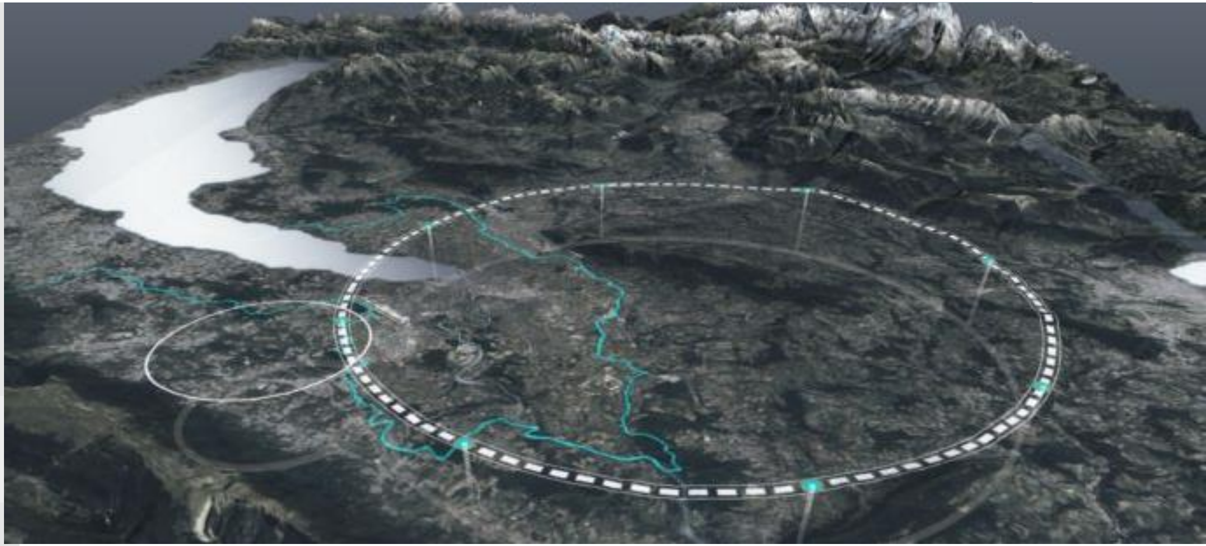


Paolo Craievich (PSI) on behalf of the CHART/FCCee Injector design collaboration

FCC-ee injector summary

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

PAUL SCHERRER INSTITUT

Injector (I and II) sessions

FUTURE CIRCULAR COLLIDER

Wednesday 7 June

10:30	**FCC-ee injector** - Barbara Dalena (CEA-Irfu & Université Paris-Saclay (FR)) (until 12:00) (Orchard Suite)
10:30	Full-energy booster - Dr Antoine Chance (CEA Irfu) (Orchard Suite)
10:50	Pre-injector baseline and options - Paolo Craievich (Orchard Suite)
11:10	Positron production, capture and acceleration until the damping ring - Dr Iryna Chaikovska (CNRS/IJCLab) (Orchard Suite)
11:25	Design of the FCC-ee positron source target: current status & challenges - Ramiro Francisco Mena Andrade (Orchard Suite)
11:40	Damping ring and transfer lines for the FCC-ee pre-injector complex - Catia Milardi (Istituto Nazionale di Fisica Nucleare (INFN))

Thursday 8 June

08:30	**FCC-ee injector** - 흥식 강 Heung-Sik Kang (until 10:00) (Orchard Suite)
08:30	Linac beam dynamics - Simona Bettoni (Paul Scherrer Institut) (Orchard Suite)
08:50	Layout and design of positron and electron linacs up to 20 GeV - Alexej Grudiev (CERN) (Orchard Suite)
09:10	SPS pre-booster option - Hannes Bartosik (CERN) (Orchard Suite)
09:30	Siting and transfer lines - Wolfgang Bartmann (CERN) (Orchard Suite)

FCCee Pre-Injector parameters (Z-pole)

K. Oide, H. Bartosik (SPS), FCC week 2023 talks

	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)	50,?	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. 2.5×10^{10} particles)

- The bunch by bunch intensity will arbitrarily vary from 0 to 100%, depending on the intensity balance between the collider rings → to be verified the impact on the booster as well
- New parameters:
  - 15000 bunches, 15 ns bunch spacing
  - Charge for top-up 2.42 nC (2.5×10^{10} particles)

Question: How can we keep different versions of parameter tables?

Full-energy booster (conclusion) – Antoine Chance

New Layout, some results are for the optics showed FCC week 2022

Optics:

- Procedures have been written to optimize the layout and booster positioning in the tunnel.
- Matching conditions have been updated to increase the transparency of the insertions.
- The dispersion suppressor needs to be improved to correct the 2nd order dispersion in the long insertions.

RF budget has been updated for 800 MHz cavities

Strong reduction of dynamic aperture and momentum acceptance due to synchro-betatron resonances

- Tune has been optimized
- Criteria stabilities under investigation to understand DA reduction

Orbit tuning

- First definition of the orbit correctors for the booster (≃ 20 mT) and orbit correction scheme.
- First specifications of elements misalignment (150 μm)
- Finalize the emittance tuning studies

HEB operation and emittance evolution

- Optimization of cycle time at Z
- IBS integrated in accumulation process
- Updates of the cycling in case of SPS as an injector

Collective effects Resisitive wall wakes

- Not real impact of injecting a mismatched beam.
- First Intensity scans at injection with PyHEADTAIL
- Confirmation of intensity above threshold for Z operation with 90 degrees FODO cells contrary to 60 degrees FODO cells.*
- Doubling the momentum compaction cures the TMCI.

An alternative optics to 60° FODO cells has been proposed.

- Momentum compaction of the HBD cell can also be tuned.

Full-energy booster (Perspectives) – Antoine Chance

Optics and layout
- Provide a full list of the elements for the mid-term review.
- Provide an optics with the HBD cell.
- Apply the momentum compaction tuning to the optics and evaluate the impact on DA and MA.
- Evaluate the impact of the fringe field of the detectors on booster optics.

Cost estimate due by end June

Dynamic aperture and momentum acceptance
- Improve DA and MA (increase the number of sextupole families for instance)
- Evaluate the dynamic aperture and momentum acceptance for the HBD optics and with a doubled momentum acceptance.

Machine tuning
- Finalize emittance tuning
  - Static and dynamic imperfections
  - Improve overall performances/cost with AI

Cycling optimization

Collective effects
- Perform a momentum compaction scan to find the threshold for TMCI
- Add the IBS
- Perform the calculations with X-Suite to include the optics

Including collimators, cavities etc..

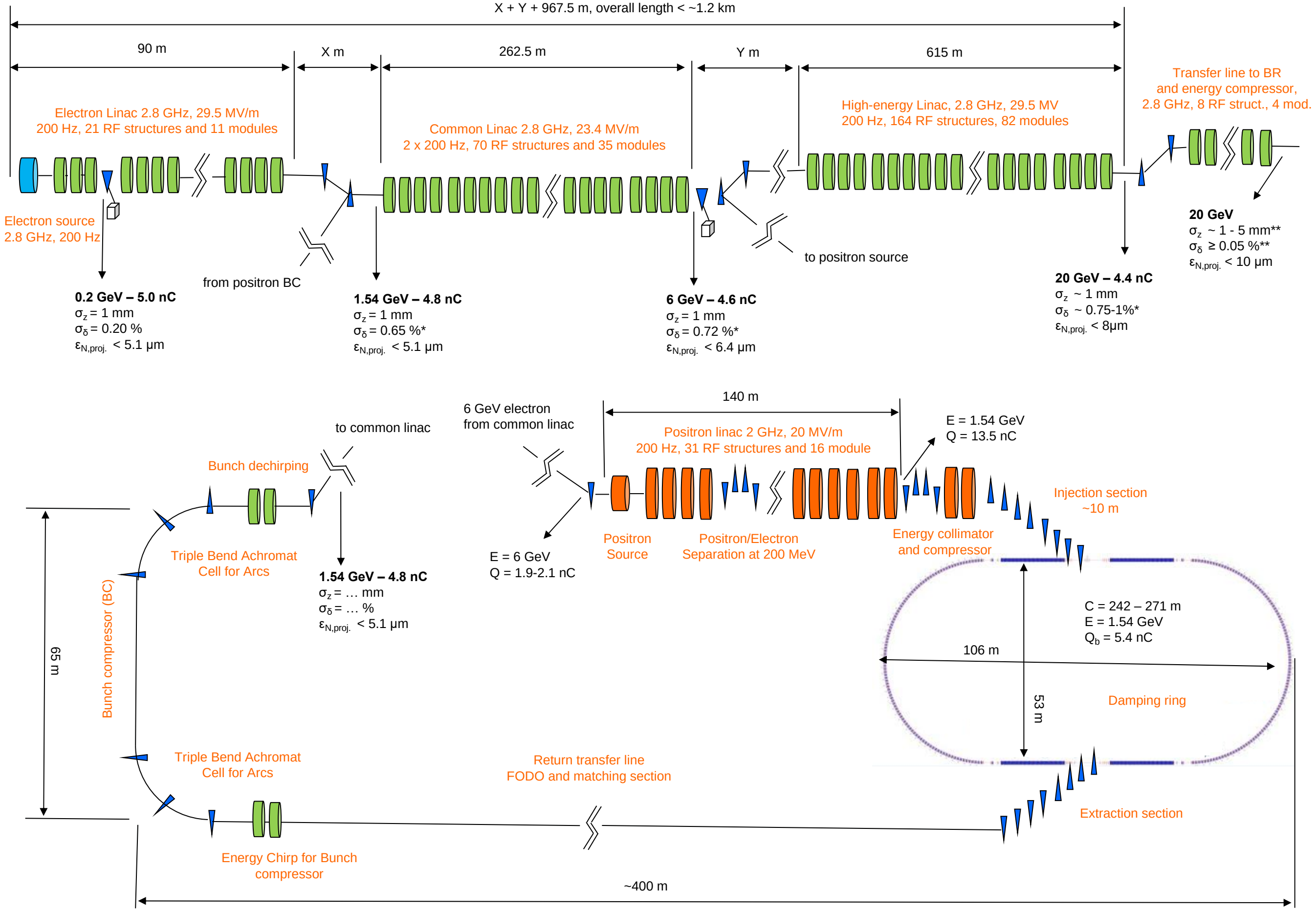
Injection:

20 GeV: recheck the beam parameters (i.e., energy spread and bunch length…)

16 GeV: check if the BR can work at this energy

BR operation with a modulated train of bunches

Pre-injector layout (baseline)



A baseline for the pre-injector layout is ready for the mid-term review

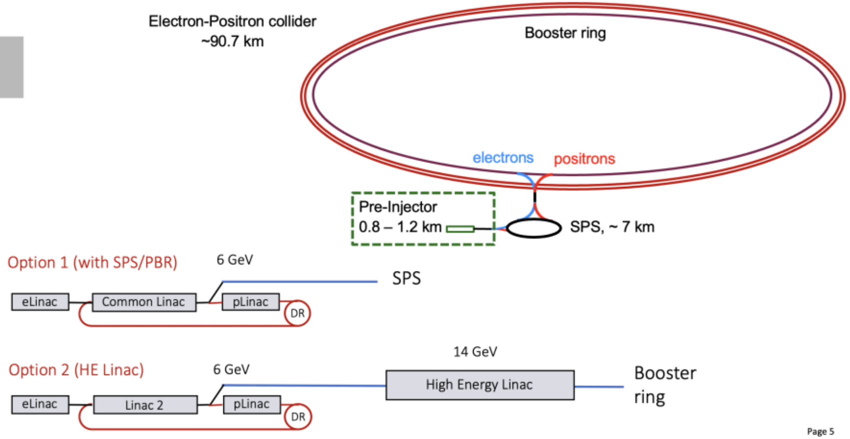
Pre-Injector can fulfill the requirements for the collider rings (to be verified with the new parameters)

Submit the cost lines by June

Draft the document (deadline mid-Sept)

Pre-injector options

FCCee Pre-Injector: SPS vs HE linac



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Pre-injector layout with DR at higher energy

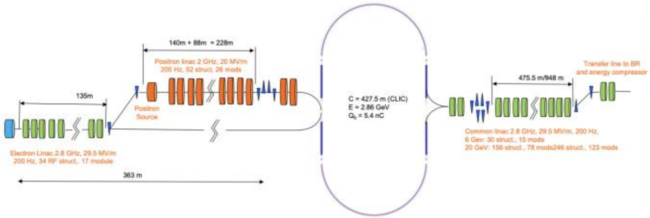


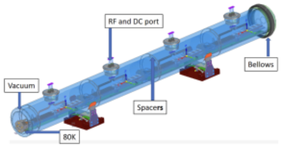
Table coutesy of O. Etisken

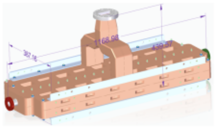
Parameters	FCC-DR	CLIC DR
Energy [GeV]	**2.86 GeV**	2.86 GeV
Bending magnet quantity	144	100
Quadrupole magnet quantity	186	458
Sextupole magnet quantity	96	282
Dipole magnet length [m]	0.65	0.58
Bending angle [degree]	2.5	3.6
Dipole magnetic field [T]	0.94 T	1.03 T
Filling factor	0.24	0.13
Damping wiggler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

C^3 Technology for FCC-ee Injector Linacs

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

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





Gradient ~70MV/m
S-band structure with $a/\lambda = 0.15$ under study (compatible with FCCee linacs)

Preliminary studies showed that the C^3 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

Courtesy of E. Nanni

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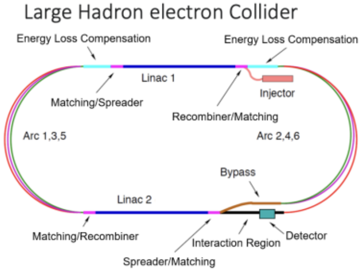
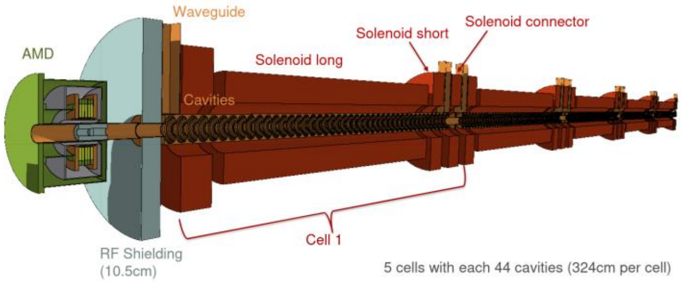
LHeC Racetrack as Injector to FCC-ee

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 (~3x10^9 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 pre-injector to (P)BR~6-20GeV

Positron production, capture and acceleration until the damping ring– Iryna Chaikovska



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		

Conclusions and outlook

– The studies on the FCC-ee positron source are well advanced: positron production, HTS technology feasibility for matching device, capture linac (RF structures and solenoid). So far, no showstoppers found that prevent a SC solenoid matching device. Studies ongoing.

– FC-based capture system requires a realistic model capable to work at the FCCee operation parameters. Collaborative work is very essential.

– Two capture system layouts (based on the FC and SC solenoid) will be eventually compared in detail in terms of the performance and cost for the mid-term project review.

– Positron linac has a robust design with full tracking simulations from production target to damping ring using the realistic field maps.

– Thermal and radiation load studies: FLUKA model is available for capture system –version 1. Still to be developed for the FC-based capture system.

– Design and integration of the production target are under investigations and to be studied for both schemes.

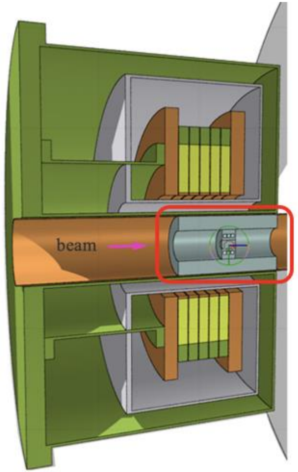
07/06/2023 FCC Week 2023, 5-9 June (London, United Kingdom)

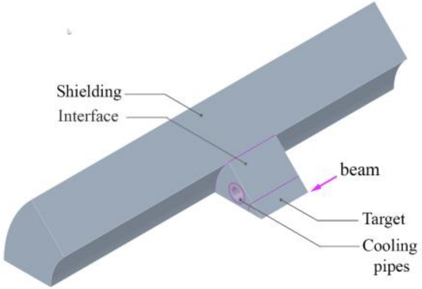
Design of the FCC-ee positron source target: current situation and challenges – Ramiro Mena Andrade

Target design: main parameters

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**

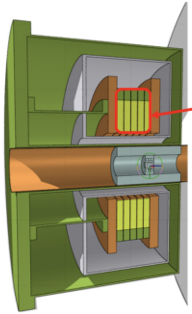
Old parameters (2022) — Current parameters (2023)

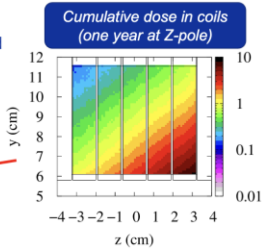




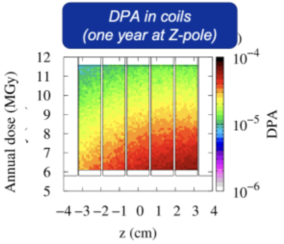
Target design: radiation load to HTS coils

In general, no showstopper, but shielding design to be further optimized





Up to **8MGy/year**



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

@Z-pole
(185 days/year
5 kW e- beam power)

DPA likely acceptable (with annealing cycles)
Limits for ionizing dose to be understood (if any)

Summary

- 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.
- The **design of the P3 target** is ongoing and it is a key factor to study the performance in terms of positron yield inside of the P3 experiment.

Preliminary cost estimate for the target system ready

Damping Ring and Transfer Lines for the FCC-ee pre-Injector Complex – Catia Milardi

DR acceptance

At large energy deviation most of the losses are concentrated in the tail of the distribution as expected. Global DR acceptance:

$$f_{ACC} = 0.939 \times 0.917 = 86.1\%$$

Recently the emittance of the beam provided by the pLINAC has been optimized -> an even larger DR acceptance is expected.
New DR acceptance is being evaluated.

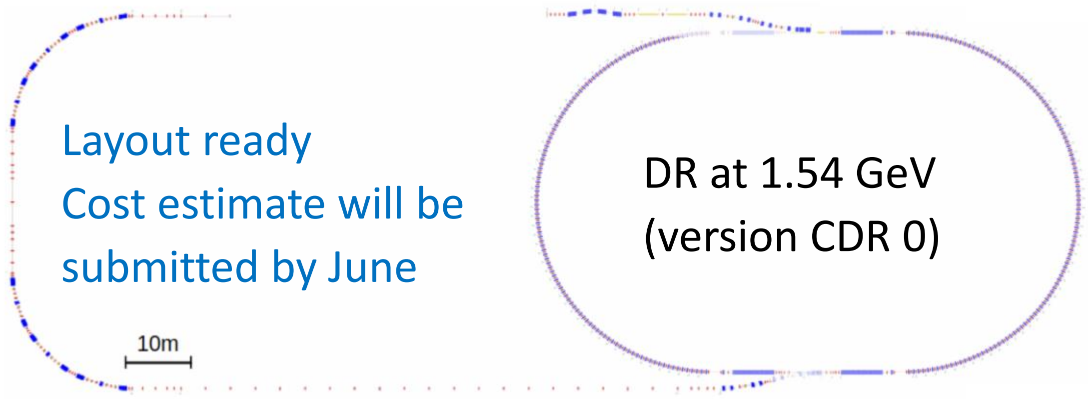
Alternative DR designs

Different options are being evaluated including different type of cell and magnet

In all the options, the number of elements was considerably reduced

In a preliminary configuration (Option-2) beam parameters were achieved even without damping wiggler insertions which helps in simplifying vacuum chamber design impedance budget and realization costs.

Option-2 also minimize curly H function which is important to avoid emittance dilution effects due to CSR



Layout ready

Cost estimate will be submitted by June

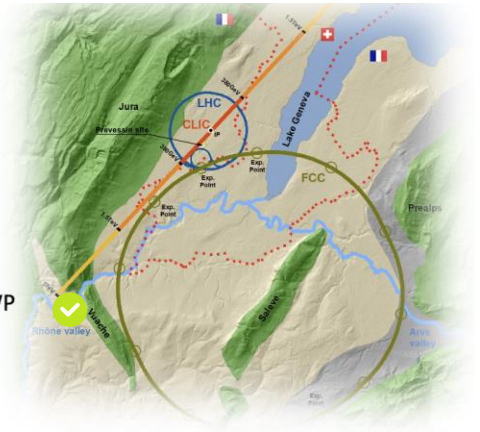
DR at 1.54 GeV (version CDR 0)

- DR and TLs design has been completed ✓
- A DR acceptance larger than 86% can be achieved with the help of an ECS installed between the pLINAC and the DR injection line. ECS reduces energy spread to ~ 2%. ✓
- A BCS has been included in the return line from the DR to Common LINAC. BCS can provide maximum compression factor C ~ 5. ✓
- A breakdown schedule of the the components used for the different parts has been prepared costs are being evaluated. ✓
- Alternative DR designs are being considered.

Linac Beam Dynamics – Simona Bettoni

Longitudinal dynamics:

- Design without energy compressor:
  - σ_z~1 mm or slightly more, $\delta E/E$~0.1-0.15% feasible
- Design with energy compressor:
  - On-crest (preferred): better for (energy efficiency) and emittance growth
  - *S-band* High Energy Linac: energy spread ≤0.05% and several mm bunch length possible
  - *C-band* High Energy Linac: energy spread ≤0.15% and several mm bunch length possible in the present design
  - Impact of different charge for the 0-100% *charge scan* determined
  - *Flexible* design to eventually accommodate different specifications coming from the booster and the transfer line WP



Transverse dynamics:

- Emittance increase due to *static misalignments* of accelerator components is under control including a factor 2 margin for the selected geometry (several steering algorithms implemented in RF-Track)
- Comparison of the obtained results using several *tracking codes*: after this work now the codes agree

Ongoing: study of the impact on the beam of:

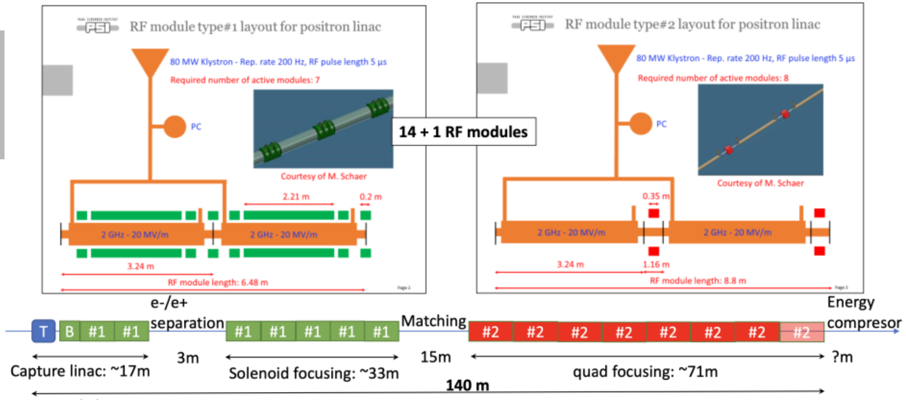
- Linacs' number of module/structure in WP1
- Optimization of the RF structure design in WP1
- In the future, possible re-optimization of the design according the booster/SPS requests

***Optimized* design(s) of the Linacs from 200 MeV to 20 GeV beam energy fulfilling the present booster requests**

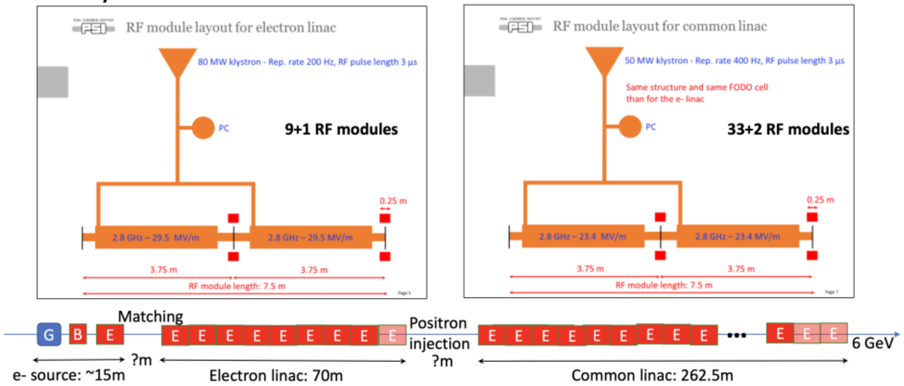
Next steps will be to refine the *best* design, given the booster/SPS target and transfer line parameters

Layout and design of positron and electron linacs up to 20 GeV – Alexej Grudiev 1/2

Layout of positron linac



Layout of electron and common 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	Inc. WG loss and 90% margin
Number of structures per klystron	2	2	2	2	2	
Number of structures total	1 + 30	1+20	70	164	172	Same for quads, corrs. and BPMs
Number of modules total	1 + 15	1+10	35	82	86	
Total length of all modules [m]	140	90	262.5	615	645	

Comparison of relative cost of linacs in a.u.

Linac	Klystron cost [a.u.]	Modulator cost [a.u.]	Cost estimation [a.u.]
p-linac	0.27	0.9	32.5
e-linac	0.18	0.82	20.5
c-linac	0.19	0.85	66.5
Total p-,e-,c-linacs			119.5
HE-linac – S-band option	0.18	0.82	152.5
HE-linac – C-band option	0.16	0.8	155

Cost estimate includes:
- RF
- LLRF
- Vacuum
- Magnets
- BI

- Cost of HE linac is comparable to the cost of all other linacs
- Cost of HE linac S-band (baseline) and C-band options is similar

Layout and design of positron and electron linacs up to 20 GeV – Alexej Grudiev 2/2

HE-linac: S- and C-band comparison

- <u>S-band (baseline)</u>
- It uses the same RF module as for the e-linac, same spares, etc
- Better for the beam: Larger aperture, smaller "RF curvature"
- Similar cost as C-band (a bit less actually)
- S-band is more commercially available and more mature

- <u>C-band</u>
- 30% (~10MW) lower power consumption. Although it is significant, but it is negligible compared to FCC overall power consumption

General comments:

- Increase accelerating gradient and repetition rate can put a limit on the on the available power source and dissipated power in the rf structures. A compromise is necessary.
- Cost of the building and infrastructures have to be considered in the final decision of the RF module (i.e. 2 vs 4 rf structures per klystron)

SPS pre-booster option – Hannes Bartosik

- **Ongoing work to consolidate the option of using the SPS as FCCee pre-booster** for cost comparison to HE-Linac option at mid-term review
- We consider the **16 GeV extraction energy** as **most interesting**
- **High synchrotron radiation power** and required **vacuum levels are challenging** – ongoing work by vacuum experts
- Installation of **damping wigglers** (and Robinson wiggler) **might be required** – ongoing studies by booster colleagues if larger horizontal emittance could be accepted
- **Additional RF system would be required** – with very high voltage at extraction when using wiggler magnets
- **Modification of power converters for bi-polar operation seems feasible**
- **Collective effects to be further studied** (in particular the fast ion instabilities and TMCI)
- **Filling time compatible with collider request** (at least for latest parameter set)

- Horizontal Emittance at the extraction (16 GeV): 35 nm (w/o wiggler), 5.6 nm (w/ wiggler) (specs for linac ~0.25 nm at 20 GeV) – to be clarified

- Plan for the protons at CERN and cost estimates will provide information for a final decision

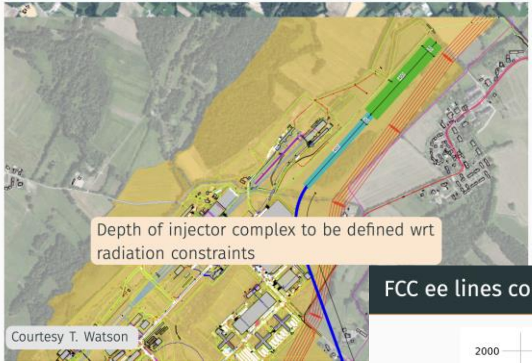
FCC-ee injector complex siting and transfer lines – Wolfgang Bartmann

Conclusions

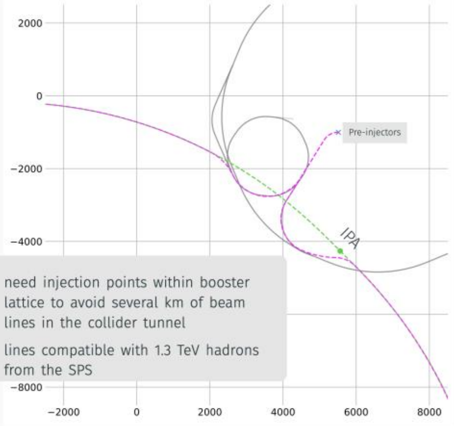
- Transfer lines have been optimized for re-using existing tunnels as much as possible and for compatibility between leptons and hadrons
- There is also synergy for the lepton injection options of 20 GeV linac or 16 GeV SPS
- Injection into the booster lattice should happen in the arc to avoid extensively long transfer line (reduce length by 2/3) which seems feasible from discussions during this week
- Energy compression can be included in the transfer line, most elegantly by using the r56 from the arcs - looks feasible, details to be confirmed between linac and booster constraints
- Upcoming
  - prepare cost lines for all required equipment
  - further optics studies on cell adaption, dispersion matching, energy compression and injection
  - specificaton of TL HW to enter into the engineering phase, in particular for magnets

Injector complex dimensions

Need ≈ 1-1.2 km length and 65 m width for half the complex



FCC ee lines compatible with hadrons from SPS



I would like to thank all colleagues involved in this collaboration in the framework of CHART.
In 2021 and 2022, most of the discussions were done on video meetings, and despite this, important progress was made.

Two mini-workshops were also organised to converge in preparation for the mid-term review. Many thanks to the organizers.

FUTURE CIRCULAR COLLIDER
FCC-ee Injector Studies Mini-Workshop

Nov 24 – 25, 2022
IJCLab
Europe/Paris timezone

Enter your search term

Chairman: Iryna Chaikovska

FUTURE CIRCULAR COLLIDER
FCC-ee Pre-Injector: CHART Collaboration Meeting

20–21 Apr 2023
INFN Frascati National Laboratories
Europe/Rome timezone

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Local Organising Committee:

A. DE SANTIS [CHAIR], *(INFN-LNF, Italy)*
M.R. FERRAZZA [Coordinator], *(INFN-LNF, Italy)*
M. GIABBAI [Coordinator], *(INFN-LNF, Italy)*
C. MILARDI *(INFN-LNF, Italy)*

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 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
CEA	A. Chance, B. Dalena, A Ghribi
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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/

FCCIS: 'This project has received funding from the European Union's Horizon 2020 research and innovation programme under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.'