FCC-ee injector design guidelines

Yannis PAPAPHILIPPOU, CERN

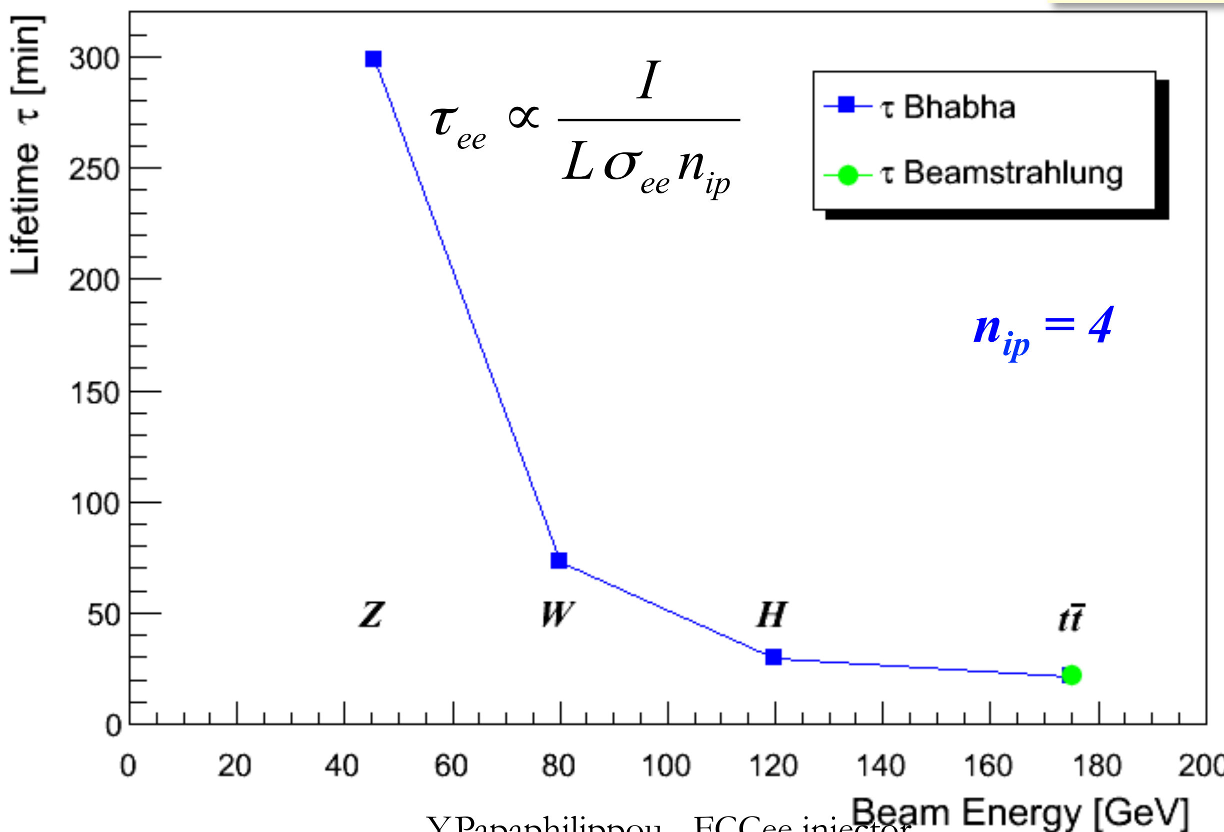
Outline

- Target parameters for injector
  - Repetition rate, particle flux
- Injector parameters for past and future projects
  - LEP, SUPERKEKB, CLIC
- Tentative parameters for FCCee injector
- FCCee design items and work units

FCCee Luminosity lifetime

- Lifetime from luminosity depends on radiative Bhabha scattering total cross-section
- For momentum acceptance of 2%, $\sigma_{ee} \approx 0.15$ b ≈ constant with energy (LEP). ⇒ Lifetimes down to ~20 minutes.

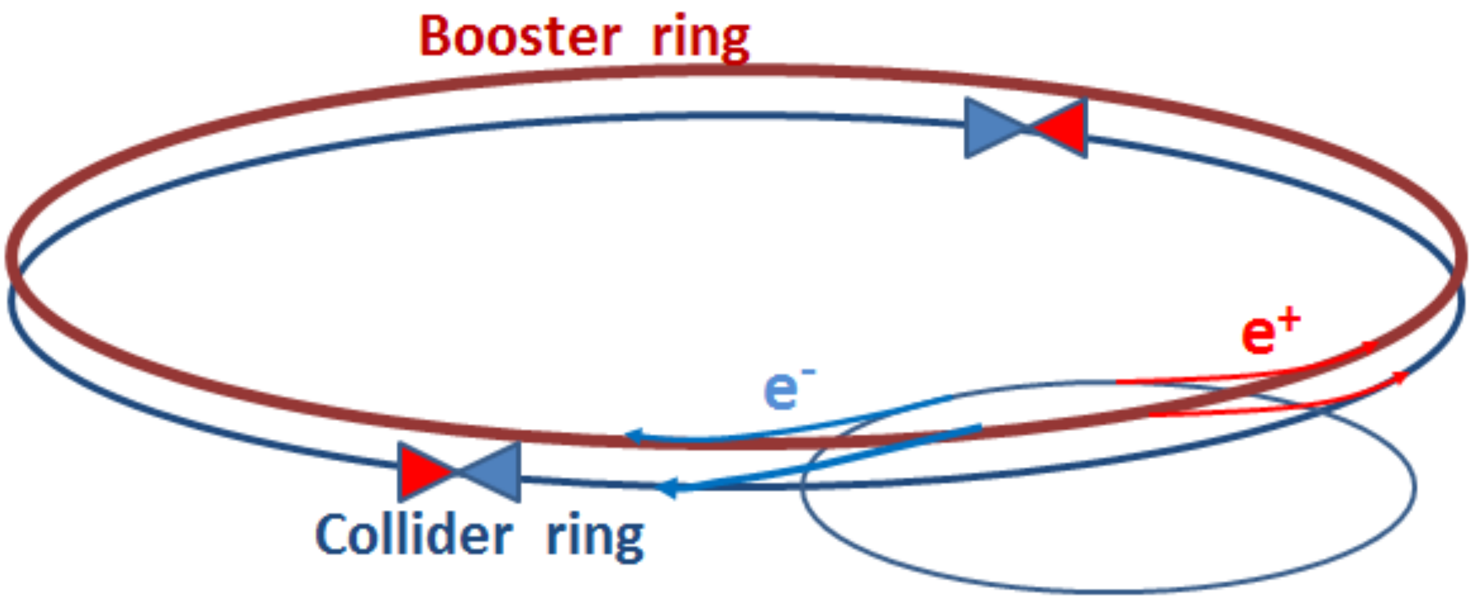
Continuous injection (top-up)



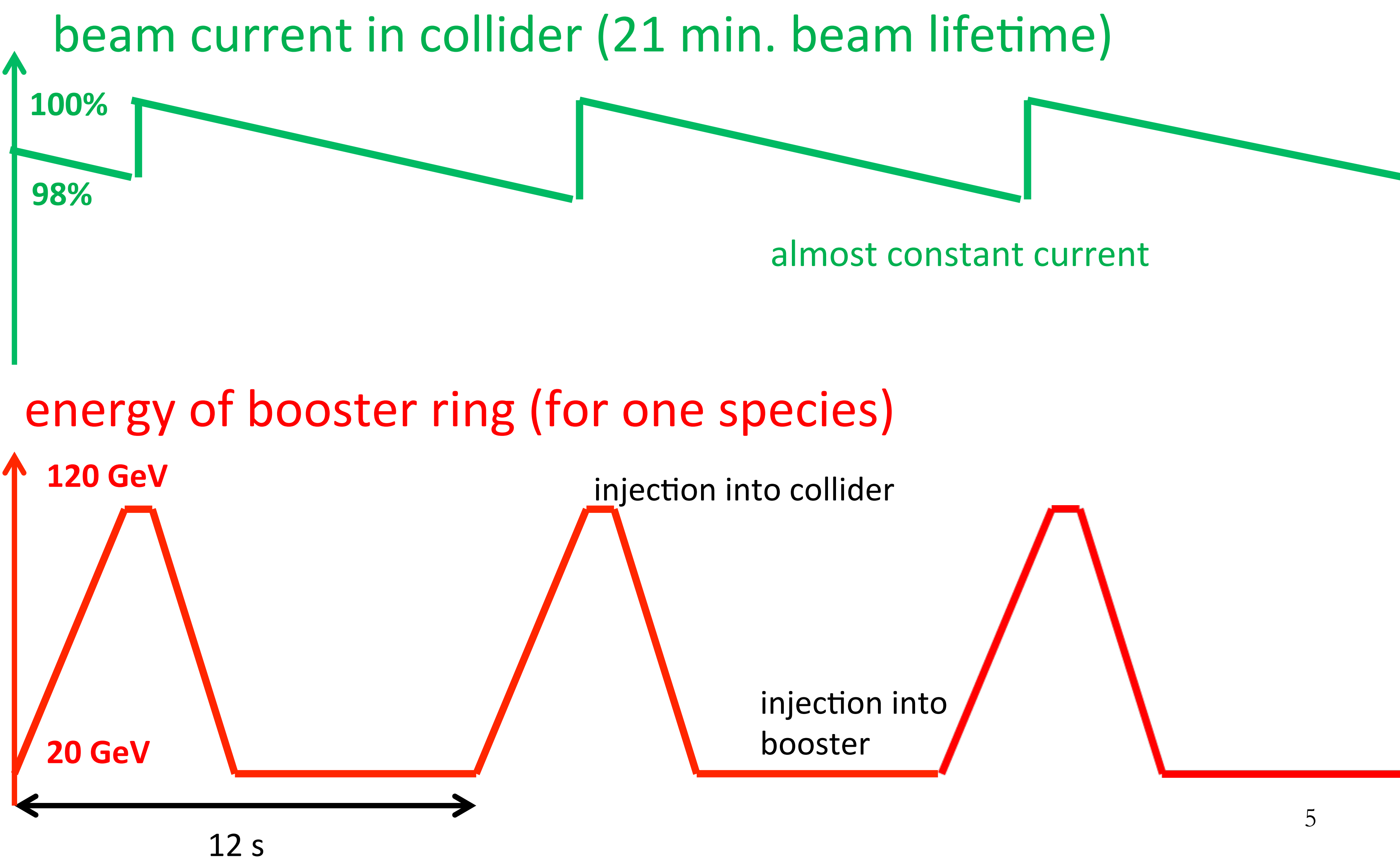
J. Wenninger

Booster ring considerations

- Besides the collider ring(s), a booster of the same size (same tunnel) must provide beams for **top-up injection**.
- **Injector complex for e+ and e- beams of ~20 GeV**



Schematic top-up cycle



Target injector parameters

Parameter	Z	W	H	tt	LEP2
E [GeV]	45.5	80	120	175	104
I [mA]	1442	151	30	7	1
No. bunches	16700	4490	1360	98	4
Bunch population [10^{11}]	1.8	0.7	0.46	1.4	4.2
Lifetime [min]	298	73	29	21	434
Time between injections [sec]	361	88	35	25	263
Injected top-up bunch population [10^{11}]	601.2	62.9	12.5	2.7	0.34
Required particle flux for top-up [10^{11}p/sec]	**2.10**	**0.89**	**0.44**	**0.13**	**0.001**
Required particle flux for full filling [10^{11}p/sec]	**31.3**	**3.3**	**0.7**	**0.1**	**0.02**
Booster injector ramp rate [GeV/sec]	**5.2**	**12.2**	**20.4**	**31.6**	**17.1**

- For defining injector cycle and flux, assumed **2%** of current decay between top-ups
  - The top energy Fcc-ee defines the maximum time between injections/species (**25sec**)
  - Considering 50% duty factor (Interleaved e^+/e^- injection), injections should be made at a minimum rate of **~0.1Hz**
- For full collider filling (0.25mA/min for LEP), assumed **20min** of filling time and **80%** transfer efficiency along the injector chain
- Ramp rate for 0.1Hz injection considering linear ramp and short flat bottom and flat top (~100ms)
- Note that LEP2 injector parameters are obtained with the same assumptions

LEP pre-injector parameters

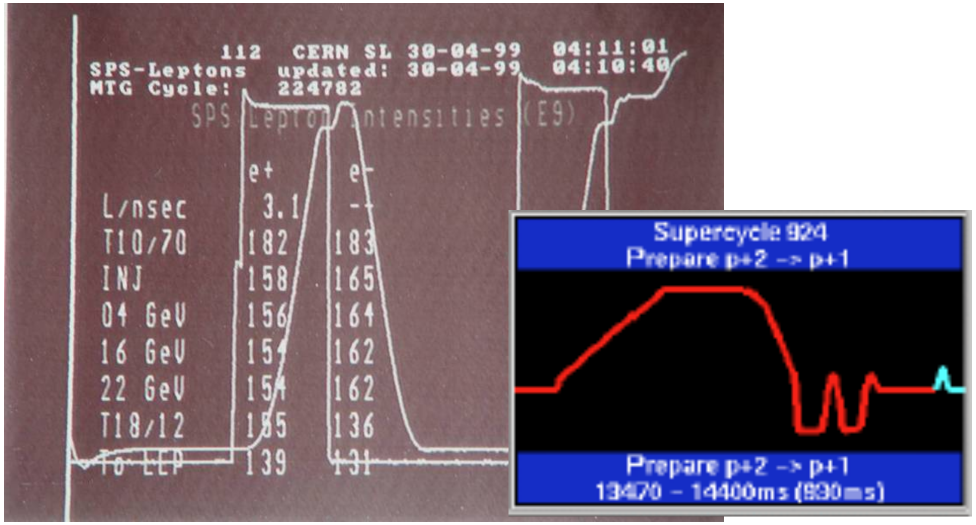
L. Rinolfi

Parameters	LIL e-	EPA e-	LIL e- for e+	EPA e+
energy [GeV]	0.2 to 0.7	0.500	0.200	0.500
bunch population [10^{10}]	2		0.5 to 20	
bunch length [ps]	15		15	
bunch interval [ns]	0.333		0.333	
beam pulse length [ns]	10		10 to 50	
Beam sizes [mm] (rms)	3		1	
Flux [10^{11} p/s]	20			0.7
repetition rate [Hz]	100	0.83	100	0.09
Number of bunches		1 to 8		1 to 8
Max. bunch population [10^{11}]		4.5		3

- Flux for electrons quite high, much lower for positrons
  - Injection efficiency through the injectors almost 100%
  - **Betatron** Injection efficiency to LEP was **~50%** (filled machine)
  - **Alternative** injection scheme was necessary for pushing injection efficiency to **~85%** (see below)
- Positron accumulation time quite long

SPS as LEP Injector

P. Collier – Academic Training 2005



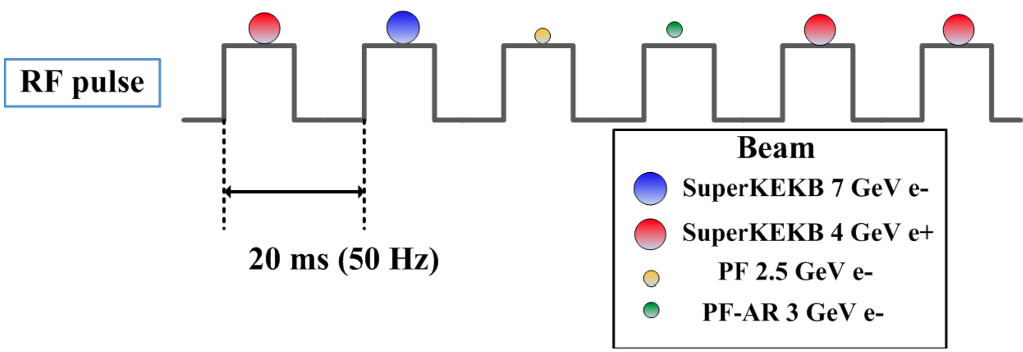
- LEP filling interleaved with FT proton operation
  - Initially supercycle of **14.4s** and later **12s**
- 4 cycles with 4 bunches ($2e^+$, $2e^-$) evolved to 2 cycles with 8 bunches (~**2.5×10^{10}** p/b)
- Energy to LEP: 18 → 20 → 22 GeV
- Lots of RF for leptons (200MHz SWC, 100MHz SWC, 352MHz SC), all **dismantled** for impedance reduction
- 2 Extractions in Point 6 towards LEP

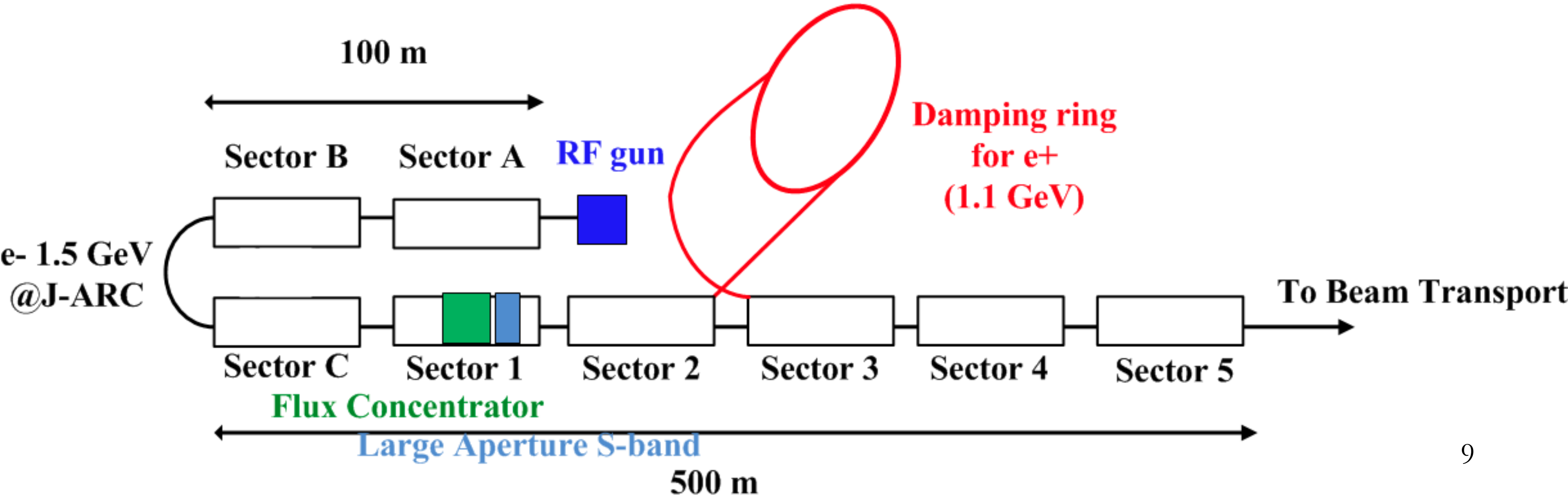
- Flux of **1.7×10^{11}** p/s for each cycle
  - An order of magnitude lower if taking into account machine duty cycle (12s supercycle)
- **Incompatible** with lepton flux requirements for Z and W production (full machine filling)
- Need to be stretched for H and tt
- Lepton acceleration to **20GeV not possible** (~**30MV RF** needed and **not compatible** with present proton program)
- Ramp rate of **62.3GeV/s** provides factor of 2 margin, i.e. even **5sec cycle** possible
  - Ramp rate can be even faster due to low field requirements (maybe ~1Hz possible)

SuperKEKB injector

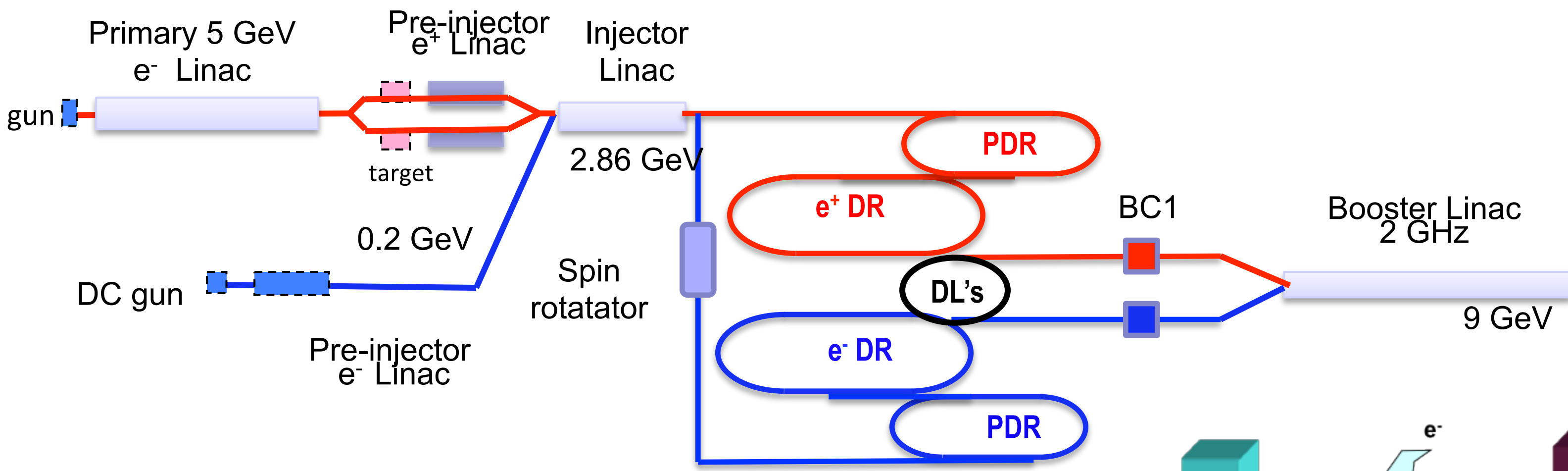
- Lifetime of 6min necessitates top-up
- Injector should serve 4 rings
  - Repetition rate 50Hz
- Positron flux rate at **2.5×10^{12}** p/s is **compatible** with FCC-ee needs
- Commissioning of the injector has already started
  - **Collaboration** with KEK colleagues essential for gaining experience

K. Oide, FCC-ee 2014

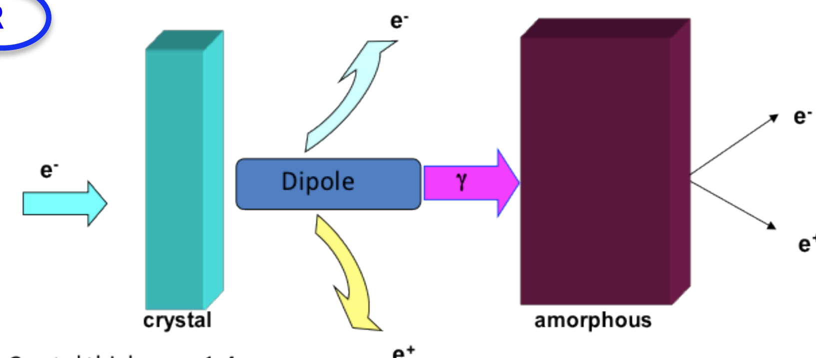




CLIC Main Beam Injector Complex



- Two hybrid positron sources (only one needed for 3 TeV collider)
- Common injector linac
- All linac's at 2 GHz, bunch spacing 1 or 2 GHz before the damping rings



Crystal thickness: 1.4 mm
Oriented along the <111> axis

Distance (crystal-amorphous) d = 2 m

Amorphous thickness e =10 mm

Target Parameters Crystal		
Material	Tungsten	W
Thickness (radiation length)	0.4	χ_0
Thickness (length)	1.40	mm
Energy deposited	~1	kW

Target Parameters Amorphous		
Material	Tungsten	W
Thickness (Radiation length)	3	χ_0
Thickness (length)	10	mm
PEDD	30	J/g
Distance to the crystal	2	m

Positron flux for linear colliders

L. Rinolfi

	SLC	CLIC (3 TeV)	CLIC (0.5 TeV)	ILC (RDR)	LHeC (pulsed)	LHeC ERL
Energy [GeV]	1.19	2.86	2.86	5	140	60
e^+/ bunch (at IP) [10^9]	40	3.7	7.4	20	1.6	2
e^+/ bunch (aft. capture) [10^9]	50	7	14	30	1.8	2.2
Bunches / macropulse	1	312	354	2625	100 000	NA
Rep. Rate (Hz)	120	50	50	5	10	CW
Bunches / s	120	15600	17700	13125	10^6	20×10^6
e^+ flux [10^{14}p/s]	0.06	1.1	2.5	3.9	18	440

- SLS injector positron flux flux already compatible with FCCee needs
- CLIC injector positron flux **satisfies FCC-ee requirements** for all energies
  - Leaves a lot of margin for capture and transfer losses
  - Design quite mature (un-polarized positrons)
  - Need **damping ring** (for positrons)
  - Different bunch structure and **20GeV linac** for injecting into booster ring
- **LHeC** is orders of magnitude above requirements (challenging design)

Possible FCC-ee injector scheme

- **LINACS** and positron production a downgraded version of the one for CLIC (or upgraded LIL/CTF3)
  - **2GHz, 50Hz repetition rate,** less than **10^9** p/b
- Trains with **3200 bunches** (1360for the Higgs and 280 for top production) injected **8 times** (7 for the top) in the SPS @ 10GeV in the required **50MHz** bunch structure and accelerated to 20GeV
  - Need new RF system in the SPS (50MHz?)
- SPS duty factor of **0.5** (apart for top) leaving time for fixed target proton physics
  - 5 cycles of 1.2s in a supercycle of 12s (2 cycles for the top)
- Injected into the booster ring (flat bottom of 6s or 2.4s for the top) to be accelerated in **3s** to required extraction energy of FCC-ee
- Interleaved injection of positrons and electrons
- **Filling time** for full filling **20min**
- **Top-up** compatible with lifetime (**25s** for FCC-ee top)

Tentative FCC-ee injector parameters

Accelerator	FCCee-Z		FCCee-W		FCCee-H		FCCee-tt	
Energy [GeV]	45.5		80		120		175	
Type of filling	Full	Top-up	Full	Top-up	Full	Top-up	Full	Top-up
LINAC # bunches	3200				1360		280	
LINAC repetition rate [Hz]	50							
LINAC RF freq [MHz]	2000							
LINAC bunch population [10^8]	5.9	0.4	0.6	0.2	0.3	0.3	0.02	0.04
# of LINAC injections	8						7	
SPS/BR bunch spacing [MHz]	50							
SPS bunches/injection	80				34		7	
SPS bunch population [10^{10}]	2.35	0.16	0.25	0.08	0.12	0.12	0.10	0.14
SPS duty factor	0.5						0.29	
SPS / BR # of bunches	640/3200				272/1360		49/98	
SPS / BR cycle time [s]	1.2 / 12						1.2 / 8.4	
Number of BR cycles	50	15	50	3	50	1	71	1
Transfer efficiency	0.8							
Total number of bunches	16700		4490		1360		98	
Filling time (both species) [sec]	1200	360	1200	72	1200	24	1193	16.8
Injected bunch population [10^{10}]	18	0.36	7	0.14	0.46	0.092	14	0.28

Booster Ring parameters

Top Energy [GeV]	45.5	80	120	175
Cycle time [s]	12			
Circumference [m]	100000			
Bending radius [m]	11000			
Injection energy [GeV]	20			
Dipole length	10.5			
Emittance @ injection [nm]	2.81	0.10	0.01	0.01
Emittance @ extraction [nm]	14.5	1.65	1.0	1.0
Bending field @ injection [G]	61			
Bending field @ extraction [G]	138	243	361	531
Energy Loss / turn @ injection [MeV]	1.287			
Energy Loss / turn @ extraction [MeV]	34.5	329.4	1667.6	7542.6
Long. Damping time @ injection [turns]	15543			
Long. Damping time @ extraction [turns]	1320	243	72	23
Average current [mA]	36.1	3.8	0.8	0.1
Average power @ injection [kW]	46.4	4.9	1.0	0.2
Average power @ extraction [MW]	1.24	1.26	1.27	0.88
Average power over 1 cycle [kW]	100	105	106	105
Power from dipoles @ extraction [W]	189	192	194	133
Power density on bends @ extraction [W/m]	18	18	18	13
Critical energy [MeV]	0.02	0.10	0.35	1.08
Radiation angle [μrad]	11.2	6.4	4.3	2.9

- "Similar" geometry as main ring to fit in the same tunnel
  - Need to by-pass experiments
- Low emittance @ extraction obtained quite naturally due to the small bending angle
  - Good for injection efficiency and top-up
- Ultra-low emittances @ injection if keeping the same optics as for collider
  - 10pm for higgs and top
  - Need detuned optics or working @ full coupling to avoid collective effects

Booster Ring parameters

Top Energy [GeV]	45.5	80	120	175
Cycle time [s]	12			
Circumference [m]	100000			
Bending radius [m]	11000			
Injection energy [GeV]	20			
Dipole length	10.5			
Emittance @ injection [nm]	2.81	0.10	0.01	0.01
Emittance @ extraction [nm]	14.5	1.65	1.0	1.0
Bending field @ injection [G]	61			
Bending field @ extraction [G]	138	243	361	531
Energy Loss / turn @ injection [MeV]	1.287			
Energy Loss / turn @ extraction [MeV]	34.5	329.4	1667.6	7542.6
Long. Damping time @ injection [turns]	15543			
Long. Damping time @ extraction [turns]	1320	243	72	23
Average current [mA]	36.1	3.8	0.8	0.1
Average power @ injection [kW]	46.4	4.9	1.0	0.2
Average power @ extraction [MW]	1.24	1.26	1.27	0.88
Average power over 1 cycle [kW]	100	105	106	105
Power from dipoles @ extraction [W]	189	192	194	133
Power density on bends @ extraction [W/m]	18	18	18	13
Critical energy [MeV]	0.02	0.10	0.35	1.08
Radiation angle [μrad]	11.2	6.4	4.3	2.9

- Energy loss/turn determined by energy and ring geometry
  - Same as for the collider at extraction (~1MeV at injection)
- Bending field at injection of **61Gauss**
  - Has to remain low as energy loss/turn at flat top is already quite high
  - Compensation of eddy currents, hysteresis effects and appropriate shielding from FCC-ee main magnets is needed

Booster Ring parameters

Top Energy [GeV]	45.5	80	120	175
Cycle time [s]	12			
Circumference [m]	100000			
Bending radius [m]	11000			
Injection energy [GeV]	20			
Dipole length	10.5			
Emittance @ injection [nm]	2.81	0.10	0.01	0.01
Emittance @ extraction [nm]	14.5	1.65	1.0	1.0
Bending field @ injection [G]	61			
Bending field @ extraction [G]	138	243	361	531
Energy Loss / turn @ injection [MeV]	1.287			
Energy Loss / turn @ extraction [MeV]	34.5	329.4	1667.6	7542.6
Long. Damping time @ injection [turns]	15543			
Long. Damping time @ extraction [turns]	1320	243	72	23
Average current [mA]	36.1	3.8	0.8	0.1
Average power @ injection [kW]	46.4	4.9	1.0	0.2
Average power @ extraction [MW]	1.24	1.26	1.27	0.88
Average power over 1 cycle [kW]	100	105	106	105
Power from dipoles @ extraction [W]	189	192	194	133
Power density on bends @ extraction [W/m]	18	18	18	13
Critical energy [MeV]	0.02	0.10	0.35	1.08
Radiation angle [μrad]	11.2	6.4	4.3	2.9

- Average current considered for full filling, from a fraction to ~**36mA**
- Average power at injection up to **46kW**
- Up to ~**1.3MW** at extraction
- Power density up to ~**18W/m**

Booster Ring parameters

Top Energy [GeV]	45.5	80	120	175
Cycle time [s]	12			
Circumference [m]	100000			
Bending radius [m]	11000			
Injection energy [GeV]	20			
Dipole length	10.5			
Emittance @ injection [nm]	2.81	0.10	0.01	0.01
Emittance @ extraction [nm]	14.5	1.65	1.0	1.0
Bending field @ injection [G]	61			
Bending field @ extraction [G]	138	243	361	531
Energy Loss / turn @ injection [MeV]	1.287			
Energy Loss / turn @ extraction [MeV]	34.5	329.4	1667.6	7542.6
Long. Damping time @ injection [turns]	15543			
Long. Damping time @ extraction [turns]	1320	243	72	23
Average current [mA]	36.1	3.8	0.8	0.1
Average power @ injection [kW]	46.4	4.9	1.0	0.2
Average power @ extraction [MW]	1.24	1.26	1.27	0.88
Average power over 1 cycle [kW]	100	105	106	105
Power from dipoles @ extraction [W]	189	192	194	133
Power density on bends @ extraction [W/m]	18	18	18	13
Critical energy [MeV]	0.02	0.10	0.35	1.08
Radiation angle [μrad]	11.2	6.4	4.3	2.9

- Critical energies @ extraction as for the collider (up to **1.1MeV** for highest energy)
- Vertical radiation angle of a few μrads
- Needs demanding shielding, absorption scheme and vacuum chamber design

FCCee-injector Design items

- Pre-injector parameters
  - Refined linac parameters
  - Positron production
- SPS as booster injector
  - Collective effects
  - RF system
  - Alternative pre-booster ring
- Booster design
  - Low injection bending field
  - Experimental by-passes
  - Shielding and vacuum chamber design (high critical energy)
  - Integration in the collider tunnel
- Top-up injection to the collider
  - Different schemes to be worked out (synchrotron, longitudinal, pulsed multi-pole, vertical injection)
  - BT element parameters and design
- Overall cost and power estimates

Lepton injector work units

Lepton injectors
Overall design parameters
Baseline layout
Baseline parameters
Functional machine design
LEP chain performance and gaps
LEP chain compatibility with hadron injectors
New injector chain baseline
Technical systems
Low energy beam transfer lines
LIL/EPA re-installation feasibility
Existing injectors to be decommissioned for lepton operation
Technologies that require R&D
SuperKEKB-type injector option
CTF3 option usability
Planned LHeC test facility usability
Electron and positron sources

Low Emittance Rings' Collaboration

- Common beam dynamics and technology issues for synchrotron light sources, linear collider damping rings and e+/e- colliders
- Formed a EU network within EUCARD2, started on 05/2013
  - Coordinated by CERN, INFN/LNF, JAI
  - Extended collaboration board including colleagues from US and Japan
  - 30 participating institutes world wide
  - First 5 network workshop with 60-80 participants @ Oxford (07/2013), Soleil (01/2014), Valencia (05/2014), Barcelona (04/2015)
- Next low emittance rings' technology workshop on September 2015 at ALBA, Barcelona
- FCCee injector but also collider design study should profit from it!