FUTURE CIRCULAR COLLIDER (FCC) FEASIBILITY STUDY PROGRESS

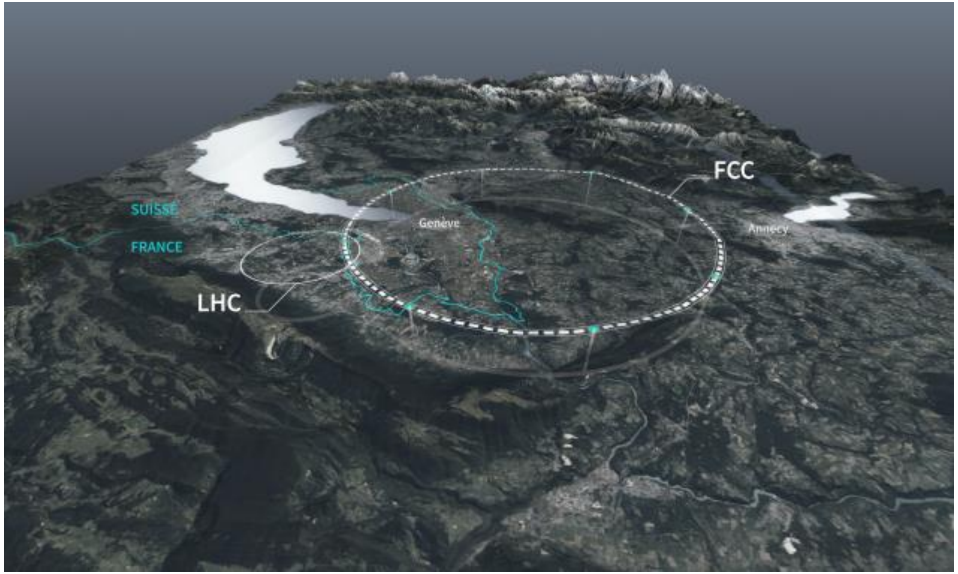
M. Hofer
On behalf of the FCC collaboration

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

The FCC integrated program

Inspired by the successful LEP-LHC programs at CERN

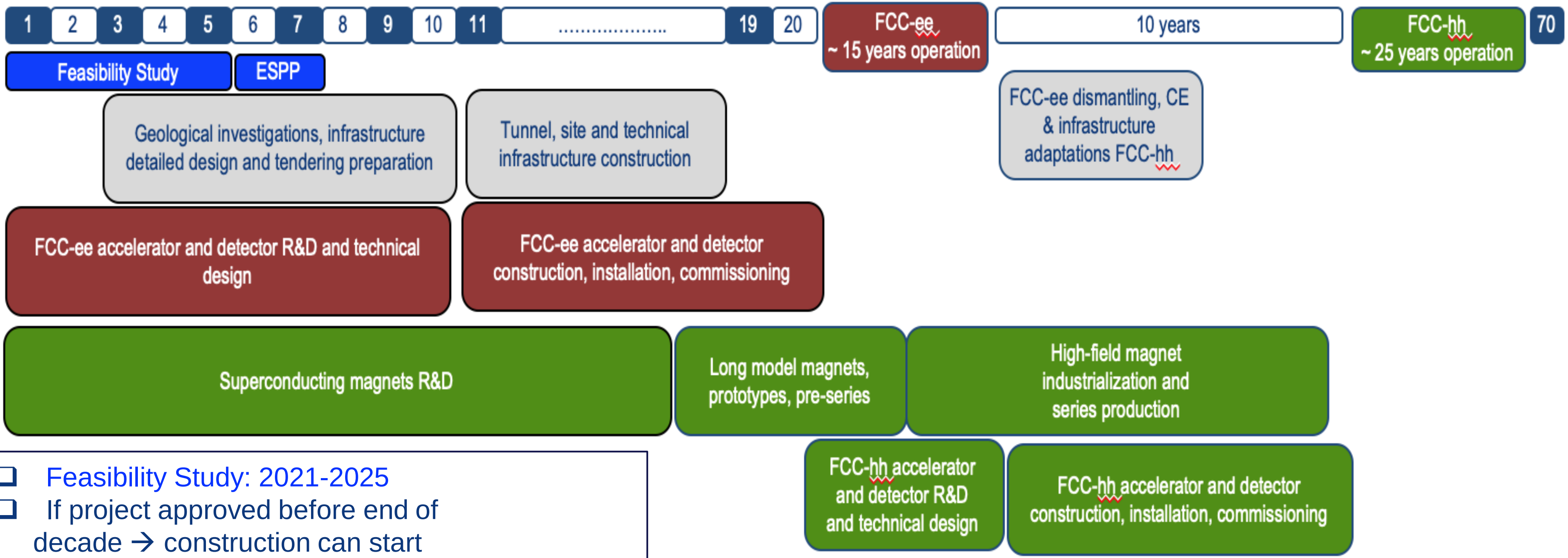
- Comprehensive long-term program maximizing physics opportunities
  - Stage 1: e^+e^- collider FCC-ee as Higgs factory, EW & top factory, targeting unprecedented luminosities
  - Stage 2: proton collider FCC-hh pushing energy frontier with target com Energy of 100 TeV, with options for ion program or eh collisions



- Common tunnel and technical infrastructure, building on existing CERN accelerator infrastructure

- FCC integrated program allows seamless transition of HEP after completion of the HL-LHC program

Timeline of the FCC integrated programme



- ❑ Feasibility Study: 2021-2025
- ❑ If project approved before end of decade → construction can start beginning 2030s
- ❑ FCC-ee operation ~2045-2060
- ❑ FCC-hh operation 2070-2090++

F. Gianotti

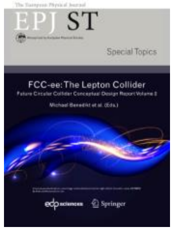
FCC Feasibility Study (FS)

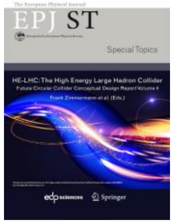
- The European Strategy for Particle Physics Update 2013 recommends that CERN should undertake design studies for future accelerator projects
  → Launch of the FCC study, culminating in the publication of a four-volume report by 2019

- The 2020 update reaffirms that
  "An electron-positron Higgs factory is the highest-priority next collider."

  "Europe, together with its international partners, should investigate the technical and financial feasibility of a **future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV** and with an **electron-positron Higgs and electroweak factory as a possible first stage**. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

  → Launch of FCC Feasibility Study





FCC Feasibility Study (FS): high-level objectives

- Feasibility study report expected by the end of 2025
  as input for the next European Strategy for Particle Physics Update

- Report to address amongst other

  - Demonstration of geological, technical, environmental and administrative feasibility of the tunnel and surface areas
  - Optimization of the collider designs and injectors,
    supported by R&D for key technology
  - Sustainable operational model for colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency

- FCC FC is organized as an international collaboration
  - Synergies with other large accelerator projects
    such as SKEKB, EIC, CEPC

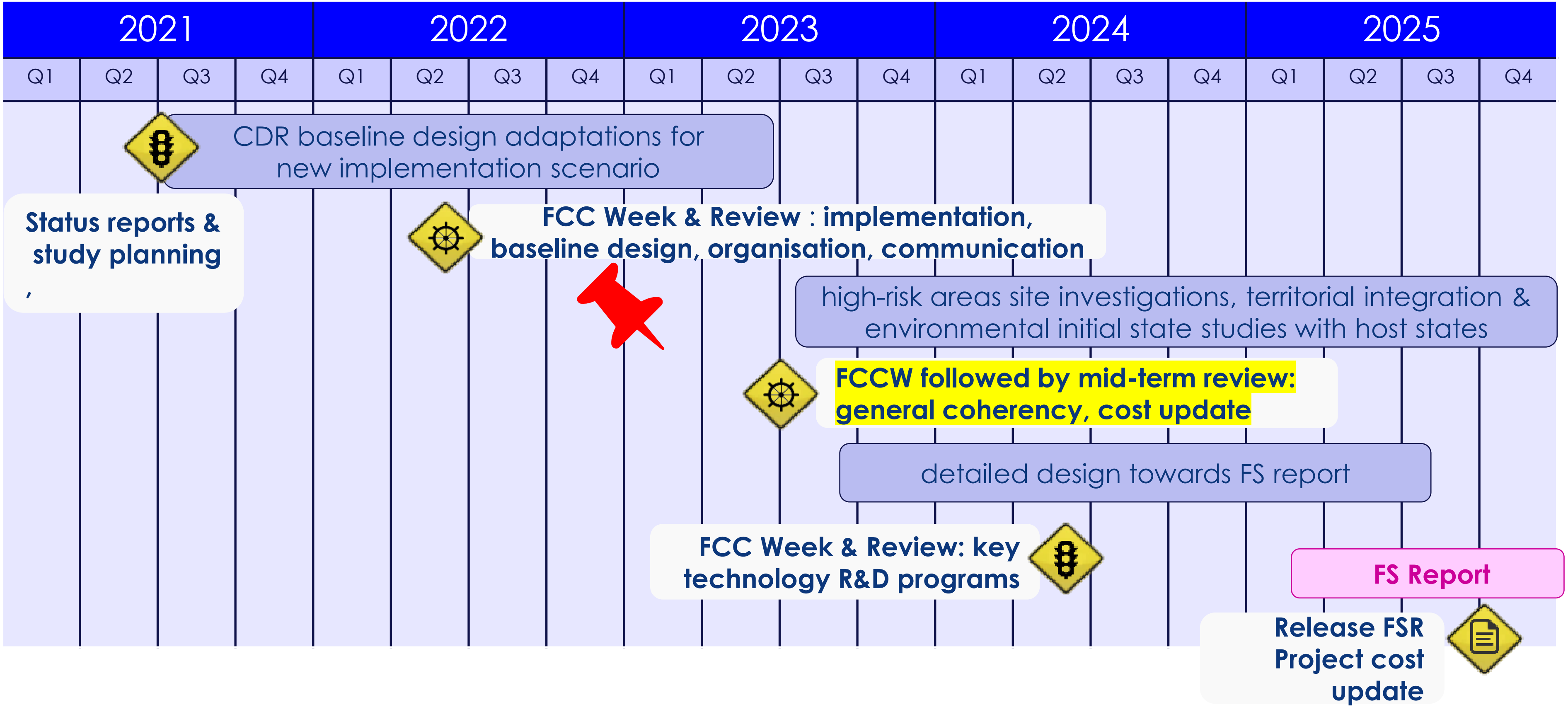
147 Institutes

30 Companies

34 Countries

EC H2020

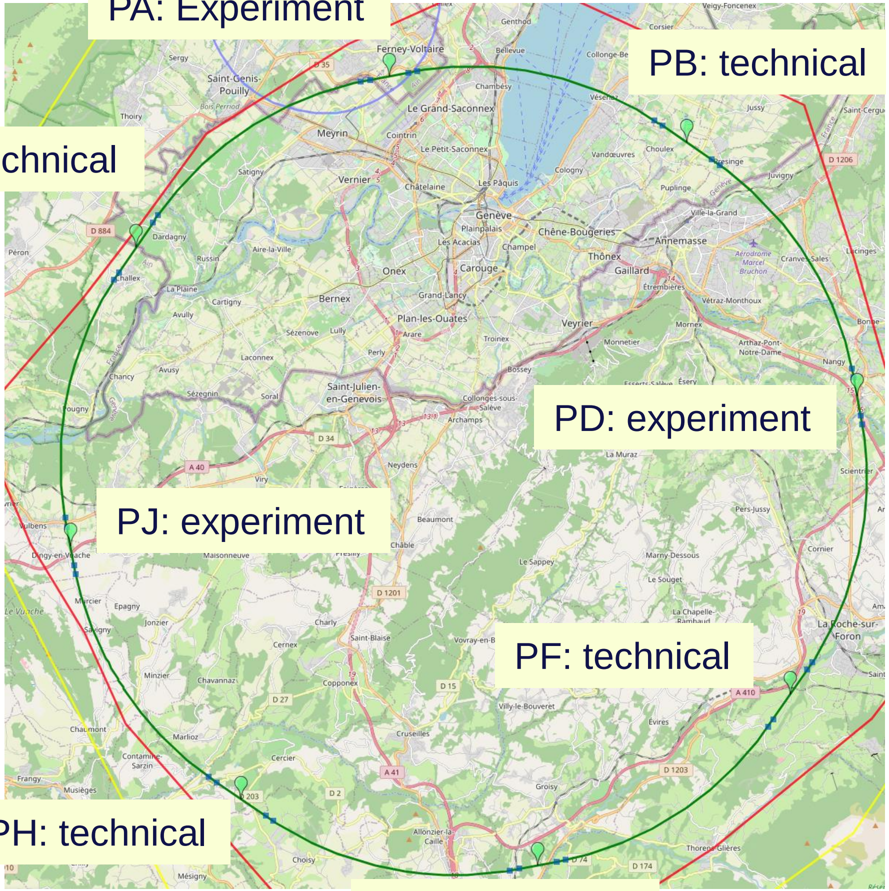
Feasibility Study timeline



Tunnel and Infrastructure

- Tunnel in the Geneva basin constrained to a circumference < 100km

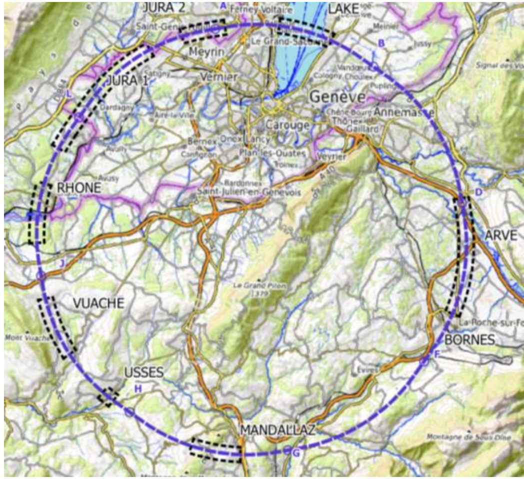
- Continued studies to optimize the placement of the ring lead to
  - Circumference of 91 km
  - Reduce number of surface sites to 8, less use of land
  - Symmetry allows for 4 experiments
  - Surface points close to 400kV grid lines and good road connection

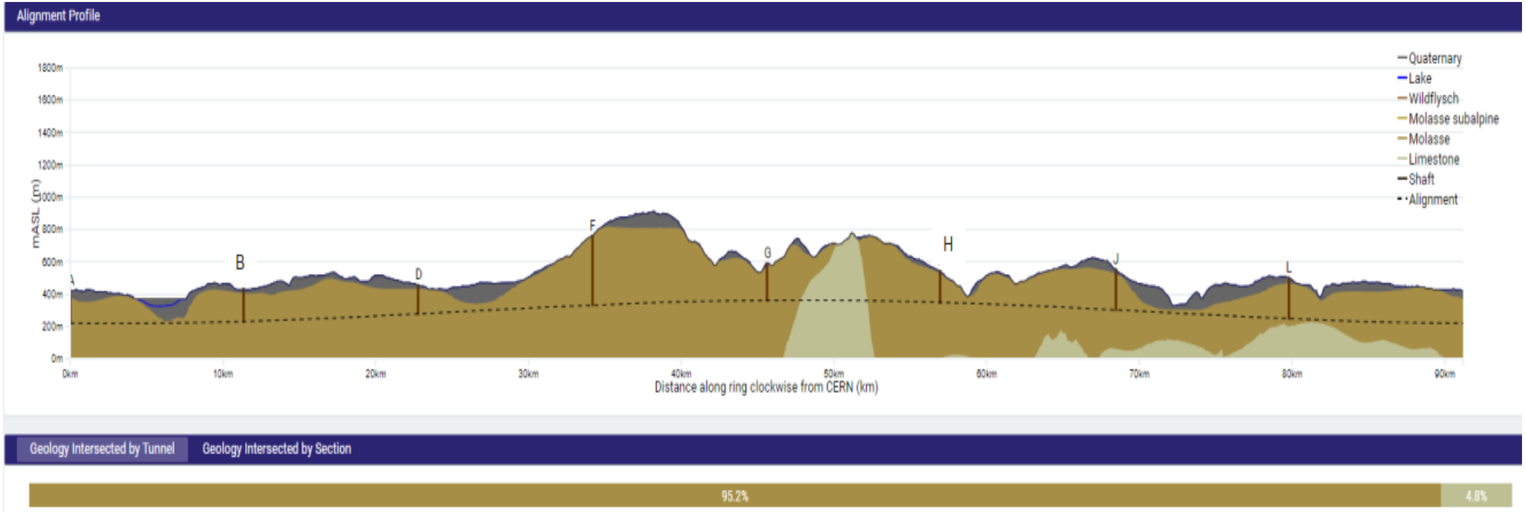


J. Gutleber

Tunnel and Infrastructure

- 95% of tunnel in molasse geology, minimizing construction risk
- Site investigations planned for 2024 and 2025 in areas with unknown geological properties

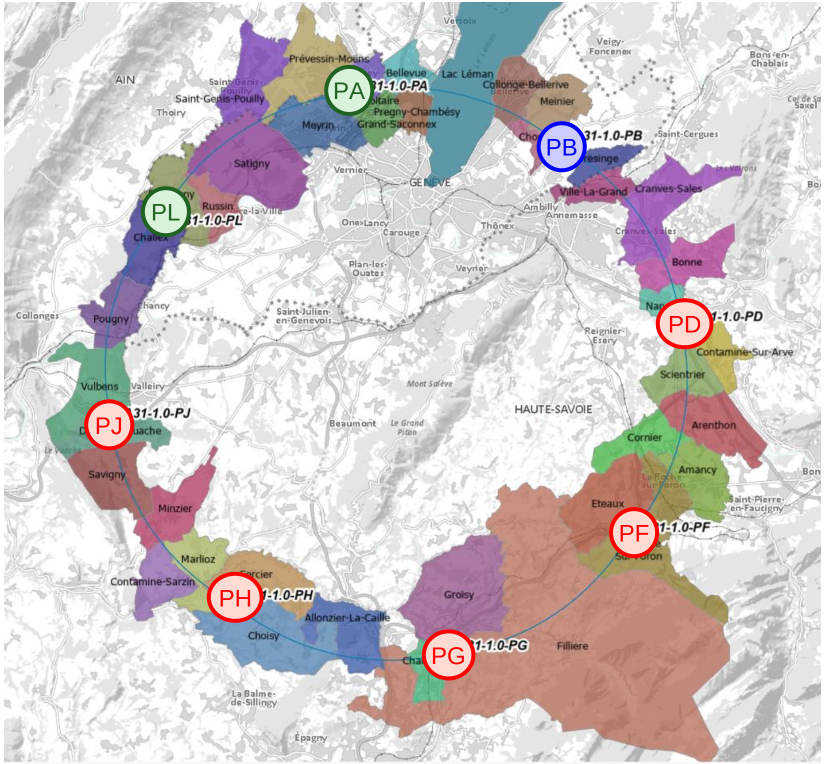




Environmental impact

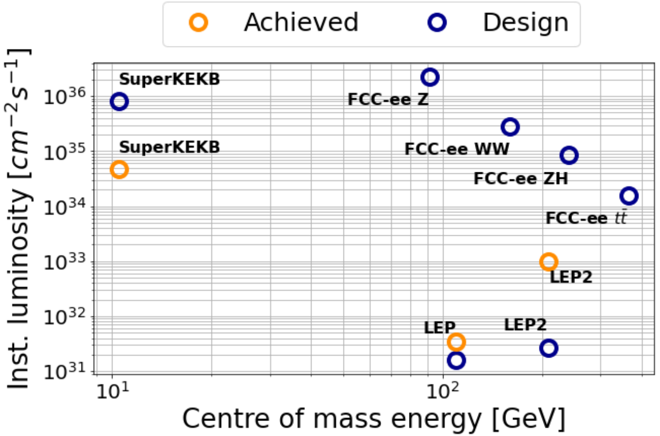
- Started to involve communes and regional authorities for consultation and to prepare regional activities
  - Provide information to general public about ongoing activities via website

- Technical discussions on territorial implementation, water use, excavation material started
  - Competition “Mining the future” concluded, shortlisting 4 innovative proposals for sustainable solutions to reuse of excavated molasse material to receive support for further R&D efforts and business planning



FCC-ee Luminosity Goal

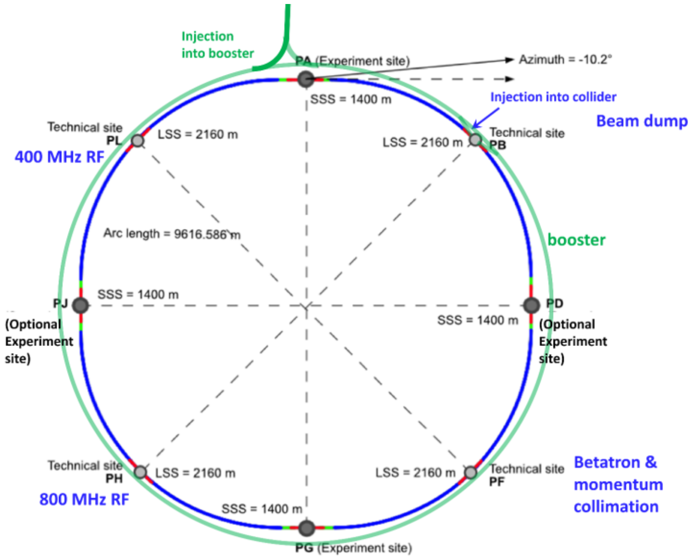
- Design of a highest-luminosity, energy frontier e^+e^- collider, optimized to study Z, W, Higgs, and top particles
  - Aim for:
    - 75 ab^{-1}/IP at Z-pole (91 GeV)
    - 5 ab^{-1}/IP at WW-threshold (161 GeV)
    - 2.5 ab^{-1}/IP at ZH (240 GeV)
    - 0.8 ab^{-1}/IP at $t\bar{t}$-threshold (365 GeV)
    - Other operation mode (direct H production) under study
  - Need to be compatible with design of the hadron collider (FCC-hh)



Sources: 1,2,3,4

Overview and design choices

- Double ring e^+e^- collider with a circumference of 91 km
- Two or four experiments
  - Asymmetric layout around interaction points to limit SR towards detector
  - Horizontal crossing angle of 30 mrad and crab waist collision scheme
- Minimal changes of the layout between operation modes and layout compatible with hadron collider
- Synchrotron radiation power limited to 50 MW/beam at all energies
- Full energy booster in the same tunnel to enable top-up injection



FCC-ee parameters

FUTURE CIRCULAR COLLIDER

K. Oide, D. Shatilov,

Parameter [4 IPs, 91.2 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter ξ_x / ξ_y	0.004/ .159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	2.02 / 2.95
luminosity per IP [10^{34} cm^{-2}s^{-1}]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr]	87	9.3	3.5	0.65
beam lifetime (rad Bhabha + BS+lattice)	8	18	6	10

Arcs optics

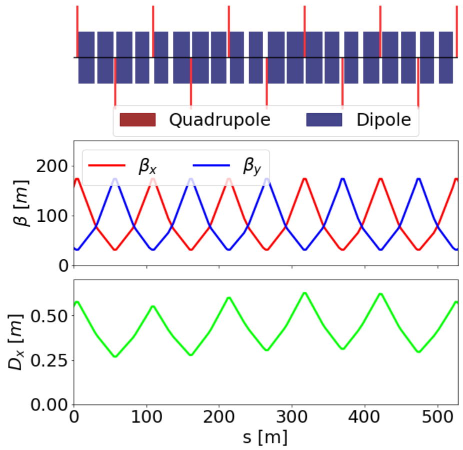
- Challenge is to find solution with large α_c at lower energies to mitigate collective instability, while keeping small ϵ_x at higher energies

- Solution is to use FODO cells in the arcs with variable cell length
  - For Z and WW operation modes, cell length of ~100 m and phase advance of $90^\circ/90^\circ$ used
  - By installing quadrupoles in the gaps between dipoles, the cell length for ZH and $t\bar{t}$ is reduced to 50 m, using again $90^\circ/90^\circ$ phase advance

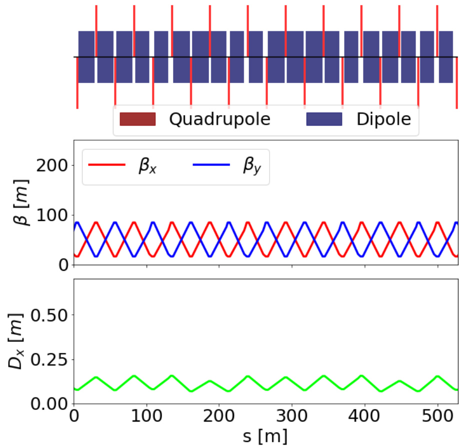
- Tapering of magnets along the ring to compensate for sawtooth effect

- Sextupole pairs with –I transform used for chromaticity correction

Z



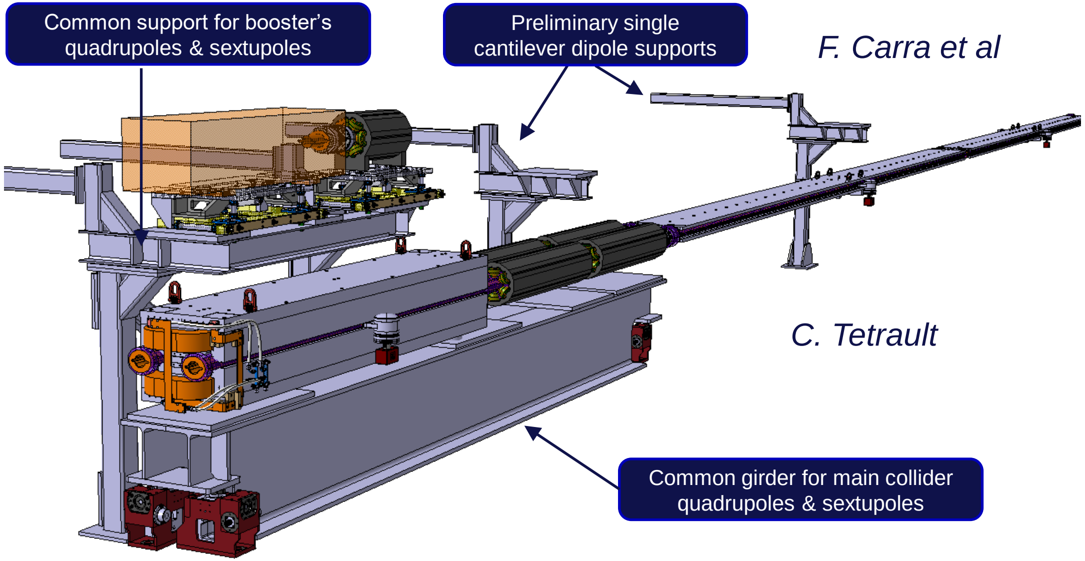
$t\bar{t}$



Optics by K. Oide

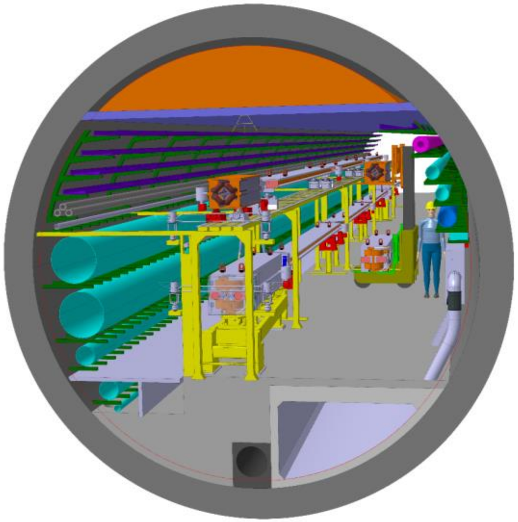
Arcs cell mockup

- For testing and optimizing fabrication, integration, and transport, a mock-up of an arc half-cell is in planning
  - Including booster hardware on top of the collider



F. Carra et al

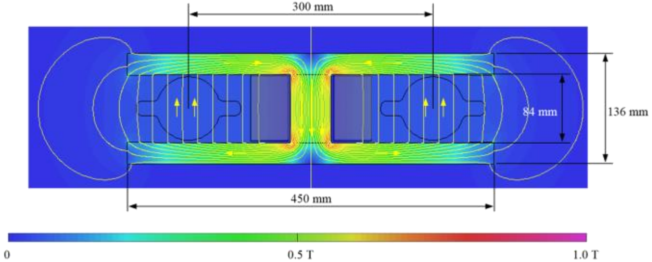
C. Tetrault

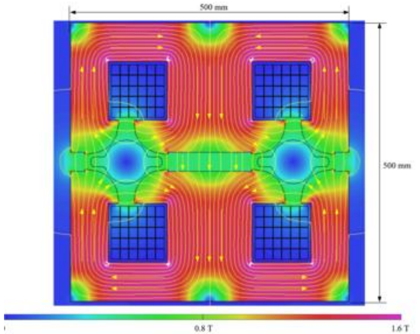


Arc perspective view, F. Valchkova-Georgieva

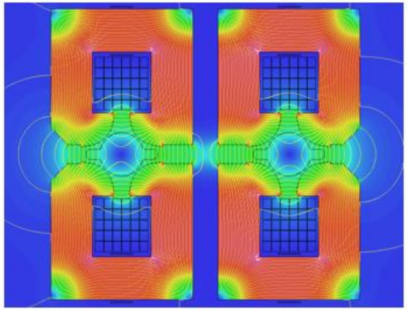
Arcs cell magnets

- In the current design, all arc magnets are normal conducting
  - Efficient and cost effective twin aperture dipole design
  - Magnetic measurements on 1m quadrupole prototype showed shift of 0.4mm of magnetic axis and design has been adapted





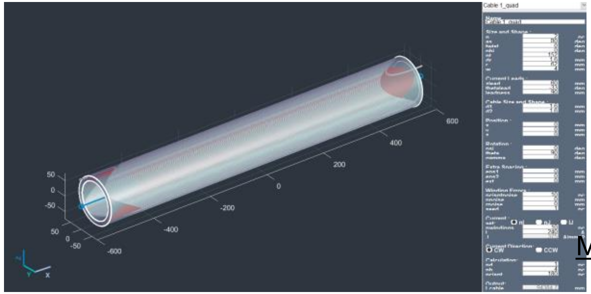
CDR cross-section



Modified cross-section

J. Bauche, C. Eriksson

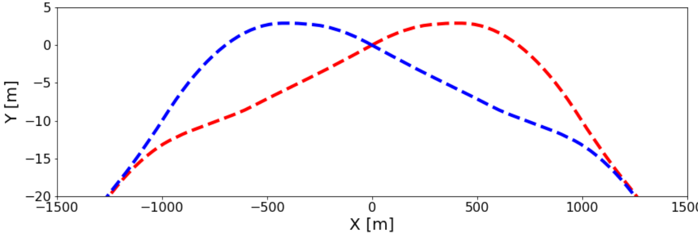
- To reduce power consumption, option with nested SC HTS quadrupoles and sextupoles under consideration
  - CHART project ongoing, developing 1m prototype section, understanding radiation environment and radiation damage

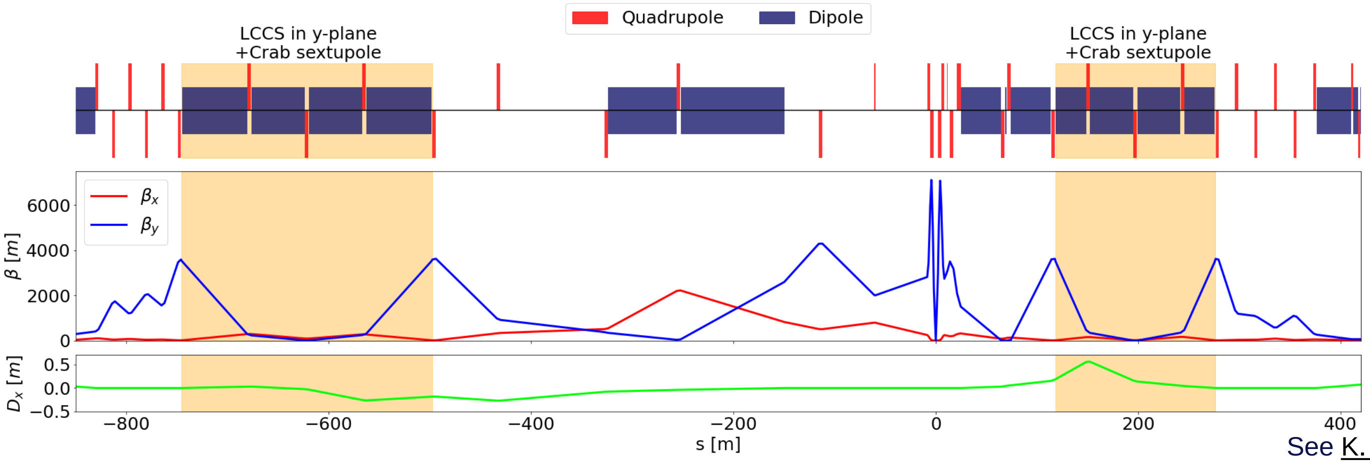


M. Koratzinos

Experimental IR

- Common IR layout for all working points
  - L* of 2.2 m and horizontal crossing angle of 30 mrad
  - Weak bending of dipoles upstream of IP to keep SR E_{crit} < 100 keV
  - Detector solenoid with 2 T locally compensated by anti-solenoids
  - Local chromaticity correction in vertical plane, combined with crab sextupoles





Operation mode	β_x^* [mm]	β_y^* [mm]
Z	100	0.8
W	200	1
H	300	1
$t\bar{t}$	1000	1.6

See K. Oide, PRAB **19**, 111005, Nov. 2016

Machine Detector Interface

- Complex integration of different elements (SC quadrupoles, LumiCal, shielding, diagnostics, ..)
  - Mechanical integration and thermal analysis ongoing, IR mock-up under discussion

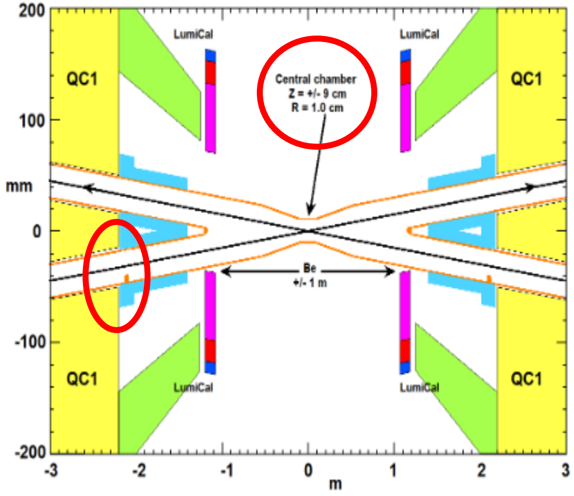
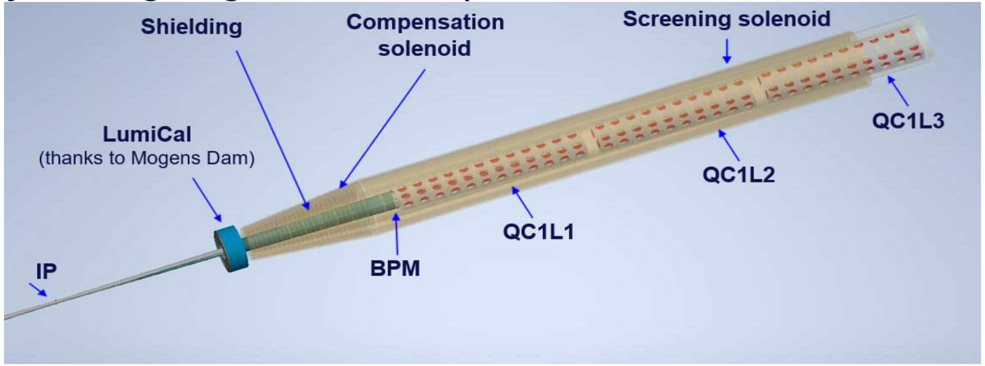
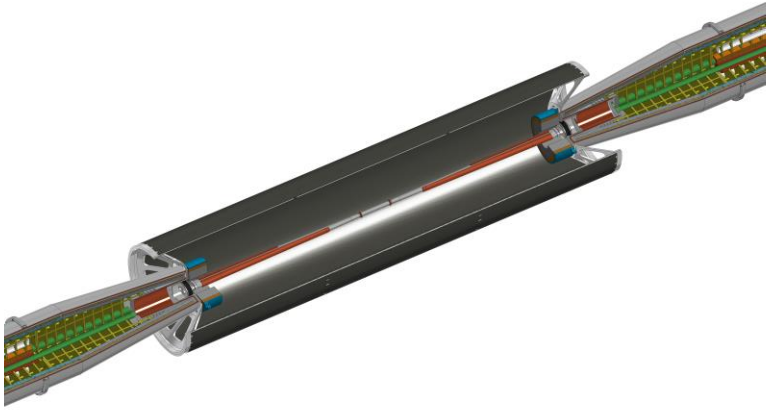


Figure 1: IR layout with 10 mm radius of the central pipe.

From arXiv:2105.09698

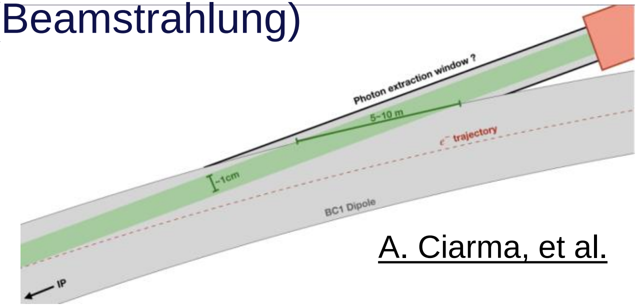




Beamstrahlung Dump

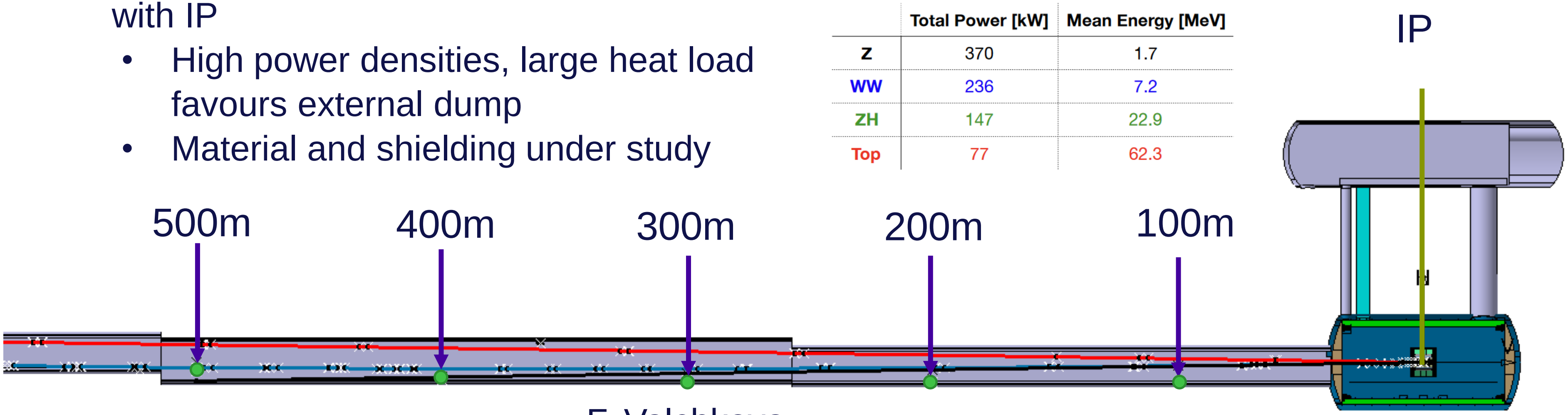
- SR photon production in the field of the counter-rotating beam (Beamstrahlung) generating 370 kW at Z-pole
  - SR radiation by solenoid and anti-solenoid giving additional 77 kW

  - Requires a high-power beam dump in direct line with IP
    - High power densities, large heat load favours external dump
    - Material and shielding under study



A. Ciarma, et al.

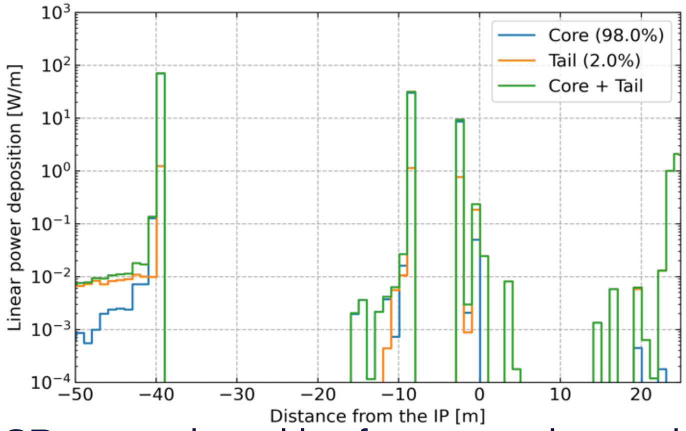
	Total Power [kW]	Mean Energy [MeV]
Z	370	1.7
WW	236	7.2
ZH	147	22.9
Top	77	62.3



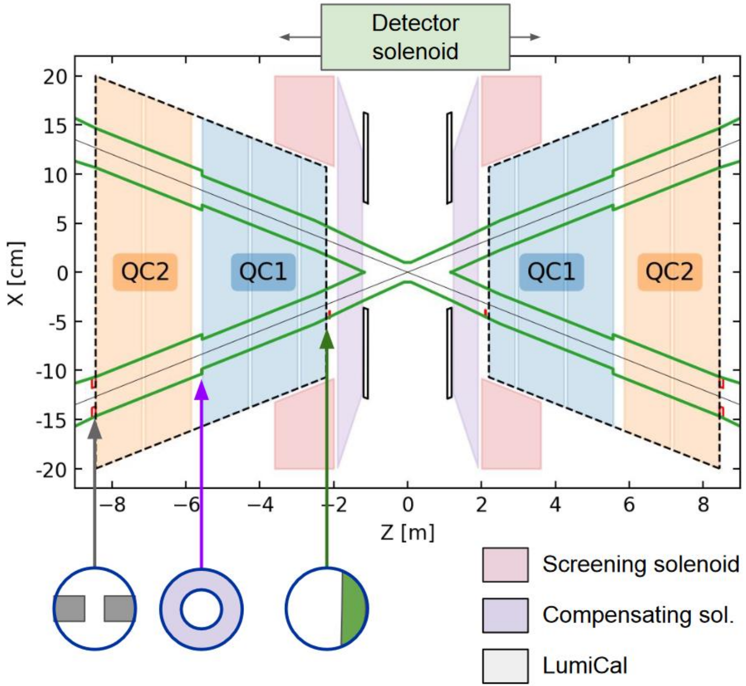
F. Valchkova

SR backgrounds

- Study of SR impacting central beam pipe, generated by the dipoles and final focus quadrupoles upstream of the IP
  - SR collimator location and settings defined, with openings larger than β-tron collimator
  - First studies on SR power deposited by injected beam conducted



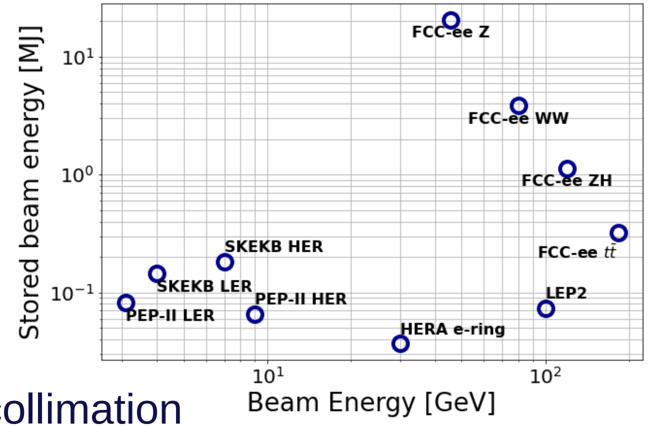
SR power deposition for tt operation mode

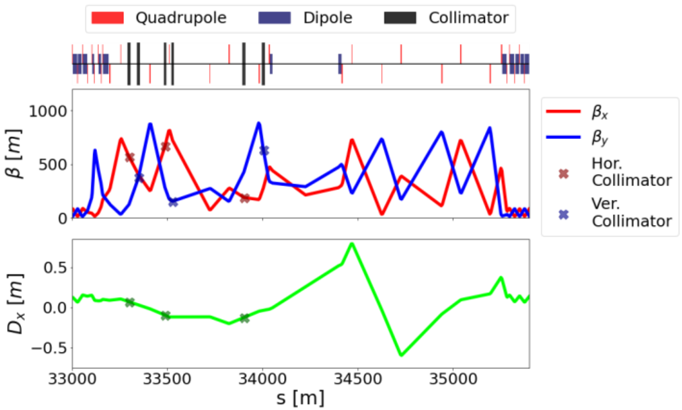


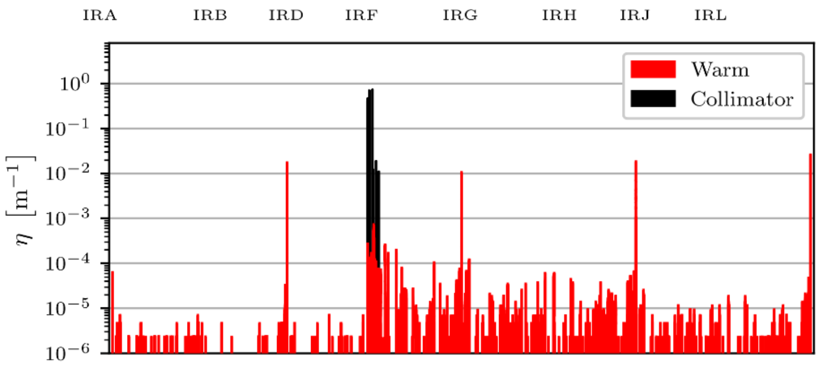
K. André

Collimation

- Stored beam energy in FCC-ee reaches 17.8 MJ, similar to heavy ion operation in LHC
  - A halo collimation system is being developed to protect equipment (e.g. SC final focus quadrupoles) from unavoidable loss
  - One straight section to host both betatron and momentum collimation
    - First collimation system design available, with β-tron, momentum, and SR-collimators
    - Currently studying different loss scenarios, including "crazy-beam" observed at SKEKB

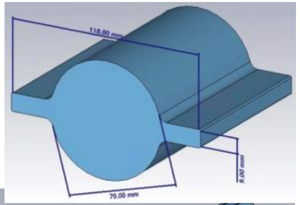
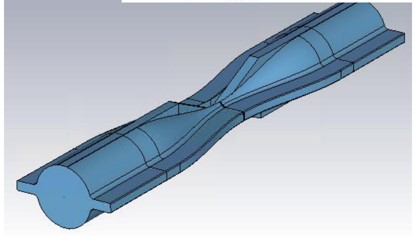




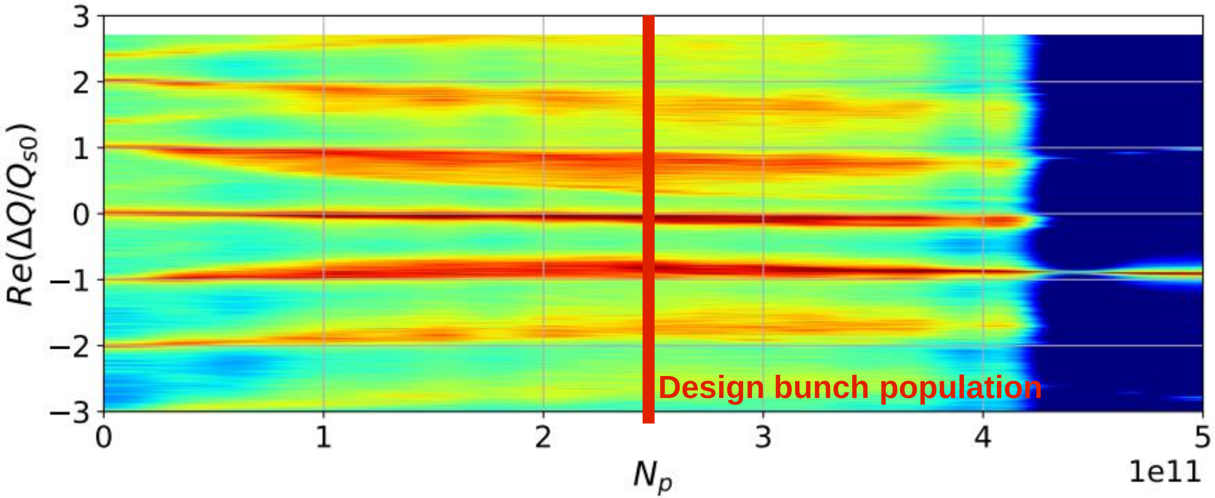


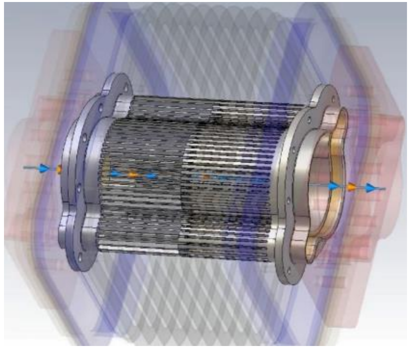
A. Abramov et al.

Impedance model and collective effects

- Detailed Impedance model is being set up for collider ring
  - Including vacuum chamber, RF, bellows, BPMs, collimators, ..
- Beam stability thresholds for current model evaluated
  - Bunch by bunch feedback system to suppress TCBI



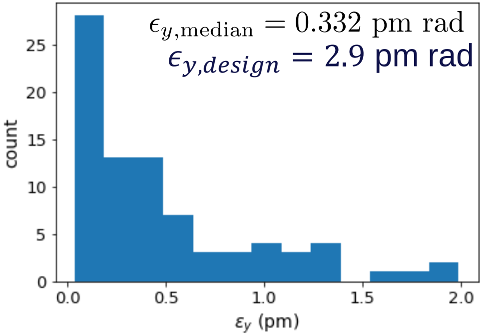


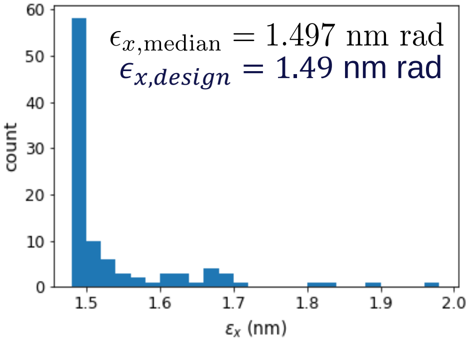
M. Migliorati, E. Carideo

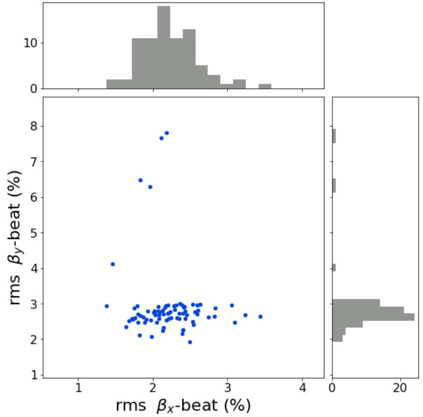
Optics corrections

- Algorithm for global correction of orbit and optics developed
  - Correction is effective in restoring optics ($\left(\Delta\beta/\beta\right)_{RMS} < 10\%$) and ϵ_y

ttbar (182.5 GeV)
4IP lattice,
after correction:







T. Charles

- Local correction of the IR optics to be studied

- Alignment strategy for arcs to be studied
  - Complicated by size of the machine, number of elements and unknown tunnel

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔTHETA (μrad)	ΔPHI (μrad)	Field Errors
Arc quadrupole*	50	50	300	150	100	100	$\Delta k/k = 2\times10^{-4}$
Arc sextupoles*	50	50	300	150	100	100	$\Delta k/k = 2\times10^{-4}$
Dipoles	1000	1000	300	1000	0	0	$\Delta B/B = 2\times10^{-4}$
Girders	150	150	-	1000	-	-	
IR quadrupole	100	100	250	250	100	100	$\Delta k/k = 2\times10^{-4}$
IR sextupoles	100	100	250	250	100	100	$\Delta k/k = 2\times10^{-4}$

* misalignment relative to girder placement

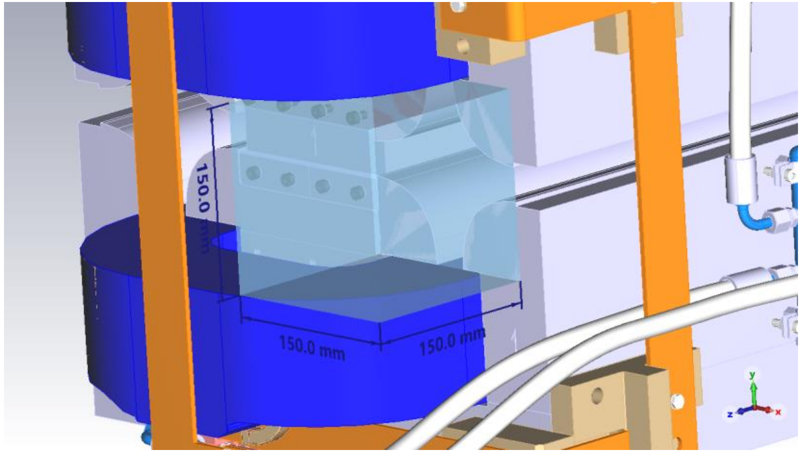
FCC-ee tuning working group

- Tuning working group started defining corrector and BPM requirements/integration
  - Experience of SKEKB and CEPC sets requirement of 10 μm sextupole-to-beam offset
- Further studies looking into the effect of field errors on DA to define tolerances

units of $[10^{-4}]$	Z	tt
b3 in arc dipoles	2	2
b3 in IR dipoles	**0.1**	0.5
b3 in arc quadrupoles	10	>8
b3 in IR quadrupoles	**0.1**	8

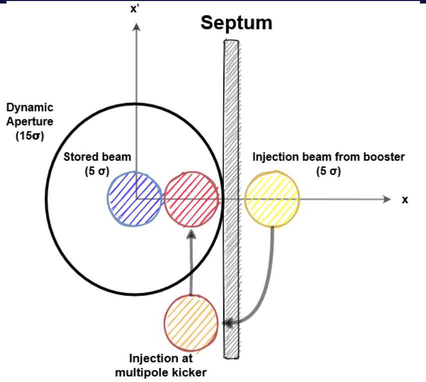
Tolerance on field errors

	SKEKB, HER	FCC-ee, Z
Number of IPs	1	4
IR sext. offset for DQy=0.005 [μm]	10	3
Target orbit control [μm] (at IR sextupoles)	10	3/√4 = **1.5 ?**
Number of IR sextupoles	4	16
β^* **[mm]**	1	0.8
ARC sext. offset for DQy=0.005 [μm]	200	250
Number of ARC sextupoles	100	832
Target orbit control [μm] (at ARC sextupoles)	-	250/√832 = **10 ?**



Potential location for BPM

Dynamic Aperture

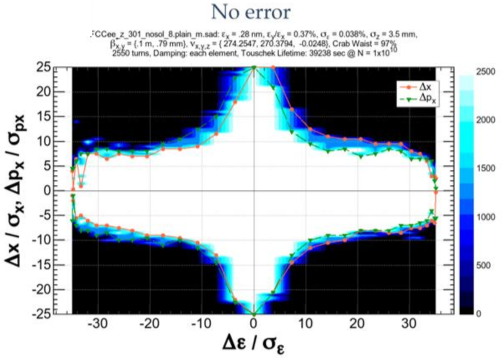


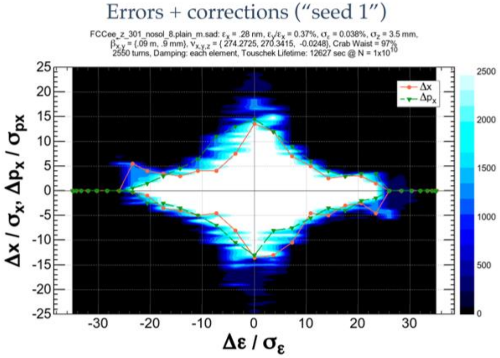
- Dynamic aperture requirement given by top-up injection
  - Target for on-momentum injection is more than 15σ

- Target for momentum acceptance based on beam lifetime in the presence of large energy spread due to beamstrahlung
  - For $t\bar{t}$, requirement is $\delta_{acceptance} > 2.8\%$, while for Z, target $\delta_{acceptance} > 1.3\%$

- DA optimization done using 75(Z) / 146 ($t\bar{t}$) non-interleaved sextupole pairs in the arcs
  - Constraints from chromaticity and chromatic optics in the IP

- Without errors, targets are met
  - Errors can significantly reduce DA, optimization in the presence of errors in progress



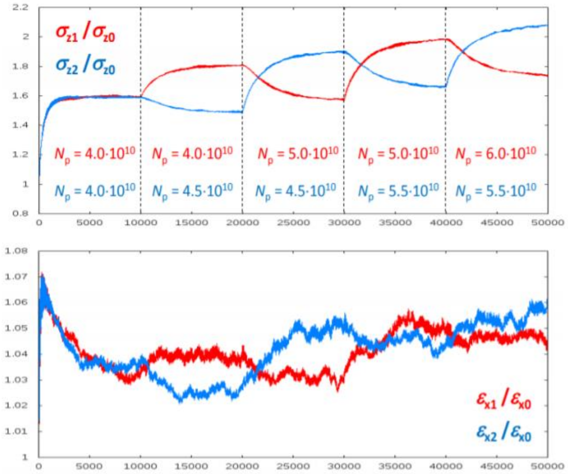


Top-up injection

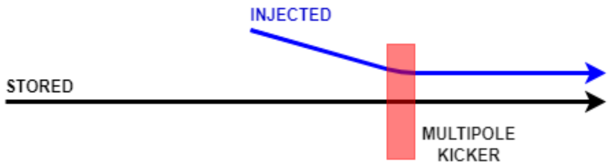
- Top-up injection essential ingredient to maximize integrated luminosity
  - Implemented in other colliders (KEKB and in PEP-II) and is common in light sources

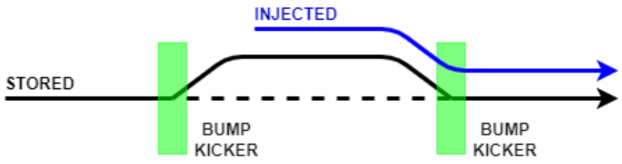
- Bootstrapping required to avoid beam-beam flip-flop instability
  - Allowed charge imbalance 3-5%

- Four feasible injection schemes have been identified for the FCC-ee
  - Multipole kicker injection using a special kicker with zero on-axis field
  - Orbit bump injection using a one turn bump
  - Both schemes also work off-momentum



D. Shatilov



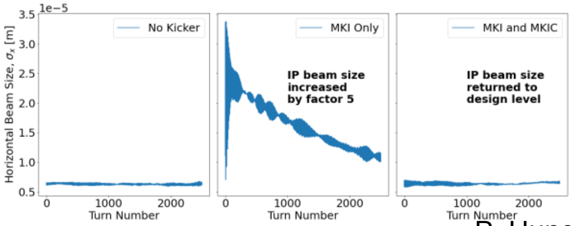


Top-up injection II

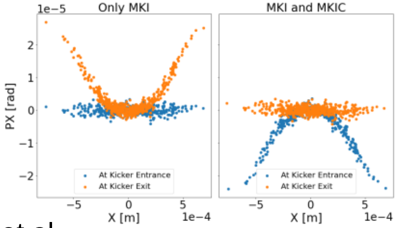
- Studies ongoing to determine a preferred scheme
  - Effects of misalignment on injection efficiency and implications of failures on machine protection

- In parallel, define hardware parameters and R&D requirements

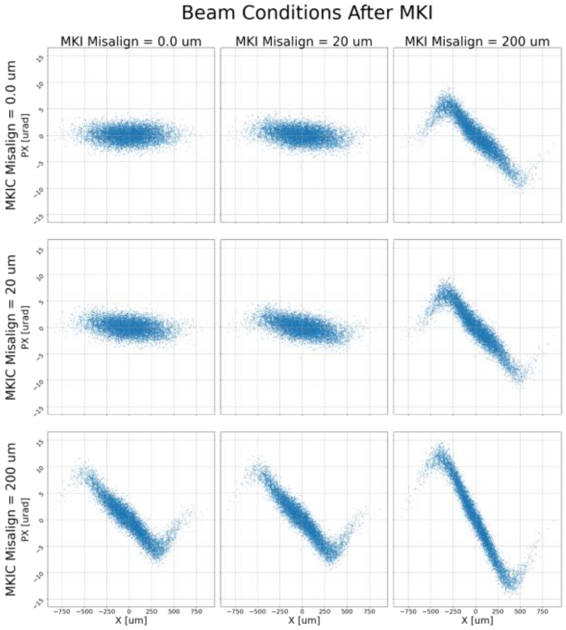
Stored beam at IP

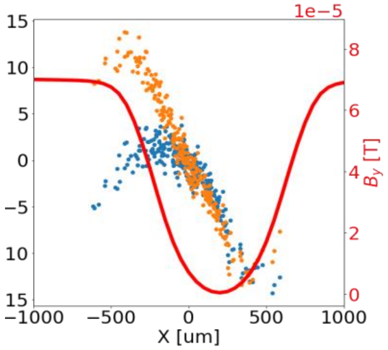


Stored beam at MKI location



P. Hunchak, et al.





At MKI

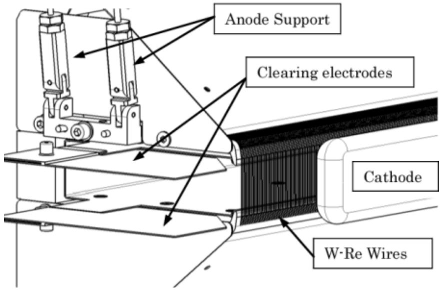
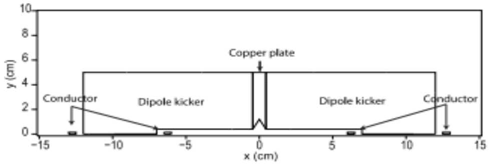
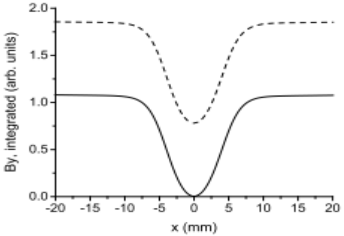


Fig. 1. ZS electrostatic septum used for SPS slow extraction





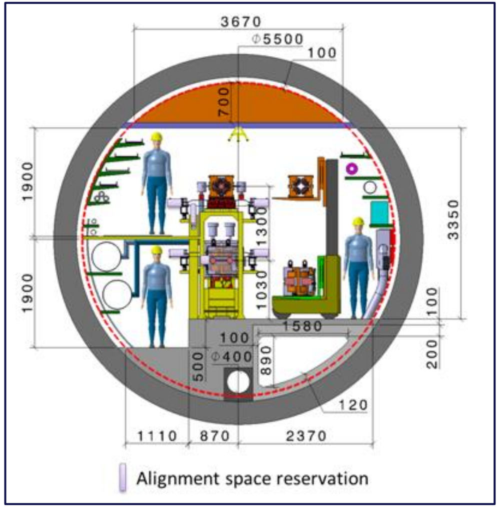
M. Aiba et al. "Top-up injection schemes for future circular lepton collider"

Booster ring

- Full energy booster ring booster ring in the same tunnel as the collider
  - Injection energy of 20 GeV,
    either using a Linac or SPS as Pre Booster Ring

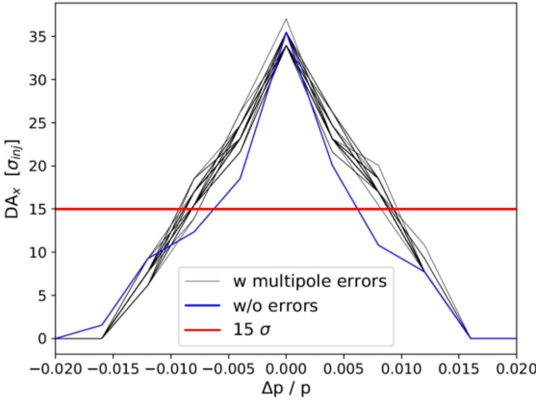
- Using FODO lattice with same cell length as collider,
  with 60°/60° Optics for Z and W, and 90°/90° for H and tt

- DA at injection energy evaluated including field errors



Courtesy of F. Zimmermann and Jie Gao

	CT dipole		Iron-core dipole	
GFR=R26	28Gs	56Gs	28Gs	56Gs
B1/B0	-5.20E-04	-1.04E-04	-1.56E-03	-2.60E-04
B2/B0	4.73E-04	5.41E-04	-2.03E-03	-2.03E-04
B3/B0	-7.03E-06	1.05E-04	3.52E-04	1.76E-04
B4/B0	-9.14E-04	-3.66E-04	4.57E-04	-1.83E-04
B5/B0	3.56E-05	-2.38E-05	-2.38E-05	-3.56E-05
B6/B0	6.18E-04	2.16E-04	-3.09E-04	9.27E-05

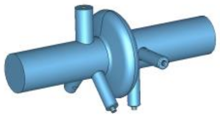


A. Chance, B. Dalena

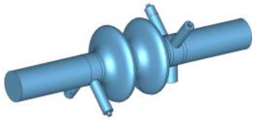
FCC-ee RF system

- Baseline using 400 MHz elliptical type cavities for Z, WW, and ZH mode, adding 800 MHz for the highest energy $t\bar{t}$ operation mode

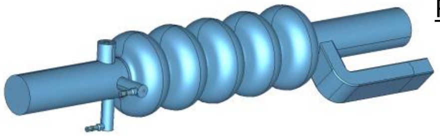
F. Peauger, et al.



Single cell Nb/Cu, 400 MHz cavity for Z

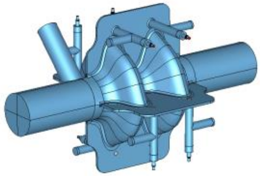


2-cell Nb/Cu, 400 MHz cavity for WW, ZH



4-cell bulk Nb, 800 MHz cavity for $t\bar{t}$

- Alternative Slotted Waveguide Elliptical Cavity with $f = 600$ MHz under study
- Staged implementation with cavities added during shutdowns
- RF section layout with crossing point for Z and WW, rebuilt to use common RF at ZH and $t\bar{t}$

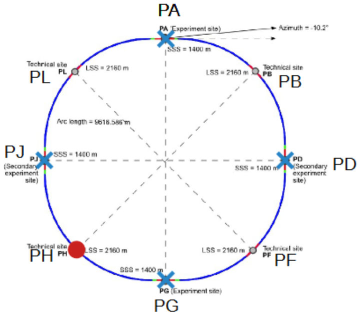


SWELL 2-cell Nb/Cu cavity with 600 MHz

- RF placement optimized to reduce infrastructure requirements
  - Single RF region for Z and WW operation to reduce uncertainty on centre-of-mass energy

IP	ΔECM [keV]	Boost [MeV]
PA	- 7.851	10.665
PD	- 7.931	- 10.108
PG	0.570	- 30.883
PJ	0.844	31.439

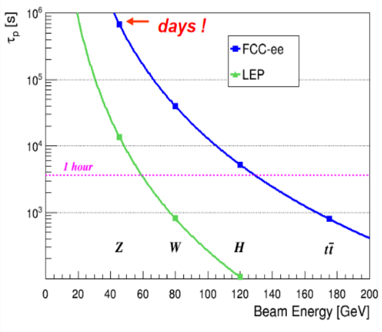
For Z operation



J. Keintzel, et al.

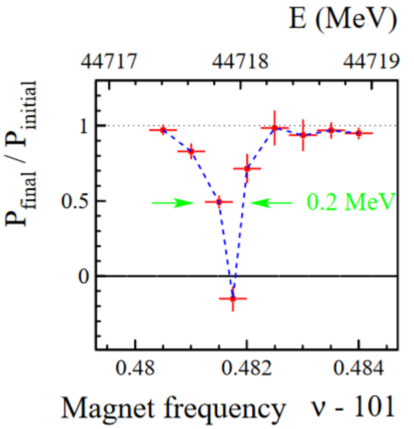
FCC-ee Energy calibration, polarization and monochromatization

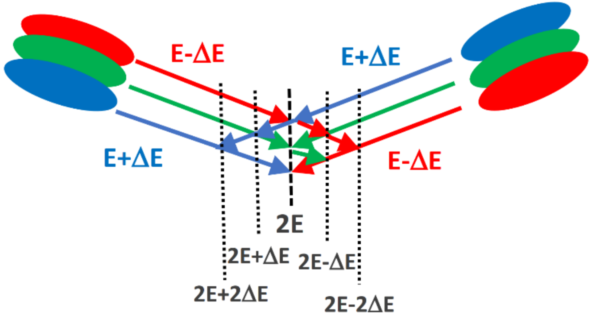
- Goal of systematic precision of 4/100 keV on Z-/W-mass
- Working group with participation from both experiments and accelerator community
  - Integration of hardware required for RDP measurements (polarimters, wiggler)
  - Study of tolerances on polarization levels and ECM shifts
  - Development of monochromatization optics for direct H production mode

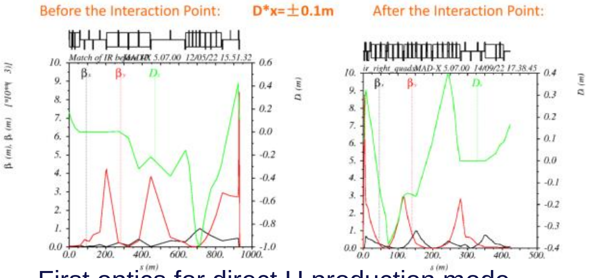


Polarization risetimes for LEP and FCC-ee

J. Wenninger, "Polarised Electron Beams/Energy Calibration", CAS 2018







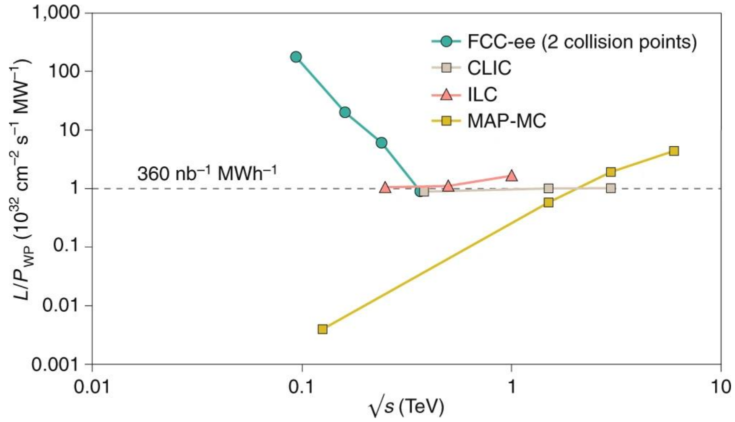
First optics for direct H production mode

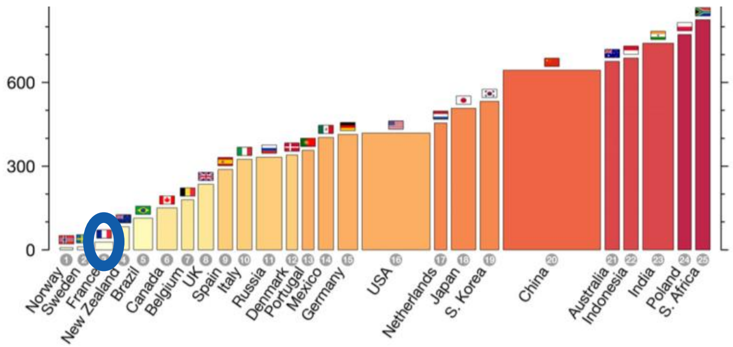
Example RDP measurement at LEP, see https://doi.org/10.1007/BF01496579

Sustainability aspects

luminosity vs. electricity consumption

- FCC-ee a very energy efficient Higgs factory thanks to twin-aperture magnets, efficient RF power sources, top-up injection, ..
- Similar annual energy consumption as (HL-)LHC
- France and Switzerland already providing very clean energy mix





https://www.carbonbrief.org/

120 GeV	Days	Hours	Power OP	Power Com	Power MD	Power TS	Power Shutdown		
Beam operation	143	3432	293					1005644	MWh
Downtime operation	42	1008	109					110266	MWh
Hardware, Beam commissioning	30	720		139				100079	MWh
MD	20	480			177			85196	MWh
technical stop	10	240				87		20985	MWh
Shutdown	120	2880					69	199872	MWh
Energy consumption / year	365	8760						1.52	TWh
Average power								174	MW

J.-P. Burnet, FCC Week 2022

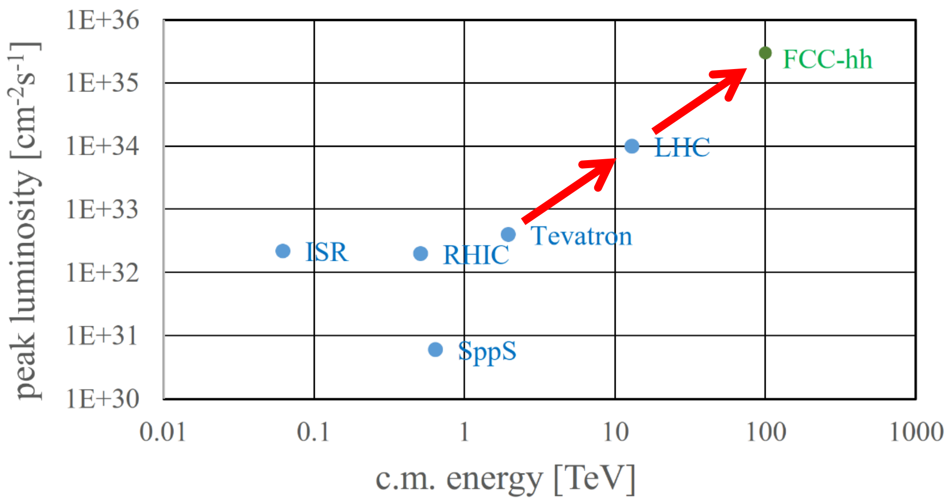
incl. CERN site & SPS

CERN Meyrin, SPS, FCC	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Energy consumption (TWh/y)	1.82	1.92	2.09	2.54

FCC-hh: highest collision energies

- Hadron collider FCC-hh to reuse the tunnel
  - Aim for an increase of an order of magnitude in both energy and luminosities
  - Target of a 100 TeV cm collision energy with $20\ ab^{-1}$ per experiment in 25 years (compared to 14 TeV and $3\ ab^{-1}$ for LHC)

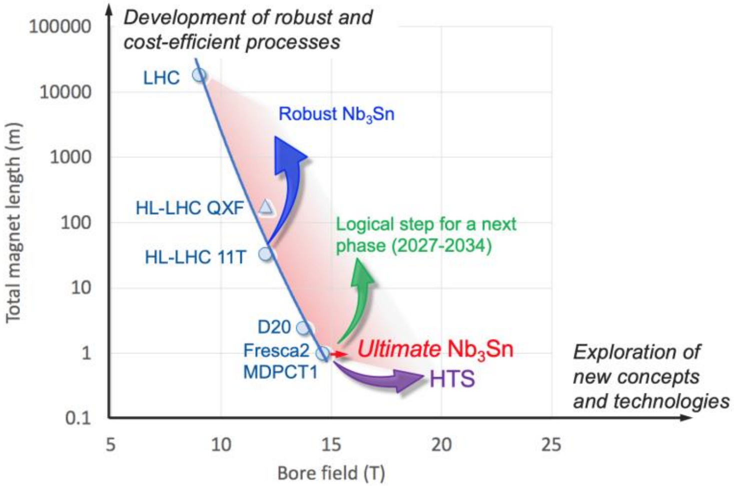
  - One of the key technologies for this machine are high field magnets



FCC-hh: High field magnets

- In parallel to FCC studies, CERN has launched a High Field Magnet development program as a separate, long-term R&D project
  - Built on the community established in preparation of the FCC-hh CDR
  - Outcome of the HFM project relevant for several future facilities

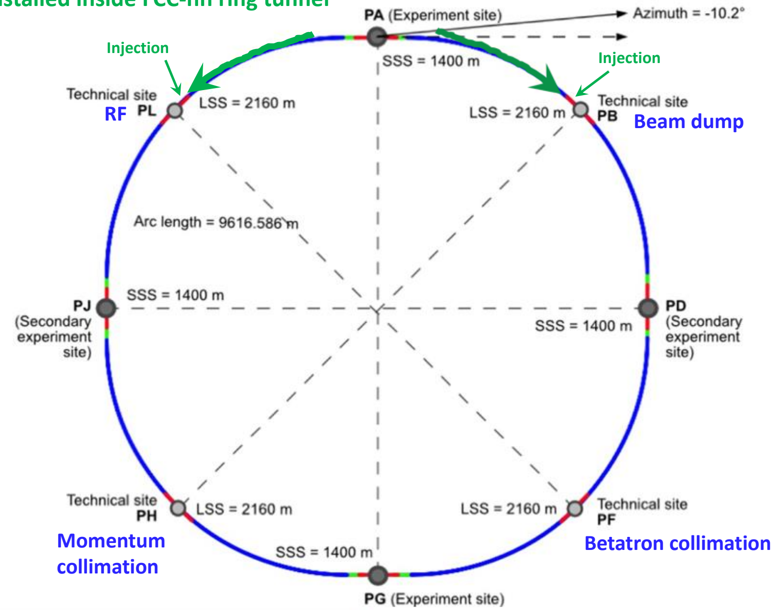
- Main goals for 2026:
  - **Demonstrate Nb3Sn potential above 14T** and in terms of ultimate performance (target 16T)
  - **Develop Nb3Sn magnet technology for collider-scale production through robust design**, industrial processes and cost reduction (benchmark 12 T)
  - **Explore and demonstrate suitability of HTS conductors for building accelerator magnets** performing beyond the reach of Nb_3Sn

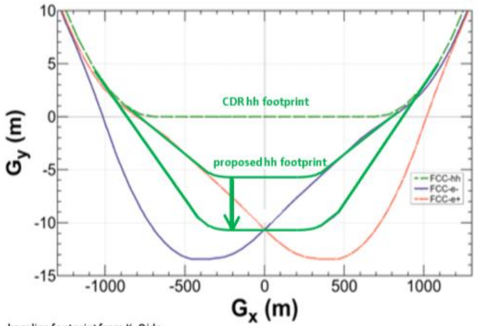


FCC-hh: layout

- FCC-hh to host 4 experiments
  - Radially displace interaction points towards FCC-ee to reduce cavern size
- New layout necessitates TL in the tunnel on top of the collider
  - Requires combined RF/injection and extraction/injection insertions
- Use of combined function (dipole-quadrupole) magnets in the arcs under study to increase filling factor and simplify production
- Continued study of collimation system to protect the machine from 8.3 GJ stored beam energy

transfer lines proposed to be installed inside FCC-hh ring tunnel





M. Giovannozzi,
T. Risselada

FCC-hh (pp) collider parameters

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	~17 (~16 comb.function)		8.33	8.33
circumference [km]	91.2		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2700		7.3	3.6
SR power / length [W/m/ap.]	32.1		0.33	0.17
long. emit. damping time [h]	0.45		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [µm]	2.2		2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	7.8		0.7	0.36

Summary & Outlook

- Following European Strategy Update 2020, FCC feasibility study launched to investigate feasibility of a **100 TeV com hadron collider** with an **electron-positron collider as first stage**

  - Main activities:
    developing & confirming concrete implementation scenario, in collaboration **with host state authorities**, including **environmental impact analysis**, and accompanied by **machine optimisation, physics studies and technology R&D - via global collaboration,** supported by **EC H2020 Design Study FCCIS and Swiss CHART.**
    Goal: demonstrate feasibility by 2025/26

- Long term goal: world-leading HEP infrastructure for 21st century to push particle-physics precision and energy frontiers far beyond present limits

Thank you for your attention!


FCC WEEK
2023
5 – 9 June
STAY TUNED