III.4.6 Future high-energy linear lepton colliders

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III.4.6.1 History

The first and only linear collider to run with beams was the Stanford Linear Collider (SLC), operational from 1989 until 1998. Electrons and positrons each reached a maximum energy of $\sim$ 46 GeV at the collision point. Figure III.4.1 shows a scheme of the collider with a linac length of 3.2 km (called 2-mile linac) working at 2.9855 GHz. In the field of particle accelerators, the RF frequencies are divided into scales called "Bands". Table III.4.1 gives current bands for accelerators and colliders. The SLC frequency corresponds to the S-Band.

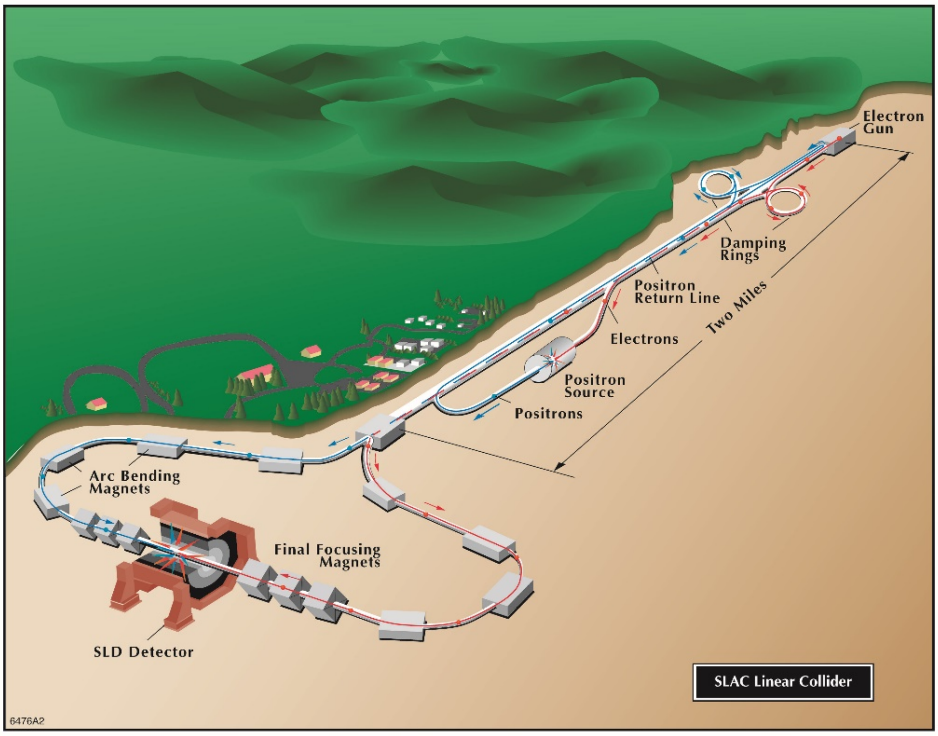

Fig. III.4.1: Schematic layout of the SLC in California.

A brief history of high energy linear colliders studies is recalled below. As of 1995, six linear colliders studies were ongoing:

– TESLA based on superconducting RF cavities working at 1.3 GHz, at DESY,
– SBLC (S-Band Linear Collider) based on normal conducting RF cavities working at 3 GHz, at DESY,

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Table III.4.1: RF frequencies bands.

Band names	Approx. wavelengths λ [cm]	Approx. frequencies f [GHz]
L	30–15	1–2
S	15–7.5	2–4
C	7.5–3.75	4–8
X	3.75–2.4	8–12
K	2.4–0.75	12–40

- NLC (Next Linear Collider) based on normal conducting RF cavities working at 11.4 GHz, at SLAC,
- JLC (Japan Linear Collider) based on normal conducting RF cavities working at 11.4 GHz, at KEK,
- VLEPP based on normal conducting RF cavities working at 14 GHz, at Novosibirsk,
- CLIC (CERN Linear Collider) based on normal conducting RF cavities working at 30 GHz, at CERN.

For the last one, the first CLIC Note [1] was published in August 1985. It quickly became obvious that six high-energy linear colliders could not be built in the world and the need for an international collaboration to design a future high-energy linear collider started to emerge. The JLC became "Joint Linear Collider" and CLIC became "Compact Linear Collider". In 2004, an international technology panel, set-up to decide which technology would be better suited to continue the future feasibility studies, opted for superconducting technology giving birth to the ILC (International Linear Collider). From then on, there were only two feasibility studies: ILC based on TESLA technology with superconducting RF cavities and CLIC using normal RF cavities.

III.4.6.2 Basic lepton linear collider

A basic lepton linear collider is composed of an electron beam colliding with a positron beam, as shown in Fig. III.4.2. GaAs photocathodes illuminated with a circularly polarized laser generate a spin-polarized electron beam by photoelectric effect. Based on this effect, a source, using a RF gun, produces a electron beam with close to 90% polarization. A damping ring reduces the transverse beam emittances before sending the beam into the main linac. At the end of this, a beam delivery system ensures the expected beam characteristics until just upstream from the Interaction Point (IP). In general, the positron beam is produced from a high-energy electron beam impinging a target, with a high Z atomic number. Due to the bremsstrahlung effect, pairs of e^+ e^- are produced inside the target. Then an optic system allows to collect, a maximum number of positrons at the exit of the target. As for the electron beam, it is necessary to design a damping ring to reduce the transverse beam emittances. Then, the positron beam is injected into the main linac to be accelerated to high energy before colliding with the electron beam.

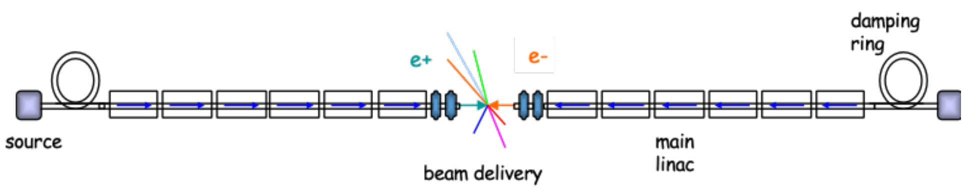

Fig. III.4.2: Layout of a basic linear collider.

III.4.6.2.1 Two main beam parameters

As discussed in Chapter III.4 on introduction to colliders, there are two main beam parameters to characterize the performance of a collider: the energy in the center-of-mass and the luminosity. In the case of linear colliders colliding similar particles, the energy in the center-of-mass E_{CM} is derived from the simple equation

$$E_{\mathrm{CM}} = 2\, F_{\mathrm{Fill}}\, L_{\mathrm{Linac}}\, E_{\mathrm{RF}}, \tag{III.4.1}$$

where F_{Fill} is the RF filling factor of the main linac, L_{Linac} is the length of the main linac and E_{RF} is the accelerating electric field. Typically, the RF filling factor is around 0.8. This means that 20% of the linac is composed of magnets, beam instrumentation, vacuum systems, etc., and not by RF cavities, providing an accelerating field. For what concerns the luminosity, Eq. III.4.20 established in Chapter III.4 can be rearranged as follows, with the number of bunches $M = n_b$, the number of particles/bunch $N_1 = N_2 = \mathrm{N}$, and the introduction of the factor H_{D},

$$L \,\propto\, \frac{N}{\sigma_x}\, N\, n_b\, f_r\, \frac{1}{\sigma_y}\, H_{\mathrm{D}}, \tag{III.4.2}$$

where $\frac{N}{\sigma_x}$ characterizes the single-bunch brightness, $N\, n_b\, f_r$ characterizes the beam current (it is related to the available RF power), $\frac{1}{\sigma_y}$ characterizes the beam quality (it is related to the optics/emittance of the collider), and finally H_{D} characterizes the pinch effect at the collision point (it is called the luminosity enhancement factor), as shown in Fig. III.4.3.

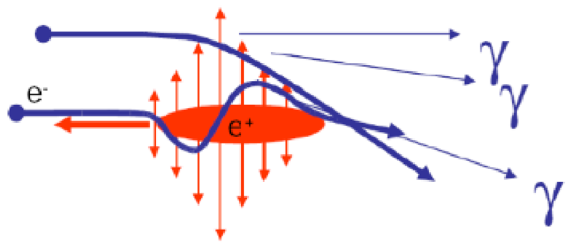

Fig. III.4.3: Pinch effect between a positron bunch and an electron bunch with emission of photons.

Looking at the example of the SLC collider over the last two running years (1997–1998), the following numbers were obtained. The collider ran during $\sim\ 28 \times 10^6$ s at an instantaneous luminosity of 2×10^{30} cm^{-2} s^{-1}. Thus, the integrated luminosity was 0.056 fb^{-1} during this period. Multiplying by the cross-section of the event, then a dimensionless number is obtained which is the number of expected scattering events. A total of 350 000 Z_0 particles were collected over these two years.

III.4.6.2.2 Discussion on two main beam parameters for future linear colliders CLIC and ILC

This chapter is focused on CLIC and ILC linear colliders. Table III.4.2 shows the evolution of two main beam parameters (energy and luminosity) between the real linear collider SLC and the possible future linear colliders CLIC and ILC. Regarding the beam energy at the IP, the jumps are a factor $\sim$ 10 for ILC and a factor $\sim$ 30 for CLIC. For the instantaneous luminosity, the factor is $\sim$ 30 000, while for the integrated luminosity the factor is roughly $\sim$ 18 000. Such large factors represent important challenges for the design of future linear colliders.

Table III.4.2: Main parameters from SLC to CLIC and ILC (in 2022).

Machines	$\mathbf{E_{CM}}$ **[GeV]**	$\mathscr{L}$ $[10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$	$\mathscr{L}_{\mathrm{Int/Year}}$ $[\mathrm{fb}^{-1}]$	**Operation years**
SLC	92	0.02	$\sim$ 0.056 over last 2 years	1989–1998
LEP (circular)	209	1	0.1	1989–2000
CLIC	380	150	180	Study
CLIC	3000	590	708	Study
ILC	250	135	240	Study
ILC	1000	511	908	Study

III.4.6.3 CLIC, a multi-TeV high-luminosity and high-energy $e^+ e^-$ linear collider, at CERN

Figure III.4.4 shows an artist's impression of CLIC. Its concept is based on high-gradient normal-conducting accelerating structures where the RF power for the acceleration of the colliding beams is extracted from a high-current drive beam that runs parallel with the main linac. It is a novel and unique two-beam acceleration technique. That implies a single tunnel as sketched in Fig. III.4.4.

Fig. III.4.4: Artist's impression of CLIC below the Jura mountains.

This $e^+ e^-$ linear collider is foreseen for the era beyond the HL-LHC (High Luminosity-LHC). The CLIC webpage can be found at: `https://clic.cern`. A conceptual design report has been published in 2012 [2]. An updated baseline for a staged Compact Linear Collider was released in 2016 [3]. A Project Implementation Plan was released in 2018 [4]. The CLIC accelerator feasibility study includes 50 institutes from 28 countries and the CLIC detector and physics includes 30 institutes from 18 countries. The cost of the first stage, at 380 GeV with a power consumption of 110 MW has been evaluated at 6 BCHF. An optimized staging scenario foresees three center-of-mass energy stages at 380 GeV, 1.5 TeV and 3 TeV for a full CLIC program spanning more than 20 years. Therefore, the total cost is distributed over several years and the Physics program can start as soon as the first stage is completed. Figure III.4.5 shows a schematic CLIC footprint between the Jura mountain and the Leman lake (mentioned as Lake Geneva in the Figure). The three colours correspond to the three stages in energy, as mentioned in the legend. The IP is situated inside the CERN laboratory. The red line indicates the border between France and Switzerland. The final length of the collider for the third stage is 50 km. The larger white circle indicates the position of the existing LHC (Large Hadron Collider).

The first stage, at 380 GeV center-of-mass, will focus on precision Standard Model physics, including Higgs and top-quark measurements. The subsequent stages will focus on measurements of rare Higgs processes, as well as searches for new physics processes. The advantage of such a staging scenario is that while collisions are taking place at the IP, during the first stage, much works (installation of RF cavities, magnets, beam diagnostics, vacuum, etc.) can be undertaken, in the tunnel, to build up the final collider. The key parameters of this scenario are given in Table III.4.3. In 2007, the CLIC RF frequency has been decreased from 30 GHz down to 12 GHz.

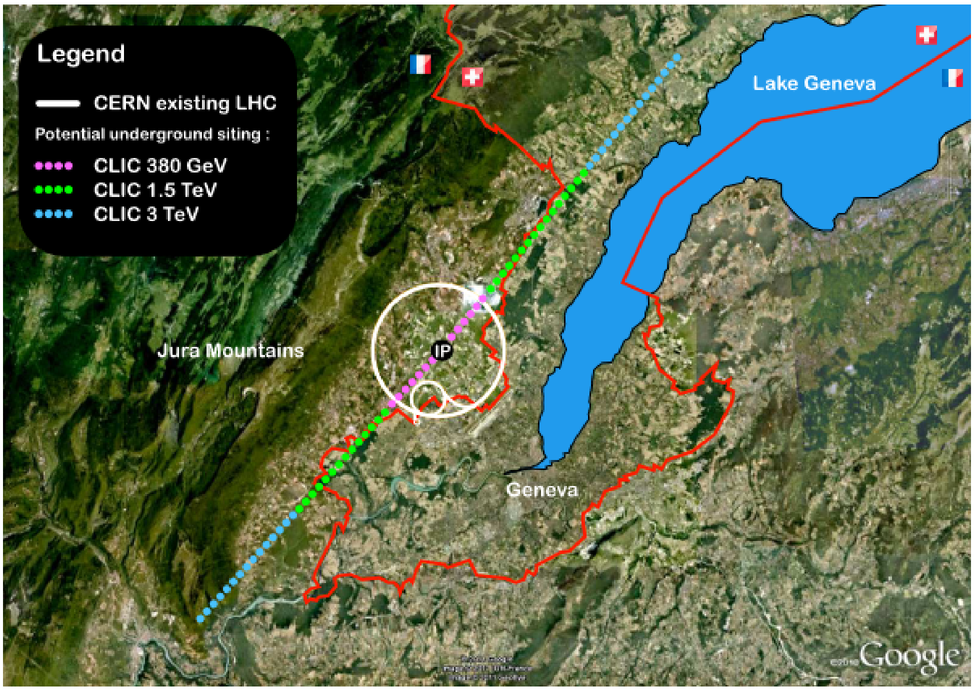

Fig. III.4.5: CLIC footprint showing the 3 implementation stages in energy.

Regarding the performance, one should consider only the useful luminosity. There is a non-negligeable reduction factor compared to the total luminosity. The luminosity optimization is an important challenge. It requires a deep understanding of beam induced background inside the detector conjugated with the constraints from the accelerator design. Considering the final stage at 3 TeV, one notices the big challenges to get 20 nm.rad. for the vertical normalized emittance and 1 nm for the vertical rms beam size, as indicated in Table III.4.3.

Estimations have been done on stability requirements assuming a tolerance of 2% loss in luminosity. Regarding the 2600 quadrupoles in the main linac, the horizontal jitter should not exceed 14 nm and the vertical jitter 1.3 nm. Regarding the two final focus quadrupoles QD0 (see Fig. III.4.6), the horizontal jitter should not exceed 4 nm while the vertical jitter should be less than 0.15 nm. For comparison, this corresponds to the distance between the two-hydrogen atoms in a water molecule.

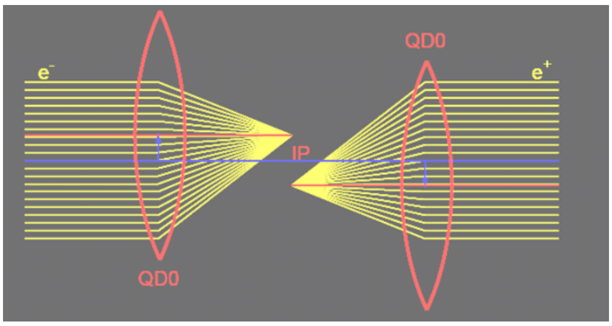

Fig. III.4.6: Vertical spot size of 1 nm at the IP.

The layout of the CLIC accelerator complex at 3 TeV is shown in Fig. III.4.7. The main beams are generated and pre-accelerated in the injector linacs and then enter the damping rings for emittance reduction (lower part of the figure). Target figures are 500 nm and 5 nm normalized beam emittances in

Table III.4.3: Parameters for the CLIC energy stages.

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1 500	3 000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
RF 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	$\mathscr{L}_{\text{int}}$	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

the horizontal and vertical planes respectively at the exit of the injector complex. The small-emittance beams are further accelerated in a common linac before being transported through the main tunnel to the turnarounds. After the turnarounds, the acceleration of the main beam begins with an accelerating gradient of 100 MV/m. In this novel acceleration scheme, the high electric field is generated by a "drive beam" and its compression and re-conversion into RF power close to the main beam accelerating structures. The top part of Fig. III.4.7 shows the drive-beam generation in two main linacs and the successive time compression of the drive-beam pulses in the delay loops and combiner rings (CR1 and CR2). The time-compressed drive beam reaches a current of about 100 A at a beam energy of about 2.4 GeV. This compressed drive beam is transported through the main linac tunnel to 25 individual turnarounds. Each drive-beam segment is directed by pulsed extraction elements, for the final RF power generation, into the accelerating structures of the main beams. The beams collide after a long beam delivery section (BDS) (collimation, final focus) in one IP in the centre of the complex.

Figure III.4.8 shows the manipulation of the drive-beam time structure to produce separated drive pulses at high current.

For the first and second CLIC stages, a single drive-beam generation complex to feed both linacs is proposed, while for the third stage, two drive-beam complexes are needed, as shown in Fig. III.4.7. Many key components need to be designed and developed. Here we give some characteristics for one key component which is the RF accelerating structure. Figure III.4.9 shows the outside of one cavity. The RF frequency for this cavity is 11.994 GHz, corresponding to X-band. To generate an accelerating gradient of 100 MV/m, the required input power is 50 MW with a pulse length of 240 ns. The repetition rate is 50 Hz. The CLIC linear collider working at 380 GeV will require roughly 20 500 cavities along the 11 km of linacs.

Figure III.4.10 shows the inside of the same RF cavity. The active length is 25 cm. The aperture diameter where the beam is passing is 6 mm. Each disk, machined with a micron-precision, includes four slots where high-order modes (HOM) damping waveguides are inserted. References given at the end of this section provide details regarding the various challenges and state of the results about the CLIC feasibility studies.

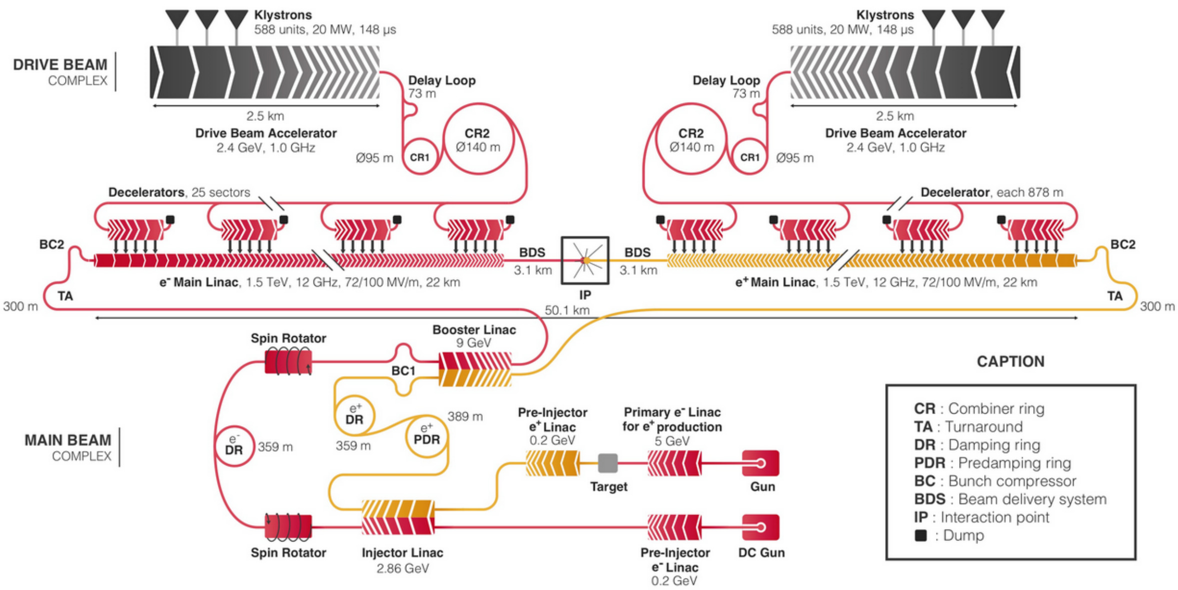

Fig. III.4.7: Layout of CLIC at 3 TeV.

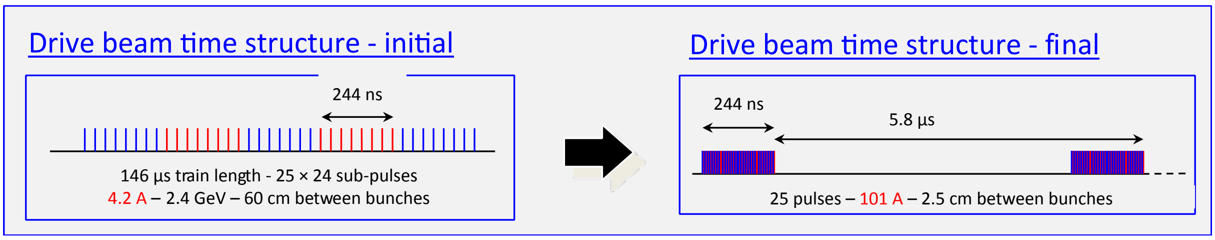

Fig. III.4.8: Drive-beam time structure gymnastic to get high current.

III.4.6.4 ILC, a high-luminosity and high-energy $e^+ e^-$ linear collider, in Japan

Figure III.4.11 shows an artist's impression of the ILC. Its concept is based on superconducting accelerating structures where the RF power for the acceleration of the colliding beams is provided by klystrons. With this technology, it is possible to implement a tunnel for the accelerator and alongside it, a tunnel for the klystron gallery. This $e^+ e^-$ linear collider is mature to be build but the date is not yet precisely defined.

ILC is envisaged as a global project with a share of the cost, mostly in the form of in-kind contributions for the accelerator. The infrastructure cost should be taken by Japan, as the host country. At the time of this report, ILC is waiting for an approval from Japanese authorities assuming an international financial support. The ILC webpage can be found at: `https://linearcollider.org`. A technical design report was released in 2013 [5] and the project implementation planning was released in 2015 [6]. The cost of the 250 GeV stage, with a power consumption of 110 MW, has been evaluated at 6 BCHF. In the Tohoku area where the ILC is planned to be built, the capacity of power generation facilities is about 28 GW. It includes 32 % of renewable power. The ILC would require only 0.5 % of the total capacity. Figure III.4.12 gives a rough footprint of ILC in Tohoku region, northend of Japan.

Figure III.4.13 gives a layout of ILC complex where the sources, the damping rings and the beam delivery system are installed in a central region. One particularity is the use of the main electron beam

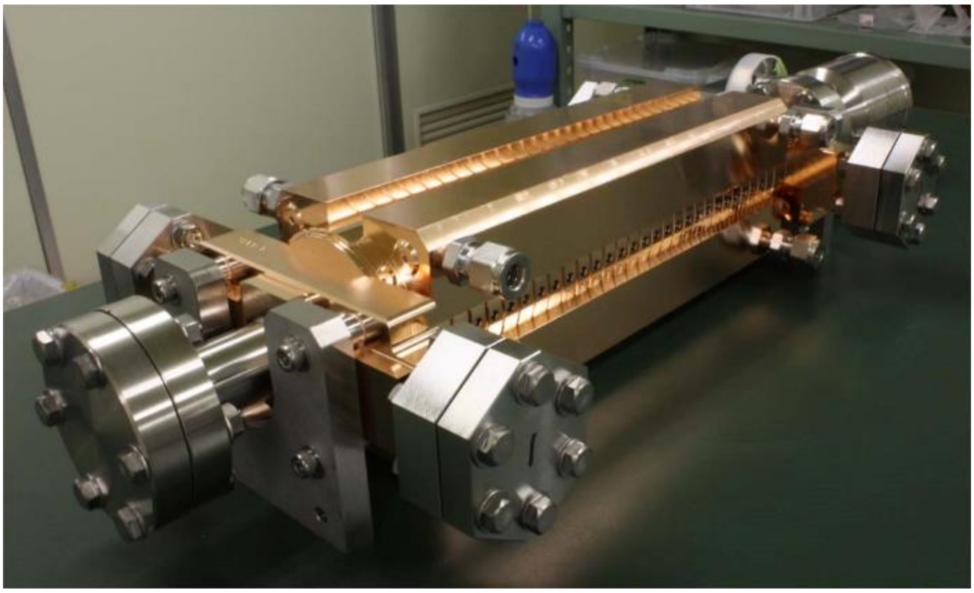

Fig. III.4.9: CLIC accelerating structure (outside).

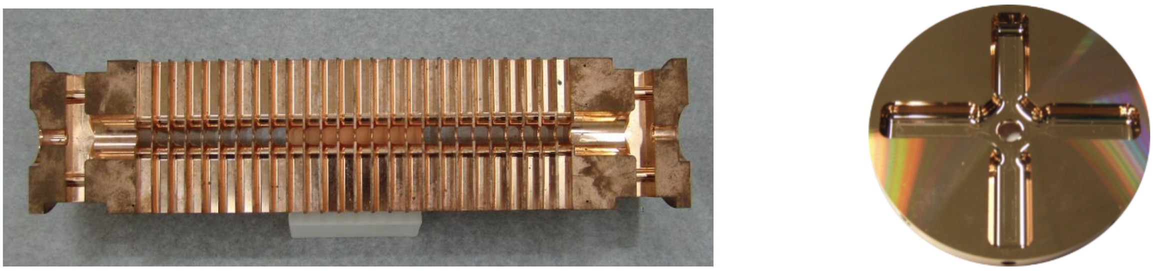

Fig. III.4.10: CLIC accelerating structure (inside).

for two purposes: a) for Physics and b) to create the positron beam.

Like CLIC, there are several accelerator-system components which are critical and could prevent smooth running of the ILC. The electron source photo-cathode gun, positron-source undulator, target and capture system, damping-rings, and beam-delivery dumps are examples of such systems. The key parameters are given in Table. III.4.4. The 6 columns show the parameters from the baseline at 250 GeV up to 1 TeV including the various steps for the luminosity upgrades $\mathscr{L}$ up.

Below we illustrate the positron-source using a helical undulator which is a specificity of ILC. The basic concept is to use polarized beams for electrons and positrons in order to maximize the potential of physics discoveries. The positron source generates the positron beam for the collider, as shown in Fig. III.4.14. To produce the positrons, the electron beam from the main linac passes through a long superconducting helical undulator. It generates a multi-MeV photon beam which hits a thin metal target to generate showers of electrons and positrons. This system pushes the state of the art in many areas. Robust R&D has been performed on several critical items, including the undulator, positron-conversion target, optical-matching device, photon collimator, normal-conducting accelerating structures, radiation shielding and remote handling. An alternative conventional positron source and beam-line lattice design has also been studied.

The main electron beam (> 150 GeV) going through a superconducting helical undulator produces

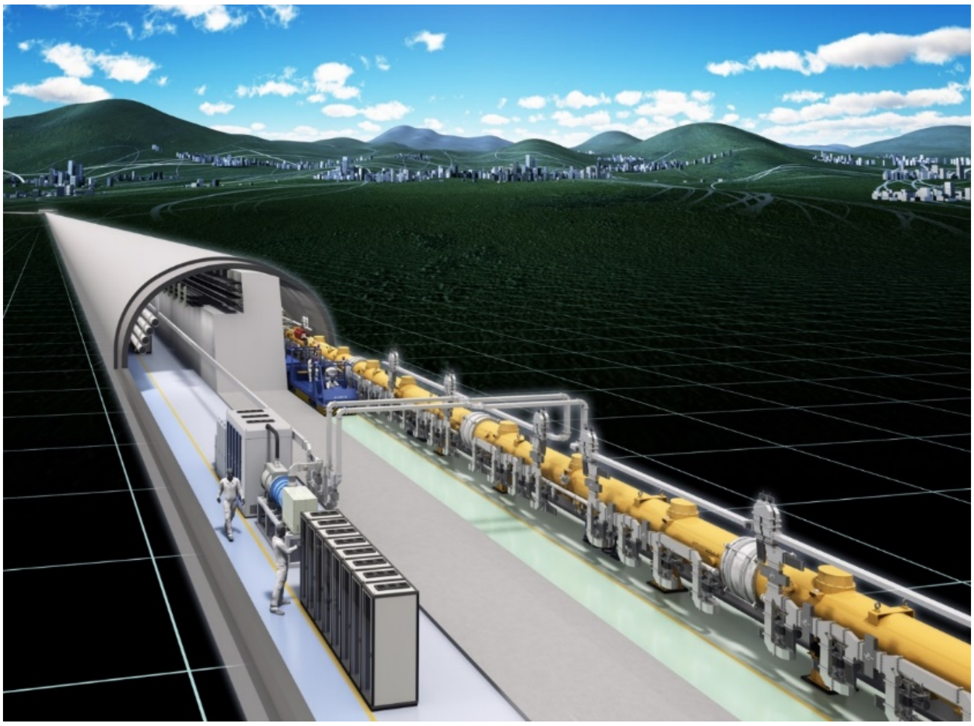

Fig. III.4.11: Artist's impression of ILC in Kitakami - Tohoku region - Japan.

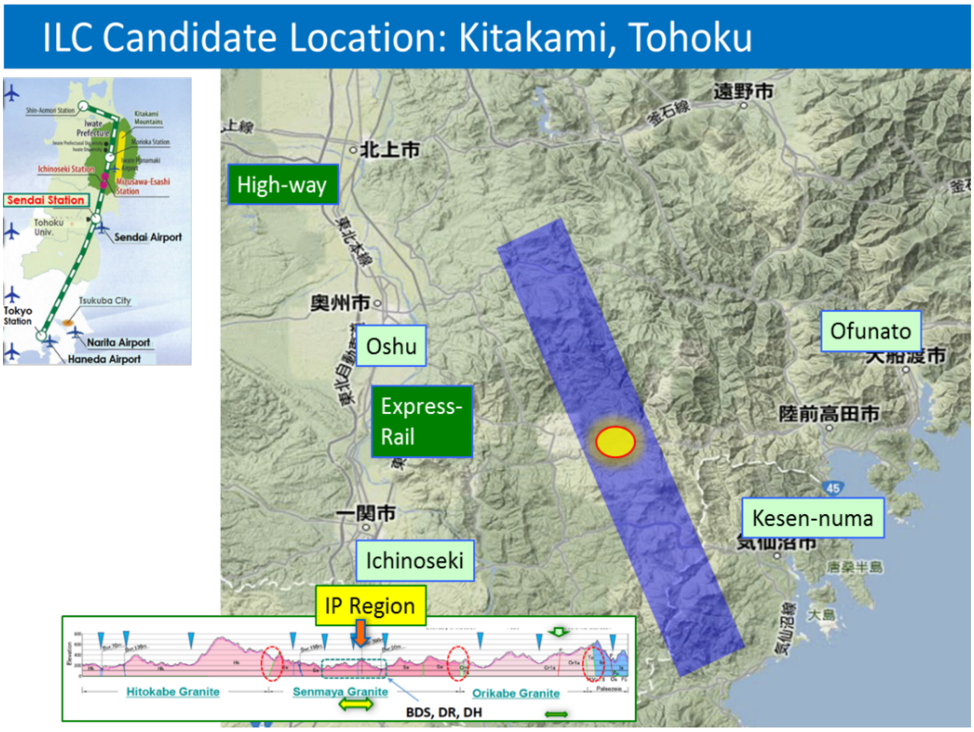

Fig. III.4.12: ILC footprint.

polarized photons. From these polarized photons, one can also produce a polarized positron beam. The polarization level is around 30 %. It has been recognized that beam polarization may be a benefit because

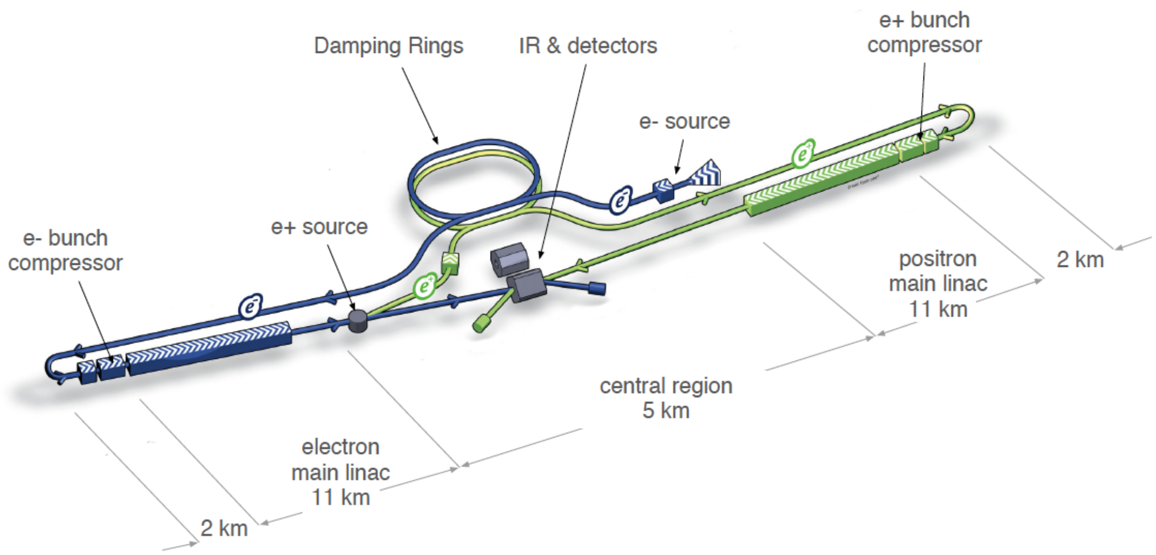

Fig. III.4.13: Layout of ILC at 500 GeV.

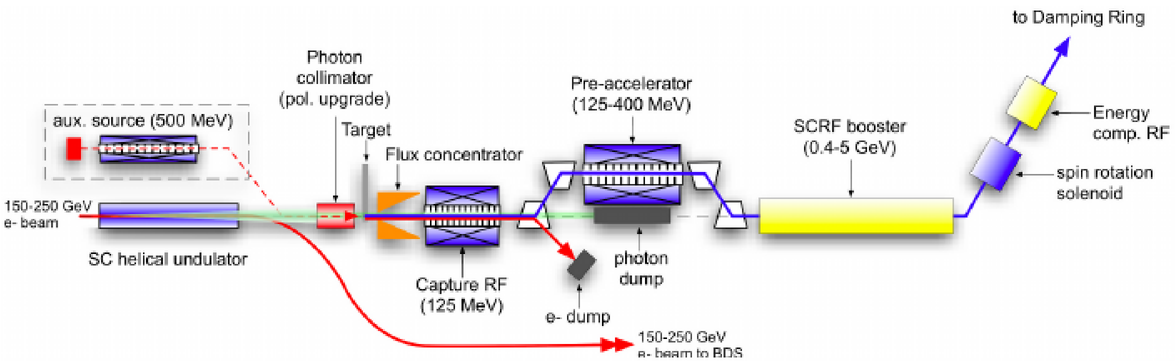

Fig. III.4.14: ILC positron source using a superconducting helical undulator.

a higher precision, in the collisions results. It allows better sensitivity to beyond the Standard Model physics. The ILC technology is based on superconducting RF cavities with $\sim$ 8370 cavities installed inside 930 cryomodules, at 250 GeV. This collider is also upgradable from 250 GeV to 1 TeV, using the beam current parameter as discussed in Eq. (III.4.2). All ILC systems are described in the references below. Various challenges and state of the results about the ILC feasibility studies are provided.

III.4.6.5 Linear colliders challenges

III.4.6.5.1 From SLC to ILC and CLIC

Table III.4.5 compares CLIC and ILC basic parameters with SLC.

For CLIC and ILC the RF cavities are crucial components. Fig. III.4.15 compares the performances for both colliders.

The accelerating gradient for CLIC is a factor 3 higher than for ILC and the RF frequency is a factor ten higher. However, both structures are faced with different but significant challenges. If the "large" ILC structure aperture relaxes the wakefields effects, the fabrication requires clean-room and

Table III.4.4: Parameters for ILC.

Parameter	Symbol	Unit	Option					
			Higgs			500 GeV		TeV
			Baseline	**$\mathscr{L}$ up**	**$\mathscr{L}$ up, 10 Hz**	**Baseline**	**$\mathscr{L}$ up**	**Case B**
Center-of-mass energy	E_{CM}	GeV	250	250	250	500	500	1 000
Beam energy	E_{Beam}	GeV	125	125	125	250	250	500
Collision rate	f_{col}	Hz	5	5	10	5	5	4
Pulse interval in electron main linac		ms	200	200	100	200	200	200
Number of bunches	n_{b}		1312	2625	2625	1312	2625	2450
Bunch population	N	10^{10}	2	2	2	2	2	1.737
Bunch separation	Δt_{b}	ns	554	366	366	554	366	366
Beam current		mA	5.79	8.75	8.75	5.79	8.75	7.6
Average power of two beams at IP	P_{B}	MW	5.26	10.5	21	10.5	21	27.3
RMS bunch length in Main Linac and IP	σ_{z}	mm	0.3	0.3	0.3	0.3	0.3	0.225
Emittance at IP (x)	γe^*_{x}	mm	5	5	5	10	10	10
Emittance at IP (y)	γe^*_{y}	nm	35	35	35	35	35	30
Beam size at IP (x)	σ^*_{x}	mm	0.515	0.515	0.515	0.474	0.474	0.335
Beam size at IP (y)	σ^*_{y}	nm	7.66	7.66	7.66	5.86	5.86	2.66
Luminosity	$\mathscr{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	5.4	1.79	3.6	5.11
AC power	P_{site}	MW	111	138	198	173	215	300
Site length	$\mathscr{L}_{\mathrm{site}}$	km	20.5	20.5	20.5	31	31	40

Table III.4.5: Comparison of parameters.

Parameter	Symbol [Unit]	SLC	ILC	CLIC
center-of-mass energy	E_{CM} [GeV]	92	500	3 000
Luminosity	$\mathscr{L}$ [10^{34} cm^{-2} s^{-1}]	0.0003	1.8	6
Peak luminosity	$\mathscr{L}_{\mathrm{Peak}}$ [10^{34} cm^{-2} s^{-1}]	0.0003	1	2
Gradient	G [MV/m]	20	31.5	100
Particles/bunch	N [10^9]	37	20	3.72
Bunch length	σ_z [µm]	1 000	300	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	1 700/600	474/5.9	40/1
Vertical emittance	ϵ_y [nm]	3 000	35	20
Bunches/pulse	n_b	1	1 312	312
Distance between bunches	Δ_z [mm]	-	554	0.5
Repetition rate	f_r [Hz]	120	5	50

chemistry treatment. Developments are ongoing to reduce the fabrication cost for thousands of all these structures.

As concerns the current six major challenges for the future high-energy colliders, the situation for the lepton linear colliders is the following:

– Synchrotron radiation: no problem since the bending radius is infinite and therefore the losses are almost zero,
– Bending magnets fields: no major problem since the magnets are based on classical technology

Normal conducting (CLIC)	Superconducting (ILC)
Gradient: 72 to 100 MV/m - Higher energy reach, shorter facility	Gradient: 31.5 to 35 (to 45) MV/m, - Higher efficiency, steady state beam power from RF input
RF Frequency: 12 GHz - High efficiency RF peak power - Precision alignment & stabilization to compensate wakefields	RF Frequency: 1.3 GHz - Large aperture gives low wakefields
Q_0: order $< 10^5$, - Resistive copper wall losses compensated by strong beam loading – 40% steady state rf-to-beam efficiency	Q_0: order 10^{10}, - High Q - losses at cryogenic temperatures
Pulse structure: 240 ns / 50 Hz	Pulse structure: 700 μs / 5 Hz
Fabrication: - driven by micron-level mechanical tolerances	Fabrication - driven by material (purity) & clean-room type chemistry
- High-efficiency RF peak power production through long-pulse, low freq. klystrons and two-beam scheme	- High-efficiency RF also from long-pulse, low-frequency klystrons

Fig. III.4.15: Challenges for CLIC and ILC about RF structures (courtesy of A. Yamamoto).

(warm electromagnets),

– Accelerating gradient: $\sim$ 100 MV/m for normal conducting cavities and $\sim$ 30 MV/m for superconducting cavities have been demonstrated. Probably the limits are higher than these values,
– Particle production for e^+: the requested performances for the final stage remain to be established,
– Power consumption: major progress has been made. However, acceptability, with the present values, remains under discussion,
– Cost: Compared to other projects, it could be acceptable. Funding agencies are asked to strongly support such linear colliders for the future.

Finally, there is also the issue of the single-pass collision and single experiment.

III.4.6.5.2 Overview of international colliders

Figure III.4.16 shows the overview presented at the Granada open symposium in May 2019. This figure shows the panorama of possible future circular and linear colliders, including CLIC and ILC discussed in this chapter. The energy is expressed in GeV and TeV. The luminosity is expressed in "ab^{-1}" (inverse atto-barn). It is remarkable that these scenarios span three quarters of a century. In this figure, proposals such as high-gradient laser and plasma for colliders are not shown. The feasibility of a collider based on plasma accelerator schemes remains to be proven. Key challenges to reach the high energy frontier include a scheme for positron bunch acceleration in plasma, which still needs to be demonstrated. It is the same for muon colliders. However, intensive studies and work are being undertaken in different laboratories around the world.

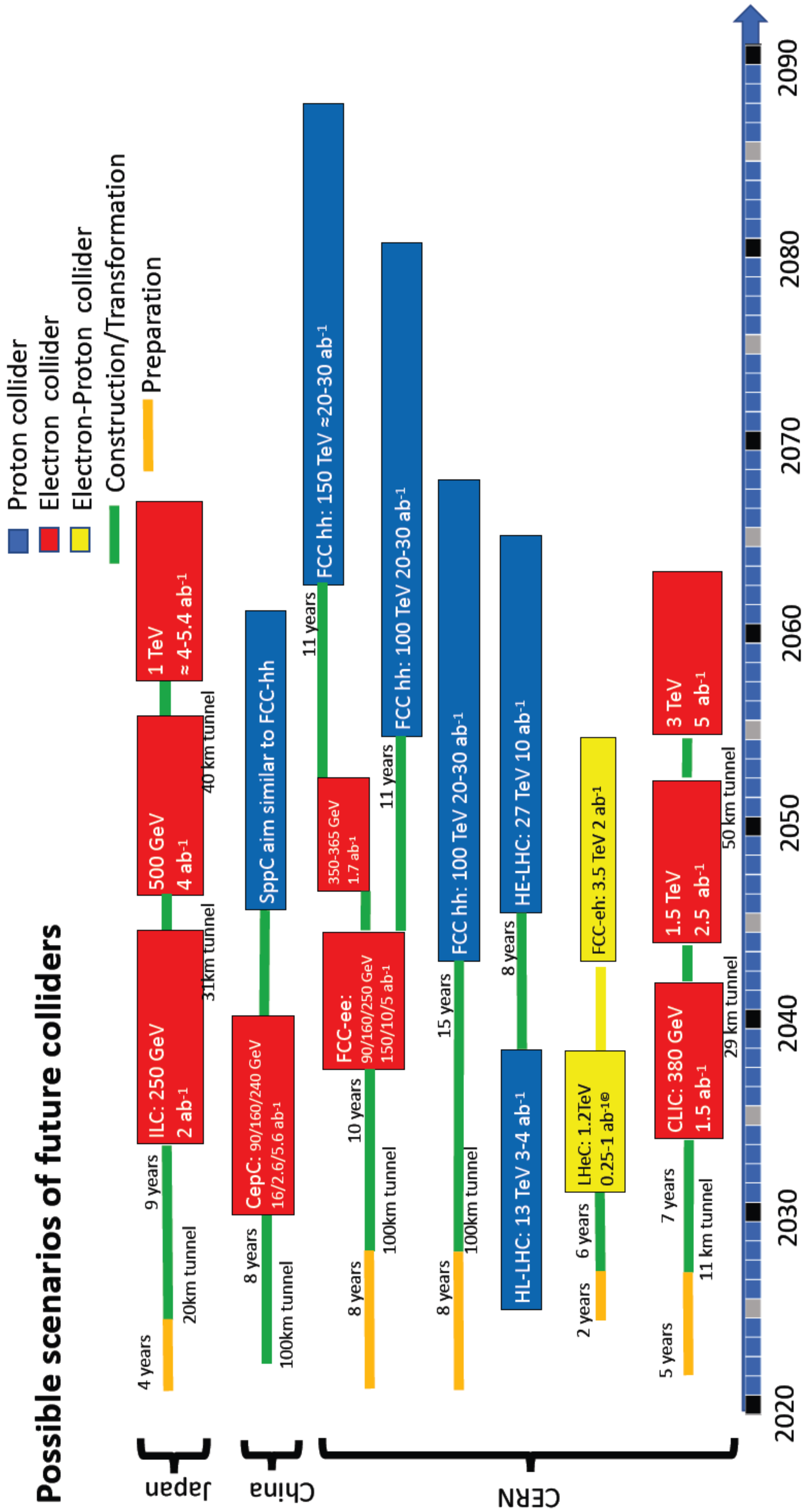

Fig. III.4.16: Possible future colliders showing energy and luminosity, 2019 data (courtesy of U. Bassler).

III.4.6.6 Conclusion

Reference [7] indicates a long-term R&D roadmap towards a compact collider with attractive intermediate experiments and studies. Required feasibility and R&D work are described in this report. Possible discoveries or results coming from LHC would allow to indicate which collider is more appropriate for future physics, assuming that not all scenarios will be implemented.

III.4.6.7 Acknowledgement

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