PSI Center for Accelerator Science and Engineering

CERN | IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis | INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati | CHART Swiss Accelerator Research and Technology

FCC | 19-23 MAY FCC WEEK 2025

FCC-ee Injector overview and outlook

Paolo Craievich on behalf of the CHART/FCCee Injector Study collaboration

FCC week, 21 May 2025

Outline

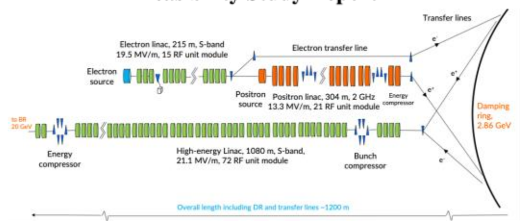
- CHART 2021-2024/FCC-ee Injector studies: few highlights
- Open questions beyond the FSR
- Next CHART phase: key developments and TDR
- Polarized pilot bunches
- Collaborations

CHART 2021-2024: FCC-ee injector study and P-cubed project

- CHART (Swiss Accelerator Research and Technology) proposal is a collaboration between PSI and CERN with external partners, CNRS-IJCLab (Orsay), INFN-LNF (Frascati) and some observers (KEK, INFN Ferrara)
- Two deliverables: (1) CDR+ → MTR → FSR + cost estimate and (2) proof of principle for the positron source

Future Circular Collider

Feasibility Study Report



FCC-ee injector complex is included in

Volume 2

Accelerators, Technical Infrastructure and Safety

CHART Swiss Accelerator Research and Technology

CHART Scientific Report (Final Report for Phase 2)

FCC-ee Injector Study and the P^3 Project at PSI

PSI:
P. Craievich, B. Auchmann, I. M. Besana, S. Bettoni, H.H. Braun, M. Duda, R. Fortunati, H. Garcia-Rodrigues, D. Hauenstein, E. Ismaili, R. Ischebeck, P. Juranic, J. Kosse, F. Marcellini, U Michlmayr, G. L. Orlandi, M. Pedrozzi, J.-Y. Raguin, S. Reiche, R. Rotundo, S. Sanfilippo, M. Schär, M. Seidel, N. Strohmaier, N. Vallis, M. Zykova, R. Zennaro

CERN:
A. Grudiev, W. Bartmann, H. Bartosik, M. Benedikt, M. Calviani, S. Doebert, Y. Dutheil, J. L. Grenard, B. Humann, A. Kurtulus, A. Latina, A. Lechner, R. Mena Andrade, A. Perillo Marcone, K. Oide, Y. Zhao, T. P. Watson, F. Zimmermann, Z. Vostrel

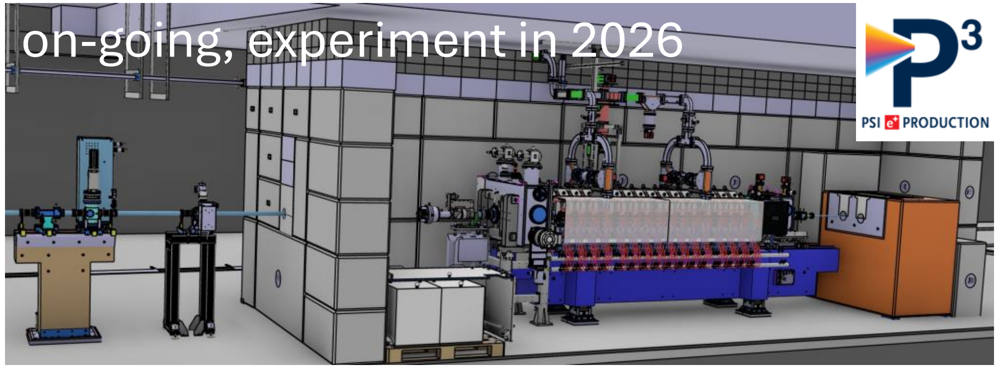
CNRS-IJCLab:
I. Chaikovska, F. Alharthi, R. Chehab, V. Mytrochenko, Y. Wang

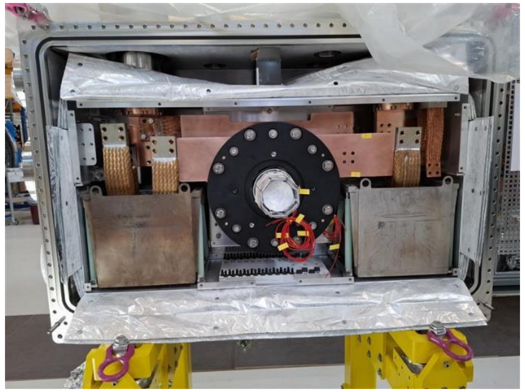
INFN-LNF:
C. Milardi, A. De Santis, O. Etisken, S. Spampinati

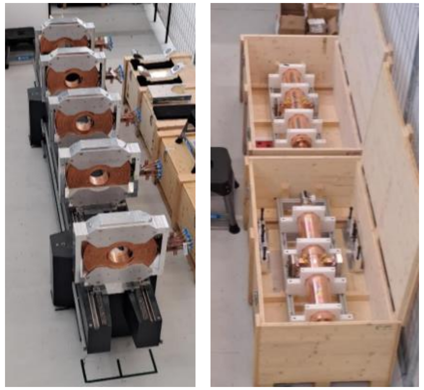
SLAC: T. Raubenheimer

KEK: Y. Enomoto, K. Furukawa

28 October 2024



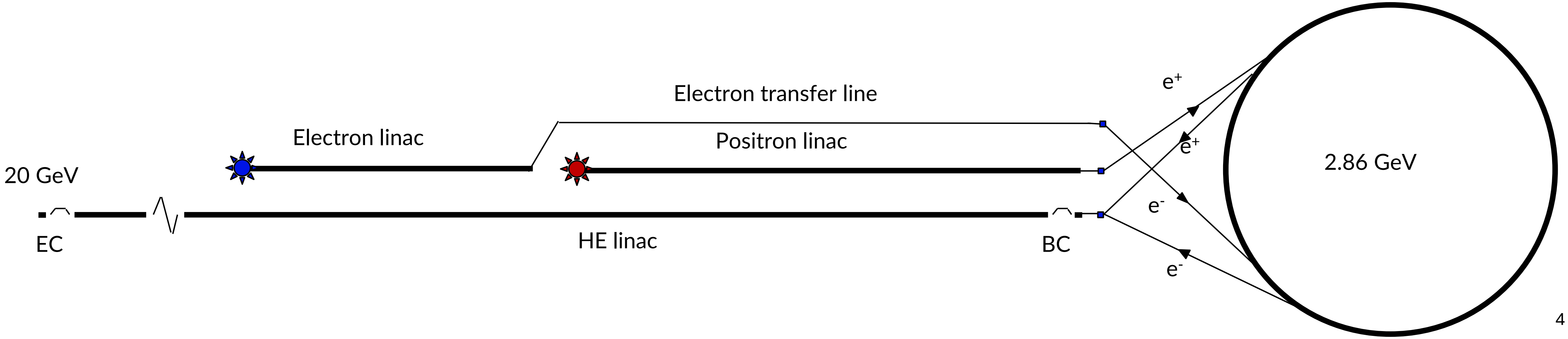




More details in the Ramiro's talk on Positron Target Design, Fabrication and Updates on P3 Integration

Optimized injector concept and parameters

- Mid-term review recommendations:
  - Optimize the linac design in term of cost and power!
  - Overall power consumption of 43.5 MW was too high. Reduction of at least factor 2 or more is necessary;
  - High average and peak power (and relatively high-gradient for S-band), operation reliability has been questioned;
  - SPS vs HE linac: keep only the HE-linac option for FS.
- New linac optimization → Power consumption (for linacs) is reduced by more than a factor 3 by means of:
  - New accelerating structures with higher shunt impedance; lower gradient (29.5 MV/m → 21 MV/m); lower repetition rate (200/400 Hz → 100 Hz) with 4 bunches per rf pulse;
  - no common linac at 400 Hz.
- New layout: Damping Ring at higher energy 2.86 GeV for both species with flat emittances (10umx1um)
- Total length of the injector complex is longer, but operation will be more reliable and layout more flexible.



New baseline layout: 4 bunches (25 ns), 100 Hz

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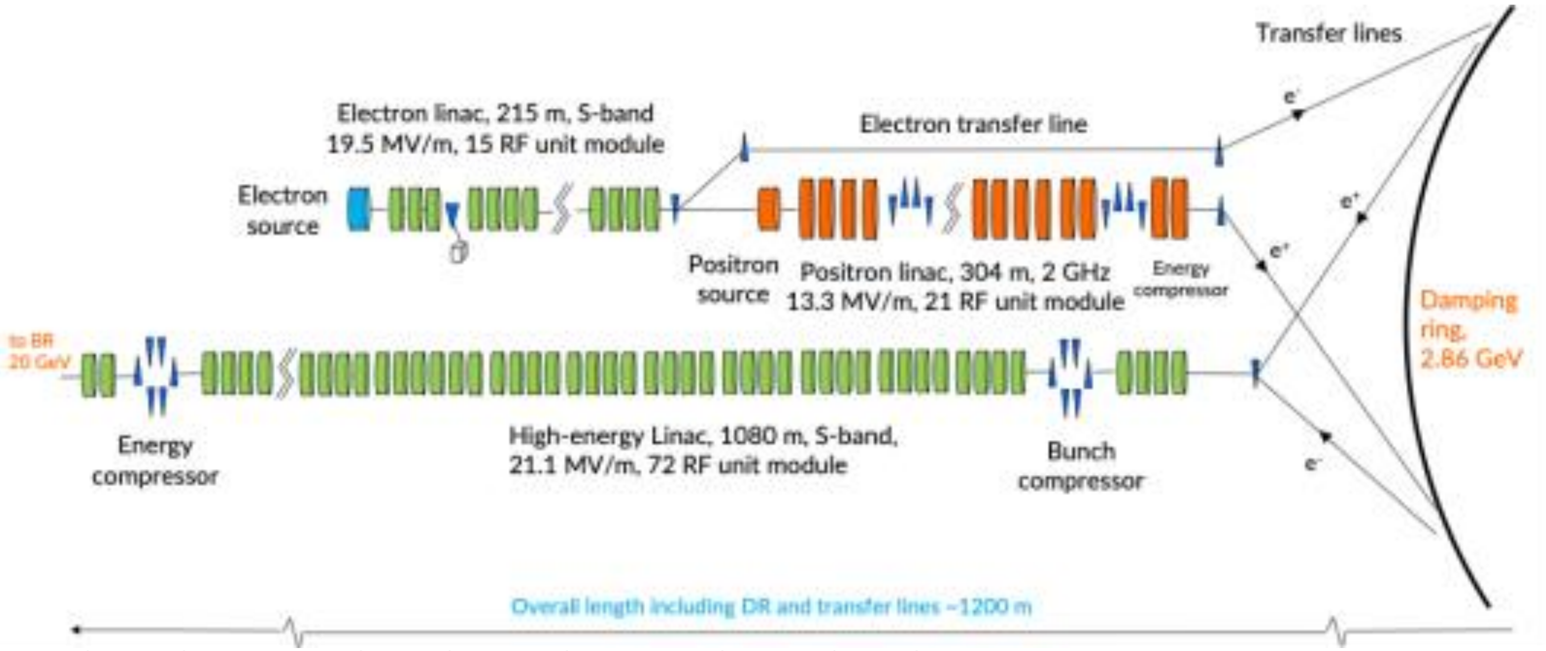


Collider and booster parameters used as specifications for the injector design

Running mode	Z	W	ZH	$t\bar{t}$	Unit
Number bunches in collider	11200	1856	300	64	
Nominal bunch charge in collider	34.40	22.08	27.04	23.68	nC
Allowable charge imbalance	5	3	3	3	%
Beam lifetime, lumi 4 IPs (q, BS, lattice)/4	916	517	428	497	s
Trains/Bunches per booster cycle	40×280	8×232	2×150	2×32	
Max injected bunch charge	3.43	3.43	1.60	1.60	nC
Number of bunches	4	4	2	2	
Linac rep. rate	100	100	50	50	Hz
Bunch spacing	25				ns
Beam energy at BR	20				GeV
Norm. emittance (x, y) (rms) (BR)	<20,2				mm mrad
Bunch length (rms) (BR)	~4				mm
Energy spread (rms) (BR)	~0.1				%

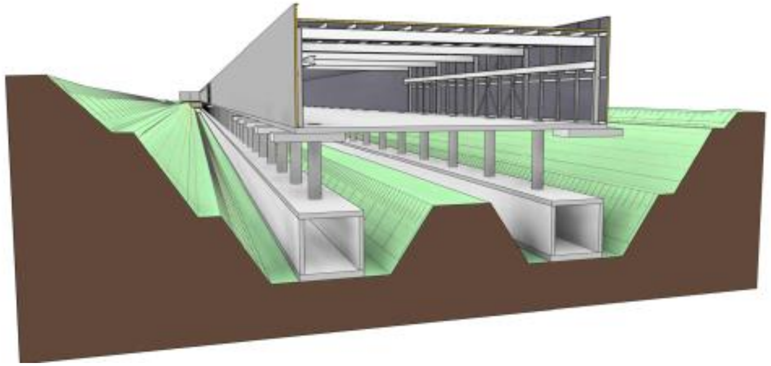
		energy (GeV)	gamma	bunch population (1e10)	bunch charge (nC)	transmission
Positron Pre-injector	LE Linac injection *	0.2	391.39	2.37	3.79	
	LE Linac exit	2.86	5596.87	2.34	3.75	0.99
	Positron source target	0.045	88.06	16.56	26.53	7.07
	Positron capture Linac exit **	0.185	362.04	9.25	14.81	0.56
	Positron Linac injection ***	0.263	514.68	7.53	12.06	0.81
	Positron Linac exit	2.86	5596.87	6.69	10.73	0.89
	Energy Compressor	2.86	5596.87	6.30	10.09	0.94
	DR injection	2.86	5596.87	3.15	5.04	0.5
	DR extraction	2.86	5596.87	3.12	4.99	0.99
Electron Pre-injector	LE Linac injection	0.2	391.39	3.24	5.20	
	LE Linac exit	2.86	5596.87	3.21	5.15	0.99
	Transfer line	2.86	5596.87	3.18	5.09	0.99
	DR injection	2.86	5596.87	3.15	5.04	0.99
	DR exit	2.86	5596.87	3.12	4.99	0.99
	Bunch Compressor	2.86	5596.87	3.09	4.94	0.99
	HE Linac injection	2.86	5596.87	3.05	4.89	0.99
	HE Linac exit	20	39138.94	3.02	4.84	0.99
	Energy Compressor	20	39138.94	2.99	4.80	0.99
	Transfer line	20	39138.94	2.84	4.56	0.95
	Booster injection	20	39138.94	2.70	4.33	0.95
Z - pole	Booster extraction	45.6	89236.79	2.68	4.29	0.99
	Collider injection	45.6	89236.79	**2.14**	3.43	0.8
WW	Booster extraction	80	156555.77	2.68	4.29	0.99
	Collider injection	80	156555.77	**2.14**	3.43	0.8
ZH	Booster extraction	120	234833.66	1.25	2.00	0.99
	Collider injection	120	234833.66	**1.00**	1.60	0.8
ttbar	Booster extraction	182.5	357142.86	1.25	2.00	0.99
	Collider injection	182.5	357142.86	**1.00**	1.60	0.8

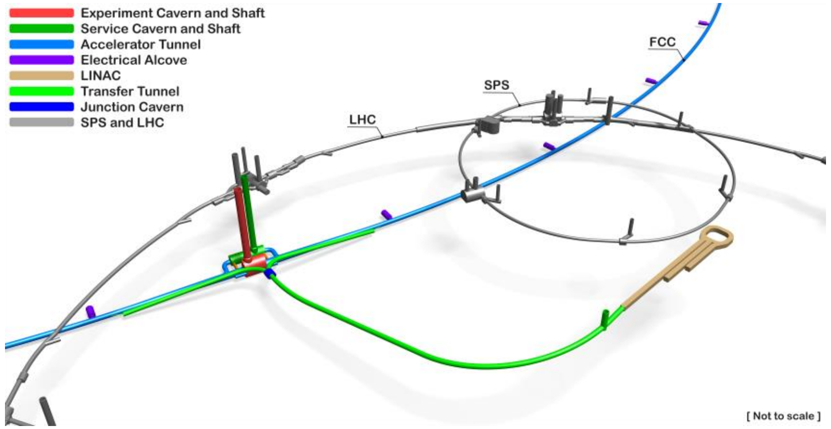
- Injector / booster synchronization and filling schemes: Hannes's talk on an *Update on the filling schemes*
- Parameters table (H. Bartosik)
  - Useful to have trace of the changes in the injector chain, i.e. charge transmission between the sources to the collider etc...
  - More parameters included in the table: bunch length, energy spread, emittances etc...

Link to the table

Injector implementation as in FSR

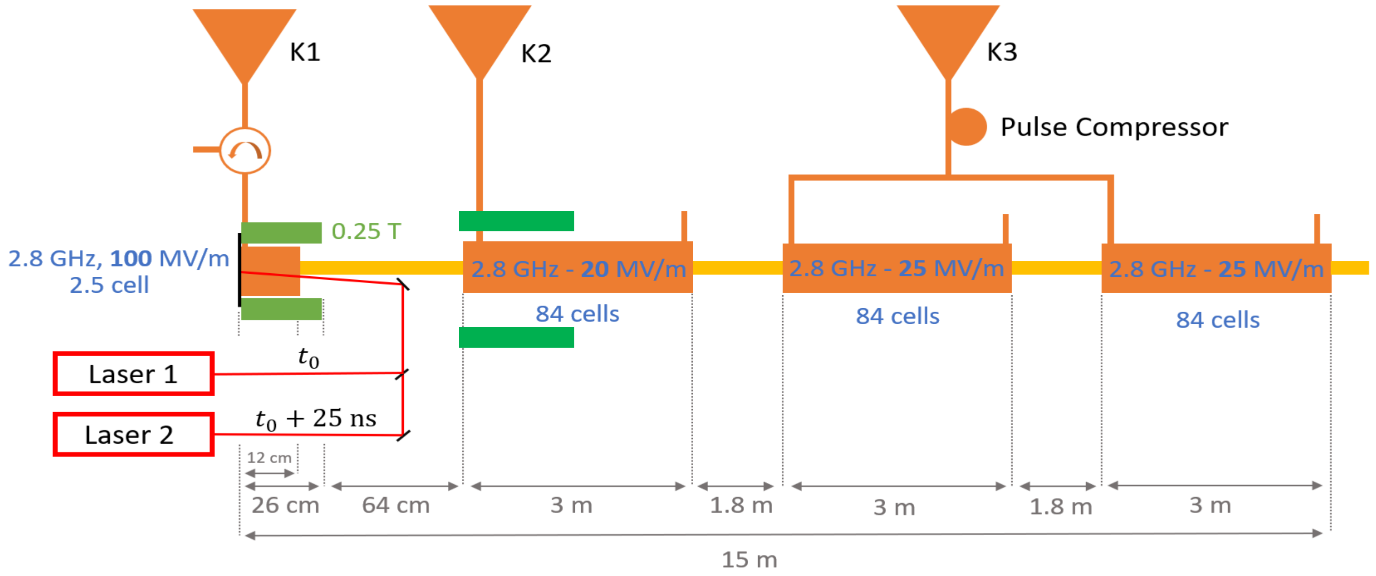
- Better integration with existing CERN Prevessin site and strongly reduced visible impact from outside.
- Ideal connection to existing experimental halls.
- Less than 5 m elevation change over the 1.2 km of terrain provides ideal conditions for “cut and cover technique”
- CERN dedicated land, small part outside fenced area but with same urbanistic classification





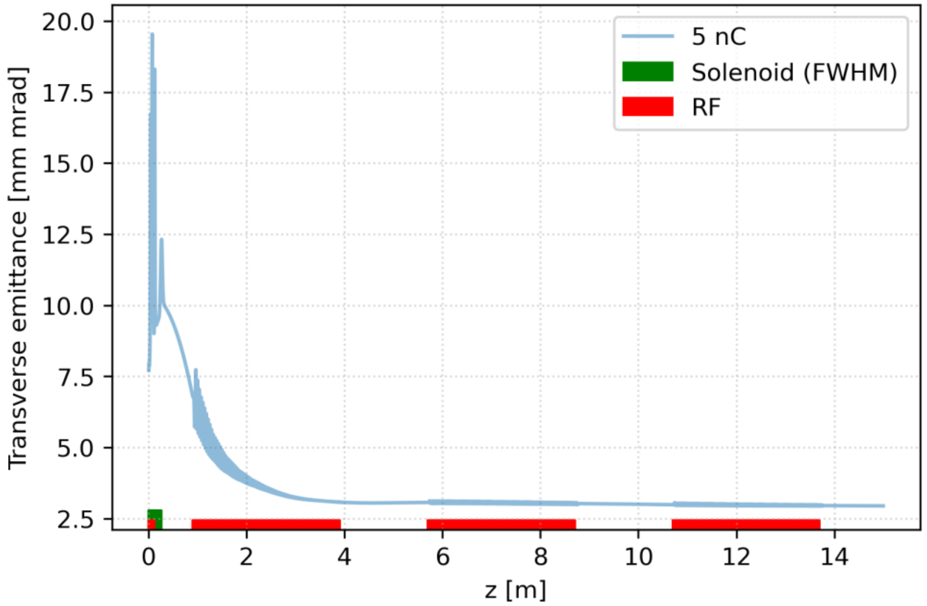
Courtesy T. Watson, W. Bartmann (CERN)

Electron source



Bunch parameter	Simulation	Target
Transverse emittance	3.14 mm mrad (rms)	< 4 mm mrad
Bunch length	0.96 mm (rms)	~ 1 mm
Energy	~ 190 MeV	~ 200 MeV
Energy spread	390 keV (0.2 %)	< 0.5 %
Bunch charge	5 nC	5 nC

- Detailed baseline design studied with errors, design documented and published in https://doi.org/10.1016/j.nima.2024.169261
- Top-up mode studied using a modulation of the laser intensity. More details in E. Granados' talk: FCC-ee top-up operation: photocathodes and laser systems.
- Next steps: Prototyping of hardware and testing of top up mode charge variation (key development)

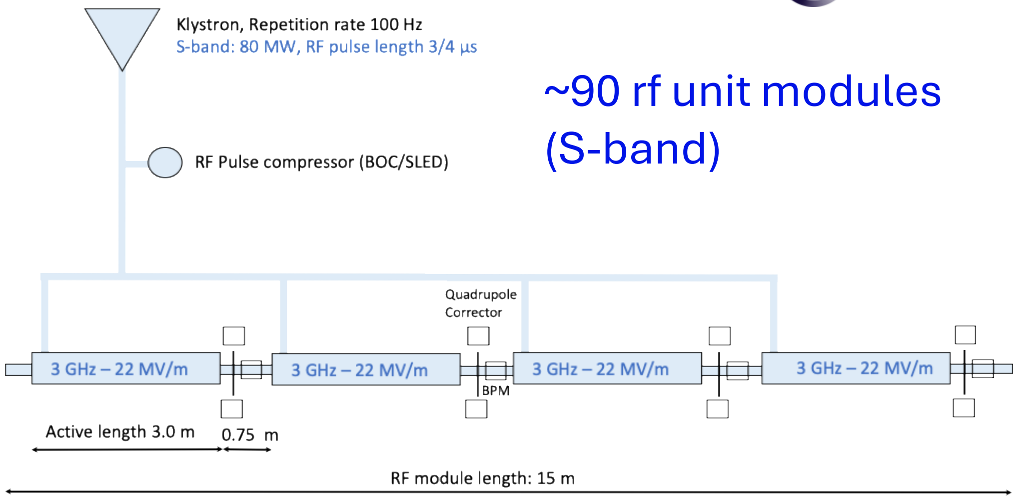


Courtesy of S. Doebert and Z. Vostřel

Highlights from linac studies (1)

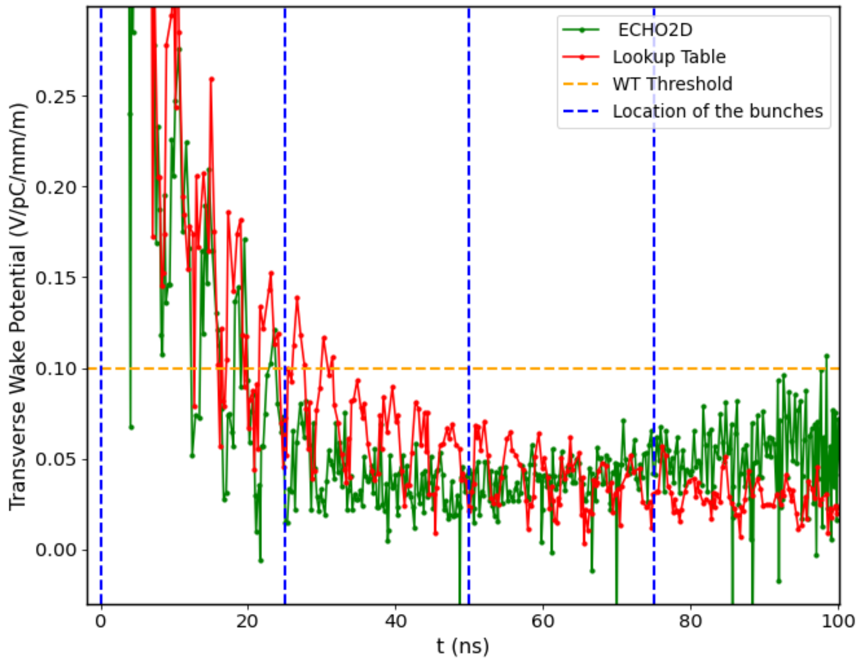
- RF unit module: 4 RF structures per module, magnets and BPM
- New RF Structure with higher impedance:
  - Active length = 3 m (compatible with PSI technology)
  - Max gradient 21 MV/m (instead of 29.5 MV/m)
- Sensitivity to static misalignments to define the aperture of the rf structures
  - Applied one-to-one correction and DFS in cascade
  - Emittance growth fulfilling the booster requirements
- Sensitivity to transverse jitter:
  - Single bunch: jitter amplification along all the linacs determined and under control
  - Multi-bunch: maximum kick defined

From these studies the maximum transverse wake kick was estimated to be <0.11 V/pC/m/mm → aperture of the rf structures fixed → RF design



~90 rf unit modules (S-band)

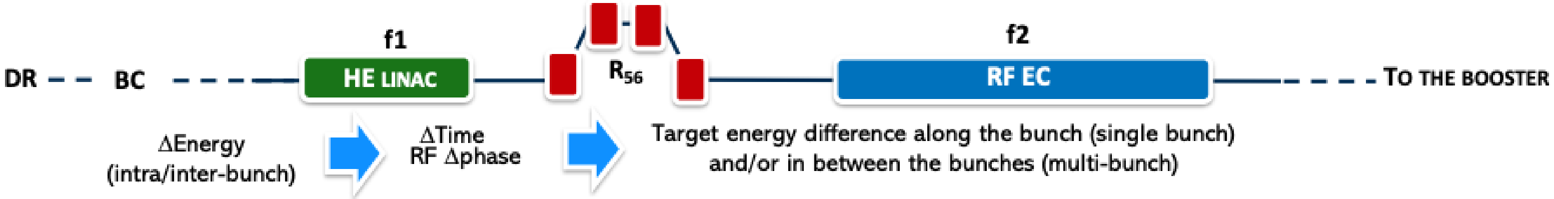
Transverse wake vs bunch temp. spacing

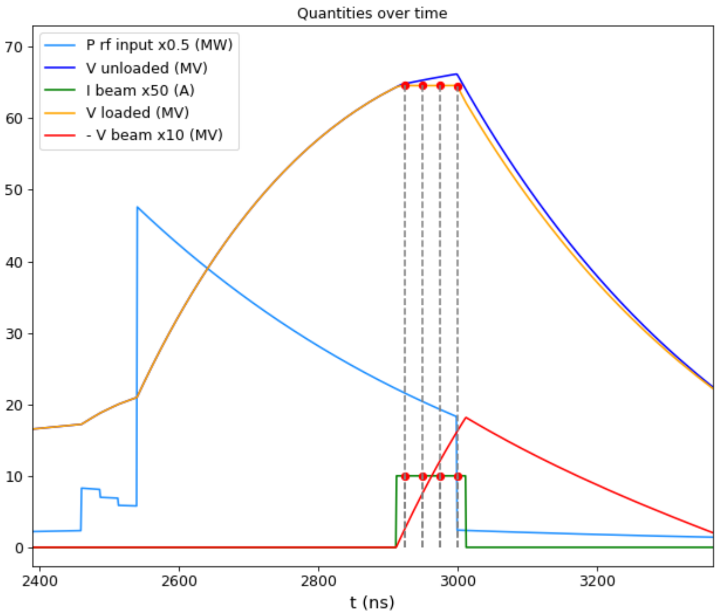


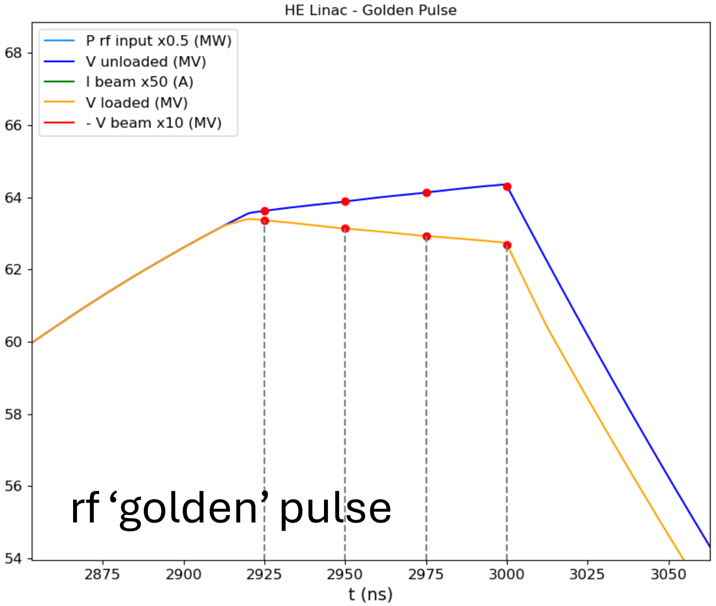
Courtesy of A. Grudiev, A. Kurtulus, S. Bettoni, A. Latina, J.-Y. Raguin et al.

Highlights from linac studies (2)

- rf ‘golden’ pulse: compensation of the beam loading and rf pulse shape, energy variation between 4 bunches below ±1.5% (also also with intensity modulation of the 4 bunches).
- High energy compressor at 20 GeV
  - Control of the single-bunch energy spread and minimization of the energy variation between the four bunches (to fulfil the BR specs)







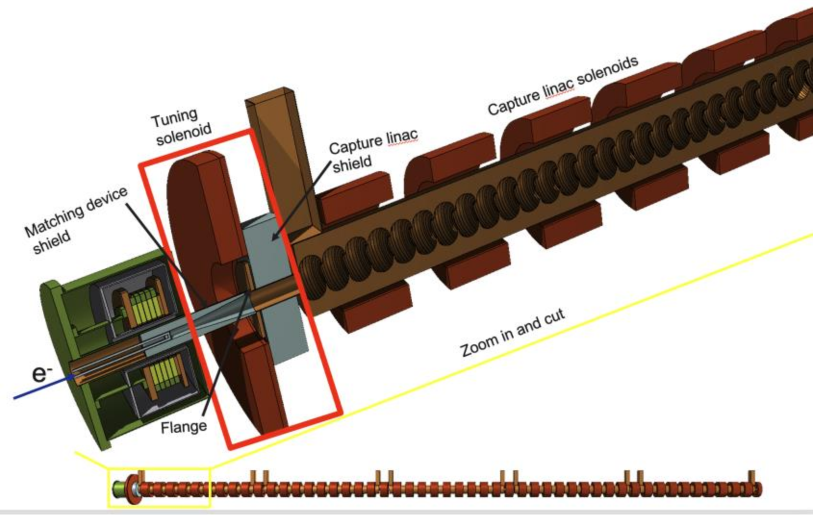
More details in:

- Injector linacs: the design and the RF frequency choices for the TDR, A. Grudiev
- Injector: linacs design for single- and multi-bunch effects, S. Bettoni
- RF Design and Optimization of the High-Energy Linac for the FCC-ee Injector Complex, A. Kurtulus (poster on Thursday)

Courtesy of A. Grudiev, A. Kurtulus, S. Bettoni et al.

Positron source and linac

- Request a positron flux of $\sim 1.1 \times 10^{13}$ e+/s. Demonstrated at SLC (a world record for existing accelerators): $\sim 6 \times 10^{12}$ e+/s
- A safety margin of 2.5 is assumed, i.e. 13.5 nC at the DR injection.
- Positron production: conventional scheme with a tungsten target
  - Matching device is based on the SC solenoid (5 HTS coils, ∅ 72 mm bore, ∅ 60 mm including shielding);
- Capture linac is based on 2 GHz TW RF structures (∅ 60 mm, 3-m long) → no rf power source on the market to test prototypes. NC solenoid B = 0.5 T.



Fluka model, Courtesy of B. Humann

- Next steps:
  - optimization of the linac based on 3 GHz RF structures (1.5 GHz for capture linac?) and Low-temperature SC solenoids around the RF structures
  - **BUT necessary start-to-end simulations from the target to (first turns in) DR**

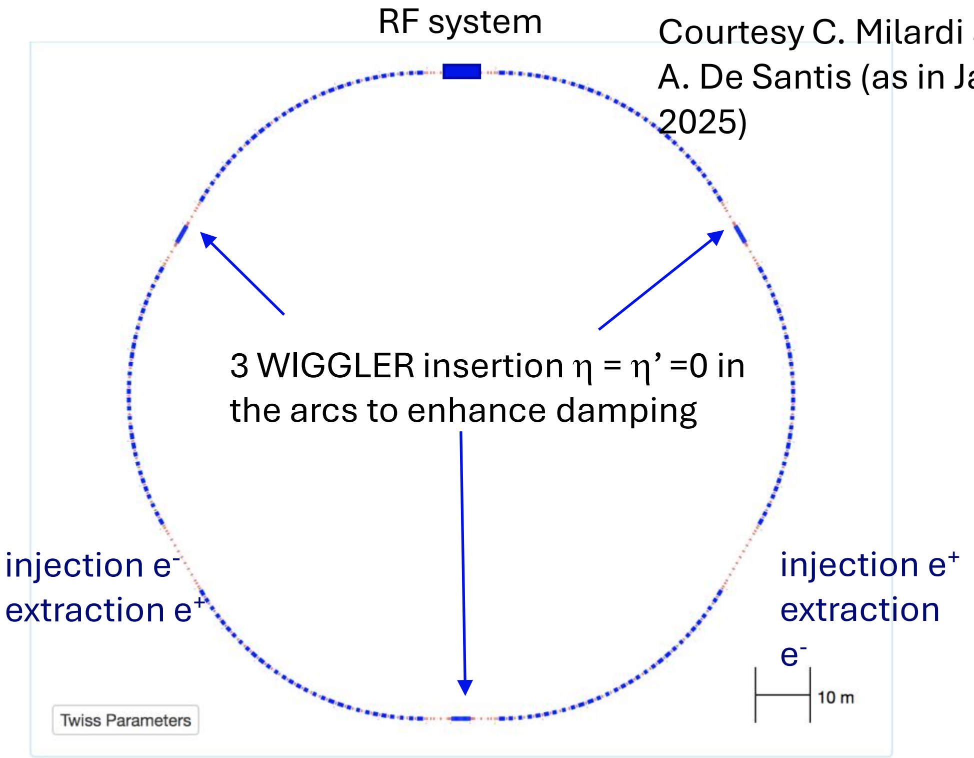
More details in:

- Positron Production for FCC-ee (this session), I. Chaikovska and
- Positron Target Design, Fabrication – Updates on P3 Integration (this session), R. Mena Andrade
- Radiation damage study of the FCC-ee crystal-based positron source (poster on Thursday) , F. Alharthi

Damping ring and transfer lines at 2.86 GeV

- Decision based on the SuperKEKB experience: also use DR for for electron (more stable beam after the DR)
- Allocated space for the DR: 122 m x 122 m
  - Wide flexibility in independently tuning the ring working point
  - Three arc cells (120 deg) providing, low emittance, damping time, large beam acceptance
- Flexible injection/extraction sections
- Dedicated space for RF system and wiggler magnets

Courtesy C. Milardi and A. De Santis (as in Jan 2025)



- Next steps:
  - Consolidate the DA aperture in synergy with the positron linac study
  - Physical design of the four transfer lines and injection/extraction systems (strong impact of the overall length of the injector complex)

More details in the two talks:

- FCC-ee Injector: New DR at 2.86 GeV, Antonio De Santis
- Approach for low impedance design of the FCC DR vacuum chamber, Shalva Bilanishvili

Open questions beyond the FSR

- Electron source for top-up operation: bunch-by-bunch charge will vary from 0 up to 5 nC at 100%, depending on the intensity balance in the collider rings – few approaches to be tested on laser system and photocathode RF gun.
- Positron linac: new optimization to use S-band frequencies as in electron linac, complete the installation of the p-cubed experiment and perform the experiment (including a radiation tests).
- Electron and HE linac: new working frequency, needed a prototypes phase to estimate the BDR, experimental verification of LLRF pulse modulation to generate the 'golden pulse'.
- Injector/booster synchronization: studying the possibilities of injecting into any given bucket.
- DR at 2.86 GeV and transfer lines, optimization of the DA based on the positron linac, collective effects, include errors. Complete the physical design of the DR, transfer lines (4x), and injection/extraction systems.
- Polarized positrons (and electrons) from the injector: assess the impact on the layout and the buildings.
- More in general: Review of the overall length of the injector complex including sub-systems.

Post-FS phase: Towards a TDR – recap and comments

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- Following the completion of the Feasibility Study phase (March 2025), a Technical Design Report for the Injector should be ready by 2028.
- TDR will provide detailed specifications for the accelerator and technical infrastructure requirements necessary for the CE design - Finalizing the layout to start the civil engineering design.
- Presently preparing a proposal to be submitted to CHART 2025-2028 with all partners that were already involved in the previous phase – Decision from CHART council beginning of June

Injector Project schedule (as presented by M. Benedikt, FCC week 2024)

Start 2025 – end 2028 TDR injector ← CHART 2025-2028

Start 2028 – end 2030 CE design and tendering

Start 2029 – end 2031 Accelerator and technical infrastructure engineering designs

Start 2031 – end 2034 Civil construction work

Start 2032 – end 2040 Component production (rates for RF structures as for SwissFEL)

Start 2034 – end 2036 Technical infrastructure installation

Start 2035 – end 2040 Component installation and testing

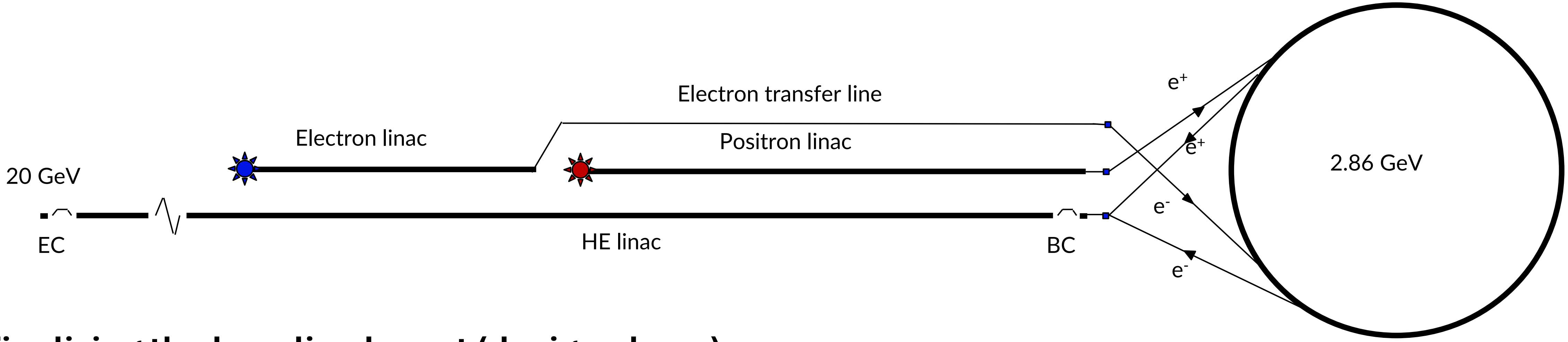
Start 2041 HW commissioning

Start 2042 beam commissioning

Activities in CHART/FCC-ee Injector – present CHART proposal

- **Key developments (PSI/CERN)**
  - Positron source: P-cubed project
    - ✓ complete the installation and perform the experiment
    - ✓ set-up the hybrid scheme
  - S-band prototypes: RF structure and pulse compressor (PSI) and definition of industrialization process
    - ✓ High power test at CERN and high-efficiency klystron development
  - Electron source: high-charge generation and modulation
    - ✓ Installation of the spare SwissFEL RF gun (baseline for FCC-ee), laser system and beamline with diagnostics (PSI)
    - ✓ Collaboration with CERN on photocathode development and laser system
- **Integration of the positron source**
- **Beam dynamics simulations**
  - Positron linac: Start-to-end simulations from target to DR (from 2 GHz to 3 GHz) – IJCLab/CERN/PSI
  - Electron and positron linacs: design of the BC, EC, including diagnostics etc.. CERN/PSI
  - …

Towards a TDR... (1)

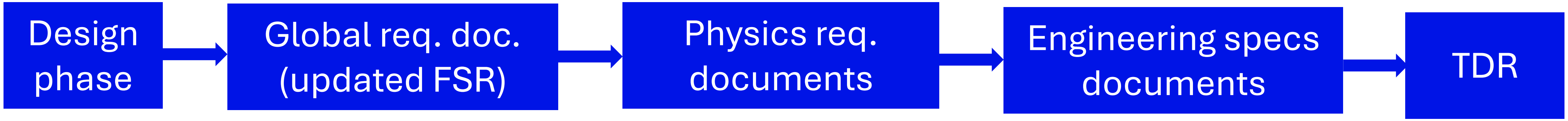


Finalizing the baseline layout (design phase)

- New working frequency for the electron and HE-linac
- Optimization of the positron linac based on the acceptance in the DR
- Physical design of the BC (2.86 GeV) and EC (20GeV)
- Including the diagnostics and matching lines
- Physical design of beam stoppers and dumps
- DR and transfer lines (INFN/LNF), injection/extraction systems
- Define the Synchronization and Timing between injector and BR

Deliverable: An FCC-ee Injector unified global requirements document outlining the performance specifications for the FCC-ee injector linacs, sources, transfer lines and DR – in practice, updating the FSR with new subsystems

Towards a TDR… (2)



- **(Specific) physics requirements documents**
  - These documents derive from the updated-FSR and define the performance criteria for each injector sub-systems. These documents are the physics-based specifications that could guide the initial stages of engineering design
    - ✓ Requirements for FCC-ee Injector linac S-Band systems (e-linac and HE-linac)
    - ✓ Requirements for FCC-ee Injector positron linac
    - ✓ Requirements for FCC-ee Injector linac magnets
    - ✓ Requirements for FCC-ee Injector positron source
    - ✓ Requirements for FCC-ee Injector electron source
    - ✓ Requirements for FCC-ee Injector bunch compressor
    - ✓ Requirements for FCC-ee Injector energy compressor at HE linac end
    - ✓ …

Part of these documents will be drafted within the next CHART collaboration

- **(Specific) engineering specifications documents → chapters of the TDR**
  - These documents should outline system- and/or component-level requirements or parameters and may serve as a basis for manufacturing specifications.

Diagnostics and beam dump requirements for linacs (an example)

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work in progress

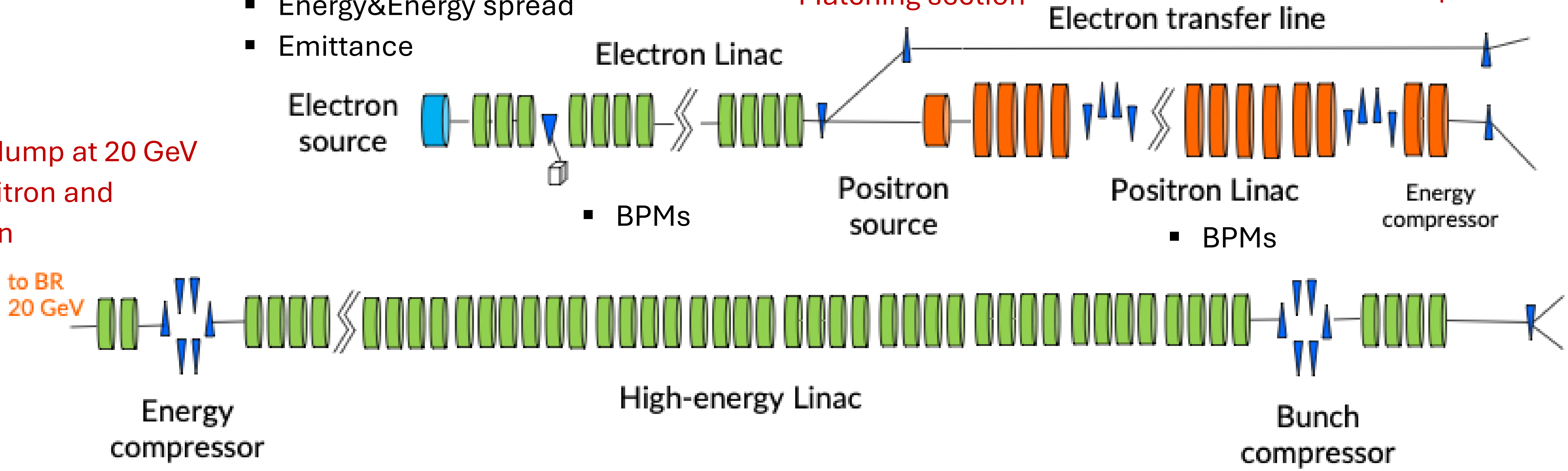
Beam Dump for Electrons
- Charge, Emittance
- Energy & En. spread
- Matching section

- Charge
- Energy&Energy spread
- Emittance

- BPMs

Beam dump at 2.86 GeV for positron and electron

Beam dump at 20 GeV for positron and electron



- BPMs

- BPMs

- Energy & Spread (screen)
- Emittance (screens)
- Compression monitor
- Arrival time monitor
- Matching section

- BPMs

- Energy & Spread (screen)
- Emittance (screens)
- Compression monitor
- Arrival time monitor
- Matching section
- Bunch length measurement

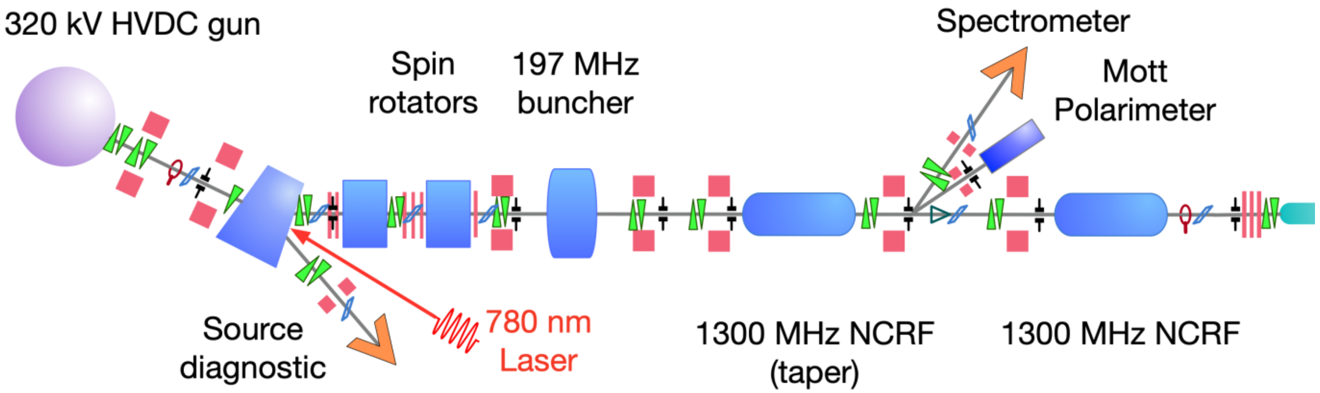
Polarized electron and positron pilot bunches (1)

~1.6 nC, ~100 bunches, twice per day

- Motivation (from J. Heron's talk at FCC week 2024):
  - *pre-polarised (electron and positron) bunches to be injected into the CR for energy calibration may be extremely valuable to boost integrated luminosity (15-40 % gain over the baseline configuration) but positive effect becomes even more relevant for increasing fault rate*

- EIC electron pre-injector concept (BNL)

Courtesy of Erdong Wang



RESEARCH ARTICLE | JUNE 17 2024

High-intensity polarized electron gun featuring distributed Bragg reflector GaAs photocathode

Erdong Wang; Omer Rahman; Jyoti Biswas; John Skaritka; Patrick Inacker; Wei Liu; Ronald Napoli; Matthew Paniccia

Check for updates

Appl. Phys. Lett. 124, 254101 (2024)

https://doi.org/10.1063/5.0216694

Charge achieved 7.5 nC, polarization >86%, rep rate 30 Hz

- Preliminary simulations for FCC-ee have shown that – using the current positron source with polarized electrons – positrons accepted in DR can preserve a polarization of about 4-5% (F. Alharthi and I. Chaikovska → not enough for pilot bunches but more detailed simulations will be done.
- Also see the K. Aulenbacher's talk on Thursday at 15:50 in EPOL (ii) session.

Polarized electron and positron pilot bunches (2)

- Small polarizer storage ring for pilot positron (and electron) bunches
  - the ring could be installed inside the perimeter of DR or even in the damping ring tunnel. This option in under investigation by C. Carli.
- In addition, spin rotators in the transfer lines are needed.
- The depolarisation in the FCC-ee booster was studied by Zhe Duan (IHEP) with inputs from F. Zimmermann, A. Chance, B. Dalena and A. Vanel. Some conclusions (link 1 and link 2):
  - Polarization transmission are typically ~90% (Z), ~60%(W), ~15%(H) and zero (top) for different lattice seeds of the two lattice designs.
  - More comprehensive error sources and more sophisticated error correction schemes are yet to be included.

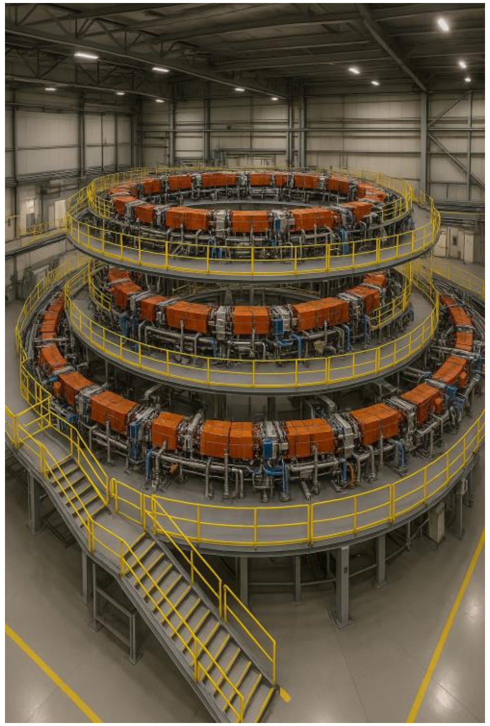


Image produced by AI

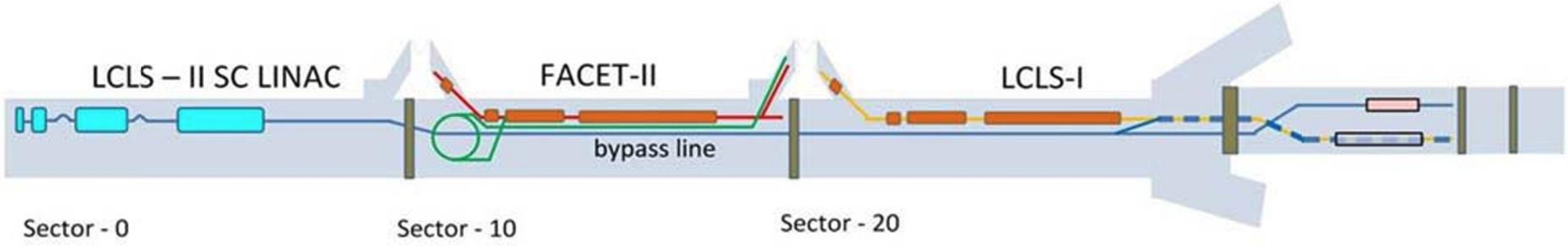
- Next steps:
  - Proposal for the polarizer small ring(s) and for their installation.
  - Electron source: keep open this possibilities during the discussion on the buildings.

Future (potential) collaborations (1)

SLAC/FACET II (more details in Brendan O'Shea's poster on Thursday)

- BUNCH COMPRESSION + EMITTANCE GROWTH
  - Measure emittance growth of 5 nC bunches, from 335 MeV to 4.5 GeV and 4.5 GeV to 10 GeV
- JITTER + WAKEFIELDS + OPTICS
  - Examine jitter amplification and damping; multiple bunch wakefields
  - Kick on one bunch due on the preceding one
  - Characterization of the wakefield; model versus measurements comparison
- PHOTOINJECTOR + TOP-UP INJECTION
  - Measure how beam parameters vary at 125 MeV by adjusting the beam energy and transverse size using "analog methods"
  - Explore methods to reach 100 Hz variation: spatial light modulator and Pockels cell at beam rate (30 Hz)

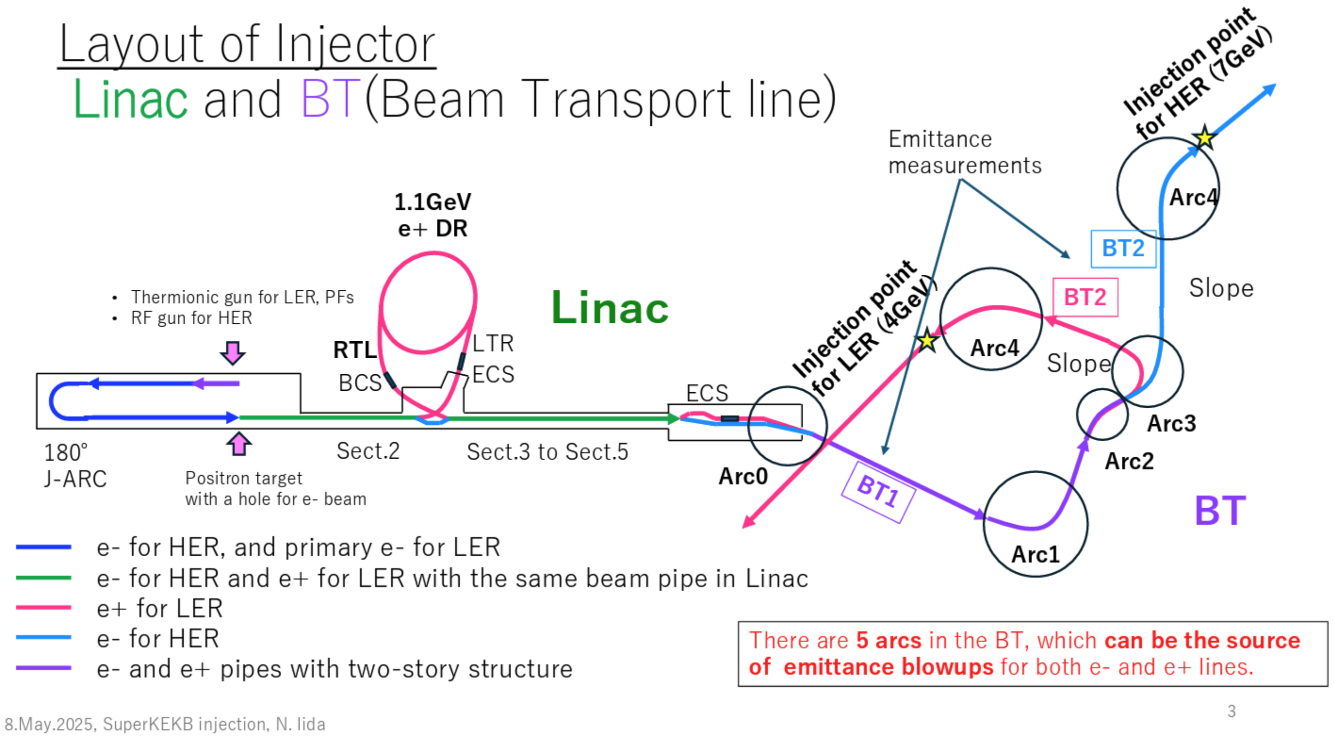
FACET-II PAC approved the experiments for beam time!



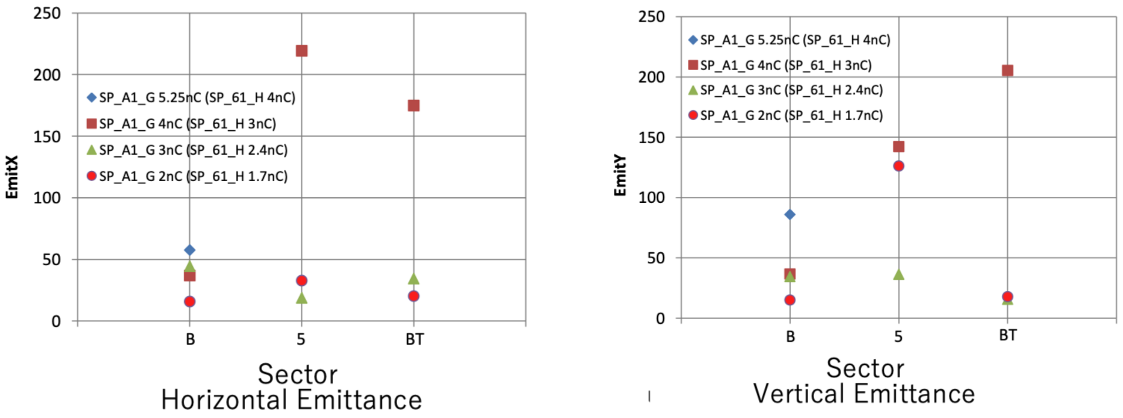
Future potential collaborations (2)

SuperKEKB (2-bunch at 96 ns)

- Study of the emittance growth in the electron linac
- Validation of the models used for the trajectory jitter amplification and damping
- Characterization of the wakefield; model versus measurements comparison
- Mini-workshop on SuperKEKB and implications for the FCC-ee: Emittance preservation simulations in the linac and transfer lines (at SuperKEKB) by Ilya Agapov (DESY)



Emittance growths along the SuperKEKB electron linac



Mitsuhiro Yoshida (INJ-Group of Injector Linac)

Fast kicker for second bunch: Five fast kickers capable of kicking only the 2nd bunch in the y-direction have been installed. *To achieve the same injection efficiency as the 1st bunch, the beam orbit of the 2nd bunch must be same as 1st bunch*
→ study of the long rang wakefields.

Conclusion

- The valuable recommendations from MTR led to a new baseline for the injector concept, coupled with a new implementation plan at the Prevessin site BUT the injector length is under review.
- The Feasibility Study Report on the injector was submitted on time, thanks mainly to the efficient collaboration within CHART, which also involved external partners.
- Optimized power consumption figures, a cost estimate, and a risk register for the injector complex have also been submitted.
- The new proposal for CHART 2025–2028 is ready for submission to the CHART Council, decision is expected at beginning of June.
- Polarized pilot bunches: the use of small ring(s) for the polarization of positrons (and electrons) is currently under study.
- Collaborations with SLAC and KEK could provide experimental verification of the models used in simulations.

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FCC

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CHART Swiss Accelerator Research and Technology

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FUTURE CIRCULAR COLLIDER

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That's all, thank you!!