The FCC-ee Lepton Collider: Design Status and Operation Concept

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Overview

- Introduction
- Basic principles
- Essential dynamical aspects
- Essential technical aspects
- Conclusion

Future Circular Collider Study

The FCC relates to the development of a higher performance particle collider(s) to extend the research currently being conducted at the LHC.

The goal of the FCC is to greatly push the energy and luminosity frontiers of particle colliders, with the aim of reaching collision energies of 100 TeV, in the search for new physics. The FCC Study, hosted by CERN, is an international collaboration of more than 70 institutes from all over the world. Three different types of particle collisions are under consideration:

- hadron (proton-proton and heavy ion) collisions, FCC-hh;
- electron-positron collisions, as in the former FCC-ee;
- and proton-electron collisions, FCC-he.

The next step for the FCC Study is to deliver, by 2018, a conceptual design report, as input to the next update of the European Strategy for Particle Physics (ESPP).

FCC site: http://cern.ch/fcc.

LEP3-TLEP-FCC-ee

12/2011 Blondel, Zimmermann, LEP3, ArXiv:1112.2518	LEP3 (26 km), 120 GeV.
02/2012 Oide, SuperTristan, KEK Semirar	SuperTristan (80 km)
03/2012 Telnov, beamstrahlung, ArXiv:1203.6563	Luminosity limitation
06/2012 CERN 1st LEP3 meeting	
07/2012 CMS Higgs observation, ArXiv:1207.7235	
09/2012 1st CEPC-SppC meeting (China)	CEPC-SppC project is announced
11/2012 1st ICFA Higgs Factories WS (Fermilab)	+ pp collider (FCC-hh)
05/2013 ESPP Update	CERN has got a commitment from ESPP
06-09/2013 Three int.meetings define the FCC-ee param.	FCC-ee: 45.5 GeV – 175 GeV
11/2013 A CW collision was proposed for the FCC-ee	Low energy luminosity ↑
02/2014 FCC Kick-off meeting, Geneva U.	FCC study launch
10/2014 ICFA Higgs Factories WS, IHEP, China	
03/2015 1st FCC week in Washington	
07/2015 CW is a baseline for FCC-ee	
04/2016 2nd FCC week in Rome	BB coherent instability is discovered (K.Ohmi)
05/2017 3rd FCC week in Berlin	
04/2018 4th FCC week in Amsterdam	
End/2018	FCC CDR issue

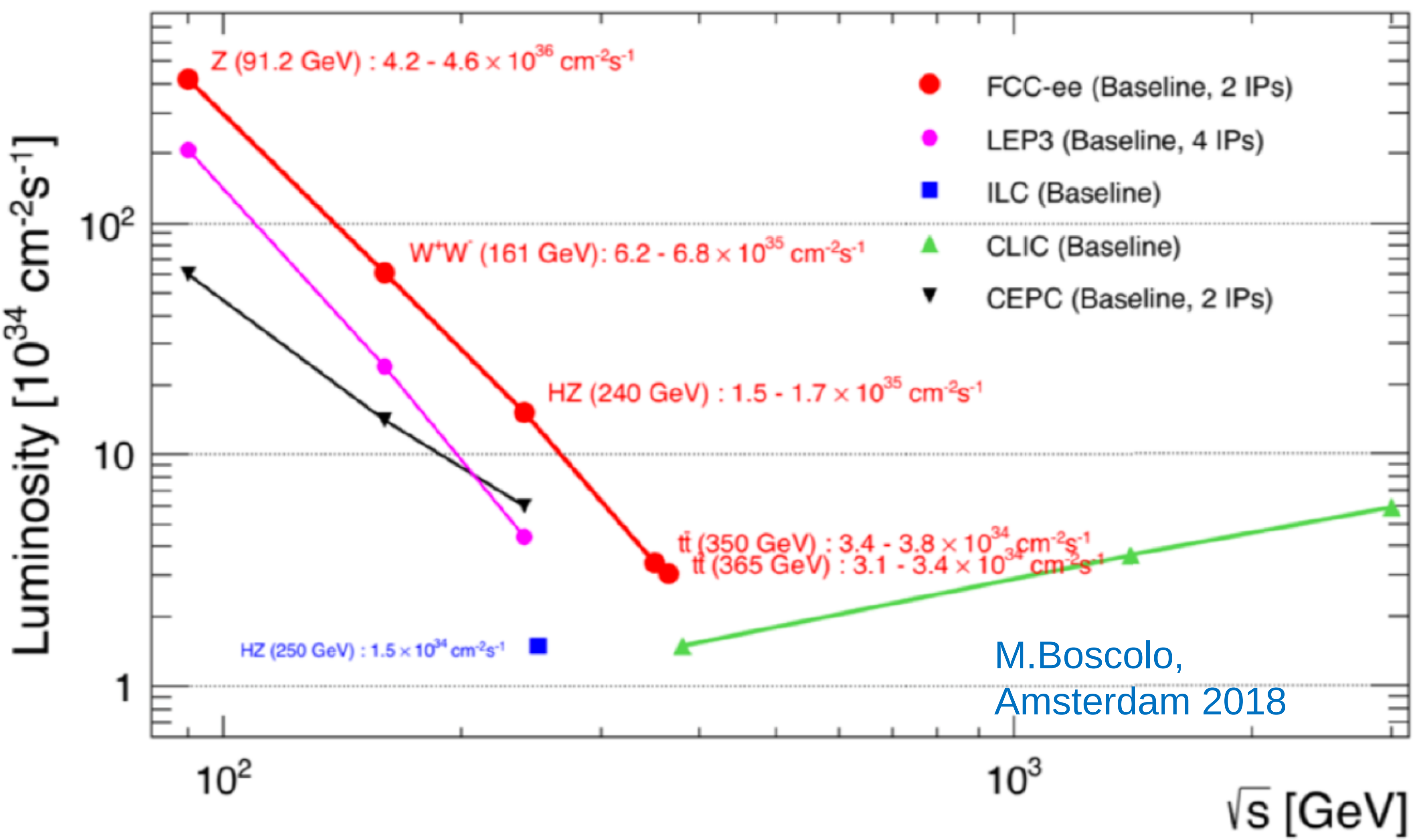
Lepton collider, which one?

"This (H(125)) discovery strongly influences the strategy for future collider projects. We are now entering the precision measurement era."

Patrick Janot, CERN, HF2012

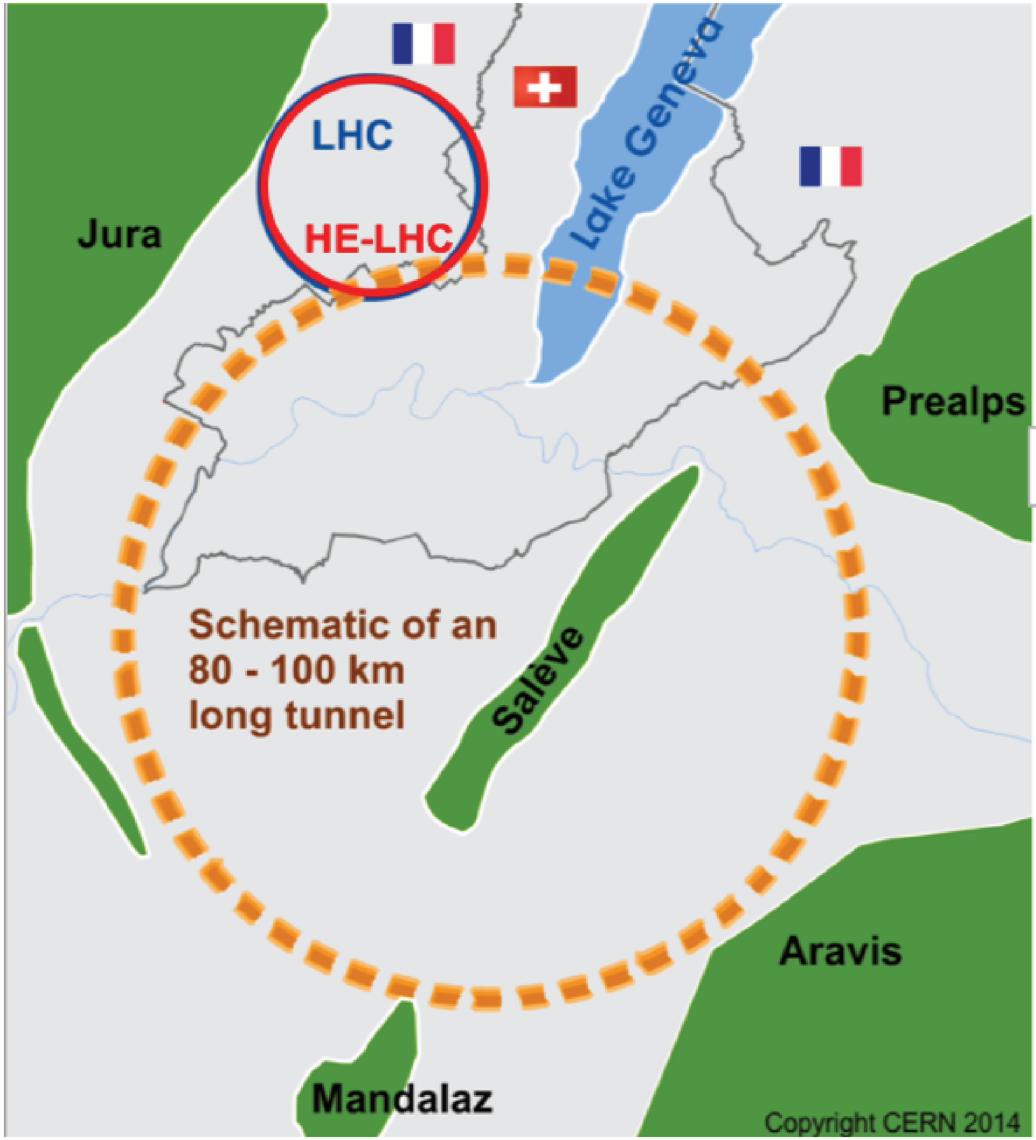
- $\mu^+\mu^-$ collider? The longest-term project (if at all feasible). Yet too hypothetical, too far in future – not addressed today.
- $\gamma\gamma$ collider? Too limited a physics program – not addressed today .
- e^+e^- collider? Physics prospects are good and solid projects exist → Today's focus. Linear colliders studied /designed for two decades. Circular colliders have more than 50 years experience. LEP1/2 has shown excellent results at high energy.

Linear or circular?



Decision after 2020

Site



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

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

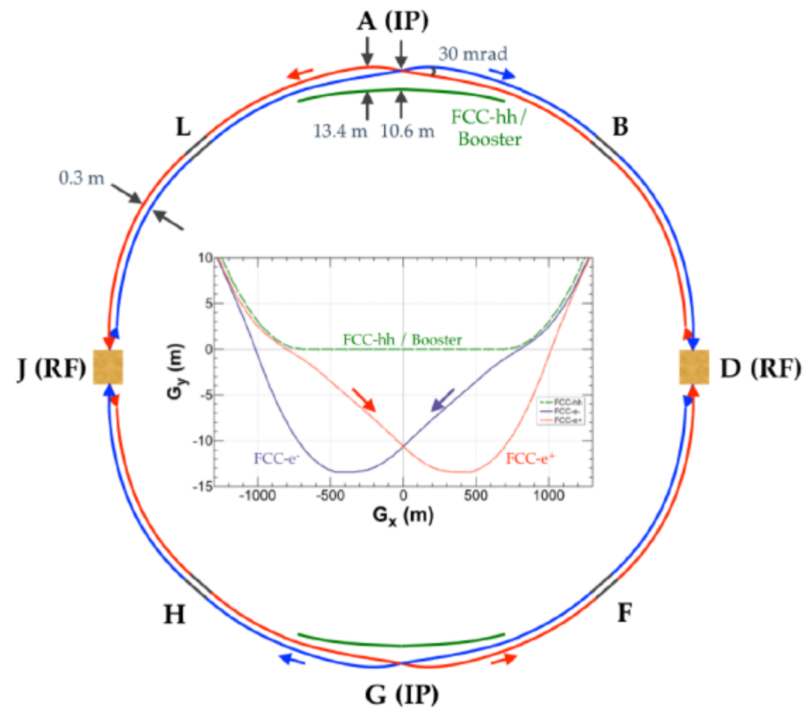
~16 T ⇒ 100 TeV *pp* in 100 km

- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, e^- from ERL

Layout and basic principles

- **Double ring** e+ e- collider ~100 km
- Follow the footprint of FCC-hh, except for around the IPs
- **2 IPs** with **crab-waist scheme**, large horizontal crossing angle of **30 mrad.**
- **Flexible design, for all energies:**
  - **common lattice,** except for a small rearrangement in the RF section
  - **$L^* = 2.2$ m** (length of the free area around the IP), **$B_{detector} = 2$ T**
  - **$E_{critical} < 100$ keV** (critical energy of the synchrotron radiation) of incoming beam toward IP from 450 m
- **Top-up injection** scheme to maintain the stored beam current and the luminosity at the highest level during experiment runs. It is necessary to have a booster synchrotron in the same tunnel as the collider.
- **Synchrotron radiation power 50 MW/beam** at all energies.
- **"Tapering"** of magnets along the ring to compensate the sawtooth effect
- Common RF cavities for e+ and e- at ttbar (RF frequency **400 MHz** and **400+800 MHz at ttbar)**

M. Boscolo, FCCWEEK18



Main parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
peak luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55
nominal luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	200	25	7	1.4
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/vertical beta* [m,mm]	0.15, 0.8	0.2, 1	0.3, 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
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

Integrated luminosity

parameter \ machine & c.m.energy	FCC-ee Z 91.2 GeV	FCC-ee WW 160 GeV	FCC-ee H (ZH) 240 GeV	FCC-ee ttbar 365 GeV
run time per year [days]	185	185	185	185
nominal luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	200	25	7	1.4
integrated luminosity 2 IPs / year [ab^{-1}]	48	6	1.7	0.34

$$L_{\rm int} \approx T\ H\ L_{\rm nominal}$$

***T* = 185 days per year**, scheduled for e+e- physics (i.e. 365 days – 17 weeks EYETS – 30 days commissioning – 20 days for MDs – 10 days for technical stops), similar to LEP/LHC schedules.

$H \approx 0.75$, Hübner factor, empirical factor defined by the above equation(s), extrapolated from other similar machines, or by simulations with average failure rate and average downtime.
Due to top-up injection: $H \cong$ availability for hadron collider (70-80%), and of KEKB and PEP-II (80%)

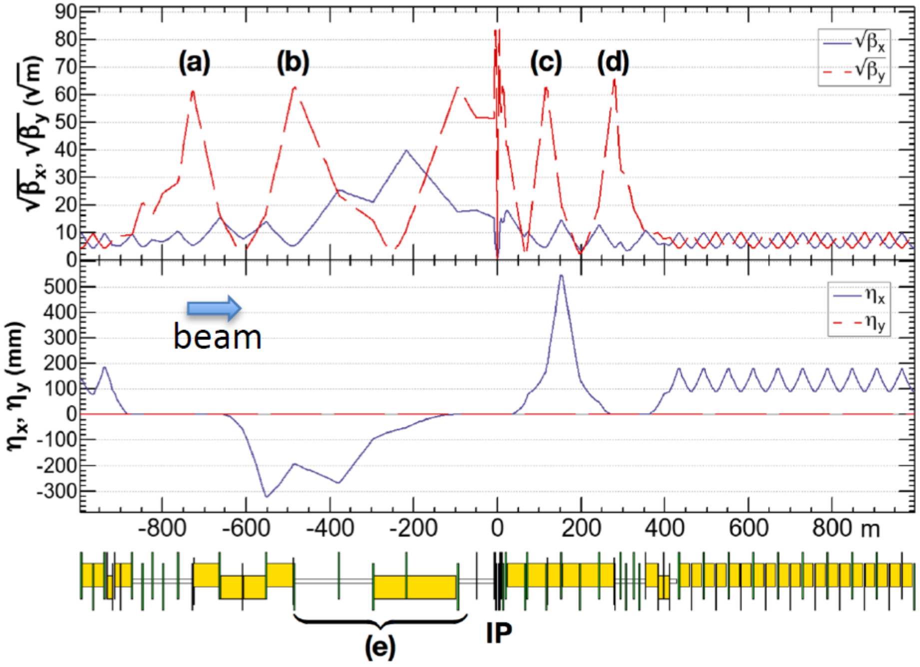
For FCC-ee physics operation model, $L_{nominal}$ assumed at half the design value in the first two years of phase 1 and in the first year of phase 2 (to account for initial operation, cf. to LEP experience)

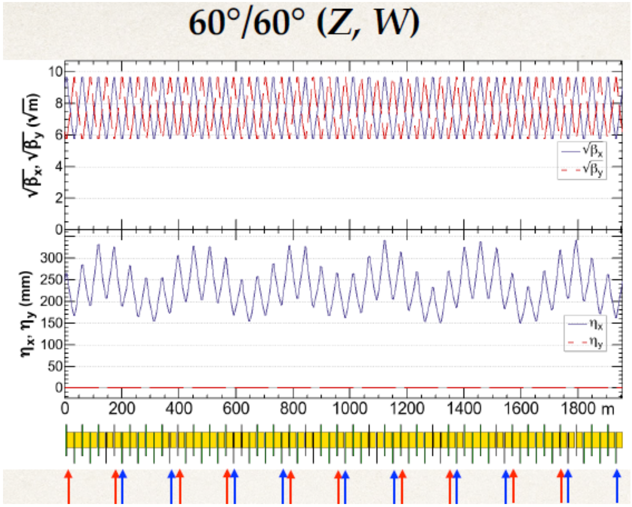
Experimental scenario

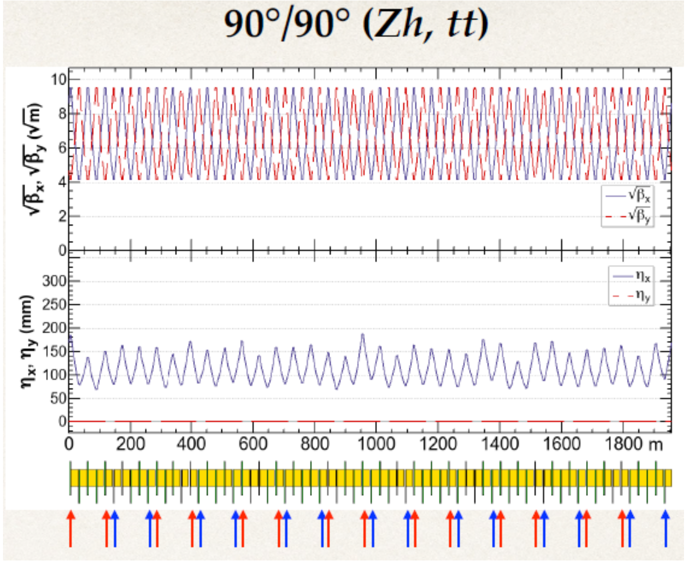
working point	nominal luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	total luminosity (2 IPs)/ yr half luminosity in first two years (Z) and first year (ttbar) to account for initial operation	physics goal	run time [years]
Z first 2 years	100	**26 ab^{-1}/year**	**150 ab^{-1}**	**4**
Z later	200	**48 ab^{-1}/year**		
W	25	**6 ab^{-1}/year**	**10 ab^{-1}**	**1 - 2**
H	7.0	**1.7 ab^{-1}/year**	**5 ab^{-1}**	**3**
machine modification for RF installation & rearrangement: 1 year				
top 1st year (350 GeV)	0.8	**0.2 ab^{-1}/year**	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.4	**0.34 ab^{-1}/year**	**1.5 ab^{-1}**	**4**

total program duration: 14 – 15 years - *including machine modifications*
phase 1 (*Z*, *W*, *H*): 8 – 9 years, phase 2 (top): 6 years

Baseline optics 2016





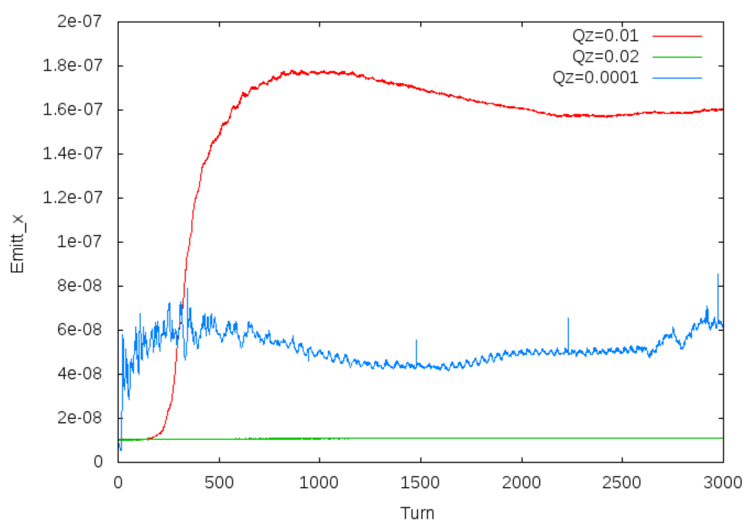


- 60/60 cell at Z, W to mitigate the beam-beam coherent instability,
- Smaller β_x*,
- Adopting "twin aperture quads" concept,
- Special section for inverse Compton spectrometer,
- Injection section optics.

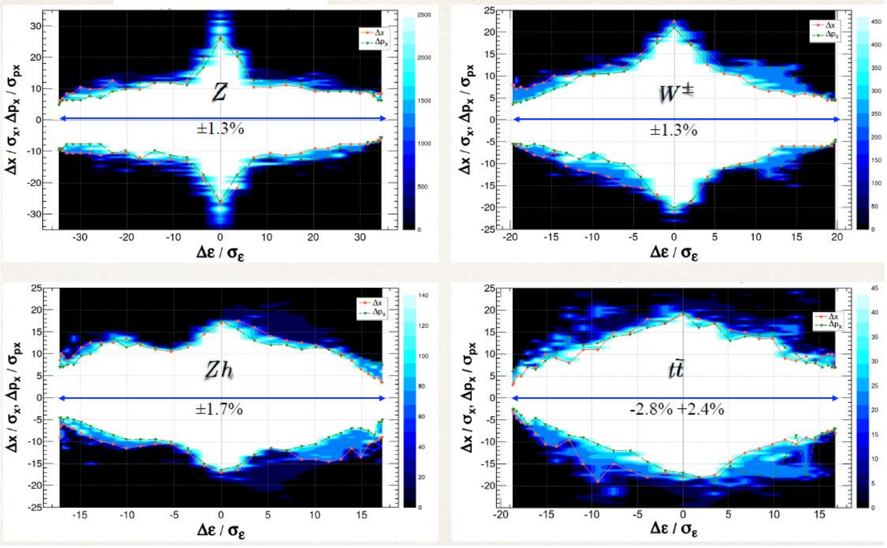
FCC-ee optics is designed by K.Oide

Beam dynamics

- New BB coherent instability limiting luminosity was discovered in 2016 by K.Ohmi and mitigated by D.Shatilov/K.Oide.
- DA/MA is optimized by non-interleaved sextupoles in the arcs and they are enough for good machine performance
- Asymmetric momentum acceptance at high energy to fit the asymmetric energy distribution tails (due to beamstrahlung).
- DA study with errors and misalignments is in progress.



Emittance increase due to the BB coherent instability.



DA at different energies.

Energy calibration: physics requirements

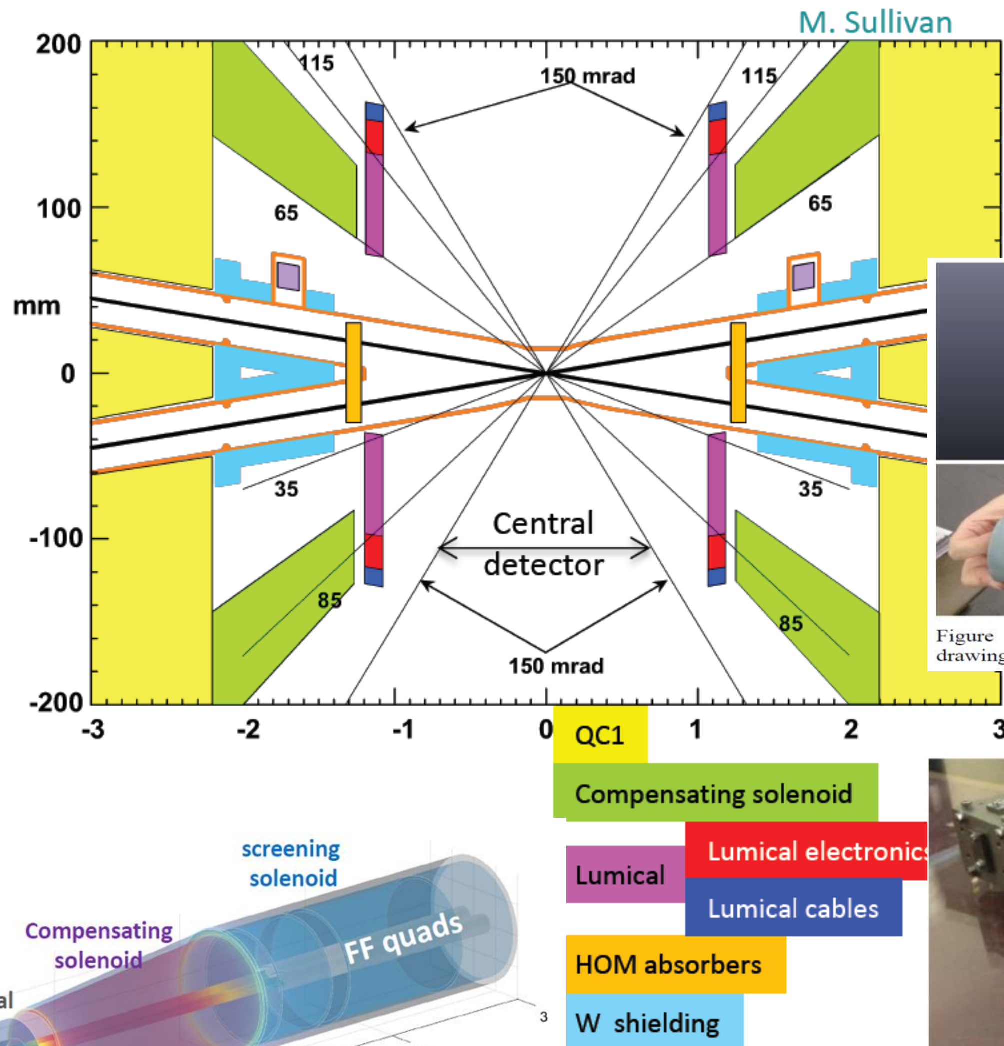
1. Center-of-mass energy determination with precision of $\pm$ 100 keV around the Z peak
2. Center-of-mass energy determination with precision of $\pm$ 300 keV at W pair threshold
3. For the Z peak-cross-section and width, require energy spread uncertainty $\Delta\sigma_E/\sigma_E$ =0.2%

- use resonant depolarization as main measuring method
- use pilot bunches to calibrate during physics data taking: 100 calibrations per day each 10^{-6} rel.
- long lifetime at Z requires the use of wigglers at beginning of fills
- take data at points where self polarization is expected

A. Blondel

MDI

Unique design for all energies.



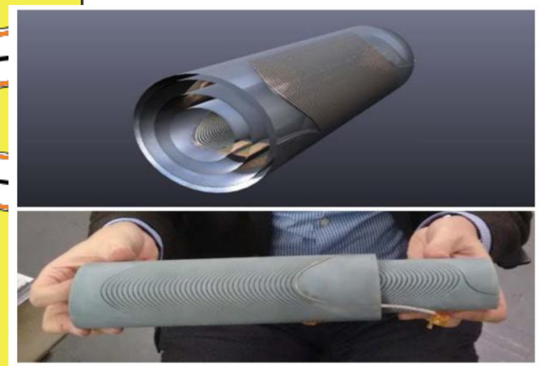
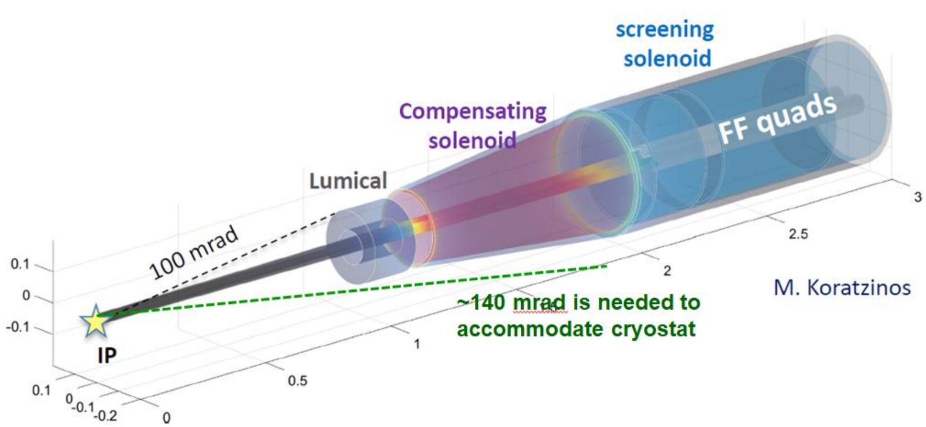
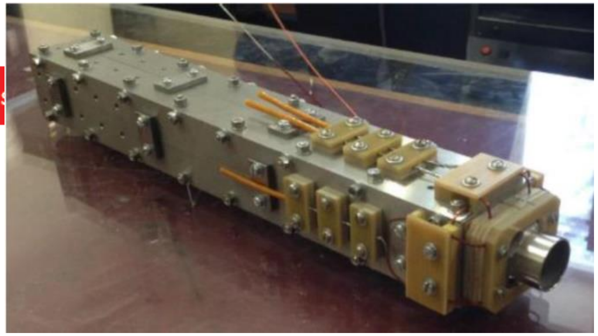


Figure 3: Prototype CCT final focus quadrupole. CAD drawing (top) and 3D printed item (bot).





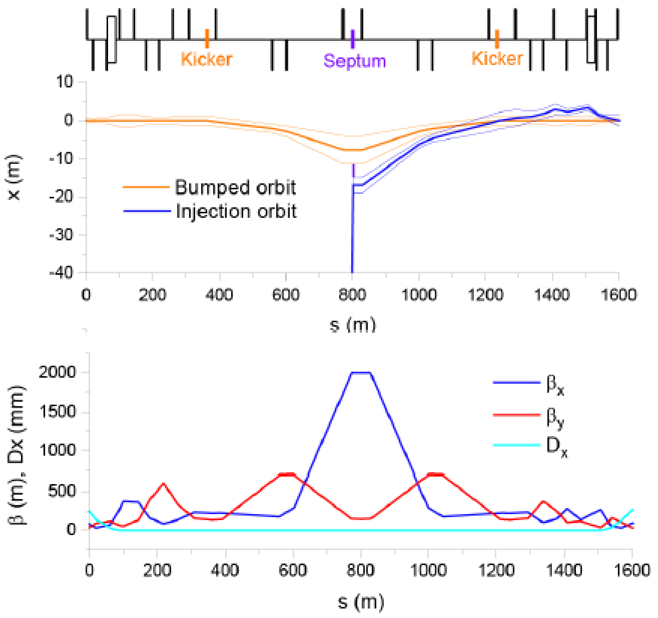
Injection

- Top-up injection, which keeps the beam current constant, is essential for FCC-ee collider rings
  - To maximise luminosity production efficiency despite the short beam lifetime, about 20 minutes when beamstrahlung is taken into account during collision
  - To stabilize the machine under the heat load of 100 MW synchrotron radiation
- Conceptual study has shown positive result:

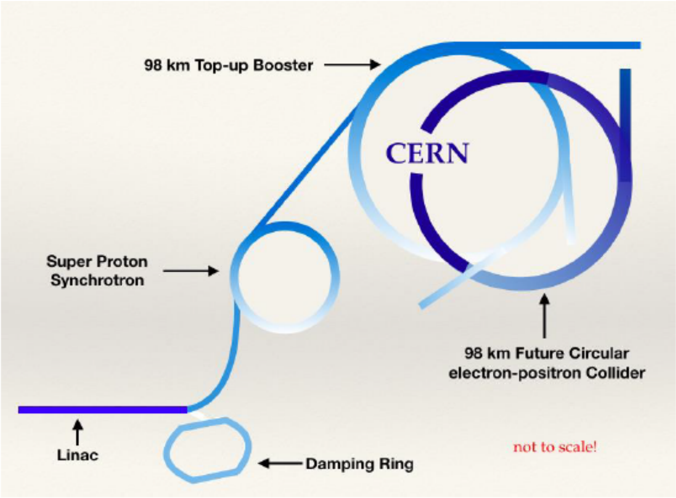
top-up injection is feasible with no strong technical challenge*

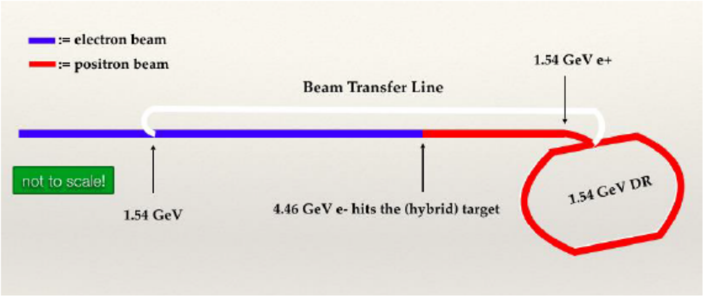
* "Top-up injection schemes for future circular lepton collider", M. Aiba et al., NIM-A, 880, pp.98-106 (2018)

Layout, orbits and optics for Conventional injection scheme



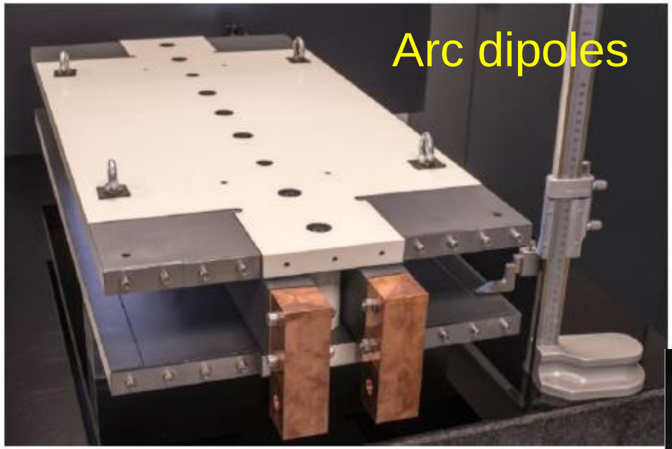
Injection facility layout

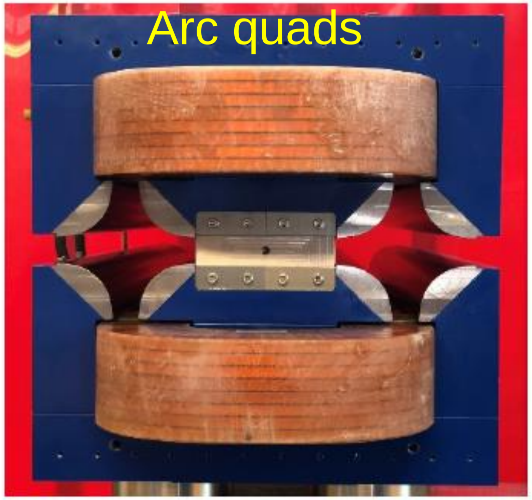




- SLC/SUPERKEKB-like linac accelerating **1** or **2** bunches with repetition rate of **100-200 Hz**
- **Same linac** used for positron production @ **4.46 GeV** Positron beam emittances reduced in DR @ **1.54 GeV**
- Injection @ **6 GeV** into of Pre-Booster Ring (SPS or new ring) and acceleration to 20 GeV
- Injection to main Booster @ **20 GeV and interleaved** filling of e+/e- (below **20 min** for full filling) and continuous top-up

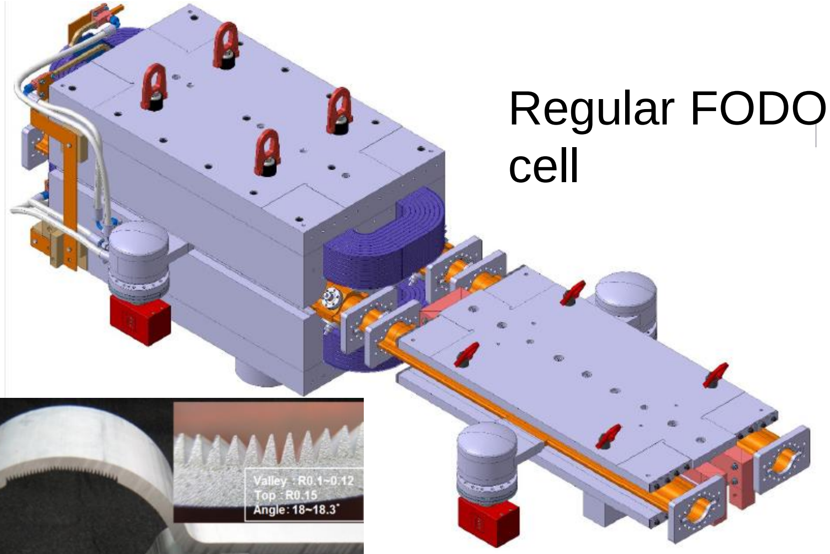
Magnet and vacuum systems



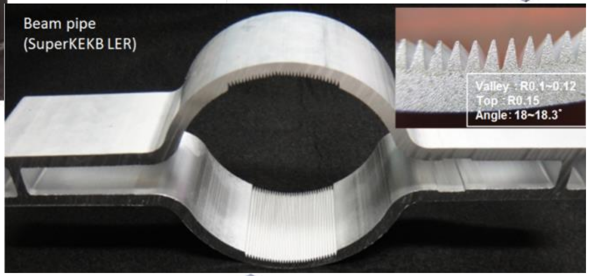


A. Milanese, FCC Week 2017

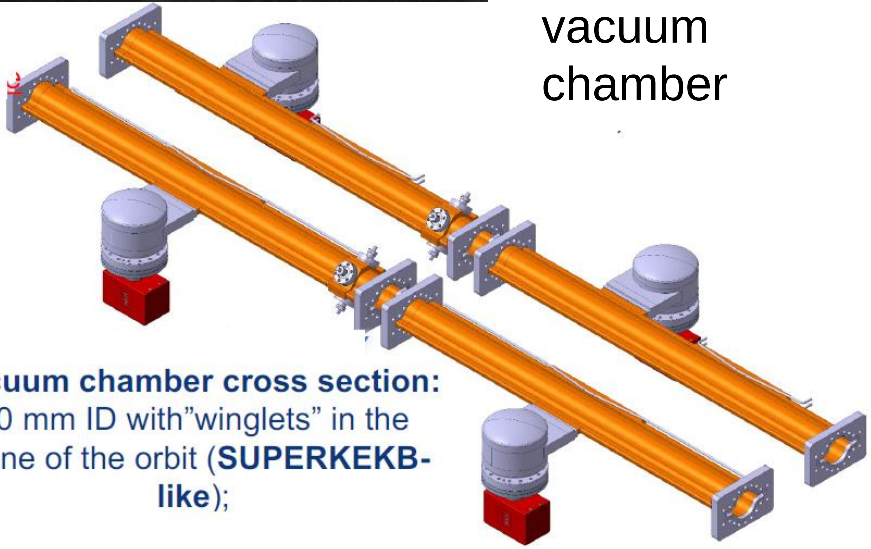
Factor 2 power saving due to the double aperture design.



Regular FODO cell



Super K vacuum chamber



Vacuum chamber cross section: 70 mm ID with"winglets" in the plane of the orbit (**SUPERKEKB-like**);

RF system

WP	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0.1	16640	1390
W	0.44	2000	147
H	2.0	393	29
ttbar	10.9	48	5.4

"high-gradient" vs high-current machine

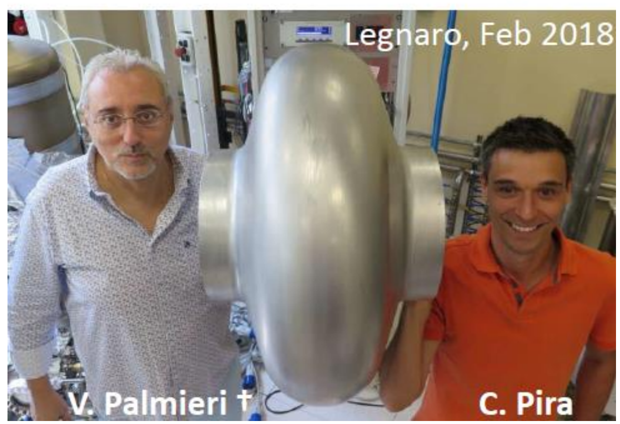
three sets of RF cavities to cover all options for FCC-ee & booster:

- **high intensity (Z, FCC-hh): 400 MHz mono-cell cavities (4/cryom.)**
- **higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule)**
- **ttbar machine complement: 800 MHz five-cell cavities (4/cryom.)**
- **installation sequence comparable to LEP (≈ 30 CM/shutdown)**

5-cell 800 MHz cavity, JLAB prototype for both FCC-ee (t-tbar) & FCC-eh ERL

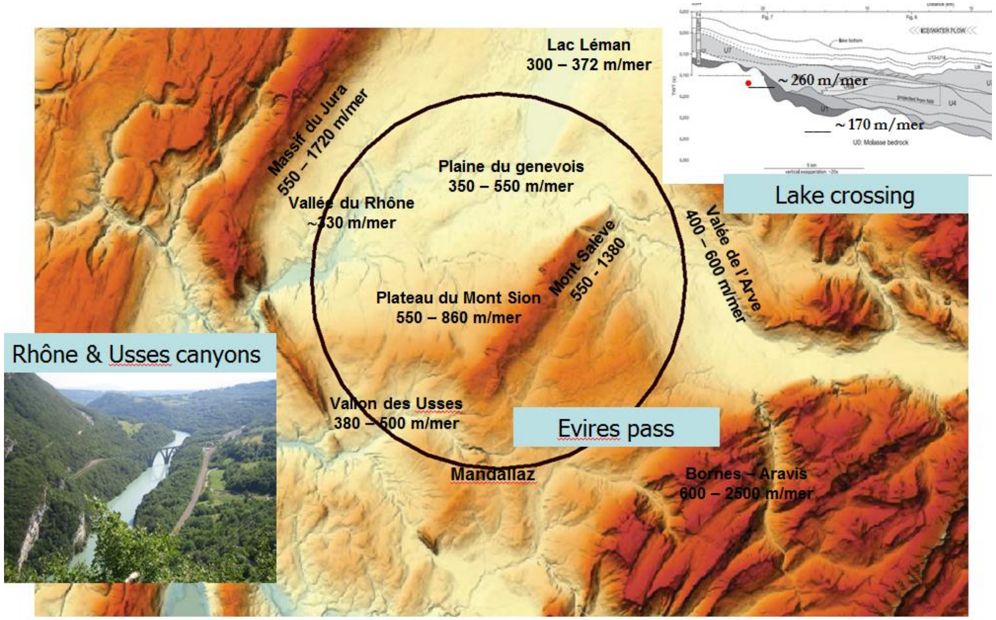
Seamless 400 MHz single-cell cavity formed by spinning at INFN-LNL

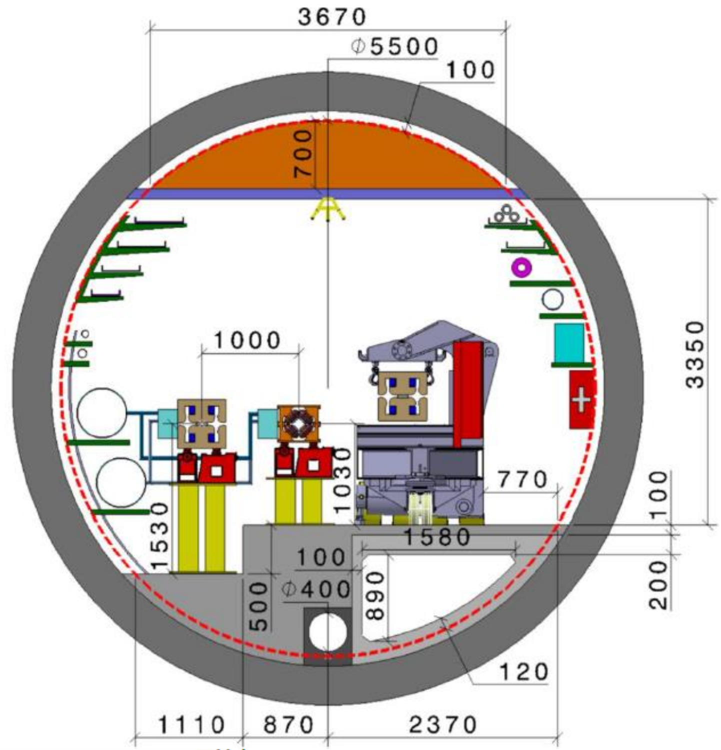
Tooling fabricated and successfully tested with an Aluminium cavity.

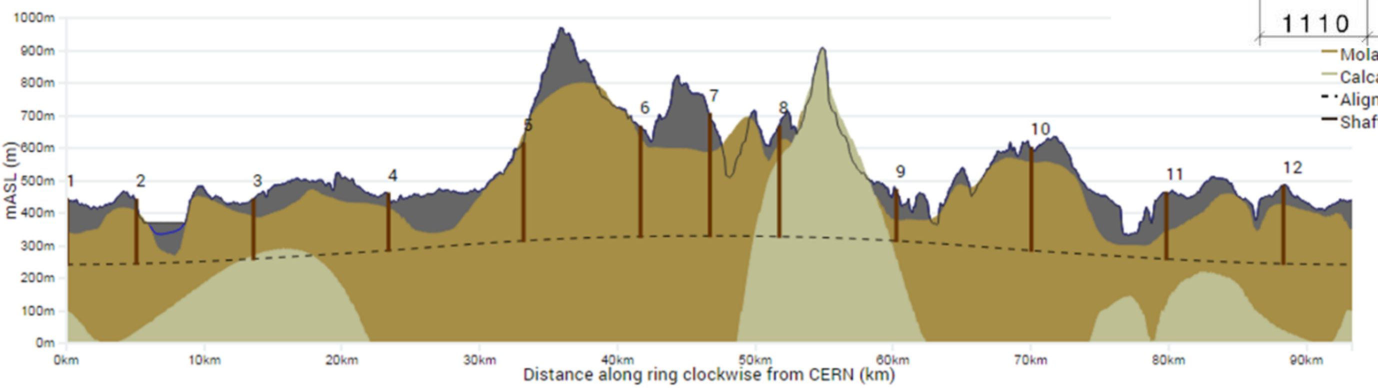


CERN half-cells formed using Electro-Hydro-Forming (EHF) at Bmax.

Footprint







∅ 5.5 m, main ring and booster 1 m distant.

20 shafts with 578 m of the deepest one

Conclusion

- FCC-ee collider is an extremely challenging but feasible with unprecedented physics potential.
- Great progress has been made in the FCC-ee collider design during last years.
- All the problems appeared (new effects limit the luminosity, DA/MA reduction, extremely precise energy measurement, etc.) seem are solved. No showstoppers are revealed.
- CDR is progressing as scheduled.