





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

Pre-Injector baseline and options

FCC Week 2023, 5-9 June (London, United Kingdom)





- Pre-Injector parameters and injection time
- SPS vs HE linac
- Energy compressor in the LTB transfer line
- Pre-Injector layout baseline (for mid-term review and cost estimate)
- New and old options
- Status of P3 experiment



Pre-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
Normalized 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 during filling from scratch 4 nC (bunch pop. 2.5x10¹⁰ particles)

Charge for top-up 2.42 nC (2.5x10¹⁰ 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 injection intensity fluctuation: 5% (Z mode), 3% (WW, ZH, tt)
- Bucket selection/filling pattern to be still studied



680.64 s (~12 min)

Collider rings, top up (Z mode)

Collider filling time 42.54 s for each species (< collider top up interval 49.4 s)

- Extraction at 20 GeV leads to a very large energy loss per turn and different extraction energy options were investigated
- Extraction at 16 GeV provides a reasonable energy spread, energy loss per turn and emittance but emittance at the extraction is higher than specification for the booster.

Some mitigations have to be provided to manage the synchrotron radiation

 \rightarrow The cost estimate could provide a motivation to use this option (comparison with HE linac cost)

Electron, Common, HE linacs

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

A. Grudiev and J.-Y. Raguin, Layout and design of positron and electron linacs, talk on Thursday

S. Bettoni, Linac Beam Dynamics, talk on Thursday

- Electron source: one RF gun for electrons and positrons prod.
- Three main linac (S-band, 2.8 GHz)
- Each rf module: one klystron/modulator, rf WG network, 2 rf structures, BPM, quad and corrector
- Common linac at 400 Hz during positron production
- Cost estimate is based on the technolgy developed for SwissFEL linac (PSI)

Courtesy of Zdenek Vostrel and Steffen Doebert

Electron sources - specifications

Transver

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Key properties listed in the table, reached

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

6

8 z [m]

Courtesy of Zdenek Vostrel and Steffen Doebert

14

10

12

Robust solution to preserve the emittance for different bunch charge

• Large contribution from 5% particles

Cutting particles based on energy or transverse position

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Positron production and linac

R. Mena Andrade et al., Design of the FCC-ee positron source target: current status & challenges, talk on Wednesday

Drive beam parameters	Alternative FC	Capture	
	system		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	.1 / 7.4 5 / 12	
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	-

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- AMD: two approaches under study, FC and SC solenoid
- Positron linac at 2 GHz with large aperture
- Safety margin for the acceptance in the DR and transport in the linac
- Drive beam parameters for the conventional target have been updated

Evolution of the Damping Ring

C. Milardi et al., Damping Ring and transfer lines for the pre-injector, talk on Wednesday

Parameters	CDR	After CDR	Option - 0	Option - 1	Option - 2	Option - 6	Option - 7.1	Option - 7.2
Bending magnet quantity	232	212	72	84	84	78	30 DQ / 12 D	27 DQ / 18 D
Dipole magnet length [m]	0.21	0.21	0.28	0.3	0.4	0.4	0.55 / 0.4	0.55 / 0.4
Bending angle [degree]	1.55	1.55	5	4.28	4.28	4.61	10 / 5	10 / 5
Dipole magnetic field [T]	0.66	0.66	1.8	1.27	1.27	1.03	1.62 / 0.81	1.62 / 0.81
Filling factor	0.2	0.19	0.07	0.09	0.12	0.15	0.11	0.10
Damping wiggler magnet	26.5 m / 1.8 T	68 m / 1.8 T	18 m / 2 T	18 m / 1.8 T	12 m / 4 .4 T	36.45 m / 2 T	-/-	- / -
Robinson wiggler magnet	-	-	3.8 m / 1.1 T	3.8 m / 1.8 T	-	-	- / -	- / -
Circumference	242 m	240 m	257.31 m	280.23 m	262.92 m	248.19 m	181.74 m	218.61 m
Emittance	2 nm.rad	2.76 nm.rad	4.89 nm.rad	2.12 nm.rad	2.06 nm.rad	2.1 nm.rad	2.07 nm.rad	2.26 nm.rad
Damping time	10.5 ms	5.9 ms	6 ms	5.7 ms	6.1 ms	8.1 s	8.5	10.8
Energy loss per turn	0.255 MeV	0.47 MeV	0.253 MeV	0.23 MeV	0.439 MeV	0.31 MeV	0.14 MeV	0.14 MeV

Motivations to review the DR design (C. Milardi):

- Minimize cell number in the arcs
- Reduce or even eliminate the use of wigglers magnets to achieve the required parameters (emittance and damping time)
- Improve Dynamic Aperture and ring acceptance
- Optimize injection extraction sections

PAUL SCHERRER INSTITUT Pre-injector layout with DR at higher energy

- The present positron yield would allow positrons to be generated at a lower electron beam energy 2.42, 2.86 or 3.30 GeV. The detailed study by Y. Zhao (CERN) 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, evtl. DR for both electrons and positrons. In principle a higher charge with higher emittance from the photo-injector is possible because can be dumped in DR. Flat beam also possible
- Experience from Pre-Damping Ring for CLIC (energy 2.86 GeV) and some preliminary study by O. Etisken for a dedicated DR
- Easier operation of the common linac, seconds instead of milliseconds between e+ and e- operations
- Higher cost for DR but lower for overall linacs (to be verified)

Technology for FCC-ee Injector Linacs

- C³ Demo is a proposed 5–7-year R&D program for to engineer and demonstrate S/C-band high gradient cryomodules (\rightarrow build 3 cryomodules)
- Demonstrations include **high-gradient testing**, damped and detuned structures, beam dynamics, heavy beam loading, demonstration of alignment tolerances for a C³ linear collider

Linac Cryomodule (~9 m) **Compatible with S/C-band Structures**

Gradient ~70MV/m S-band structure with a/λ . = 0.15 under study (compatible with FCCee linacs

Preliminary studies showed that the C³ approach could reduce significantly the length OR reduce rf power of FCC-ee HE linac (compared to the baseline)

A more systematic comparison is ongoing

FUTURE

LHeC Racetrack as Injector to FCC-ee

Y. Papaphilippou, FCC week 2021

- Based on 2 SRF Linacs (~800 MHz) with 3 recirculating arcs, total length of ~5.3 km (~1/5 of LHC), reaching energy of ~49 GeV - LHeC recirculating linac injector (RLI)
- Bunch intensity of ~500 pC (~3x10⁹ p/b) for ~25ns spacing, average current of 20 mA
- Could be used for full energy top-up injector for FCCee-Z and pre-injector for other collider energies
- Small footprint PERLE-like version could be used as preinjector to (P)BR~6-20GeV

Approach could be interesting if:

- The lifetime is too short (this is currently not the case), and to keep the beam luminosity and current constant, almost continuous top-up injection is required but
 - BR cycle time of tens of sec dominates the overall injection time \rightarrow full-energy injection
- Higher average intensity is required, LHeC ERL can provide about 4 orders of magnitude higher average current than the FCCee injector (positron source and DR to be studied)

Status of PSI Positron Production exp.

- Design phase well advanced, some components are ordered. Cryostat, NC solenoids and diagnostic
- Installation on the Porthos extraction line ongoing
- Ongoing collaboration with CERN STI for the target

N. Vallis et al., A Positron Source Demonstrator for Future Colliders, poster

- A baseline for the pre-injector layout is ready for the mid-term review
 - Pre-Injector can fulfill the (partially new) requirements for the collider rings
- SPS vs HE linac: both options will be presented at the mid-term review with a cost estimate, costs will be an important aspect for the final decision
- Layout with DR at higher energy: very promising in terms of simplifying the preinjector and perhaps reducing overall costs
- C³ technology is very promising but a more detailed comparison is needed
- LHeC Racetrack as (Full) Injector for FCCee: attractive if the lifetime decreases and the intensity increases (no further studies before mid-term review)
- P³ project is underway, and will be a first step towards the FCCee positron source

- 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 P3 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, 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, P. Raimondi
- SLAC T. Rauberheimen, E. Nanni
- KEK: Y. Enomoto, K. Furukawa

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

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Injection time for each specie (20 GeV Linac, 4 IP)

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	Z	WW	ZH	tt
Collider energy [GeV]	45.6	80	120	182.5
Collider & BR bunches / ring	16000	1800	450	60
Collider particles / bunch N_b [10 ¹⁰]	15.1	14.5	11.5	15.5
Allowable charge imbalance Δ [±%]	5		3	
Injector particles / bunch $N_{ m max}$ [10 ¹⁰]	≤ 2.5 (4 nC)			
Bootstrap particles / bunch $[10^{10}] = 2N_b \Delta$ 2.4	2 nC 1.51	0.87	0.69	0.93
[#] of BR ramps (up to 1/2 stored current, with $N_{\rm max}$)	3	3	3	4
$\#$ of BR ramps (bootstrap with 2 $N_b\Delta$)	4	4	4	4
BR ramp time (up + down) <i>t</i> _{ramp} [s]	0.6	1.5	2.5	4.1
Linac bunches / pulse	2			
Linac pulses needed $n_{\rm p}$	8000	900	225	30
Linac repetition frequency [Hz] f_{rep}	200	100	50	
Collider filling time from scratch [s]	284.2	73.5	49	35.2
Collider filling time for top-up [s] = $n_p/f_{rep} + t_{ramp}$	40.6	10.5	7	4.7
Lum. lifetime (4 IP) [s]	1340	970	840	730
Lattice+BS lifetime (4 IP) [s]	15000	4000	6000	6000
(real lattice lifetime)/(design lattice lifetime)	0.25	0.25	0.25	0.25
Collider lifetime (4 IP) τ ₂ [s]	987.2	492.4	538.5	491.0
Collider top-up interval (between e+ and e-)(4 IP) [s] = $\tau_2 \Delta$	49.4	14.8	16.2	14.7

June 1, 2023 K. Oide