OVERVIEW OF THE FCC-ee COLLIDER DESIGN

M. Hofer

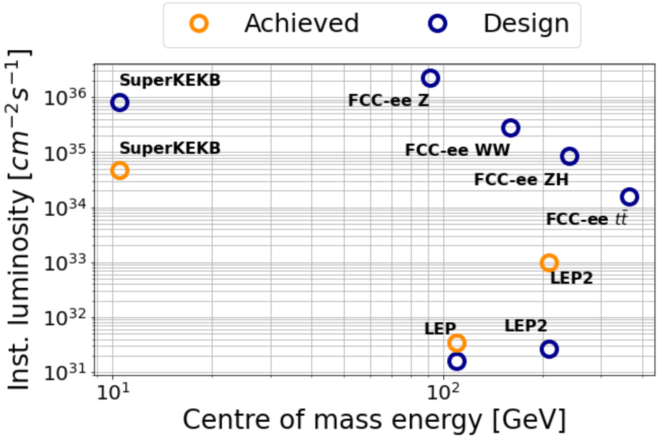
Many thanks to K. Oide, T. Raubenheimer, D. Shatilov, R. Tomás, F. Zimmermann, and all colleagues from the FCC-ee collaboration

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

Introduction

- Following the 2020 update of the European Strategy for Particle Physics, CERN, together with international partners, launched the FCC Feasibility Study to address the feasibility of
  - A hadron collider with a center of mass energy of $100\,TeV$ (FCC-hh)
  - with a highest-luminosity, energy frontier e^+e^- collider as first stage (FCC-ee)

- FCC-ee fills the need for a precision EW/Higgs factory
  - Design targets
    - 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



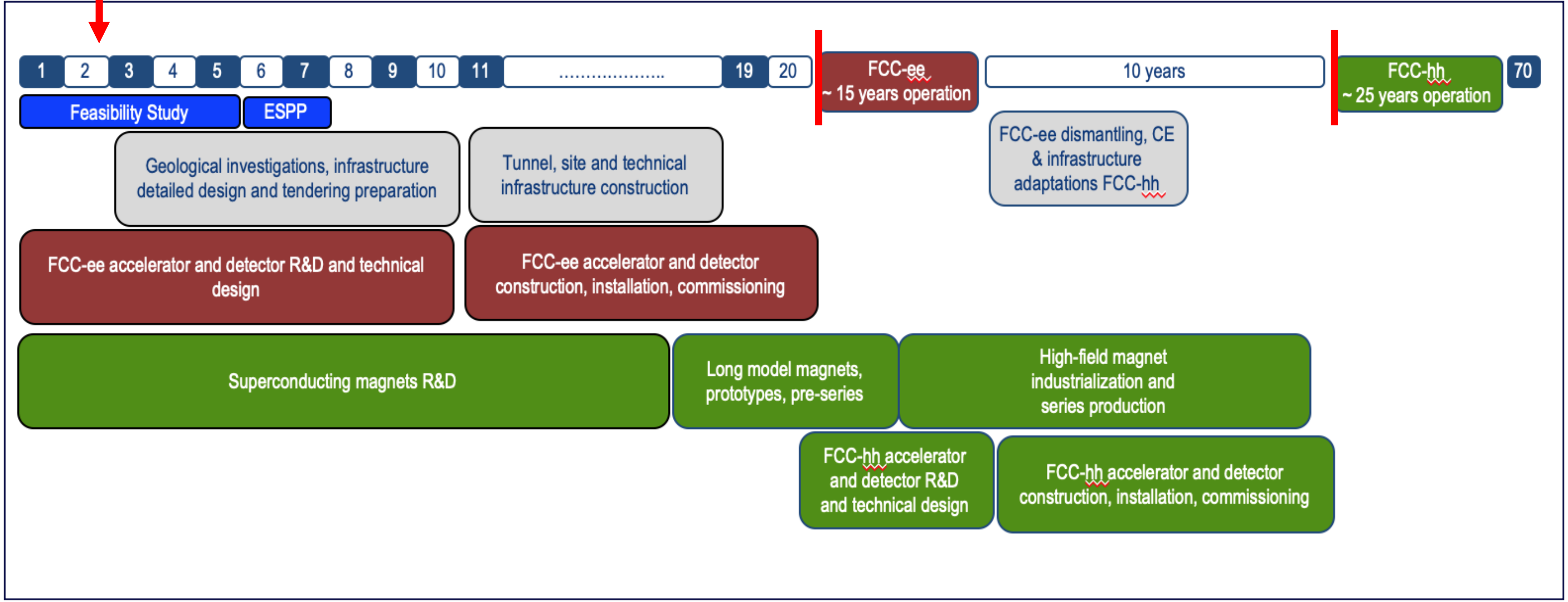
Sources: 1,2,3,4

Tentative Technical Timeline

We are here

If project approval before end of this decade
FCC-ee start ~2045-2060

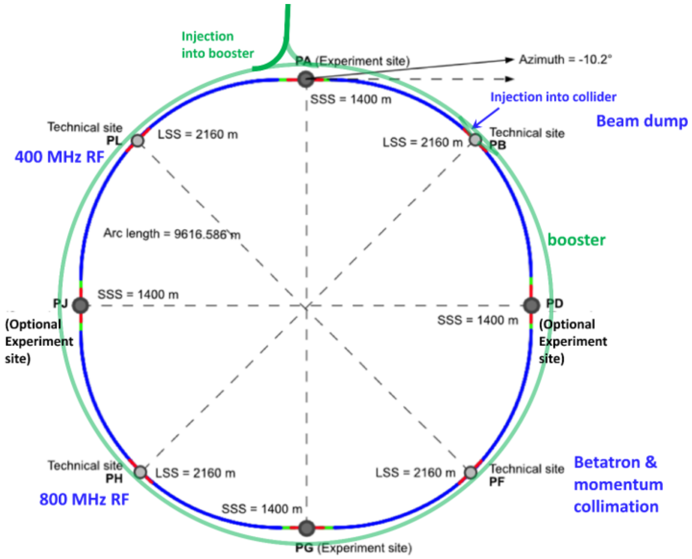
FCC-hh ~2070-2090



M. Benedikt, FCC Feasibility Study overview

Overview and design choices

- Double ring e^+e^- collider with a circumference of 91 km
- Four experimental straights
  - 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



Parameters

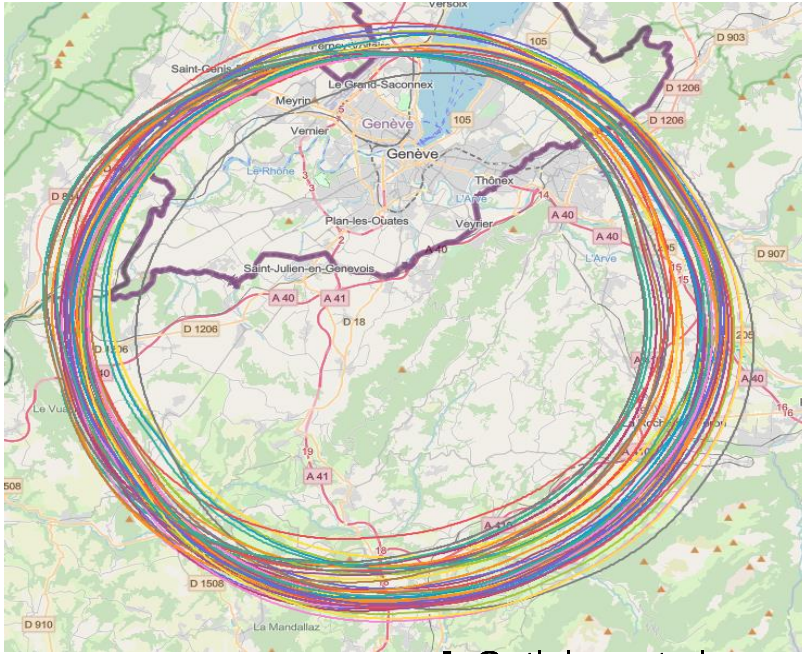
Parameter [4 IPs, 91.1 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	40
bunch intensity [10^{11}]	2.43	2.91	2.04	2.37
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400 / 800 MHz [GV]	0.120 / 0	1.0 / 0	2.08 / 0	2.5 / 8.8
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 / 0.159	0.011 / 0.111	0.0187 / 0.129	0.093 / 0.140
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	1.95 / 2.75
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	182	19.4	7.26	1.25
total integrated luminosity / year [ab^{-1}/yr]	87	9.3	3.5	0.65
beam lifetime rad Bhabha + BS [min]	19	18	6	9

Reference

Evolution of tunnel layout

- Continued studies to optimize the placement of the ring in the Geneva basin have concluded on a new baseline tunnel layout
  - Many factors to consider: Geology, Infrastructure, Access tunnels, Periodicity, ..
  - For feasibility study, new tunnel baseline with circumference of 91 km, 8 access shafts, and four-fold periodicity

- Detailed investigations of high-risk area foreseen

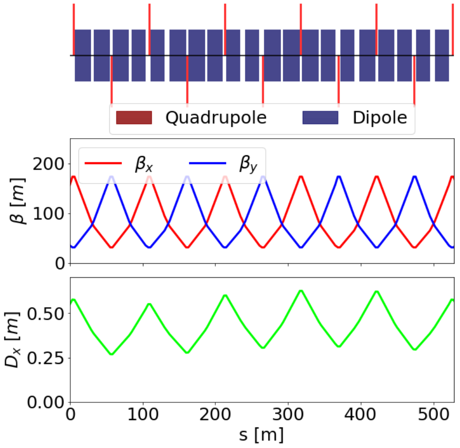


J. Gutleber, et al.

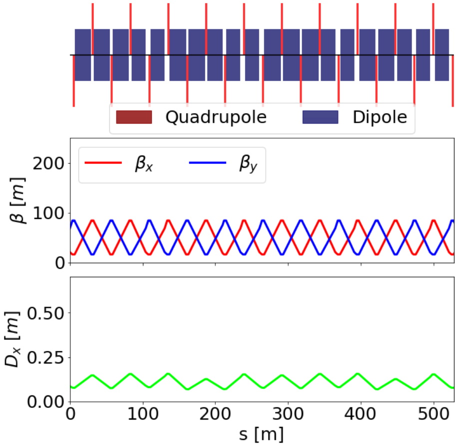
Arc cell optics

- FODO cell is used in the arcs due to high packing factor
  - Large momentum compaction at Z and W required for mitigation of collective instabilities and low ϵ_x for H and $t\bar{t}$ operation
  - In current lattice, variable cell length implemented
    - For Z and W, cell length of ~100m
    - Reduce cell length for H and $t\bar{t}$ to 50m by installing quadrupoles in the gaps between dipoles
  - Tapering of magnets along the ring to compensate for sawtooth effect
  - Tuning studies ongoing to define required correctors and tolerable field quality (see presentation by J. Keintzel)

Z



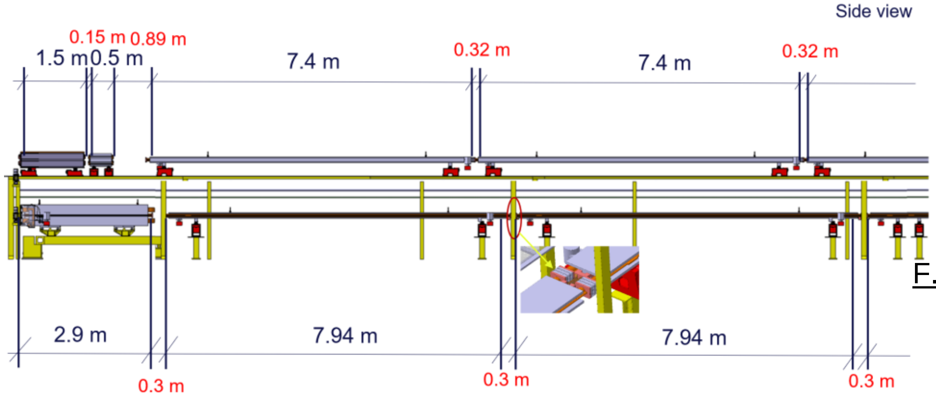
$t\bar{t}$



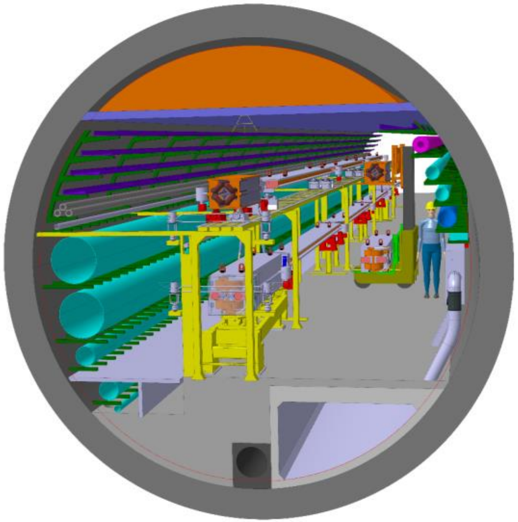
K. Oide

Arcs cell design

- 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
  - See presentation by J. Bauche on Tuesday on Magnet design

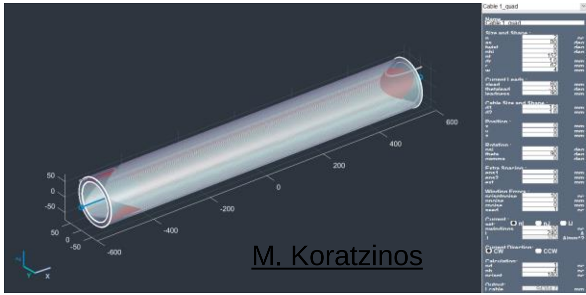


F. Carra et al.



Arc perspective view, F. Valchkova-Georgieva

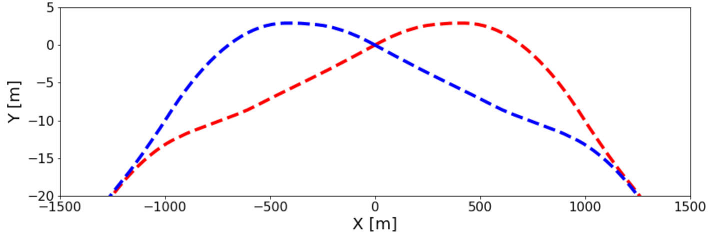
- In the current design, all arc magnets are normal conducting
  - To reduce power consumption, option with nested SC quadrupoles and sextupoles under consideration

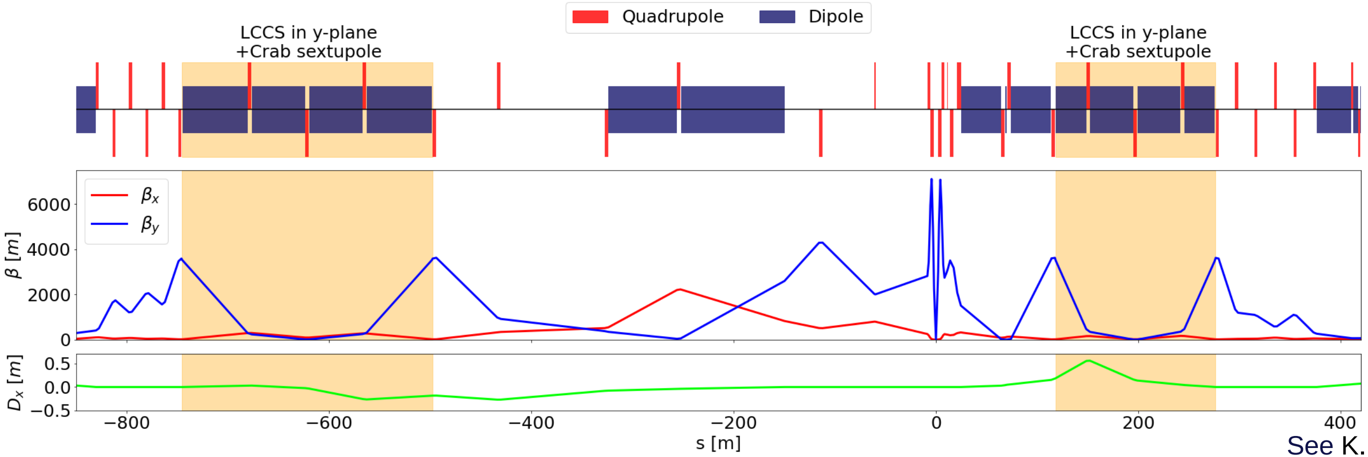


M. Koratzinos

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, thermal analysis, and discussion on alignment strategy ongoing

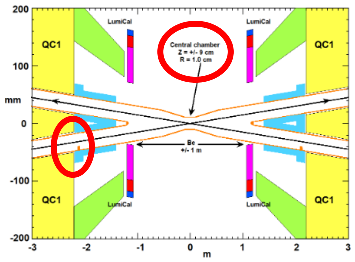
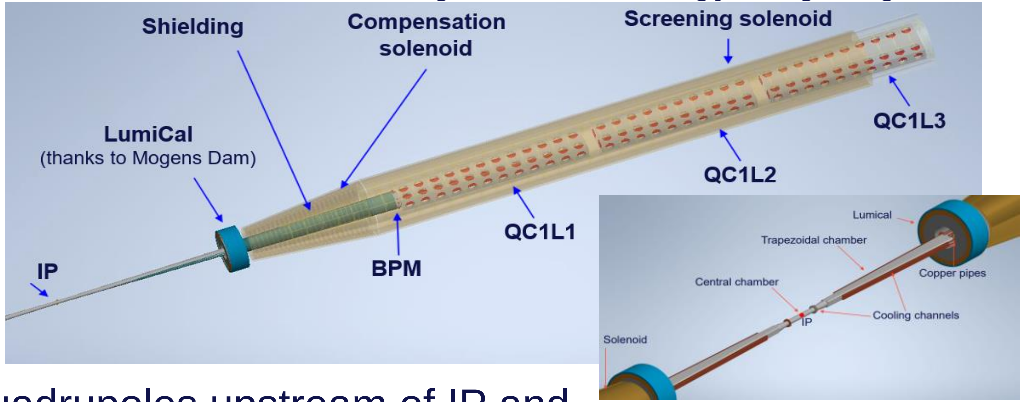


Figure 1: IR layout with 10 mm radius of the central pipe.

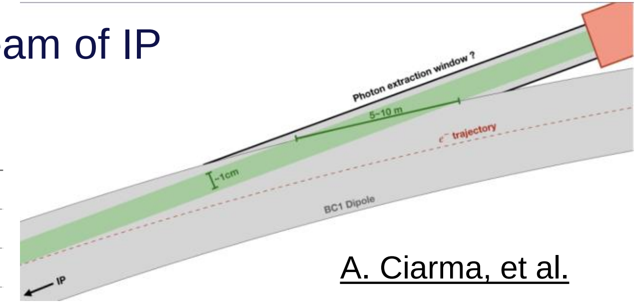
From arXiv:2105.09698



- SR background from last dipoles and quadrupoles upstream of IP and location for SR collimators under study
- Beamstrahlung radiation to require a photon dump downstream of IP
- Studies on vibration tolerances ongoing

(see presentation by E. Montbarbon on Thursday)

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

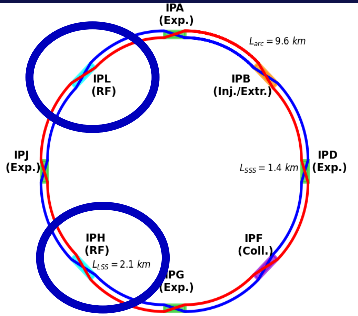


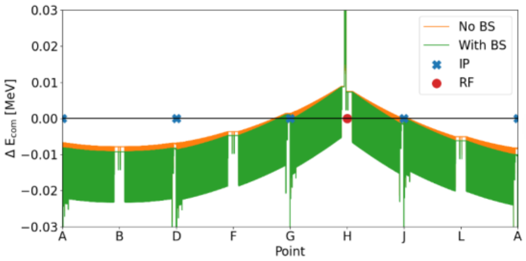
A. Ciarma, et al.

RF insertions

- After preliminary survey of surface sites, recommendation is to place RF in points H and L
  - To reduce the uncertainty on center-of-mass energy, RF located in a single place for Z and W operation
  - In $t\bar{t}$ operation, RF cavities distributed between points H and L

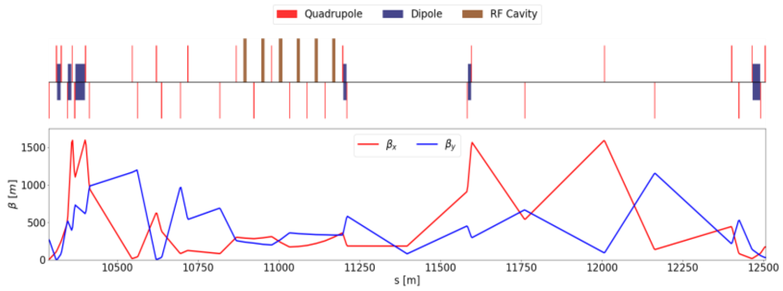
- At Z and W, separate RF for each beam
  - Beam crossing in the middle of the insertion
- Common RF for H and $t\bar{t}$ operation modes



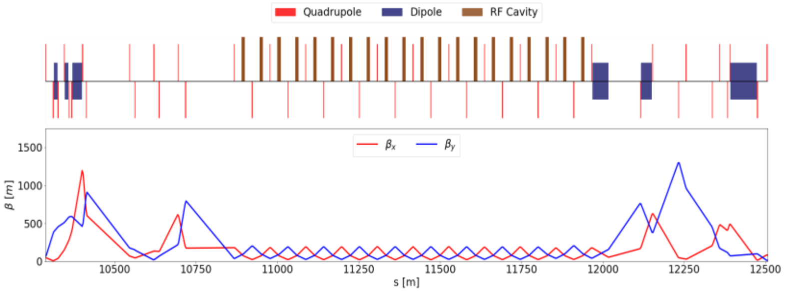


J. Keintzel

Z



$t\bar{t}$

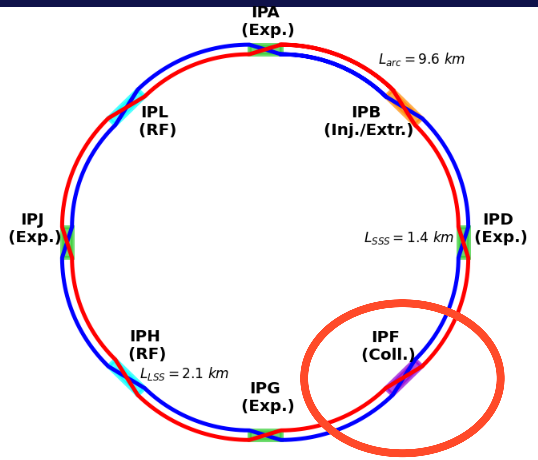


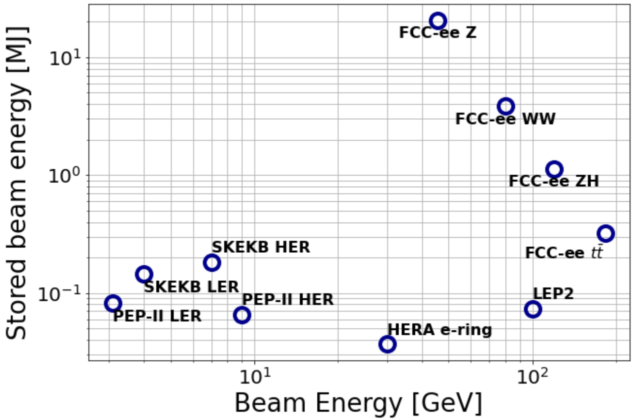
K. Oide

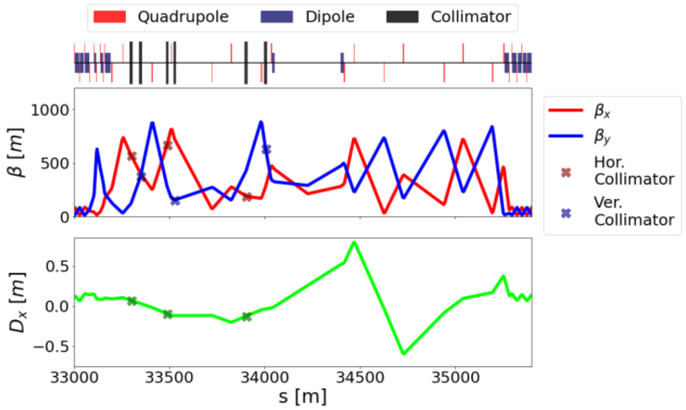
Collimation

- Stored beam energy in FCC-ee reaches 20.7 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

  (see presentation by A. Abramov on Wednesday)

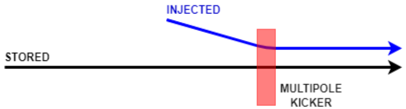


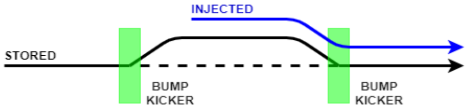


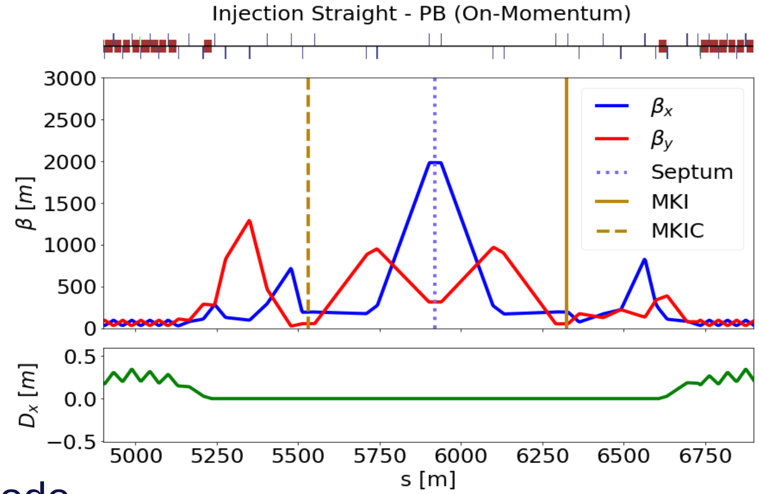


Top-up injection

- Top-up injection essential ingredient to maximize integrated luminosity
- Four feasible injection schemes have been identified
  - 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

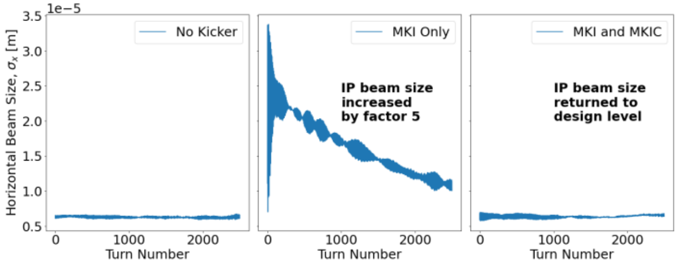


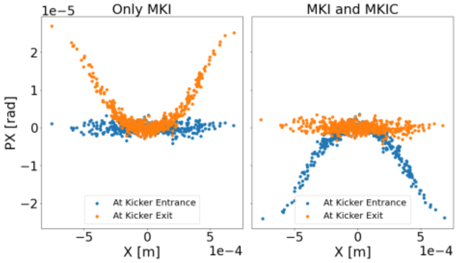




M. Aiba, P. Hunchak

Tracking studies under way to determine impact on stored beam and evaluate injection efficiency of each mode in the presence of errors



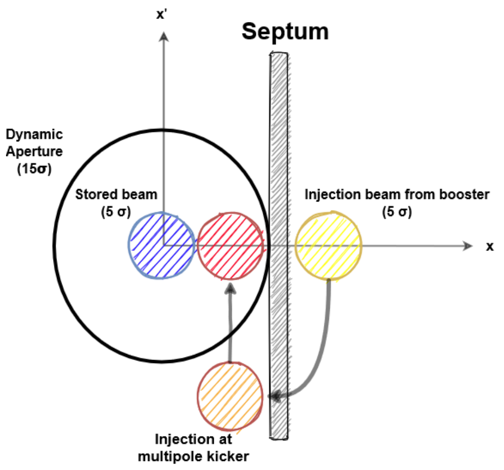


Sextupoles and DA optimization

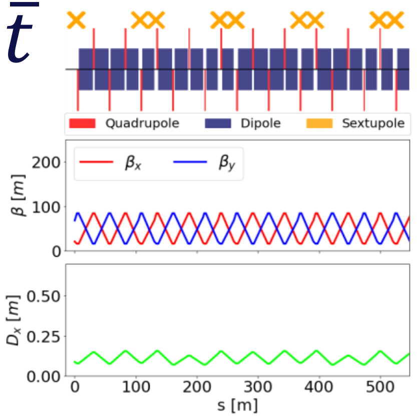
- For on-momentum top-up injection,
  a dynamic aperture of more than 15σ is required
  - For off-momentum injection, DA > 5σ for chosen setting of ${}^{\Delta p}/_{p}$
- Target for momentum acceptance based on beam lifetime
  in the presence of large energy spread due to beamstrahlung
  - For $t\bar{t}$, requirement is $\delta_{acceptance} > 2.8\%$, while for
    Z, threshold $\delta_{acceptance} > 1.3\%$

- Chromaticity correction by families of non-interleaved sextupole pairs,
  with –I transform between sextupoles

  - All 75(Z) / 146 ($t\bar{t}$) sextupole pair used in
    dynamic aperture optimization



$t\bar{t}$



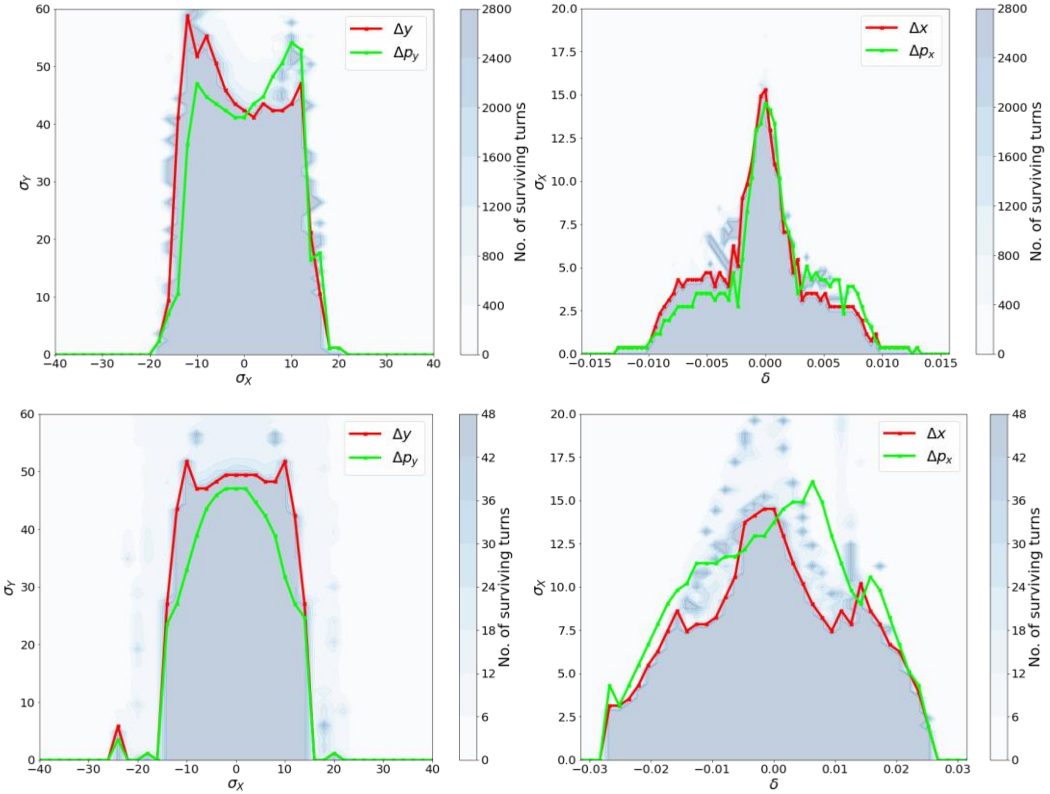
Sextupoles and DA optimization

- Sufficient dynamic aperture and momentum acceptance is found
  - Tracking for 2 times long. damping time 45 turns ($t\bar{t}$) / 2500 turns (Z), including tapering & SR

- Achievable performance in presence of misalignments together with different sextupole powering schemes to be studied

Z

$t\bar{t}$



Conclusions

- The European Strategy Update 2020 recommends feasibility study of a 100 TeV centre-of-mass hadron collider with an electron-positron collider as first stage
  - Profiting from many accelerator developments in the past decades, the FCC-ee aims at e^+e^- collision with unprecedented energies and record luminosity
  - Sheer size and ambitious parameter set provide interesting challenges
- Next steps are to provide a consistent baseline design for the mid-term review in mid 2023
  - Iteration in time for the completion of the Feasibility Study Report in 2025
  - Investigate alternative options with significant impact on cost or performance to define required R&D and timeline

Thanks for your attention!