OVERVIEW OF THE FCC-ee COLLIDER DESIGN

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

2020 Update of the European Strategy for Particle Physics

- The 2020 update of the European Strategy for Particle Physics states:

  "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 the FCC Feasibility Study in 2020 to address feasibility and provide input for the next ESPP update

- Integrated programme foresees operation of the lepton collider (FCC-ee), followed by the hadron collider (FCC-hh) in the same tunnel
- Builds on the work published in the conceptual design reports (published in European Physical Journal C and ST)

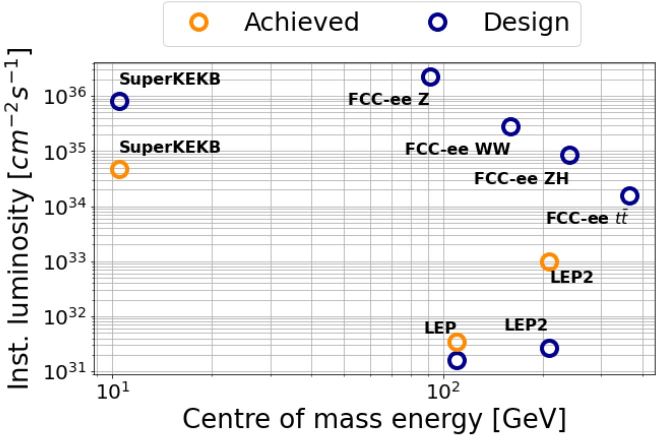
FCC-ee Luminosity Goal

- 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)

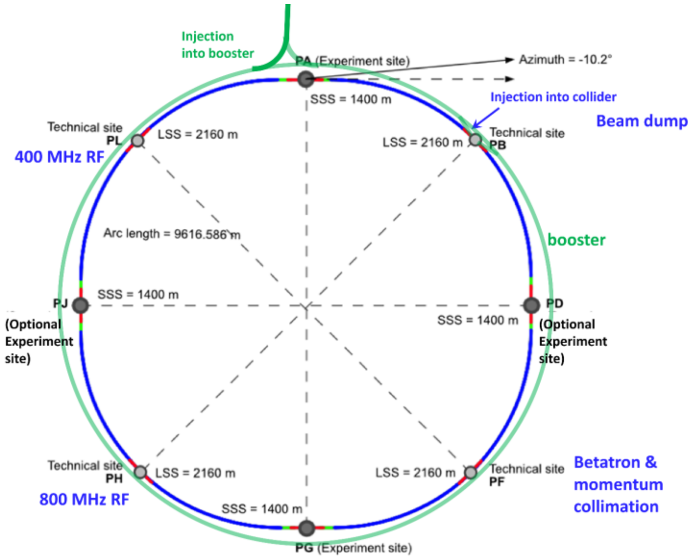
      see presentation by M. Giovannozzi, Thu 3:40 pm



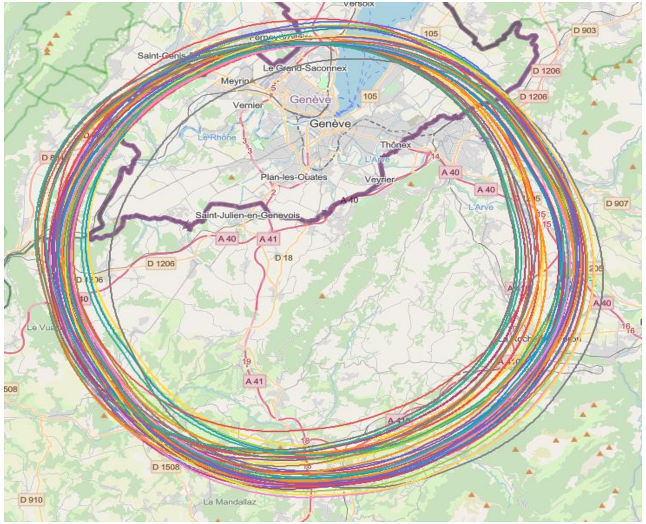
Sources: 1,2,3,4

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



Evolution of tunnel layout



- For the CDR, tunnel with circumference of 98 km,
  12 access shafts, and two-fold periodicity was studied
  - Various drawbacks, such as requiring deep access shafts, surface areas in in challenging terrain, …

- Continued studies to optimize the placement of the ring in the Geneva basin have concluded on a new baseline
  - 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

- Small adjustments foreseen, together with detailed investigations of high-risk area

J. Gutleber, et al.

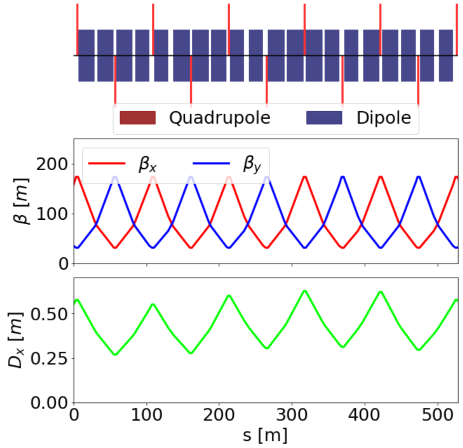
Arcs optics

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

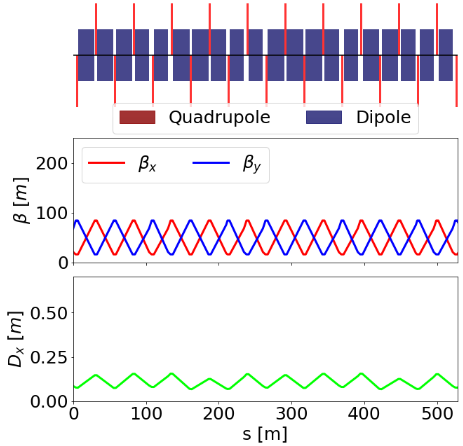
- Solution is to use FODO cells in the arcs with variable cell length
    - For Z and WW operation modes, cell length of ~100 m and phase advance of $90^{\circ}/90^{\circ}$ used
    - By installing quadrupoles in the gaps between dipoles, the cell length for ZH and $\mathrm{t\bar{t}}$ is reduced to 50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

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

Z



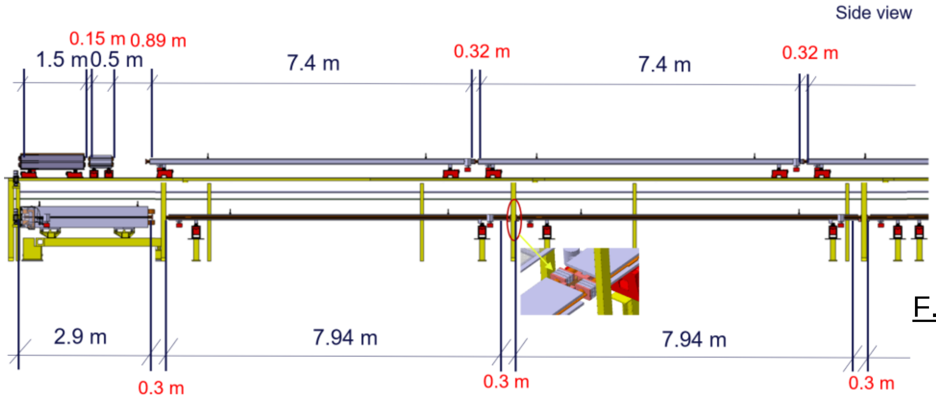
$\mathrm{t\bar{t}}$



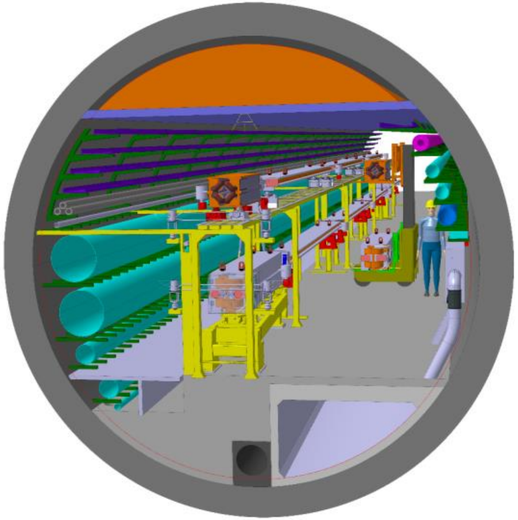
Optics by K. Oide

Arcs optics II

- 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

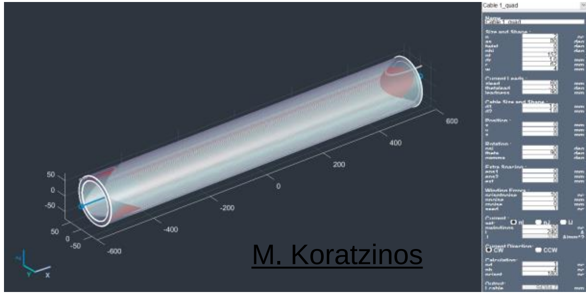


F. Carra et al.



Arc perspective view,
F. Valchkova-Georgieva

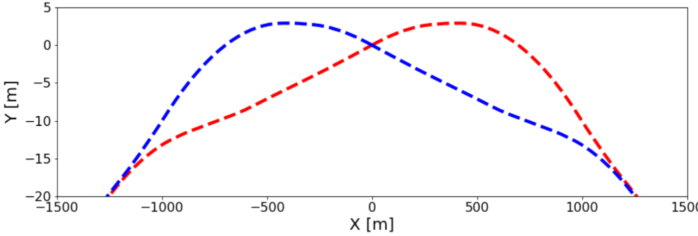
- In the current design, all arc magnets are normal conducting
  - To reduce power consumption, option with nested SC quadrupoles and sextupoles under consideration

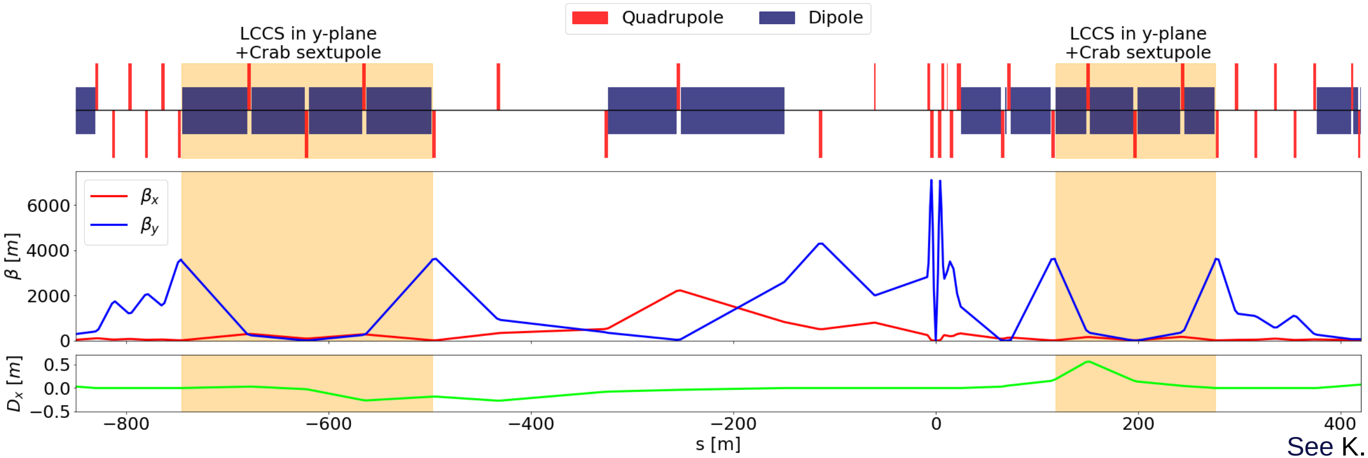


M. Koratzinos

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 and thermal analysis ongoing, IR mock-up under discussion

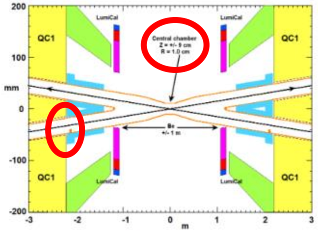
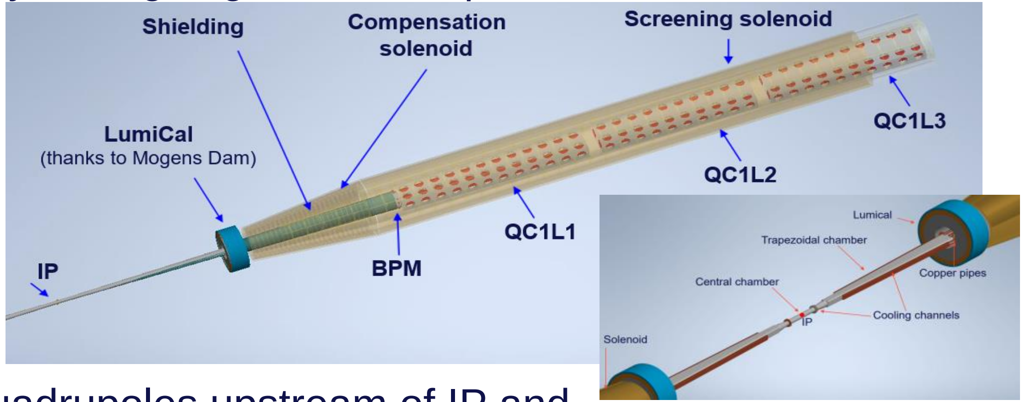


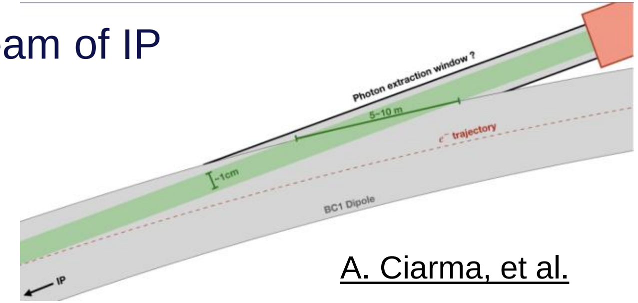
Figure 1: IR layout with 10 mm radius of the central pipe.

From arXiv:2105.09698



- 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

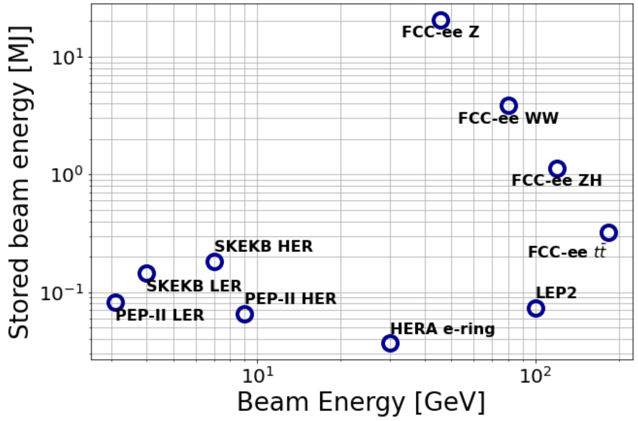
	Total Power [kW]	Mean Energy [MeV]
Z	370	1.7
WW	236	7.2
ZH	147	22.9
Top	77	62.3

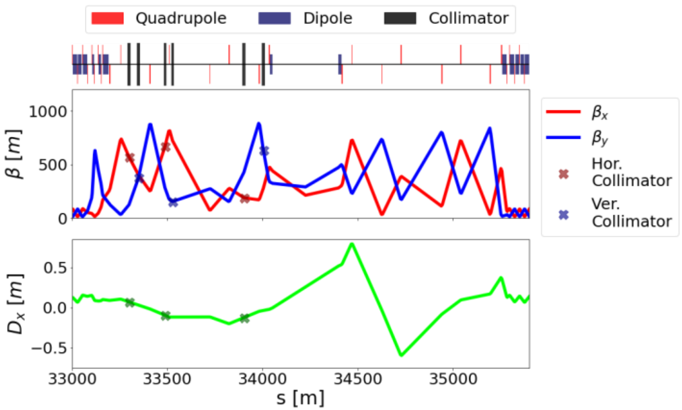


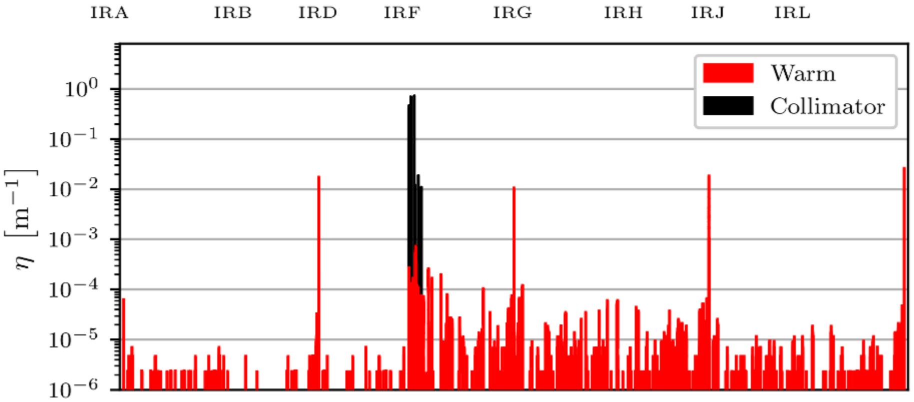
A. Ciarma, et al.

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



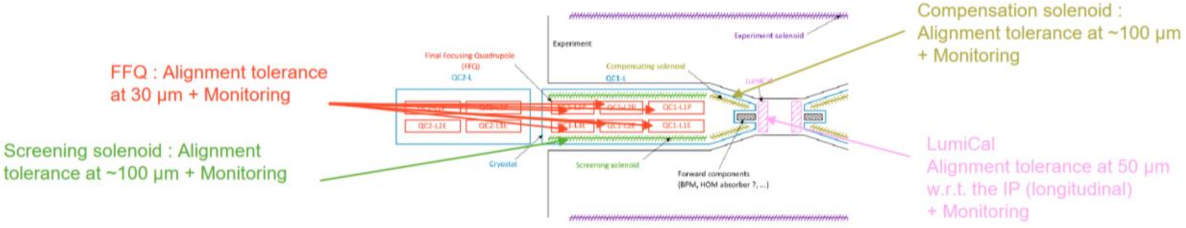




A. Abramov et al.

Alignment and Vibration

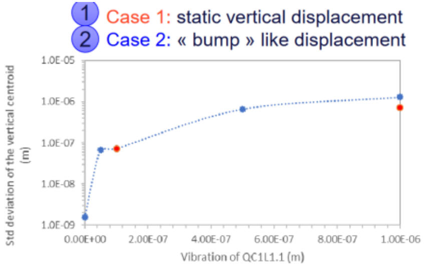
- Alignment of the machine critical to achieve design performance
  - MDI region of particular importance
    - Challenging due to many components in little space, harsh radiation environment, and tight alignment tolerances



L. Watrelot et al.

    - No existing or planned alignment and monitoring solution found that could be adapted for FCC-ee MDI
    - Sensor and alignment strategies for FCC-ee under development
      - Simulations for new interferometric sensors ongoing, some R&D required

- In parallel, studies to define vibration tolerances
  - Model to study magnet dynamic behaviour and impact on beam dynamics

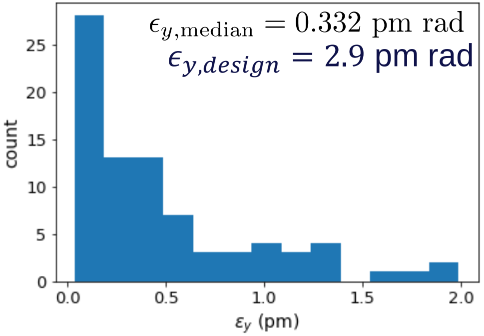


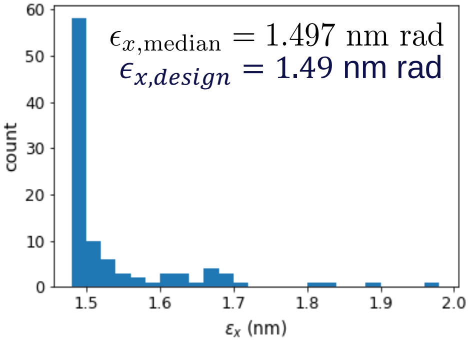
E. Montbarbon, S. Grabon, et al.

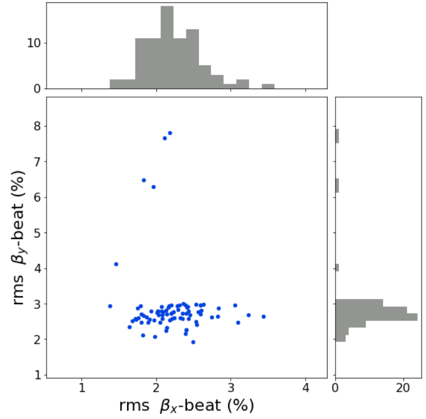
Optics corrections

- 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

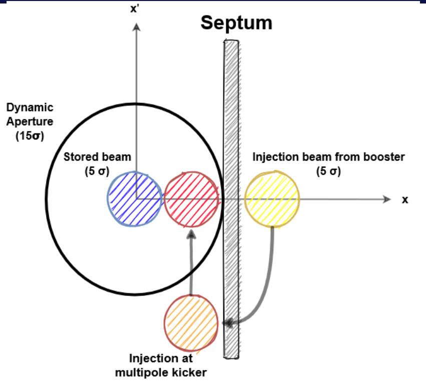
- Local correction of the IR optics to be studied

- 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

Dynamic Aperture

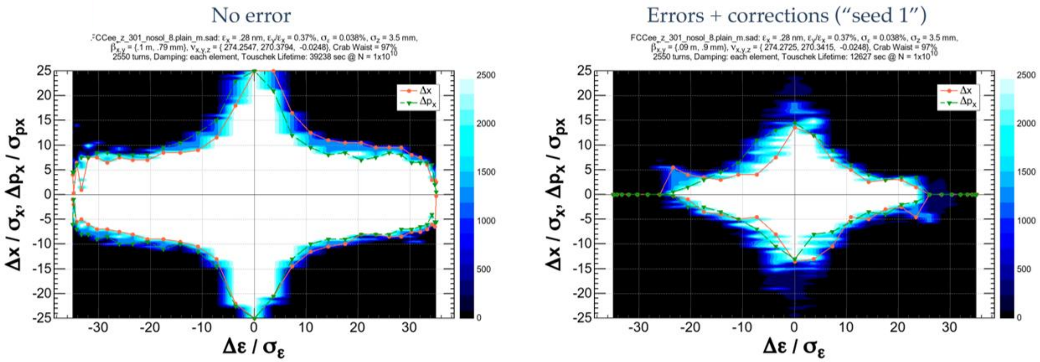


- Dynamic aperture requirement given by top-up injection
  - Target for on-momentum injection is more than 15σ

- 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

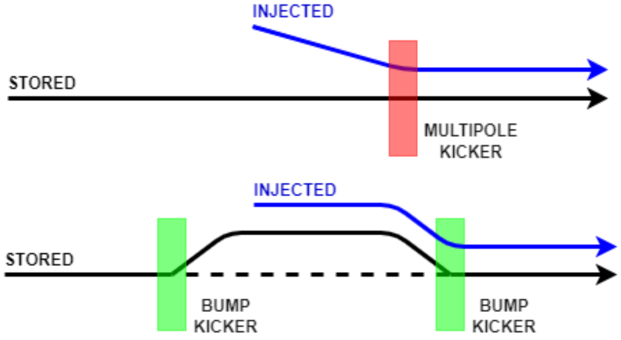
- Without errors, targets are met
  - Errors can significantly reduce DA, optimization in the presence of errors in progress



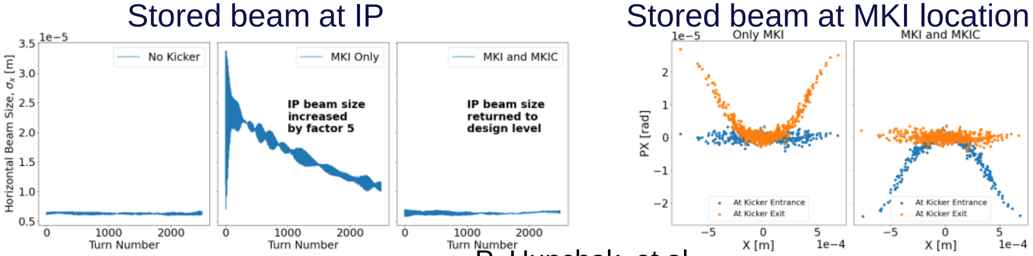
Top-up injection

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

- 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



- Tracking studies under way to determine impact on stored beam and evaluate injection efficiency of each mode in the presence of errors
  - Feasibility and required R&D for injection hardware under study

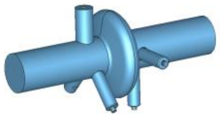


P. Hunchak, et al.

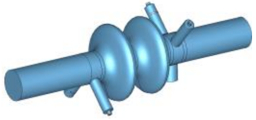
FCC-ee RF system

- 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

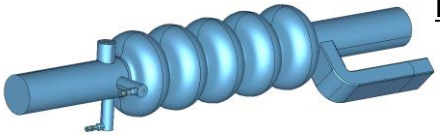
F. Peauger, et al.



Single cell Nb/Cu, 400 MHz cavity for Z

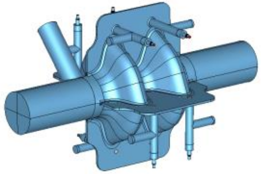


2-cell Nb/Cu, 400 MHz cavity for WW, ZH



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 $t\bar{t}$

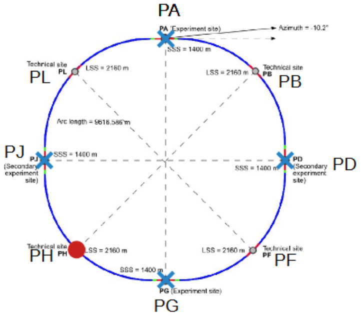


SWELL 2-cell Nb/Cu cavity with 600 MHz

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

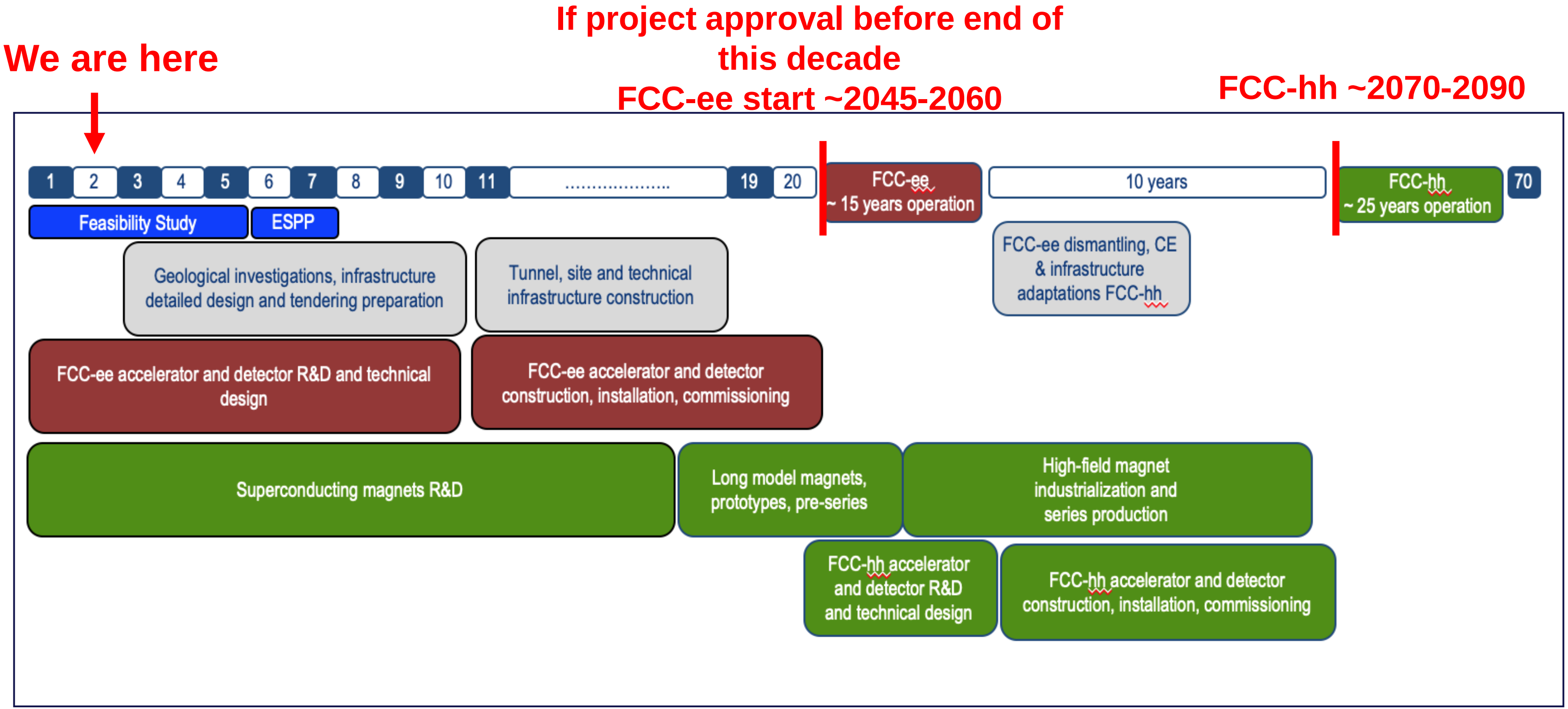
IP	ΔECM [keV]	Boost [MeV]
PA	- 7.851	10.665
PD	- 7.931	- 10.108
PG	0.570	- 30.883
PJ	0.844	31.439

For Z operation



J. Keintzel, et al.

Tentative Technical Timeline



M. Benedikt, FCC Feasibility Study overview

Summary & Outlook

- 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!