Future High-Energy Collider Projects I

D. Schulte

Introduction

- What will be the next high energy frontier project for particle physics?
- What will be the next high energy frontier project for Europe (and CERN)?

- Actually, we do not know

- There is a process ongoing “European Strategy for Particle Physics” to figure out what to do
  - Proposals have been sent in by end of last year
  - Selected presentations were given in Granada this year
  - A summary document is being prepared by September
  - Recommendation report writing will start next January
  - Results will be known and approved by council May 2020

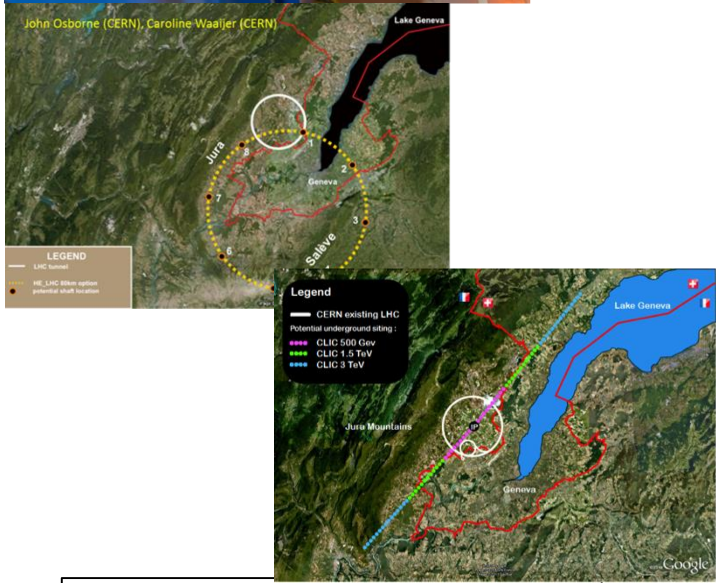
- I will present candidates for future colliders

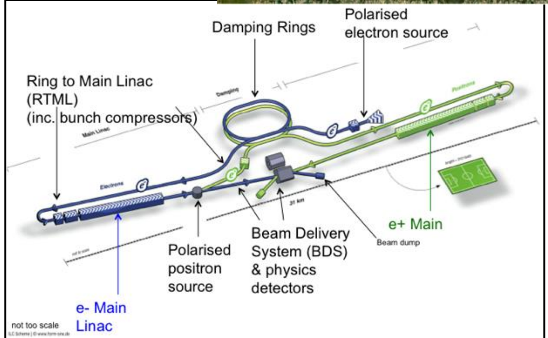
Previous European Strategy

Conclusion in 2012

- Highest priority is exploitation of the LHC including luminosity upgrades
- Europe should be able to propose an ambitious project after the LHC
  - Either a high energy proton collider (**FCC-hh**) with lepton collider (**FCC-ee**) as potential (now likely) intermediate step
  - Or a high energy linear lepton collider (**CLIC**)
- Europe welcomes Japan to make a proposal to host **ILC**
- Long baseline neutrino facility (not covered here)

New process ongoing 2018-2020
Decision expected in May 2020





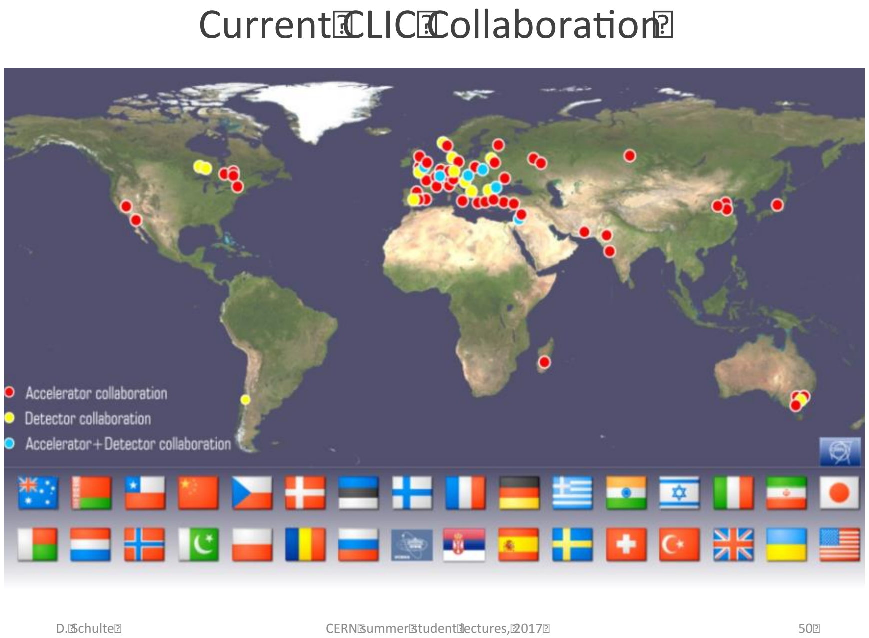
Collaborations

Work is done in collaborations

Global collaborations for FCC and CLIC

Also for ILC

Some collaboration for CEPC / SppC



Current CLIC Collaboration

● Accelerator collaboration
● Detector collaboration
● Accelerator + Detector collaboration

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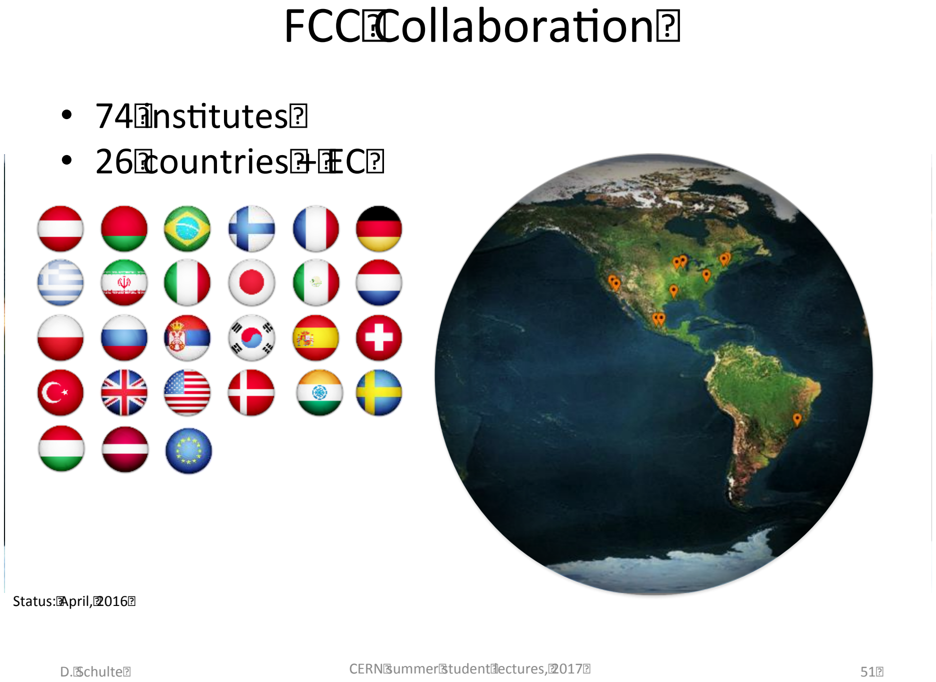

FCC Collaboration

- 74 institutes
- 26 countries + EC

Status: April, 2016

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Collaborations are still dynamic

A way to contribute to a project while not at CERN

Considered High Energy Frontier Collider

Circular colliders:

- FCC (Future Circular Collider)
  - FCC-hh: 100 TeV proton-proton cms energy, ion operation possible
  - FCC-ee: First step 90-350 GeV lepton collider
  - FCC-he: Lepton-hadron option
  - HE-LHC: Stronger magnets in LHC tunnel
  - Lower field version of FCC-hh
- CEPC / SppC (Circular Electron-positron Collider/Super Proton-proton Collider)
  - CepC : e^+e^- 90 - 240 GeV cms
  - SppC : pp 70 TeV cms

Linear colliders

- ILC (International Linear Collider): e^+e^- 250 GeV cms energy, Japan considers hosting project
- CLIC (Compact Linear Collider): e^+e^- 380 GeV - 3 TeV cms energy (also lower possible), CERN hosts collaboration

Mentioned

- Muon collider, past effort in US, maybe new interest in Europe
- Plasma acceleration in linear collider
- Photon-photon collider
- LHeC

Key Collider Considerations

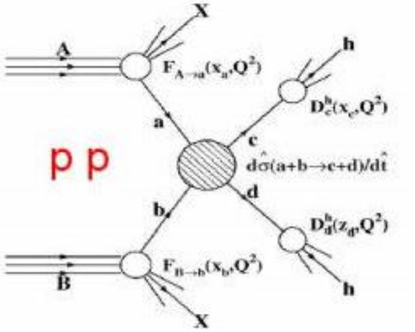
Physics potential	Particle type The collider energy The collider luminosity
Feasibility	The technical maturity The risk The schedule
Affordability	The collider cost The collider power consumption Availability of site

Comparisons

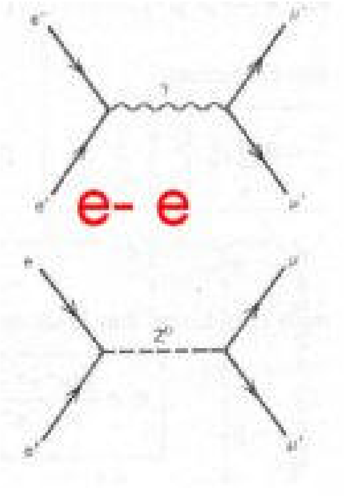
Project	Type	Energy [TeV]	Int. Lumi. $[a^{-1}]$	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Collider Choices

- Hadron collisions: compound particles
  - Protons or ions
  - Mix of quarks, anti-quarks and gluons: variety of processes
  - Parton energy spread
  - QCD processes large background sources
  - Hadron collisions ⇒ can typically achieve higher collision energies

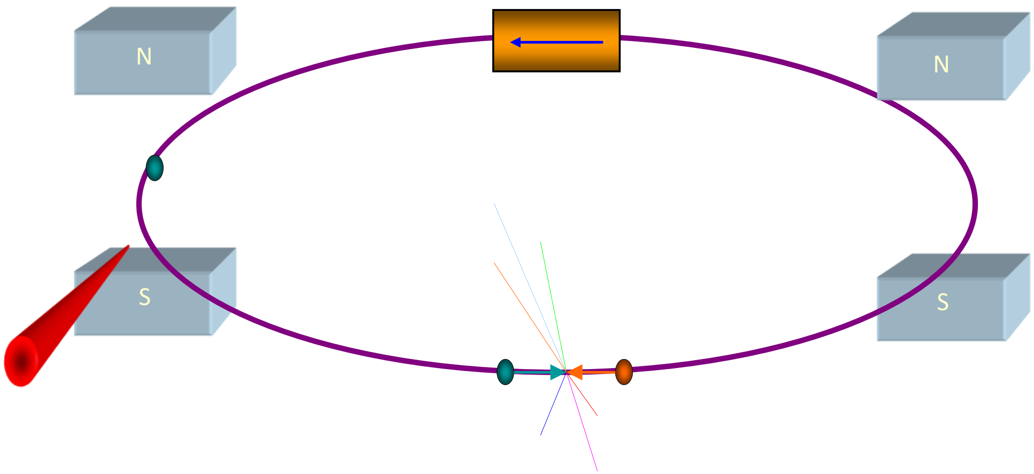


- Lepton collisions: elementary particles
  - Electrons, positrons and probably muons
  - Collision process known
  - Well defined energy
  - Less background
  - Lepton collisions ⇒ precision measurements



- Photons also possible

Energy Limit



Hadron collider is typically circular
Maximum energy defined by ability to keep particle on circular orbit

Required radius R of the ring is given by

$$R \mu \frac{E}{B}$$

⇒ Make magnetic field B of bending dipoles as big as possible

Very convenient

- Accelerate beam in many turns
- Let beam collide many times

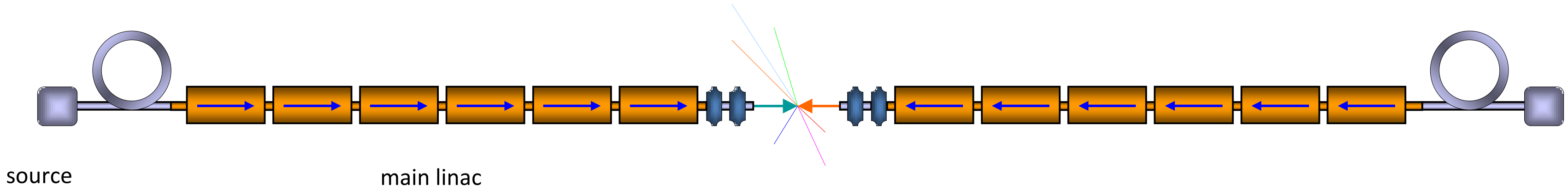
Electron-positron colliders have been mostly circular sofar (one exception)

Energy (and luminosity) are limited by synchrotron radiation

$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

Electrons are 2000 time lighter than protons
At LEP2 lost 2.75GeV/turn for E=105GeV

Solutions for Leptons



Use a linear collider
- Essentially no synchrotron radiation
- But
  - Have to accelerate beams rapidly
  - Only collide once

Hence challenges
- High accelerating gradient
- Small beams at collision

$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

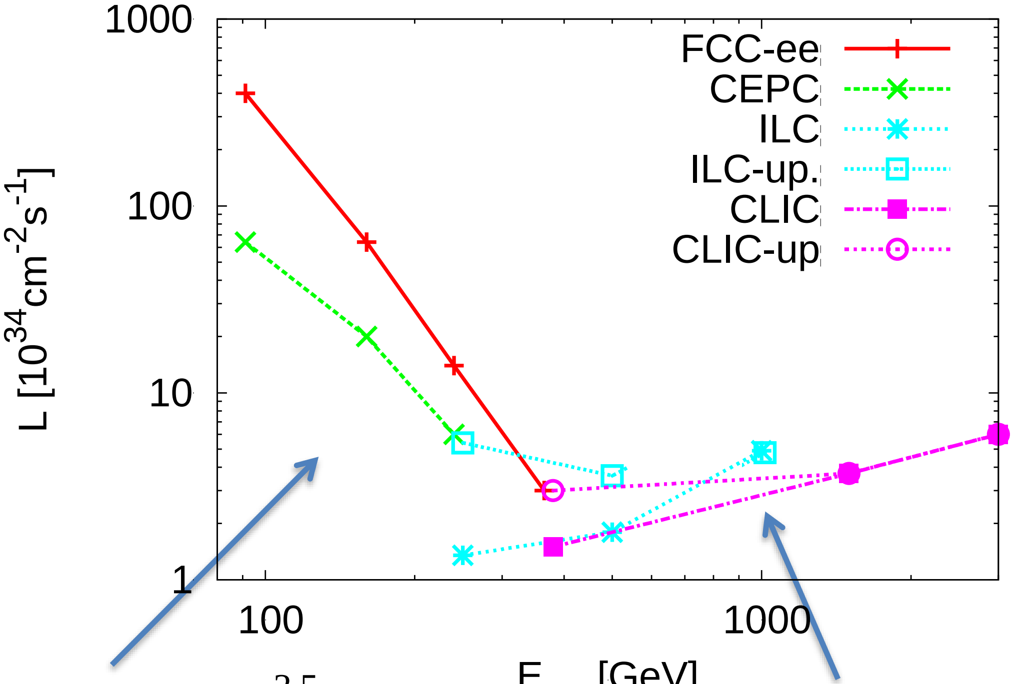
Or use heavier particles

Muons are 200 times heavier than electrons

But they have a short lifetime

Electron-positron Luminosity

Luminosity per facility



$$L \mu P_{synrad} E_{cm}^{-3.5}$$

$$L \mu P_{RF} E_{cm}$$

Energy dependence:

At low energies circular colliders look good

- Reduction at high energy due to synchrotron radiation

At high energies linear colliders excel

- Luminosity per beam power roughly constant

Note: The typical higgs factory energies are close to the cross over in luminosity

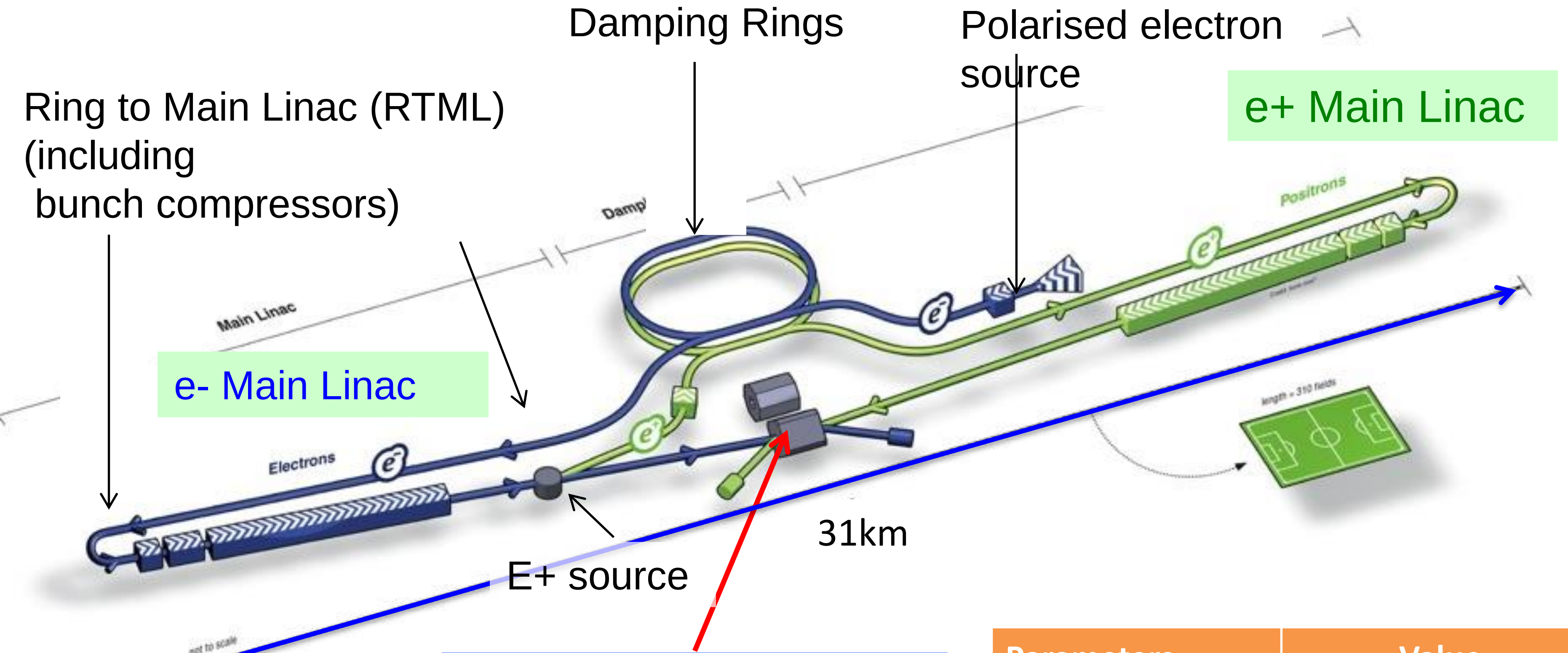
Linear collider have polarised beams (80% e^-, ILC also 30% e^+) and beamstrahlung

- All included in the physics studies

The picture is much clearer at lower or higher energies

Linear Colliders

ILC



Damping Rings

Polarised electron source

Ring to Main Linac (RTML) (including
bunch compressors)

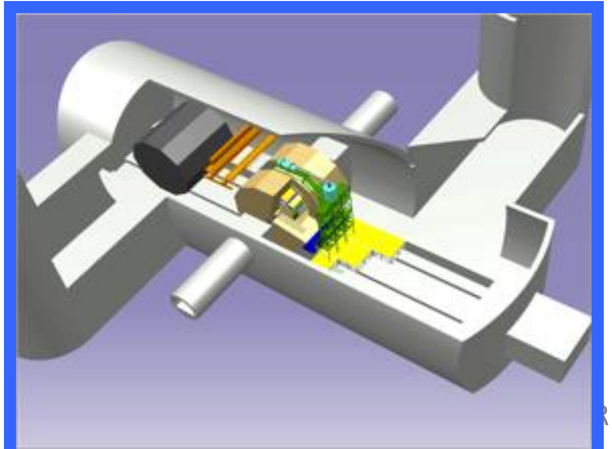
e+ Main Linac

e- Main Linac

31km

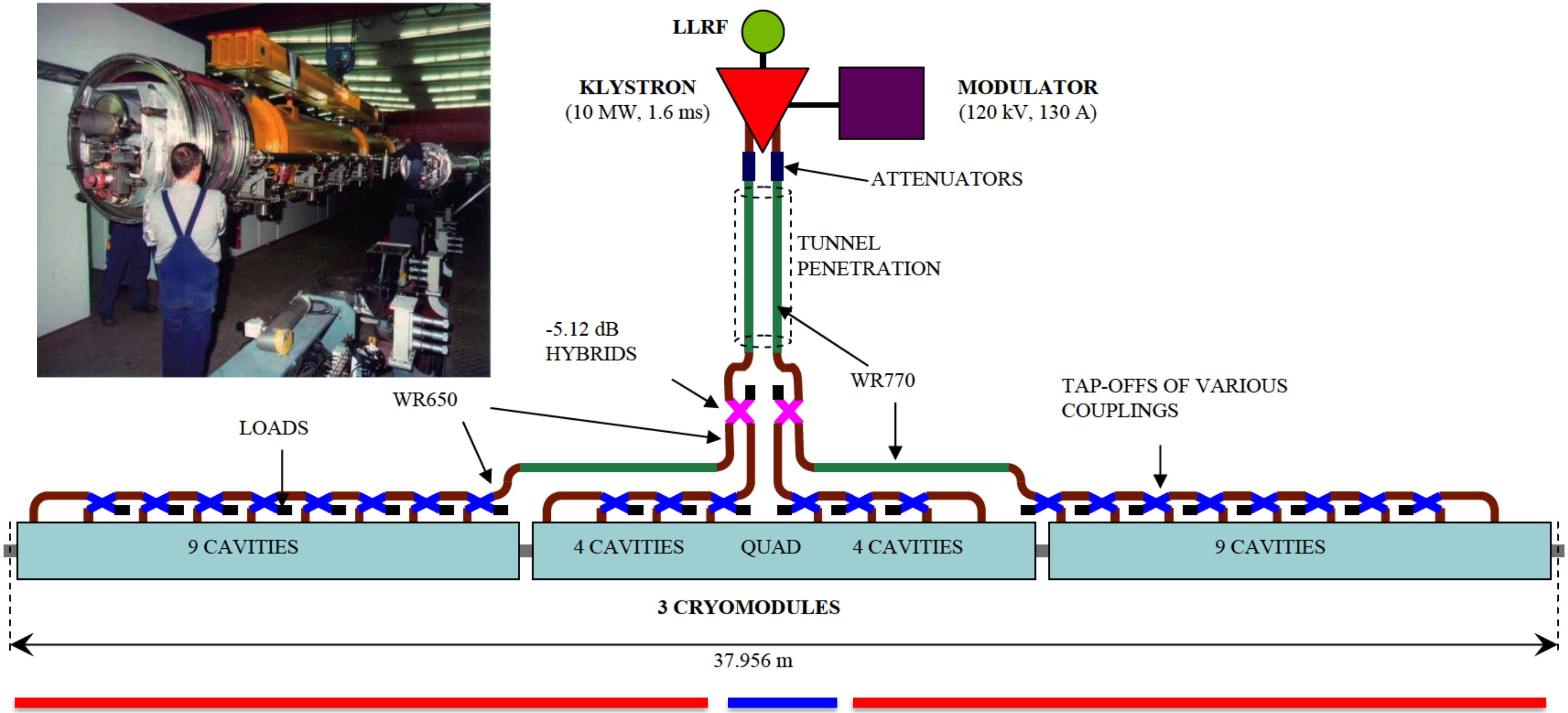
E+ source

ILC Scheme | © www.form-one.de



Parameters	Value
C.M. Energy	250 GeV
Peak luminosity	1.35 x10^{34} cm^{-2}s^{-1}
Beam power	5 MW
Beam Rep. rate	5 Hz
E gradient	31.5 MV/m +/-20%

Main Linac Unit



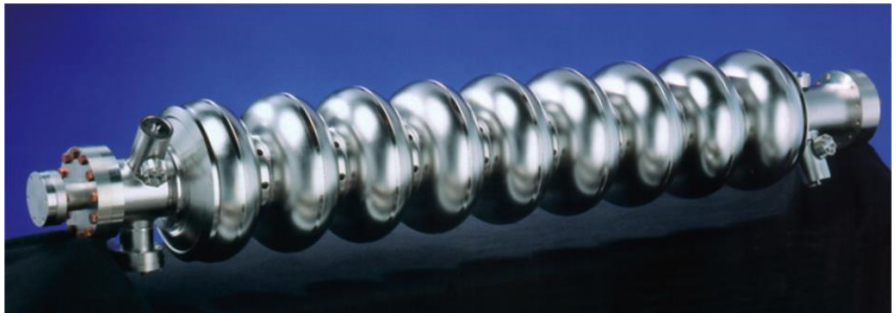
Accelerating cavities
O(65%) of linac length

Beam guiding quadrupole
Beam position monitor
Corrector kicker

Accelerating cavities

Total length for 500 GeV cms 31 km, some length for beam cleaning and focusing

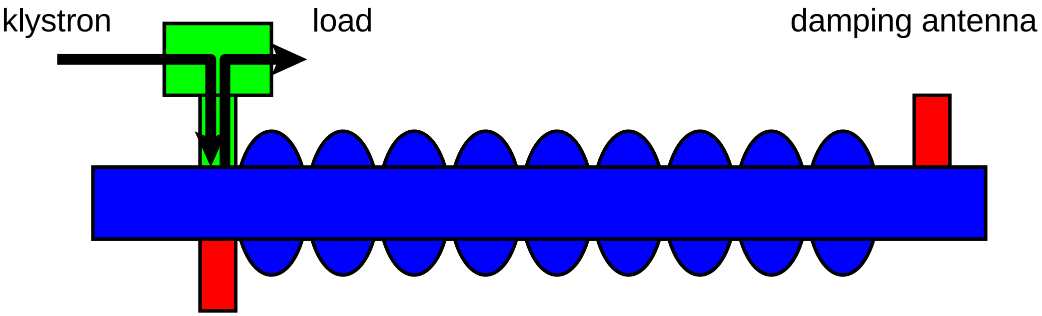
ILC Cavities



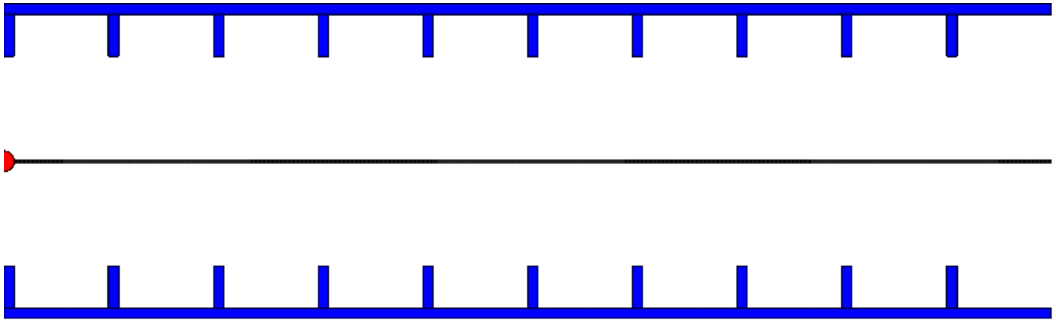
Superconducting cavity (Ni at 2 K)

RF frequency is 1.3 GHz, 23 cm wavelength

Length is 9 cells = 4.5 wavelengths = 1 m



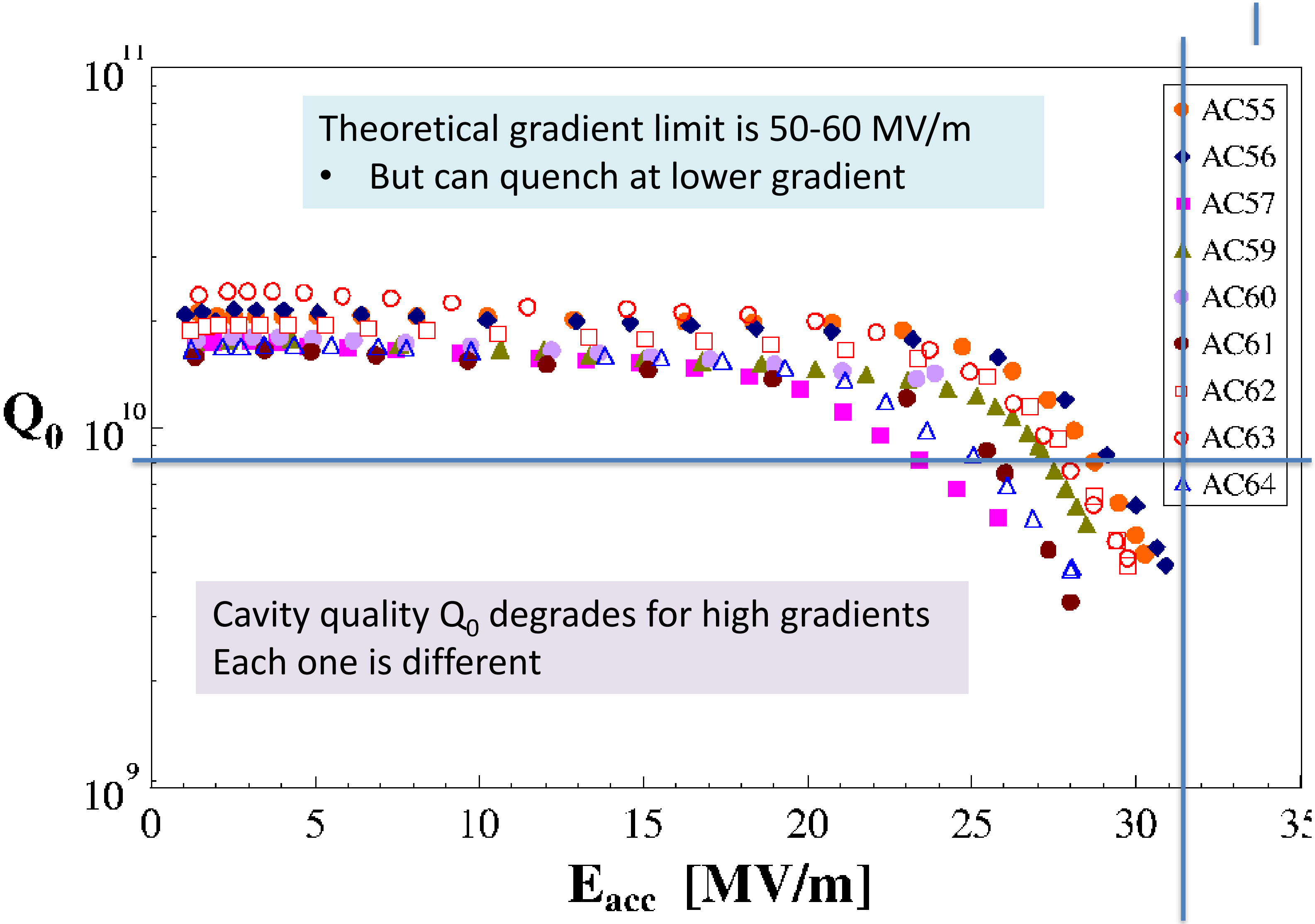
Standing wave structure



Gradient is 31.5 MV/m

Need about 8000 cavities

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

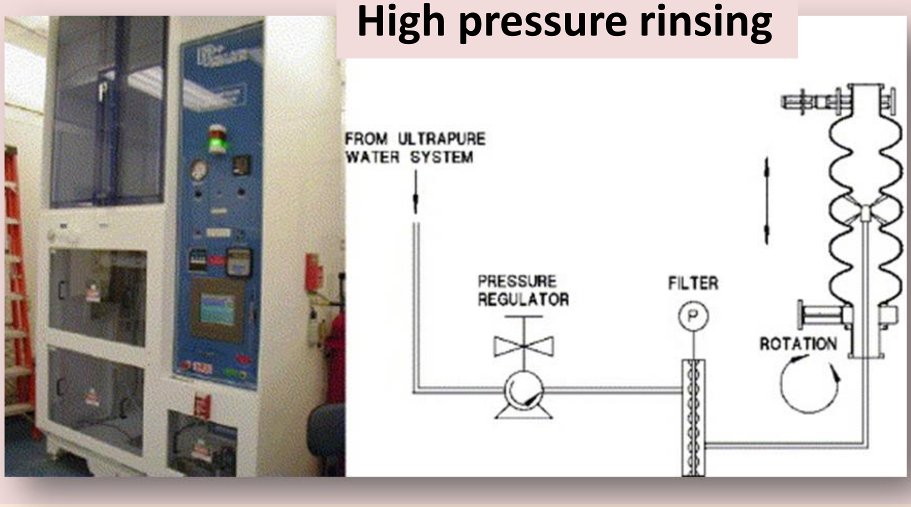
ILC Cavity Treatment

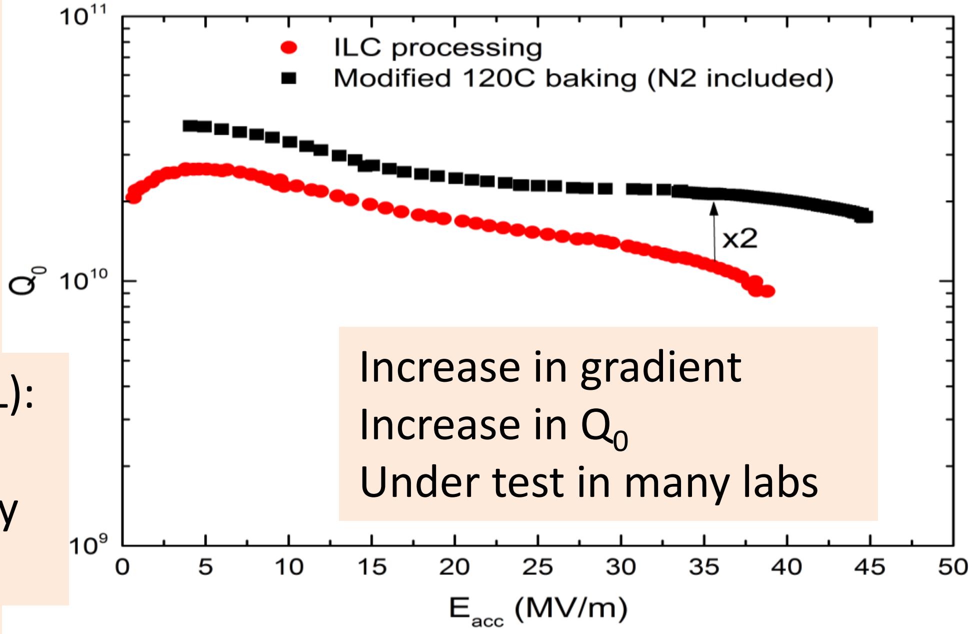
Control of material
Avoid defects
Ensure high quality

Electropolishing
-> fill with H_2SO_4, apply current to remove thin surface layer

Bakeout

High pressure rinsing

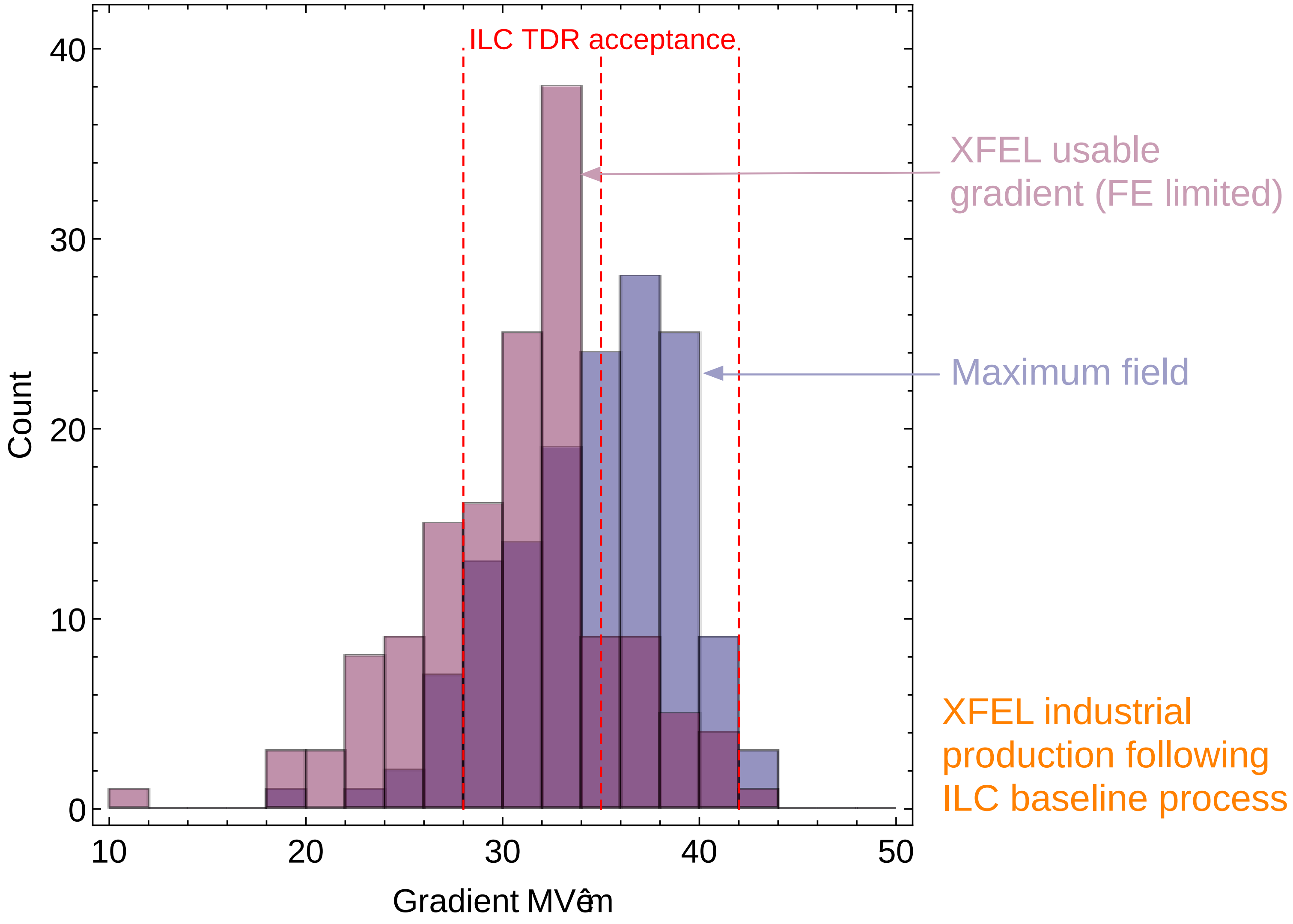




Increase in gradient
Increase in Q_0
Under test in many labs

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

ILC Achieved Gradient



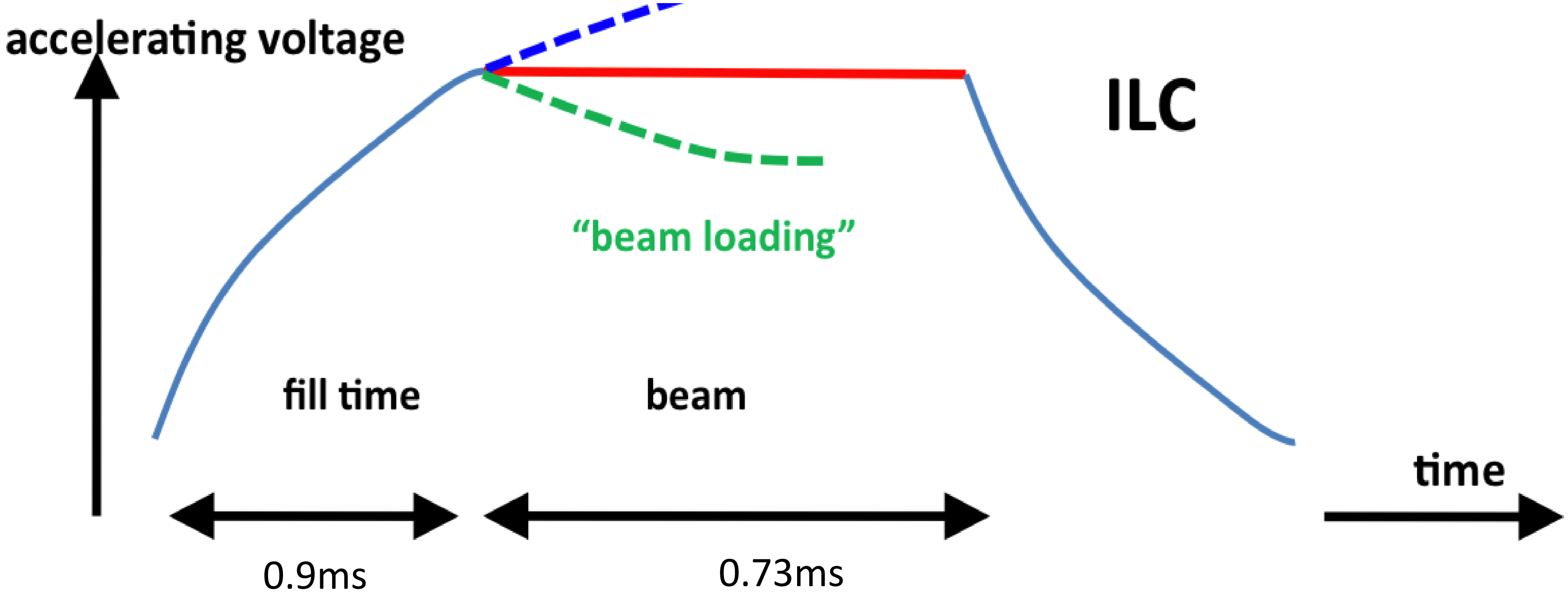
XFEL usable gradient (FE limited)

Maximum field

XFEL industrial production following ILC baseline process

From N. Walker

Note: Pulsed Operation



5 RF pulses of 1.6 ms per second (1312 bunches in 0.73 ms):

Because field leads to losses in the wall

- About 1 W/m
- With no pulsing losses would be O(100) times worse

RF power in pulse: 5 MW / (5 x 0.73 ms) = O(1500 MW) = O (150 klystrons)

Note: Cryogenics

Cavities have small losses

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

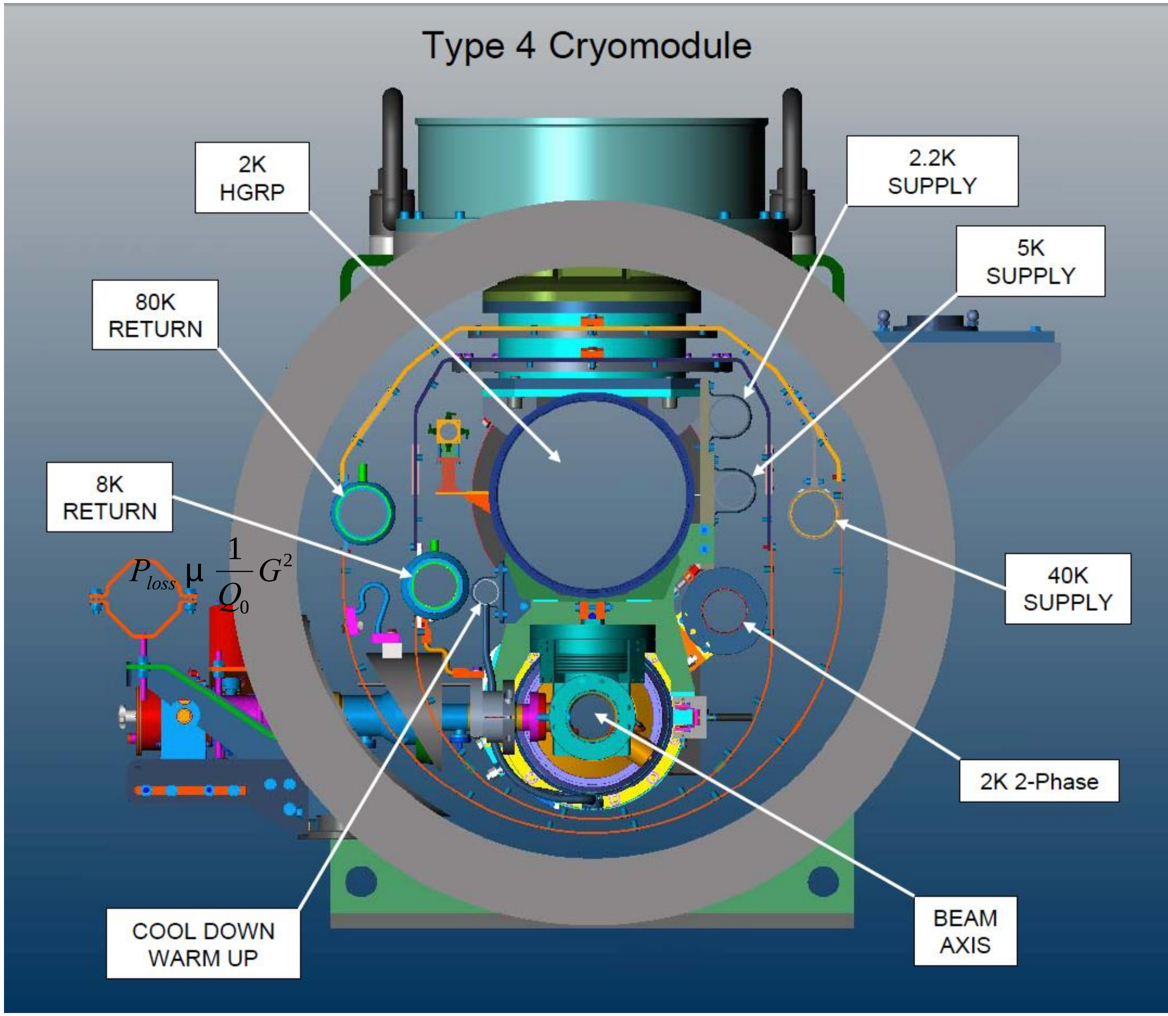
About 1W/m

But cooling costly at low temperatures

Remember Carnot:

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

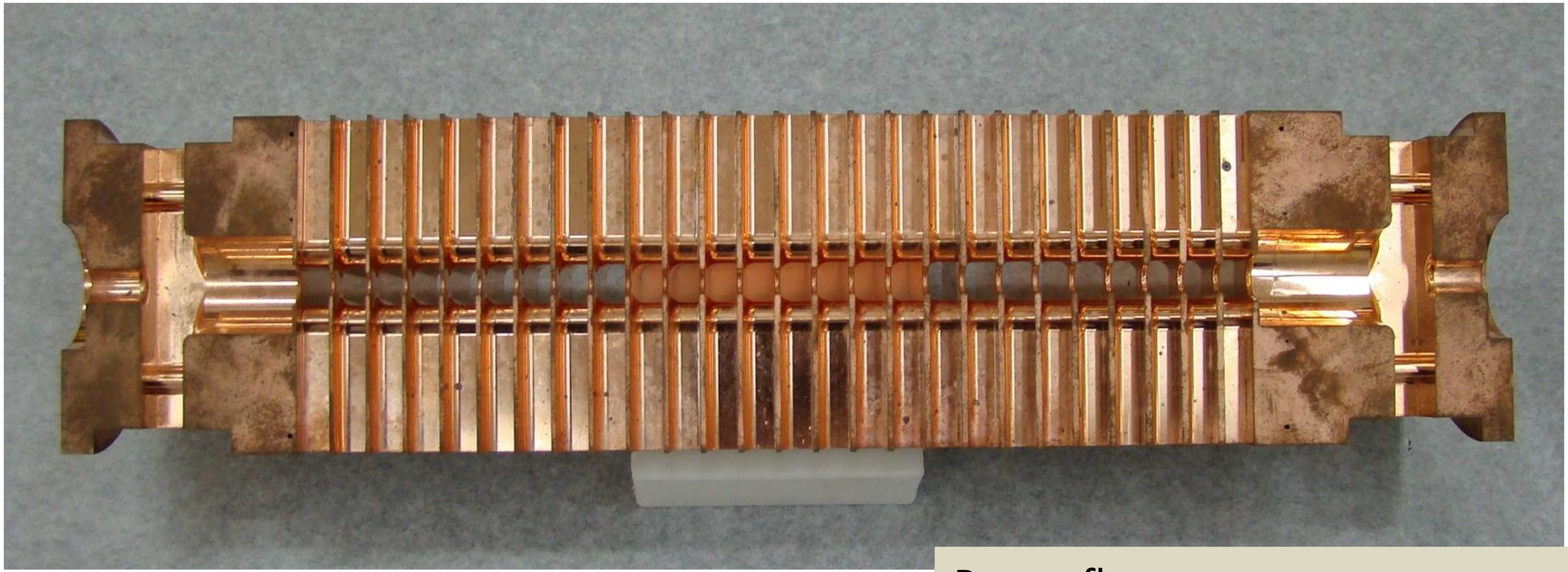
$$P_{cryo} \approx 700 \times P_{loss}$$



The typical heat load of 1 W/m
$\Rightarrow$ about 1 kW/m for cryogenics

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

CLIC Accelerating Structure



12 GHz, 23 cm long, normal conducting
Loaded gradient 100 MV/m
⇒ Allows to reach higher energies
⇒ 140,000 structures at 3 TeV

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

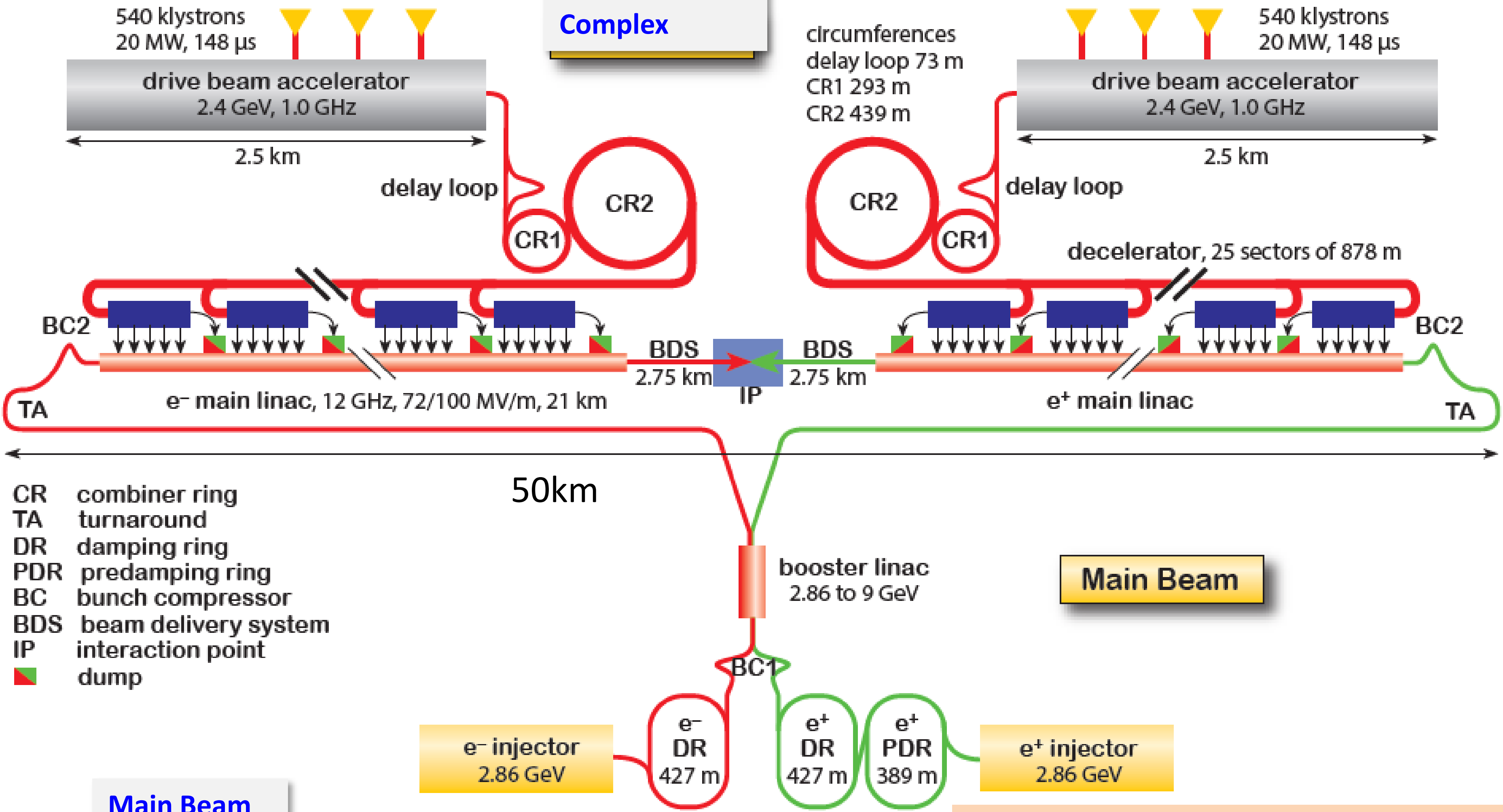
But strong losses in the walls
⇒ 50 RF bursts per second
⇒ 240 ns, 60 MW, 312 bunches
⇒ Power during pulse 8.5 x 10^6 MW (3000 x ILC)

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

CLIC: The Basis

Goal: Lepton energy frontier

CLIC at 3TeV shown



Drive Beam Generation Complex

Main Beam

Main Beam Generation Complex

Stages at E_{cms}=0.38, 1.5 and 3TeV

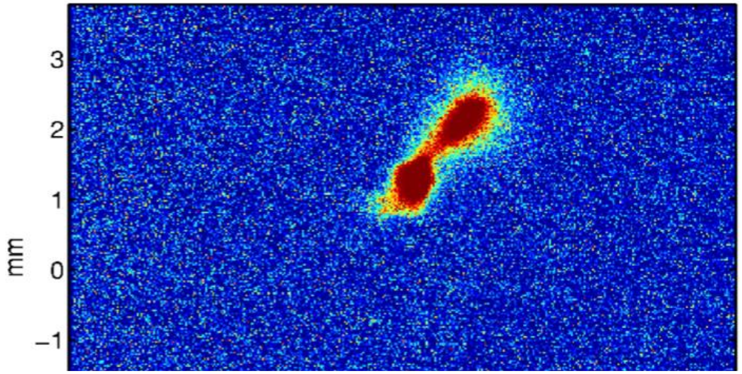
L=6×10^{34}cm^{-2}s^{-1} at 3TeV

Beam power 30MW at 3TeV

CLIC Gradient Limitations

Breakdowns (discharges during the RF pulse)

- Require $p \leq 3 \times 10^{-7}\ \mathrm{m}^{-1}\mathrm{pulse}^{-1}$

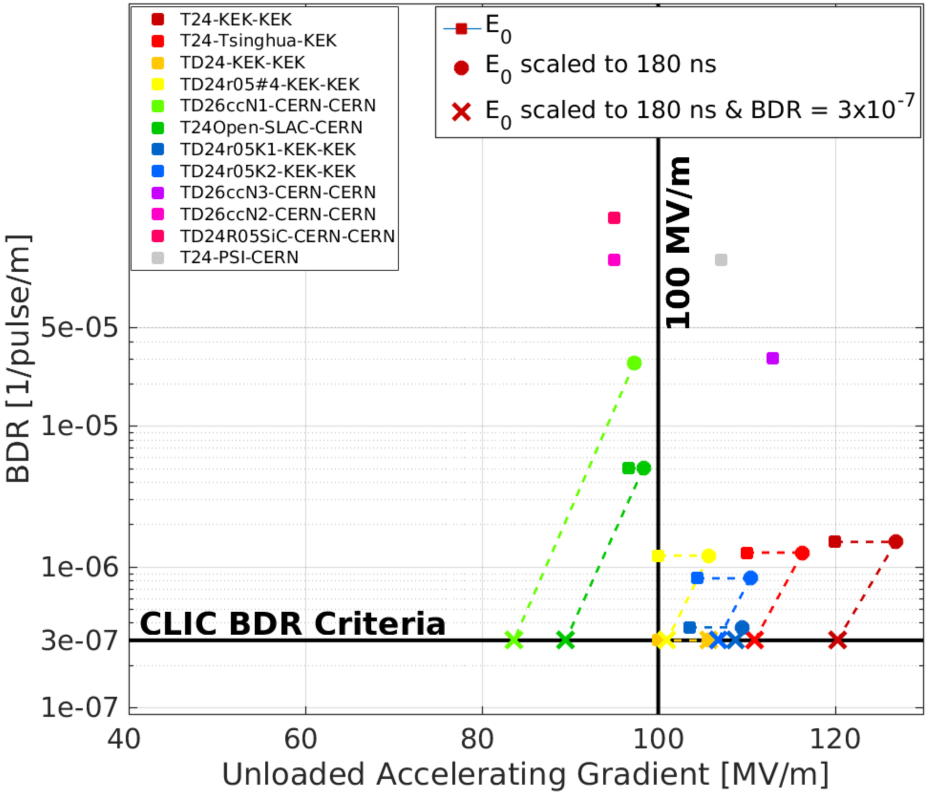


Structure design based on empirical constraints, not first principle

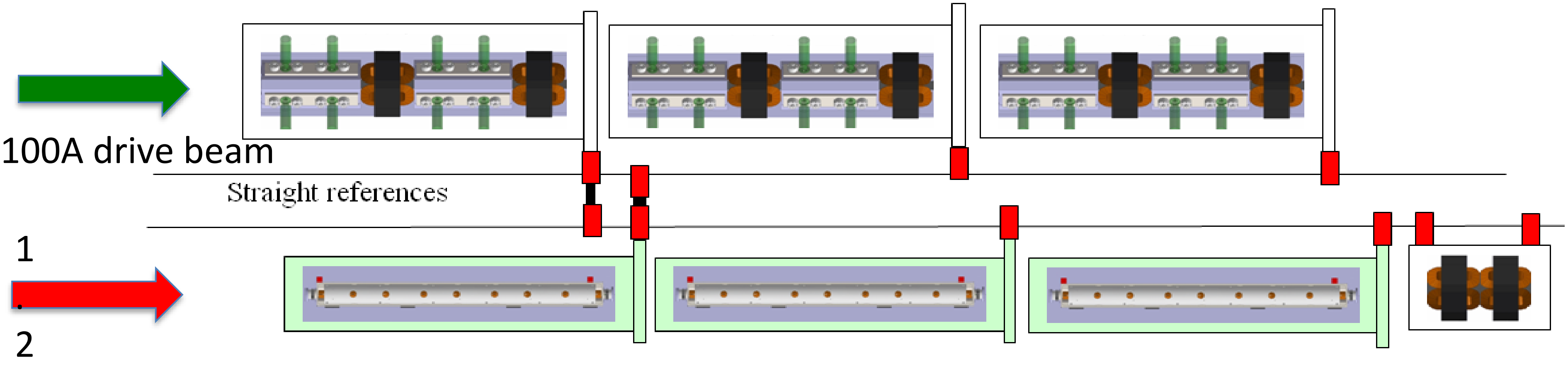
- Maximum surface field
- Maximum temperature rise
- Maximum power flow

R&D programme established gradient O(100 MV/m)

Shorter pulses have less breakdowns



CLIC Two-beam Concept

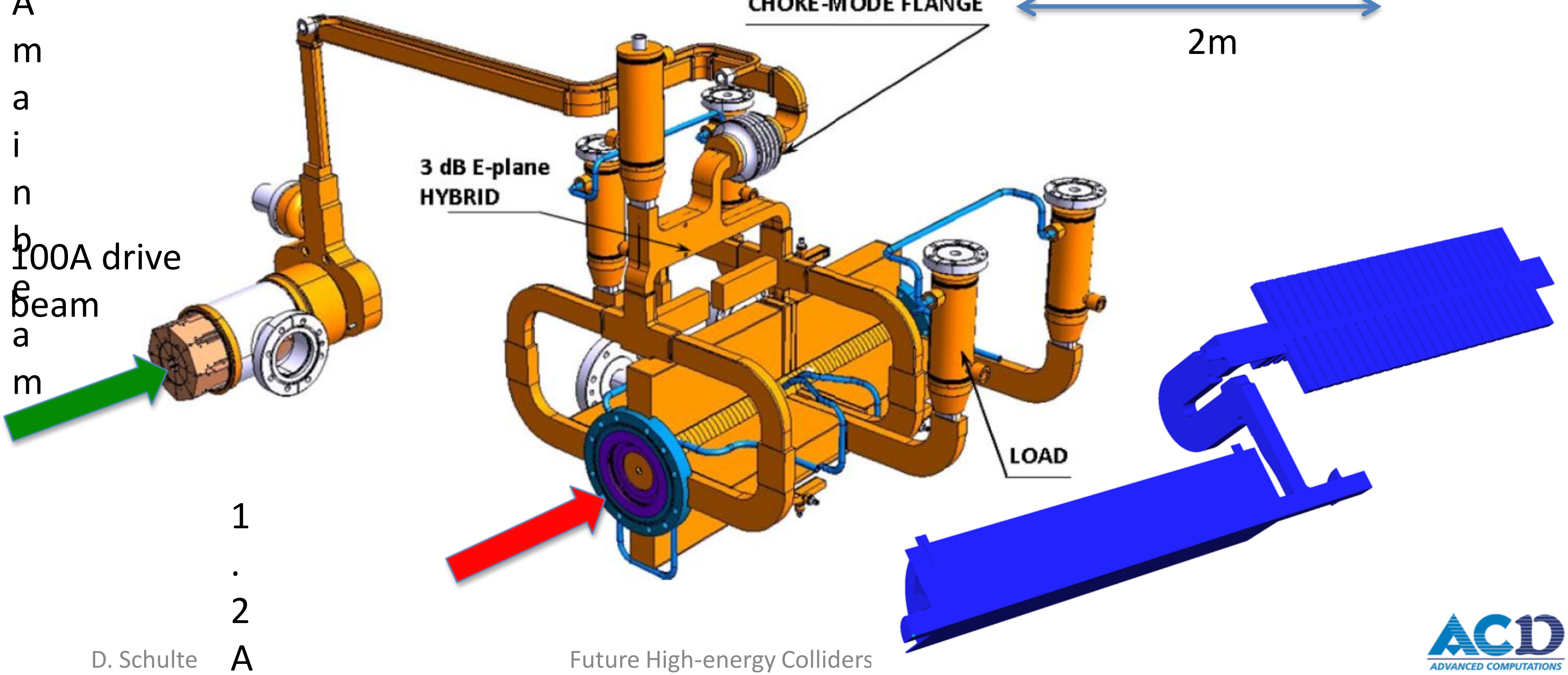


100A drive beam

Straight references

1.2A main beam

2m



100A drive beam

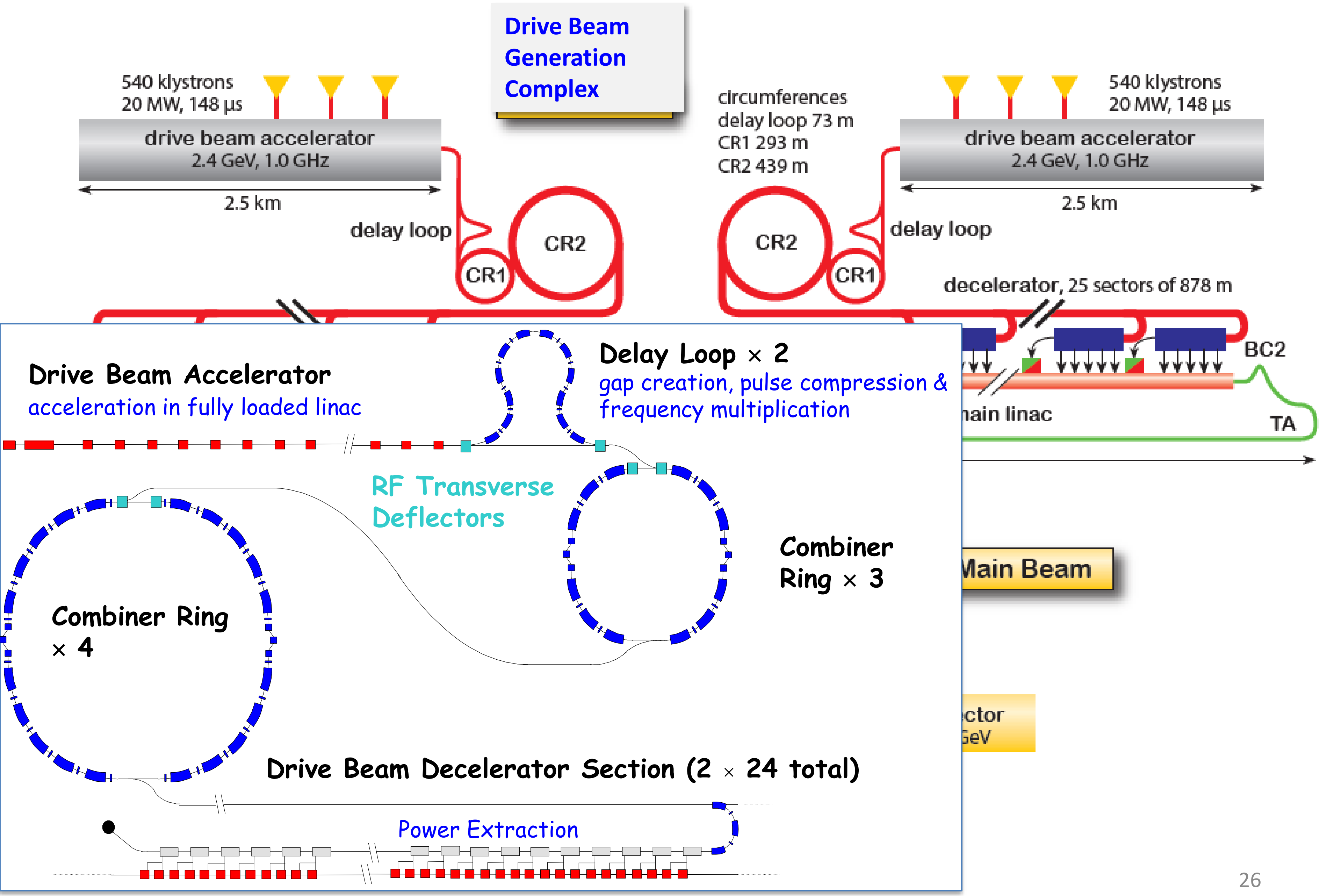
1.2A

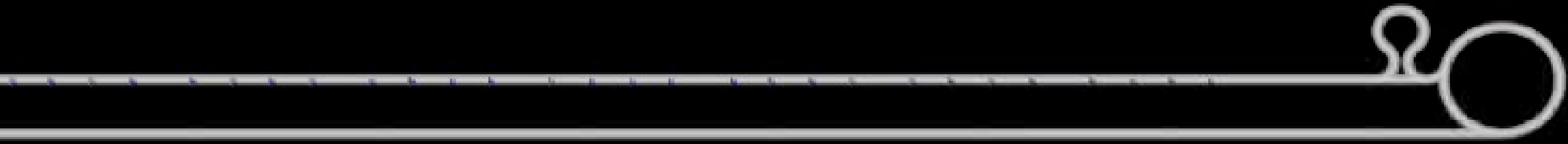
CLIC Two-beam Module

1st module

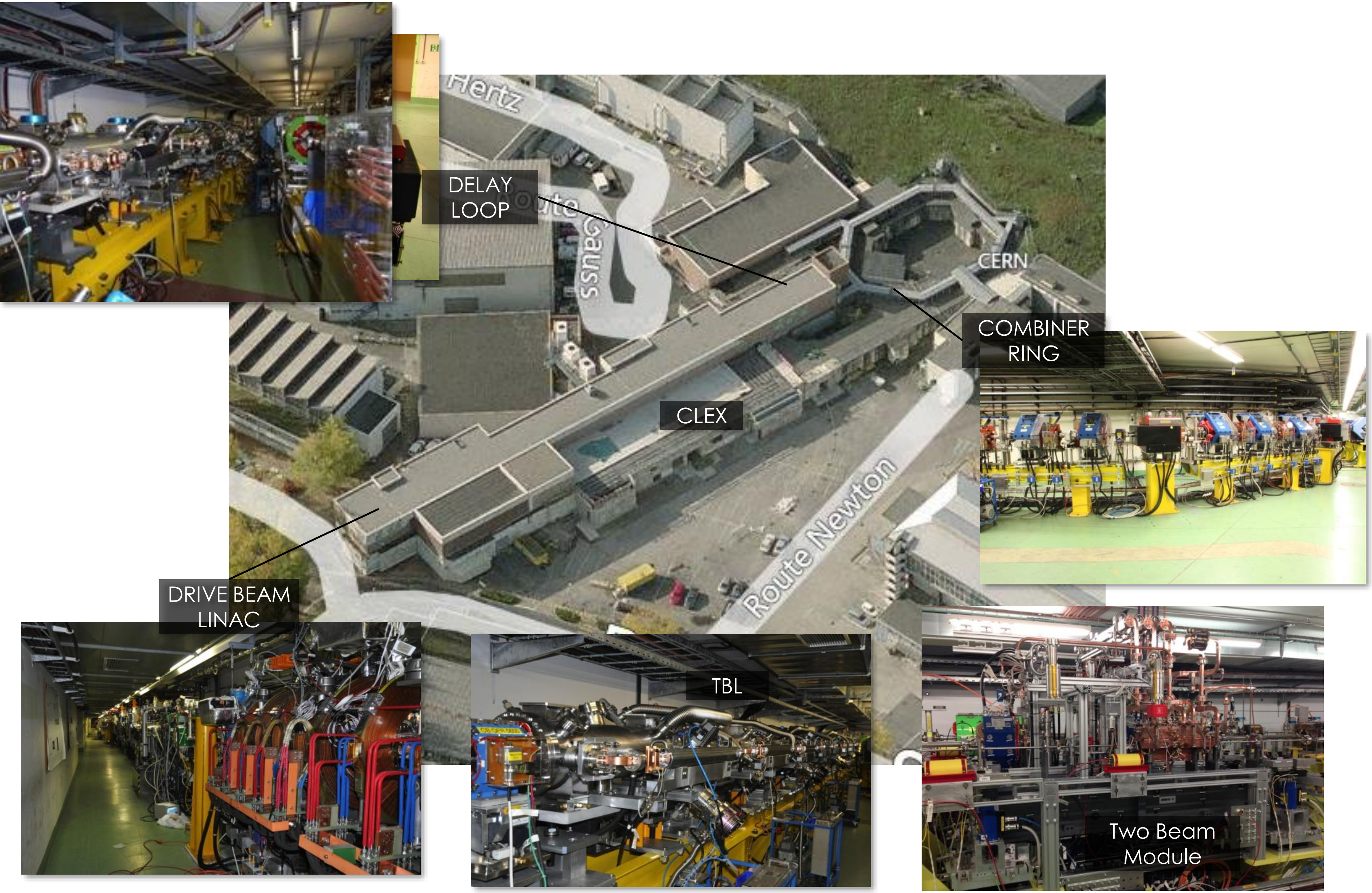
80 % filling with accelerating structures
11 km for 380 GeV cms
50 km for 3 TeV

CLIC: The Basis





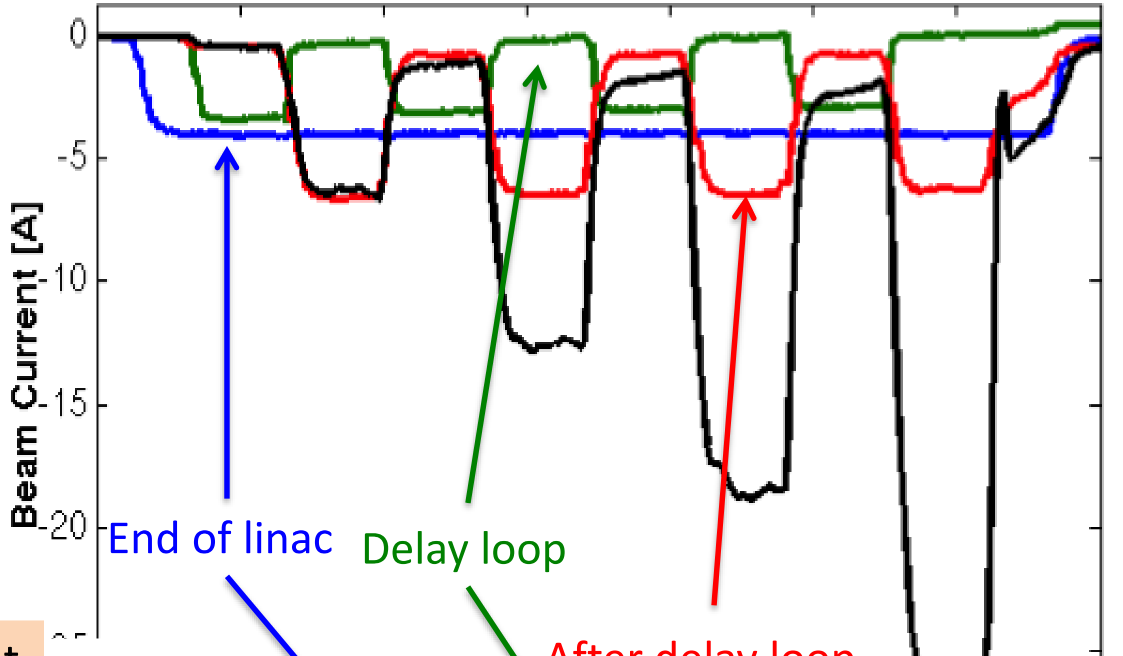
CLIC Test Facility (CTF3)

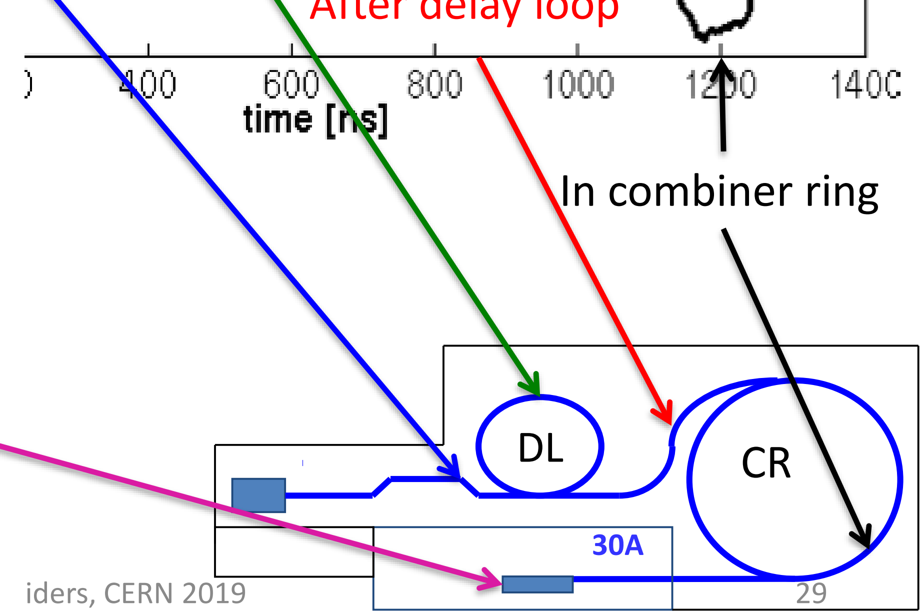


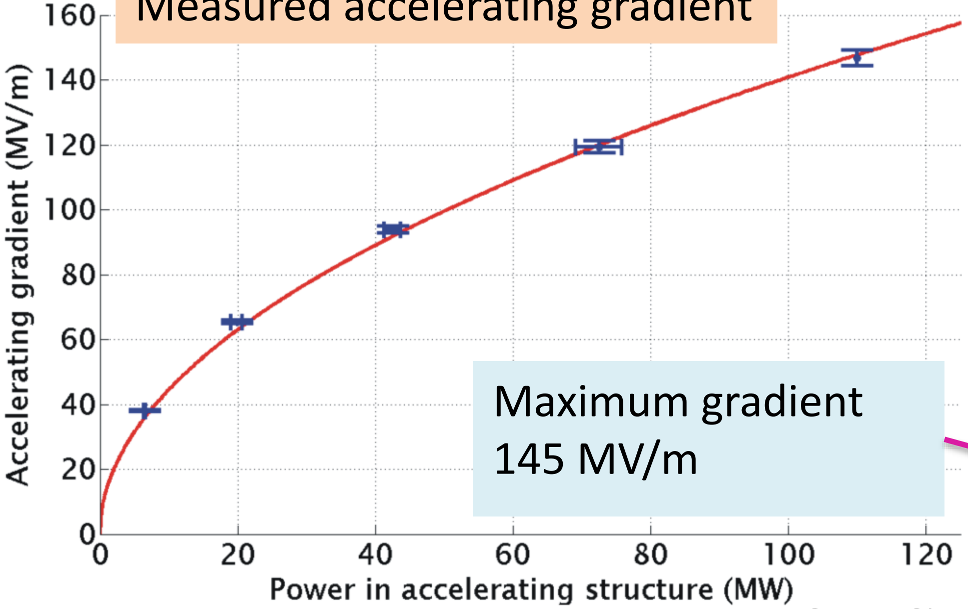
Drive Beam Combination in CTF3

Note: Efficiencies
RF to drive beam >95%
Drive beam to RF >95%

Total efficiency wall plug to main beam is about 10%







Measured accelerating gradient

Maximum gradient 145 MV/m

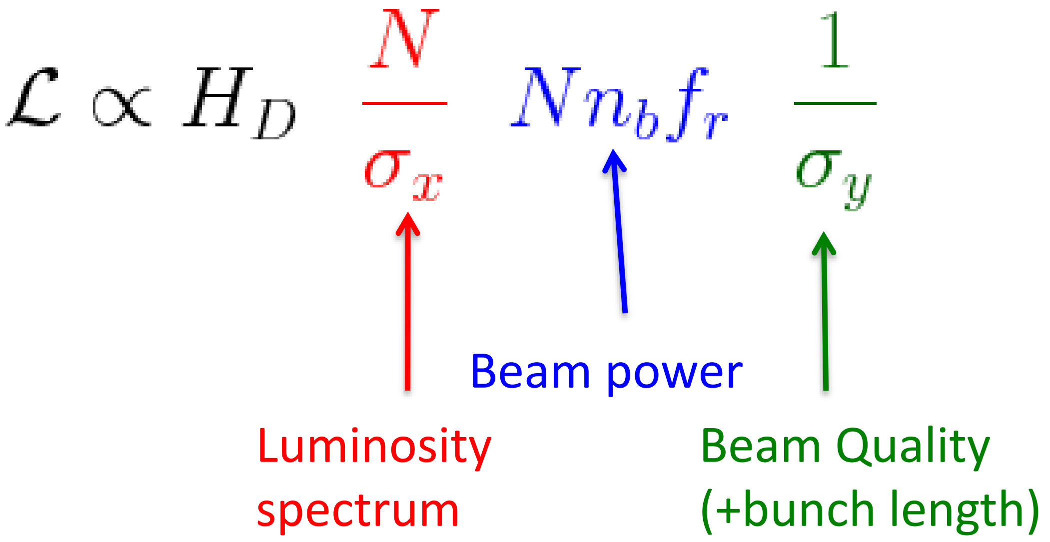
Examples of ILC and CLIC Main Parameters

Parameter	Symbol [unit]	SLC	ILC	CLIC	CLIC
Centre of mass energy	E_{cm} [GeV]	92	250	380	3000
Luminosity	L [$10^{34}cm^{-2}s^{-1}$]	0.0003	1.35	1.5	6
Luminosity in peak	$L_{0.01}$ [$10^{34}cm^{-2}s^{-1}$]	0.0003	1	0.9	2
Gradient	G [MV/m]	20	31.5	72	100
Particles per bunch	N [10^9]	37	20	5.2	3.72
Bunch length	σ_z [μm]	1000	300	70	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	1700/600	516/7.7	149/2.9	40/1
Vertical emittance	$\varepsilon_{x,y}$ [nm]	3000	35	30	20*
Bunches per pulse	n_b	1	1312	352	312
Bunch distance	Δz [mm]	-	554	0.5	0.5
Repetition rate	f_r [Hz]	120	5	50	50

Luminosity and Parameter Drivers

Can re-write normal luminosity formula

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



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

Beam power

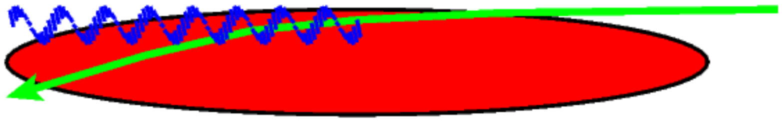
Luminosity spectrum

Beam Quality (+bunch length)

Need to ensure that we can achieve each parameter

Beam-beam Effect

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

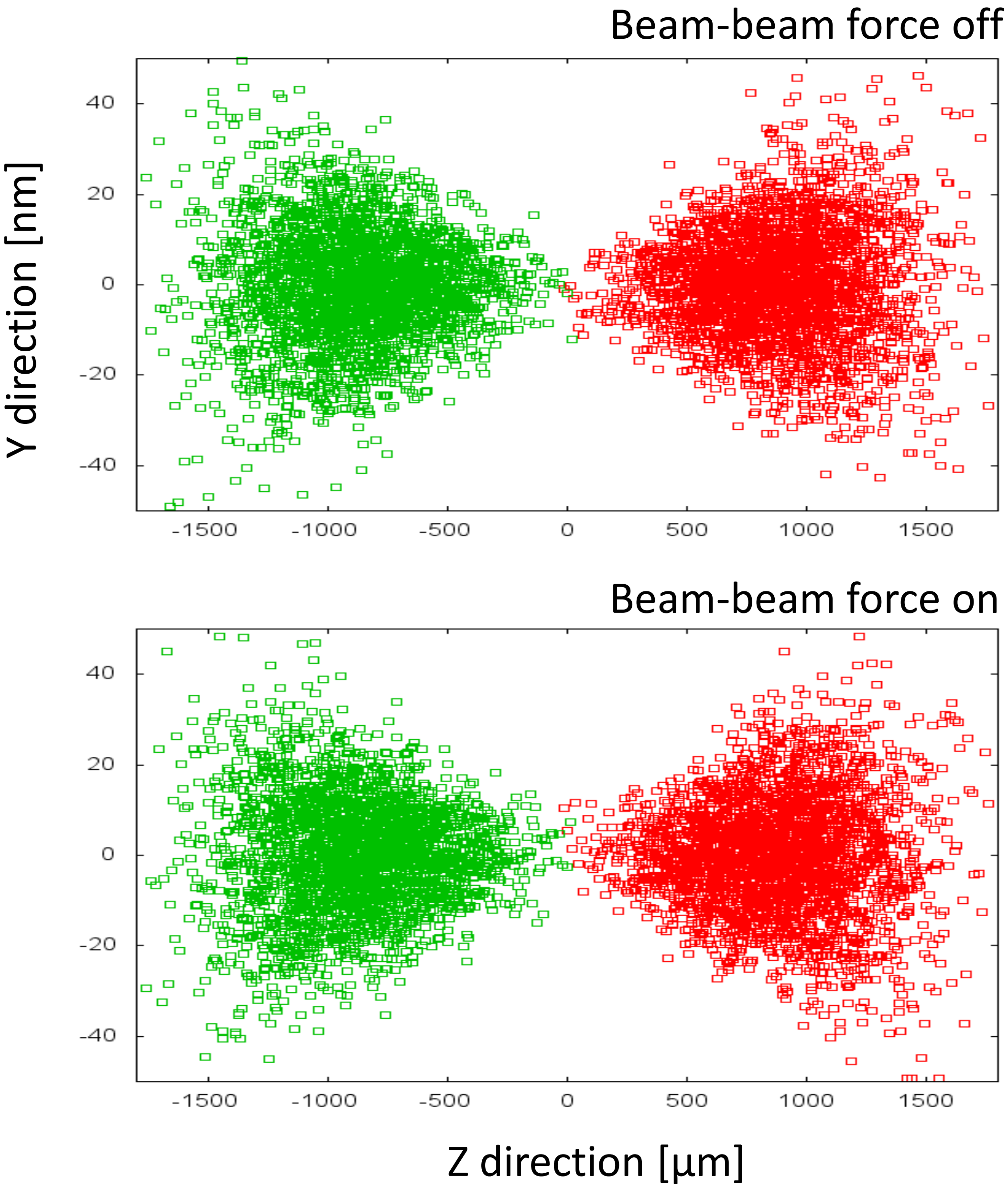


Dense beams to reach high luminosity

Beam focus each other

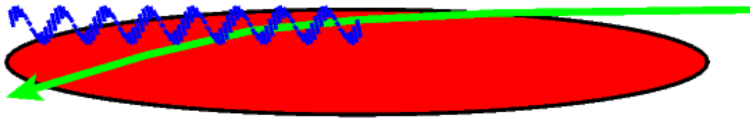
$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

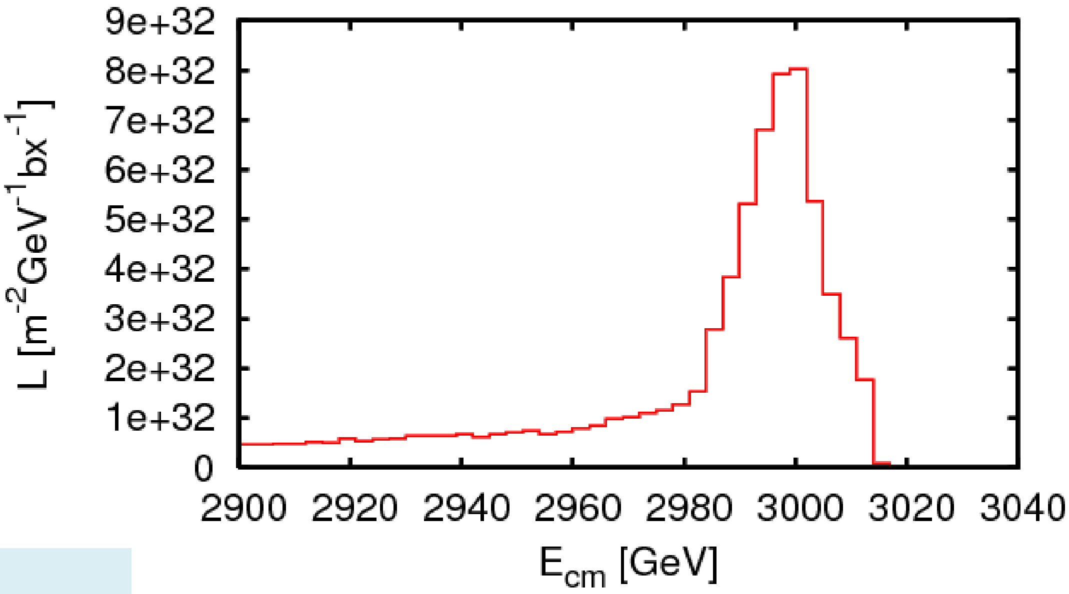
$$\sigma_x \gg \sigma_y \qquad \sigma_x + \sigma_y \approx \sigma_x$$



Beam-beam Effect

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





Emitt beamstrahlung

Develop luminosity spectrum

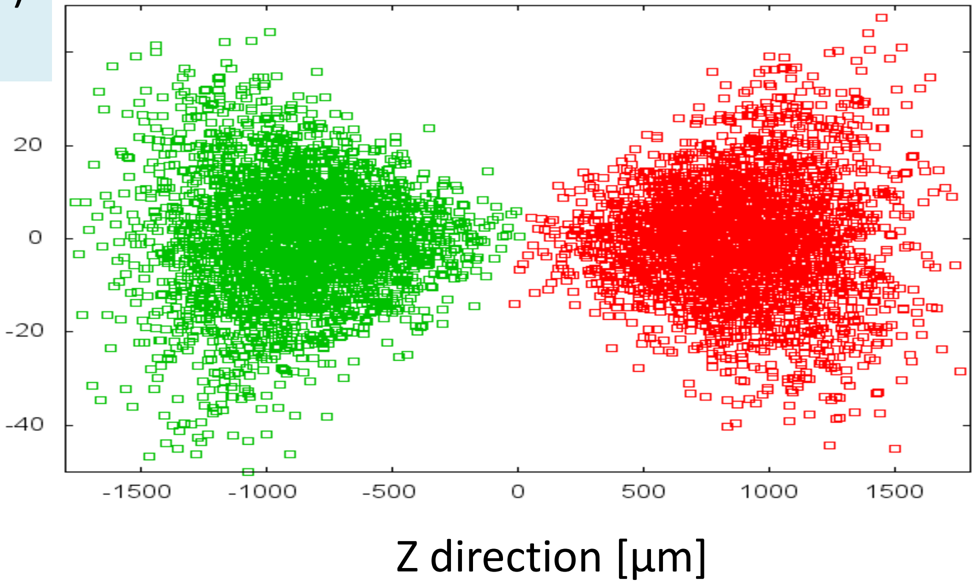
$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

Typically aim for O(1)

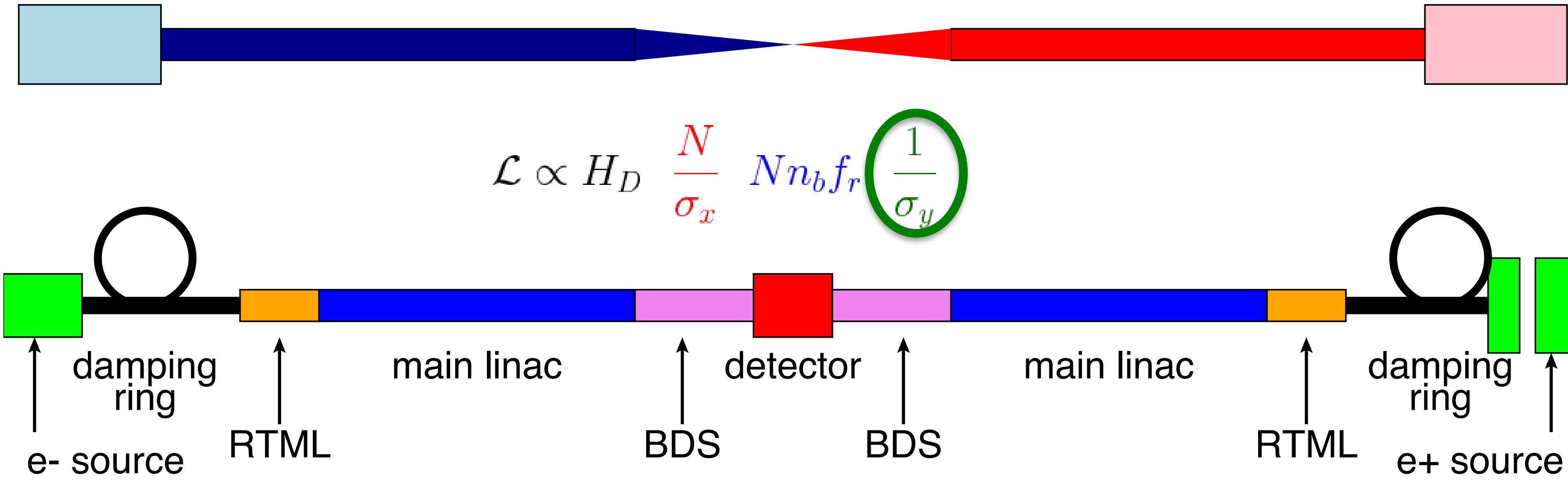
$$n_\gamma \propto E_\gamma \propto \frac{N}{\sigma_x + \sigma_y}$$

$$\sigma_x \gg \sigma_y \qquad \sigma_x + \sigma_y \approx \sigma_x$$

Beam-beam force on



Beam Quality



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

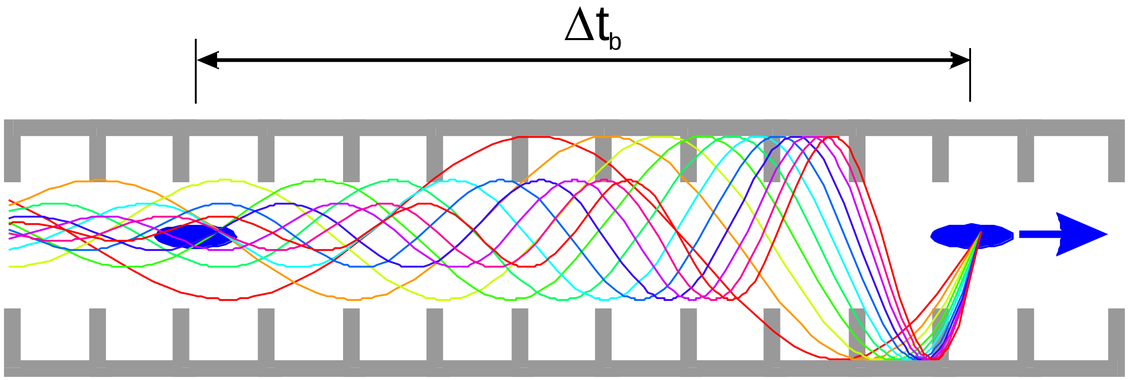
- Cannot cover the very rich field of studies

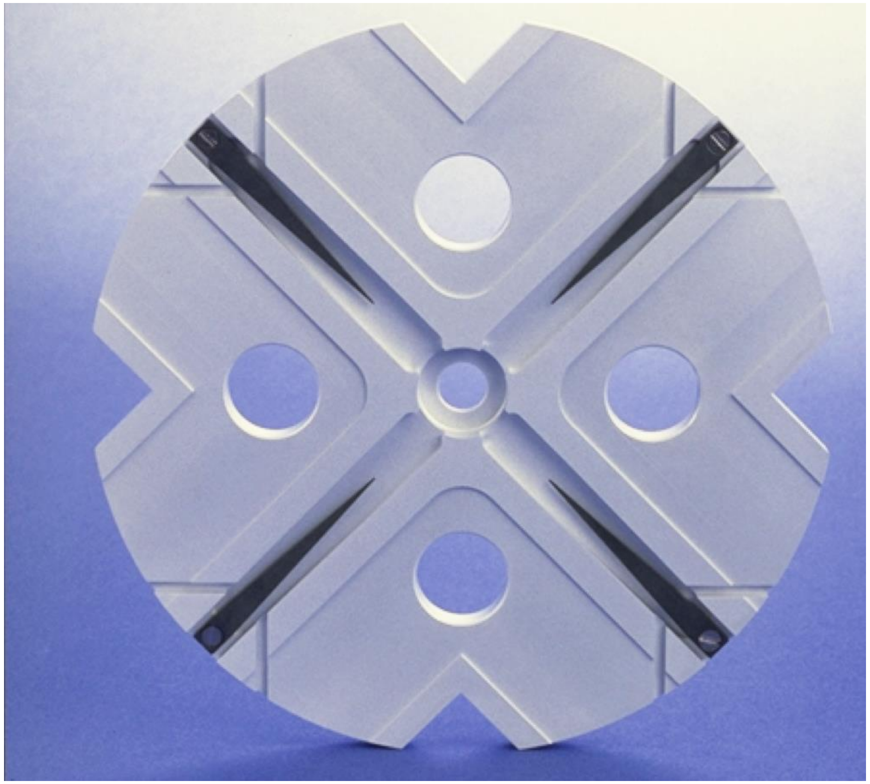
- Address the issue by
  - Clever system design
  - Clever tuning algorithms
  - Technical development of components
  - Experiments

Example: Wakefields

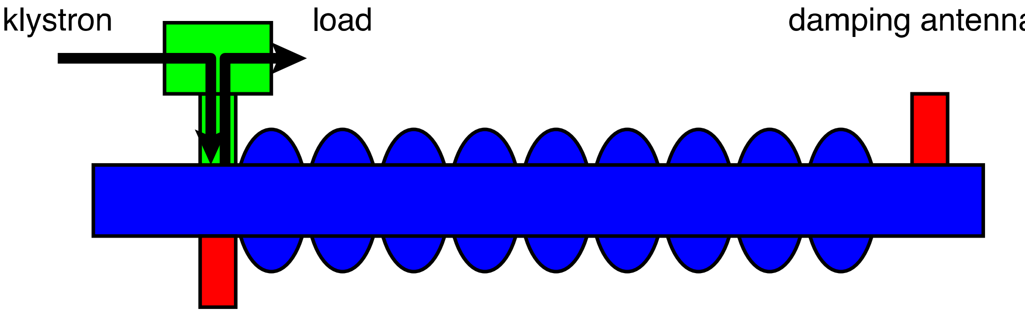
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

Wakefields can lead to instability/emittance growth



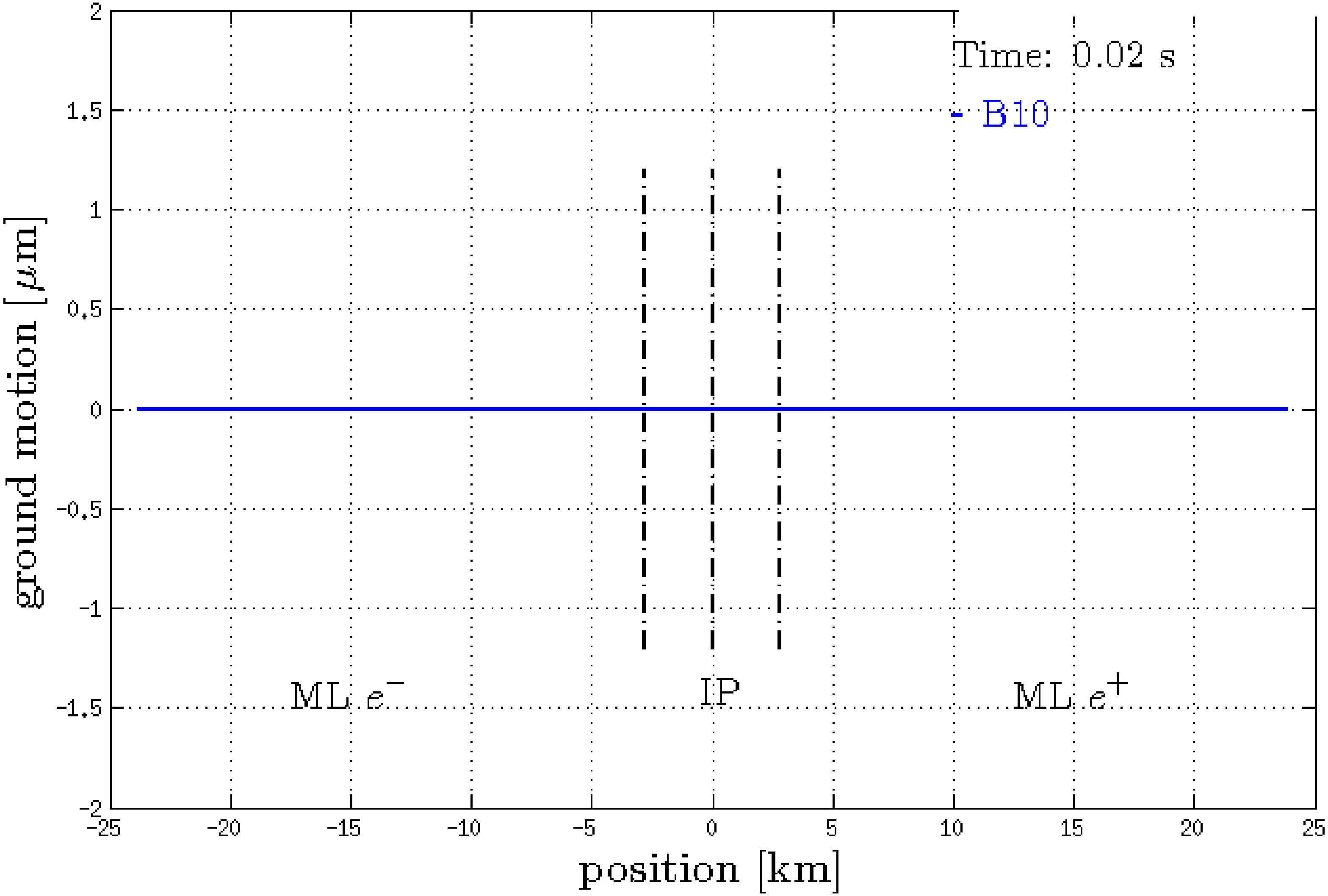


This effect is larger in higher frequency structures, hence N=2x10^{10} vs. N=4x10^{9}



Example Issue: Ground Motion at CLIC

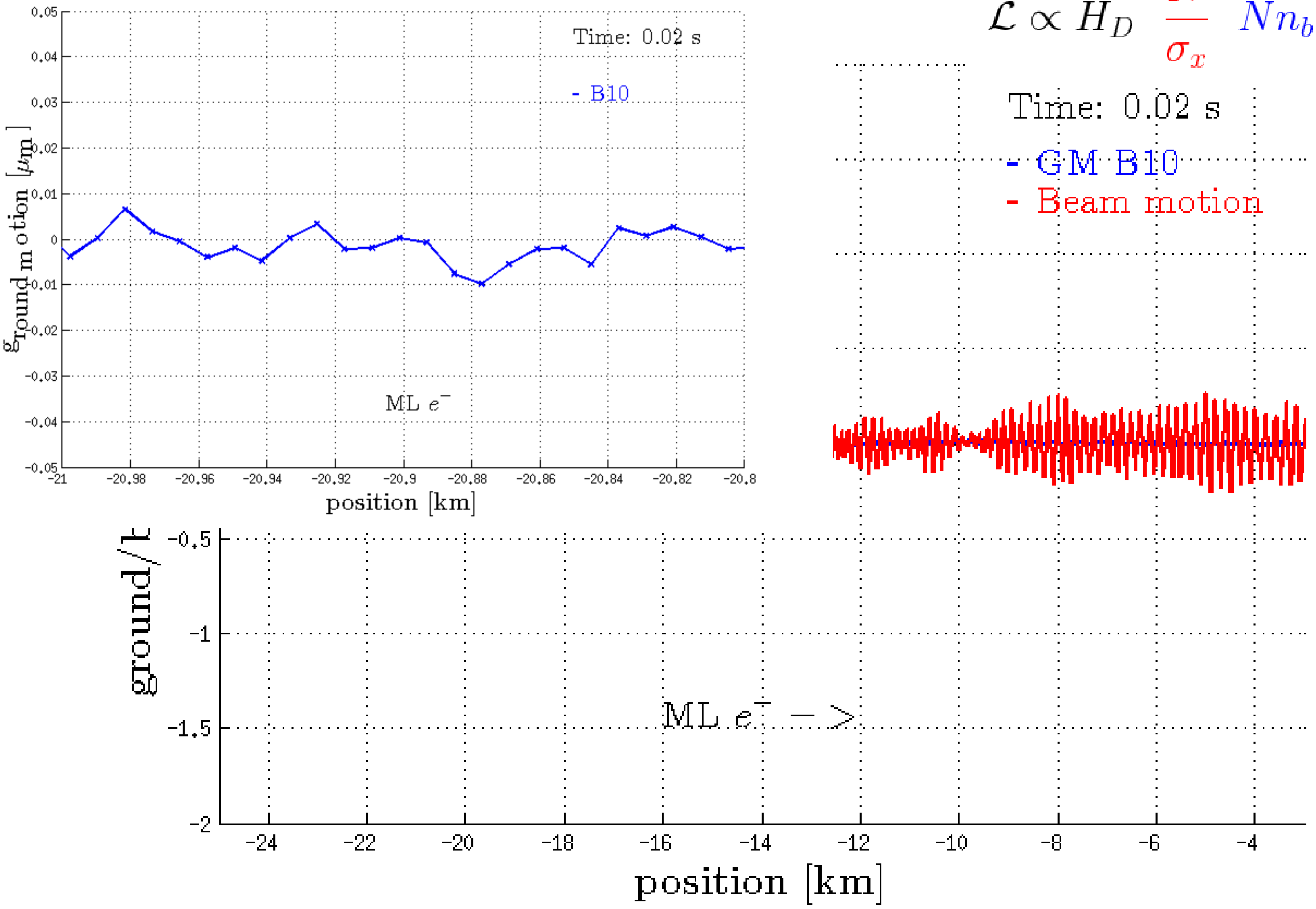
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}}$$



J. Pfingstner

Resulting Beam Jitter

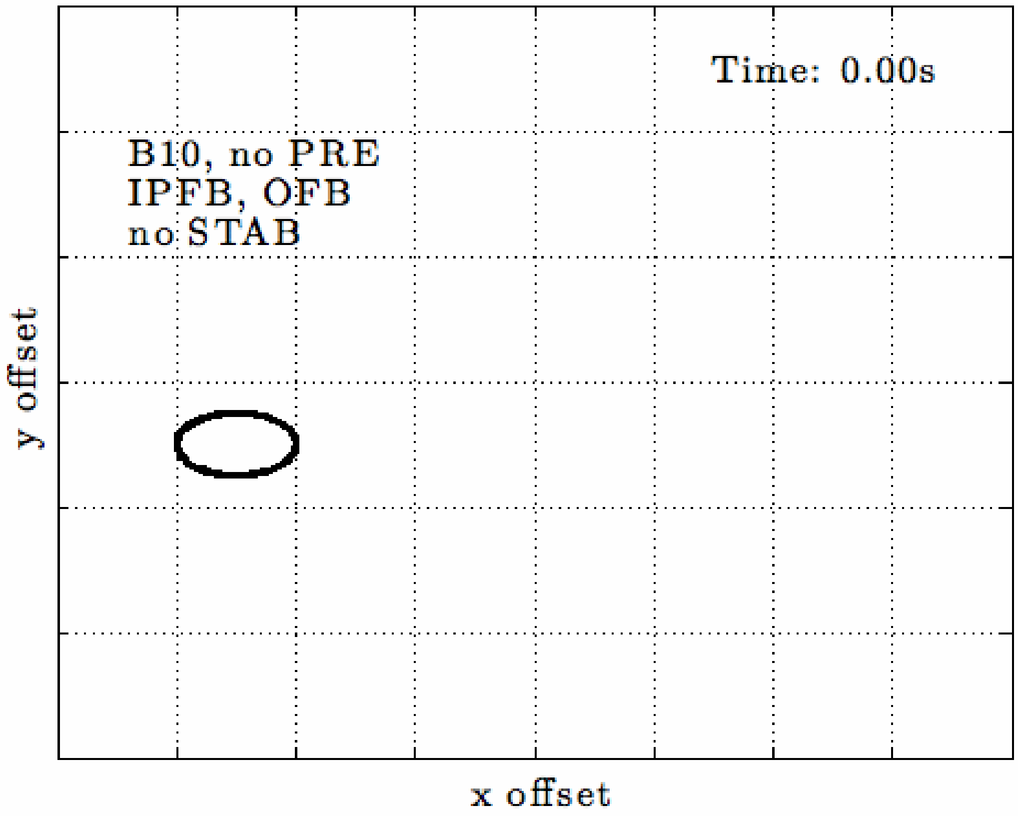
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}}$$



J. Pfingstner

Beams at Collision

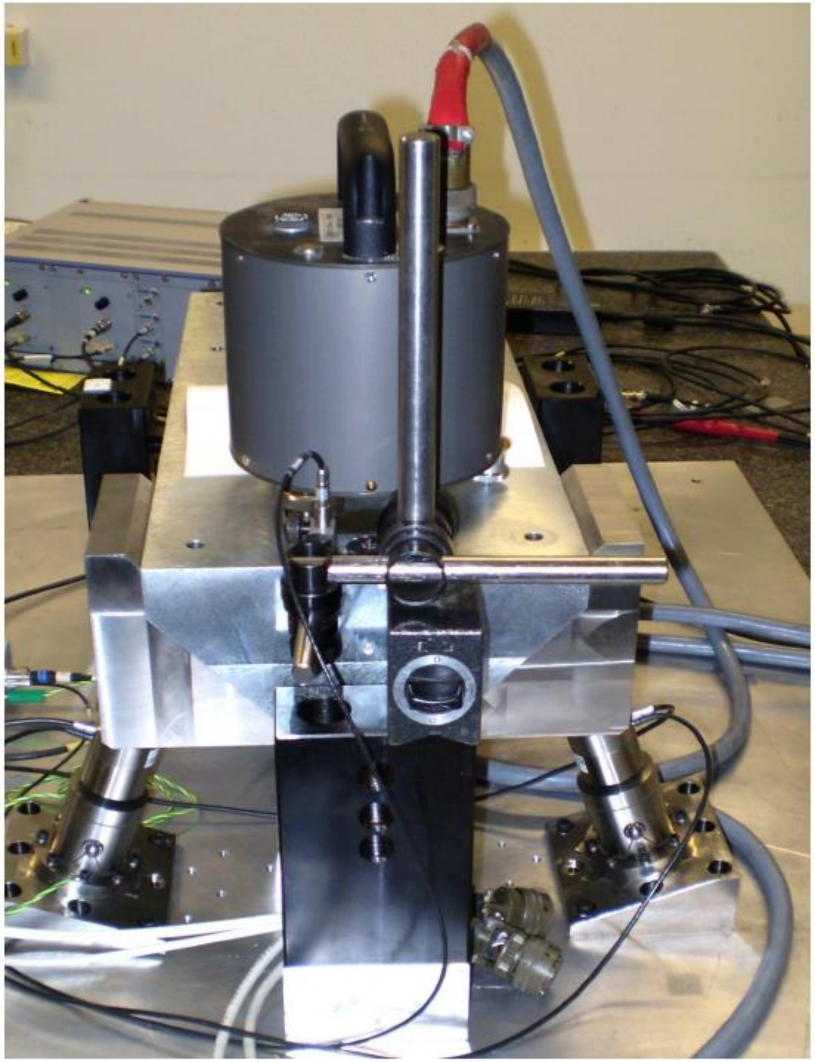
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}}$$



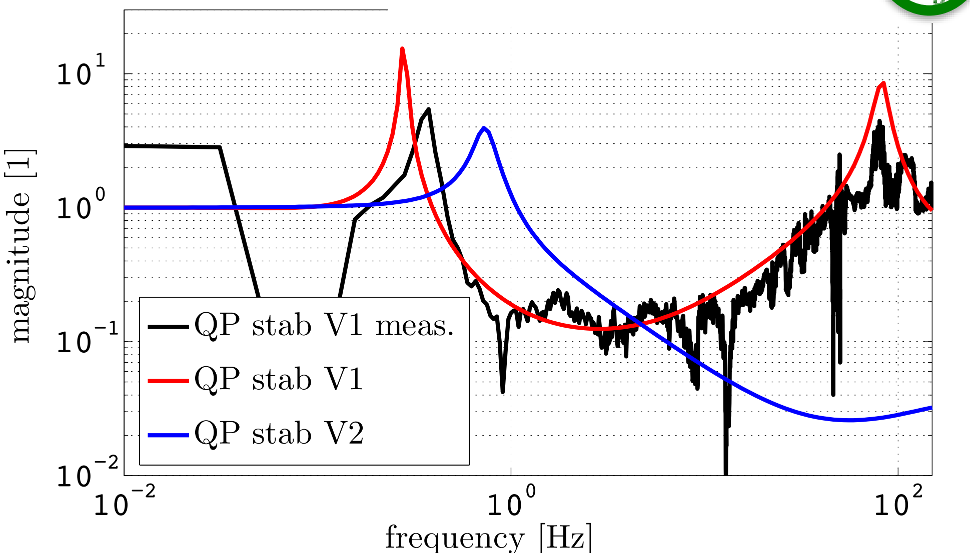
J. Pfingstner

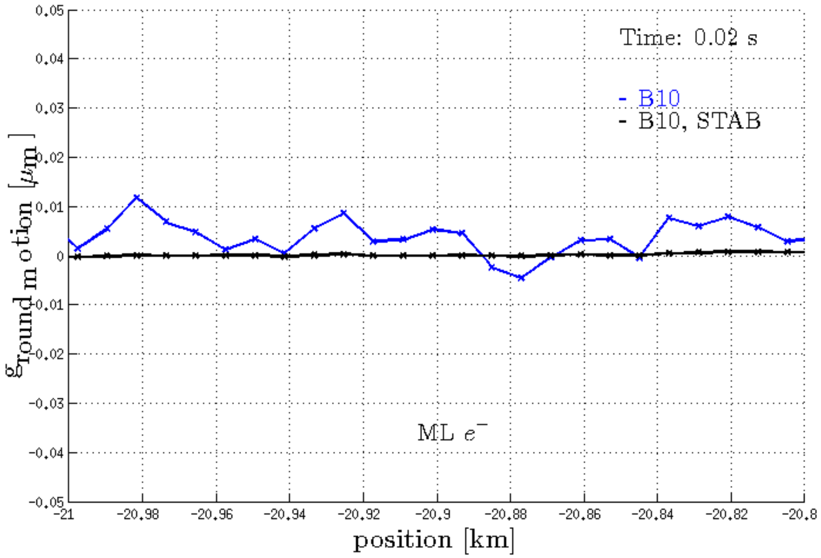
Stabilisation System

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



K. Artoos et al.

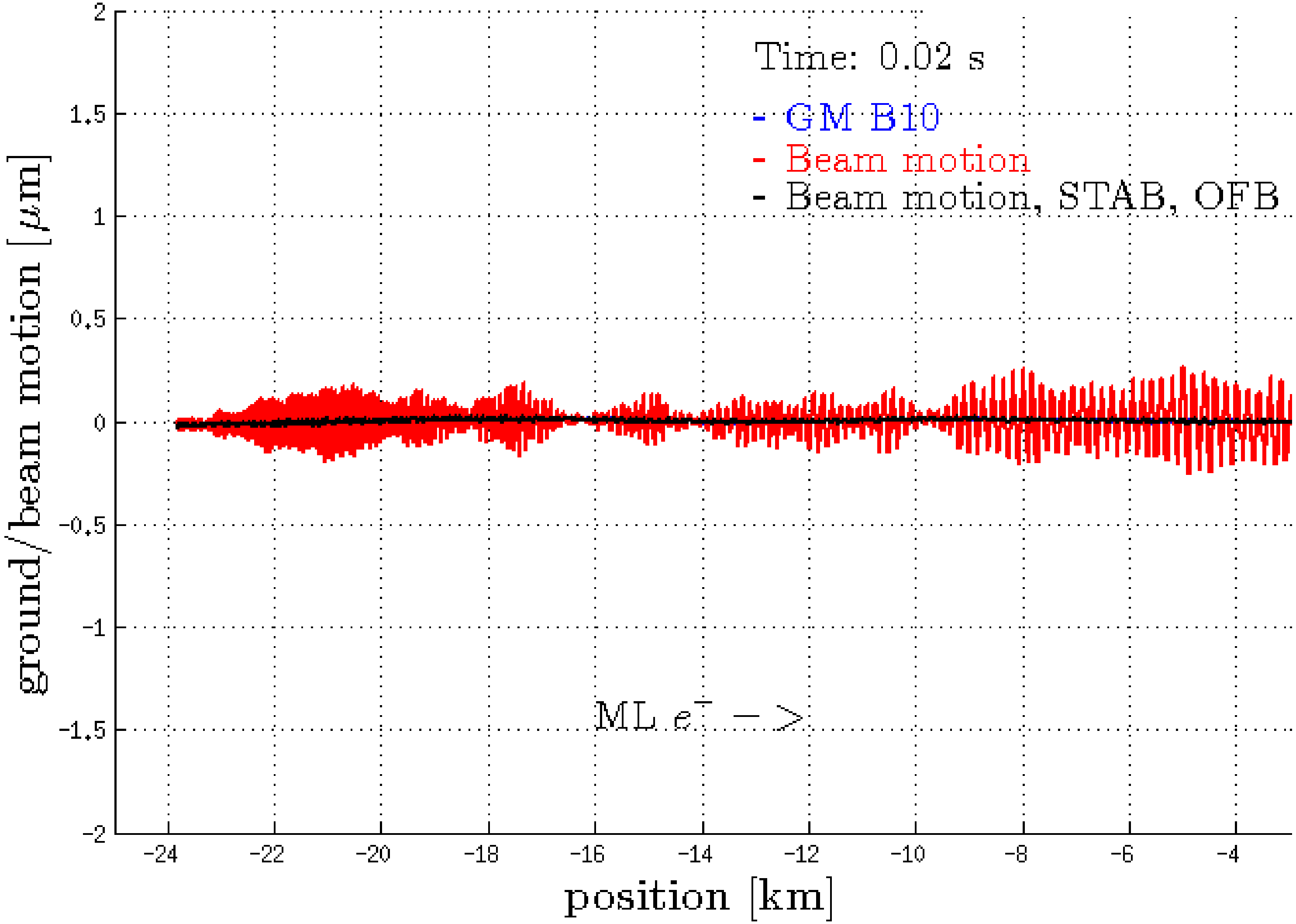




J. Snuverink, et al.

Impact of Stabilisation on Beam

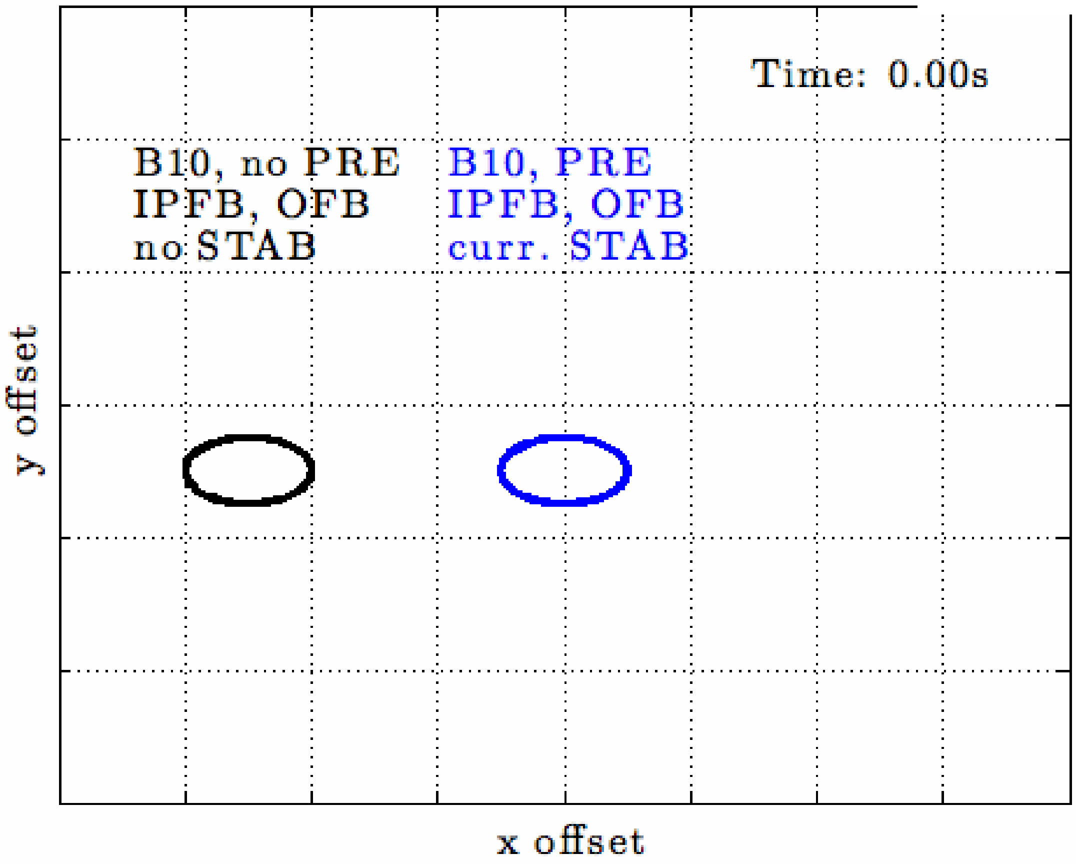
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}}$$



J. Pfingstner

Beam at Collision

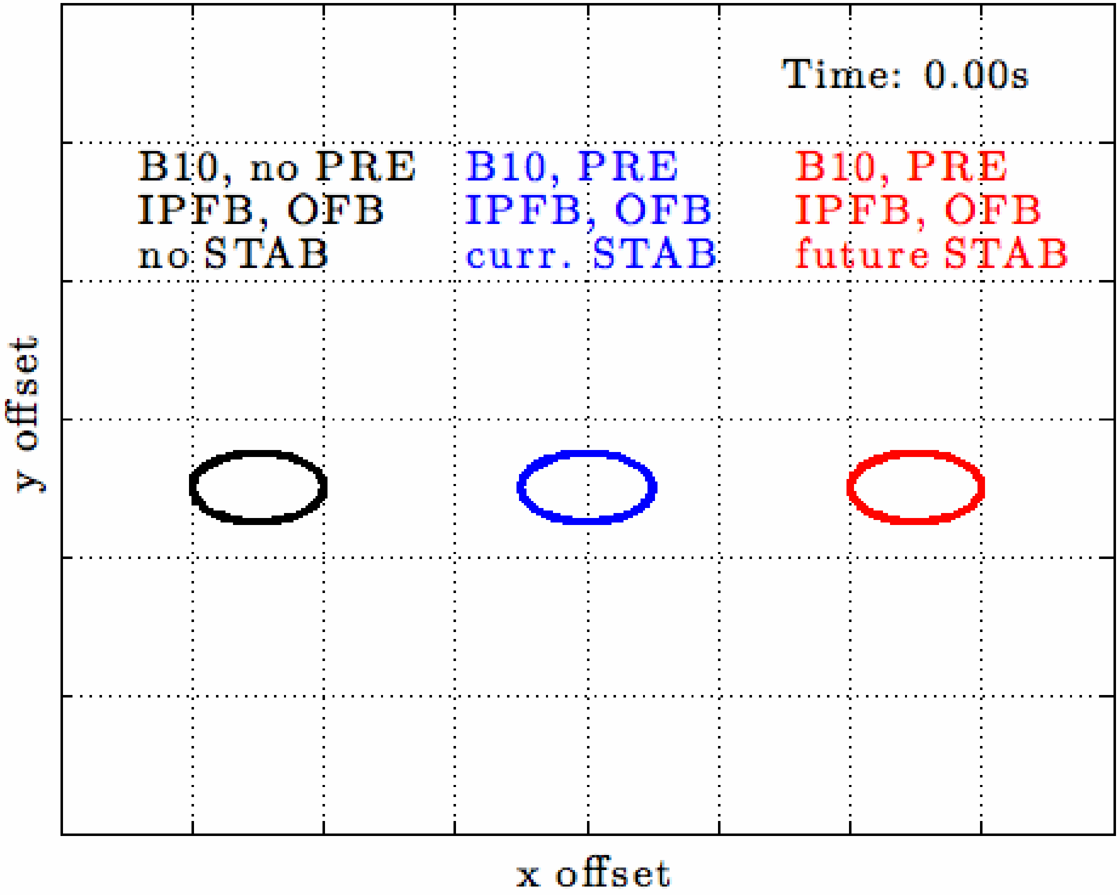
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}}$$



J. Pfingstner

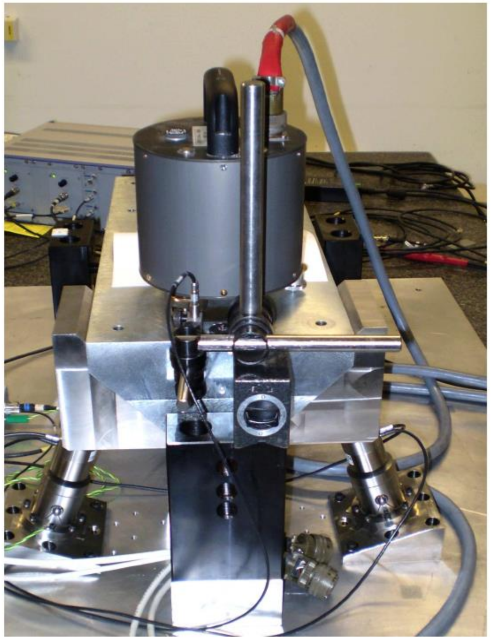
Beam at Collision

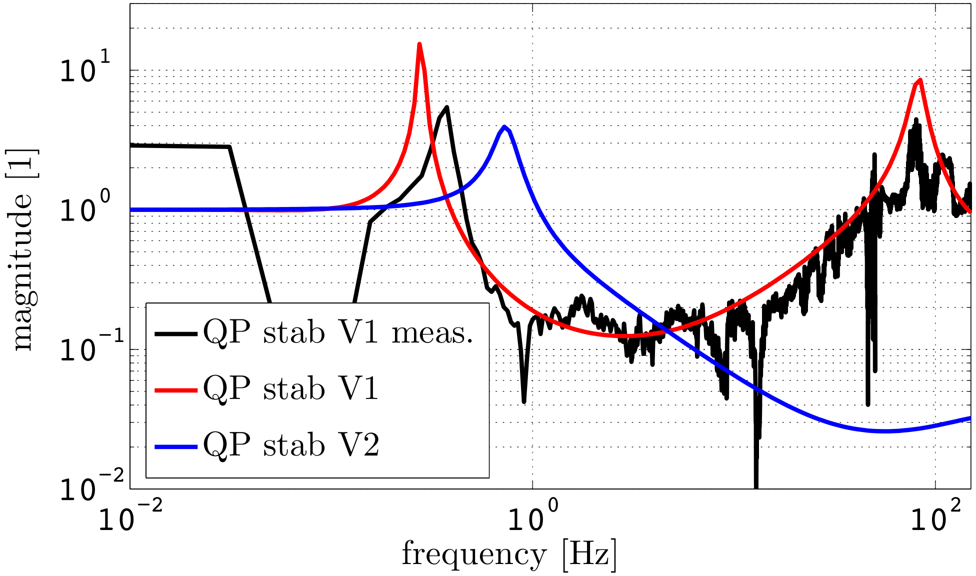
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

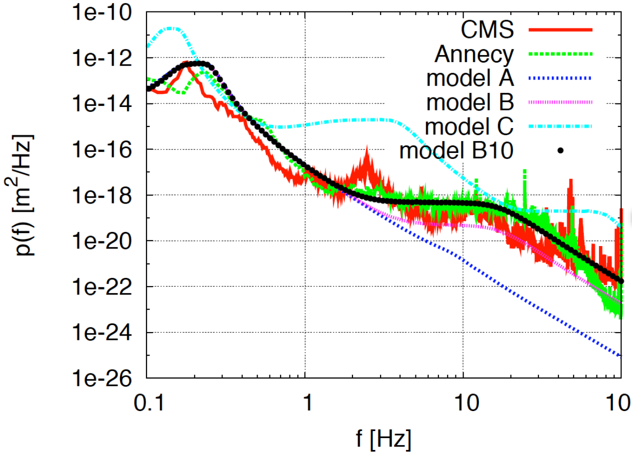


J. Pfingstner

Active Stabilisation Results







Code

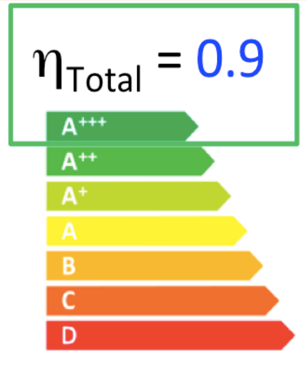
Machine model
Beam-based feedback

Luminosity achieved/lost [%]	B10
No stab.	53%/68%
Current stab.	108%/13%
Future stab.	118%/3%

Close to/better than target

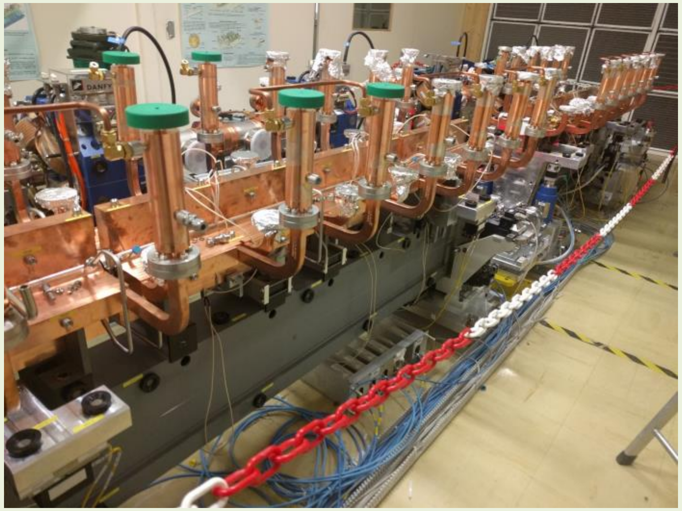
Other CLIC Technology Development

Redesign CLIC modulators and klystrons
Increase efficiency from 62% to 90%
Reduce cost (low voltage, no oil)



Permanent magnets
Use tunable permanent magnets where possible

- Quadruoles in drive beam
- Strongest permanent magnet developed in UK



New module design
Reduce cost of mechanical system and control

Klystron-based first energy stage
As alternative

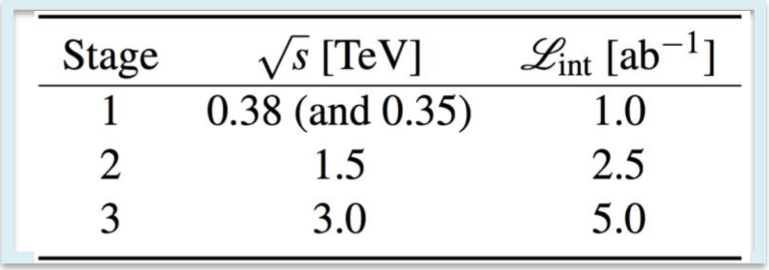
Main beam injector
e.g. halved power for positron production

Instrumentation
Further improvements

Active alignment
Further improvements

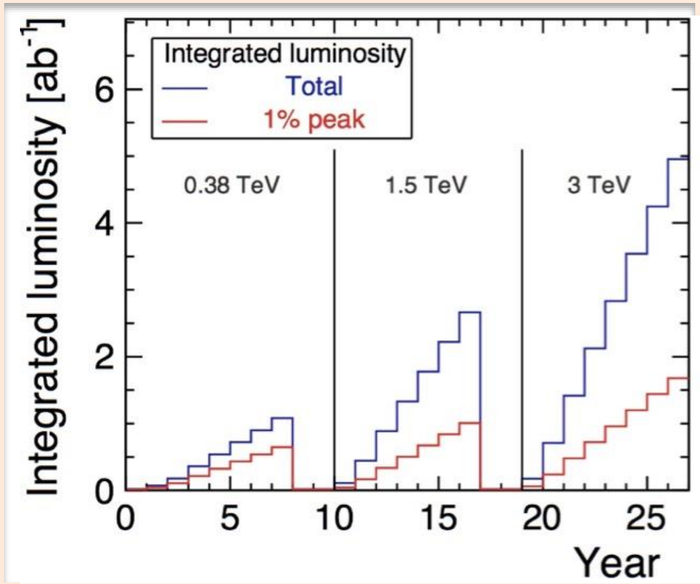
And many more …

CLIC Staged Scenario

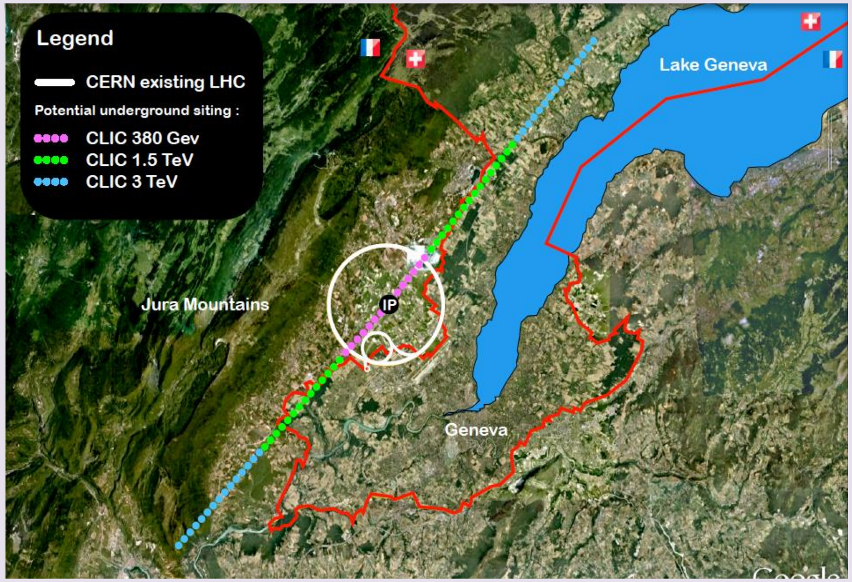


Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0
2	1.5	2.5
3	3.0	5.0

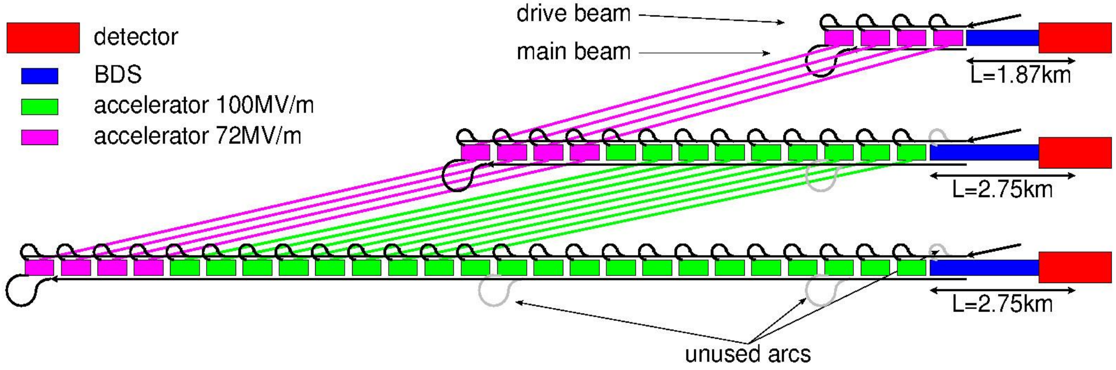
Luminosity targets from Physics Study group
Hopefully input from LHC



Luminosity evolution



Central complex on Prevessin site

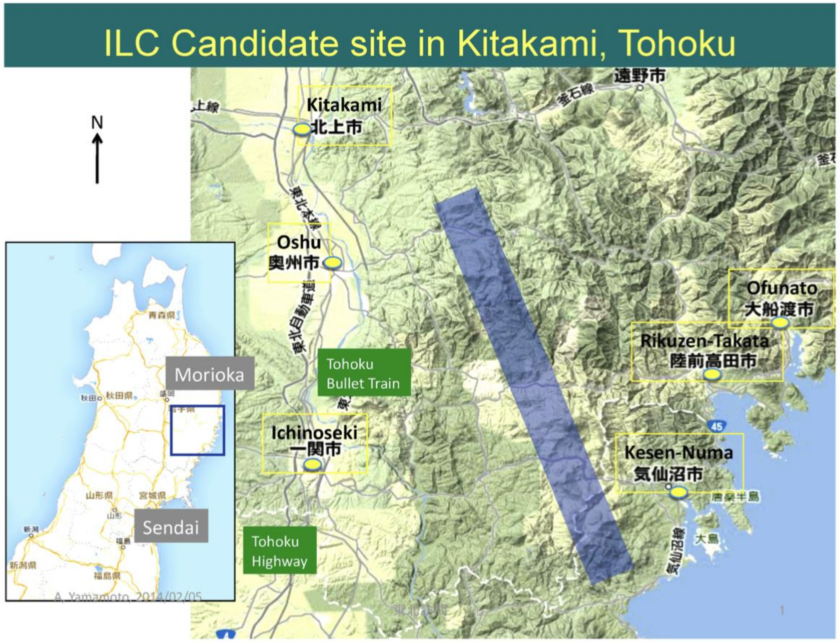


Lower gradient optimum for lower energy

ILC Scenarios

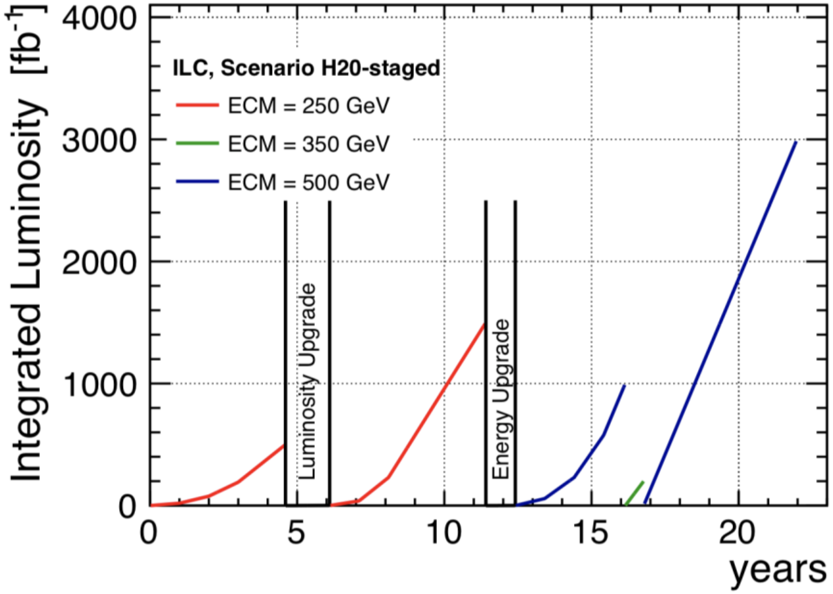
Waiting for Japan to make a commitment

- Site identified and being investigated
- But executive not yet endorsed project
- Process is going on for many years



Baseline running example

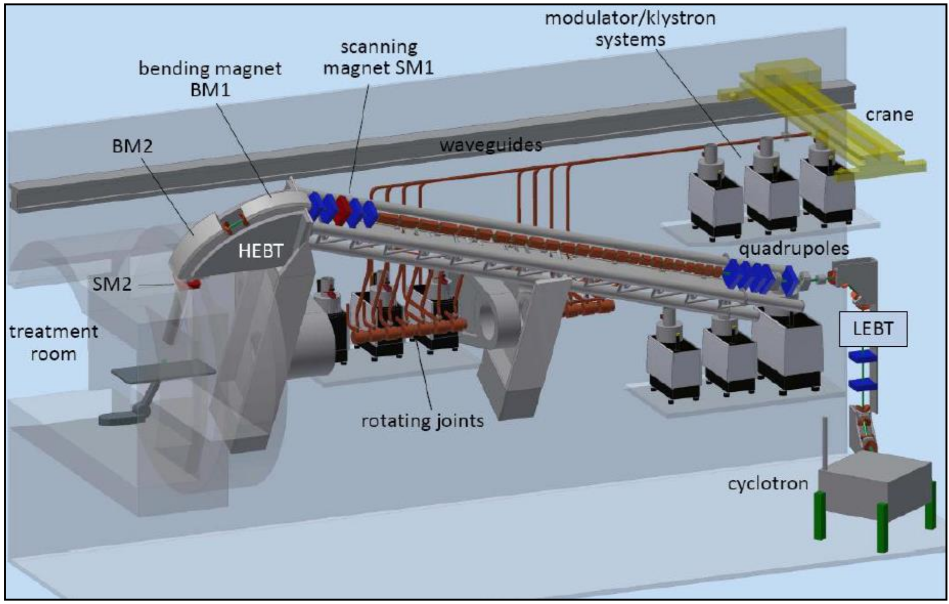
Note: contains up to 500 GeV, which is not part of current baseline proposal

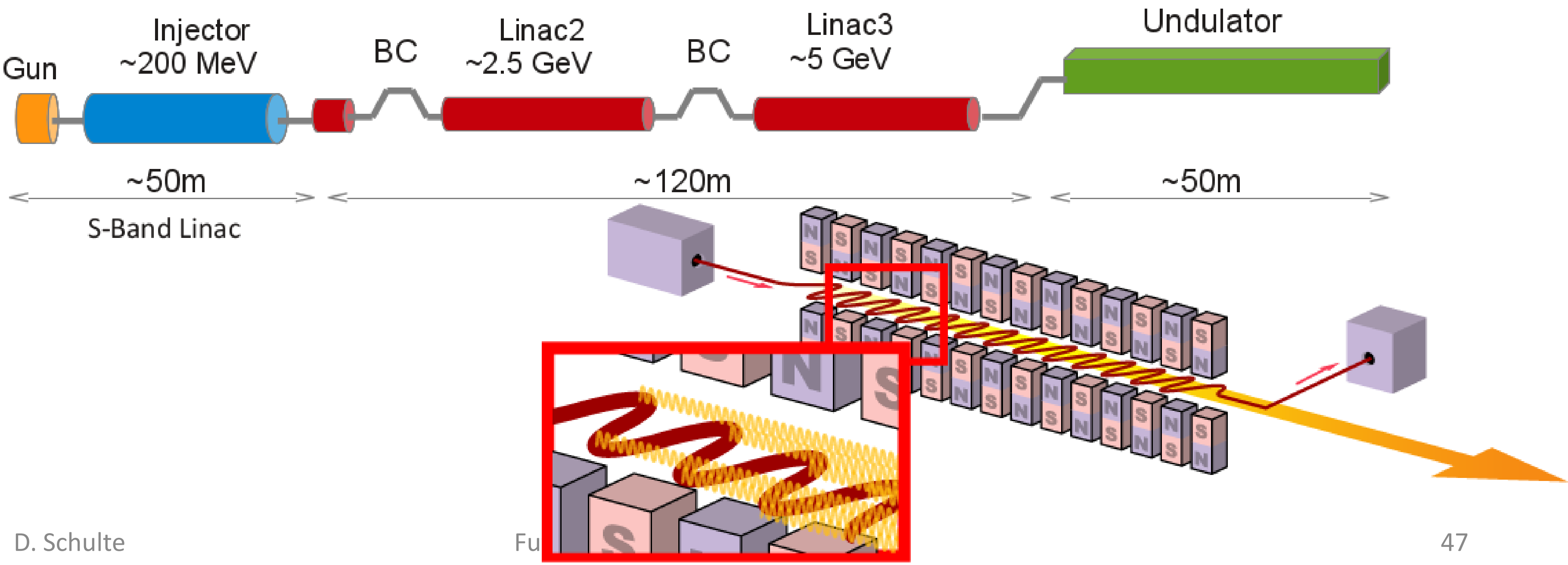


Note: Technology Transfer

The technology developed for linear colliders is useful for other fields, e.g.

- FELs (Examples: European X-FEL in Hamburg, LCLS at SLAC, SACLA in Japan, Swiss FEL, …)
- Medical facilities
- Safety
- Industrial applications





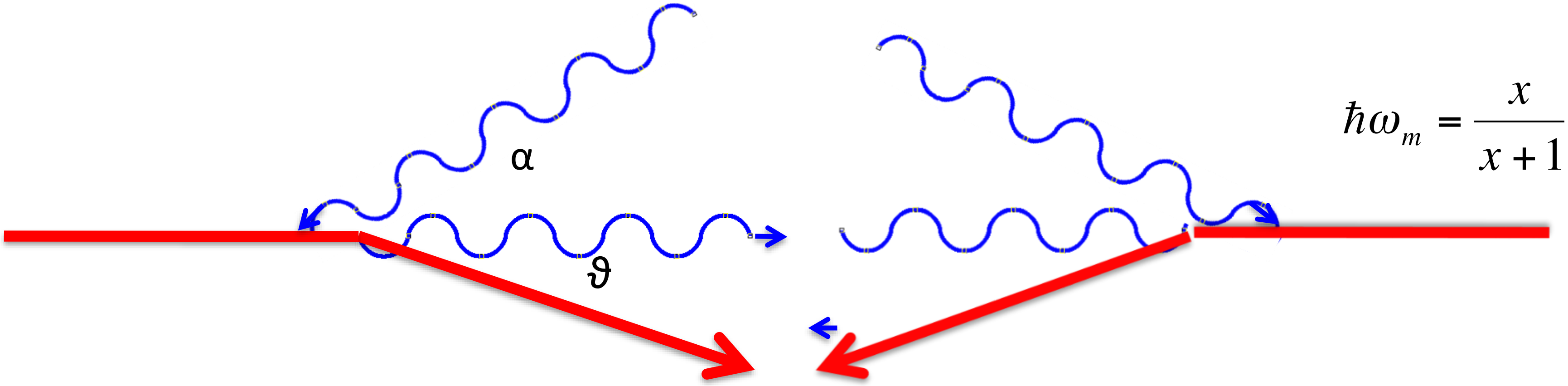
Note: Gamma-gamma Collider Concept

Based on e^-e^- collider

Collide electron beam with laser beam before the IP

$$x = \frac{4E_0\hbar\omega_0}{m^2c^4}$$

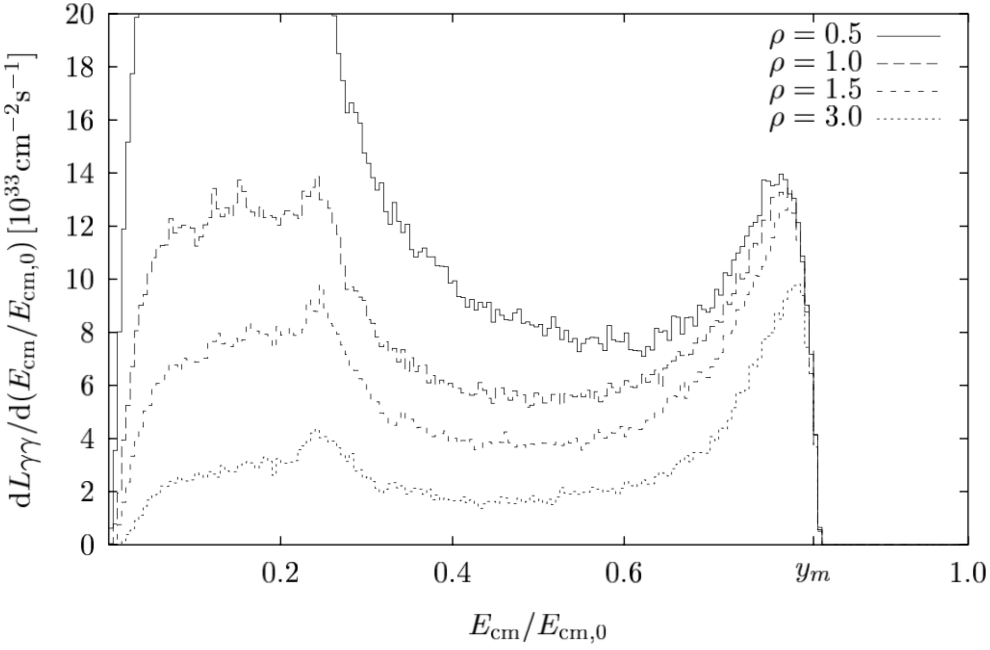
$$\hbar\omega_m = \frac{x}{x+1}E_0$$



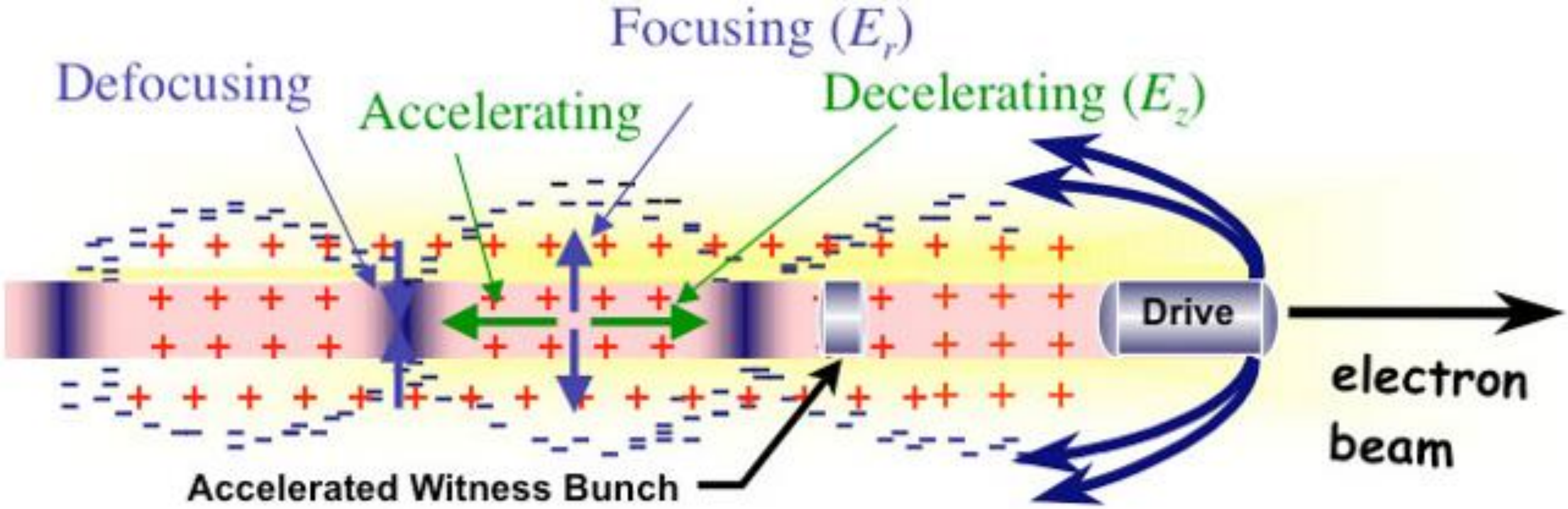
Backscattered photons form a spectrum

Practical maximum energy is 83% of electron energy

Luminosity



Note: Plasma Acceleration



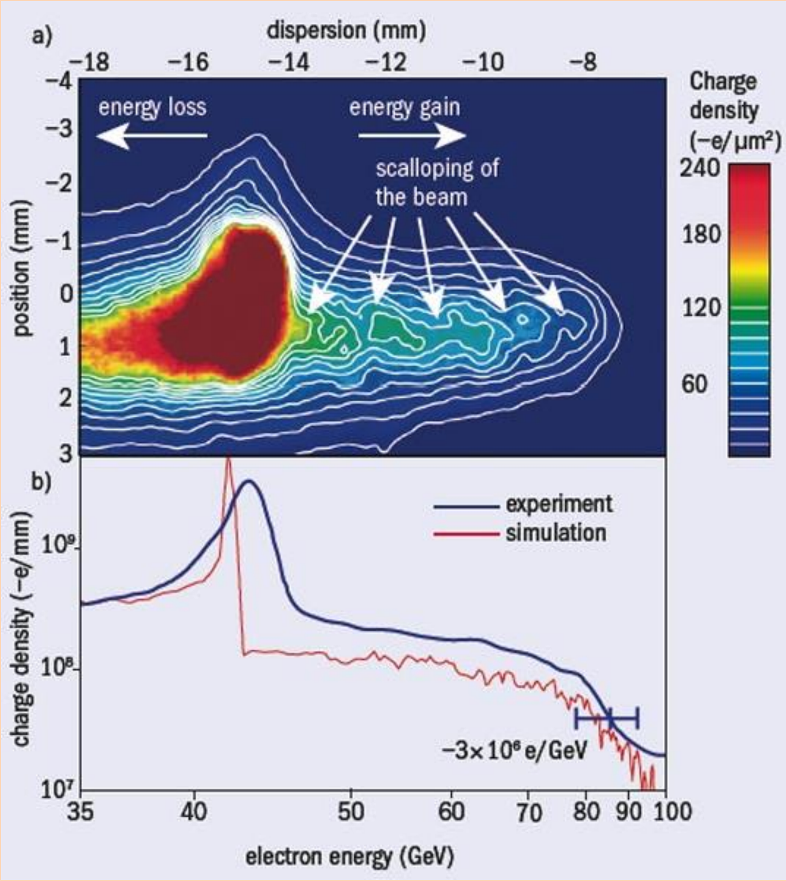
Plasma can be generated by electron beam, proton beam or laser beam

See also additional slides

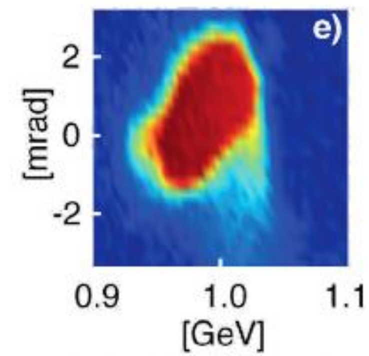
Examples of Achieved Accelerations

Using SLC beam L=0.85m, G=O(50 GV/m)
⇒ 42 GeV

E167 collaboration SLAC, UCLA, USC
I. Blumenfeld et al, Nature 445, p. 741 (2007)



Using laser beam to generate the plasma at Berkeley
=> 1GeV

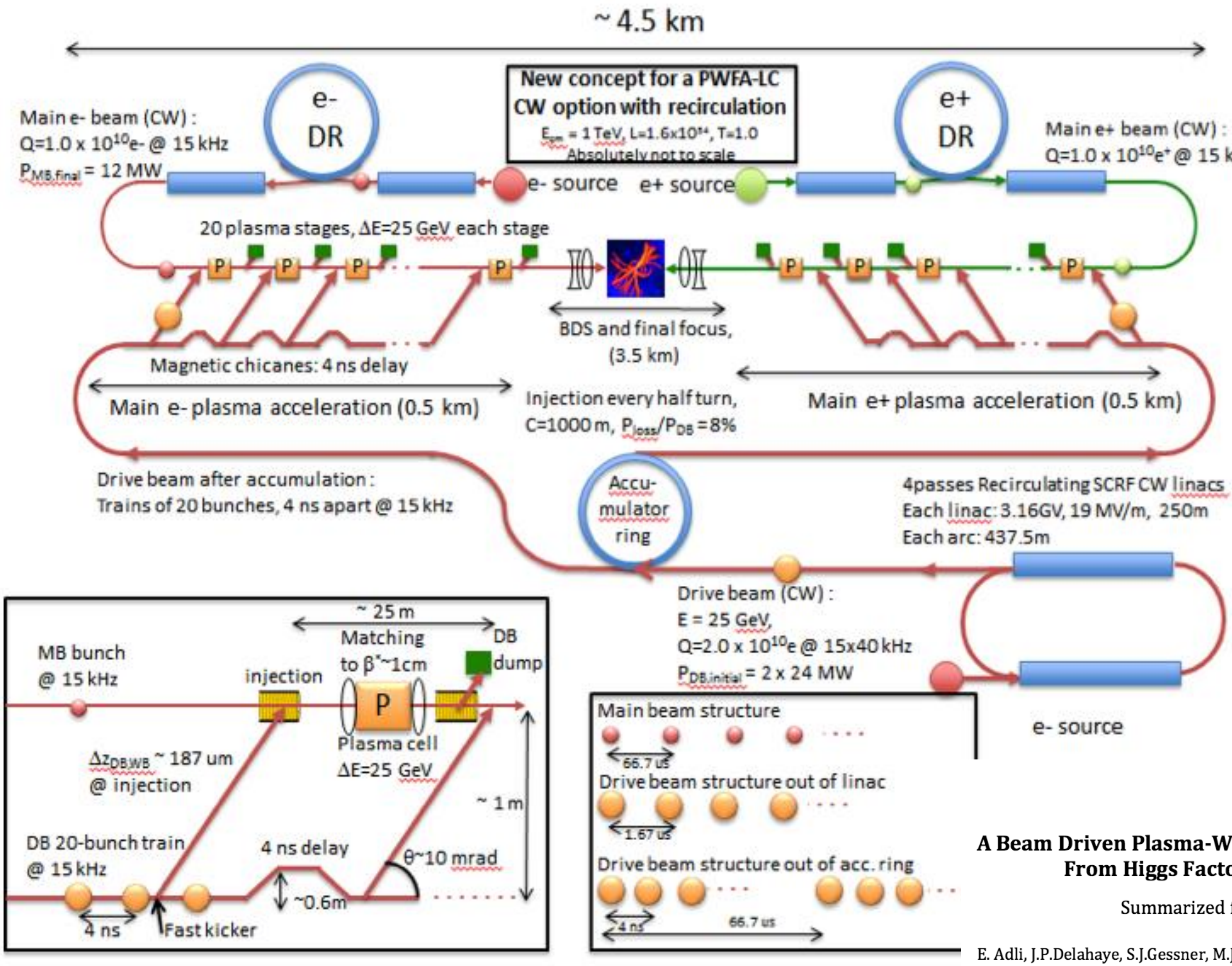


Beam energy =1.0 GeV
Charge= Q~30 pC
1.6 mrad rms divergence
2.5% rms energy spread

Leemans *et al.*, Nature Phys. (2006).
Nakamura *et al.*, Phys. Plasmas (2007).

Driving plasma with protons is planned in AWAKE
Using a proton bunch to create many minibunches

Example: Beam-driven Plasma Collider (PWFA)



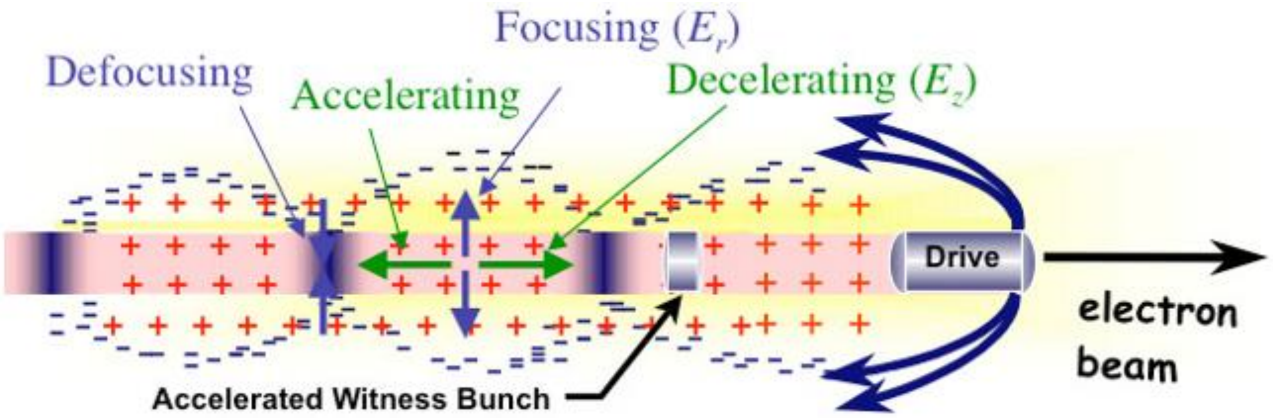
SLAC-PUB-15426
arXiv:1308.1145

A Beam Driven Plasma-Wakefield Linear Collider: From Higgs Factory to Multi-TeV

Summarized for CSS2013

E. Adli, J.P.Delahaye, S.J.Gessner, M.J. Hogan, T. Raubenheimer (SLAC)
W.An, C. Joshi, W.Mori (UCLA)

Plasma Collider Issues



- Practical solution for acceleration of positrons is missing
- Efficiency and beam quality has to be addressed

- Significant effort needed to arrive at a paper design
- Need very important technology development to make it real
- A long-term effort

References

ILC

The International Linear Collider
A European Perspective

Prepared by: Philip Bambade[1], Ties Behnke[2], Mikael Berggren[2], Ivanka Bozovic-Jelisavcic[3], Philip Burrows[4], Massimo Caccia[5], Paul Colas[6], Gerald Eigen[7], Lyn Evans[8], Angeles Faus-Golfe[1], Brian Foster[2,4], Juan Fuster[9], Frank Gaede[2], Christophe Grojean[2], Marek Idzik[10], Andrea Jeremie[11], Tadeusz Lesiak[12], Aharon Levy[13], Benno List[2], Jenny List[2], Joachim Mnich[2], Olivier Napoly[6], Carlo Pagani[14], Roman Poeschl[1], Francois Richard[1], Aidan Robson[15], Thomas Schoerner-Sadenius[2], Marcel Stanitzki[2], Steinar Stapnes[8], Maksym Titov[6], Marcel Vos[9], Nicholas Walker[2], Hans Weise[2], Marc Winter[16].

[1]LAL-Orsay/CNRS, [2]DESY, [3]INN VINCA, Belgrade, [4]Oxford U., [5]U. Insubria, [6]CEA/Irfu, U. Paris-Saclay, [7]U. Bergen, [8]CERN, [9]IFIC, U. Valencia-CSIC, [10]AGH, Kraków, [11]LAPP/CNRS, [12]IFJPAN, Kraków, [13]Tel Aviv U., [14]INFN, [15]U. Glasgow, [16]IPHC/CNRS.

(Dated: December 20, 2018)

Abstract

The International Linear Collider (ILC) being proposed in Japan is an electron-positron linear collider with an initial energy of 250 GeV. The ILC accelerator is based on the technology of superconducting radio-frequency cavities. This technology has reached a mature stage in the European XFEL project and is now widely used.

The ILC will start by measuring the Higgs properties, providing high-precision and model-independent determinations of its parameters. The ILC at 250 GeV will also search for direct new physics in exotic Higgs decays and in pair-production of weakly interacting particles. The use of polarised electron and positron beams opens new capabilities and scenarios that add to the physics reach. The ILC can be upgraded to higher energy, enabling precision studies of the top quark and measurement of the top Yukawa coupling and the Higgs self-coupling.

The international - including European - interest for the project is very strong. Europe has participated in the ILC project since its early conception and plays a major role in its present development covering most of its scientific and technological aspects: physics studies, accelerator and detectors. The potential for a wide participation of European groups and laboratories is thus high, including important opportunities for European industry.

Following decades of technical development, R&D, and design optimisation, the project is ready for construction and the European particle physics community, technological centers and industry are prepared to participate in this challenging endeavour.

Supporting documents web page:
`https://ilchome.web.cern.ch/content/ilc-european-strategy-document`

The International Linear Collider
A Global Project

Prepared by: Hiroaki Aihara[1], Jonathan Bagger[2], Philip Bambade[3], Barry Barish[4], Ties Behnke[5], Alain Bellerive[6], Mikael Berggren[5], James Brau[7], Martin Breidenbach[8], Ivanka Bozovic-Jelisavcic[9], Philip Burrows[10], Massimo Caccia[11], Paul Colas[12], Dmitri Denisov[13], Gerald Eigen[14], Lyn Evans[15], Angeles Faus-Golfe[3], Brian Foster[5,10], Keisuke Fujii[16], Juan Fuster[17], Frank Gaede[5], Jie Gao[18], Paul Grannis[19], Christophe Grojean[5], Andrew Hutton[20], Marek Idzik[21], Andrea Jeremie[22], Kiyotomo Kawagoe[23], Sachio Komamiya[1,24], Tadeusz Lesiak[25], Aharon Levy[26], Benno List[5], Jenny List[5], Shinichiro Michizono[16], Akiya Miyamoto[16], Joachim Mnich[5], Hugh Montgomery[20], Hitoshi Murayama[27], Olivier Napoly[12], Yasuhiro Okada[16], Carlo Pagani[28], Michael Peskin[8], Roman Poeschl[3], Francois Richard[3], Aidan Robson[29], Thomas Schoerner-Sadenius[5], Marcel Stanitzki[5], Steinar Stapnes[15], Jan Strube[7,30], Atsuto Suzuki[31], Junping Tian[1], Maksym Titov[12], Marcel Vos[17], Nicholas Walker[5], Hans Weise[5], Andrew White[32], Graham Wilson[33], Marc Winter[34], Sakue Yamada[1,16], Akira Yamamoto[16], Hitoshi Yamamoto[35] and Satoru Yamashita[1].

[1]U. Tokyo, [2]TRIUMF, [3]LAL-Orsay/CNRS, [4]Caltech, [5]DESY, [6]Carleton U., [7]U. Oregon, [8]SLAC, [9]INN VINCA, Belgrade, [10]Oxford U., [11]U. Insubria, [12]CEA/Irfu, U. Paris-Saclay, [13]Fermilab, [14]U. Bergen, [15]CERN, [16]KEK, [17]IFIC, U. Valencia-CSIC, [18]IHEP, [19]Stony Brook U., [20]Jefferson Lab, [21]AGH, Kraków, [22]LAPP/CNRS, [23]Kyushu U., [24]Waseda U., [25]IFJPAN, Kraków, [26]Tel Aviv U., [27]U. California, Berkeley, [28]INFN, [29]U. Glasgow, [30]PNNL, [31]Iwate Prefecture U., [32]U. Texas, Arlington, [33]U. Kansas, [34]IPHC/CNRS, [35]U. Tohoku

(Representing the Linear Collider Collaboration and the global ILC community.)

(Dated: December 20, 2018)

Abstract

A large, world-wide community of physicists is working to realise an exceptional physics program of energy-frontier, electron-positron collisions with the International Linear Collider (ILC). This program will begin with a central focus on high-precision and model-independent measurements of the Higgs boson couplings. This method of searching for new physics beyond the Standard Model is orthogonal to and complements the LHC physics program. The ILC at 250 GeV will also search for direct new physics in exotic Higgs decays and in pair-production of weakly interacting particles. Polarised electron and positron beams add unique opportunities to the physics reach. The ILC can be upgraded to higher energy, enabling precision studies of the top quark and measurement of the top Yukawa coupling and the Higgs self-coupling.

The key accelerator technology, superconducting radio-frequency cavities, has matured. Optimised collider and detector designs, and associated physics analyses, were presented in the ILC Technical Design Report, signed by 2400 scientists.

There is a strong interest in Japan to host this international effort. A detailed review of the many aspects of the project is nearing a conclusion in Japan. Now the Japanese government is preparing for a decision on the next phase of international negotiations, that could lead to a project start within a few years. The potential timeline of the ILC project includes an initial phase of about 4 years to obtain international agreements, complete engineering design and prepare construction, and form the requisite international collaboration, followed by a construction phase of 9 years.

Supporting documents web page:
`https://ilchome.web.cern.ch/content/ilc-european-strategy-document`

These papers and supporting documents in:
https://ilchome.web.cern.ch/content/ilc-european-strategy-document

More about ILC: https://ilchome.web.cern.ch

CLIC

The Compact Linear e^+e^- Collider (CLIC):
Accelerator and Detector

Input to the European Particle Physics Strategy Update
on behalf of the CLIC and CLICdp Collaborations

18 December 2018

Abstract

The Compact Linear e^+e^- Collider (CLIC):
Physics Potential

Input to the European Particle Physics Strategy Update
on behalf of the CLIC and CLICdp Collaborations

18 December 2018

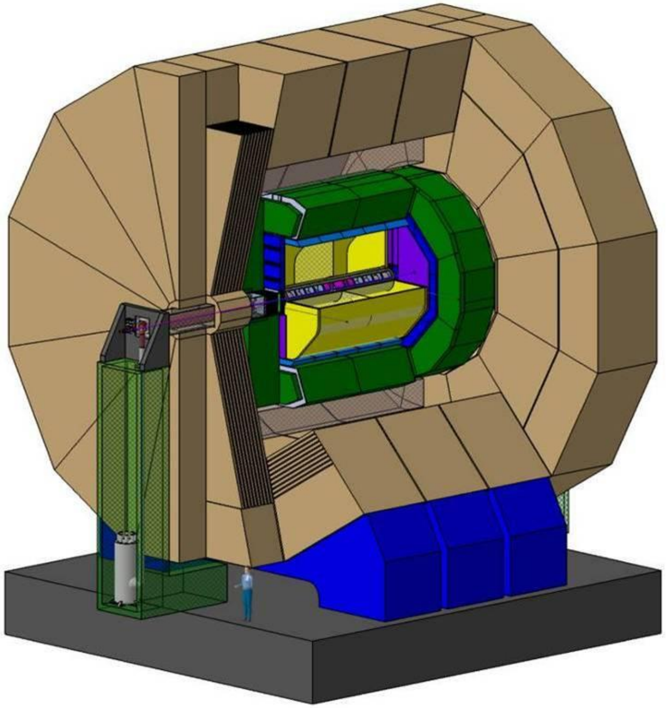
Abstract

These paper and supporting documents in:
https://clic.cern/european-strategy

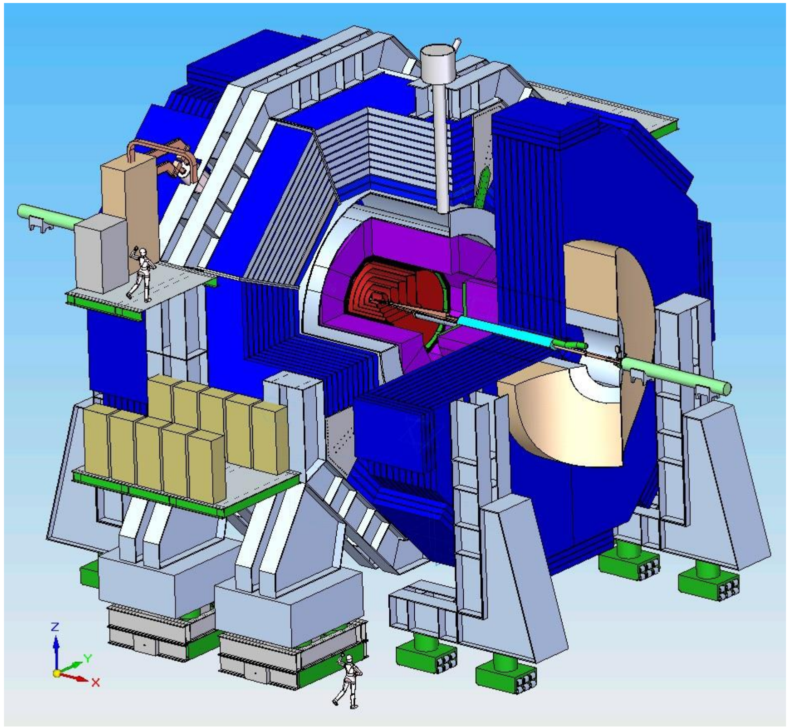
More about CLIC: https://clic.cern

Reserve

ILC Detector Concepts



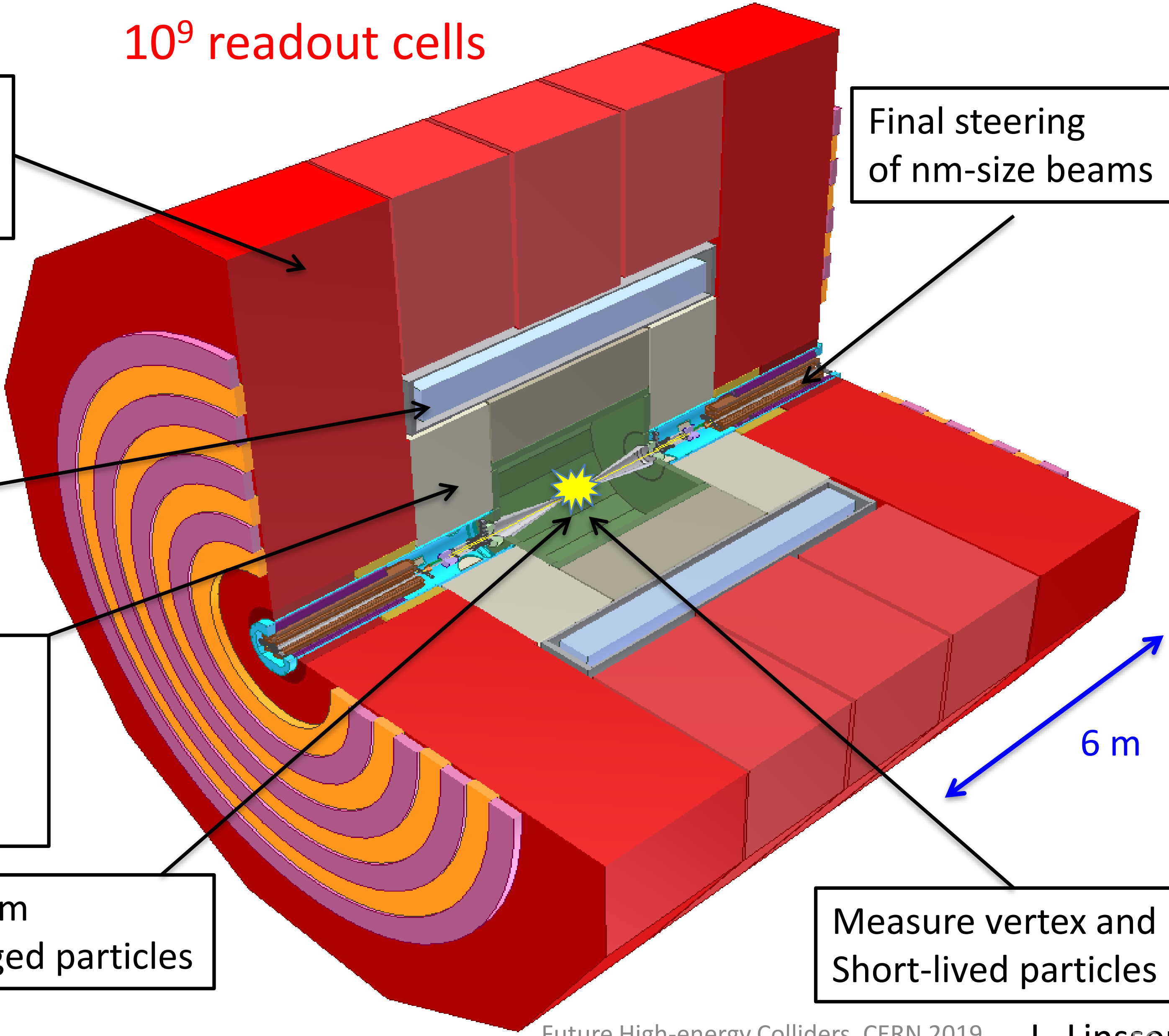
ILD



SiD

CLIC detector concepts are based on SiD and ILD.
Modified to meet CLIC requirements

Linear Collider Experiment



10^9 readout cells

Field return and muon particle identification

Final steering of nm-size beams

B-field for momentum and charge measurement

Energy measurement of (charged and) neutral particles

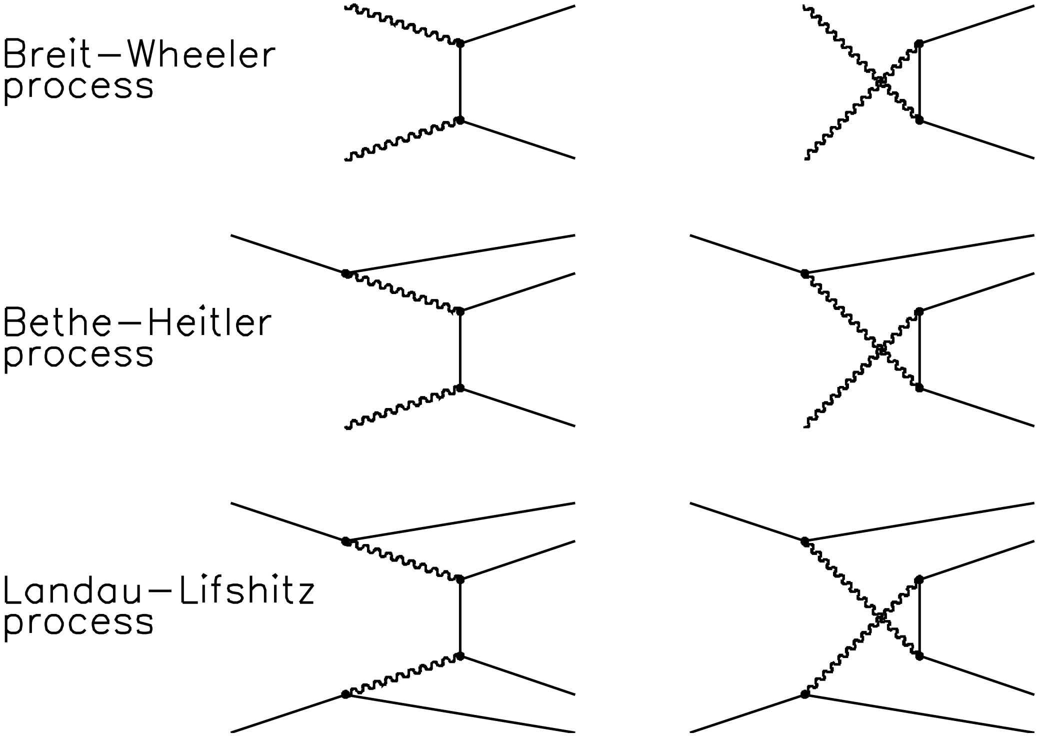
Measure momentum and charge of charged particles

Measure vertex and Short-lived particles

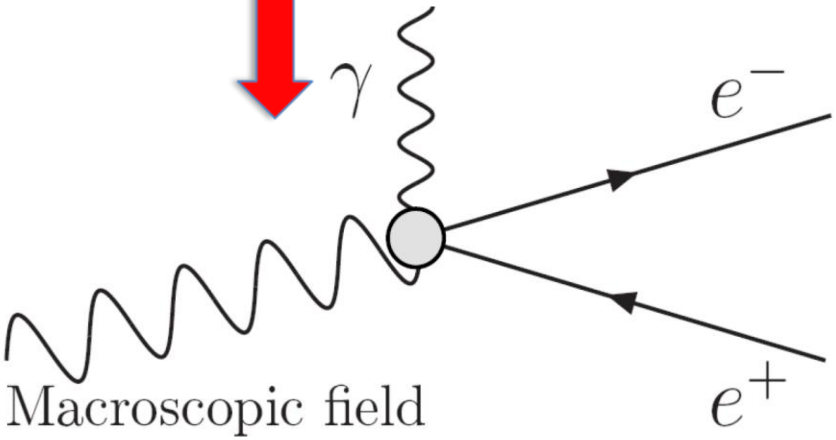
L. Linssen

Lepton Pair Production

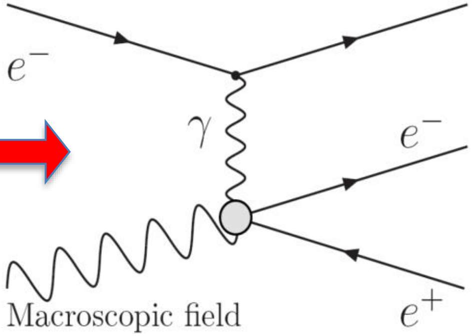
Colliding Photons can produce electron-positron pairs (incoherent pair production)
O(10^5) per bunch crossing



Beamstrahlung photons can turn into pair in strong field (coherent pair production)
O(1-10^8) per bunch crossing



Trident cascade



Spent Beam Content

Spent beam particles

Beamstrahlung

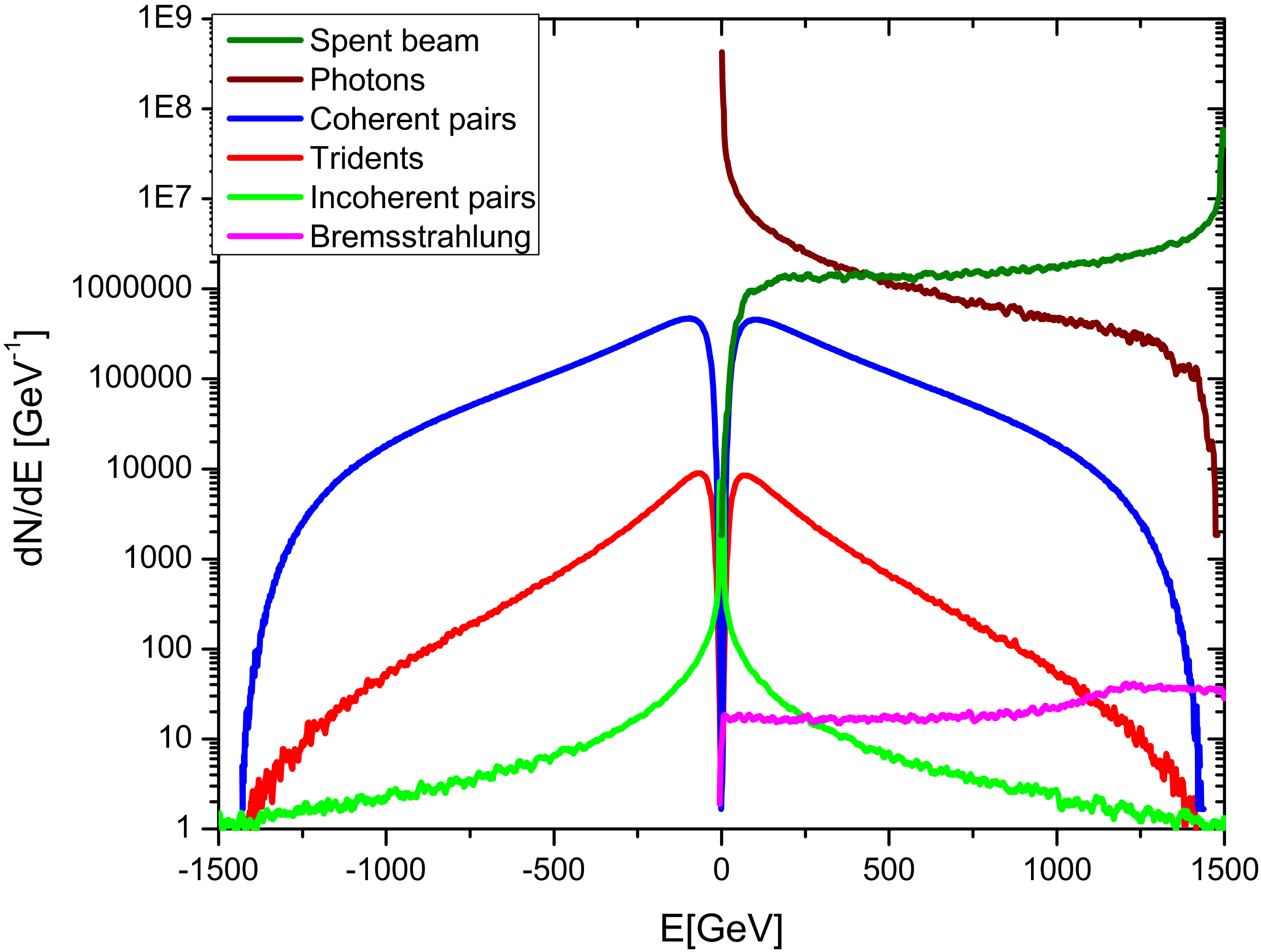
Coherent pairs

Trident cascade pairs

Incoherent pairs

Hadrons

…



J. Esberg

Spent Beam Divergence

Beam particles are focused by oncoming beam

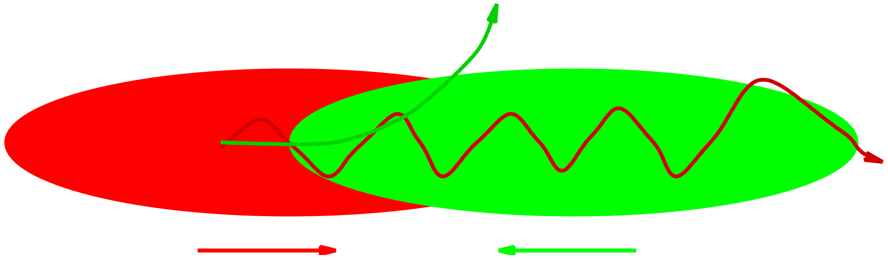
Photons are radiated into direction of beam particles

Coherent pair particles can be focused or defocused by the beams but deflection limited due to their high energy

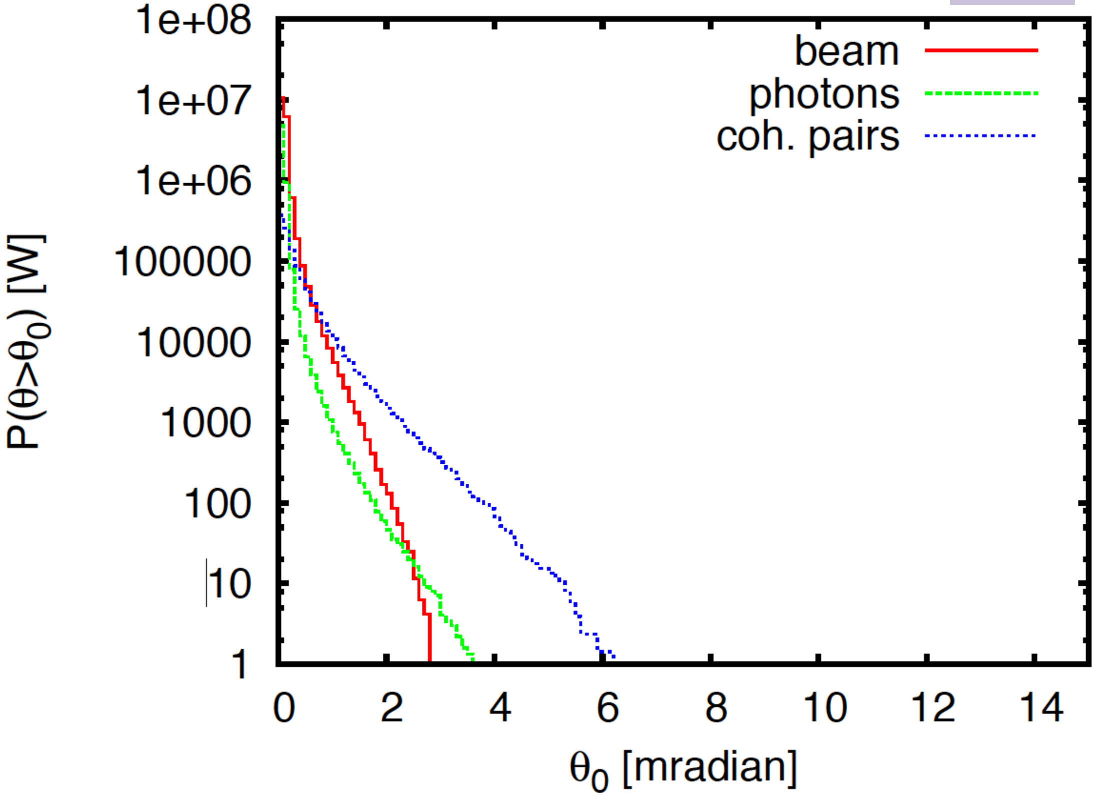
-> Extraction hole angle should be significantly larger than 6mradian

We chose 10mradian for CLIC
-> 20mradian crossing angle

ILC requires 14mradian crossing angle

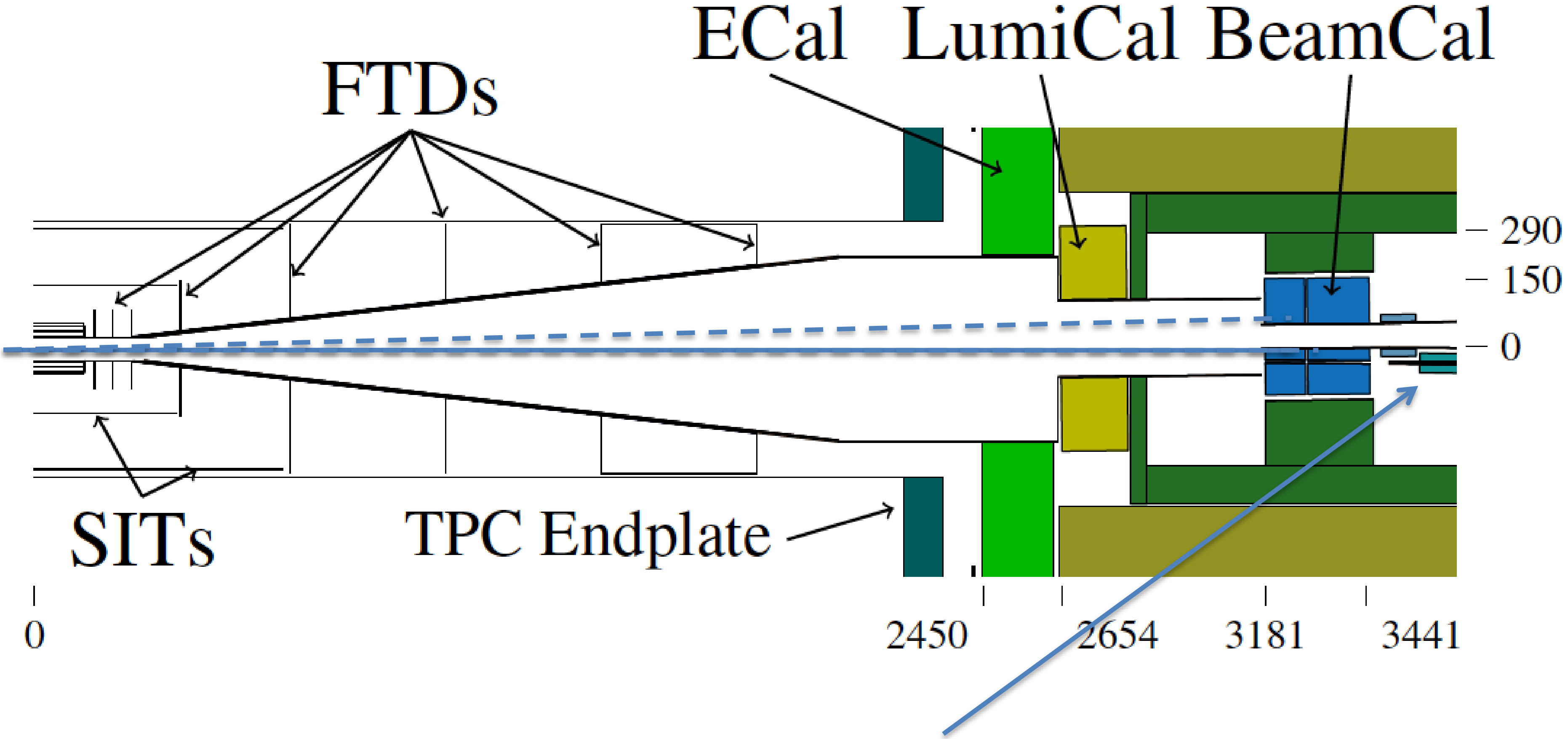


CLIC



$1\,\mathrm{W} \approx 400\,\mathrm{TeV/bx} \approx 300\,\mathrm{beamparticles/bx}$

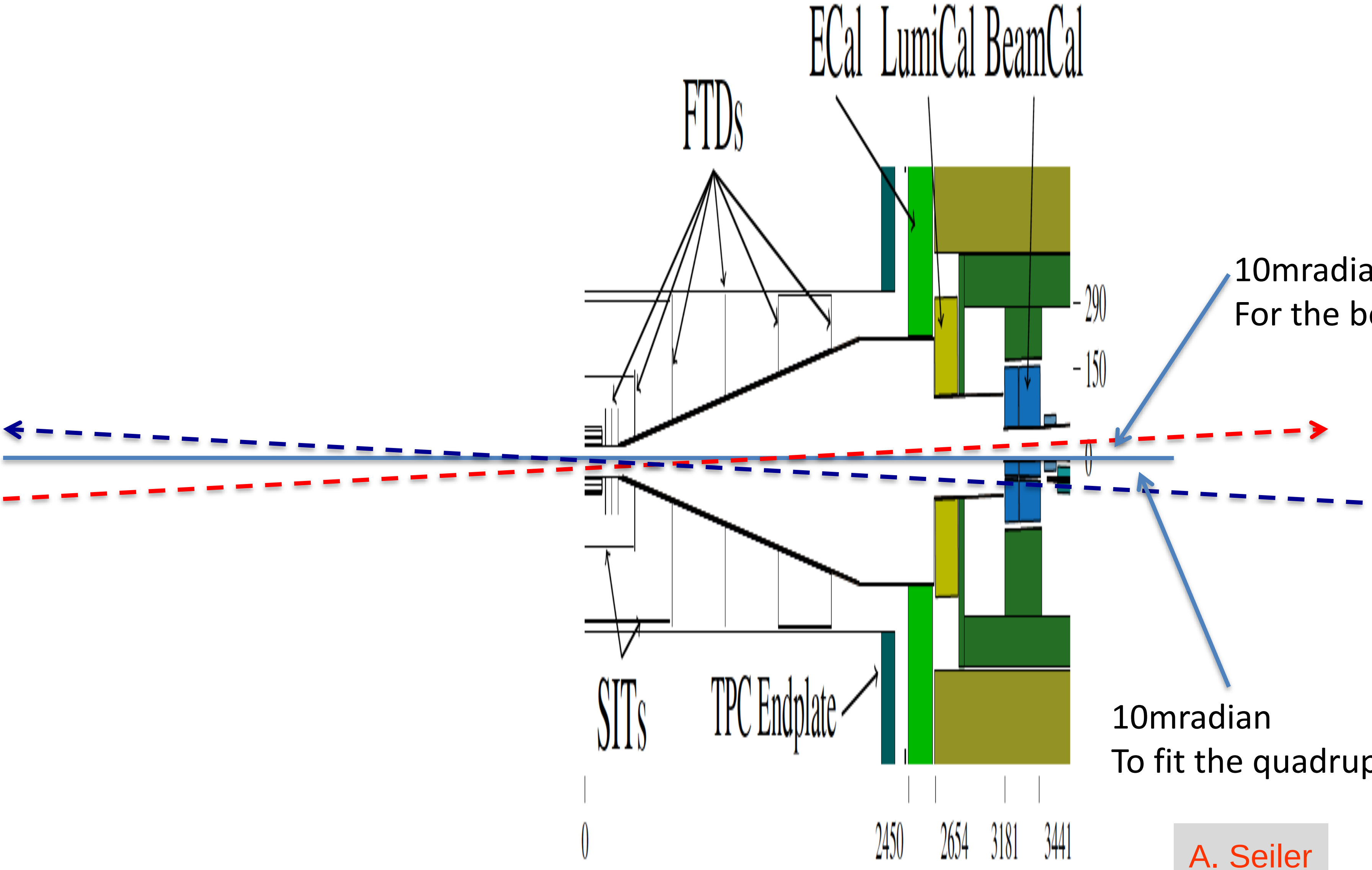
CLIC Inner Detector Layout



The last focusing magnet of the machine is inside of the detector

A. Seiler

Inner Detector Layout

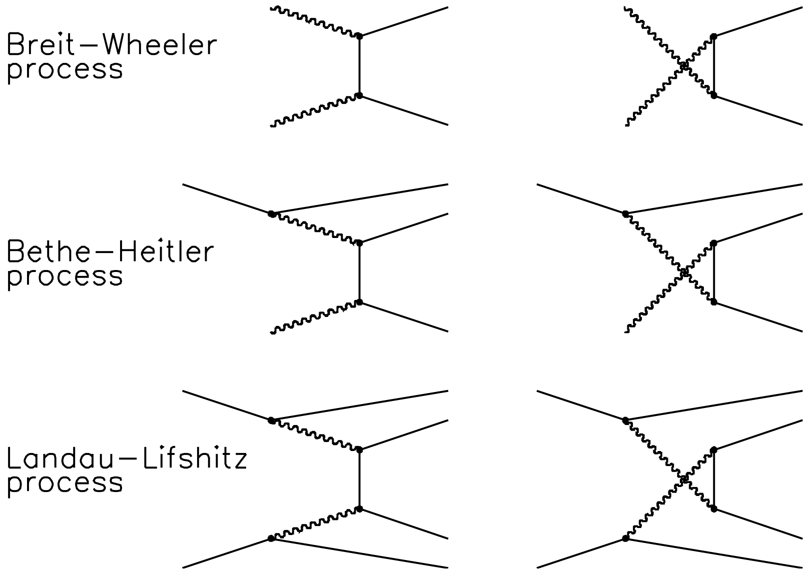


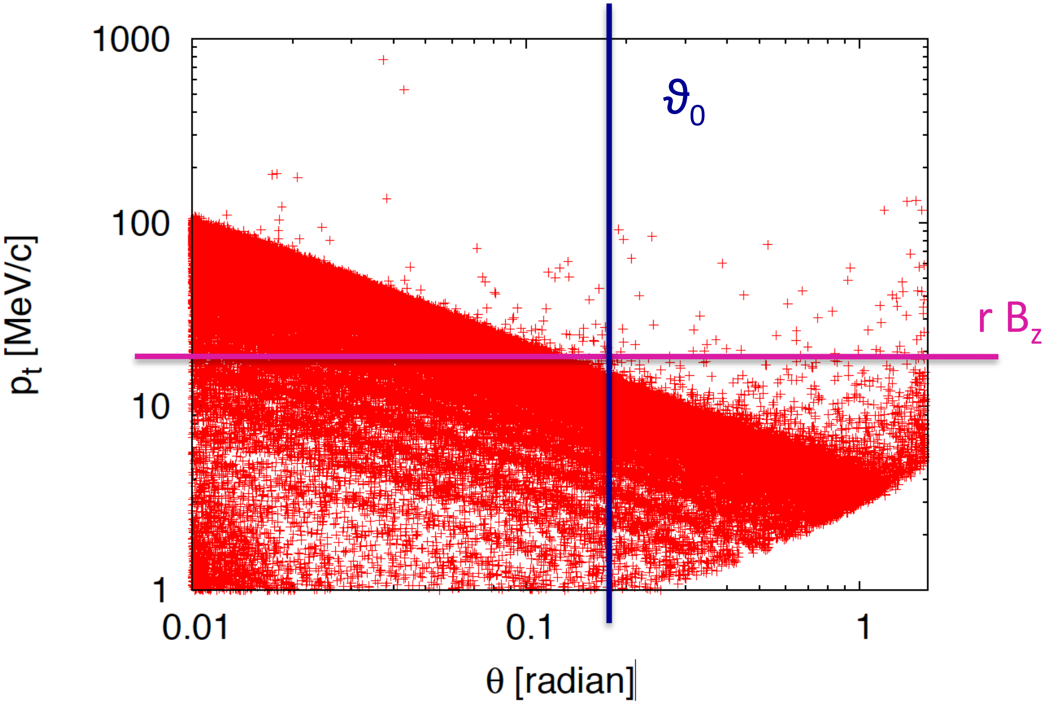
10mradian
For the beam

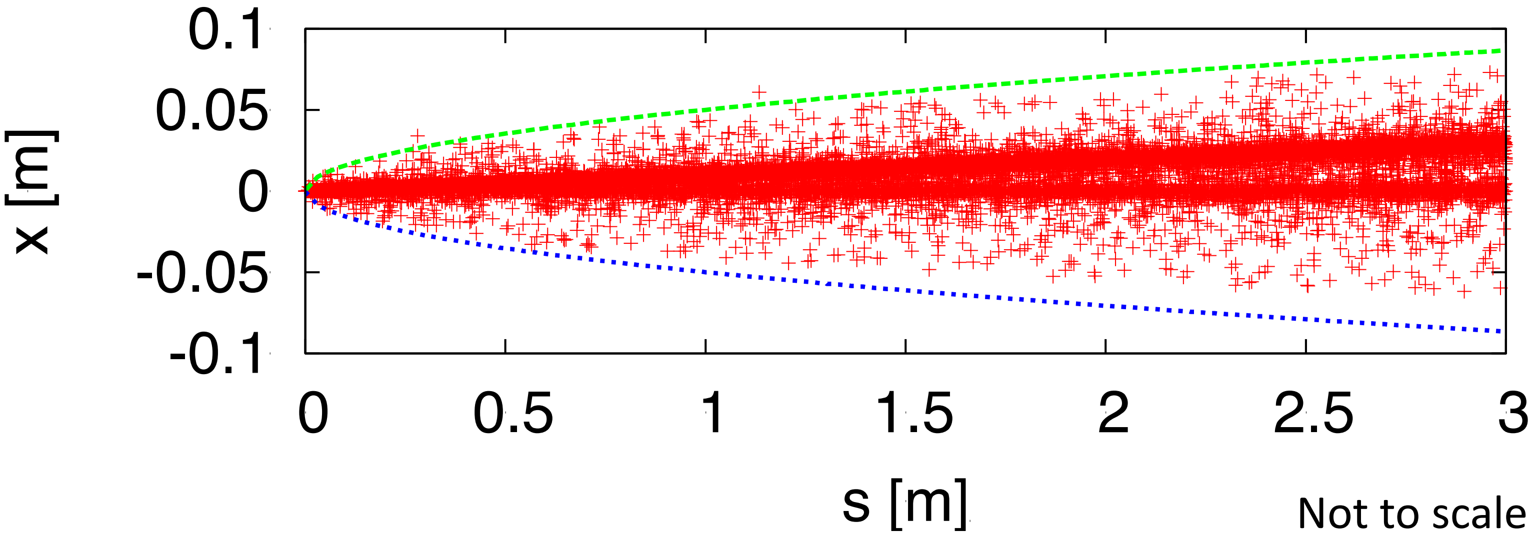
10mradian
To fit the quadrupole

A. Seiler

Incoherent Pairs

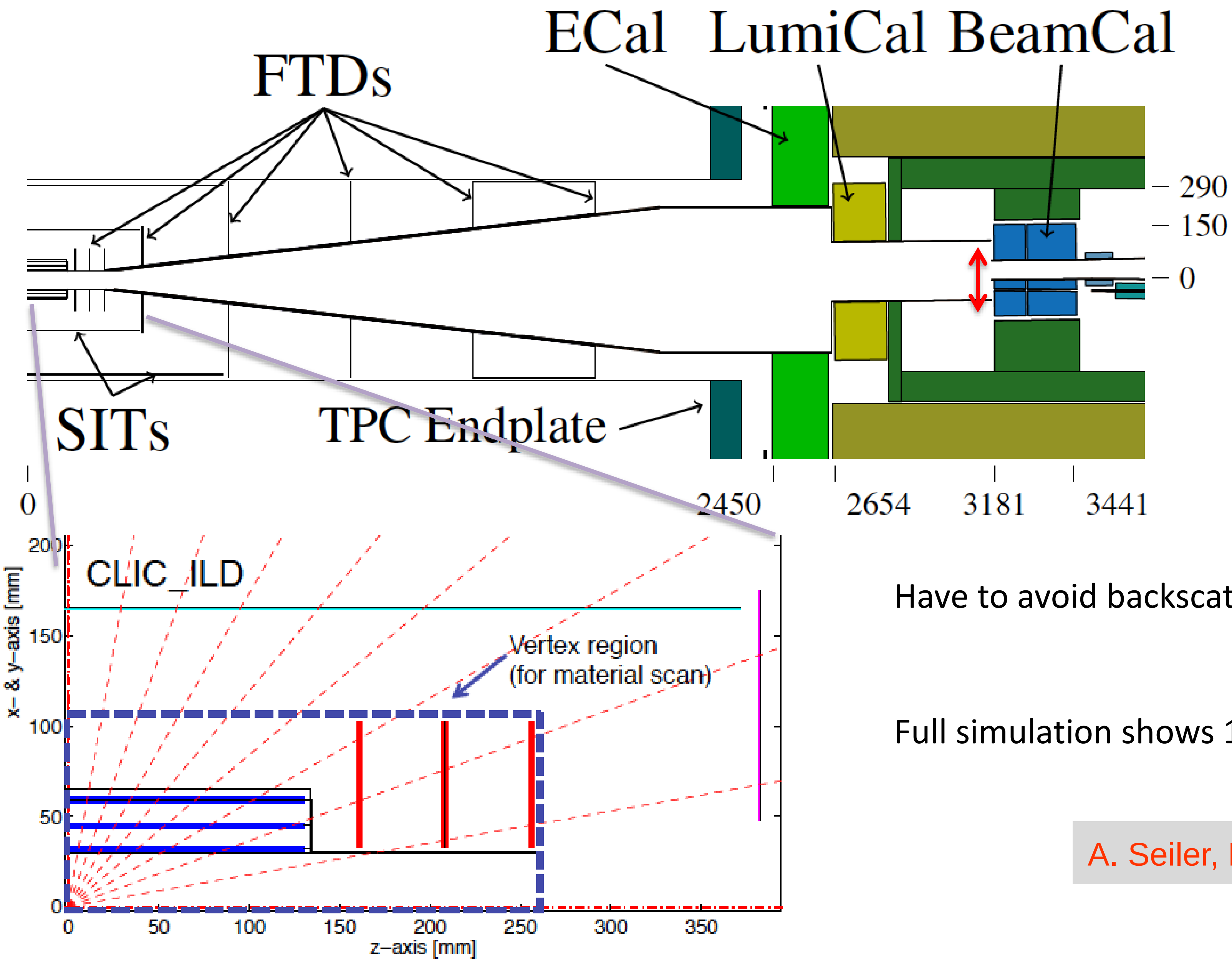






Not to scale

Vertex Detector Design



Have to avoid backscattering

Full simulation shows 1.5hits/mm^{-2}

A. Seiler, D. Dannheim

Hadronic Background

Only events used with

$$W_{\gamma\gamma} \geq 5\,\mathrm{GeV}$$

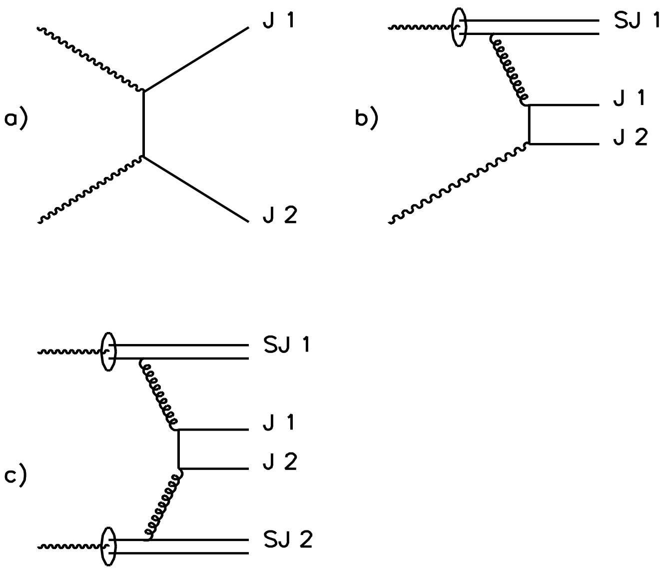
Most energy is in forward/backward direction

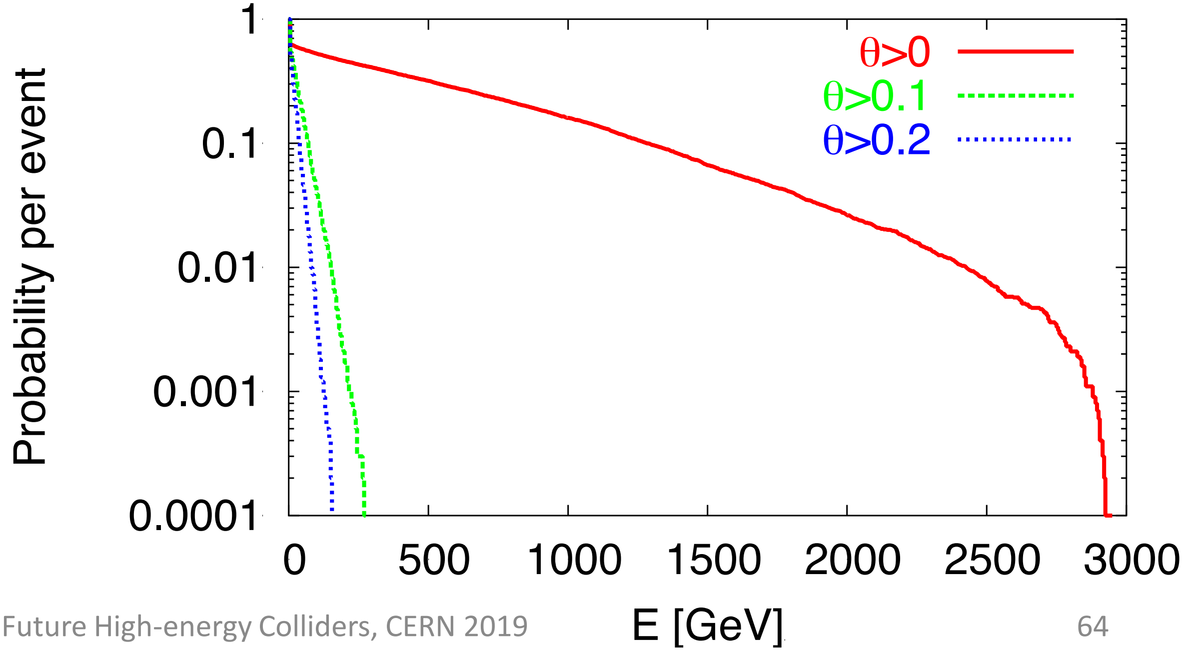
- E_{vis}≈ 450GeV per hadronic event
- E_{vis}≈23GeV for θ>0.1
- E_{vis}≈12GeV for θ>0.2

-20% from e^+e^- (cannot be reduced)

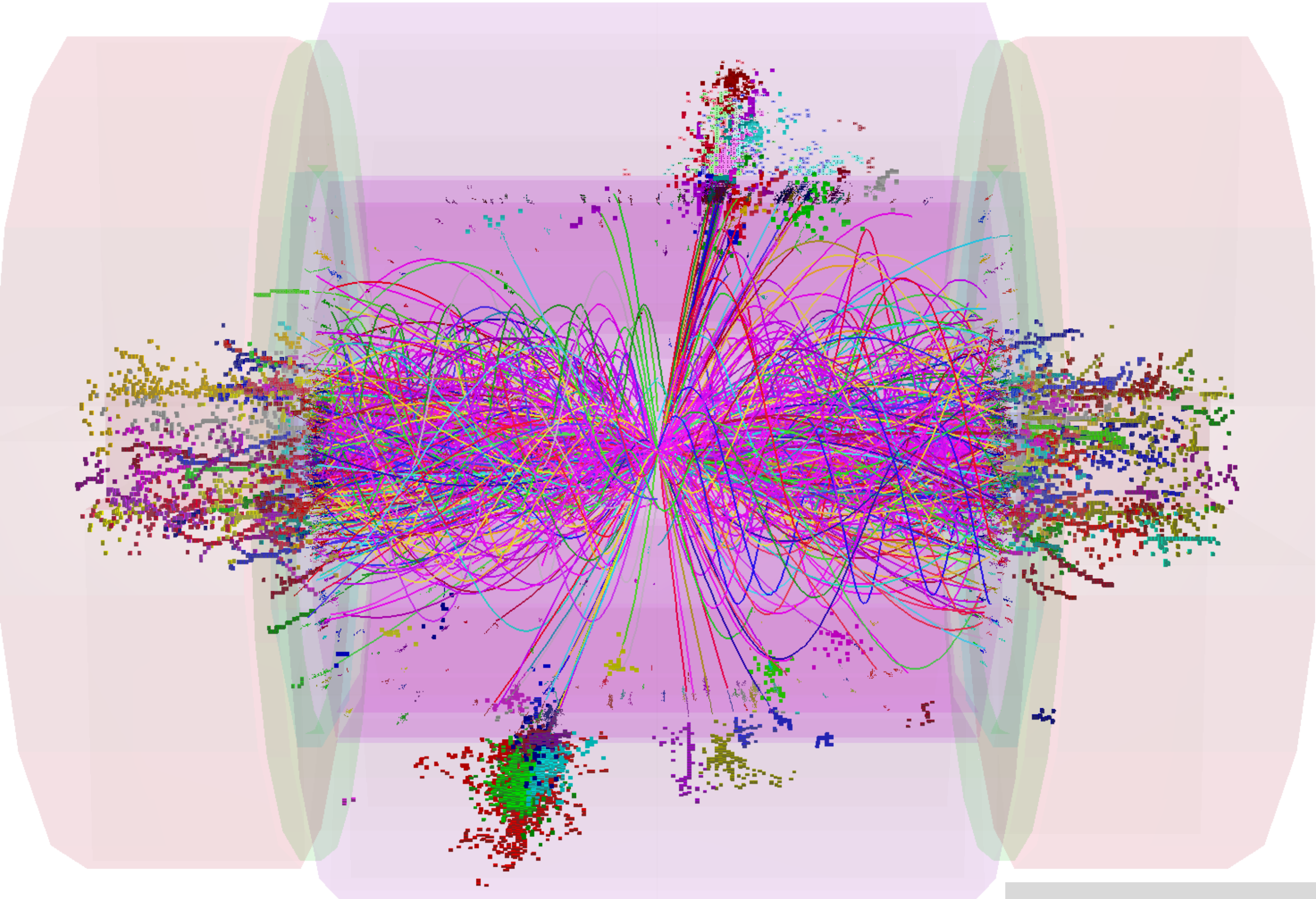
Adds about 20% charged hits in the inner layer of the vertex detector

Can be used to monitor luminosity





PandoraNewPFAs



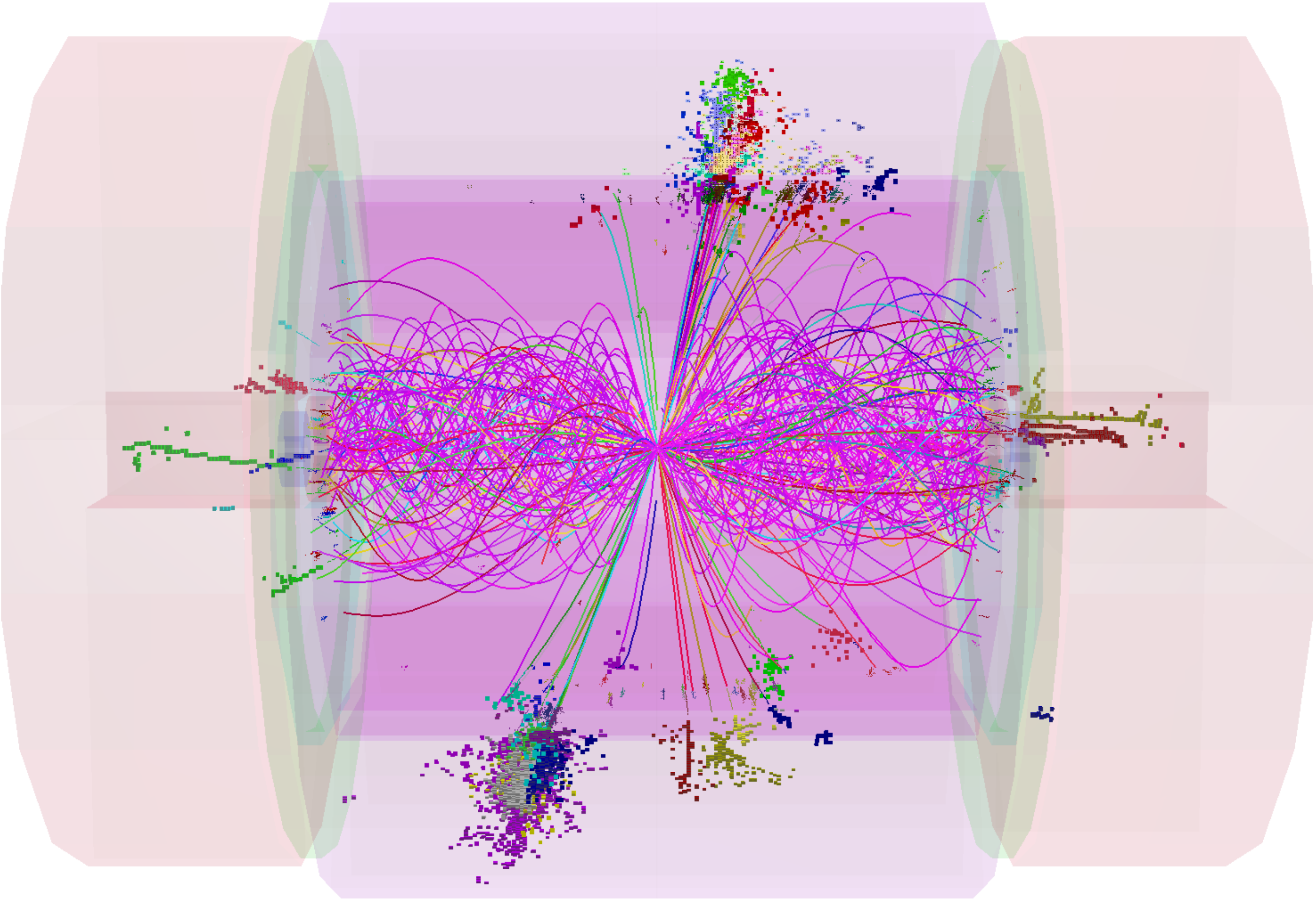
M. Thomson. J. Marshall

1 TeV Z=>qqbar

1.4 TeV of background !

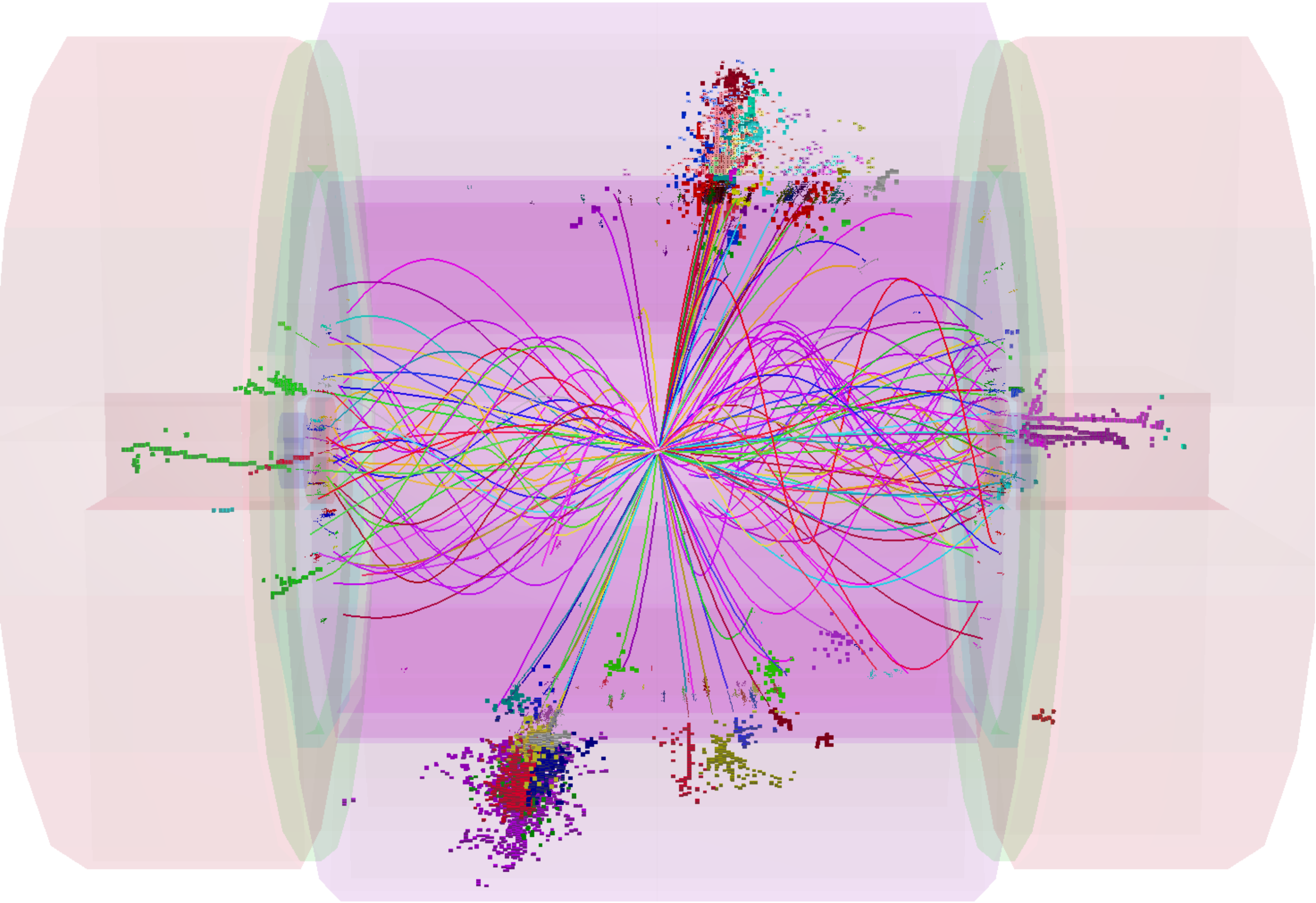
with 60 BX background

LooseSelectedPandoraNewPFAs



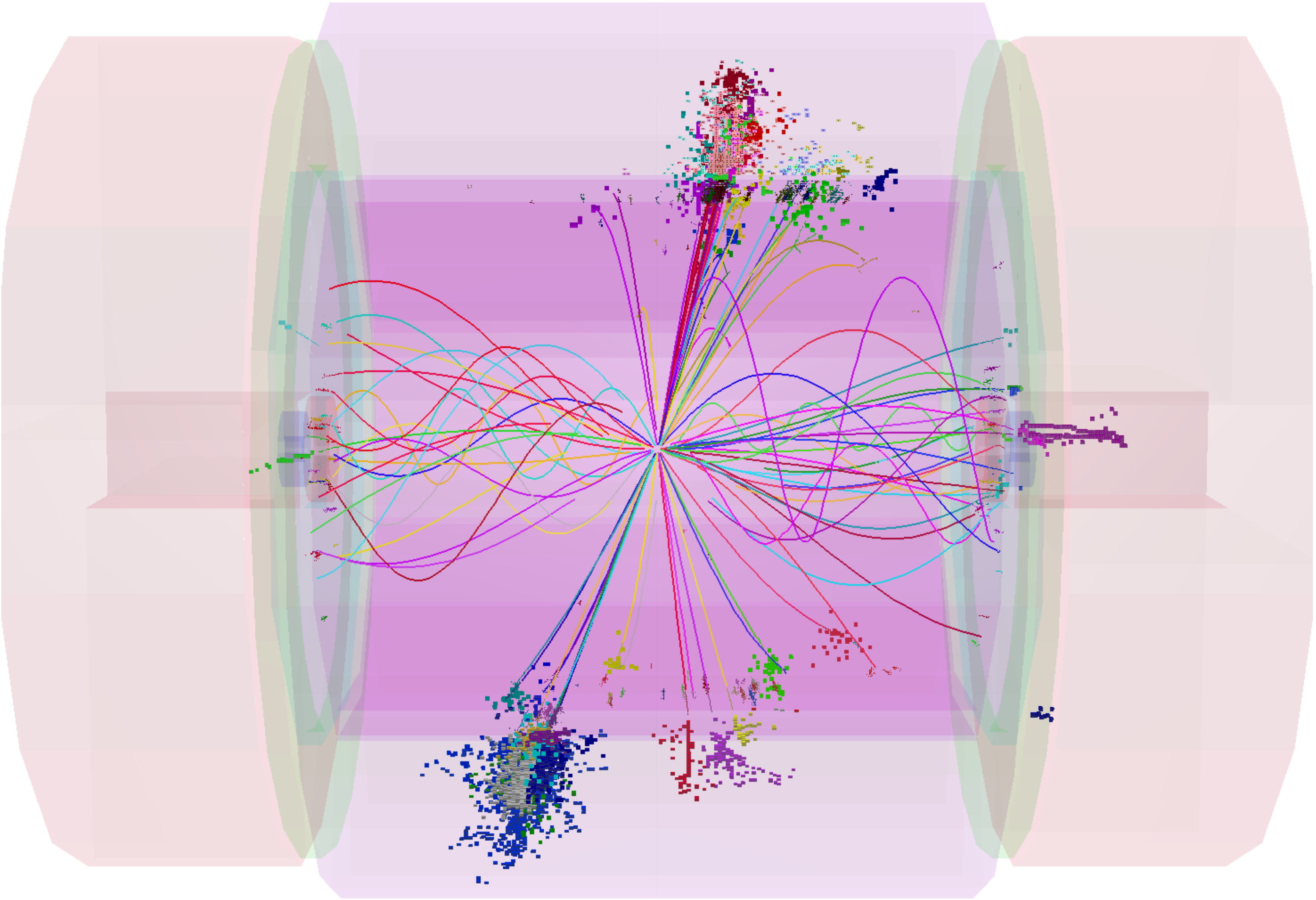
0.3 TeV of background

SelectedPandoraNewPFAs



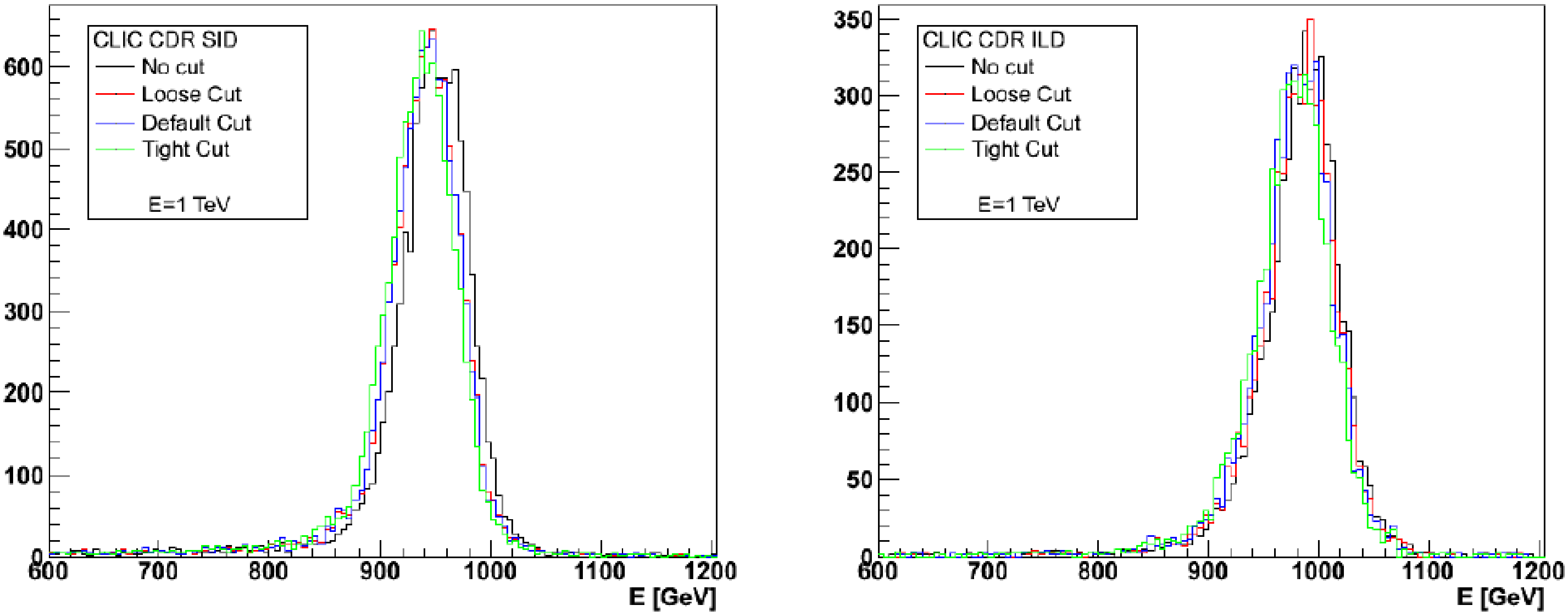
0.2 TeV of background

TightSelectedPandoraNewPFAs



0.1 TeV of background

Impact of timing cuts on jets



Impact of the PFOSelector timing cuts on the jet energy resolution

E_{jet} [GeV]	45	100	250	500
no cut	3.98 ± 0.05	3.15 ± 0.04	3.00 ± 0.04	3.26 ± 0.06
loose cut	4.40 ± 0.06	3.34 ± 0.04	3.08 ± 0.04	3.29 ± 0.06
default cut	5.15 ± 0.07	3.64 ± 0.05	3.17 ± 0.04	3.33 ± 0.06
tight cut	5.95 ± 0.08	3.99 ± 0.05	3.30 ± 0.04	3.37 ± 0.06

ILD

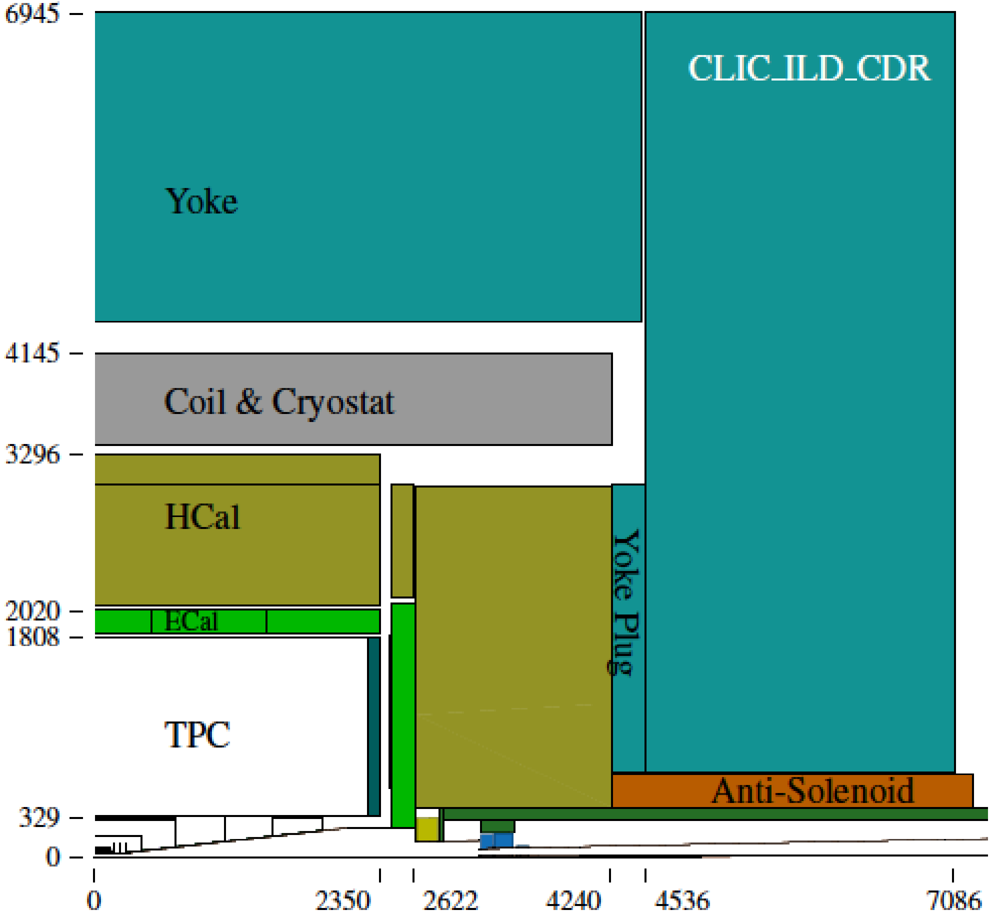
Beam-Induced Background Summary

parameter	units	CLIC	CLIC	ILC (RDR)
E_{cms}	$[\mathrm{TeV}]$	0.5	3.0	0.5
f_{rep}	$[\mathrm{Hz}]$	50	50	5
n_b		354	312	2625
Δt	$[\mathrm{ns}]$	0.5	0.5	369
L_{total}	$[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	2.3	5.9	2.0
$L_{0.01}$	$[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1.4	2.0	1.45
n_γ		1.3	2.2	1.3
$\Delta E/E$		0.07	0.29	0.024
N_{coh}	$[10^5]$	10^{-3}	3.8×10^3	—
E_{coh}	$[10^3\,\mathrm{TeV}]$	0.015	2.6×10^5	—
n_{incoh}	$[10^6]$	0.08	0.3	0.1
E_{incoh}	$[10^6\mathrm{GeV}]$	0.36	22.4	0.2
$n_\perp$		20.5	45	28
n_{had}		0.19	2.7	0.12

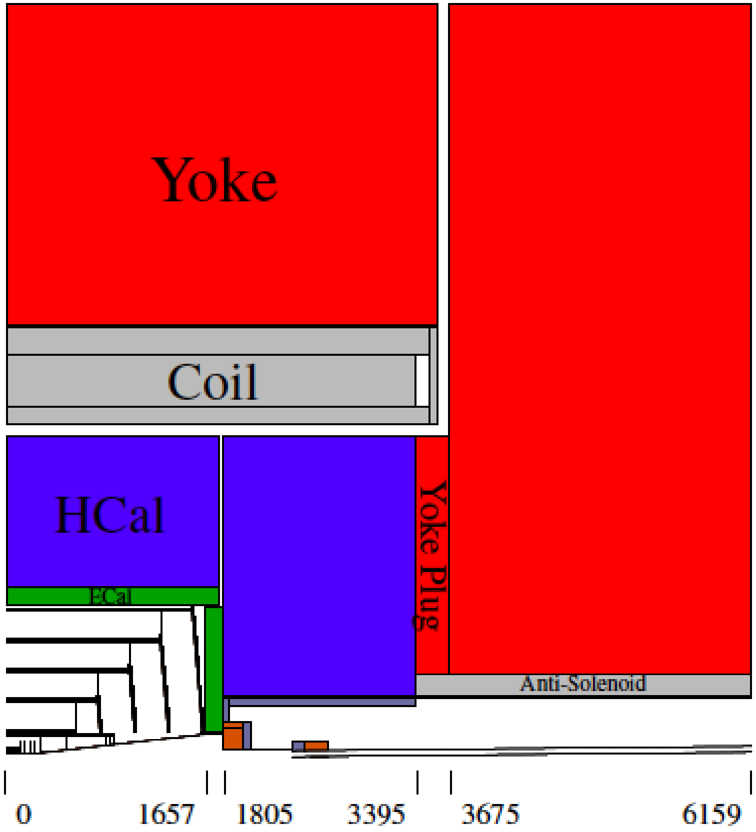
- Beamstrahlung
  - Disappear in the beam pipe
- Coherent pairs
  - Largely disappear in beam pipe
- Incoherent pairs
  - Suppressed by strong solenoid-field
- Hadronic events
  - Impact reduced by time stamping
- Muon background from upstream linac
  - Not discussed here

CLIC_ILD and CLIC_SiD

CLIC_ILD_CDR



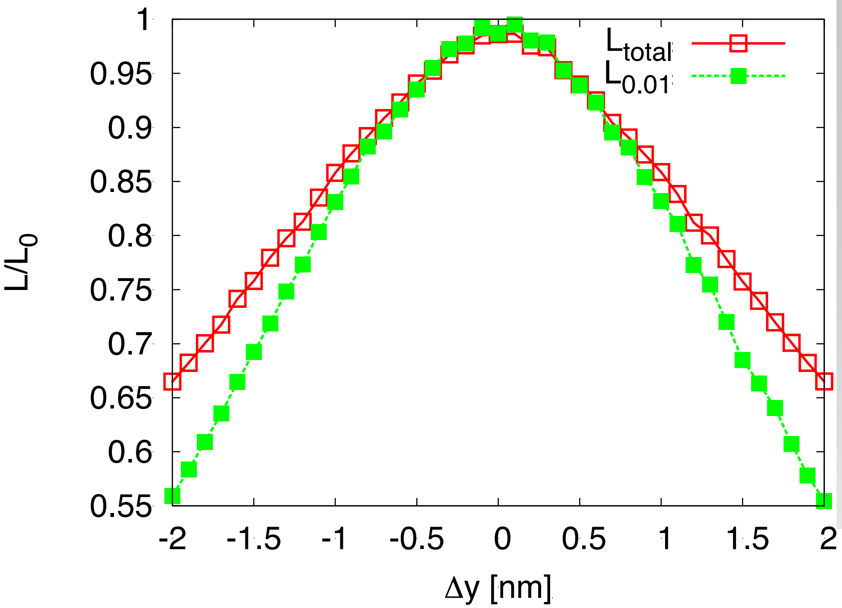
CLIC_SiD_CDR

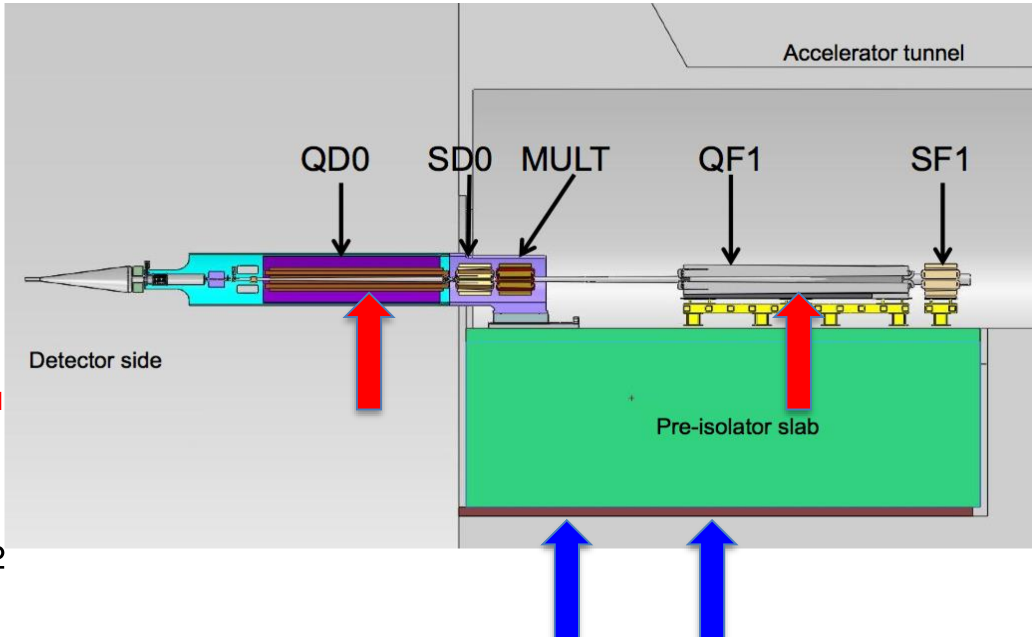


These images are derived from the simulation models for the CDR

Linear Collider
Some Detailed Issues

Ground Motion and Its Mitigation

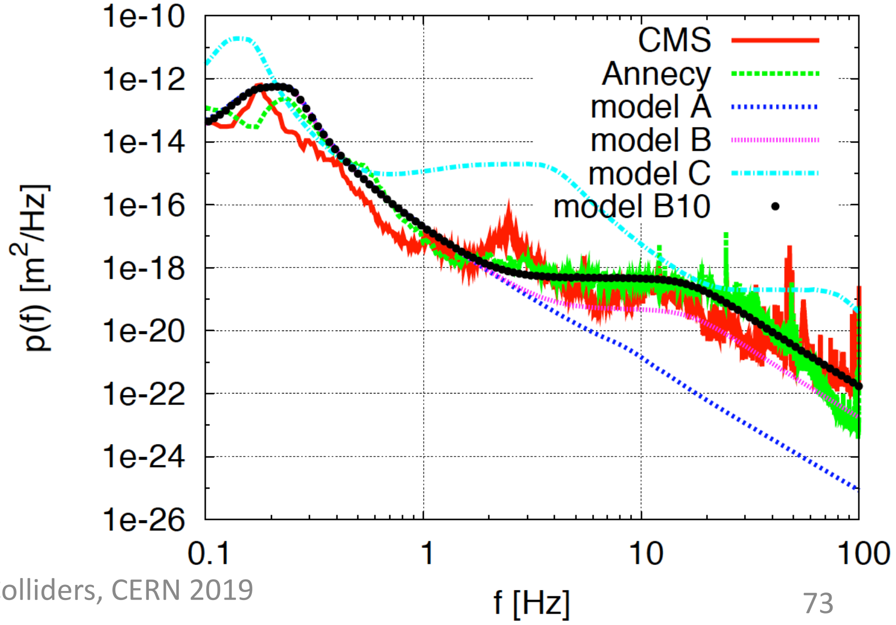




Natural ground motion can impact the luminosity

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

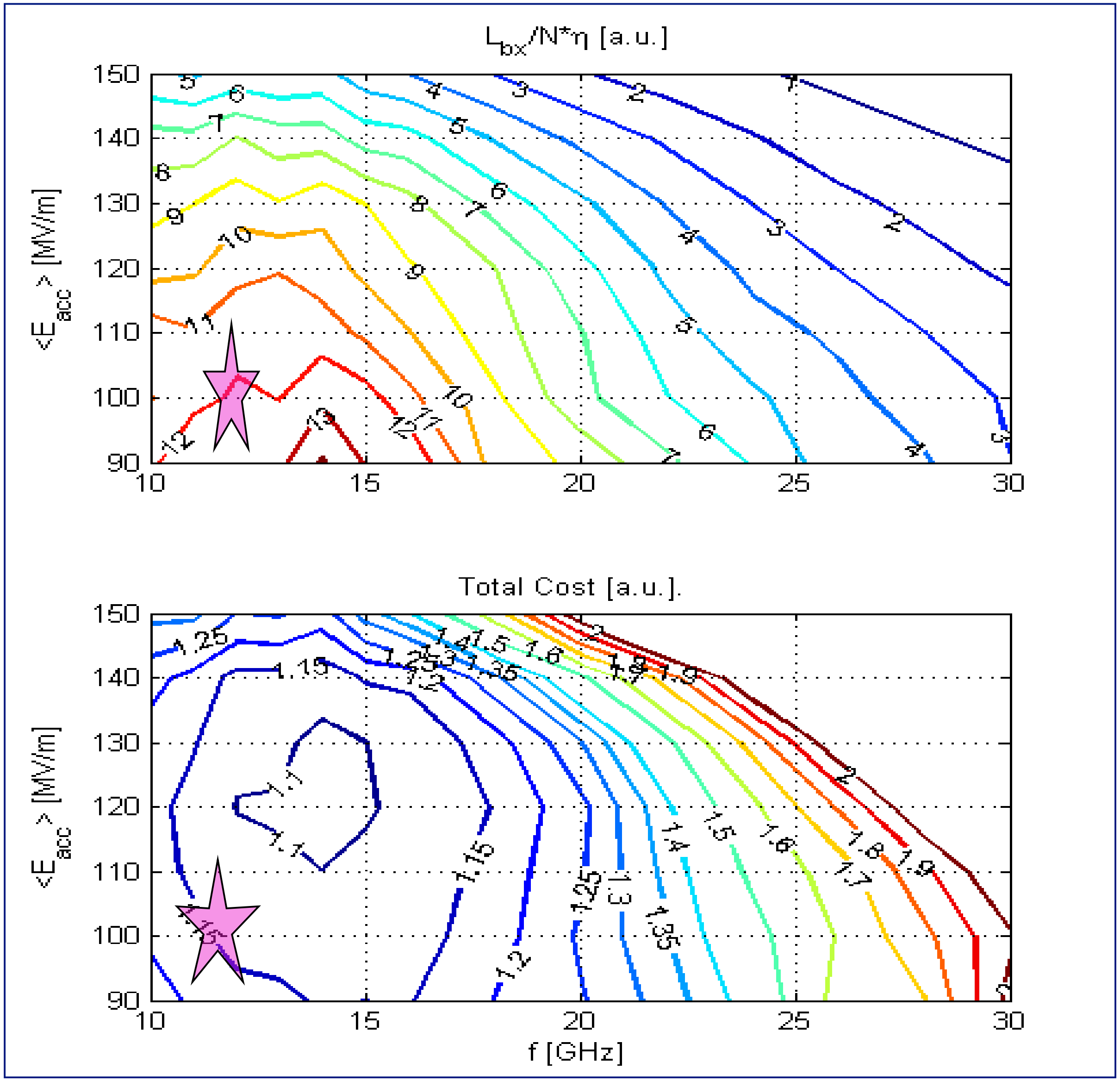
-> develop stabilisation for beam guiding magnets



CLIC: Why 100 MV/m and 12 GHz ?

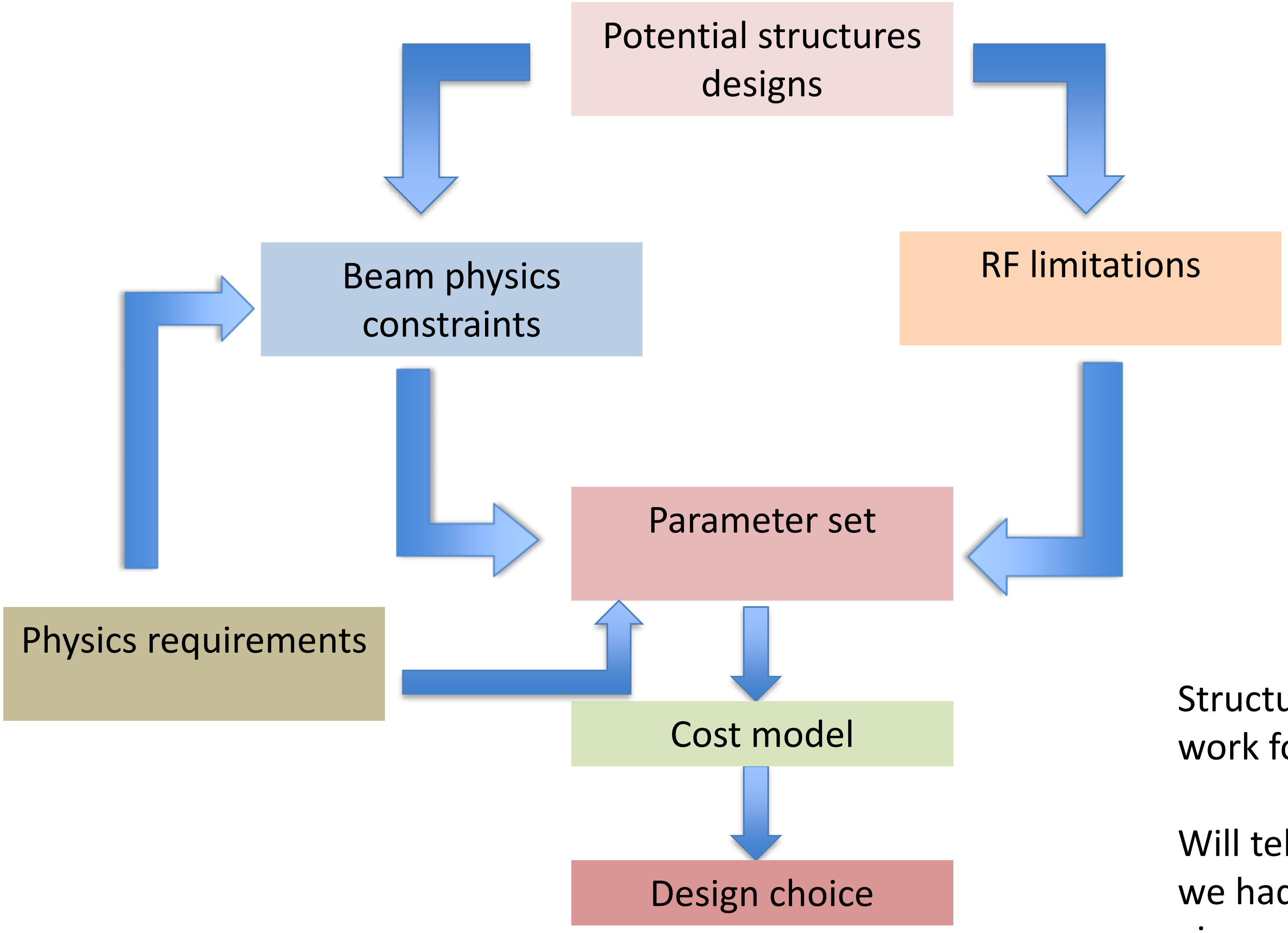
- Optimisation 1
  - Luminosity per linac input power

- Optimisation 2
  - Total project cost



A.Grudiev

Parameter and Structure Choice



Potential structures designs

Beam physics constraints

RF limitations

Parameter set

Physics requirements

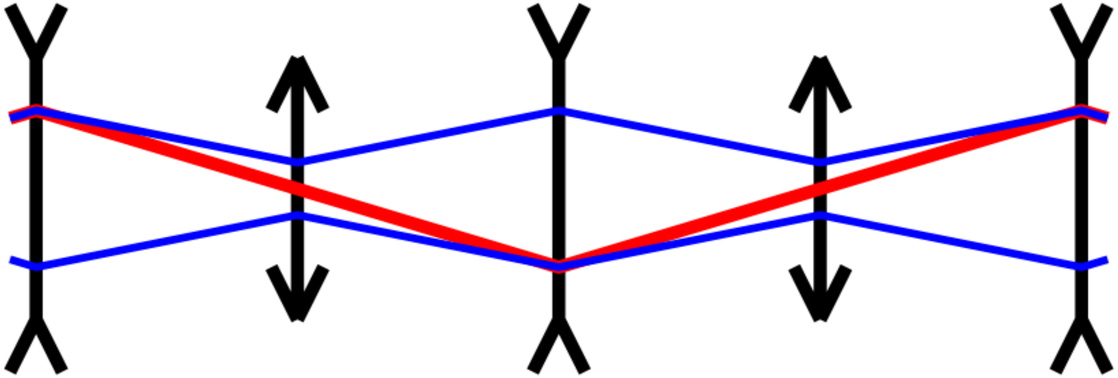
Cost model

Design choice

Structure chosen to work for beam physics

Will tell the story as if we had a structure given

Pushing the Bunch Charge



Single bunch wakefields kick the tail of a bunch

Guiding quadrupoles act like a spring

Comparable to driven oscillator

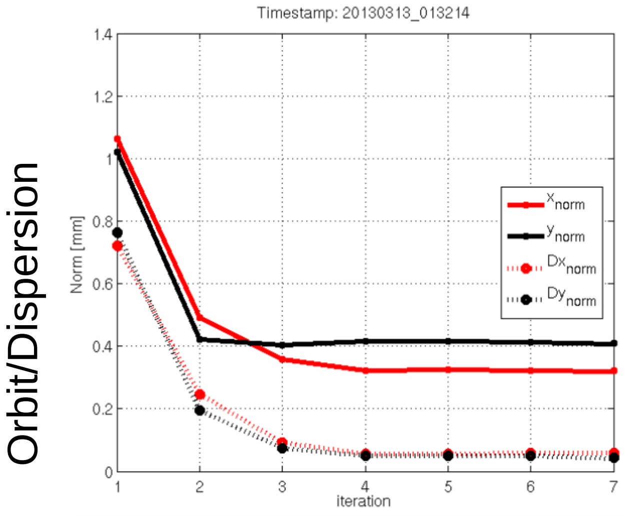
$$x'' + \frac{1}{\beta^2}x = \frac{F(s)}{E(s)}$$

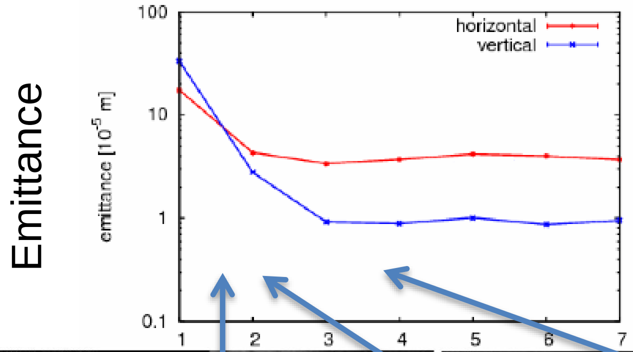
Increasing spring strength reduces oscillation → Put in as many strong quadrupoles as reasonable (O(10%) of CLIC main linac) → Become sensitive to quadrupole position errors

CLIC Beam-Based Alignment Tests at FACET

Dispersion-free Steering (DFS) proof of principle – March 2013

A. Latina,
J. Pfingstner,
E. Adli,
D. Schulte

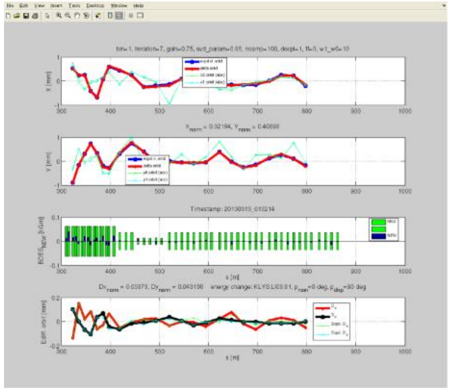


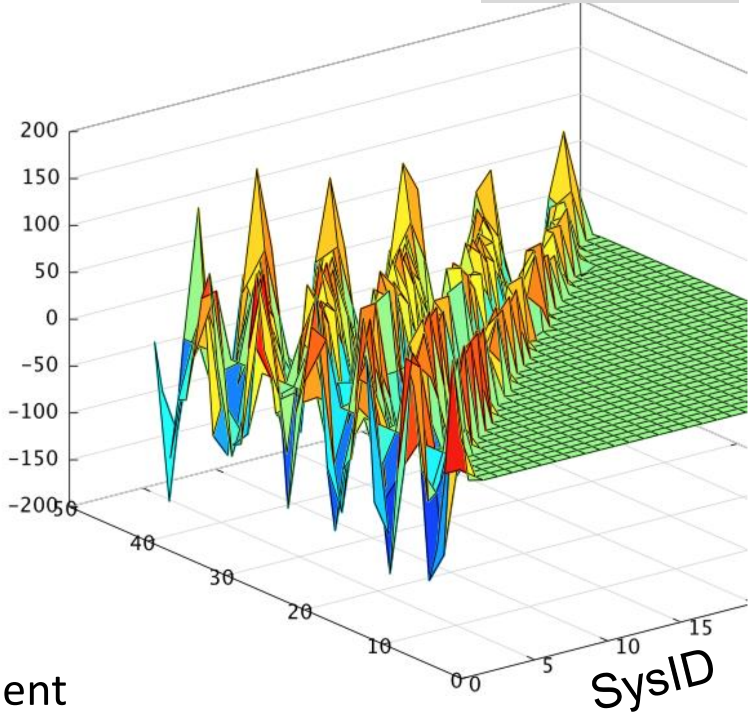


DFS correction applied to 500 meters of the SLC linac

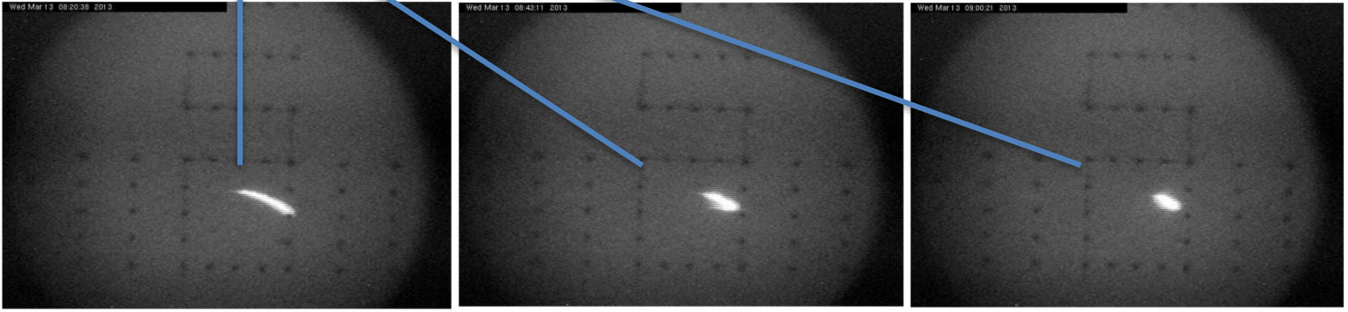
- SysID algorithms for model reconstruction
- DFS correction with GUI
- Emittance growth is measured

Graphic User Interface:





Beam profile measurement



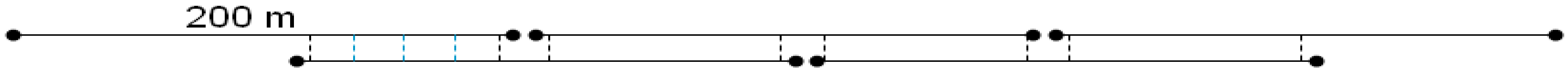
Before correction

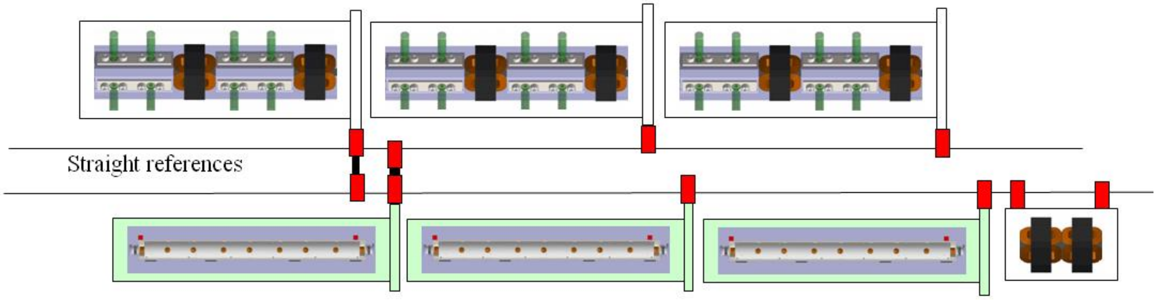
After 1 iteration

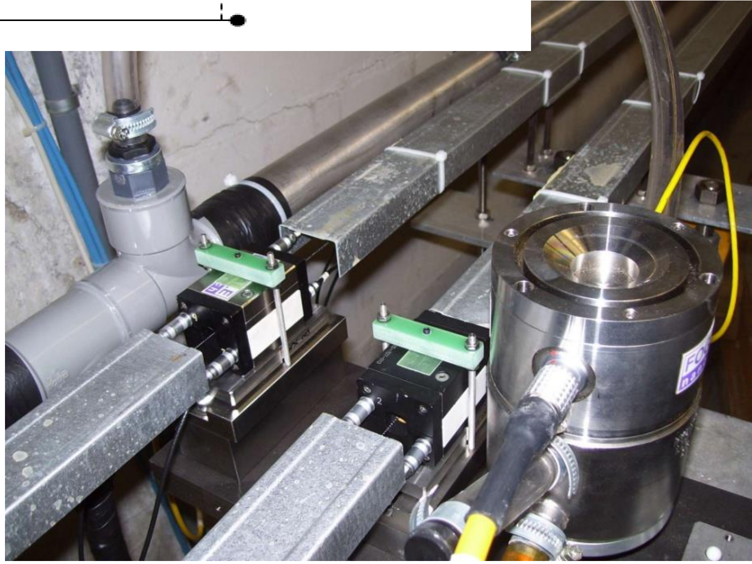
After 3 iterations

Incoming oscillation/dispersion is taken out and flattened; emittance in LI11 and emittance growth significantly reduced.

CLIC Pre-alignment System



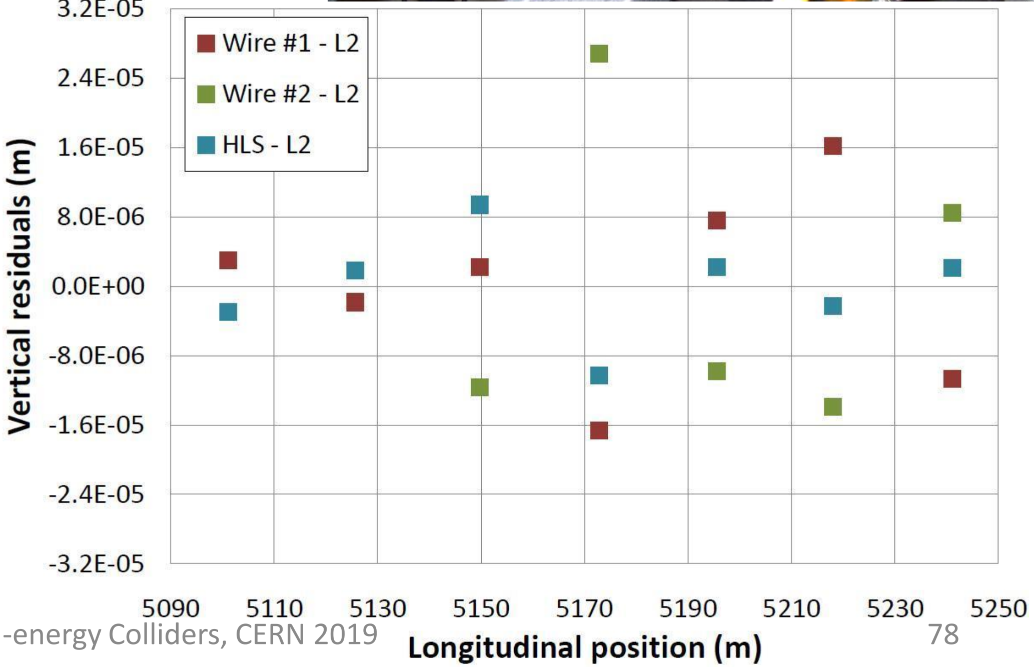




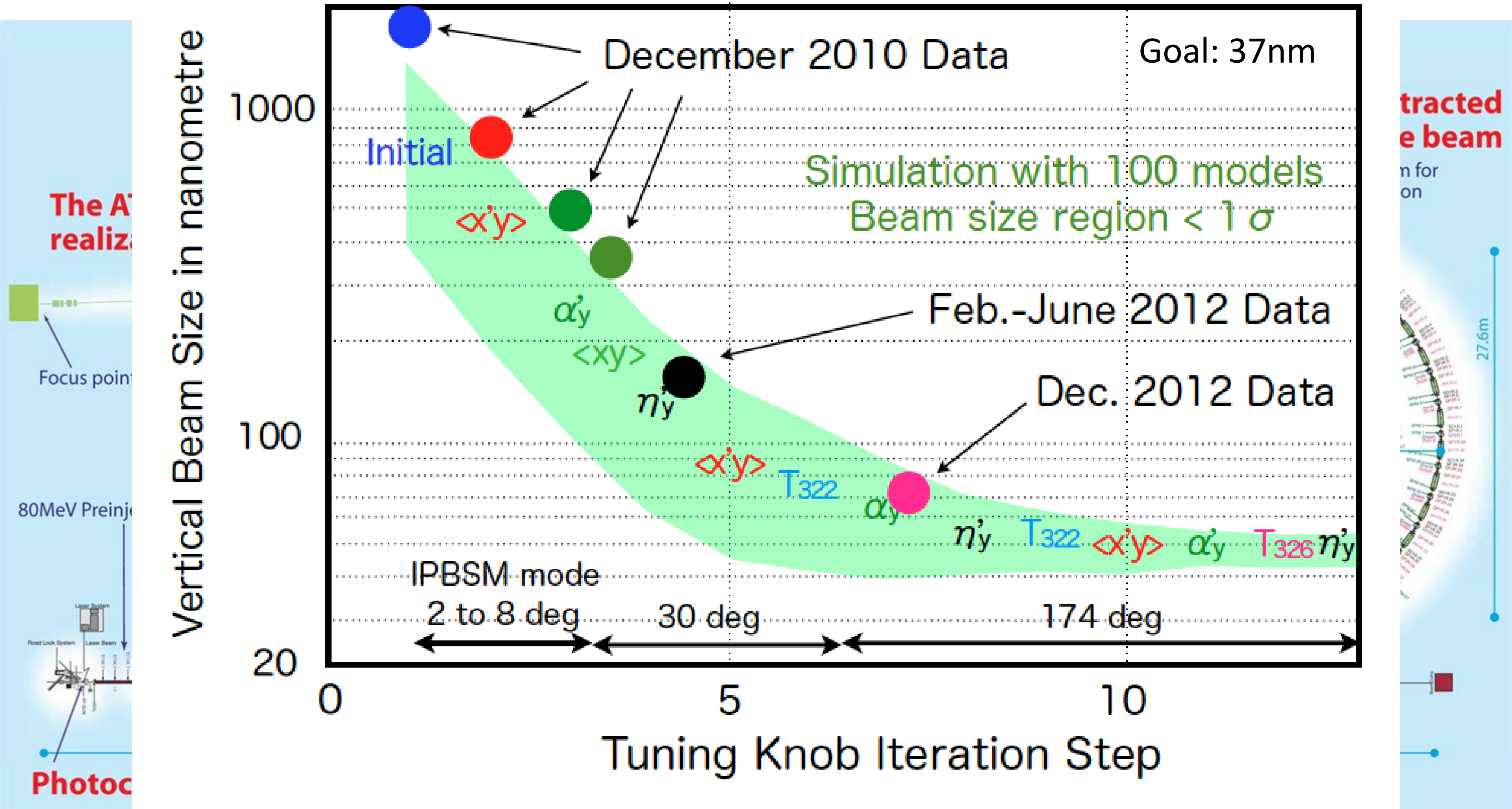
- Required accuracy of reference points is 10µm

- Test of prototype shows
    - vertical RMS error of 11µm
    - i.e. accuracy is approx. 13.5µm

- Improvement path identified



Beam Delivery System Test



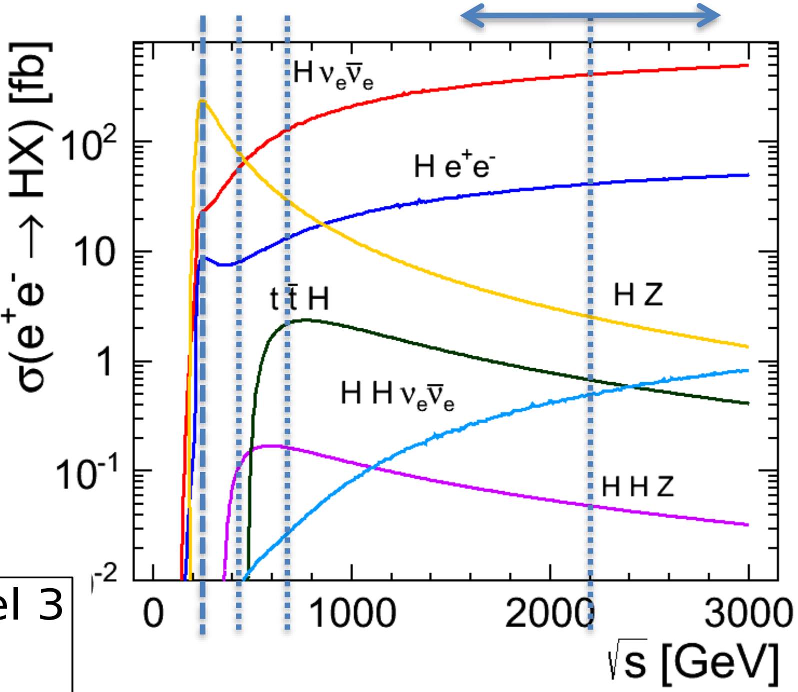
Lepton Collider Physics Case

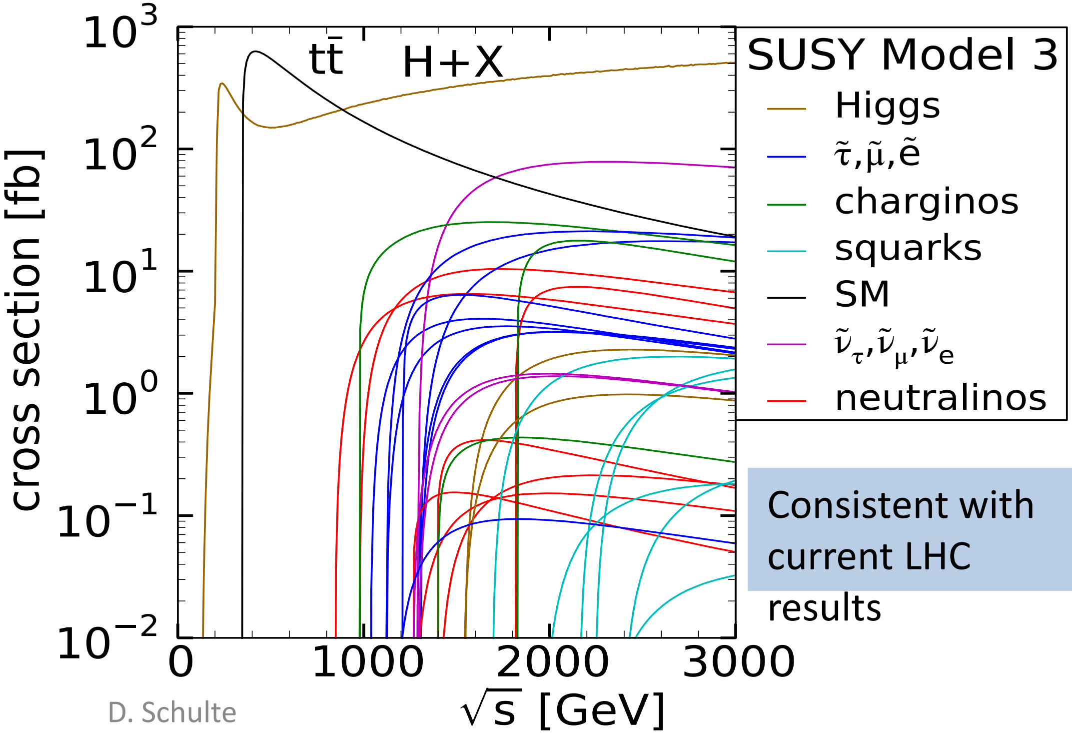
Know physics for Higgs and top

- low energies for many branching rations
- high energies for others, e.g. Hνν
- 350GeV for top threshold scan
- maybe precision measurements at Z and W

Currently not known physics

- hope to get hints from LHC
- e.g. SUSY





Consistent with current LHC results

Have to wait for LHC input
But need to prepare scenarios

Beamstrahlung Optimisation

For low energies (classical regime) number of emitted photons

$$n_\gamma \propto E_\gamma \propto \frac{N}{\sigma_x + \sigma_y}$$

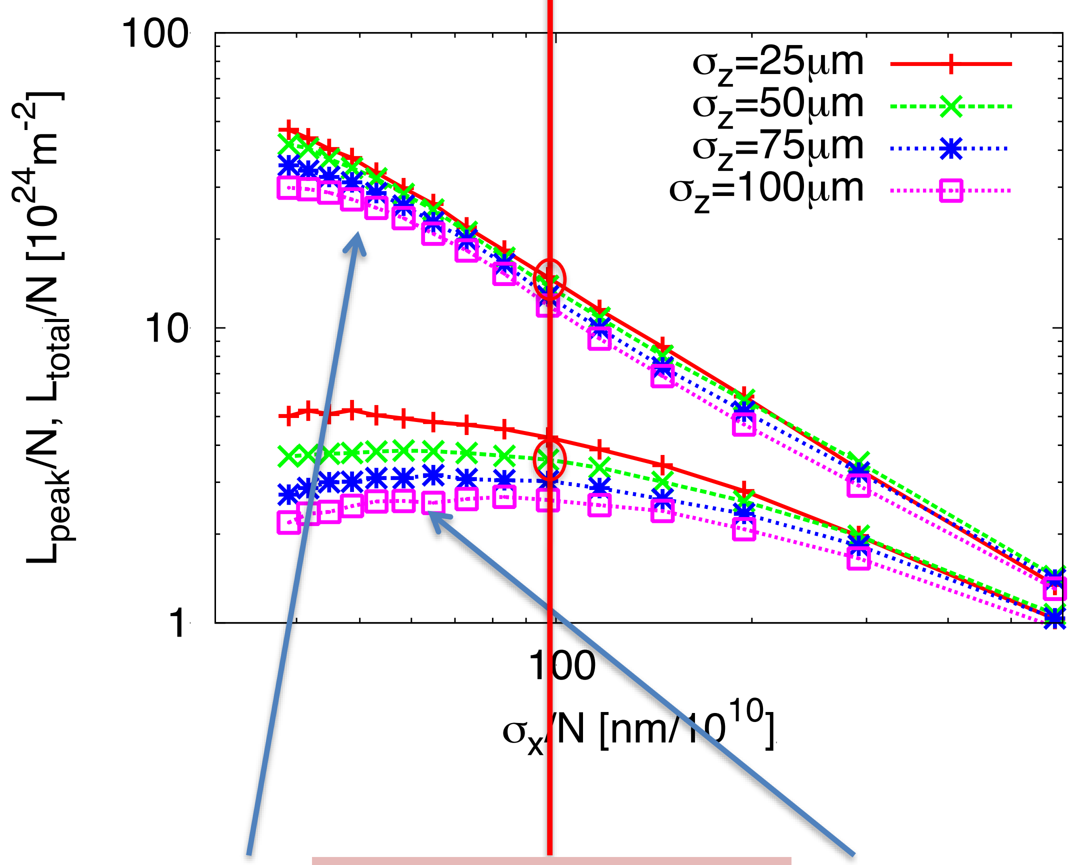
$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

Hence use $\sigma_x \gg \sigma_y$

$$\sigma_x + \sigma_y \approx \sigma_x$$

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

For CLIC at 3TeV (quantum regime)



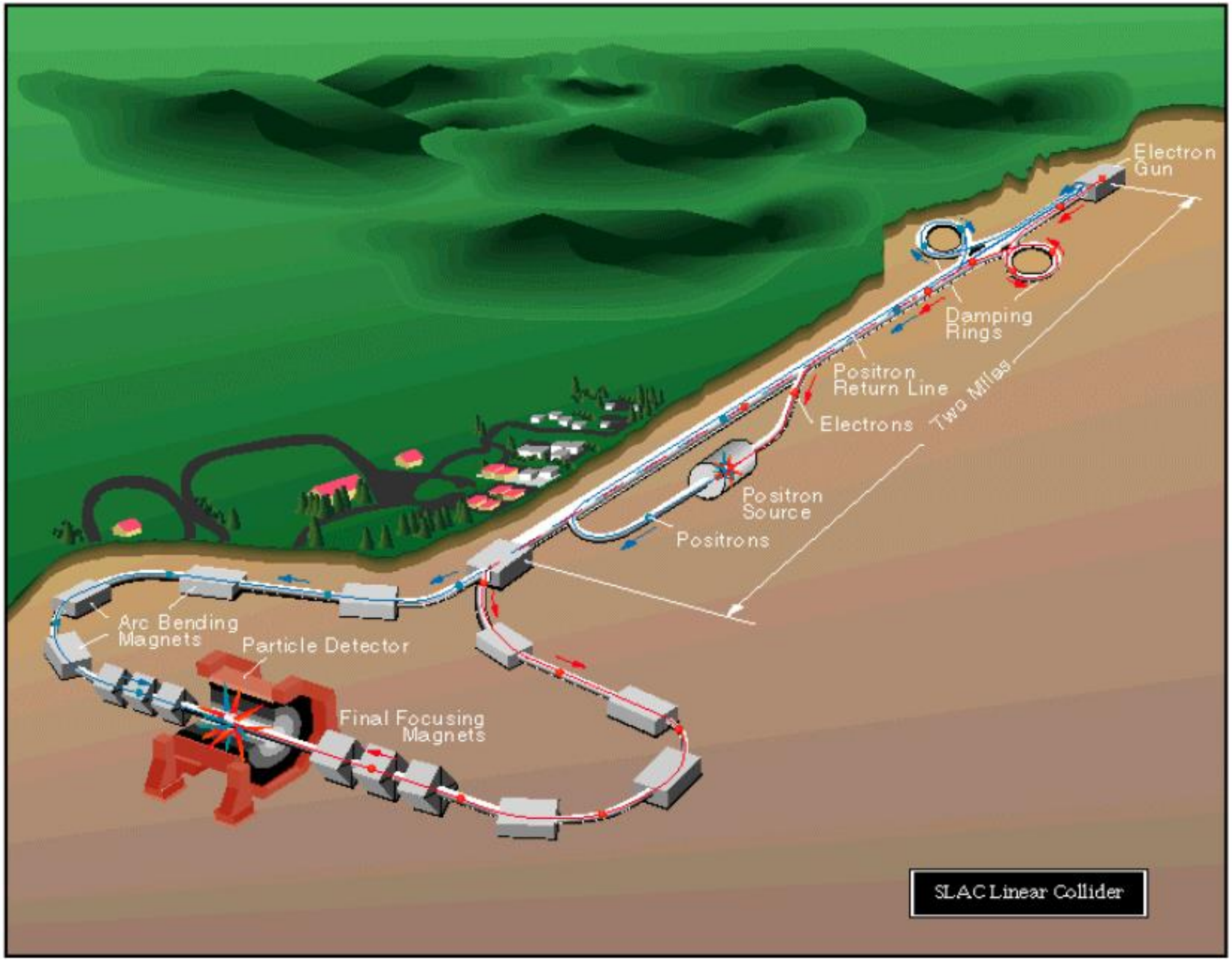
Total lumin

grows for smaller beams

CLIC parameter choice

minosity in peak starts to decrease again

SLC: The only Linear Collider that existed



Built to study the Z^0 and demonstrate linear collider feasibility

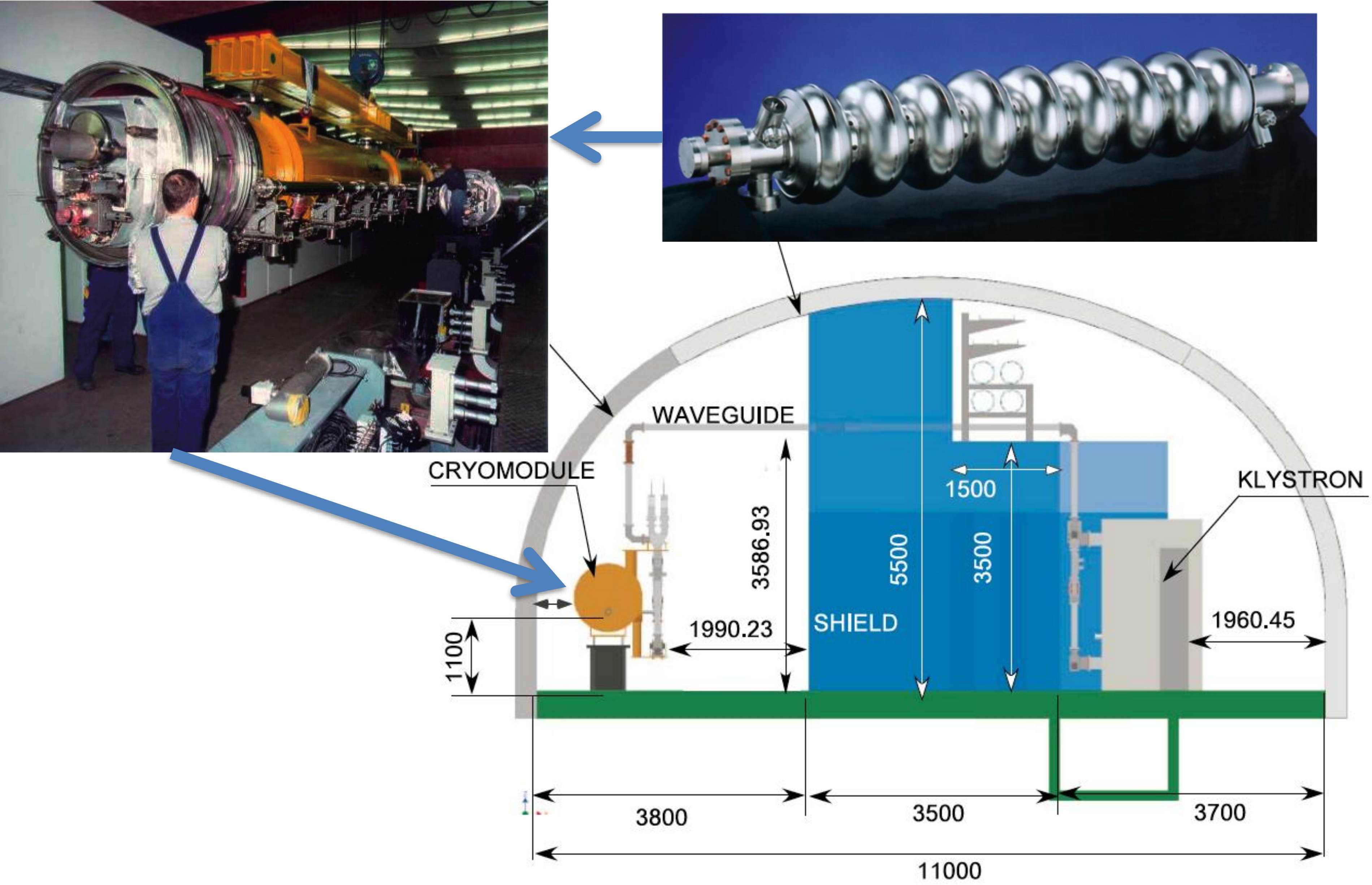
Energy = 92 GeV

Luminosity = 2e30

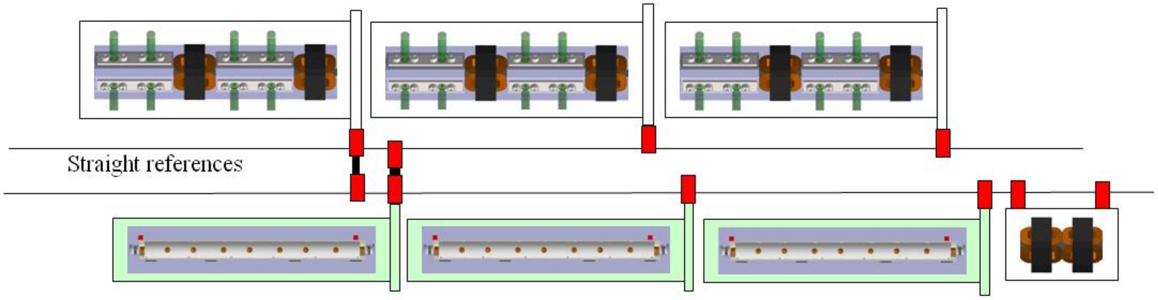
Has all the features of a 2nd gen. LC except both e+ and e- used the same linac

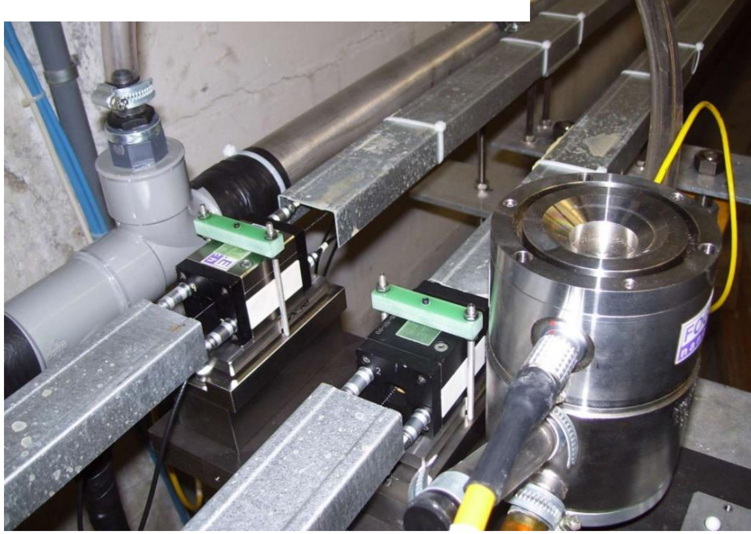
A 10% prototype!

ILC Main Linac Layout



CLIC Pre-alignment System





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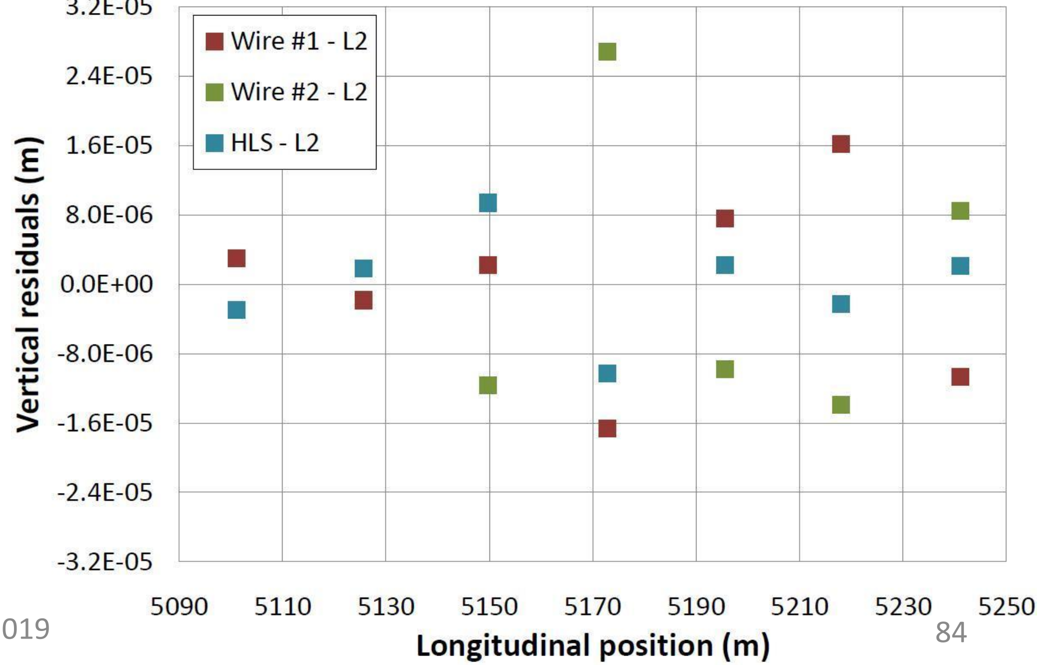
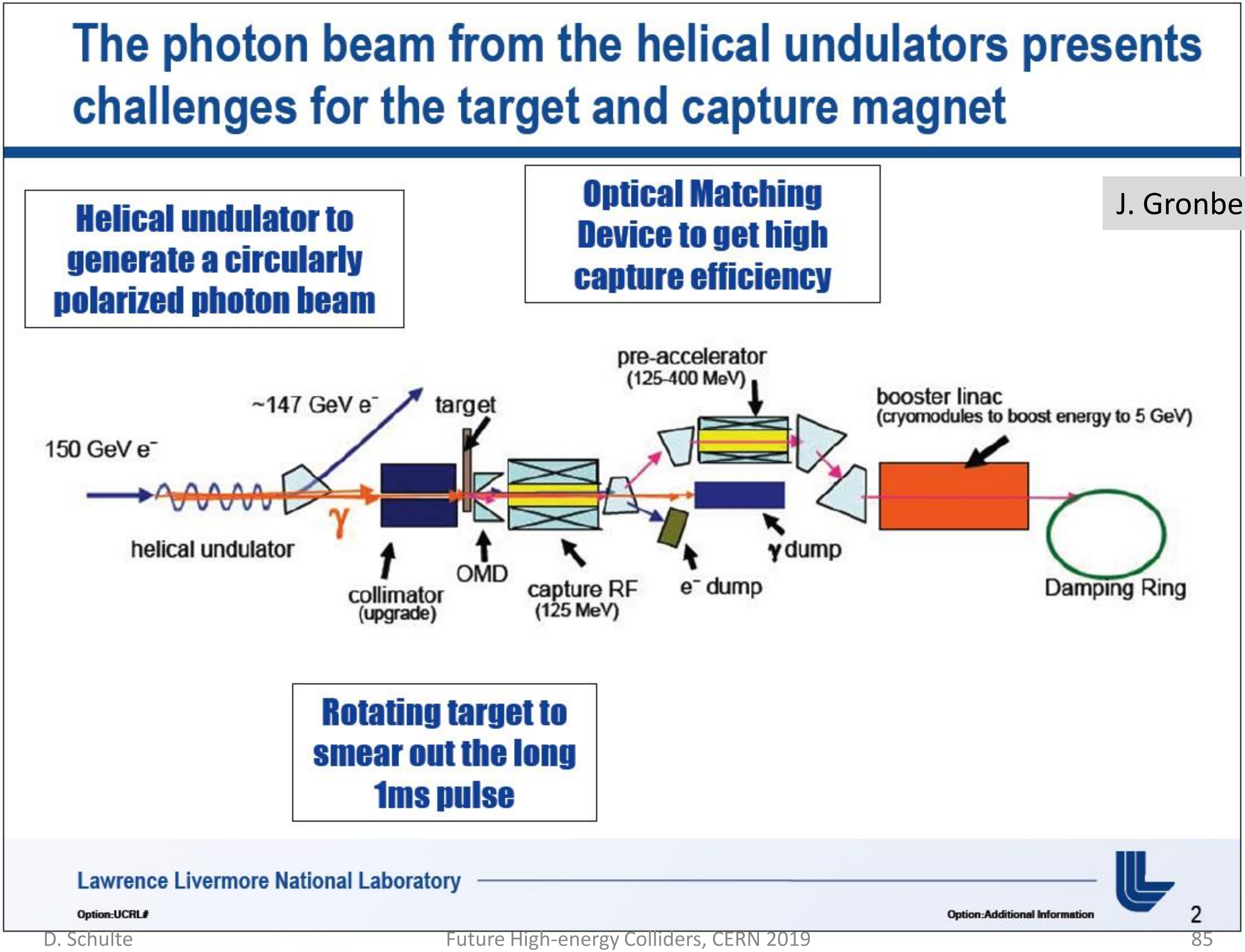




The photon beam from the helical undulators presents challenges for the target and capture magnet

J. Gronberg

Helical undulator to generate a circularly polarized photon beam

Optical Matching Device to get high capture efficiency

Rotating target to smear out the long 1ms pulse

Lawrence Livermore National Laboratory

Option:UCRL#

Option:Additional Information

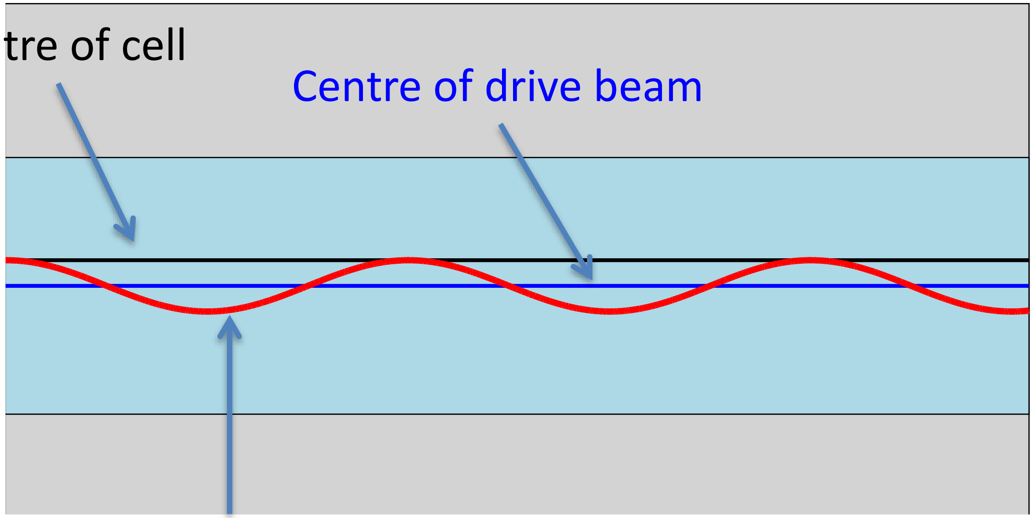
2

Example Transverse Tolerance

First order estimate for middle part of cell

Laser or drive beam centre defines centre of the focusing

$$\sigma_y \approx 42\ \mathrm{nm} \left(\frac{\mathrm{GeV}}{\mathrm{E}} \frac{10^{16}\ \mathrm{cm}^{-3}}{\mathrm{n}_0} \right)^{\frac{1}{4}} \sqrt{\frac{\epsilon_\mathrm{y}}{\mathrm{nm}}}$$



PWFA beam at 1.5TeV has σ_y=O(30 nm) for $n_0=2\mathrm{x}10^{16}\mathrm{cm}^{-3}$

$\Rightarrow$ Beam jitter stability O(1 nm)?

  $\Rightarrow$ Tough for laser/drive beam

$\Rightarrow$ Static misalignment is also critical

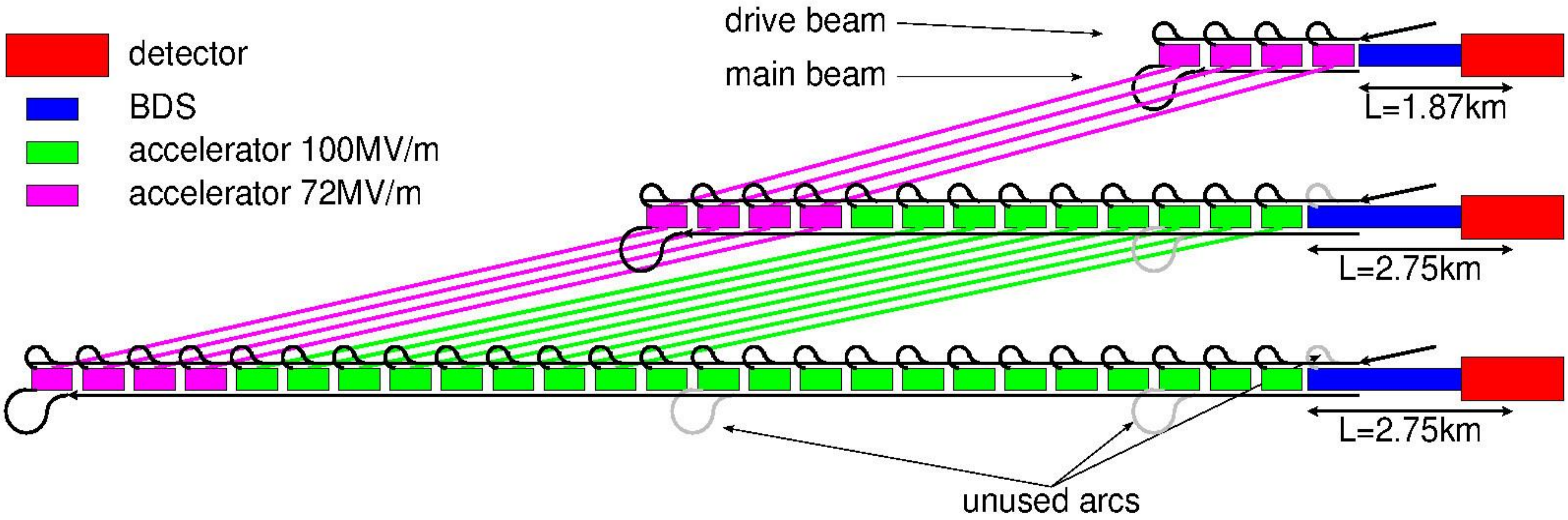
  $\Rightarrow$ but depends on beam energy spread and tuning methods

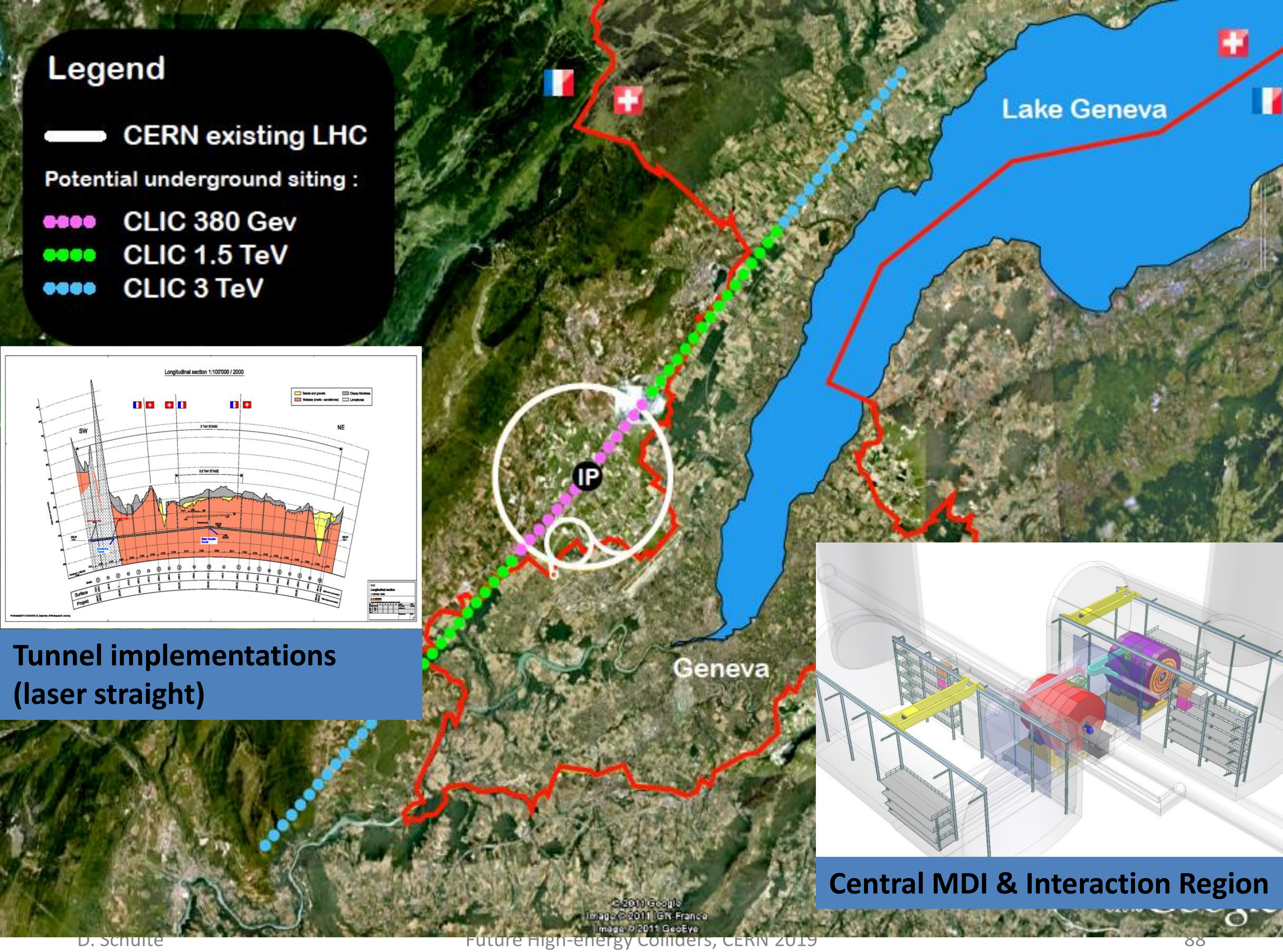
Important to understand tolerances correctly

R&D programme essential on transverse alignment and stabilisation

Note: Linear Collider Staging

- Design has been done for 500 GeV (ILC) and 3 TeV (CLIC)
  - Staging is a good option
- CLIC is planned to be constructed in stages
  - 0.38, 1.5 and 3 TeV
  - Just add more length as needed/money becomes available
- ILC could also be done in stages (250 GeV)





Tunnel implementations (laser straight)

Central MDI & Interaction Region