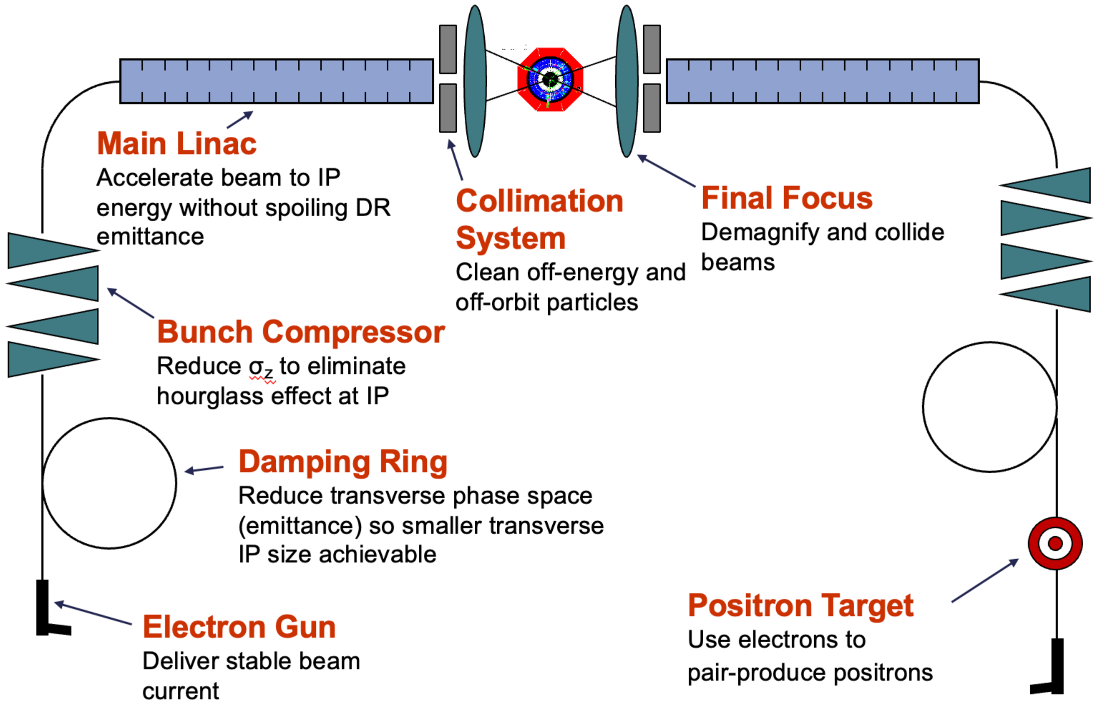
Previous Lecture

- Particle production
- Damping rings with wiggler magnets
- Bunch compressor with magnetic chicane
- Small, short bunches to be accelerated w/o emittance blowup
- Main linac:
  - longitudinal wakefields ⇒ energy spread, chromatic effects
  - Transverse wakefields, minimized by structure design



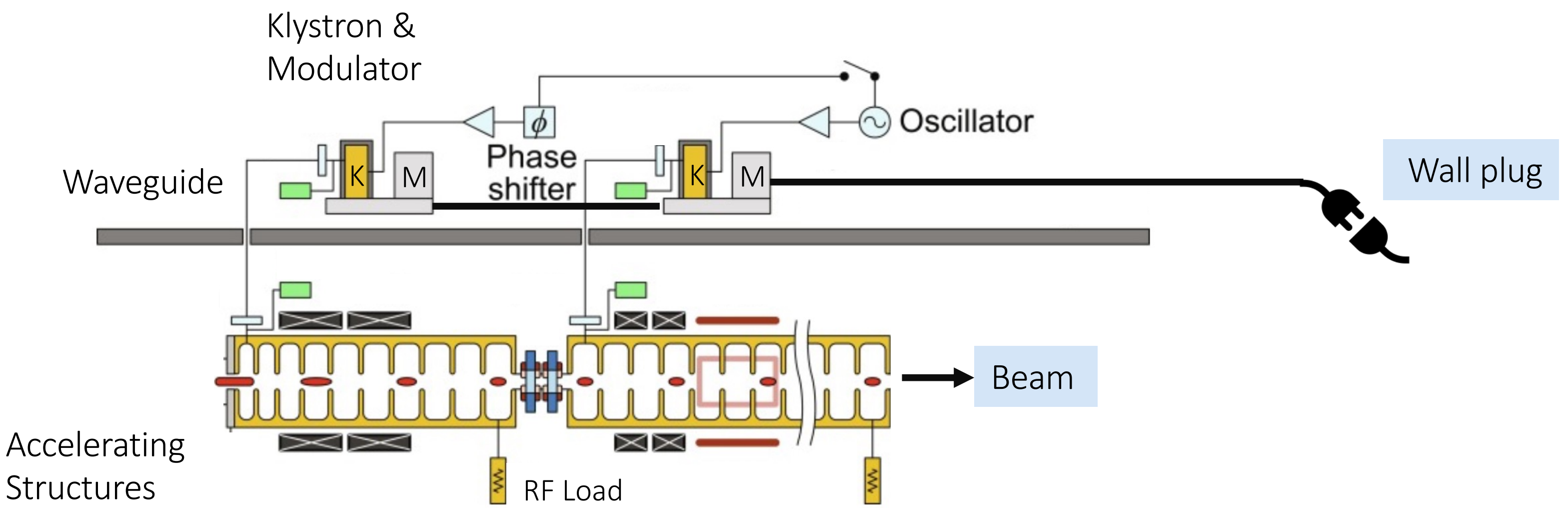
Now: Acceleration in the linac & Beam delivery (collimation, final focus)

Acceleration by RF systems

Need efficient acceleration in main linac

- 4 primary components in the efficiency chain:

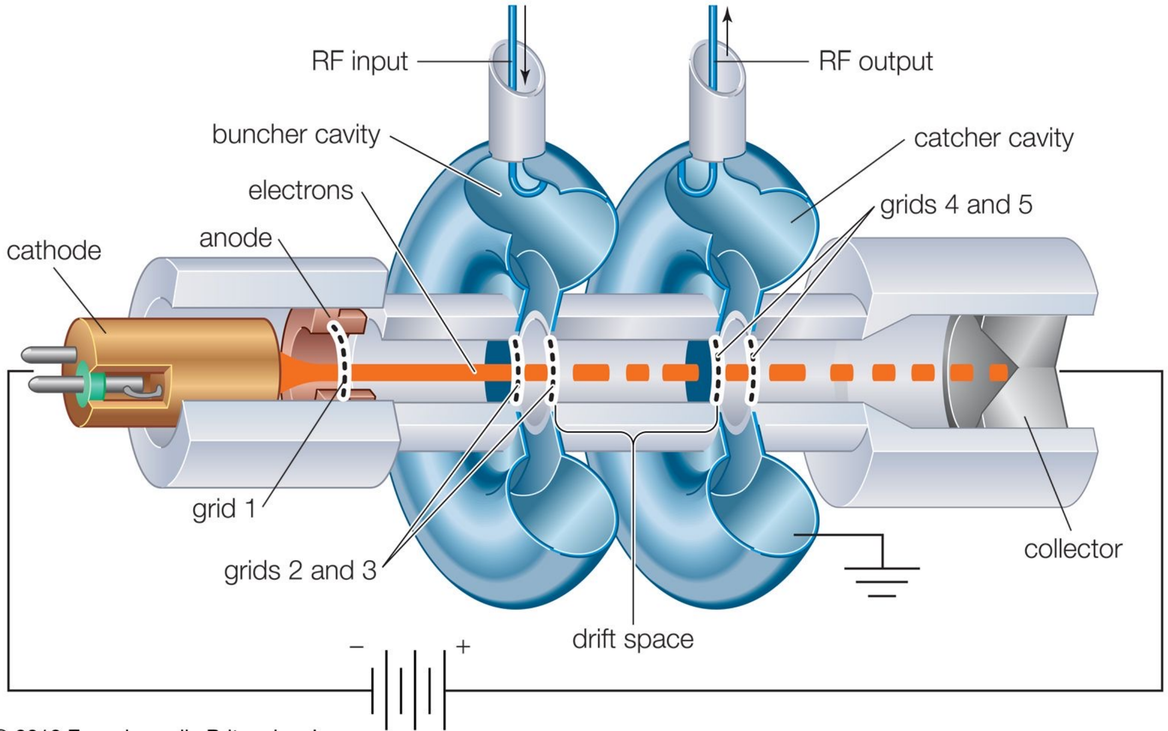
				Typical efficiencies
• Modulators:	convert line AC	→	pulsed DC for klystrons	→ 80%
• Klystrons:	convert DC	→	RF at given frequency	→ 60%
• RF distribution:	transport RF power	→	accelerating structures	→ 90%
	(may include RF pulse compression to increase peak power)			→ 60%
• Accelerating structures:	transfer RF power	→	beam	→ 35%



Klystron amplifier

Converts pulsed DC to RF

- Narrow-band vacuum-tube amplifier at RF frequencies (electron-beam based)
- Low-power signal at the design frequency excites input cavity
- Velocity modulation becomes time modulation in the drift tube
- Bunched beam excites output cavity

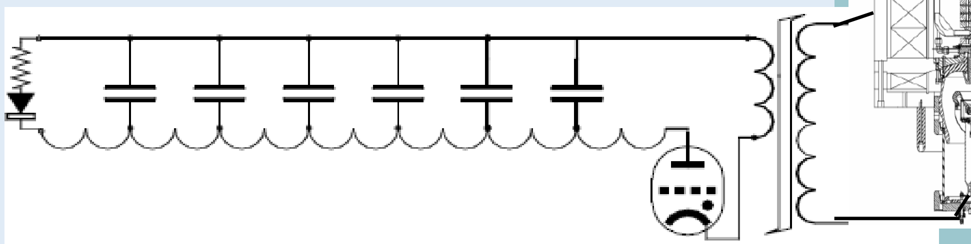


Two-cavities klystron amplifier

Modulator & Klystron

Modulator

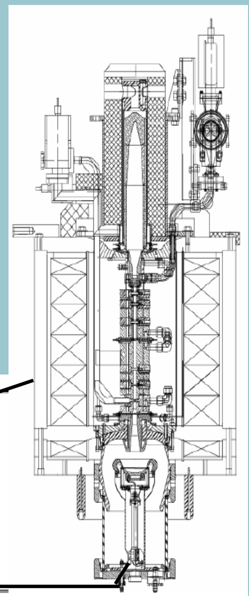
Energy storage in capacitors
charged up to 20-50 kV (between pulses)



High voltage switching and
voltage transformer
rise time > 300 ns

Or solid state device

Klystron



U	150 -500 kV
I	100 -500 A
f	0.2 -20 GHz
P_{ave}	< 1.5 MW
P_{peak}	< 150 MW

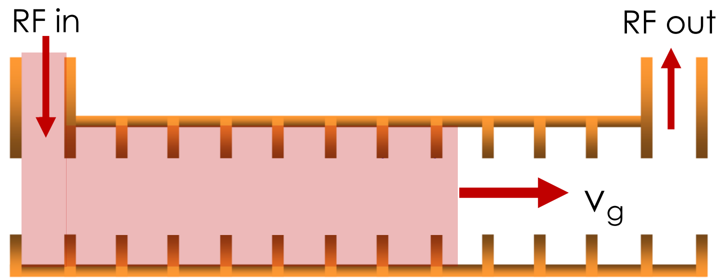
efficiency 40-70%

=> for power efficient operation
pulse length t_P >> 300 ns favourable

RF efficiency: cavities

- Fields established after cavity fill time T_{fill}
- Only then the beam pulse can start
- Steady state: power goes to beam, cavity losses, and (for TW) output coupler

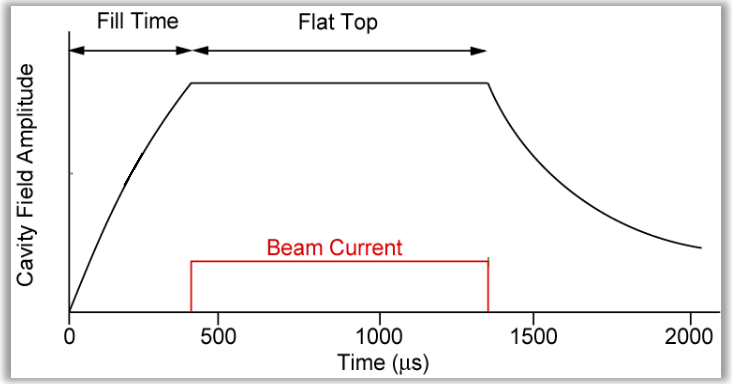
For a travelling wave (TW) structure, the fill time is the time it takes for the electromagnetic energy to propagate down the cavity of a given length.



- Efficiency:

$$\eta_{RF\to beam} = \underbrace{\frac{P_{beam}}{P_{beam}+P_{loss}+P_{out}}}_{\approx 1 \text{ for SC SW cavities}} \frac{T_{beam}}{T_{fill}+T_{beam}}$$

For a standing wave (SW) structure, it's the time it takes for the field to build up to its steady-state value after the RF power is turned on.



- NC TW cavities have larger P_{loss} and P_{out} but smaller fill time T_{fill}

The CLIC Two Beam Scheme

Very high gradients (>100 MV/m) possible with NC accelerating structures at high RF frequencies (~12 GHz)

- High frequencies in NC TW structures→ short RF pulses (~ 100 ns)

BUT

- Modulators/klystrons have lower efficiencies at high frequencies and short pulses
- High-power klystrons more difficult at high frequencies

⇒ Two-Beam scheme: use low frequency efficient modulators/klystrons units to accelerate high current long electron pulses ("drive beam") and extract required high-frequency RF power from the drive beam

The CLIC Two Beam Scheme

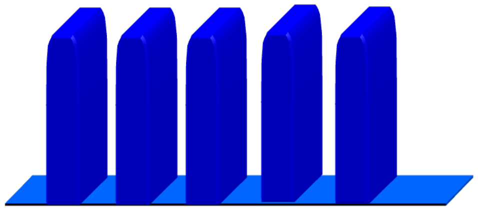
"Few" Klystrons
Low frequency
High efficiency

Power stored in
electron beam

Power extracted
from beam
in resonant structures

Many Acc. Structures
High Frequency
High gradient

RF



RF

Long RF Pulses
P_0 , n_0 , t_0

Electron beam manipulation
Power compression
Frequency multiplication

"Black Box"

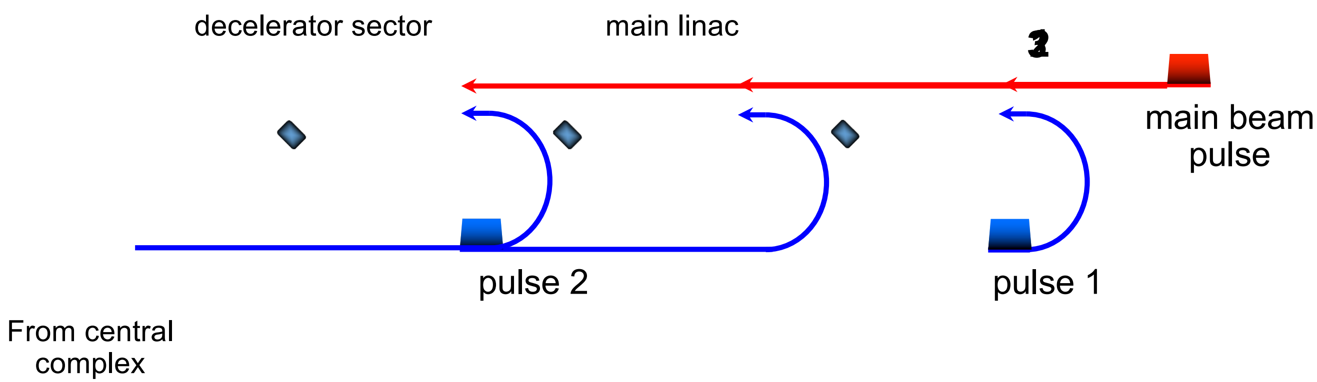
Short RF Pulses
$P_A = P_0 \times N_1$
$t_A = t_0 / N_2$
$n_A = n_0 \times N_3$

The CLIC Two Beam Scheme

Counter propagation from central complex

Instead of using a single drive beam pulse for the whole main linac, several (N_S = 25) short drive beam pulses are used

Each one feed a ~ 880 m long sector of two-beam acceleration (TBA)

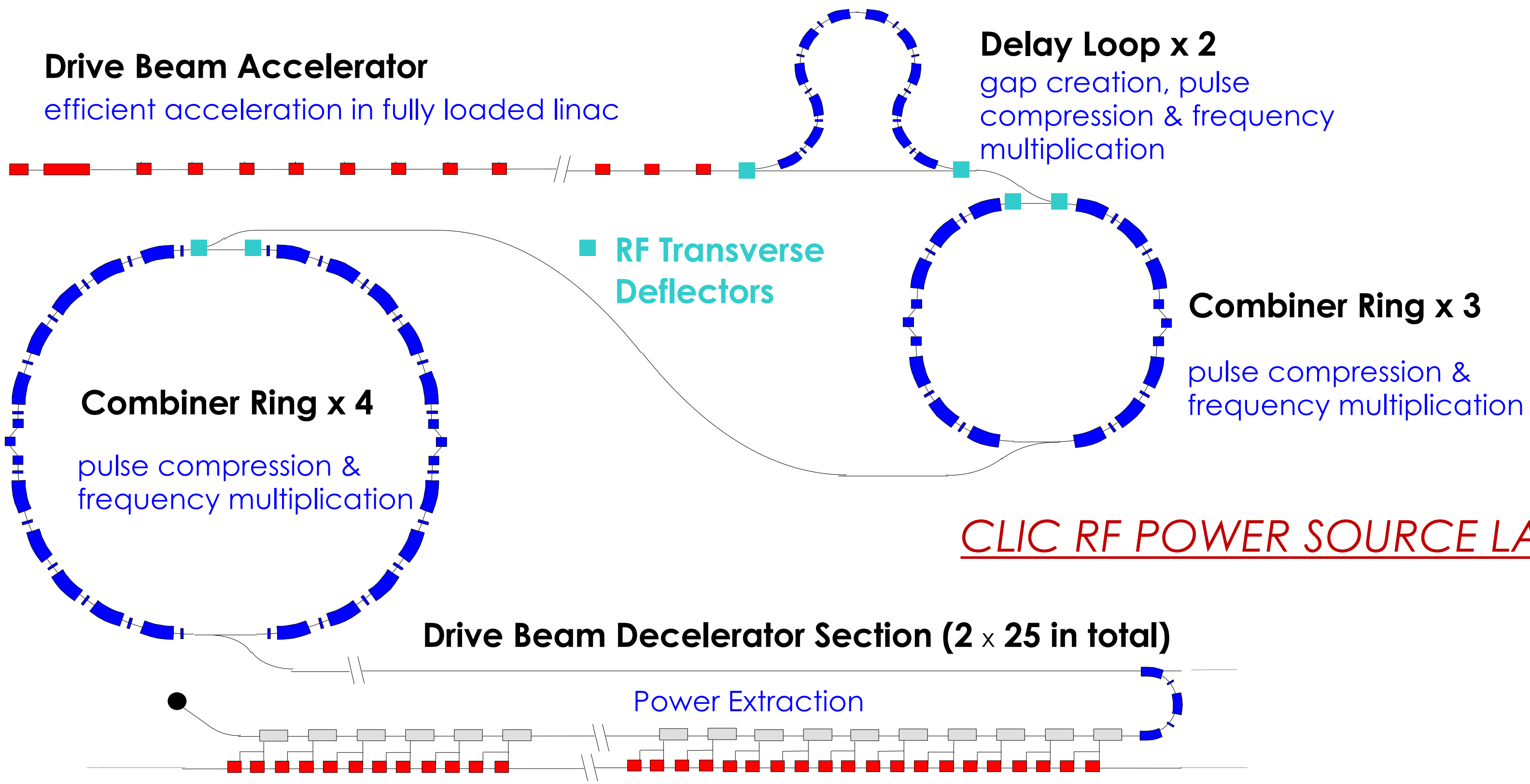


Counter flow distribution allows to power different sectors of the main linac with different time bins of a single long electron drive beam pulse

The distance between the pulses is $2\ L_s = 2\ L_{main}/N_S$ (L_{main}= single side linac length)
The initial drive beam pulse length t_{DB} is given by twice the time of flight through one single linac

⇒ so $t_{DB} = 2\ L_{main} / c$, 148 μs for the 3 TeV CLIC

The Drive Beam Generation Complex



Drive beam time structure - initial

240 ns

148 μs train length – 25 x 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final

240 ns

5.8 μs

25 pulses – **101 A** – 2.5 cm between bunches

Limitations of Gradient

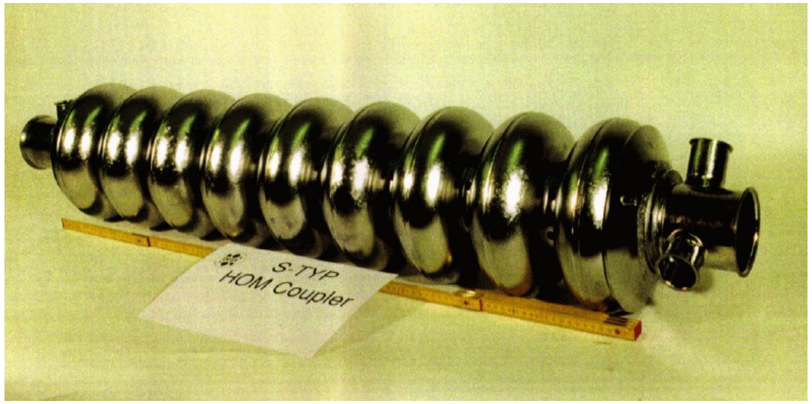
- Surface magnetic field
  - SC structures become normal conducting above H_{crit}
  - NC: Pulsed surface heating ⇒ material fatigue ⇒ cracks ⇒ RF break downs

- Field emission due to surface electric field
  - Vacuum arcs - RF break downs
    - Break down rate ⇒ Operation efficiency
    - Local plasma triggered by field emission ⇒ Erosion of surface
  - Dark current capture
    ⇒ Efficiency reduction, activation, detector backgrounds

- RF power flow
  - RF power flow and/or iris aperture apparently have a strong impact on achievable E_{acc} and on surface erosion
    Mechanism not fully understood (more energy available for RF breakdowns?)

Superconducting cavity technology

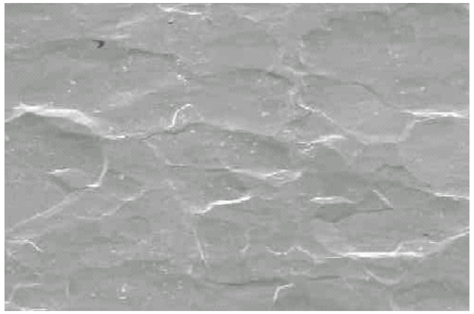
- In the past, SC gradient typically 5 MV/m and expensive cryogenic equipment
- TESLA development (then E-XFEL): new material specs, new fabrication and cleaning techniques, new processing techniques
  - Significant cost reduction
  - Gradient substantially increased



Electropolishing technique has reached ~35 MV/m in 9-cell cavities

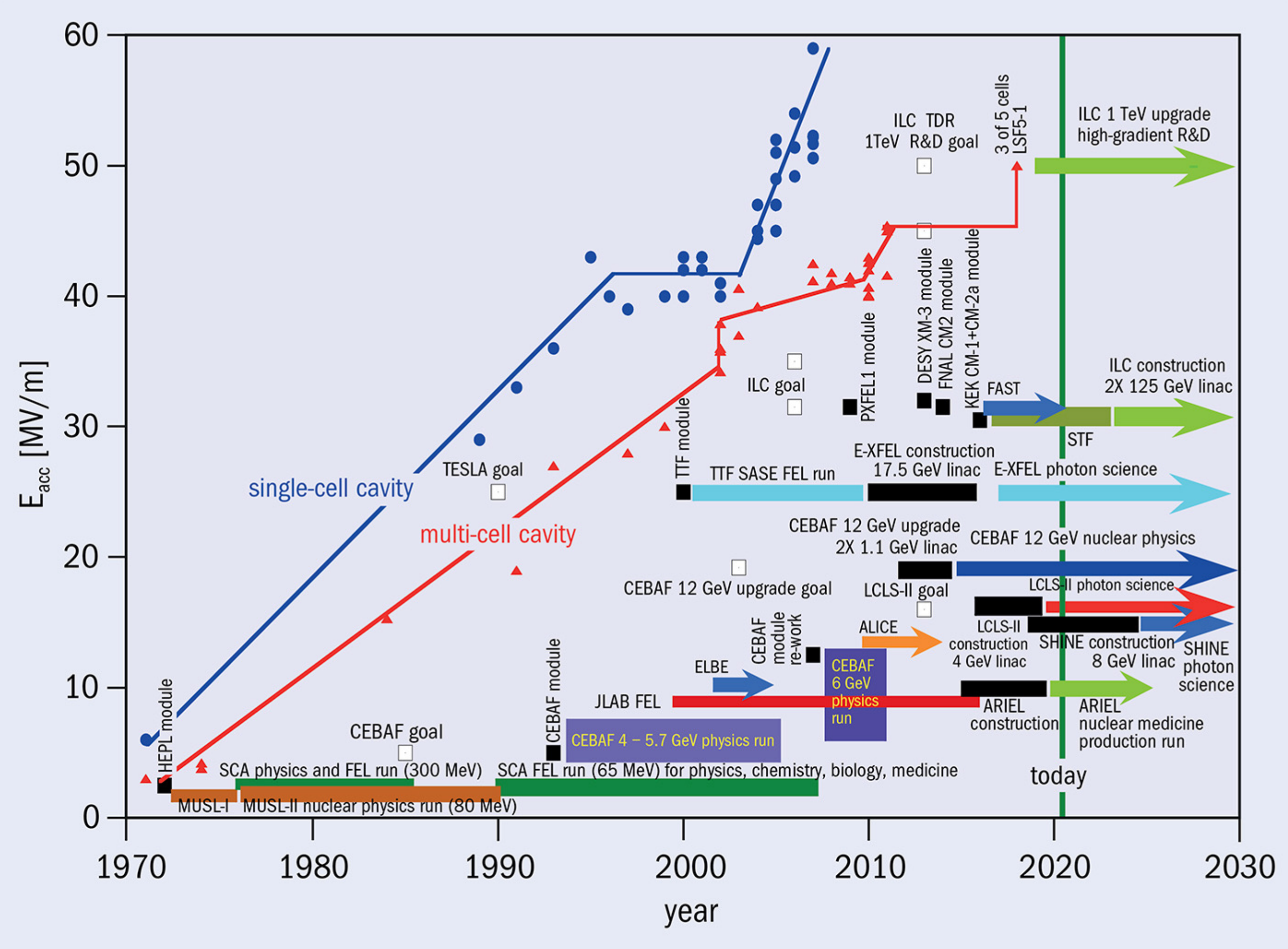
⇒ 31.5 MV/m ILC baseline

- Mainly limited by critical magnetic field H_{crit} above which no superconductivity exists



⇒

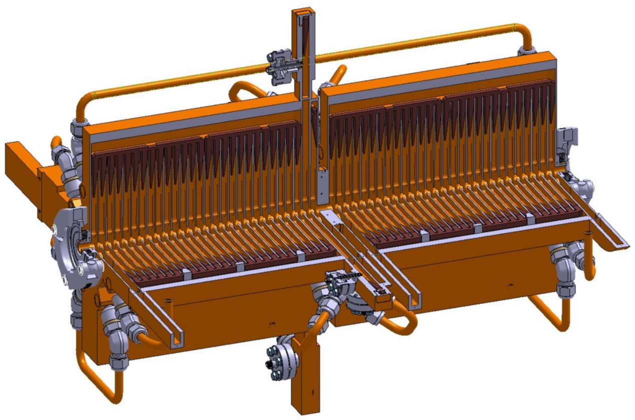
Achieved SC accelerating gradients

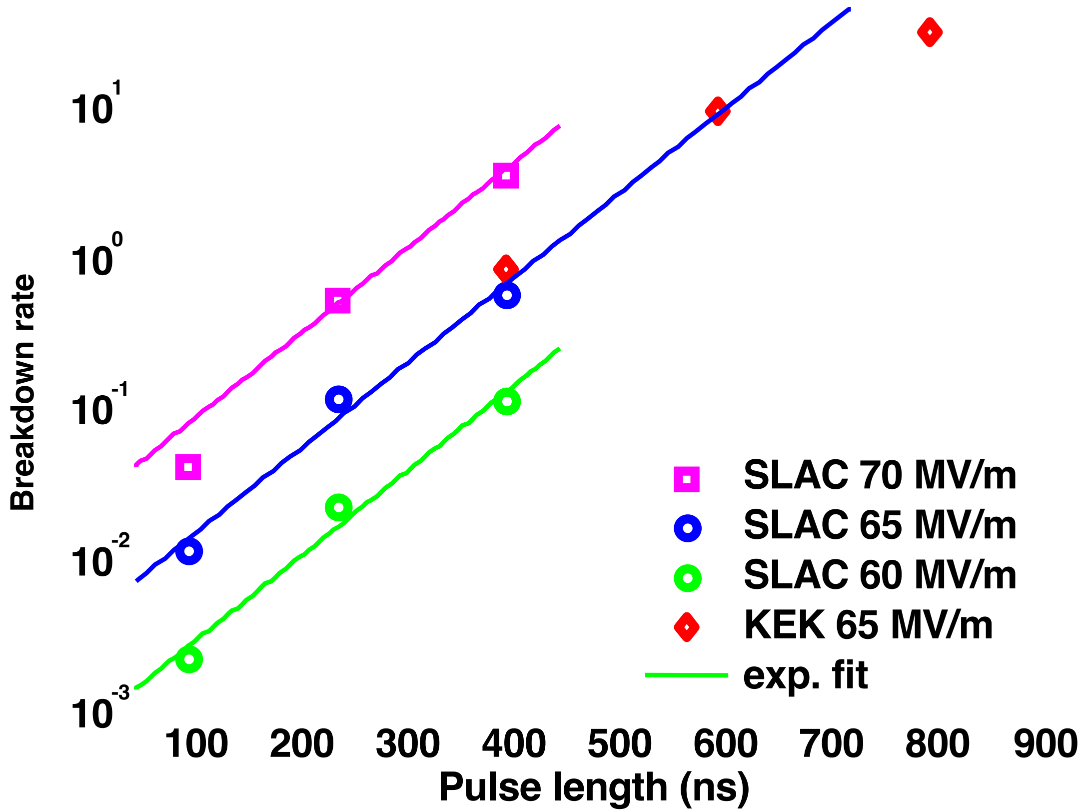


CERN Courier 2020

Breakdown-rate vs pulse length

- Higher breakdown rate for longer RF pulses
- Usable gradient scaling with the inverse square root of the pulse length

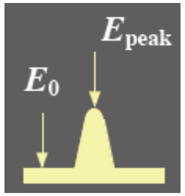




NC Structure gradient and RF conditioning

- Material surface has some intrinsic roughness (e.g., from machining)

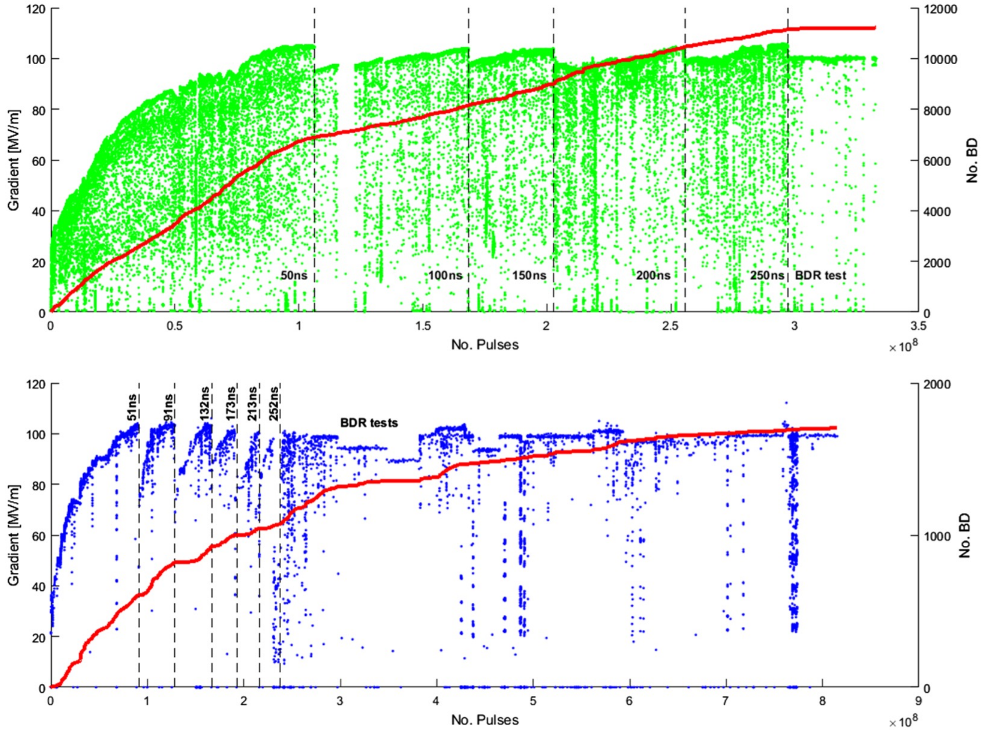
$$E_{peak} = \beta E_0$$



- Leads to field enhancement
  β field enhancement factor
- Need conditioning to reach ultimate gradient
  RF power gradually increased with time
  - RF processing can melt field emission points
  - Surface becomes smoother
  - Field enhancement reduced

  ⇒ higher fields less breakdowns
- More energy: molten surface splatters and generates new field emission points!
- Excessive fields can also damage the structures

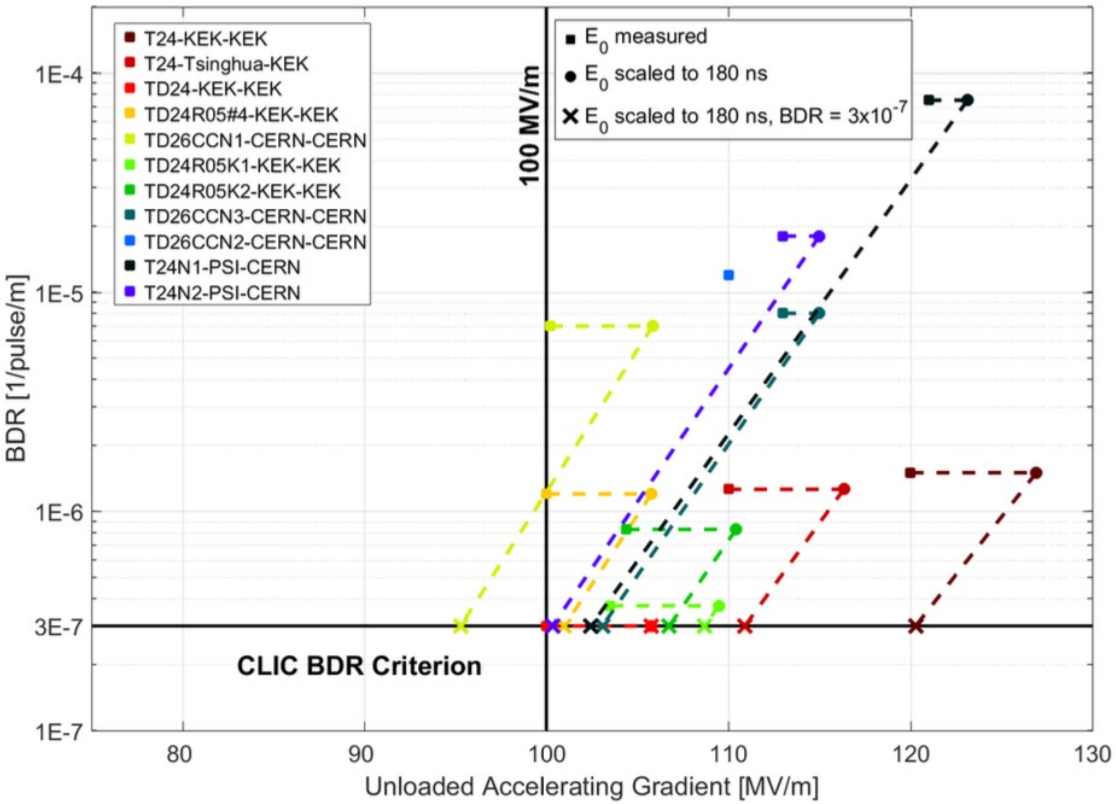
RF conditioning process of CLIC structures @ CERN and KEK

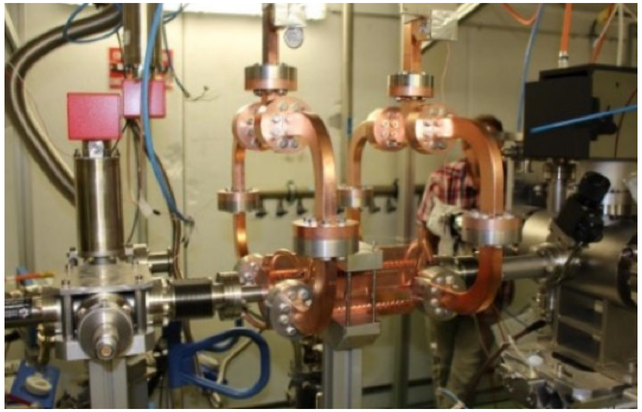


W. Wuensch

Breakdown-rate vs gradient

Achieved performances of CLIC acceleration structures





Structure under high-power test

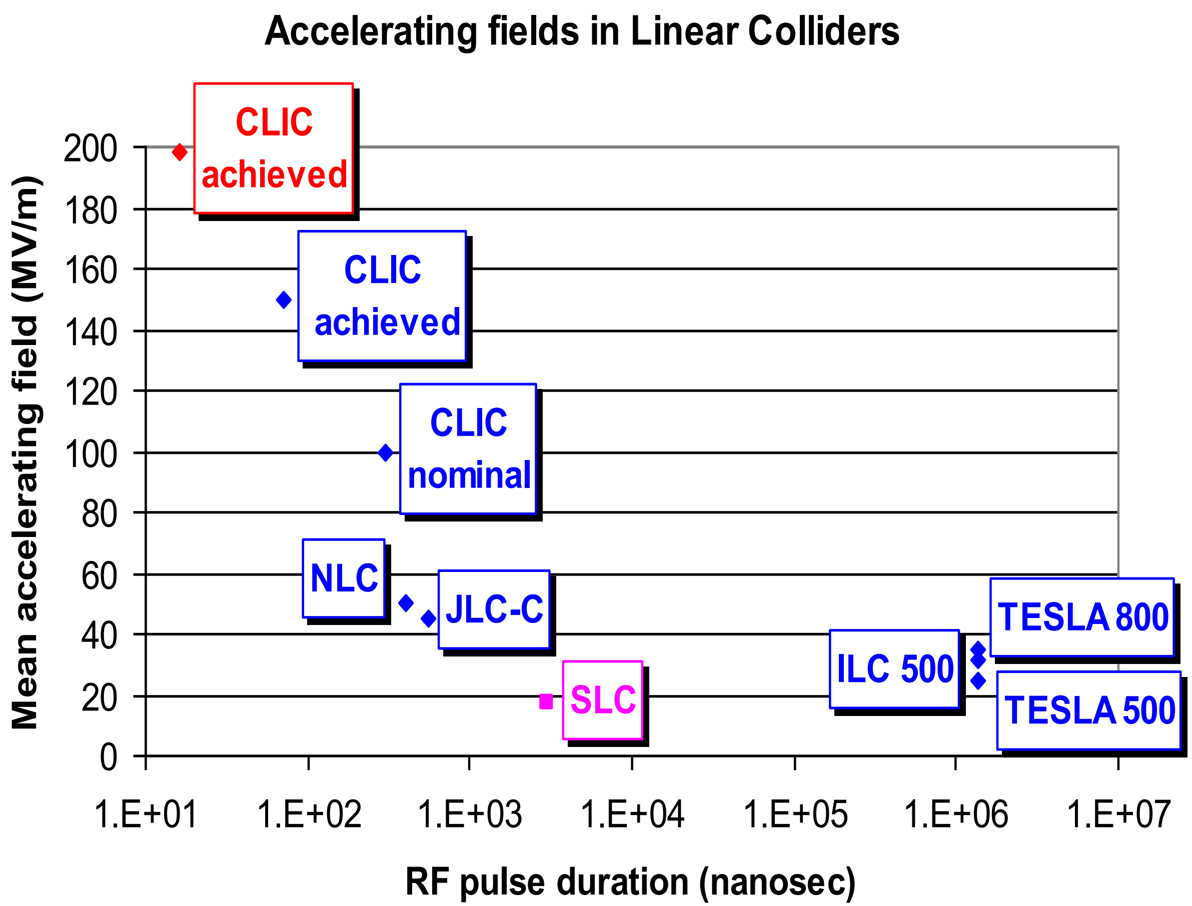
The vertical axis represents the breakdown rate per metre (BDR).

The final operating conditions of the tests are indicated by squares. Known scaling is used to determine the performance for the nominal CLIC pulse duration (dashed lines connecting squares to circles) and subsequently for the CLIC-specified breakdown rate of 3×10^{-7} m^{-1} (dashed lines connecting circles to crosses).

Accelerating gradient

- Normal conducting cavities have higher gradient with shorter RF pulse length

- Superconducting cavities have lower gradient (fundamental limit) with long RF pulse

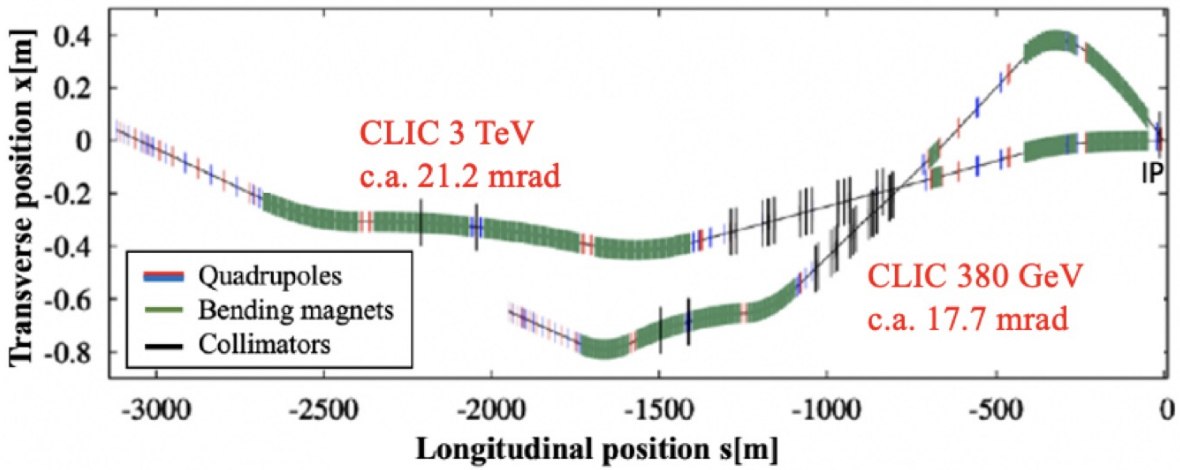


The beam delivery system

The beam delivery system (BDS) in a linear collider transports e+ e- beams from the accelerating linacs to the interaction point (IP)

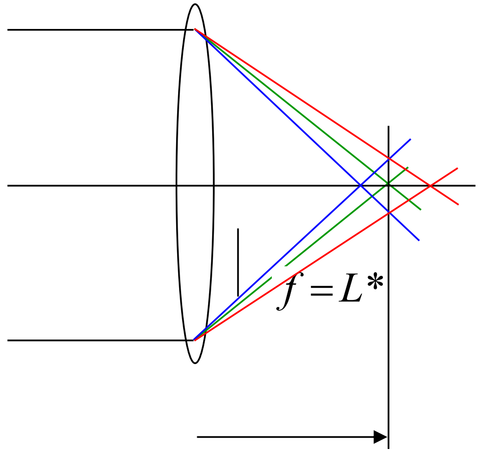
Its key functions include

- Precisely focusing the beams to nanometer sizes at the IP to maximize luminosity
- Collimating the beam halo to protect the detector from background
- Performing precise diagnostics to measure beam parameters like energy, emittance, and polarization



Final Focus: chromaticity

- Need strong quadrupole magnets for the final doublet
- Typically hundreds of Tesla/m
- Get strong chromatic aberrations



for a *thin-lens* of length *l*: $$\frac{1}{f} \approx k_1 l$$

change in deflection: $$\Delta y'_{quad} \approx -k_1 l\, y_{quad} \frac{\delta}{1+\delta} \approx -k_1 l\, y_{quad}\, \delta$$

change in IP position: $$\Delta y_{IP} \approx f\, \Delta y'_{quad} = y_{quad} \delta$$

RMS spot size: $$\left\langle \Delta y_{IP}^2 \right\rangle = \left\langle y_{quad}^2 \right\rangle \left\langle \delta^2 \right\rangle = \beta_{quad} \varepsilon_y \delta_{\mathrm{rms}}^2$$

Final focus: Chromaticity

- Small β^* $\Rightarrow$ β_{FD} very large (~ 100 km)

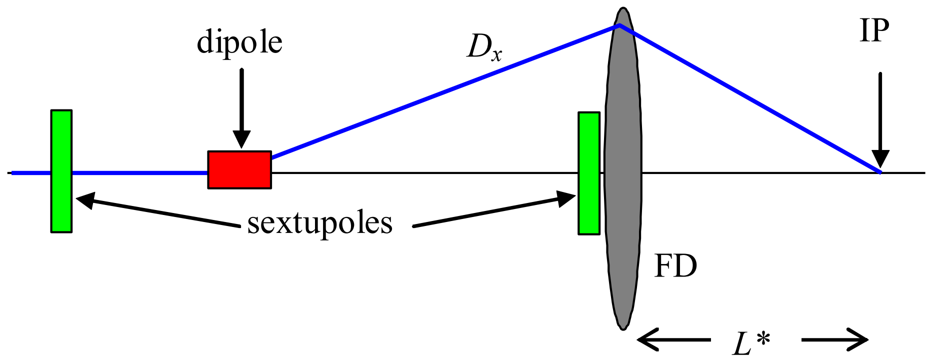
for δ_{rms} ~ 0.3% $\Rightarrow$ $\sqrt{\langle \Delta y_{IP}^2 \rangle} \approx 20-40\ \mathrm{nm}$

- Definitely much too large
- We need to correct chromatic effects

$\Rightarrow$ introduce sextupole magnets

$$B_x = s\,x\,y$$

$$B_y = \frac{1}{2} s \left(x^2 + y^2 \right)$$

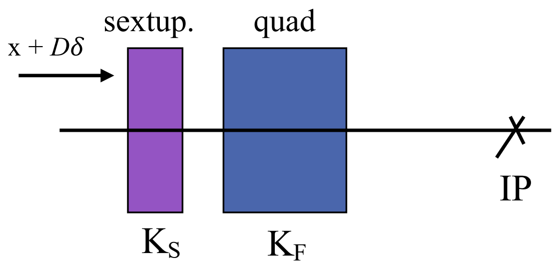


- Use dispersion D_x:

$$x = x_o + D_x \delta$$

Chromaticity correction

Combine quadrupole with sextupole and dispersion



y plane straightforward
x plane more tricky

Quad: $$\Delta x' = \frac{K_F}{(1+\delta)}(x + D\delta) \Rightarrow K_F(-\delta x - D\delta^2)$$

chromaticity

Second order dispersion

Sextupole: $$\Delta x' = \frac{K_S}{2}(x + D\delta)^2 \Rightarrow K_S D(\delta x + \frac{D\delta^2}{2})$$

$$\Delta x' = \frac{K_F}{(1+\delta)}(x + D\delta) + \frac{K_{\beta\text{-match}}}{(1+\delta)} x \Rightarrow 2K_F(-\delta x - \frac{D\delta^2}{2})$$

$$K_{\beta\text{-match}} = K_F \qquad K_S = \frac{2K_F}{D}$$

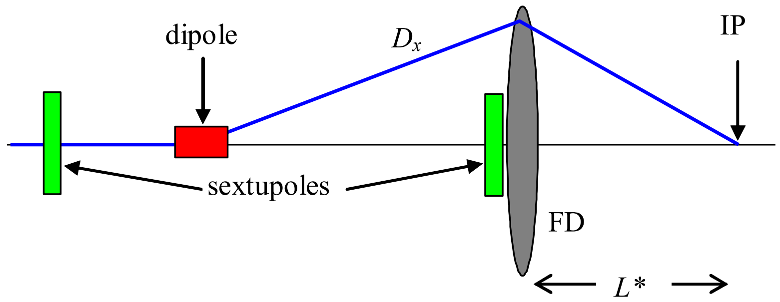
Could require $K_S = K_F/D$

⇒ ½ of second order dispersion left

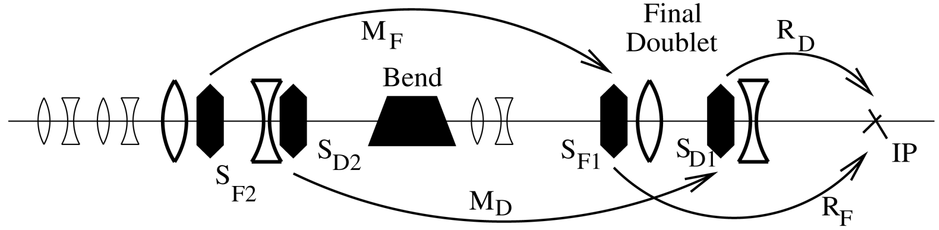
Create as much chromaticity as FD upstream

⇒ second order dispersion corrected

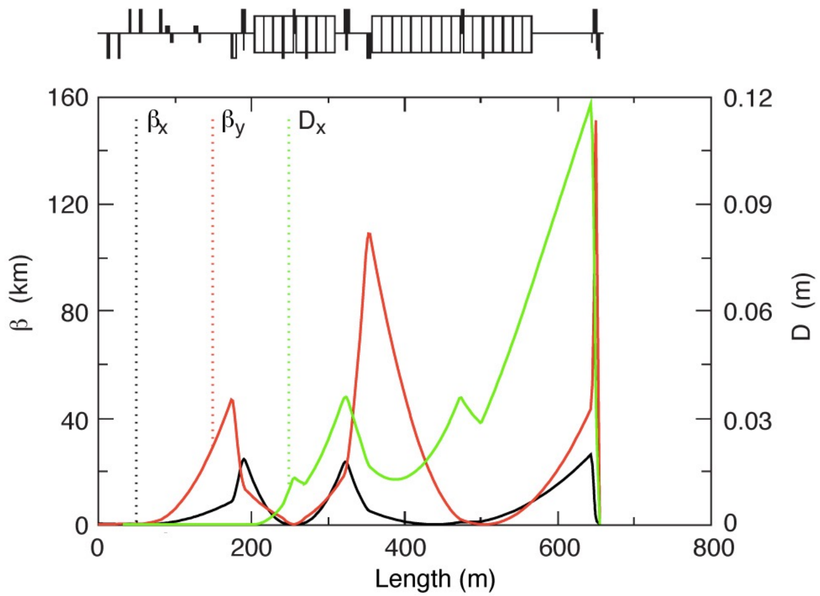
Final Focus: Chromatic Correction



Correction in both planes



- Relatively short (few 100 m)
- Local chromaticity correction
- High bandwidth (energy acceptance)



- FF tested at ATF2 (KEK Japan)
  - 44 nm achieved (37 nm design)
  - scales to 6 nm at ILC (5 nm)

"2001 Report on the Next Linear Collider", SLAC-R-0571

Final focus: fundamental limits

- From the hour-glass effect: $\beta_y \cong \sigma_z$

- For highest energies, there is an additional fundamental limit:
  synchrotron radiation in the final focusing quadrupoles
  ⇒ beamsize growth at the IP

- So-called Oide Effect: the minimum beam size is $\sigma \approx 1.83 \left(\frac{r_e \lambda_e}{2\pi} F\right)^{1/7} \varepsilon_n^{5/7}$

  equivalent to $\beta \approx 2.39 \left(\frac{r_e \lambda_e}{2\pi} F\right)^{2/7} \varepsilon_n^{3/7}$

  λ_e is the Compton wavelength of the electron

  F is a function of the focusing optics: typically F ~ 7 (minimum value ~ 0.1)

- σ_{Oide} = 0.85 nm for 3 TeV CLIC

Stability and Alignment

- Tiny emittance beams, nm vertical beam size at collision
- Any quadrupole misalignment $\Delta y_{Q,i}$ and jitter will cause orbit oscillations and displacement at the IP (designated by *)

$$\Delta y^* = \sum_i^{Quads} k_{Q,i} \Delta y_{Q,i} \sqrt{\frac{\gamma_i}{\gamma^*}} \sqrt{\beta_i \beta^*} \sin(\Delta\phi_i)$$

$k_{Q,I}$ quad. strength
γ rel. gamma
β opt. beta funct.
$\Delta\phi_i$ opt. phase adv.

⇒ Tight component tolerances

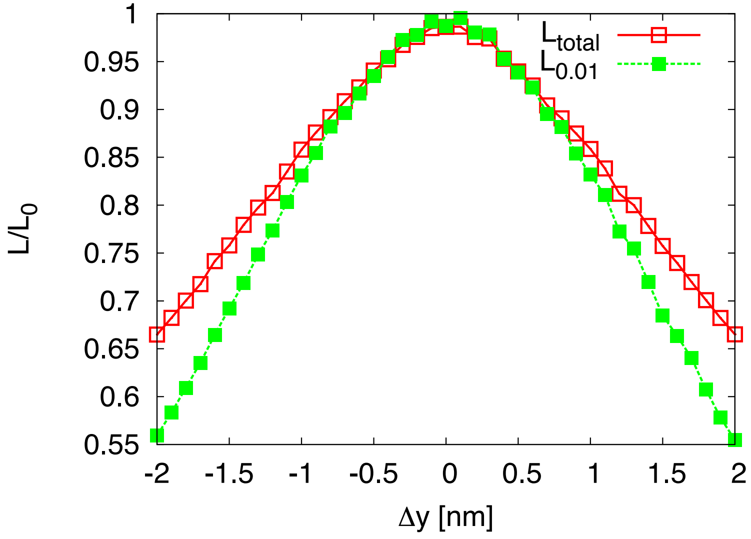
- Field quality
- Alignment

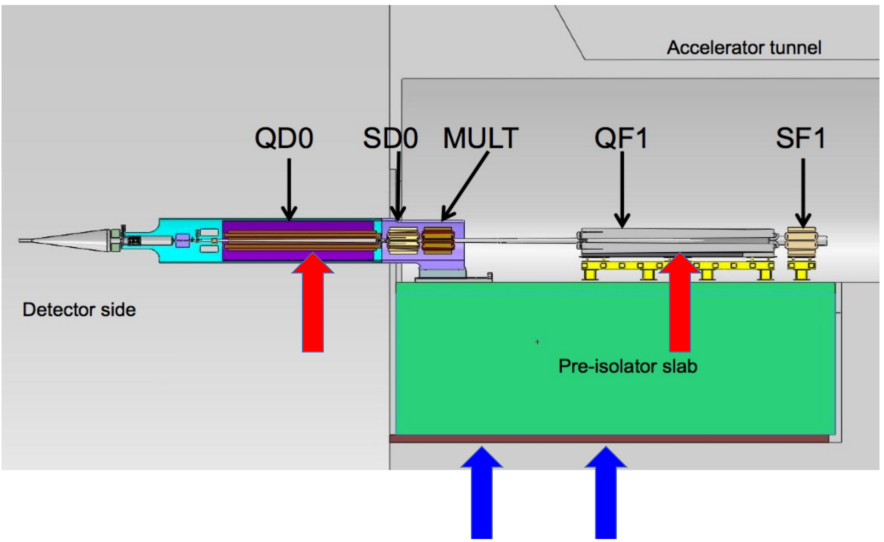
- Vibration and Ground Motion issues
- Active stabilisation
- Feedback systems
- Demonstrate Luminosity performance in presence of motion

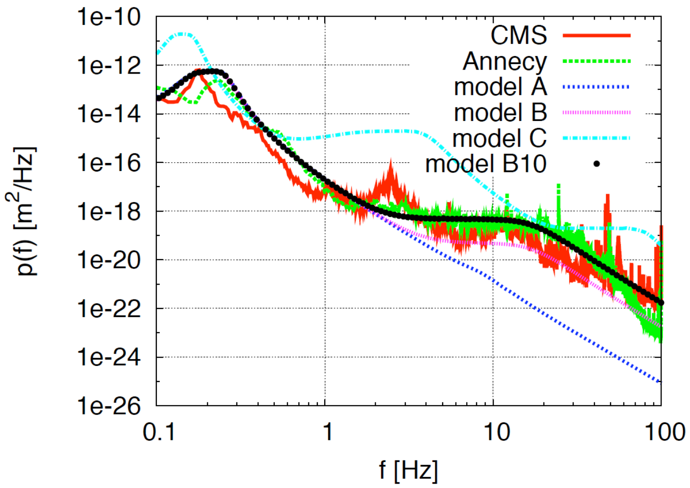
Some numbers (CLIC):

- Cavity alignment (RMS) 17 µm
- Main Beam quad alignment: 14 µm
- vert. MB quad stability: 1.5 nm @>1 Hz
- hor. MB quad stability: 5 nm @>1 Hz
- Final quadrupole: 0.15 nm @>4 Hz !!!

Ground Motion and Its Mitigation







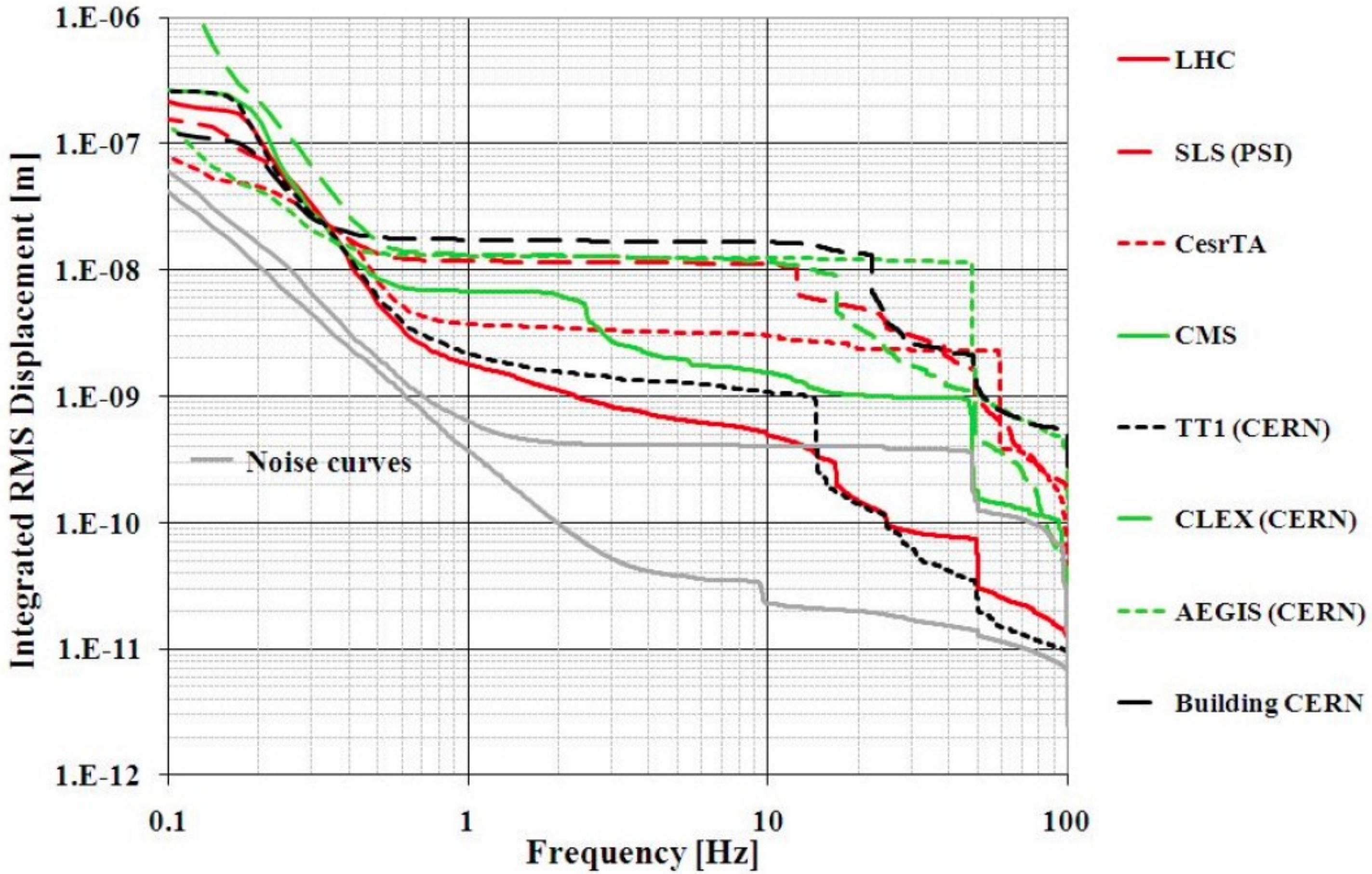
Natural ground motion can impact the luminosity

- Typical quadrupole jitter tolerance O (1 nm) in main linac and O (0.1nm) in final doublet

⇒ develop stabilization for beam guiding magnets

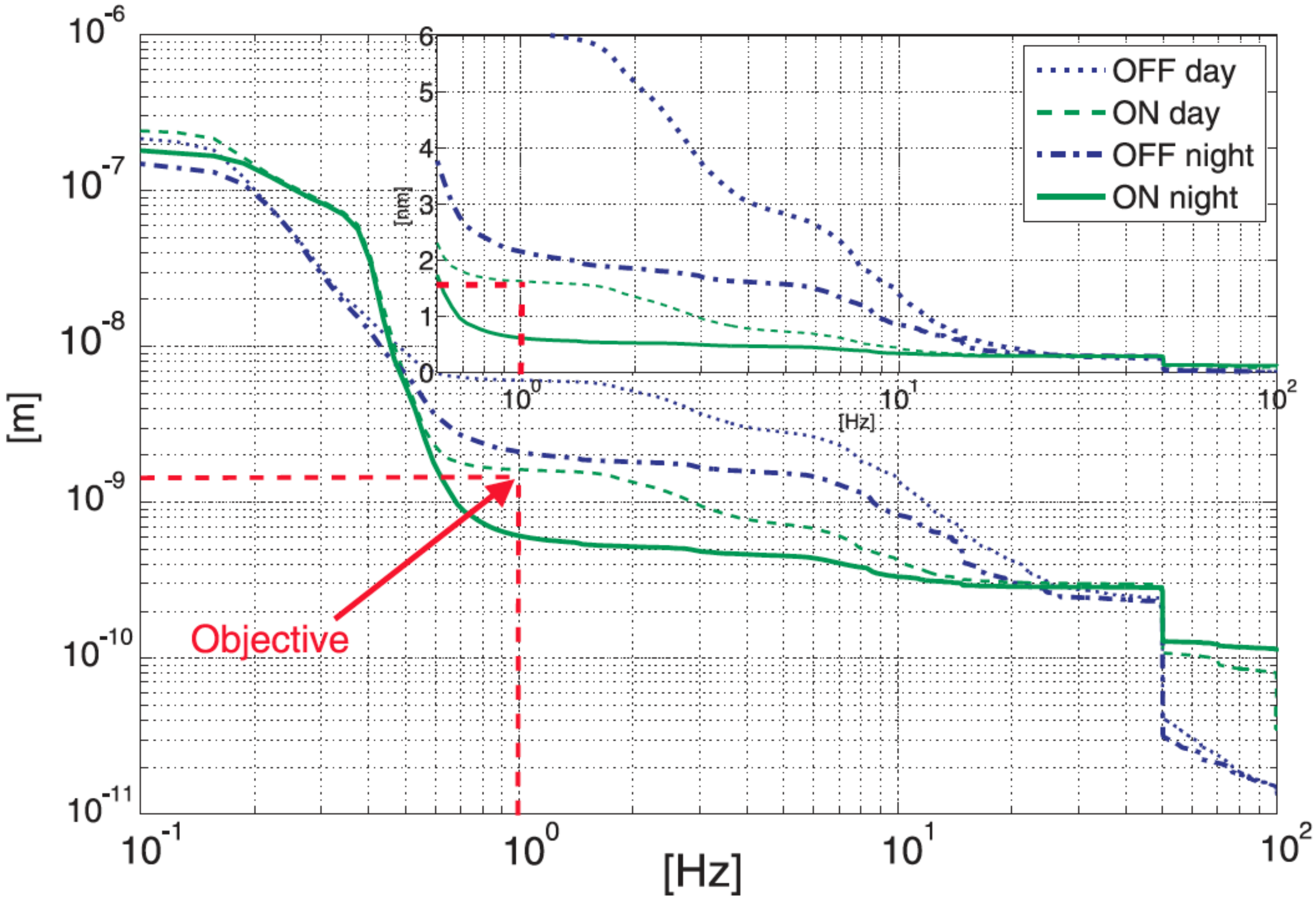
Ground Motion

Site dependent ground motion with decreasing amplitude for higher frequencies



Active stabilization

Test bench reaches required stability of CLIC MB quadrupole



Ground motion: ATL law

- Need to consider both short and long term stability of the collider
- Ground motion model: ATL law

$$\langle \Delta y^2 \rangle = ATL$$

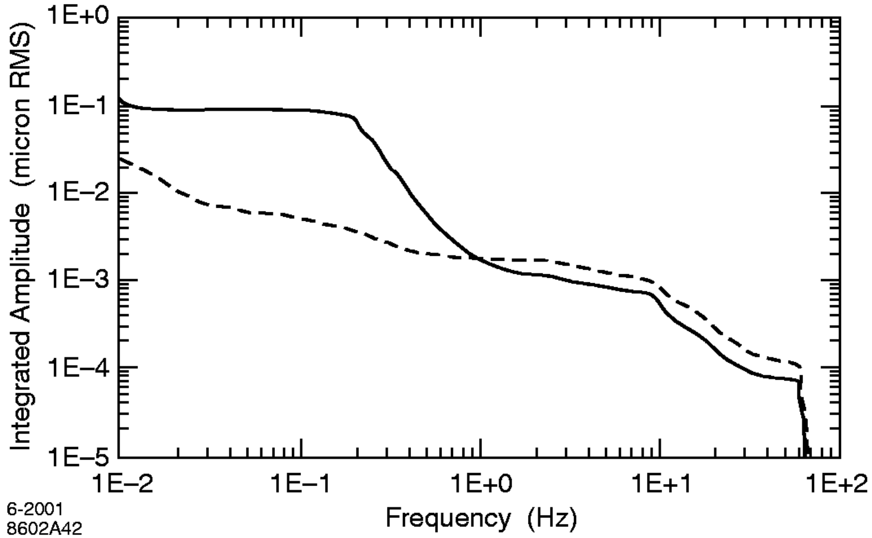
A site dependent constant

T time

L distance

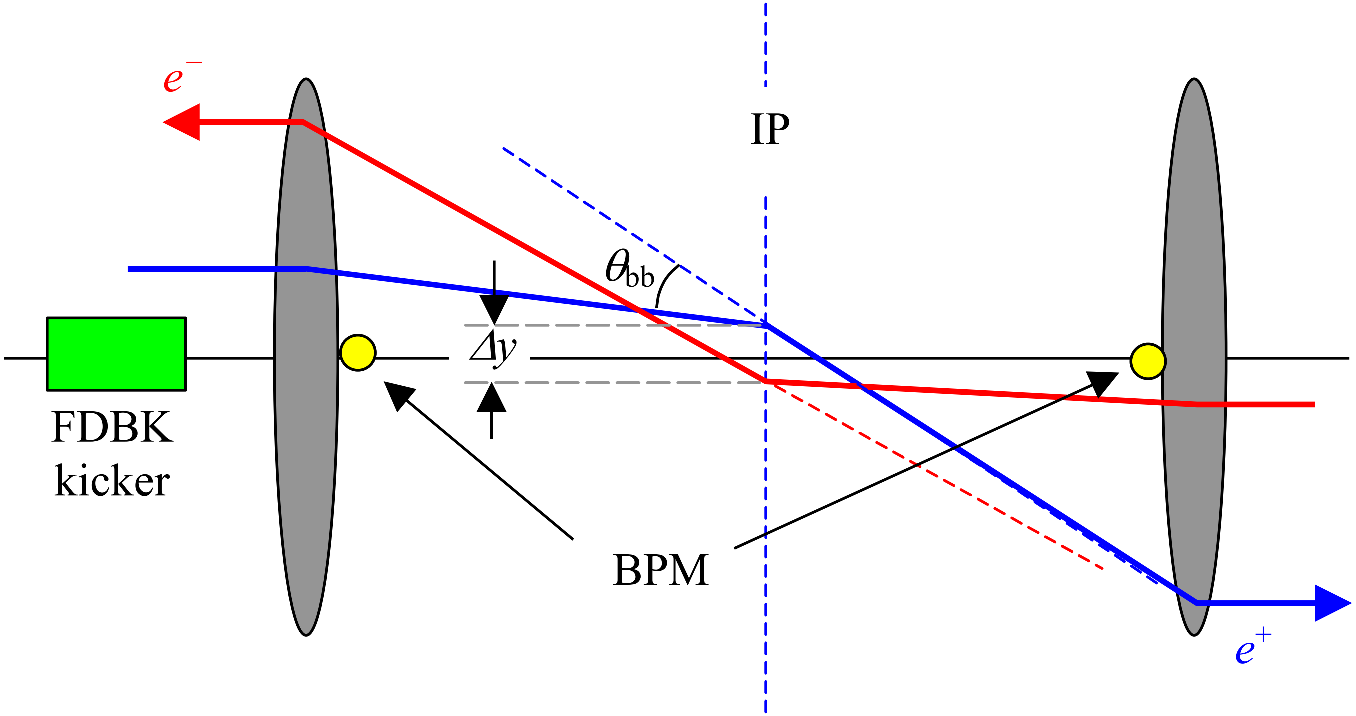
A range 10^{-5} to 10^{-7} $\mu m^2/m/s$

- This allows you to simulate ground motion effects
- Relative motion smaller
- Long range motion less disturbing



Beam-Beam feedback

- Use the strong beam-beam deflection kick for keeping beams in collision
- Sub-nm offsets at IP cause well detectable offsets (micron scale) a few meters downstream



Other IP issues

- Collimation
  - Beam halo will create background in detector
  - Collimation section to eliminate off-energy and off-orbit particle
  - Material and wakefield issues
- Crossing angle
  - NC small bunch spacing requires crossing angle at IP to avoid parasitic beam-beam deflections
  - Luminosity loss (≈10% when $\theta = \sigma_x/\sigma_z$)
- Crab cavities
  - Introduce additional time dependent transverse kick to improve collision
- Spent beam
  - Large energy spread after collision
  - Design for spent beam line not easy

Beam size and stability studies: ATF2 (KEK)

Goals of ATF2 project

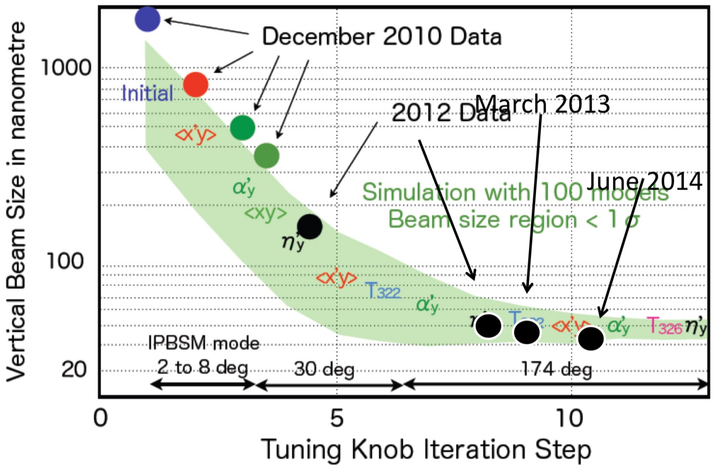
Goal1: Produce and Confirm Small Beam Size

- 37 nm (sigma) (Emittance 12 pm, beta* 0.1 mm)
- Single bunch

Goal2: Produce and Confirm Stable Beam

- 2 nm RMS position jitter at focal point (As required in ILC Interaction Point)
  – Tail bunch(es) in multi-bunch beam with fast feedback.

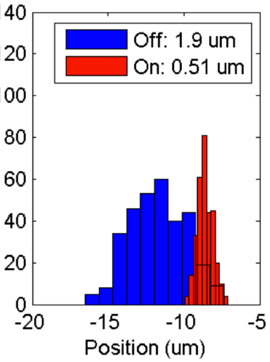
History of minimum beam size in ATF2



Common ILC/CLIC experimental activity

Measured beam jitter, tipically ~20% of rms beam size

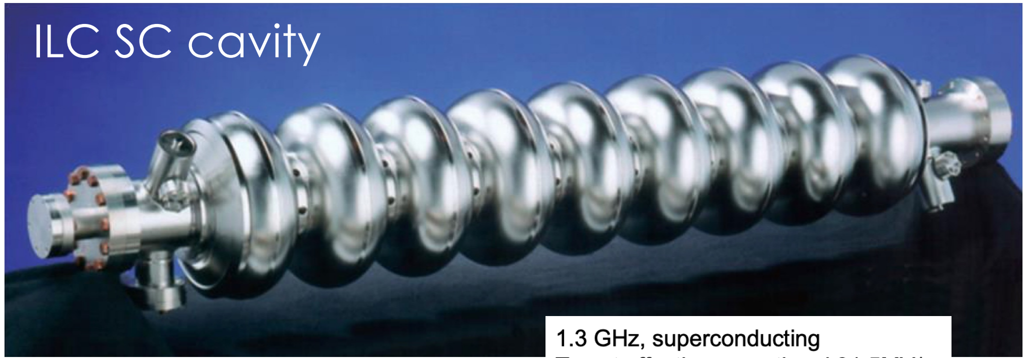
Intra pulse feedback results



End part III

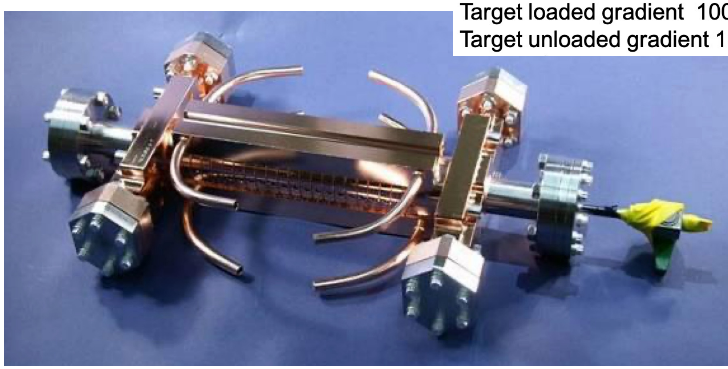
Linear Collider proposals & outlook

Impact of the choice of cavity/accelerating structure



1.3 GHz, superconducting
Target effective operational 31.5MV/m
Target gradient 35MV/m

12 GHz, normal conducting
Target loaded gradient 100MV/m
Target unloaded gradient 120MV/m

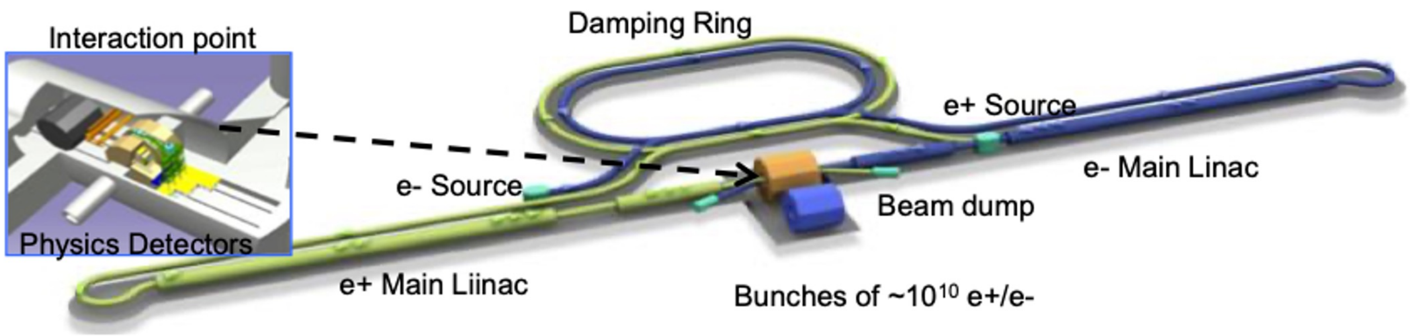


CLIC NC accelerating structure

- Long pulse ⇒ low peak power ☺
- Large structure dimensions ⇒ low WF ☺
- Very long pulse train ⇒ feedback within train ☺
- SC structures ⇒ high efficiency ☺
- Gradient limited <40 MV/m ⇒ longer linac ☹
- Low rep. rate ⇒ bad GM suppression (ε_y dilution) ☹
- Large number of e+ per pulse ☹
- Large DR ☹

- High gradient ⇒ short linac ☺
- High rep. rate ⇒ ground motion suppression ☺
- Small structures ⇒ strong wakefields ☹
- Generation of high peak RF power ☹
- Small bunch distance ☹
- Small Damping Ring ☺

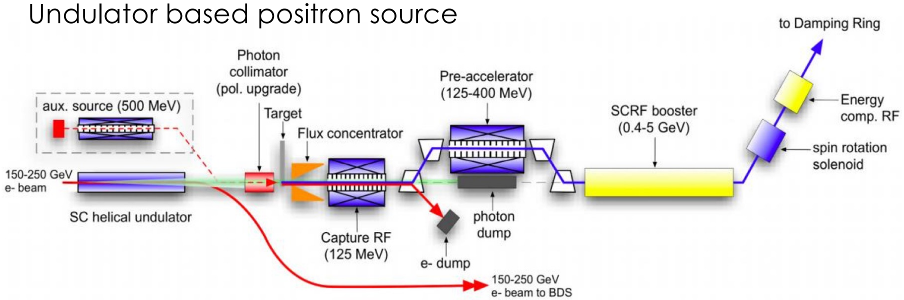
The ILC250 accelerator facility

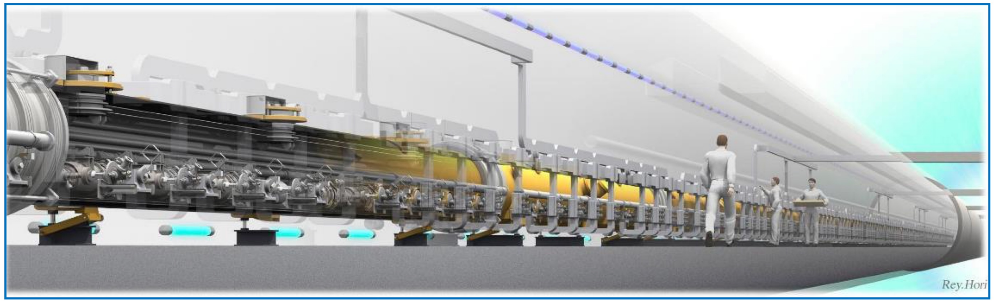


Parameters	Value
Beam Energy	125 + 125 GeV
Luminosity	1.35 / 2.7 x 10^{10} cm^2/s
Beam rep. rate	5 Hz
Pulse duration	0.73 / 0.961 ms
# bunch / pulse	1312 / 2625
Beam Current	5.8 / 8.8 mA
Beam size (y) at FF	**7.7** nm
SRF Field gradient	< 31.5 > MV/m (+/-20%) Q_0 = 1x10^{10}
#SRF 9-cell cavities (CM)	~ 8,000 (~ 900)
AC-plug Power	111 / 138 MW

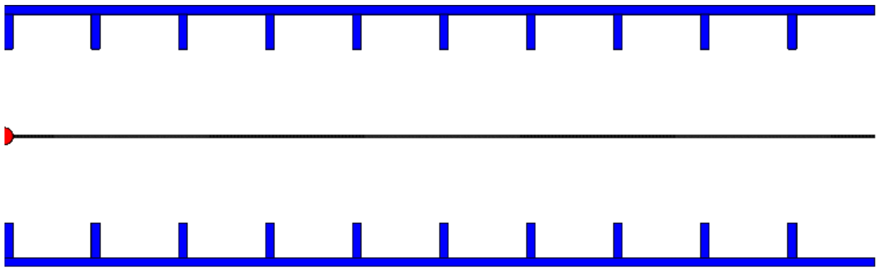
S. Michizono

Undulator based positron source





ILC Cavities



Gradient is 31.5 MV/m

Need about 16000 cavities
(500 GeV cm)

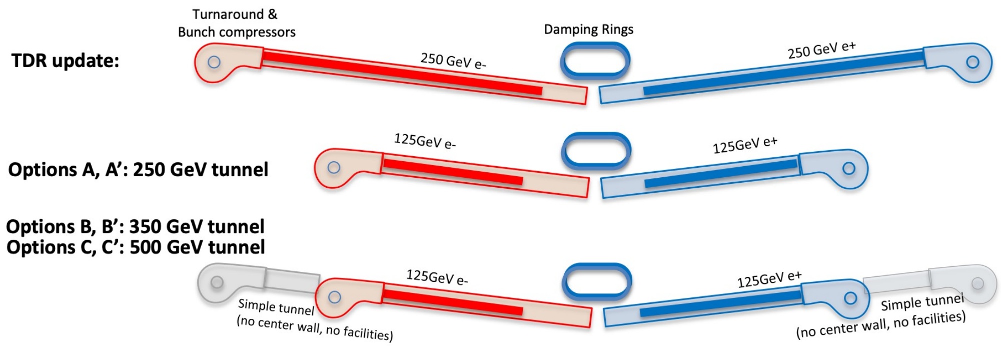
Superconducting cavity (Ni at 2 K)

Standing wave structure

RF frequency is 1.3 GHz, 23 cm wavelength

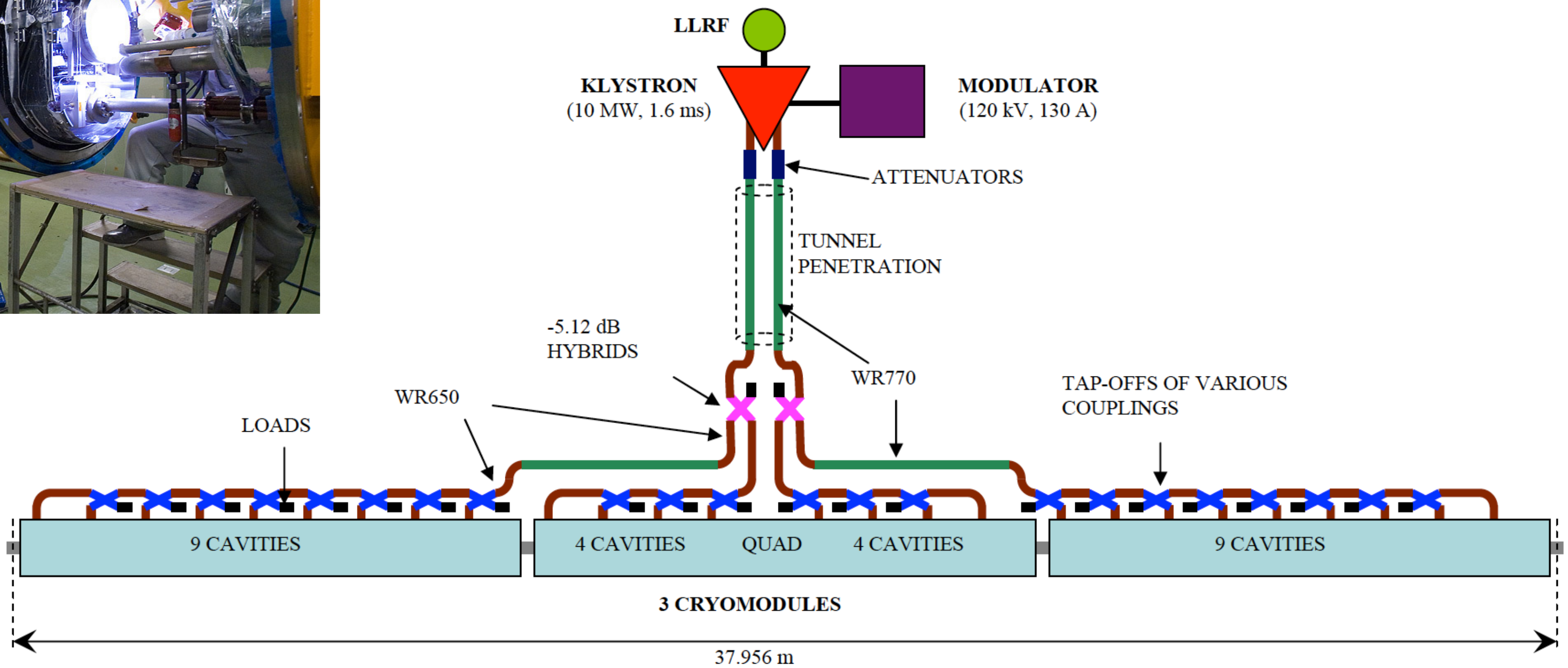
Length is 9 cells = 4.5 wavelengths = 1 m

Several energy upgrade options up to 500 GeV



Total length:	27	km for Ecm = 250 GeV
	33.5	km for Ecm = 500 GeV

Main Linac Unit



Accelerating cavities
~ 65% of linac length

Quadrupole
Beam position monitor
Corrector kicker

Accelerating cavities

Efficiency of Cryogenics

Cavities have small losses

$$P_{loss} = const \frac{1}{Q_0} \times G^2$$

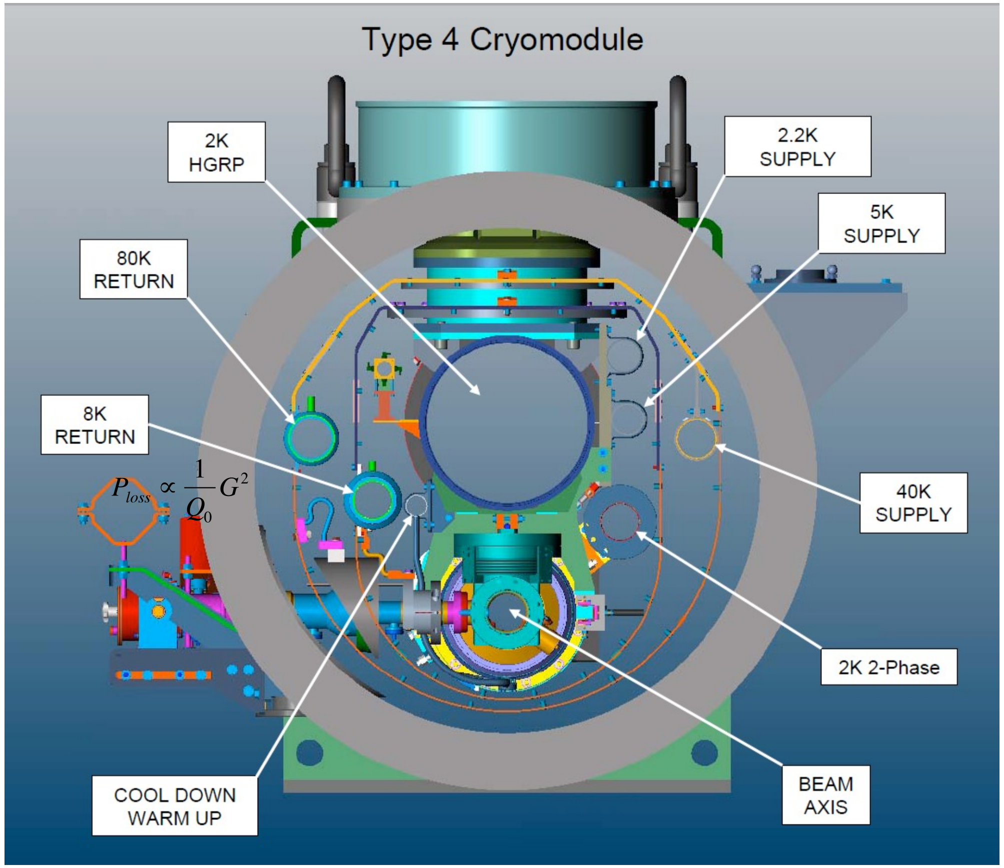
About 1W/m

But cooling costly at low temperatures

Remember Carnot:

$$P_{cryo} = \frac{1}{\eta} \frac{T_{room} - T_{source}}{T_{source}} \times P_{loss}$$

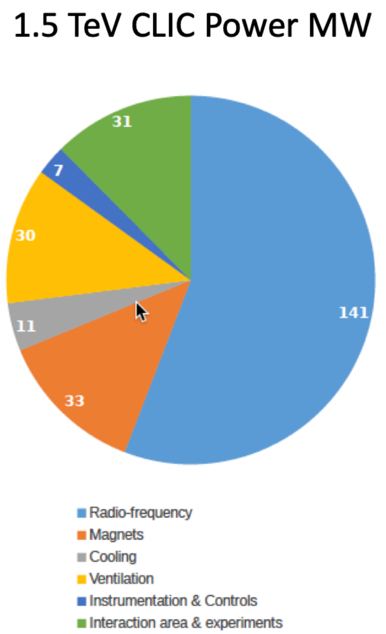
$$P_{cryo} \approx 700 \times P_{loss}$$

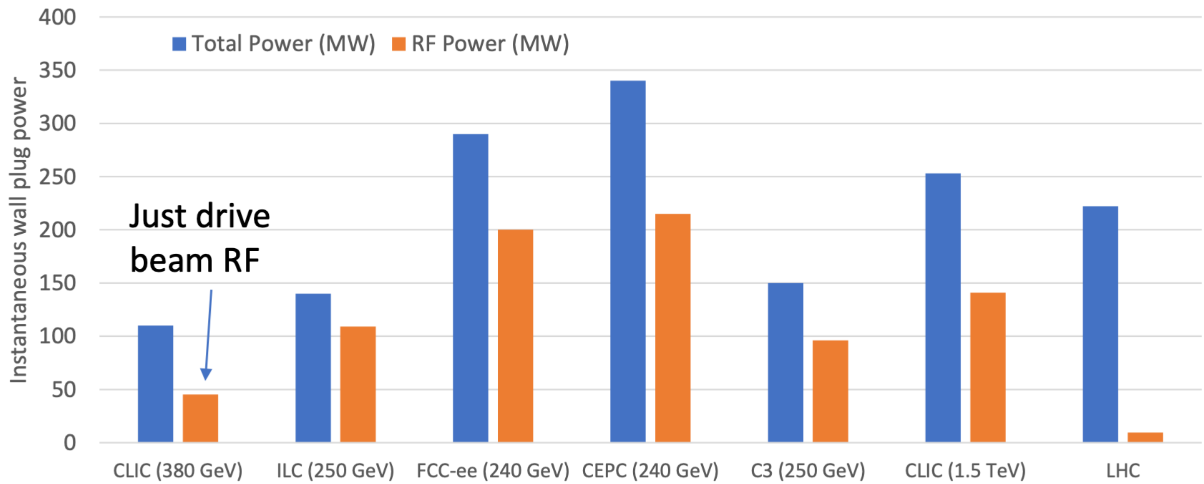


Typical heat load ~ 1 W/m
⇒ about 1 kW/m for cryogenics

Average RF power: 1.6kW/m (3kW/m)
Power into beam about 0.7kW/m

How much of the power budget for future machines is RF?



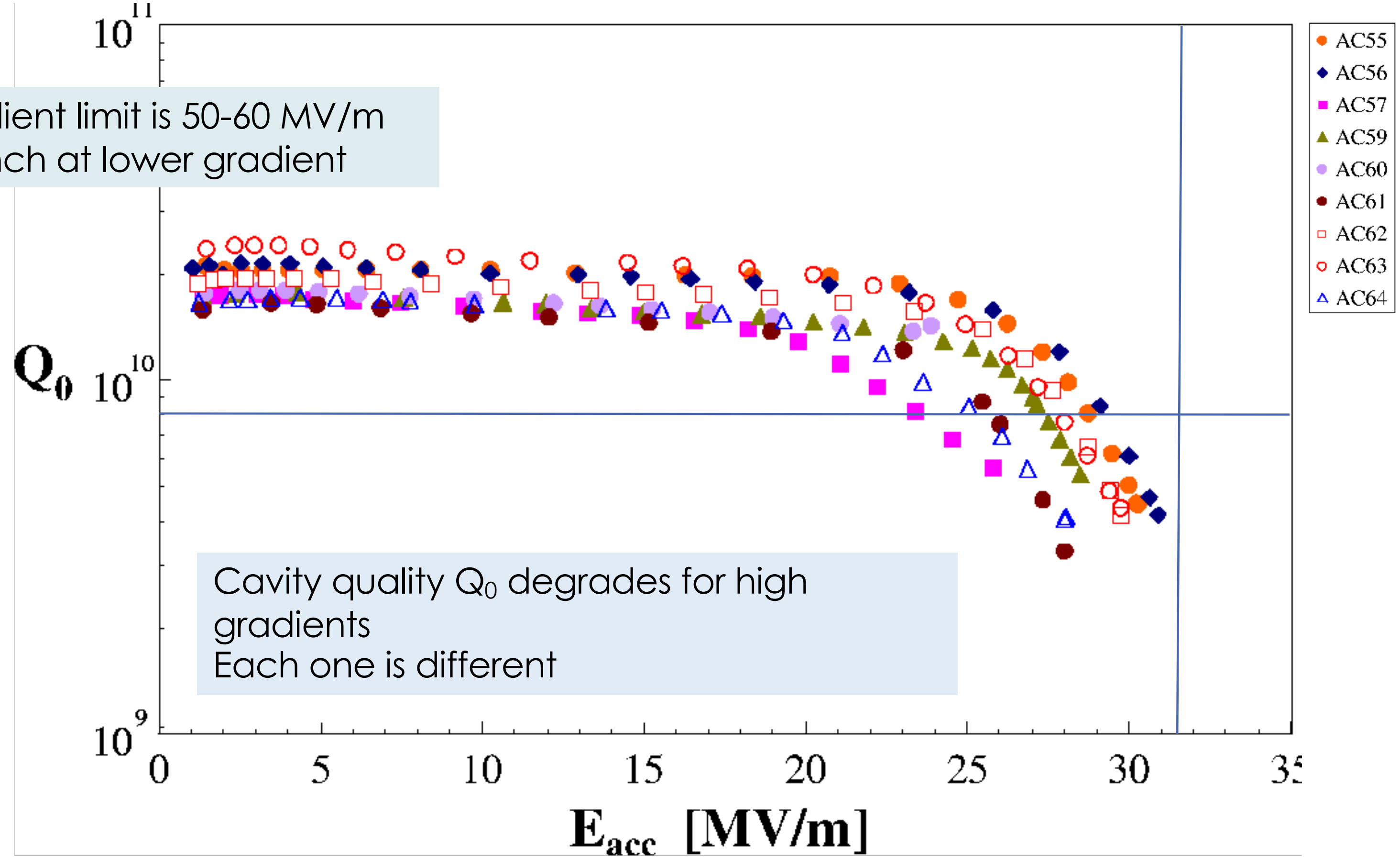


- RF power includes all DC power, modulators, chillers, liquifiers and pumps, and magnets required as part of the entire RF system
- Most linacs have between **40-77%** of their total site power going into the RF system.
- Synchrotron need more RF power at higher energy due to frequency scaling of synchrotron radiation

S. Stapnes

ILC Gradient Limitations

Theoretical gradient limit is 50-60 MV/m
- But can quench at lower gradient



Cavity quality Q_0 degrades for high gradients
Each one is different

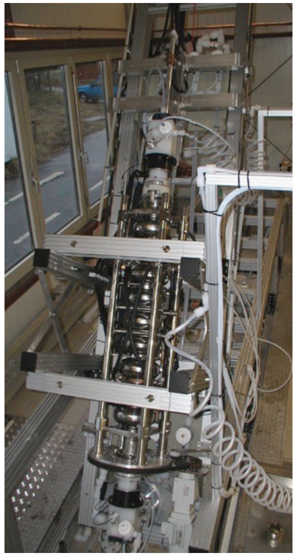
ILC Cavity Treatment

Control of material

Avoid defects
Ensure high quality

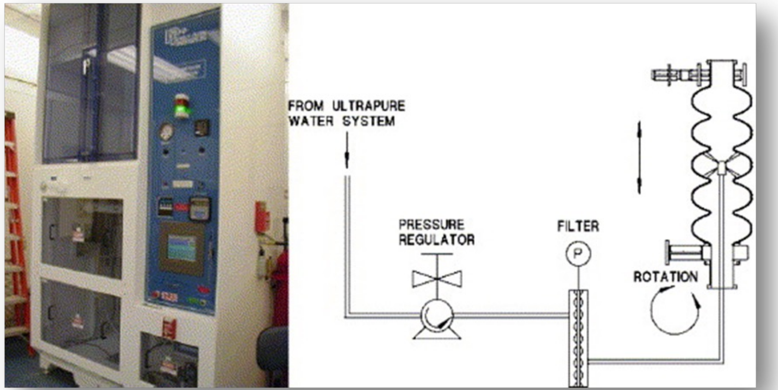
Electropolishing

→ fill with H_2SO_4, apply current to remove thin surface layer

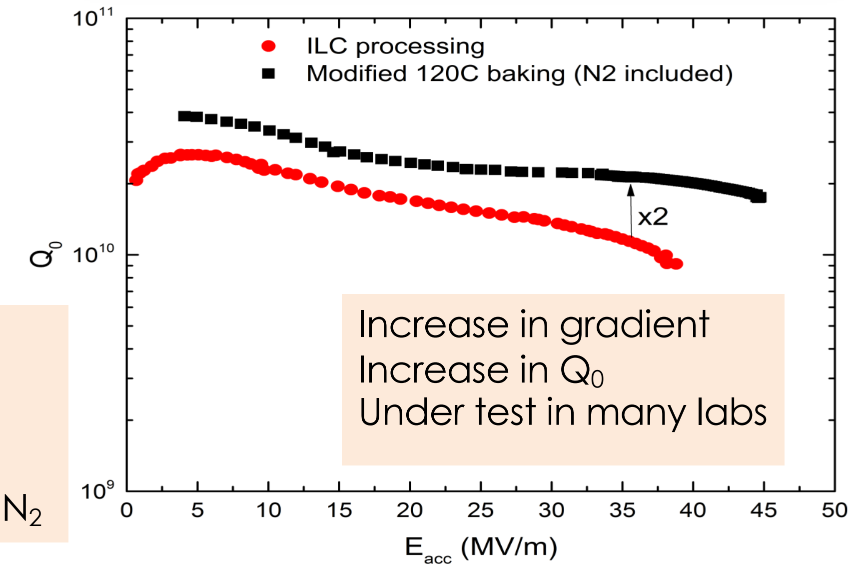


Bakeout

High pressure rinsing

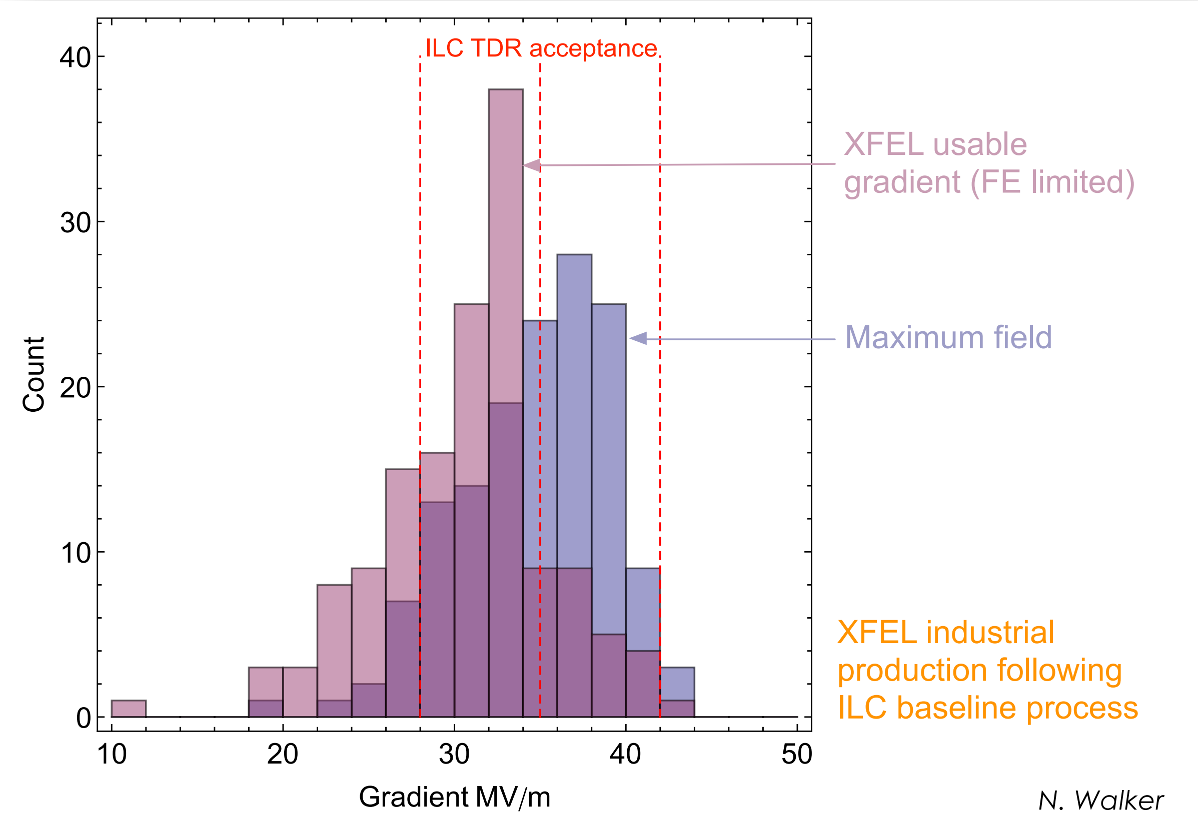


Novel process found (FNAL):
Nitrogen infusion
Fill cavity at 120°C for a day with low pressure of N_2



Increase in gradient
Increase in Q_0
Under test in many labs

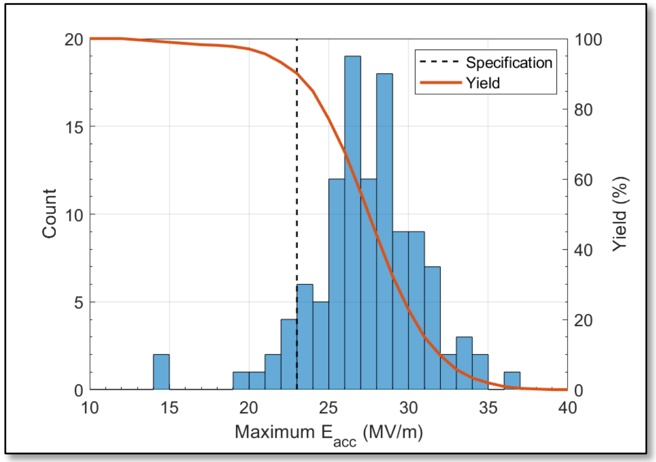
ILC Achieved Gradient



E-XFEL cavity performance

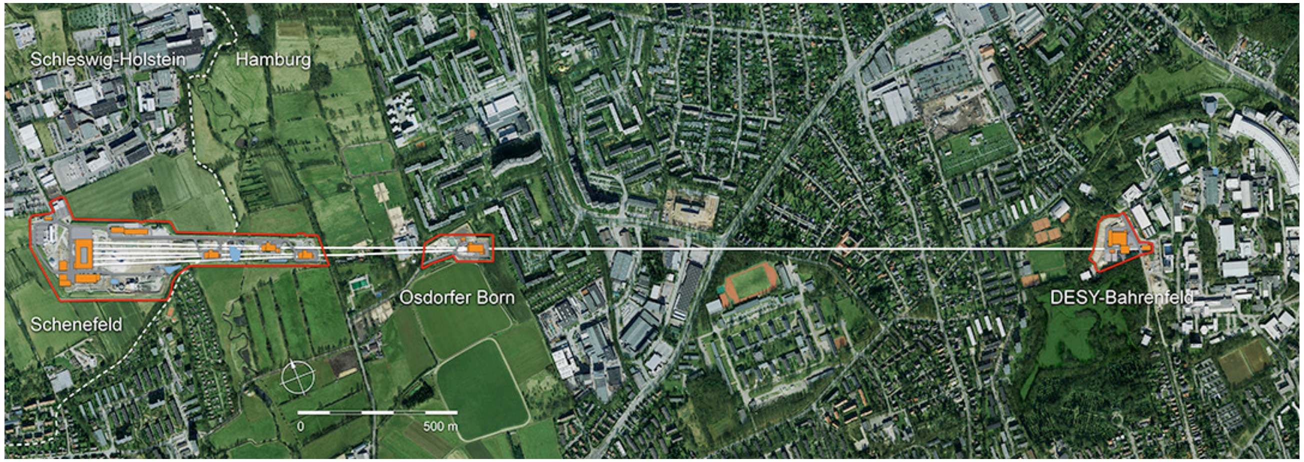
The SRF cavity technology thanks to TESLA, E-XFEL and LCLS-II experiences

LCLS-II cavity production statistics *E. Snively*

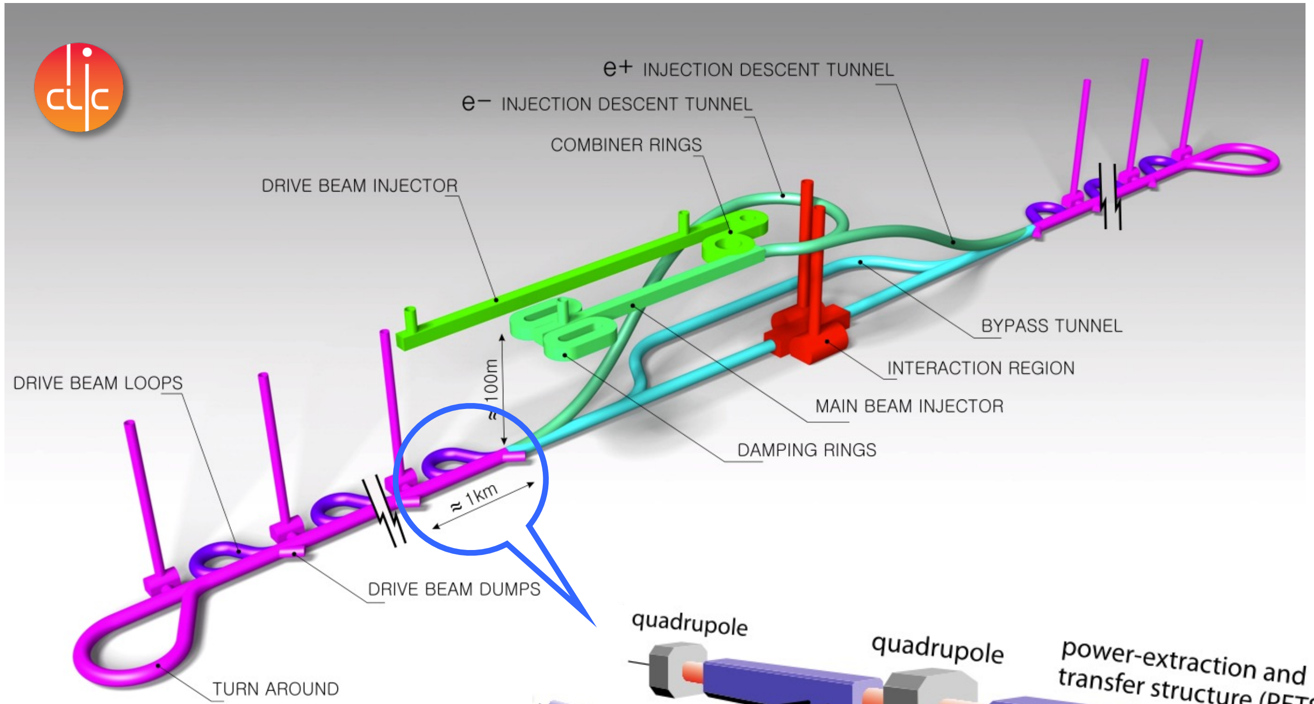


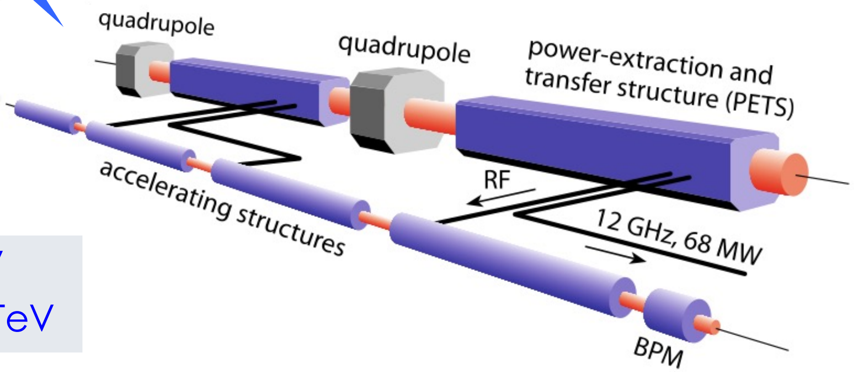
European X-FEL @ DESY

- The European XFEL is the Hard X-ray Free Electron Laser based on superconducting accelerator technology.
- The 3.4 km long facility runs from the DESY campus in Hamburg to the town of Schenefeld
- The European XFEL accelerator uses 768 cavities over a 1.7 km length.
- Electron beam energy 17.% GeV



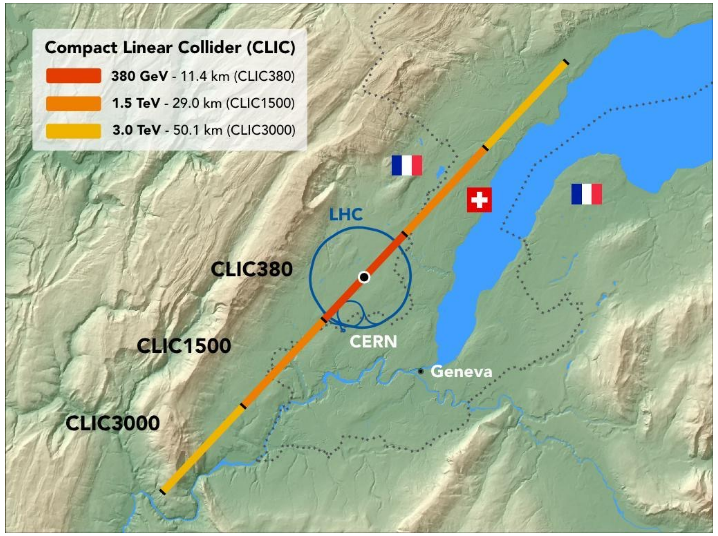
The Compact Linear Collider - CLIC





L = 6 x10^{34} cm^{-2}s^{-1} at 3TeV

Beam power 30MW at 3TeV



CLIC can be built in stages of increasing collision energy: starting from 380 GeV, then ~ 1- 2 TeV, and up to a final energy of 3 TeV.

To limit the collider length, the accelerating gradient must be very high - CLIC aims at 100 MV/m, 20 times higher than the LHC.

CLIC is based on a two-beam acceleration scheme, in which a high current e- beam (the drive beam) is decelerated in special structures (PETS), and the generated RF power is used to accelerate the main beam.

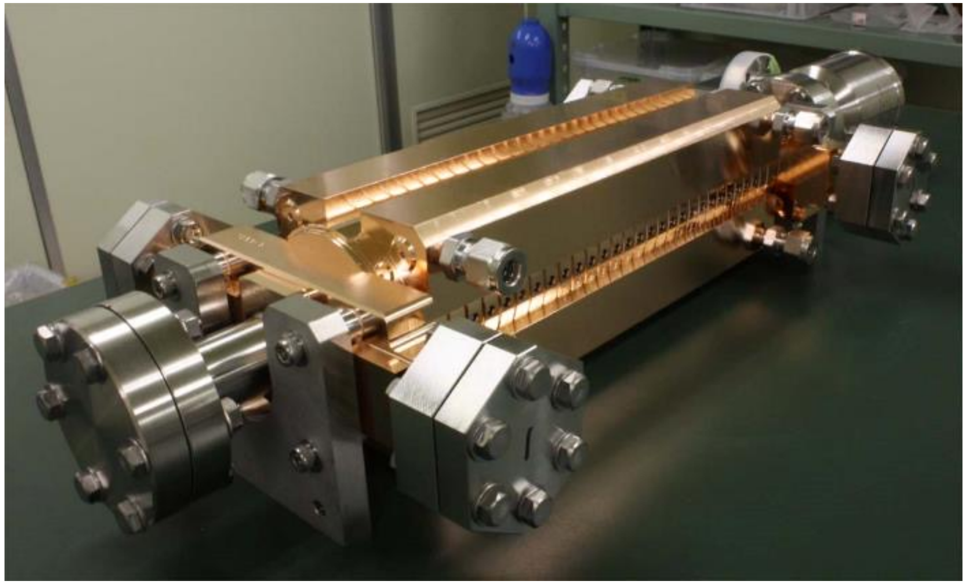
Accelerating Structure

12 GHz, 25 cm long, normal conducting
Loaded gradient 100MV/m

⇒ Allows to reach higher energies
⇒ 140,000 structures at 3 TeV

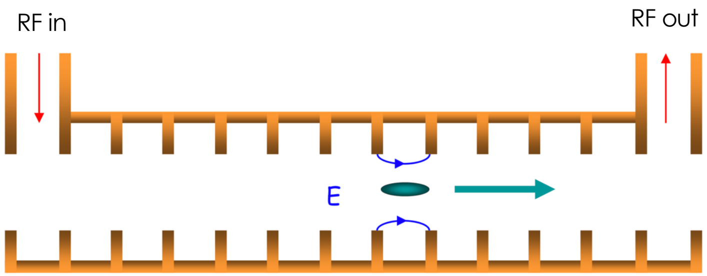
losses in the walls and in the load

⇒ 50-100 Hz
⇒ 240 ns, 60 MW, 312 bunches
⇒ Power during pulse 8.5 x 10^6 MW (3000 x ILC)



Power flow
- 1/3 lost in cavity walls
- 1/3 in filling the structure and into load
- 1/3 into the beam

Average RF power about 3 kW/m
About 1 kW/m into beam



Travelling wave

Particles "surf" the electromagnetic wave

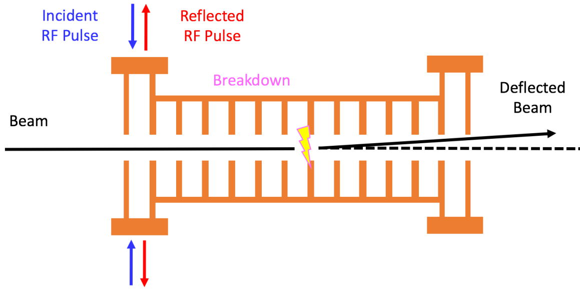
CLIC Gradient Limitations

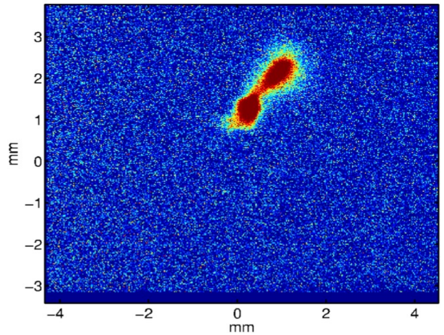
Breakdowns (discharges during the RF pulse)

⇒ Require breakdown rate (BDR) ≤ 3 x 10^{-7} $m^{-1}pulse^{-1}$

Structure design based on empirical constraints

- Maximum surface field
- Maximum temperature rise
- Maximum power flow
- Pulse length dependence ~ $t^{-1/2}$

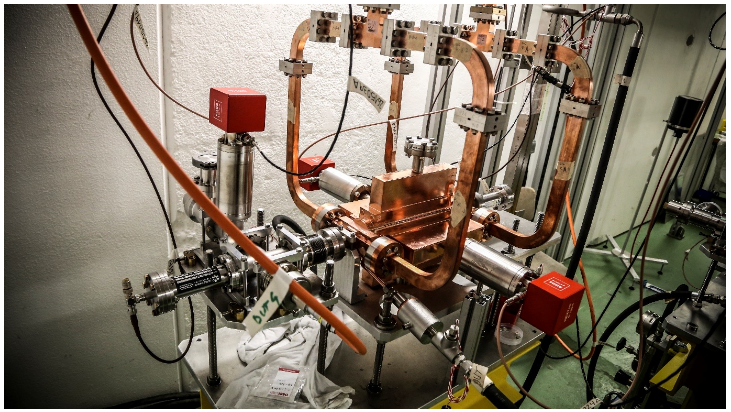


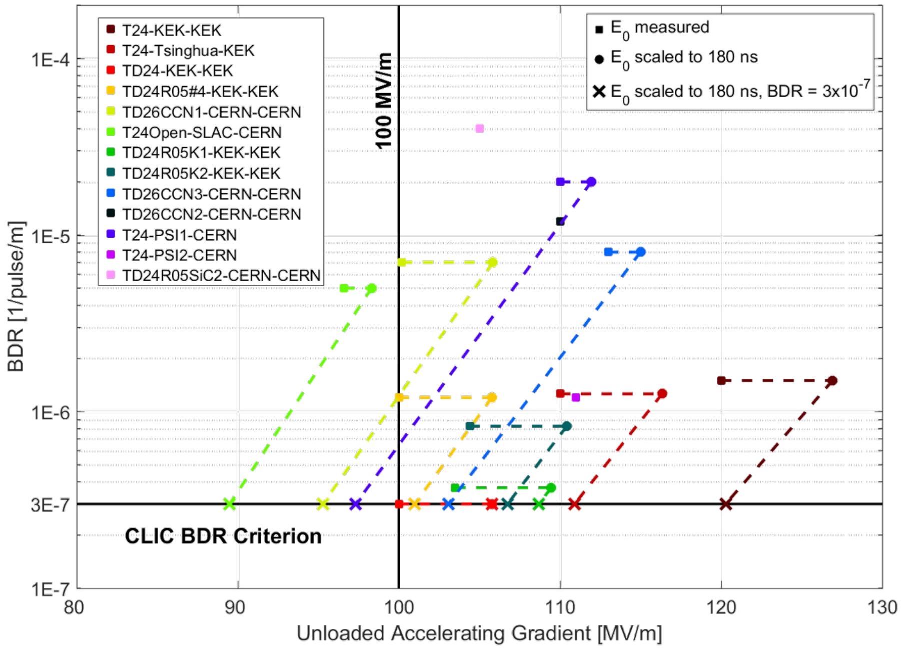


Achieved gradient

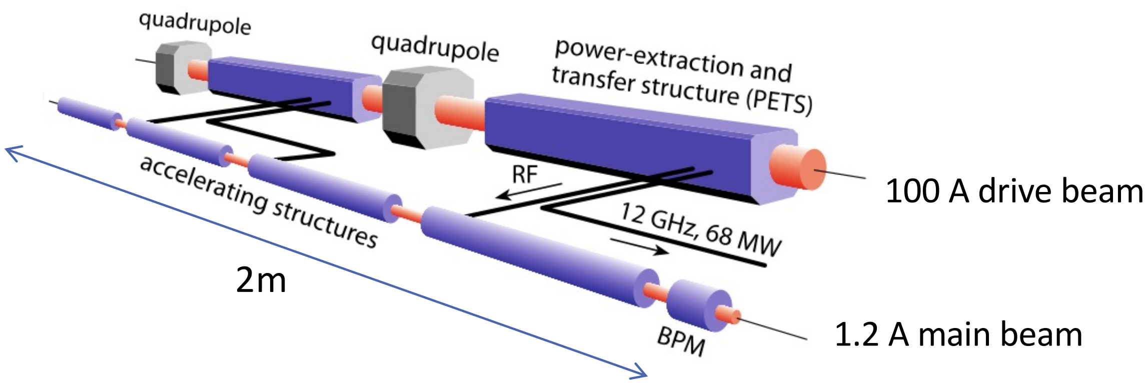
~ 100 MV/m

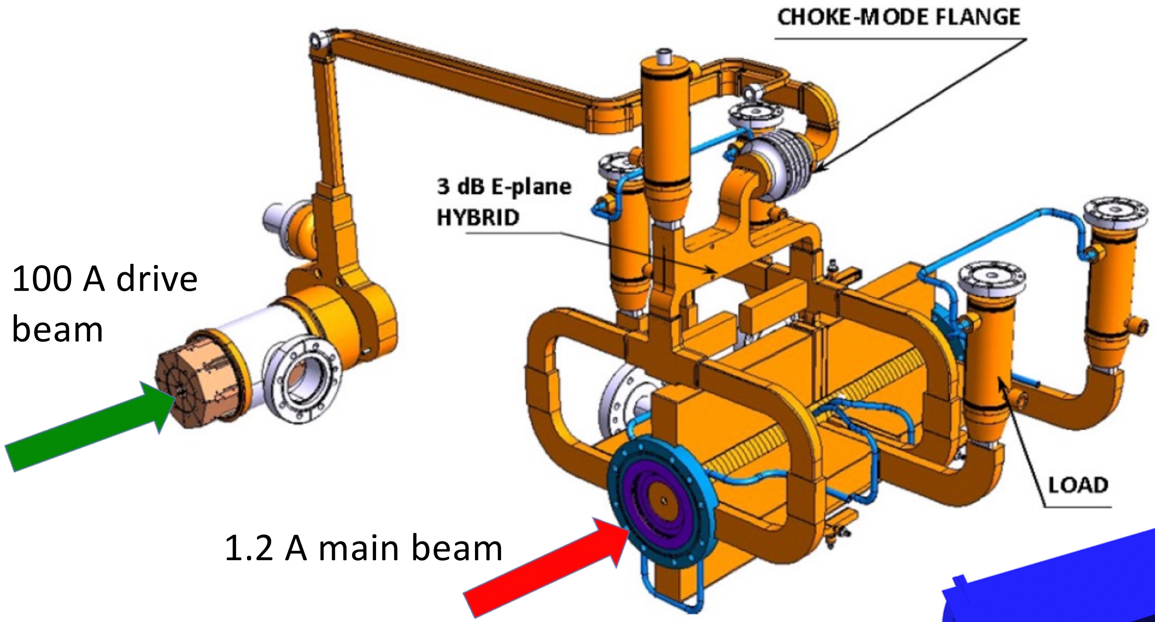
@BDR ≤ 3 x 10^{-7} $m^{-1}pulse^{-1}$ and 240 ns

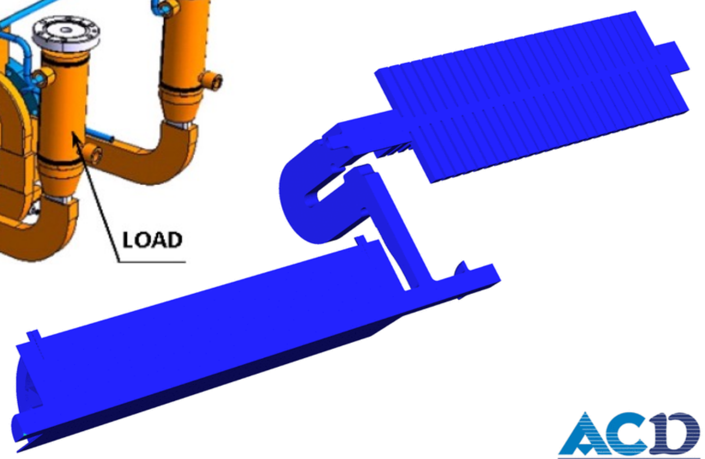




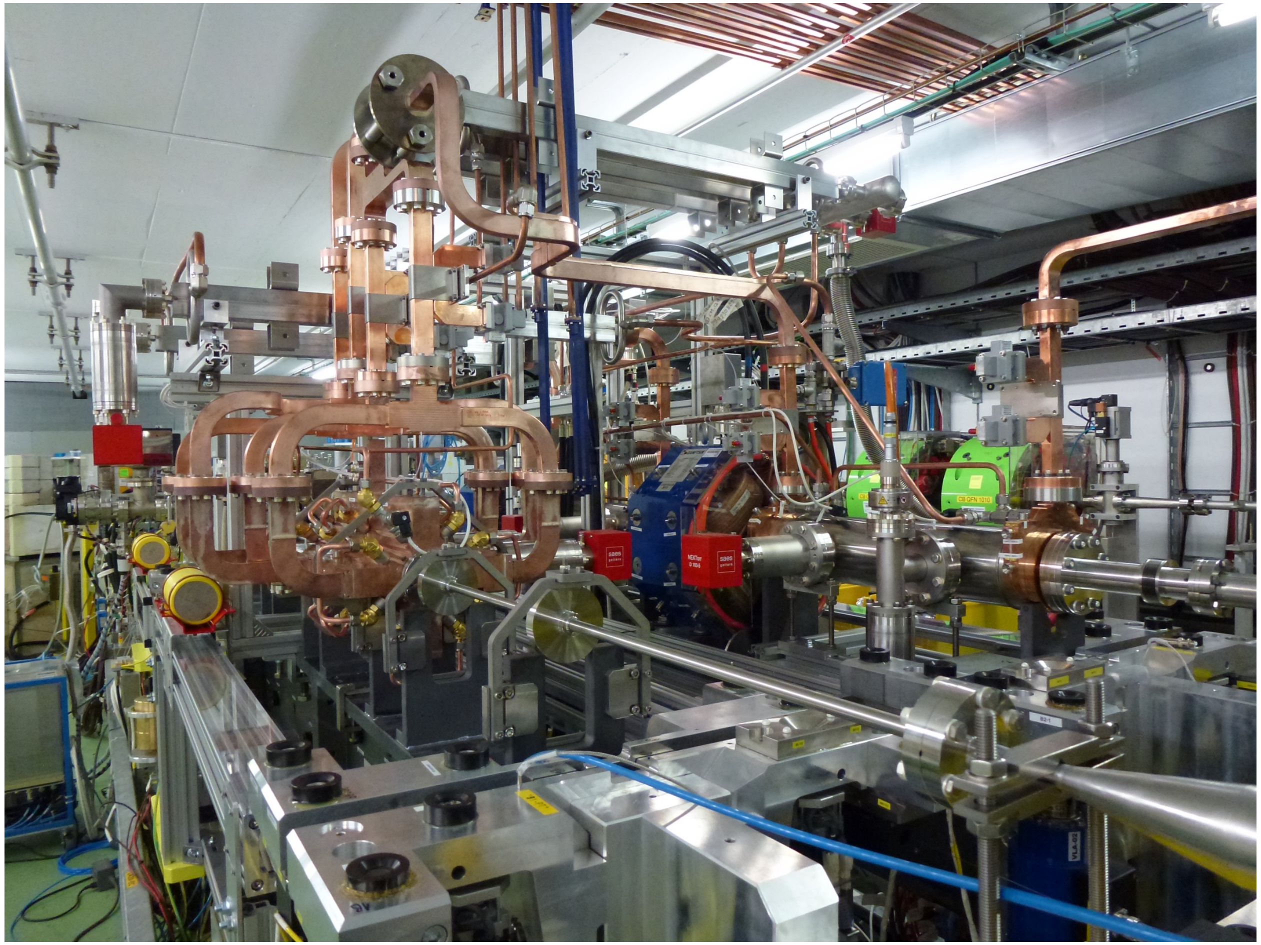
CLIC Two-beam Concept

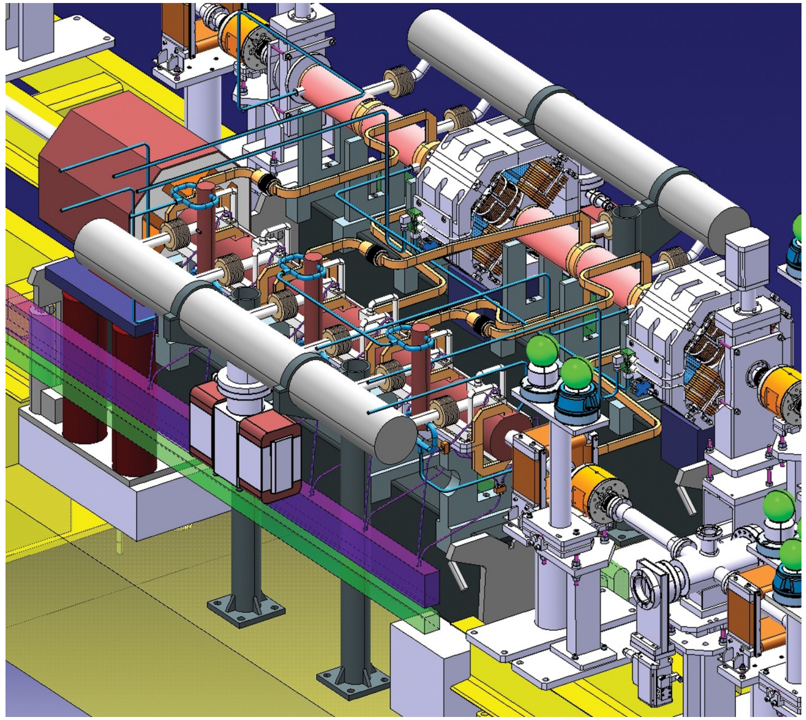






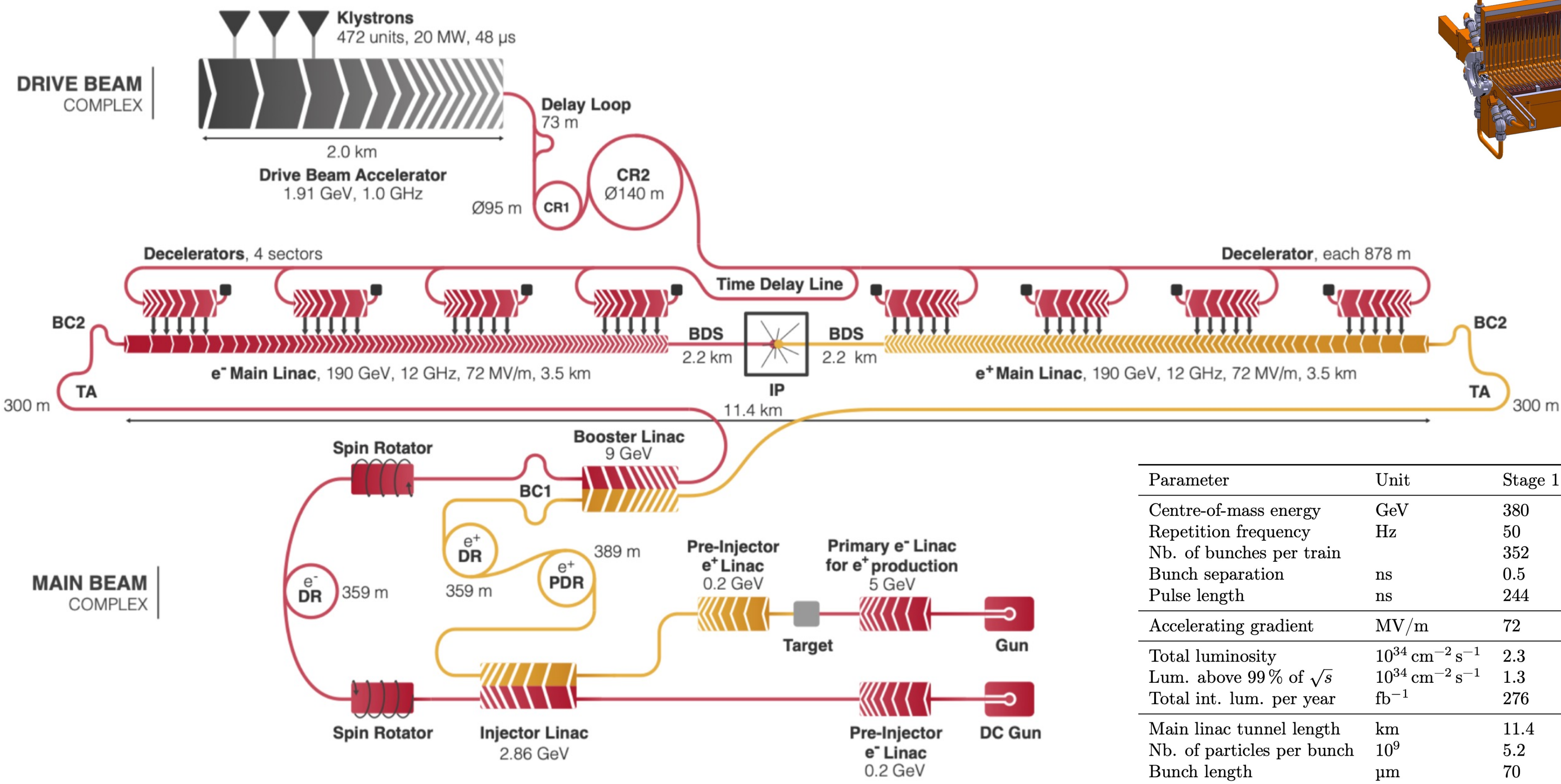
CLIC Two-beam Module

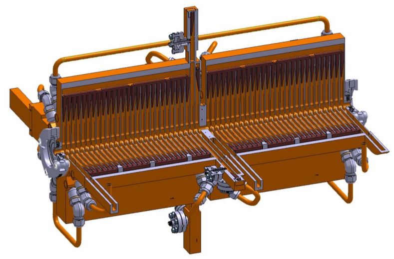




80 % filling with accelerating structures
11 km for 380 GeV cms
50 km for 3 TeV

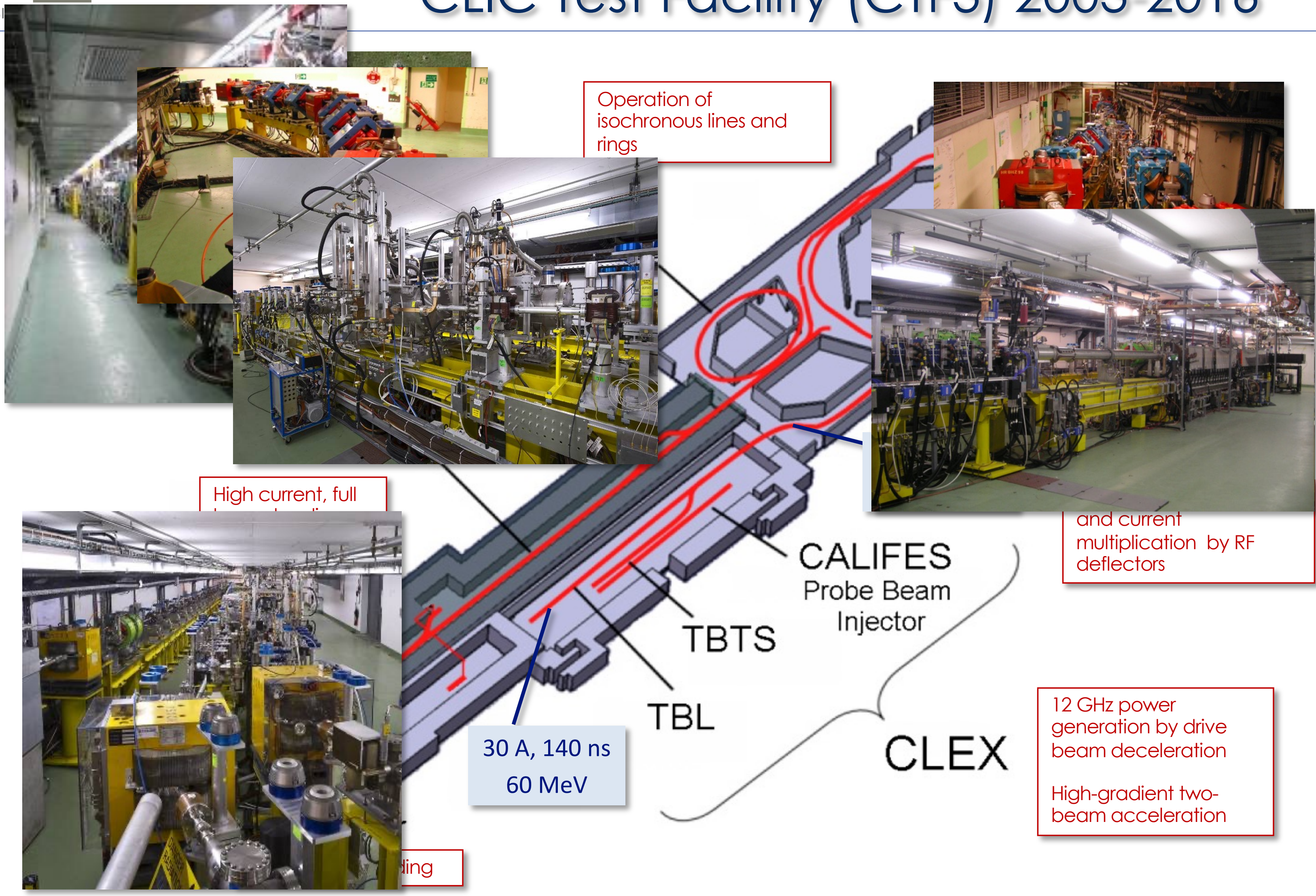
CLIC Layout (380 GeV cm) and parameters





Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	10^{34} cm^{-2} s^{-1}	2.3	3.7	5.9
Lum. above 99% of $\sqrt{s}$	10^{34} cm^{-2} s^{-1}	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	10^9	5.2	3.7	3.7
Bunch length	µm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20

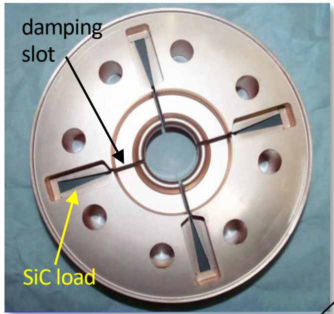
CLIC Test Facility (CTF3) 2003-2016



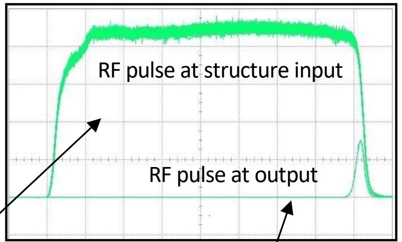
First beam
June 2003

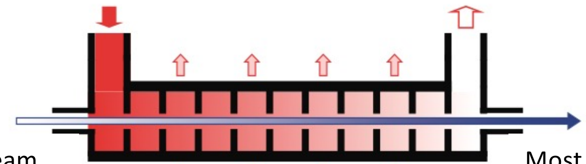
Last beam
December 2016

Drive Beam Generation – Power Production



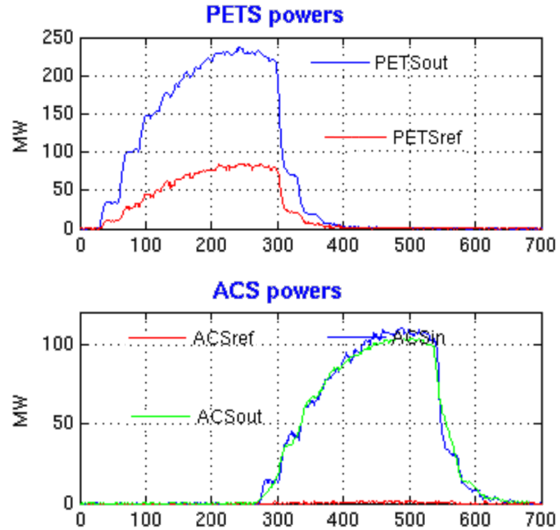
Full beam loading acceleration

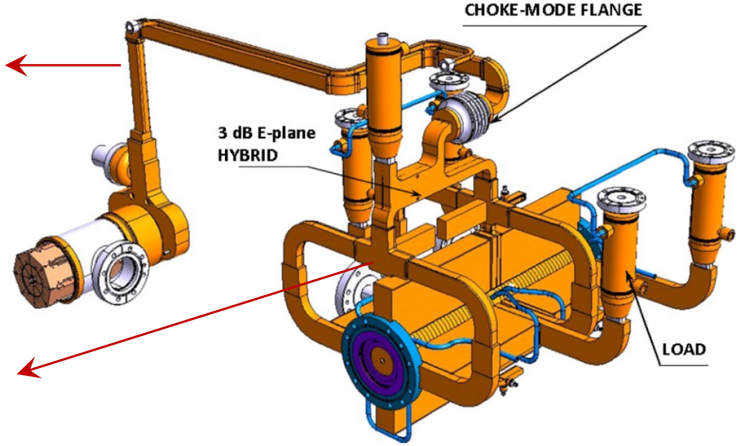


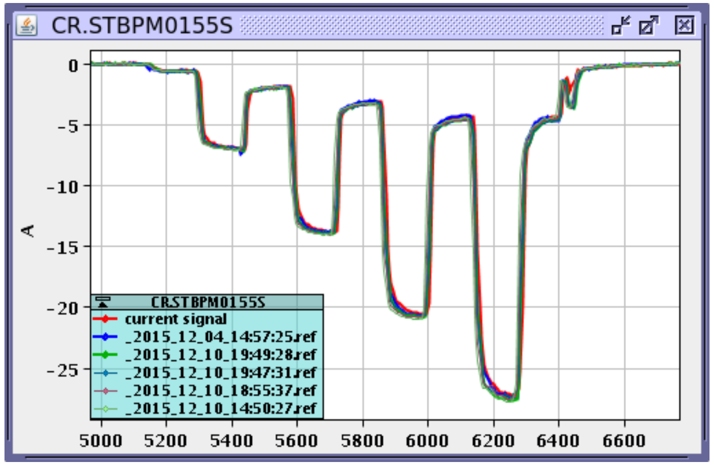


95.3% RF to beam efficiency
Stable high current acceleration

Factor 8 current & frequency multiplication







PETS operated routinely above **200 MW** peak RF power

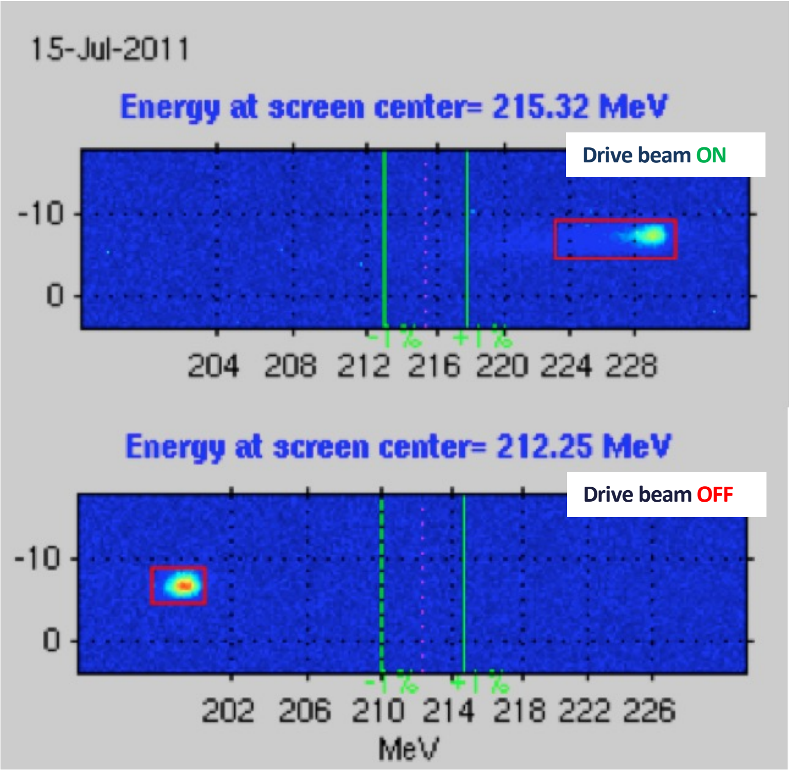
providing reliably pulses ~ 100 MW to accelerating structure.

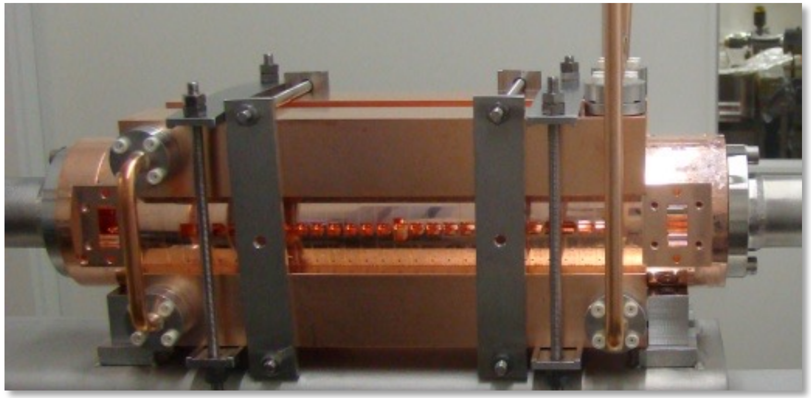
About twice the power needed to demonstrate 100 MV/m acceleration

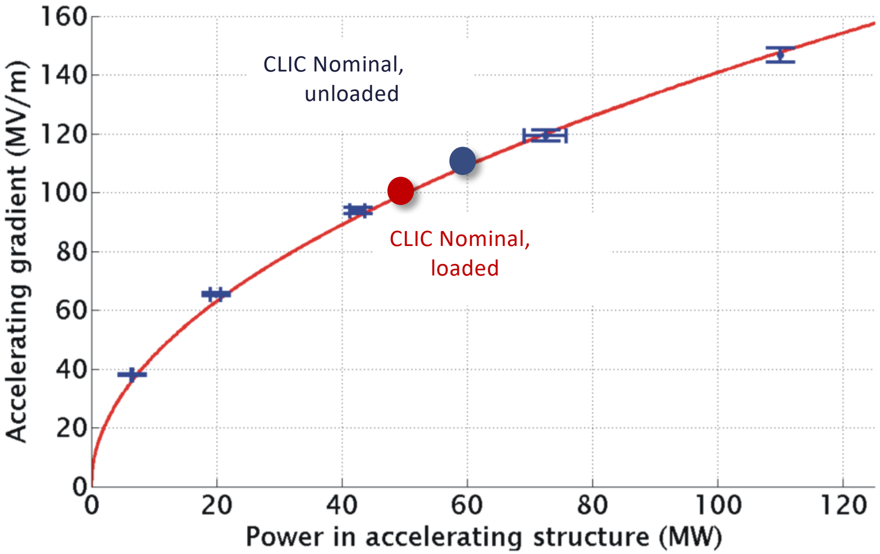
Two-Beam Acceleration demonstration in CTF3

Maximum stable probe beam acceleration measured: 31 MeV

⇒ Corresponding to a gradient of **145 MV/m**







Luminosity and Parameter Drivers

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

Can re-write normal luminosity formula in a slightly different way

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

- $\frac{N}{\sigma_x}$: Luminosity spectrum
- $N n_b f_r$: Beam power
- $\frac{1}{\sigma_y}$: Beam Quality

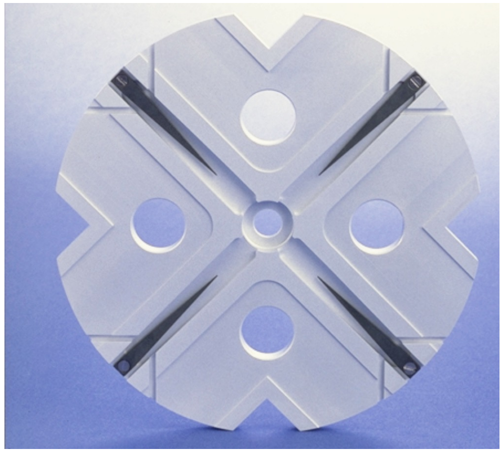
Need to ensure that we can achieve each parameter

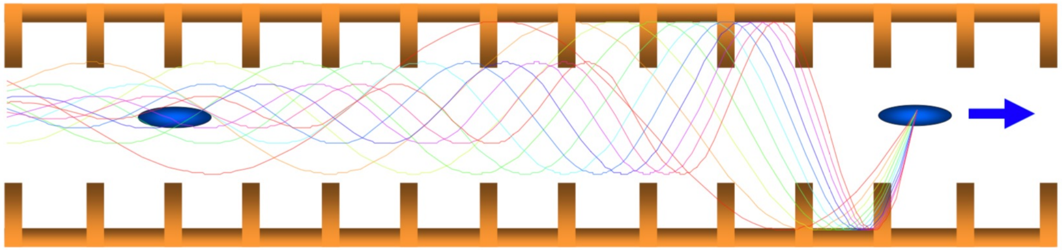
Example: Wakefields

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

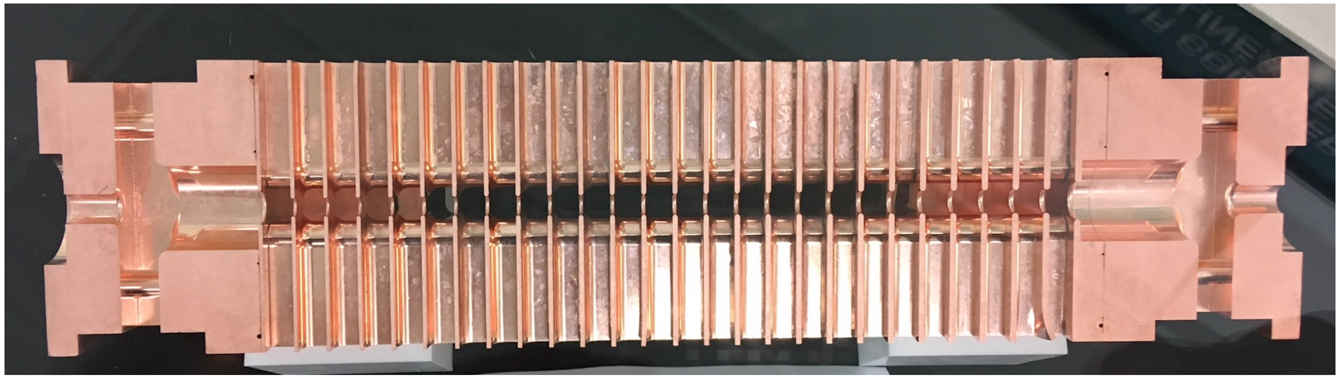
- Bunches traveling in accelerating structures induce fields which perturbs later bunches
- Bunches passing off-centre excite transverse higher order modes (HOM)
- Later bunches are kicked transversely

beam break-up ⇒ Emittance growth !!!





Damping & Detuning



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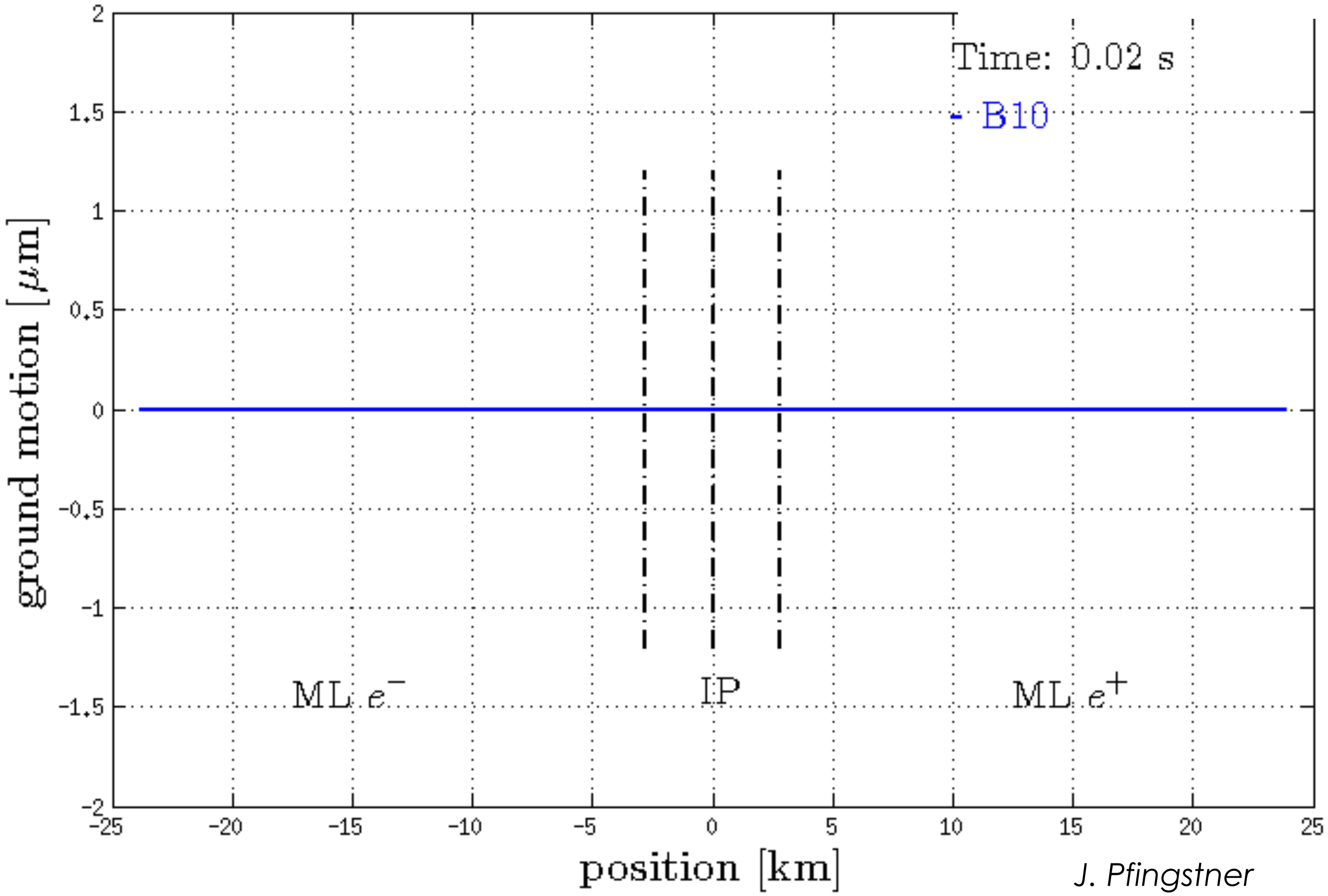
Example Issue: Ground Motion at CLIC

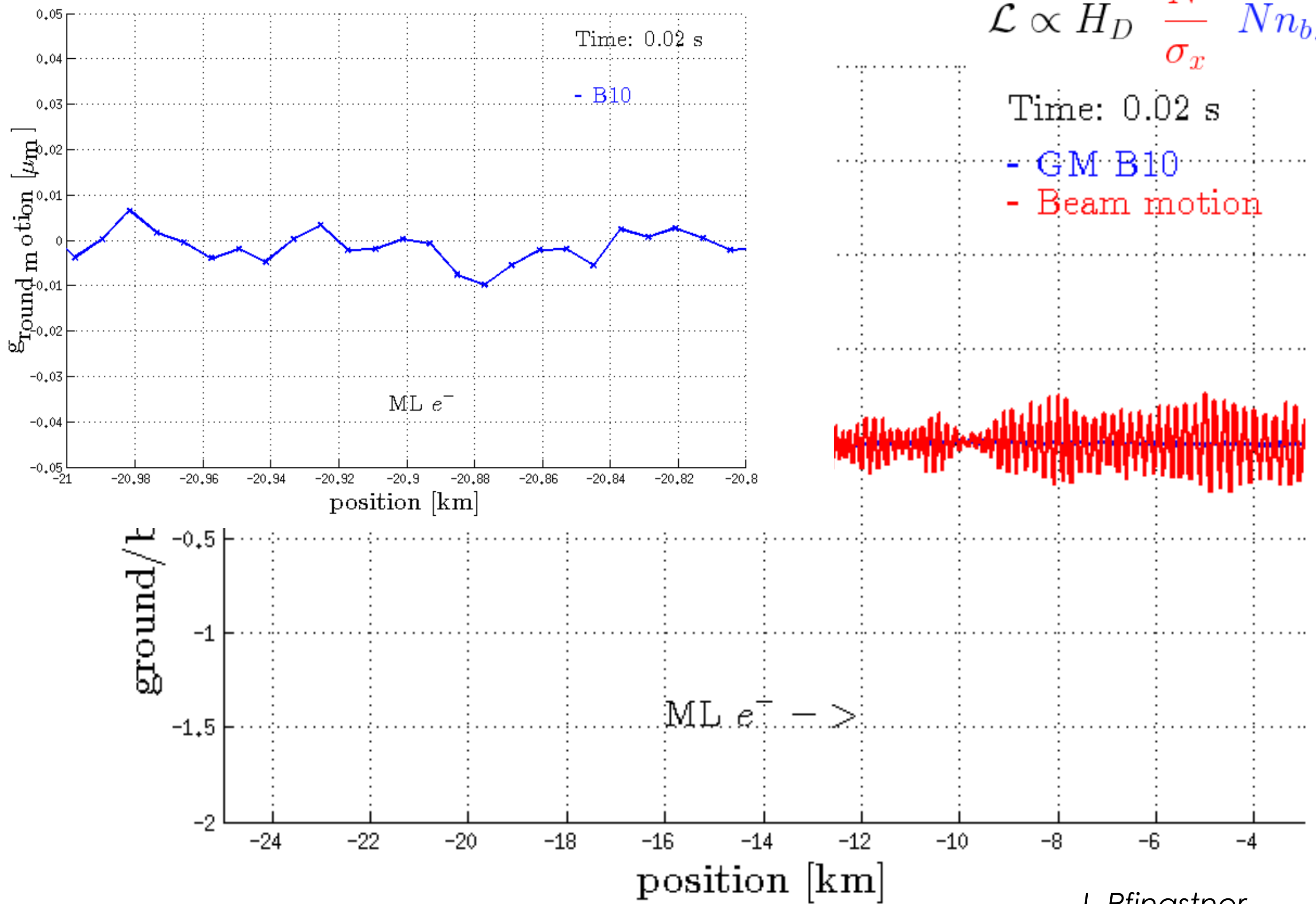
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$



J. Pfingstner

Resulting Beam Jitter

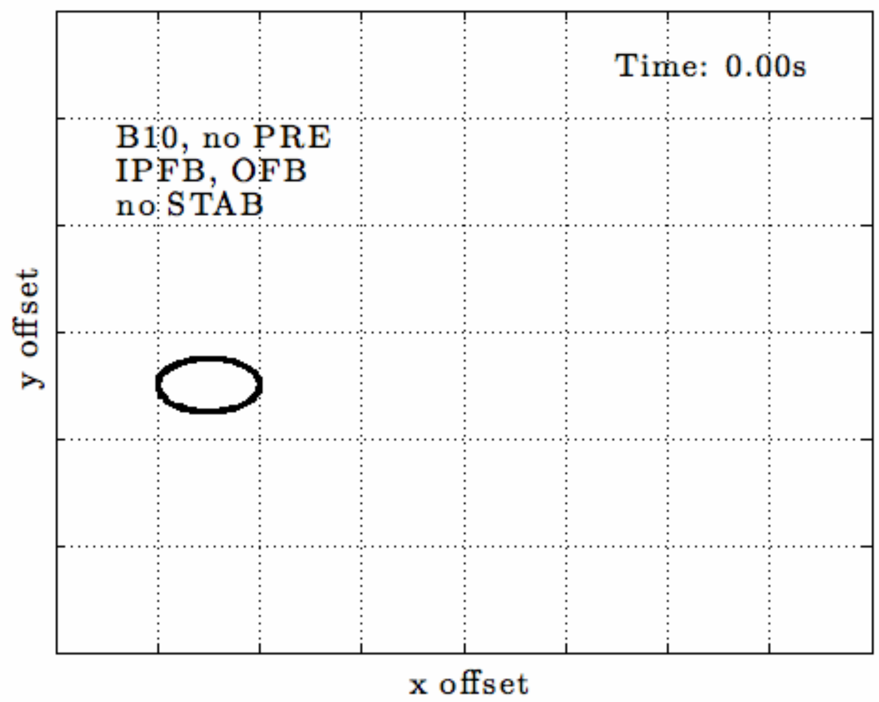
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$



J. Pfingstner

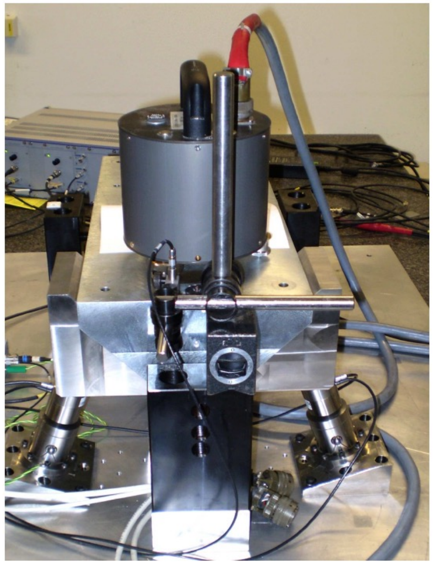
Beams at Collision

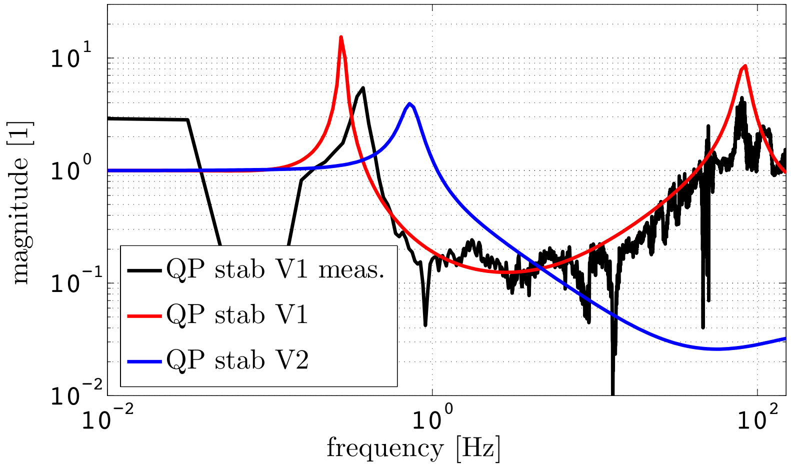
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$



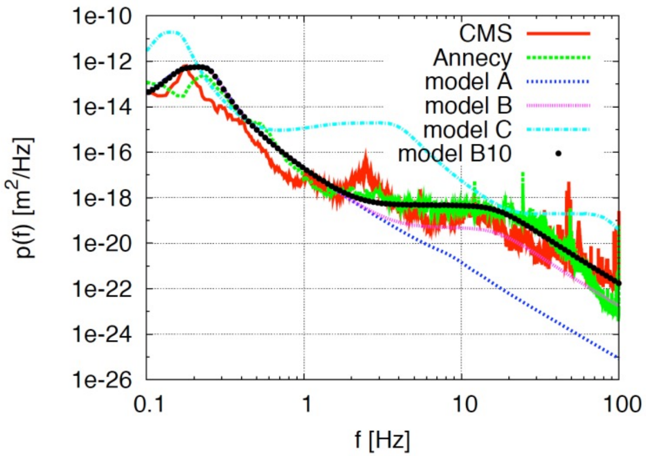
J. Pfingstner

Stabilization System





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

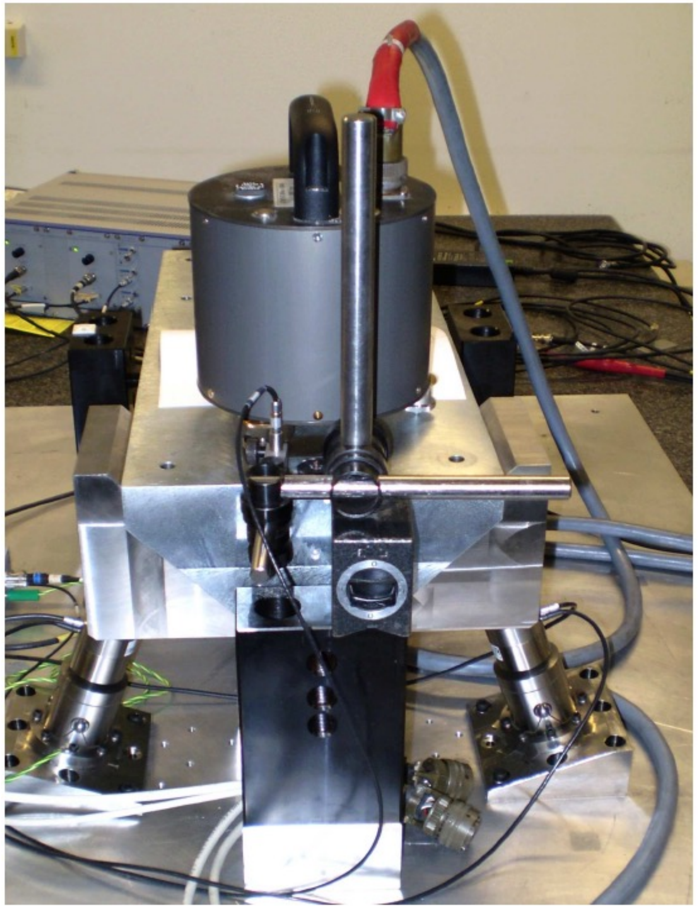


Code

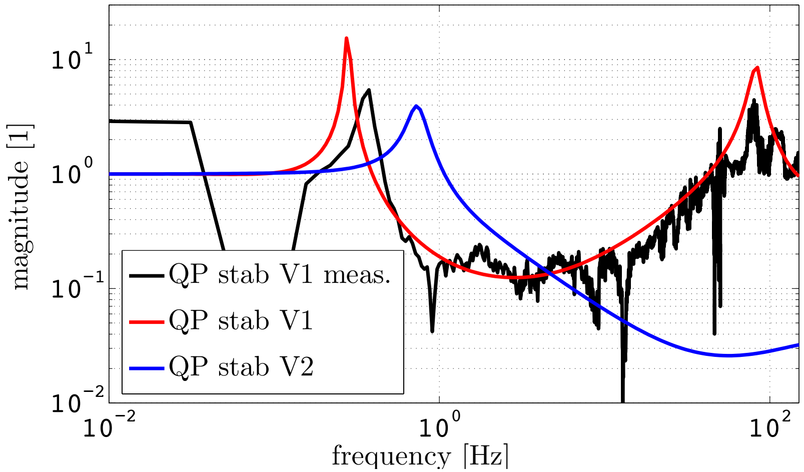
Machine model
Beam-based feedback

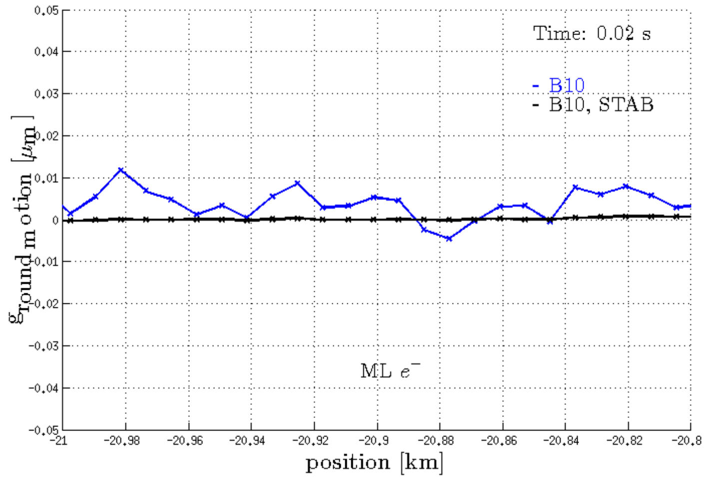
Luminosity achieved/lost	
	B10
No stab.	53%/68%
Current stab.	114%/7%
Future stab.	118%/3%
Close to/better than target	

Stabilisation System



K. Artoos et al.

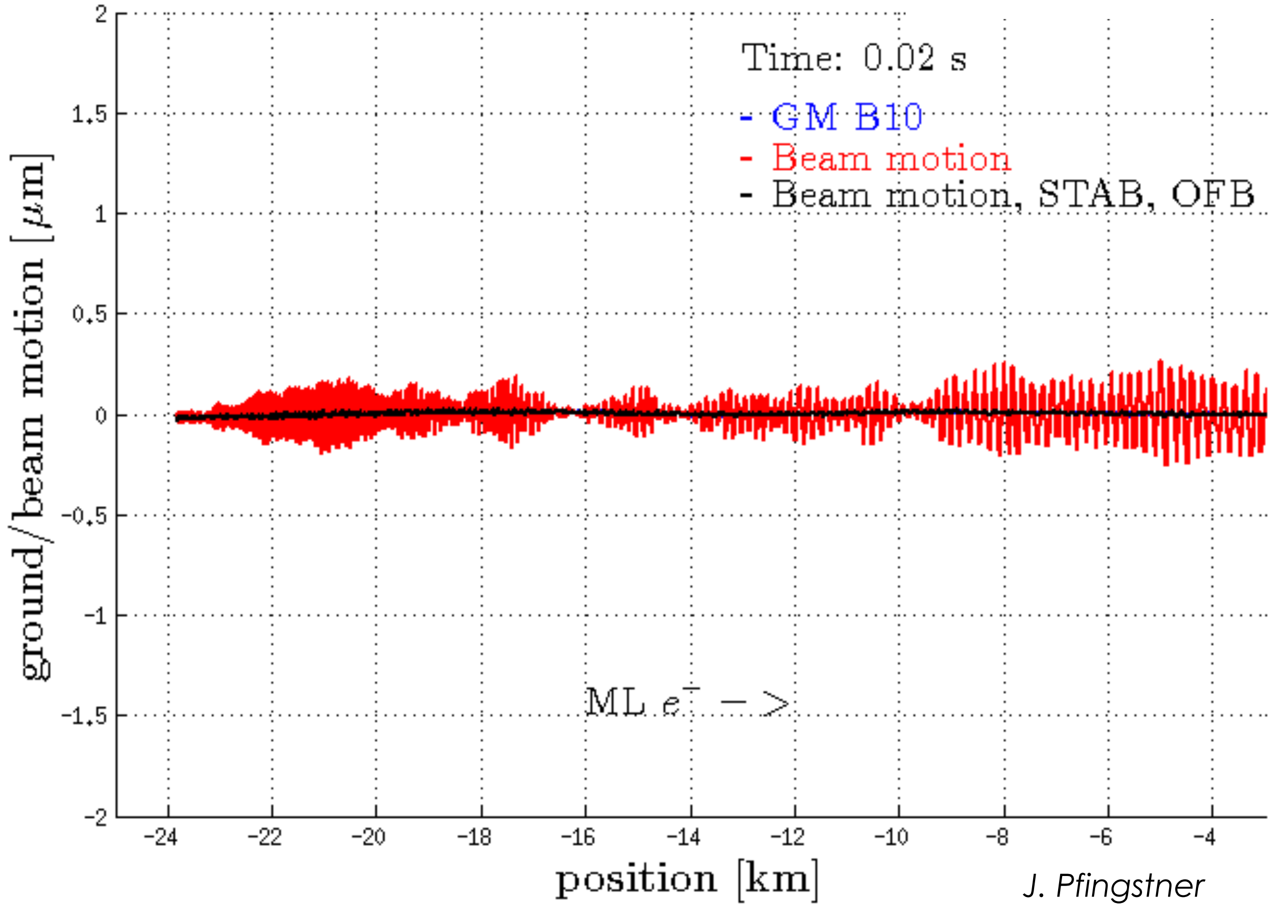




J. Snuverink, et al.

Impact of Stabilisation on Beam

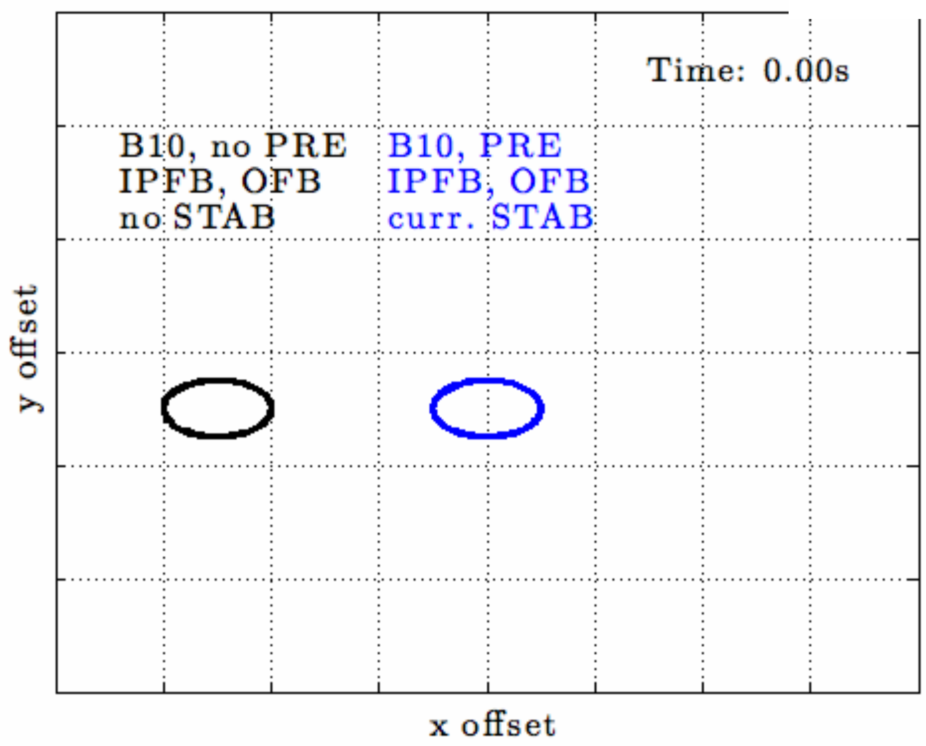
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$



J. Pfingstner

Beam at Collision

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



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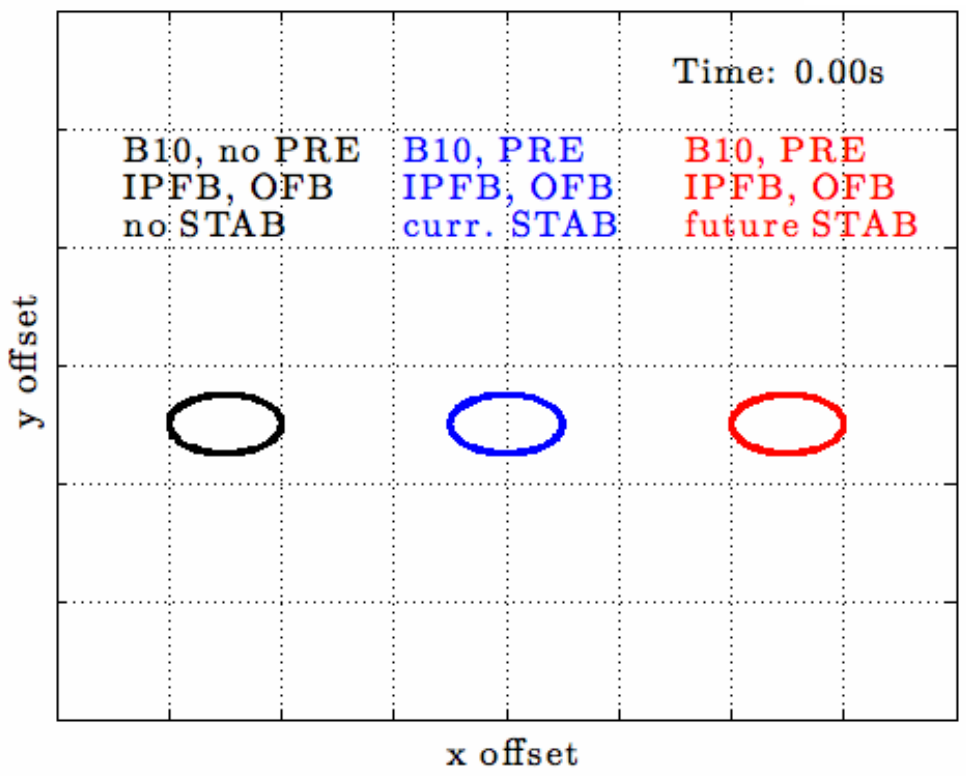


J. Pfingstner

European Strategy for Particle Physics

The European Strategy for Particle Physics (ESPP) is a periodic planning process mandated by the CERN Council to set long-term scientific priorities for the field, including community consultations, input collection, a preparatory group and an open symposium, a drafting session, and final approval by the CERN Council.

The process actively involves the global particle physics community and identifies key future projects, such as accelerator upgrades, to ensure optimal resource use and advancements in fundamental physics.

2020 Update

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.

High Energy Frontier Colliders under consideration

Circular colliders:

- FCC (Future Circular Collider)
  - FCC-ee — e^+e^- 90 - 350 GeV cm, CERN hosts collaboration
  - FCC-hh — ~ 100 TeV cm energy proton-proton, CERN hosts collaboration
- CEPC / SppC (Circular Electron-positron Collider/Super Proton-proton Collider)
  - CepC — e^+e^- 90 - 240 GeV cm
  - SppC — pp 70 TeV cm

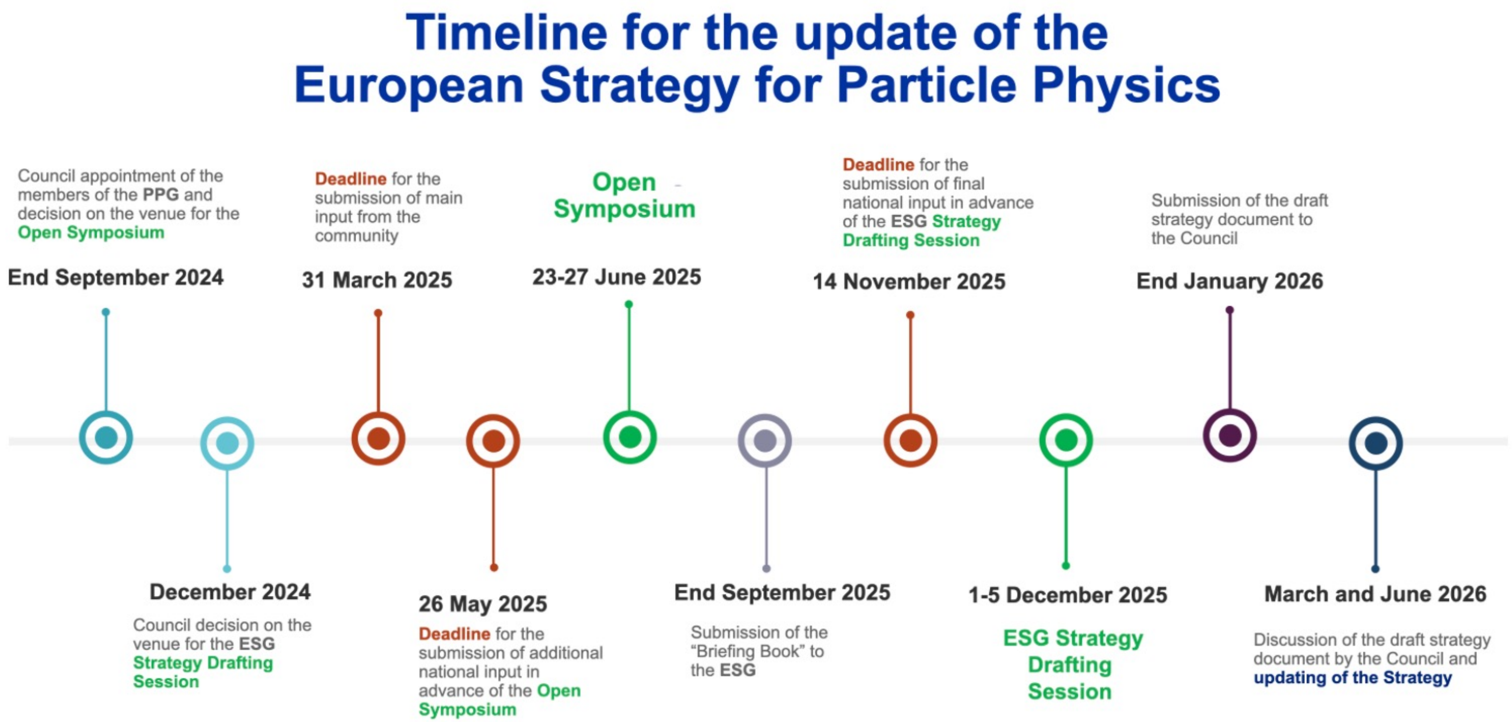
Linear colliders

- ILC (International Linear Collider) — e^+e^- 250 - 500 GeV cm, Japan considers hosting project
- CLIC (Compact Linear Collider) — e^+e^- 380 GeV - 3 TeV cm, CERN hosts collaboration
- C^3 (Cool Copper Collider) — e^+e^- 250 – 550 GeV cm, US study

Others:

- Muon collider
- Plasma acceleration in a linear collider (HALHF, …)

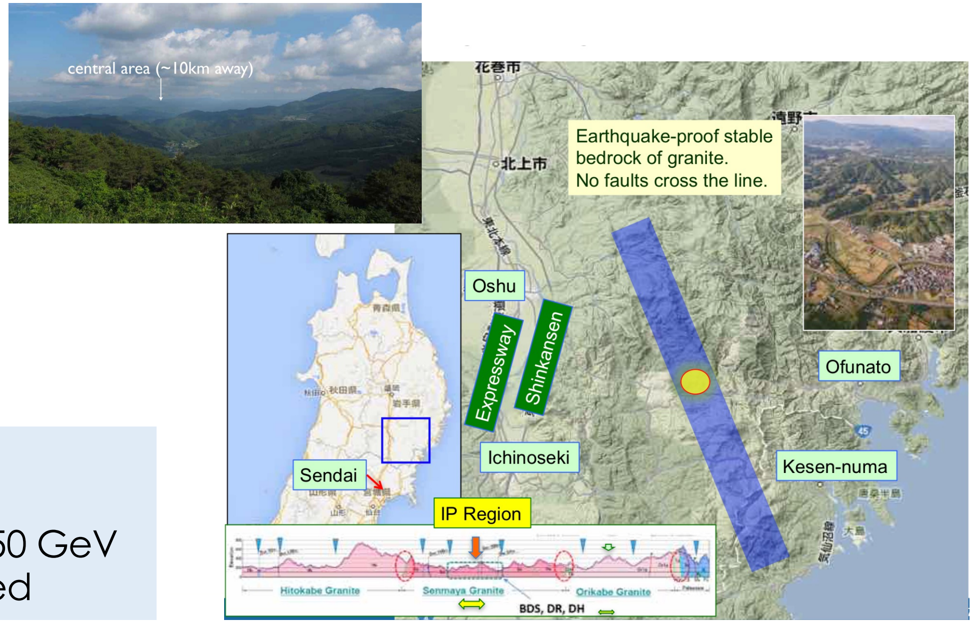
2025 Update of the European Strategy for Particle Physics



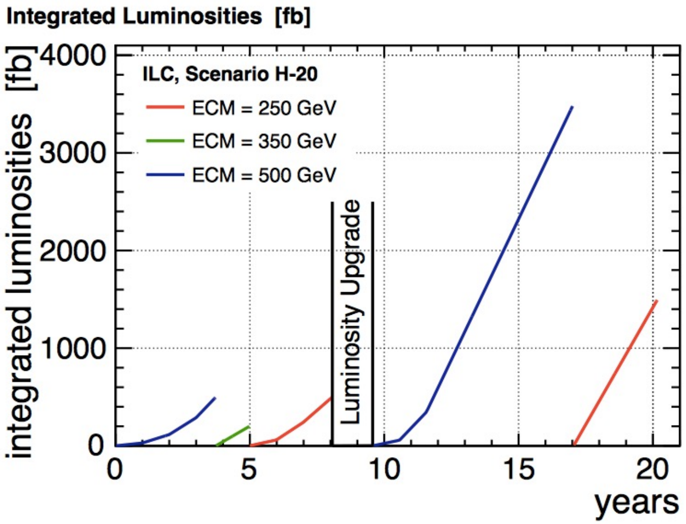
Outlook - ILC in Japan Scenarios

Waiting for Japan to make a commitment

- Site identified and being investigated
- But executive has to endorse project

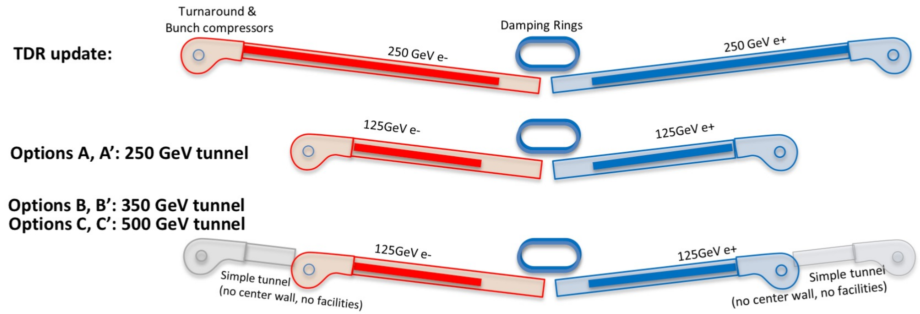


Baseline 500 GeV running example



Cost is a concern

Project at E_{cm} = 250 GeV has been proposed



ILC statement to the 2025 Update

- The ILC is a candidate next-generation collider based on well-established SRF technology and a mature technical design and offering polarized beams. ILC will be a capable electron-positron Higgs factory in its first phase and could be upgraded to 550 GeV to 1 TeV using the same technology.

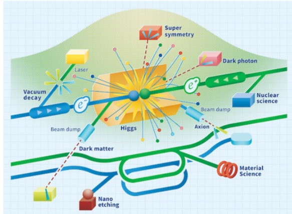
- Although the ILC has not yet gained political acceptance by the Japanese government, stewarded by the International Development Team and through the work of ILC-Japan and KEK, progress has been made since the Technical Design Report.

CLIC submission to the EU strategy

- The CLIC baseline at 380 GeV is now 100 Hz operation, with a luminosity of 4.5×10^{34} $cm^{-2}\,s^{-1}$ and a power consumption of 166 MW. Compared to the 2018 design, this gives three times higher luminosity-per-power.
- The new baseline has two beam-delivery systems, allowing for two detectors operating in parallel, sharing the luminosity.
- The cost estimate of the 380 GeV baseline is approximately 7.17 billion CHF.
- The construction of the first CLIC energy stage could start as early as 2033 and first beams would be available by 2041, marking the beginning of a physics programme spanning 20-30 years.

Linear Collider Vision submission to the EU strategy

Linear Collider Vision



A Linear Collider Vision for the Future of Particle Physics

Contact persons: Jenny List* Roman Pöschl†

on behalf of the LCVision Editorial Board: Masaya Ishino (U. Tokyo), Benno List (DESY), Jenny List (DESY), Tatsuya Nakada (EPFL Lausanne), Michael Peskin (SLAC), Roman Pöschl (IJCLab), Aidan Robson (U. Glasgow), Thomas Schörner (DESY/CERN), Steinar Stapnes (CERN)

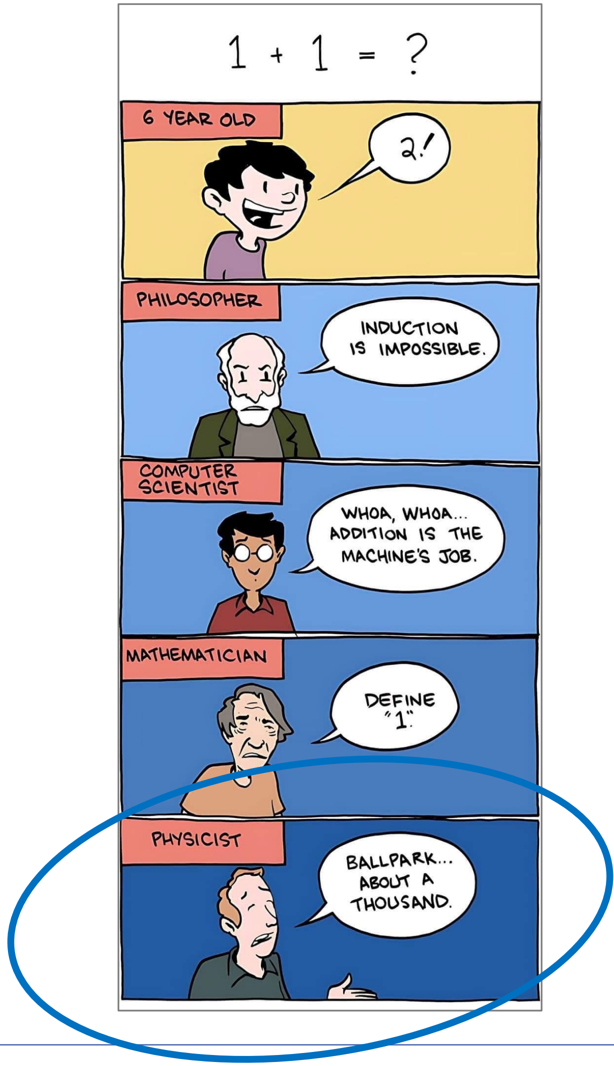
In this paper we review the physics opportunities at linear e^+e^- colliders with a special focus on high centre-of-mass energies and beam polarisation, take a fresh look at the various accelerator technologies available or under development and, for the first time, discuss how a facility first equipped with a technology that is mature today could be upgraded with technologies of tomorrow to reach much higher energies and/or luminosities. In addition, we discuss detectors, alternative collider modes, as well as opportunities for beyond-collider experiments and R&D facilities as part of a linear collider facility (LCF). The material of this paper supports all plans for e^+e^- linear colliders and additional opportunities they offer, independently of technology choice or proposed site, as well as R&D for advanced accelerator technologies. This joint perspective on the physics goals, early technologies and upgrade strategies has been developed by the LCVision team based on an initial discussion at LCWS2024 in Tokyo and a follow-up at the LCVision Community Event at CERN in January 2025. It heavily builds on decades of achievements of the global linear collider community, in particular in the context of CLIC and ILC.

Table 11: Key parameters for the updated superconducting Linear Collider Facility (LCF) compared to the ILC baseline options. Values for ILC250 and ILC500 are taken from Table 4.1 in [14]

Parameter	Unit	ILC250	ILC500	LCF250	LCF550
Centre-of-mass energy	GeV	250	500	250	550
Luminosity	10^{34}cm^{-2}s^{-1}	1.35/2.7/5.4	1.8/3.6	2.7/5.4	3.9/7.7
Polarisation, $P(e^-)/P(e^+)$	%	80 / 30	80 / 30	80 / 30	80 / 60
Number of interaction points		1	1	2	2
Repetition frequency	Hz	5/5/10	5	10	10
Number of bunches per train		1312/2625/2625	1312/2625	1312/2625	1312/2625
Bunch spacing	ns	554/366/366	554/366	554/366	554/366
Bunch train duration	μs	727/961/961	727/961	727/961	727/961
Cavity quality factor	10^{10}	1	1	2	2
Klystron efficiency	%	65	65	80	80
Bunch population	10^{10}	2	2	2	2
Accelerating gradient	MV/m	31.5	31.5	31.5	31.5
Length of 2 SCRF linacs	km	10	22.3	10	24.1
Total facility length	km	20.5	33.5	33.5	33.5
Site power consumption	MW	111/138/198	173/215	148/182	250/322

Parameter	Unit	250 GeV	380 GeV	550 GeV	1500 GeV
Centre-of-mass energy	GeV	250	380	550	1500
Repetition frequency	Hz	100	100	100	50
Nb. of bunches per train		352	352	352	312
Bunch separation	ns	0.5	0.5	0.5	0.5
Pulse length	ns	244	244	244	244
Accelerating gradient	MV/m	72	72	72	72/100
Total luminosity	10^{34} cm^{-2} s^{-1}	~3.0	4.5	~6.5	3.7*
Lum. above 99% of $\sqrt{s}$	10^{34} cm^{-2} s^{-1}	(n/c)	1.3	(n/c)	1.4
Total int. lum. per year	fb^{-1}	~350	540	~780	444
Average power consumption	MW	~130	166	~210	287
Main linac tunnel length	km	11.4	11.4	~15	29.0
Nb. of particles per bunch	10^9	5.2	5.2	5.2	3.7
Bunch length	µm	70	70	70	44
IP beam size	nm	~180/2.5	149/2.0	~120/1.7	60/1.5
Final RMS energy spread	%	0.35	0.35	0.35	0.35
Crossing angle (of main linacs)	mrad	16.5	16.5	16.5	20

Thanks for your attention!



Acknowledgements:

F. Tecker, D. Schulte, S. Stapnes, W. Wuensch, and many others ...

Documentation on ILC & CLIC

ILC:

- https://linearcollider.org Web Site
- https://linearcollider.org/technical-design-report/ Technical Design Report (2013)
- https://cds.cern.ch/record/2293461/files/CERN-ACC-2017-0097.pdf Staging Report (2017)

CLIC:

- https://clic.cern Web site
- https://clic.cern/european-strategy Reports 2012 - 2022
- https://indico.cern.ch/event/1439855/contributions/6461475/ Input to the 2025 European Strategy