) at critical locations, leading to the tightest alignment tolerances in the entire machine. In addition, careful correction of the strong chromaticity and geometric aberrations requires a delicate balance of higher-order optical terms. The tight tolerances on magnet motion (down to tens of nanometres), makes continuous trajectory correction and the use of fast beam-based feedback systems mandatory. Furthermore, several critical components (e.g. the final focusing doublet) may well require mechanical stabilisation.



Parameter Tables

FCC-ee collider parameters (stage 1)

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

PDG 2020

Table 31.1: Tentative parameters of selected future e^+e^- high-energy colliders. Parameters associated with different beam energy scenarios are comma-separated.

	FCC-ee	CEPC	ILC	CLIC
Species	e^+e^-	e^+e^-	e^+e^-	e^+e^-
Beam energy (GeV)	46, 120, 183	46, 120	125, 250	190, 1500
Circumference / Length (km)	97.75	100	20.5, 31	11, 50
Interaction regions	2	2	1	1
Est. integrated luminosity per experiment (ab^{-1}/year)	26, 0.9, 0.17	4, 0.4	0.2, 0.2	0.2, 0.6
Peak luminosity (10^{34}/cm^2/s)	230, 8.5, 1.6	32, 3	1.4, 1.8	1.5, 6
Time between collisions (μs)	0.015, 0.75, 8.5	0.025, 0.68	0.55	0.0005
Energy spread (rms, 10^{-3})	1.3, 1.65, 2.0	0.4, 1.0	e^-: 1.9, 1.2 e^+: 1.5, 0.7	3.5
Bunch length (rms, mm)	12.1, 5.3, 3.8	8.5, 3.3	0.3	0.09, 0.044
IP beam size (μm)	H: 6.3, 14, 38 V: 0.03, 0.04, 0.07	H: 5.9, 21 V: 0.04, 0.07	H: 0.52, 0.47 V: 0.008, 0.006	H: 0.15, 0.04 V: 0.003, 0.001
Injection energy (GeV)	on energy (topping off)	on energy (topping off)	5.0 (linac)	9.0 (linac)
Transv. rms emittance (pm)	H: 270, 630, 1340 V: 1, 1, 3	H: 170, 1210 V: 2, 3	H: 20, 10 V: 0.14, 0.07	H: 2.4, 0.22 V: 0.8, 0.01
β^* at interaction point (cm)	H: 15, 30, 100 V: 0.08, 0.1, 0.16	H: 20, 36 V: 0.1, 0.15	H: 1.3, 2.2 V: 0.041, 0.048	H: 0.8, 0.69 V: 0.01, 0.0068
Full crossing angle (mrad)	30	33	14	20
Crossing scheme	crab waist	crab waist	crab crossing	crab crossing
Piwinski angle $\phi = \sigma_z\theta_c/(2\sigma_x^*)$	28.5, 5.8, 1.5	23.8, 2.6	0	0
Beam-beam param. ξ_y (10^{-3})	133, 118, 144	72, 109	n/a	n/a
Disruption parameter D_y	0.9, 1.1, 1.9	0.3, 1.0	34, 25	8, 12
Average Upsilon Υ	0.0002,0.0004,0.0006	0.0001,0.0005	0.03, 0.06	0.26, 3.4
RF frequency (MHz)	400, 400, 800	650	1300	11994
Particles per bunch (10^{10})	17, 15, 27	8, 15	2	0.52, 0.37
Bunches per beam	16640, 328, 33	12000, 242	1312 (pulse)	352, 312 (trains at 50 Hz)
Average beam current (mA)	1390, 29, 5.4	19.2	6 (in train)	1660, 1200 (in train)
RF gradient (MV/m)	1.3, 9.8, 19.8	3.6, 19.7	31.5	72, 100
Polarization (%)	≥10, 0, 0	5–10, 0	e^-: 80% e^+: 30%	e^-: 70% at IP
SR power loss (MW)	100	64	n/a	n/a
Beam power/beam (MW)	n/a	n/a	5.3, 10.5	3, 14
Novel technology	—	—	high grad. SC RF	two-beam accel.

	LHeC	HE-LHC	FFC-hh	SPPC	μ collider
Species	ep	pp	pp	pp	$\mu^+\mu^-$
Beam Energy (TeV)	0.06(e), 7 (p)	13.5	50	37.5	0.063, 3
Circumference (km)	9(e), 26.7 (p)	26.7	97.75	100	0.3, 6
Interaction regions	1	2 (4)	4	2	1, 2
Estimated integrated luminosity per experiment (ab^{-1}/year)	0.1	0.5	0.2–1.0	0.4	0.001, 1.0
Peak luminosity (10^{34}/cm^2/s)	0.8	16	5–30	10	2.2, 71
Time between collisions (μs)	0.025	0.025	0.025	0.025	1, 20
Energy spread (rms, 10^{-3})	0.03 (e), 0.1(p)	0.1	0.1	0.2	0.04, 1
Bunch length (rms, mm)	0.06 (e), 75.5(p)	80	80	75.5	63, 2
IP beam size (μm)	4.3 (round)	8.8	6.7-3.5 (init.)	6.8 (init.)	75, 1.5
Injection energy (GeV)	1(e), 450(p)	1300	3300	2100	on energy
Transverse emittance (rms, nm)	0.45(e), 0.27(p)	0.17	0.04 (init.)	0.06 (init.)	335, 0.9
β^*, amplitude fcn. at IP (cm)	5.0(e), 7.0(p)	45	110–30	75	1.7, 0.25
Beam-beam parameter/IP (10^{-3})	−(e), 0.4(p)	12	5–15	7.5	20, 90
RF frequency (MHz)	800(e), 400(p)	400	400	400/200	805
Particles per bunch (10^{10})	0.23(e), 22(p)	22	10	15	400, 200
Bunches per beam	−(e), 2808(p)	2808	10600	10080	1
Average beam current (mA)	15(e), 883(p)	1120	500	730	640, 16 (peak)
Length of standard cell (m)	52.4(e arc), 107(p)	137	213	148	N/A
Phase advance per cell (deg)	310/90(eH/V) 90(p)	90	90	90	N/A
Peak magnetic field (T)	0.264(e), 8.33(p)	16	16	12	10
Polarization (%)	90(e), 0(p)	0	0	0	0
SR power loss/beam (MW)	30(e), 0.01(p)	0.1	2.4	1.1	3×10^{-5}, 0.068
Novel technology	high-energy ERL	16T Nb_3Sn magnets	16T Nb_3Sn magnets	HTS magnets	muon prod.

https://pdg.lbl.gov/2020/reviews/rpp2020-rev-accel-phys-colliders.pdf

KEKB and SuperKEKB

Table 1: Machine Parameters of KEKB and SuperKEKB. Values in parentheses for SuperKEKB denote parameters without intrabeam scattering. Note that horizontal emittance increases by 30% owing to intrabeam scattering in the LER. The KEKB parameters are those achieved at the crab crossing [2], where the effective crossing angle was 0. (*)Before the crab crossing, the luminosity of $1.76 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ was achieved at the half crossing angle of 11 mrad, where $\phi_{\mathrm{Piw}} \sim 1$ [6].

		KEKB		SuperKEKB		
		LER (e+)	HER (e-)	LER (e+)	HER (e-)	Units
Beam energy	E	3.5	8.0	4.0	7.007	GeV
Circumference	C	3016.262		3016.315		m
Half crossing angle	θ_x	0 (11$^{(*)}$)		41.5		mrad
Piwinski angle	ϕ_{Piw}	0	0	24.6	19.3	rad
Horizontal emittance	ε_x	18	24	3.2 (1.9)	4.6 (4.4)	nm
Vertical emittance	ε_y	150	150	8.64	12.9	pm
Coupling		0.83	0.62	0.27	0.28	%
Beta function at IP	β_x^*/β_y^*	1200/5.9	1200/5.9	32/0.27	25/0.30	mm
Horizontal beam size	σ_x^*	147	170	10.1	10.7	μm
Vertical beam size	σ_y^*	940	940	48	62	nm
Horizontal betatron tune	ν_x	45.506	44.511	44.530	45.530	
Vertical betatron tune	ν_y	43.561	41.585	46.570	43.570	
Momentum compaction	α_p	3.3	3.4	3.20	4.55	10^{-4}
Energy spread	σ_ε	7.3	6.7	7.92(7.53)	6.37(6.30)	10^{-4}
Beam current	I	1.64	1.19	3.60	2.60	A
Number of bunches	n_b	1584		2500		
Particles/bunch	N	6.47	4.72	9.04	6.53	10^{10}
Energy loss/turn	U_0	1.64	3.48	1.76	2.43	MeV
Long. damping time	τ_z	21.5	23.2	22.8	29.0	msec
RF frequency	f_{RF}	508.9		508.9		MHz
Total cavity voltage	V_c	8.0	13.0	9.4	15.0	MV
Total beam power	P_b	$\sim$3	$\sim$4	8.3	7.5	MW
Synchrotron tune	ν_s	-0.0246	-0.0209	-0.0245	-0.0280	
Bunch length	σ_z	$\sim$7	$\sim$7	6.0 (4.7)	5.0 (4.9)	mm
Beam–beam parameter	ξ_x/ξ_y	0.127/0.129	0.102/0.090	0.0028/0.088	0.0012/0.081	
Luminosity	L	2.108×10^{34}		8×10^{35}		$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Integrated luminosity	$\int L$	1.041		50		ab^{-1}

ILC TDR

Table 2.1. Summary table of the 200–500 GeV baseline parameters for the ILC. The reported luminosity numbers are results of simulation [12]

Centre-of-mass energy	E_{CM}	GeV	200	230	250	350	500
Luminosity pulse repetition rate		Hz	5	5	5	5	5
Positron production mode			10 Hz	10 Hz	10 Hz	nom.	nom.
Estimated AC power	P_{AC}	MW	114	119	122	121	163
Bunch population	N	$\times 10^{10}$	2	2	2	2	2
Number of bunches	n_b		1312	1312	1312	1312	1312
Linac bunch interval	Δt_b	ns	554	554	554	554	554
RMS bunch length	σ_z	μm	300	300	300	300	300
Normalized horizontal emittance at IP	$\gamma\epsilon_x$	μm	10	10	10	10	10
Normalized vertical emittance at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35
Horizontal beta function at IP	β_x^*	mm	16	14	13	16	11
Vertical beta function at IP	β_y^*	mm	0.34	0.38	0.41	0.34	0.48
RMS horizontal beam size at IP	σ_x^*	nm	904	789	729	684	474
RMS vertical beam size at IP	σ_y^*	nm	7.8	7.7	7.7	5.9	5.9
Vertical disruption parameter	D_y		24.3	24.5	24.5	24.3	24.6
Fractional RMS energy loss to beamstrahlung	δ_{BS}	%	0.65	0.83	0.97	1.9	4.5
Luminosity	L	$\times 10^{34}$ cm^{-2} s^{-1}	0.56	0.67	0.75	1.0	1.8
Fraction of L in top 1% E_{CM}	$L_{0.01}$	%	91	89	87	77	58
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30
Electron relative energy spread at IP	$\Delta p/p$	%	0.20	0.19	0.19	0.16	0.13
Positron relative energy spread at IP	$\Delta p/p$	%	0.19	0.17	0.15	0.10	0.07

Table 8.2. Energy-dependent parameters of the Beam Delivery System [84].

		Center-of-mass energy, E_{cm} (GeV)							
		Baseline				Upgrades			
Parameter		200	250	350	500	500	1000 (A1)	1000 (B1b)	Unit
Nominal bunch population	N	2.0	2.0	2.0	2.0	2.0	1.74	1.74	$\times 10^{10}$
Pulse frequency	f_{rep}	5	5	5	5	5	4	4	Hz
Bunches per pulse	N_{bunch}	1312	1312	1312	1312	2625	2450	2450	
Nominal horizontal beam size at IP	σ_x^*	904	729	684	474	474	481	335	nm
Nominal vertical beam size at IP	σ_y^*	7.8	7.7	5.9	5.9	5.9	2.8	2.7	nm
Nominal bunch length at IP	σ_z^*	0.3	0.3	0.3	0.3	0.3	0.250	0.225	mm
Energy spread at IP, e$^-$	$\delta E/E$	0.206	0.190	0.158	0.124	0.124	0.083	0.085	%
Energy spread at IP, e$^+$	$\delta E/E$	0.190	0.152	0.100	0.070	0.070	0.043	0.047	%
Horizontal beam divergence at IP	θ_x^*	57	56	43	43	43	21	30	μrad
Vertical beam divergence at IP	θ_y^*	23	19	17	12	12	11	12	μrad
Horizontal beta-function at IP	β_x^*	16	13	16	11	11	22.6	11	mm
Vertical beta-function at IP	β_y^*	0.34	0.41	0.34	0.48	0.48	0.25	0.23	mm
Horizontal disruption parameter	D_x	0.2	0.3	0.2	0.3	0.3	0.1	0.2	
Vertical disruption parameter	D_y	24.3	24.5	24.3	24.6	24.6	18.7	25.1	
Energy of single pulse	E_{pulse}	420	526	736	1051	2103	3409	3409	kJ
Average beam power per beam	P_{ave}	2.1	2.6	3.7	5.3	10.5	13.6	13.6	MW
Geometric luminosity	L_{geom}	0.30	0.37	0.52	0.75	1.50	1.77	2.64	$\times 10^{34}$ cm^{-2} s^{-1}
– with enhancement factor		0.50	0.68	0.88	1.47	2.94	2.71	4.32	$\times 10^{34}$ cm^{-2} s^{-1}
Beamstrahlung parameter (av.)	Υ_{ave}	0.013	0.020	0.030	0.062	0.062	0.127	0.203	
Beamstrahlung parameter (max.)	Υ_{max}	0.031	0.048	0.072	0.146	0.146	0.305	0.483	
Simulated luminosity (incl. waist shift)	L	0.56	0.75	1.0	1.8	3.6	3.6	4.9	$\times 10^{34}$ cm^{-2} s^{-1}
Luminosity fraction within 1 %	$L_{1\%}/L$	91	87	77	58	58	59	45	%
Energy loss from BS	δE_{BS}	0.65	0.97	1.9	4.5	4.5	5.6	10.5	%
e$^+$e$^-$ pairs per bunch crossing	n_{pairs}	45	62	94	139	139	201	383	$\times 10^3$
Pair energy per B.C.	E_{pairs}	25	47	115	344	344	1338	3441	TeV

Figure 8.3
BDS optics, subsystems and vacuum chamber aperture; S is the distance measured from the entrance.

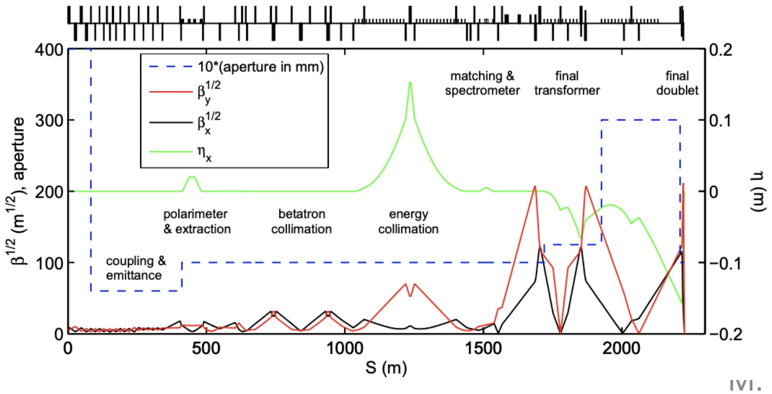


Table 8.1
Key parameters of the BDS [12]. The range of L^*, the distance from the final quadrupole to the IP, corresponds to values considered for the existing SiD and ILD detector concepts.

Parameter	Value	Unit
Length (start to IP distance) per side	2254	m
Length of main (tune-up) extraction line	300 (467)	m
Max. Energy/beam (with more magnets)	250 (500)	GeV
Distance from IP to first quad, L^*, for SiD / ILD	3.51 / 4.5	m
Crossing angle at the IP	14	mrad
Normalized emittance $\gamma\epsilon_x$ / $\gamma\epsilon_y$	10 000 / 35	nm
Nominal bunch length, σ_z	300	μm
Preferred entrance train to train jitter	<0.2–0.5	σ_y
Preferred entrance bunch to bunch jitter	< 0.1	σ_y
Typical nominal collimation aperture, x/y	6-10 / 30-60	beam sigma
Vacuum pressure level, near/far from IP	0.1 / 5	μPa

ILC 2019

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	TDR	Upgrades	
Centre of mass energy	$\sqrt{s}$	GeV	250	250	250	500	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.82	1.8/3.6	4.9
Polarisation for $e^-(e^+)$	$P_-(P_+)$		80 %(30 %)	80 %(30 %)	80 %(30 %)	80 %(30 %)	80 %(20 %)
Repetition frequency	f_{rep}	Hz	5	5	5	5	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312	1312/2625	2450
Bunch population	N_{e}	10^{10}	2	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	366	554	554/366	366
Beam current in pulse	I_{pulse}	mA	5.8	5.8	8.8	5.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727	727/961	897
Average beam power	P_{ave}	MW	5.3	10.5	10.5	10.5/21	27.2
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5	10	10	10
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35	30
RMS hor. beam size at IP	σ^*_{x}	nm	516	516	729	474	335
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7	7.7	5.9	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	87.1 %	58.3 %	44.5 %
Energy loss from beamstrahlung	δ_{BS}		2.6 %	2.6 %	0.97 %	4.5 %	10.5 %
Site AC power	P_{site}	MW	129		122	163	300
Site length	L_{site}	km	20.5	20.5	31	31	40

TABLE I: Summary table of the ILC accelerator parameters in the initial 250 GeV staged configuration (with TDR parameters at 250 GeV given for comparison) and possible upgrades. A 500 GeV machine could also be operated at 250 GeV with 10 Hz repetition rate, bringing the maximum luminosity to $5.4 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [10].

FCC-hh

Table 2.11. Baseline parameters and estimated peak luminosities of future electron–proton collider configurations for the electron ERL when used in concurrent ep and pp operating mode.

Parameter (unit)	**LHeC CDR**	**ep at HL-LHC**	**ep at HE-LHC**	**FCC-eh**
E_p (TeV)	7	7	12.5	50
E_e (GeV)	60	60	60	60
$\sqrt{s}$ (TeV)	1.3	1.3	1.7	3.5
Bunch spacing (ns)	25	25	25	25
Protons per bunch (10^{11})	1.7	2.2	2.5	1
$\gamma\epsilon_p$ (μm)	3.7	2	2.5	2.2
Electrons per bunch (10^9)	1	2.3	3.0	3.0
Electron current (mA)	6.4	15	20	20
IP beta function β_p^* (cm)	10	7	10	15
Hourglass factor H_{geom}	0.9	0.9	0.9	0.9
Pinch factor H_{b-b}	1.3	1.3	1.3	1.3
Proton filling H_{coll}	0.8	0.8	0.8	0.8
Luminosity (10^{33} cm^{-2} s^{-1})	1	8	12	15

Parameter Table

Table 7.1: Key numbers relating the detector challenges at the different accelerators.

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
Total number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm, est.(FLUKA)	GHz cm^{-2}	0.1	0.7	2.7	8.4 (10)
1 MeV-neq fluence at 2.5 cm, est.(FLUKA)	10^{16} cm^{-2}	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm, est.(FLUKA)	MGy	1.3	13	54	270 (300)
$dE/d\eta\|_{\eta=5}$ [331]	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0
90% $b\bar{b}$ $p_T^b > 30$ GeV/c [332]	$\|\eta\|<$	3	3	3.3	4.5
VBF jet peak [332]	$\|\eta\|$	3.4	3.4	3.7	4.4
90% VBF jets [332]	$\|\eta\|<$	4.5	4.5	5.0	6.0
90% $H \rightarrow 4l$ [332]	$\|\eta\|<$	3.8	3.8	4.1	4.8

First tracking layer:

10GHz/cm^2 charged particles

10^{18} hadrons/cm^2 for 30ab^{-1}

Increased Boost at 100TeV 'spreads out' light SM physics by 1-1.5 units of rapidity.

Heavy Ions

Table 7.4: Key parameters defining the detector requirements for PbPb collisions.

Parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm} per nucleon	TeV	5.5	5.5	10.6	39.4
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$	10^{27} cm^{-2}s^{-1}	1	6.5	15-50	320
Bunch spacing	ns	100	50	50	50
Number of bunches		1232	1232	1232	5400
Goal $\int \mathcal{L}$	nb^{-1}	1	10	10/month	110/month
σ_{inel}	b	7.8	7.8	8	9
σ_{tot}	b	515	515	530	597
BC rate	MHz	13.8	13.8	13.8	16.6
Peak PbPb collision rate	kHz	7.8	50.7	400	2880
RMS luminous region σ_z	mm	50-70	50-70	35-70	30-60
$dN_{ch}/d\eta\|_{\eta=0}$		500	500	610	900
Charged tracks per collision N_{ch}		5800	5800	7500	12500
Rate of charged tracks	GHz	0.05	0.3	3	36
$< p_T >$	GeV/c	0.47	0.47	0.49	0.55
Bending radius for $< p_T >$ at B=4T	cm	39	39	41	46

The general purpose detector will also be able to perform well for PbPb collisions at the predicted Luminosities.

Continuous readout, PID from TOF with the timing detectors are good features for Heavy Ion Physics.

Operating at a lower field than 4T would of course be desirable (calibration questions to be worked out …)

The significantly lower radiation requirement allows of course optimized detector solutions that can outperform a general purpose detector.

We definitely have to keep the door open for a dedicated HI experiment setup.