THE FCC-ee INJECTOR COMPLEX: AN OVERVIEW

Alexej Grudiev on behalf of the CHART/FCCee Injector design collaboration
Slides (most of) are kindly provided by Paolo Craievich

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CHART Swiss Accelerator Research and Technology

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Swiss Accelerator Research and Technology

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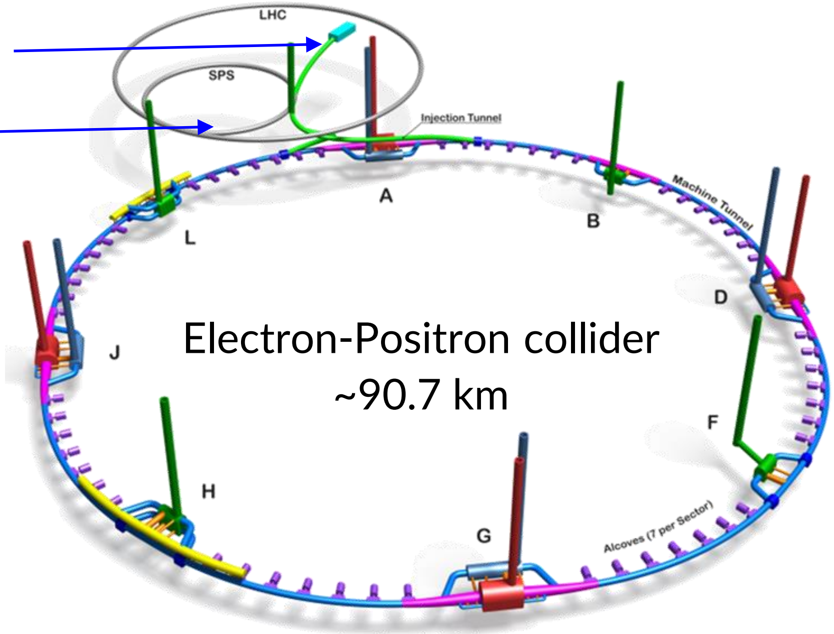
Content

- Where we are in FCCee
- Injector parameters (for the choice of key technology)
    - Pre-requisite for linacs technology: conventional normal conducting technology based on the SwissFEL facility (at the Paul Scherrer Institut)
    - FCC CDR0 as a starting point
- Baseline layout: linacs, positron source and damping ring
- Some remarks
- Summary

Where we are in FCCee

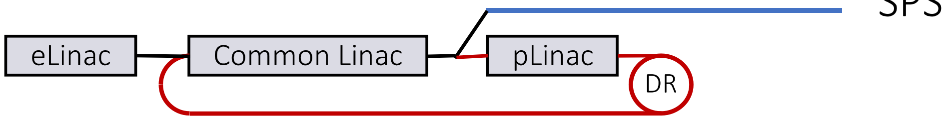
Injector complex, total length ~1.1 km

SPS to be used as a Pre-booster



Electron-Positron collider
~90.7 km

Option 1 (with SPS/PBR)



Option 2 (HE Linac)

Injector parameters (Z-mode)

K. Oide, 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	%

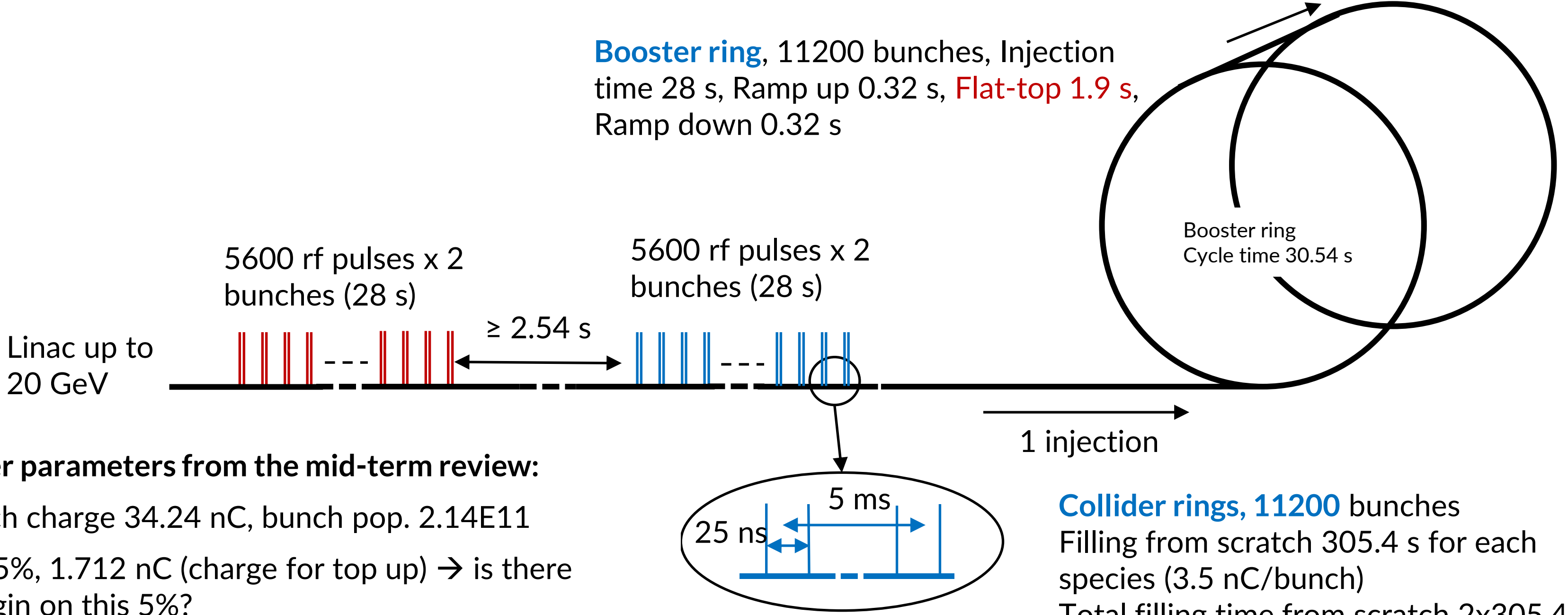
*Maximum charge to be injected into the collider rings 4 nC (bunch pop. 2.5×10^{10} particles)

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
- Bunch-by-bunch intensity fluctuation: 5% (Z mode), 3% (WW, ZH, tt)

Injection time – HE linac option

Booster ring, 11200 bunches, Injection time 28 s, Ramp up 0.32 s, Flat-top 1.9 s, Ramp down 0.32 s



Collider parameters from the mid-term review:

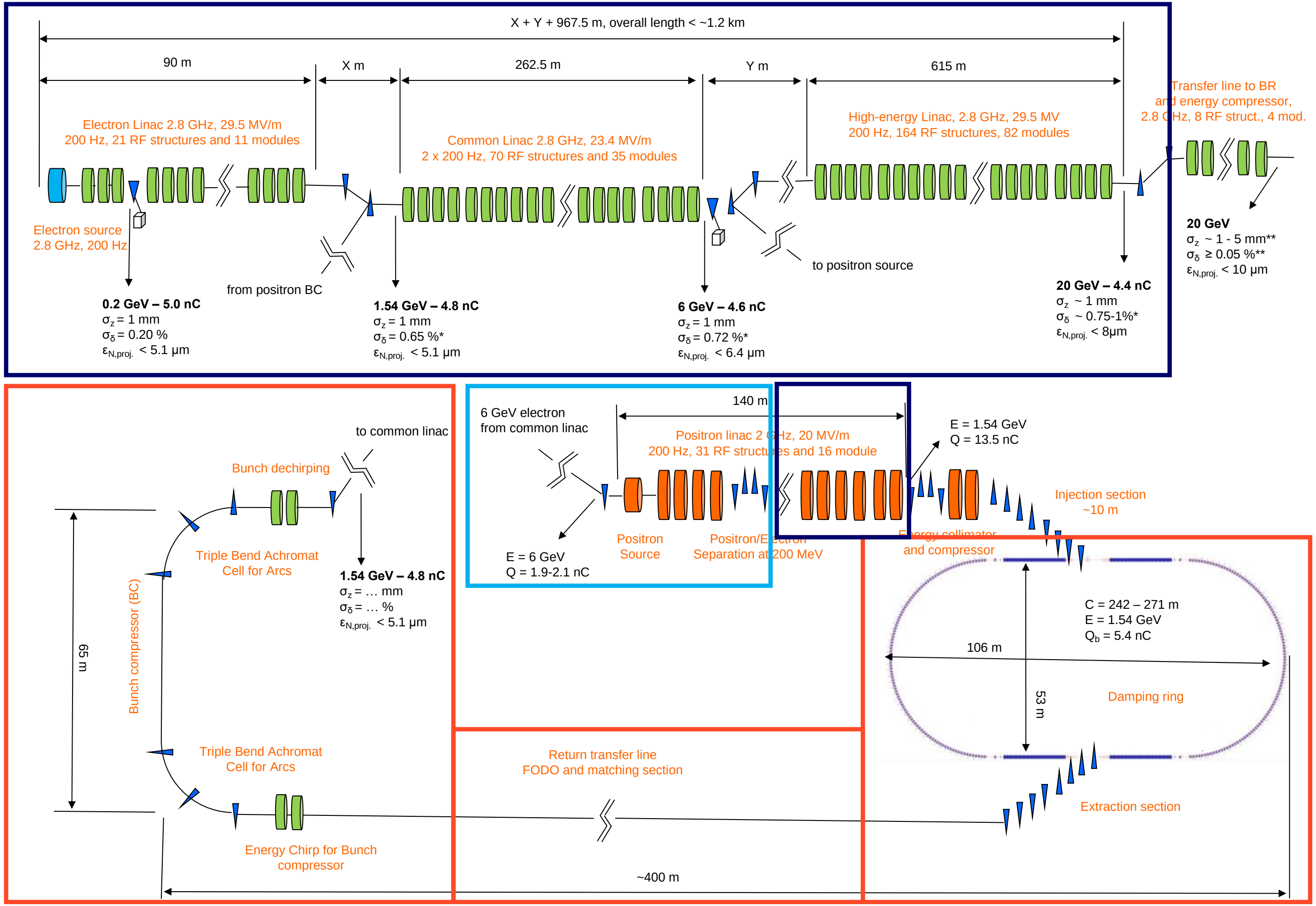
- Bunch charge 34.24 nC, bunch pop. 2.14E11
- Δ = 5%, 1.712 nC (charge for top up) → is there margin on this 5%?
- Lifetime (τ_2): 1240 s (~21 min)
- $\tau_{\text{top-up}} = \Delta\tau_2$ = 62 sec ($\Delta = \tau_{\text{top-up}}/\tau_2$)
- Injection time for one specie: 30.54 s, top-up time for both species 61 sec

Collider rings, 11200 bunches
Filling from scratch 305.4 s for each species (3.5 nC/bunch)
Total filling time from scratch 2x305.4 s = **610.8 s (~10 min)**

Collider rings, top up (Z mode) – 200 Hz
Collider filling time 30.54 s for each species

In top up, the injector will run continuously, and the reliability becomes an important aspect for the Injector design.

Schematic layout of Injector complex – work breakdown structure

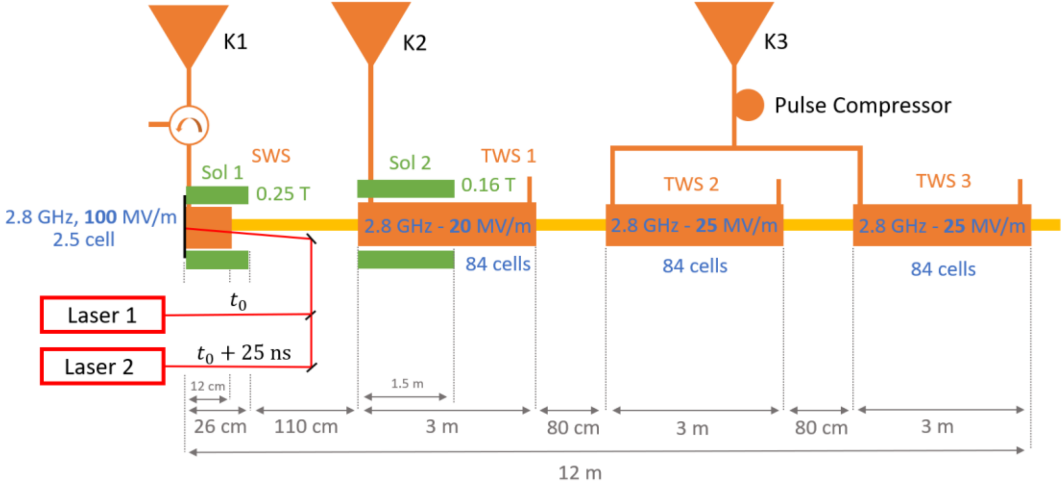


WP1. Electron source and linacs (A. Grudiev, CERN)

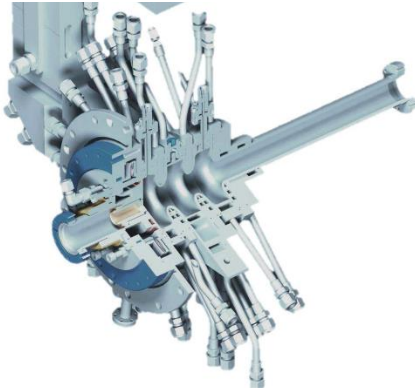
WP3. Positron source and capture system (I. Chiakovska, IJCLab)

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 CR, it is based on the SwissFEL gun
- Two laser systems, each for one bunch (as in SwissFEL)
- Top up injection scheme: Robust solution to preserve the emittance for different bunch charge
- Bunch-by-bunch intensity fluctuation: 5% (Z mode), 3% (WW, ZH, tt)

Courtesy of Zdenek Vostrel and Steffen Doebert

Electron source

Key properties listed in the table, reached

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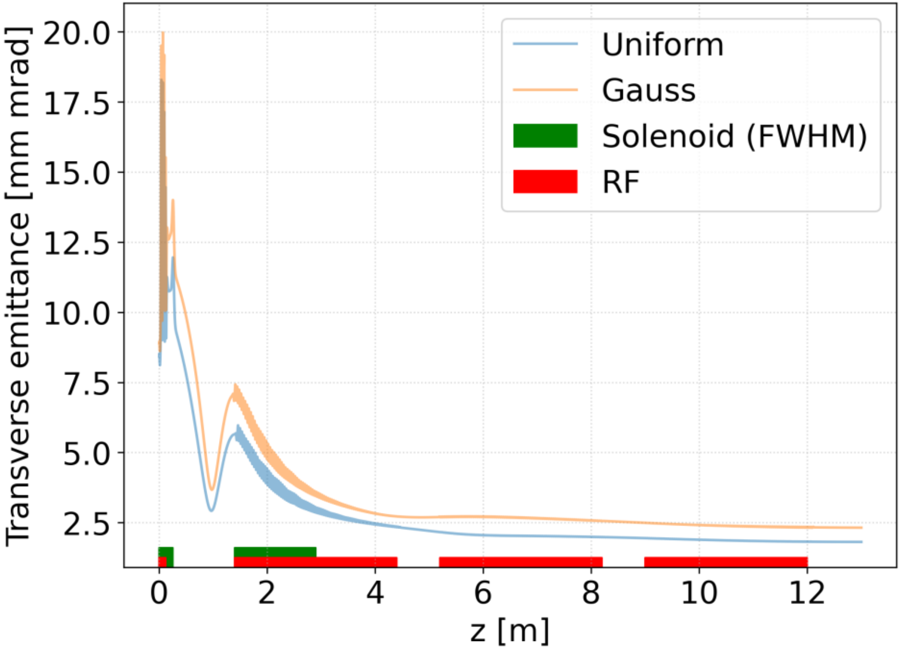
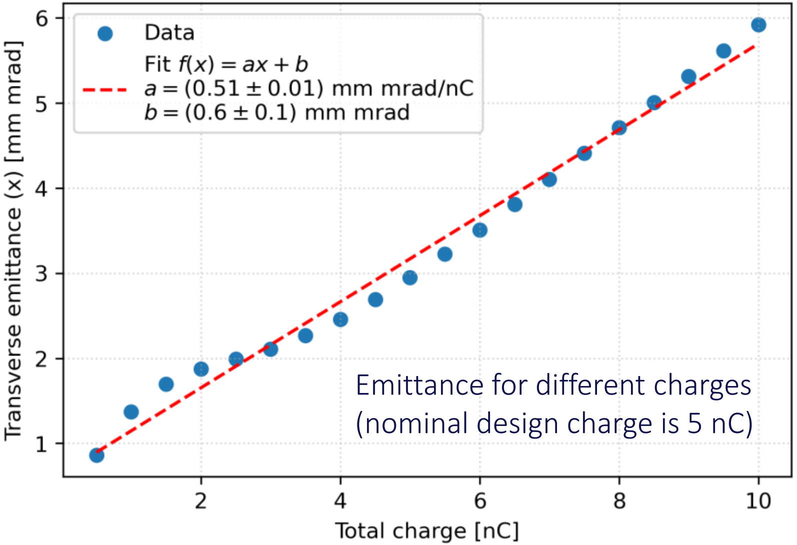
Emittance evolution for 5 nC charge



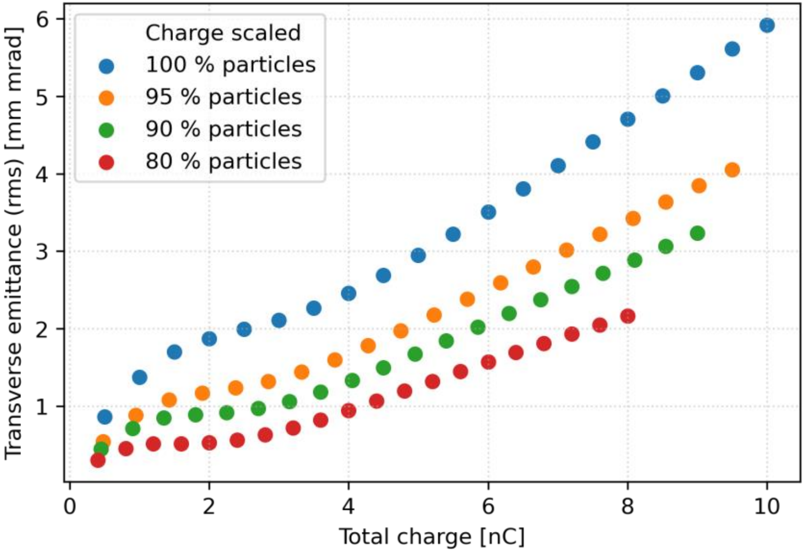
Courtesy of Zdenek Vostrel and Steffen Doebert

Electron source

Robust solution to preserve the emittance for different bunch charge



Emittance for different charges (nominal design charge is 5 nC)



- Large contribution from 5% particles
- Cutting particles based on energy or transverse position

Courtesy of Zdenek Vostrel and Steffen Doebert

e-, common, e+ and HE-linacs: design steps

1. Beam dynamics design (start-to-end simulations) provides specification for accelerating structure design: aperture, RF frequency, structure length, gradient, etc.
2. RF design of accelerating structures (S-, C-band, 2.0 GHz)
3. RF module layout and parameters are put together based on the above input and the parameters of the RF power sources

Klystron abbrev.	Linac	Freq.	Peak power specification	Rep. Rate	RF pulse length	Duty factor	Average power	Required numbers
		[MHz]	[MW]	[Hz]	[μs]	[1e-3]	[kW]	
Kly_p	p-linac + Ecomp	2004	80	200	5	1	80	16 + 1
Kly_e	e-linac + e-source HE-linac S-band	2806	80	200	3	0.6	48	10 + 1 82
Kly_c	c-linac	2806	50	400	3	1.2	60	35
Kly_HE_C	HE-linac C-band	5611	50	200	3	0.6	30	86

A. Grudiev, J.-Y. Raguin, S. Bettoni, M. Schär et al.

Positron, Electron, Common, HE linacs

RF module summary table for all linacs

	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

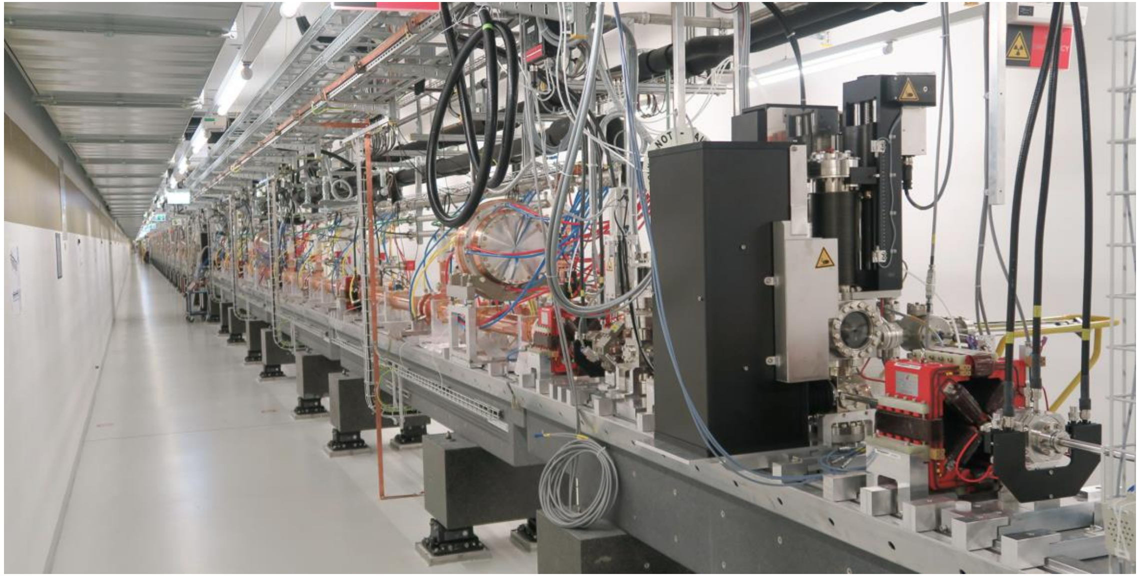
Inc. WG loss and 90% margin

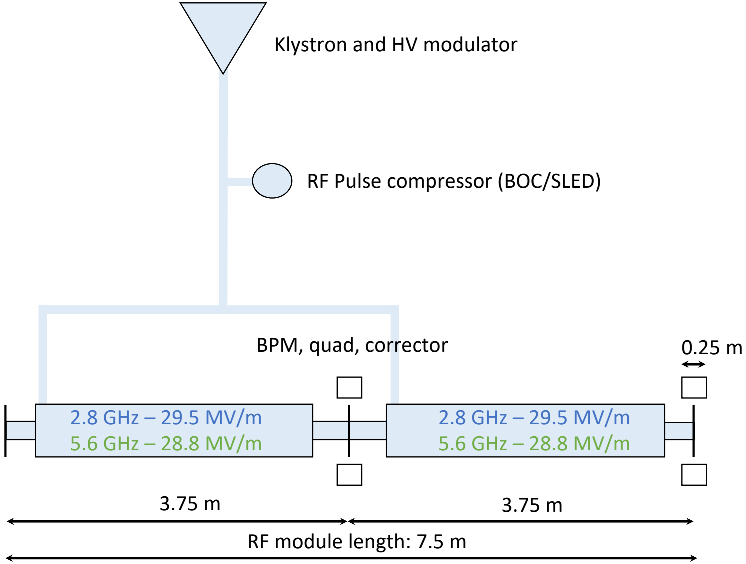
Same for quads, corrs. and BPMs

A. Grudiev, A. Kurtulus et al.

Electron-, Common, Positron and HE-linacs

- RF technology: tuning-free from PSI
- 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
- Common linac at 400 Hz during positron production



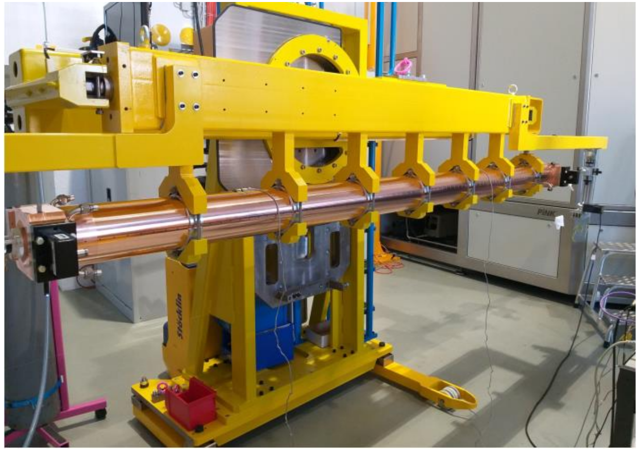


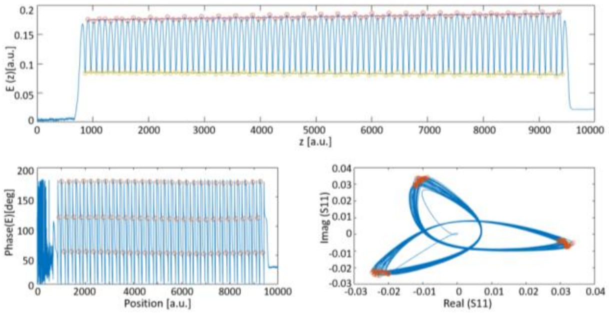
High gradient & Breakdown rate

- 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

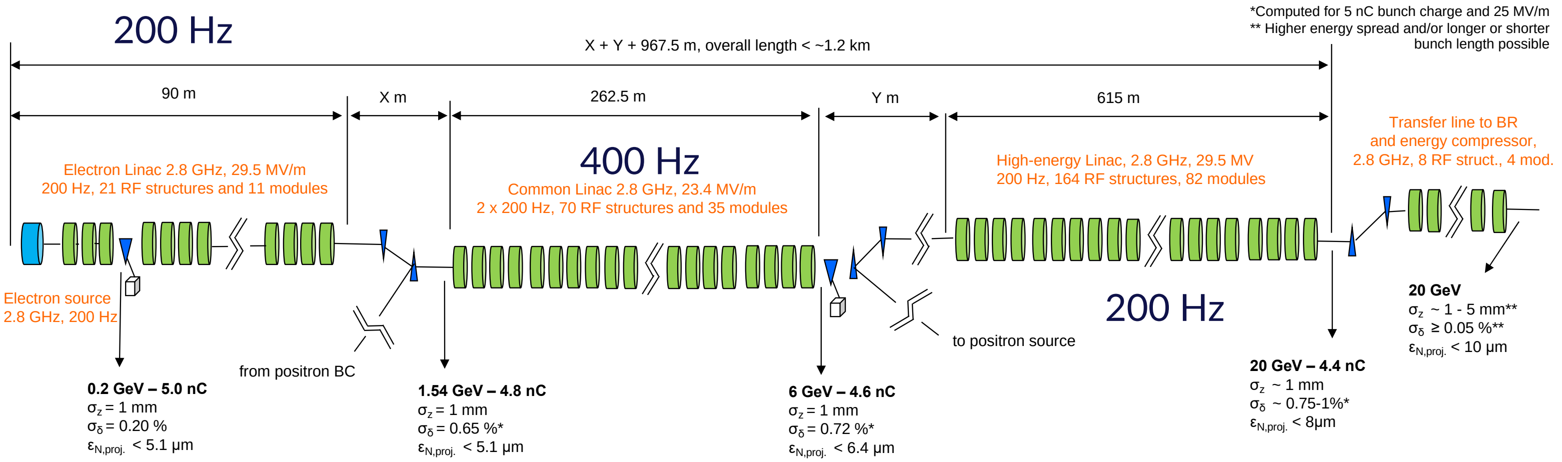
As a conclusion: present gradients (30 MV/m at 200 Hz, 21.5 MV/m at 400 MV/) are well supported by experiences, thermo-mechanical analysis to be performed with higher dissipated power density

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





Electron, Common, HE linacs – RF power density



*Computed for 5 nC bunch charge and 25 MV/m

** Higher energy spread and/or longer or shorter bunch length possible

200 Hz

X + Y + 967.5 m, overall length < ~1.2 km

90 m

X m

262.5 m

Y m

615 m

Electron Linac 2.8 GHz, 29.5 MV/m
200 Hz, 21 RF structures and 11 modules

400 Hz

Common Linac 2.8 GHz, 23.4 MV/m
2 x 200 Hz, 70 RF structures and 35 modules

High-energy Linac, 2.8 GHz, 29.5 MV
200 Hz, 164 RF structures, 82 modules

Transfer line to BR
and energy compressor,
2.8 GHz, 8 RF struct., 4 mod.

Electron source
2.8 GHz, 200 Hz

from positron BC

to positron source

200 Hz

0.2 GeV – 5.0 nC
$\sigma_z = 1$ mm
$\sigma_\delta = 0.20$ %
$\varepsilon_{N,proj.} < 5.1$ µm

1.54 GeV – 4.8 nC
$\sigma_z = 1$ mm
$\sigma_\delta = 0.65$ %*
$\varepsilon_{N,proj.} < 5.1$ µm

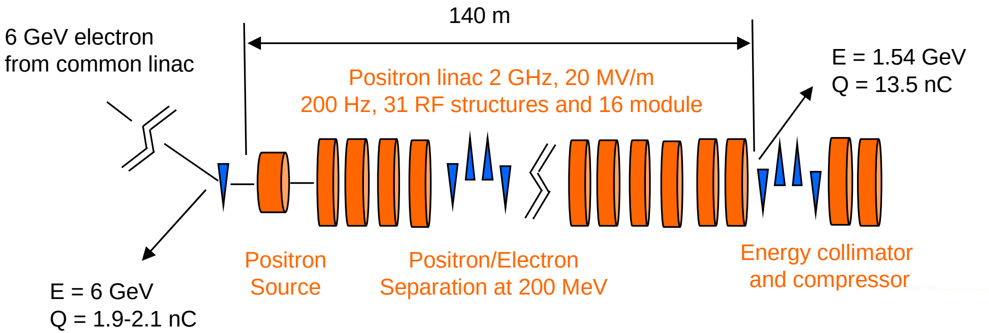
6 GeV – 4.6 nC
$\sigma_z = 1$ mm
$\sigma_\delta = 0.72$ %*
$\varepsilon_{N,proj.} < 6.4$ µm

20 GeV – 4.4 nC
$\sigma_z \sim 1$ mm
$\sigma_\delta \sim 0.75$-1%*
$\varepsilon_{N,proj.} < 8$µm

20 GeV
$\sigma_z \sim 1$ - 5 mm**
$\sigma_\delta \geq 0.05$ %**
$\varepsilon_{N,proj.} < 10$ µm

Linac	Freq.	Peak gradient	Average power <Pin>	Structure length	Average power <Pin>/L*3/4	Outer wall radius	Power density on outer wall radius
	[GHz]	[MV/m]	[kW/structure]	[m]	[kW/m]	[mm]	[kW/m^2]
p-linac	2.0	20	31	3	7.5	60	125
e-linac HE-linac S-band	2.8	29.5	18	3	4.5	~40	112.5
c-linac	2.8	23.4	22.5	3	5.6	~40	141
HE-linac C-band	5.6	28.8	11	3	2.8	~20	140
SwissFEL C-band	5.7	30	5	2	1.9	~20	95

Positron source and capture linac



6 GeV electron from common linac

140 m

Positron linac 2 GHz, 20 MV/m
200 Hz, 31 RF structures and 16 module

E = 1.54 GeV
Q = 13.5 nC

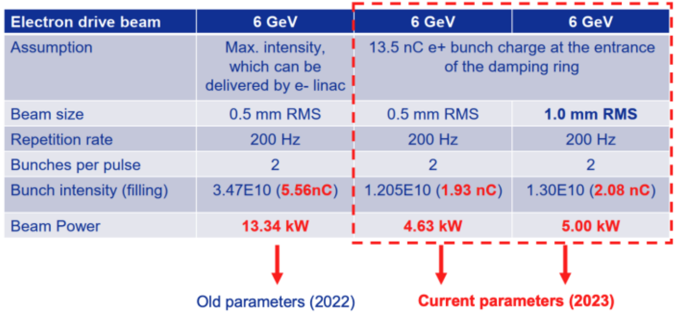
E = 6 GeV
Q = 1.9-2.1 nC

Positron Source

Positron/Electron Separation at 200 MeV

Energy collimator and compressor

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

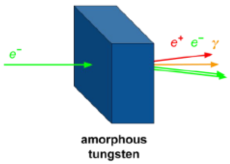


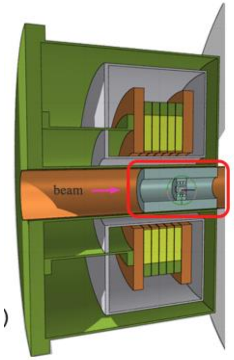
Electron drive beam	**6 GeV**	**6 GeV**	**6 GeV**
Assumption	Max. intensity, which can be delivered by e- linac	13.5 nC e+ bunch charge at the entrance of the damping ring	
Beam size	0.5 mm RMS	0.5 mm RMS	**1.0 mm RMS**
Repetition rate	200 Hz	200 Hz	200 Hz
Bunches per pulse	2	2	2
Bunch intensity (filling)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

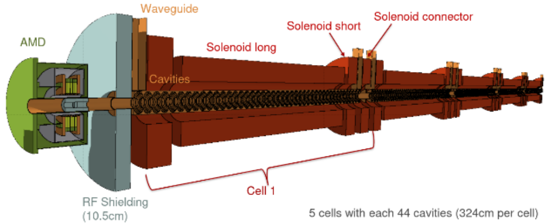
Old parameters (2022)

Current parameters (2023)

Conventional target







Primary (drive) beam parmeters

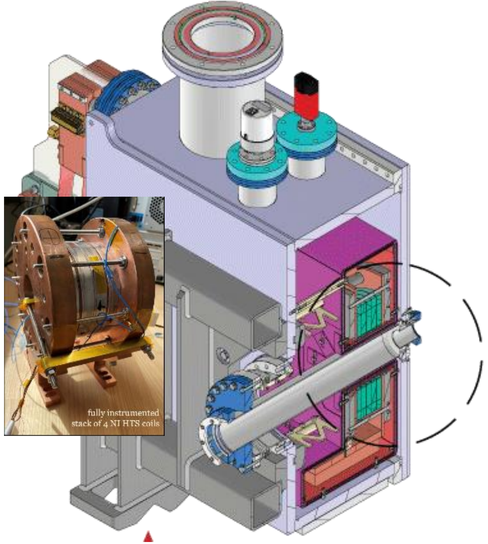
Conventional target

Matching device (MD)

Capture linac and solenoid focusing

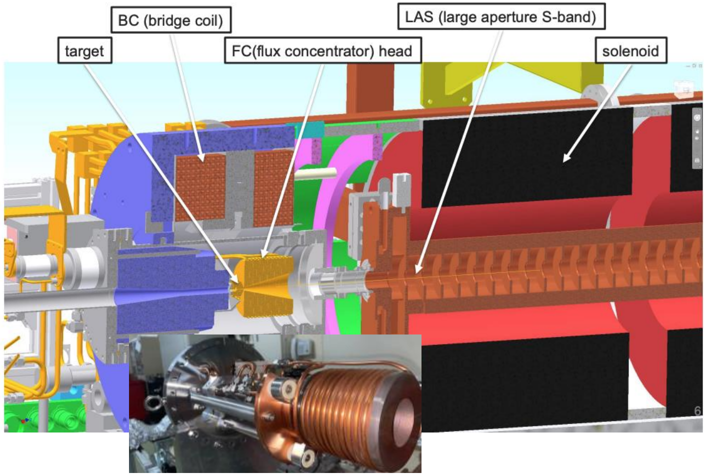
I. Chaikovska et al.

Positron source: matching device

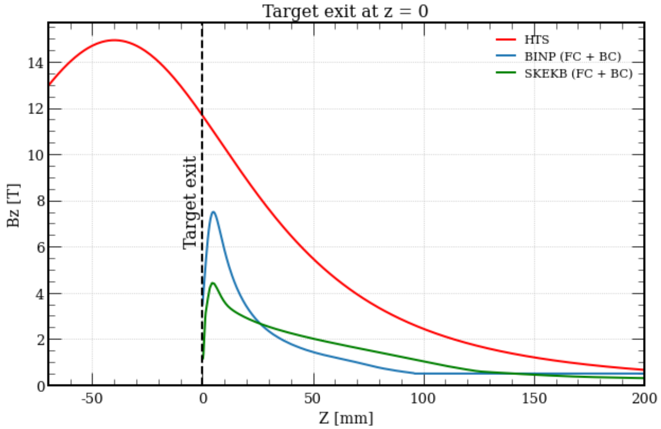


SC solenoid (PSI)

18.2 T @15K@2kA reached



Flux concentrator (FC) - SuperKEKB source



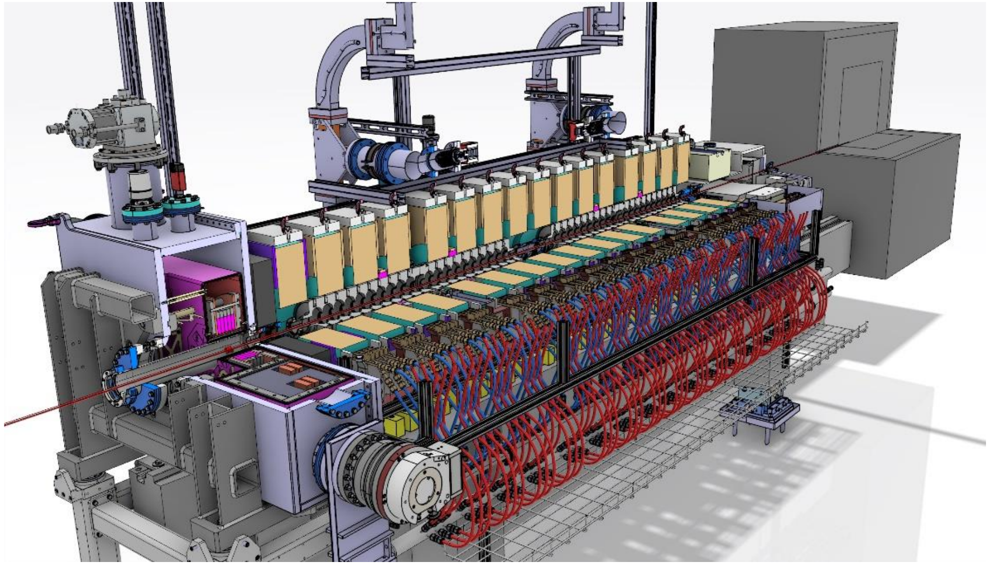
Magnetic field profiles

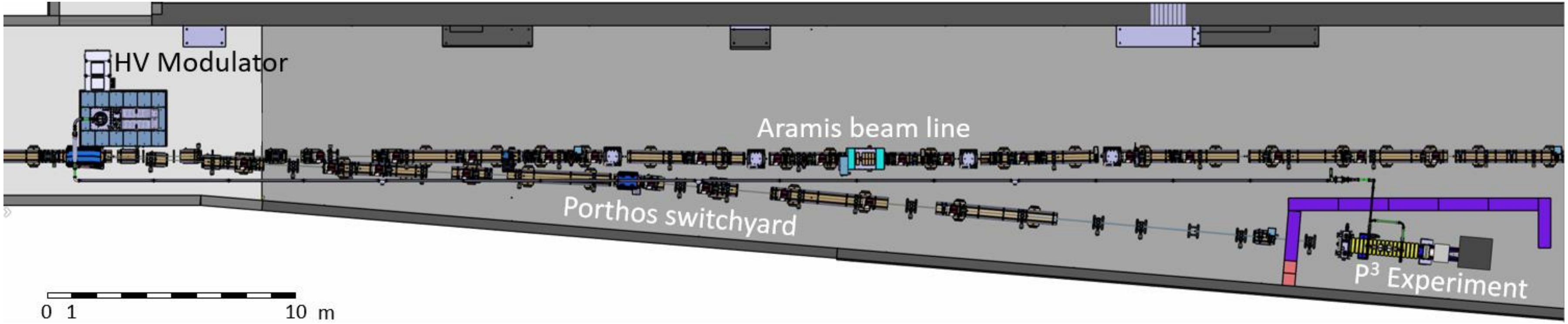
<u>FC:</u> lower peak field and aperture, fixed target position, challenging power source working at 200 Hz, **robust and reliable solution**…

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

PSI Positron Production (p-cubed) experiment

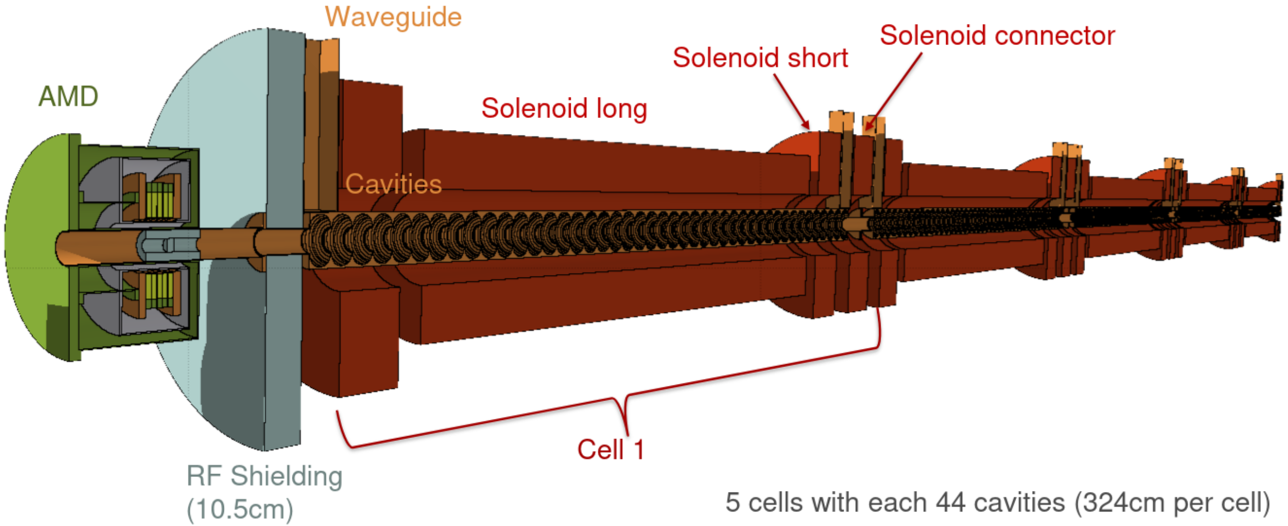
- Design phase well advanced, several components are ordered
- Installation on the Porthos extraction line ongoing
- Ongoing collaboration with CERN STI for the target
- Experiments in 2025/2026





N. Vallis et al., Proof-of-principle e + source for future colliders, accepted PR AB.

Positron source: capture linac



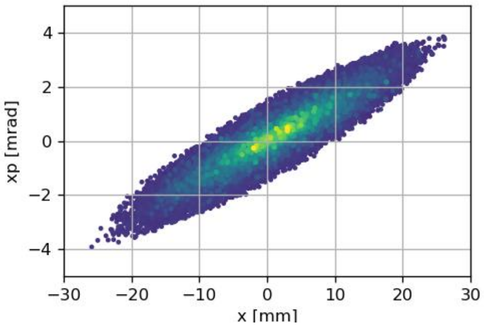
5 cells with each 44 cavities (324cm per cell)

- **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

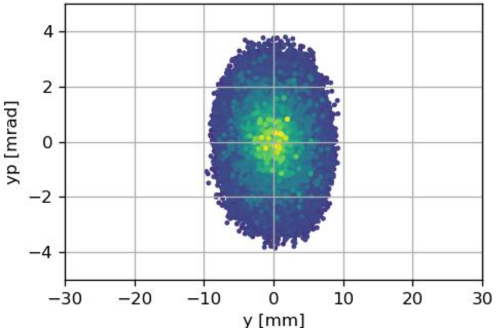
Positron source and capture linac

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**		

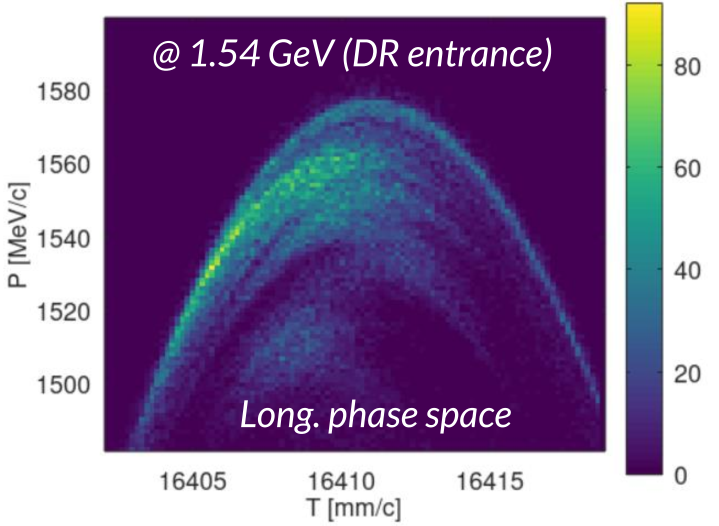
- Safety margin for the acceptance in the DR and transport in the linac (13.5 nC)
- Drive beam parameters have been also updated based on this safety margin
- The studies on the positron source based on the SC solenoid are well advanced



Horizontal phase space



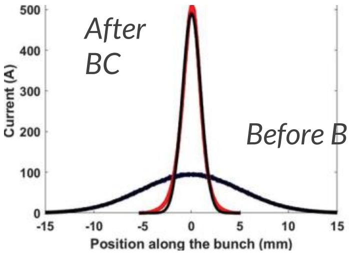
Vertical Phase space

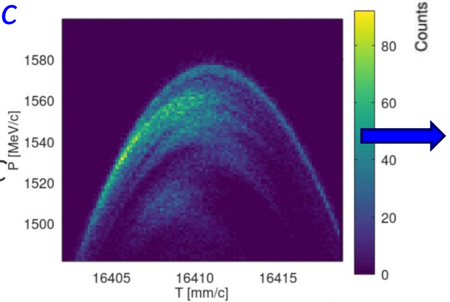


I. Chaikovska et al.

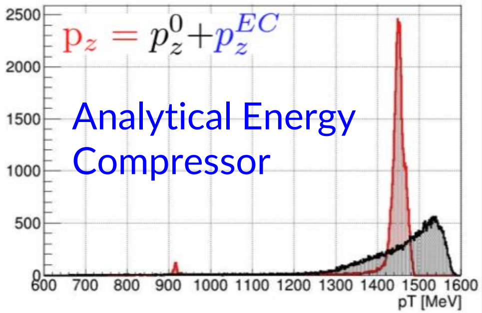
Damping Ring and Return Transfer Lines

Bunch profile to c-linac

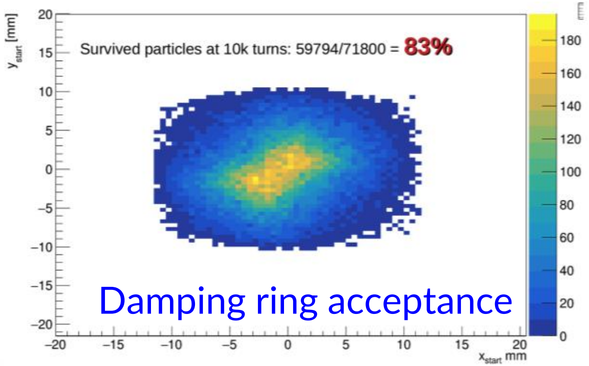




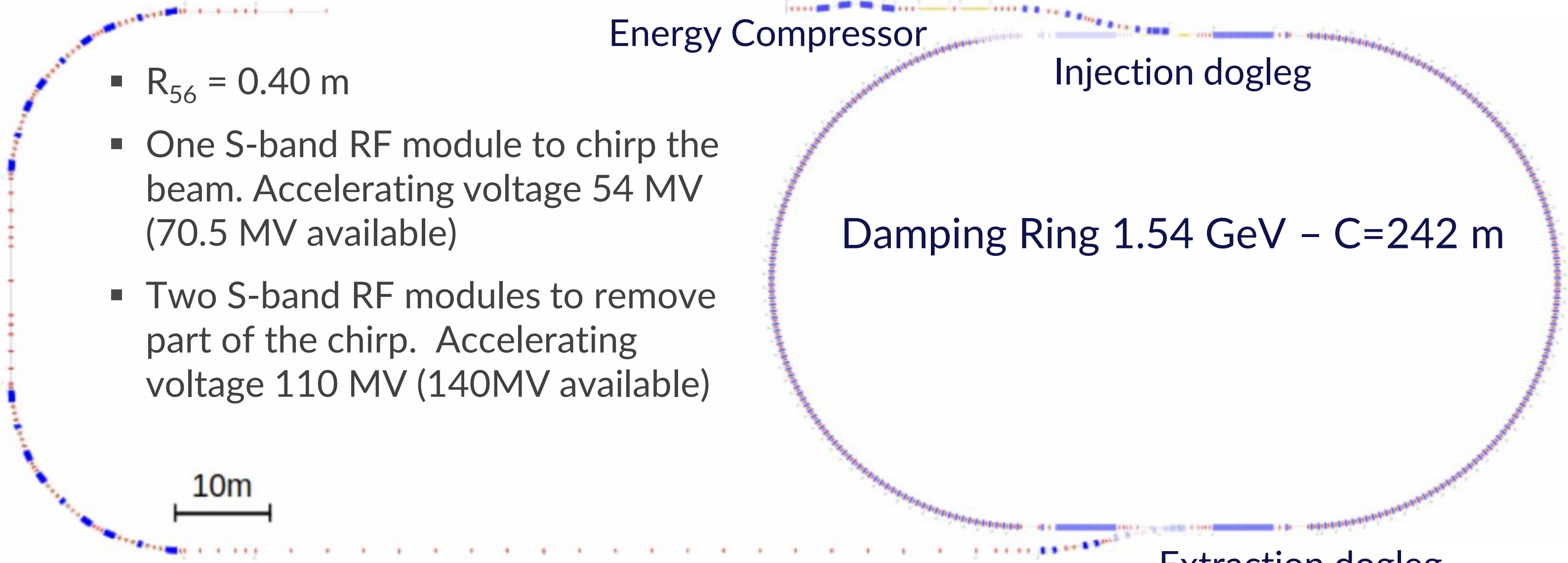
LPS from positron linac



Analytical Energy Compressor



Damping ring acceptance



Energy Compressor

Injection dogleg

Bunch Compressor

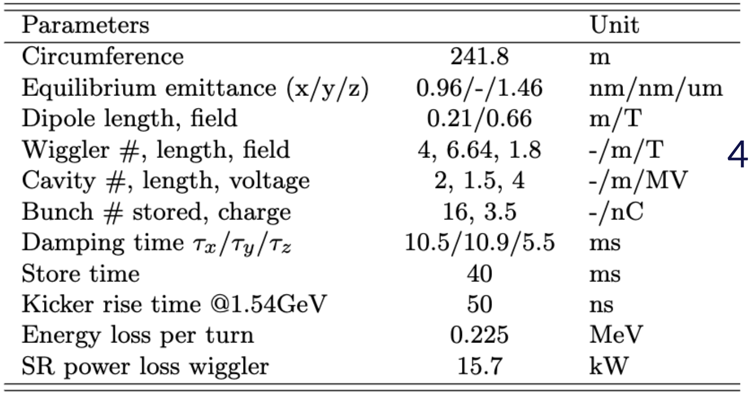
- R_{56} = 0.40 m
- One S-band RF module to chirp the beam. Accelerating voltage 54 MV (70.5 MV available)
- Two S-band RF modules to remove part of the chirp. Accelerating voltage 110 MV (140MV available)

Damping Ring 1.54 GeV – C=242 m

Extraction dogleg

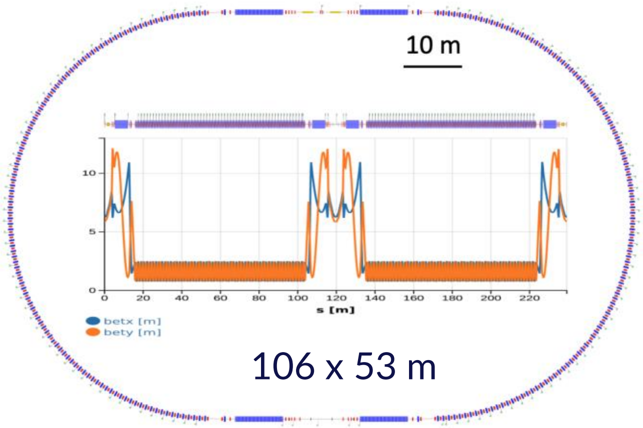
C. Milardi, A. De Santis, S. Spampinati, O. Etisken

Damping Ring and Return Transfer Lines



Parameters		Unit
Circumference	241.8	m
Equilibrium emittance (x/y/z)	0.96/-/1.46	nm/nm/um
Dipole length, field	0.21/0.66	m/T
Wiggler #, length, field	4, 6.64, 1.8	-/m/T
Cavity #, length, voltage	2, 1.5, 4	-/m/MV
Bunch # stored, charge	16, 3.5	-/nC
Damping time $\tau_x/\tau_y/\tau_z$	10.5/10.9/5.5	ms
Store time	40	ms
Kicker rise time @1.54GeV	50	ns
Energy loss per turn	0.225	MeV
SR power loss wiggler	15.7	kW

400 MHz, RF cavity



106 x 53 m

- Layout in CDR0 for cost estimate: DR and TLs design has been complete
- **DR acceptance larger than 83% can be achieved with the help of the ECS installed between the p-linac and the DR injection line**
- A BCS has been included in the return line from DR to c-linac (max compression factor 5)
- Alternative DR designs are being considered
  - Different types of cells and magnets are being evaluated to reduce the number of elements
  - Preliminary study for a DR at higher energy is on-going

Summary

- A baseline for the pre-injector layout was ready for the mid-term review (week 42)
  - Cost estimates for the hardware, technical infrastructures and civil engineering are available for the project
- Pre-Injector can fulfill the (partially new) requirements for the collider rings
  - but there is still room for some optimizations
- P^3 project is underway, and will be a first step towards the FCCee positron source
- Several presentations with more details were given at FCC week 2023

Credits

PSI	R. Zennaro, M. Schaer, N. Vallis, B. Auchmann, I. Besana, S. Bettoni, H. Braun, M. Duda, R. Fortunati, H. Garcia-Rodrigues, D. Hauenstein, E. Hohmann, R. Ischebeck, P. Juranic, J. Kosse, F. Marcellini, U. Michlmayr, S. Muller, G. L. Orlandi, M. Pedrozzi, J.-Y. Raguin, S. Reiche, M. Seidel, R. Rotundo, S. Sanfilippo, M. Zykova all the technical groups involved in the P^3 experiment
IJCLab	I. Chaikovska, F. Alharthi, V. Mytrochenko, R. Chehab
CERN	A. Grudiev, A. Latina, S. Doebert, Z. Vostrel, Y. Zhao, B. Humann, A. Lechner, A. Kurtulus, R. Mena Andrade, J.L. Grenard, A. Marcone, M. Calviani, W. Bartmann, Y. Duthell, H. Bartosik, K. Oide, F. Zimmermann, M. Benedikt
INFN-LNF	C. Milardi, A. De Santis, O. Etisken, S. Spampinati
SLAC	T. Rauberheimen
KEK:	Y. Enomoto, K. Furukawa

and L. Bandiera, M. Soldani, A. Sytov (INFN/Ferrara), A. Bacci, M. Rossetti Conti (INFN/Milano)

This work was done under the auspices of CHART (Swiss Accelerator Research and Technology) Collaboration, https://chart.ch - **CHART Scientific Report 2022: https://chart.ch/reports/**

Thank for your attention!!

Warm autumn colours at the PSI Campus

Reduction of gradient (and dissipated power)

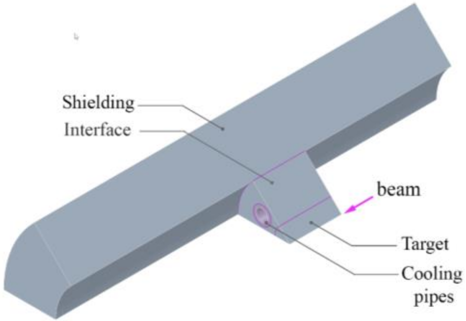
Common linac	Baseline	Option 1*
Repetion rate (Hz)	400	400
Gradient (MV/m)	23.4	16.5
Length (m)	262.5	360
Cost for module (MCHF/module)	1.840	2.455
# module	35	26
Total cost (MCHF)		
Cost per meter (kCHF/m)		
Plug power red.		-26%

HE linac	Baseline	Option 1*
Repetion rate (Hz)	200	200
Gradient (MV/m)	29.5	20.9
Length (m)	615	885
Cost for module (MCHF/module)	1.805	2.415
# module	82	59
Total cost (MCHF)		
Cost per meter (kCHF/m)		
Plug power red.		-28%

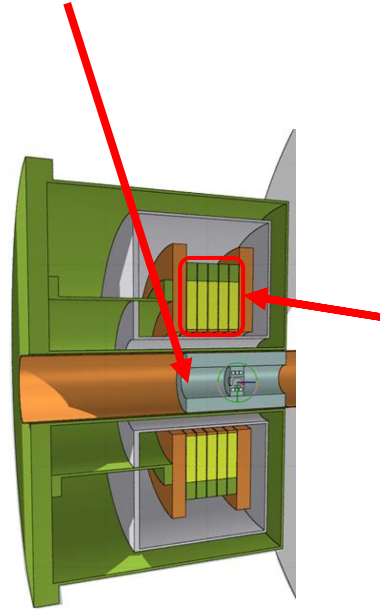
*Option 1: four RF structures per klystron, total module length: 15 m

Positron source: target

R. Mena Andrade (SY-STI) et al., FCC week 2023

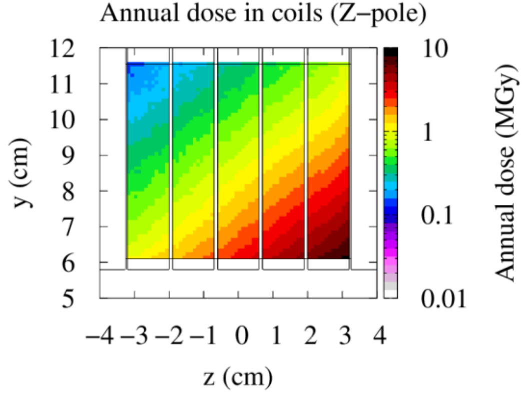


- After several iterations, the current beam parameters provide a solid baseline for the design of the FCC-ee positron source target.
- A target made of pure tungsten now is a feasible option. The thermo-mechanical studies show values of temperature and stresses inside of the safety limits of tungsten.
- As a next step, a R&D test campaign is foreseen to evaluate different manufacturing options for the target and the hipping of the tubes for the cooling system.



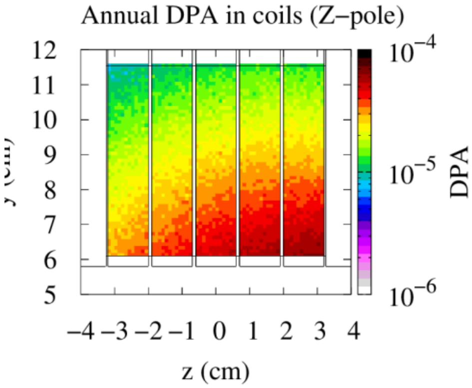
Radiation load to HTS coils

Cumulative dose in coils (one year at Z-pole)



Up to **8MGy/year**

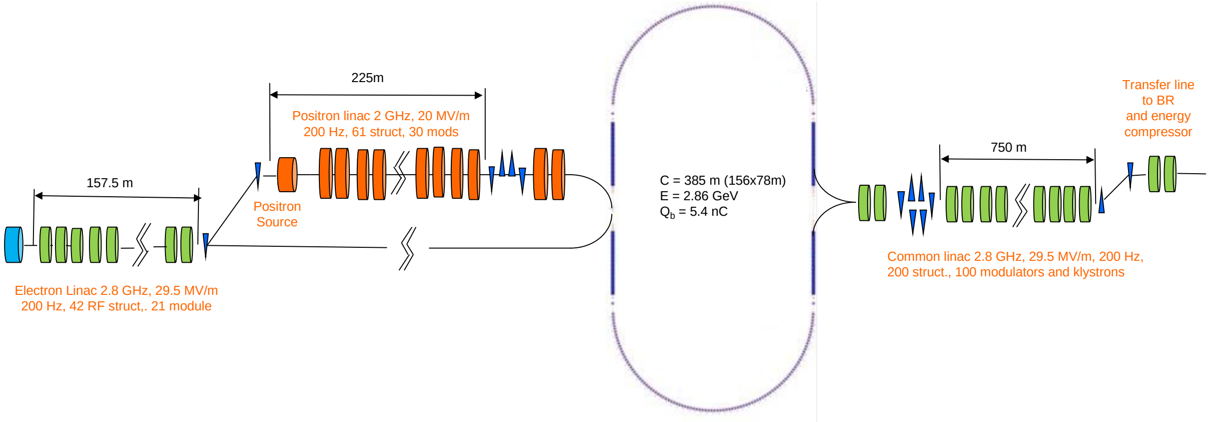
DPA in coils (one year at Z-pole)

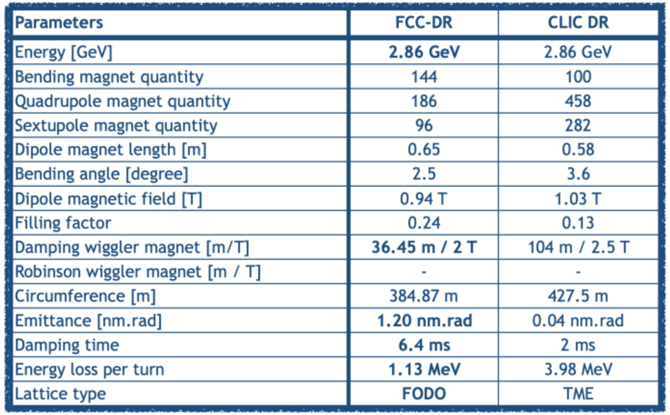


Up to **8E-5 DPA/year**

- In general, no showstopper, but shielding design to be further optimized
- DPA likely acceptable (with annealing cycles)
- Limits for ionizing dose to be understood (if any)

Injector layout with DR at higher energy





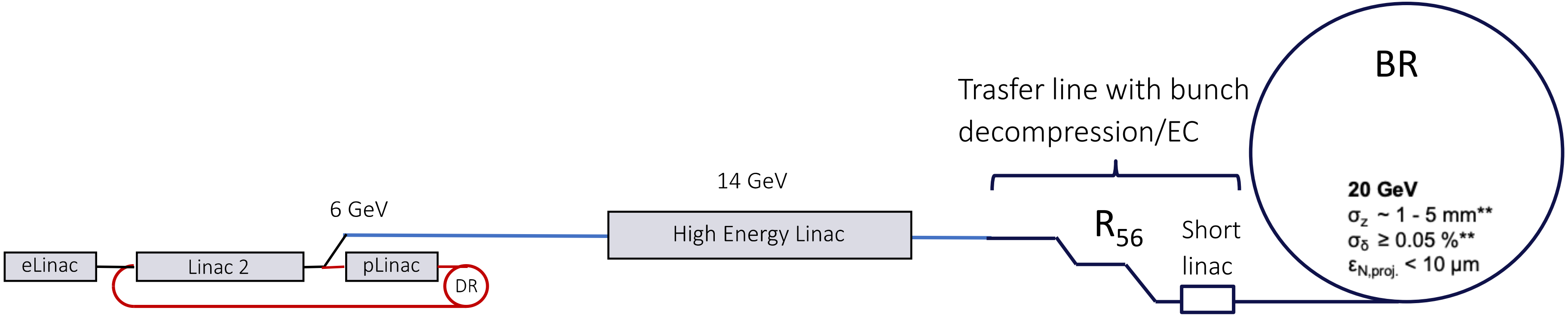
Parameters	FCC-DR	CLIC DR
Energy [GeV]	**2.86 GeV**	2.86 GeV
Bending magnet quantity	144	100
Quadrupole magnet quantity	186	458
Sextupole magnet quantity	96	282
Dipole magnet length [m]	0.65	0.58
Bending angle [degree]	2.5	3.6
Dipole magnetic field [T]	0.94 T	1.03 T
Filling factor	0.24	0.13
Damping wiggler 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

Some general remarks

- RF systems at 2.0, 2.8 and 5.6 GHz to be developed: Pulsed RF sources are moving to higher repetition rate but still not mature, 400 Hz is challenging for klystrons and HV modulators → collaboration with suppliers for development of prototypes
- RF structures: peak gradient vs dissipated power and breakdown rate (prototypes), high power density to be dissipated → thermo-mechanical analysis to be performed
- Damping ring acceptance must be confirmed with collective effects, IBS, etc…
- Positron source: AMD based on SC solenoid, demonstrator will provide several information, AMD based on FC to be verified the operation at 200 Hz in term of ohmic losses on the FC and high-power requirement for the pulsed PS
- Electron source: stability and top-up scheme to be verified up to 5 nC

Energy compressor at linac end



Trasfer line with bunch decompression/EC

BR

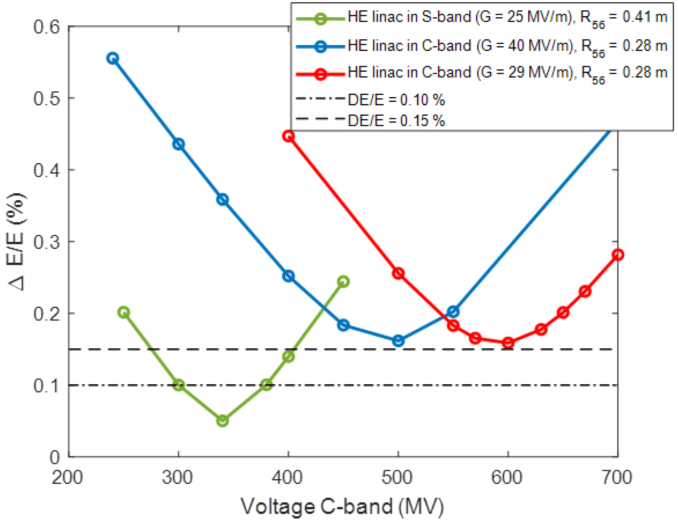
20 GeV

σ_z ~ 1 - 5 mm**

$\sigma_\delta \geq 0.05$ %**

$\varepsilon_{N,proj.}$ < 10 µm

- With this option, the specifications for the linac end and for injection into the BR can be partially decoupled
- More flexibility for the linac but more complex transfer line
- Independent tuning of the bunch length (operating rf phase, R_{56}, zero-crossing) and energy spread (RF voltage)



SPS vs HE linac performances

- HE linac delivers beam with 4x small energy spread and 16x smaller transverse emittance. The Booster injection will be difficult and will need additional time at max energy to damp.
- Collective effects in the SPS have not been evaluated for the FCC-ee bunch train (5 nC!)
- HE linac allows for higher injection energy into the booster (e.g., 20 GeV versus 16 GeV from SPS) and injection into the booster would be much more flexible (low magnetic field at booster injection and impedance effects)
  - further energy increases through linac extensions could be possible, should an even higher injection energy turn out to be desirable AND would be fully independent of any hadron beam operation, and it could serve for many additional applications.
  - the construction and commissioning could proceed in parallel to any SPS or LHC hadron beam operation, while the reconstruction and use of the SPS could not begin before the end of the HL-LHC programme
- SPS as a pre-booster during Z running would be used most of the time for lepton operation. HE linac would not impact hadron beam operation. SPS option would have major repercussions for any hadron beam programme in the SPS, and also implications for any use of the SPS as a future hadron beam injector to the LHC or FCC-hh