The FCC-ee injector scheme

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with input from

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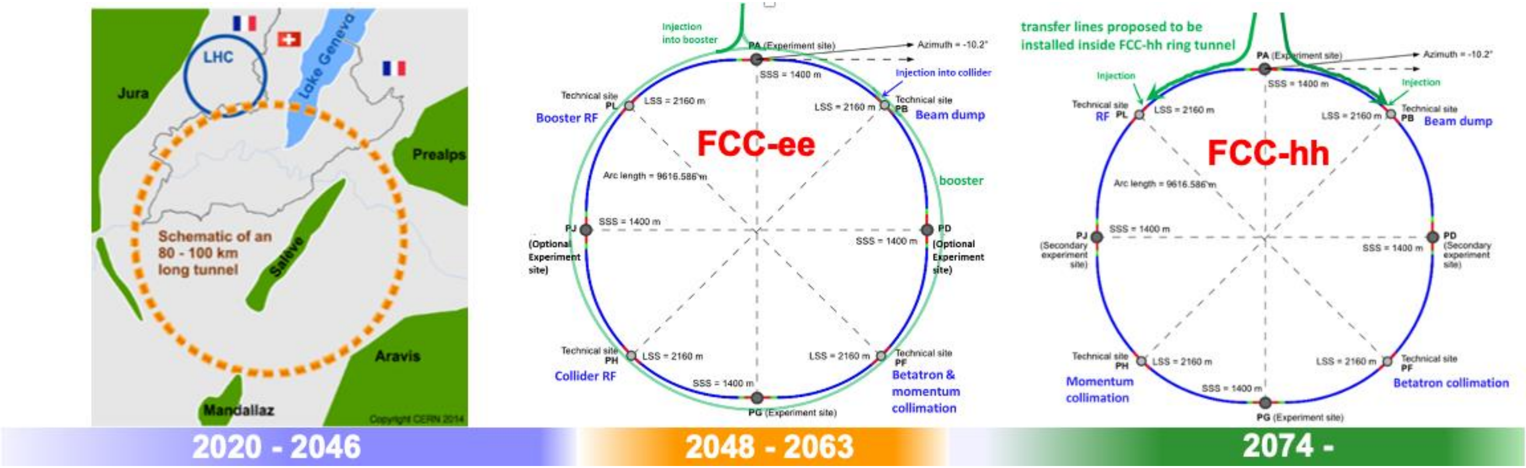
Introduction

- FCC (Future Circular Collider) is an ongoing study of an electron-positron collider (FCC-ee) to be followed later by a hadron collider (FCC-hh) with a centre-of-mass energy of ~100 TeV
  - About 91 km circumference tunnel to be embedded in the CERN accelerator complex to be used first for FCC-ee and then for FCC-hh
  - Feasibility study to be concluded in 2025 as input for the next ESPP update



Introduction

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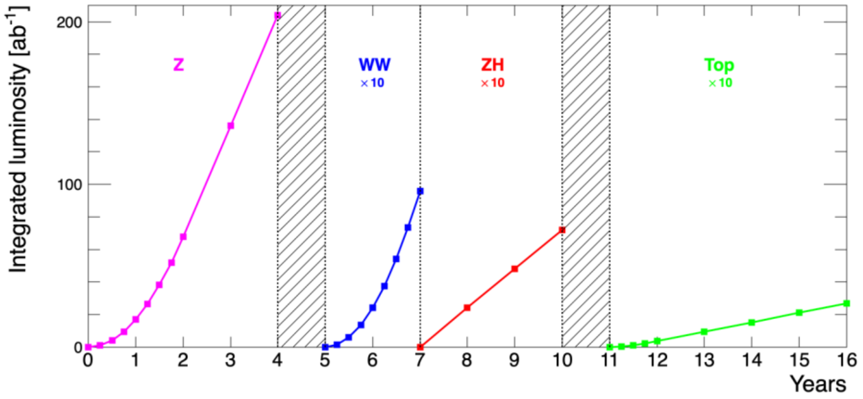
  - About 91 km circumference tunnel to be embedded in the CERN accelerator complex to be used first for FCC-ee and then for FCC-hh
  - Feasibility study to be concluded in 2025 as input for the next ESPP update
- **FCC-ee will require a new lepton (e+/e-) injector complex**
- The aim of this presentation is to illustrate the potential of this injector complex and hopefully trigger ideas of possible exploitation of the new complex beyond FCC-ee itself

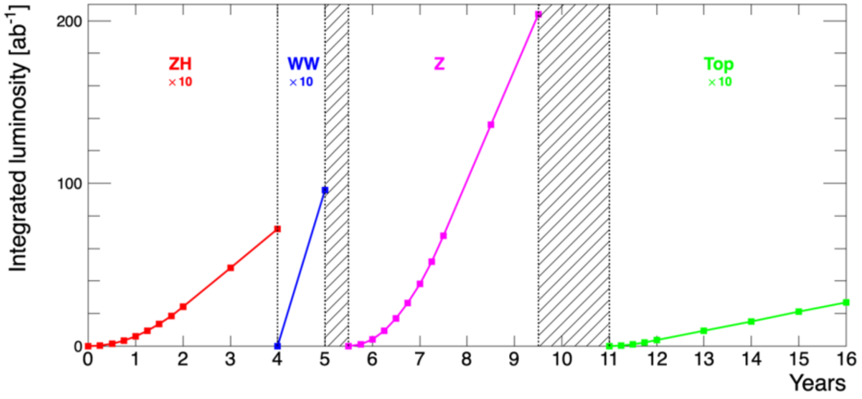
Operation sequences for FCC-ee

- FCC-ee accommodates 4 experiments
- Dedicated runs for Z, WW, Z-H and Top measurements
- Shutdown periods for rearrangement (installation / removal) of RF systems required for different modes (e.g. high beam loading for Z, high gradient for Top)

Baseline



Alternative



FCC-ee parameter table

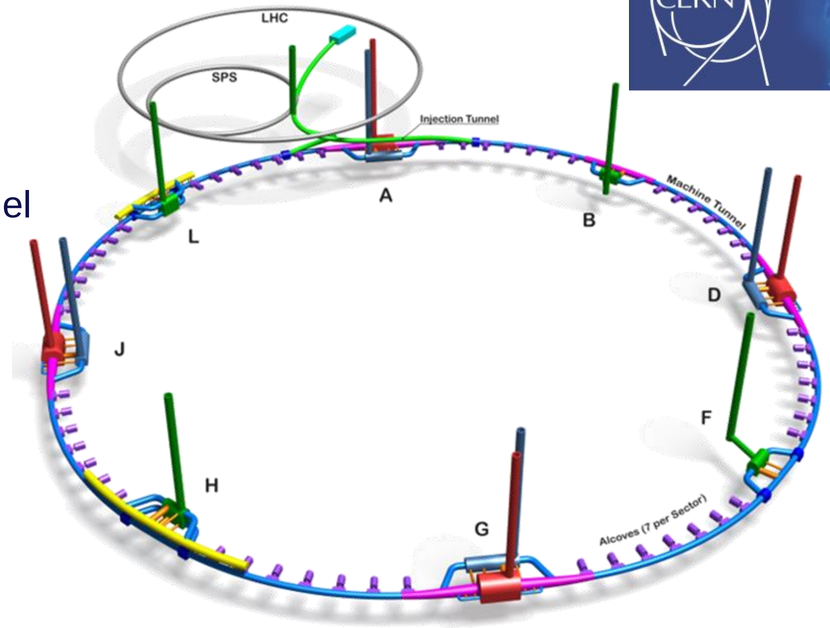
Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11

Total intensity limited by synchrotron radiation power (100 MW)

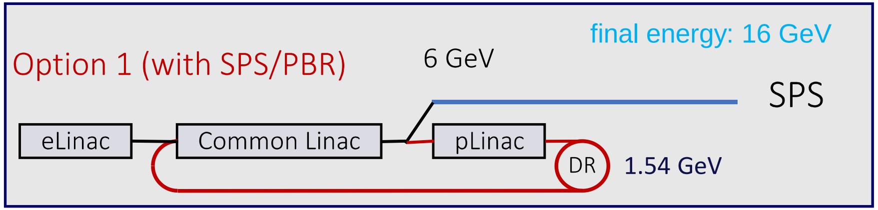
Short beam lifetime requires **booster** for top-up operation and **continuous beam delivery from injector**

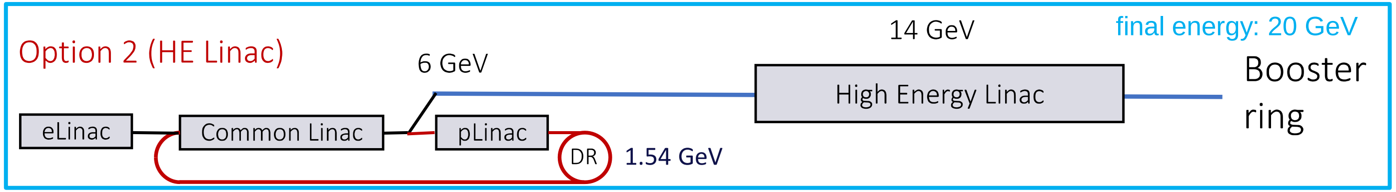
FCC-ee complex

FCC-ee collider and booster (top-up) in the same tunnel



Injector complex from mid-term review:

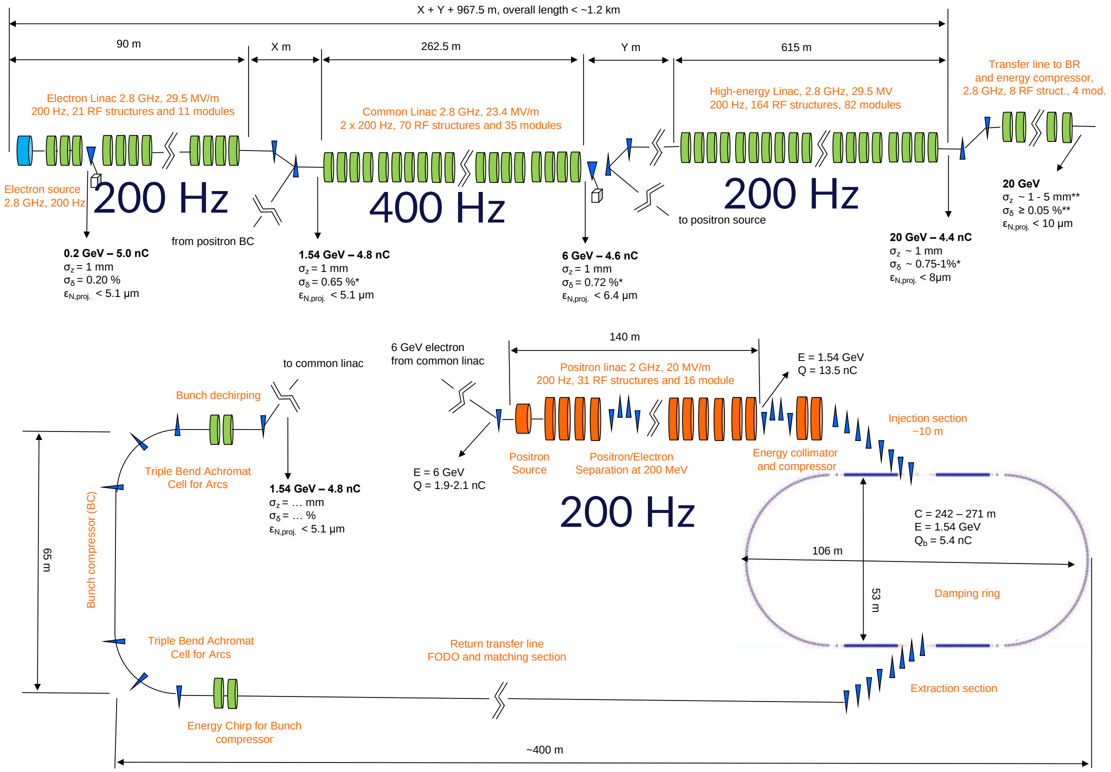




Option 2 is present baseline

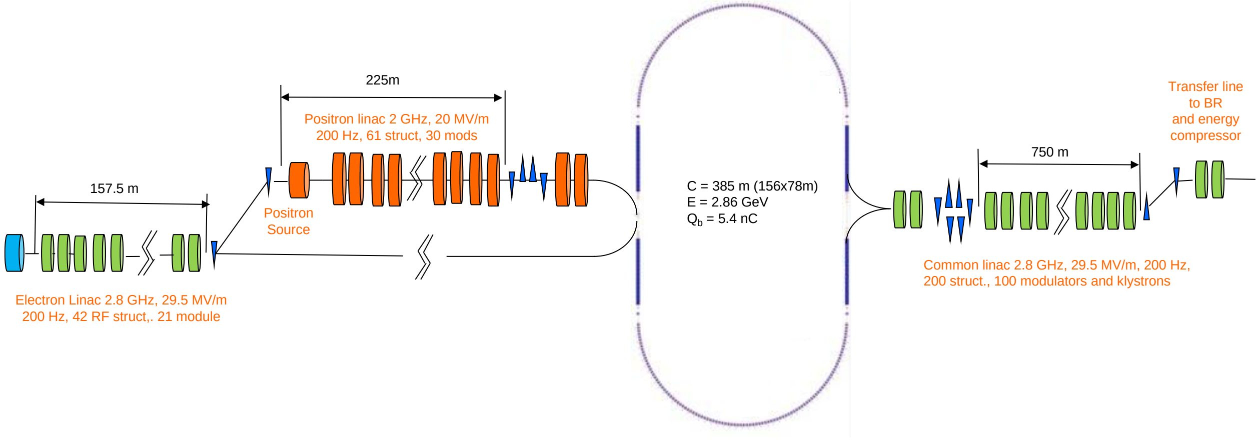
Injector complex - baseline

- Electron linac up to 1.54 GeV
- Common linac to 6 GeV, thus operating at twice repetition rate
- Positron target at 6 GeV and linac to accelerate resulting positrons to 1.54 GeV
- Positron damping ring at 1.54 GeV (compatible with polarization) and return line into common linac
- High energy linac to reach 20 GeV



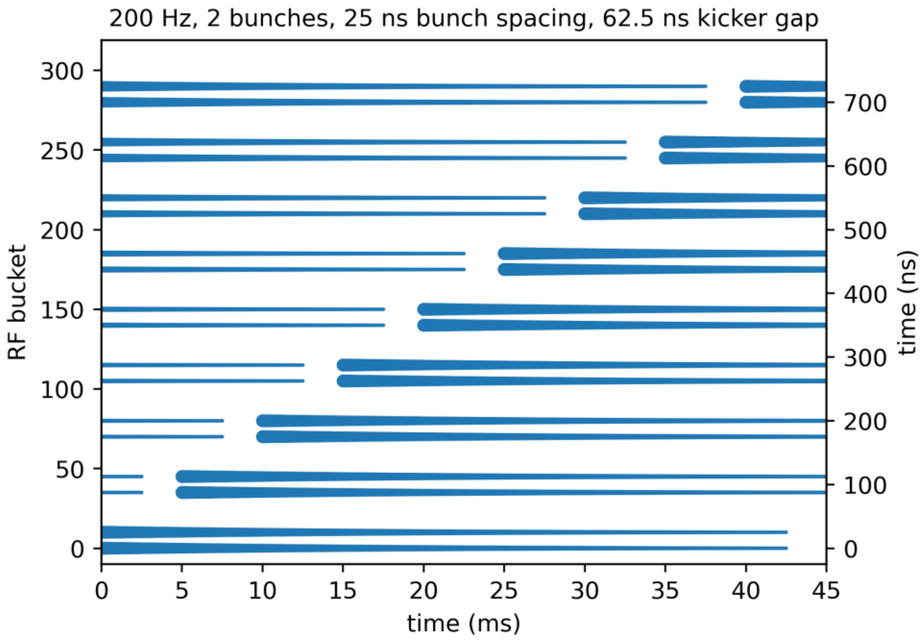
Injector complex – alternative proposal

- Alternative scheme to avoid 400 Hz operation of a common linac for e+/e-
  - Electron linac up to 2.86 GeV
  - Positron target at 2.86 GeV (positron yield OK) and positron linac to reach again 2.86 GeV
  - Damping ring for both e+ and e- at 2.86 GeV (compatible with polarization)
  - High energy linac to reach 20 GeV



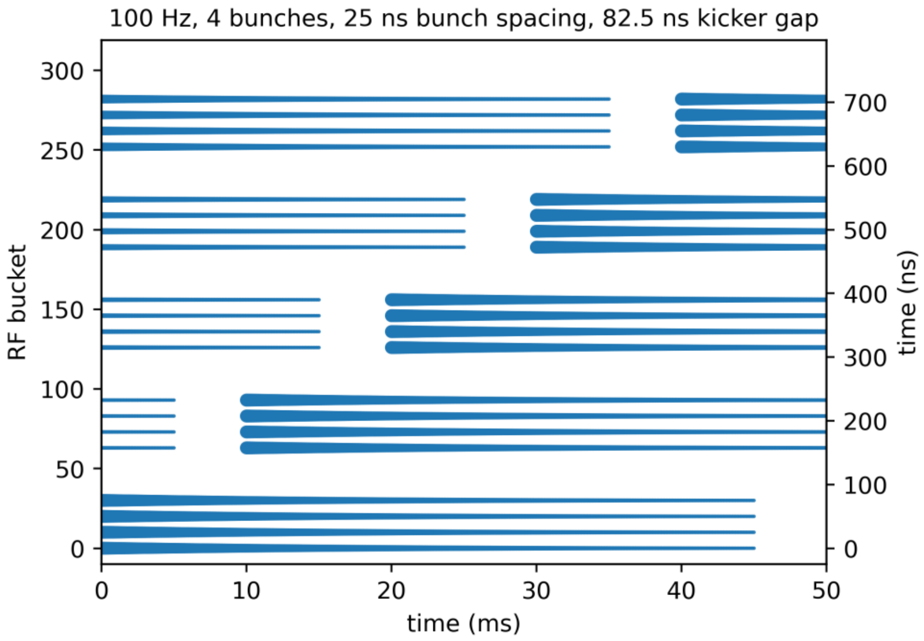
Damping ring filling scheme

- Continuous re-filling scheme (FIFO)
  - Staggered injection
  - 25 ns bunch spacing
  - Storage for ~42.5 ms (4x transverse damping times)
  - Staggered extraction
- **Present scheme**
  - **2 bunches @200 Hz**



Damping ring filling scheme

- Continuous re-filling scheme (FIFO)
  - Staggered injection
  - 25 ns bunch spacing
  - Storage for ~42.5 ms (4x transverse damping times)
  - Staggered extraction
- Present scheme
  - 2 bunches @200 Hz
- **Alternative option under study**
  - **4 bunches @100 Hz**



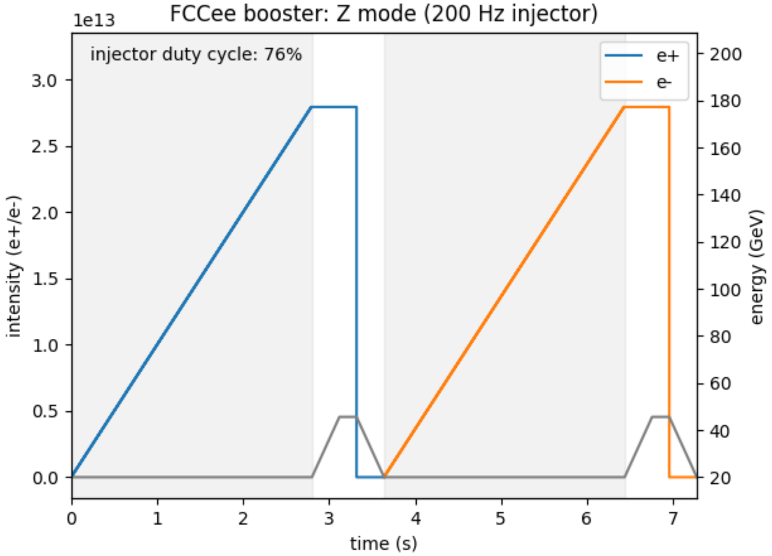
FCC-ee injection scheme

- Alternating booster cycles for e+/e-
  - Bunch intensity in the injector is maximum of 10% of final bunch intensity in the collider
  - Maximum intensity in the booster is limited by machine protection constraints for transfer to collider
- Bunches colliding in the FCC-ee right from the start
- Booster in the FCC tunnel for continuous top-up operation to keep bunch intensity imbalance within tolerance
  - Tight requirements on bunch intensity imbalance in the collider due to instabilities
  - Tolerable intensity imbalance depends on operation mode of collider

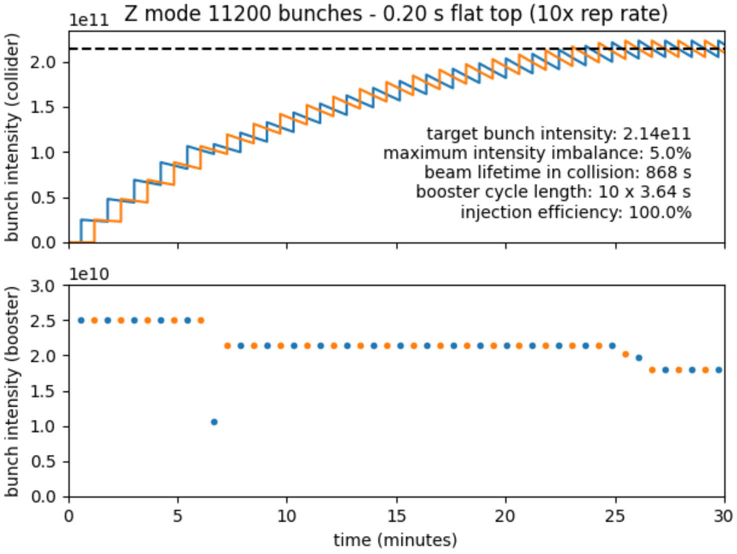
Injector operation for FCC-ee: Z

- **76% injector duty cycle (Z) –** most demanding for injectors (highest bunch intensity)
- 10 booster cycles for one top-up of all bunches due to machine protection limitations

Cycling of the FCC-ee booster



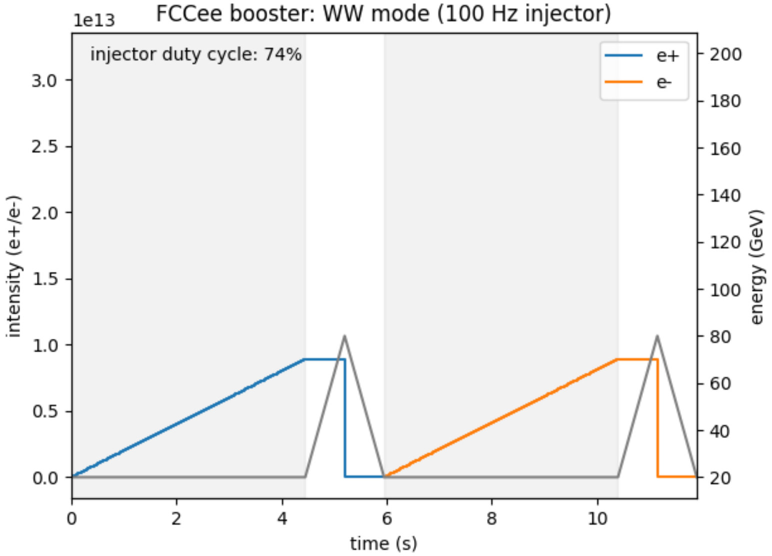
Beam accumulation in FCC-ee collider



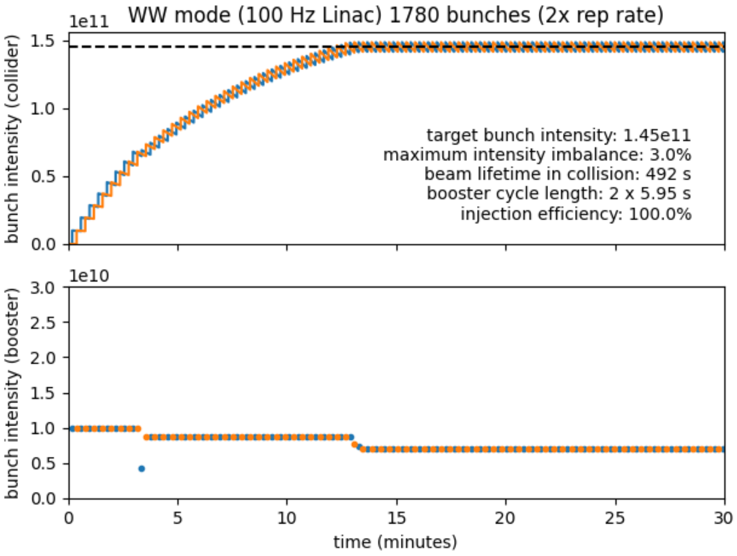
Injector operation for FCC-ee: WW

- **74% injector duty cycle (WW) for 100 Hz injection (baseline)**

Cycling of the FCC-ee booster



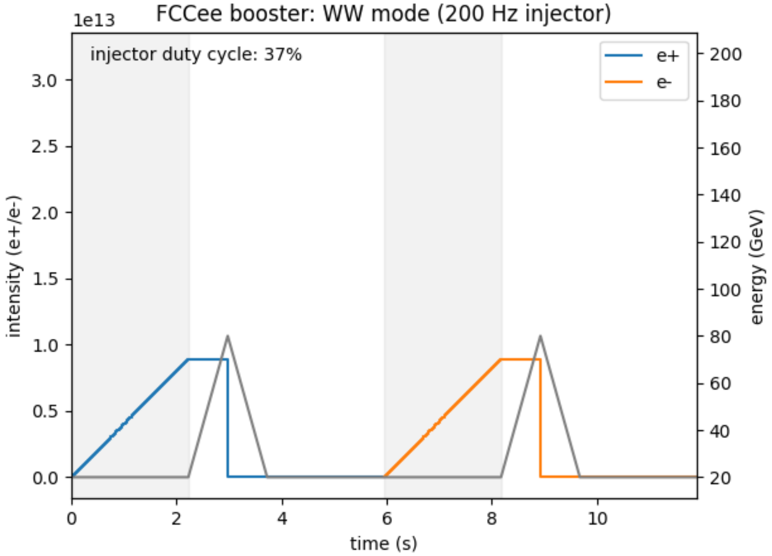
Beam accumulation in FCC-ee collider



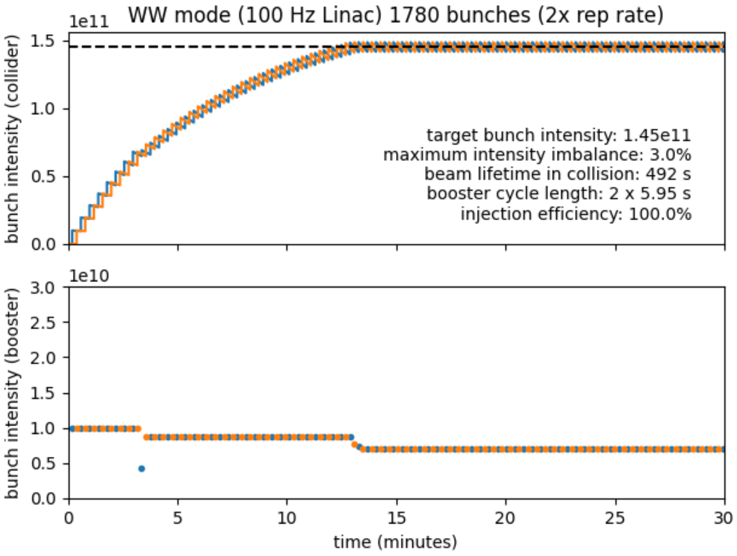
Injector operation for FCC-ee: WW

- **74% injector duty cycle (WW) for 100 Hz injection (baseline)**
- **37% injector duty cycle (WW) for 200 Hz injection (like for Z)**

Cycling of the FCC-ee booster



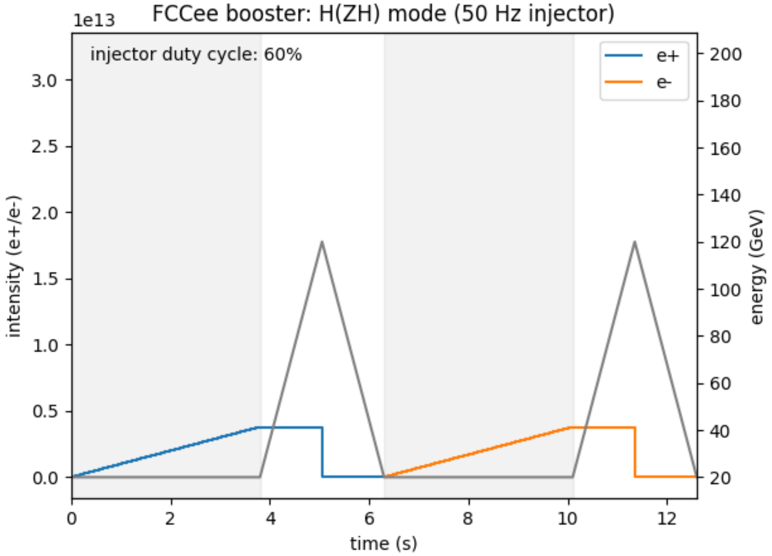
Beam accumulation in FCC-ee collider



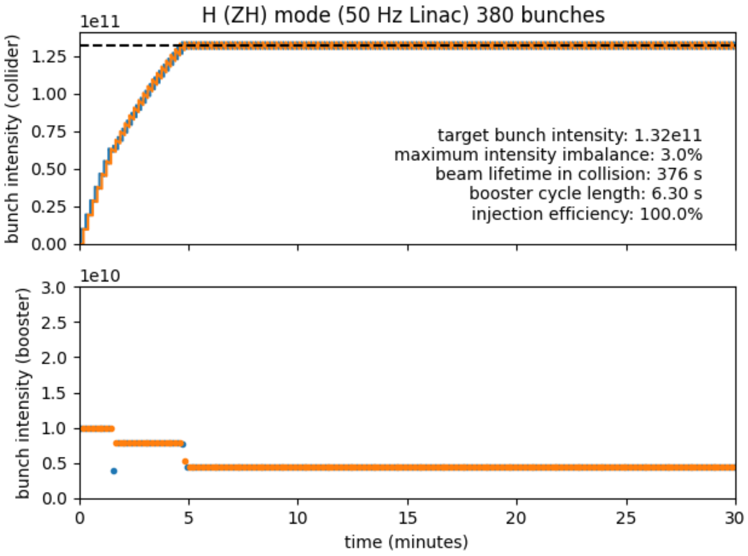
Injector operation for FCC-ee: ZH

- **60% injector duty cycle (ZH) for 50 Hz injection (baseline)**

Cycling of the FCC-ee booster



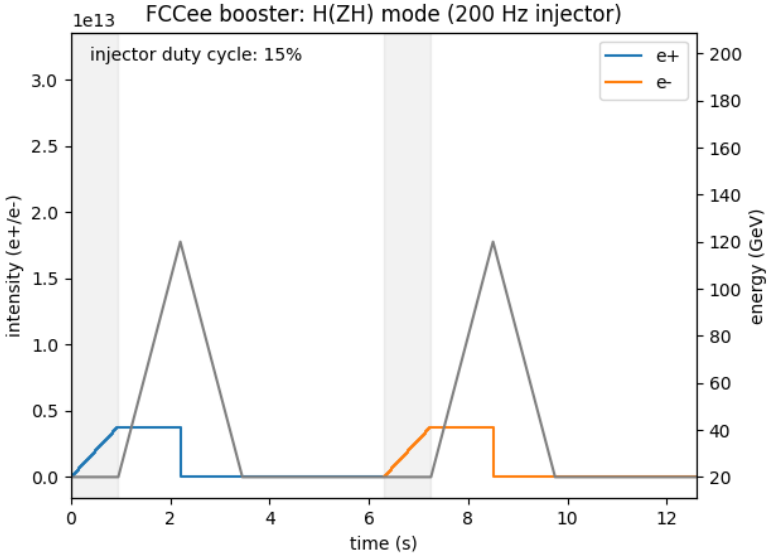
Beam accumulation in FCC-ee collider



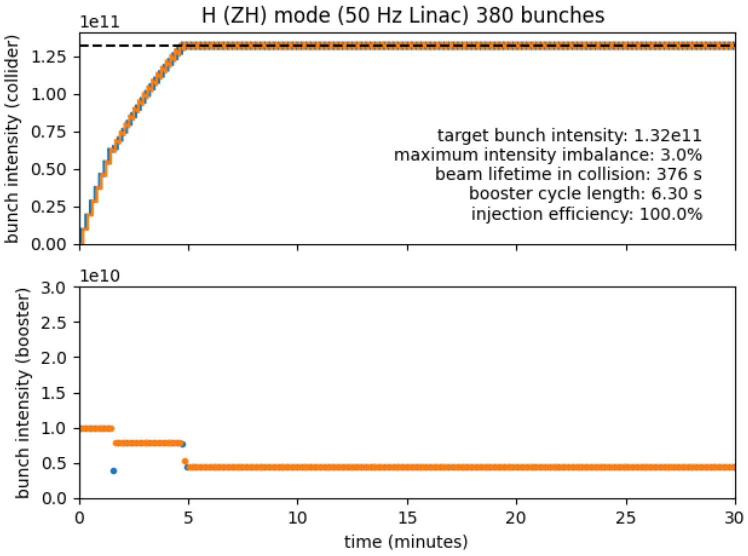
Injector operation for FCC-ee: ZH

- **60% injector duty cycle (ZH) for 50 Hz injection (baseline)**
- **15% injector duty cycle (ZH) for 200 Hz injection (like for Z)**

Cycling of the FCC-ee booster



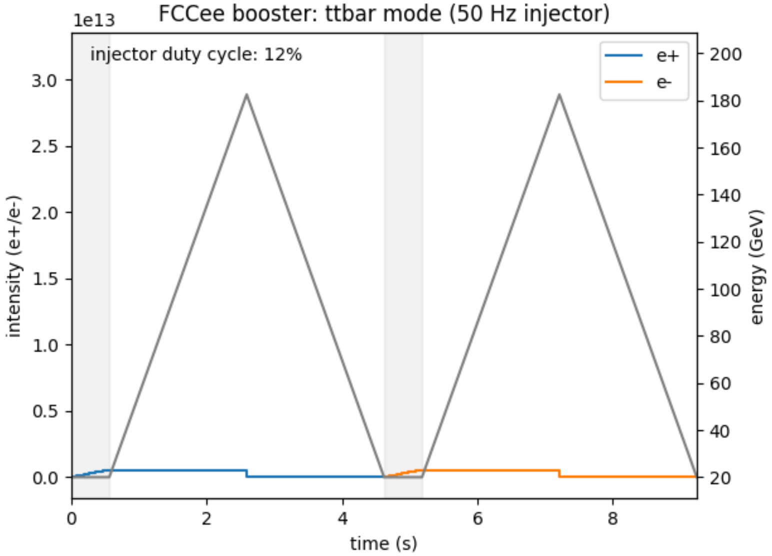
Beam accumulation in FCC-ee collider



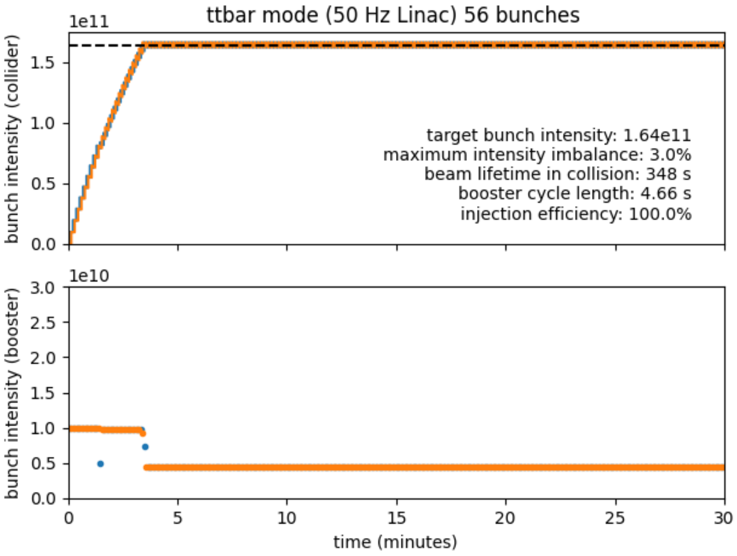
Injector operation for FCC-ee: Top

- **12% injector duty cycle (Top) assuming 50 Hz injection**
- Very few bunches, booster cycles completely dominated by ramping to high energy

Cycling of the FCC-ee booster



Beam accumulation in FCC-ee collider

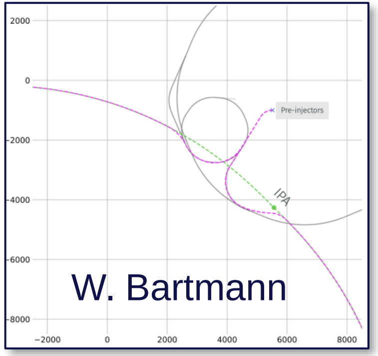


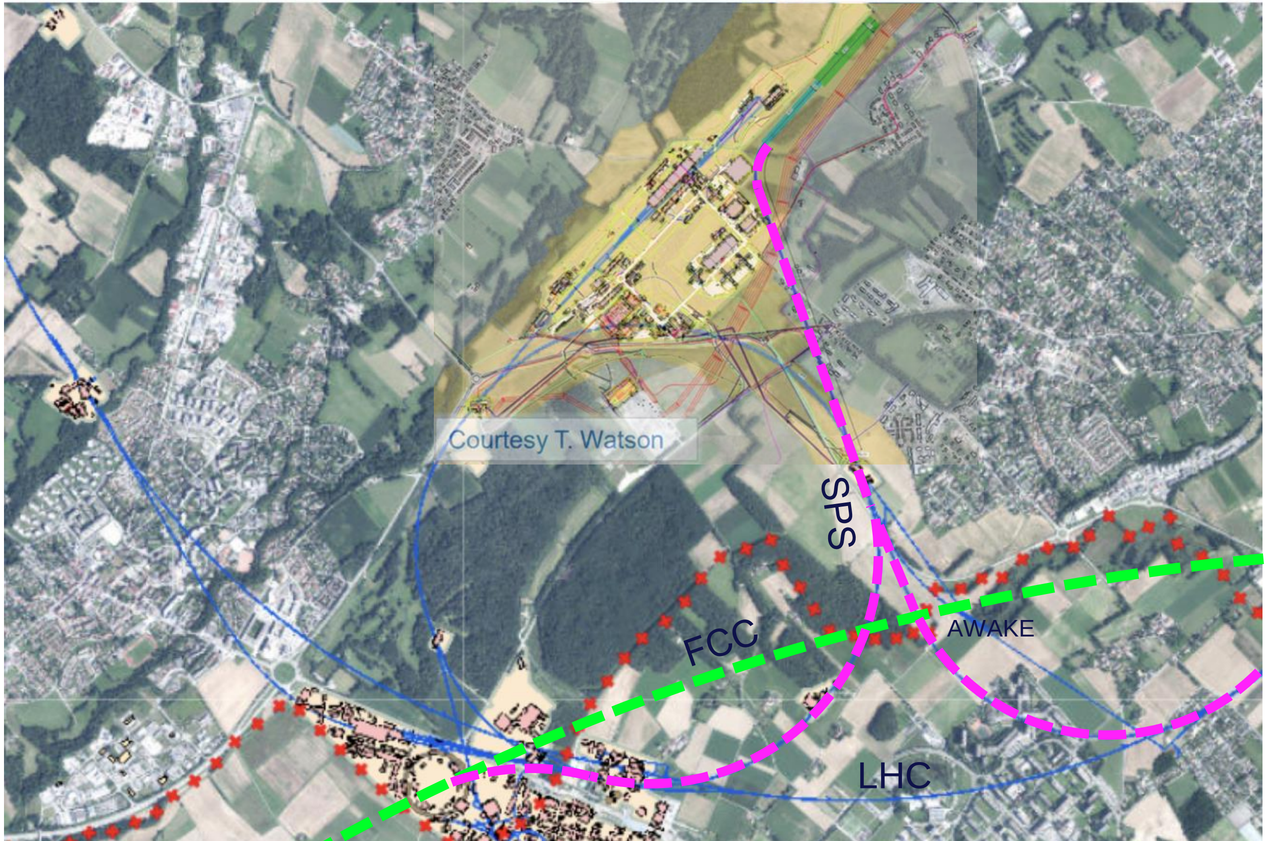
FCC-ee injector beam parameters

Running mode	Z	WW	ZH	ttbar	Unit
Beam energy at exit of injector	**20**				GeV
Number bunches/collider ring	11200	1780	380	56	
Number bunches/booster cycle	1120	980	380	56	
Booster cycle length	3.64	5.95	6.3	4.66	s
Maximum bunch charge	**≥ 4**	1.6	1.6	1.6	nC
Maximum bunch intensity	**≥ 2.5**	1	1	1	10^{10}
Number of bunches per pulse	**2**	2	2	2	
Linac repetition rate	**200**	100 (200)	50 (200)	50	Hz
Norm. emittance (x, y) (rms)	**<10,10**				mm mrad
Bunch length (rms)	**~1**				mm
Energy spread (rms)	**~0.1**				%
Bunch spacing from injector	**25**				ns
Injector duty cycle for FCC-ee	**76**	**74 (37)**	**60 (15)**	**12**	%

Integration of FCC-ee complex

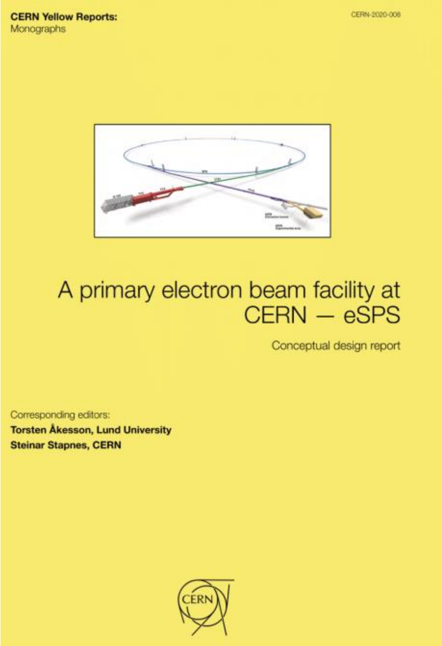
- Linac & damping ring on Prevessin site
- Transfer line to SPS BA4 (keep option to use SPS as in the original scheme)
- 1 beam through SPS tunnel
- 1 beam through TT40/TI8





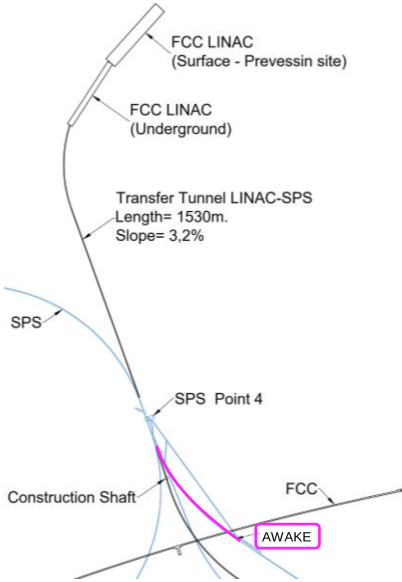
Other exploitation of FCC-ee injectors?

- Proposal for primary electron facility already made in context of eSPS (original proposal for Light Dark Matter eXperiment – LDMX)
- Inspired by this proposal, FCC-ee injector beams could be used for a **CLEAR-like facility** (including also damping ring):
  - **R&D for accelerator components and beam diagnostics for FCC-ee** or the injector itself (in particular if injector goes online ahead of FCC-ee and/or is built in stages)
  - **Irradiation facility** (e.g. for testing electronics components)
  - **Medical research**
  - **Use synchrotron light from damping ring** to test coatings, photon desorption
  - **Plasma wakefield acceleration test facilities** (electron driven, but maybe even in combination with proton driven plasma, see next slide)
- FCC-ee injector layout could still work for eSPS proposal (especially if SPS is part of the FCC-ee injector)


CERN Yellow Reports: Monographs
CERN-2020-008
A primary electron beam facility at CERN — eSPS
Conceptual design report
Corresponding editors:
Torsten Åkesson, Lund University
Steinar Stapnes, CERN

e+/e- beams interesting for AWAKE !

- The layout of the FCC-ee injector complex passes through SPS BA4, i.e. the SPS extraction point of protons for the plasma wakefield acceleration experiment AWAKE
- Keeping SPS operation with protons, there would be a unique opportunity to perform **proton driven plasma wakefield acceleration of 20 GeV electrons and *positrons***
  - Lepton beam parameters fit extremely well for wakefield experiments
  - Unique possibility of positron acceleration (currently no experiments worldwide)
- With the two-bunches setup, also electron driven plasma wakefield acceleration experiments can be performed
  - 1st electron beam is the drive beam, 2nd one is the witness beam
  - In addition, another unique possibility to test positron acceleration
- Proton beam line, experimental facility as well as lepton injection area and tunnel to the experiment exists
  - Would only require ~800 m transfer line for e+/e- in TT40/41 tunnel



Summary and conclusions

- The FCC-ee injector complex has potential to provide beams for other facilities

- The injector complex can provide
  - Pairs of 20 GeV e+ or e- bunches spaced by 25 ns (maybe longer if needed) with up to 2.5e10 particles per bunch (4 nC), normalized emittance <10 mm mrad and bunch length of ~ 1 mm
  - Only between 12% and 76% of the duty cycle is needed for top-up of FCC-ee, the rest would be available for other users / facilities
  - A typical other facility could use bursts of bunch pairs at 200 Hz for ~ seconds with the possibility to vary the bunch intensity accurately
  - Longer trains of bunches might be possible – to be studied in case of interest

- This opens the possibility for new facilities and applications (e.g. plasma wakefield acceleration of electrons and positrons in proton or electron-driven plasma wakefield experiments)

Thanks for your attention!

Parameter table for the FCC-ee filling

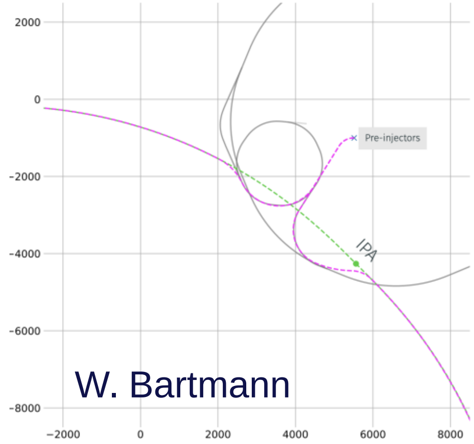
Mar. 5, 2024 K. Oide

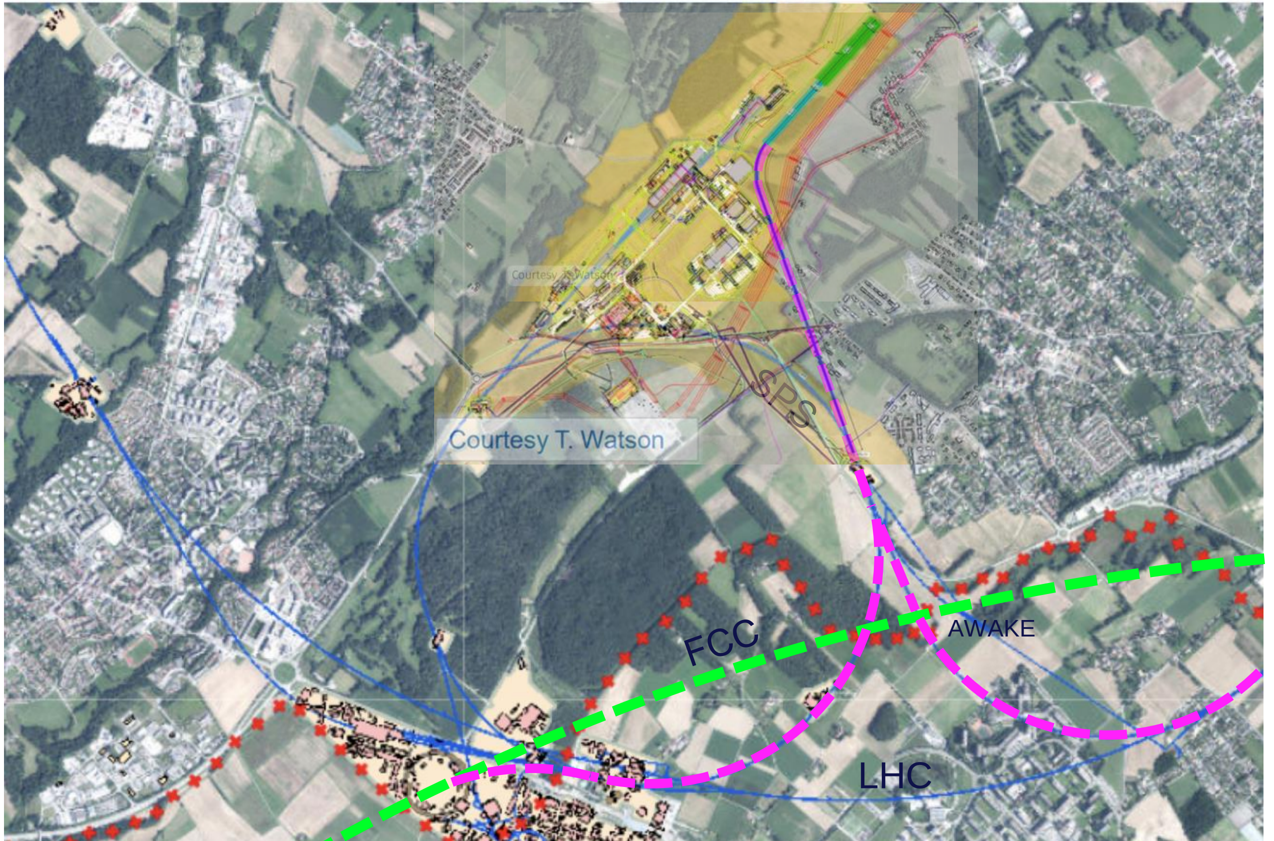
	Z		WW	ZH	tt
Collider energy [GeV]	45.6		80	120	182.5
Collider bunches / ring	11200		1780	380	56
BR bunches / ring	11200	5600			
Collider particles / bunch N_b [10^{10}]	21.4		14.5	13.2	16.4
Allowable charge imbalance Δ [±%]	5		3		
Injector particles / bunch N_{max} [10^{10}]	≦ 2.5				
Bootstrap particles / bunch [10^{10}] $= 2N_b\Delta$	2.14		0.87	0.792	0.984
# of BR ramps (up to 1/2 stored current, with N_{max})	3	6	3	3	4
# of BR ramps (bootstrap with $2N_b\Delta$)	5	10	4	4	5
BR ramp time (up + down) t_{ramp} [s]	0.6		1.5	2.5	4.1
Linac bunches / pulse	2 / 4 / 8		2 / 4		
Linac pulses needed n_p	5600		890	190	28
Linac repetition frequency [Hz] f_{rep}	200 / 100 / 50		100 / 50	50	
Collider filling time from scratch [s]	228.8	457.6	72.8	30.8	39.42
Collider filling time for top-up [s] $= n_p/f_{rep} + t_{ramp}$	28.6	29.2	10.4	6.3	4.66
Lum. lifetime (4 IP) [s]	1330		970	660	650
Lattice+BS lifetime (4 IP) [s]	10000		4000	3500	3000
(real lattice lifetime)/(design lattice lifetime)	0.25		0.25	0.25	0.25
Collider lifetime (4 IP) τ_2 [s]	868.1		492.4	376.2	348.2
Collider top-up interval (between e+ and e-)(4 IP) [s] $= \tau_2\Delta$	43.4		14.8	11.3	10.4

Integration of FCC-ee complex

CERN Physics Beyond Colliders

- Linac & damping ring on Prevessin site
- Transfer to SPS BA4
- 1 beam through SPS tunnel
- 1 beam through TT40/TI8





Old integration of FCC-ee complex

- Linac & damping ring on Prevessin site
- Transfer line down to SPS BA4 (keep option to use SPS as in the original scheme)
- New transfer lines to FCC-ee (booster)