Advanced Accelerator System Requirements for Future Linear Colliders

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Linear collider-purpose and requirements

The high-energy electron-positron linear collider (LC) is a precision tool for the exploration of elementary particle physics at the energy frontier.

• To reach the energy frontier, a high beam energy E_b is required.

• Current generation LC designs are in the cm energy range $E=2E_b \sim$ 0.5-3 TeV, and use “conventional” acceleration schemes (disc-loaded traveling wave linacs)

• Next-generation machines must aim for the 10 TeV scale, and may require advanced acceleration techniques.

Linear collider requirements

Affordability and constructability

• Current generation LC's in the 1 TeV range cost of order $6B, with half the cost in the linacs, which have a 30 km length with a gradient of .050 GV/m.

• A factor of 10 increase in energy with no improvement in gradient => $30B, 300 km long. This is neither affordable nor constructible.

• We require an increase in linac gradient by factor of order 10-20 => to 0.5-1 GV/m or higher, *with same or lower cost for the acceleration system.*

Linear collider-luminosity requirements

- The cross-section for electron-positron collisions falls as $1/E^2$. In order to provide sufficient data rates for the expected physics processes, we require that the luminosity scale with energy as

$$\mathcal{L} \approx \mathrm{E[TeV]}^2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Beam power

Transverse density

$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x^*\sigma_y^*}\right)$$

Bunch population

Rms horizontal beam size at the IP

Rms vertical beam size at the IP

Linear collider-luminosity requirements

Affordability and operability

• With no change in transverse density, a factor of 100 in luminosity would require 100 times more beam power. Current generation LC's have AC power requirements in the few hundred MW range, and are already relatively efficient. We cannot go to tens of GW's, as the machine will be too expensive to operate.

• The only route to enhance luminosity is an increase in the transverse density. How far we can go in this direction is limited by

-the performance of the injectors, which determine the initial emittance of the beam,

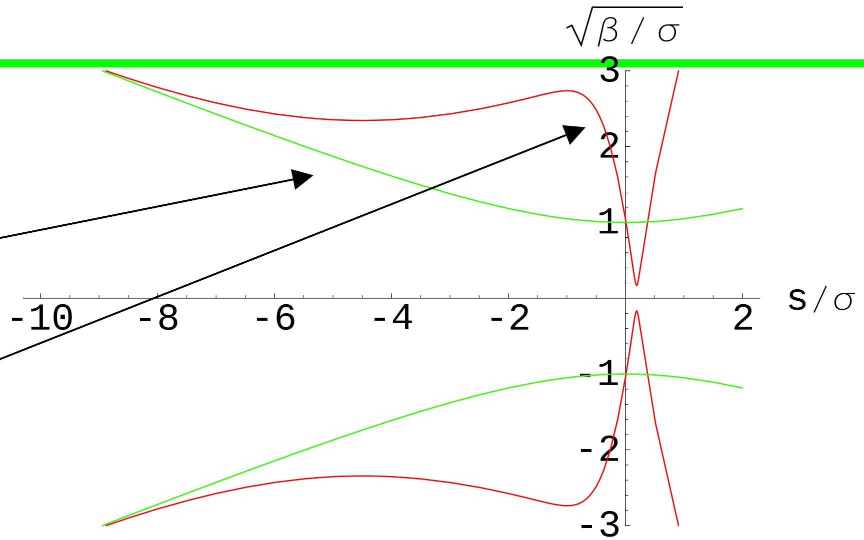
-emittance growth in the main linacs

- the final focus optics and the beam-beam interaction at the collision point.

When dense beams collide

Beam envelope
w/o beam-beam

Beam envelope
with beam-beam



Beam-beam interaction- the strong electromagnetic fields of the opposing bunch produce:

1. Pinch ("disruption"): a luminosity enhancement factor H_D

2. Radiation ("beamstrahlung"): a source of background and energy spread

Beamstrahlung

Beamstrahlung is characterized by the beamstrahlung parameter:

$$\Upsilon = \frac{2\hbar\omega_c}{3E_b} \cong \left(\frac{5r_e^2}{6\alpha}\right)\left(\frac{\gamma}{\sigma_z}\right)\left(\frac{N}{\sigma_x^* + \sigma_y^*}\right)$$

E_b/mc^2

Rms bunch length

Next-generation LC designs, with higher energies and densities, will operate in the quantum beamstrahlung regime, for which $\Upsilon \gg 1$. In terms of this parameter, the average number of photons radiated per electron is

$$n_\gamma \cong \frac{12\alpha^2\sigma_z}{5r_e\gamma}\Upsilon^{2/3} \cong 2\alpha\left(\frac{6\alpha r_e}{5}\right)^{1/3}\frac{1}{\gamma^{1/3}}\left(\frac{N\sqrt{\sigma_z}}{\sigma_x^* + \sigma_y^*}\right)^{2/3}$$

Beamstrahlung

- n_γ must be limited to keep backgrounds under control and constrain the cm energy spread. Typically we require $n_\gamma \lesssim 1$.

- We can keep n_γ limited while maximizing the luminosity by operating with flat beams, for which $\sigma_y^* \ll \sigma_x^*$.
In this case, the luminosity per unit beam power can be written

$$\frac{\mathcal{L}}{P_b} \cong \frac{\sqrt{5}}{16\alpha^2\sqrt{3r_e\pi}} \frac{\sqrt{\gamma n_\gamma^3}}{E_b\sqrt{\sigma_z}\sigma_y^*}$$

We see that it is advantageous in this high energy regime to operate with very short bunches.

Prescription for achieving high luminosity

- **Maximize the beam power-**
  - Limited by the wall plug power and wall plug -> beam power efficiency
- **Minimize the vertical beam size and bunch length at the IP**
  - Limited by the beam emittance and bunch length provided by the injector, emittance dilution in the linac, and the final focus optics.
- **Stabilize the vertical beam position at the IP**
  - Limited by component physical motion (natural ground motion, man-made sources) and EM field fluctuations

Linear collider design parameters

- In the following slide, the key top level parameters for current-generation LC designs are given.
- In addition, the parameters of a specific example design for a next-generation 10 TeV collider, which might utilize advanced acceleration concepts, are included. This example will be used in the rest of the talk to provide the basis for requirements for the advanced accelerator systems.
- The disadvantage of choosing a specific example design is some loss of generality in specifying the requirements. The origin of the requirements will be stated as generally as possible in the subsequent discussion, so that extensions to other examples can easily be made.

Linear collider design parameters

Table 2: Linear Collider Top-level parameters

Parameter	GLC/NLC 1 TeV	CLIC 3000 3 TeV	Example at 10 TeV
E_b (Beam energy) [TeV]	0.5	1.5	5.0
N (Electrons/bunch)[$\times 10^9$]	7.5	4	2
f (Bunch repetition rate) [kHz]	23	15.4	18
P_b (Average beam power/beam) [MW]	13.8	14.8	28.8
$\sigma^*_{x,g}$ [nm]	218	61	7.8
$\sigma^*_{y,g}$ [nm]	2.1	0.49	0.13
σ_z [μm]	110	35	4
n_γ	1.18	1.36	1.25
δ_B [%]	8.3	29.8	37.4
$\mathcal{L}$ [$\times 10^{34}$ cm^{-2} s^{-1}]	3.1	11.3	106.5

Parameter tradeoff with *N*: $f \propto P_b/N$ $\sigma^*_x \propto N/n_\gamma$

GLC/NLC linear collider

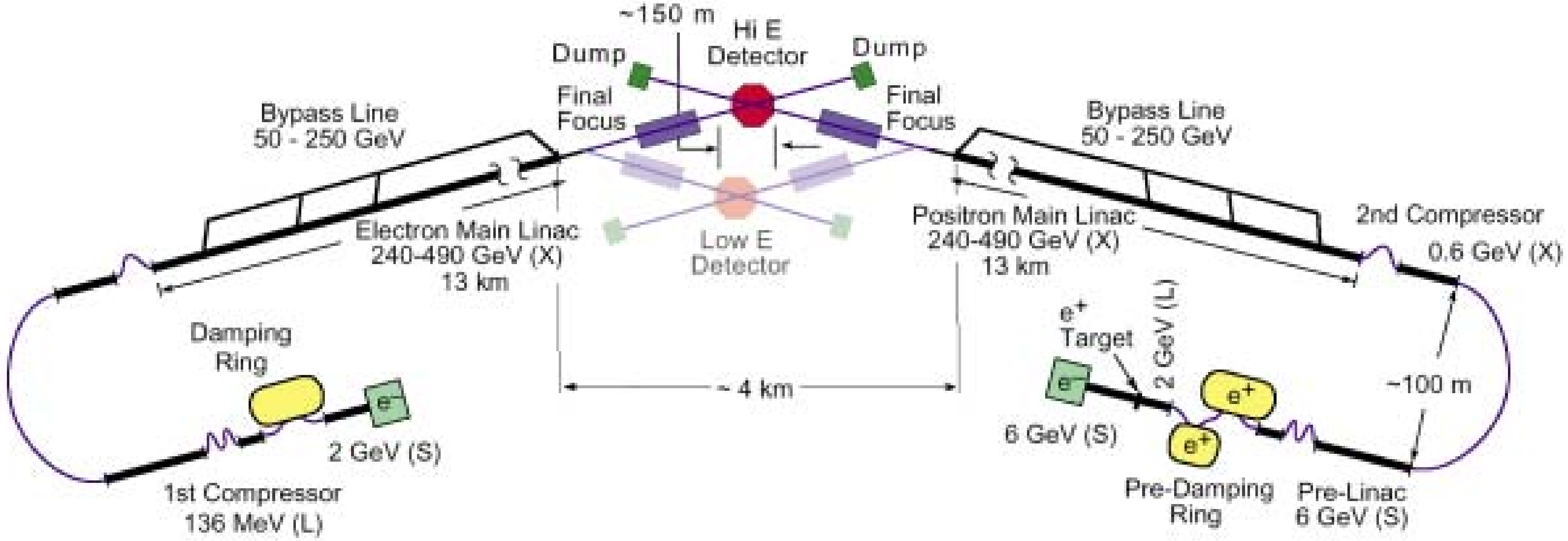


Figure 1.1: Schematic of the JLC/NLC

GLC/NLC: 11.4 GHz, 50 MV/m accelerating structures, modulator/klystron power source, E=1 TeV, efficiency~9%, overall length~ 30 km, wall plug power ~ 300 MW

Compact Linear Collider (CLIC)

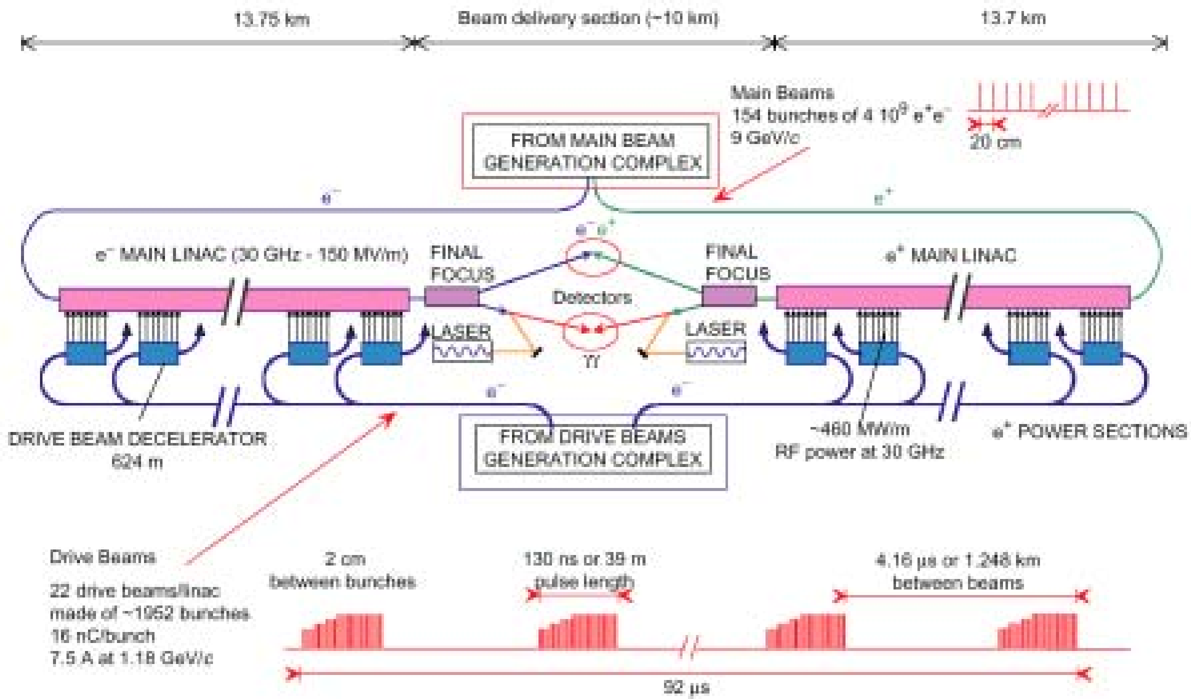
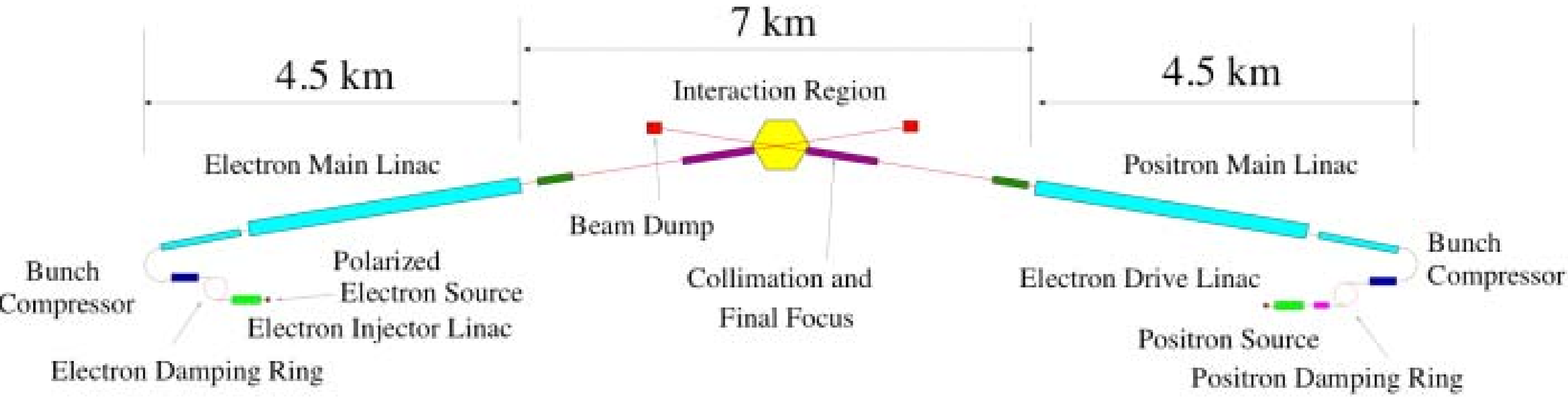


***Fig. 1.1:** Overall layout of CLIC for a centre-of-mass energy of 3 TeV.*

CLIC: 30 GHz, 150 MV/m accelerating structures, two-beam power source, E=3 TeV, efficiency ~9%, overall length ~ 33 km, wall plug power ~ 320 MW

Example 10 TeV LC design with high-gradient acceleration system



10 TeV example: 2 GV/m accelerating structures, E=10 TeV, efficiency ~16%, overall length ~ 16 km, wall plug power ~ 360 MW

Injector requirements

Table 3: Injector requirements

Parameter	GLC/NLC 1 TeV	CLIC 3000 3 TeV	Example at 10 TeV
Beam Energy [GeV]	7.98	8.92	78.92
Electrons/bunch [$\times 10^9$]	7.5	4	2
Bunches/pulse	192	154	150
Pulse repetition rate [Hz]	120	100	120
Beam pulse width [ns]	270	102	30
Bunch separation [ns]	1.4	0.66	0.2
Peak beam current [A]	0.854	0.967	1.60
$\gamma\epsilon_x$ [nm-rad]	3100	600	525
$\gamma\epsilon_y$ [nm-rad]	26	4	3
$\gamma mc^2\delta_E\sigma_z$ [eV-m]	9900	4090	4876

Injector design

- Current-generation injector designs use
  - Particle sources to produce large emittance (polarized) electrons and positrons
  - Damping rings to reduce the beam emittance and flatten the beam
  - Bunch compressors to shorten the bunch
- Direct production of electron beams satisfying the injector requirements is well beyond the current state of the art. Positron beams of this quality would be even more difficult to produce.
- For this reason, our next-generation example injector design is similar to that of the current generation.

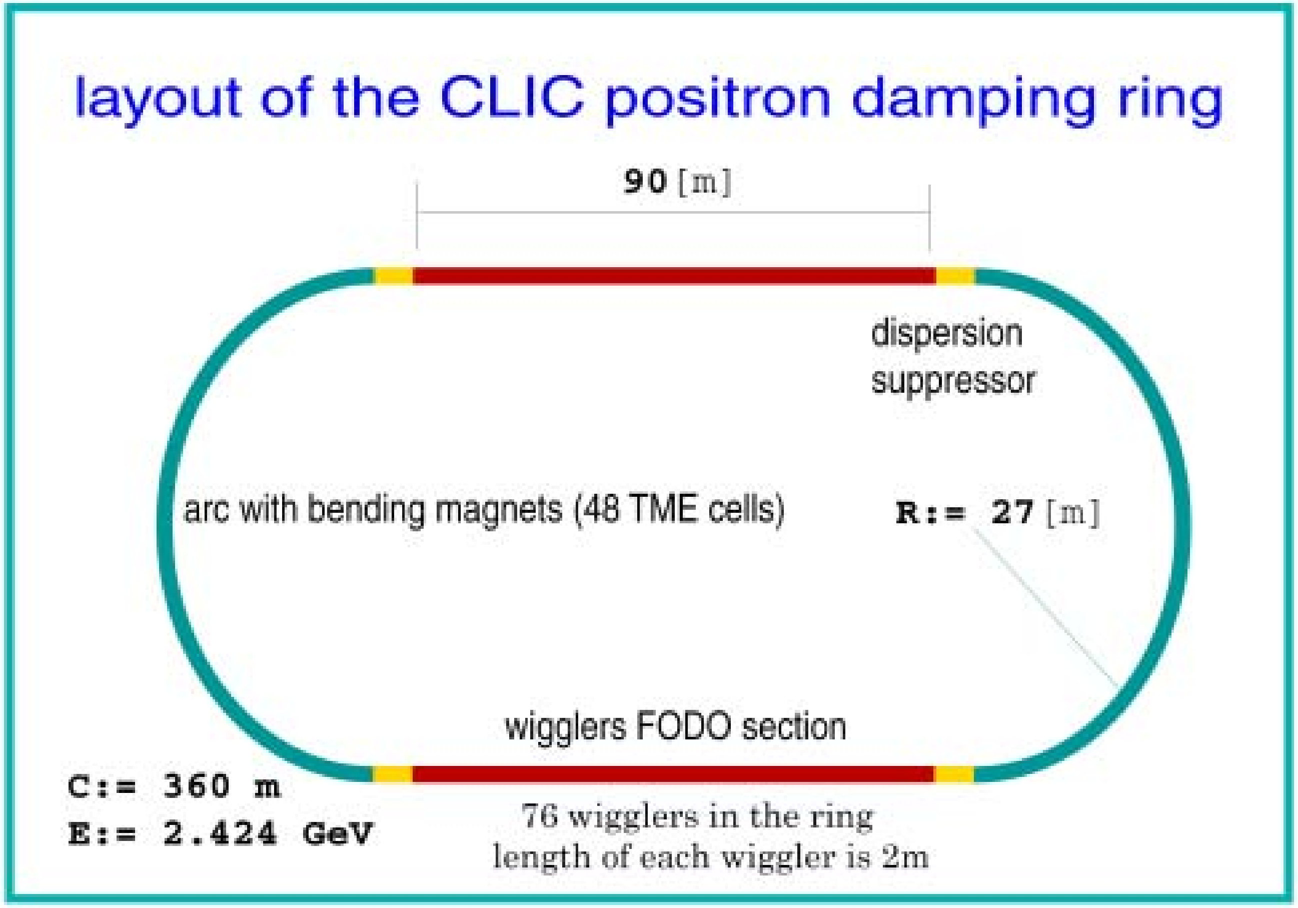
Electron and positron sources

- Electron sources
  - DC polarized photocathode guns
  - Polarization >80%, normalized transverse rms emittance ~50-100 μm-rad, round beams
- Positron sources
  - Conventional (GLC/NLC, CLIC): Bombard a thick high-Z target with a few GeV electron beam, collect positrons from shower
  - Normalized transverse edge emittances ~30,000 μm-rad, round beams
- For this 10 TeV collider example, conventional electron and positron sources should be adequate, although development of polarized-beam cathodes with higher peak current capabilities may be required.

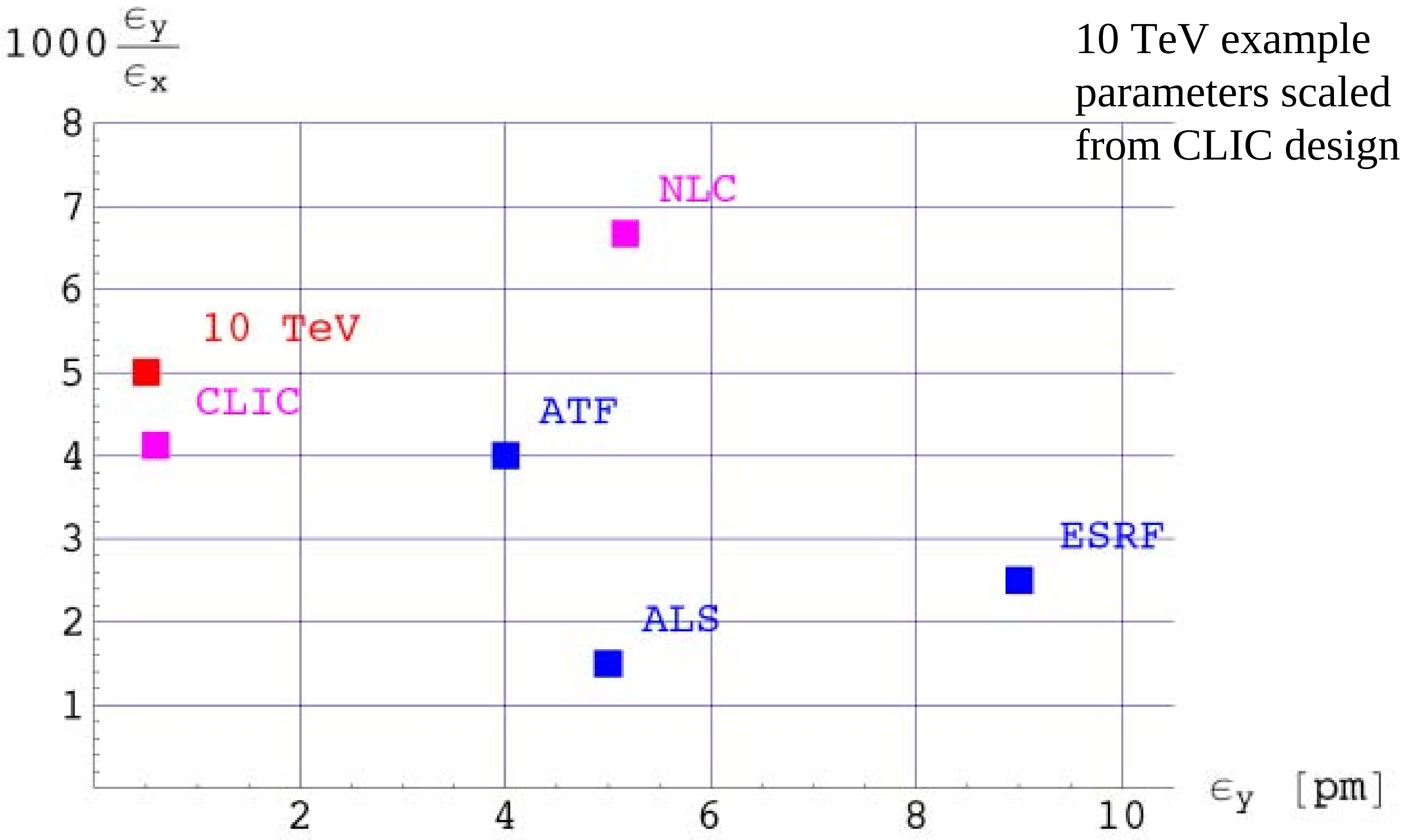
Damping rings-generating low emittance beams

- The very small emittance beams required for high luminosity result from synchrotron radiation damping in specially designed *damping rings*. Some key issues are
  - Magnetic lattice design for low emittance and rapid damping: extensive use of wiggler magnets. The dynamic aperture is limited primarily by sextupole and wiggler nonlinearities.
  - Emittance growth control: intrabeam scattering (IBS), space charge effects, and beam gas scattering must be limited. CLIC damping ring emittances are limited by IBS.
  - Instabilities: interaction of the stored beams with ions generated by ionization of the residual gas (fast ion instability), or (for positrons) with photoelectrons generated by the synchrotron radiation (electron cloud).
  - Beam jitter: Ground motion and vibration of ring magnets must be controlled; extraction devices must be very stable.

CLIC positron damping ring



Demonstrated and required damping ring emittances and coupling



10 TeV example parameters scaled from CLIC design

Bunch compressors

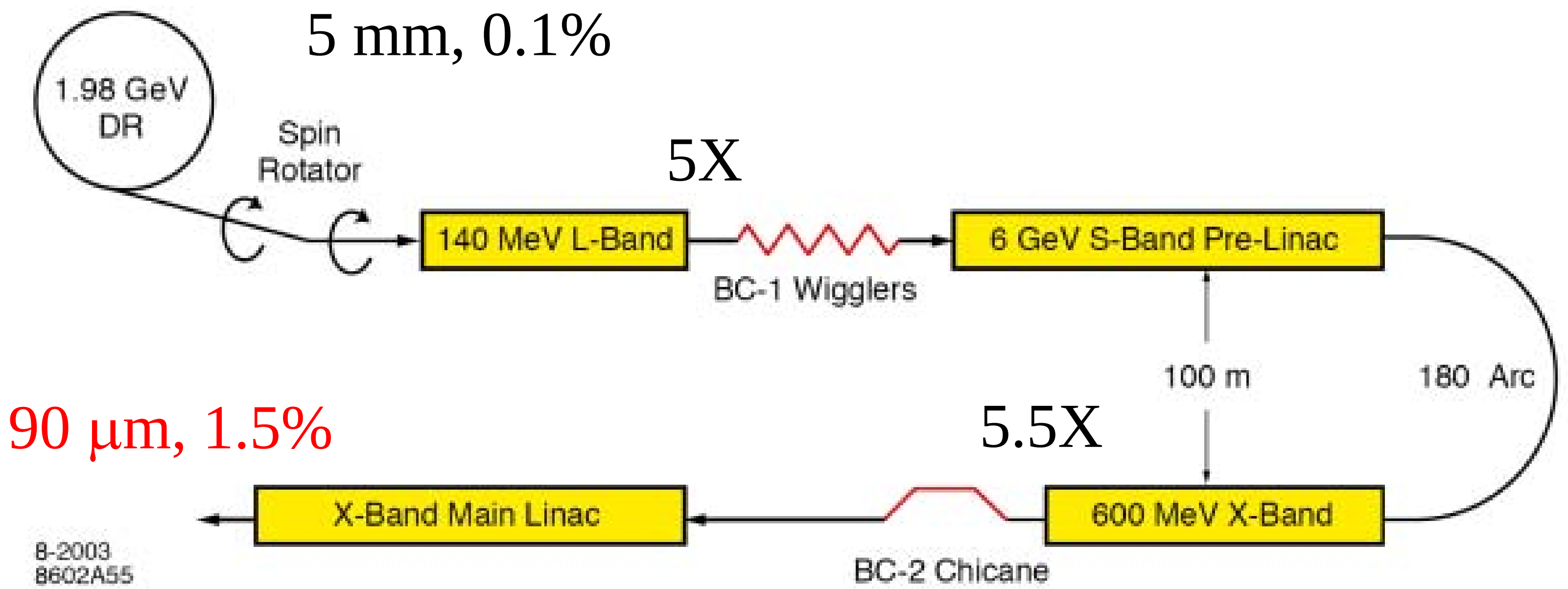
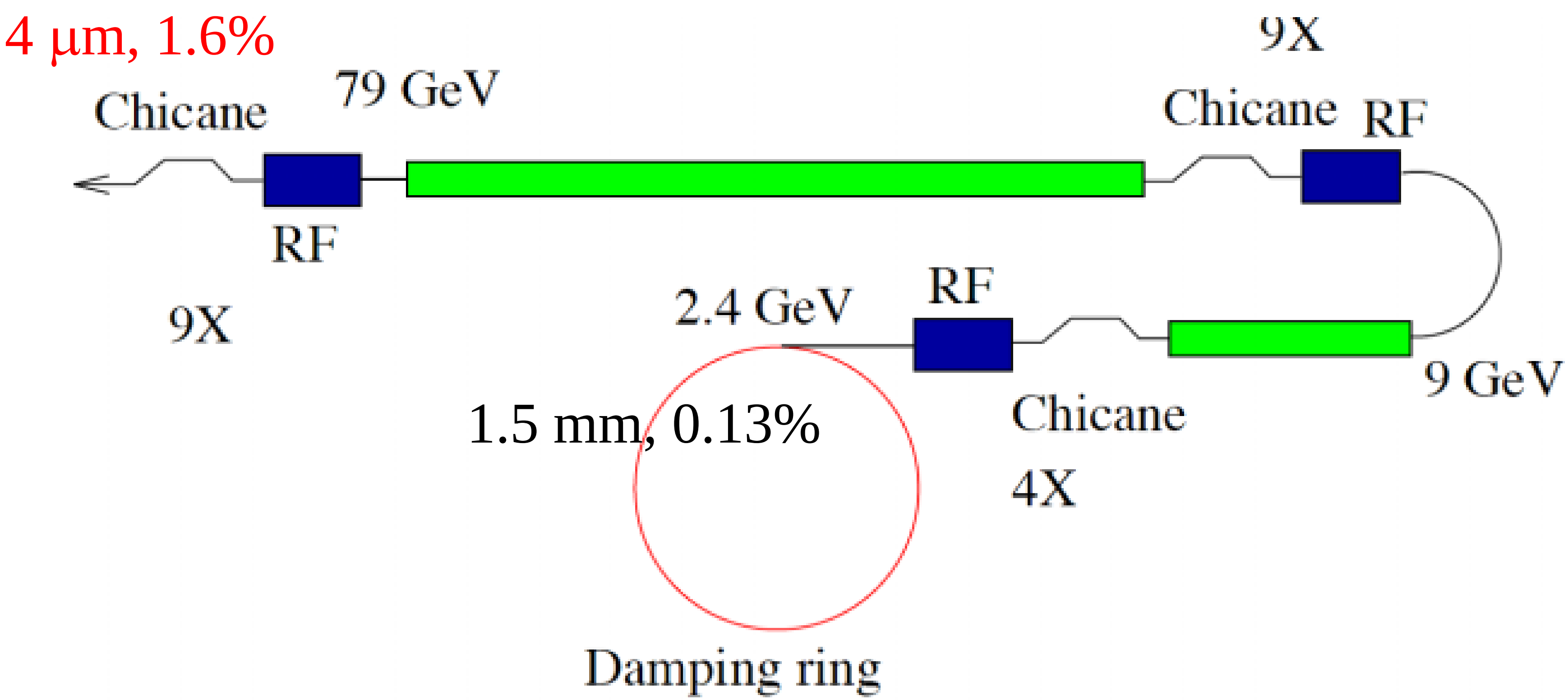


Figure 3.4.4.1: Schematic of two-stage bunch compressor layout.

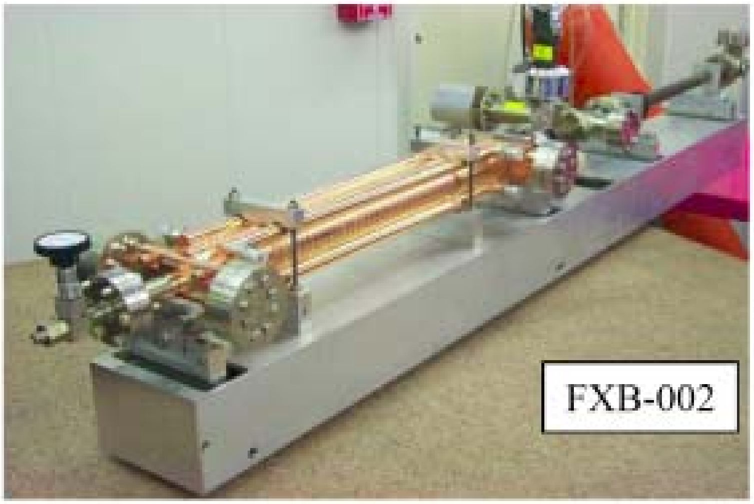
GLC/NLC Two-stage bunch compressor

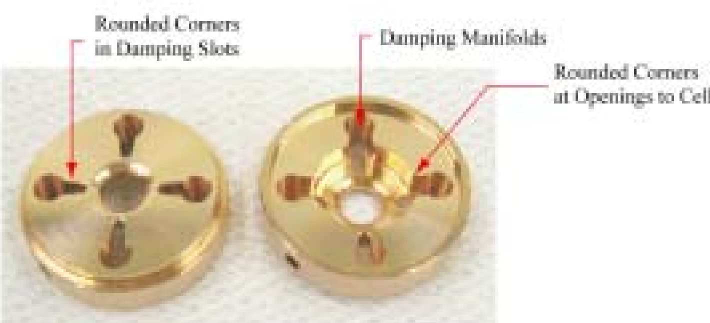
10 TeV example bunch compressor

- 10 Tev example requires 3-stage bunch compressor.
- Coherent synchrotron radiation will probably be an issue in the final stage



Main linac structures: GLC/NLC





GLC/NLC structure

Length: 0.6 m

G=0.05 GV/m

GLC/NLC Power source

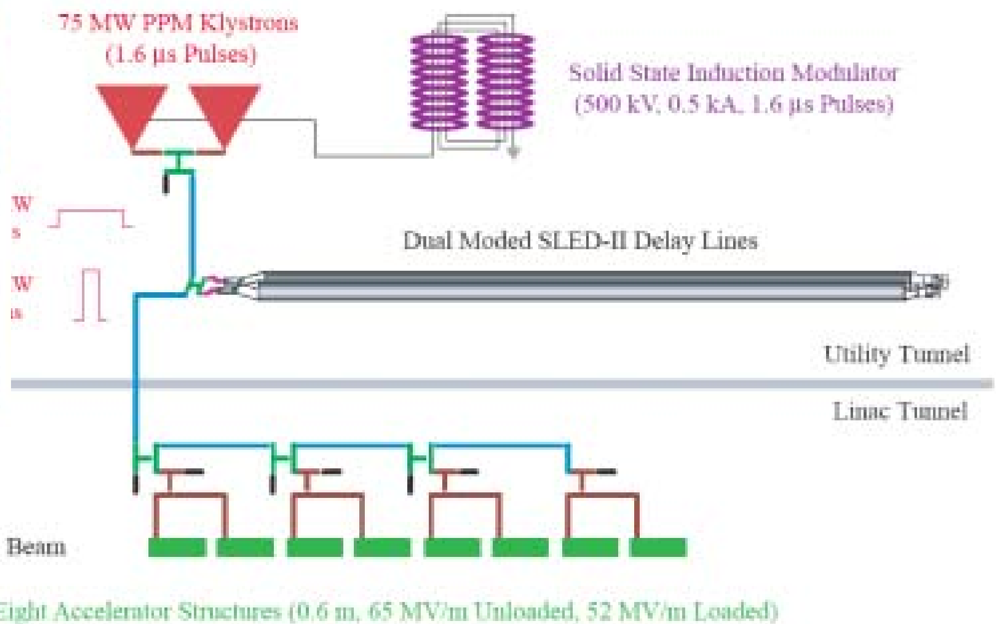
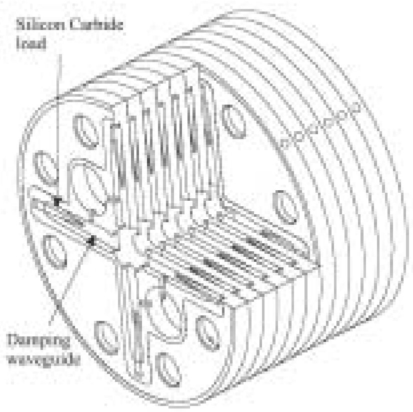


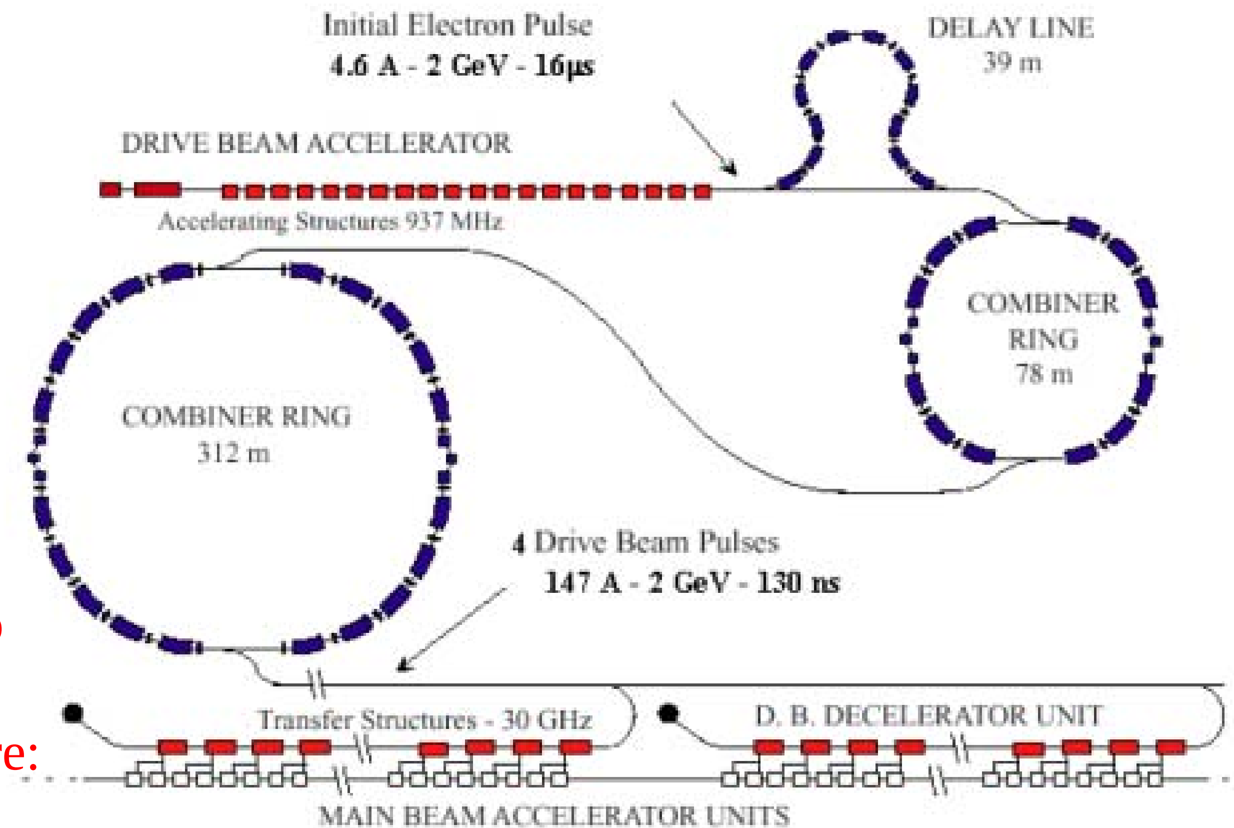
Figure 3.4.5.2: Schematic of an X-band linac RF unit.

Peak power delivered to beam/structure: 27 MW
Energy to beam/structure: 7.2 J

Main linac structures: CLIC



CLIC power source



CLIC structure

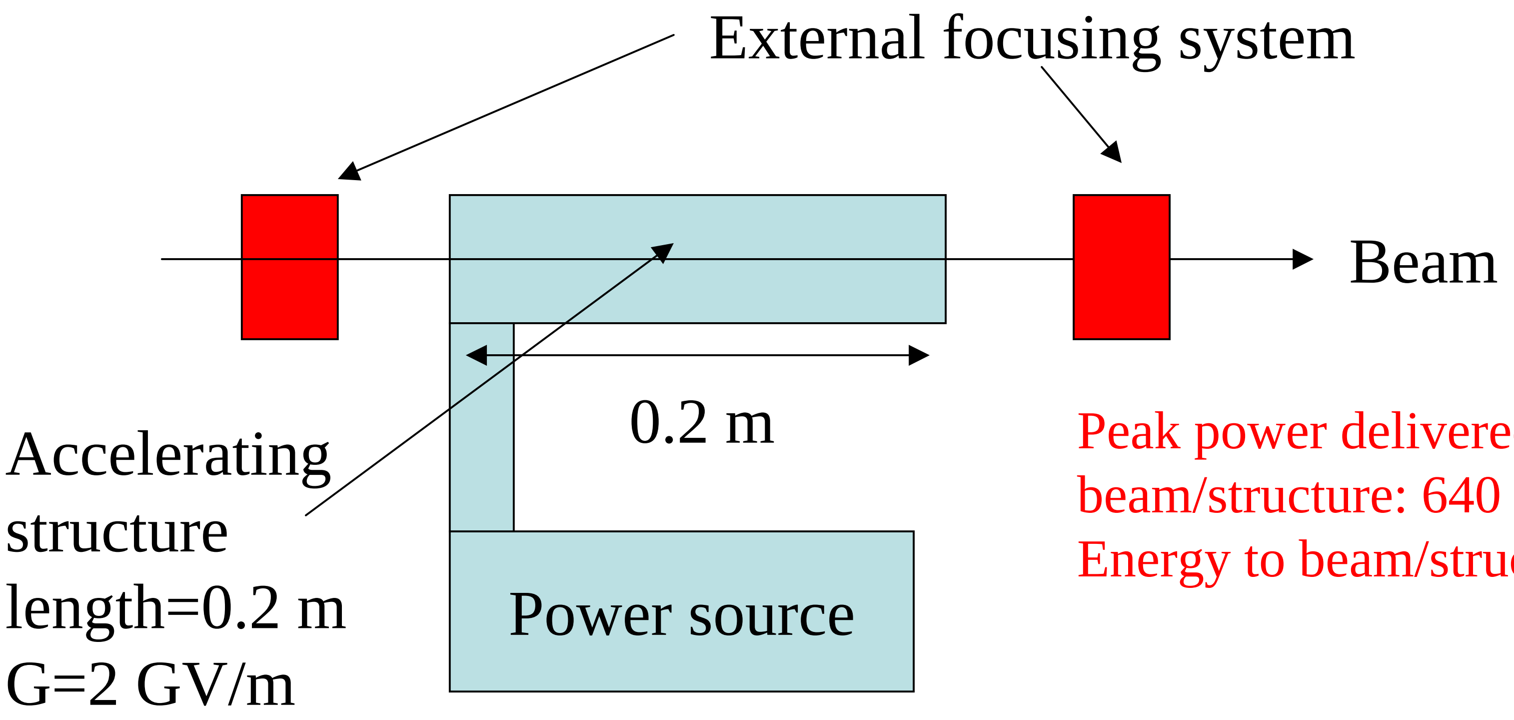
G=0.15 GV/m

Length: 0.5 m

Peak power delivered to beam/structure: 73 MW

Energy to beam/structure: 7.4 J

Main linac structures: 10 TeV example



Peak power delivered to beam/structure: 640 MW
Energy to beam/structure: 19 J

Affordability requirements

Goal: The hardware cost of the advanced acceleration systems for the 10 TeV machine should be roughly the same as the hardware cost of the linacs for the current-generation 1 TeV machine: i.e, x10 reduction in cost/TeV.

Current-generation design cost estimate (in mass production) is about $650K for 4.8 m of structure (0.24 GeV) plus power source => $2700K per GeV.

So the example advanced acceleration system (including power source) should cost $270K per GeV (in mass production). For this example of a 0.2 m unit with 400 MeV of energy gain, the cost should be about $100K.

RF frequency and longitudinal wakefield requirements

On-crest relative energy spread $< \delta_E$ requires RF wavelength :

$$\lambda \geq \pi\sigma_z\sqrt{\frac{2}{\delta_E}}.$$

Longitudinal wakefield compensation at ϕ degrees off-crest:

$$W_{||}(1.5\sigma_z) \lesssim \frac{G\cos\phi}{2\pi\varepsilon_0 N r_e}\left(\frac{\delta_E}{1.25}+\frac{3\pi\sigma_z\tan\phi}{\lambda}\right)$$

For δ_E= 0.5% FWHM energy spread and ϕ=10 degrees:

Parameter	GLC/NLC	CLIC 3000	10 TeV
Maximum RF frequency [GHz]	43.3	136.3	1192.8
Design RF frequency [GHz]	11.3	30	500
$W_{\parallel}(1.5\sigma_z)$ [V/pC/m]	9.21×10^2	4.57×10^3	1.85×10^5

Acceleration of low emittance beams

•To achieve high luminosity, very small vertical emittance beams must be accelerated in very long linacs with small emittance growth (~1-10 nm-rad) and small beam jitter (~0.1σ).

Table 5: Beam sizes and emittance growth budgets in main linacs

Parameter	GLC/NLC	CLIC 3000	10 TeV
rms horizontal beam size at injection [μm]	36.6	11.26	3.77
rms vertical beam size at injection [μm]	3.0	0.8	0.27
Injection energy [GeV]	8	9	79
Injected vertical emittance [nm-rad]	20	2.8	2.4
Budgeted emittance growth [nm-rad]	10	4.9	1.75

•Sources of emittance growth:

- Wakefield induced emittance growth
- Dispersive emittance growth

Control of wakefield-induced single-bunch emittance growth

- The development of head-tail growth (BBU) due to coherent oscillations at injection is controlled through the use of “BNS damping”. This suppresses the resonant driving of the tail via a tune difference between the head and tail of the bunch, established by phasing the bunch off-crest in the rf wave, resulting in a difference in energy between the head and the tail.
- Tolerable energy differences are on the order of 1%. For a 1% energy difference, we need the transverse wakefield to satisfy

$$W_\perp(2\sigma_z) \lesssim \frac{0.038\gamma_i}{\pi\varepsilon_0 N r_e L_{cell}^2}.$$

Injection gamma (γ_i)

Focusing cell length (L_{cell})

Control of single-bunch emittance growth

Structure misalignments will also cause emittance growth. The requirement on the rms structure misalignments is

$$\langle y_{acc}^2 \rangle \lesssim \frac{0.0777\Delta(\gamma\epsilon_y)G}{\delta_{BNS}^2\gamma_i^2\left(\sqrt{\frac{\gamma}{\gamma_i}}-1\right)}\frac{L_{cell}^3}{L_{str}}.$$

Emittance growth can also result from dispersive effects caused by off-axis passage through the quadrupoles. The BPM's are used to measure and align the beam to the quadrupoles, and the tolerance on the BPM-quad rms alignment is

$$\langle y_{BPM}^2 \rangle \lesssim \frac{0.1887\Delta(\gamma\epsilon_y)GL_{cell}^2}{\delta_{BNS}^2\gamma_i^2\left(\frac{\gamma}{\gamma_i}-1\right)}$$

Control of multi-bunch emittance growth due to long-range wakefields

- Requirement on long-range wakefield at the location of the following bunch:

$$W_{\perp}(\Delta_b) < \left| \frac{G}{4\pi\varepsilon_0 N r_e \sqrt{\frac{\gamma}{\gamma_i}}} \right|.$$

• In disc-loaded waveguides, emittance growth due to long range wakes is controlled by RF structure design methods which suppress the effects of dipole modes. This is done by a combination of detuning of the cell dipole modes along the length of a multi-cell cavity, together with damping manifolds which couple out the dipole modes.

Control of wakefield and dispersive emittance growth

Table 6: Transverse Wakefield and alignment requirements

Parameter	GLC/NLC	CLIC 3000	10 TeV
Phase advance/cell [°]	80	80	80
Cell length (injection) [m]	8	4.5	2
Average β_y (injection) [m]	7	3.9	1.75
Number of FODO cells	263	314	274
Allowed $W_\perp(2\sigma_z)$ for 1% BNS energy spread [V/pC/m^2]	1.58×10^4	1.05×10^5	9.36×10^6
Allowed rms structure misalignments [μm]	14	5.3	0.8
Allowed rms BPM misalignments [μm]	2.0	0.74	0.13
Δ_b[ns]	1.4	0.67	0.2
Allowed $W_\perp(\Delta_b)$ [V/pC/m^2]	789	4.65×10^3	4.48×10^5
$\frac{W_\perp(2\sigma_z)}{W_\perp(\Delta_b)}$	20	22.6	20.9

- High injection energy and strong focusing allows for high tolerance for transverse wakes
- Structure and BPM misalignment tolerances are very tight, will require beam-based alignment with very good diagnostics

Jitter of focusing system components

- High frequency component motion which cannot be compensated by train-to-train feedback (frequency of order 1/10 cycle rate and higher) can cause the beams to miss at the collision point. Tolerance is at the 0.1σ level.
- Natural ground motion at these frequencies is ~1-10 nm, or less, at very quiet sites.

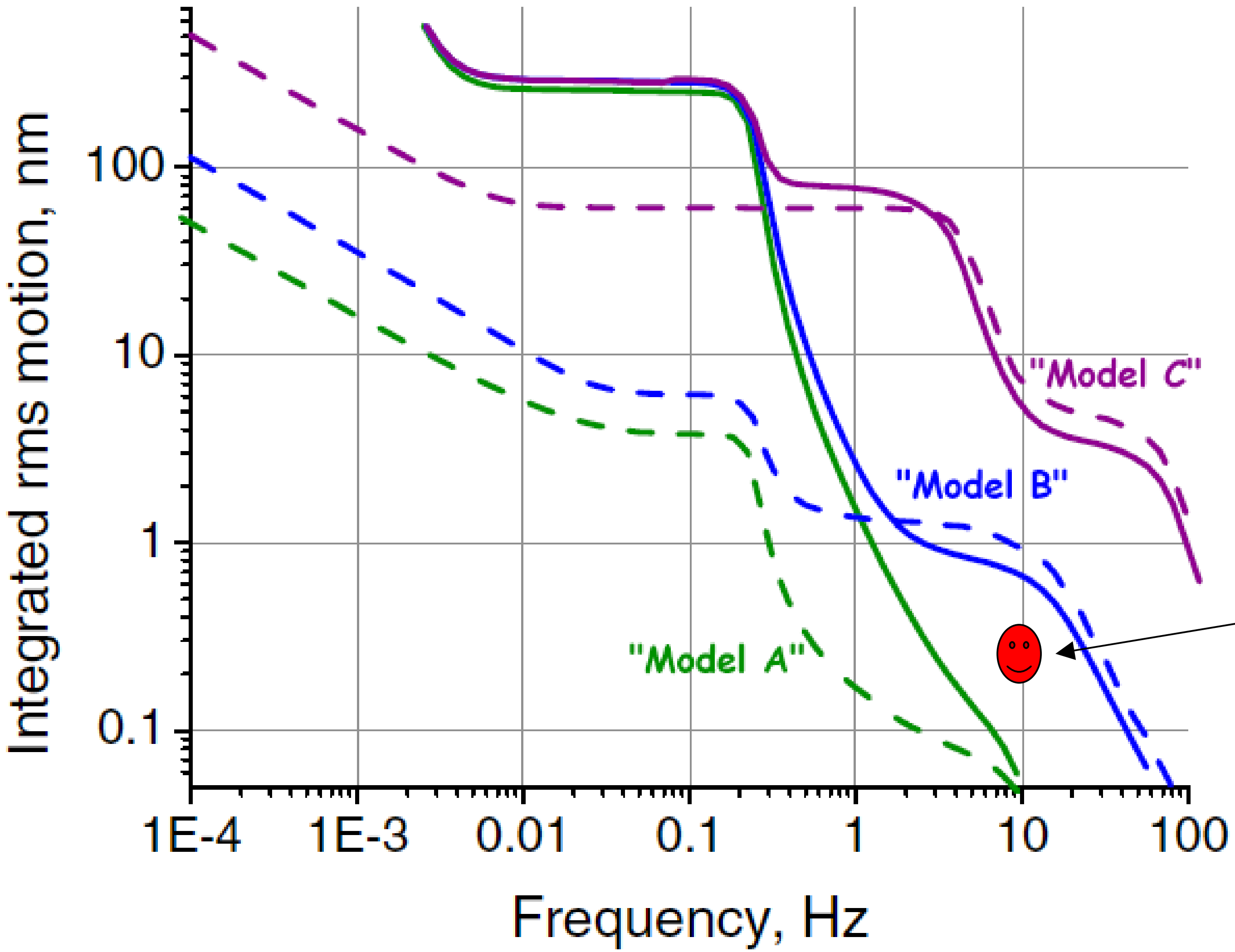
Tolerance on uncorrelated quad jitter for 0.1 σ beam jitter at end of the linac

$$\langle y_q^2 \rangle \lesssim 10^{-2} \times \frac{G\Delta(\gamma\epsilon_y)L_{cell}^2}{6.7128\,(\gamma - \gamma_i)\,\gamma_i}$$

Table 11: Linac quadrupole vibration requirements

Parameter	GLC/NLC	CLIC 3000	10 TeV
$\sqrt{\langle y_q^2 \rangle}$ [nm]	5.1	1.3	0.28

ILC-TRC integrated ground motion models



Solid: Absolute

Dashed: Relative Over 50 m

10 Tev Linac req'm

Residual gas

Multiple Coulomb scattering in residual gas in the linac will cause emittance growth. The limit on gas density is

$$n \lesssim \frac{G}{320\pi\Delta(\gamma\epsilon_y)r_e^2 Z(Z+1)L_{cell}\left(\sqrt{\frac{\gamma}{\gamma_i}}-1\right)}.$$

Assuming Z=1, the requirements for growth at 10% of the emittance budget are

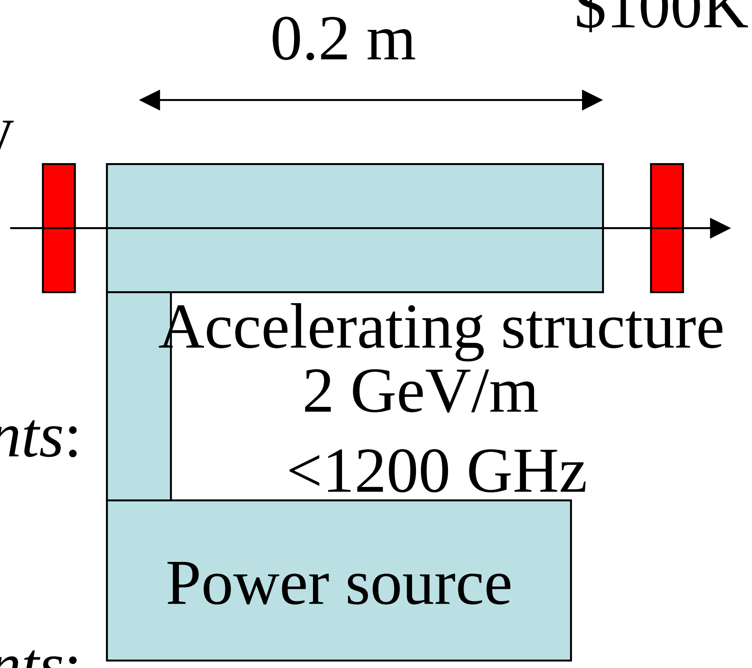
Table 9: Vacuum requirements

Parameter	GLC/NLC	CLIC 3000	10 TeV
Density [cm^{-3}]	1.33×10^{11}	1.9×10^{11}	3.52×10^{12}
Pressure [Torr]	2×10^{-6}	3×10^{-6}	5.5×10^{-5}

Strong transverse focusing fields within the accelerating structure, as in a plasma, could reduce L_{cell}, thus raising this limit, as well as those on the wakefields. However, the jitter requirements will be more severe.

Summary of requirements for accelerating system for 10 TeV LC example

Beam size at injection:
3.8 μm (H) by
0.3 μm (V)



Structure misalignments:
0.8 μm rms

BPM misalignments:
0.13 μm rms

Focusing system jitter:
0.28 nm rms

Gas density < 3.5×10^{12} cm^{-3} hydrogen-equiv.

$100K

15% wall plug->beam efficiency

Delivered to beam:
640 MW peak power;
19 J

RF phase stability: 0.1^{o}
RF amp. stability 0.1%

Transverse wake field
< 9×10^{6} V/pC/m^{2}

Longitudinal wake field
< 2×10^{5} V/pC/m

Beam delivery and final focus system

Table 15: Linear Collider Interaction point parameters

Parameter	GLC/NLC 1 TeV	CLIC 3000 3 TeV	Next-generation 10 TeV
Beam Energy [TeV]	0.5	1.5	5.0
$\gamma\epsilon_x^*$ [nm-rad]	3600	680	600
$\gamma\epsilon_y^*$ [nm-rad]	40	10	5
β_x^* [mm]	13	16	1
β_y^* [μm]	110	70	25
σ_z [μm]	110	35	4
$\sigma_{x,g}^*$ [nm]	218	61	7.8
$\sigma_{y,g}^*$ [nm]	2.1	0.49	0.13
H_D	1.41	1.71	1.93
$\mathcal{L}$ [$\times 10^{34}$ cm^{-2} s^{-1}]	3.1	11.3	106.5
Υ	0.275	4.98	562
n_γ	1.18	1.36	1.25
δ_B [%]	8.3	29.8	37.4

$$\frac{\mathcal{L}}{P_b\sqrt{n_\gamma^3}} \propto \frac{H_{D_y}}{\sqrt{\sigma_z \gamma\epsilon_y^* \beta_y^*}}$$

Issues in beam delivery/final focus system

- Stabilization of final focus quadrupoles at the level of 0.01 nm (0.1 σ) needed…State of the art inertial stabilization now is a few tenths of a nm.
- High gradient final focus magnet design (e.g, 400 T/m). 10 TeV design is at the Oide limit.
- Chromatic correction=>energy bandwidth of the final focus required at the 0.5% FWHM level.
- Coherent e^+-e^- pairs: 0.36/electron
- Collimation and beam halo-collimator wakefields
- Reliability, availability, and machine protection
- Diagnosis and transport of beamstrahlung and spent beam to dump

Conclusions

- Next-generation (10 TeV scale) energy-frontier linear colliders will require inexpensive high gradient acceleration systems to be affordable.
- The high beam power required for high luminosity will require relatively efficient conversion of wall plug to beam power.
- Short bunches are favored to keep beamstrahlung under control.
- Injector systems can be similar to existing designs, although there will be more challenges in the damping rings and bunch compressors.
- Emittance preservation requirements in the linacs will put tight tolerances on structure and focusing system alignments and jitter, as well as limits on structure wakefields and residual gas.
- There will be additional challenges in the beam delivery and final focus systems.