FCC

THE FCC-ee INJECTOR COMPLEX: AN OVERVIEW OF LINACS, POSITRON SOURCE AND DAMPING RING

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

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Cool Copper Collider Workshop, SLAC, Feb 12-13, 2024

Credits

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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/**

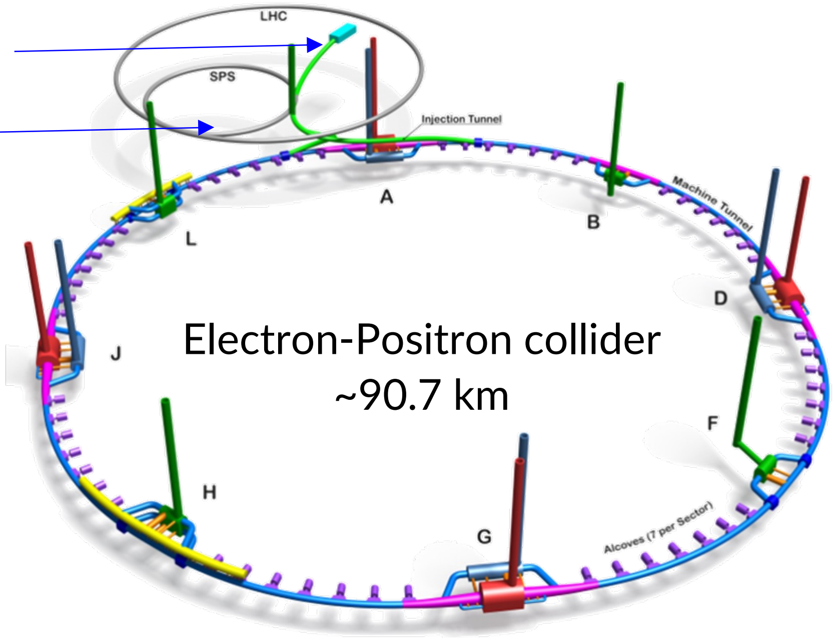
Content

- Where we are in FCCee context
- Injector parameters
  - Pre-requisite for linacs technology: conventional normal conducting technology based on the SwissFEL facility (at the Paul Scherrer Institut)
  - FCCee CDR0 as a starting point
- Baseline layout: linacs, positron source and damping ring
- A few general remarks and summary

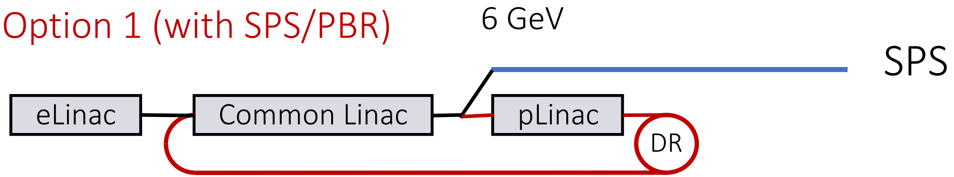
Where we are in FCCee

Injector complex, total length ~1.1 km

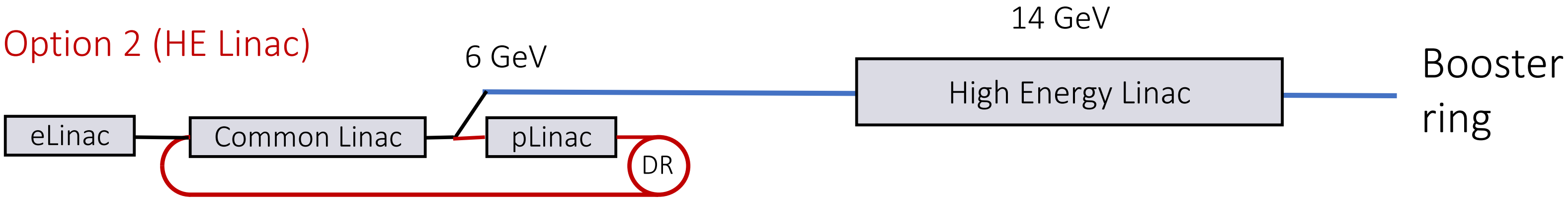
SPS to be used as a Pre-booster



Option 1 (with SPS/PBR)



Option 2 (HE Linac)



Injector parameters (Z-mode)

parameters extracted from K. Oide's talk, FCC week 2023 talk

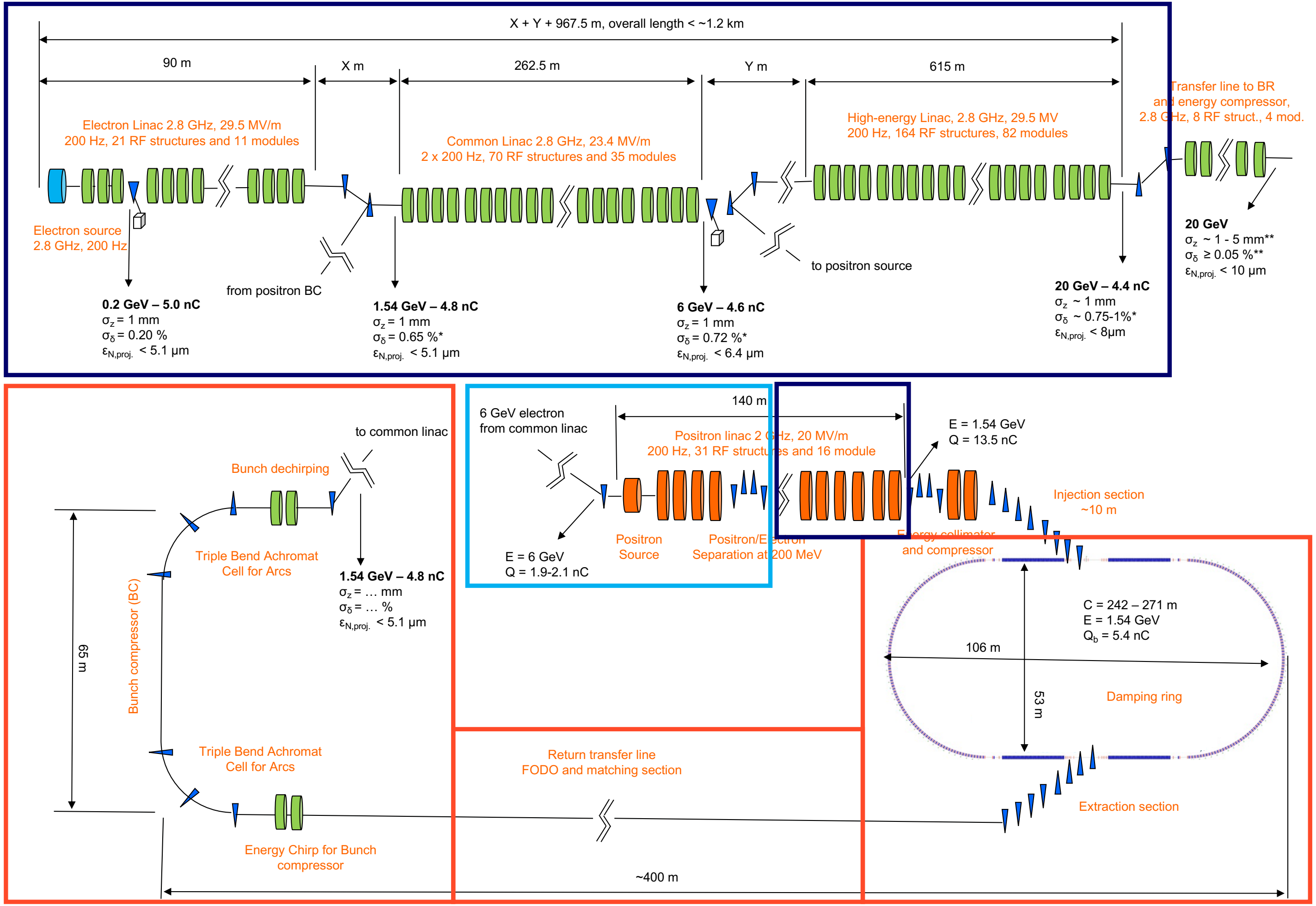
	SPS	HE Linac	Unit
Injection energy	6	20	GeV
Bunch charge both species	4.0*	4.0*	nC
Repetition rate	200	200	Hz
Number of bunches	2	2	
Bunch spacing	25	25	ns
Norm. emittance (x, y) (rms)	10,10	10,10	mm mrad
Bunch length (rms)	~1	~1	mm
Energy spread (rms)	0.3	~0.1	%

*Maximum charge to be injected into the collider rings 4 nC (bunch pop. $2.5x10^{10}$ particles)

Target bunch length and energy spread at the linac end, TL from HE linac to booster will include an energy compression (and bunch decompression)

- The bunch-by-bunch intensity will arbitrarily vary from 0 to 100%, depending on the intensity balance between the collider rings (for top-up injection)
- In top up, the injector will run continuously, and the reliability becomes an important aspect for the Injector design.

Schematic layout of Injector complex

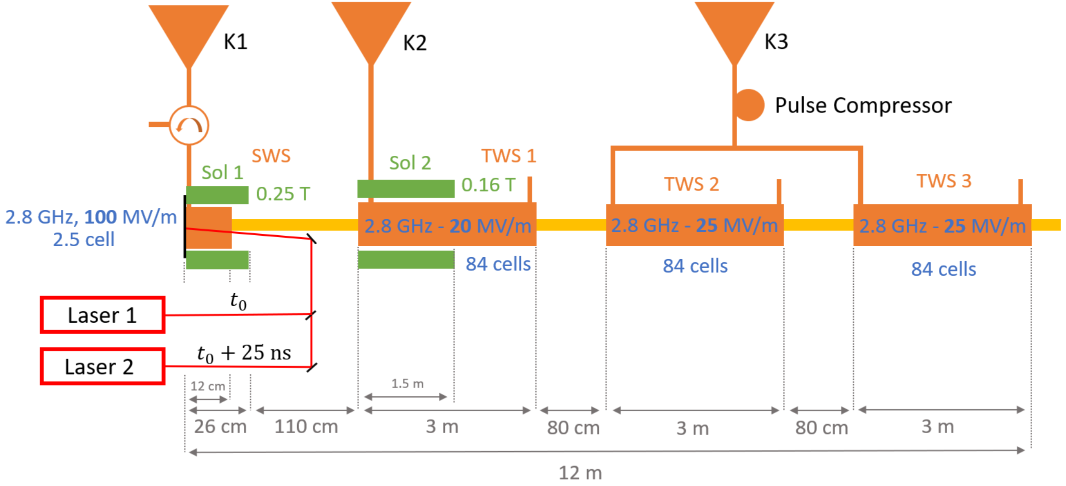


WP1. Electron source and e^- and e^+ linacs (A. Grudiev, CERN)

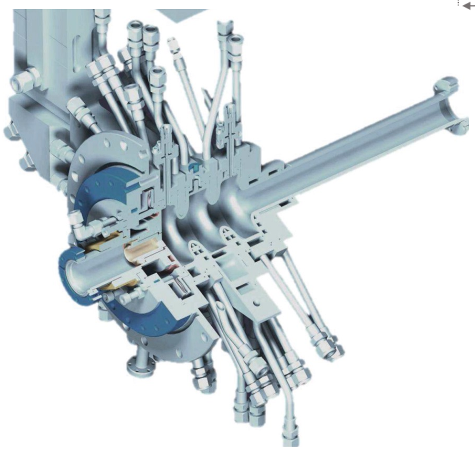
WP3. Positron source and capture system (I. Chiakovska, IJCLab)

WP4. Damping ring and return transfer line (C. Milardi LNF INFN)

Electron source



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

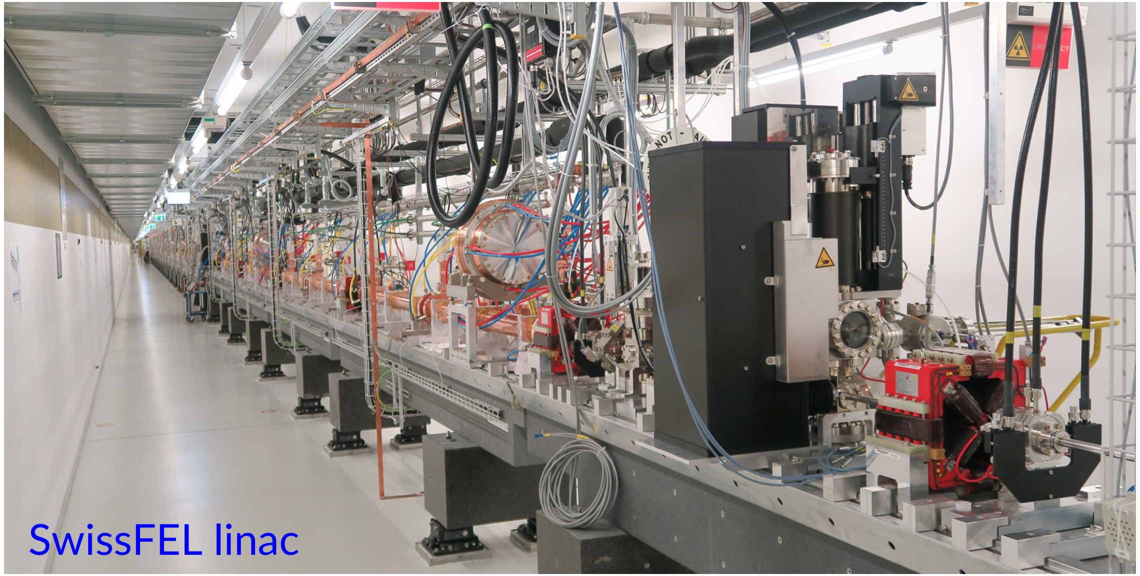


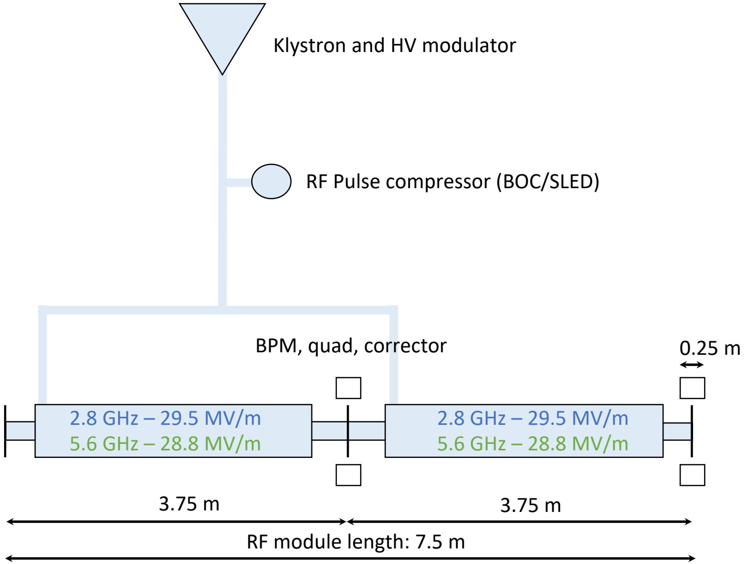
- Provide electrons for positron production and injection into Collider Rings, it is based on the SwissFEL gun (designed for 400 Hz)
- Two laser systems, each for one bunch (as in SwissFEL)
- Top up injection scheme: Robust solution to preserve the shot-by-shot emittance for different bunch charges
- Bunch-by-bunch intensity fluctuation: 5% (Z mode), 3% (WW, ZH, tt)

Courtesy of Zdenek Vostrel and Steffen Doebert

Electron-, Common, Positron and HE-linacs

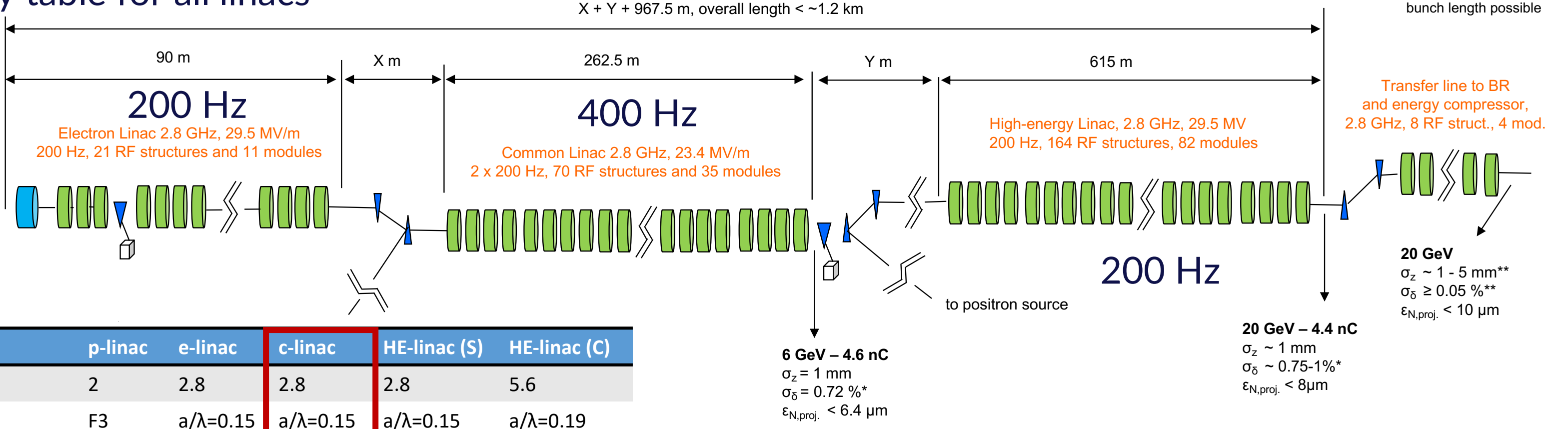
- Beam dynamic simulations → RF design → RF module design based on RF power sources
- Each RF module: one klystron/modulator, rf WG network, 2 rf structures (3-m long), LLRF, cooling system, 2 BPMs, 2 quads and 2 correctors. Total length: 7.5 m
- Cost model using the unit RF module to optimize the cost per unit length (also considering the CE and TI costs)





RF module summary table for all linacs

*Computed for 5 nC bunch charge and 25 MV/m
** Higher energy spread and/or longer or shorter bunch length possible



	p-linac	e-linac	c-linac	HE-linac (S)	HE-linac (C)
Frequency [GHz]	2	2.8	2.8	2.8	5.6
Accelerating structure	F3	a/λ=0.15	a/λ=0.15	a/λ=0.15	a/λ=0.19
Repetition rate [Hz]	200	200	400	200	200
Aperture radius [mm]	30	16.1	16.1	16.1	10.2
Length [m]	3	3	3	3	3
Filling time [ns]	447	486	486	486	334
SLED coupling	17	15	15	15	10
Klystron RF pulse length [µs]	5	3	3	3	3
Average gradient [MV/m]	**20**	**29.5**	**23.4**	**29.5**	**28.8**
Energy gain per structure [MeV]	60	88.5	70.2	88.5	86.4
Klystron power per structure [MW]	31	30	18.9	30	18.2
Klystron output power specification [MW]	80	80	50	80	50
Number of structures per klystron	2	2	2	2	2
Number of structures total	1 + 30	1+20	70	164	172
Number of modules total	1 + 15	1+10	35	82	86
Total length of all modules [m]	140	90	262.5	615	645

Peak gradient → Average power: up to 7.5 kW/m, power density on outer wall radius up to 104 kW/m^2

Inc. WG loss and 90% margin

Same for quads, corrs. and BPMs

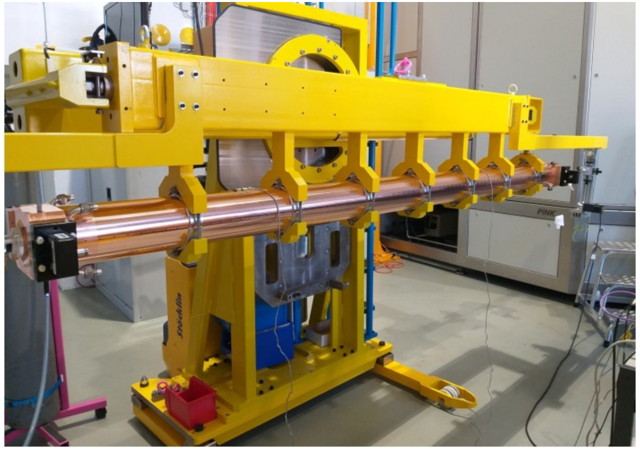
A. Grudiev, A. Kurtulus et al.

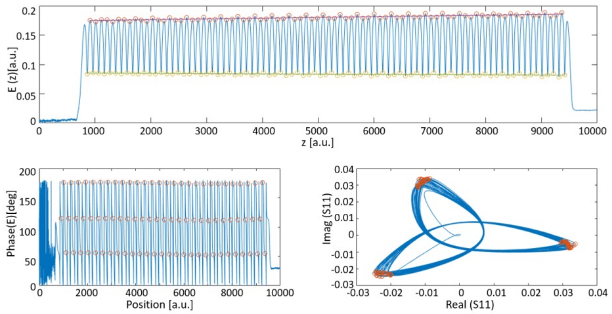
High gradient & Breakdown rate

- Tuning-free technology: PSI has developed a production line of high technological content for high-quality, high gradient C-band accelerating structures for the SwissFEL project (~120 structures) https://doi.org/10.1038/s41566-020-00712-8
  - Gradient and BDR at 100 Hz: max 55 MV/m, BDR=1E-07, operation at 30 MV/m
- Collaboration CERN-PSI on first-tuning-free X-band Accelerating Structures: CLIC X-band prototypes (max gradient ~120 MV/m at 100 Hz) https://doi.org/10.1109/TNS.2022.3230567
- Collaboration Elettra-PSI: free tuning free S-band Accelerating Structures https://doi.org/10.1016/j.nima.2023.168543
  - Gradient and BDR at 100 Hz: max 40 MV/m, BDR=1E-07, operation at 30 MV/m
  - Max gradient was limited by the RF source

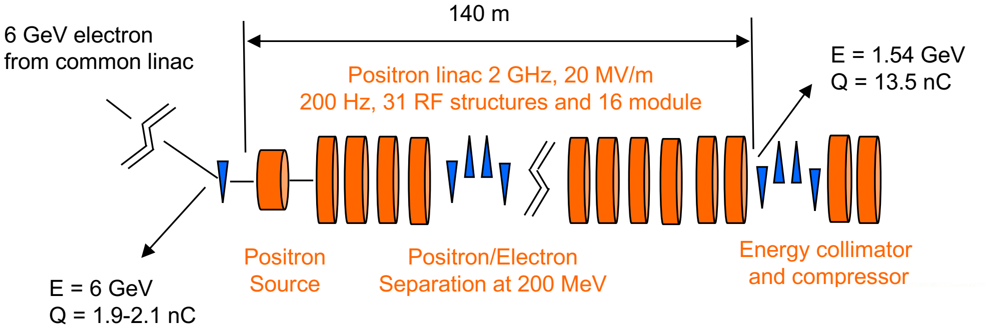
As a conclusion: present gradients (30 MV/m at 200 Hz, 21.5 MV/m at 400 MV/) are well supported by experiences, thermo-mechanical analysis to be performed with higher dissipated power density

3m-long S-band structure brazed in one piece





Positron source and capture linac

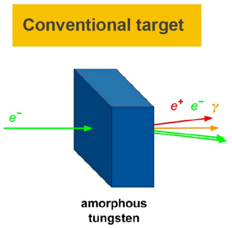


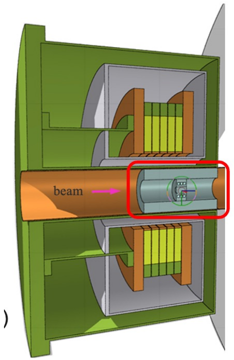
Accepted e^+ yield is a function of **primary beam characteristics** + **target** + **matching device** + **capture linac** + **beam transport** + **DR acceptance**

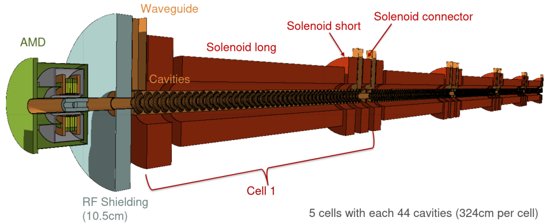
Electron drive beam	6 GeV	6 GeV	6 GeV
Assumption	Max. intensity, which can be delivered by e- linac	13.5 nC e+ bunch charge at the entrance of the damping ring	
Beam size	0.5 mm RMS	0.5 mm RMS	**1.0 mm RMS**
Repetition rate	200 Hz	200 Hz	200 Hz
Bunches per pulse	2	2	2
Bunch intensity (filling)	3.47E10 (**5.56nC**)	1.205E10 (**1.93 nC**)	1.30E10 (**2.08 nC**)
Beam Power	**13.34 kW**	**4.63 kW**	**5.00 kW**

Old parameters (2022)

Current parameters (2023)







Primary (drive) beam parameters

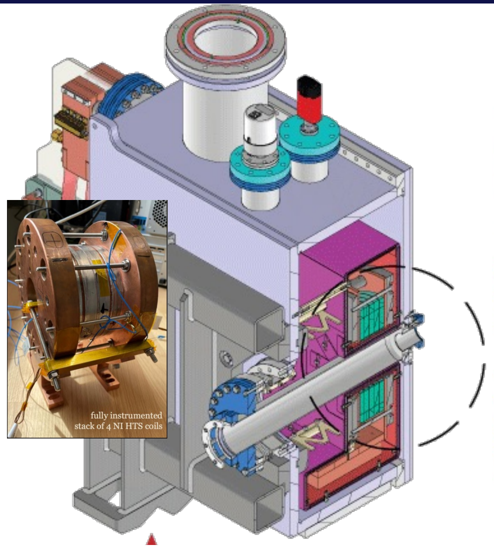
Conventional target

Matching device (MD)

Capture linac and solenoid focusing

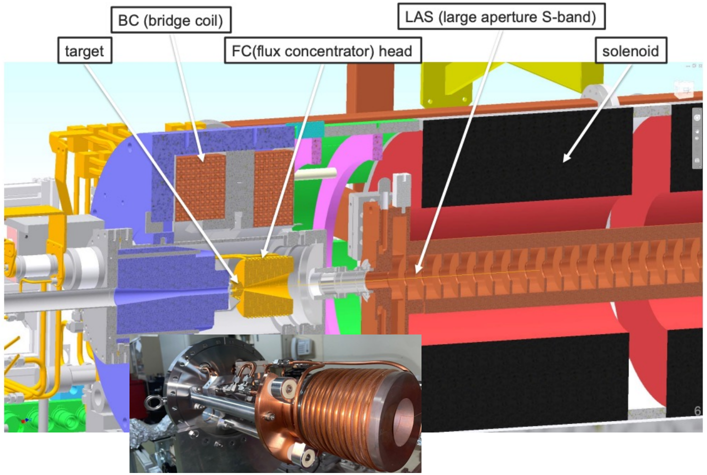
I. Chaikovska et al.

Positron source: matching device

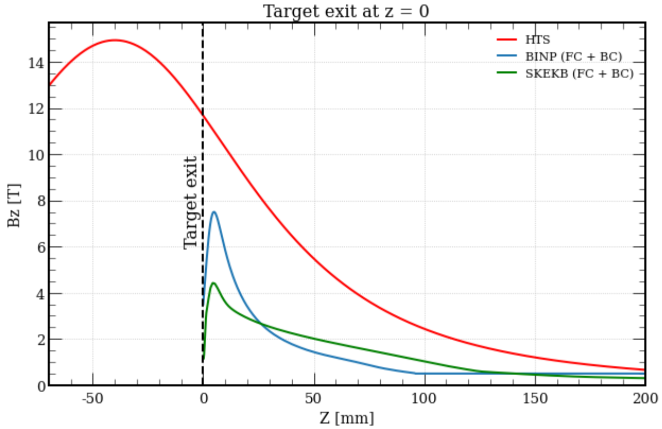


SC solenoid (PSI)

18.2 T @15K@2kA reached



Flux concentrator (FC) - SuperKEKB source

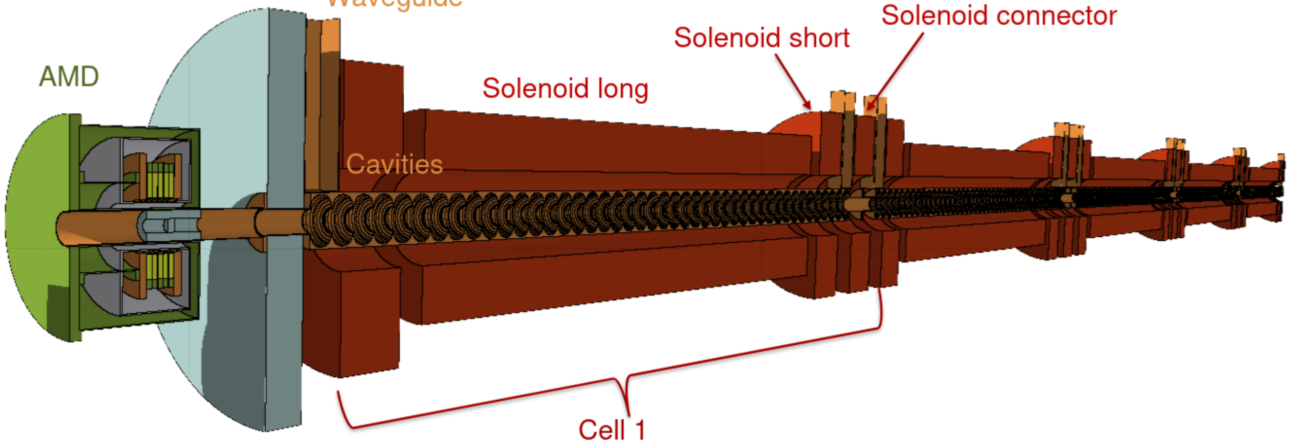


Magnetic field profiles

FC: lower peak field and aperture, fixed target position, challenging power source working at 200 Hz, **robust and reliable solution…**

HTS solenoid: higher peak field and aperture, flexibility on the field profile and target position, DC operation, **innovative solution in application for e^+ capture…**

Positron source: capture linac



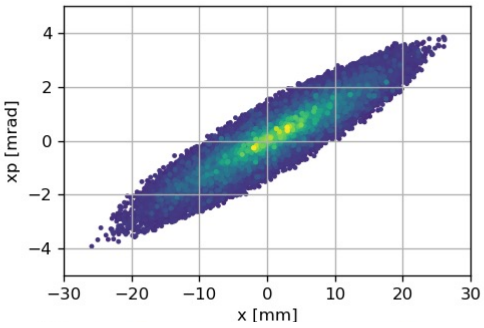
– **Baseline structure:** large-aperture (Φ = 60 mm) TW L-band @ 2 GHz, 9π/10, 3-m long, 20 MV/m. 5 RF structures are used to accelerate the e^+ beam up to ~200 MeV where there is the electron/positron separation

– **Baseline solenoid configuration:** 0.5 T NC solenoid, magnetic field uniformity, solenoid focusing first 50 m, quadrupole focusing downstream

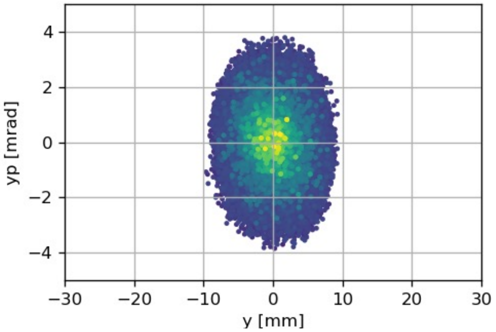
Positron source and capture linac

Drive beam parameters	Alternative FC-based capture system		Capture system –v1
Matching device	BINP FC	SuperKEKB FC	HTS solenoid
Matching device aperture	2a=8-44mm	2a=7-52mm	$2a_{min}$=30 mm (bore 72mm)
Matching device peak magnetic field (@Target) [T]	7.5 (3.5)	4.4 (1.1)	15 (12)
e- beam bunch charge [nC] / e- beam power [kW]	**3.1 / 7.4**	**5 / 12**	**2.1 / 5**
Target deposited power [kW] / PEDD [J/g]	1.7 / 11.1	2.9 / 18.3	1.2 / 3.1
Positron yield @CS [Ne^+/Ne^-]	4.9	3.3	8
Positron yield @DR [Ne^+/Ne^-]	**4.4**	**2.7**	**6.5**
Normalized emittance (rms) [mm.rad]	12.2	11.9	13.7
Energy spread (rms) [%]	1.2	1.1	1.4
Bunch length (rms) [mm]	2.9	2.6	2.9
e+ beam bunch charge [nC]	**13.5**		

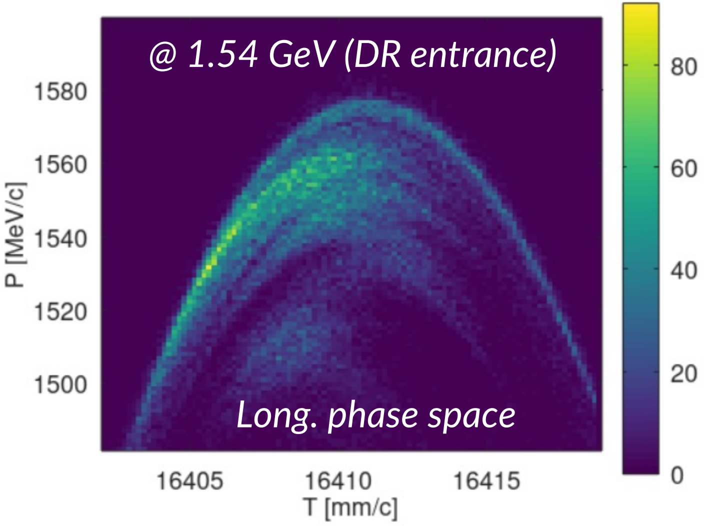
- Safety margin for the acceptance in the DR and transport in the linac (13.5 nC)
- Drive beam parameters have been also updated based on this safety margin
- The studies on the positron source based on the SC solenoid are well advanced



Horizontal phase space



Vertical Phase space



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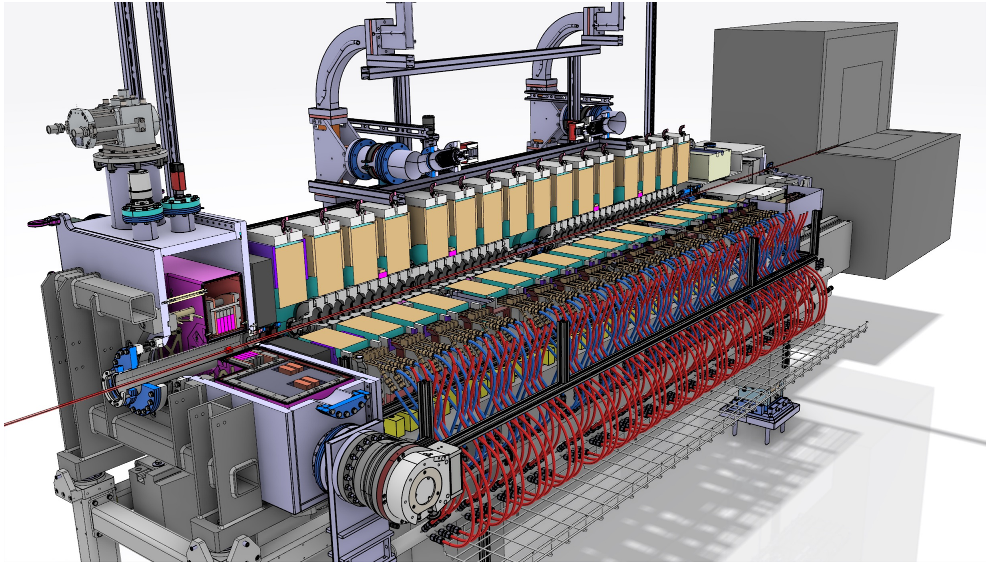
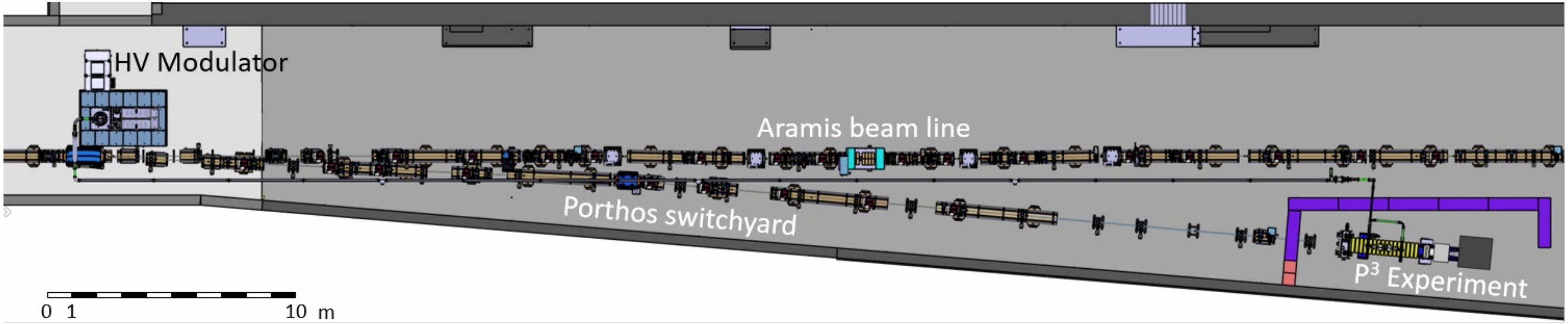
PSI Positron Production (p-cubed) experiment

- Design phase well advanced, several components are ordered
- Installation on the Porthos extraction line ongoing
- Ongoing collaboration with CERN STI for the target integration
- Experiments in 2025/2026

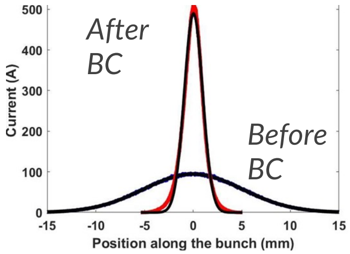


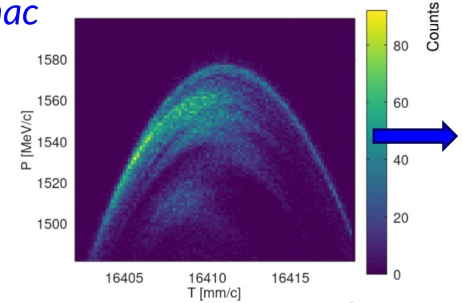


N. Vallis et al., Proof-of-principle e + source for future colliders, Phys. Rev. Accel. Beams 27, 013401, 2024

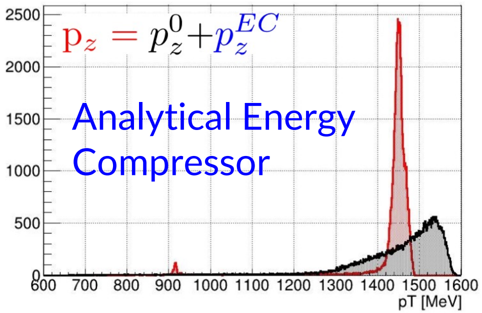
Damping Ring and Return Transfer Lines

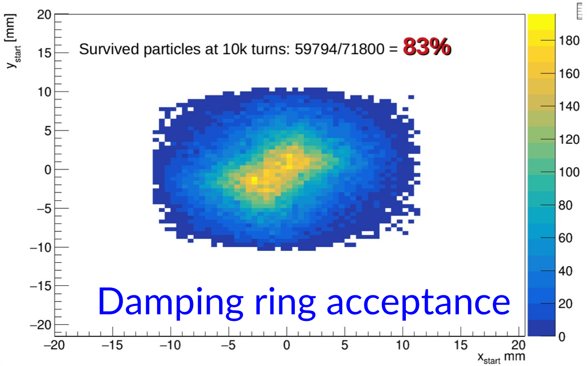
Bunch profile to c-linac

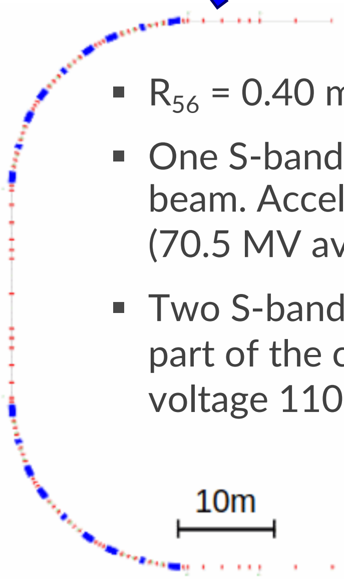




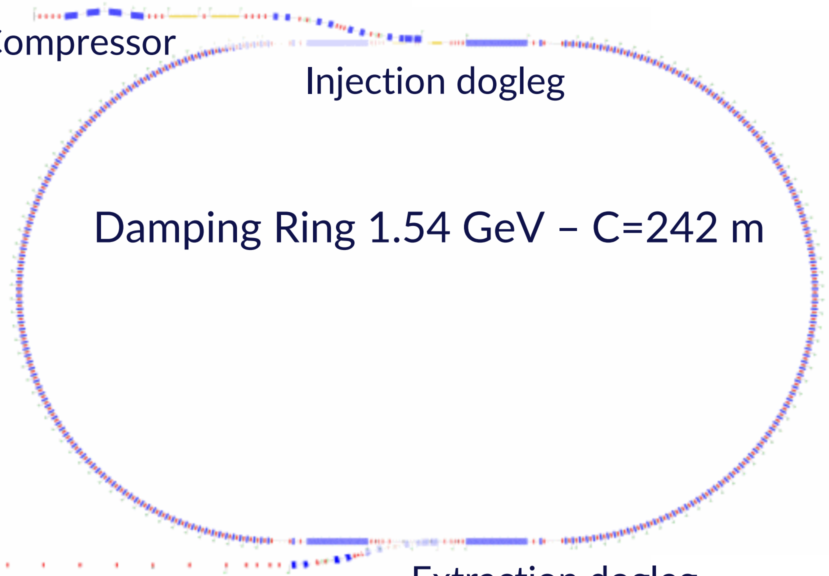
LPS from positron linac





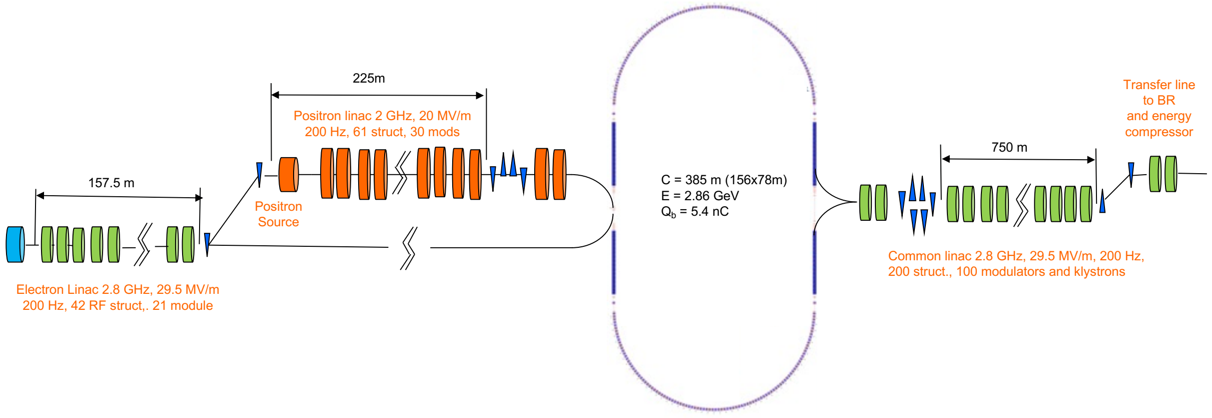


- R_{56} = 0.40 m
- One S-band RF module to chirp the beam. Accelerating voltage 54 MV (70.5 MV available)
- Two S-band RF modules to remove part of the chirp. Accelerating voltage 110 MV (140MV available)



C. Milardi, A. De Santis, S. Spampinati, O. Etisken

Injector layout with DR at higher energy



Parameters	FCC-DR	CLIC DR
Energy [GeV]	**2.86 GeV**	2.86 GeV
Bending magnet quantity	144	100
Quadrupole magnet quantity	186	458
Sextupole magnet quantity	96	282
Dipole magnet length [m]	0.65	0.58
Bending angle [degree]	2.5	3.6
Dipole magnetic field [T]	0.94 T	1.03 T
Filling factor	0.24	0.13
Damping wiggler magnet [m/T]	**36.45 m / 2 T**	104 m / 2.5 T
Robinson wiggler magnet [m / T]	-	-
Circumference [m]	384.87 m	427.5 m
Emittance [nm.rad]	**1.20 nm.rad**	0.04 nm.rad
Damping time	**6.4 ms**	2 ms
Energy loss per turn	**1.13 MeV**	3.98 MeV
Lattice type	**FODO**	TME

- The present positron yield would allow positrons to be generated at a lower electron beam energy. Preliminary study showed no more stringent specifications for the target, compatibility with present target study.
- Common linac: Rep rate 200 Hz instead of 400 Hz → less average rf power, **higher accelerating gradient**, shorter linac
- Dedicated linac for electron and positron before the DR.
- Overall, the cost of the hardware remains approximately the same, the costs of the CE and TI to be evaluated

Summary

- A baseline for the injector layout was ready for the mid-term review (Oct 23)
  - Cost estimates for the hardware, technical infrastructures and civil engineering are available for the project
- Injector can fulfill the (partially new) requirements for the collider rings
  - but there is still room for some optimizations in term of TI cost for length and power density (*i.e., using 4 bunches and DR at higher energy* → *operation at 100* Hz)
- P^3 project is underway, and will be a first step towards the FCCee positron source

Thank for your attention!!