PSI Center for Accelerator Science and Engineering

FCC

Injector Concept and Parameters

Paolo Craievich on behalf of the CHART/FCCee Injector Study collaboration
Scientific Advisory Committee #08, University of Cambridge, 18-20 November 2024

Table of Contents for FS final report

FCC-ee injector study and P-cubed project 2020-2024...

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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 P^3 project (strong support from them)
  - INFN-Ferrara – radiation from crystal (possible future activity for p-cubed)
- we started in summer 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

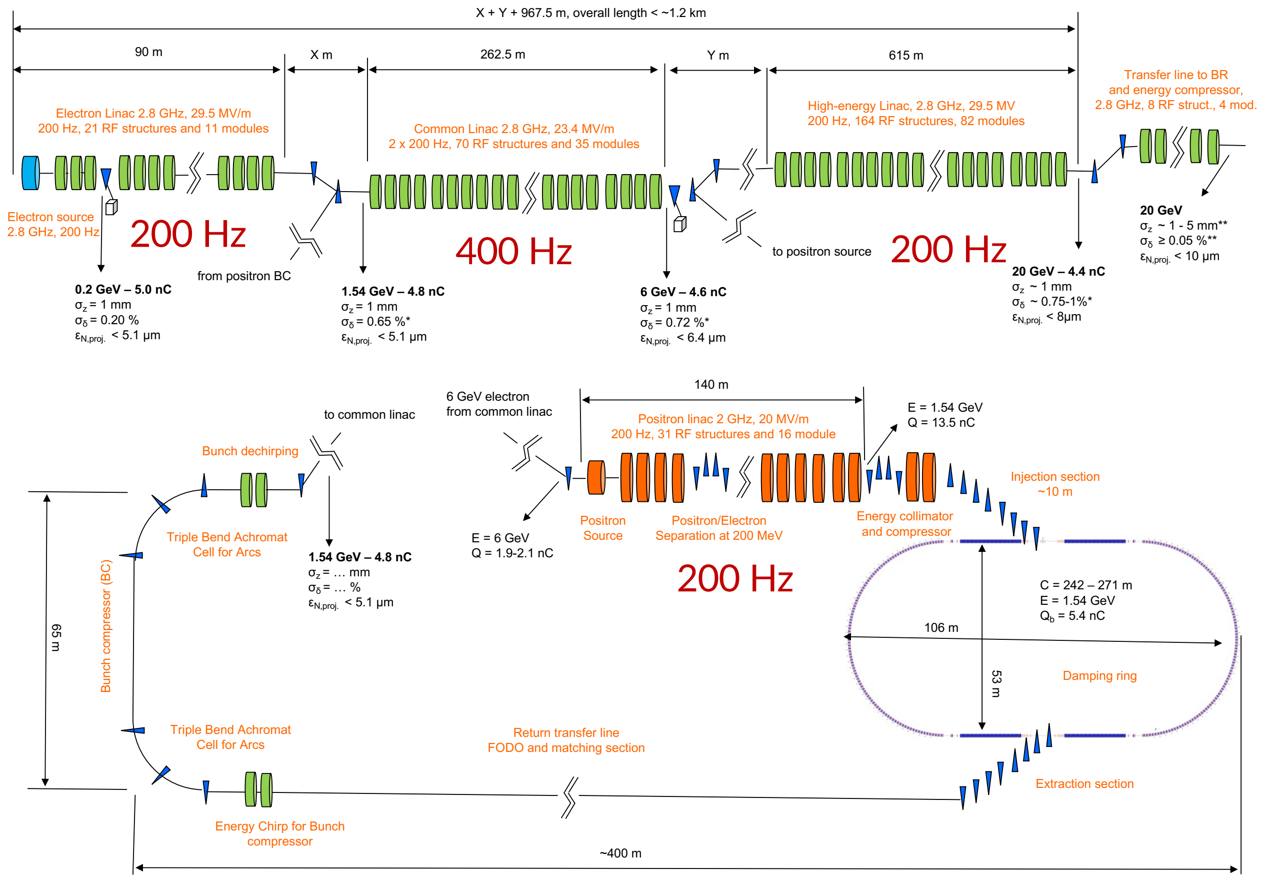
CDR+ and cost estimate

PSI Positron Production (P^3) project

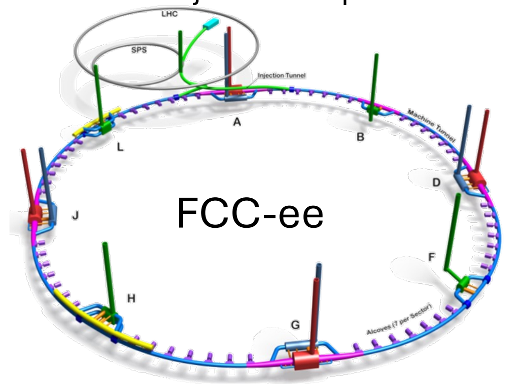
WP6. Proof of Principle positron source and capture in SwissFEL (PSI)

PSI PRODUCTION

Recap: Baseline layout presented at MTR (2 bunches/rf pulse)



injector complex



MTR recommendations:

- **Optimize linac design in term of cost and power!**
- **Overall power consumption 43.5 MW is too high.** Reduction of at least factor 2 or more is necessary
- **High average and peak power** (relatively high gradient for S-band) **operation reliability** has been questioned.
- SPS vs HE linac: keep only the HE-linac option for FS

Collider and booster parameters related to the Injector

Source: H. Bartosik, FCC week 2024 – please for some parameters refer to the next presentation by C. Carli, changes for W mode

Running mode	**Z**	**W**	**ZH**	**tt bar**	**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	%
Booster cycle/number of bunches	10x1120	2x928	1x300	1x64	
Injector duty cycle	73%	40%	19%	5%	
Max injected bunch charge	3.43	1.6	1.6	1.6	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				%

Injector parameter and transmission table – Z mode

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		energy (GeV)	bunch population (1e10)	bunch charge (nC)	transmission
Positron Pre-injector	LE Linac injection *	0.2	2.74	4.38	
	LE Linac exit	2.86	2.71	4.34	0.99
	Positron source target	0.045	19.23	30.80	7.1
	sitron capture Linac exit **	0.2	10.21	16.35	0.531
	ositron Linac injection ***	0.28	8.09	12.95	0.792
	Positron Linac exit	2.86	6.69	10.73	0.828
	Energy Compressor	2.86	6.30	10.09	0.9405
	DR injection	2.86	3.15	5.04	0.5
	DR extraction	2.86	3.12	4.99	0.99
Electron Pre-injector	LE Linac injection	0.2	3.21	5.15	
	LE Linac exit	2.86	3.18	5.09	0.99
	Transfer line				
	DR injection	2.86	3.15	5.04	0.99
	DR exit	2.86	3.12	4.99	0.99
	Bunch Compressor	2.86	3.09	4.94	0.99
	HE Linac injection	2.86	3.05	4.89	0.99
	HE Linac exit	20	3.02	4.84	0.99
	Energy Compressor	20	2.99	4.80	0.99
	Transfer line	20	2.84	4.56	0.95
	Booster injection	20	2.70	4.33	0.95
	Booster extraction	45.6	2.68	4.29	0.99
	Collider injection	45.6	**2.14**	3.43	0.8

* the electron source current should stay below 5 nC
** values before chicane
*** values after chicane plus 2 RF structures

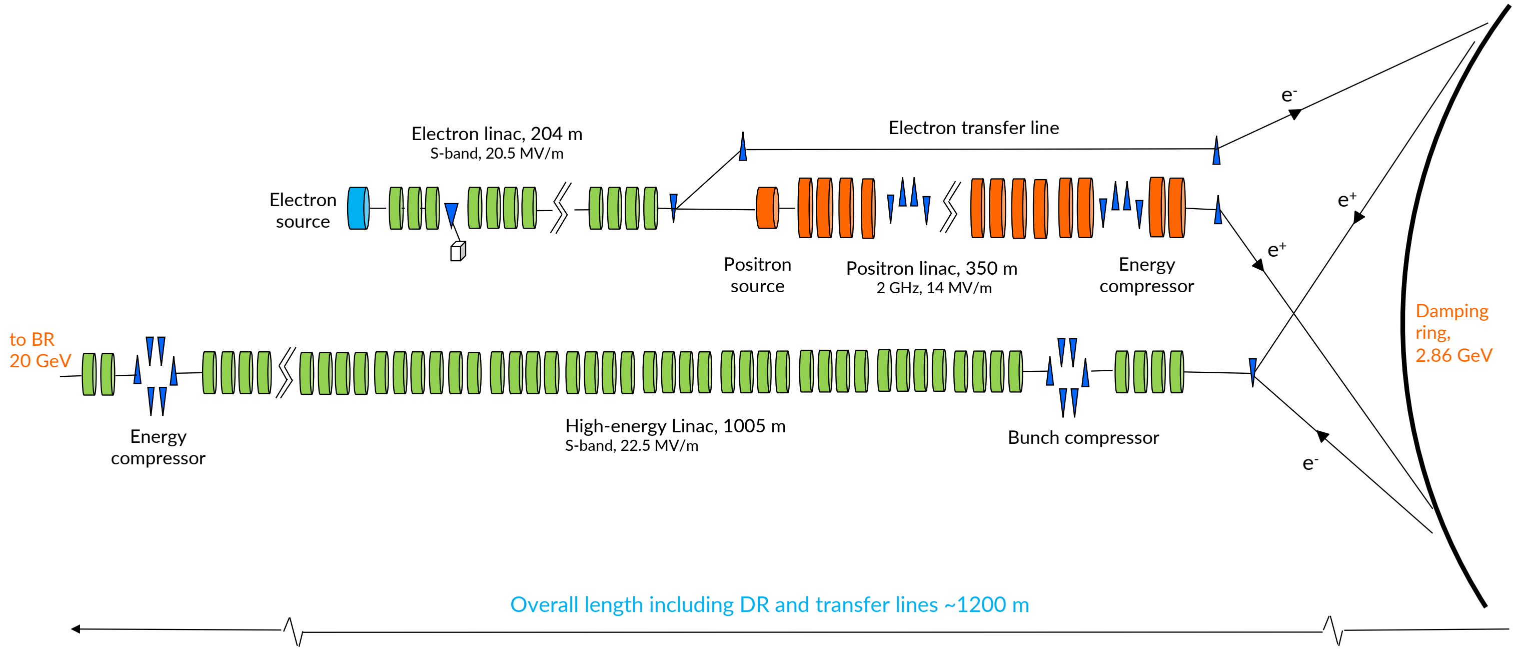
More parameters included in the table: bunch length, energy spread, emittances etc…

Useful to have trace of the changes in the injector chain, i.e. injection parameters in the BR, parameters in the collider etc..

link for the table

Courtesy of H. Bartosik

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



Recap: New damping ring at higher energy 2.86 GeV, no common linac (would require doubling repetition rate), for both species with flat emittances, beam size smaller at the injection

General comment: Considering the energy compressor, the bunch compressor, the matching and diagnostic sections and the beam dumps, the total length of the injector exceeds 1.2 km (about 150 m).

Possible solutions to address this point (after the FS):

- Review of the injector layout, i.e. DR on the other side of the road or extension of the HE linac after the river.
- Lower beam energy for BR injection, option to be also considered for commissioning of the BR.
- Shorter transfer lines and smaller DR.
- Bunch compressor included in the linac optimization.
- HE linac with higher gradient, 3 ASs for klystron (gradient ~25 MV/m).

Electron and positron linacs (rf design)
Electron linacs (beam dynamics)

New Baseline for linacs

Bunch repetition rate (from 400/200Hz to 100 Hz)

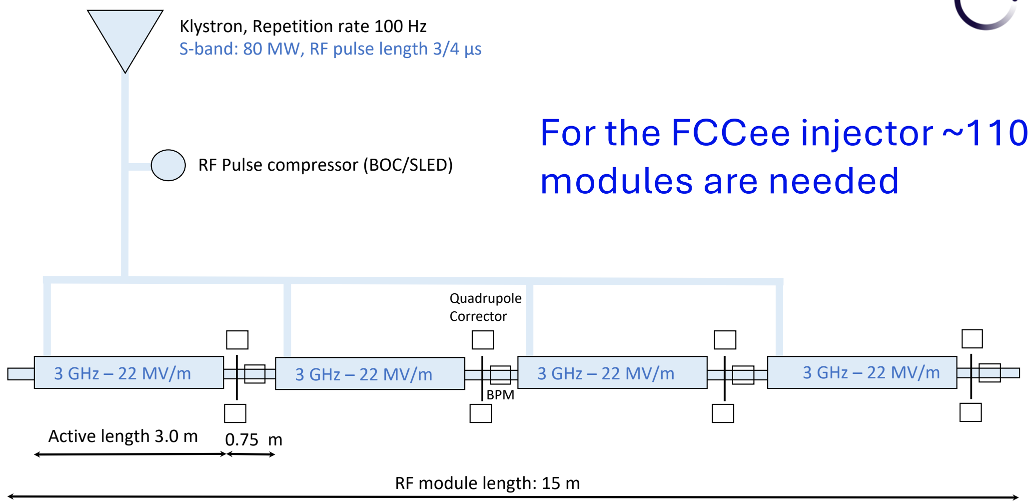
- 100 Hz x 4 bunches in Z-mode,
- 100 Hz or lower in other modes

RF module layout:

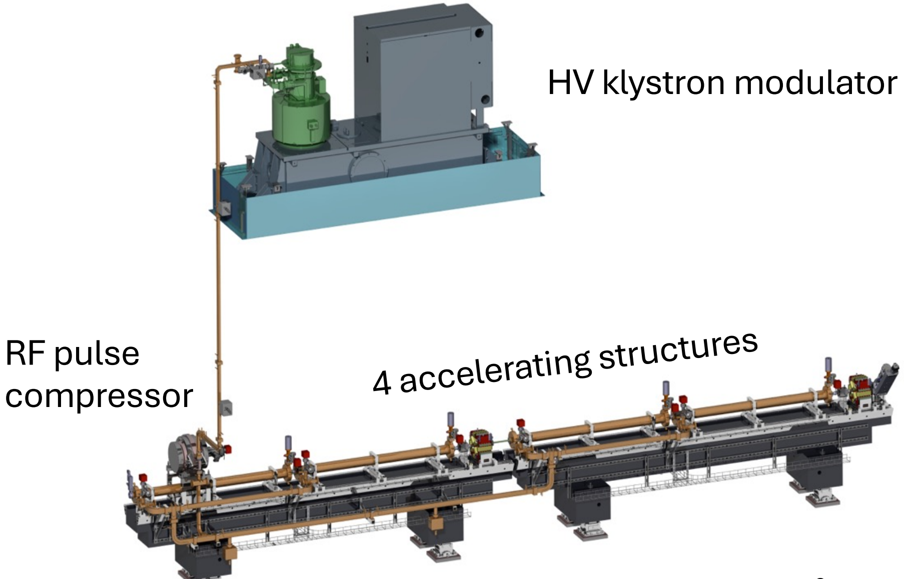
- 4 RF structures per module,
- 1 quad per RF structure

New RF Structure with higher impedance:

- Active length = 3 m (compatible with PSI technology)
- average aperture <a>/λ (higher impedance)
  - 0.15 (16.1 mm) <2.86GeV (e-linac)
  - 0.12 (12.8 mm) >2.86GeV (HE-linac)
- RF frequency = 2.8 GHz (for FS report)
- Max gradient 22 MV/m (instead of 29.5 MV/m)
- Rep. rate of 100 Hz with 4 bunches per rf pulse, necessary beam loading compensation and long range wakefield suppression.



For the FCCee injector ~110 rf modules are needed



Courtesy of A. Grudiev, A. Kurtulus and WP1 working group members

Accelerating structure parameters (single bunch case)

	HE-linac	E-linac	P-linac
Frequency [GHz]	2.8	2.8	2
Avg. Aperture	0.12λ	0.15λ	0.2λ
Entr., exit aperture	14.85 mm, 10.85 mm	17.13 mm, 14.99 mm	30 mm, 30 mm
Iris thickness	2.84 mm → 4.04 mm	10.4 mm → 13.7 mm	14.3 mm → 20 mm
Vg (% c)	3.92 → 1.25	3.14→ 1.38	2.58 → 1.92
r/Q (kOhm/m)	3.63 → 4.38	3.28 → 3.67	1.49 → 1.52
Q	16571 → 16039	14599 → 13668	20977 → 19102
Structure Length [m]	3	3	3
Filling time	460 ns	486 ns	447 ns
SLED coupling	15	15	17
Eff. shunt impedance	102 .25 MΩ/m	87.17 MΩ/m	38.73 MΩ/m
Repetition rate [Hz]	100	100	100
Klystron power per structure	14.2MW	14.2 MW	15.4 MW
Average Structure Input Power	3.72 kW	3.76 kW	3.68 kW
G_{avg}	22 MV/m	20.3 MV/m	14.1 MV/m
E_{max} (instant.)	73 MV/m	77 MV/m	55 MV/m
$S_{c,max}$ (instant.)	501 mW/μm^2	453 mW/μm^2	298 mW/μm^2

Courtesy of A. Grudiev and A. Kurtulus

Accelerating structure parameters (four bunches case)

Beam loading reduces the average accelerating gradient of ~4-5%

	HE-linac	E-linac	P-linac		
Eff. shunt impedance (Four bunches)	95.65 MΩ/m	81.69 MΩ/m	36 MΩ/m		
Klystron power per structure	14.2MW	14.2 MW	15.4 MW		
	21.28 MV/m	19.66 MV/m	13.59 MV/m		
Bunch Charge	5 nC	5 nC	5 nC	10 nC	15 nC
Loaded G_{avg}	21.06 MV/m	19.49 MV/m	13.5 MV/m	13.42 MV/m	13.31 MV/m

Courtesy of A. Grudiev and A. Kurtulus

Linac Specifications and Power Consumptions

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Max. Klystron Power: 80 MW, Operating Klystron Power: 64 MW i.e., 20 % Margin

Linac	RF AS per mod.	Rep. Rate [Hz]	Modules	Loaded G [MV/m]	Linac lengths [m]	Pkly/AS [MW]	$P_{consumpt.}$ in operation [MW]	$P_{consumpt.}$ [MW]
e-linac * <a/λ>=0.15	4	100	14+1	19.5 5 nC	215	14.2	2	2.5
p-linac** <a/λ>=0.2	4	100	22	13.3 15 nC from S1Linac	319	15.4	8	9
HE-linac * <a/λ>=0.12	4	100	72	21.1 5 nC	1080	14.2	9.5	11.5

* 3 μs RF pulse length, 6 μs HV pulse length
Assumes 25 m WR284 waveguide system length for one RF module

Total 19.5 MW
(MTR 43.5 MW)

** 5 μs RF pulse length, 8 μs HV pulse length,
Assumes 25 m WR510 waveguide system length for one RF module
Assumes 6 structures (2 modules) for Capture Linac, 20 structures (5 modules) for S1 Linac and 260 solenoids

MTR: E-linac + Common linac + HR linac = 37.6 MW
Present baseline: E-linac + HE linac = 11.5 MW, reduction factor >3

Courtesy of Jean-Yves Raguin (15.11.2024)

Beam loading and rf pulse shape compensation (4 bunches)

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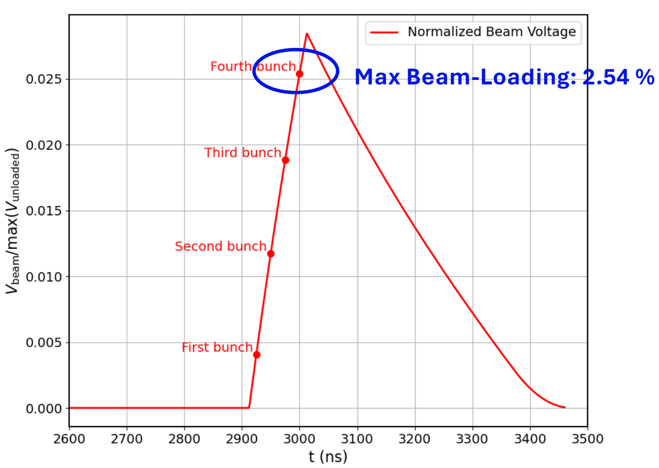
Example for the HE linac but this approach can keep the energy variation for the other linacs within +/- 1.5%

P_{klys} = 14.2 MW,
L = 3m G = V/L

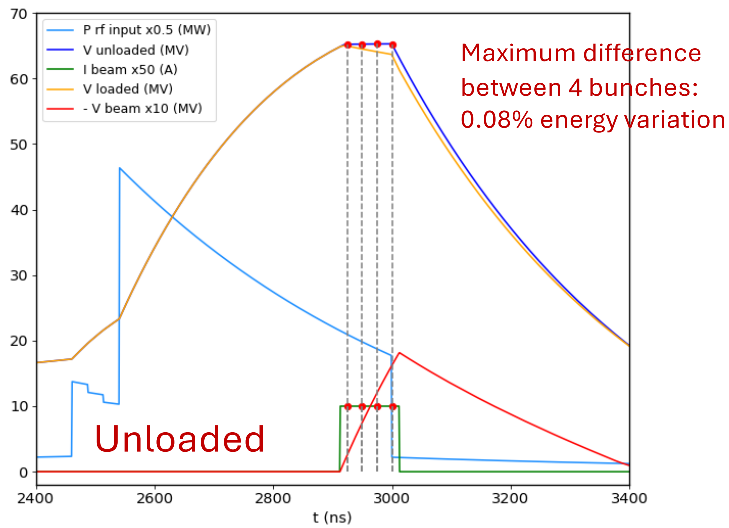
Unloaded Voltages	1st Bunch	2nd Bunch	3rd Bunch	4th Bunch	R_{sh}
Single Bunch	66 MV				102.25 MΩ/m
4 Bunches	63.81 MV	63.84 MV	63.86 MV	63.82 MV	95.65 MΩ/m

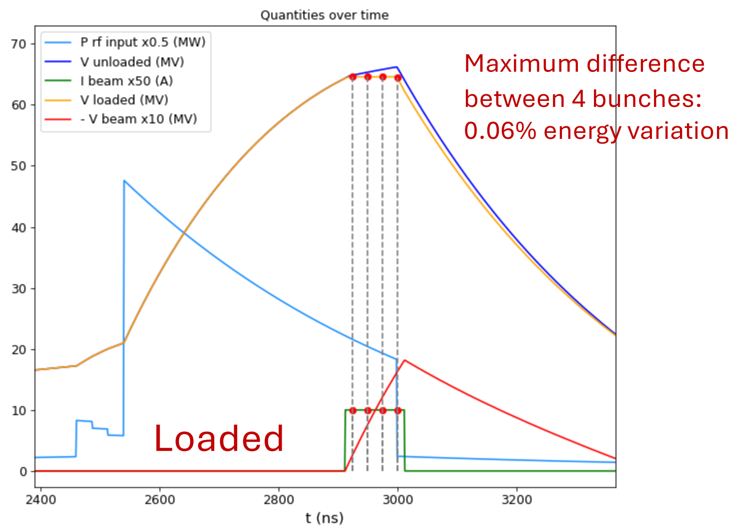
For bunch charge: 5 nC,
25 ns of bunch spacing

Loaded Voltages	1st Bunch	2nd Bunch	3rd Bunch	4th Bunch
Single Bunch	65.75 MV			
4 Bunches	63.19 MV	63.19 MV	63.20 MV	63.16 MV



Beam loading effect





Courtesy of A. Grudiev and A. Kurtulus

Beam loading and rf 'golden' pulse compensation

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Golden pulse applied

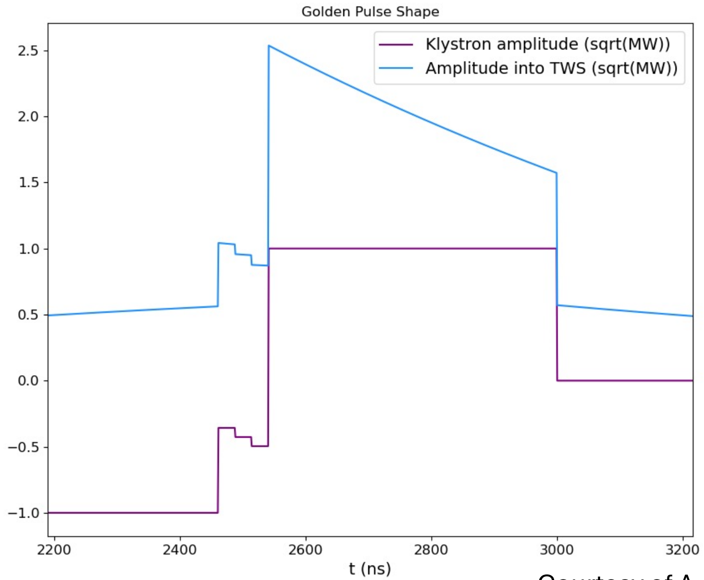
Unloaded Voltages	1st Bunch	2nd Bunch	3rd Bunch	4th Bunch
Single Bunch	66 MV			
4 Bunches	63.63 MV	63.89 MV	64.13 MV	64.30 MV

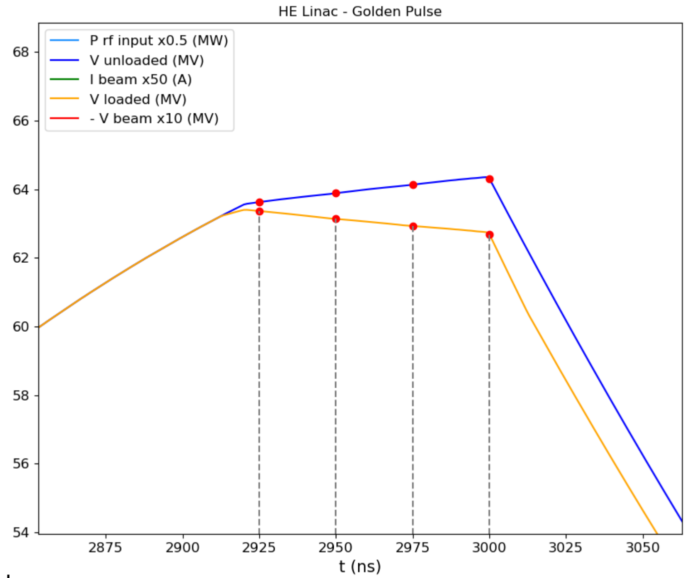
+1.1% energy variation

Loaded Voltages	1st Bunch	2nd Bunch	3rd Bunch	4th Bunch
Single Bunch	65.75 MV			
4 Bunches	63.37 MV	63.14 MV	62.93 MV	62.68 MV

-1.1 % energy variation

For bunch charge: 5 nC
25 ns of bunch spacing



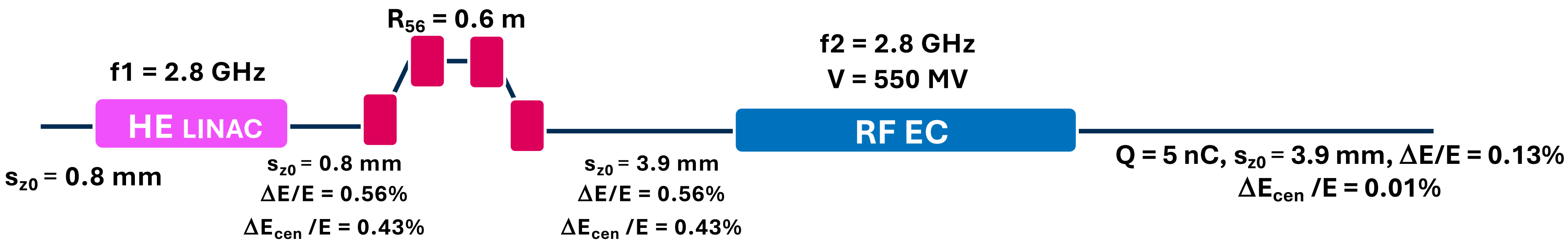


Courtesy of A. Grudiev and A. Kurtulus

High Energy Compressor (at 20 GeV)

Longitudinal dynamics: single and multi-bunch bunch length and energy spread fulfil the booster requests

- On-crest operating phase to optimize the transverse beam quality
- Energy compressor to match the target parameters single and four bunches
- Energy compressor allows for the 0-100% scan charge
- Total length ~70 m including matching sections upstream and downstream of EC
- Ongoing verification of the parameters for low charge by the booster group



Q = 5 nC: ΔE/E~0.1-0.15% but a factor 2-3 less possible

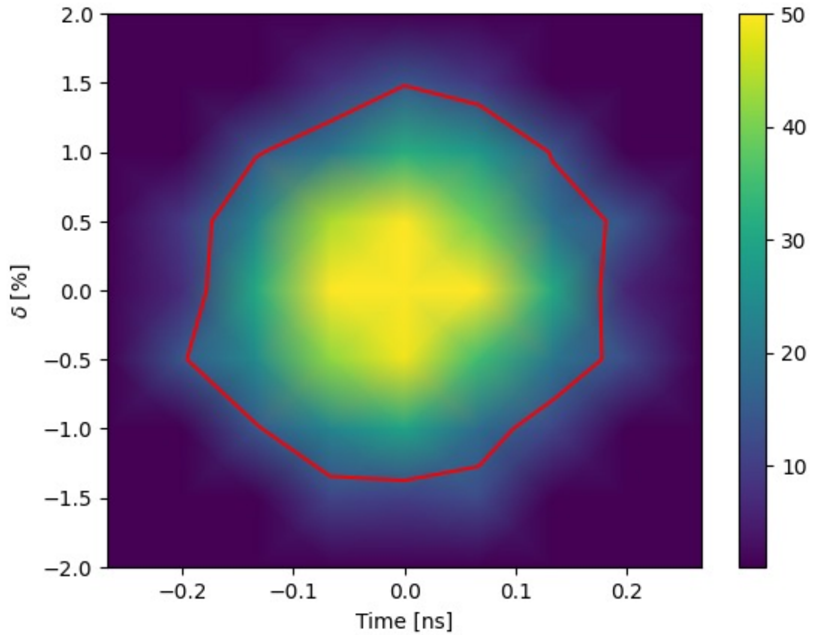
	Bunch 1	Bunch 2	Bunch 3	Bunch 4
Single bunch DE/E (%)	0.16	0.16	0.15	0.13
Rms bunch length (mm)	3.93	3.89	3.86	3.82
DE/E centroid from bunch 1 (%)	0	-0.018	-0.019	-0.042
Dt from bunch 1 (ps)	0	7.8	15.5	23.2

Q = 5 pC → all the machine settings on the high Q bunch

	Bunch 1	Bunch 2	Bunch 3	Bunch 4
Single bunch DE/E (%)	0.15	0.15	0.14	0.13
Rms bunch length (mm)	1.1	1.1	1.1	1.1
DE/E centroid from bunch 1 (%)	0	-0.012	-0.051	-0.12
Dt from bunch 1 (ps)	0	7.6	15.2	22.7

Courtesy of S. Bettoni et al.

Booster Ring dynamic aperture at injection (preliminary)



Courtesy of A. Chance

Normalized emittance at injection 10 μm x 10 μm

1000 turns, initial grid in number of σ, angles (in the X-Y plane), time and delta.

The red region corresponds to a region with a DA of 15σ

Single bunch length: 5 σ = 20 mm (~67 ps)

Temporal acceptance 45 mm (0.15 ns)

→ this leaves margin to accepted temporal jitter and offset of 25 mm (83 ps), compatible with beam parameters at the exit of the EC

Electron Linac(s) beam dynamics studies 1/2

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Sensitivity to <u>static</u> misalignments

- Assumed very "generous" rms Gaussian distributed misalignments: 50 μm for quadrupoles, 100 μm per RF structures, and 30 μm per BPM
- Applied one-to-one correction and DFS (including 10 μm resolution) in cascade
- More than the 98% of the good seeds considered in the calculation of the emittance growth

E- LINAC (0.2-2.86 GeV)

$a/\lambda = 0.15$

N_bins	Δε (mm.mrad)	ε (mm.mrad)
3	0.5	3.7
4	0.4	3.6
5	**0.3**	**3.5**
7	0.3	3.5
10	0.3	3.5

HE LINAC (2.86-20 GeV)

$a/\lambda = 0.12$

N_bins	Δε (mm.mrad)	ε (mm.mrad)
8	**0.6**	**1.6**
9	0.6	1.6
10	0.6	1.6
12	0.6	1.6

Normalized emittance growth under control

ε_x (mm.mrad)		ε_y (mm.mrad)	
Maximum	Design	Maximum	Design
20	<12	2	1.6

- **e- linac:**
  - Emittance good enough for the positron production (e-linac)
  - Emittance expected to be good enough for the injection to DR (tbc by the DR group)
- **HE linac:**
  - Emittance growth fulfilling the booster requirements

Courtesy of S. Bettoni and A. Latina

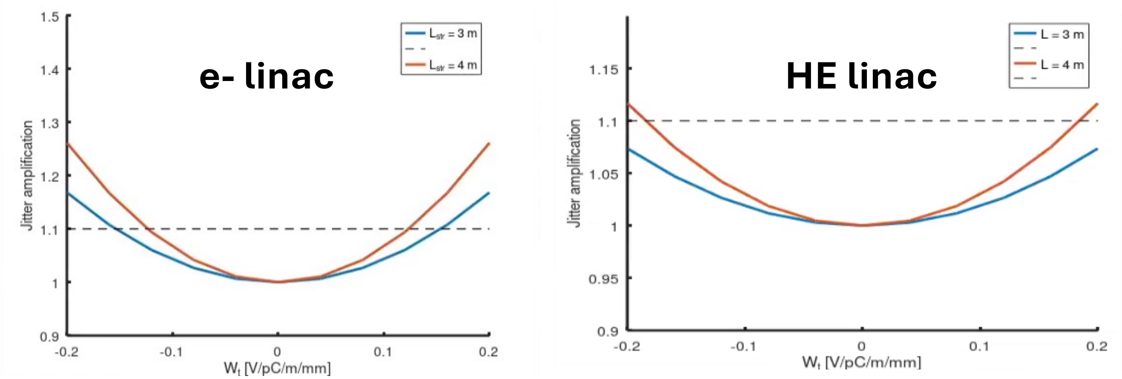
Electron Linac(s) beam dynamics studies 2/2

Sensitivity to transverse jitter: under control

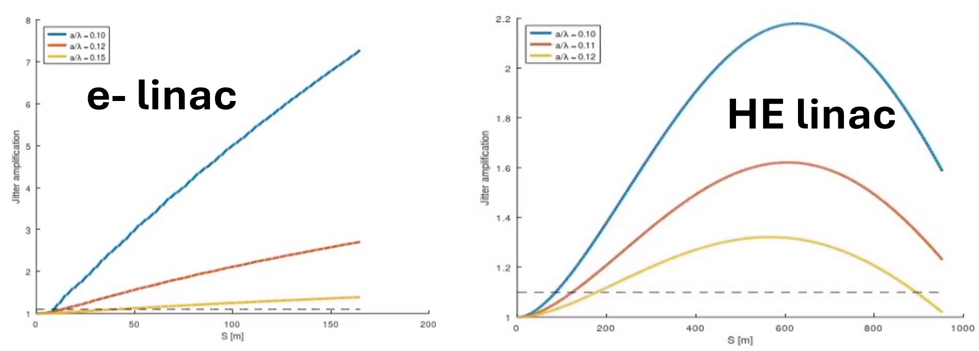
- Single bunch: jitter amplification along all the linacs determined
- Multi-bunch: maximum kick defined (input for the RF design)
  - Maximum transverse wake kick <0.11 V/pC/m/mm

$$JA = JA_{Single} . JA_{Multi} = \left(\prod_{k=1}^{N} JA_k\right)_{Single} . \left(\prod_{k=1}^{N} JA_k\right)_{Multi}$$

Multi-bunch



Single bunch



Transverse jitter under control

E- linac		HE linac	
Multi-bunch	**Single bunch**	**Multi-bunch**	**Single bunch**
1.08	1.40	1.03	1.02

Courtesy of S. Bettoni and A. Latina

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Positron source, capture and linac (beam dynamics) and p-cubed experiment

PSI CERN IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Positron source specifications

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The complete filling for Z running => Requirement ~2.75 × 10^{10} e^+/bunch (4.8 nC) at the linac end

or 5.4 nC accepted in the DR

$$N_{e-}/\text{bunch} \times \eta^{e+}_{Accepted} \geq \underbrace{5.4\ \text{nC/bunch} \times 2.5}_{13.5\ \text{nC}}$$

A safety margin of 2.5 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)

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

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

Beam energy	2.86 GeV
Bunch charge	~5.6 nC (max)
Bunch length	1 mm
Bunch transverse size	≳ 0.5 mm

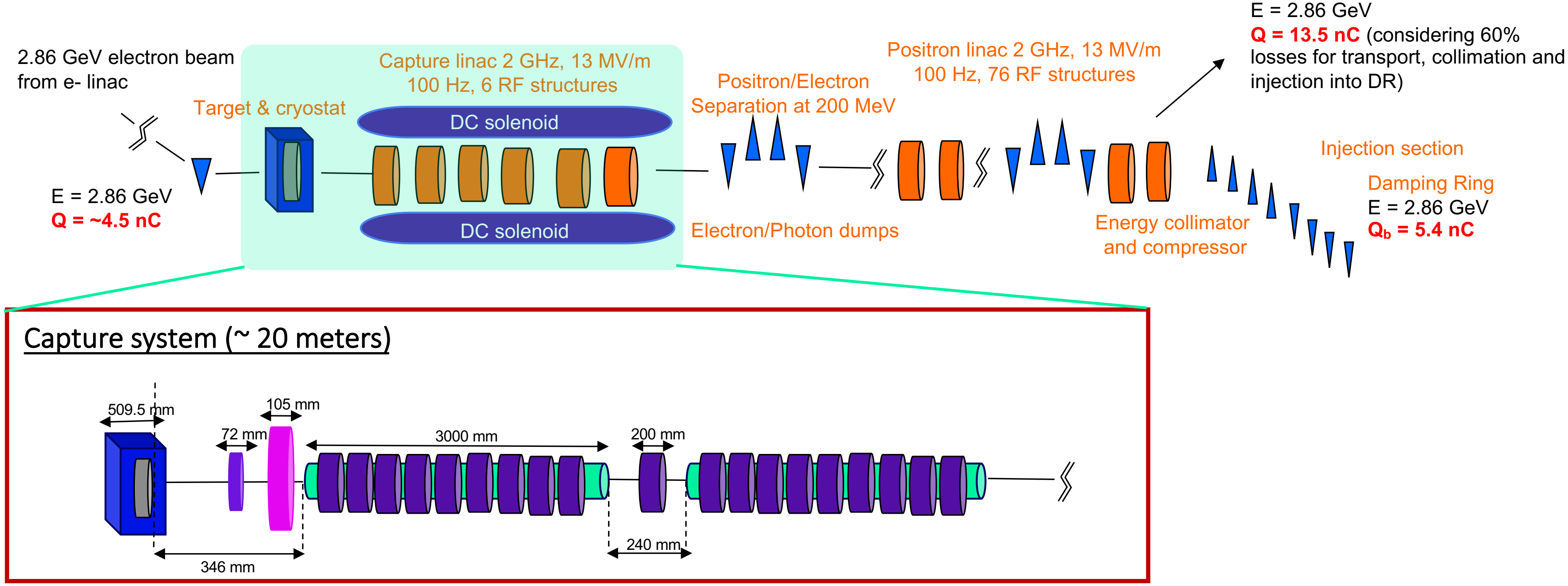
Nb of bunches per pulse	4
Bunch separation	25 ns
Repetition rate	100 Hz
Beam power	~ 6.4 kW (max)

→ positron flux of ~1.1×10^{13} e^+/s (×2.5). *Demonstrated at SLC (a world record for existing accelerators): ~6 ×10^{12} e+/s*

slide prepared by I. Chaikovska et al.

Positron source physics design

HTS solenoid – based option => baseline



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, ∅ 60 mm 72 mm bore, ∅ 60 mm including shielding)

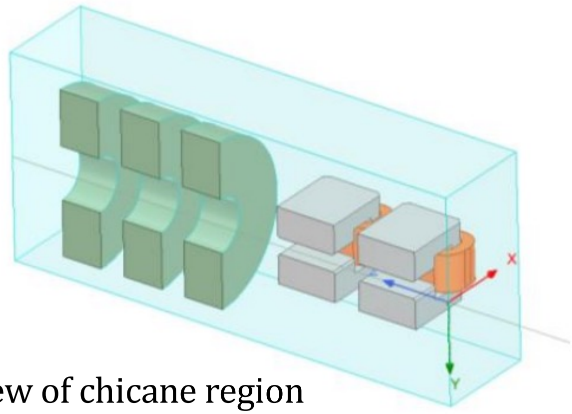
Capture linac is based on the L-band TW RF structures (2 GHz, ∅ 60 mm, 3-m long)

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

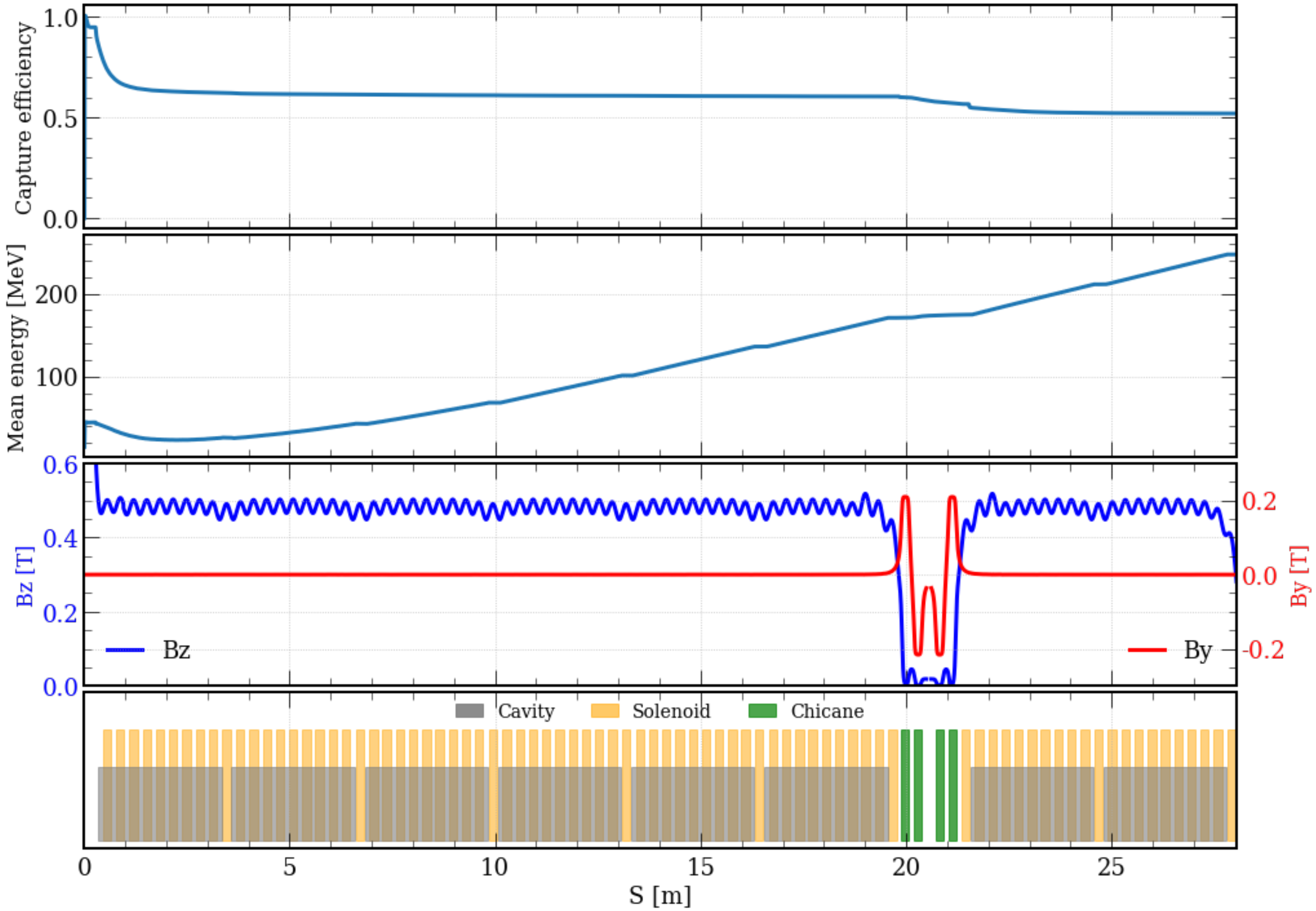
slide prepared by I. Chaikovska et al.

Capture section design and performance

- **RF structures**: 2GHz L-band with aperture (2a) = 60mm , 3m long and 13 MV/m.
- **Solenoids**: 10 NC short solenoids surrounding each RF structure to create 0.5 T magnetic channel.
- **Chicane**: 4 dipoles (0.2T) to separate e- and e+, with electron stopper at the middle.



1/4 view of chicane region



slide prepared by I. Chaikovska, simulations by Y. Zhao

Positron source physics design

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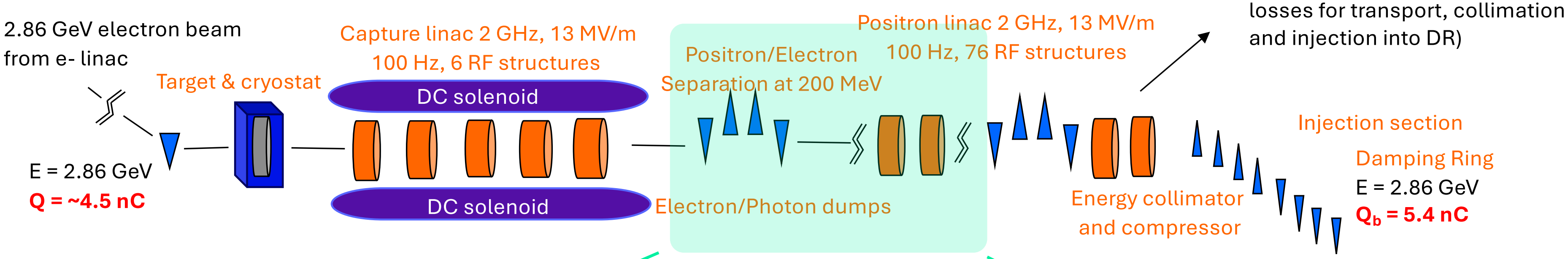
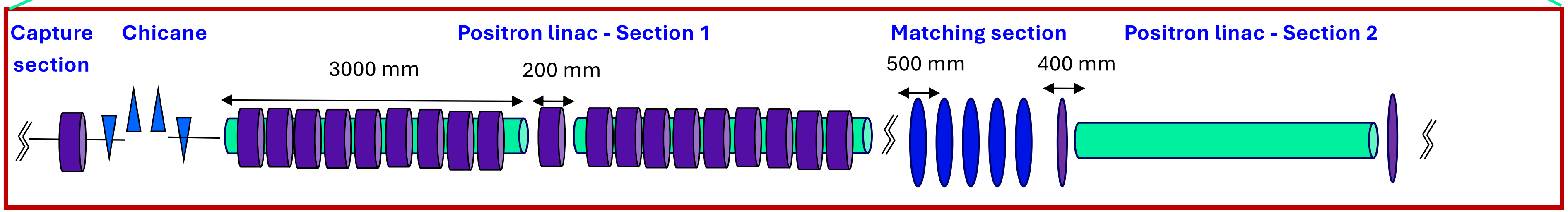
HTS solenoid – based option => baseline



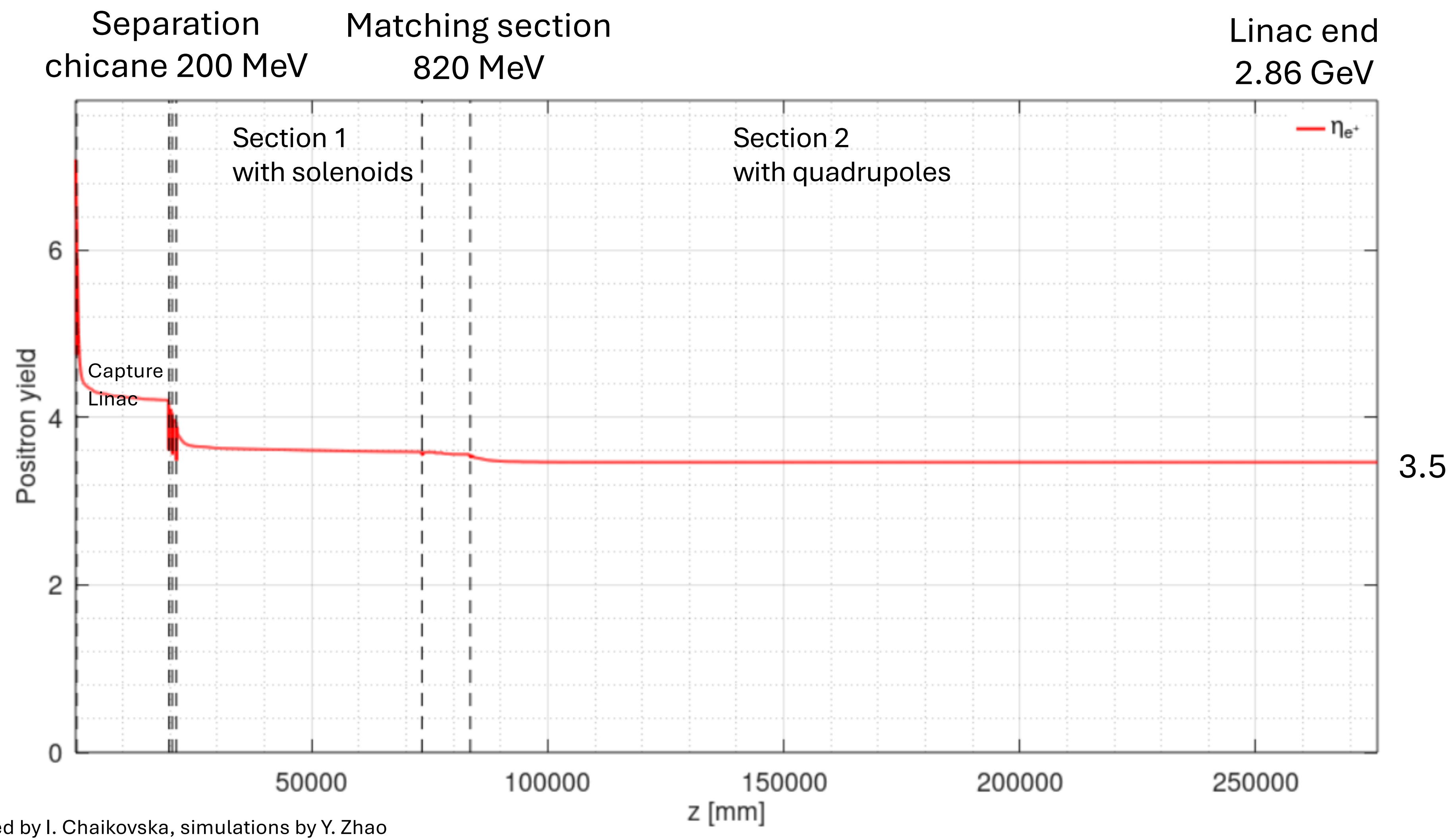
- **Separator chicane :** Rectangular beampipe and hor./vert. collimators, Dipole peak field: ~0.2 T
- **Section 1** : up to ~ 820 MeV. Same RF structure with Capture Linac (CL). 20 structures. G = 14 → 13 MV/m
- **Matching section** : 5 quadrupoles. Quadrupole (0.4 m long)
- **Section 2** : up to 2.86 GeV. Same RF structure with CL. 56 structures. Quadrupole (0.4 m long), 2 structures per FODO cell. G = 13.5 MV/m



Positron linac (~ 280 meters)

slide prepared by I. Chaikovska et al.

Positron linac design and performance (positron yield)



slide prepared by I. Chaikovska, simulations by Y. Zhao

Summary of the simulation results

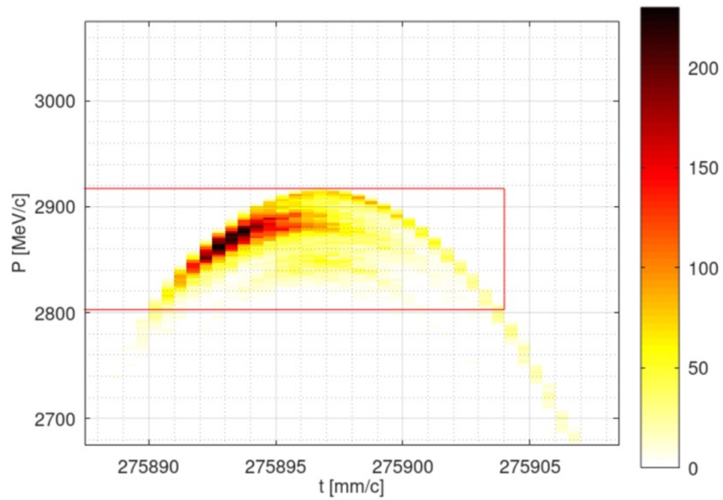
Parameter	Unit	
e^- beam energy	GeV	2.86
Number of bunches		4
Repetition rate	Hz	100
e^- bunch charge	nC	4.5
e^- beam power	kW	5.1
Target thickness	mm	15
Beam size, x/y	mm	1
Positron yield @ Target	Ne^+/Ne^-	7.1
Positron yield @ CS *	Ne^+/Ne^-	4.3/4.0/3.6
Positron yield @ PL**	Ne^+/Ne^-	3.5
Positron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

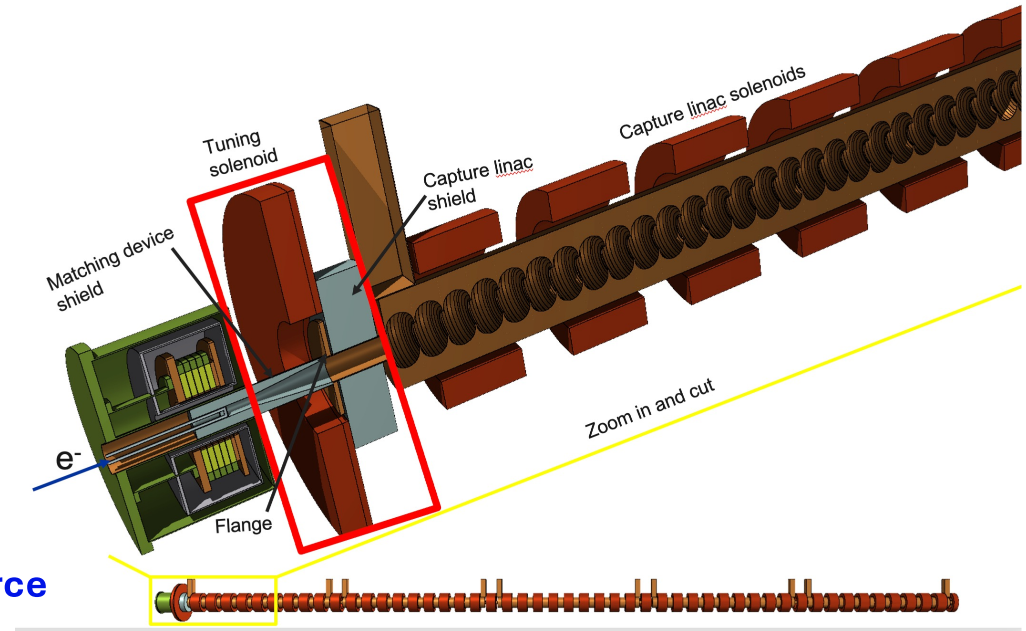
slide prepared by I. Chaikovska, simulations by Y. Zhao

Summary for the positron source and linac

– Baseline design relies on the HTS solenoid. The accepted e^+ yield is ~3 N_{e+}/N_{e-}. So far, no showstoppers found that prevent a SC solenoid matching device (proof-of-principle with P^3 experiment @PSI in 2026).

– For 2.86 GeV injector option, to fulfil the requirements for positron bunch charge, higher e^- drive beam charge is needed (~4.5 nC).

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

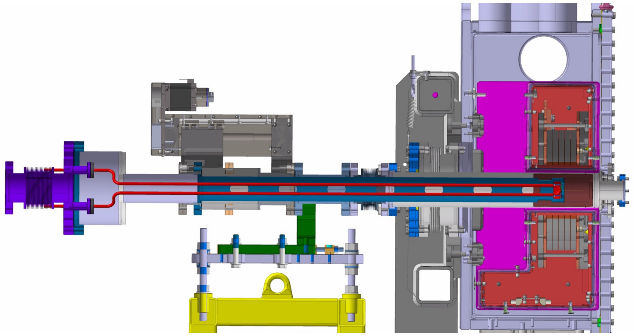


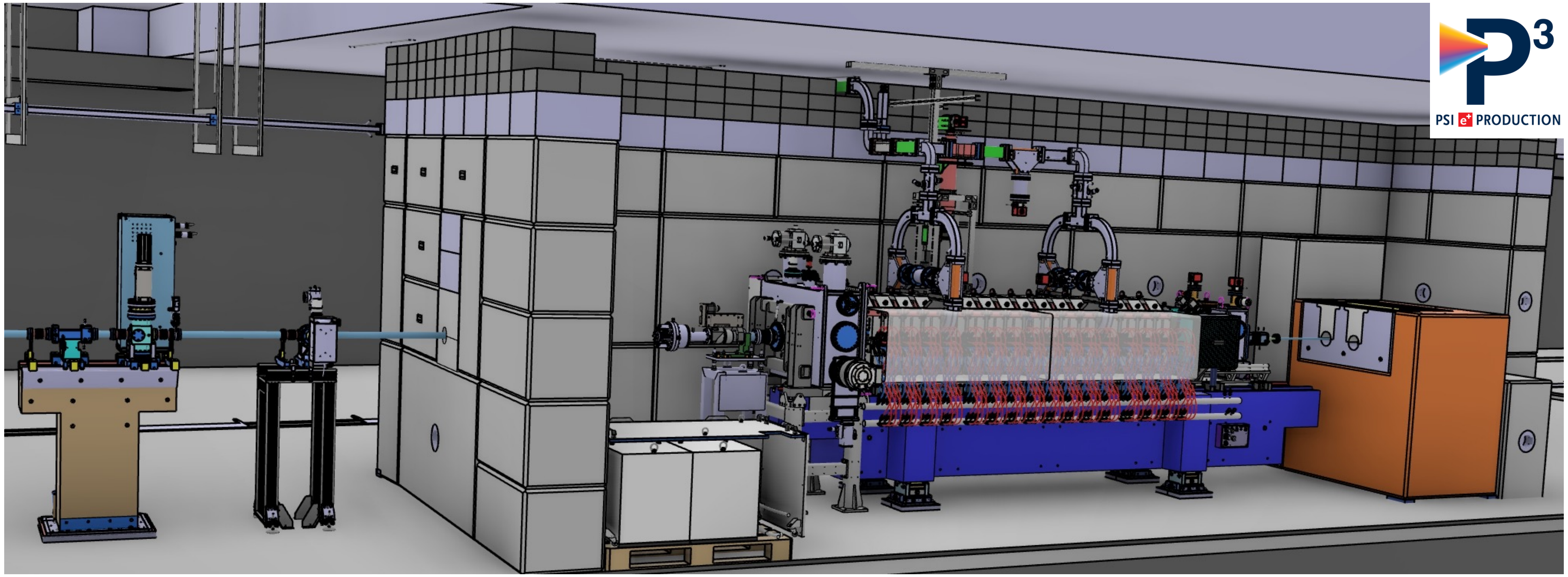
FLUKA model of the e^+ source

The PSI Positron Production Experiment

- P^3 or *P-cubed* is a Proof-of-principle study of a e+ source and capture system that can enhance the state-of-the-art e+ yield.
- Based on the conventional principles of pair-production-driven e+ sources but will use novel technology (e.g. HTS solenoids).
- Design complete and currently in construction at SwissFEL at PSI.

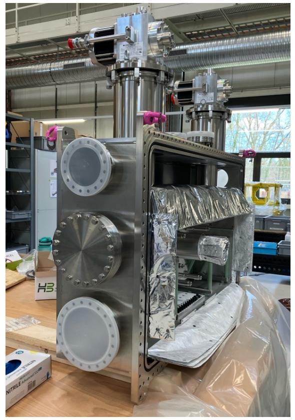
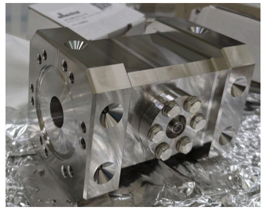
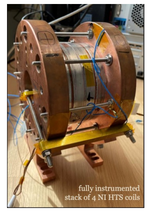
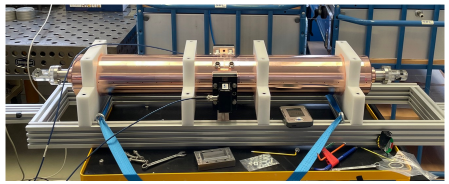
- Target system by STI group at CERN





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).
  - Radiation tests on a dedicated HTS solenoid in the beamline of the PSI cyclotron is under discussion.
- 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.

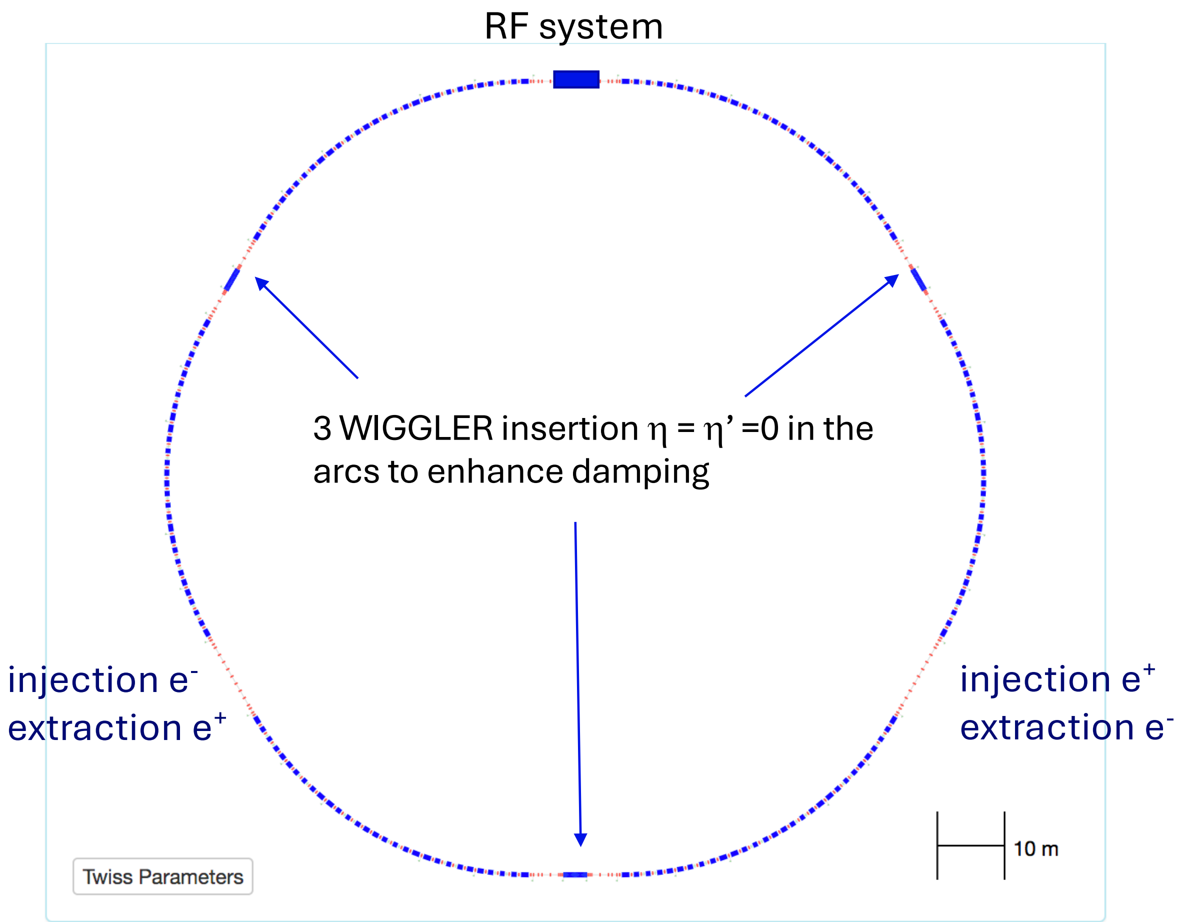






Damping ring and bunch compressor

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

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

- Best use of allocated space (120 m x 120 m)
- Flexible injection/extraction sections
- Dedicated space for RF system and wiggler magnets
- Wide flexibility in independently tuning the ring working point
- Suppress in principle six order resonances
- Three arc cells (120 deg) providing, low emittance, damping time, large beam acceptance
- Overall dimension 122 m x 122 m



Courtesy of C. Milardi

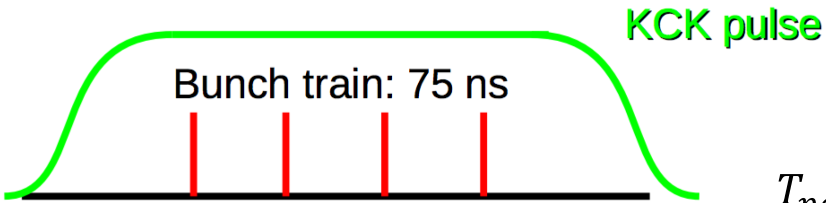
Dampig ring parameters (6-fold symmetry, min emittance arc cell)

FCC

	DS_2p1.madx		Comments
Beam energy	2.86	GeV	
Circumference	378.14	m	
Number of dipoles	179		Average 0.34 T
Br	9.54	T m	
Revolution time	1.26134	ms	
Eq. Geometric emittance no wiggler/wiggler	2.23/1.36	nm	Only horizontal (Normalized 12.8/7.8 μm)
Bunch length	To be calculated		
Natural en. spread No wiggler/wiggler	0.05076/0.06947	%	
Damping time x, y No wiggler/wiggler	29.37, 29.25/17.9,17.9	ms	Wiggler length 3x3.5 m, 1.7 T If wiggler length is 3x7.5 → ~13 ms
Momentum compaction no wiggler/wiggler	0.0015525/0.0015525		
Tune x,y	To be calculated		
Energy loss per turn no wiggler/wiggler	246.7/403.2	keV	
Wiggler length/magnetic field	3.5/1.7	m/T	
Chromaticity x/y	-37.57/-28.18		
Max β_x/β_y	9.66/6.49	m	Geom. X and Y emit. at the injection: 2.3 μm
Min β_x/β_y	0.5/1.1	m	Beam size X/Y (5s): 24 mm/19 mm

Courtesy of C. Milardi

Injection Strategy and damping time



$$n(train) = \frac{T_{per}}{\Delta t + t_K} \simeq 10$$

$$\epsilon(t) = \epsilon_{inj} e^{-\frac{2t}{\tau}}$$

$T_{per} \approx 1.2\ \mu s\ revolution\ period$

$\Delta t\ \approx 25\ ns\ bunch\ spacing$

$t_k \approx 25\ ns + 25\ ns$ rise and fall time of the injection kiker

$$T_{store} = -\frac{\tau}{2} \ln\left(\frac{\varepsilon_{ext}}{\varepsilon_{inj}}\right) \approx 5\tau$$

Example: vertical emittance from 2.1 mm.mrad to 0.18 nm

$$T_{store,max} = n(train) \cdot T_{rep\ rate}$$

$$\tau \leq \frac{n(train) \cdot T_{rep\ rate}}{5} \approx 20\ ms$$

Condition to be fullfilled for the damping time(s) based on the # of bunch in the DR → shorter kicker length
Approach: keeping max number of trains circulating if the collective effects permit (40 bunches at 5.5 nC)

Courtesy of A. De Santis

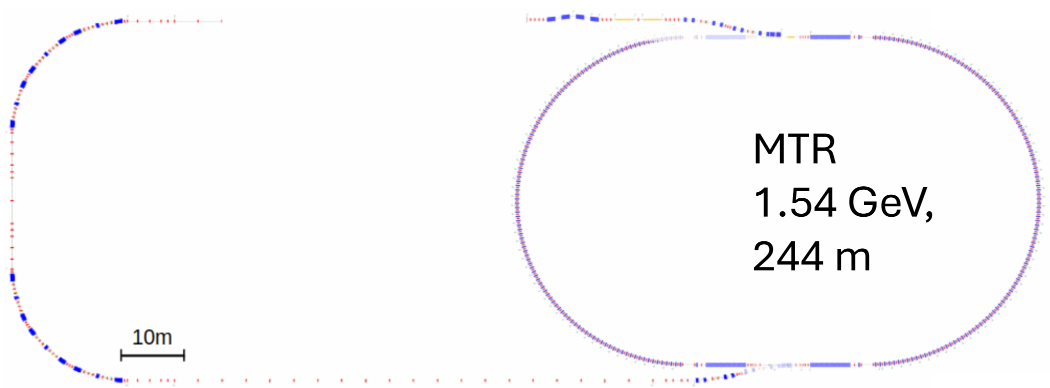
Damping ring: power consumption and cost

FCC

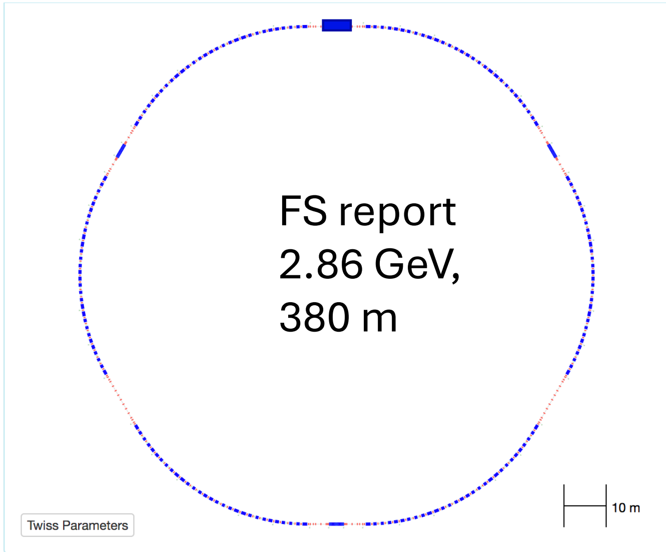
SLS 2.0: power consumption

- Power for the machine including the RF systems: 4.1 MW (max)
- Local data centre, personal safety systems, IT Network, radiation protection and the infrastructure for various hutches at the technical gallery: 1.6 MW
- Process cooling: 1.6 MW
- Total: 7.3 MW (max)

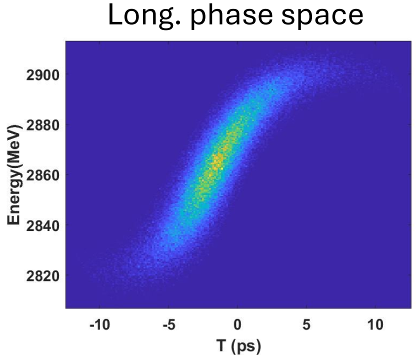
DR cost based on simple scaling to 2.86 GeV from the MTR (detailed) cost estimate at 1.54 GeV → +60% should be a reasonable approach (it is consistent with SLS 2.0 cost/m)



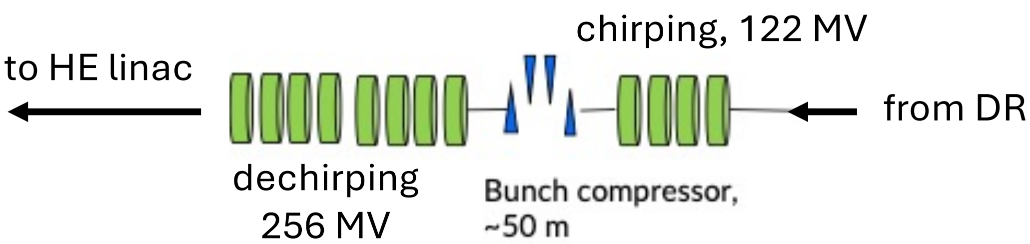
cost estimate presented at MTR



Bunch compressor (BC) at 2.86 GeV



Total length 55 m



- Magnetic chicane (four C-shape bending), magnetic length 1.9 m, max magnetic field 1 T.
- R_{56}= -0.336m, angle = 11 deg, max dispersion = 0.98 m.
- Distance between dipoles 1(3) and 2 (4) 2.9 m. Distance between dipoles 2 and 3 is 2 m
- Two rf structures to induce the chirp, max accelerating voltage 122 MV.
- Four rf structures to remove part of the residual chirp. Max accelerating voltage 256 MV.

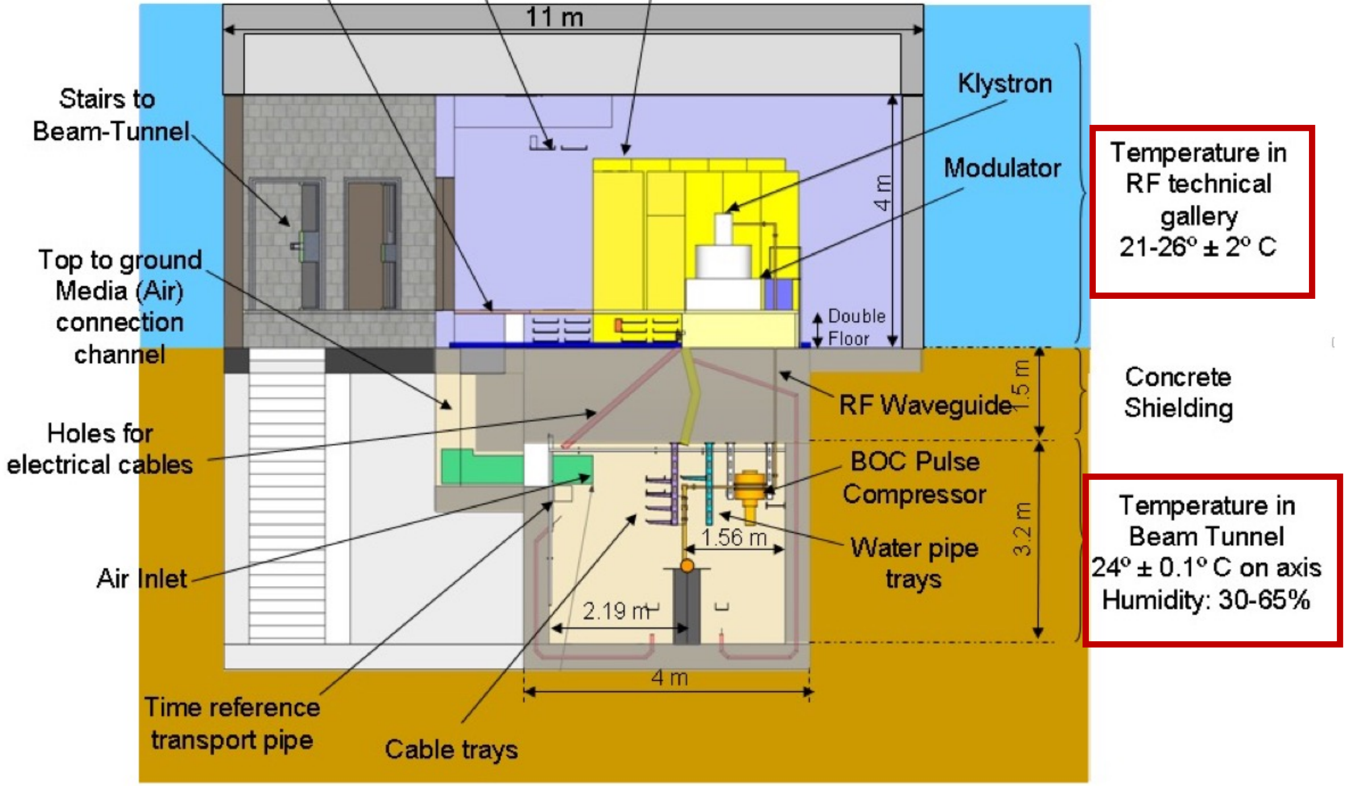
ELEGANT simulations (5 nC)

- Residual energy spread 0.7% (after dechirping)
- Compression factor 5.75, bunch length from 4.6 mm → 0.8 mm
- Horizontal emittance growth ~20%
- Vertical emittance growth <1%

Courtesy of S. Spampinati

Linac infrastrutures

SwissFEL linac



FCC-ee RF unit module with 80 MW, 3 us
Total active power: 158.8 kW

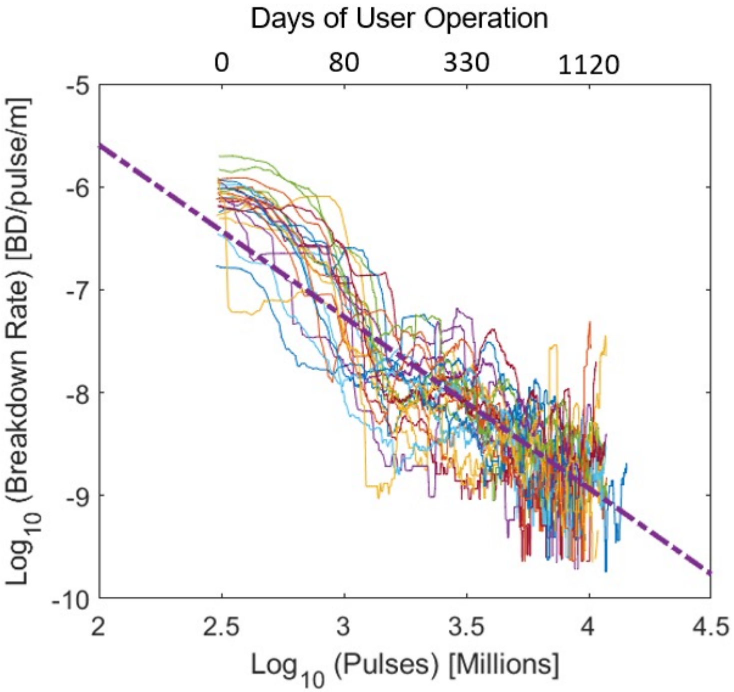
Dissipation in air (only modulator and klystron): 12.1 kW
Dissipation in water 122.7 kW

Dissipation in water: 24 kW

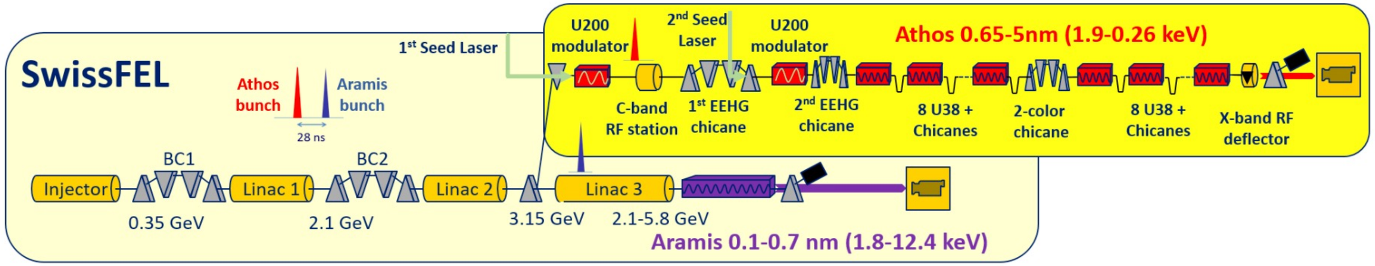
- Beam tunnel: 24 C ± 0.5 °C and ± 0.1 °C (near the beam axis), Humidity 30-65%
- Infrastrcuture Gallery and Rooms: 21-26 °C ± 2 °C over 24 h, Humidity 25-65%

Availability and breakdown rate (SwissFEL 6 GeV linac)

FCC

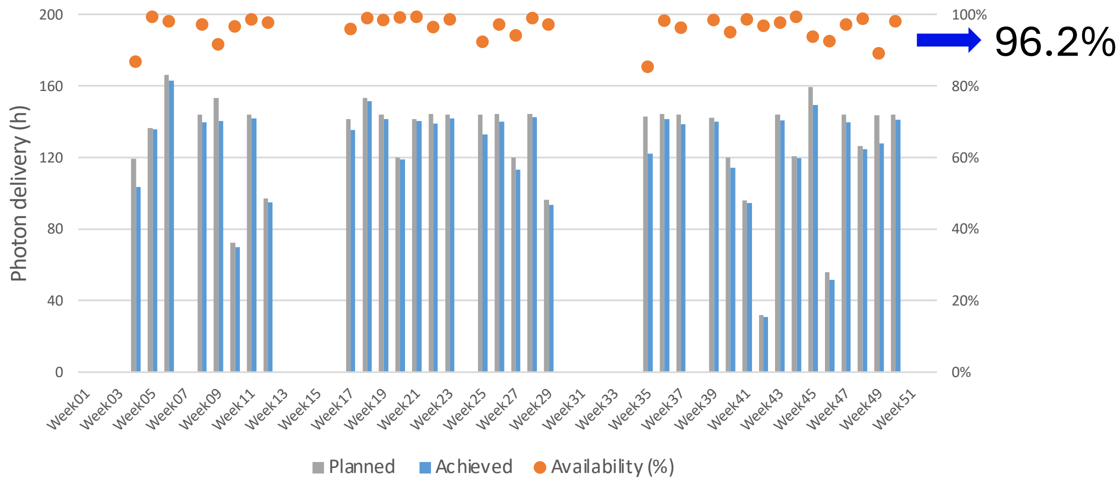


SwissFEL C-band linacs: RF breakdown rate change against the cumulative number of pulses at the nominal operational gradient (30 MV/m)
T. Lucas et al., to be submitted.



Linac 1, 2 and 3: C-band, 100 Hz, 26 rf module, 104 rf structures

Beam availability in photon-delivery weeks (2023)



Courtesy of D. Voulot

For example: 4 years operation to reduce the the BDR from ~850 per day to 8.5 per day considering 1 km linac and 100 Hz.

Important topics beyond feasibility study report

- New baseline needs a new DR at 2.86 GeV to be included in the FS report
  - but optimization of the DA still pending and collective effects to be evaluated (40 bunches, 5.5 nC)
- Electron source: top-up operation requires that the bunch-by-bunch charge will vary from 0 up to 5 nC, depending on the intensity balance in the collider rings – to be verified the approach changing the laser intensity, i.e. Micromirror Device (MDM). Discussion is started at PSI and CERN.
- 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.
  - What is the effect of short interruptions due to BDs in linacs for top-up operation?
- Working RF frequency: presently we assume a multiple frequency of the main rings to keep flexibility but no power source on the market!
  - bunch temporal spacing is fixed at ~25 ns → S-band frequency 3006 MHz
- Positron linac: new optimization to use S-band commercial frequency (presently 2 GHz). Positron linac: new optimization to use S-or L- band commercial frequencies or mixed (presently 2 GHz).
- Polarized positron (and electron) from the injector?

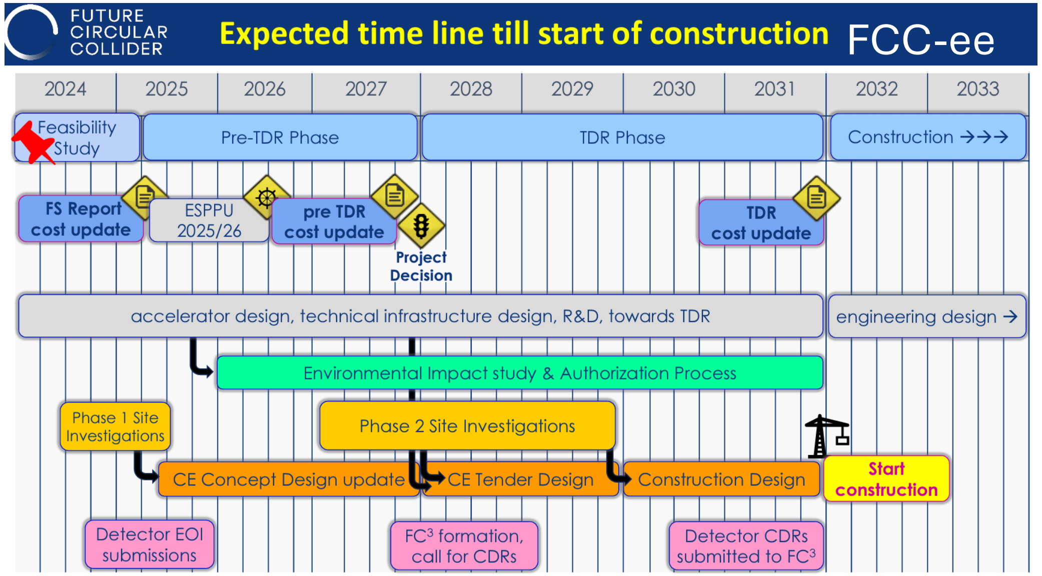
Next steps (post FS phase)

Plans for technical design of injector complex and beyond

FCC

- Strong support from Switzerland and PSI to continue CHART collaboration on FCC-ee injector towards technical design report.
- Presently preparing a proposal for CHART III phase with all partners that were already involved in the CHART II phase.
- Development of the realisation model for the injector included in the TDR work, to be available in 2027, before potential project decision.
- Partially also dependent on progress with funding model discussions, in-kind contributions, host-states, etc…

Time plan FCC-ee and FCC-ee Injector



FCC-ee Injector: Technical Design Report, 2025-2028:

- Following the completion of the Feasibility Study phase (March 2025), a preliminary technical design report (pre-TDR) will be produced by mid-2027.
- The objective of the pre-TDR is to provide detailed specifications for the accelerator and technical infrastructure requirements necessary for the initial phase of the civil engineering (CE) design.
- By the end of 2028, the final Technical Design Report (TDR) for both the accelerator and the technical infrastructure will have been completed.

Injector Project schedule (as proposed by Michael Benedikt in preliminary discussion)

- Start 2028 – end 2030 CE design and tendering (3 years)
- Start 2029 – end 2031 Accelerator engineering and technical infrastructure designs
- Start 2030 – end 2033 Civil construction (4 years)
- Start 2031 – end 2040 Component production (assuming similar production rates for RF structures as for SwissFEL)
- Start 2034 – end 2036 Technical infrastructure installation
- Start 2035 – end 2040 Component installation and testing
- Start 2042 beam commissioning

FCC-ee Injector Technical Design Report (TDR), 2025-2028

FCC

WP	Description	Lead	Collab.	2025	2026	2027	2028	Comments
0	Coordination and drafting of the TDR	PSI/CERN	All			◇1	⬡1	Main parameter and technical choices, delivery model
1	Electron source	PSI	CERN				◇2	Demostrator for the top-up scheme. Need a test stand
2	Electron and positron linac	CERN	PSI/IJCLab				◇3	Protoypes and high power test of the RF structures for the linacs.
3	Positron source and capture system	IJCLab	PSI/CERN		◇4			Optmiziation based on the acceptance in DR, explore SC solenoids for capture system, commercial rf frequency
	3.1 P-cubed experiment	PSI	CERN /IJCLab		◇5			P-cubed experiment, implementation of the hybrid scheme, test with high power beam?
4	Damping ring, injection and extraction lines	INFN	PSI/CERN		◇6			Design of the DR at 2.86 GeV, drafting of the TDR with cost estimate. PSI can support this WP from 2025.
5	Civil Engineering (CE)	CERN	PSI					Start of the CE tender design
6	Infrastructures (including Radiation and machine protection systems)	CERN	PSI					Design of building infrastructure, personnel and machine safety issues.
7	Technical systems interfaces and integration in CERN environment	CERN	All					Operation concept for the whole complex including diagnostics, LLRF, powering....

Deliverable:

⬡1 TDR ready

Milestones:

◇1 Pre-TDR (ready to start CE design)

◇2 Top-up scheme demostrated

◇3 BDRs defined for all prototypes.

◇4 Baseline for capture system defined

◇5 Positron source with conventinal target demostrated with lower power beam

◇6 Acceptance DR defined.

Collaboration with SLAC/FACET II

Proposal to be submitted to Program Advisory Committee by this week

<u>**SLAC National Accelerator Laboratory**</u>

<u>**FACET-II PROPOSAL**</u>

Date: 10/31/24

A. EXPERIMENT TITLE: FCC-ee Pre-injector Complex Studies at FACET-II

B. PROPOSERS & REQUESTED FACILITY:

Principal Investigator:	Brendan O'Shea
Institution:	SLAC
Contact Information:	Phone: 2527 Email:boshea@slac.stanford.edu
Experiment Members:	Paolo Craievich and Simona Bettoni PSI, Andrea Latina CERN
Collaborating Institutions:	PSI, CERN
Funding Source (optional)	
Approximate Duration:	1.5 years

Science Goals

1. Emittance as a function of compression at high charge
2. Transverse jitter amplification and damping for bunches separated by multiples of 25 ns
3. Injector performance when varying charge

Conclusion

- The valuable recommendations from MTR led to a re-baselining of the injector concept coupled to a new implementation on the Prevessin site.
- The FCC-ee injector study for the feasibility study is advancing as planned, thanks to the very efficient CHART collaboration including also external partners.
- Drafting of the final report started
  - Most challenging point for the completion of the feasibility study is the update for the damping ring at 2.86 GeV.
- Cost estimate for linacs is ready (manpower estimate for installation on-going)
- Risk register ongoing for the injector complex
- New proposal for CHART 2025-2028 is nearly ready (main deliverables: TDR, prototyping and high power tests, P-cube experiment and proof-of-principle for the electron source)

Acknowledgements

FCC

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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KEK: Y. Enomoto, K. Furukawa

PSI CERN IJCLab Irène Joliot-Curie INFN SLAC KEK

28 October 2024

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That’s all, thank you!!