Electron Source Requirements for Future Electron-Positron Colliders

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Outline

- Introduction

- Future Electron-Positrons Colliders
  - CLIC
  - ILC
  - FCC-ee
  - CEPC

- Electron Sources
  - Requirements and Characteristics

Luminosity in an e^+e^- collider

Luminosity formula:

$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r$$

$$\sigma_y = \sqrt{\beta_y \epsilon_y / \gamma}$$

$$\mathcal{L} \propto H_D \; \frac{N}{\sigma_x} \; N n_b f_r \; \frac{1}{\sigma_y}$$

Luminosity spectrum

Beam current

Beam Quality (+bunch length)

H_D = disruption parameter

The limit for N is the beam stability in the main linac

The limit for n_b is the RF pulse length

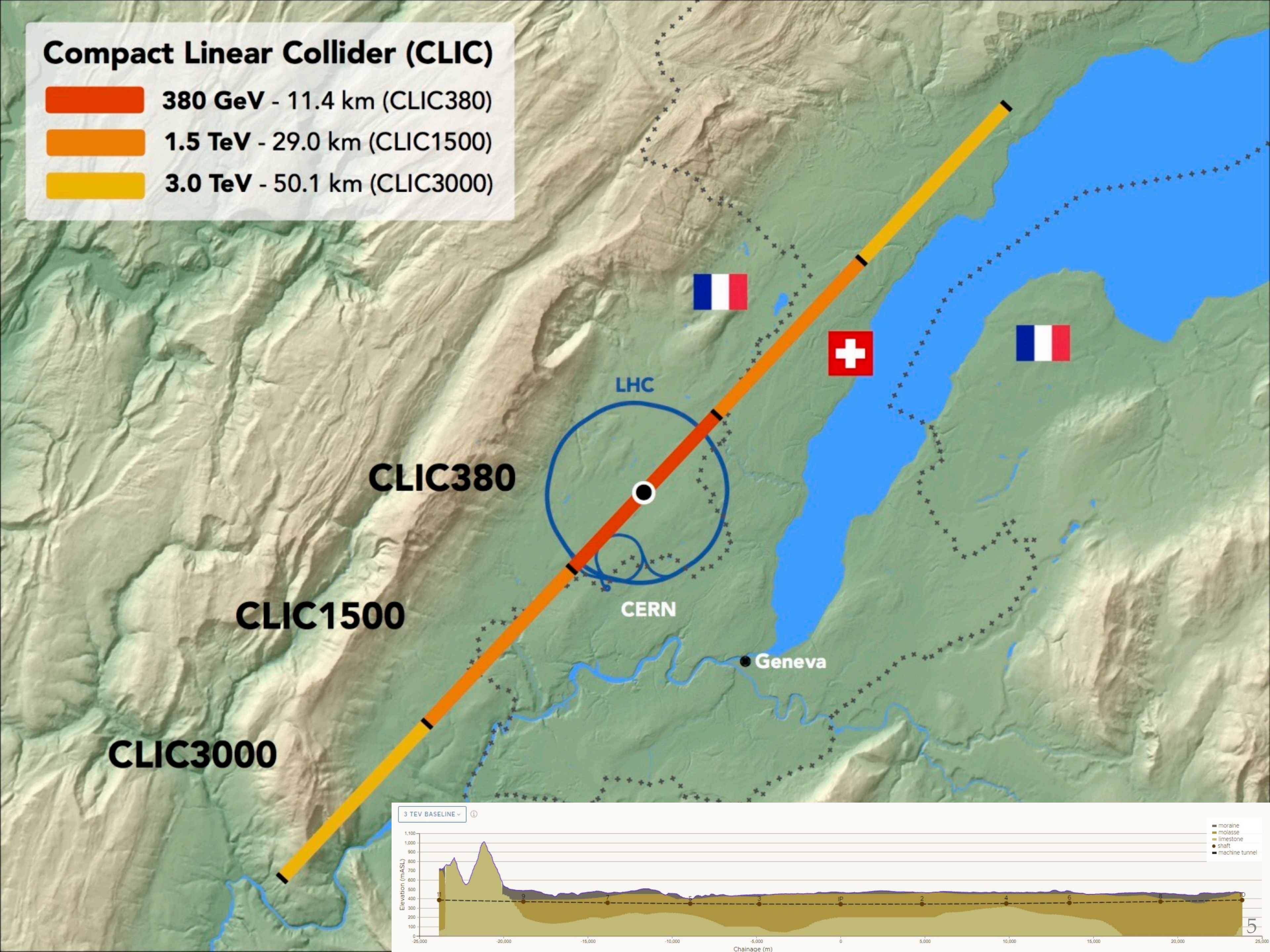
To maximize luminosity

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

$$\sigma_y = \sqrt{\beta_y \epsilon_y / \gamma}$$

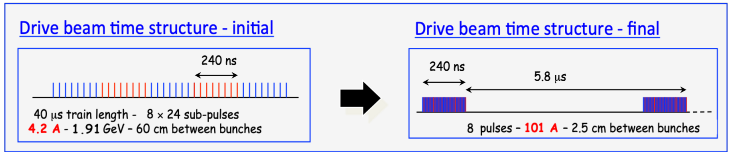
- **Small vertical emittance**
  - Nanometer level normalized emittance
  - Damping rings required
  - Challenging emittance preservation
- Small beta function at IP
  - Challenging optics in the beam delivery system
  - Challenging stability requirements
- **High average current**
  - Challenges the RF
- To improve the luminosity spectrum
  - **Flat beam**: $\sigma_y << \sigma_x$
  - Comes naturally from damping rings

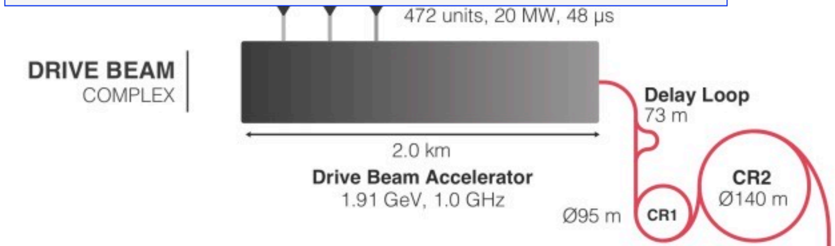
This applies to both electrons and positrons

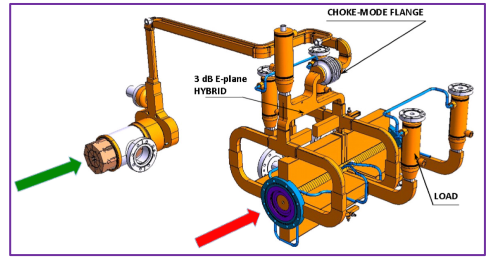

Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva
3 TEV BASELINE
moraine
molasse
limestone
shaft
machine tunnel
Elevation (mASL)
Chainage (m)
IP

CLIC 380 GeV

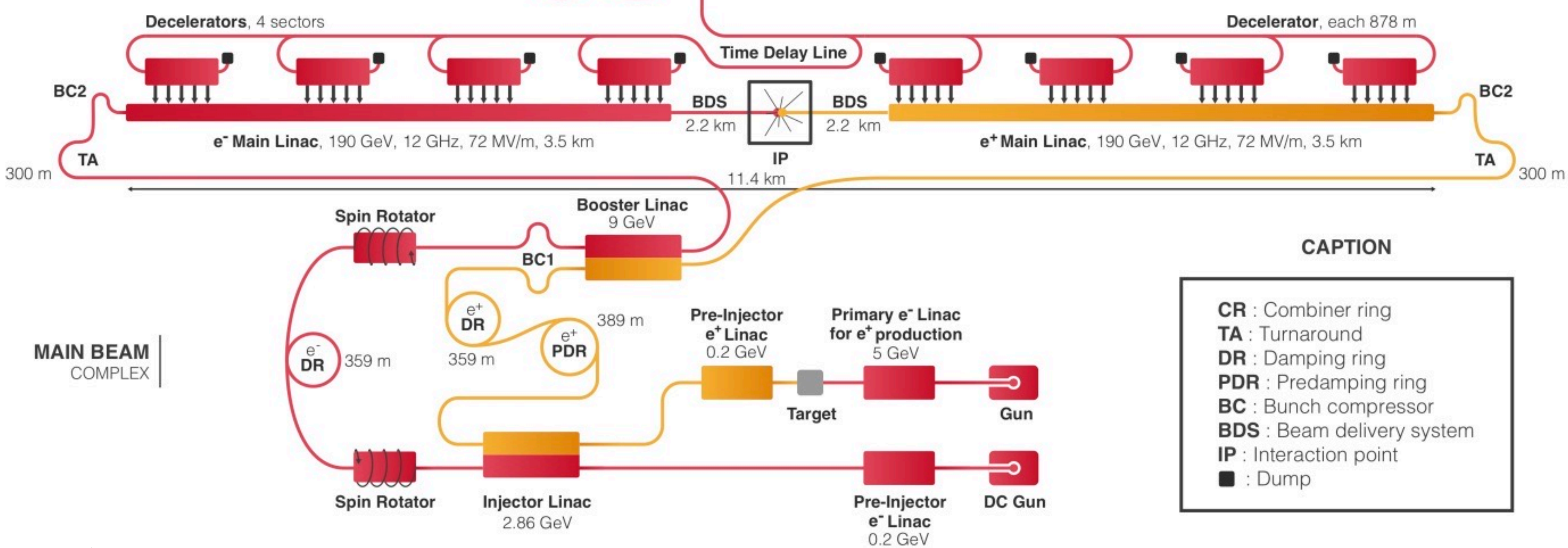
IP beam energy = 190 GeV
IP beam size = 149/2.9 nm
IP e=spread = 0.35%
Bunch length = 70 um
Crossing angle = 16.5 mrad
DB beam power = 20 MW
MB beam power = 2.78 MW







PETS – Power Extraction and transfer structures
To provide 72 MV/m accelerating gradient

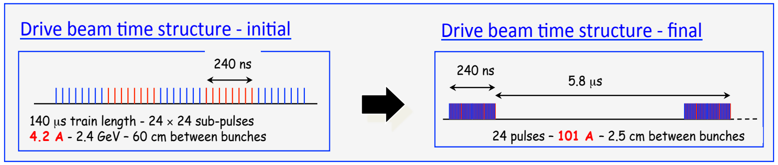


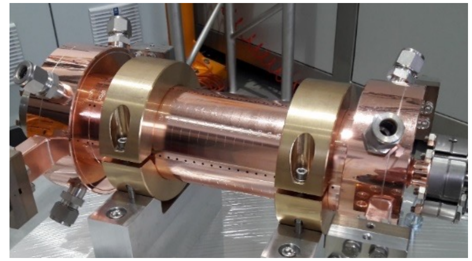
Main beam emittances
at DR exit: 700 nm / 5 nm
IP beam size: 149 nm / 2.9 nm

Section	ϵ_x [nm]	$\Delta\epsilon_x$ [nm] Design	Static	Dynamic	ϵ_y [nm]	$\Delta\epsilon_y$ [nm] Design	Static	Dynamic
DR	700	-	-	-	5	-	-	-
RTML	850	100	20	30	10	1	2	2
ML	900	0	25	25	20	0	5	5
BDS	950	0	25	25	30	0	5	5

Baseline electron polarisation ±80%

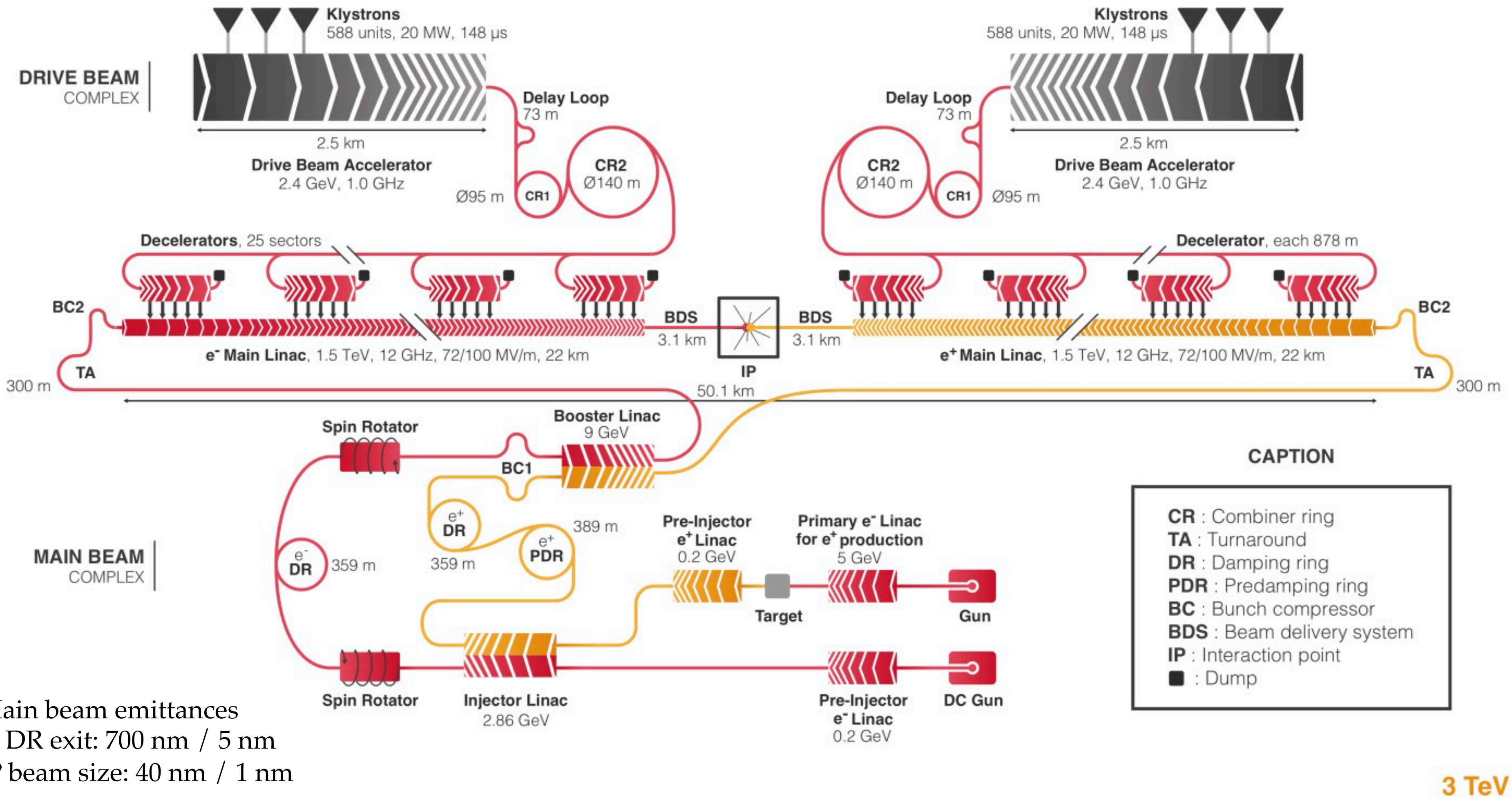
CLIC 3 TeV





NC X-band: 12 GHz - 100 MV/m

IP beam energy = 1.5 TeV
IP beam size = ~40/1 nm
IP e-spread = 0.35%
Bunch length = 44 um
Crossing angle = 20 mrad
DB beam power = 20 MW
MB beam power = 13.8 MW



Main beam emittances
at DR exit: 700 nm / 5 nm
IP beam size: 40 nm / 1 nm

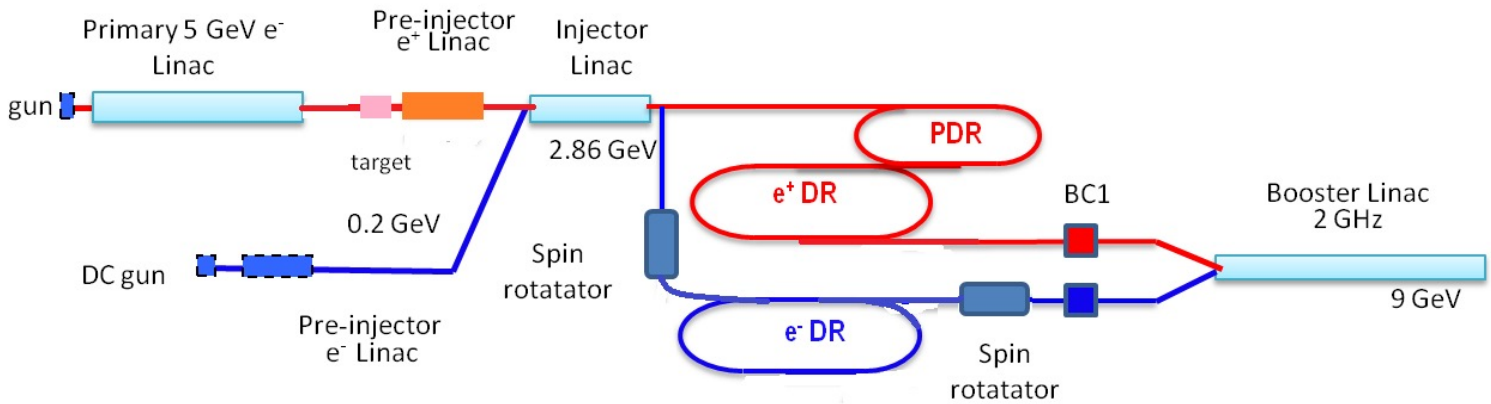
Baseline electron polarisation ±80%

CLIC main parameters

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2} s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2} s^{-1}	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\mathrm{int}}$	fb^{-1}	180	444	708
Main linac tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	900/20	660/20	660/20
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

Physics driven **Technology driven (limited)** **Luminosity driven**

CLIC main beam injector complex

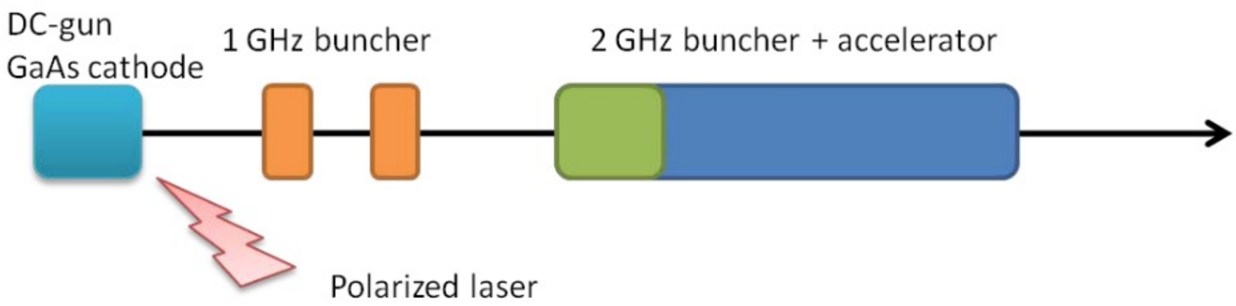


Beam parameters at the entrance of the damping rings

Parameter	Unit	Polarized electrons	Positrons
E	GeV	2.86	2.86
N	10^9	6	6
n_b	-	352	352
Δt_b	ns	0.5	0.5
t_{pulse}	ns	176	176
$\epsilon_{x,y}$	mm mrad	< 25	7071, 7577
σ_z	mm	< 4	3.3
σ_E	%	< 1	1.63
Charge stability shot-to-shot	%	1	1
Charge stability flatness on flat top	%	1	1
f_{rep}	Hz	50	50
P	kW	45	45

DR = Damping ring
PDR = Pre-damping ring

CLIC main beam electron source



The CLIC polarized electron source uses a DC-photo injector followed by a 2 GHz bunching and accelerating system

The spin-polarized electrons are generated using a polarized laser impinging on a strained GaAs cathode

Such cathodes have been used at several accelerator laboratories and demonstrated the CLIC requirements in terms of lifetime and charge extraction [1]

The electrons are accelerated in a pre-injector up to 200 MeV before being injected into the common injector linac which boosts their energy to 2.86GeV

A spin rotator orients the spin vertically before injection into the DR

[1] F. Zhou, A. Brachmann, T. Maruyama, and J. C. Sheppard, "Polarized photocathode R&D for future linear colliders", *AIP Conference Proceedings*, vol. 1149, no. 1, pp. 992–996, 2009, SLAC-PUB-13514. DOI: 10.1063/1.3215803.

Spin polarization at cathode

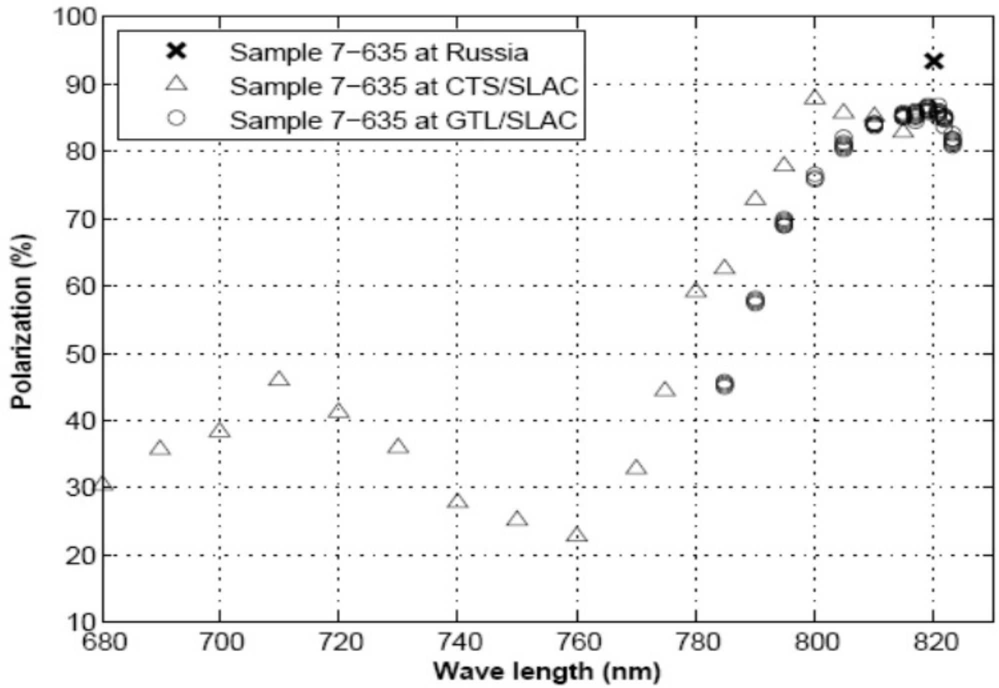
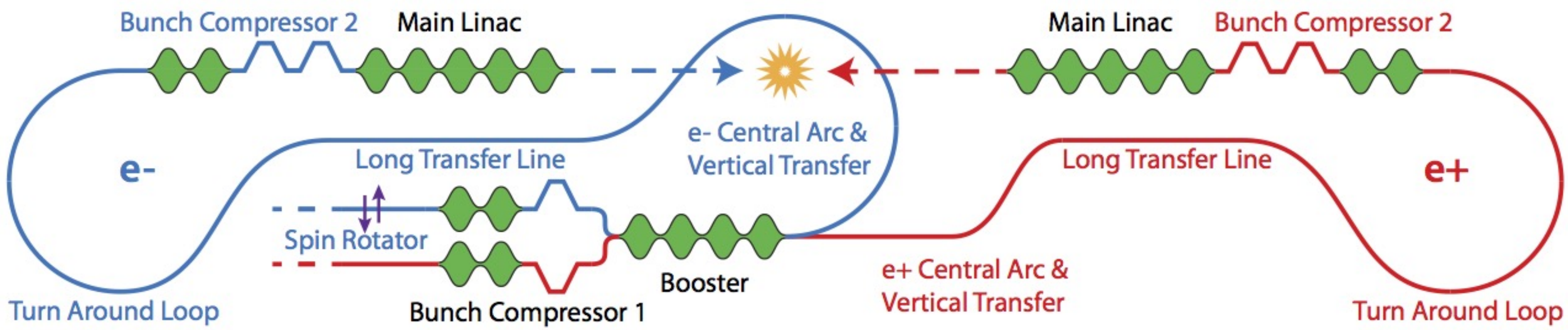


FIGURE 1. The comparison of the polarization spectrum measured at St. Petersburg in Russia, CTS/SLAC and GTL/SLAC.

The maximum polarization measured at the SLAC CTS / GTL is ~87% versus ~91% measured in Russia.

From the paper cited in the previous slide.

CLIC Ring-to-Main-Linac section



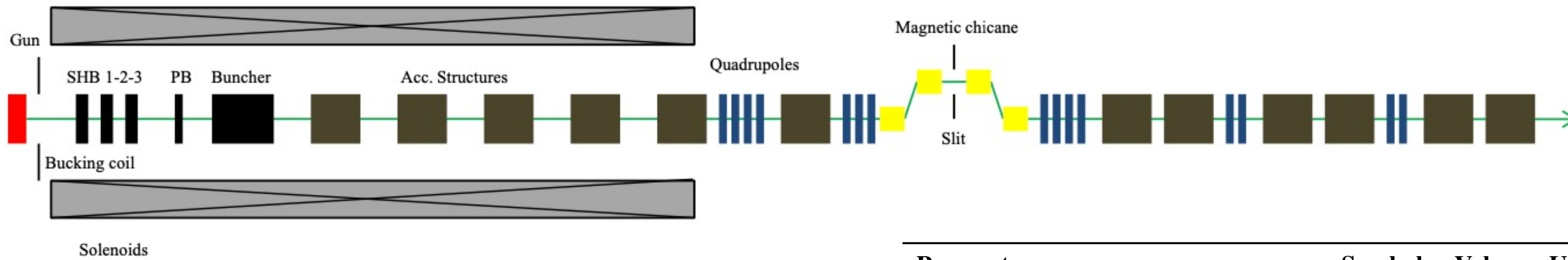
Beam parameters

Property	RTML entrance	RTML end	Unit
Energy	2.86	9	GeV
Bunch charge	0.84		nC
Bunch length	1800	72	µm
Energy spread	0.12	1.7	%
Norm. emittance x/y	700/5	850/10	nm

With arbitrary polarization for the electrons

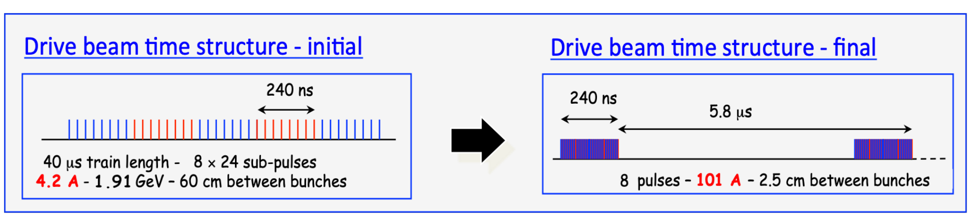
CLIC Drive beam electron source

The Drive-Beam pulses are generated by a 140 keV thermionic gun.

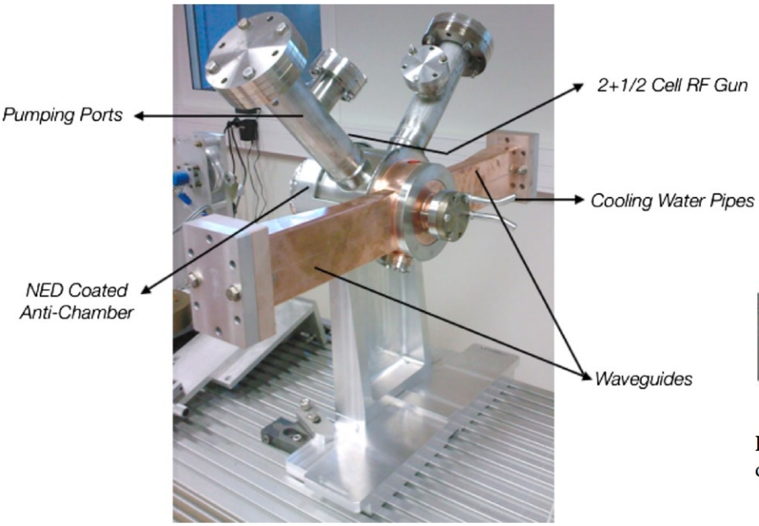


Parameter	Symbol	Value	Unit
Injector parameters			
Beam energy	E	50	MeV
Bunch length	σ_b	3	mm
Energy spread r.m.s.	Δ E/E	< 1	%
Normalized transverse emittance	$\gamma\varepsilon$	< 100	μm
Drive Beam linac parameters			
RF frequency	f_{RF}	1	GHz
No. of structures in injector	$N_{s.INJ}$	12	–
No. of structures at DBL1	$N_{s.DBL1}$	92	–
No. of structures at DBL2	$N_{s.DBL2}$	715	–
Final beam energy	E_f	2.4	GeV
Bunch charge	q_b	8.4	nC
Initial bunch length	$\sigma_{b,i}$	3	mm
Final bunch length	$\sigma_{b,f}$	1	mm
Bunch separation	Δt_b	0.6	m
Pulse length	τ_{pulse}	142	μs
No. of bunches /pulse	N_b	70882	–
Energy spread	$\Delta E/E_f$	< 0.35	%
Normalized r.m.s. transverse emittance	$\gamma\varepsilon$	< 110	μm

The bunching system is composed of three sub-harmonic bunchers (SHB) which operate at a frequency of 499.75 MHz, followed by a pre-buncher (PB) and a travelling-wave buncher, both operating at 999.5 MHz.



CTF3 PHIN gun high-current operation



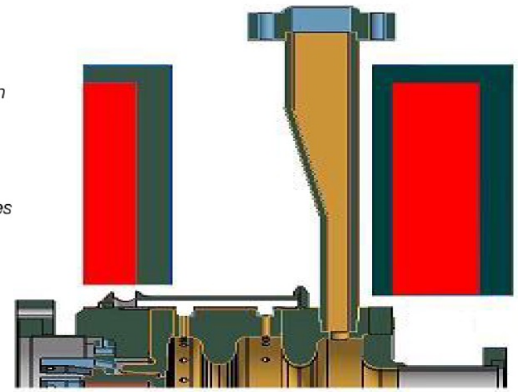


Figure 2: cut in the horizontal plane of the technical drawing of the photo-injector. Red blocks are coils.

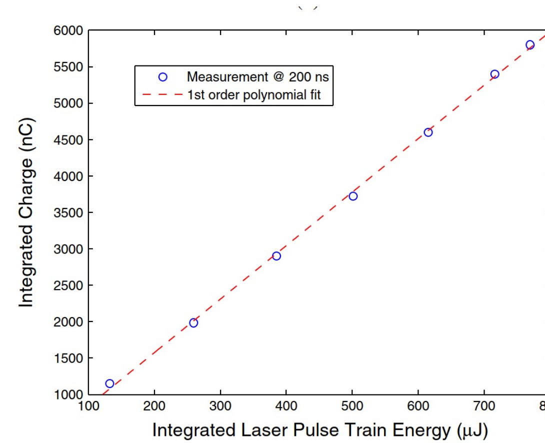
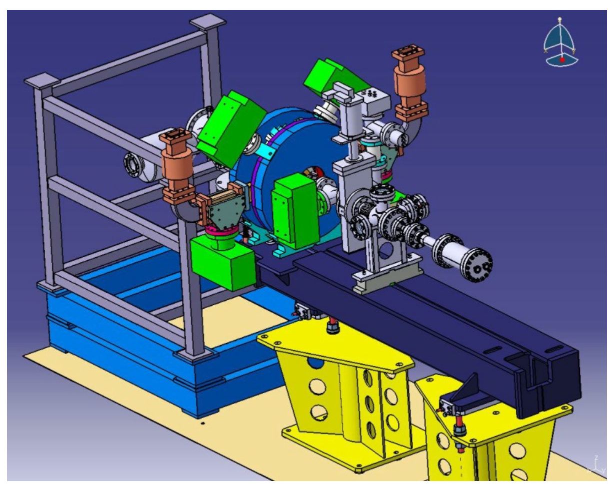


TABLE IV. The specifications for the PHIN photoinjector in comparison with the achieved values during the short intermittent runs between 2008–2011.

Parameter	Specification	Achieved
Laser		
UV laser pulse energy (nJ)	370	400
Micropulse repetition rate (GHz)	1.5	1.5
Macropulse repetition rate (Hz)	1–5	1
Train length (ns)	1273	1300
Electron beam		
Charge per bunch (nC)	2.33	8.1@50 ns 4.4@200 ns
Charge per train (nC)	4446	5800
Bunch length (ps)	8	6.5
Current (A)	3.5	6.6
Transverse normalized emittance (mm mrad)	<25	14
Energy spread (%)	<1	0.7
Energy (MeV)	5.5	5.5
Charge stability (%, rms)	<0.25	0.8
rf gun		
rf gradient (MV/m)	85	85
Quantum efficiency (%)	3	3–18

Cs2Te cathode

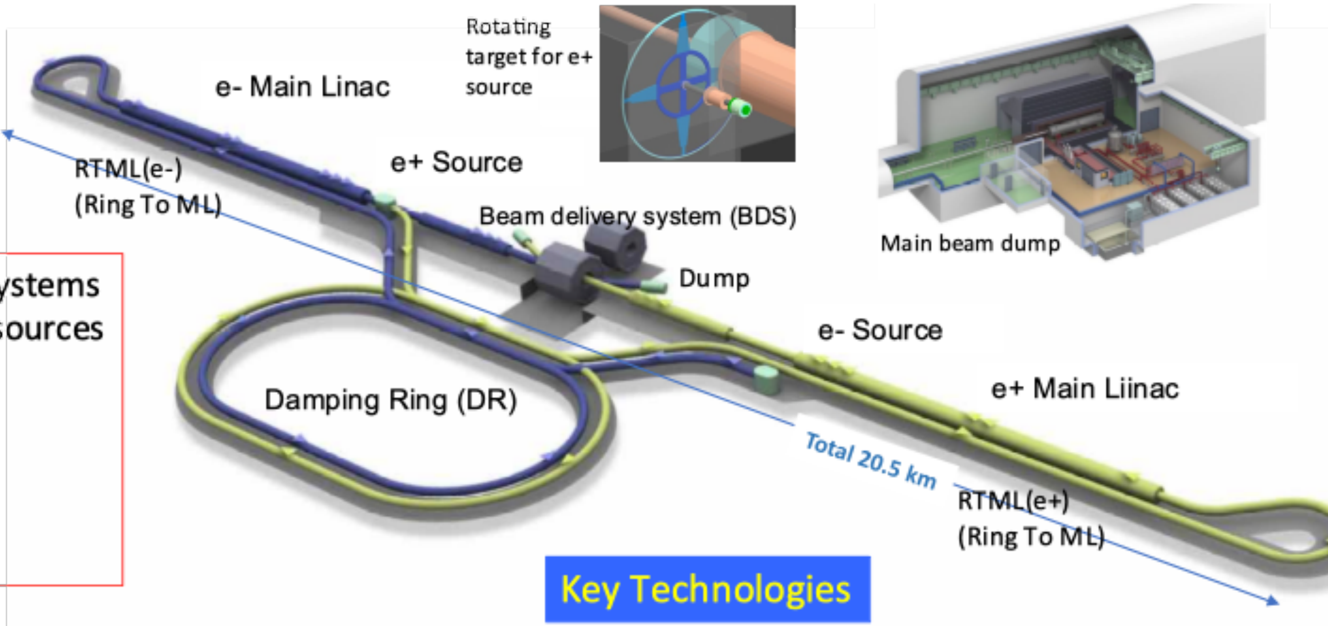


Demonstrated at CTF3:
- 1908 bunches,
- 2.33 nC each,
- 1.5 GHz bunch frequency

Total charge of 4.4 μC extracted and accelerated

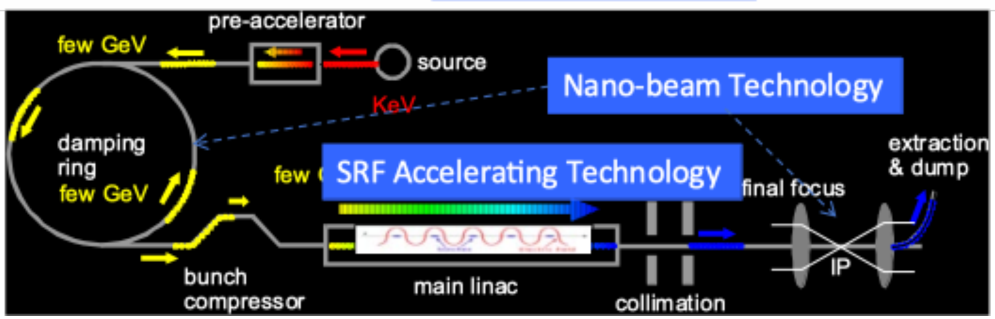
https://doi.org/10.1103/PhysRevSTAB.15.022803

ILC250 GeV



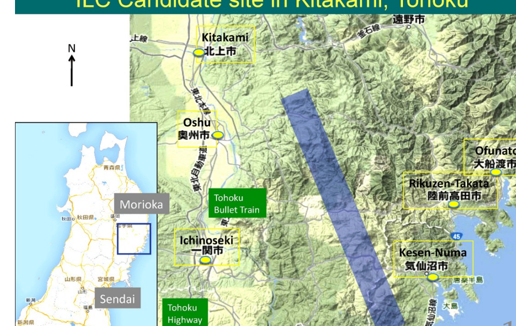
Area systems
e-/e+ sources
DR
RTML
ML
BDS
Dump

Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) Q_0 = 1x10^{10}



8,000 SRF cavities will be used.

ILC Candidate site in Kitakami, Tohoku



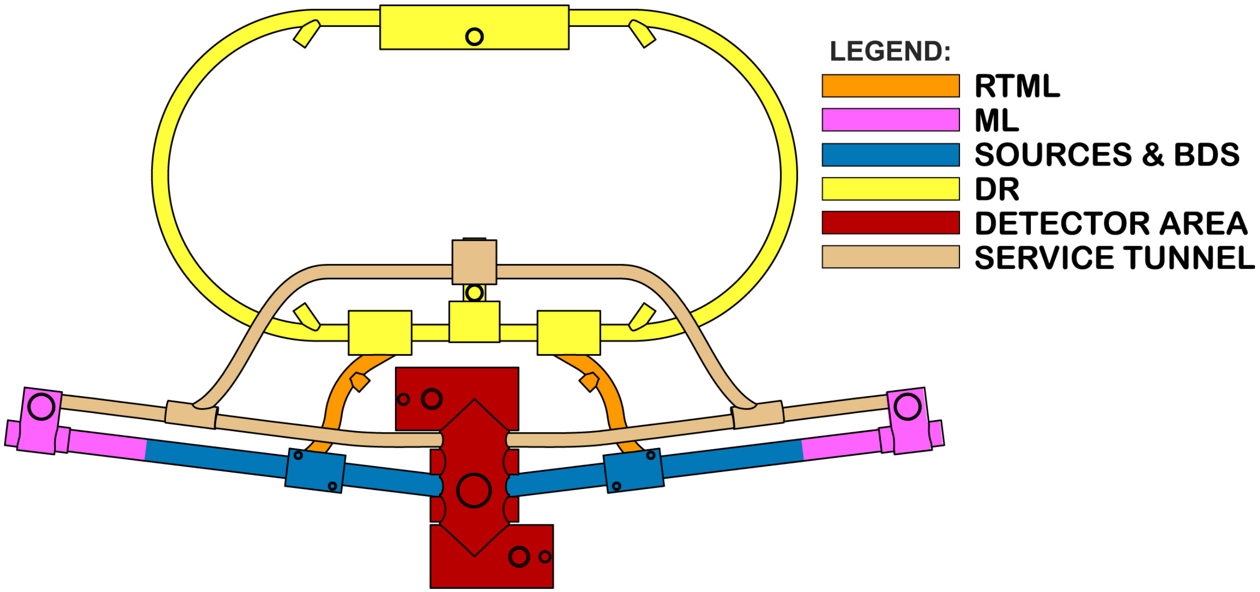
ILC 250 accelerator is 20 km long e-/e+ collider -> a Higgs factory.
Key technologies at the ILC are superconducting RF (SRF) and nano-beams.

- Nano-beam technology has been demonstrated at ATF hosted by KEK
- SRF technology has been widely adopted at XFELs such as European XFEL.

[Shinichiro MICHIZONO, Report on ILC status, LCWS2021]

ILC electron source

ILC central region



The polarized electron source is located in the central-region accelerator tunnel together with the positron Beam Delivery System

[ILC TDR, Volume 3.II: Accelerator Baseline Design, 2013]

ILC electron source

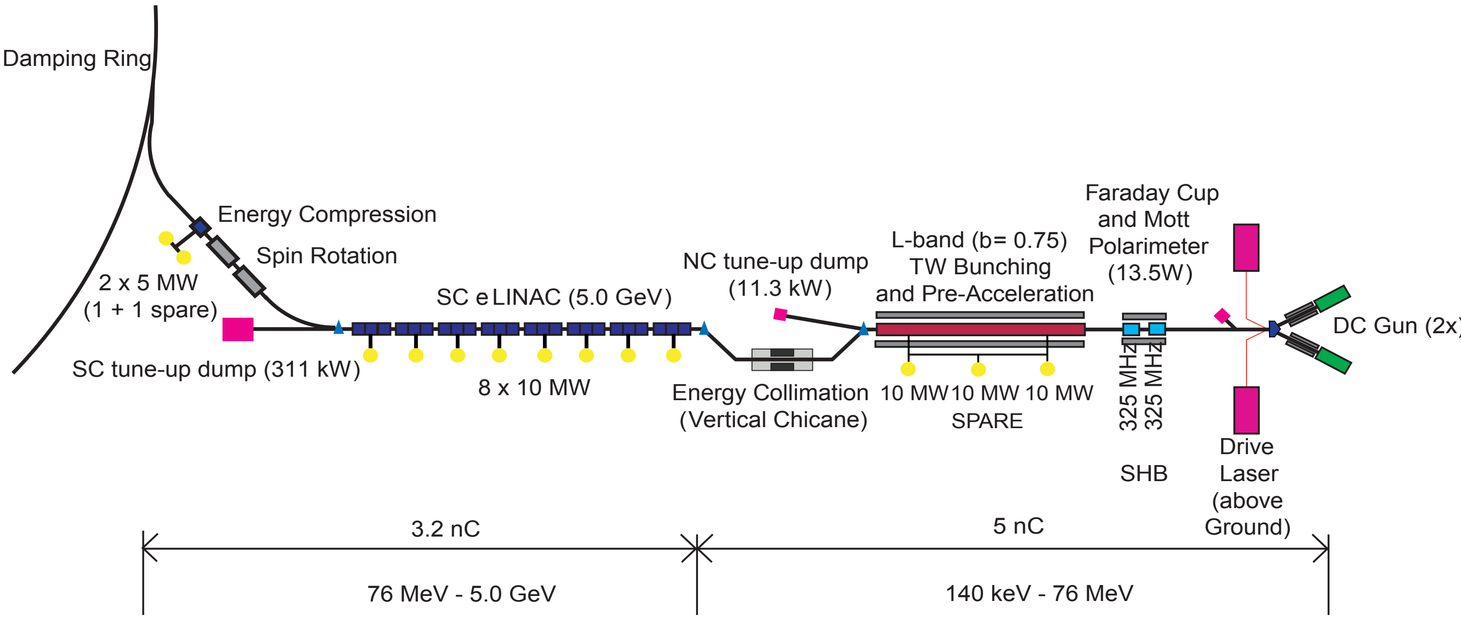


Figure 2.7. Schematic View of the Polarised Electron Source.

The beam is produced by a laser illuminating a strained **GaAs photocathode** in a **DC gun**, providing the bunch train with **90% polarization**. Two independent laser and gun systems provide redundancy.

Normal-conducting structures are used for bunching and **pre-acceleration to 76 MeV**, after which the beam is accelerated to **5 GeV** in a superconducting linac using 21 standard ILC cryomodules.

Before injection into the damping ring, **superconducting solenoids rotate the spin vector into the vertical,** and a separate superconducting RF structure is used for energy compression.

[ILC TDR, Volume 3.II: Accelerator Baseline Design, 2013]

ILC electron source

Table 4.1
Electron Source system parameters.

Parameter	Symbol	Value	Units
Electrons per bunch (at gun exit)	N_{-}	3×10^{10}	Number
Electrons per bunch (at DR injection)	N_{-}	2×10^{10}	Number
Number of bunches	n_b	1312	Number
Bunch repetition rate	f_b	1.8	MHz
Bunch train repetition rate	f_{rep}	5 (10)	Hz
FW Bunch length at source	Δt	1	ns
Peak current in bunch at source	I_{avg}	3.2	A
Energy stability	σ_E/E	<5	% rms
Polarization	P_e	80 (min)	%
Photocathode Quantum Efficiency	QE	0.5	%
Drive laser wavelength	λ	790 ± 20 (tunable)	nm
Single bunch laser energy	u_b	5	μJ

The SLC polarized electron source already meets the requirements for polarization, charge and lifetime.

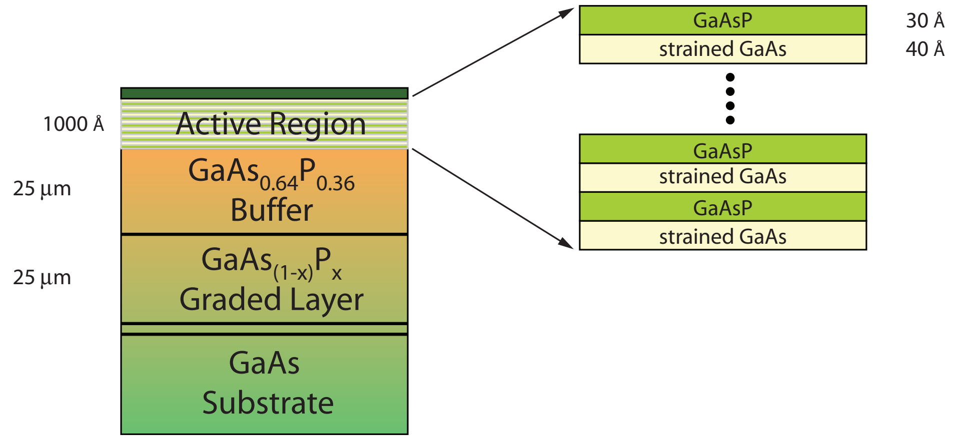
The primary challenge for the ILC source is the long bunch train, which demands a laser system beyond that used at any existing accelerator, and normal conducting structures which can handle high RF power.

R&D prototypes have demonstrated the feasibility of both systems

[ILC TDR, Volume 3.II: Accelerator Baseline Design, 2013]

ILC photocathode and laser system

Figure 4.2
Structure of a strained GaAs/GaAsP superlattice photocathode for polarized electrons.



The most promising candidate photocathodes for the ILC polarized electron source are strained GaAs/GaAsP superlattice structures (see Fig. 4.2).

GaAs/GaAsP superlattice photocathodes routinely yield at least 85 % polarization with a maximum QE of ~1 % (routinely 0.3 to 0.5 %) [62–64].

The present cathodes consist of very thin quantum-well layers (GaAs) alternating with lattice-mismatched barrier layers (GaAsP).

The laser system is based on Ti:sapphire technology. To match the bandgap energy of GaAs photocathodes, the wavelength of the laser system must be 790nm and provide tunability (±20 nm) to optimize conditions for a specific photocathode.

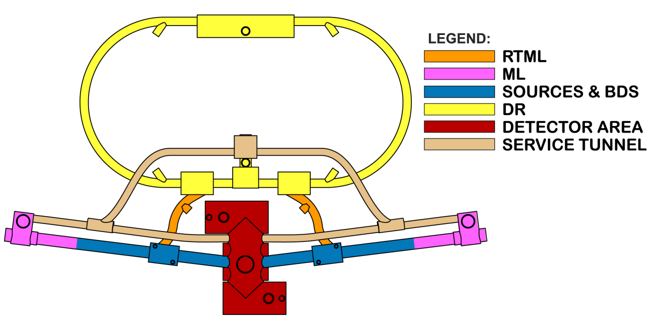
[ILC TDR, Volume 3.II: Accelerator Baseline Design, 2013]

ILC beam parameters at damping ring

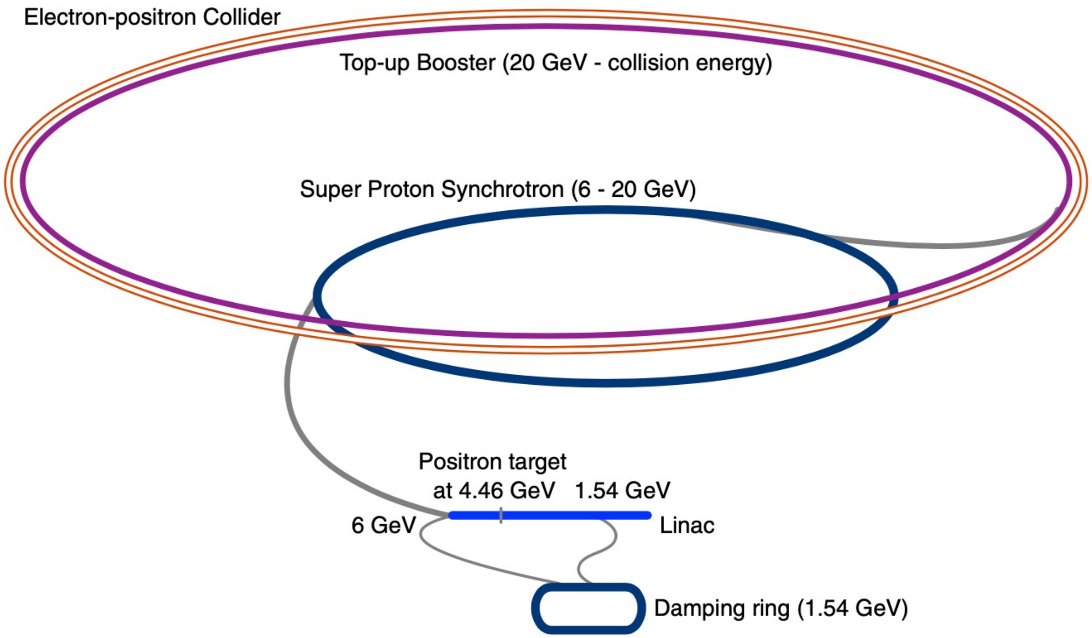
Table 6.1
Nominal parameters of injected and extracted beams for the baseline configuration.

Parameter	Electron Beam	Positron Beam
Train repetition rate [Hz]	5.0	
Main Linac Bunch separation [ns]	554	
Nom. # bunches per train	1312	
Nom. bunch population	2×10^{10}	
Required acceptance:[†]		
Norm. betatron amplitude $(a_x + a_y)_{\max}$ [m rad]	0.07	
Long. emittance $(\Delta E/E \times \Delta l)_{\max}$ [% $\times$ mm]	0.75×33	
Extraction Parameters:		
Norm. horizontal emittance $\gamma\epsilon_x$ [µm rad]	5.5	
Norm. vertical emittance $\gamma\epsilon_x$ [nm rad]	20	
RMS relative energy spread σ_p/p [%]	0.11	
RMS Bunch length σ_z [mm]	6	
Max. allowed transfer jitter $[\sigma_{x,y}]$	0.1	

[†] specified for the positron damping ring



FCC-ee injector complex



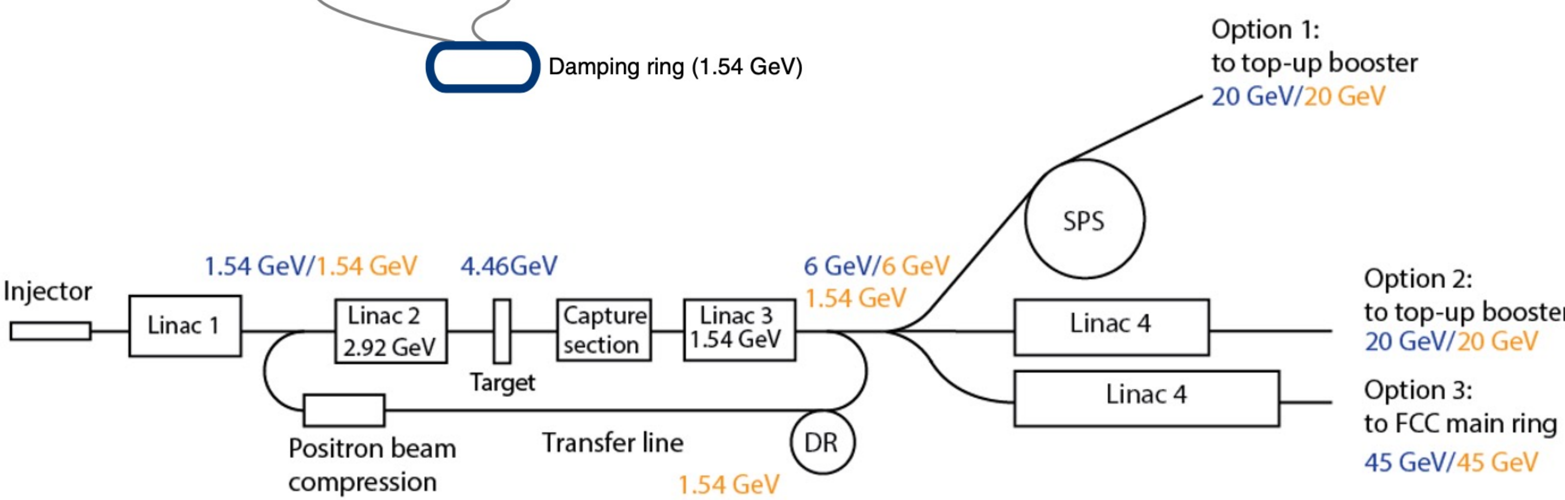


Figure 1: Schematic layout of the FCC-ee injector complex with high energy options. Blue: electron beam energy, orange: positron beam energy.

FCC-ee injector parameters

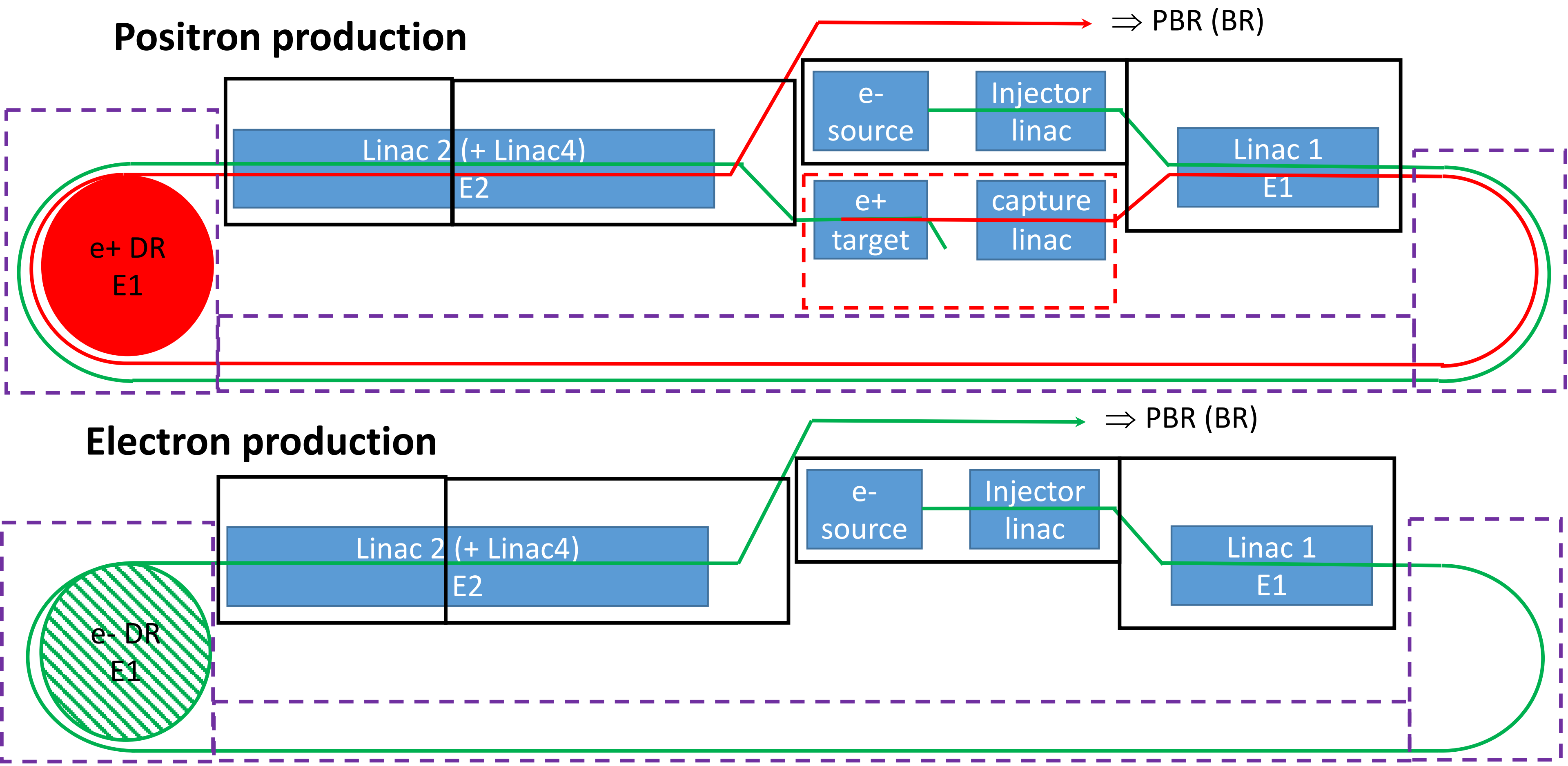
Table 6.1. FCC-ee injector parameters.

Parameter (unit)	Z		W		H		$t\bar{t}$	
Beam energy (GeV)	45.6		80		120		182.5	
Type of filling	Initial	Top-up	Initial	Top-up	Initial	Top-up	Initial	Top-up
Linac bunches/pulse	2				1			
Linac repetition rate (Hz)	200		100					
Linac RF frequency (GHz)	2.8							
Bunch population (10^{10})	2.13	1.06	1.88	0.56	1.88	0.56	1.38	0.83
No. of linac injections	1040		1000		328		48	
PBR minimum bunch spacing (ns)	10		10		70		477.5	
No. of PBR cycles	8		1					
No. of PBR bunches	2080		2000		328		48	
PBR cycle time (s)	6.3		11.1		3.7		0.9	
PBR duty factor	0.84		0.56		0.30		0.08	
No. of BR/collider bunches	16640		2000		328		48	
No. of BR cycles	10	1	10	1	10	1	20	1
Filling time (both species) (s)	1034.8	103.5	266	26.6	137.6	13.8	223.2	11.2

FCC-ee CDR

FCC-ee injector complex

New layout: On-going re-design effort



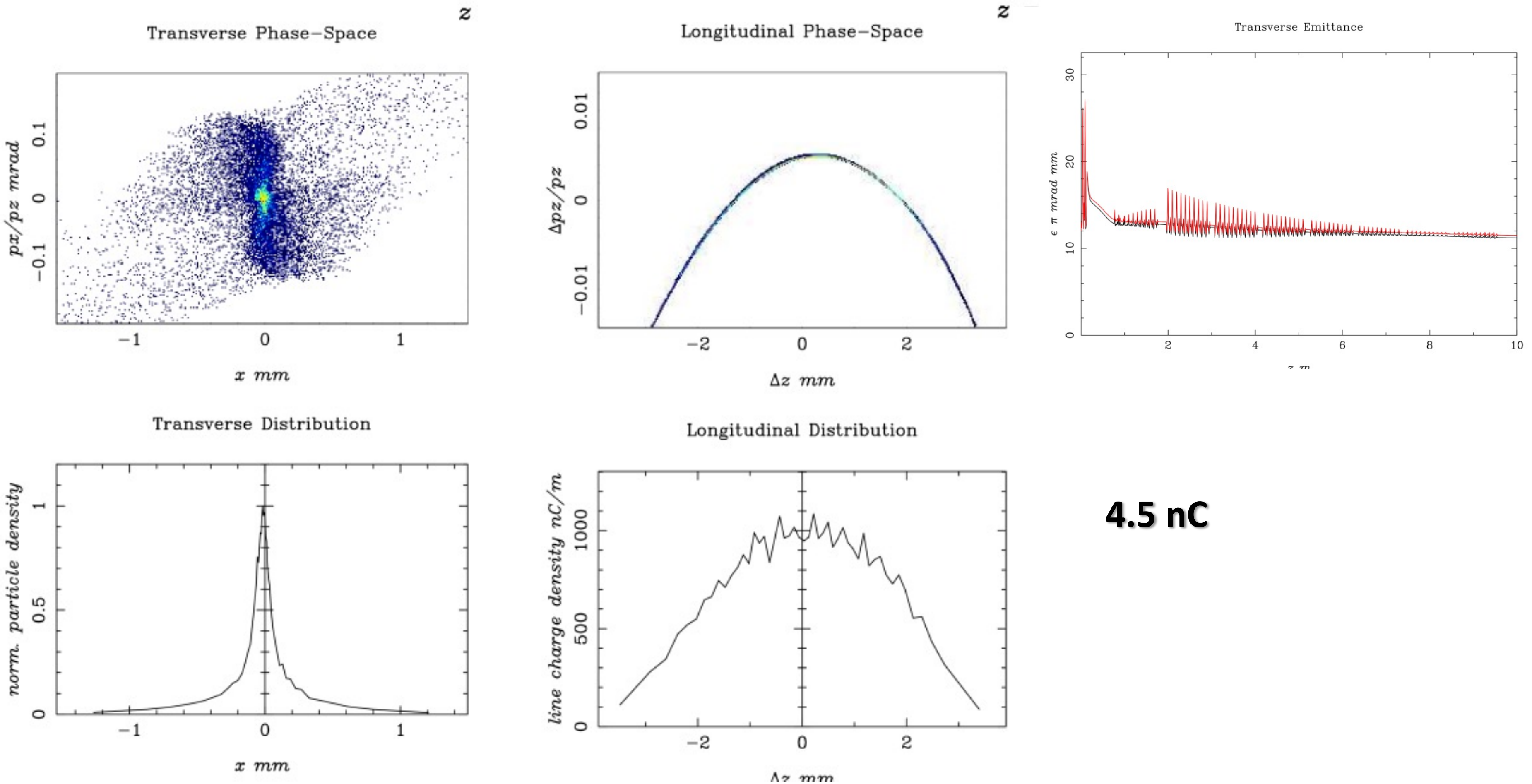
FCC-ee injector complex

Electron beam requirements at source

Parameter	Value/unit
Bunch charge	~4 nC (**8nC** for positron production?)
No of bunches	2
Bunch distance	> 17.5 ns
Emittance at 200 MeV, normalized	< 10 mm mrad
Bunch length at 200 MeV	1-2 mm
Repetition rate max.	200 Hz
Energy Spread	< 1%
Bunch to bunch stability	3 %

FCC-ee electron source

Example of PHIN-type photoinjector



4.5 nC

A thermionic-gun option is also being studied

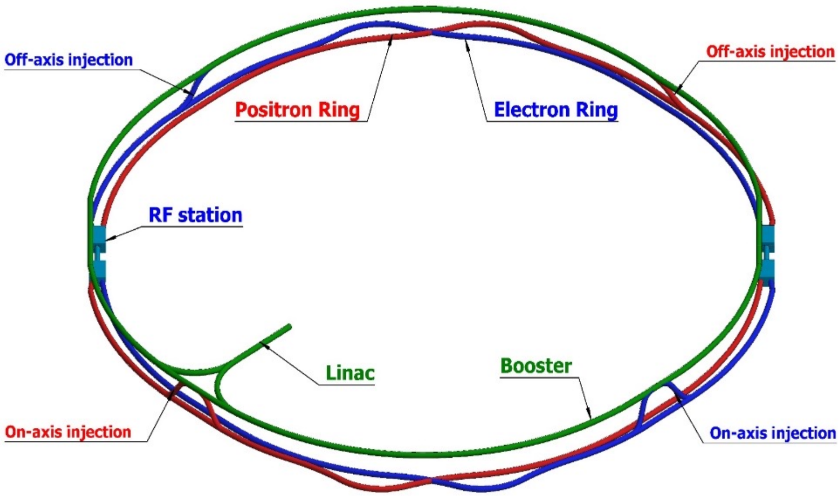
FCC-ee electron source

Still several questions are open

- Detailed operation mode, true 200 Hz repetition rate ?
  Filling and then top up, Electrons , Positrons
- Which bunch to bunch stability, charge, energy, phase, emittance ?
- Bunch distance ?
- Charge modulation for top up 0-100% ?
- Laser base line parameters
- Choice of cathode type
- What level of design do we need at which point in the study
- How much margin: beam loss budget along the injector chain
- Feedback from linac design on bunch distributions
- Are the parameters fixed now, in particular bunch charge

CEPC, China

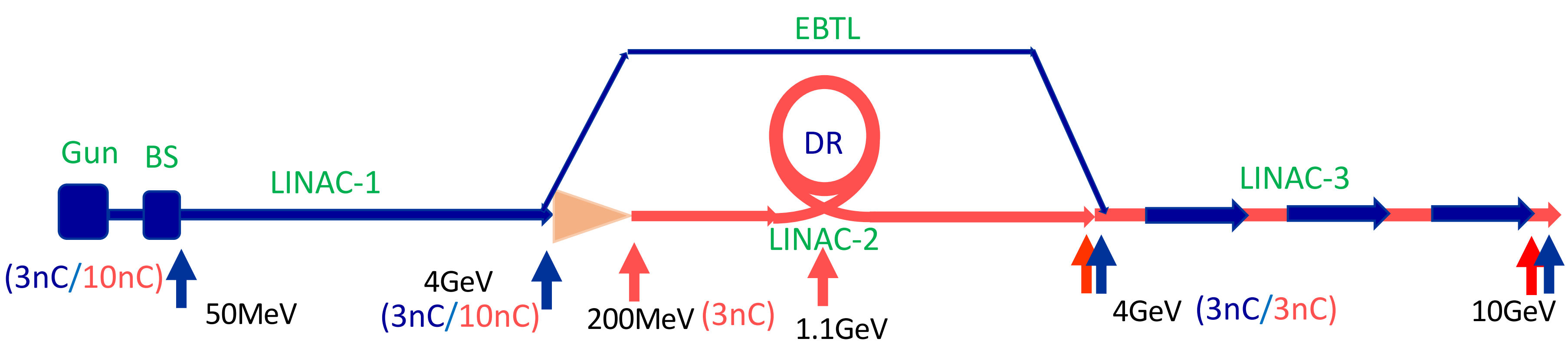
- CEPC consists of Linac, Booster and Collider
  - The energy of the Collider is 120 GeV.
  - The injector linac provides 10 GeV electron and positron beam to the Booster.



- The booster and collider circumference is about 100 km.
- The total length of the linac is about 1.2 km.

CEPC Injector

- Electron linac
  - Gun and Bunching System (BS) : 50 MeV && 3nC for electron
  - LINAC-1: Electron beam @ 4 GeV && 3 nC
  - Electron Bypass Transport Line (EBTL): Electron beam @ 4 GeV && 3 nC
  - LINAC-3: Electron beam to 10 GeV && 3 nC
- Positron linac
  - Gun BS and LINAC-1: 4 GeV && 10 nC
  - Positron Source and Pre-Accelerating Section: Positron beam Energy larger than 200 MeV
  - LINAC-2: Positron beam to 4 GeV. A 1.1 GeV damping Ring (DR) with circumference of 75.4 m
  - LINAC-3: Positron beam to 10 GeV && 3 nC

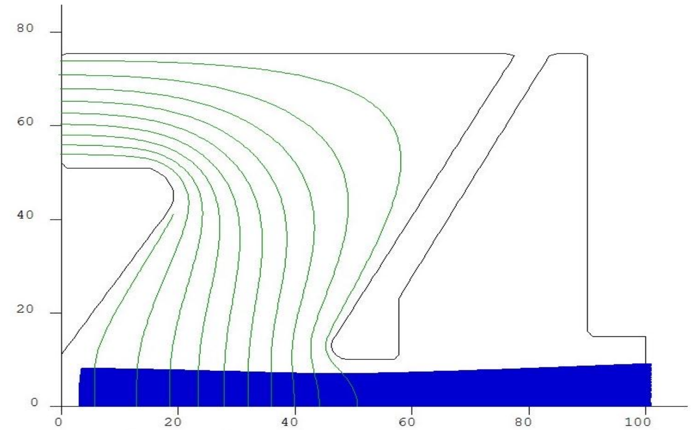


CEPC Injector

Parameter	Symbol	Value	Unit
e^- /e^+ beam energy	E_{e-}/E_{e+}	10	GeV
Repetition rate	f_{rep}	100	Hz
Bunch numbers per pulse		1	
e^- /e^+ bunch population	$Ne\text{-}/Ne\text{+}$	$>9.4\times10^9$	
		>1.5	nC
Energy spread (e^- /e^+)	σ_E	$<2\times10^{-3}$	
Norm. emittance (e^- /e^+)	ε_r	<2500	mm.mrad

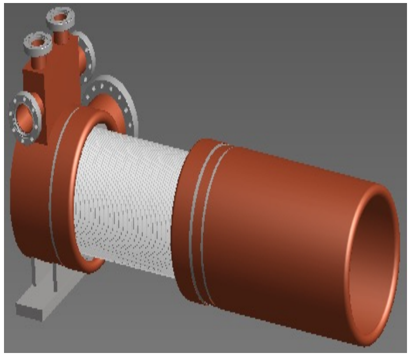
CEPC Injector

- Electron source
  - Thermionic electron gun (mature technology)
    - Pulser System
    - High Voltage System
    - Cathode grid assembly



Beam trajectory of the injector electron gun

Parameters	Values
Type	Triode
Maximum Beam Current(A)	10
Anode High Voltage(kV)	120~200
Filament voltage(V)	6~8
Filament current(A)	5~7.5
Grid bias voltage(V)	0~200
Pulse width (ns)	1
Pulse rate (pps)	100



cathode-grid assembly

CEPC Injector

- Positron damping ring

DR V2.0	Unit	Value
Energy	**GeV**	**1.1**
Circumference	m	75.4
Storage time	ms	20
Bending radius	M	3.565
Dipole strength B_0	T	1.03
U_0	keV	36.3
Damping time x/y/z	ms	15.2/15.2/7.6
δ_0	%	0.05
ε_0	mm.mrad	376.7
$\sigma_{z,\ inj}$	**mm**	**5.0**
Nature σ_z	mm	7.5
ε_{inj}	**mm.mrad**	**2500**
$\varepsilon_{ext\ x/y}$	mm.mrad	530/180
$\delta_{inj}/\delta_{ext}$	%	0.2/0.05
Energy acceptance by RF	%	1.0
f_{RF}	MHz	650
V_{RF}	MV	2.0

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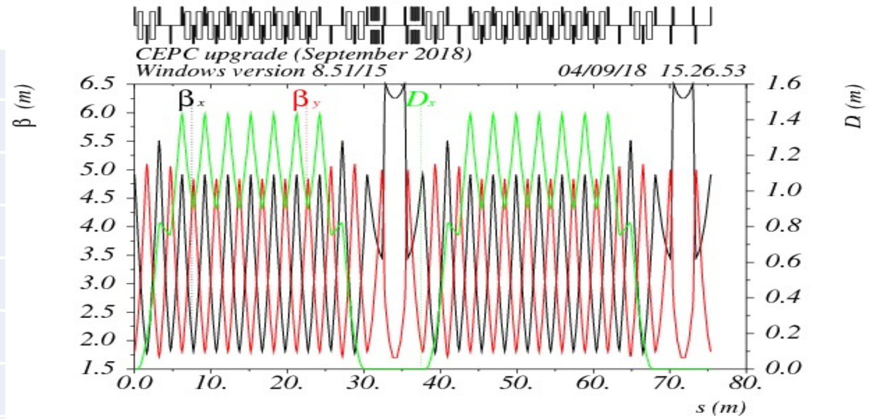

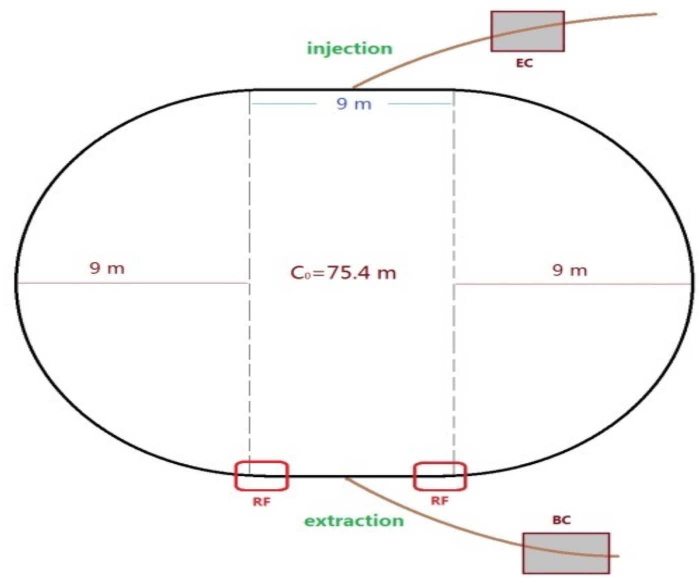

Summary

- An overview of the future electron-positron colliders has been given:
  - CLIC, ILC, FCC-ee, and CEPC

- The electron beam requirements have been presented, as well as the technological solutions currently envisaged

THANK YOU FOR YOUR ATTENTION.