Paolo Craievich (PSI) on behalf of the CHART/FCCee Injector design collaboration

FCC-ee injector summary

FCC Week 2023, 5-9 June (London, United Kingdom)
### Injector (I and II) sessions

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
<th>Speaker(s)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:30</td>
<td><strong>FCC-ee injector</strong> - Barbara Dalena (CEA-Irfu &amp; Université Paris-Saclay (FR)) (until 12:00)</td>
<td>Orchard Suite</td>
<td></td>
</tr>
<tr>
<td>10:30</td>
<td>Full-energy booster - Dr Antoine Chance (CEA Irfu)</td>
<td>Orchard Suite</td>
<td></td>
</tr>
<tr>
<td>10:50</td>
<td>Pre-injector baseline and options - Paolo Craievich</td>
<td>Orchard Suite</td>
<td></td>
</tr>
<tr>
<td>11:10</td>
<td>Positron production, capture and acceleration until the damping ring - Dr Iryna Chaikovska (CNRS/IJCLab)</td>
<td>Orchard Suite</td>
<td></td>
</tr>
<tr>
<td>11:25</td>
<td>Design of the FCC-ee positron source target: current status &amp; challenges - Ramiro Francisco Mena Andrade</td>
<td>Orchard Suite</td>
<td></td>
</tr>
<tr>
<td>11:40</td>
<td>Damping ring and transfer lines for the FCC-ee pre-injector complex - Catia Milardi (Istituto Nazionale di Fisica Nucleare (INFN))</td>
<td>Orchard Suite</td>
<td></td>
</tr>
<tr>
<td>08:30</td>
<td><strong>FCC-ee injector</strong> - 홍식 강 Heung-Sik Kang (until 10:00)</td>
<td>Orchard Suite</td>
<td></td>
</tr>
<tr>
<td>08:30</td>
<td>Linac beam dynamics - Simona Bettoni (Paul Scherrer Institut)</td>
<td>Orchard Suite</td>
<td></td>
</tr>
<tr>
<td>08:50</td>
<td>Layout and design of positron and electron linacs up to 20 GeV - Alexej Grudiev (CERN)</td>
<td>Orchard Suite</td>
<td></td>
</tr>
<tr>
<td>09:10</td>
<td>SPS pre-booster option - Hannes Bartosik (CERN)</td>
<td>Orchard Suite</td>
<td></td>
</tr>
<tr>
<td>09:30</td>
<td>Siting and transfer lines - Wolfgang Bartmann (CERN)</td>
<td>Orchard Suite</td>
<td></td>
</tr>
</tbody>
</table>
### FCCee Pre-Injector parameters (Z-pole)

K. Oide, H. Bartosik (SPS), FCC week 2023 talks

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SPS</th>
<th>HE Linac</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection energy</td>
<td>6</td>
<td>20</td>
<td>GeV</td>
</tr>
<tr>
<td>Bunch charge both species</td>
<td>4.0*</td>
<td>4.0*</td>
<td>nC</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>200</td>
<td>200</td>
<td>Hz</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>25</td>
<td>25</td>
<td>ns</td>
</tr>
<tr>
<td>Normalized emittance (x, y) (rms)</td>
<td>50,?</td>
<td>10,10</td>
<td>mm mrad</td>
</tr>
<tr>
<td>Bunch length (rms)</td>
<td>~1?</td>
<td>~1</td>
<td>mm</td>
</tr>
<tr>
<td>Energy spread (rms)</td>
<td>0.3</td>
<td>~0.1</td>
<td>%</td>
</tr>
</tbody>
</table>

*Maximum charge to be injected into the collider rings during filling from scratch 4 nC (bunch pop. 2.5x10¹⁰ particles)*

- The bunch by bunch intensity will arbitrarily vary from 0 to 100%, depending on the intensity balance between the collider rings → to be verified the impact on the booster as well

- New parameters:
  - 15000 bunches, 15 ns bunch spacing
  - Charge for top-up 2.42 nC (2.5x10¹⁰ particles)

**Question:** How can we keep different versions of parameter tables?
Full-energy booster (conclusion) – Antoine Chance

New Layout, some results are for the optics showed FCC week 2022

Optics:
- Procedures have been written to optimize the layout and booster positioning in the tunnel.
- Matching conditions have been updated to increase the transparency of the insertions.
- The dispersion suppressor needs to be improved to correct the 2nd order dispersion in the long insertions.

RF budget has been updated for 800 MHz cavities

Strong reduction of dynamic aperture and momentum acceptance due to synchro-betatron resonances
- Tune has been optimized
- Criteria stabilities under investigation to understand DA reduction

Orbit tuning
- First definition of the orbit correctors for the booster (≈ 20 mT) and orbit correction scheme.

- First specifications of elements misalignment (150 μm)
- Finalize the emittance tuning studies

HEB operation and emittance evolution
- Optimization of cycle time at Z
- IBS integrated in accumulation process
- Updates of the cycling in case of SPS as an injector

Collective effects  Resisitive wall wakes
- Not real impact of injecting a mismatched beam.
- First Intensity scans at injection with PyHEADTAIL
- Confirmation of intensity above threshold for Z operation with 90 degrees FODO cells contrary to 60 degrees FODO cells.*
- Doubling the momentum compaction cures the TMCI.

An alternative optics to 60° FODO cells has been proposed.
- Momentum compaction of the HBD cell can also be tuned.
Optics and layout
• Provide a full list of the elements for the mid-term review.
• Provide an optics with the HBD cell.
• Apply the momentum compaction tuning to the optics and evaluate the impact on DA and MA.
• Evaluate the impact of the fringe field of the detectors on booster optics.

Cost estimate due by end June

Dynamic aperture and momentum acceptance
• Improve DA and MA (increase the number of sextupole families for instance)
• Evaluate the dynamic aperture and momentum acceptance for the HBD optics and with a doubled momentum acceptance.

Machine tuning
• Finalize emittance tuning
  • Static and dynamic imperfections
  • Improve overall performances/cost with AI

Cycling optimization
Collective effects
• Perform a momentum compaction scan to find the threshold for TMCI
• Add the IBS
• Perform the calculations with X-Suite to include the optics

Injection:
  20 GeV: recheck the beam parameters (i.e., energy spread and bunch length...)
  16 GeV: check if the BR can work at this energy

Including collimators, cavities etc..

BR operation with a modulated train of bunches
Pre-injector layout (baseline)

A baseline for the pre-injector layout is ready for the mid-term review.

Pre-Injector can fulfill the requirements for the collider rings (to be verified with the new parameters).

Submit the cost lines by June.

Draft the document (deadline mid-Sept)
Pre-injector options

**Pre-injector layout with DR at higher energy**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-EE</th>
<th>CLEO DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (GeV)</td>
<td>2.56</td>
<td>3.88</td>
</tr>
<tr>
<td>Longitudinal beam length (m)</td>
<td>196</td>
<td>458</td>
</tr>
<tr>
<td>Emittance (mm-mrad)</td>
<td>6.5</td>
<td>4.3</td>
</tr>
<tr>
<td>Polarization (mm-mrad)</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Alignment (mm-mrad)</td>
<td>3.7</td>
<td>3.6</td>
</tr>
</tbody>
</table>

**C³ Technology for FCC-ee Injector Linacs**

- C³ Demo is a proposed 5–7-year R&D program for to engineer and demonstrate S/C-band high gradient cryomodules (→ build 3 cryomodules)
- Demonstrations include high-gradient testing, damped and detuned structures, beam dynamics, heavy beam loading, demonstration of alignment tolerances for a C³ linear collider

**Linac Cryomodule (~9 m)**

- Compatible with S/C-band Structures

**Gradient ~70MV/m**

- 5-band structure with a/λ ~ 0.15 under study (compatible with FCCee linacs)

Preliminary studies showed that the C³ approach could reduce significantly the length OR reduce rf power of FCC-ee HE linac (compared to the baseline)

A more systematic comparison is ongoing

**LHeC Racetrack as Injector to FCC-ee**

- Based on 2 SRF Linacs (~800 MHz) with 3 recirculating arcs, total length of ~5.3 km (~1/5 of LHC), achieving energy of ~49 GeV - LHeC recirculating linac injector (RLI)
- Bunch intensity of ~500 pC (~3x10^10 p/b) for ~25ns spacing, average current of 20 mA
- Could be used for full energy top-up injector for FCCee-Z and pre-injector for other collider energies
- Small footprint PERLE-like version could be used as pre-injector to P8R, ~6-20GeV

**FCCee Pre-Injector: SPS vs HE linac**

- Pre-injector 0.8 – 1.2 km
- Booster ring ~90.7 km
- 6 GeV SPS
- 14 GeV HE Linac

**Option 1 (with SPS/PB) R**

- e linac
- Common linac
- p linac

**Option 2 (HE Linac)**

- Linac 2
- Booster ring

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Conclusions and outlook

– The studies on the FCC-ee positron source are well advanced: positron production, HTS technology feasibility for matching device, capture linac (RF structures and solenoid). So far, no showstoppers found that prevent a SC solenoid matching device. Studies ongoing.

– FC-based capture system requires a realistic model capable to work at the FCCee operation parameters. Collaborative work is very essential.

– Two capture system layouts (based on the FC and SC solenoid) will be eventually compared in detail in terms of the performance and cost for the mid-term project review.

– Positron linac has a robust design with full tracking simulations from production target to damping ring using the realistic field maps.

– Thermal and radiation load studies: FLUKA model is available for capture system –version 1. Still to be developed for the FC-based capture system.

– Design and integration of the production target are under investigations and to be studied for both schemes.
Design of the FCC-ee positron source target: current situation and challenges – Ramiro Mena Andrade

**Target design: main parameters**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron drive beam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assumption</td>
<td>Max. intensity, which can be delivered by e+ linac</td>
<td>13.5 nC e+ bunch charge at the entrance of the damping ring</td>
<td></td>
</tr>
<tr>
<td>Beam size</td>
<td>0.5 mm RMS</td>
<td>0.5 mm RMS</td>
<td>1.0 mm RMS</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>200 Hz</td>
<td>200 Hz</td>
<td>200 Hz</td>
</tr>
<tr>
<td>Bunches per pulse</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Bunch intensity (filling)</td>
<td>3.47E10 (5.56nC)</td>
<td>1.205E10 (1.93 nC)</td>
<td>1.30E10 (2.08 nC)</td>
</tr>
<tr>
<td>Beam Power</td>
<td>13.34 kW</td>
<td>4.63 kW</td>
<td>5.00 kW</td>
</tr>
</tbody>
</table>

In general, no showstoppers, but shielding design to be further optimized.

**Summary**

- After several iterations, the current **beam parameters** provide a solid baseline for the design of the FCC-ee positron source target.
- A target made of pure tungsten now is a **feasible option**. The thermo-mechanical studies show values of temperature and stresses inside of the safety limits of tungsten.
- As a next step, a **R&D test campaign** is foreseen to evaluate different manufacturing options for the target and the hipping of the tubes for the cooling system.
- The **design of the P3 target** is ongoing and it is a key factor to study the performance in terms of positron yield inside of the P3 experiment.

**Preliminary cost estimate for the target system ready**
Damping Ring and Transfer Lines for the FCC-ee pre-Injector Complex – Catia Milardi

**DR acceptance**

At large energy deviation most of the losses are concentrated in the tail of the distribution as expected. Global DR acceptance:

\[ f_{\text{ACC}} = 0.939 \times 0.917 = 86.1\% \]

Recently the emittance of the beam provided by the pLINAC has been optimized -> an even larger DR acceptance is expected. New DR acceptance is being evaluated.

**Alternative DR designs**

Different options are being evaluated including different type of cell and magnet

In all the options, the number of elements was considerably reduced

In a preliminary configuration (Option-2) beam parameters were achieved even without damping wiggler insertions which helps in simplifying vacuum chamber design impedance budget and realization costs.

Option-2 also minimize curly H function which is important to avoid emittance dilution effects due to CSR

**Layout ready**

Cost estimate will be submitted by June

**DR at 1.54 GeV (version CDR 0)**

- DR and TLs design has been completed
  - A DR acceptance larger than 86% can be achieved with the help of an ECS installed between the pLINAC and the DR injection line.
  - ECS reduces energy spread to ~ 2%.
- A BCS has been included in the return line from the DR to Common LINAC.
  - BCS can provide maximum compression factor C ~ 5.
- A breakdown schedule of the the components used for the different parts has been prepared costs are being evaluated.

**Alternative DR designs are being considered.**
Linac Beam Dynamics – Simona Bettoni

- **Longitudinal dynamics:**
  - Design without energy compressor:
    - $\sigma_z \sim 1$ mm or slightly more, $\delta E/E \sim 0.1$-0.15% feasible
  - Design with energy compressor:
    - On-crest (preferred): better for (energy efficiency) and emittance growth
    - **S-band** High Energy Linac: energy spread $\leq 0.05\%$ and several mm bunch length possible
    - **C-band** High Energy Linac: energy spread $\leq 0.15\%$ and several mm bunch length possible in the present design
    - Impact of different charge for the 0-100% charge scan determined
    - Flexible design to eventually accommodate different specifications coming from the booster and the transfer line WP

- **Transverse dynamics:**
  - Emittance increase due to static misalignments of accelerator components is under control including a factor 2 margin for the selected geometry (several steering algorithms implemented in RF-Track)
  - Comparison of the obtained results using several tracking codes: after this work now the codes agree

- **Ongoing: study of the impact on the beam of:**
  - Linacs’ number of module/structure in WP1
  - Optimization of the RF structure design in WP1
  - In the future, possible re-optimization of the design according the booster/SPS requests

*Optimized* design(s) of the Linacs from 200 MeV to 20 GeV beam energy fulfilling the present booster requests

Next steps will be to refine the *best* design, given the booster/SPS target and transfer line parameters
Layout and design of positron and electron linacs up to 20 GeV – Alexej Grudiev 1/2

Layout of positron linac

- RF module type 1 layout for positron linac
- RF module type 2 layout for positron linac
- RF module layout for electron linac
- RF module layout for common linac

RF module summary table for all linacs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>p-linac</th>
<th>e-linac</th>
<th>c-linac</th>
<th>HE-linac (N)</th>
<th>HE-linac (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [GHz]</td>
<td>2</td>
<td>2.8</td>
<td>2.8</td>
<td>5.6</td>
<td>5.3</td>
</tr>
<tr>
<td>Accelerating structure</td>
<td>F3</td>
<td>a/λ&lt;0.15</td>
<td>a/λ&lt;0.15</td>
<td>a/λ&lt;0.15</td>
<td>a/λ&lt;0.19</td>
</tr>
<tr>
<td>Repetition rate [Hz]</td>
<td>200</td>
<td>200</td>
<td>400</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Aperture radius [mm]</td>
<td>30</td>
<td>16.1</td>
<td>16.1</td>
<td>16.1</td>
<td>10.2</td>
</tr>
<tr>
<td>Length [m]</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Filling time [ns]</td>
<td>447</td>
<td>486</td>
<td>486</td>
<td>486</td>
<td>334</td>
</tr>
<tr>
<td>SLED coupling</td>
<td>17</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Klystron RF pulse length [μs]</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Average gradient [MV/m]</td>
<td>20</td>
<td>29.5</td>
<td>23.4</td>
<td>29.5</td>
<td>29.8</td>
</tr>
<tr>
<td>Energy gain per structure [MeV]</td>
<td>60</td>
<td>88.5</td>
<td>70.2</td>
<td>88.5</td>
<td>86.4</td>
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<tr>
<td>Klystron power per structure [MW]</td>
<td>31</td>
<td>40</td>
<td>28.9</td>
<td>40</td>
<td>18.2</td>
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<tr>
<td>Klystron output power specification [MW]</td>
<td>60</td>
<td>80</td>
<td>50</td>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td>Klystron RF pulse length [μs]</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Number of structures total</td>
<td>1 + 30</td>
<td>1 + 10</td>
<td>0</td>
<td>140</td>
<td>35</td>
</tr>
<tr>
<td>Number of modules total</td>
<td>1 + 15</td>
<td>1 + 10</td>
<td>0</td>
<td>140</td>
<td>35</td>
</tr>
<tr>
<td>Total length of all modules [m]</td>
<td>140</td>
<td>90</td>
<td>262.5</td>
<td>615</td>
<td>645</td>
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</table>

Comparison of relative cost of linacs in a.u.

<table>
<thead>
<tr>
<th>Linac</th>
<th>Klystron cost [a.u.]</th>
<th>Modulator cost [a.u.]</th>
<th>Cost estimation [a.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-linac</td>
<td>0.27</td>
<td>0.9</td>
<td>32.5</td>
</tr>
<tr>
<td>e-linac</td>
<td>0.18</td>
<td>0.82</td>
<td>20.5</td>
</tr>
<tr>
<td>c-linac</td>
<td>0.19</td>
<td>0.85</td>
<td>66.5</td>
</tr>
<tr>
<td>Total p- e-c-linacs</td>
<td>0.64</td>
<td>1.65</td>
<td>119.5</td>
</tr>
<tr>
<td>HE-linac – S-band option</td>
<td>0.18</td>
<td>0.82</td>
<td>152.5</td>
</tr>
<tr>
<td>HE-linac – C-band option</td>
<td>0.16</td>
<td>0.8</td>
<td>155</td>
</tr>
</tbody>
</table>

Cost estimate includes:
- RF
- LLRF
- Vacuum
- Magnets
- BI

- Cost of HE linac is comparable to the cost of all other linacs
- Cost of HE linac S-band (baseline) and C-band options is similar
**HE-linac: S- and C-band comparison**

- **S-band (baseline)**
  - It uses the same RF module as for the e-linac, same spares, etc
  - Better for the beam: Larger aperture, smaller “RF curvature”
  - Similar cost as C-band (a bit less actually)
  - S-band is more commercially available and more mature

- **C-band**
  - 30% (~10MW) lower power consumption. Although it is significant, but it is negligible compared to FCC overall power consumption

**General comments:**
- Increase accelerating gradient and repetition rate can put a limit on the available power source and dissipated power in the rf structures. A compromise is necessary.
- Cost of the building and infrastructures have to be considered in the final decision of the RF module (i.e. 2 vs 4 rf structures per klystron)
SPS pre-booster option – Hannes Bartosik

- Ongoing work to consolidate the option of using the SPS as FCCee pre-booster for cost comparison to HE-Linac option at mid-term review
- We consider the 16 GeV extraction energy as most interesting
- High synchrotron radiation power and required vacuum levels are challenging – ongoing work by vacuum experts
- Installation of damping wigglers (and Robinson wiggler) might be required – ongoing studies by booster colleagues if larger horizontal emittance could be accepted
- Additional RF system would be required – with very high voltage at extraction when using wiggler magnets
- Modification of power converters for bi-polar operation seems feasible
- Collective effects to be further studied (in particular the fast ion instabilities and TMCI)
- Filling time compatible with collider request (at least for latest parameter set)
  - Horizontal Emittance at the extraction (16 GeV): 35 nm (w/o wiggler), 5.6 nm (w/ wiggler) (specs for linac ~0.25 nm at 20 GeV) – to be clarified
  - Plan for the protons at CERN and cost estimates will provide information for a final decision
Conclusions

- Transfer lines have been optimized for re-using existing tunnels as much as possible and for compatibility between leptons and hadrons.
- There is also synergy for the lepton injection options of 20 GeV linac or 16 GeV SPS.
- Injection into the booster lattice should happen in the arc to avoid extensively long transfer line (reduce length by 2/3) which seems feasible from discussions during this week.
- Energy compression can be included in the transfer line, most elegantly by using the r56 from the arcs - looks feasible, details to be confirmed between linac and booster constraints.
- Upcoming
  - prepare cost lines for all required equipment
  - further optics studies on cell adaption, dispersion matching, energy compression and injection
  - specification of TL HW to enter into the engineering phase, in particular for magnets.
I would like to thank all colleagues involved in this collaboration in the framework of CHART.

In 2021 and 2022, most of the discussions were done on video meetings, and despite this, important progress was made.

Two mini-workshops were also organised to converge in preparation for the mid-term review. Many thanks to the organizers.
# Credits

<table>
<thead>
<tr>
<th>Institute</th>
<th>Contributors</th>
</tr>
</thead>
<tbody>
<tr>
<td>IJCLab</td>
<td>I. Chaikovska, F. Alharthi, V. Mytrochenko, R. Chehab</td>
</tr>
<tr>
<td>INFN-LNF</td>
<td>C. Milardi, A. De Santis, O. Etisken, S. Spampinati, P. Raimondi</td>
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<tr>
<td>CEA</td>
<td>A. Chance, B. Dalena, A Ghribi</td>
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<tr>
<td>SLAC</td>
<td>T. Rauberheimen, E. Nanni</td>
</tr>
<tr>
<td>KEK</td>
<td>Y. Enomoto, K. Furukawa</td>
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<tr>
<td></td>
<td>and L. Bandiera, M. Soldani, A. Sytov (INFN/Ferrara), A. Bacci, M. Rossetti Conti (INFN/Milano)</td>
</tr>
</tbody>
</table>

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