Compact Linear Collider (CLIC) Status and Plans

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On Behalf of the CLIC Physics and Detector Study, and the CLIC Accelerator Team

International Conference on New Frontiers in Physics
Kolymbari, Crete, Greece
June 10 – 16, 2012

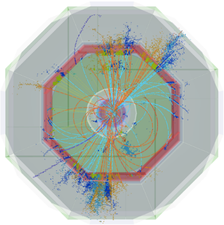
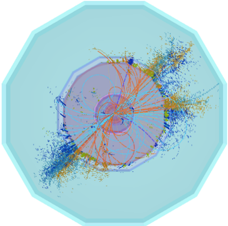
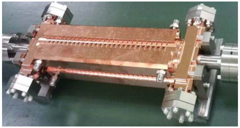
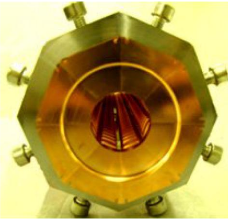
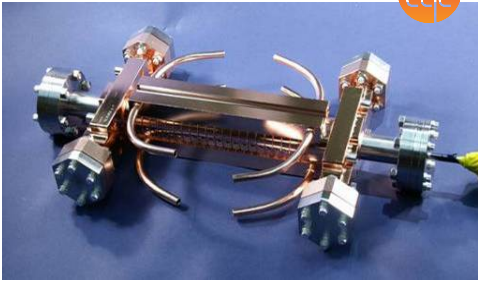
   

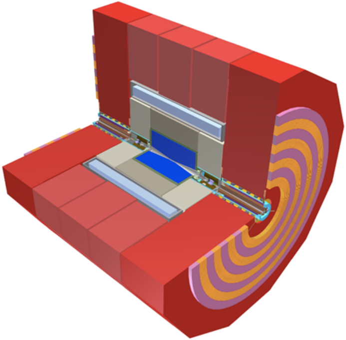
Table of Contents

Introduction

Compact Linear Collider

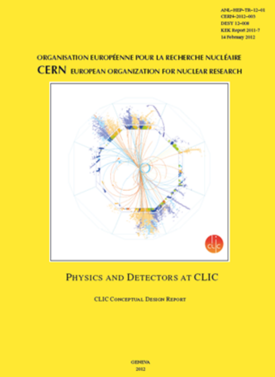
- Accelerator
  - Linear e^+e^- collider with c.m. energy between few hundred GeV and 3 TeV
  - Compact: 100 MV/m acceleration gradient using room-temperature 12 GHz copper cavities
  - Two-beam acceleration scheme: Klystrons used to efficiently accelerate a low energy high current drive-beam which transports the power to the low current main beam
- Detectors&Physics
  - Two detector concepts, based on ILC (International Linear Collider, see presentation by B. List) concepts
  - Studies focused on 3 TeV, also looking at lower energies





Conceptual Design Reports

- Physics and Detector
  - Reviewed externally (October 2011)
  - Presented to CERN Scientific Policy Committee (December 2011)
  - Published: CERN-2012-003 `http://arxiv.org/abs/1202.5940`
- Accelerator and Site Facilities
  - Presented to CERN SPC (March 2012)
  - To be published soon
  - `http://clic-study.org/accelerator/CLIC-ConceptDesignRep.php`
- Executive summary (plus energy staging, cost, and power consumption)
  - Foreseen for summer this year
  - Input to *European Strategy for Particle Physics*



Physics&Detector CDR

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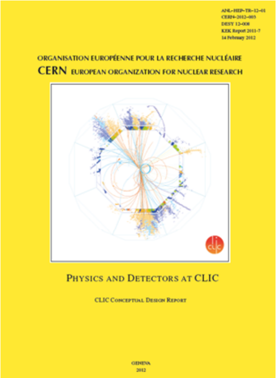


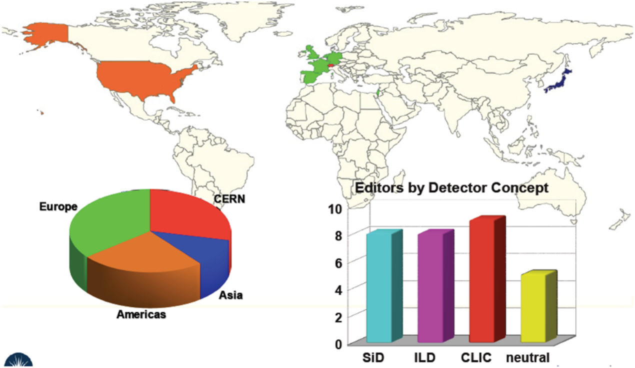
Physics&Detector CDR

The following slides are just an excerpt of more than 1000 pages of CDRs

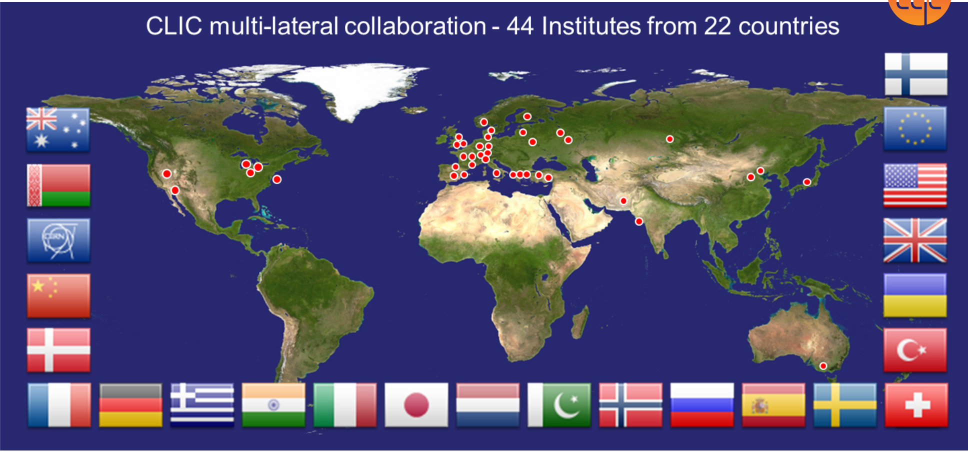
Participants in the CLIC CDR Detector Studies

CLIC physics and detector CDR studies were carried out within a broad international *Linear Collider physics and detector* effort,
adapting ILC concepts to the more challenging CLIC experimental conditions

36 editors + further authors for CDR from all regions



CLIC/CTF3 Accelerator Collaboration



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Aarhus University (Denmark)
Ankara University (Turkey)
Argonne National Laboratory (USA)
Athens University (Greece)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
ETH Zurich (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)
Joint Institute for Power and Nuclear Research SOSNY / Minsk (Belarus)
John Adams Institute / RHUL (UK)
JINR (Russia)
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Tsinghua University (China)
University of Oslo (Norway)
University of Vigo (Spain)
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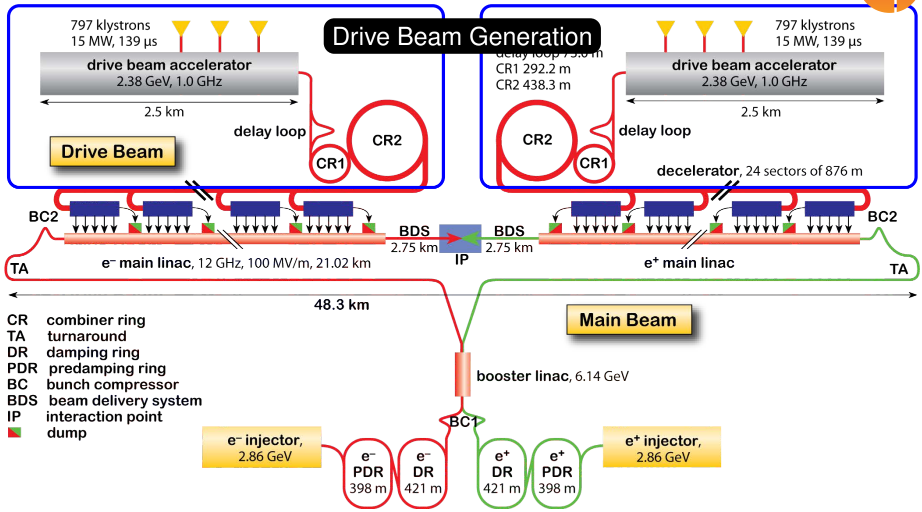
UCSC SCIPP (USA)

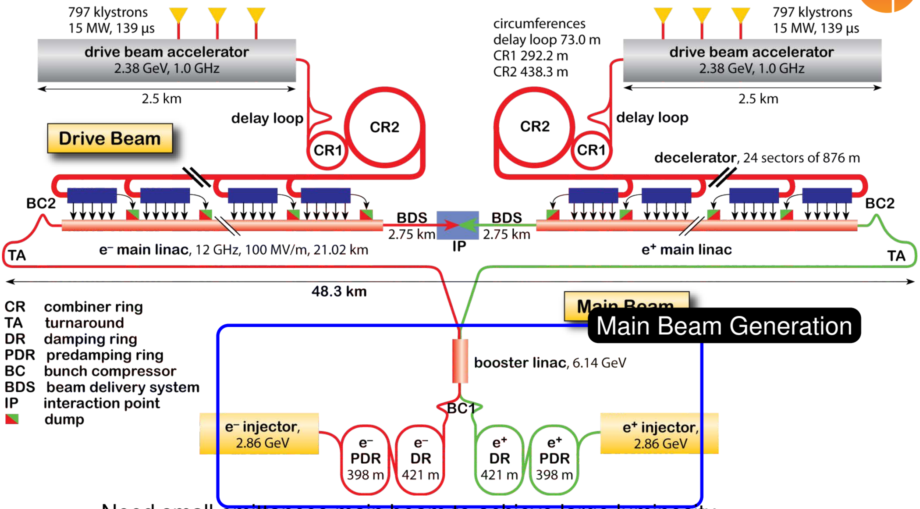
CLIC Accelerator

CLIC $\sqrt{s} = 3$ TeV Layout and Critical Issues



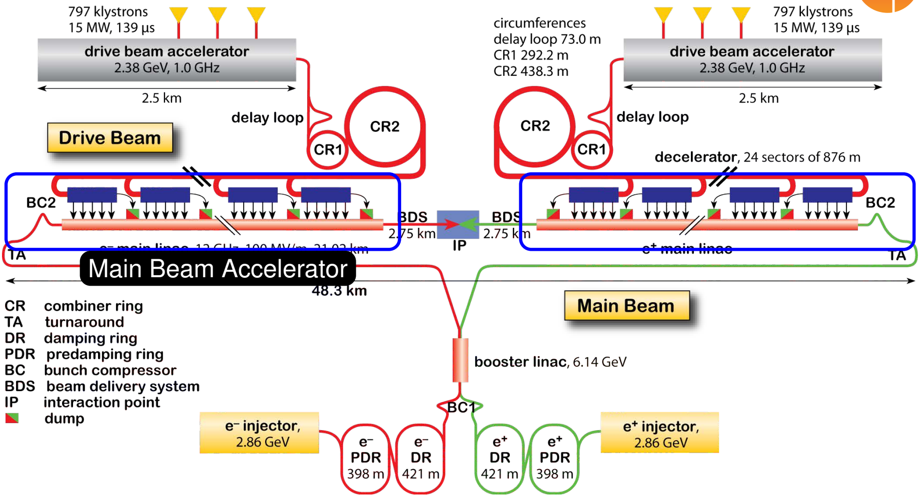
- Generation of high current (100 A) drive beam with delay loop and combiner rings

CLIC $\sqrt{s} = 3$ TeV Layout and Critical Issues



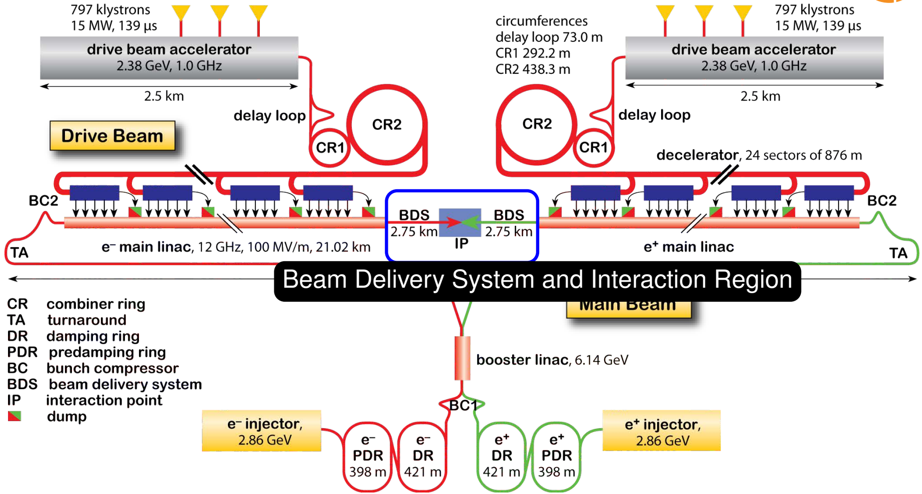
- Need small emittances main beam to achieve large luminosity
- Generation and conservation of small emittance
- Alignment and stabilisation of accelerator components

CLIC $\sqrt{s} = 3$ TeV Layout and Critical Issues



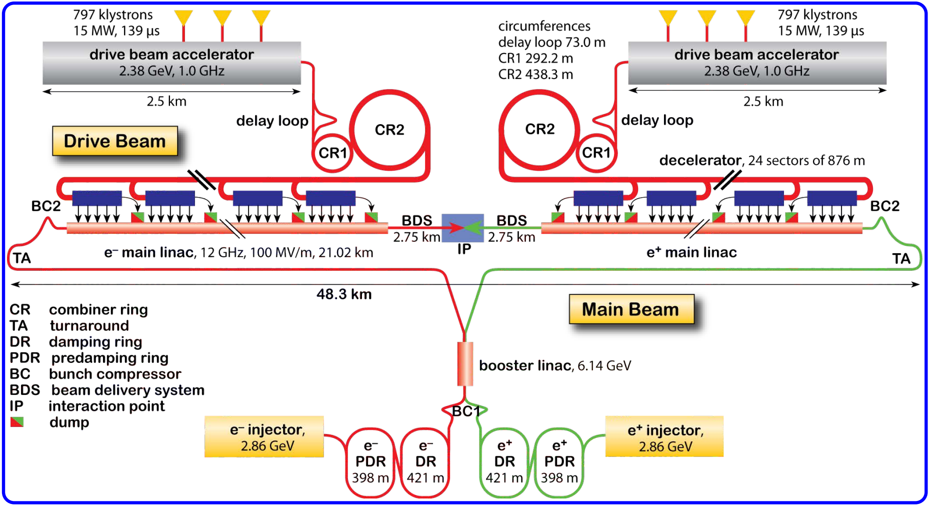
- Drive beam deceleration: Power Extraction and Transfer Structures (PETS)
- Two beam acceleration: Transfer RF from drive beam to main beam
- Main linac gradient: Accelerating structures/Break down rate

CLIC $\sqrt{s} = 3$ TeV Layout and Critical Issues



- Final focus magnets
- Very stringent requirements for alignment and stabilisation

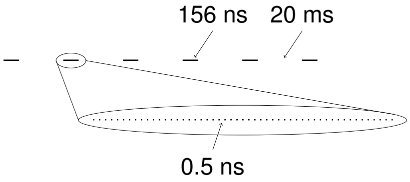
CLIC $\sqrt{s} = 3$ TeV Layout and Critical Issues



- Operation and machine protection system (robustness)

CLIC Accelerator Parameters

- Nanometre beam sizes
- Very short bunch crossing separation: 0.5 ns
- 50 trains per second with 312 bunches per train
- Has large impact on detector requirements (see later)

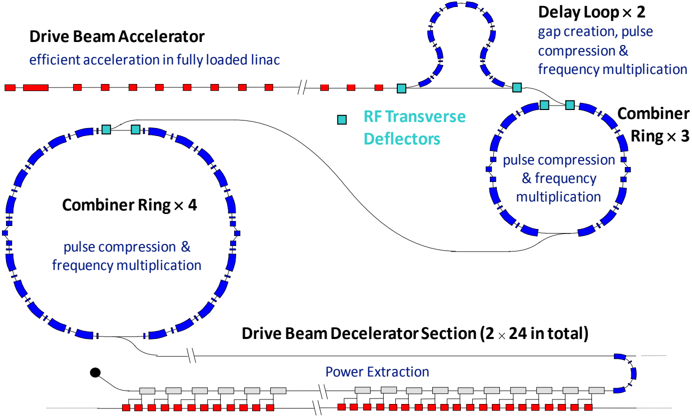


CLIC: trains at 50 Hz, 1 train = 312 bunches

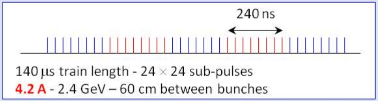
	CLIC 3 TeV	LHC 14 TeV
Colliding particles	Electron–Positron	Proton–Proton
Luminosity [$10^{34}/\mathrm{cm}^2/\mathrm{s}$]	5.9	1.0
Beam size in $X/\ Y/\ Z$	45 nm/1 nm/44 µm	16.7 µm/16.7 µm/7.55 cm
Bunch charge	$3.72 \cdot 10^9$	$1.15 \cdot 10^{11}$
BX separation	0.5 ns	25 ns
Bunches per train	312	2808
Repetition rate	50 Hz	11.2 kHz

Drive Beam Generation

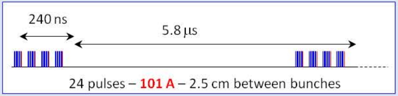
Full CLIC drive beam complex



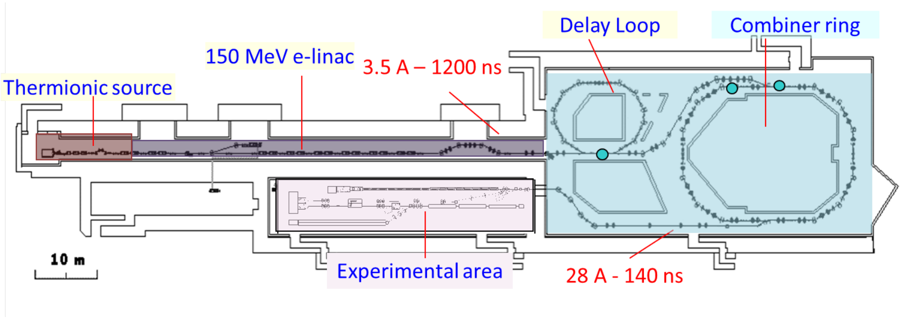
Drive beam time structure - initial



Drive beam time structure - final



CLIC Test Facility (CTF) 3

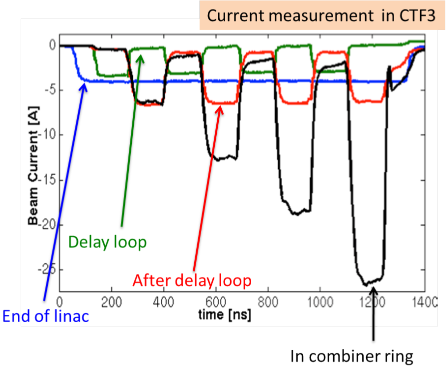


parameter	unit	CLIC	CTF3
accelerated current	A	4.2	3.5
combined current	A	101	28
final energy	MeV	2400	≈ 120
accelerated pulse length	μs	140	1.2
final pulse length	ns	240	140
acceleration frequency	GHz	1	3
final bunch frequency	GHz	12	12

- Scaled down compared to final CLIC parameters
- Only delay loop and one combiner ring for drive beam generation
- Experimental area (CLEX) to test power extraction, two beam acceleration etc.

Drive Beam Combination in CTF3

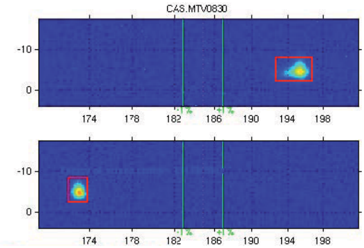
- Drive beam generation principle successfully demonstrated
- Starting with 3.5 A beam
- Routinely reaching 25 A
- Maximum current reached: 29 A

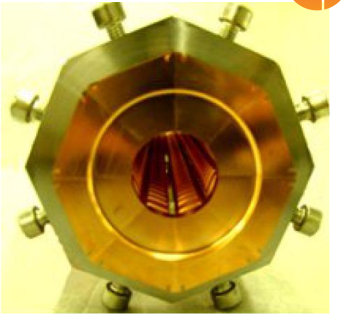


Beam current after Linac, in delay loop, after DL (×2), and combiner ring (×4)

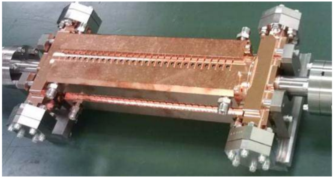
Two Beam Acceleration

- Required break down rate achieved for power extraction modules (upper right) and acceleration cavities (lower right)
- Two beam acceleration successfully tested in CTF3
- Main beam energy with(top) and without(bottom) RF power. Energy gain of 23.08 MeV, corresponding to a gradient of 106 MV/m.





Power extraction module

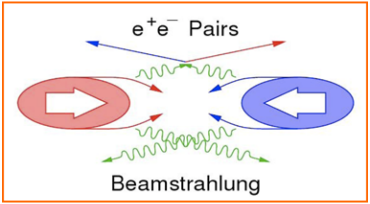


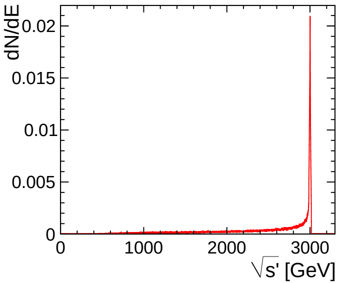
Acceleration cavity

Physics and Detectors

Beam–Beam Interactions

- Large luminosities require high bunch charge and small beams $L \propto \frac{N^2}{\sigma_x \sigma_y}$
- Electromagnetic fields during bunch crossing $B \propto \frac{\gamma N}{\sigma_z(\sigma_x + \sigma_y)}$ approach or surpass quantum mechanical critical field $B_C = \frac{m_e^2 c^2}{e\hbar} = 4.4$ GT
  - Fields also found on the surface of neutron stars
- Deflection of particles by the other bunch leads to synchrotron radiation (beamstrahlung)
- Energy loss leads to luminosity spectrum
  - Still 30% of lumi. above 99% of nominal energy

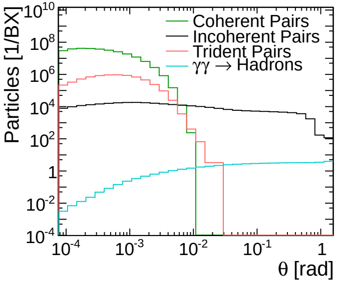


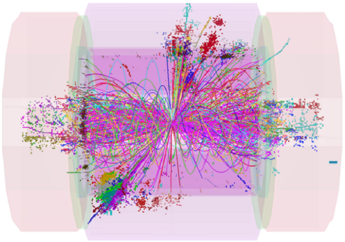


Lumi. spectrum for 3 TeV CLIC

Beam-Induced Backgrounds

- Beamstrahlung photons converted to Electron–Positron pairs through different processes
  - Most at very small angle, but impact on very forward calo and vertex detector
  - Can be suppressed with solenoid field
- $\gamma\gamma \rightarrow$ hadron events
  - Harder p_T spectrum
  - Large amount of visible energy in detector acceptance
  - 5000 tracks with total 7 TeV/Train, 19 TeV/Train in Calorimeter
  - Background has to be identified and rejected

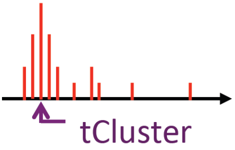


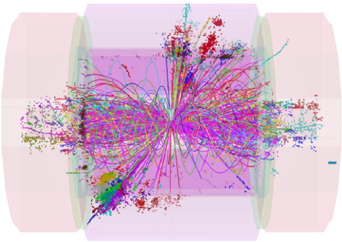


1.2 TeV within 10 ns of physics event

Rejection of Background Particles I

- Rejection of background particles based on average cluster time, precisely measurable; 1 ns single hit resolution
  - Time corrected for time-of-flight
- Timing cuts depend on particle type (charged/neutral), transverse momentum, and detector region





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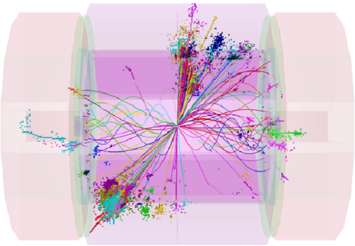
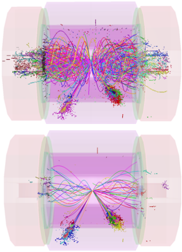
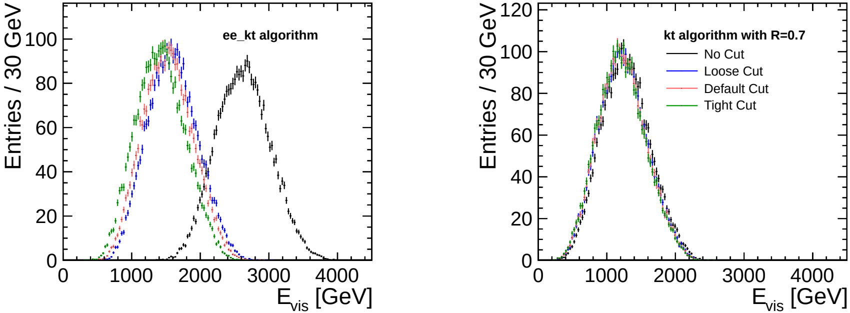


100 GeV after tight timing cuts

Rejection of Background Particles II

- $\gamma\gamma \to$ hadron events very forward peaked
  - Jet clustering: using hadron collider jet algorithms
  - Background clustered to beam-jets
- After timing cuts and jet clustering: Energy distribution mostly unaffected, even at 3 TeV

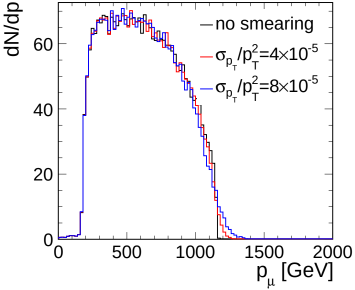


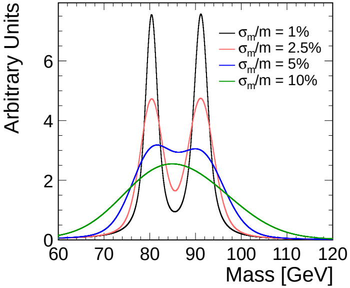


1.1 TeV jets with $\gamma\gamma \to$ hadron background and different clustering algorithms

Detector Requirements

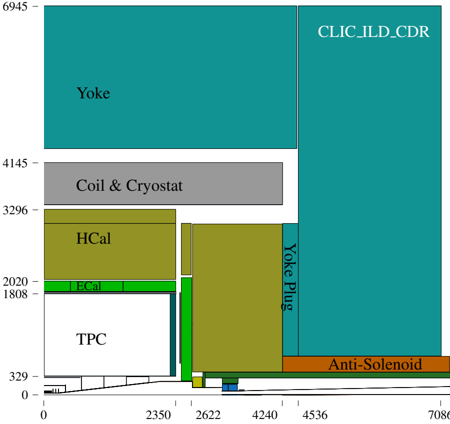
- Momentum resolution
  - $\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}\ \text{GeV}^{-1}$
  - High p_T leptons (e.g., smuon endpoint fit), Higgs recoil mass, Higgs decay to muons
- Jet energy resolution
  - $\frac{\sigma_E}{E} \approx 3.5\%–5\%$
  - W/Z/h jet mass separation
- Impact-parameter resolution
  - $\sigma_{r\phi} = (5 \oplus 15/(p[\text{GeV}]\sin^{\frac{3}{2}}\theta))\mu\text{m}$
  - c/b-tagging, Higgs BR
- Lepton identification, angular coverage & hermeticity, very forward electron tagging





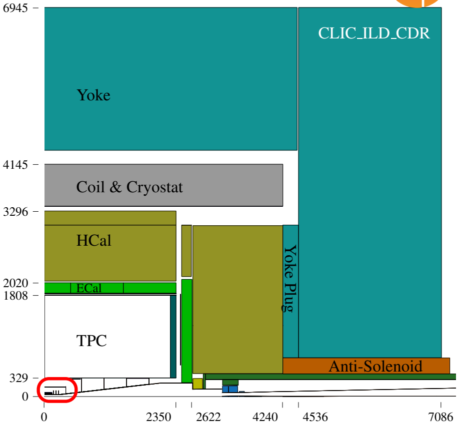
CLIC Detector

- CLIC detectors based on detectors for the ILC
  - Optimised for Particle Flow: Reconstruct all visible final state particles
- Detector models adapted to higher CLIC energy (3 TeV) and different beam-induced background conditions



Vertex Detector

- Precise vertexing
- Requires very low material vertex detector, $\approx 0.2\%$ radiation lengths per layer and low power consumption
- Small pixels $\approx 20 \times 20\ \mu m^2$
- Fast time-stamping of 10 ns



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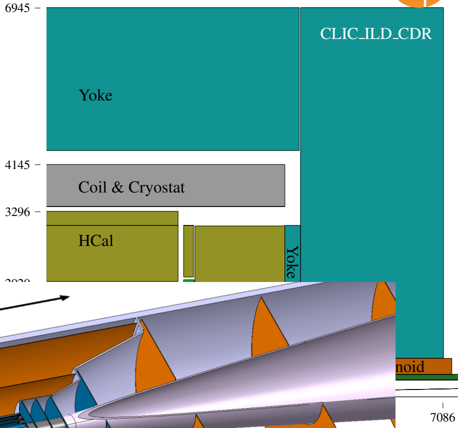
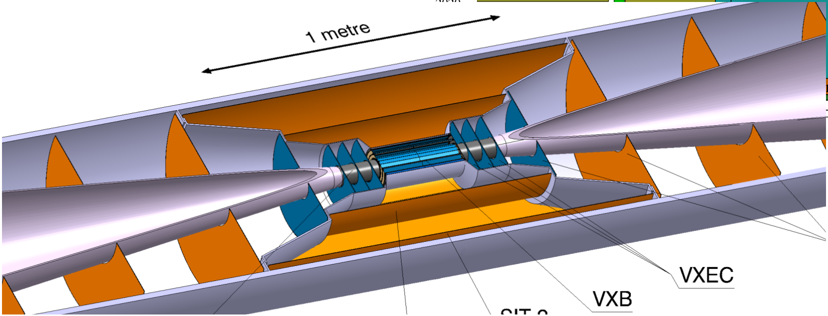
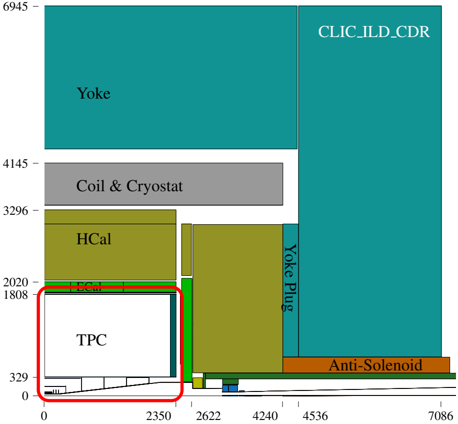




Tracker

- Different tracking technologies in the two models
  - Time Projection Chamber
  - All-Silicon tracking
- Tracking coverage down to 7°



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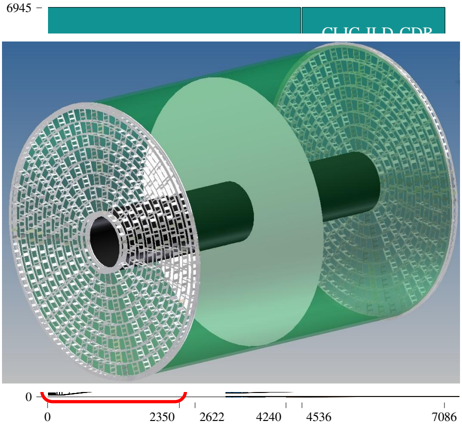

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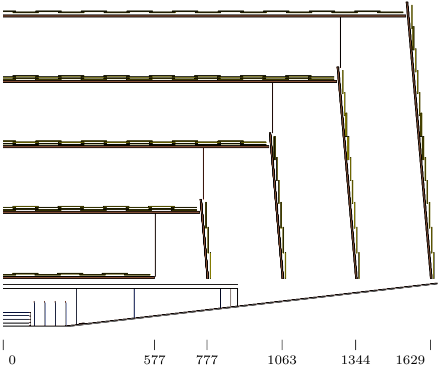
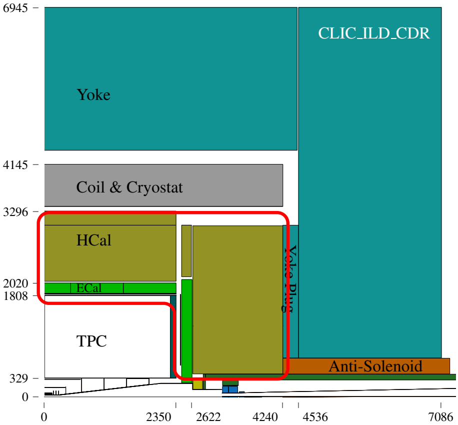


Calorimeter

- Highly segmented in all dimensions: crucial for particle flow
- ECal: Tungsten sandwich calorimeter
  - ≈ 25 radiation lengths, 1 nuclear interaction length
- HCal Barrel: Tungsten absorber to limit coil radius
- HCal Endcap: Steel absorber
- Both HCal parts
  - 7.5 nuclear interaction lengths



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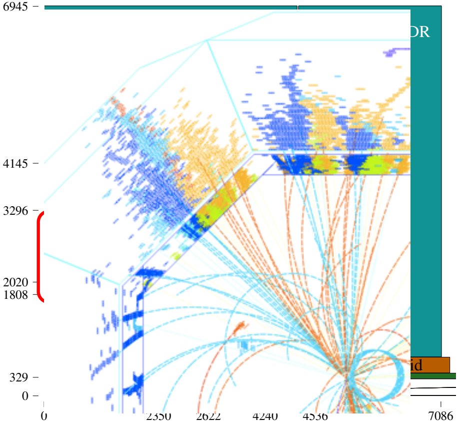
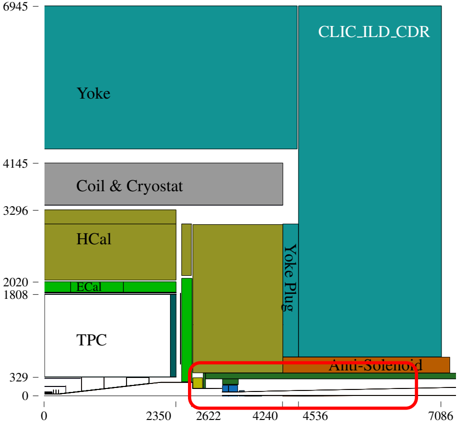


Very Forward Region

- Very complex region
- Critical for backgrounds in the detector
- Contains two e.m. calos
  - LumiCal for luminosity measurement
  - BeamCal for electron tagging (down to 10mrad), most affected by electromagnetic background
- Final focus quadrupole
- Beam instrumentation
- Vacuum systems



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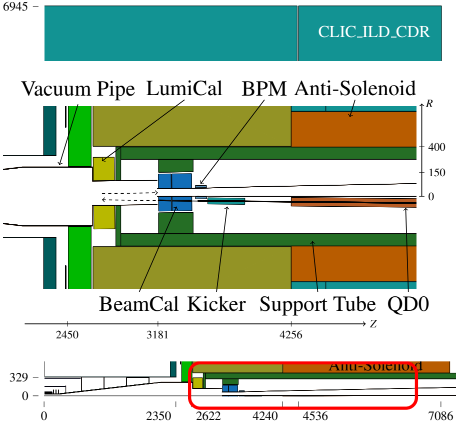

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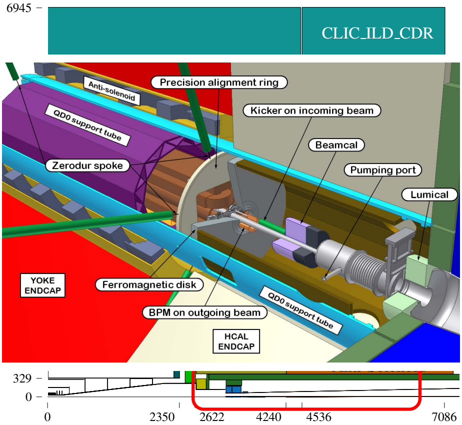
- Beam instrumentation
- Vacuum systems

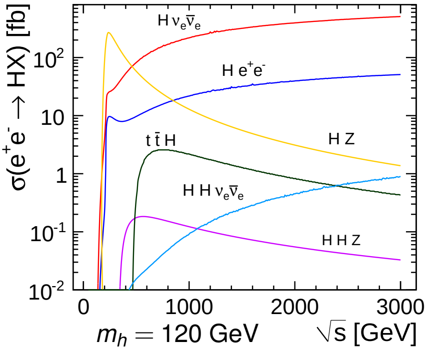


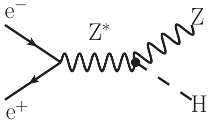
Detector Benchmark Studies

- Evaluate impact of CLIC beam structure and backgrounds on physics observables at $\sqrt{s} = 3$ TeV
- Determine required detector capabilities (spatial resolution, timing, etc.)
- All done in full GEANT4 simulation and with full reconstruction
- With 60 BX of $\gamma\gamma \to$ hadron events overlaid
- Integrated luminosity of 2 ab^{-1}($\approx$ 4 years of nominal operation)

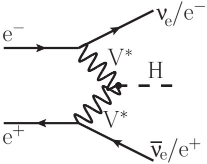
SM Higgs Boson

- Linear collider allows to measure fundamental properties of the Higgs boson with high precision
- Vector boson fusion cross-section rising with centre-of-mass energy
- At 3 TeV access to rare Higgs decays, enabling branching ratio measurements: $h \to \mu\mu, h \to c\bar{c}$
- Measurement of tri-linear Higgs coupling possible





$\propto 1/s$



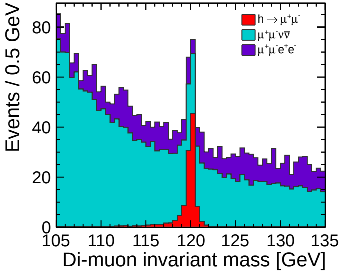
$\propto \log s$

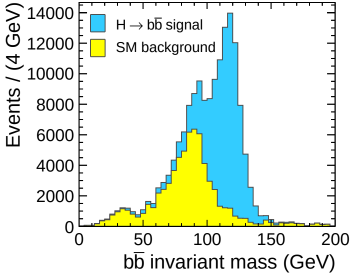
Higgs Measurements at 3 TeV

- Measuring branching ratios
  - $m_h = 120$ GeV
- Invariant mass peaks clearly visible
  - Requires excellent momentum measurement
  - Jet reconstruction
  - B-tagging

Statistical uncertainty on cross-section $\times$ branching-ratio

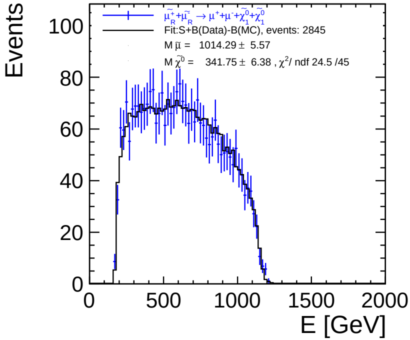
$h \to b\bar{b}$	0.22%
$h \to c\bar{c}$	3.2 %
$h \to \mu^+\mu^-$	15.7 %





Slepton Pair Production at 3 TeV

- Measurement of slepton (selectron, smuon, sneutrino) and Chargino/Neutralino masses from endpoints of lepton energy spectra
- $m_{\tilde{\ell}} \approx 1000$ GeV, $m_{\tilde{\chi}^0} \approx 340$ GeV or $m_{\tilde{\chi}^{\pm}} \approx 640$ GeV
- Cross-sections: 0.72 fb (smuon) to 14 fb (sneutrino)
- Test high energy lepton reconstruction/identification



Statistical Errors

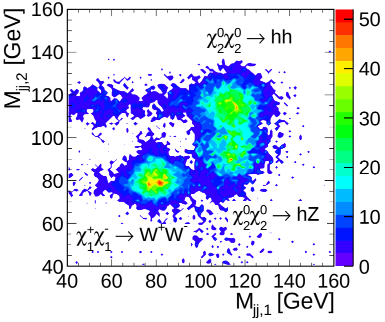
Process	Decay Mode	σ [fb]	$m_{\tilde{\ell}}$ [GeV]	$m_{\tilde{\chi}^0}$ or $m_{\tilde{\chi}^{\pm}}$ [GeV]
$e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^-$	$\mu^+\mu^-\tilde{\chi}^0\tilde{\chi}^0$	0.02	5.6	6.4
$e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-$	$e^+e^-\tilde{\chi}^0\tilde{\chi}^0$	0.05	2.8	3.4
$e^+e^- \to \tilde{e}_L^+\tilde{e}_L^-$	$\tilde{\chi}^0\,\tilde{\chi}^0\,e^+e^-\,(h/Z^0\,h/Z^0)$	0.20		
$e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e$	$\tilde{\chi}^0\,\tilde{\chi}^0\,e^+e^-\,W^+W^-$	0.32	3.9	3.7

Gaugino Pair Production at 3 TeV

- Chargino/Neutralino Pair Production

$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$$
$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0 hh$$
$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0 Zh$$

- $m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_2^0} \approx 643$ GeV
- Cross-sections: $\sigma_{\tilde{\chi}_1^+\tilde{\chi}_1^-} = 3.3$ fb, $\sigma_{\tilde{\chi}_2^0\tilde{\chi}_2^0} = 10.6$ fb
- Same topology for all final states (4 jets plus missing energy)
- Must identify via di-jet invariant mass, test for the particle flow reconstruction of boosted bosons



Statistical errors:

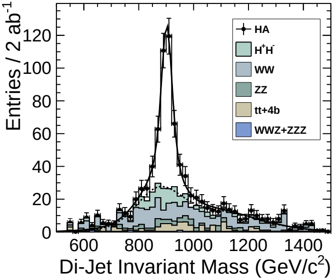
Particle	Mass [GeV]	σ [fb]
$\tilde{\chi}_2^0$	10	0.25
$\tilde{\chi}_1^\pm$	7	0.11

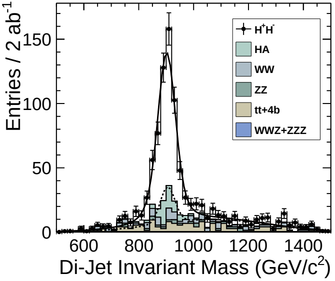
Heavy Higgs Bosons at 3 TeV

- Heavy SuSy Higgs Bosons:
  $m_{\mathrm{H}^0/\mathrm{A}^0} \approx m_{\mathrm{H}^\pm} \approx 900$ GeV
- $\mathrm{e}^+\mathrm{e}^- \to \mathrm{H}^0\mathrm{A}^0 \to \mathrm{b}\bar{\mathrm{b}}\mathrm{b}\bar{\mathrm{b}}$
- $\mathrm{e}^+\mathrm{e}^- \to \mathrm{H}^+\mathrm{H}^- \to \mathrm{t}\bar{\mathrm{b}}\mathrm{b}\bar{\mathrm{t}}$
- Testing flavour-tagging and invariant mass reconstruction in high multiplicity environment

Statistical uncertainties:

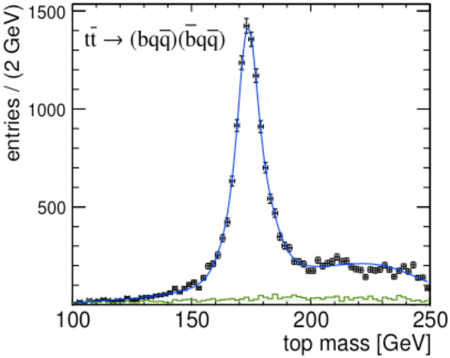
Particle	Mass [GeV]	Width [GeV]
$\mathrm{H}^0\ \mathrm{A}^0$	2.8	6.3
$\mathrm{H}^+\ \mathrm{H}^-$	2.4	5.4

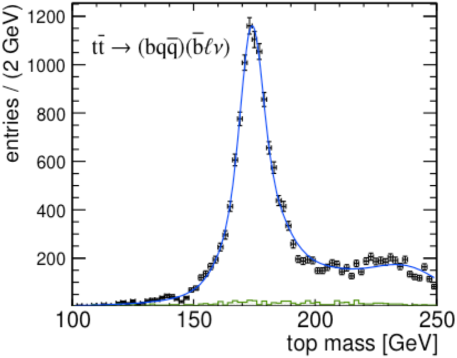




Top Mass Measurement at 500 GeV

- Study top mass with CLIC background at 500 GeV
- Fully hadronic and semi-leptonic final state used
- Reconstruction with: b-tagging, invariant masses and kinematic fits
- With 100 fb^{-1}: Statistical error $\sigma(m_t) \approx 80$ MeV





Physics Reach

LC physics potential is complementary to the LHC

- Beyond the LHC discovery reach
  - e^+e^- collisions give access to additional physics processes
    - ★ Weakly interacting states (e.g. slepton, chargino, neutralino searches)
    - ★ Cleaner conditions than at the LHC
  - Defined initial state and more precise measurements

Physics reach at different colliders

	LHC14 $100\ fb^{-1}$	SLHC14 $1\ ab^{-1}$	LC800 $500\ fb^{-1}$	CLIC3 $1\ ab^{-1}$
squarks [TeV]	2.5	3	0.4	1.5
sleptons [TeV]	0.3		0.4	1.5
$Z'_{\text{(SM couplings)}}$ [TeV]	5	7	8	20
2 extra dims M_D [TeV]	9	12	5–8.5	20–30
μ contact scale [TeV]	15		20	60
Higgs compos. scale [TeV]	5–7	9–12	45	60
TGC (95%) (λ_γ coupling)	0.001	0.0006	0.0004	0.0001

CERN-2012-003, CERN-TH/2001-023

Physics and Detectors: Future Plans

- Physics studies
  - CLIC at various energies (staging), following LHC results
- Simulation studies and detector optimisation
  - Detector-design and connection to detector R&D
- Detector R&D and engineering
  - Vertex detector: ultra-thin, small pixel, 10 ns time-stamping
  - Tracking detectors: (TPC/Si) integrated designs
  - Electronics: timing, low-power, power pulsing
  - Calorimetry: Highly granular,very compact active layers,1 ns hit time resolution
  - Engineering design: support, stability, alignment, cooling
  - Solenoid Coil: Superconducting cables, movable services (push-pull)

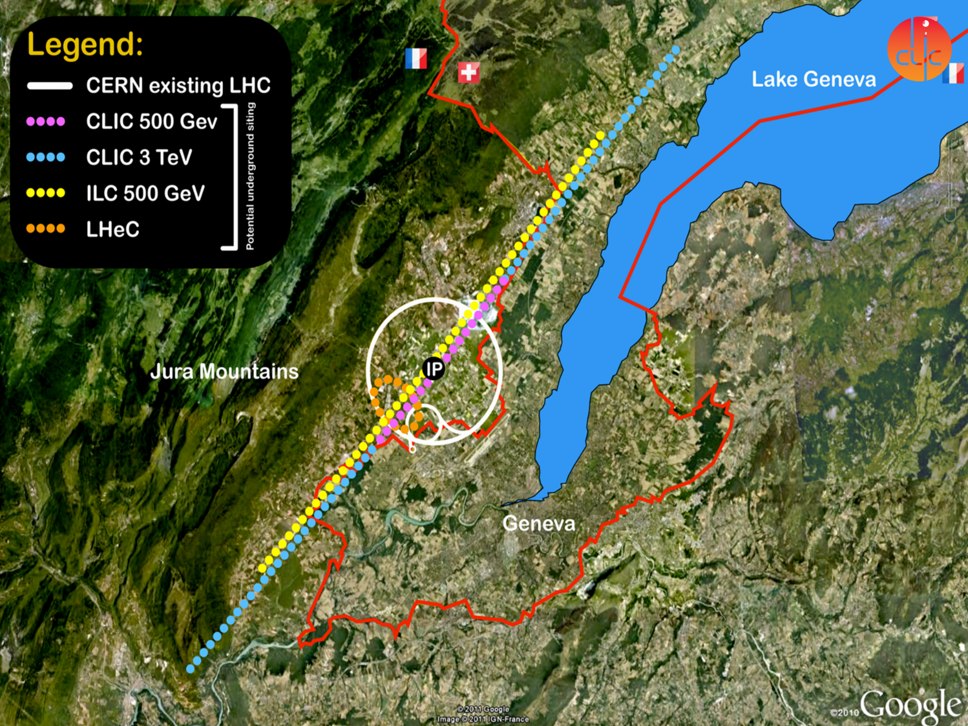
Summary

- Good results on feasibility of CLIC accelerator technologies for the CDR and progress continues
- Physics can be measured with high precision, despite challenging background and beam conditions
- CLIC has large physics potential, complementary to LHC
- Ongoing R&D program for next project phase 2012-2016

Acknowledgement

Thanks to all the people providing material/slides
(L. Linssen, D. Schulte, S. Stapnes, P. Roloff, M. Thomson, S. Poss, and many more)

Thank you for your attention

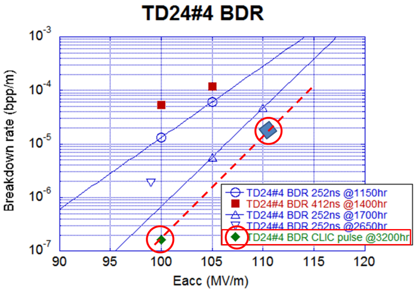

Legend:
CERN existing LHC
CLIC 500 Gev
CLIC 3 TeV
ILC 500 GeV
LHeC
Potential underground siting
Lake Geneva
Jura Mountains
IP
Geneva
CLIC
©2011 Google
Image © 2011 IGN-France
©2010 Google

Links

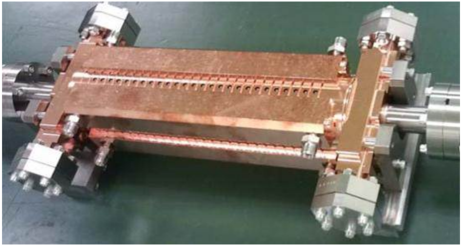
- Accelerator CDR
  `http://project-clic-cdr.web.cern.ch/project-CLIC-CDR/`
- Detector&Physics CDR `http://lcd.web.cern.ch/LCD/CDR/CDR.html`
- Video of CERN Seminar about CLIC: Physics and Detectors
  `https://indico.cern.ch/conferenceDisplay.py?confId=189815`

Backup Slides

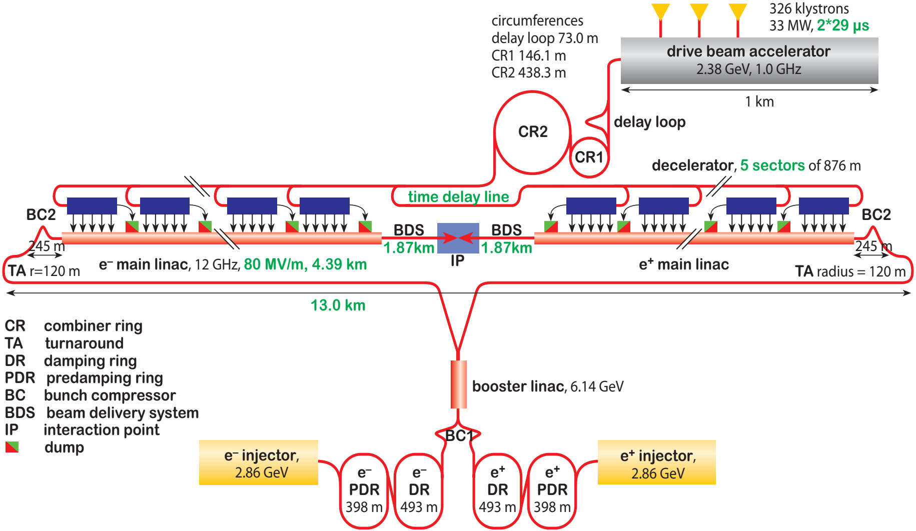
Accelerating Structures/Break Down Rate



- Require $< 1\%$ probability of break down in a single structure (along the 44 km of accelerator)
  - $P_{\mathrm{BDR}} < 3 \times 10^{-7} \mathrm{m}^{-1} \mathrm{pulse}^{-1}$
- Required break down rate achieved with TD24#4 structure (see right bottom) at CLIC gradient (100 MV/m) after RF conditioning



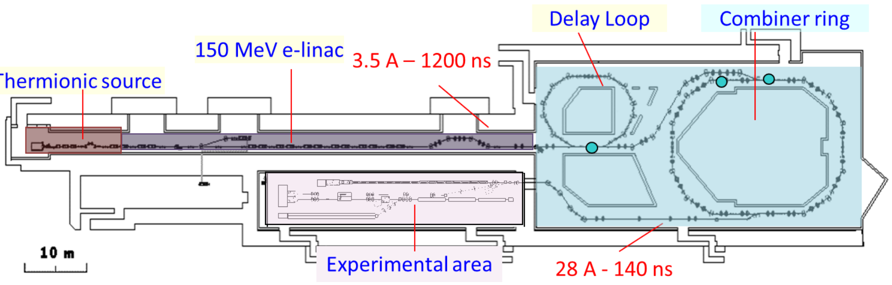
500 GeV Layout



CLIC Parameters

parameter	symbol		
centre of mass energy	E_{cm} [GeV]	500	3000
luminosity	$\mathcal{L}$ [10^{34} cm^{-2}s^{-1}]	2.3	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [10^{34} cm^{-2}s^{-1}]	1.4	2
gradient	G [MV/m]	80	100
site length	[km]	13	48.3
charge per bunch	N [10^9]	6.8	3.72
bunch length	σ_z [μm]	72	44
IP beam size	σ_x/σ_y [nm]	200/2.26	40/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20
bunches per pulse	n_b	354	312
distance between bunches	Δ_b [ns]	0.5	0.5
repetition rate	f_r [Hz]	50	50
est. power cons.	P_{wall} [MW]	271	582

CTF3



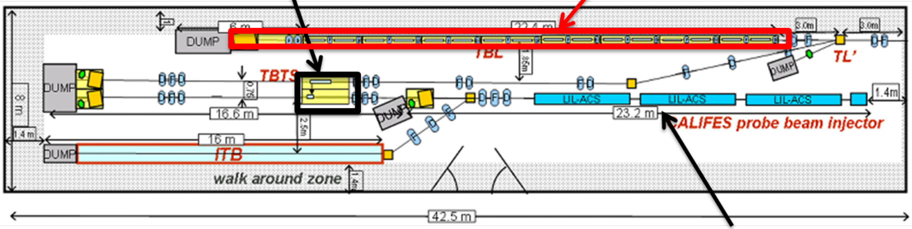
parameter	unit	CLIC	CTF3
accelerated current	A	4.2	3.5
combined current	A	101	28
final energy	MeV	2400	≈ 120
accelerated pulse length	μs	140	1.2
final pulse length	ns	240	140
acceleration frequency	GHz	1	3
final bunch frequency	GHz	12	12

Recycled infrastructure
- made it affordable
- causes lots of headache

CTF3: Experimental Area

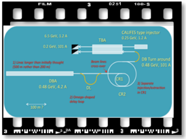
TBTS (two-beam test stand)
- power transfer to main beam
- module design

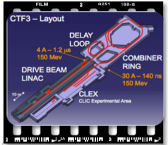
TBL (test beam line)
- drive beam stability during deceleration



Main beam injector

CLIC project time-line





Final CLIC CDR and feasibility established, also input for the Eur. Strategy Update

From 2016 – Project Implementation phase, including an initial project to lay the grounds for full construction:

- CLIC 0 – a significant part of the drive beam facility: prototypes of hardware components at real frequency, final validation of drive beam quality/main beam emittance preservation, facility for reception tests – and part of the final project)
- Finalization of the CLIC technical design, taking into account the results of technical studies done in the previous phase, and final energy staging scenario based on the LHC Physics results, which should be fully available by the time
- Further industrialization and pre-series production of large series components for validation facilities
- Other system studies addressing luminosity issues (emittance conservation) …
- Environmental Impact Study

2004 - 2012	2012 - 2016	2016 – 2022	~ 2020 onwards

2011-2016 – Goal: Develop a project implementation plan for a Linear Collider:

- Addressing the key physics goals as emerging from the LHC data
- With a well-defined scope (i.e. technical implementation and operation model, energy and luminosity), cost and schedule
- With a solid technical basis for the key elements of the machine and detector
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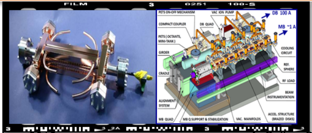
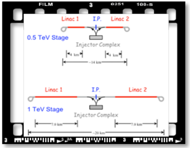
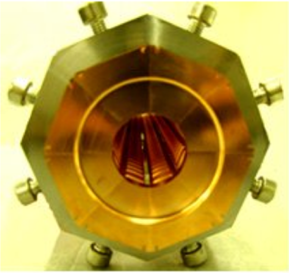
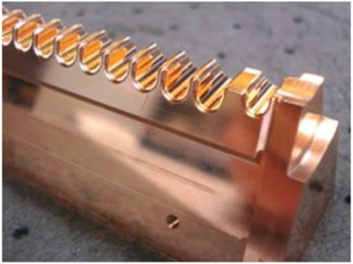


CLIC project construction – in stages, making use of CLIC 0



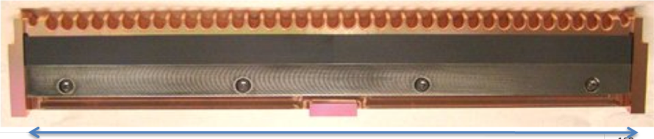
Power Extraction





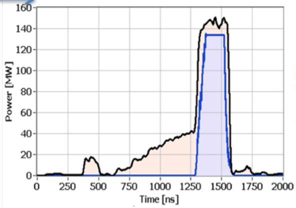
Designed with more margin than accelerating structures

$P_{out} \approx 130MW$



0.25m

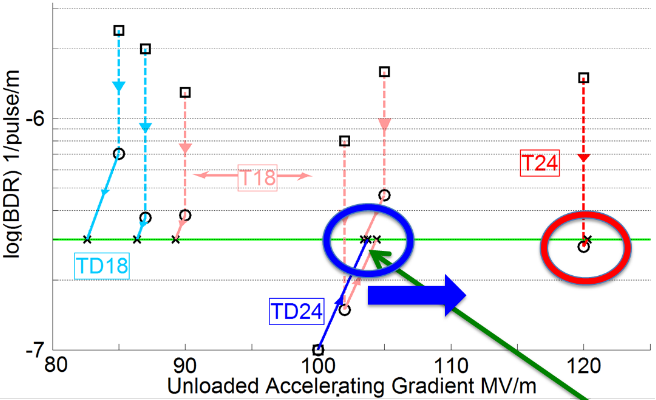
Pulse used for measurement and nominal pulse (blue)



Measurements at SLAC:
No breakdown last O($8\ 10^6$ pulses)
-> P consistent with $p \leq 10^{-7}$/m/pulse

Achieved Gradient

Tests at KEK and SLAC



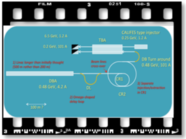
Measurements scaled according to

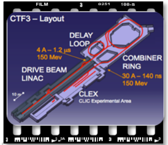
$$p \propto G^{30} \tau^{5}$$

Unloaded 103 MV/m
Expected with beam loading 86-103 MV/m

	Simple early design to get started	More efficient fully optimised structure
No damping waveguides	T18	T24
Damping waveguides	TD18	TD24 = CLIC goal

CLIC project time-line





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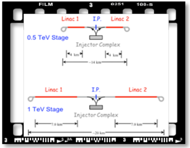
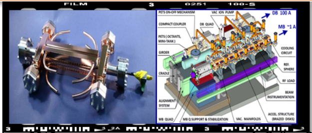


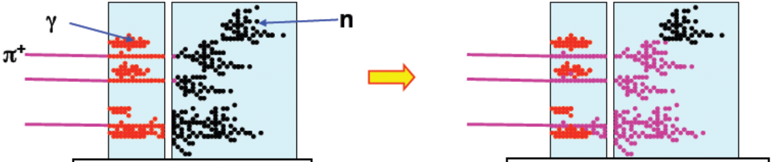


Objectives and Plans for 2012–2016 (S. Stapnes)

- Define the scope, strategy, and cost of the project implementation
- Main input: The evolution of the physics findings at LHC and other relevant data
- Findings from the CDR and further studies, in particular concerning minimization of the technical risks, cost, power as well as the site implementation
- A Governance Model as developed with partners
- Define and keep an up-to-date optimized overall baseline design that can achieve the scope within a reasonable schedule, budget, and risk.
- Beyond beam line design, the energy, and luminosity of the machine: key studies will address stability and alignment, timing and phasing, stray fields and dynamic vacuum including collective effects.
- Other studies will address failure modes and operation issues.
- Identify and carry out system tests and programs to address the key performance and operation goals and mitigate risks associated to the project implementation.
- The priorities are the measurements in: CTF3+, ATF and related to the CLIC zero Injector addressing the issues of drive-beam stability, RF power generation and two beam acceleration, as well as the beam delivery system.
- Technical work-packages and studies addressing system performance parameters

Particle Flow Basics

- In a typical jet, energy is :
  - 60 % charged hadrons, 30 % in photons, 10 % in neutral hadrons
- Traditional calorimetric approach:
  - Measure all components of jet energy in ECAL/HCAL
  - ~70 % of energy measured in HCAL, limits jet energy resolution



$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

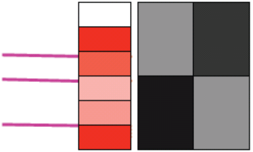
- Particle Flow Calorimetry paradigm:
  - charged particles measured in tracker (essentially perfectly)
  - Photons in ECAL: $\sigma_E/E < 20\%/\sqrt{E(\mathrm{GeV})}$
  - Neutral hadrons (ONLY) in HCAL
  - Only 10 % of jet energy from HCAL ⟹ much improved resolution

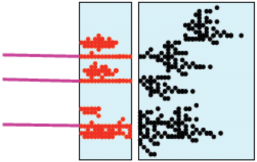
Particle Flow Basics

Hardware:

★Need to be able to resolve energy deposits from different particles

⇨ Highly granular detectors (as studied in CALICE)

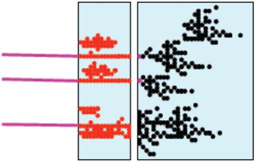


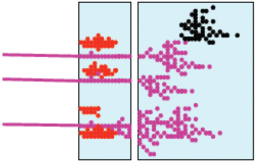


Software:

★Need to be able to identify energy deposits from individual particles

⇨ Sophisticated reconstruction software



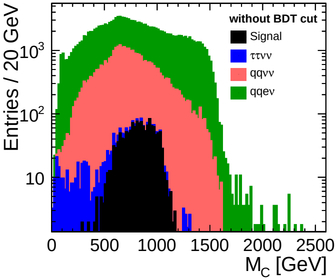


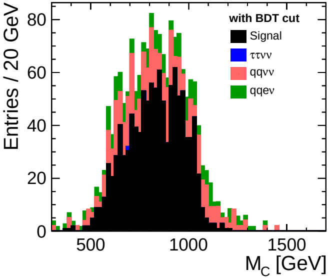
Squark Pair Production

- $e^+e^- \to \widetilde{q}_R\widetilde{q}_R \to q\bar{q}\widetilde{\chi}^0_1\widetilde{\chi}^0_1$
  - $m_{\widetilde{u}_R} = m_{\widetilde{c}_R} = 1125.7$ GeV
  - $m_{\widetilde{d}_R} = m_{\widetilde{s}_R} = 1116.1$ GeV
  - $\sigma_{\widetilde{q}_R\widetilde{q}_R} = 1.5$ fb
- Large cross-section SM backgrounds:
  - $\sigma_{q\bar{q}e^\pm\nu} = 5300$ fb
  - $\sigma_{q\bar{q}\nu\bar{\nu}} = 1500$ fb
- Reconstruction via the modified invariant mass $M_C = \sqrt{2(E_1E_2 + \vec{p}_1\vec{p}_2)}$ and $M_C^{max} = (m^2_{\widetilde{q}} - m^2_{\widetilde{\chi}})/m_{\widetilde{q}}$

Statistical Errors on average values:

Mass [GeV]	σ [fb]
5.9	0.07



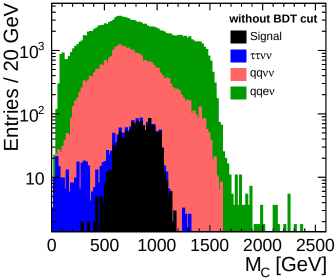


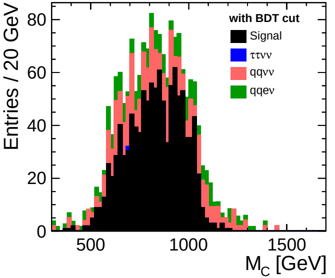
Squark Pair Production

- $e^+e^- \to \tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$
  - $m_{\tilde{u}_R} = m_{\tilde{c}_R} = 1125.7$ GeV
  - $m_{\tilde{d}_R} = m_{\tilde{s}_R} = 1116.1$ GeV
  - $\sigma_{\tilde{q}_R\tilde{q}_R} = 1.5$ fb
- Large cross-section SM backgrounds:
  - $\sigma_{q\bar{q}e^\pm\nu} = 5300$ fb
  - $\sigma_{q\bar{q}\nu\bar{\nu}} = 1500$ fb
- Reconstruction via the modified invariant mass $M_C = \sqrt{2(E_1E_2 + \vec{p}_1\vec{p}_2)}$ and $M_C^{max} = (m_{\tilde{q}}^2 - m_{\tilde{\chi}}^2)/m_{\tilde{q}}$

Statistical Errors on average values:

Mass [GeV]	σ [fb]
5.9	0.07





Systematic Uncertainties

- Started studying the impact of systematic errors
- Knowledge of the shape of the luminosity spectrum
- Increased $\gamma\gamma \rightarrow$ hadron background

Distinguishing BSM Models