Positron production for FCC-ee

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on behalf of the FCC-ee injector positron source/linac WG

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FCC-ee positron source: current requirements

The complete filling for Z running => Requirement ~ 3 × 10^{10} e^+/bunch (4.8 nC) at the linac end or 5 nC accepted in the DR

e^- drive beam

Beam energy	2.86 GeV
Bunch charge	~5 nC (max)
Bunch length	1 mm
Bunch transverse size	≳ 0.5 mm

Nb of bunches per pulse	4
Bunch separation	25 ns
Repetition rate	100 Hz
Beam power	~5.7 kW (max)

$$N_{e-}/\text{bunch} \times \eta^{e+}_{Accepted} \geq 5\ \text{nC/bunch} \times 2.6$$

~ 13 nC

$$\eta^{e^+}_{\text{Accepted}} = \frac{N^{e^+}_{\text{DR accepted}}}{N^{e^-}_{\text{Primary}}}$$

with N_{e-}~5 nC ➔ $\eta^{e+}_{Accepted}$ ≳ 2.6

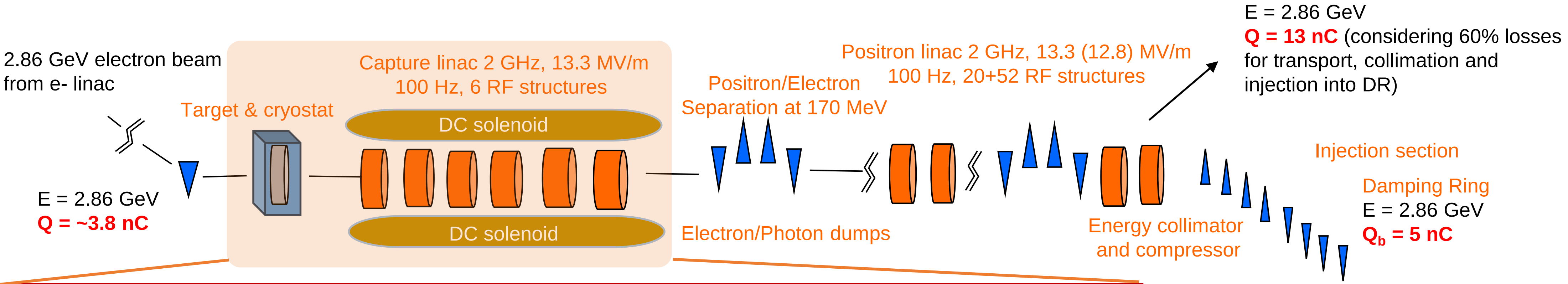
**A safety margin of 2.6 is currently applied for the whole studies (~50% losses for injection in the DR + ~20 % losses from target up to the end of the e+ linac)*

Accepted e^+ yield is a function of primary beam characteristics + target + capture system + DR acceptance

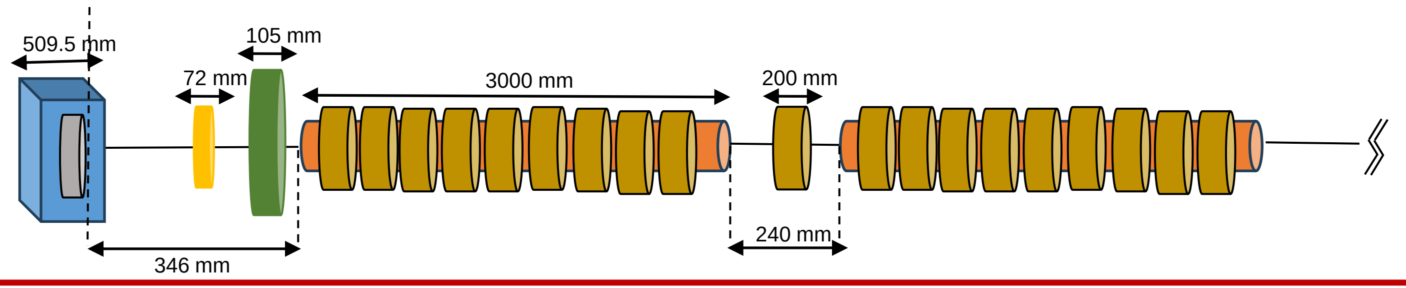
DR acceptance window: (Energy : 2.86 GeV ± **2%** ; Time : **20 mm/c**)

➔ positron flux of ~1.2×10^{13} e^+/s (×2.6). *Demonstrated at SLC (a world record for existing accelerators): ~ 6 ×10^{12} e+/s*

Positron production: capture system (FS baseline)



Capture system (~ 20 meters)



DR design: Talk by A. De Santis

Dedicated FLUKA model is developed for the target and e^+ capture section.

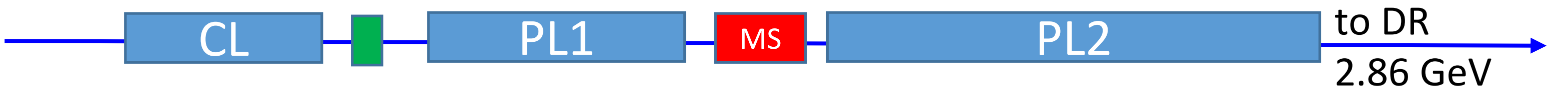
Target design: Talk by R. Mena Andrade

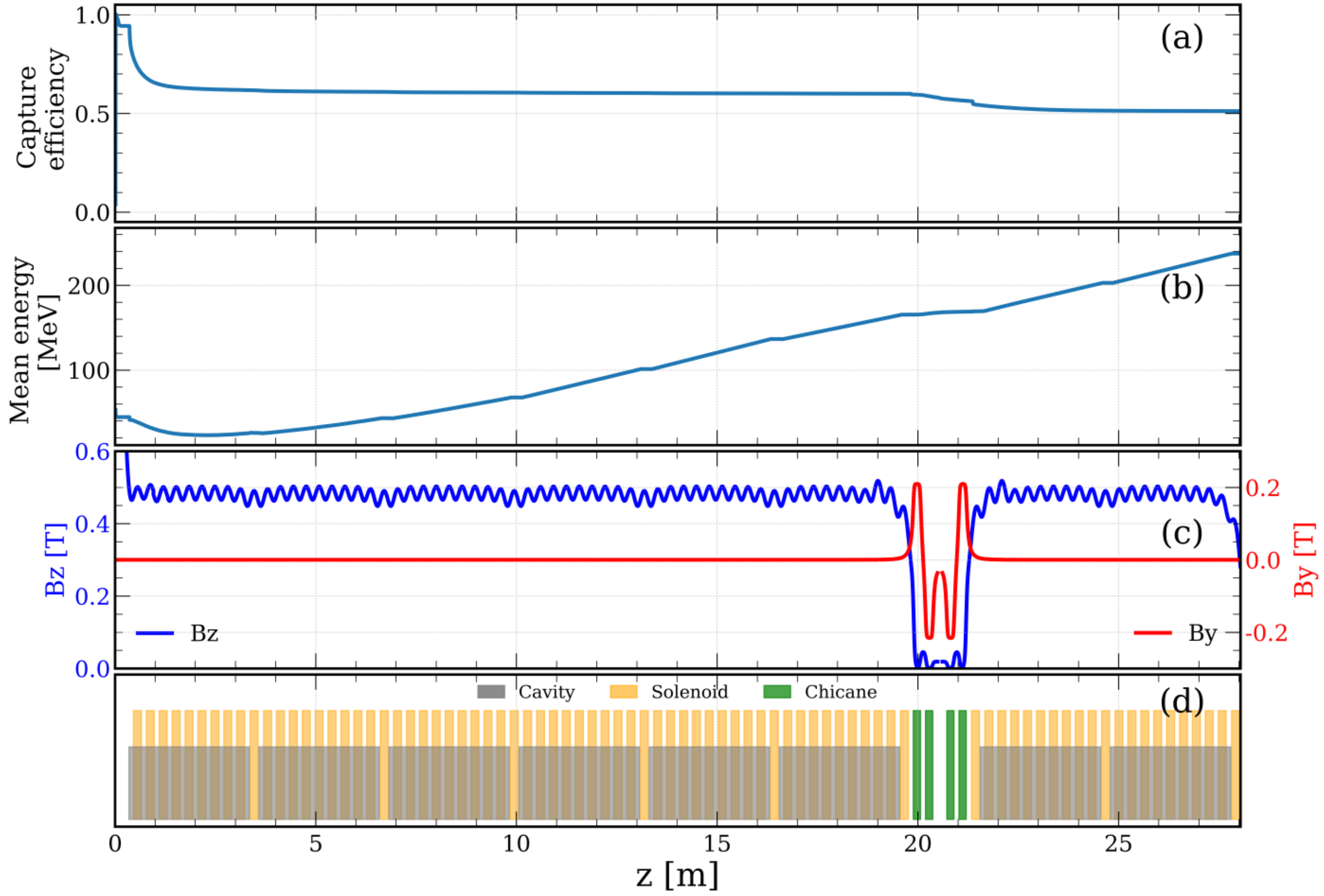
Positron production : conventional scheme (e- beam size on target = 1 mm rms). Target exit located at 40 mm w.r.t. HTS solenoid peak field.

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

Capture linac is based on the 6 L-band TW RF structures (2 GHz, ∅ 60 mm, 3-m long)

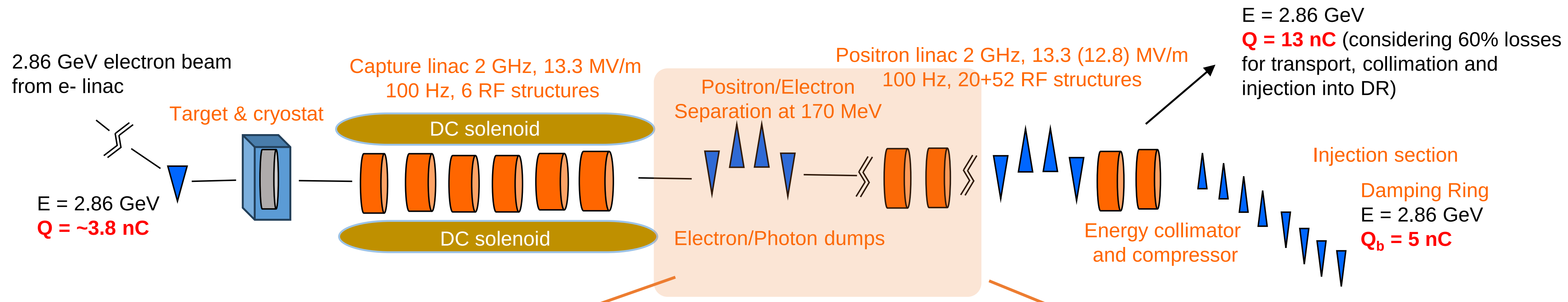
NC solenoid B = 0.5 T (realistic conventional design based on the short coils B = 0.31 T) + short "tuning" solenoid B = 0.25 T before the 1st RF structure





- Capture section is based on the conventional NC solenoid technology.
- The first RF structure operates in deacceleration phase improving bunching and longitudinal phase space.
- ~ 35% e^+ losses occur between the AMD and the first RF structure and ~ 9% additional losses at the chicane.

Positron production: positron linac (FS baseline)



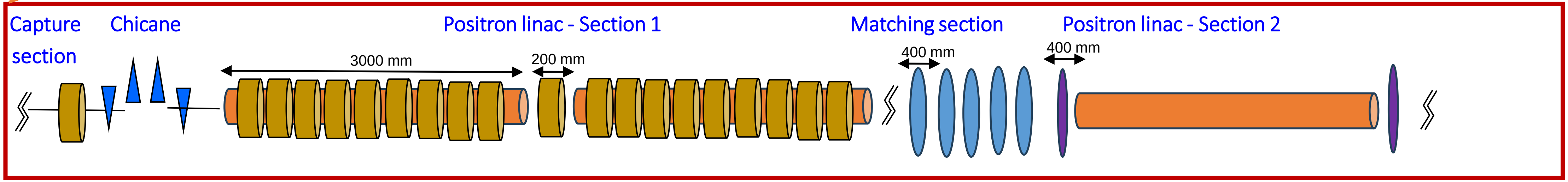
Positron linac (~ 280 meters)

Separator chicane : Rectangular beampipe and hor./vert. collimators, Dipole peak field: ~0.2 T

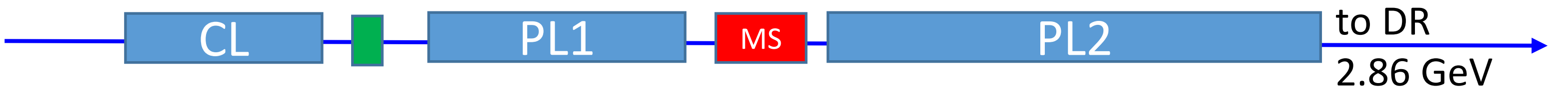
Section 1 : up to ~ 930 MeV. Same RF structure as that of the Capture Linac (CL). 20 structures. G = 13.3 MV/m

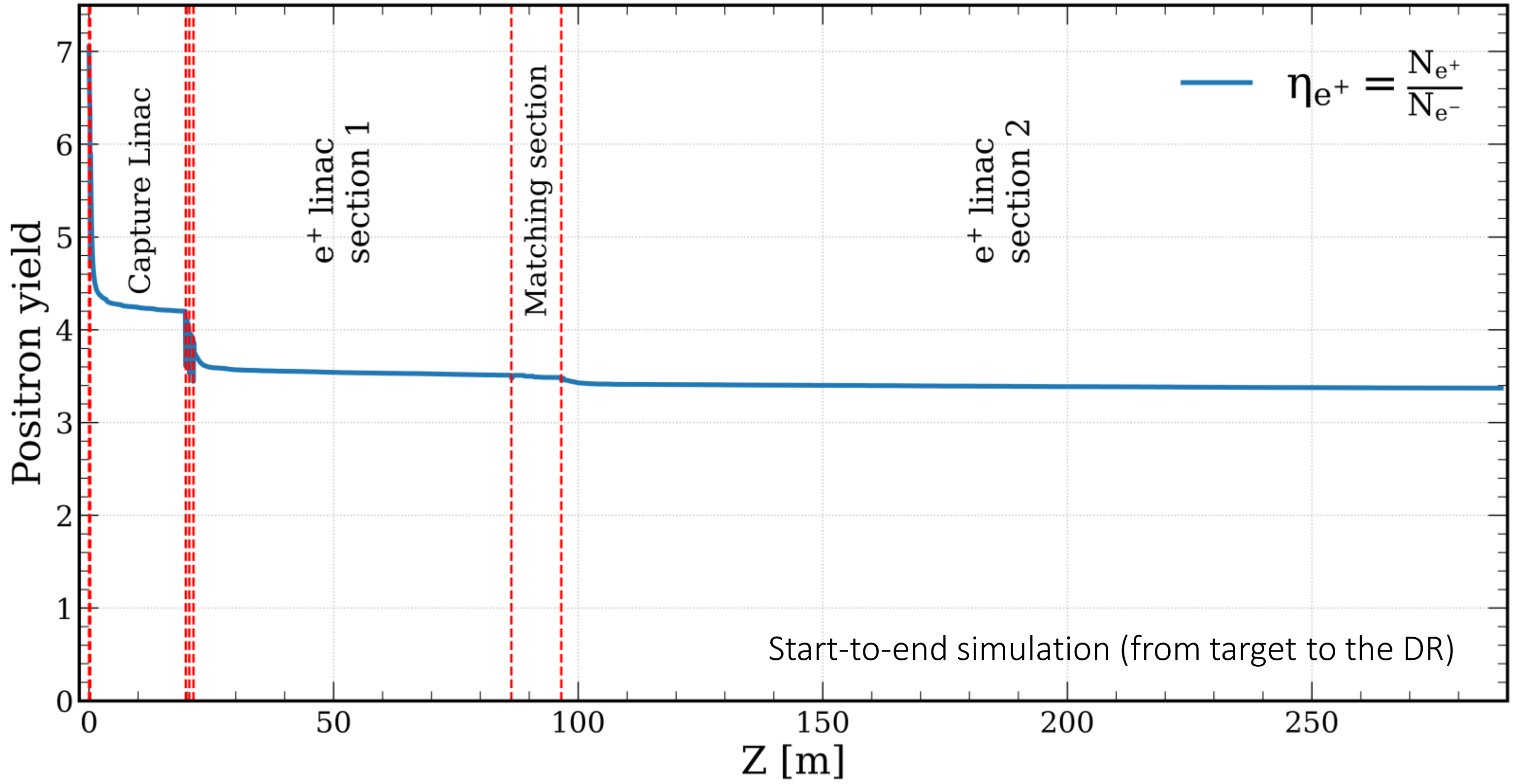
Matching section : 5 quadrupoles (0.4 m long)

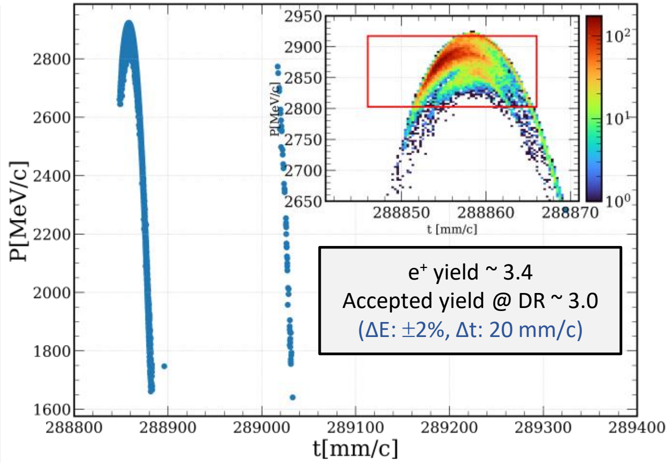
Section 2 : up to 2.86 GeV. Same RF structure as that of the CL. 52 structures. Quadrupole (0.4 m long), 2 structures per FODO cell. G = 12.8 MV/m



Positron capture and linac overall efficiency (FS baseline)







*Simulations include collective effects (space charge and short-range wakefield)

Imperfection	Unit	Value
Transverse position error	μm	100
Transverse angular error (soleoids and dipoles)	μrad	200
Transverse angular error (other elements)	μrad	100
Magnetic strength error	%	0.1
RF gradient error	%	1
RF phase error	°	0.1
Beam position error	μm	100
Beam divergence error	μrad	100

FS design ensures reliable e^+ production and meets the requirements set by FCC-ee (Z-pole) with the safety margins

The impact of these imperfections is found to be negligible: e^+ yield ↓1.3%, emittance x/y ↓0.4/0.8 %

Summary of the simulation results (FS baseline)

e^- Drive beam

Beam energy [GeV]	2.86
Repetition rate [Hz]	100
Number of bunches	4
Bunch charge [nC]	3.8
Bunch length [mm]	1
Beam size @Target [mm]	1
Beam power [kW]	4.3

e^+ Capture system

AMD peak field [T]	15 (12)
Solenoid strength [T]	0.5
AMD/CS aperture [mm]	60
Average energy [MeV]	173
Positron yield [N_{e+}/N_{e-}]	4.2

Target-converter

Thickness [mm]	15
Production rate [N_{e+}/N_{e-}]	7.07
Deposited power [kW]	1
PEDD [J/g]	5.8

e^+ Linac

Average energy [GeV]	2.87
Positron yield [N_{e+}/N_{e-}]	3.4
Accepted positron yield @DR [N_{e+}/N_{e-}]	3
Bunch length [mm]	2.8
Energy spread	0.9
Spots size [mm]	5.3/2.8
Normalized emittance [mm·rad]	~13

Towards TDR: RF frequency from 2 GHz to 3 GHz

The current design assumes L-band 2 GHz RF frequency ➜ limited availability of the power sources

Strong recommendation: investigate the feasibility of adopting "commercial" S-band frequency for the positron capture and linac.

FS baseline RF structure:

- Large-aperture (Φ = 60 mm) TW L-band @ 2 GHz, 9π/10, 3-meter long, ~14 MV/m. designed by H. Pommerenke and A. Grudiev
- Used in capture linac and positron linac

For the layouts, the final accepted e^+ yield as well as the beam emittance (DR acceptance is crucial) have to be compared.

RF frequency, NC vs. SC solenoid focusing, Solenoid vs. Quadrupole focusing, e^- driver (max. charge) ➞ impact on overall cost and power consumption

☞ Comprehensive figure of merit must guide choices

Candidates 3 GHz RF structures for initial studies:

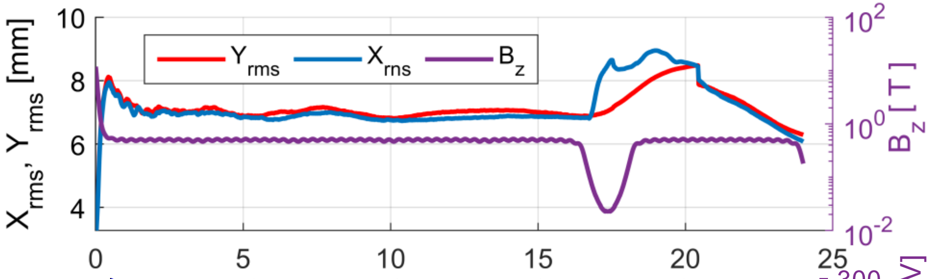
1) LAS (Φ = 30 mm) TW S-band @ 3 GHz, 2π/3, 3-meter long, ~20 MV/m (scaled from SuperKEKB LAS fieldmap 2856 MHz).
2) Large-aperture (Φ = 40 mm) TW S-band @ 3 GHz, 2π/3, 3-meter long, ~20 MV/m (analytical fieldmap).

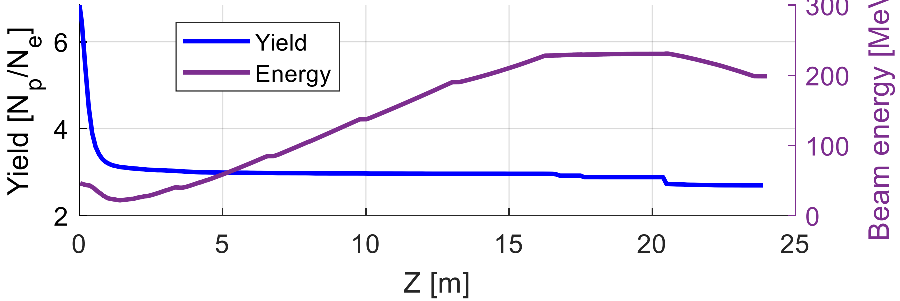
Applied in capture linac and for longitudinal tracking (analytical) in the positron linac

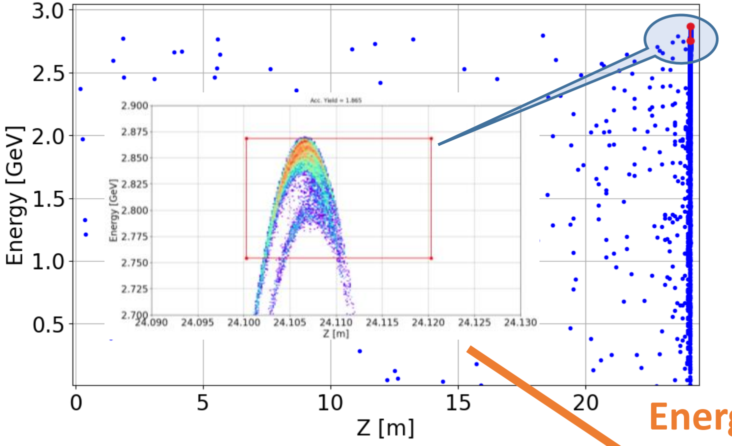
Positron capture system @3 GHz (preliminary)

Capture system : 5 RF structures (3 GHz, 20 MV/m, 3-m long) + separator chicane + 1 RF structure (B_z = 0.5 T)

Φ = 40 mm, TW 3 GHz, 2π/3, 20 MV/m (analyt.)



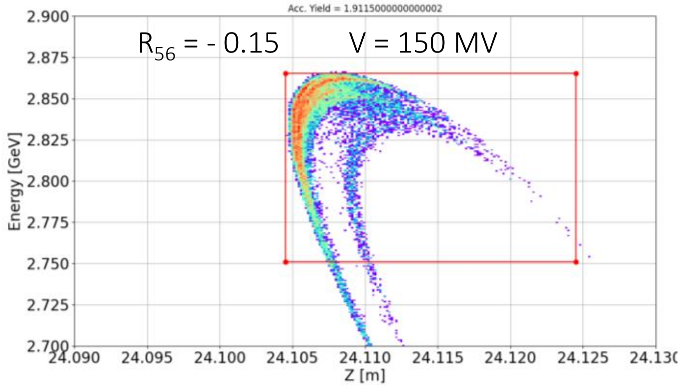




Main RF bucket with e^+ beam (> 90%)

Energy Compressor System (ECS)

Application of the ECS can improve the accepted e^+ charge in the DR (± *2%, ~20 mm/c*)



Configuration	**2GHz ∅60 (FS)**	**3 GHz ∅30 (LAS)**	**3 GHz ∅40**
e^+ yield @ Linac end [N_{e+}/N_{e-}]	3.4	1.6	2.1
e^+ yield @ DR, acc./acc. with ECS	3 (≳ 2.6*)	1.4/1.5 (≲ 2.6*)	1.9/2.0 (≲ 2.6*)
Norm. emittance [mm·rad]	~13.1	~4.1	~6.4

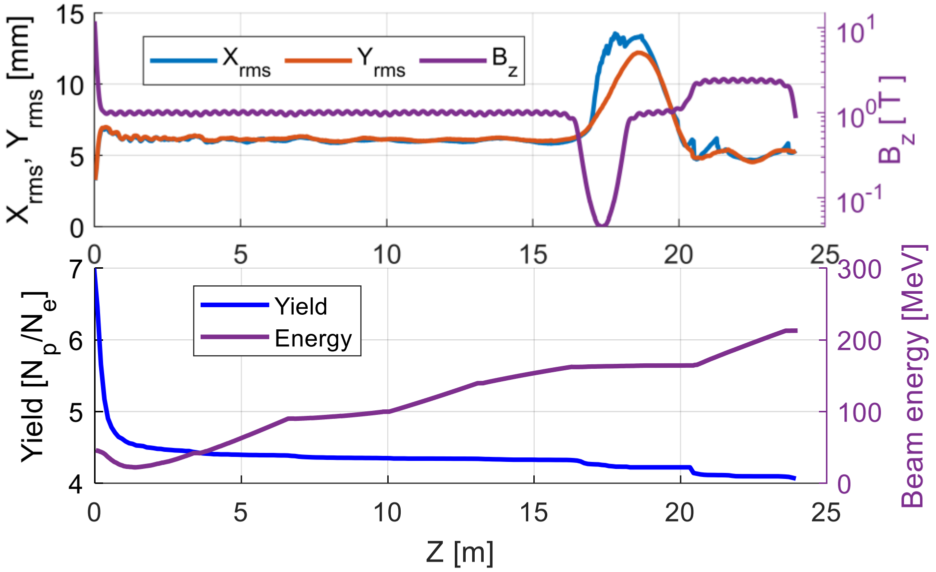
*Minimum required e^+ yield for an e^- bunch charge of 5 nC

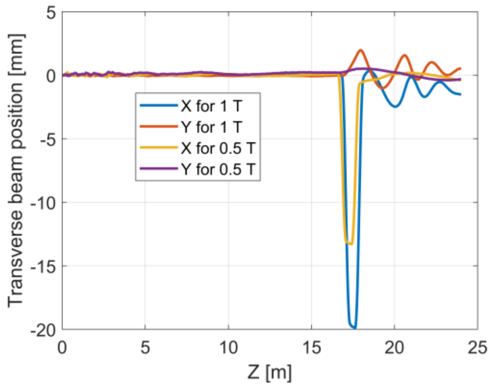
Positron capture system @3 GHz and SC solenoid (preliminary)

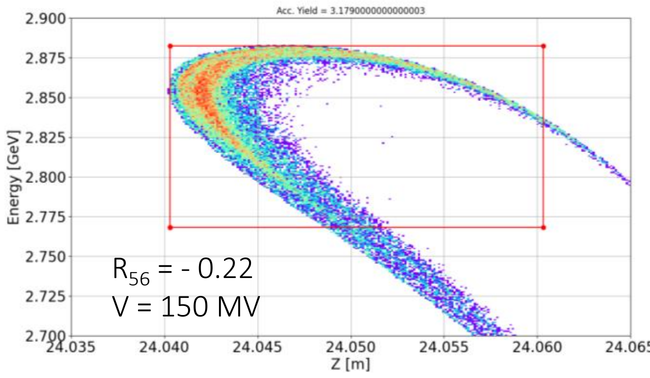
work in progress

Capture system : 5 RF structures (3 GHz, Φ = 40 mm, LAS 20 MV/m, 3-m long) + separator chicane + 1 RF structure

Solenoid field: B_z = 1-2 T







e^+ yield @ Linac end [N_{e+}/N_{e-}]	3.9
e^+ yield @ DR accepted/acc. with ECS	2.7/3.2 (≳ 2.6*)
Norm. emittance [mm*rad]	~13
Energy spread (RMS) [%]	1/1.6
Bunch length (RMS) [mm]	2/2.6

*Minimum required e^+ yield for an e^- bunch charge of 5 nC

- Proposed solution could potentially improve the efficiency of the capture section @ 3 GHz using a smaller aperture, while keeping the same e^- source requirements (≲ 5 nC).
- Further studies are needed to:
  - Assess the feasibility of such a SC solenoid / Evaluate radiation load in the capture linac
  - Compare with an alternative layout using quadrupole focusing before and after the chicane

Summary and outlook

- FS baseline design relies on the HTS solenoid. The accepted e^+ yield is ~3 N_{e+}/N_{e-}. Proof-of-principle with P^3 experiment @PSI starting from 2026.
    - With safety margins, an e^- drive beam charge of 3.8 nC is required to meet FCC-ee specifications (within the current e- source limit ≲ 5 nC).
- The very first studies to investigate the feasibility of 3 GHz RF frequency in the e^+ capture and 2.86 GeV linac are started showing:
    - Reduced e^+ yield assuming FS solenoidal focusing. Thermionic e^- gun ? Clear preference for large-apertures $\Phi \geq 40$ mm.
    - ECS is needed to match e^+ phase space to DR acceptance (~15% gain in accepted e^+ yield). DR energy acceptance is a key parameter!
    - SC solenoids in the capture system could further improve efficiency and should be explored.
- A new layout of 2.86 GeV e^+ linac based on 3GHz RF structures to be developed. Solenoid vs. quadrupole focusing before/after the chicane needs reevaluation.
- Impact on overall injector design and total cost must also be assessed and guide the final choice.
- Conceptual design studies of the crystal-based positron source for the FCC-ee are ongoing. Potential proof-of-principle at P^3 experiment 2^{nd} phase (*see F. Alharthi's poster*).

Credits

PSI	B. Auchmann, I. M. Besana, S. Bettoni, P. Craievich, M. Duda, R. Fortunati, H. Garcia-Rodrigues, D. Hauenstein, 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, N. Strohmaier, N. Vallis, M. Zykova, R. Zennaro, H.H. Braun, M. Seidel all the technical groups involved in the P3 experiment
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