PSI Center for Accelerator Science and Engineering

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# The FCC-ee injector complex

Paolo Craievich on behalf of the CHART/FCCee Injector Study collaboration
Chamonix Workshop 2025 (CERN), 27-30 January 2025

# Agenda

- CHART 2020-2024
- Optimized injector concept and parameters (after MTR)
- New baseline layout and some highlights
- CHART 2025-2028: Towards the TDR

# CHART 2020-2024: FCC-ee injector study and P-cubed project

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- CHART proposal is a collaboration between PSI and CERN with external partners, CNRS-IJCLab (Orsay), INFN-LNF (Frascati)
- other collaborators and/or observers:
  - KEKB is also interested in the positron source topic
  - INFN-Ferrara – hybrid scheme using a radiation from crystal for the positron source
- we started in summer/fall 2021 due to Covid, delay in budget setting, and long hiring process.

Work Breakdown Structure and deliverables:

1. Report with cost estimate for FS MTR (Oct 2023)
2. Report with optimized layout and new cost estimate for FS (March 2025)

WP0. Coordination (PSI/CERN)
Task 0.1 Coordination
Task 0.2 Overall parameter optimization

WP1. e+/e- 6 GeV Injector Linacs CERN

WP2. Electron and positron Linac extension study (PSI)

WP3. Positron source: target and capture system (IJCLab)

WP4. Damping ring and transfer lines (INFN/LNF)

WP5 CDR+, all partners ❖

CDR+ and cost estimate

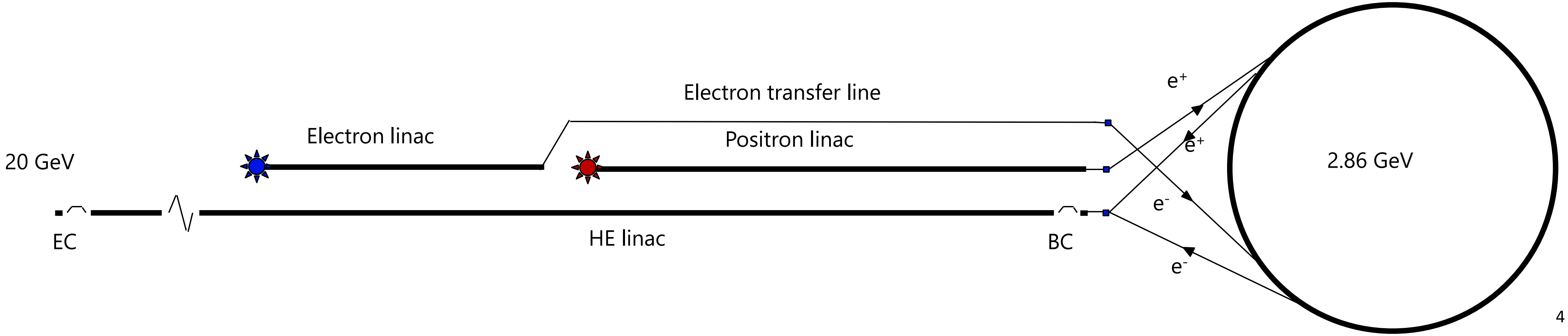
PSI Positron Production ($P^3$) project

WP6. Proof of Principle positron source and capture in SwissFEL (PSI) ❖

P3 PSI PRODUCTION

# 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.
– 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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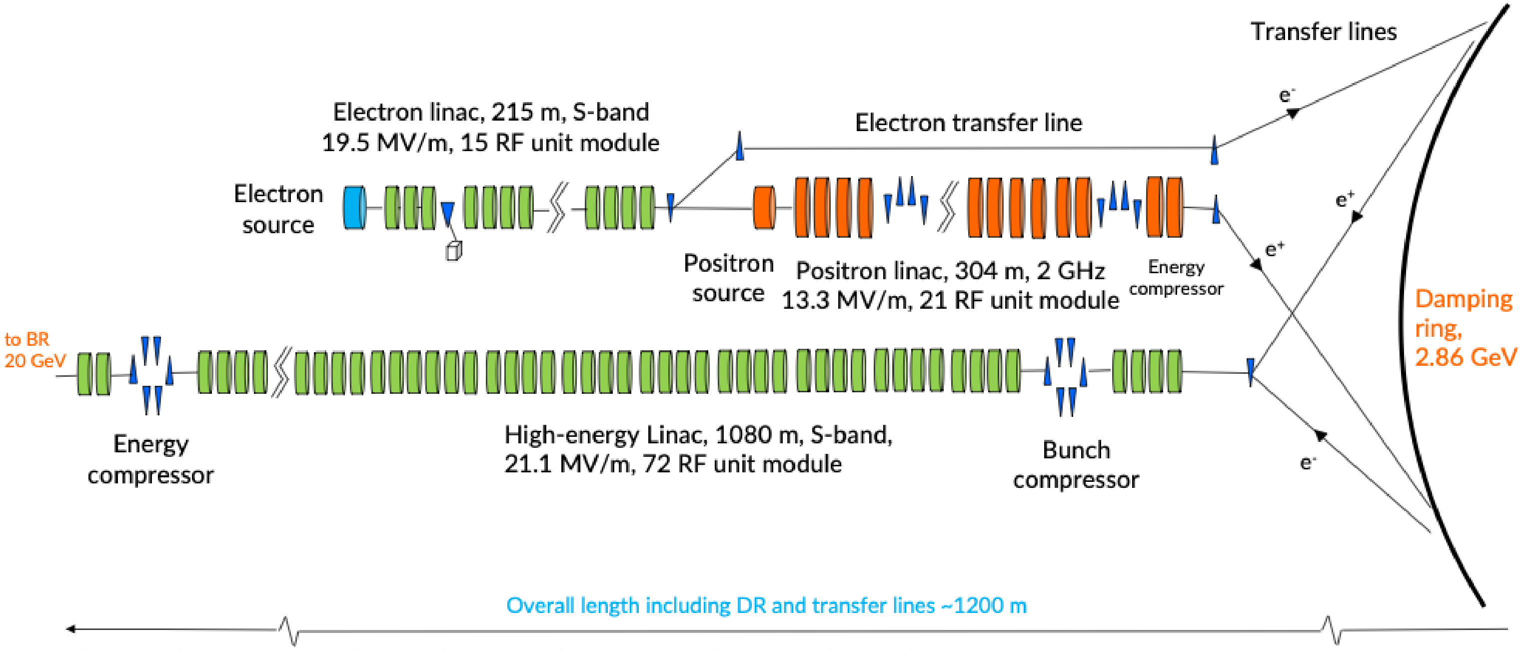



## Specification for Z-mode

| | | |
|---|---|---|
| Max injected bunch charge | 3.5 | nC |
| Number of bunches | 4 | |
| Linac rep. rate | 100 | 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 |

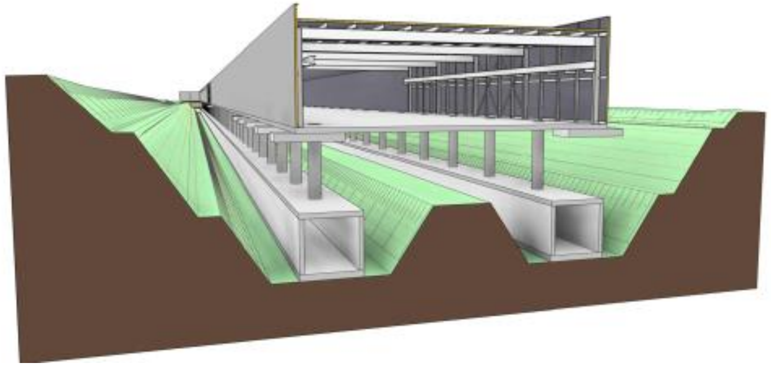
## Parameter table (H. Bartosik)

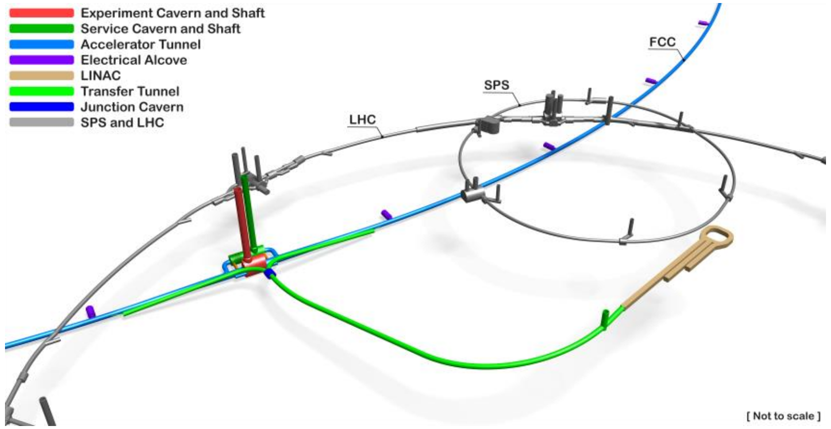
- Useful to have trace of the changes in the injector chain, i.e. charge transmission between the sources to the collider etc…
- More parameters included in the table: bunch length, energy spread, emittances etc…

Link to the table

# Optimised injector implementation

- 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



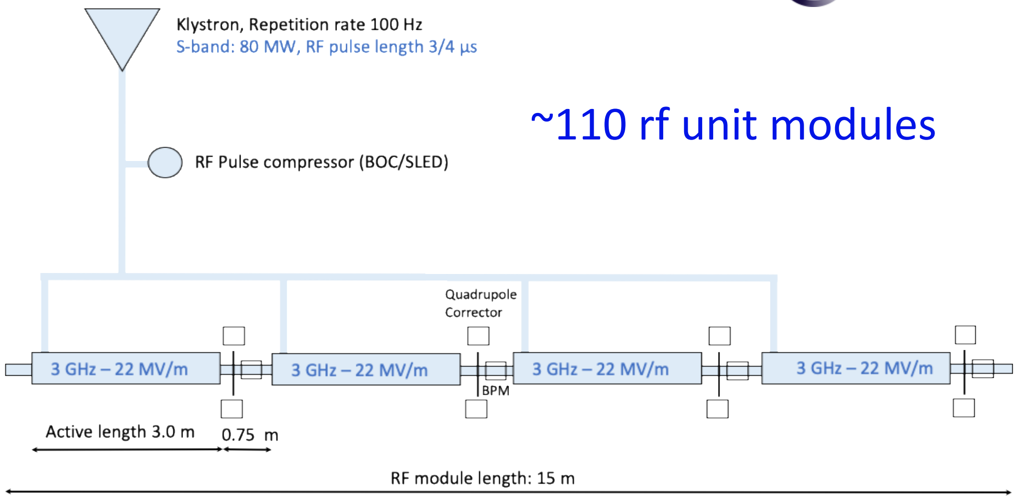



Courtesy T. Watson, W. Bartmann (CERN)

# Highlights from linac studies – 1/2

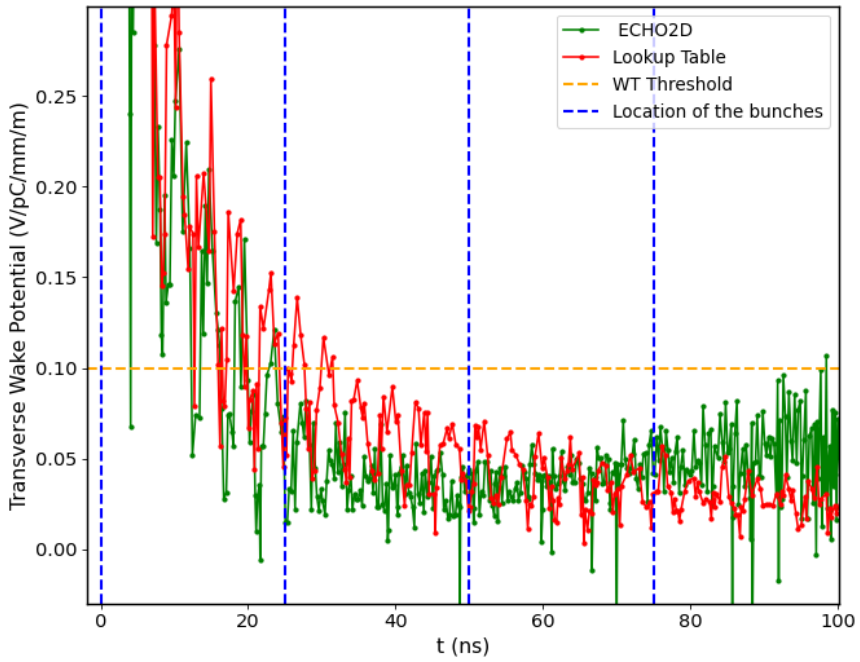
- RF unit module: 4 RF structures per module, magnets and BPM
- New RF Structure with higher impedance:
  - Active length = 3 m (compatible with PSI tuning-free technology)
  - Max gradient 21 MV/m (instead of 29.5 MV/m)
- Sensitivity study to static misalignments to define the aperture of the rf structures
  - Applied one-to-one correction and DFS in cascade
  - Emittance growth fulfilling the booster requirements
- Sensitivity study 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




~110 rf unit modules

Transverse wake vs bunch temp. spacing

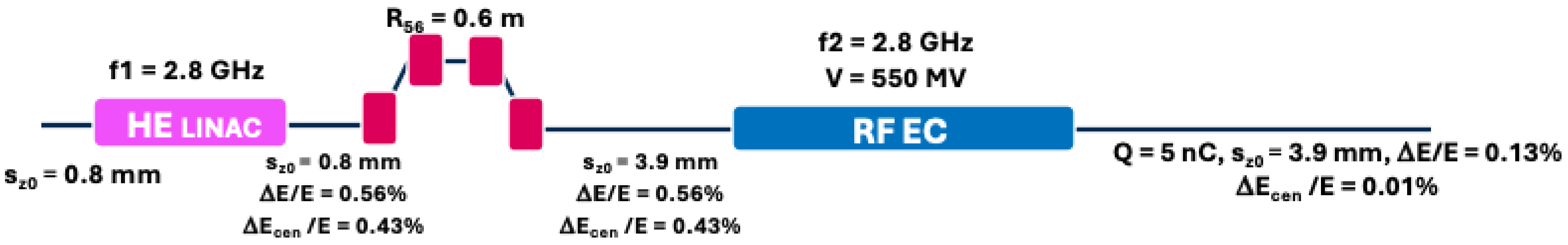




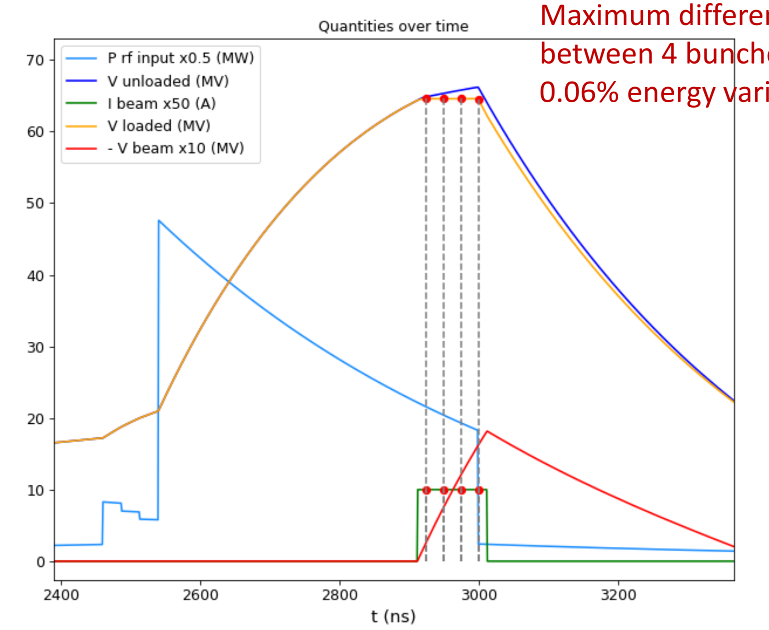

Courtesy of A. Grudiev, A. Kurtulus, S. Bettoni, A. Latina, J.-Y. Raguin et al.

# Highlights from linac studies – 2/2

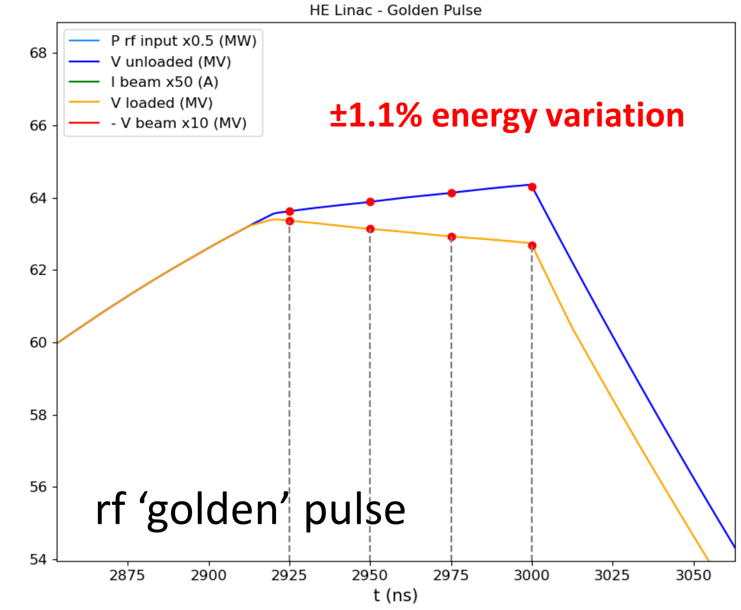
- Beam loading and rf pulse shape compensation (4 bunches)
  - keeping the energy variation between 4 bunches below ±1.5%.
- Beam loading and rf 'golden' pulse compensation
  - approach to keep the energy variation under control also with intensity modulation of the 4 bunches.
- High energy compressor 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)
  - Energy compressor allows for the ~0-100% scan charge




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

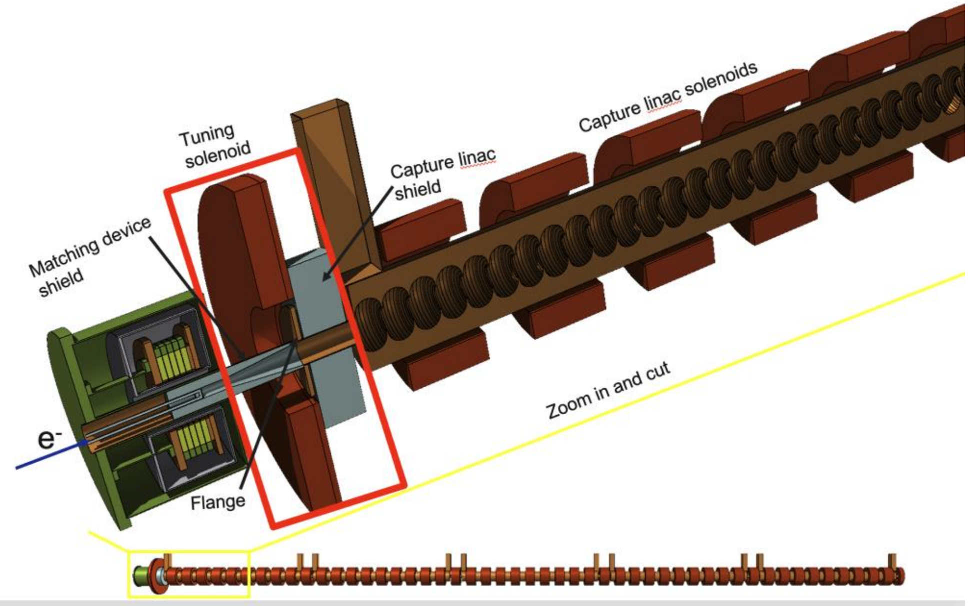



Maximum difference between 4 bunches: 0.06% energy variation



# Positron source and linac

- Request a positron flux of $\sim 1.1\times10^{13}$ e+/s. Demonstrated at SLC (a world record for existing accelerators): $\sim 6\times10^{12}$ 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);
  - e- beam size on target is 1 mm rms;
  - Target exit located at 40 mm from HTS magnetic peak field (one of the advantages of the HTS solenoid).
- Capture linac is based on the L-band TW RF structures (2 GHz, ∅ 60 mm, 3-m long) → BUT no rf power source on the market.
- NC solenoid B = 0.5 T.

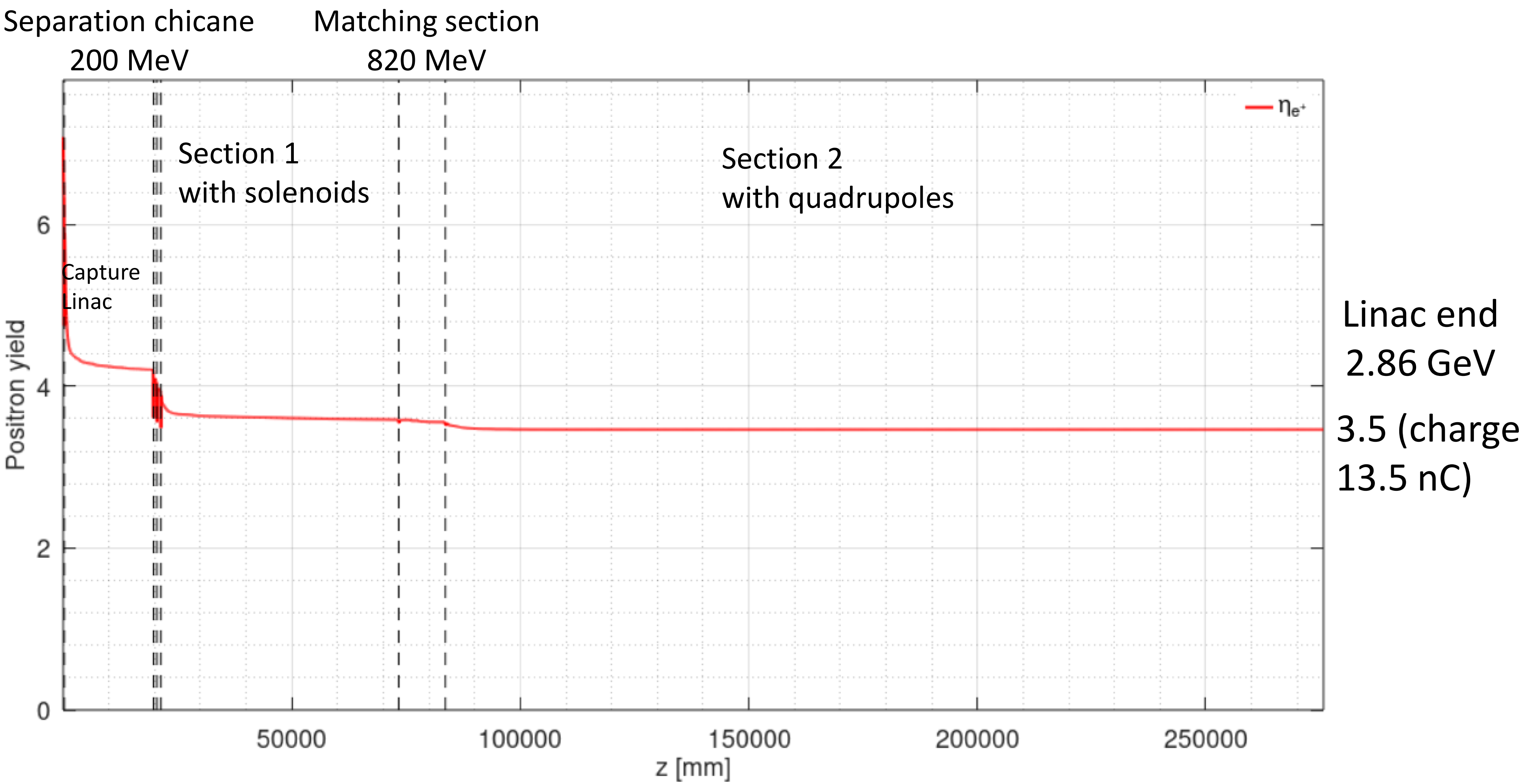


Fluka model, Courtesy of B. Humann

→ So far, no showstoppers found that prevent a SC solenoid matching device (P-cubed will provide more information)

# Highlight from positron source and linac

The start-to-end simulations from production target to the DR using the realistic field maps and the latest parameters are completed including collective effects and machine imperfections. The studies pointed out negligible impact of typical imperfections (~1 % reduction in $e^+$ yield and < 1% emittance increase).




Courtesy of Y. Zhao

# Parameters for positron source and linac

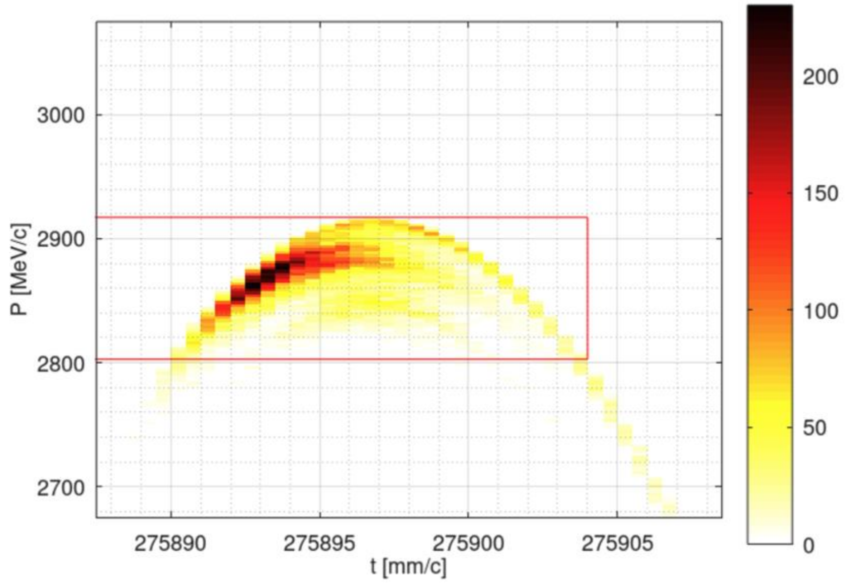
| Parameter | Unit | |
|---|---|---|
| $e^-$ beam energy | GeV | 2.86 |
| Number of bunches | | 4 |
| Repetition rate | Hz | 100 |
| $e^-$ bunch charge | nC | 4.5 |
| $e^-$ beam power | kW | 5.1 |
| Target thickness | mm | 15 |
| Beam size, x/y | mm | 1 |
| Positron yield @ Target | $Ne^+/Ne^-$ | 7.1 |
| Positron yield @ CS * | $Ne^+/Ne^-$ | 4.3/4.0/3.6 |
| Positron yield @ PL** | $Ne^+/Ne^-$ | 3.5 |
| Positron yield @ DR*** | $Ne^+/Ne^-$ | 3.0 |
| Target deposited power | kW | 1.18 |
| Target PEDD | J/g | 6.72 |
| $e^+$ beam emittance, $\varepsilon_n$ x/y | mm.rad | 13.3 |

** Yield before chicane/ after chicane/ @ s1 point (2 RF structures after chicane)*

*** full beam*

**** Estimated with the cut window.*
*Energy : 2.86 GeV ± 2 % ; Time : ± 10 mm/c*

- Total yield: **3.47**
- Yield with cuts (2.86 GeV ± 2% in energy, ±10 mm/c time): 3.04




*Emittance is estimated for the full $e^+$ beam*



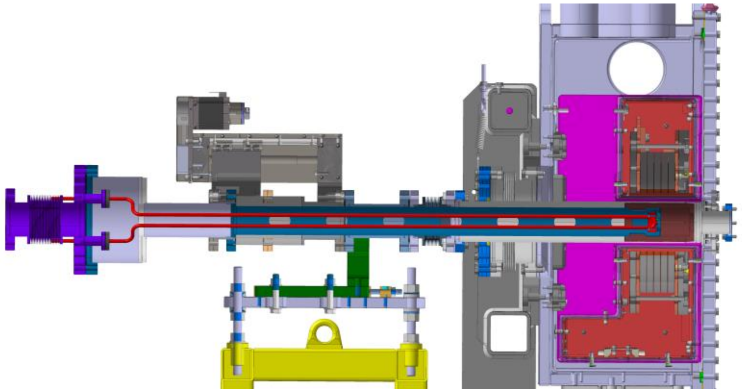
I. Chaikovska et al.

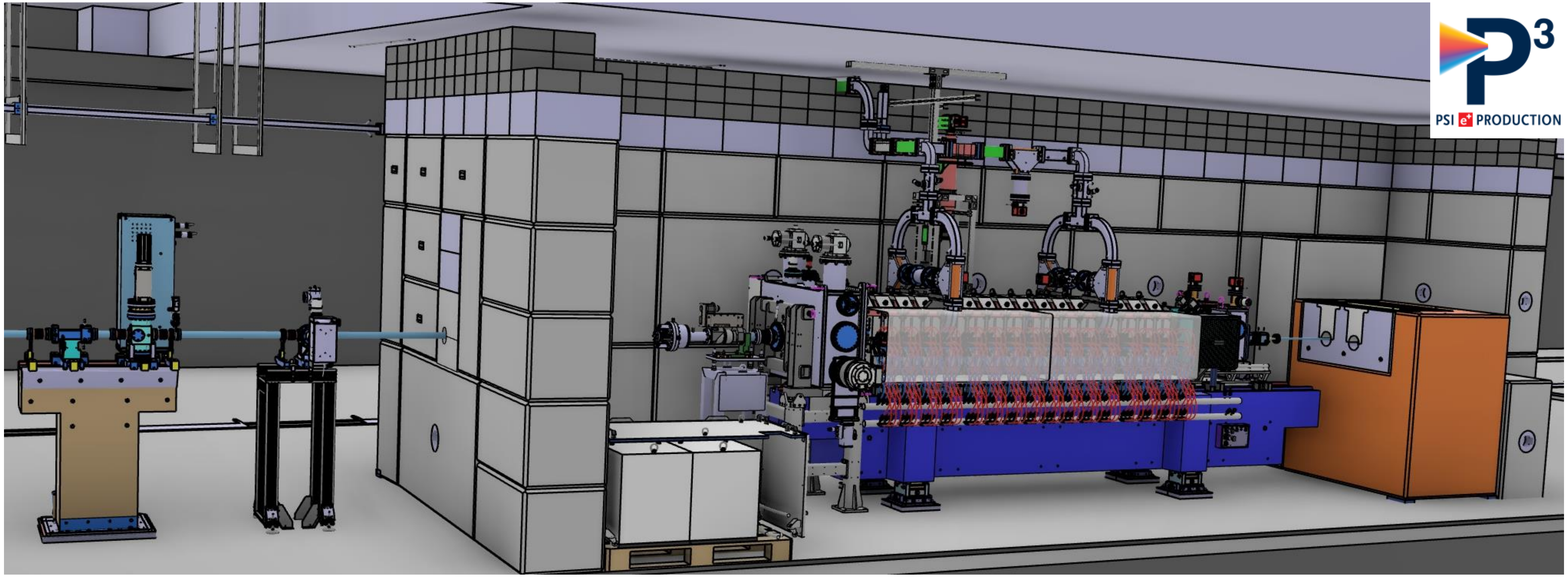
# The PSI Positron Production Experiment

- P$^3$ or *P-cubed* is a proof-of-principle study of a e+ source and capture system for the FCC-ee injector
- Based on the conventional approach of pair-production-driven e+ sources but will use novel technology (e.g. HTS solenoids).

- Target system by STI group at CERN

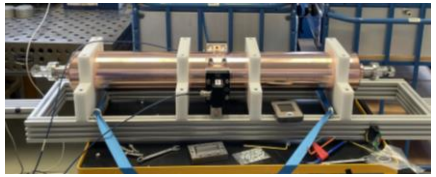
J.-L. Grenard, A. Perillo Marcone, R, Mena Andrade et al.





# Current status

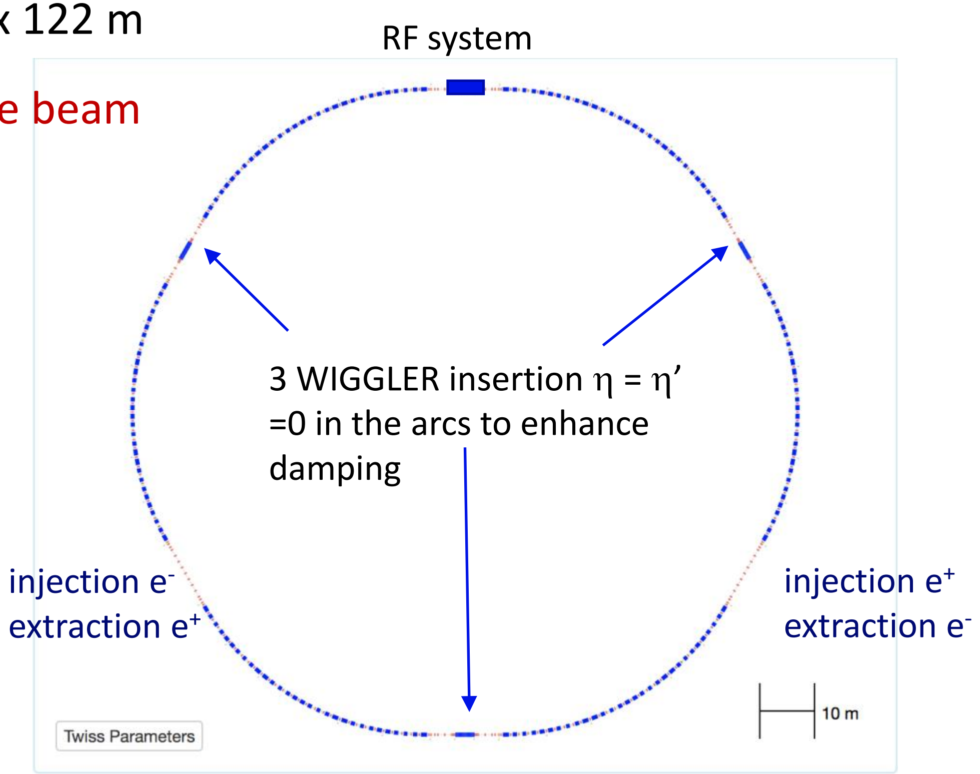
- The installation works at SwissFEL are progressing smoothly during the SwissFEL shutdown (3 for year):
  - parts of the dedicated extraction line and the HV klystron-modulator system accommodated in the tunnel.
  - **procurement and assembly of most accelerator and diagnostics components is progressing on schedule.**
  - operation of the HTS solenoid, which is probably the most critical component of the experiment, has been successfully demonstrated at PSI (up to 18 T).
  - fabrication of the target and its support is on-going at CERN
- Based on the current progress, the major part of the installation work is expected to conclude by the end of 2025, making it possible to start the operation with e+ in 2026.



# Damping ring for $e^+$ and $e^-$ at 2.86 GeV (conceptual design)

- Best use of allocated space (120 m x 120 m), overall dimension 122 m x 122 m
- Three arc cells (120 deg) providing, low emittance, damping time, large beam acceptance

| Parameters | Value |
|---|---|
| Energy [GeV] | 2.86 |
| Circumference [m] | 373.46 |
| Arc Cell | multi-bend |
| Lattice shape | six-fold symmetry |
| Nat. emittance [nm rad] (WGL on/off) | 1.3 / 2.3 |
| Bunch Lenght [mm] | 5.1 |
| Damping time $\tau_{x,y}$ (WGL on/off) [ms] | 16.9 / 29.4 |
| Nat. Cromaticity (x/y) | -38.2/-28.3 |
| Nat. energy spread (WGL on/off) [$10^{-4}$] | 7.1 / 5.2 |
| Betatron amplitude max (x/y) [m] | 9.66 / 6.49 |
| Betatron amplitude min (x/y) [m] | 0.5 / 1.1 |
| Tune ($Q_x$,$Q_y$) | 27.8707 / 22.3728 |
| Momentum compaction (WGL on/off) [$10^{-3}$] | 1.55 / 1.57 |
| Revolution period [$\mu$s] | 1.2457 |
| Dipole #, length [m], field [T] | 180 , 0.7 1.13, 0.34 0.39 |
| Wiggler #, length [m], field [T] | 3, 3.5 , 1.8 |
| Cavity #, length, voltage [MV] | 1.5, 4 |
| Max. # Bunch stored, Bunch Curr. [mA] | 40 / 4 |
| Store time | 5 $\tau_y$ |
| Energy loss per turn (WGL on/off) [keV] | 422.2 / 246.7 |
| SR power loss wiggler [kW] | 27.83 |
| Kicker rise time [ns] | 50 |




- Flexible injection/extraction sections
- Dedicated space for RF system and wiggler magnets

Courtesy of C. Milardi nd A. De Santis

# Important topics beyond feasibility study report

New CHART proposal could address some of these open questions

- Electron source for top-up operation: bunch-by-bunch charge will vary from ~0 up to 5-7 nC, depending on the intensity balance in the collider rings – few approaches to be tested on laser systems
- Linac reliability for top-up operation: Injector will run continuously, and the reliability and availability become important aspect for the new baseline (→ low-gradient injector!) – to be experimentally verified the BDR.
- New working RF frequency: we assumed a multiple frequency of the main rings to keep flexibility but no power source on the market!
  - now, bunch temporal spacing is fixed at ~25 ns → rf frequency (3.006 GHz) is close to the EU S-band freq.
- Positron linac: new optimization based on S-or L- band commercial frequencies or mixed (presently 2 GHz).
- New baseline needs a new DR at 2.86 GeV, lattice design included in the FS report
  - BUT optimization of the DA still pending and collective effects to be evaluated (40 bunches, 5.5 nC)
- Polarized positron (and electron) from the injector… it becomes an option to be studied

# Post-FS phase: Towards a TDR

- 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.
- Strong support from Switzerland and PSI to continue the collaboration on the injector.
- Presently preparing a proposal to be submitted to CHART 2025-2028 with all partners that were already involved in the previous phase.

## Injector Project schedule (as presented by M. Benedikt)

| | |
|---|---|
| Start 2025 – end 2028 | TDR injector |
| 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

# CHART 2025-2028 activities and resources

Main investigators: P. Craievich (PSI), A. Grudiev (CERN), I. Chaikovska (IJCLab), W. Bartmann (CERN), version 22.01.2025

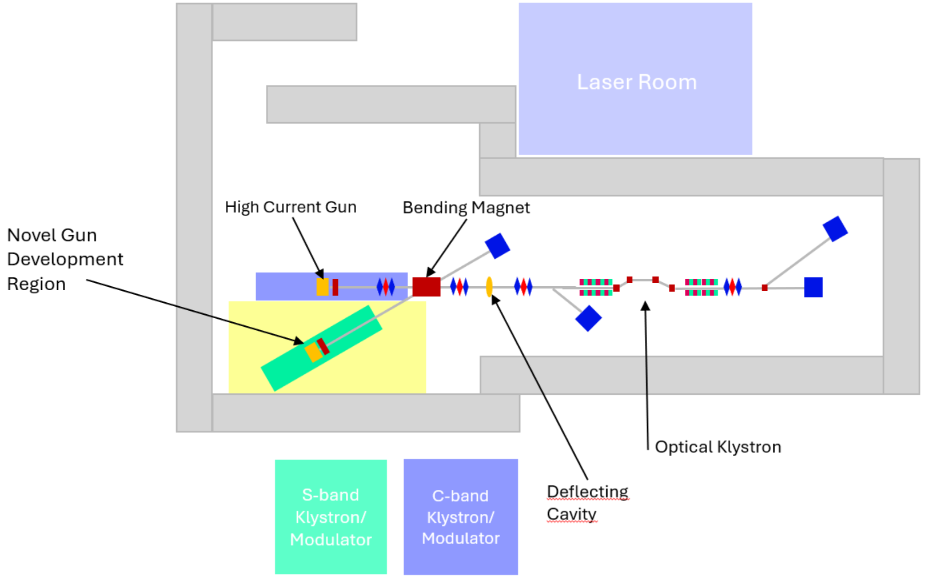
- WP0: Coordination of planned activities in the various WPs and collaborations
- WP1: Electron source
- WP2: Electron and HE linacs, accelerating structures for positron linac
- WP3: Positron linac: beam dynamics, target system and p-cubed experiment
- WP4: Definition of the technical system interfaces for linacs, electron and positron sources

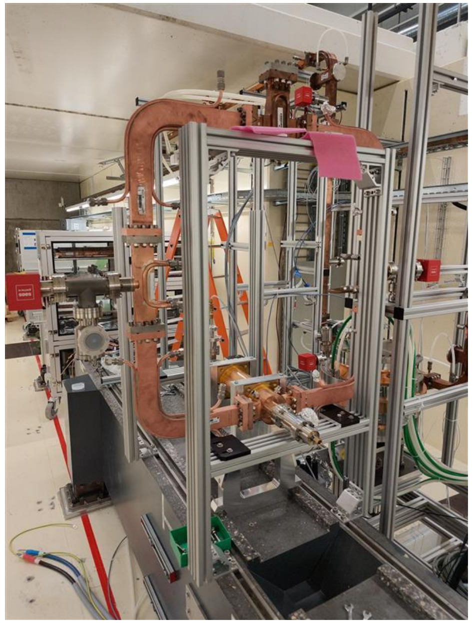
## Not included in the CHART proposal

- Damping ring and transfer lines from DR to linacs (BUT DR acceptance remains a key parameter)
- Civil engineering
- Technical infrastructures
  - Cooling and ventilation, electrical supply, cabling
  - Personnel safety system (PSYS)

# WP1: Electron source – PSI/CERN

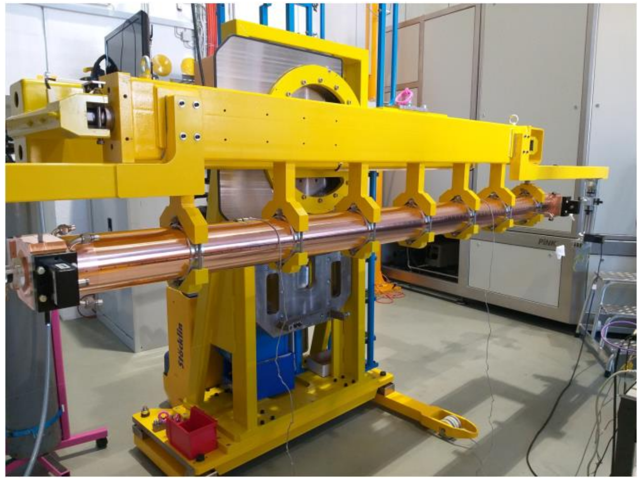
- WP1.1: Comparison between Photoinjector and DC/RF thermoionic gun on beam dynamics level.
- WP1.2: RF gun test stand – PSI
  - Spare SwissFEL gun (2998.8MHz) and solenoid, new load lock etc..
  - New laser and synchronization system
  - S-band HV modulator – 20 MW
- WP1.3: Photocathode development – PSI/CERN
  - Photocathode development in synergy with CERN STI group
- WP1.4: Commissioning and measurements – PSI/CERN
  - Proof of principle of the electron source for top-up operations: charge modulation, 1 or 2 (or 4) bunches, ~0-7 nC at 100 Hz.



# WP2.1: Electron and HE linacs – CERN/PSI

- WP2.1: Beam dynamic studies in electron and HE linacs, with the EU S-band frequency – PSI/CERN
- WP2.2: RF structures design – CERN
- WP2.3: Mechanical design and fabrication with tuning-free technology – PSI
- WP2.4: Design and fabrication of the rf pulse compressor – PSI
- WP2.5: S-band RF test stand and high-power test – CERN.
- Definition of the industrialisation process for series production (RF structures and HV mod.) – PSI/CERN
- **Post-CHART phase:** Test of the complete rf unit module with 4 rf structures and pulse compressor without and with electron (4) bunches (**presently not in CHART proposal**) – future decision at higher level management on how proceed with an injector test facility



# WP2.2: Positron linac – accelerating structures - CERN/PSI

Two options based on results from beam dynamic studies (WP3):

WP2.2.1 (1) Positron linac at 3 GHz, design (CERN) and fabrication with tuning-free technology (PSI)

- High power test at CERN, same test stand as in WP2.1 – CERN/PSI
- Testing of RF structure with/without solenoids.
- Goal: Verify the accelerating gradients, power dissipation and break-down rate (BDR)

WP2.2.1 (2) Positron linac at 2.0 GHz, design (CERN) and fabrication with tuning-free technology (PSI)

- Low rf power measurements BUT no high-power test because no power source available

**Post-CHART phase:** Test of the positron source and capture linac with one or two rf modules (**presently not in CHART proposal**) – future decision at higher lever management on how proceed.

# WP3: Positron linac – IJCLab/PSI/CERN

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- WP3.1: Beam dynamic studies in positron target, capture and linac – IJCLAB
  - Optimization to operate the linac at 3 GHz, start-to-end simulations and optimization including energy compressor, DA in damping ring, errors and RF stability
- WP3.2 Design and integration of positron target area – CERN/STI
  - Design of target mechanical system (including thermomechanical studies), target specifications.
  - Radiation studies and shielding for whole assembly (including capture linac, chicane).
  - Integration and remote handling capabilities (target assembly replacement, etc).
- WP3.3 P-cubed experiment – PSI
  - Completion of the P-cubed experiment. Beam commissioning and operation (from 2026).
  - Phase II:
    1. Feasibility studies and implementation of the crystal target.
    2. Test with high-power beam in FACET II.

# WP4: Definition of the technical system interfaces – CERN/PSI (for linacs, electron and positron sources)

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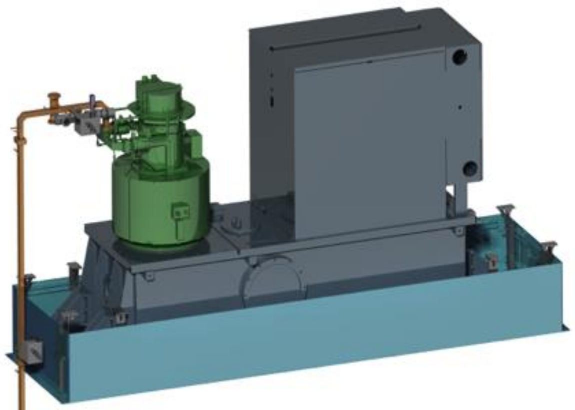
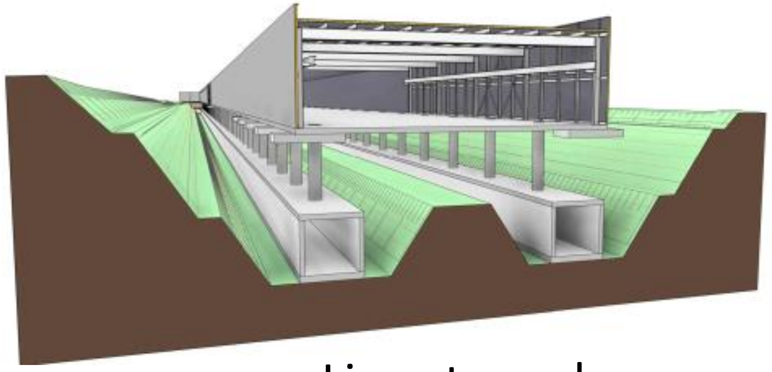
- Bilateral meetings between CERN and PSI technical groups will be scheduled for this WP. Functional analysis of accelerator technical systems to define where interface management is needed.
- **Deliverable (in the CHART proposal):** proposal with interface specifications, resources and responsibilities for the sub-systems. It should be ready by 6/8 months (from start of the CHART activities).
- The proposal will be discussed with higher level management to define the level of details for the Technical Design Report including timeline and deadline. **TDR will be part of a specific future agreement.**
- Sub-systems to be included in the dedicated bilateral meetings:
  - RF unit module (example in the next slide)
  - Electron and positron sources
  - Intercepting devices (beam dumps, beam stoppers, collimator)
  - Timing, synchronization, feedback system, machine protection system
  - Control systems and filling pattern feedbacks
  - Survey and alignment
  - other sub-systems that could be addressed during bilateral meetings

# Example of sub-system: RF unit module (~110 modules)



**Service area**
- HV klystron modulator
- LLRF
- Electronics for BPMs
- Power supplies for vacuum pumps
- Power converters for magnets
- Timing and synchronization
- Electricity
- Cooling water

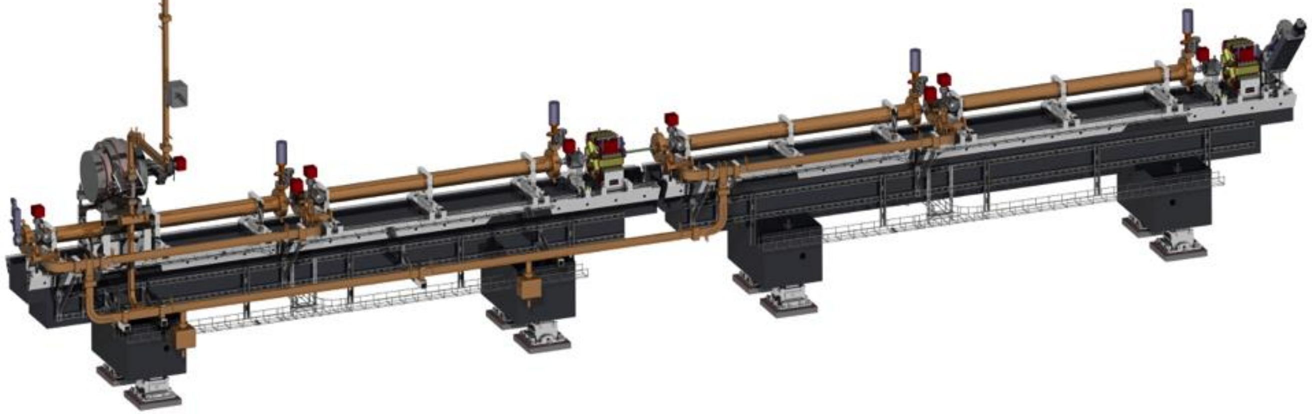
Service area



Linac tunnels

Service area

Tunnel



**RF unit module to be installed in the tunnel**

For example these components could be fully provided by PSI – in kind contribution:
- RF structures, pulse compressor and waveguide components
- Quadrupoles and steerers
- BPM pickups
- Vacuum system

Interface with:
- Alignement
- Cabling
- Electricity
- Cooling water

# Conclusion

- The valuable recommendations from MTR led to a new baseline of the injector concept coupled to a new implementation on the Prevessin site.
- The Injector Feasibility Study is on schedule to provide the final report, thanks to the very efficient CHART collaboration including also external partners.
- Cost estimate and risk register for the injector complex have also been submitted.
- The new proposal for CHART 2025-2028 is (almost) defined and should be soon submitted to the CHART Council. Hopefully, the proposal will be approved by February and the kick-off meeting will be organised in mid-March.

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Swiss Accelerator Research and Technology

CHART Scientific Report (Final Report for Phase 2)

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

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**That's all, thank you!!**