PSI Center for Accelerator Science and Engineering

FCC-ee Injector complex

status, highlights and outlook

Paolo Craievich (PSI) on behalf of the CHART collaboration and Injector pillar

33rd LINAC Conference, 16-21 August 2026, Daejeon, Korea

TU1P003

Outline

FCC-ee injector specifications and layout

Electron source

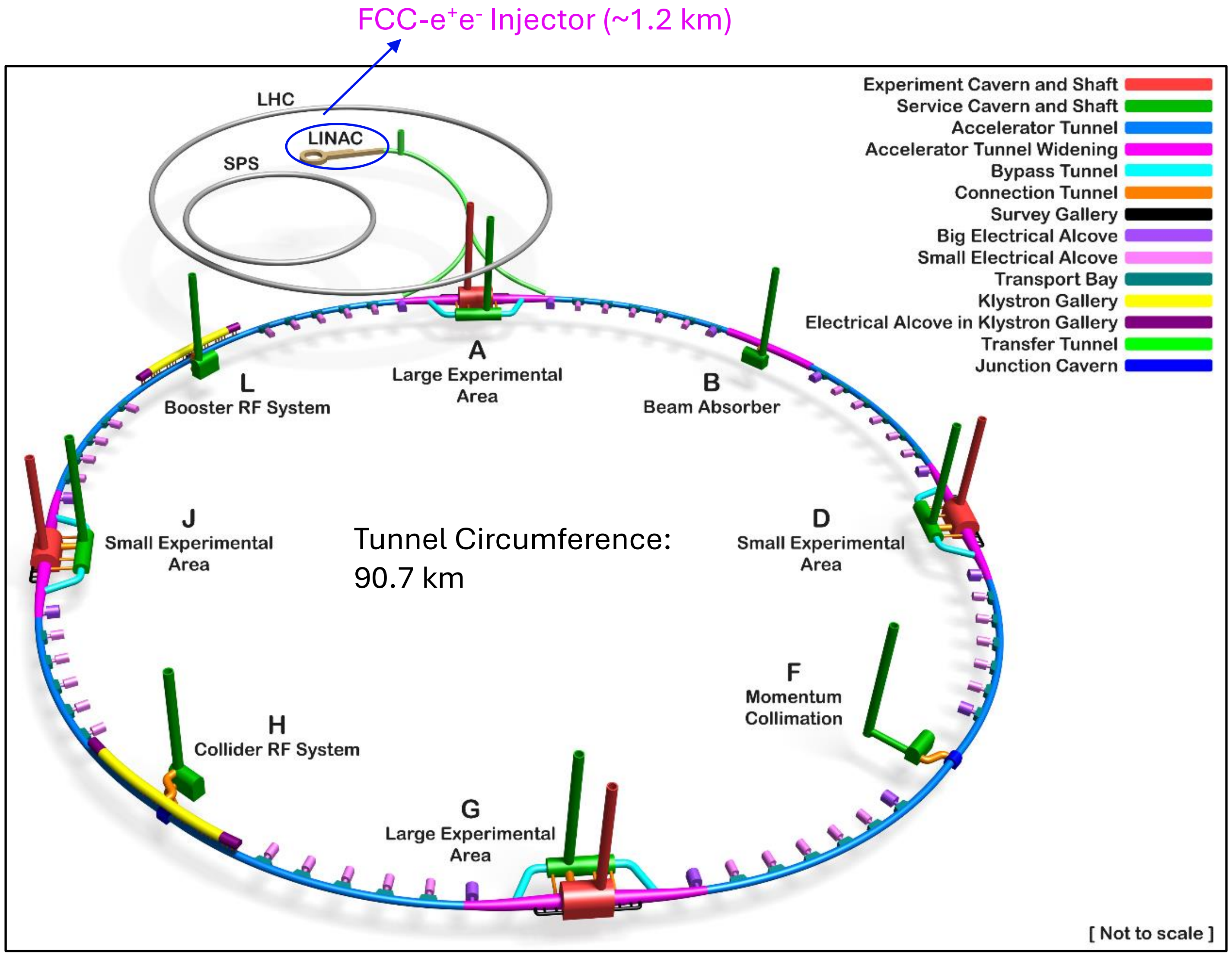
Electron and High-Energy linacs

Positron source and linac

Damping ring

Conclusion and final remarks

Future Circolar Collider e-/e+ - FCC-ee



M. Benedikt (FCC project leader) at FCC week 2026:

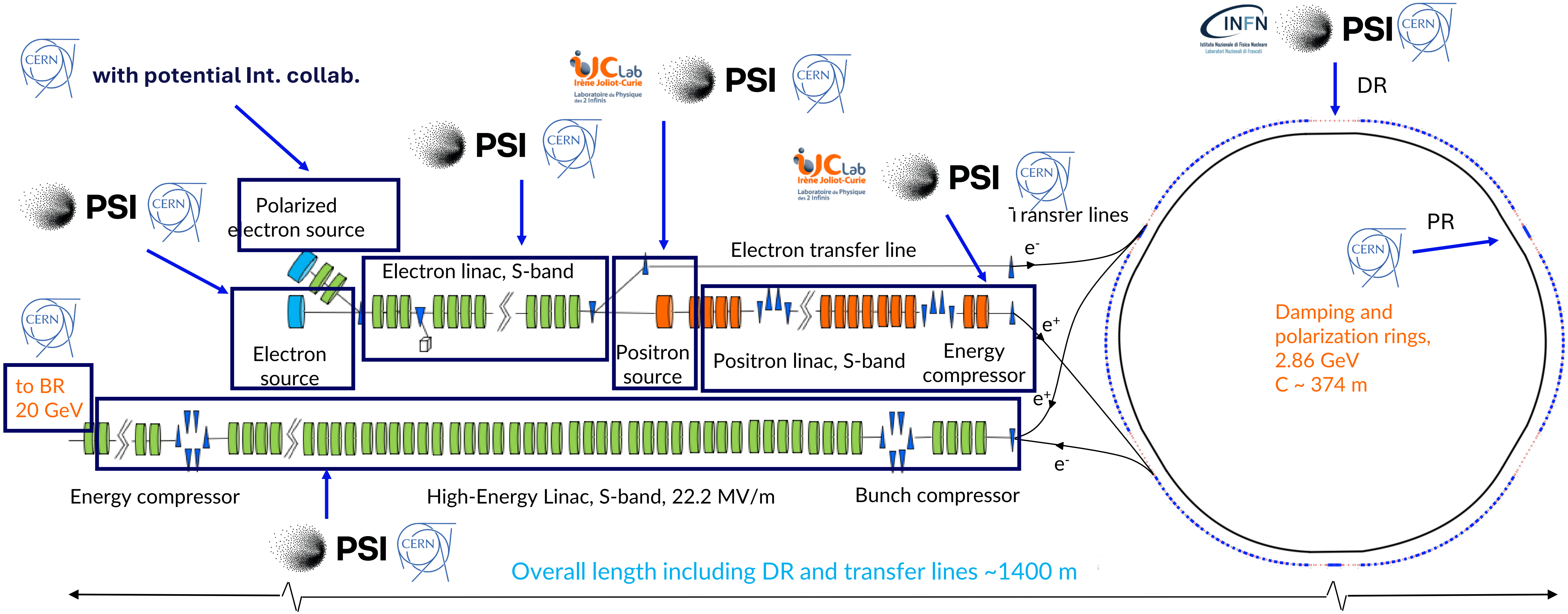
- Following the **positive assessment** of the Feasibility Study and CERN Council approving the **continuation**, the FCC moves towards technical design.
- **Expertise across CERN and from collaboration partners** is required to be able to deliver an integrated technical design, with cost estimate and schedule, taking into account project authorisation processes, societal acceptance, procurement strategy.

Two phases:

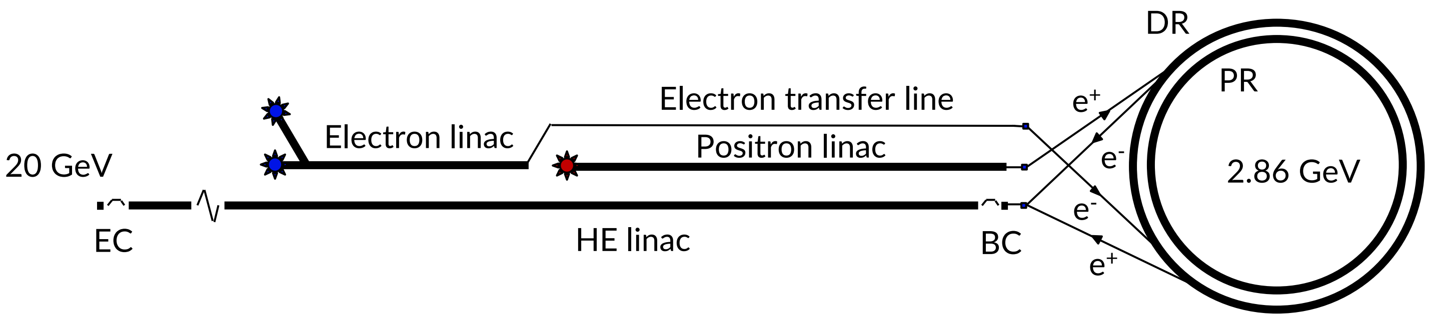
- **2026-2028 Reference Design Phase (RDP)**
- 2029-2032 Technical Design Phase

Referecne: CERN-FCC-ACC-2025-0004

The Injector complex: layout



The Injector complex: specifications



Injector main specifications

- Beam energy 20 GeV (injection energy into the booster ring)
- Normalized emittance 20x2 mm mrad, energy spread 0.1%
- @ Z-pole (most demanding):
  - Injectors provide pulses of 4 bunches (up to 5 nC) with 25 ns bunch spacing, at 100 Hz repetition rate
  - 1/10th of all collider bunches with 1/10th of the collider bunch intensity per booster cycle.
- Top-up operation:
  - Pulse-to-pulse modulation of the charge for each bunch
  - Reliability and availability become important aspect → well-proven conventional RF NC technology as SwissFEL

Table as in FSR.

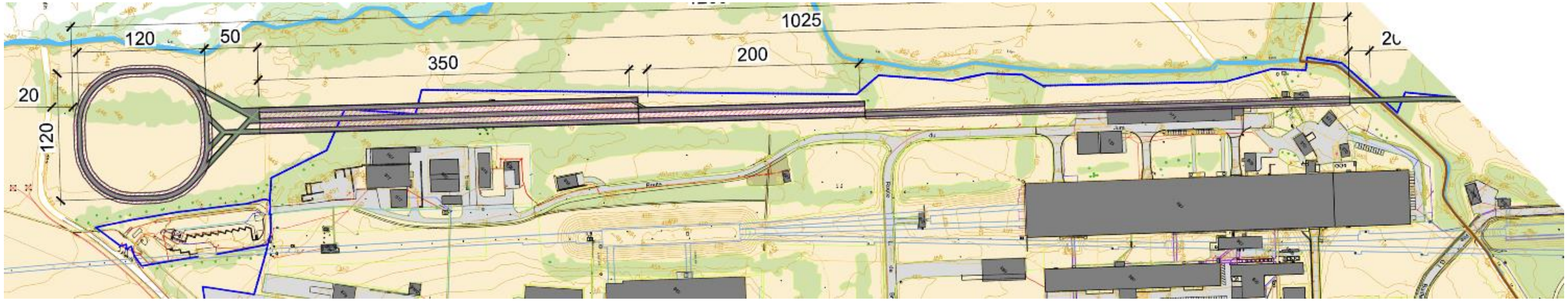
Running mode	Z	W	ZH	$t\bar{t}$	Unit
Number of bunches in collider	11200	1856	300	64	
Nominal bunch charge in collider	34.40	22.08	27.04	23.68	nC
Allowable charge imbalance	5	3	3	3	%
Beam lifetime, lumi 4 IPs	916	517	428	497	s
Trains/Bunches per booster cycle	40×280	8×232	2×150	2×32	
Max injected bunch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

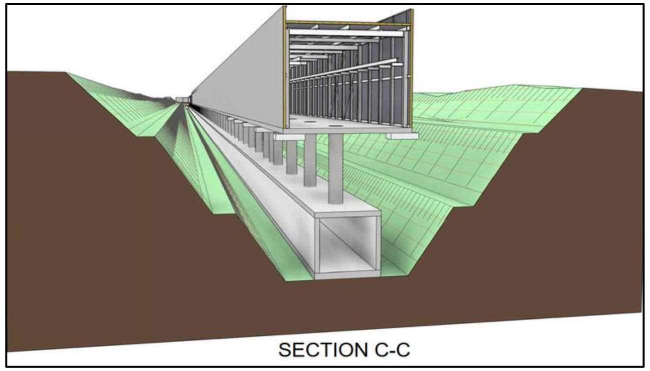
With high reliability, excellent maintainability, low operational costs, low power consumption

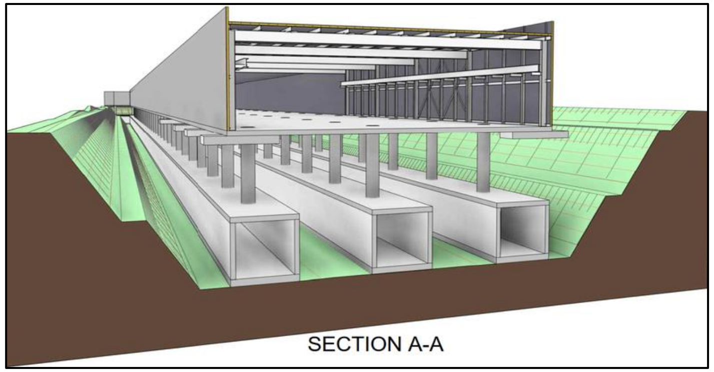
New spec.: Provide on request by the collider, polarized electron and positron as non-colliding bunches

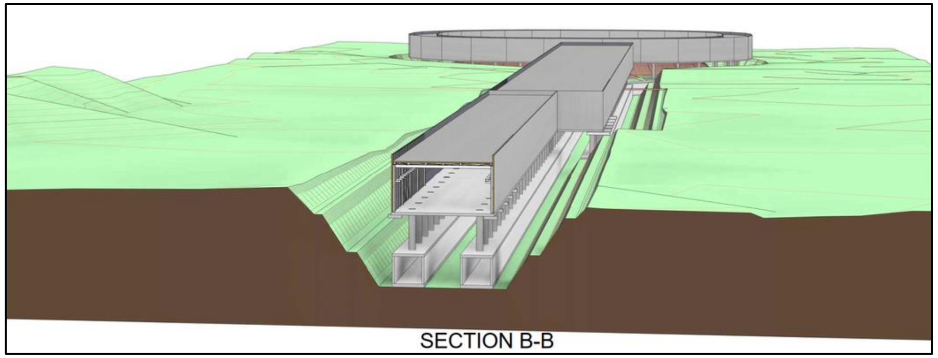
The Injector complex: siting on CERN site (Prévessin option)

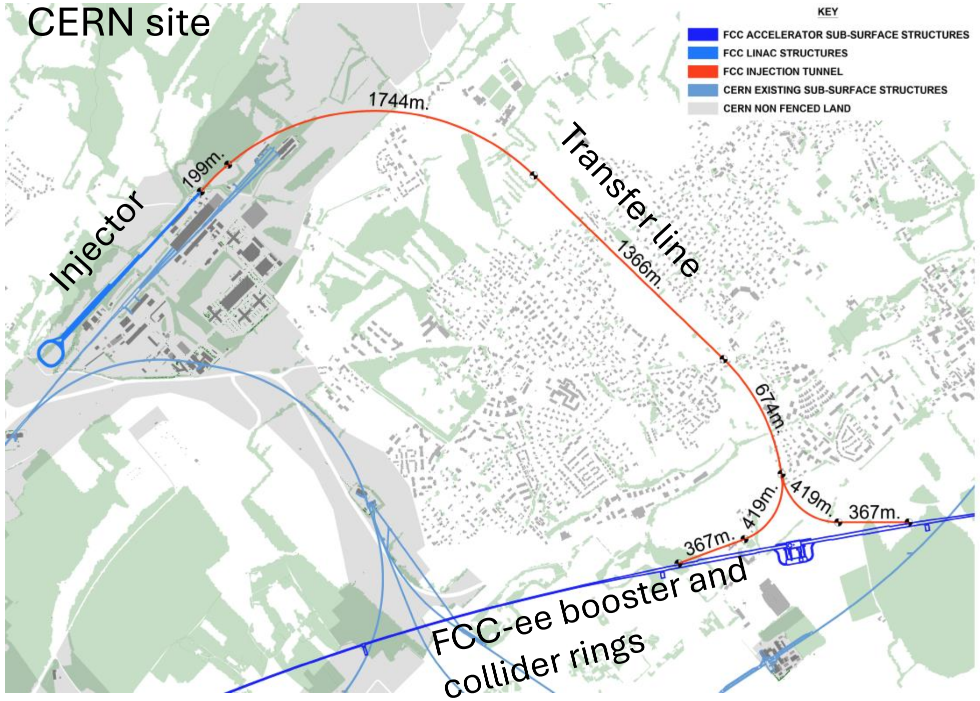
work in progress at CERN











Courtesy of T. Watson (CERN)

The Injector complex: (main) high level goals

specific to the injector complex for the Reference Design Phase (RDP)

- Finalisation of the injector complex design, including damping ring, polarisation schemes and input for placement, together with CHART 25-28 and CERN-led system integration – end 2027
- Definition of placement, civil engineering requirements, surface integration and technical infrastructure needs – end 2027
- Validation of the positron source performance (yields) through a dedicated experiment (P3) at the Swiss X-ray Free Electron Laser (SwissFEL) at PSI - end 2027
- Validation of the electron bunches modulation – end 2028
- Integration of injector operations with non-collider physics and test-beam programmes – end 2028

New **Injector pillar** at CERN, S. Gilardoni (CERN)

Technical groups involved
WBS and PBS under preaparation

now part of the pillar organisation

CHART/FCC-ee injector project, 2025-2028
Beam physics study
Electron and positron sources validation
RF prototypes manufacturing

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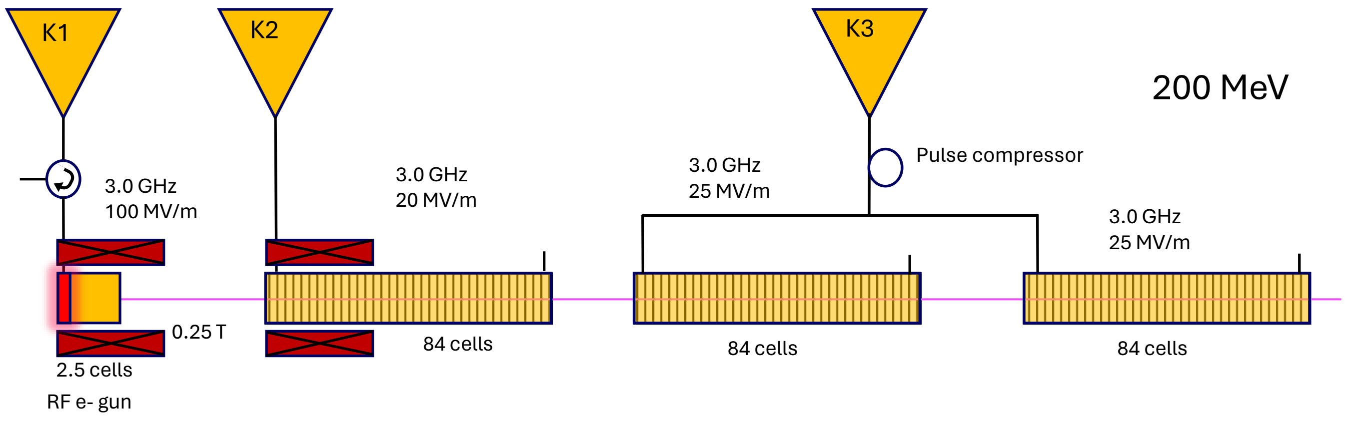
Electron source: beam dynamic simulations



Baseline: Photoemission RF gun based on the SwissFEL RF gun

Charge up to 5 nC, bunches for collider & positron source (no polarized electrons)

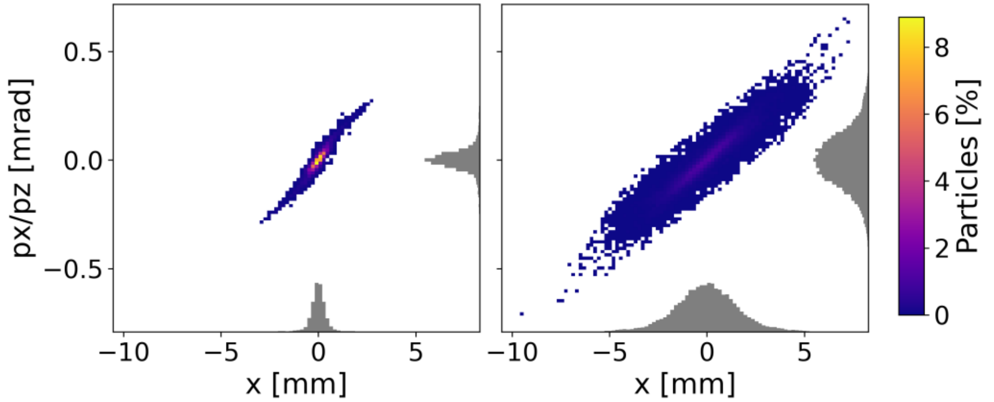
4 bunches with 25 ns spacing at 100 Hz to complain with filling scheme → **baseline is to use 4 laser systems**

Shot-to-shot charge modulation at 100% for top-up operation

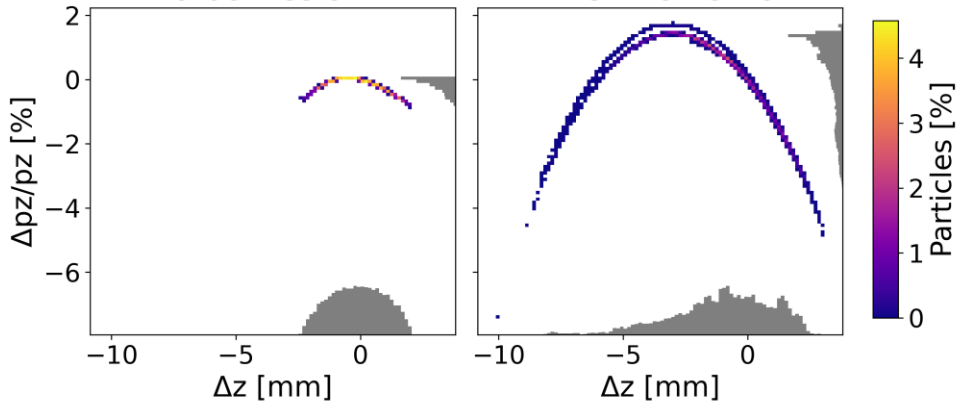
Details in: https://doi.org/10.1016/j.nima.2024.169261

Possibility to use the damping ring for electron as well → explore thermionic gun to provide input for comprehensive comparison (bunch properties, charge variation)

Transv. phase spaces



Long. phase spaces



work in prgress to estimate the effect on the positron production

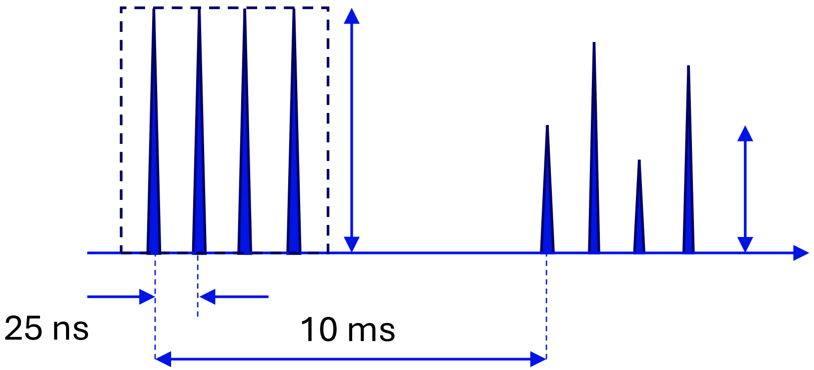
Contacts: Z. Vostrel (EPFL, CERN) and S. Doebert (CERN)

Electron source: UV laser manipulation

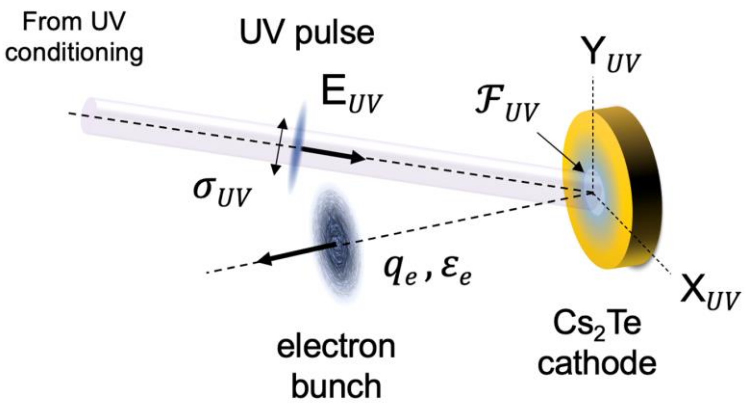
beam shaping techniques for top-up operations

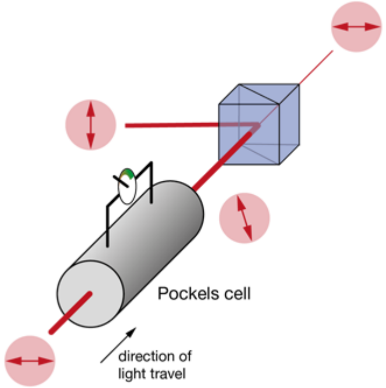
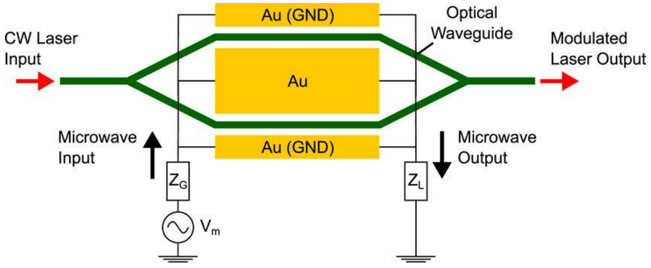
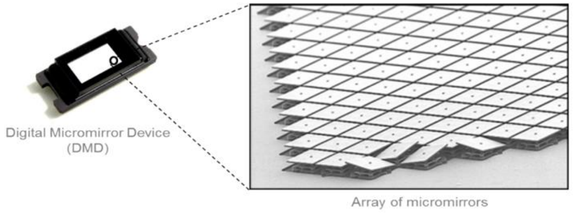
Requirements

1. Fast and precise amplitude modulation scheme



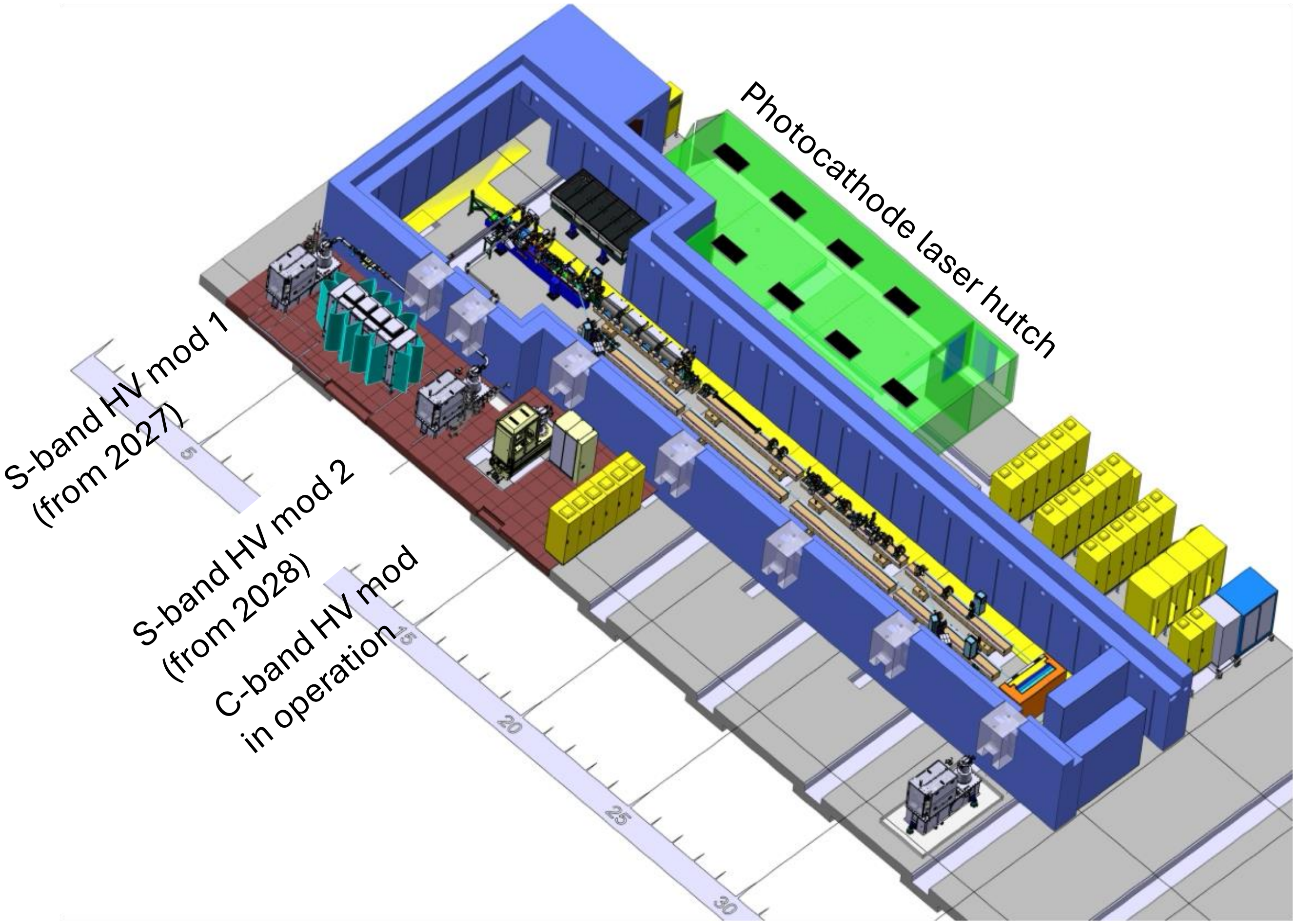
2. Tailoring of transverse beam profile to keep the electron density

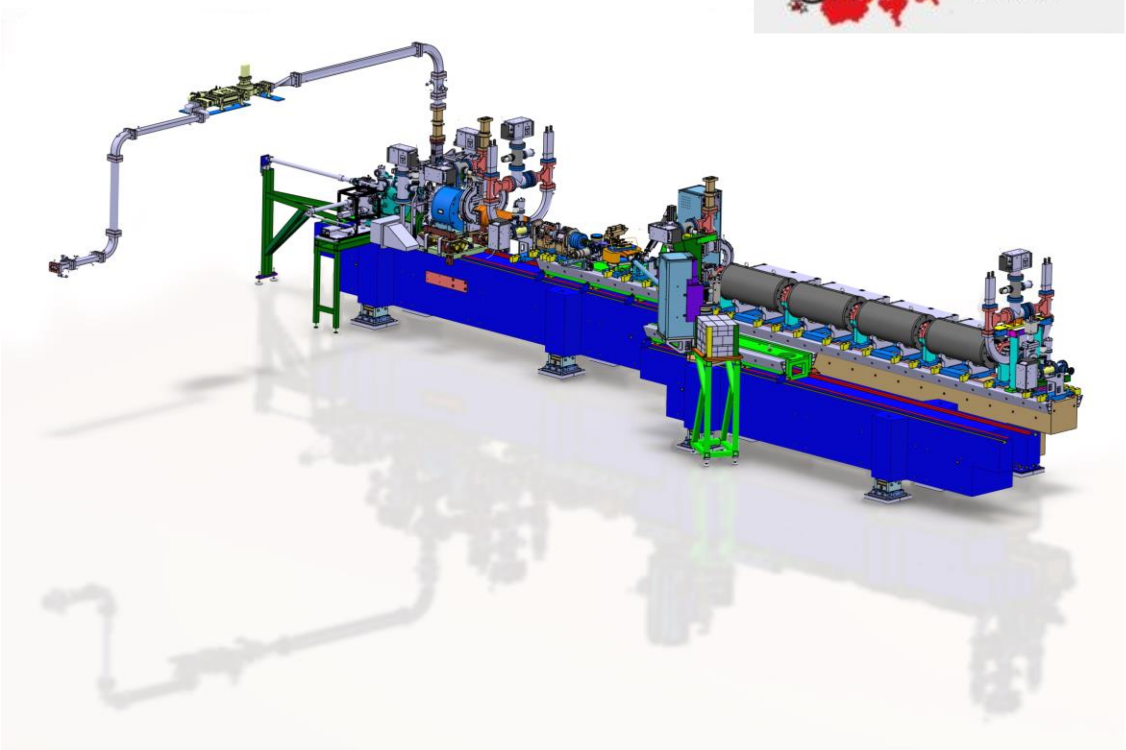


	PSI	CERN
On-demand amplitude modulation	Pockels cell 	Electro-Optic front-end laser (MZM) 
Transverse profile shaping devices	Deformable mirror  It allows for high pulse energy on photocathode	Digital Micromirror Device (MDM)  It allows fast masking of the UV beam profile

Contacts: C. Vicario (PSI), E. Granados (CERN)

Electron Source: Test Facility @ PSI





- Proof of principle of the **electron source for top-up operations:** charge modulation
- 1 or 2 bunches, ~0-5 (7) nC at 100 Hz.
- **Procurement of the components is ongoing**
- **First electron beam, second half 2027**

Contact: T. Lucas (PSI)

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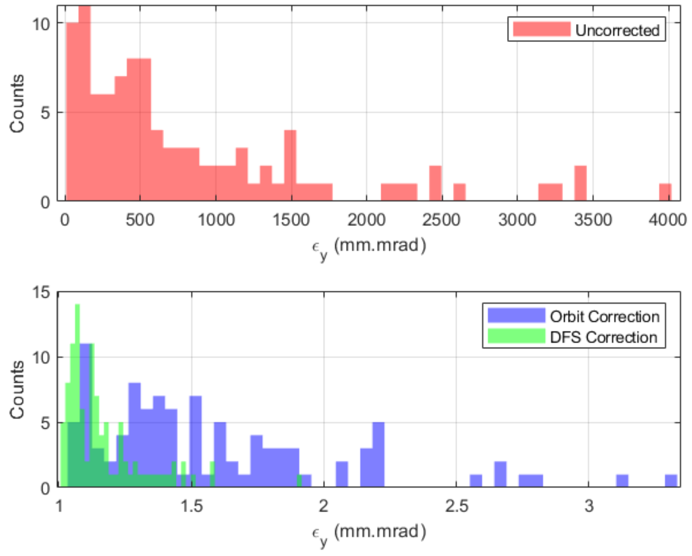
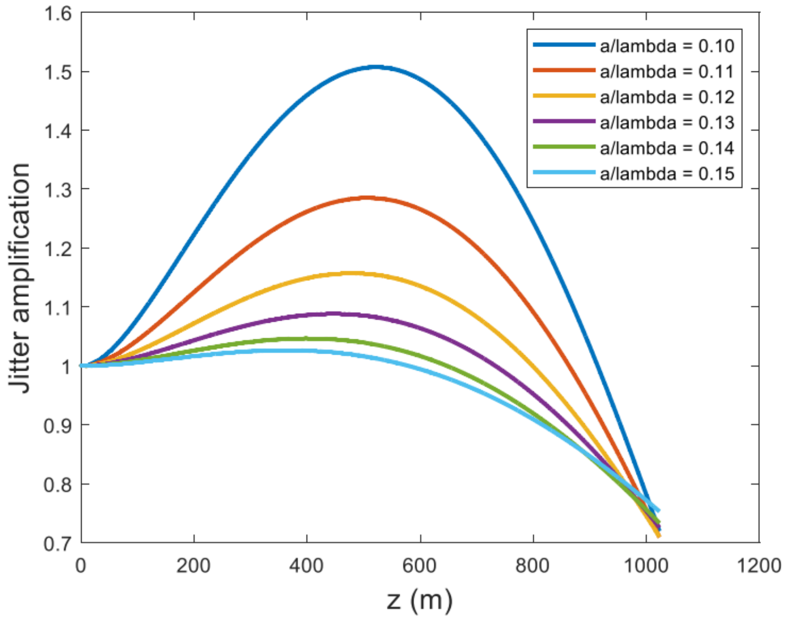
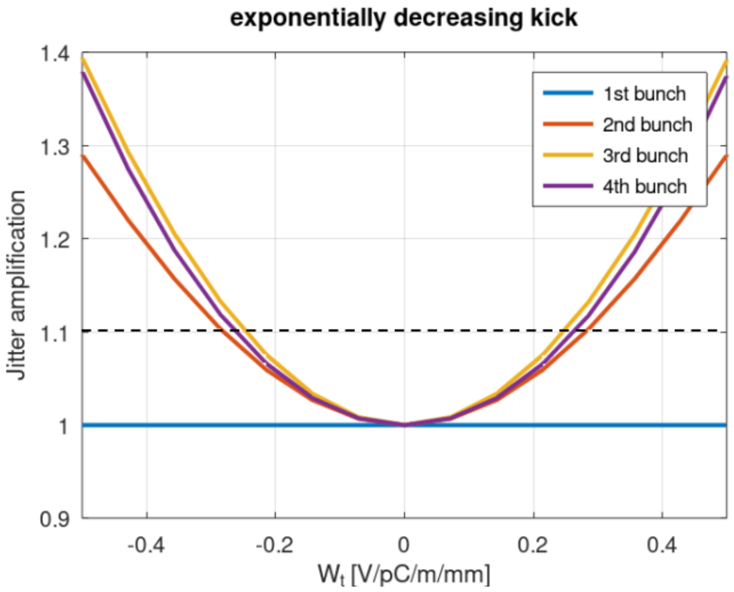
Conclusion and final remarks

Linac design: optimize what by what?

Overall design: single bunch effects		Multi- bunch effects
Static effects: Emittance growth	Dynamic effects: Jitter amplification	







Aperture and length of the RF structure, lattice	Wake suppression

Slide courtesy of A. Grudiev (CERN) and S. Bettoni (PSI)

Linac design: specifications

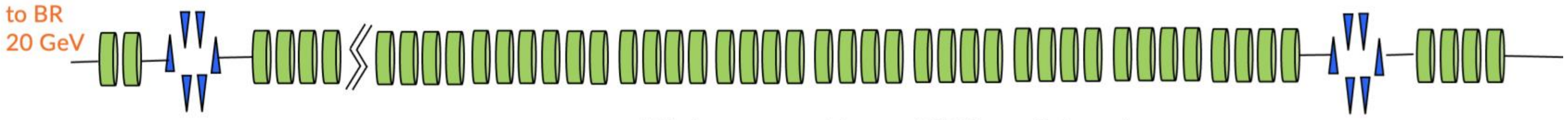
General consideration

- Beam-dynamics-driven RF design:
  - **Iris aperture**, working **frequency**, structure **length**, **gradient**,
  - Lattice parameters, like **quadrupole separation** and **phase advance**.

  → Chosen based to maximise **robustness** and beam **performance**.
- **FODO** lattice with **90-degree** phase advance.
- Focus on **wakefield effects** as **main source of instability:**
  - Single-bunch short-range → determines the average iris aperture radius
  - Multi-bunch long-range → determines the damping requirements

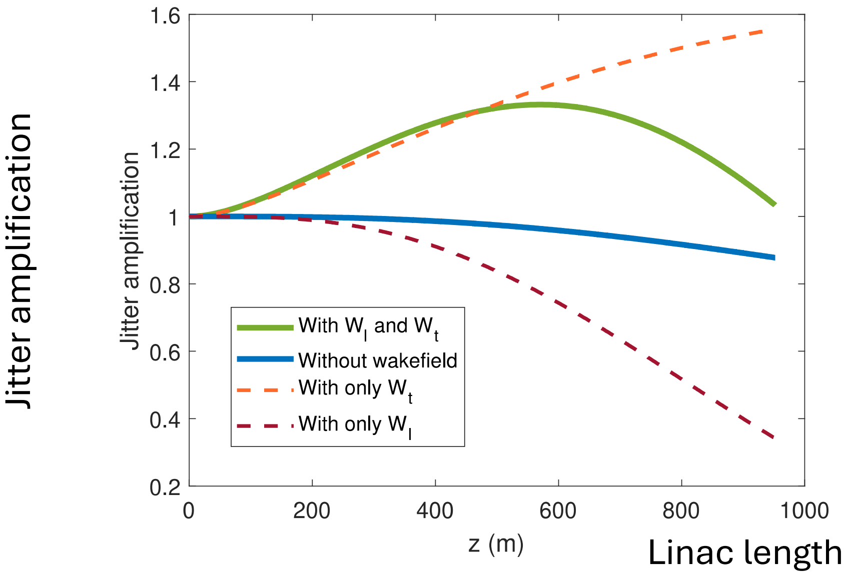
High-energy linac

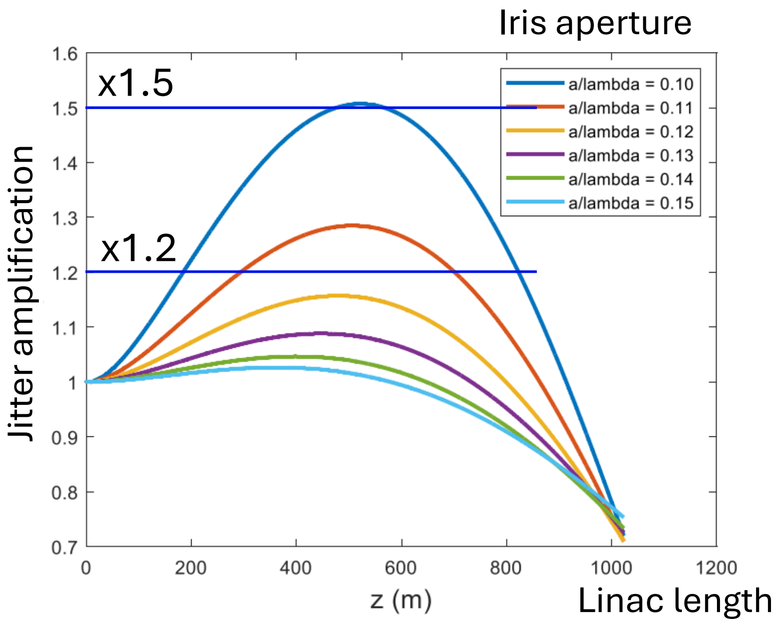
- Strict bunch requirements at the **BR injection**:
  - Bunch length = 4 mm
  - Momentum spread = 0.1%
  - **Flat** normalised emittance X / Y = 20 /2 mm.mrad
- The RF curvature and the longitudinal short-range wakefield induce a **non-negligible energy spread.**
  - A **bunch compressor** after the DR is needed to **shorten** the bunch length.
- **Energy variation** is a key parameter ← Beam Loading effects must be accounted for and mitigated when the bunch charge is changed.
  - An **energy compressor** is needed before injection into the Booster Ring to reduce the energy spread and energy variation between bunches.



Linac design: Jitter amplification in HE linac

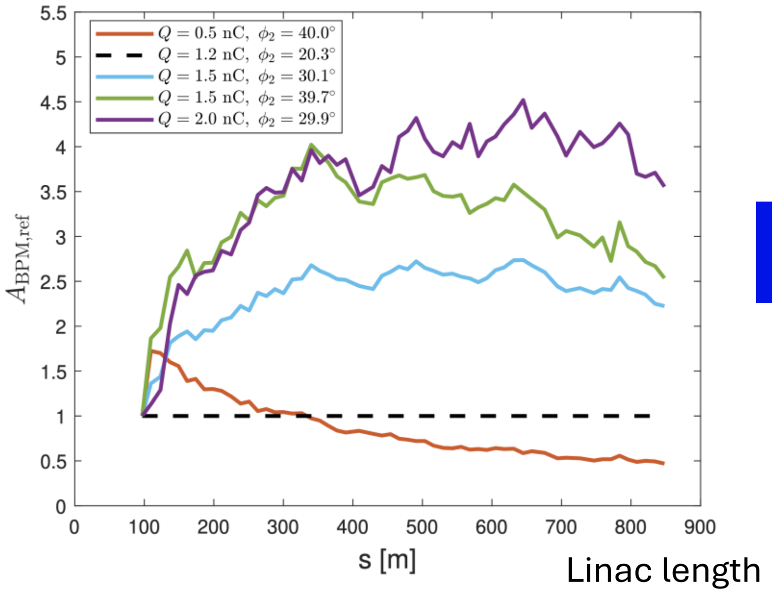
example for single bunch and short range wake





BNS damping, where the correlated energy spread comes from both the RF curvature (even on-crest) and the longitudinal wake.

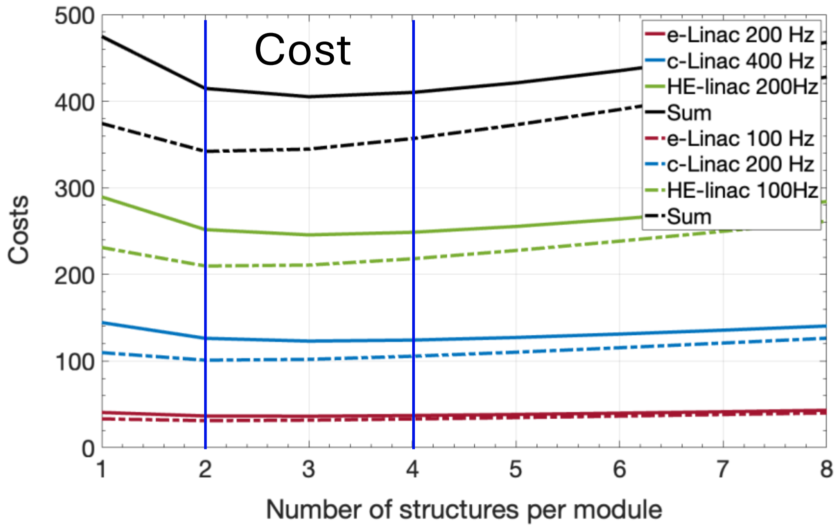
S. Bettoni, A. Latina, A. Grudiev
Phys. Rev. Accel. Beams **28**, 061601 (**2025)**

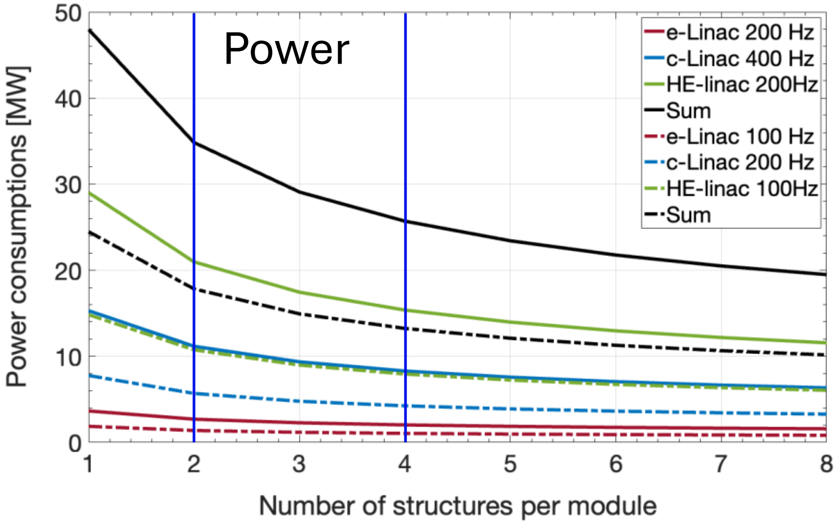


Experiment in FACET-II at SLAC

Contacts: S. Bettoni (PSI) and A. Latina (CERN)

Linac design: Cost, power and length optimizations

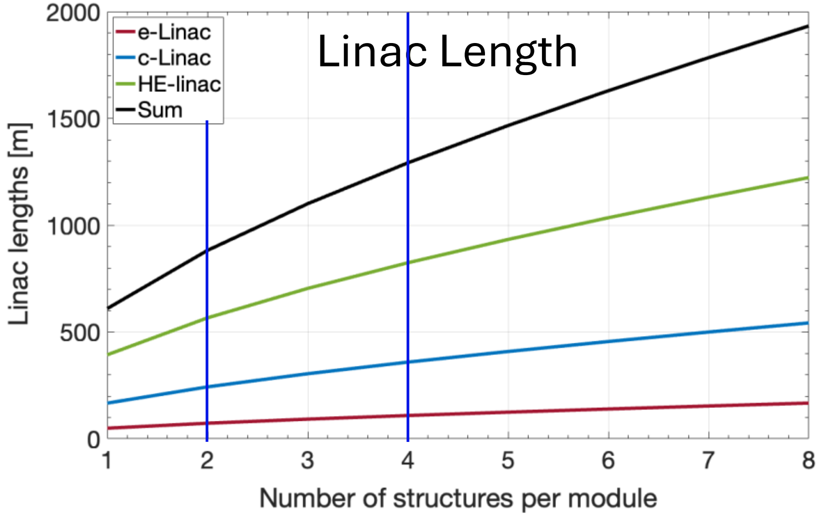




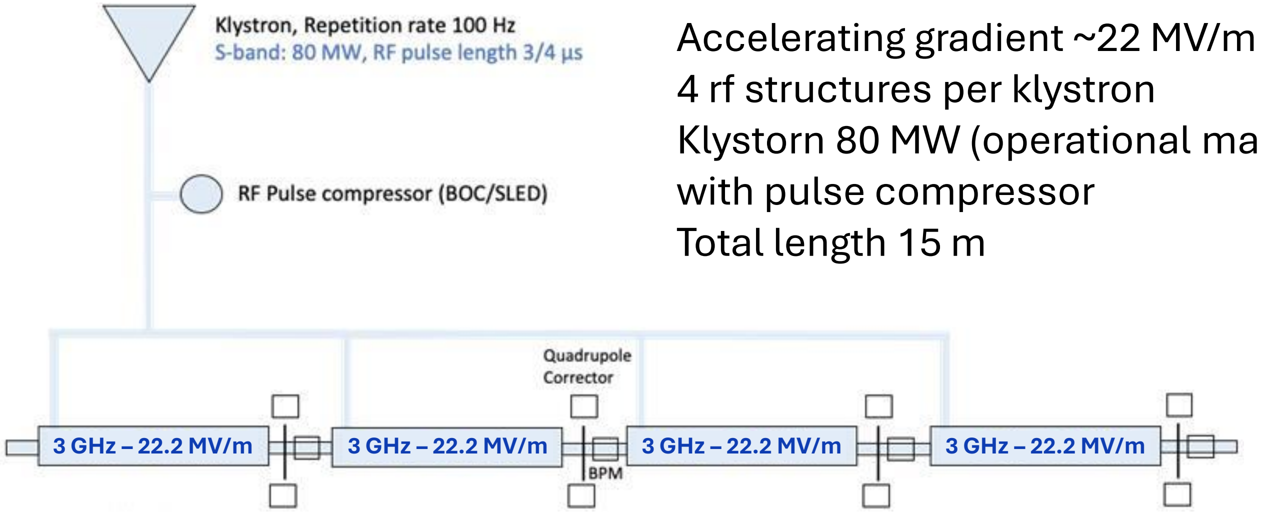
Specification: *High reliability, excellent maintainability, low operational costs, lower power consumption*

- Small cost difference between 2 and 4 AS/module
- Lower cost for lower rep. rate

- Power consumption is reduced:
- **200 and 100 Hz, by factor 2**
- **2 and 4 AS/module, by ~30%**



Baseline:
Accelerating gradient ~22 MV/m
4 rf structures per klystron
Klystorn 80 MW (operational margin 20%) with pulse compressor
Total length 15 m



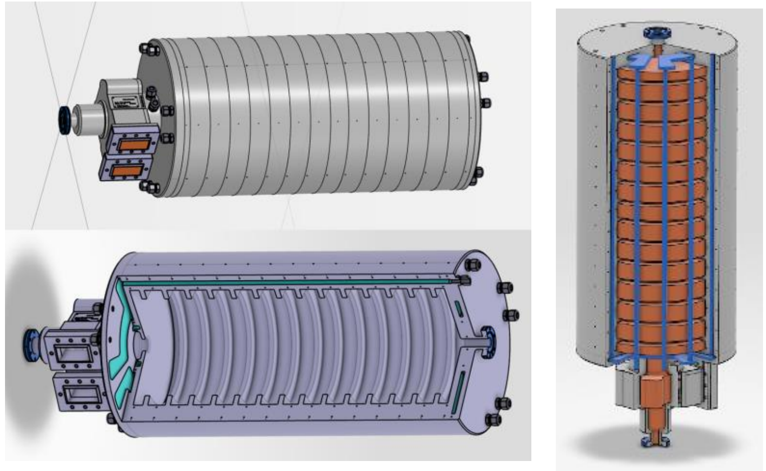
Linac design: S-band RF structures

Optimized to fulfil beam dynamics requirements

3 meters long	a/λ= 0.12
Frequency [GHz]	3
Delta	1.4 mm
Entr., exit aperture	13.39 mm, 10.59 mm
Iris thickness	2.3 mm → 3.50 mm
Vg (% c)	3.66 → 1.50
r/Q (kOhm/m)	4.01 → 4.62
Q	16121 → 15733
Filling time	430 ns
SLED coupling	15
Eff. shunt impedance	107.24 MΩ/m
Klystron power per structure	14.2 MW
V_{acc}	66.64 V
G_{avg}	22.21 MV/m
E_{max} (instant.)	79 MV/m
$S_{c,max}$ (instant.)	624 mW/μm^2

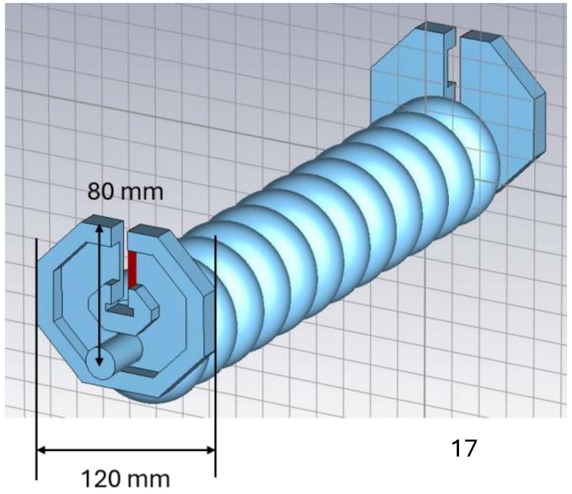
A. Kurtulus, A. Grudiev et al., Phys. Rev. Accel. Beams **28**, 101601 (**2025**)

S-band pulse compressor (Q=200’000, β=15)
Contact: Riccardo Zennaro (PSI)



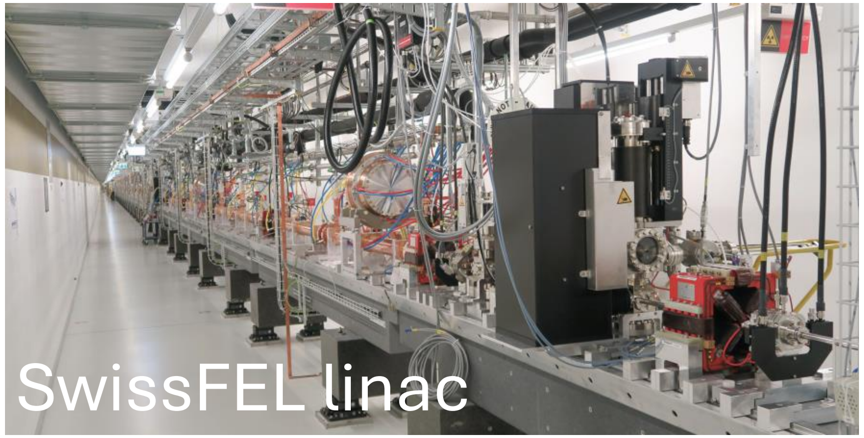
Compact double-feed RF power coupler
P. Martinez-Reviriego et al., this conference MOPO049

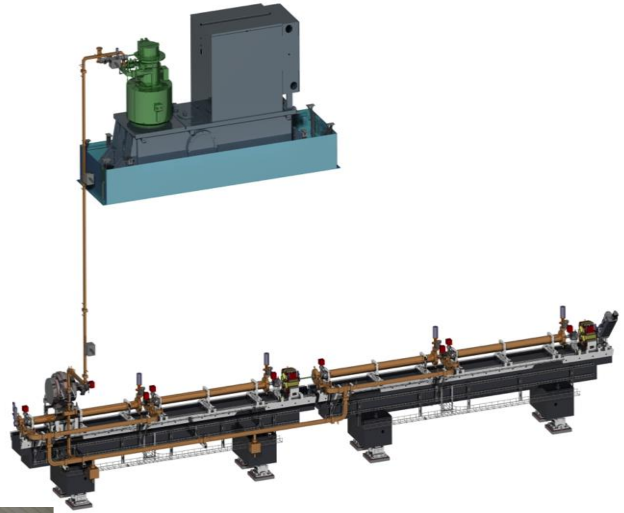
Ridge waveguide allows for a more compact design compared with standard rectangular waveguides. Dipolar and quadrupolar effects considered in the design.



Linac production – PSI tuning free technology

Demonstration of the gradient and (most important) reliability



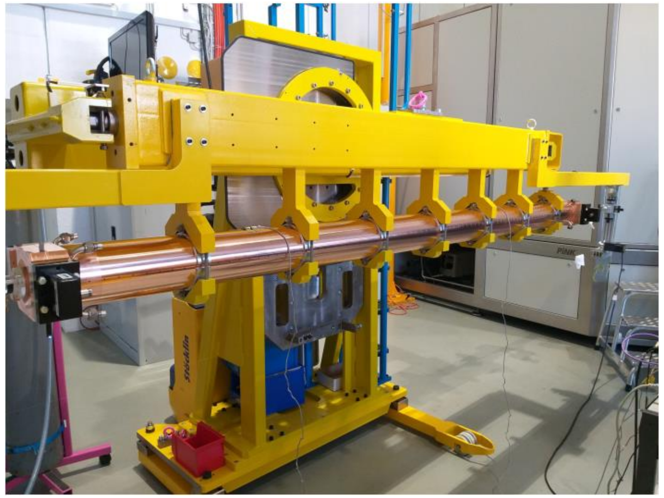


PSI Tuning-free technology developed for the SwissFEL project and extended to S-band and X-band frequencies.

SwissFEL C-band linacs:
27 RF modules and 108 RF structures

FCC-ee injector: ~110 RF unit module (~440 rf structures)

Deliverable: Definition of the industrialization process for large-scale series production for linacs → Potential industry involvement for production cost and schedule estimate



Example of the S-band RF structure produced at PSI

Vacuum brazing furnace at PSI

RF design under development at CERN.

High power tests at CERN in the CTF area once refurbished

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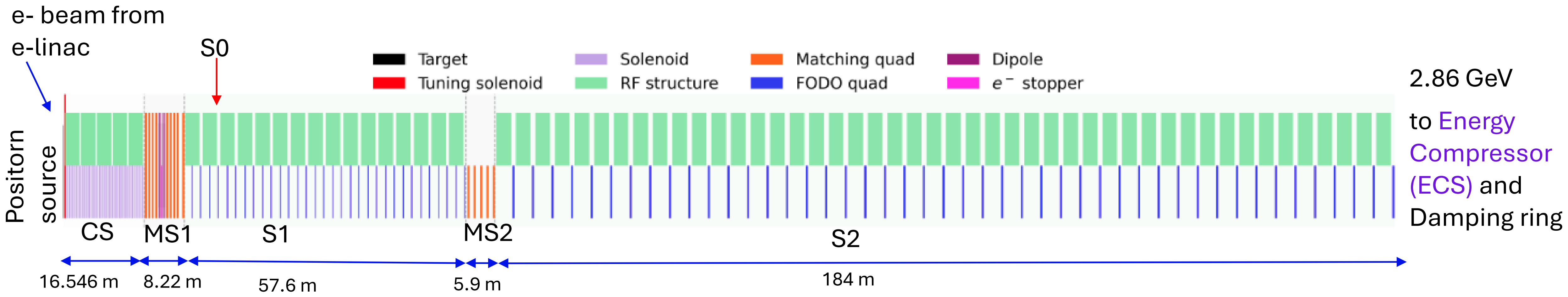
Positron source and linac - layout



Charge accepted in DR: up to 5 nC

Positron production: conventional scheme (e- beam size on target = 1 mm rms). Target exit located at 40 mm w.r.t. HTS solenoid peak field.

Matching device is based on the SC solenoid (5 HTS coils, diam. 72 mm bore, diam. 60 mm including shielding).

Drive beam from e-linac up to 5 nC, 2.86 GeV, 100 Hz, 4 bunches

RF: traveling wave, 3 GHz, max gradient = 15 MV/m, **ϕ=40 mm**

CS: 5 RFs, Bz=0.5T formed by solenoid channel

MS1 (include chicane): 4 Quads + chicane + 5 Quads, energy ~200 MeV

S0: 2 RFs after chicane

S1: 16 RFs, quad focusing, energy ~850 MeV

MS2: 5 quads

S2: 46 RFs (2.86 GeV), quad focusing

TL: Defined by RF-Track element

ECS: analytical formulae

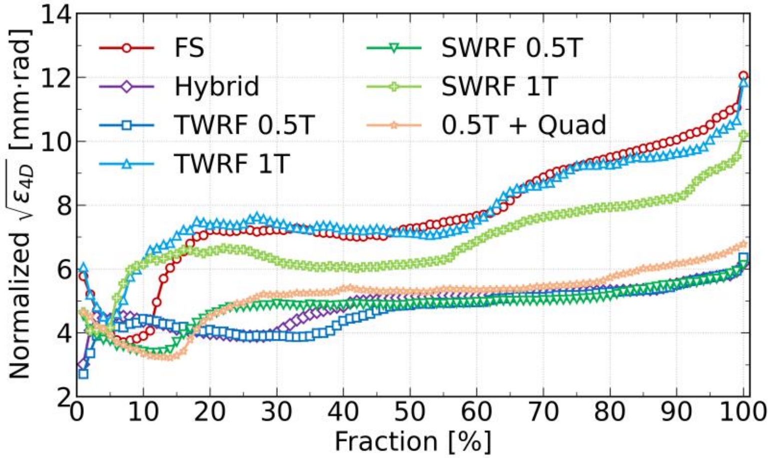
Contacts: I. Chaikovska and Y. Wang (IJCLab)

Positron linac – simulation strategy

Capture systems: 6D Beam core analysis for capture system comparison. It identifies the highest particle density region of the 6D e+ distribution and then computes beam properties for a controlled fraction of the particles (that will be accepted in the DR).

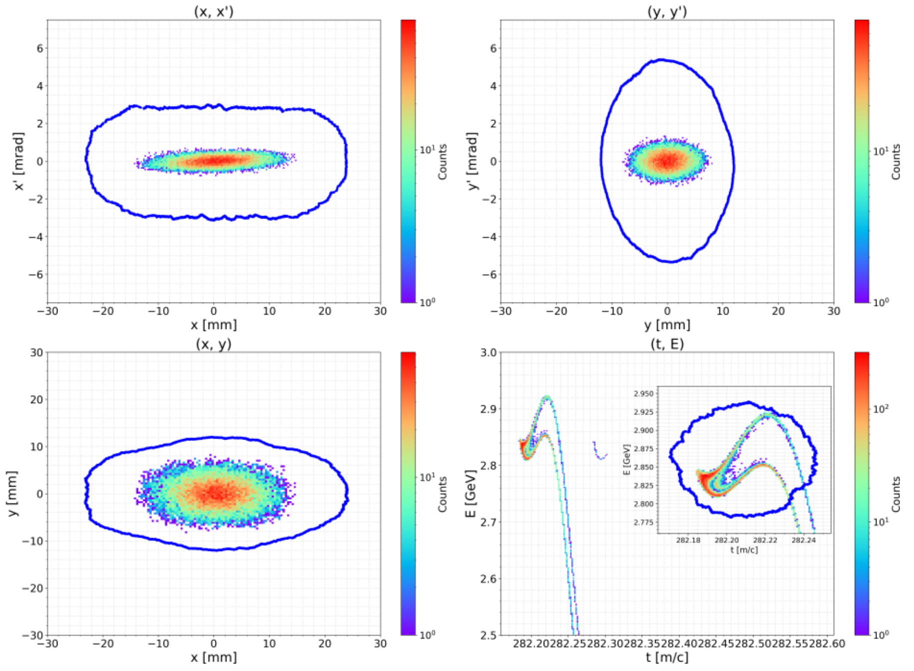
Positron linac and acceptance in DR: start to end simulations

- 6D phase-space acceptance in DR is used as a fast tool for design comparison and optimization → several DR options were verified
- Final results are validated by direct particle tracking up to DR.



Parameters	3GHz RF - QUAD DR 2.86 GeV
Yield @ before / after chicane / S1 / S2	2.67 / 2.55 / 2.35 / 2.29
Normalized Emittance x/y @ S2 (main bucket) [mm.rad]	6.07/5.98
Energy spread @ S2 (main bucket) [%]	6.34
Bunch length @ S2 (main bucket) [mm]	4.73
Accepted yield from 6D DR acceptance	1.95
Accepted yield from DR tracking	1.96
Beam size x/y [mm]	4.92/2.59 / 4.91/2.60
Normalized Emittance x/y [mm.rad]	5.91/5.80 / 5.96/5.80
Energy spread [%]	0.83 / 1.09
Bunch length [mm]	13.80 / 15.92

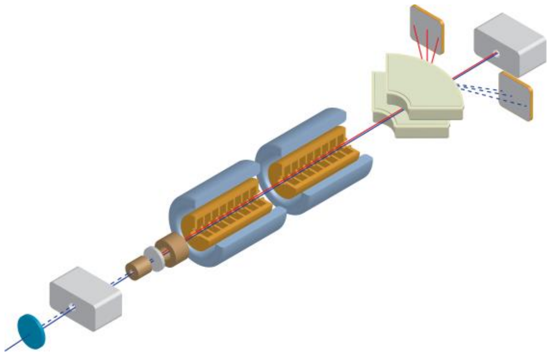
Blue: 6D acceptance estimate
Red: particle-ID traceback from DR tracking



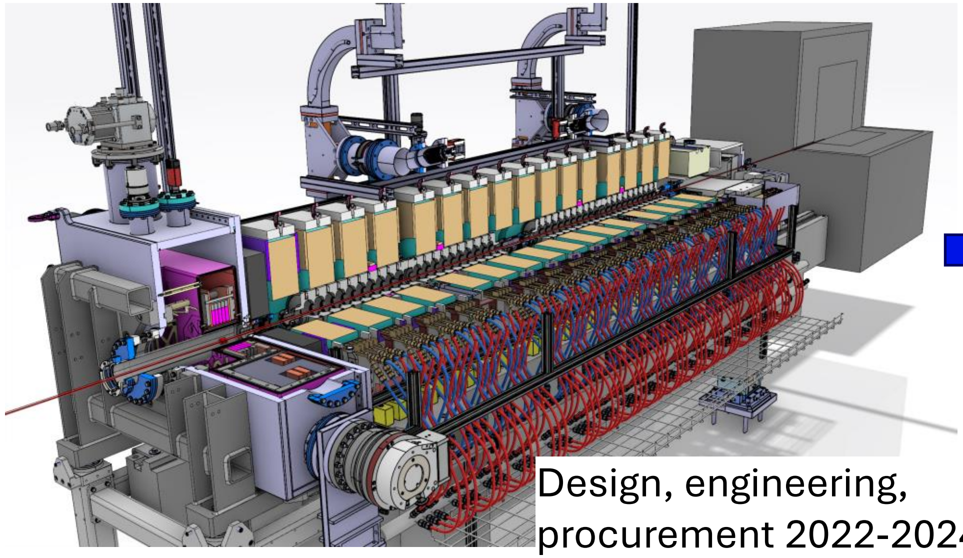
Contacts: I. Chaikovska and Y. Wang (IJCLab), simulation tools RF Track by A. Latina (CERN)

The PSI Positron Production (P^3) Experiment

- **P^3 : Proof-of-principle study of a e+ source and capture system that can enhance the state-of-the-art e+ yield**
- Based on conventional principles of pair-production-driven e+ sources but will use novel technology (**HTS solenoids, new larger aperture SW RF structures, diagnostics**)
- CERN developed the target system.

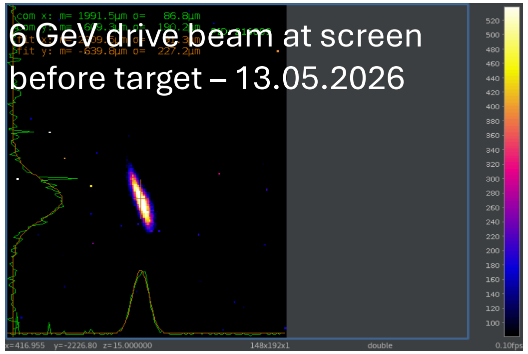


Concept 2020-2021



Design, engineering, procurement 2022-2024

Installation 2025-2026



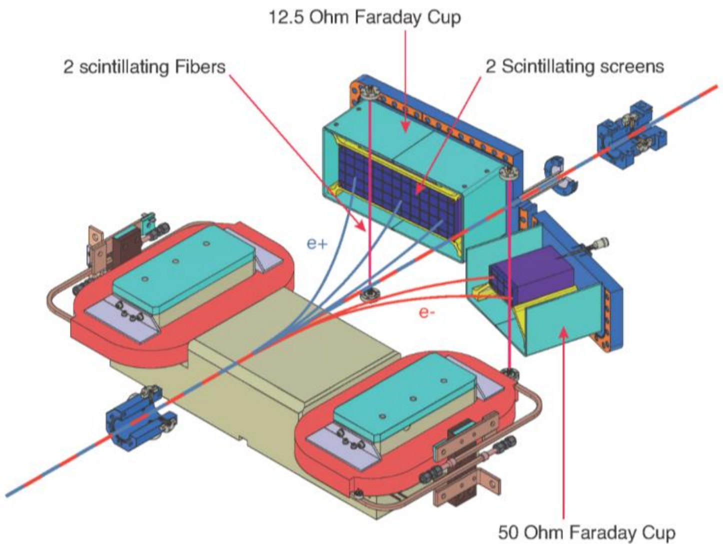
6 GeV drive beam at screen before target – 13.05.2026

Experiment in 2026:

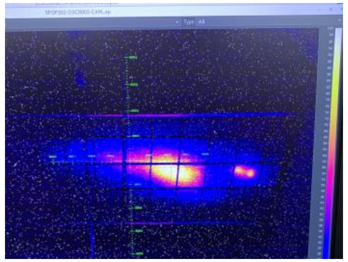
- Beamline commissioning done
- HTS solenoid ON end of June
- RF conditioning started
- (first) e+ production in summer

First positron in P^3 (July 2026)

drive beam energy 6 GeV, 200 pC, 1Hz

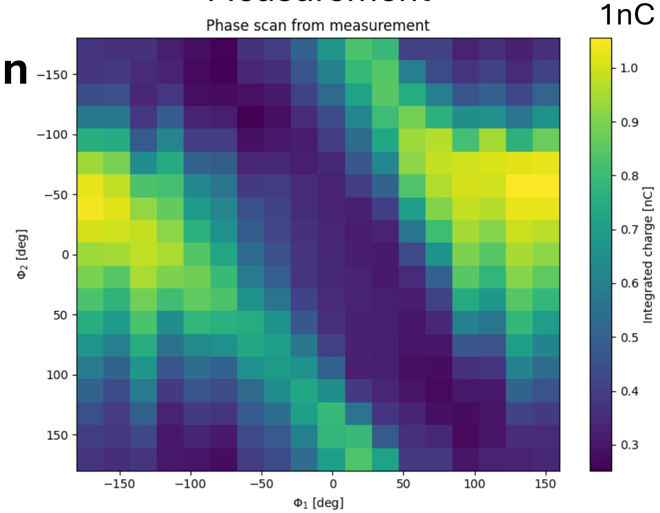


Scintillating screen

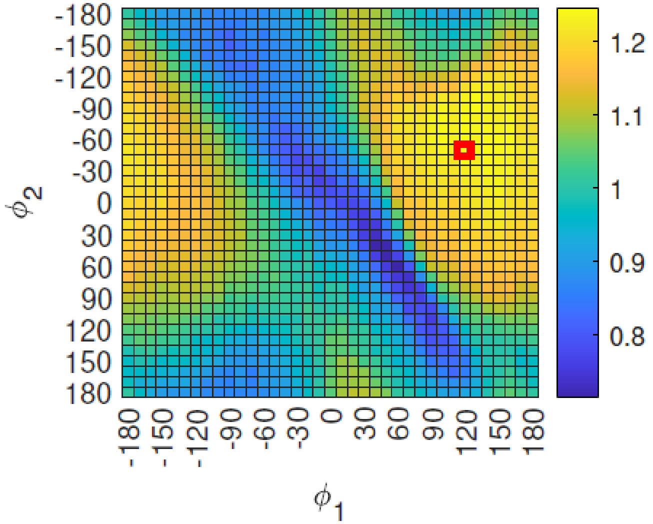


Faraday cup

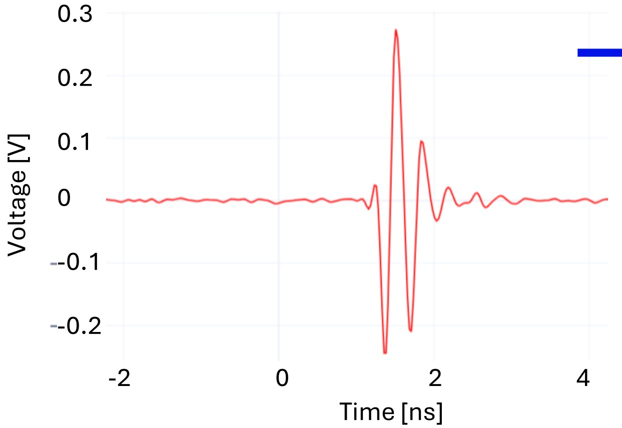
Measurement



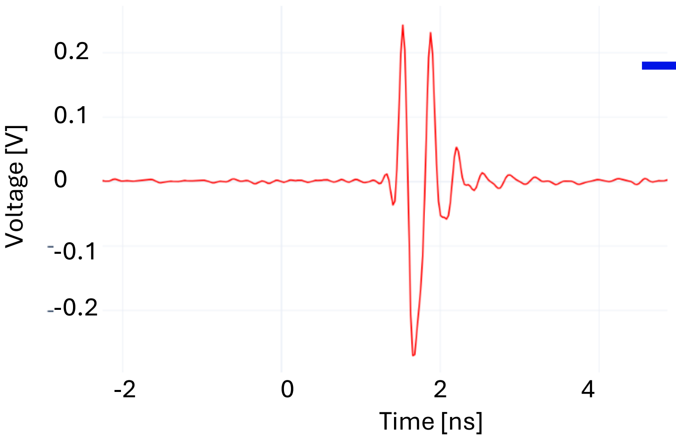
Simulation



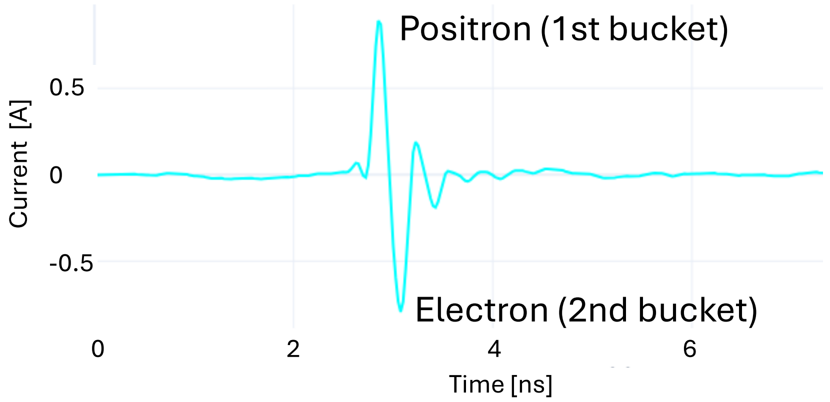
Broadband pickup signal



RF phase swap of 180



Charge reconstruction accounting for cable attenuation and pickup transfer function



Contact: R. Zennaro (PSI)

FCC-ee injector specifications and layout

Electron source

Electron and High-Energy linacs

Positron source and linac

Damping ring

Conclusion and final remarks

Damping ring at 2.86 GeV

The primary function of the damping ring design is to accept the 2.86 GeV **positron and electron beams coming from the respective linacs, reduce their beam emittances**, and deliver the required beam quality for injection into the HE-linac.

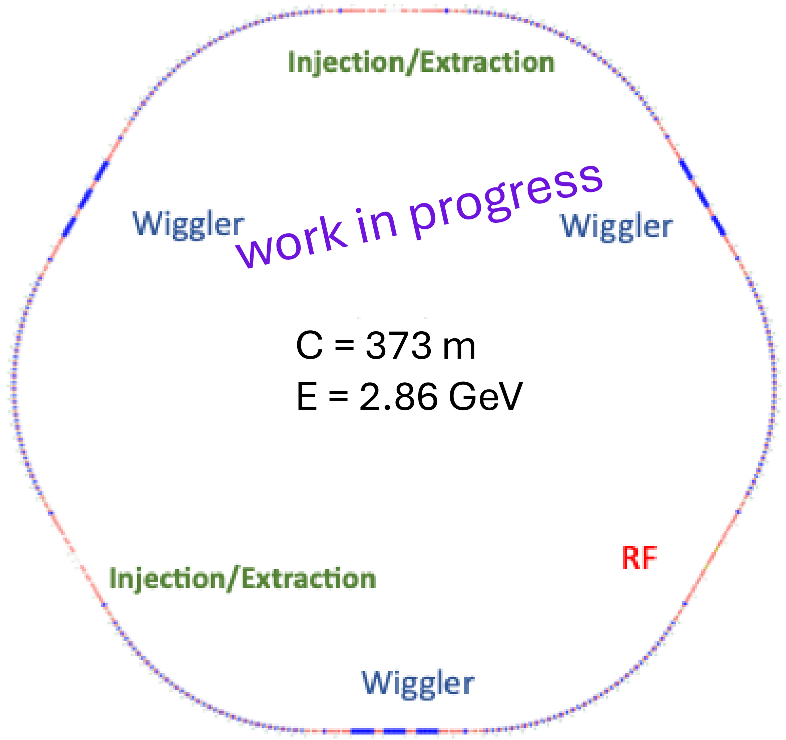
DR is essential for decreasing the emittance of the incoming positron beam by three orders of magnitude

DR design approach

- Six Arc based on FODO cells + right and left Dispersion Suppressors
- Six straight sections to host Damping wiggler magnets, RF, and Injection extraction sections

9 wigglers, 3.5 m long and 1.9 T

To achieve an optimal Dynamic Aperture several DR optics have been studied and verified with the start-to-end simulations.



Geom. Emittance 3.4 nm.rad

Damping time: 6 ms

Energy loss per turn 1.2 MeV

Contact: C. Milardi (INFN-LNF)

Conclusion and final remarks

FCC

- Injector complex study after the FSR is now in the RDP (2025-2028**), main goals**:
  - Finalisation of the injector complex design, including damping ring, polarisation schemes and input for placement, together with CHART 25-28 and CERN-led system integration – end 2027;
  - definition of placement, civil engineering requirements, surface integration and technical infrastructure needs – end 2027.
- **Injector pillar** at CERN is working to take the injector from the physical design phase to the technical design phase and to integrate it into the infrastructure; for example. the integration of the HE-linac is currently ongoing.
- Demonstration of the **feasibility of the electron and positron sources** are also ongoing at PSI.
- Physics design of the **positron linac** and **damping ring** must be finalized.
- **Polarised electrons and positrons must be produced at the injector**, as established following the publication of the FSR.
  - **CERN is currently evaluating polarized electron-source concepts**, while some concepts for a **positron polarisation ring** are also under consideration.

Acknowledgements

PSI	R. Zennaro, S. Bettoni, T. G. Lucas, S. Giroldi, M. Zyrkova, N. Strohmaier, D. Hauenstein, D. Martins Araujo, I. M. Besana, H.H. Braun, M. Duda, R. Fortunati, H. Garcia-Rodrigues, R. Ischebeck, P. Juranic, J. Kosse, F. Marcellini, T. U. Michlmayr, G. L. Orlandi, M. Pedrozzi, J.-Y. Raguin, S. Sanfilippo, S. Reiche, M. Seidel. all the technical groups involved in the P^3 and electron source experiments
CERN	S. Gilardoni, A. Grudiev, R. Principe, B. Auchmann, S.W. Bartmann, M. Benedikt, M. Calviani, S. Döbert, Y. Dutheil, O. Etisken, J. L. Grenard, A. Kurtulus, B. Humann, A. Latina, A. Lechner, P. Martinez-Reviriego, A. Perillo-Marcone, H. Pommerenke, R. Ramjiawan, Y. Zhao, F. Zimmermann, T. Watson, Z. Vostrel, H. Bartosik, C. Carli, A. Omoumi. Members of the FINPRO and FINTEC
IJCLab	I. Chaikovska, V. Mytrochenko, Y. Wang
INFN-LNF	C. Milardi, A. De Santis, O. Etisken, S. Bilanishvili
SLAC	Z. Buschmann, R. Loney, B. O'Shea, T. Raubenheimer,
KEK	Y. Enomoto, K. Furukawa

CHART Swiss Accelerator Research and Technology

This work was done under the auspices of CHART (Swiss Accelerator Research and Technology) Collaboration, https://chart.ch - **CHART Scientific Report: https://chart.ch/reports/**