FCC Accelerator Overview
FCC Week Workshop
June 5, 2023

Tor Raubenheimer
on behalf of FCC collaboration & FCCIS DS team

Particular thanks to Andrey Abramov, Wolfgang Bartmann, Jeremie Bauche, Michael Benedikt, Manuela Boscolo, Olivier Brunner, Federico Carra, Antoine Chance, Paolo Craievich, Barbara Dalena, Massimo Giovannozzi, Michael Hofer, Jacqueline Keintzel, Fani Kuncheva-Valchikova, Anton Lechner, Mauro Migliorati, Katsunobu Oide, Vittorio Parma, Franck Peauger, Dmitry Shatilov, Rogelio Thomas, Frank Zimmermann
Outline

- Siting and Parameters
- Main Rings
  - Optics and correction
  - Collimation and Tuning
  - Arc cell Integration
  - SRF
- Booster ring
- Transport line and Pre-Injector
- FCC-hh

Will focus on the Baseline which is being developed for the Mid-Term Review. Alternatives are being developed in some cases to improve performance or reduce costs.

Lots of progress over the last two years! Convey the depth of the design work and level of detail supporting the Mid-Term Review.
**FCC-ee layout**

**Double ring** e+e- collider with 91 km circ.

**Common footprint with FCC-hh**, except around IPs

**Perfect 4-fold super-periodicity allowing** 2 or 4 IPs; large horizontal crossing angle 30 mrad, crab-waist collision optics

**Synchrotron radiation power** 50 MW/beam at all beam energies

**Top-up injection** scheme for high luminosity Requires **booster synchrotron** in collider tunnel and 20 GeV e+/e- source and linac
present baseline implementation

- Layout chosen out of ~ 50 initial variants
- 95% in molasse geology for minimising tunnel construction risk
- Well matched to existing electrical power distribution
- <4 km of new roads in total to connect the surface sites to existing roads and other networks

site investigations planned for 2024 and 2025 to verify geological conditions:
- limestone-molasse border, karstification, water pressure, moraine properties, etc.
- ~40-50 drillings, 100 km of seismic lines
### FCC-ee: main machine parameters and run plan

<table>
<thead>
<tr>
<th>Running mode</th>
<th>Z</th>
<th>W</th>
<th>ZH</th>
<th>t(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of IPs</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Beam energy (GeV)</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
</tr>
<tr>
<td>Bunches/beam</td>
<td>12000</td>
<td>688</td>
<td>260</td>
<td>40</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>1270</td>
<td>134</td>
<td>26.7</td>
<td>4.94</td>
</tr>
<tr>
<td>Luminosity/IP (10^{34} \text{ cm}^{-2} \text{ s}^{-1})</td>
<td>180</td>
<td>21.4</td>
<td>6.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Energy loss / turn [GeV]</td>
<td>0.039</td>
<td>0.039</td>
<td>0.37</td>
<td>1.89</td>
</tr>
<tr>
<td>Synchr. Rad. Power [MW]</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF Voltage 400/800 MHz [GV]</td>
<td>0.08/0</td>
<td>1.0/0</td>
<td>2.1/0</td>
<td>2.1/9.4</td>
</tr>
<tr>
<td>Rms bunch length (SR) [mm]</td>
<td>5.60</td>
<td>3.55</td>
<td>2.50</td>
<td>1.67</td>
</tr>
<tr>
<td>Rms bunch length (+BS) [mm]</td>
<td>13.1</td>
<td>7.02</td>
<td>4.45</td>
<td>2.54</td>
</tr>
<tr>
<td>Rms hor. emittance (\varepsilon_{x,y}) [nm]</td>
<td>0.71</td>
<td>2.16</td>
<td>0.67</td>
<td>1.55</td>
</tr>
<tr>
<td>Rms vert. emittance (\varepsilon_{x,y}) [pm]</td>
<td>1.42</td>
<td>4.32</td>
<td>1.34</td>
<td>3.10</td>
</tr>
<tr>
<td>Longit. damping time [turns]</td>
<td>1158</td>
<td>215</td>
<td>64</td>
<td>18</td>
</tr>
<tr>
<td>Horizontal IP beta (\beta_x^*) [mm]</td>
<td>110</td>
<td>200</td>
<td>300</td>
<td>1000</td>
</tr>
<tr>
<td>Vertical IP beta (\beta_y^*) [mm]</td>
<td>0.7</td>
<td>1.0</td>
<td>1.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Beam lifetime (q+BS+lattice) [min.]</td>
<td>50</td>
<td>&lt;28</td>
<td>&lt;70</td>
<td></td>
</tr>
<tr>
<td>Beam lifetime (lum.) [min.]</td>
<td>35</td>
<td>16</td>
<td>10</td>
<td>13</td>
</tr>
</tbody>
</table>

- Very high luminosity at Z, W, and Higgs
- Accumulate > luminosity in 1st 10 years at Higgs, W, and Z than ILC at Higgs
- Accommodates up to 4 experiments → robustness, statistics, specialized detectors, engage community
- Run plan naturally starts at low energy with the Z and ramps but could be adjusted using an RF Bypass to start at Higgs

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP x 10^5</td>
<td>5 x 10^{12} Z</td>
</tr>
<tr>
<td>WW</td>
<td>&gt;2x10^8</td>
</tr>
<tr>
<td>H</td>
<td>2 x 10^6</td>
</tr>
<tr>
<td>tt pairs</td>
<td>2 x 10^5</td>
</tr>
</tbody>
</table>
Accelerator Design

Well developed layout that will deliver (extremely) high luminosity \(Z \rightarrow t\overline{t}\)

Design benefits from LEP, LHC, DAFNE, and B-factory experience as well as LC, EIC and CEPC development

Have detailed lattices for collider rings and booster
Full simulations of beam-beam effects
Working on alignment and correction strategies

The accelerator has highly repetitive Arcs with challenging IRs
   \(\rightarrow\) Develop prototype of half arc-cell
   \(\rightarrow\) Develop IR mock-up

Most R&D is focused on optimizing systems for power efficiency & cost
FCC-ee collider optics development: 2 options

**FODO lattice, many -/+ sext pairs; periodic unit cell length ~260 m**

**hybrid FODO lattice, with few sext. families, periodic unit cell length ~300 m**

**design in progress - further relaxed tolerances, reduced power consumption, larger momentum acceptance**

**“1.5” sext.s per final focus, asymmetric**

**Phys. Rev. Accel. Beams 19, 111005**

**Phys. Rev. Accel. Beams 26, 021601**
Excellent progress over last 6 months

Tuning beam optics and chromatic correction while optimizing for both 4 and 2 IPs

Established configurations for all four working points with lifetime >> than minimum reqs.
Dynamic aperture exceeds requirements at all four working points

Impact of errors is being evaluated but tolerances will be tight for DA as well as the optics
Alignment Correction and Tuning

Alignment is a serious challenge for the main rings and Booster

Have developed an algorithm to correct using an iterative approach based in MADX but need better performance

Planning to start from ‘realistic’ mechanical alignment and iterate with Beam-Based Alignment techniques to achieve ~10 um effective alignment.

Working to develop tuning knobs to tune the IP parameters after main alignment procedures

<table>
<thead>
<tr>
<th>Length</th>
<th>Mech. align.</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 m</td>
<td>20 - 50 um</td>
<td>Pre-align on girder</td>
</tr>
<tr>
<td>50 m</td>
<td>200 um</td>
<td>Structured laser tracker or analogous</td>
</tr>
<tr>
<td>200 m</td>
<td>500 um</td>
<td>Structured laser tracker or analogous</td>
</tr>
<tr>
<td>1000 m</td>
<td>2 mm</td>
<td>Smoothed alignment from local and surface</td>
</tr>
<tr>
<td>10000 m</td>
<td>5 mm</td>
<td>Surface alignment → tunnel</td>
</tr>
</tbody>
</table>
Collaborating with modern synchrotron light sources to develop alignment algorithms and linear colliders on IP tuning knobs.

Will also need to develop and model feedback to maintain the rings.

The workshop will bring together experts from the circular and linear collider community and the high brightness synchrotron radiation sources to discuss the tuning and correction of beam optics.

Topics to be covered are:

- correction of linear and nonlinear beam optics through the accelerator;
- sensitivity and optimization of dynamic aperture;
- impact of collective effects on the beam optics;
- component errors, drifts, and correlations;
- transport and preservation of polarization;
- modeling tools and optimization techniques.
Main Ring Collimation

• Dedicated halo collimation system in PF
  – Two-stage betatron and off-momentum collimation in PF
  – Defines the global aperture bottleneck
  – First collimator design (G. Broggi)

• Synchrotron radiation collimators around the IPs
  – 6 collimators and 2 masks upstream of the IPs (K. André)
  – Designed to reduce detector backgrounds and power loads in the inner beampipe due to photon losses

[Graphs and images showing aperture profiles and beam size variations]
Main Ring Collimation

Complete simulation package for modeling performance in FCC-ee and FCC-hh (these tools are now being used at EIC as well)

Three layered collimation system has excellent performance

With a pessimistic 5-minute lifetime at $Z \rightarrow 59.2$ kW absorbed in PF while < 2 W reach experimental IRs

Super KEKB observations of ‘fast beam loss’ needs to be understood as it would be hard to protect against
Main Ring Collective Effects

Building models for transverse and longitudinal impedance

Resistive wall dominates but collimators, tapers, bellows, ... are all important

wake for 0.4 mm bunch
Impedance has some impact on the longitudinal distribution

Transverse beam is unstable → bunch-by-bunch feedback similar to Super KEKB with 2 ms damping time but many fewer turns

Collimators are a significant source of transverse impedance and working to balance the geometric and resistive contributions

There is a strong interplay between the longitudinal and transverse wakefields, beam-beam, and feedback systems. Must study all effects together → simulation and modeling tools are critical
Arc Cell Integration

Arc cells are repeated 1500 times → optimize the layout for performance, cost, installation, maintenance, ...

Arc half-cell team developed detailed layout for the repeating structure of Booster and Main Rings

Considered many aspects including cost, alignment, stability, and maintenance

Fully documented and starting phase-II with detailed engineering of a mockup
**Main challenge:** cumulative ionizing dose (@ttbar) much higher than in LEP and HL-LHC arcs (over an arc length of > 70 km!)

- **Cable insulation**
  - Few 100kGy issue for most cables

- **Magnet insulation**
  - O(MGy) can damage insulation

- **Electronics**
  - Designing a system with commercial-off-the-shelf electronics (with some level of complexity) considered as unfeasible for a dose above 1 kGy

**Radiation to materials and electronics are an essential aspect - solutions still to be developed! (shielding, rad-hard by design, ...)**

### Table: Radiation Protection

<table>
<thead>
<tr>
<th></th>
<th>LEP (100GeV, 15A*h)</th>
<th>HL-LHC (per year)</th>
<th>FCC-ee (182.5GeV, 15A*h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td>400kGy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2)</td>
<td>600kGy</td>
<td>1.4Gy</td>
<td>600kGy</td>
</tr>
<tr>
<td>3)</td>
<td></td>
<td>1.5MGy</td>
<td></td>
</tr>
<tr>
<td>4)</td>
<td>700kGy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5)</td>
<td>350kGy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6)</td>
<td>150kGy</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Per year @ttbar (w/o booster contribution)
Superconducting RF Systems

SRF systems replenish the energy lost to synchrotron radiation in the main ring and accelerate the beam in the Booster.

Main Ring RF is very high power while the Booster has low duty cycle and low current. Voltages are similar in both rings: 100 MV (Z), 1 GV (W), 2 GV (Higgs), 11 GV (t-tbar).

For Z thru Higgs, Main Ring RF is based 400 MHz Nb coated Cu cavities operating at 4.5K while the Booster uses 800 MHz solid Nb at 2K.

For t-tbar both rings would be upgraded with high-Q 800 MHz cavities operating at 2K.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Point H</th>
<th>Point L</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>400 MHz CMs</td>
<td>800 MHz CMs</td>
</tr>
<tr>
<td>Z</td>
<td>4.5K</td>
<td>NO CMs</td>
</tr>
<tr>
<td>W</td>
<td>4.5K</td>
<td>NO CMs</td>
</tr>
<tr>
<td>Higgs</td>
<td>4.5K</td>
<td>NO CMs</td>
</tr>
<tr>
<td>ttbar</td>
<td>4.5K</td>
<td>2K</td>
</tr>
<tr>
<td>12-May-23</td>
<td>Z</td>
<td>W</td>
</tr>
<tr>
<td>------------</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>per beam, booster</td>
<td>per beam, booster</td>
<td>per beam, booster</td>
</tr>
<tr>
<td>RF Frequency [MHz]</td>
<td>400</td>
<td>800</td>
</tr>
<tr>
<td>RF voltage [MV]</td>
<td>120</td>
<td>140</td>
</tr>
<tr>
<td>Eacc [MV/m]</td>
<td>5.72</td>
<td>6.23</td>
</tr>
<tr>
<td>#cell / cav</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Vcavity [MV]</td>
<td>2.14</td>
<td>5.83</td>
</tr>
<tr>
<td>#cells</td>
<td>56</td>
<td>120</td>
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<td>#cavities</td>
<td>56</td>
<td>24</td>
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<tr>
<td># CM</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>+ #CM</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>T operation [K]</td>
<td>4.5</td>
<td>2</td>
</tr>
<tr>
<td>dyn losses/cav * [W]</td>
<td>19</td>
<td>0.3</td>
</tr>
<tr>
<td>stat losses/cav * [W]</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Qext</td>
<td>5.8E+04</td>
<td>3.1E+05</td>
</tr>
<tr>
<td>Detuning [kHz]</td>
<td>9.885</td>
<td>4.385</td>
</tr>
<tr>
<td>Pcav [kW]</td>
<td>910</td>
<td>210</td>
</tr>
<tr>
<td>energy loss / turn ** [MV]</td>
<td>39.40</td>
<td>39.40</td>
</tr>
<tr>
<td>cos phi</td>
<td>0.33</td>
<td>0.28</td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>1.280</td>
<td>0.128</td>
</tr>
<tr>
<td>Lacc [m]</td>
<td>0.375</td>
<td>0.937</td>
</tr>
<tr>
<td>#cav/CW</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>R/Q [ohm]</td>
<td>87.6</td>
<td>521</td>
</tr>
<tr>
<td>G [ohm]</td>
<td>238.50</td>
<td>272.90</td>
</tr>
<tr>
<td>Q0</td>
<td>2.7E+09</td>
<td>3.0E+10</td>
</tr>
<tr>
<td>Ep/Eacc</td>
<td>2.20</td>
<td>2.05</td>
</tr>
<tr>
<td>Bp/Eacc</td>
<td>5.36</td>
<td>4.33</td>
</tr>
<tr>
<td>Ep [MV/m]</td>
<td>12.58</td>
<td>12.76</td>
</tr>
<tr>
<td>Bp [mT]</td>
<td>30.65</td>
<td>26.96</td>
</tr>
<tr>
<td>Cavity design</td>
<td>QUASI-LHC</td>
<td>UROSS</td>
</tr>
<tr>
<td>Prf no beam [kW]</td>
<td>225.14</td>
<td>52.53</td>
</tr>
</tbody>
</table>
FCC-ee SRF Technology

### Z
1-cell
400 MHz, Nb/Cu

- low R/Q, HOM damping, powered by 1 MW RF coupler and high efficiency klystron

### W, H
2-cell
400 MHz, Nb/Cu

- moderate gradient and HOM damping requirements; 500 kW / cavity, allowing reuse of klystrons already installed for Z

### ttbar, booster
5-cell
800 MHz, bulk Nb

- high RF voltage and limited footprint thanks to multicell cavities and higher RF frequency; 200 kW / cavity

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**Broad R&D collaborations on SRF**

- First attempt of HiPIMS* niobium coating on a 400 MHz Cu cavity

  *High-power impulse magnetron sputtering

  F. Peauger, O. Brunner
FCC-ee SRF Tech.

Broad R&D collaborations on SRF

5-cell bare cavity development (2018), successful collaboration with JLAB

F. Marhauser

Promising R&D towards ultra-high $Q_0$. Collaboration with FNAL

F. Peauger, O. Brunner

5-cell bare
650 MHz @ PIP2

Q0 = $6e10$ @ 25 MV/m with 2/6 N-doping + EP + cold EP

5-cell Jacketed
650 MHz @ PIP2

Q0 = $3.5e10$ @ 25 MV/m with 2/6 N-doping or midT bake + EP
FCC-ee SRF Tunnel Cross-sections

Collider

- 400 MHz (5.5 m tunnel)
- 800 MHz (5.5 m tunnel)

Booster

- 800 MHz (5.5 m tunnel)
• Distance between $e^+e^-$ quadrupoles 52 m, length 3.1 m.
• Distance between booster quadrupoles 52 m, length 1.5 m.

800 MHz cryomodules ($\phi$ 1.09 m x 7.5 m), half RF LSS
• 61 $e^+e^-$ CM (539.2 m)
• 122 klystrons

400 MHz cryomodules ($\phi$ 1.17 m x 11.4 m), half RF LSS
• 33 $e^+e^-$ CM (435.9 m)
• 66 klystrons
Cryomodule engineering just starting. Baseline assumptions start from existing CERN cryomodules. Collaborations beginning with FNAL, INFN, ….

**400 MHz with 4 cavities**
Example of the LHC cryomodule (400 MHz, 4.5 K)

**800 MHz with 4 cavities but may be extended to 6 or more to optimize filling factor**
Example of the SPL cryomodule (704 MHz, 2 K)
**FCC-ee SRF Cryodistribution Options**

- **A1 (baseline):** fully segmented with separate cryo line

- **AC2:** 800 MHz cont. with integr. cryo lines

- **AC3:** 400 MHz vac. cont. with separate cryo line; 800 MHz cont. with integr. cryo lines.

- **AC4:** 400 MHz and 800 MHz cont. with integrated cryo lines;

*End Cap module, CM interconnection, Service Module, Vac.Barr., Jumper (quads not shown)*
• Mechanical model:
  - engineered IR beam pipe with cooling system and support
  - vertex detector designed, integrated in MDI, modeled with Key4HEP
  - integration of the lumical

• Backgrounds simulations:
  - beam losses in the MDI: halo collimation and loss maps in the MDI
  - synchrotron radiation in the MDI with SR collimators and masking
  - Detector backgrounds simulations with refined and more realistic software model

• Beamstrahlung Photon dump:
  - optimal location at 500 m from IP, study on the magnet aperture yoke to allow an extraction line
  - started radiation studies with Fluka
Novel outer support tube for central beam pipe and vertex

Manuela Boscolo, Fabrizio Palla, Filippo Bosi

• Inside the same volume of the support tube that holds also the LumiCal
  • Vertex detector supported by the beam pipe
  • Outer Tracker (1 barrel and 6 disks) fixed to the support tube

IR heat load distribution

Alexander Novokhatski

Heat load distribution
A. Novokhatski 04/11/22 30
Gold 24 W
AlBeMet 30 W
AlBeMet 130 W
AlBeMet 130 W
Cu 157 W
Cu 157 W
Cu 157 W
Cu 157 W
Scale is distorted
Ongoing work to develop IR quadrupoles with ~100 T/m

Magnets have 2cm radius. More like LC final quads than LHC. Ongoing collaboration with BNL on direct-wind tech.

Integration of complete cryostat with magnets, correctors, and diagnostics is required.
Beamstrahlung Dumps

Two 400 kW dumps are needed at each IP to accommodate the high power beamstrahlung

- High-power dumps needed to safely dispose of the high photon flux from IP
- Challenges for the dump design:
  - High-power density (MeV photons) → challenging for absorber material and windows
  - Activation (through photo-nuclear interactions)
  - Radiation environment around dump (ionizing dose to equipment, radiation to electronics)

First considerations on radiation fields/power deposition, but more studies and R&D needed to develop a conceptual dump design and shielding – liquid metal considered as core material
Motivation

This workshop aims to better organize the FCC-ee community within the US and identify the most important and feasible areas of research to enable optimal FCC-ee accelerator, detectors and physics output by leveraging our domestic expertise. We will discuss the most needed elements.

Focused on US activities aimed at IR design and magnets, MDI, Collimation, etc.
Booster is placed above main rings
Detailed layout is ongoing
Operates with roughly 10% Main Ring current. Bunches are accumulated from Pre-Injector at 400 Hz and extracted in single turn
Booster is ramped from 20 GeV to Main Ring energy. Two phase advance options: 60° for Z and W and 90° for Higgs and t-tbar.

Beam current is roughly 10% of Main Ring but stainless-steel vacuum chamber and 800 MHz RF have larger impedance.

Intra-Beam Scattering is an impact at 20 GeV → damp for ~1s at top energy.

TMCI study requires both longitudinal and transverse impedance leads to threshold close to nominal bunch. Work is ongoing.
Pre-Injector generates e+ and e- bunches at 400 Hz (2x200Hz)
Supplies Booster ring with full bunch train at 20 GeV
and roughly 10% current

Baseline Pre-Injector uses HE linac to accelerate from 6 GeV to 20 GeV Booster. SPS is also possible to use with slightly longer cycle time.
Pre-Injector generates e+ and e- bunches at 400 Hz (2x200Hz). Positron target at 6 GeV. E+ rate is within a factor of 2x shown by the SLC at SLAC and is an order of magnitude lower than typical for LC designs. Experiment planned at PSI to demonstrate target and capture.

HTS NI target solenoid and capture

P. Craievich, J. Kosse, T. Michlmayr, H. Rodrigues
FCC-ee Transport Lines

Pre-injector located on Prevesin site with transport lines down to SPS and then down to FCC-ee

Layout is consistent with 20 GeV linac

Courtesy T. Watson
Pre-injector located on Prevessin site with transport lines down to SPS and then down to FCC-ee

Configuration allows use for SPS-SC or LHC for FCC-hh.

Initial transport line would be electro-magnets and would need to be switched while final lines of the SPS could be permanent magnets

Working to clarify requirements
FCC-ee R&D Examples

Efficient RF power sources (400 & 800 MHz)

- High efficiency klystrons & scalable solid-state amplifiers
- FPC & HOM coupler, cryomodule, thin-film coatings

Efficient high-Q SC cavities

- 400 MHz 1- & 2-cell Nb/Cu, 4.5 K
- Slotted Waveguide Elliptical cavity (SWELL) for high beam current & for high gradient, seamless by nature – links to past work at ANL (Liu & Nassiri, PRAB 13, 012001)

Energy efficient twin aperture arc dipoles

- Under study: CCT HTS quad’s & sext’s for arcs
- Reduce energy consumption by O(50 MW)
SuperKEKB*

world’s highest luminosity & lowest $\beta^* e^+e^-$ collider

3 km double ring, top-up injection

world record luminosity of $4.7 \times 10^{34}$ cm$^{-2}$s$^{-1}$, $\beta_y^* = 1.0$ mm (= FCC), also $\beta_y^* = 0.8$ mm shown – with “virtual” crab-waist collision scheme originally developed for FCC-ee (K. Oide)

DAFNE and SuperKEKB have demonstrated the crab-waist optics

Critical to understand (not necessarily fix) Super KEKB luminosity versus current and ‘fast beam loss’ challenges!
US Electron Ion Collider (EIC)

US EIC Electron Storage Ring similar to, but more challenging than, FCC-ee
beam parameters almost identical, but twice the maximum electron beam current, or half the bunch spacing, and lower beam energy

>10 areas of common interest identified by the FCC and EIC design teams, addressed through joint EIC-FCC working groups, still evolving

EIC will start beam operation about a decade prior to FCC-ee
The EIC will provide an invaluable opportunity to train next generation of accelerator physicists on an operating collider as well as testing hardware prototypes, beam control schemes, etc.

<table>
<thead>
<tr>
<th></th>
<th>EIC</th>
<th>FCC-ee-Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [GeV]</td>
<td>10 (18)</td>
<td>45.6 (80)</td>
</tr>
<tr>
<td>Bunch population [10^{11}]</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>10</td>
<td>15, 17.5 or 20</td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>2.5 (0.27)</td>
<td>1.39</td>
</tr>
<tr>
<td>SR power / beam /meter [W/m]</td>
<td>7000</td>
<td>600</td>
</tr>
<tr>
<td>Critical photon energy [keV]</td>
<td>9 (54)</td>
<td>19 (100)</td>
</tr>
</tbody>
</table>
Multiple FCC-EIC workshops held over last year
FCC-EIC EPOL Workshop September 2022, FCC-EIC MDI Workshop October 2022, FCC-US Workshop April 2023

Focus on Machine-Detector Interface (MDI) and Beam Physics
Developing common tools, e.g. the Collimation simulation and Polarization packages, and comparing hardware implementation for diagnostics, collimators, vacuum, SRF, ....
FCC-hh Design Status

- The FCC-hh layout has been updated to match the new placement

- Optimization of the Arc Cells improves the filling factor and alignment with FCC-ee

- Updated parameters for different magnets technology options and AC power constraints

- Work ongoing to evaluate the collimation, injection/extraction straight sections, and align the transport lines with SPS-SC or LHC
HFM: preparing for FCC stage 2 (FCC-hh)

In parallel to FCC studies, CERN High Field Magnet development program as long-term separate R&D project working with European, US and Asian efforts

CERN budget for high-field magnets doubled in 2020 Medium-Term Plan (~ 200 MCHF over ten years)

Main R&D activities:
- **materials**: goal is ~16 T for Nb$_3$Sn, at least ~20 T for HTS inserts
- **magnet technology**: engineering, mechanical robustness, insulating materials, field quality
- **production of models and prototypes**: to demonstrate material, design and engineering choices, industrialisation and costs
- **infrastructure and test stations**: for tests up to ~ 20 T and 20-50 kA

Detailed deliverables and timescale being defined through Accelerator R&D roadmap under development

L. Bottura, F. Gianotti, A. Siemko
## FCC-hh Accelerator Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>HL-LHC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>collision energy cms [TeV]</td>
<td>80-116</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>14 (Nb₃Sn) – 20 (HTS/Hybrid)</td>
<td>8.33</td>
<td>8.33</td>
</tr>
<tr>
<td>circumference [km]</td>
<td>90.7</td>
<td>26.7</td>
<td>26.7</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.5</td>
<td>1.1</td>
<td>0.58</td>
</tr>
<tr>
<td>bunch intensity [10¹¹]</td>
<td>1</td>
<td>1</td>
<td>2.2</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>synchr. rad. power / ring [kW]</td>
<td>2700</td>
<td>7.3</td>
<td>3.6</td>
</tr>
<tr>
<td>SR power / length [W/m/ap.]</td>
<td>32.1</td>
<td>0.33</td>
<td>0.17</td>
</tr>
<tr>
<td>long. emit. damping time [h]</td>
<td>0.45</td>
<td>12.9</td>
<td>12.9</td>
</tr>
<tr>
<td>beta* [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.15 (min.)</td>
</tr>
<tr>
<td>normalized emittance [μm]</td>
<td>2.2</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>peak luminosity [10³⁴ cm⁻²s⁻¹]</td>
<td>5</td>
<td>30</td>
<td>5 (lev.)</td>
</tr>
<tr>
<td>events/bunch crossing</td>
<td>170</td>
<td>1000</td>
<td>132</td>
</tr>
<tr>
<td>stored energy/beam [GJ]</td>
<td>7.8</td>
<td>0.7</td>
<td>0.36</td>
</tr>
</tbody>
</table>
Mid-term review report, supported by additional documentation on each deliverable, will be submitted to review committees and to Council and its subordinate bodies, as input for the review.

Results of both general mid-term review and the cost review should indicate the main directions and areas of attention for the second part of the Feasibility Study

**Infrastructure & placement**
- Preferred placement and progress with host states (territorial matters, initial states, dialogue, etc.)
- Updated civil engineering design (layout, cost, excavation)
- Preparations for site investigations

**Technical Infrastructure**
- Requirements on large technical infrastructure systems
- System designs, layouts, resource needs, cost estimates

**Accelerator design FCC-ee and FCC-hh**
- FCC-ee overall layout with injector
- Impact of operation sequence: Z, W, ZH, tī vs start at ZH
- Comparison of the SPS as pre-booster with a 10-20 GeV linac
- Key technologies and status of technology R&D program
- FCC-hh overall layout & injection lines from LHC and SC-SPS

**Physics, experiments, detectors:**
- Documentation of FCC-ee and FCC-hh physics cases
- Plans for improved theoretical calculations to reduce theoretical uncertainties towards matching FCC-ee statistical precision for the most important measurements.
- First documentation of main detector requirements to fully exploit the FCC-ee physics opportunities

**Organisation and financing:**
- Overall cost estimate & spending profile for stage 1 project

**Environmental impact, socio-economic impact:**
- Initial state analysis, carbon footprint, management of excavated materials, etc.
- Socio-economic impact and sustainability studies
Summary

• FCC-ee has highest luminosity at Z, W and H@240 GeV of all proposed factories

• Feasibility Study is preparing for Mid-Term review with a ‘complete’ design
  o Beam optics and beam physics, inc. collective effects, addressing major challenges
  o Describe high-cost technical systems, e.g. SRF, arc magnets, vacuum, ...
  o Layout identified to ensure complete civil / infrastructure cost estimates
  o Alternative options and R&D identified to further improve performance / cost

• Based on 60 years of experience with circular e^+e^- colliders, some of which currently in operation, hence no need for a large demonstrator facility
  o Super KEKB and EIC will provide important information
  o R&D on components focused on improved performance, increased efficiency, industrialization, cost aspects, sustainability and minimizing environmental impact
  o R&D timelines are consistent with construction in 2030’s

• Very significant progress over the last two years!
**Version: 0.28**  
**Date: 26.05.2023**

<table>
<thead>
<tr>
<th>Day</th>
<th>Sunday</th>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
<th>Saturday</th>
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</thead>
<tbody>
<tr>
<td>Time</td>
<td>Registration desk</td>
<td>Plenary</td>
<td>Parallel 1</td>
<td>Parallel 2</td>
<td>Parallel 3</td>
<td>Parallel 4</td>
<td>Governance</td>
</tr>
<tr>
<td>Room</td>
<td>Santosha Suite</td>
<td>Orchard Suite</td>
<td>Orchard Suite 1+2</td>
<td>Cromwell 3+4</td>
<td>Kensington Suite</td>
<td>Cromwell 6</td>
<td>Orchard Suite</td>
</tr>
</tbody>
</table>

- **Opening**
  - CERN Council expectations for FCC FS
- **Keynote**
  - Physics perspectives
- **Coffee Break (Santosha Suite)**
- **Collimation & collective effects**
- **Baseline design**
  - Physics Case + Theoretical calculations (I)
- **FCCS WP3: Integrate Europe (I)**
- **UK industrial event**
- **Optics correction**
- **Detector requirements from Physics (I)**
- **FCCS WP3: Integrate Europe (III)**
- **UK industrial event**
- **Lunch break (Santosha Suite)**
- **FCC Accelerator**
- **Machine Detector Interface (I)**
- **RF Points for FCC-ee**
- **FCCS WP4: Impact & Sustainability (I)**
- **Lunch break (Santosha Suite)**
- **Coffee Break (Santosha Suite)**
- **Technical Infrastructure**
  - Machine Detector Interface (II)
  - Integration and Cooling
  - FCCS WP4: Impact & Sustainability (II)
- **Plenary UK Session**
- **Alternative FCC-ee optics Development**
  - Detectors (II)
  - Technologies
  - Early Career Researchers
- **Scientific Advisory Committee in Brussels**

**Thank you!**