# Linear Colliders

## From physics requirements to today's projects

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**CERN Accelerator School**
**Trondheim, Norway, August 23, 2013**

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## Norway and particle accelerators

A great legacy!

Rolf Wideröe
Pioneer for both the betatron principle and for linear accelerators

Odd Dahl
Instrumental in the construction of the CERN Proton Synchrotron, still an important part of the CERN accelerators

Bjørn Wiik
Director of the particle accelerator lab. DESY in Hamburg, and instrumental in the development of the TESTA/ILC technology.

Kjell Johnsen
In charge of the CERN Intersecting Storage Ring and instrumental in the founding of the CERN accelerator school

New push for Norwegian accelerator research since mid-2000, with 6 University of Oslo PhD students currently studying accelerator physics.

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## Outline

**Why a linear collider?**

General considerations

CLIC

ILC

Summary

- **Change of gears** with respect to earlier lectures
- A linear collider pushes the **state of the art** of most accelerator aspects – all lectures relevant
- **A bird's eye view** on the current projects
- Will indicate some collider parameter dependences in a **simplified** manner

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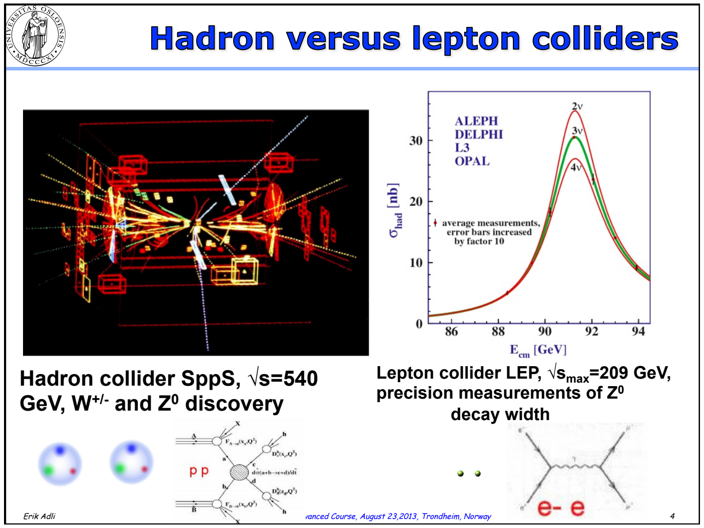
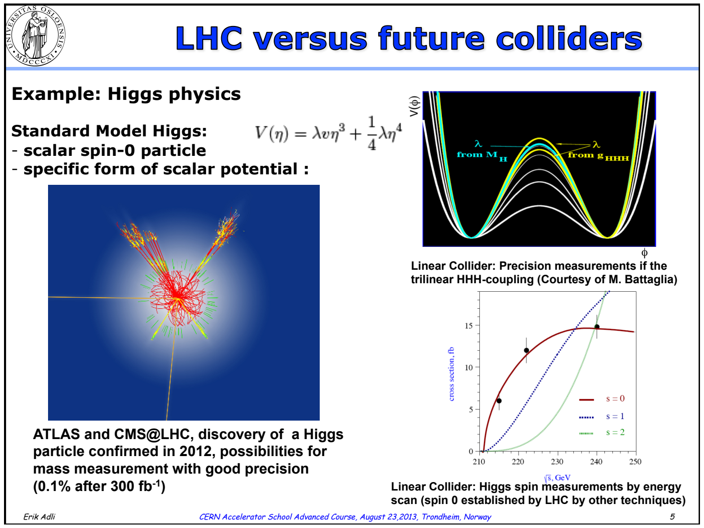


## Hadron versus lepton colliders

Hadron collider SppS, √s=540 GeV, $W^{+/-}$ and $Z^0$ discovery

Lepton collider LEP, $\sqrt{s_{max}}$=209 GeV, precision measurements of $Z^0$ decay width



### LHC versus future colliders

**Example: Higgs physics**

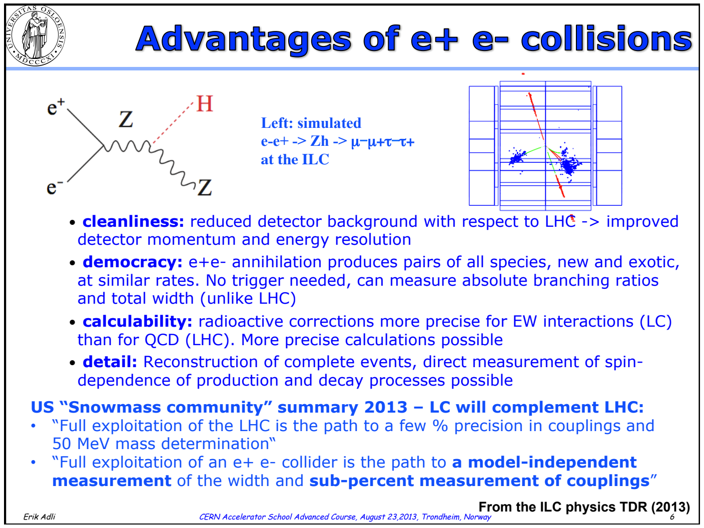
**Standard Model Higgs:**
**- scalar spin-0 particle**
**- specific form of scalar potential :**

$$V(\eta) = \lambda v \eta^3 + \frac{1}{4}\lambda\eta^4$$

**Linear Collider: Precision measurements if the trilinear HHH-coupling (Courtesy of M. Battaglia)**

**ATLAS and CMS@LHC, discovery of a Higgs particle confirmed in 2012, possibilities for mass measurement with good precision (0.1% after 300 fb$^{-1}$)**

**Linear Collider: Higgs spin measurements by energy scan (spin 0 established by LHC by other techniques)**



### Advantages of e+ e- collisions

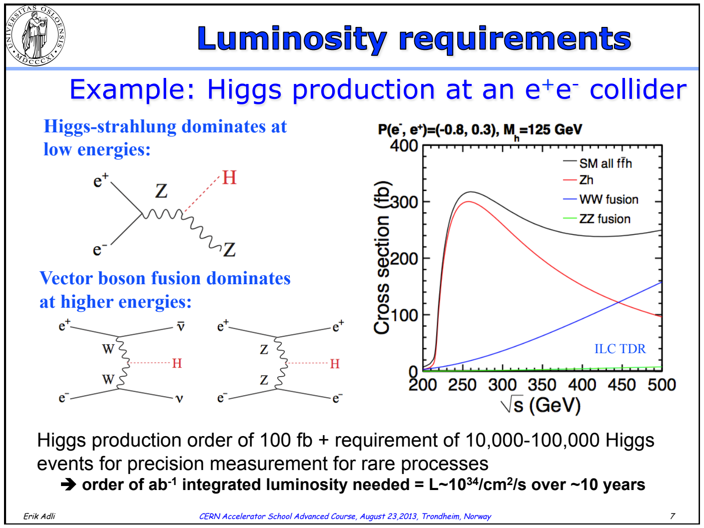
Left: simulated e-e+ -> Zh -> μ−μ+τ−τ+ at the ILC

- **cleanliness:** reduced detector background with respect to LHC -> improved detector momentum and energy resolution
- **democracy:** e+e- annihilation produces pairs of all species, new and exotic, at similar rates. No trigger needed, can measure absolute branching ratios and total width (unlike LHC)
- **calculability:** radioactive corrections more precise for EW interactions (LC) than for QCD (LHC). More precise calculations possible
- **detail:** Reconstruction of complete events, direct measurement of spin-dependence of production and decay processes possible

**US "Snowmass community" summary 2013 – LC will complement LHC:**

- "Full exploitation of the LHC is the path to a few % precision in couplings and 50 MeV mass determination"
- "Full exploitation of an e+ e- collider is the path to **a model-independent measurement** of the width and **sub-percent measurement of couplings**"

**From the ILC physics TDR (2013)**



### Luminosity requirements

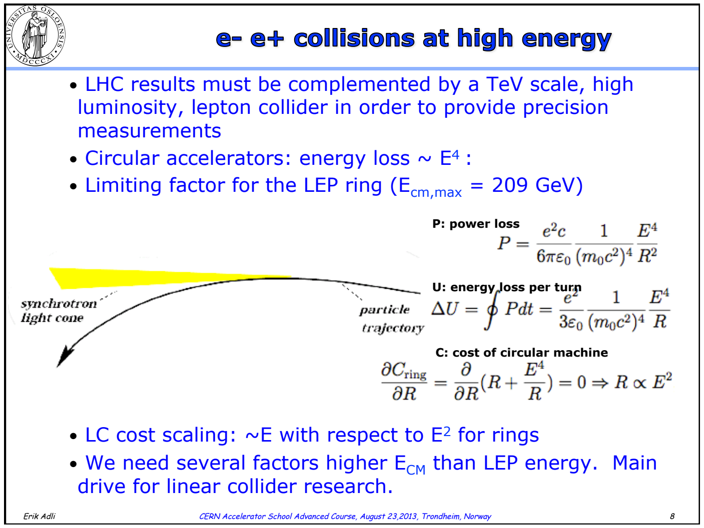
Example: Higgs production at an e$^+$e$^-$ collider

Higgs-strahlung dominates at low energies:

Vector boson fusion dominates at higher energies:

Higgs production order of 100 fb + requirement of 10,000-100,000 Higgs events for precision measurement for rare processes

**➔ order of ab$^{-1}$ integrated luminosity needed = L~10$^{34}$/cm$^2$/s over ~10 years**



### e- e+ collisions at high energy

- LHC results must be complemented by a TeV scale, high luminosity, lepton collider in order to provide precision measurements
- Circular accelerators: energy loss ~ E$^4$ :
- Limiting factor for the LEP ring (E$_{cm,max}$ = 209 GeV)

**P: power loss**

$$P = \frac{e^2 c}{6\pi\varepsilon_0}\frac{1}{(m_0c^2)^4}\frac{E^4}{R^2}$$

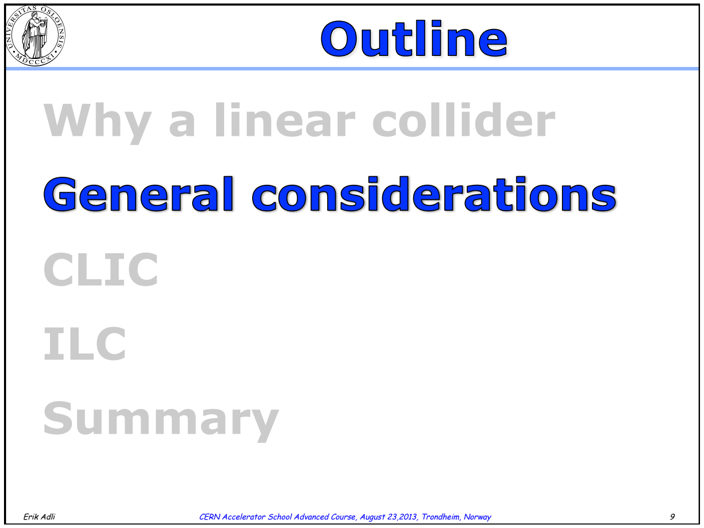
**U: energy loss per turn**

$$\Delta U = \oint P dt = \frac{e^2}{3\varepsilon_0}\frac{1}{(m_0c^2)^4}\frac{E^4}{R}$$

**C: cost of circular machine**

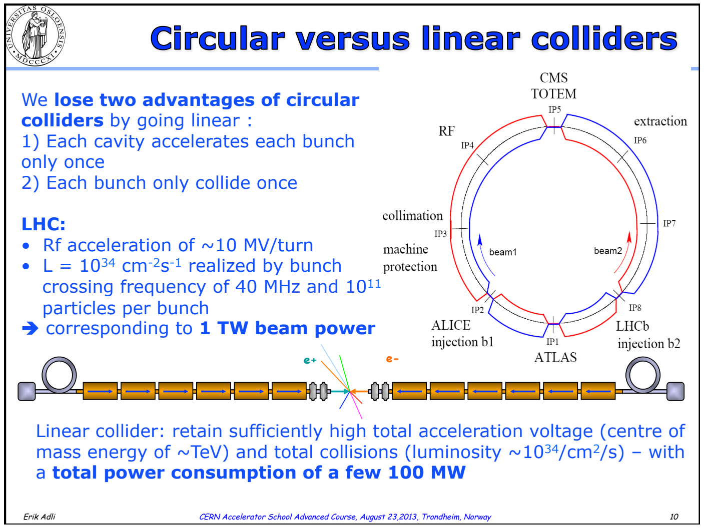
$$\frac{\partial C_{\text{ring}}}{\partial R} = \frac{\partial}{\partial R}(R + \frac{E^4}{R}) = 0 \Rightarrow R \propto E^2$$

- LC cost scaling: ~E with respect to E$^2$ for rings
- We need several factors higher E$_{CM}$ than LEP energy. Main drive for linear collider research.



# Outline

- Why a linear collider
- **General considerations**
- CLIC
- ILC
- Summary



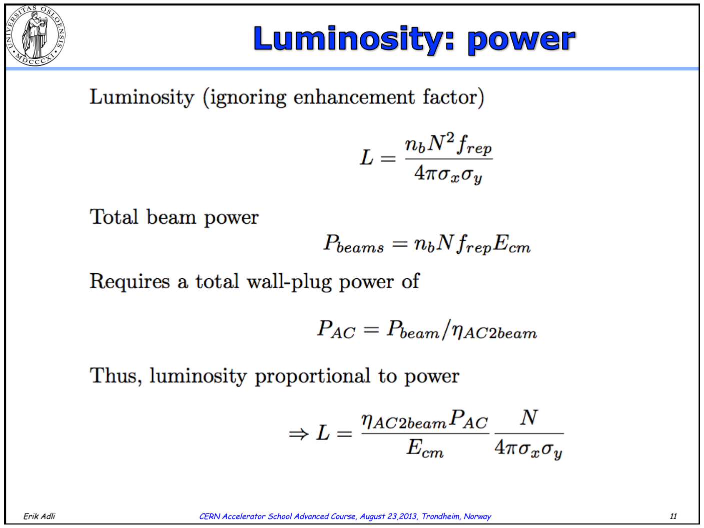
# Circular versus linear colliders

We **lose two advantages of circular colliders** by going linear :
1) Each cavity accelerates each bunch only once
2) Each bunch only collide once

**LHC:**
- Rf acceleration of ~10 MV/turn
- L = $10^{34}$ cm$^{-2}$s$^{-1}$ realized by bunch crossing frequency of 40 MHz and $10^{11}$ particles per bunch

➔ corresponding to **1 TW beam power**

Linear collider: retain sufficiently high total acceleration voltage (centre of mass energy of ~TeV) and total collisions (luminosity ~$10^{34}$/cm$^2$/s) – with a **total power consumption of a few 100 MW**



# Luminosity: power

Luminosity (ignoring enhancement factor)

$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x\sigma_y}$$

Total beam power

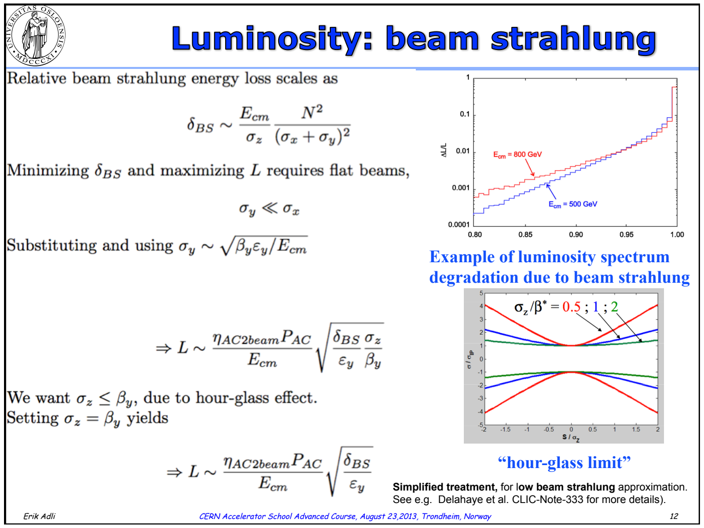
$$P_{beams} = n_b N f_{rep} E_{cm}$$

Requires a total wall-plug power of

$$P_{AC} = P_{beam}/\eta_{AC2beam}$$

Thus, luminosity proportional to power

$$\Rightarrow L = \frac{\eta_{AC2beam} P_{AC}}{E_{cm}} \frac{N}{4\pi\sigma_x\sigma_y}$$



# Luminosity: beam strahlung

Relative beam strahlung energy loss scales as

$$\delta_{BS} \sim \frac{E_{cm}}{\sigma_z} \frac{N^2}{(\sigma_x + \sigma_y)^2}$$

Minimizing $\delta_{BS}$ and maximizing $L$ requires flat beams,

$$\sigma_y \ll \sigma_x$$

Substituting and using $\sigma_y \sim \sqrt{\beta_y \varepsilon_y / E_{cm}}$

$$\Rightarrow L \sim \frac{\eta_{AC2beam} P_{AC}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_y} \frac{\sigma_z}{\beta_y}}$$

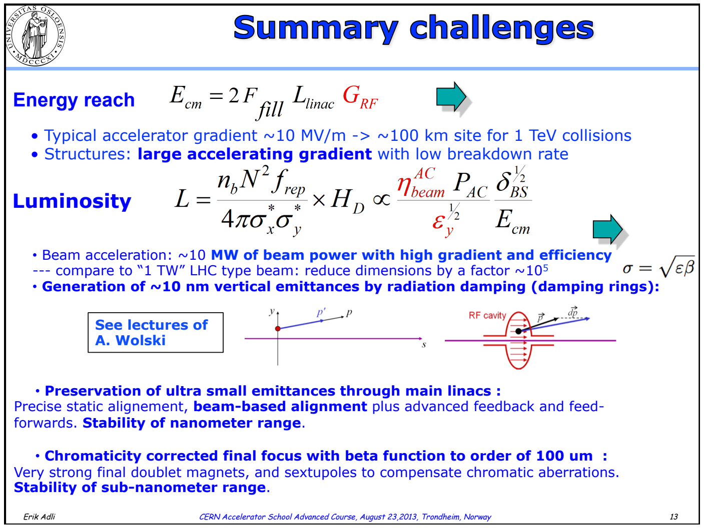
We want $\sigma_z \leq \beta_y$, due to hour-glass effect.
Setting $\sigma_z = \beta_y$ yields

$$\Rightarrow L \sim \frac{\eta_{AC2beam} P_{AC}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_y}}$$

Example of luminosity spectrum degradation due to beam strahlung

“hour-glass limit”

**Simplified treatment,** for l**ow beam strahlung** approximation. See e.g. Delahaye et al. CLIC-Note-333 for more details).



## Summary challenges

**Energy reach** $E_{cm} = 2F_{fill} L_{linac} G_{RF}$

- Typical accelerator gradient ~10 MV/m -> ~100 km site for 1 TeV collisions
- Structures: **large accelerating gradient** with low breakdown rate

**Luminosity** $L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x^*\sigma_y^*} \times H_D \propto \frac{\eta_{beam}^{AC} P_{AC}}{\varepsilon_y^{1/2}} \frac{\delta_{BS}^{1/2}}{E_{cm}}$

- Beam acceleration: ~10 **MW of beam power with high gradient and efficiency**
--- compare to “1 TW” LHC type beam: reduce dimensions by a factor ~$10^5$ $\sigma = \sqrt{\varepsilon\beta}$
- **Generation of ~10 nm vertical emittances by radiation damping (damping rings):**

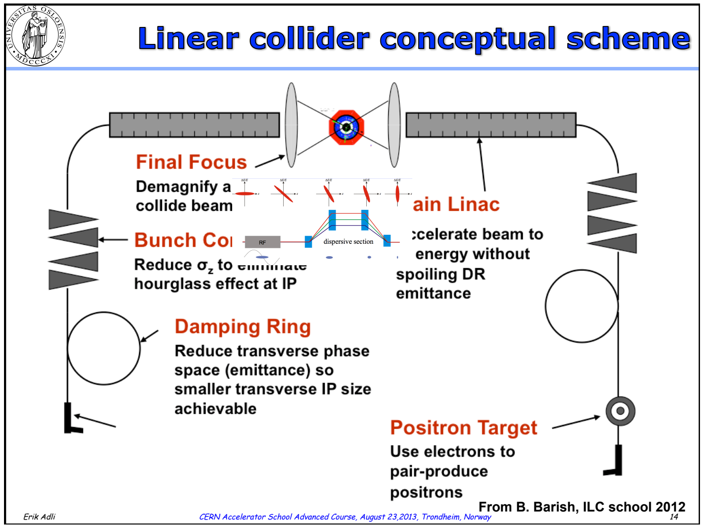
**See lectures of A. Wolski**

- **Preservation of ultra small emittances through main linacs :**

Precise static alignement, **beam-based alignment** plus advanced feedback and feed-forwards. **Stability of nanometer range**.

- **Chromaticity corrected final focus with beta function to order of 100 um :**

Very strong final doublet magnets, and sextupoles to compensate chromatic aberrations. **Stability of sub-nanometer range**.



## Linear collider conceptual scheme

**Final Focus**
Demagnify a
collide beam

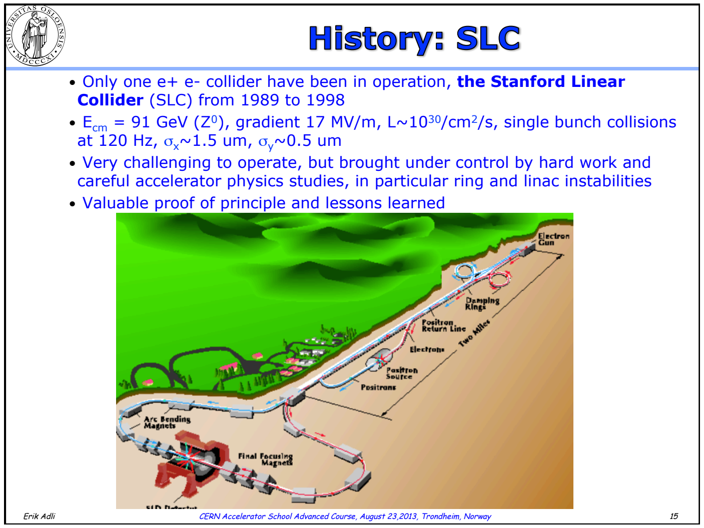
**Bunch Co**
Reduce $\sigma_z$ to
hourglass effect at IP

**ain Linac**
ccelerate beam to
energy without
spoiling DR
emittance

**Damping Ring**
Reduce transverse phase
space (emittance) so
smaller transverse IP size
achievable

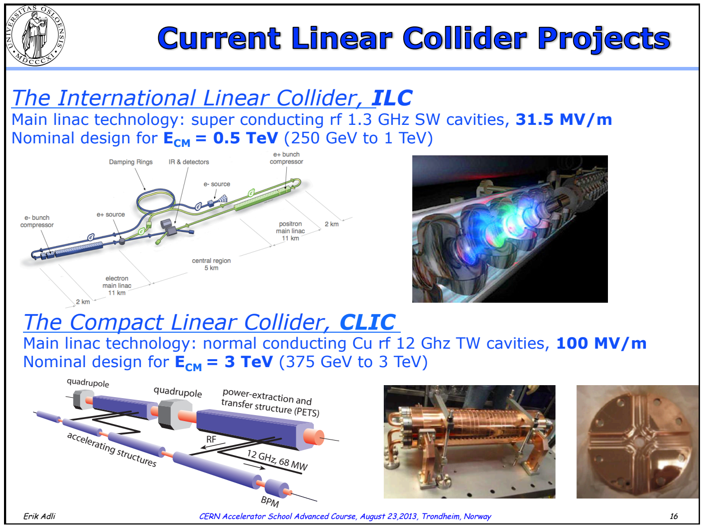
**Positron Target**
Use electrons to
pair-produce
positrons

From B. Barish, ILC school 2012



## History: SLC

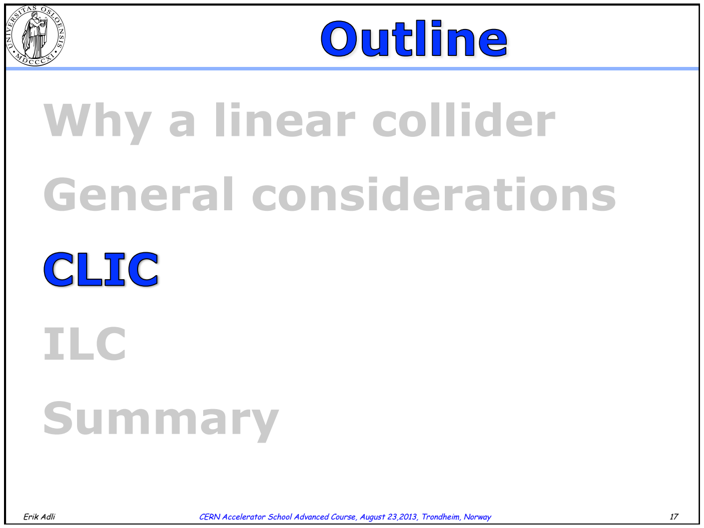
- Only one e+ e- collider have been in operation, **the Stanford Linear Collider** (SLC) from 1989 to 1998
- $E_{cm}$ = 91 GeV ($Z^0$), gradient 17 MV/m, L~$10^{30}$/cm²/s, single bunch collisions at 120 Hz, $\sigma_x$~1.5 um, $\sigma_y$~0.5 um
- Very challenging to operate, but brought under control by hard work and careful accelerator physics studies, in particular ring and linac instabilities
- Valuable proof of principle and lessons learned



## Current Linear Collider Projects

*The International Linear Collider, **ILC***
Main linac technology: super conducting rf 1.3 GHz SW cavities, **31.5 MV/m**
Nominal design for $\mathbf{E_{CM}}$ **= 0.5 TeV** (250 GeV to 1 TeV)

*The Compact Linear Collider, **CLIC***
Main linac technology: normal conducting Cu rf 12 Ghz TW cavities, **100 MV/m**
Nominal design for $\mathbf{E_{CM}}$ **= 3 TeV** (375 GeV to 3 TeV)



# Outline

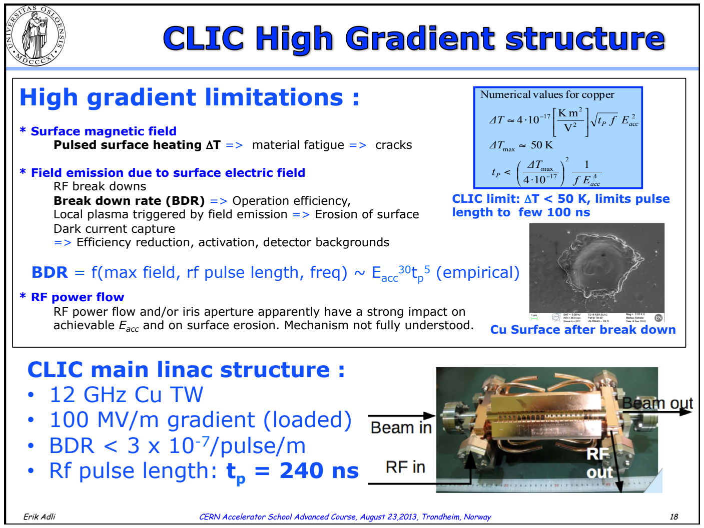
Why a linear collider

General considerations

**CLIC**

ILC

Summary



# CLIC High Gradient structure

## High gradient limitations :

*** Surface magnetic field**
**Pulsed surface heating ΔT** => material fatigue => cracks

*** Field emission due to surface electric field**
RF break downs
**Break down rate (BDR)** => Operation efficiency,
Local plasma triggered by field emission => Erosion of surface
Dark current capture
=> Efficiency reduction, activation, detector backgrounds

**BDR** = f(max field, rf pulse length, freq) ~ $E_{acc}^{30} t_p^{5}$ (empirical)

*** 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.

Numerical values for copper

$$\Delta T \approx 4 \cdot 10^{-17} \left[\frac{\mathrm{K\,m^2}}{\mathrm{V^2}}\right] \sqrt{t_P f}\, E_{acc}^2$$

$$\Delta T_{\max} \approx 50\ \mathrm{K}$$

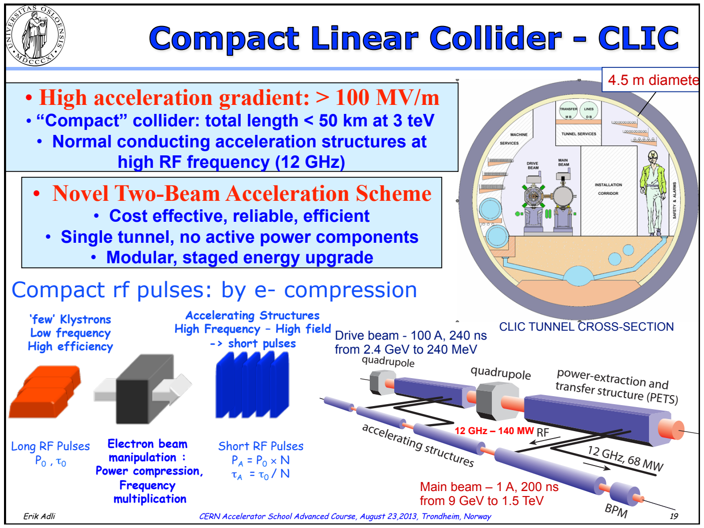
$$t_P < \left(\frac{\Delta T_{\max}}{4 \cdot 10^{-17}}\right)^2 \frac{1}{f E_{acc}^4}$$

**CLIC limit: ΔT < 50 K, limits pulse length to few 100 ns**

**Cu Surface after break down**

## CLIC main linac structure :

- 12 GHz Cu TW
- 100 MV/m gradient (loaded)
- BDR < 3 x $10^{-7}$/pulse/m
- Rf pulse length: **$t_p$ = 240 ns**



# Compact Linear Collider - CLIC

- **High acceleration gradient: > 100 MV/m**
  - "Compact" collider: total length < 50 km at 3 teV
  - Normal conducting acceleration structures at high RF frequency (12 GHz)

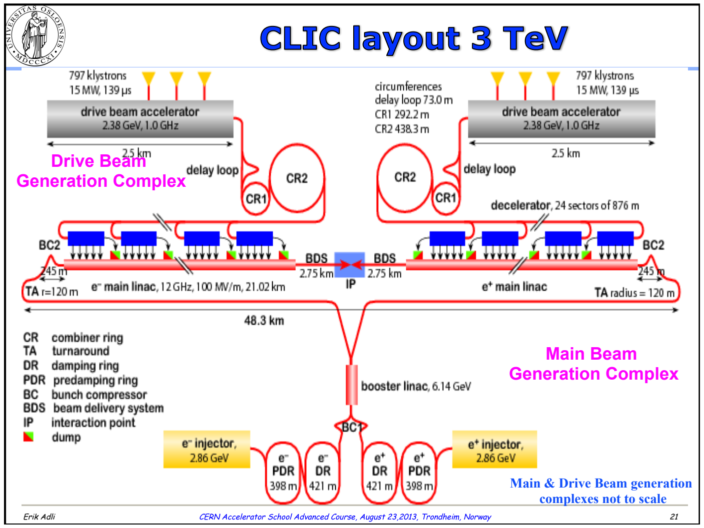
- **Novel Two-Beam Acceleration Scheme**
  - Cost effective, reliable, efficient
  - Single tunnel, no active power components
  - Modular, staged energy upgrade

Compact rf pulses: by e- compression

# The CLIC collaboration

**CLIC multi-lateral collaboration**
**48 Institutes from 25 countries**

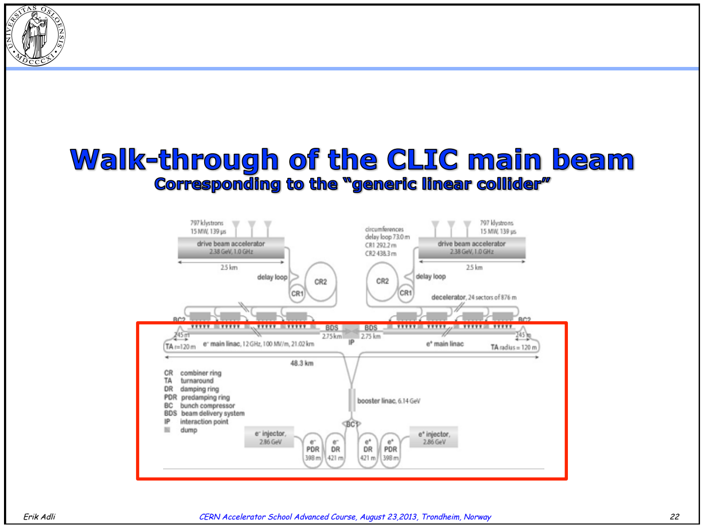
ACAS (Australia)
Aarhus University (Denmark)
Ankara University (Turkey)
Argonne National Laboratory (USA)
Athens University (Greece)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
ETHZurich (Switzerland)
FNAL (USA)
Gazi Universities (Turkey)
Helsinki Institute of Physics (Finland)
IAP (Russia)
IAP NASU (Ukraine)
IHEP (China)
INFN / LNF (Italy)
Instituto de Fisica Corpuscular (Spain)
IRFU / Saclay (France)
Jefferson Lab (USA)
John Adams Institute/Oxford (UK)
John Adams Institute/RHUL (UK)
JINR (Russia)
Karlsruhe University (Germany)
KEK (Japan)
LAL / Orsay (France)
LAPP / ESIA (France)
NIKHEF/Amsterdam (Netherland)
NCP (Pakistan)
North-West. Univ. Illinois (USA)
Patras University (Greece)
Polytech. University of Catalonia (Spain)
PSI (Switzerland)
RAL (UK)
RRCAT / Indore (India)
SLAC (USA)
Thrace University (Greece)
Tsinghua University (China)
University of Oslo (Norway)
Uppsala University (Sweden)
UCSC SCIPP (USA)



## CLIC layout 3 TeV

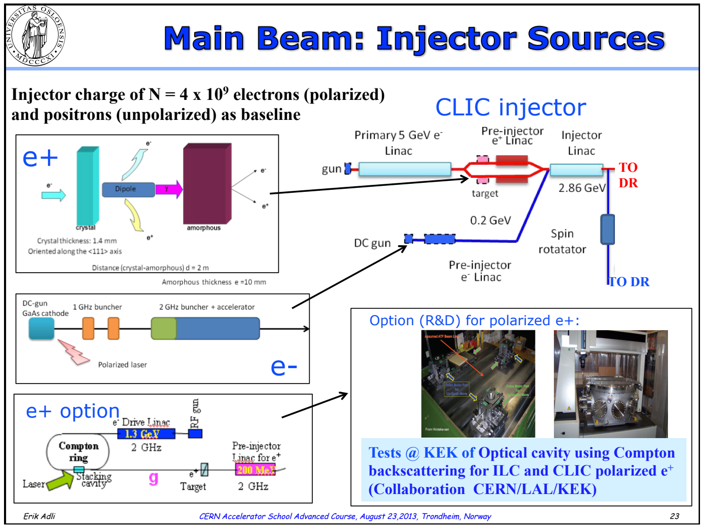
| | |
|---|---|
| CR | combiner ring |
| TA | turnaround |
| DR | damping ring |
| PDR | predamping ring |
| BC | bunch compressor |
| BDS | beam delivery system |
| IP | interaction point |
| ◩ | dump |

Main & Drive Beam generation complexes not to scale



## Walk-through of the CLIC main beam

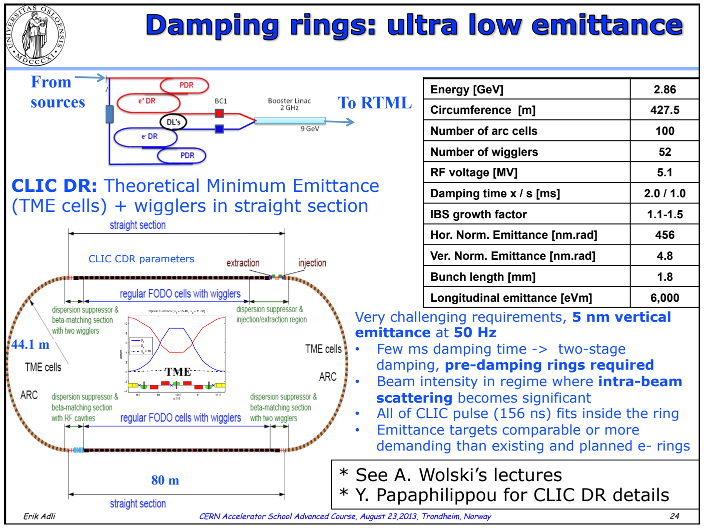
### Corresponding to the "generic linear collider"



## Main Beam: Injector Sources

**Injector charge of N = 4 x $10^9$ electrons (polarized) and positrons (unpolarized) as baseline**

Tests @ KEK of Optical cavity using Compton backscattering for ILC and CLIC polarized $e^+$ (Collaboration CERN/LAL/KEK)



## Damping rings: ultra low emittance

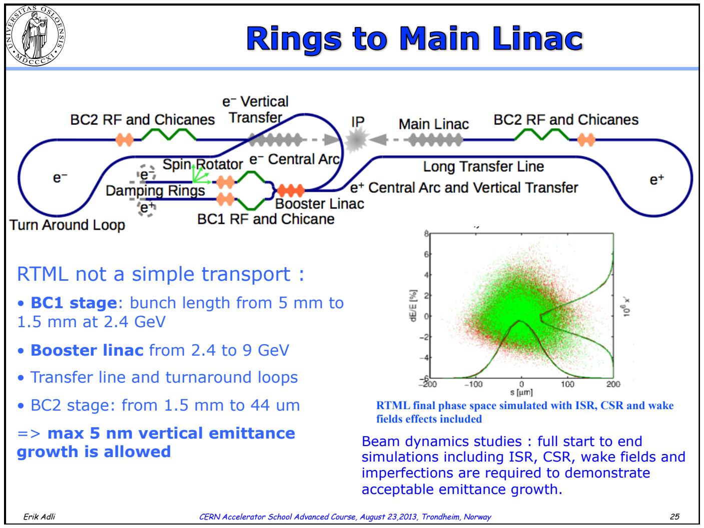
**CLIC DR:** Theoretical Minimum Emittance (TME cells) + wigglers in straight section

| | |
|---|---|
| Energy [GeV] | 2.86 |
| Circumference [m] | 427.5 |
| Number of arc cells | 100 |
| Number of wigglers | 52 |
| RF voltage [MV] | 5.1 |
| Damping time x / s [ms] | 2.0 / 1.0 |
| IBS growth factor | 1.1-1.5 |
| Hor. Norm. Emittance [nm.rad] | 456 |
| Ver. Norm. Emittance [nm.rad] | 4.8 |
| Bunch length [mm] | 1.8 |
| Longitudinal emittance [eVm] | 6,000 |

Very challenging requirements, **5 nm vertical emittance** at **50 Hz**

- Few ms damping time -> two-stage damping, **pre-damping rings required**
- Beam intensity in regime where **intra-beam scattering** becomes significant
- All of CLIC pulse (156 ns) fits inside the ring
- Emittance targets comparable or more demanding than existing and planned e- rings

* See A. Wolski's lectures
* Y. Papaphilippou for CLIC DR details



## Rings to Main Linac

RTML not a simple transport :

- **BC1 stage**: bunch length from 5 mm to 1.5 mm at 2.4 GeV
- **Booster linac** from 2.4 to 9 GeV
- Transfer line and turnaround loops
- BC2 stage: from 1.5 mm to 44 um

**=> max 5 nm vertical emittance growth is allowed**

**RTML final phase space simulated with ISR, CSR and wake fields effects included**

Beam dynamics studies : full start to end simulations including ISR, CSR, wake fields and imperfections are required to demonstrate acceptable emittance growth.

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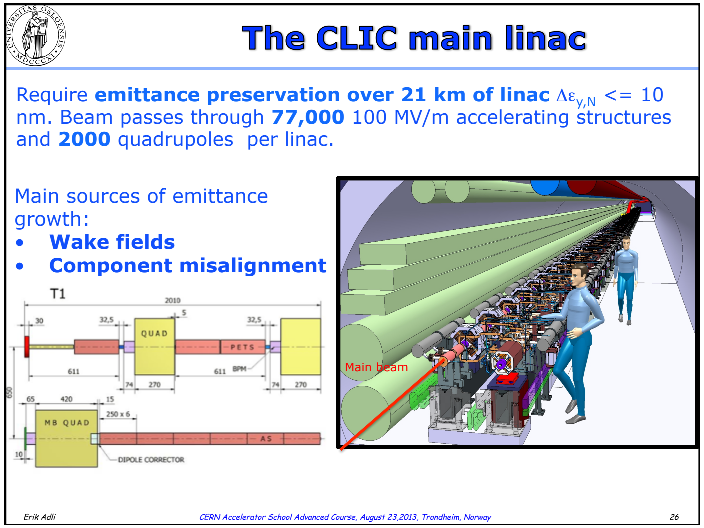

## The CLIC main linac

Require **emittance preservation over 21 km of linac** $\Delta\varepsilon_{y,N}$ <= 10 nm. Beam passes through **77,000** 100 MV/m accelerating structures and **2000** quadrupoles per linac.

Main sources of emittance growth:

- **Wake fields**
- **Component misalignment**

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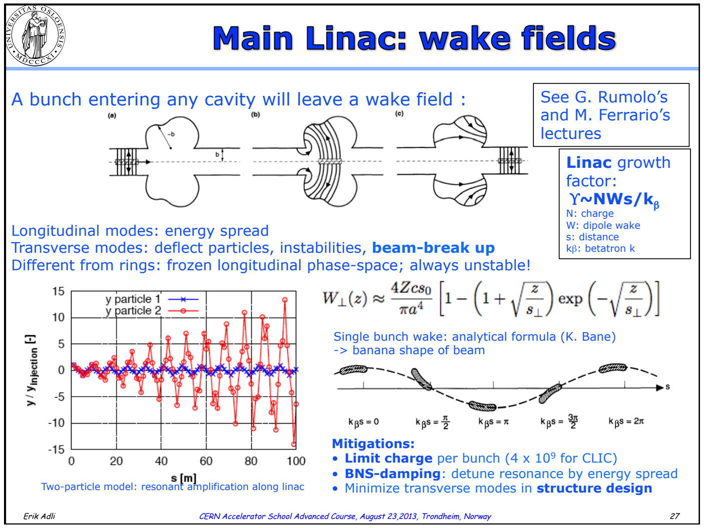

## Main Linac: wake fields

A bunch entering any cavity will leave a wake field :

See G. Rumolo's and M. Ferrario's lectures

**Linac** growth factor:
**ϒ~NWs/k$_\beta$**
N: charge
W: dipole wake
s: distance
kβ: betatron k

Longitudinal modes: energy spread
Transverse modes: deflect particles, instabilities, **beam-break up**
Different from rings: frozen longitudinal phase-space; always unstable!

Two-particle model: resonant amplification along linac

$$W_\perp(z) \approx \frac{4Zcs_0}{\pi a^4}\left[1-\left(1+\sqrt{\frac{z}{s_\perp}}\right)\exp\left(-\sqrt{\frac{z}{s_\perp}}\right)\right]$$

Single bunch wake: analytical formula (K. Bane)
-> banana shape of beam

**Mitigations:**

- **Limit charge** per bunch (4 x $10^9$ for CLIC)
- **BNS-damping**: detune resonance by energy spread
- Minimize transverse modes in **structure design**

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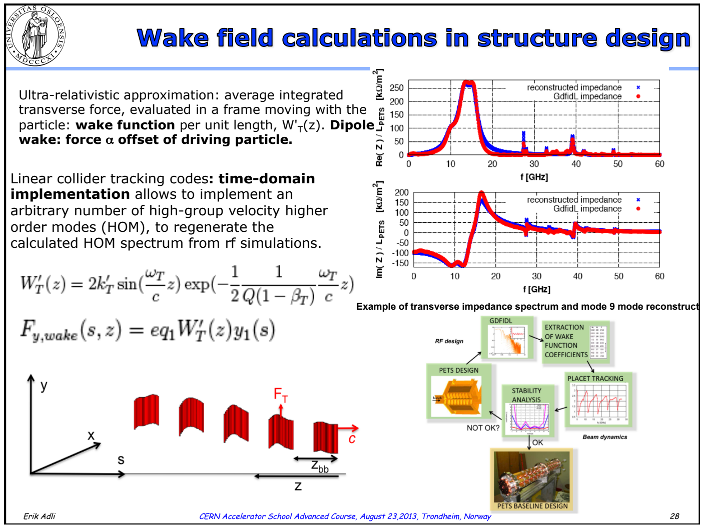

## Wake field calculations in structure design

Ultra-relativistic approximation: average integrated transverse force, evaluated in a frame moving with the particle: **wake function** per unit length, W'$_T$(z). **Dipole wake: force α offset of driving particle.**

Linear collider tracking codes**: time-domain implementation** allows to implement an arbitrary number of high-group velocity higher order modes (HOM), to regenerate the calculated HOM spectrum from rf simulations.

$$W'_T(z) = 2k'_T \sin(\frac{\omega_T}{c}z)\exp(-\frac{1}{2}\frac{1}{Q(1-\beta_T)}\frac{\omega_T}{c}z)$$

$$F_{y,wake}(s,z) = eq_1 W'_T(z) y_1(s)$$

**Example of transverse impedance spectrum and mode 9 mode reconstruct**

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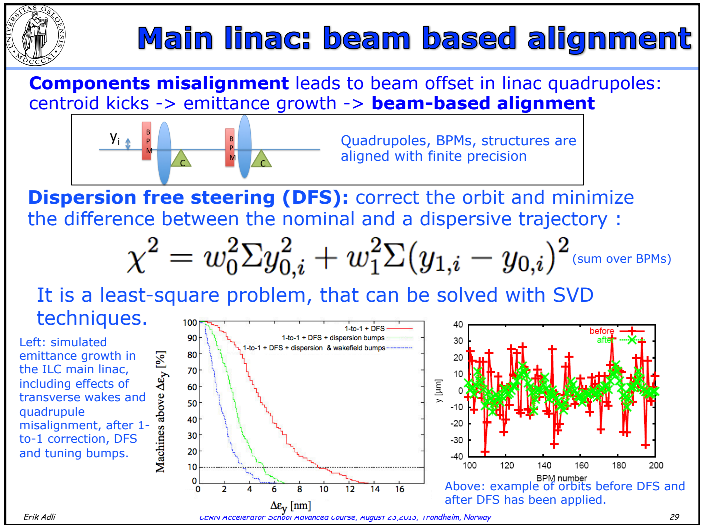


## Main linac: beam based alignment

**Components misalignment** leads to beam offset in linac quadrupoles: centroid kicks -> emittance growth -> **beam-based alignment**

Quadrupoles, BPMs, structures are aligned with finite precision

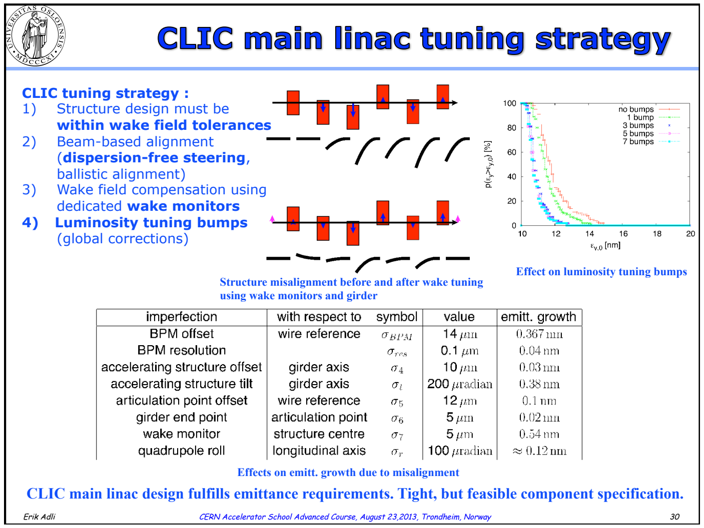
**Dispersion free steering (DFS):** correct the orbit and minimize the difference between the nominal and a dispersive trajectory :

$$\chi^2 = w_0^2 \Sigma y_{0,i}^2 + w_1^2 \Sigma (y_{1,i} - y_{0,i})^2$$ (sum over BPMs)

It is a least-square problem, that can be solved with SVD techniques.

Left: simulated emittance growth in the ILC main linac, including effects of transverse wakes and quadrupule misalignment, after 1-to-1 correction, DFS and tuning bumps.

Above: example of orbits before DFS and after DFS has been applied.



## CLIC main linac tuning strategy

**CLIC tuning strategy :**

1) Structure design must be **within wake field tolerances**
2) Beam-based alignment (**dispersion-free steering**, ballistic alignment)
3) Wake field compensation using dedicated **wake monitors**
4) **Luminosity tuning bumps** (global corrections)

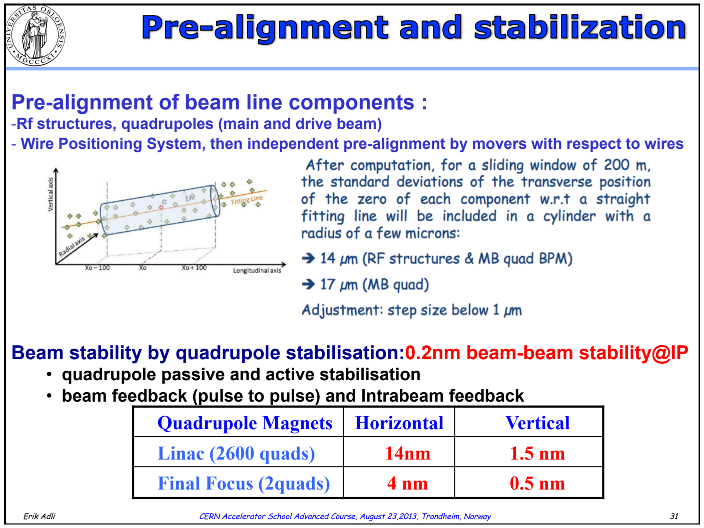
**Structure misalignment before and after wake tuning using wake monitors and girder**

**Effect on luminosity tuning bumps**

| imperfection | with respect to | symbol | value | emitt. growth |
|---|---|---|---|---|
| BPM offset | wire reference | $\sigma_{BPM}$ | 14 $\mu$m | 0.367 nm |
| BPM resolution | | $\sigma_{res}$ | 0.1 $\mu$m | 0.04 nm |
| accelerating structure offset | girder axis | $\sigma_4$ | 10 $\mu$m | 0.03 nm |
| accelerating structure tilt | girder axis | $\sigma_t$ | 200 $\mu$radian | 0.38 nm |
| articulation point offset | wire reference | $\sigma_5$ | 12 $\mu$m | 0.1 nm |
| girder end point | articulation point | $\sigma_6$ | 5 $\mu$m | 0.02 nm |
| wake monitor | structure centre | $\sigma_7$ | 5 $\mu$m | 0.54 nm |
| quadrupole roll | longitudinal axis | $\sigma_r$ | 100 $\mu$radian | $\approx$ 0.12 nm |

**Effects on emitt. growth due to misalignment**

**CLIC main linac design fulfills emittance requirements. Tight, but feasible component specification.**



## Pre-alignment and stabilization

**Pre-alignment of beam line components :**

**-Rf structures, quadrupoles (main and drive beam)**

**- Wire Positioning System, then independent pre-alignment by movers with respect to wires**

After computation, for a sliding window of 200 m, the standard deviations of the transverse position of the zero of each component w.r.t a straight fitting line will be included in a cylinder with a radius of a few microns:

➔ 14 μm (RF structures & MB quad BPM)

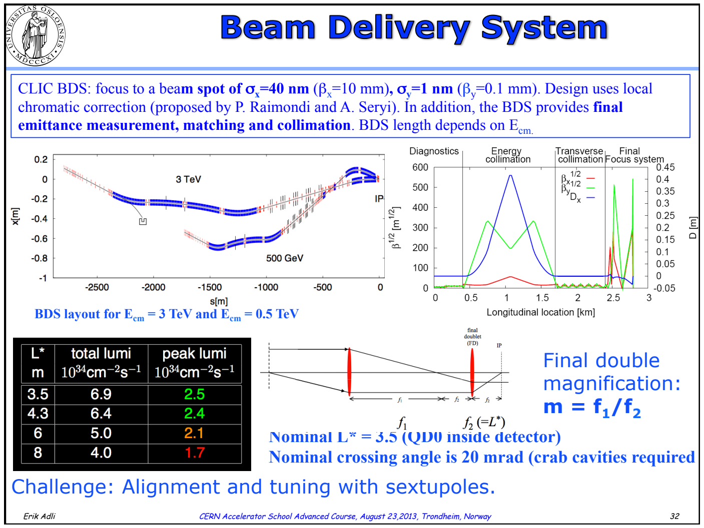
➔ 17 μm (MB quad)

Adjustment: step size below 1 μm

**Beam stability by quadrupole stabilisation:0.2nm beam-beam stability@IP**

- **quadrupole passive and active stabilisation**
- **beam feedback (pulse to pulse) and Intrabeam feedback**

| Quadrupole Magnets | Horizontal | Vertical |
|---|---|---|
| Linac (2600 quads) | 14nm | 1.5 nm |
| Final Focus (2quads) | 4 nm | 0.5 nm |



## Beam Delivery System

CLIC BDS: focus to a bea**m spot of $\sigma_x$=40 nm** ($\beta_x$=10 mm)**, $\sigma_y$=1 nm** ($\beta_y$=0.1 mm). Design uses local chromatic correction (proposed by P. Raimondi and A. Seryi). In addition, the BDS provides **final emittance measurement, matching and collimation**. BDS length depends on $E_{cm.}$

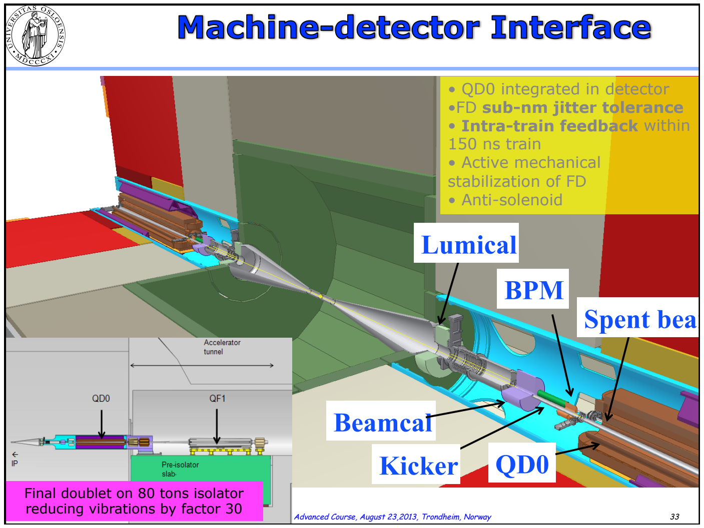
**BDS layout for $E_{cm}$ = 3 TeV and $E_{cm}$ = 0.5 TeV**

| L* m | total lumi $10^{34}$cm$^{-2}$s$^{-1}$ | peak lumi $10^{34}$cm$^{-2}$s$^{-1}$ |
|---|---|---|
| 3.5 | 6.9 | 2.5 |
| 4.3 | 6.4 | 2.4 |
| 6 | 5.0 | 2.1 |
| 8 | 4.0 | 1.7 |

Final double magnification:
**m = $f_1/f_2$**

**Nominal L* = 3.5 (QD0 inside detector)**
**Nominal crossing angle is 20 mrad (crab cavities required**

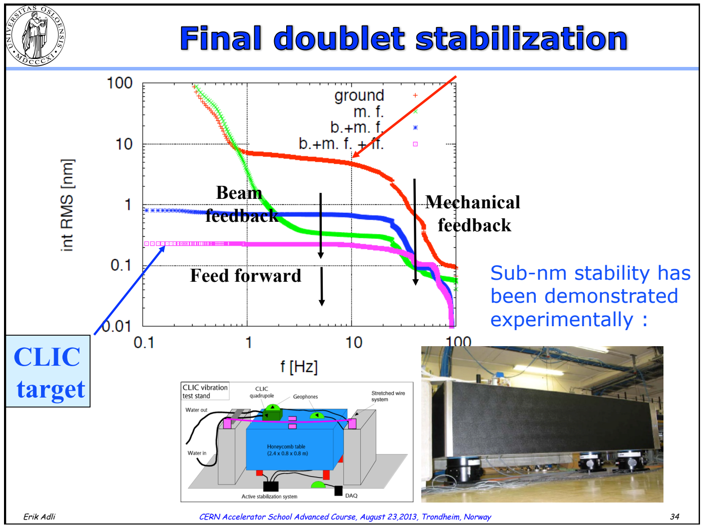
Challenge: Alignment and tuning with sextupoles.



## Machine-detector Interface

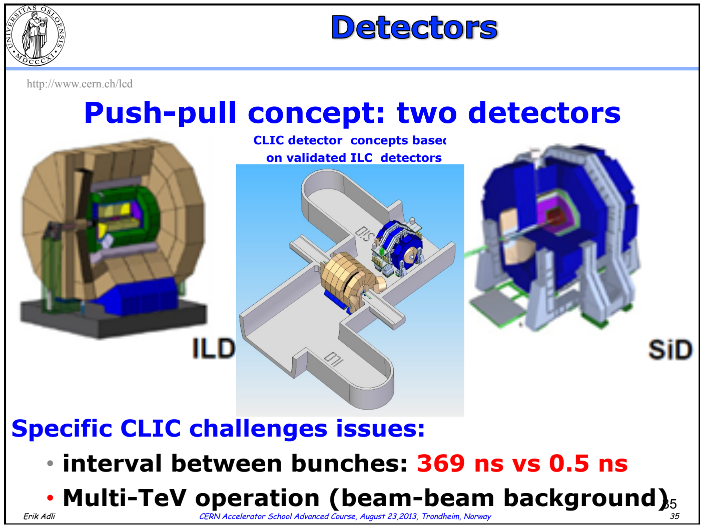
- QD0 integrated in detector
- FD **sub-nm jitter tolerance**
- **Intra-train feedback** within 150 ns train
- Active mechanical stabilization of FD
- Anti-solenoid

Final doublet on 80 tons isolator reducing vibrations by factor 30



## Final doublet stabilization

Sub-nm stability has been demonstrated experimentally :



## Detectors

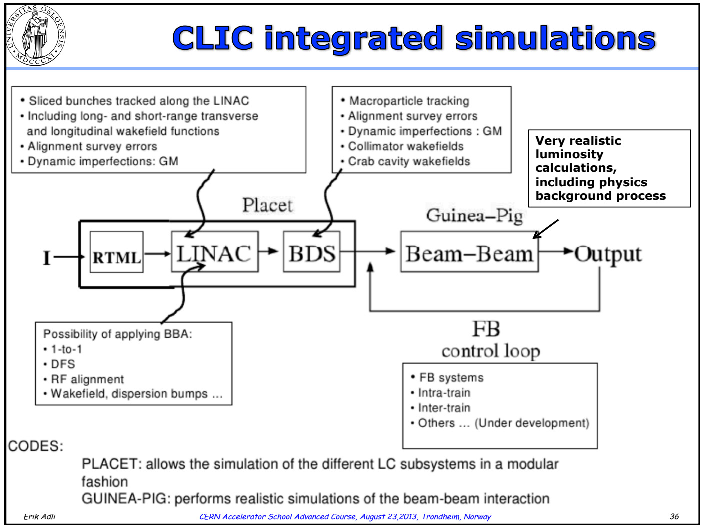
http://www.cern.ch/lcd

### Push-pull concept: two detectors

CLIC detector concepts based on validated ILC detectors

**Specific CLIC challenges issues:**

- **interval between bunches: 369 ns vs 0.5 ns**
- **Multi-TeV operation (beam-beam background)**



## CLIC integrated simulations

- Sliced bunches tracked along the LINAC
- Including long- and short-range transverse and longitudinal wakefield functions
- Alignment survey errors
- Dynamic imperfections: GM

- Macroparticle tracking
- Alignment survey errors
- Dynamic imperfections : GM
- Collimator wakefields
- Crab cavity wakefields

**Very realistic luminosity calculations, including physics background process**

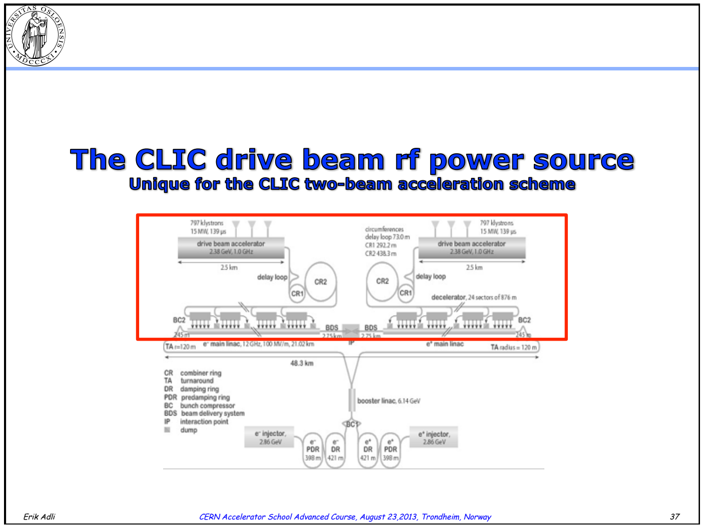
Possibility of applying BBA:
- 1-to-1
- DFS
- RF alignment
- Wakefield, dispersion bumps …

- FB systems
- Intra-train
- Inter-train
- Others … (Under development)

CODES:

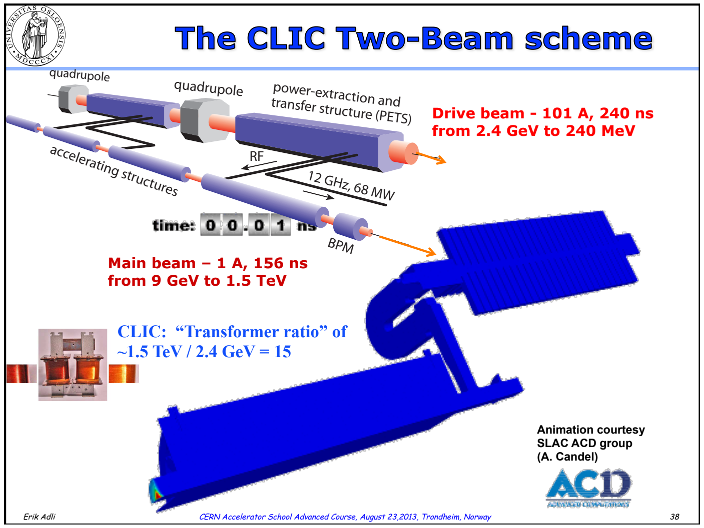
PLACET: allows the simulation of the different LC subsystems in a modular fashion

GUINEA-PIG: performs realistic simulations of the beam-beam interaction



## The CLIC drive beam rf power source

**Unique for the CLIC two-beam acceleration scheme**



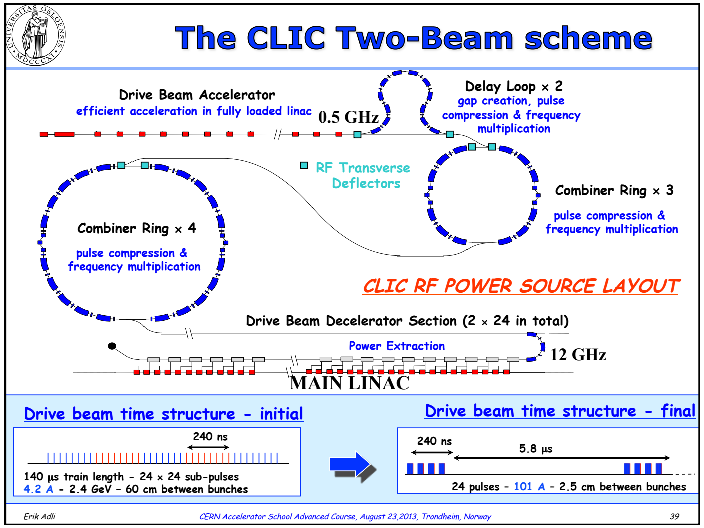
## The CLIC Two-Beam scheme

**Drive beam - 101 A, 240 ns from 2.4 GeV to 240 MeV**

**Main beam – 1 A, 156 ns from 9 GeV to 1.5 TeV**

**CLIC: "Transformer ratio" of ~1.5 TeV / 2.4 GeV = 15**

**Animation courtesy SLAC ACD group (A. Candel)**



## The CLIC Two-Beam scheme

Drive Beam Accelerator
efficient acceleration in fully loaded linac

0.5 GHz

Delay Loop × 2
gap creation, pulse compression & frequency multiplication

RF Transverse Deflectors

Combiner Ring × 3
pulse compression & frequency multiplication

Combiner Ring × 4
pulse compression & frequency multiplication

*CLIC RF POWER SOURCE LAYOUT*

Drive Beam Decelerator Section (2 × 24 in total)

Power Extraction

12 GHz

MAIN LINAC

**Drive beam time structure - initial**

240 ns

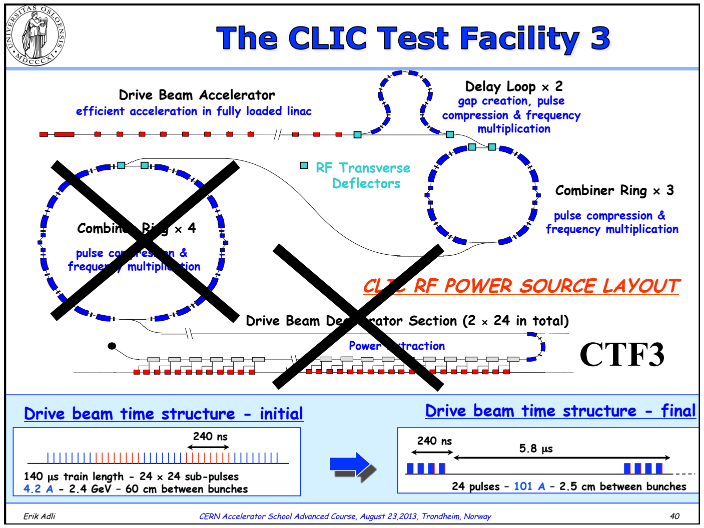
140 μs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

**Drive beam time structure - final**

240 ns

5.8 μs

24 pulses – 101 A – 2.5 cm between bunches



## The CLIC Test Facility 3

Drive Beam Accelerator
efficient acceleration in fully loaded linac

Delay Loop × 2
gap creation, pulse compression & frequency multiplication

RF Transverse Deflectors

Combiner Ring × 3
pulse compression & frequency multiplication

~~Combiner Ring × 4
pulse compression & frequency multiplication~~

~~*CLIC RF POWER SOURCE LAYOUT*~~

~~Drive Beam Decelerator Section (2 × 24 in total)~~

~~Power Extraction~~

**CTF3**

**Drive beam time structure - initial**

240 ns

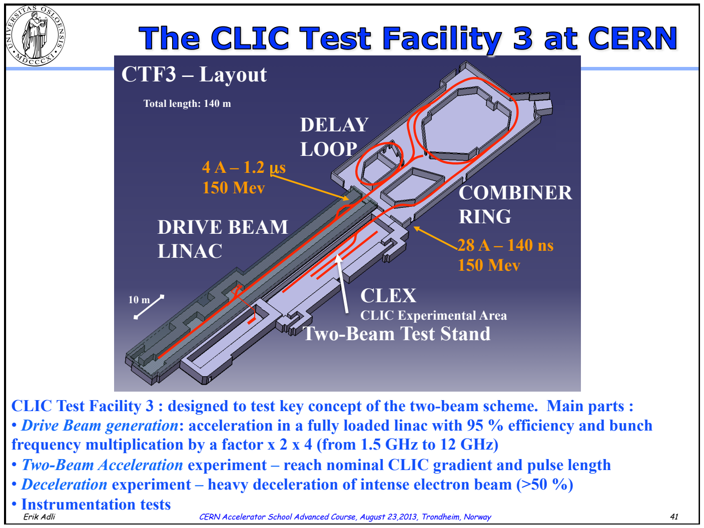
140 μs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

**Drive beam time structure - final**

240 ns

5.8 μs

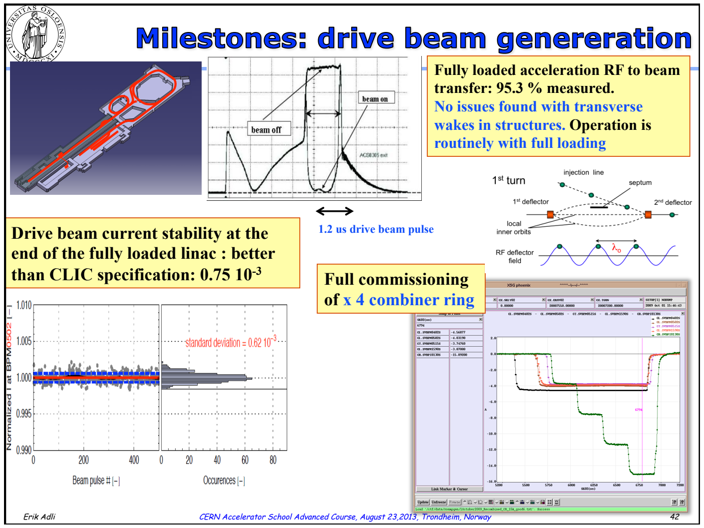
24 pulses – 101 A – 2.5 cm between bunches



## The CLIC Test Facility 3 at CERN

CLIC Test Facility 3 : designed to test key concept of the two-beam scheme. Main parts :

- *Drive Beam generation*: acceleration in a fully loaded linac with 95 % efficiency and bunch frequency multiplication by a factor x 2 x 4 (from 1.5 GHz to 12 GHz)
- *Two-Beam Acceleration* experiment – reach nominal CLIC gradient and pulse length
- *Deceleration* experiment – heavy deceleration of intense electron beam (>50 %)
- Instrumentation tests



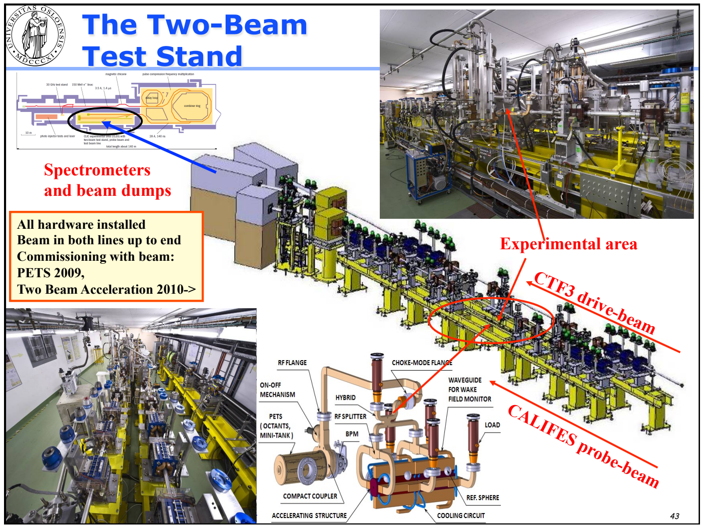
## Milestones: drive beam genereration

Fully loaded acceleration RF to beam transfer: 95.3 % measured. No issues found with transverse wakes in structures. Operation is routinely with full loading

1.2 us drive beam pulse

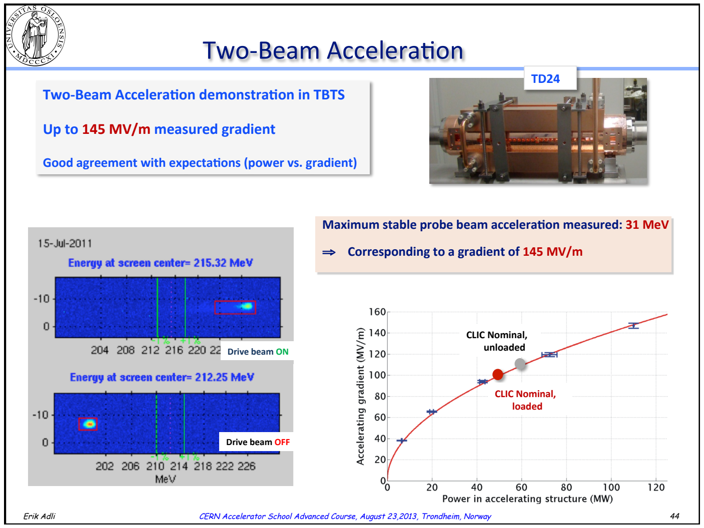
Drive beam current stability at the end of the fully loaded linac : better than CLIC specification: $0.75\ 10^{-3}$

Full commissioning of x 4 combiner ring



## The Two-Beam Test Stand

All hardware installed
Beam in both lines up to end
Commissioning with beam:
PETS 2009,
Two Beam Acceleration 2010->



## Two-Beam Acceleration

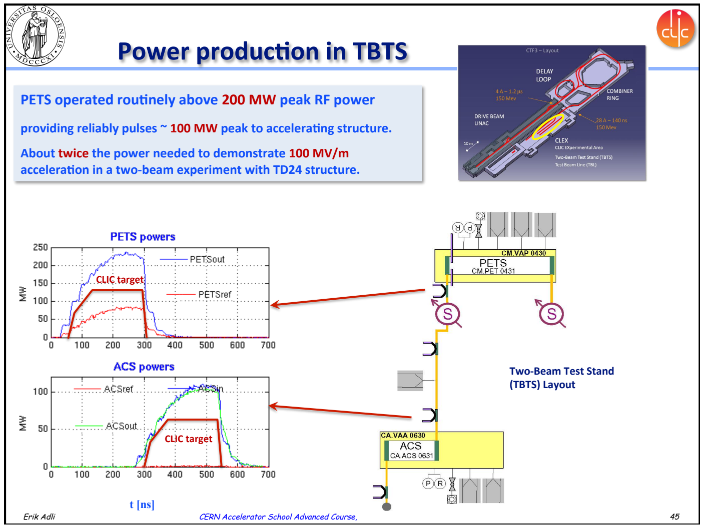
Two-Beam Acceleration demonstration in TBTS

Up to 145 MV/m measured gradient

Good agreement with expectations (power vs. gradient)

Maximum stable probe beam acceleration measured: 31 MeV

⇒ Corresponding to a gradient of 145 MV/m



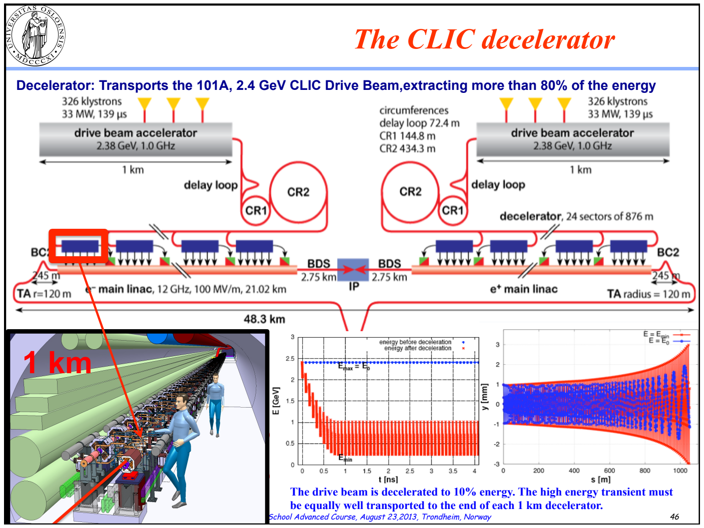
## Power production in TBTS

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

**providing reliably pulses ~ 100 MW peak to accelerating structure.**

**About twice the power needed to demonstrate 100 MV/m acceleration in a two-beam experiment with TD24 structure.**

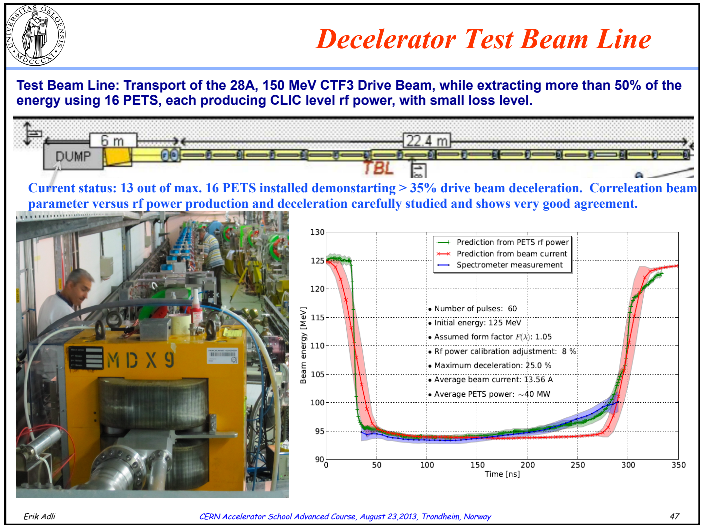
**Two-Beam Test Stand (TBTS) Layout**



## The CLIC decelerator

**Decelerator: Transports the 101A, 2.4 GeV CLIC Drive Beam,extracting more than 80% of the energy**

The drive beam is decelerated to 10% energy. The high energy transient must be equally well transported to the end of each 1 km decelerator.

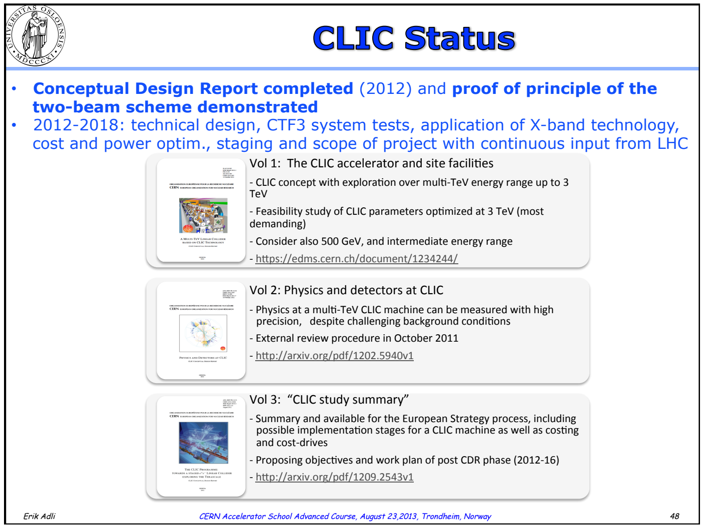


## Decelerator Test Beam Line

**Test Beam Line: Transport of the 28A, 150 MeV CTF3 Drive Beam, while extracting more than 50% of the energy using 16 PETS, each producing CLIC level rf power, with small loss level.**

Current status: 13 out of max. 16 PETS installed demonstarting > 35% drive beam deceleration. Correleation beam parameter versus rf power production and deceleration carefully studied and shows very good agreement.

- Number of pulses: 60
- Initial energy: 125 MeV
- Assumed form factor $F(\lambda)$: 1.05
- Rf power calibration adjustment: 8 %
- Maximum deceleration: 25.0 %
- Average beam current: 13.56 A
- Average PETS power: ~40 MW



## CLIC Status

- **Conceptual Design Report completed** (2012) and **proof of principle of the two-beam scheme demonstrated**
- 2012-2018: technical design, CTF3 system tests, application of X-band technology, cost and power optim., staging and scope of project with continuous input from LHC

Vol 1: The CLIC accelerator and site facilities

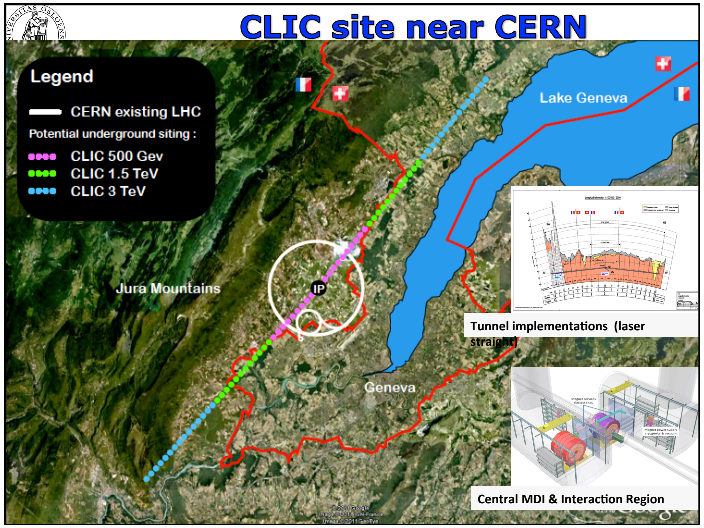
- CLIC concept with exploration over multi-TeV energy range up to 3 TeV
- Feasibility study of CLIC parameters optimized at 3 TeV (most demanding)
- Consider also 500 GeV, and intermediate energy range
- https://edms.cern.ch/document/1234244/

Vol 2: Physics and detectors at CLIC

- Physics at a multi-TeV CLIC machine can be measured with high precision, despite challenging background conditions
- External review procedure in October 2011
- http://arxiv.org/pdf/1202.5940v1

Vol 3: "CLIC study summary"

- Summary and available for the European Strategy process, including possible implementation stages for a CLIC machine as well as costing and cost-drives
- Proposing objectives and work plan of post CDR phase (2012-16)
- http://arxiv.org/pdf/1209.2543v1



## CLIC site near CERN

Legend

CERN existing LHC

Potential underground siting :

- ●●●● CLIC 500 Gev
- ●●●● CLIC 1.5 TeV
- ●●●● CLIC 3 TeV

Tunnel implementations (laser straight)

Central MDI & Interaction Region

## Outline

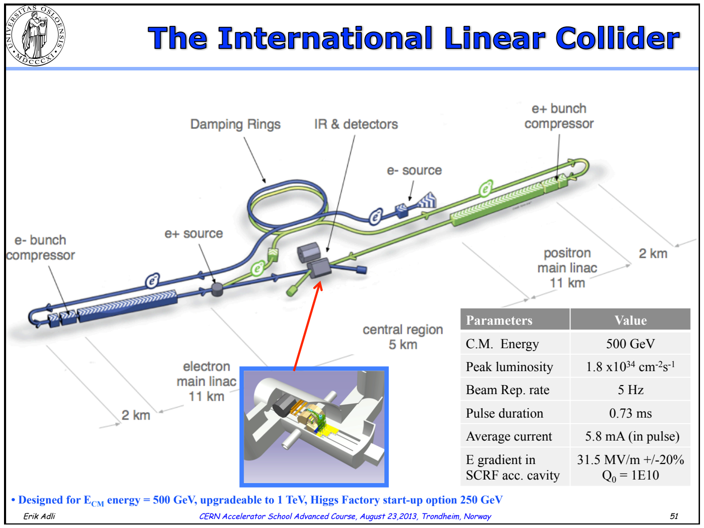
Why a linear collider

General considerations

CLIC

**ILC**

Summary



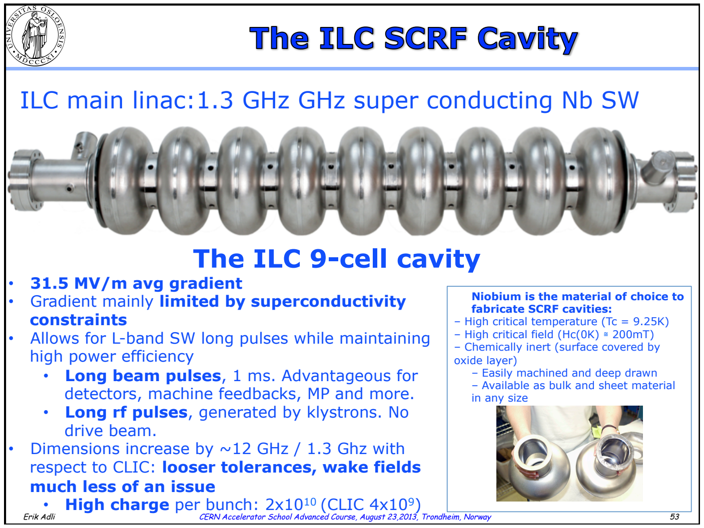
## The International Linear Collider

| Parameters | Value |
|---|---|
| C.M. Energy | 500 GeV |
| Peak luminosity | 1.8 x$10^{34}$ cm$^{-2}$s$^{-1}$ |
| Beam Rep. rate | 5 Hz |
| Pulse duration | 0.73 ms |
| Average current | 5.8 mA (in pulse) |
| E gradient in SCRF acc. cavity | 31.5 MV/m +/-20%<br>$Q_0$ = 1E10 |

- Designed for $E_{CM}$ energy = 500 GeV, upgradeable to 1 TeV, Higgs Factory start-up option 250 GeV

## ILC collaboration

Truly global, with Americas, Europe and Asia as equal partners – no "home institute"



# The ILC SCRF Cavity

ILC main linac:1.3 GHz GHz super conducting Nb SW

**The ILC 9-cell cavity**

- **31.5 MV/m avg gradient**
- Gradient mainly **limited by superconductivity constraints**
- Allows for L-band SW long pulses while maintaining high power efficiency
  - **Long beam pulses**, 1 ms. Advantageous for detectors, machine feedbacks, MP and more.
  - **Long rf pulses**, generated by klystrons. No drive beam.
- Dimensions increase by ~12 GHz / 1.3 Ghz with respect to CLIC: **looser tolerances, wake fields much less of an issue**
  - **High charge** per bunch: $2x10^{10}$ (CLIC $4x10^9$)

**Niobium is the material of choice to fabricate SCRF cavities:**
– High critical temperature (Tc = 9.25K)
– High critical field (Hc(0K) ≅ 200mT)
– Chemically inert (surface covered by oxide layer)
– Easily machined and deep drawn
– Available as bulk and sheet material in any size

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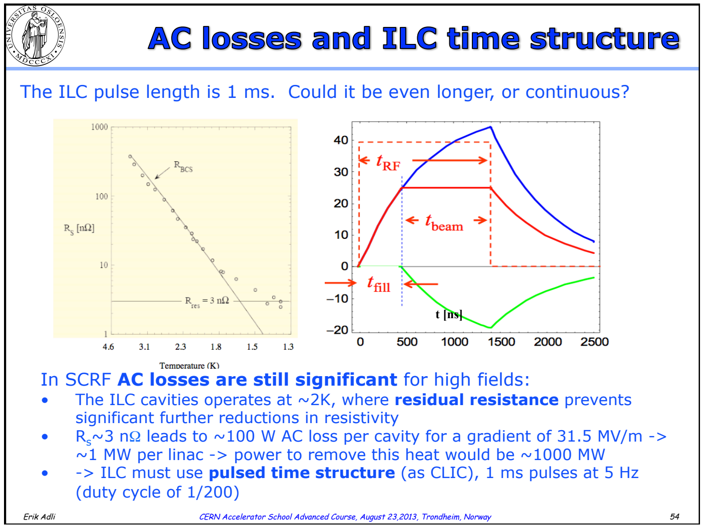

# AC losses and ILC time structure

The ILC pulse length is 1 ms. Could it be even longer, or continuous?

In SCRF **AC losses are still significant** for high fields:

- The ILC cavities operates at ~2K, where **residual resistance** prevents significant further reductions in resistivity
- $R_s$~3 nΩ leads to ~100 W AC loss per cavity for a gradient of 31.5 MV/m -> ~1 MW per linac -> power to remove this heat would be ~1000 MW
- -> ILC must use **pulsed time structure** (as CLIC), 1 ms pulses at 5 Hz (duty cycle of 1/200)

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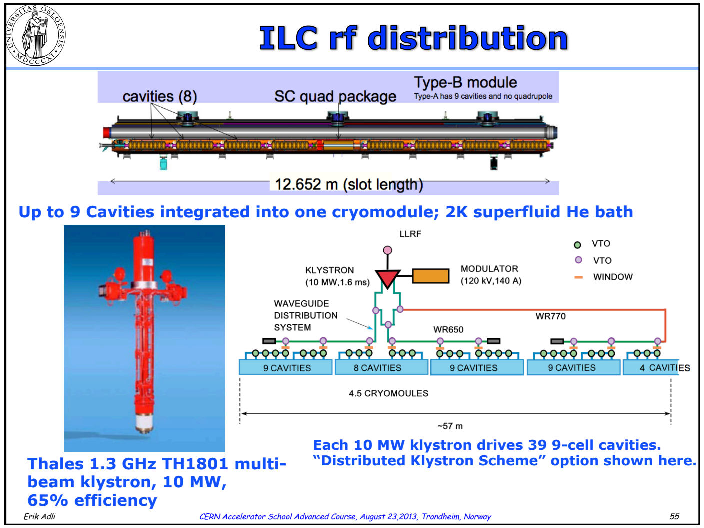

# ILC rf distribution

**Up to 9 Cavities integrated into one cryomodule; 2K superfluid He bath**

**Thales 1.3 GHz TH1801 multi-beam klystron, 10 MW, 65% efficiency**

**Each 10 MW klystron drives 39 9-cell cavities. "Distributed Klystron Scheme" option shown here.**

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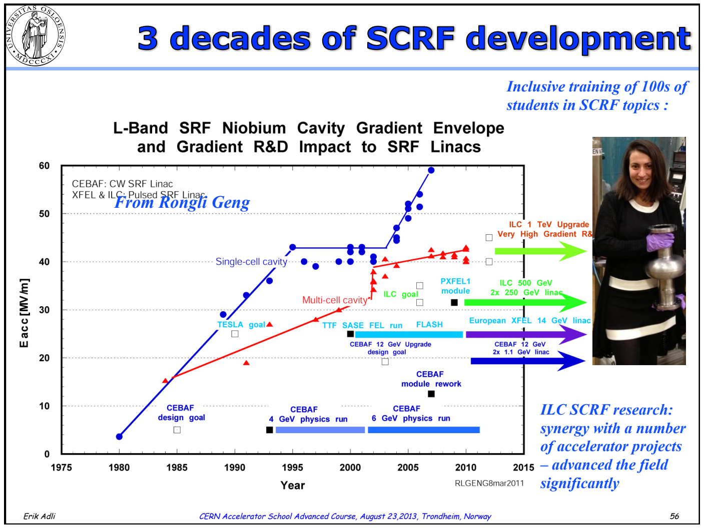

# 3 decades of SCRF development

*Inclusive training of 100s of students in SCRF topics :*

*ILC SCRF research: synergy with a number of accelerator projects – advanced the field significantly*

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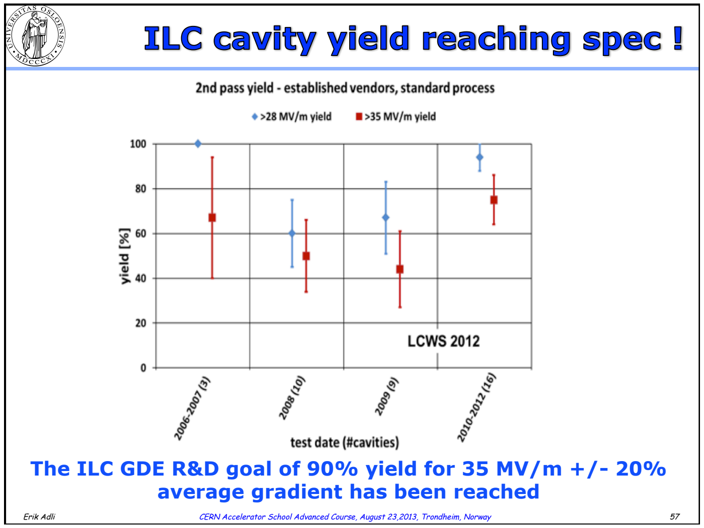
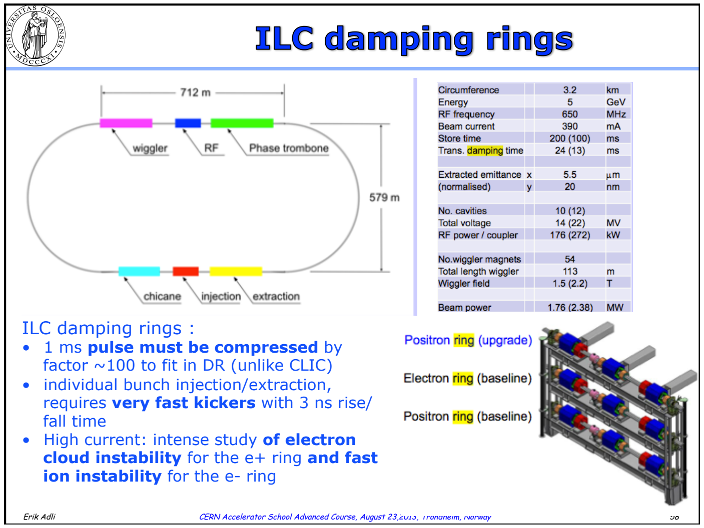


## ILC cavity yield reaching spec !

**The ILC GDE R&D goal of 90% yield for 35 MV/m +/- 20% average gradient has been reached**

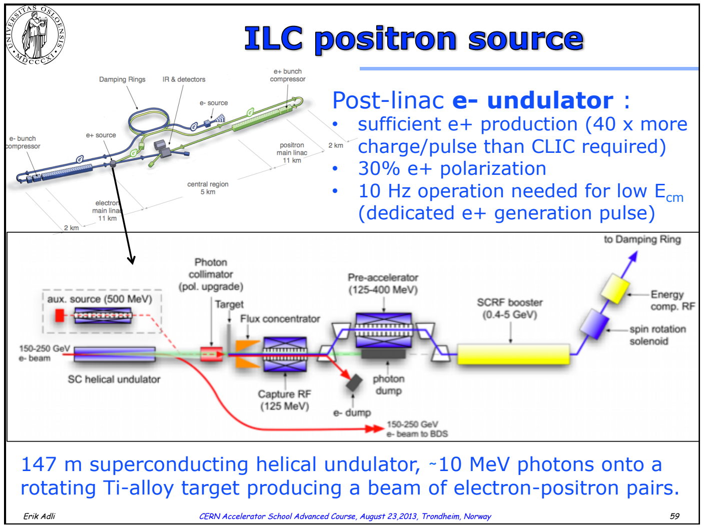


## ILC damping rings

| | | | |
|---|---|---|---|
| Circumference | | 3.2 | km |
| Energy | | 5 | GeV |
| RF frequency | | 650 | MHz |
| Beam current | | 390 | mA |
| Store time | | 200 (100) | ms |
| Trans. damping time | | 24 (13) | ms |
| | | | |
| Extracted emittance | x | 5.5 | µm |
| (normalised) | y | 20 | nm |
| | | | |
| No. cavities | | 10 (12) | |
| Total voltage | | 14 (22) | MV |
| RF power / coupler | | 176 (272) | kW |
| | | | |
| No.wiggler magnets | | 54 | |
| Total length wiggler | | 113 | m |
| Wiggler field | | 1.5 (2.2) | T |
| | | | |
| Beam power | | 1.76 (2.38) | MW |

ILC damping rings :

- 1 ms **pulse must be compressed** by factor ~100 to fit in DR (unlike CLIC)
- individual bunch injection/extraction, requires **very fast kickers** with 3 ns rise/fall time
- High current: intense study **of electron cloud instability** for the e+ ring **and fast ion instability** for the e- ring



## ILC positron source

Post-linac **e- undulator** :

- sufficient e+ production (40 x more charge/pulse than CLIC required)
- 30% e+ polarization
- 10 Hz operation needed for low $E_{cm}$ (dedicated e+ generation pulse)

147 m superconducting helical undulator, ~10 MeV photons onto a rotating Ti-alloy target producing a beam of electron-positron pairs.

## ILC status

### ILC TDR finalized !

http://www.linearcollider.org/ILC/Publications/Technical-Design-Report

Volume 1 - Executive Summary
Download the pdf (9.5 MB)

Volume 2 - Physics
Download the pdf (9.5 MB)

Volume 3 - Accelerator
Part I:
R&D in the Technical Design Phase
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Volume 3 - Accelerator
Part II:
Baseline Design
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Volume 4 - Detectors
Download the pdf (66 MB)

From Design to Reality
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Visit the web site

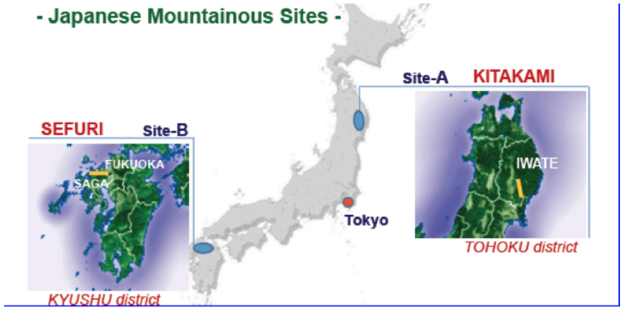
The International Linear Collider
– A Worldwide Event
From Design to Reality

12 June 2013
Tokyo, Geneva, Chicago

www.linearcollider.org/worldwideevent

# ILC: Japanese proposal

The Japanese scientific community has proposed **to host the ILC in Japan**, and commit to fund 50% of the material costs (**70% of an $E_{cm}$ = 250 GeV first stage**), with construction to start as soon as feasible. Europe and USA positive, but financial level of support not yet clear.



# *** NEWSFLASH ***

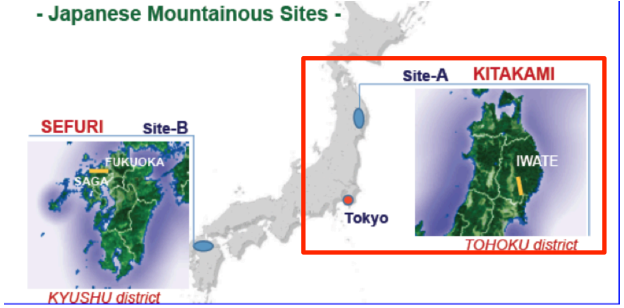

**Ross, Marc C. <mcrec@slac.stanford.edu>** 23 August 2013 14:55
Til: Erik Adli
Kopi: Ross, Marc C. <mcrec@slac.stanford.edu>
RE: ILC site (before 8am SLAC time?)

Erik -

The Japanese site selection committee (physicists and engineers) recommended the site in northern Japan, in the Tohoku District . The area is called 'kita-kami' and it is rural. (both sites were rural).

The press conference lasted about 2 1/2 hours and was very lively (my opinion) showing a healthy interest in ILC.

Marc

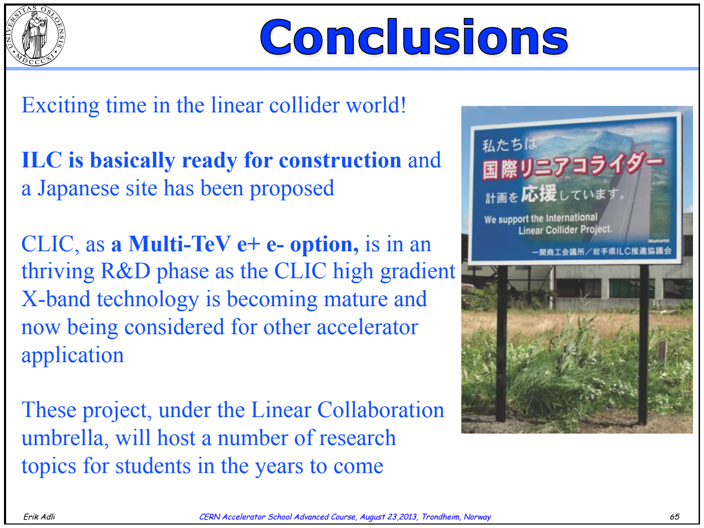


# Outline

- Why a linear collider
- General considerations
- CLIC
- ILC
- **Summary**

# Comparison ILC - CLIC

| **From F. Tecker** | | **ILC<br>0.5 TeV** | **CLIC<br>3 TeV** | **remarks** |
|---|---|---|---|---|
| **Technology readiness** | | **TDR complete** | **CDR complete** | **CLIC: proof of principle of two-beam acc. demonstrated (CDR, 2012)<br>ILC: as good as ready for construction (TDR, 2013)** |
| **No. of particles / bunch** | **$10^9$** | **20** | **3.7** | **CLIC can't go higher because of short range wakefields** |
| **Bunch separation** | **ns** | **370** | **0.5** | **Short spacing essential for CLIC to get comparable RF to beam efficiency, but CLIC requirements on long range wakefield suppression much more stringent<br>forces detectors to integrate over several bunch crossings** |
| **Bunch train length** | **∝s** | **970** | **0.156** | **One CLIC pulse fits easily in small damping ring, simple single turn extraction from DR.<br>But intra train feedback very difficult.** |
| **Charge per pulse** | **nC** | **8400** | **185** | **Positron source much easier for CLIC** |
| **Linac repetition rate** | **Hz** | **5** | **50** | **Pulse to pulse feedback more efficient for CLIC<br>(less linac movement between pulses)** |
| **$\gamma \varepsilon_x , \gamma \varepsilon_y$** | **nm** | **10000, 40** | **660, 20** | **Because of smaller beam size CLIC has more stringent requirements for DR equilibrium emittance and emittance preservation<br>(partly offset by lower bunch charge and smaller DR)** |



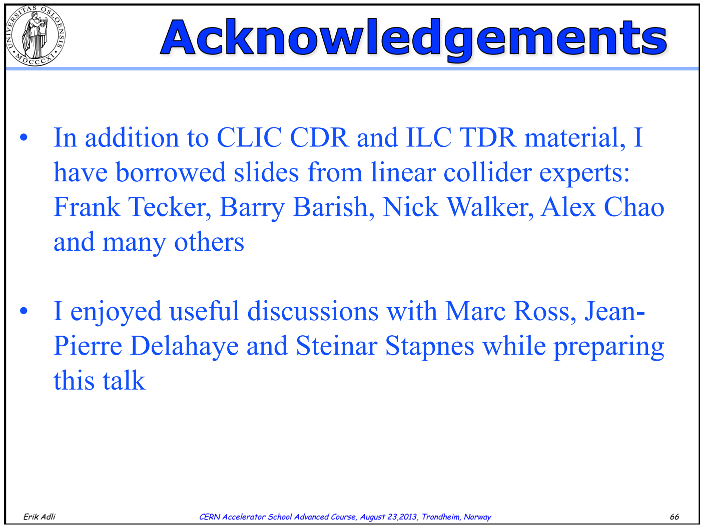
## Conclusions

Exciting time in the linear collider world!

**ILC is basically ready for construction** and a Japanese site has been proposed

CLIC, as **a Multi-TeV e+ e- option,** is in an thriving R&D phase as the CLIC high gradient X-band technology is becoming mature and now being considered for other accelerator application

These project, under the Linear Collaboration umbrella, will host a number of research topics for students in the years to come



## Acknowledgements

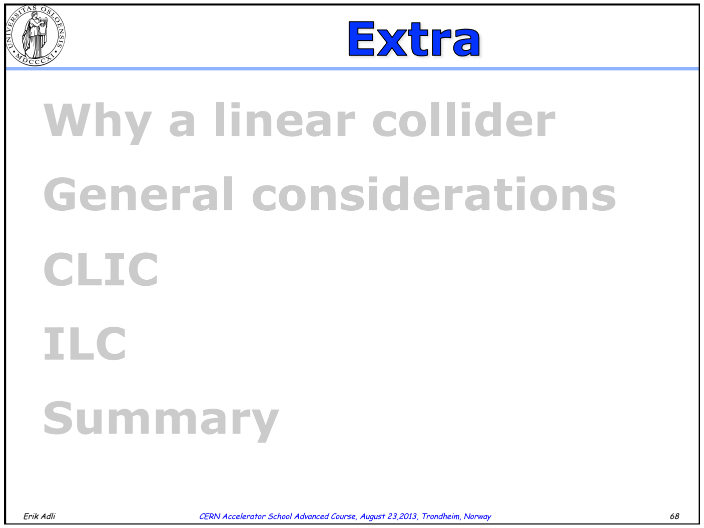
- In addition to CLIC CDR and ILC TDR material, I have borrowed slides from linear collider experts: Frank Tecker, Barry Barish, Nick Walker, Alex Chao and many others
- I enjoyed useful discussions with Marc Ross, Jean-Pierre Delahaye and Steinar Stapnes while preparing this talk

**Eighth International Accelerator School for Linear Colliders**

**December 4 – 15, 2013 Hotel Rixos Downtown, Antalya, Turkey** • Hosted by the Institute of Accelerator Technologies of Ankara University

**TOPICS**: ILC • CLIC • Superconducting & Warm RF Technology • Beam Dynamics of Colliders • Linac & Damping Rings • Ring Colliders • Beam Instrumentation • Beam-Beam

http://www.linearcollider.org/school/2013 **Online application deadline: September 10, 2013**



## Extra

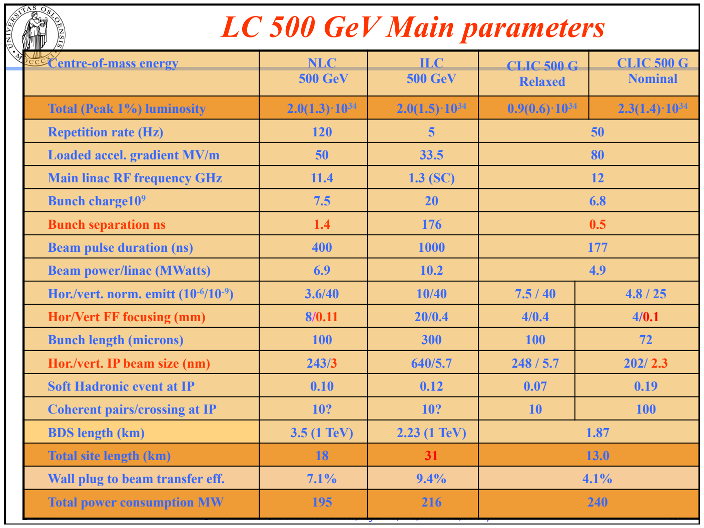
Why a linear collider

General considerations

CLIC

ILC

Summary



# LC 500 GeV Main parameters

| Centre-of-mass energy | NLC<br>500 GeV | ILC<br>500 GeV | CLIC 500 G<br>Relaxed | CLIC 500 G<br>Nominal |
|---|---|---|---|---|
| Total (Peak 1%) luminosity | 2.0(1.3)·$10^{34}$ | 2.0(1.5)·$10^{34}$ | 0.9(0.6)·$10^{34}$ | 2.3(1.4)·$10^{34}$ |
| Repetition rate (Hz) | 120 | 5 | 50 | |
| Loaded accel. gradient MV/m | 50 | 33.5 | 80 | |
| Main linac RF frequency GHz | 11.4 | 1.3 (SC) | 12 | |
| Bunch charge$10^9$ | 7.5 | 20 | 6.8 | |
| Bunch separation ns | 1.4 | 176 | 0.5 | |
| Beam pulse duration (ns) | 400 | 1000 | 177 | |
| Beam power/linac (MWatts) | 6.9 | 10.2 | 4.9 | |
| Hor./vert. norm. emitt ($10^{-6}/10^{-9}$) | 3.6/40 | 10/40 | 7.5 / 40 | 4.8 / 25 |
| Hor/Vert FF focusing (mm) | 8/0.11 | 20/0.4 | 4/0.4 | 4/0.1 |
| Bunch length (microns) | 100 | 300 | 100 | 72 |
| Hor./vert. IP beam size (nm) | 243/3 | 640/5.7 | 248 / 5.7 | 202/ 2.3 |
| Soft Hadronic event at IP | 0.10 | 0.12 | 0.07 | 0.19 |
| Coherent pairs/crossing at IP | 10? | 10? | 10 | 100 |
| BDS length (km) | 3.5 (1 TeV) | 2.23 (1 TeV) | 1.87 | |
| Total site length (km) | 18 | 31 | 13.0 | |
| Wall plug to beam transfer eff. | 7.1% | 9.4% | 4.1% | |
| Total power consumption MW | 195 | 216 | 240 | |

# Accelerating Structure Performances