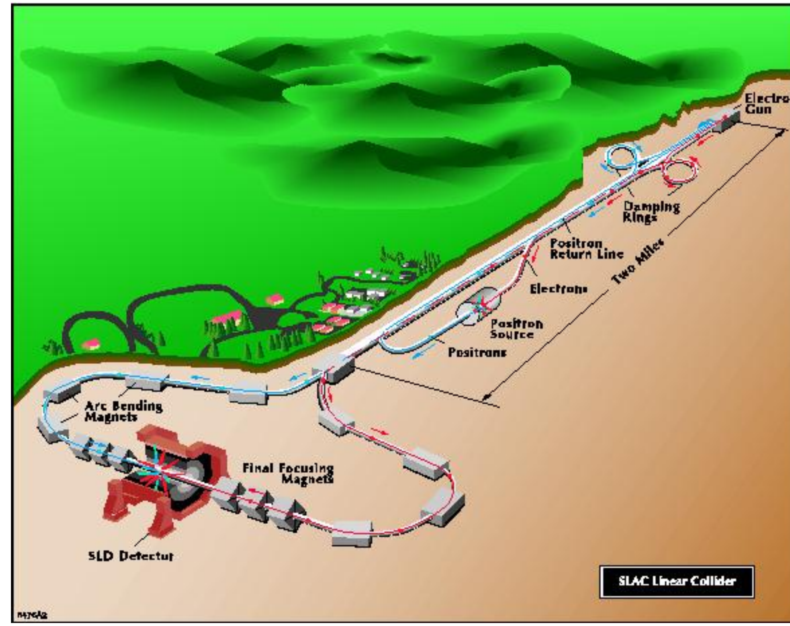
Linear Colliders (LC)

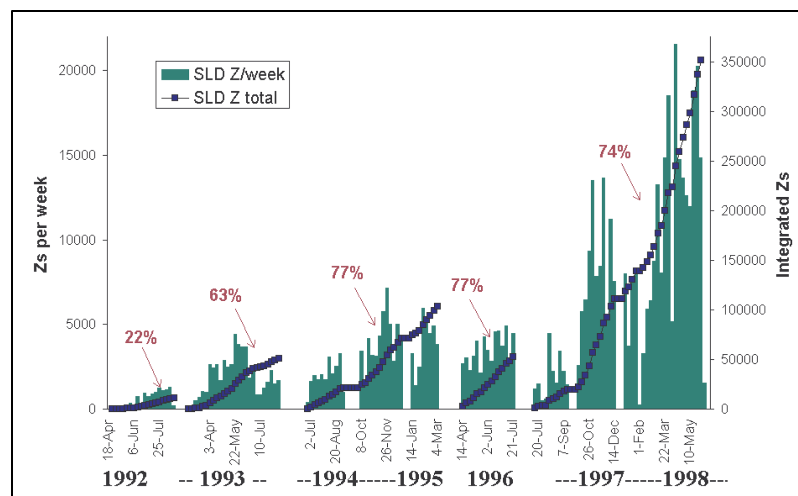
Outline:

- Why linear ?
- Physics at a LC (brief)
- ILC and CLIC – technology developments, commonality and differences
- Detectors at a LC (very brief)
- A global LC effort
- Main points

LC colliders

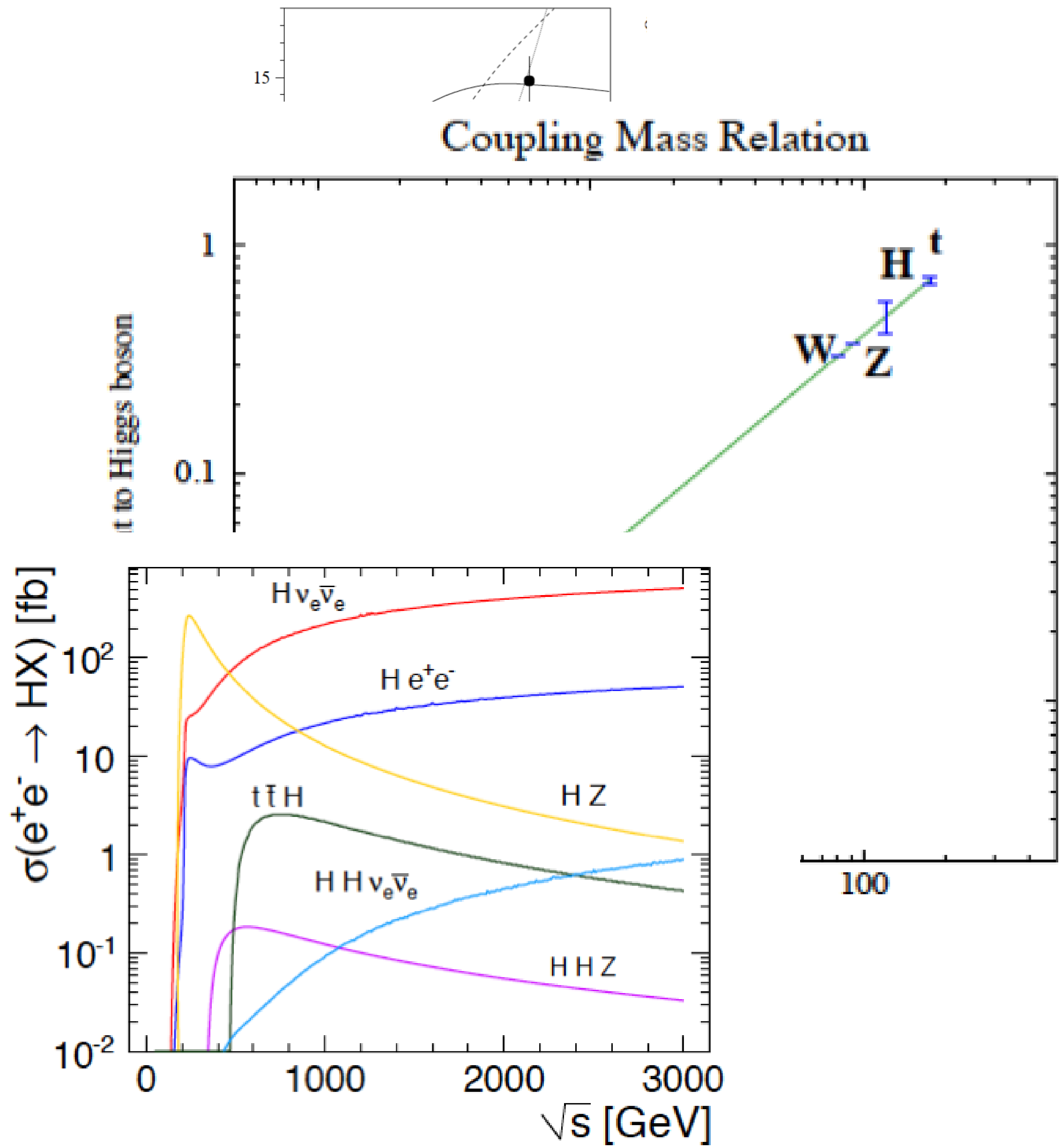
- Synchrotron radiation P, emitted in a ring of fixed radius, r, scales as P ~ $E^4/(r^2m^3)$.
  - Electron/positron circular colliders must have a very large radius, with the radius/cost scaling roughly as the square of the beam energy.
- On the other hand electrons/positrons are very accessible fundamental particles that are easy to accelerate, so go linear
- In the SLC, electron and positron beams were accelerated in a single pass through a two-mile linear structure.
- The Z^0 production rate increased steadily as improvements were made to the operation SLC
  - In 1992-1995, 150 thousand Z^0 events were accumulated. In 1996-1998, 380 thousand Z^0 events were accumulated, including over 200 thousand events in less than 6 months of operation in 1998.
  - The numbers shown in red are the polarization of the electron beam.



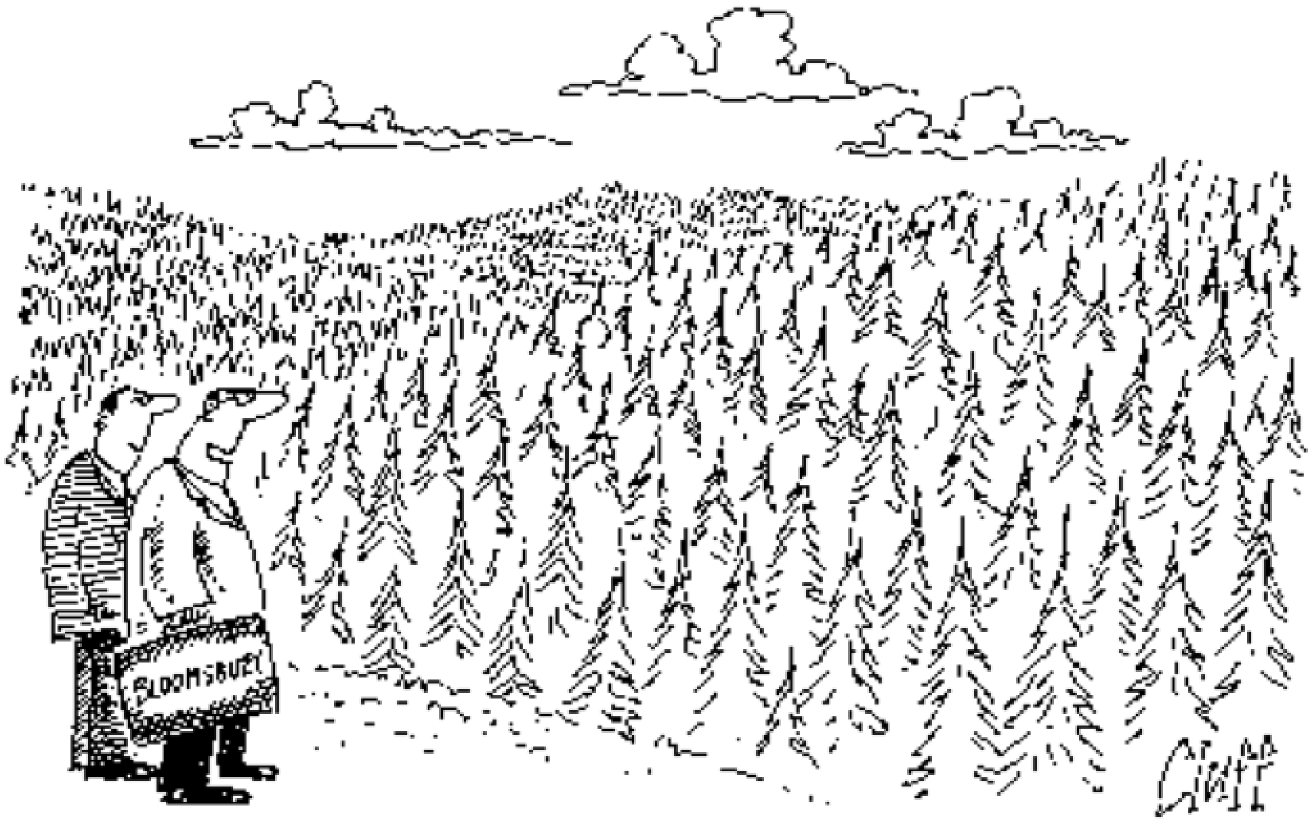


Higgs – 120 GeV in this case

- Precision measurements from ILC RDR and CLIC CDR (volume 2 in both cases)
- 20 fb^{-1} per point for spin measurements
- Couplings (in this plot): 300 GeV and 500 fb^{-1} for b, τ, e, 500 GeV for W, Z, H (self-coupling), 700 GeV for top (ab^{-1})
- Higgs self coupling error reduced to 12% if running at 1 TeV (1 ab^{-1})
- CLIC studies compatible, has focused on running at 3 TeV (large WW fusion cross-section) and 2 ab^{-1} leading to reduced statistical errors and access to difficult cases as coupling to muons (23% error)
- Note that these measurements are "not theory dependent" and provide an absolute measure (important for BSM scenarios)
- To be compared – at some point - to LHC at 1-2 ab^{-1} and dedicated triggers, analyses and upgrades, which can cover some of the same measurements



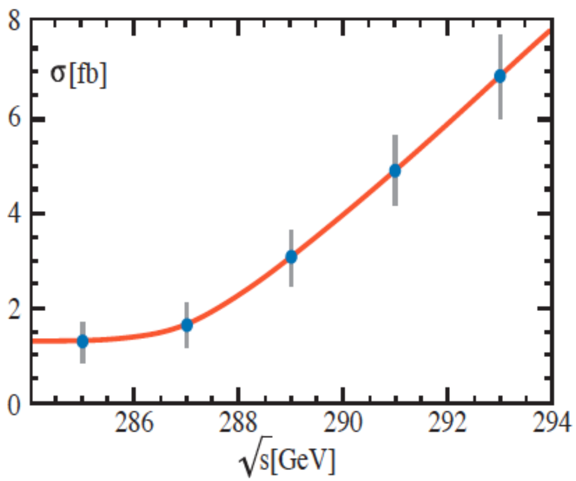
… there might be more

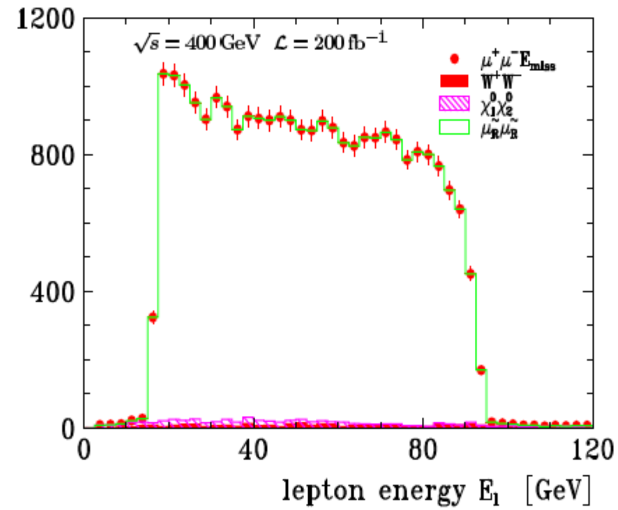


"One day, all of these will be supersymmetric phenomenology papers."

Supersymmetry

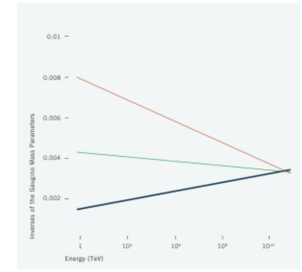
- Complex and exiting arena for a LC where high precision and energy flexibility will be paramount
- Energies determined from threshold scans, or edges of lepton energy spectrum in decays of for example slepton -> lepton + neutralino





Process	Decay Mode	σ (fb)	$m_{\tilde{\ell}}$ (GeV)	$m_{\tilde{\chi}_1^0}$ or $m_{\tilde{\chi}_1^\pm}$ (GeV)
$e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^-$	$\mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	0.71 ± 0.02	1014.3 ± 5.6	341.8 ± 6.4
$e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-$	$e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	6.20 ± 0.05	1001.6 ± 2.8	340.6 ± 3.4
$e^+e^- \to \tilde{e}_L^+\tilde{e}_L^-$	$\tilde{\chi}_1^0\,\tilde{\chi}_1^0\,e^+e^-\,(h/Z^0\,h/Z^0)$	2.77 ± 0.20		
$e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e$	$\tilde{\chi}_1^0\,\tilde{\chi}_1^0 e^+e^-\,W^+W^-$	13.24 ± 0.32	1096.4 ± 3.9	644.8 ± 3.7

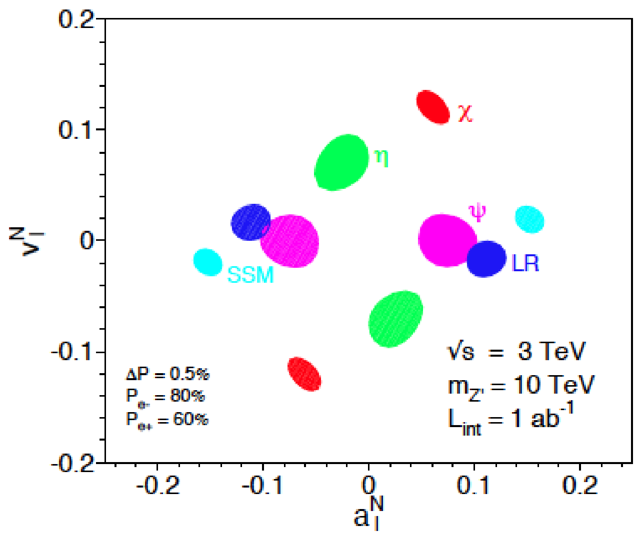
Precision important in order to understand a complex spectrum, to be able to disentangle various models and to extrapolate towards high energies, as well as addressing key questions – e.g. as if the theory provides a suitable Dark Mark Matter candidate.

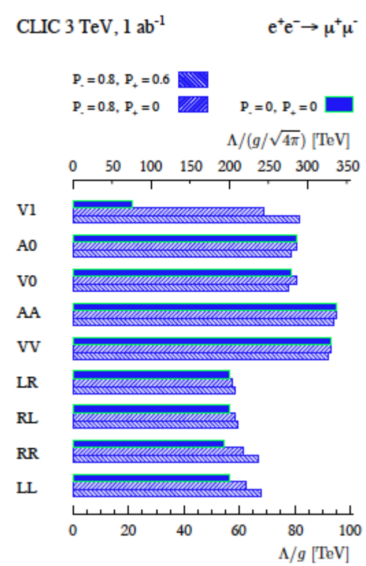


Other physics

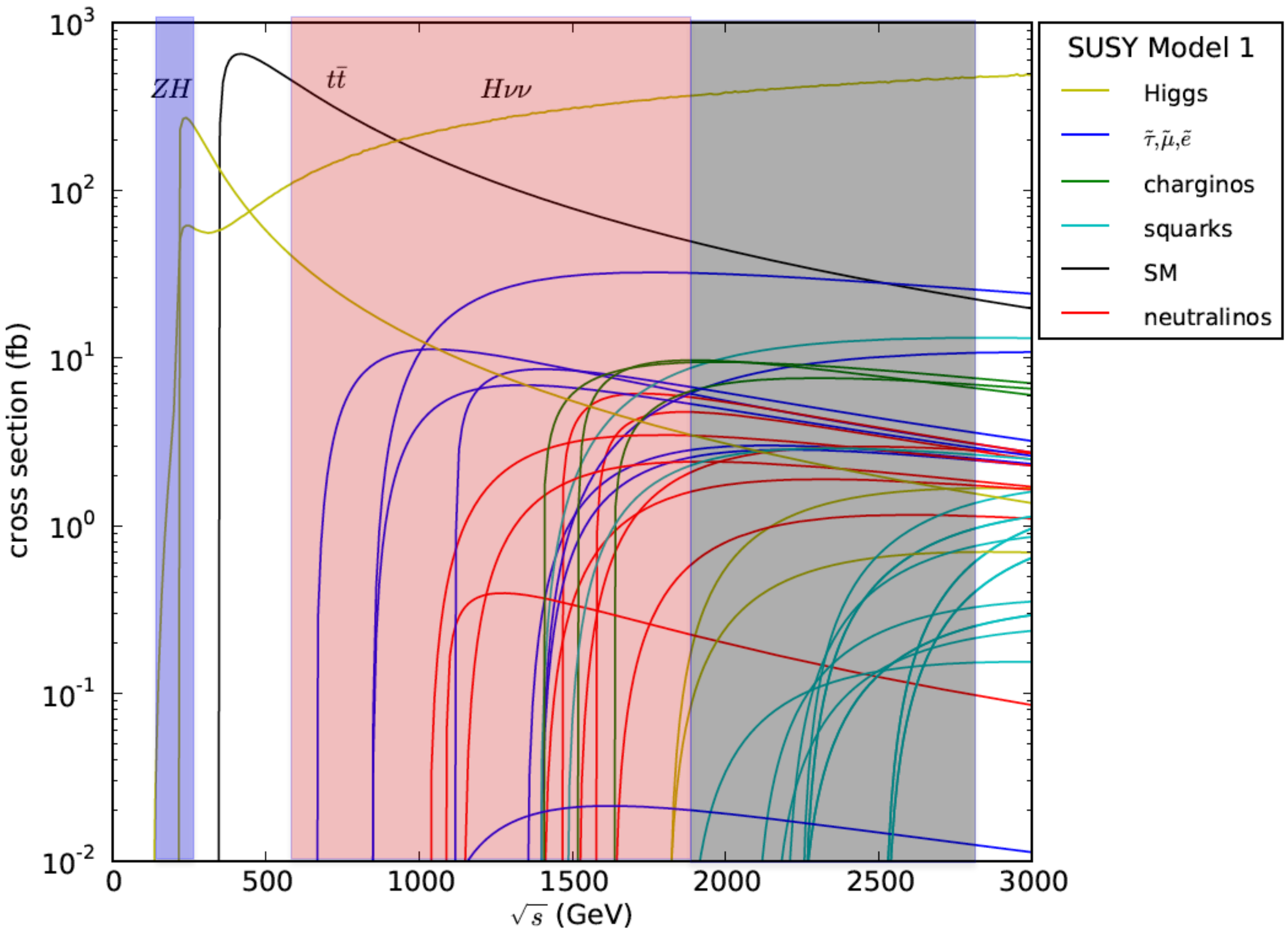
A wealth of other physics related to top and SM precision tests, new forces, extra dimensions, little Higgs, strong interaction models …
And a LC can have reach way beyond its CMS energy (illustrated in the plots below)

.. but beyond the scope of this talk, see:
http://www.linearcollider.org/about/Publications/Reference-Design-Report
http://lcd.web.cern.ch/LCD/CDR/CDR.html#Overview





A very rich physics to be addressed
…. need LHC to guide the way

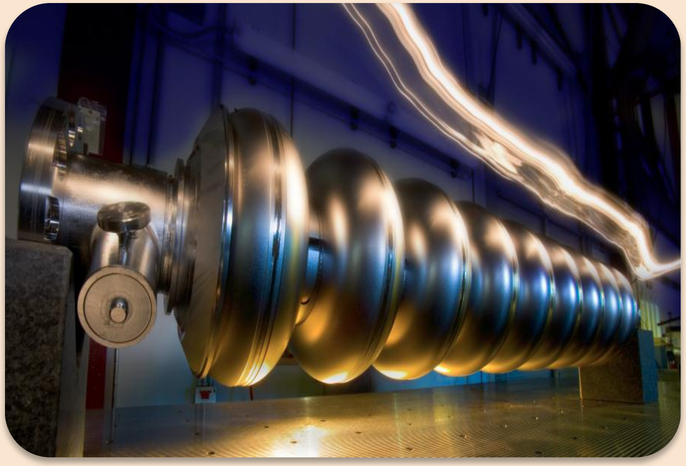


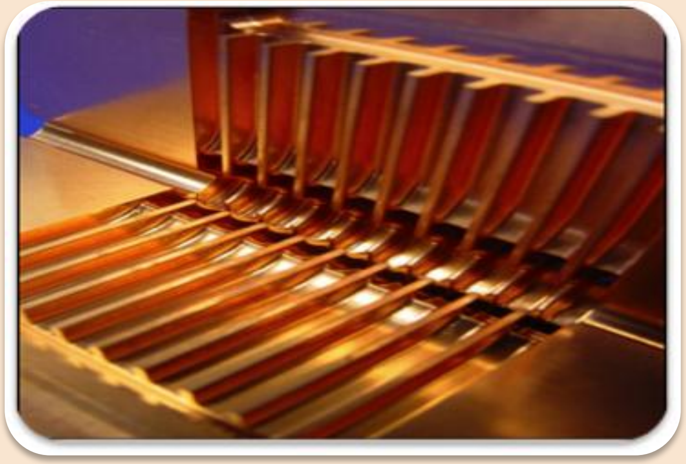
LHC is currently probing the low energy part (SM Higgs or similar) – providing justification for a "low" energy machine

LHC is also addressing a large number of other possible models, in particular a part of the SUSY parameter space and could provide a higher energy scale as well.

Furthermore, intermediate energy scales can also open up (directly or through cascade decays)

.. or something very different





ILC (International Linear Collider)

1.3 GHz superconducting RF

500 GeV – 1 TeV

Focus on 500 GeV machine and detector/physics studies but parameter set exists for 1 TeV, as well as physics studies at other energies

Detector R&D and detector concepts (ILC, SiD)

CLIC (Compact Linear Collider)

12 GHz room temperature copper RF, powered by intense drive beam

500 GeV – 1.5 – 3.0 TeV stages

Focus on 3 TeV and parameter set for 500 GeV, intermediate range now being considered – both for accelerator and detectors

Detector and physics studies carried out for CLIC conditions and adapted detector concepts

Main parameters

		500GeV Reference noTF	TF
Ecm	GeV	500	500
gamma		4.89E+05	4.89E+05
N	e10	2.0	2.0
frep	Hz	5.0	5.0
Nb		1312	1312
PB	MW	10.5	10.5
sigz	mm	0.3	0.3
enx	m	1.0E-05	1.0E-05
eny	m	3.5E-08	3.5E-08
betax	mm	11.00	11.00
betay	mm	0.48	0.20
sigx	nm	474.2	474.2
sigy	nm	5.9	3.8
theta_x	ur	43.1	43.1
theta_y	ur	12.2	18.9
Dx		0.3	0.3
Dy		24.6	38.2
Upsilon		0.1	0.1
Ngamma		1.7	1.7
deltaB		4%	4%
HDx		1.1	1.1
HDy		6.1	2.8
HDy		2.0	1.5
Dp/p e+	%	0.087	0.087
Dp/p e-	%	0.22	0.22
P e+	%	22	22
P e-	%	80	80
L			
Lgeo		7.51E+33	1.16E+34
L (formula)		**1.47E+34**	**1.75E+34**
Simulation (noTF)			
Ngamma			
deltaB(%)		4.30	
L		1.49E+34	
L(1%)		62.5	
Simulation (TF)			
Ngamma			
deltaB(%)			4.33
L			2.05E+34
L(1%)			60.8
L(TR)/L(no)			

parameter	symbol		
centre of mass energy	E_{cm} [GeV]	500	3000
luminosity	$\mathcal{L}$ $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	2.3	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	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]	70	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]	240	560

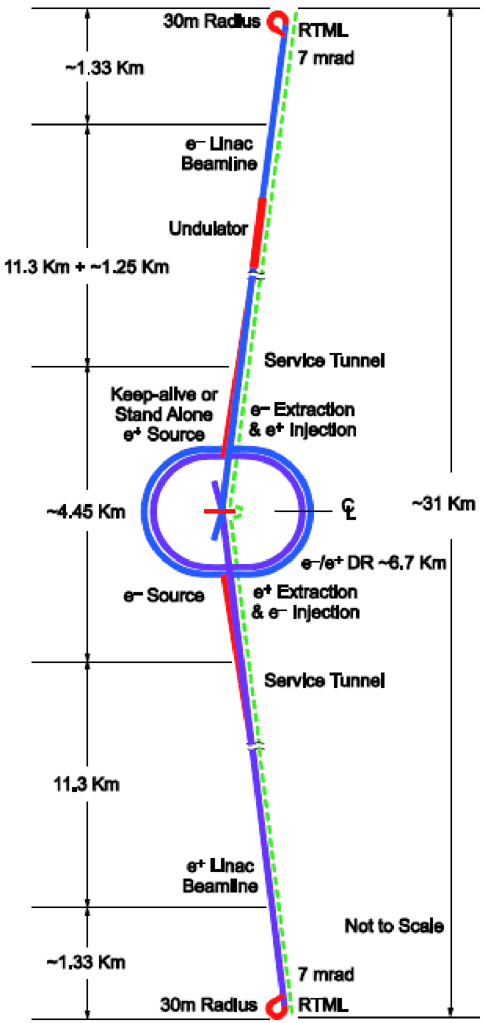
1-2 TeV interm. parameter sets exists for CLIC – using 3 TeV performance parameters

Other key ILC parameters, 31 km, 31.5 MV/m gradient, distance between bunches 700 ns, power 215 MW (RDR value)
1 TeV parameter set(s) being developed for ILC:

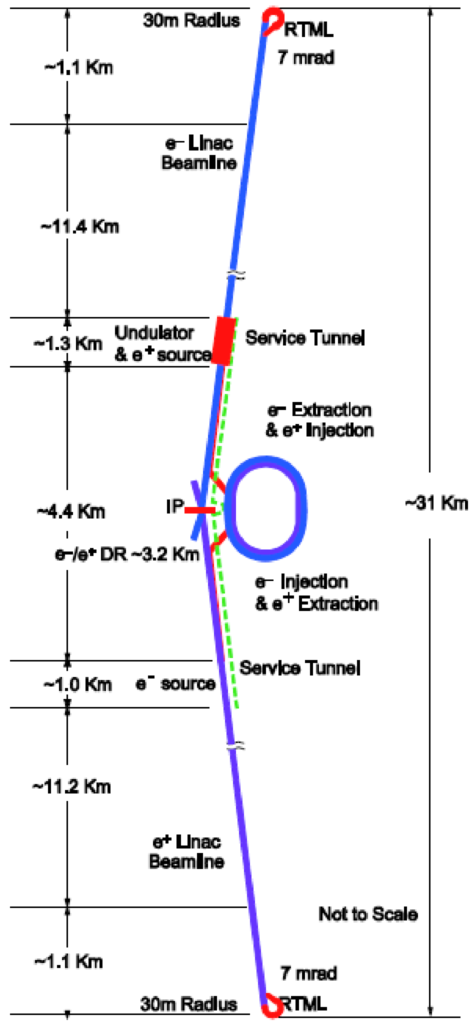
- Power < 300MW AC
- New linac grad = 45 MV/m
- Improved $Q_0 = 2\ 10^{10}$

Proposed Design changes for TDR

RDR

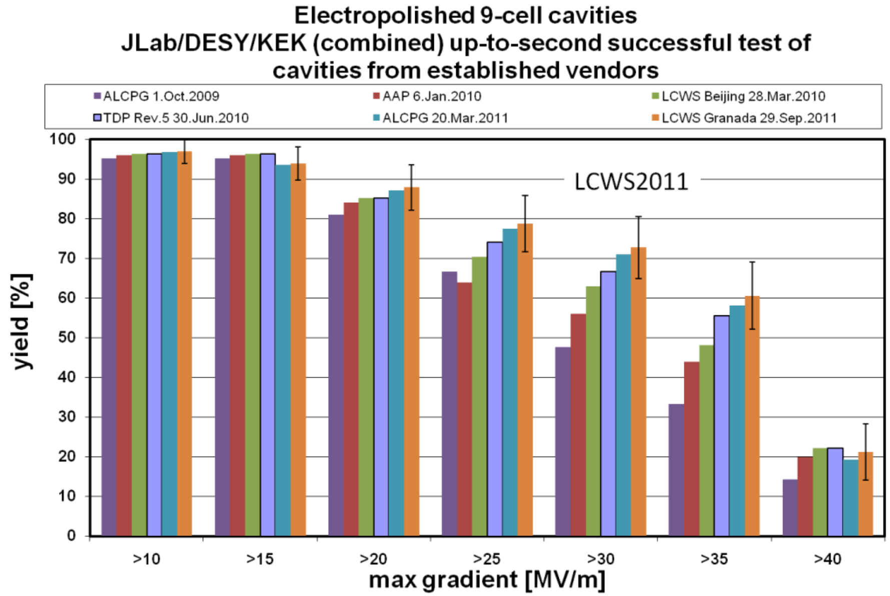


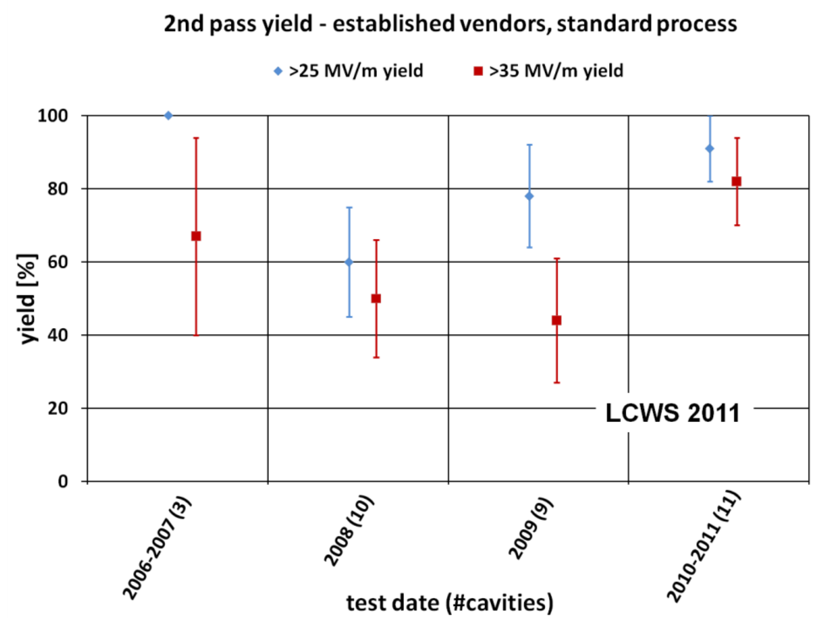
SB2009



- **Single Tunnel for main linac**
- **Move positron source to end of linac**
- **Reduce number of bunches factor of two (lower power)**
- **Reduce size of damping rings (3.2km)**
- **Integrate central region**
- **Single stage bunch compressor**

- Toward TDR goal (90%)
- Field emission; mechanical polishing
- Other progress





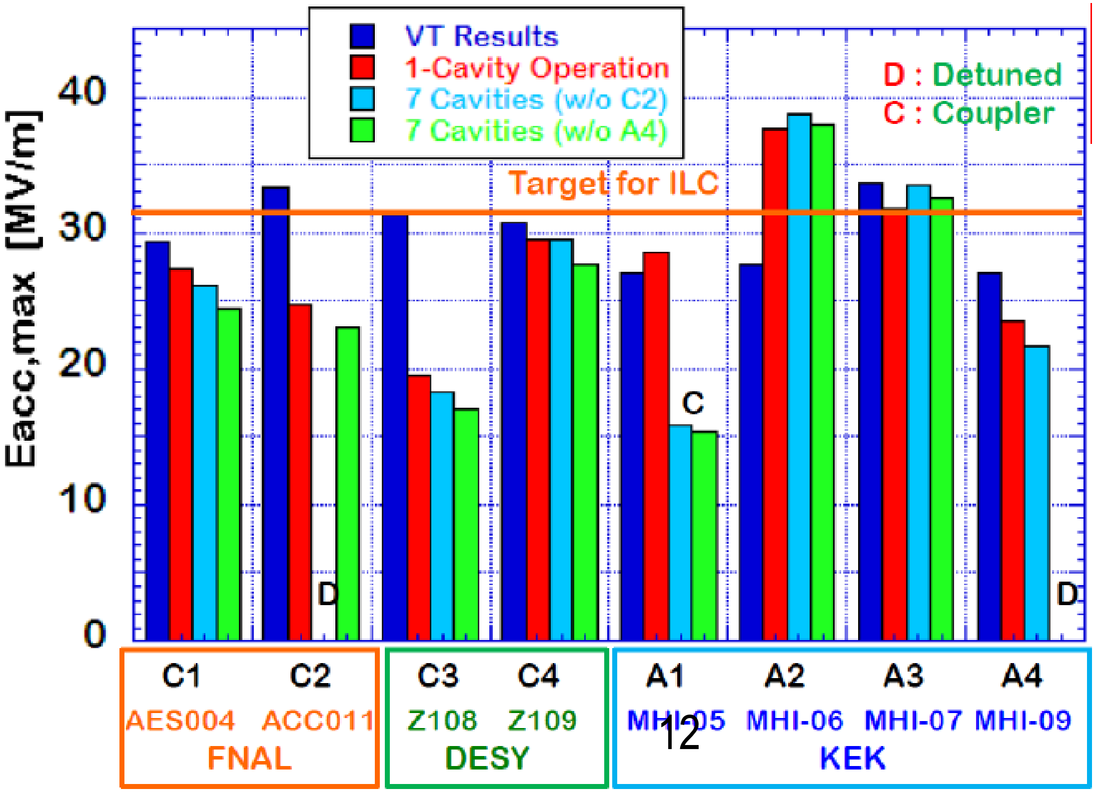
2011/9/30 LCWS11 K.Yokoya

C.Ginzburg Sep.29.2011

S1Global

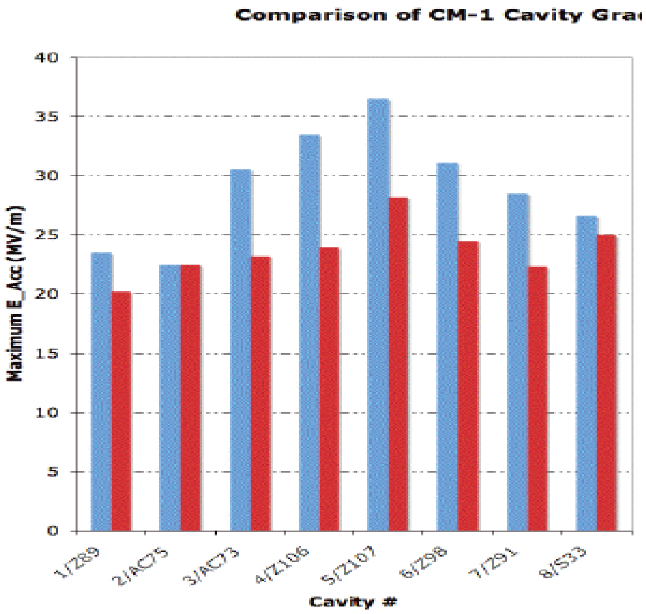
- 8 cavities in 2 cryostat from over the world tested at KEK
- Goal
  - 31.5MV/m, stability DV/V<0.07%, Df<0.24deg)
  - Plug-compatibility
  - Various tests (heat load, LFD, etc)

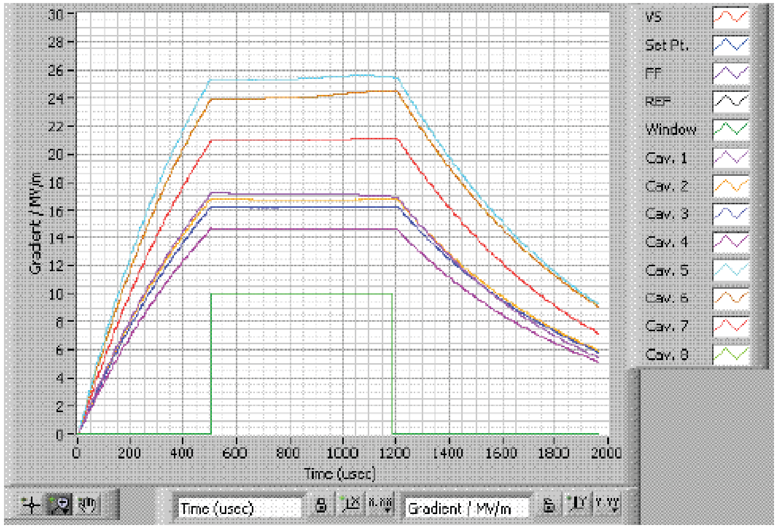
- Achieved gradient (VT: 30MV/m)
  27MV/m (1cav), 26MV/m (7cav)
- Successfully finished before the 3.11 earthquake
- Summary Report writing in progress



NML Module 1 at FNAL

- TTF Type III+ 8-cavity (DESY 'kit', assembly at FNAL) "**S1-Local**"
- Test since Jan.2010
- Average 23.7MV/m (82.7% of Chechia test)
- LFD compensation test
- LLRF



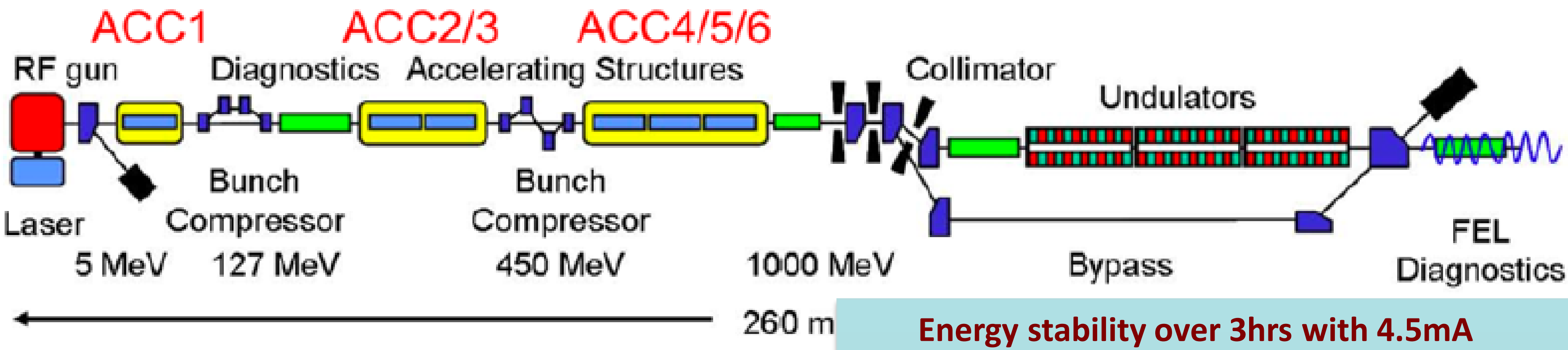


From E.Harms

2011/9/30 LCWS11 K.Yokoya

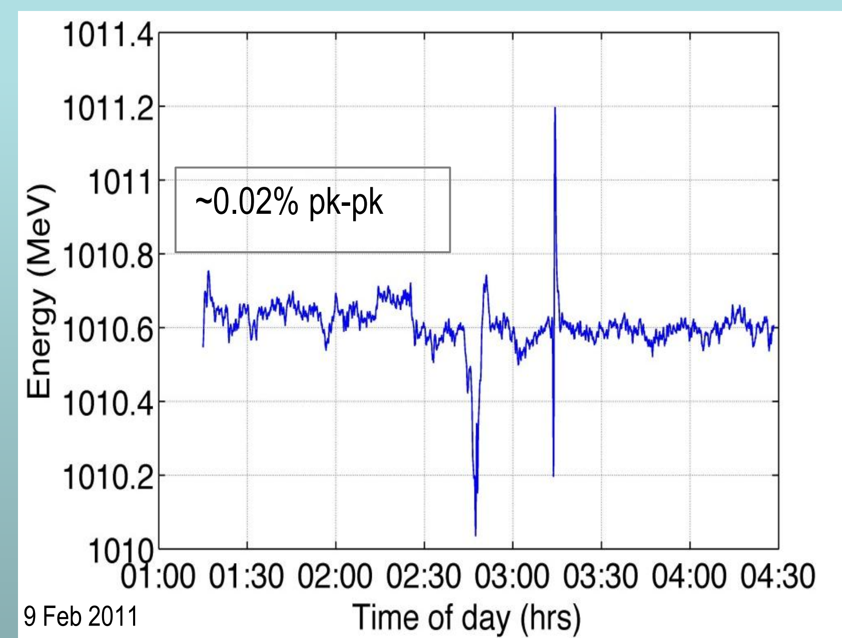
TTF/FLASH 9mA Experiment

Full beam-loading long pulse operation → "S2"

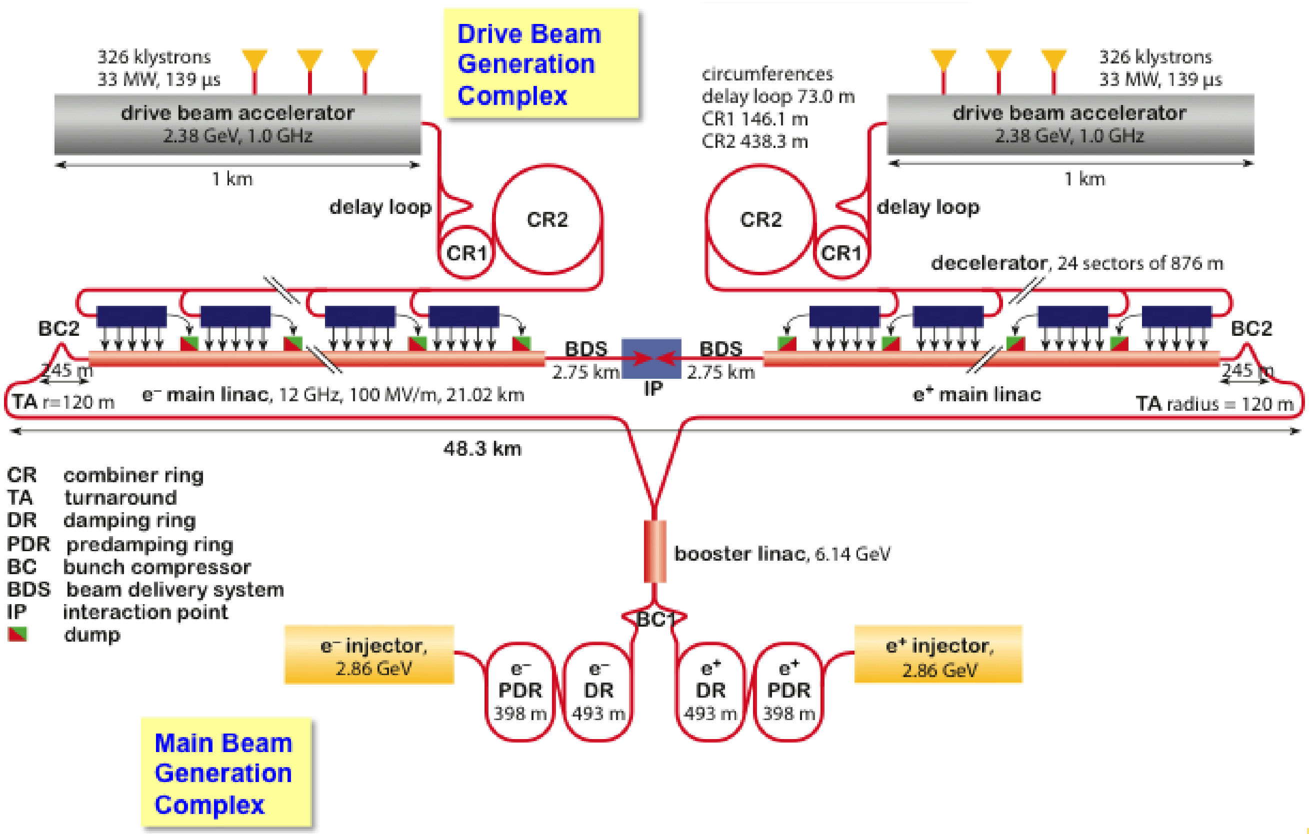


		XFEL	ILC	FLASH design	9mA studies
Bunch charge	nC	1	3.2	1	3
# bunches		3250	2625	7200'	2400
Pulse length	μs	650	970	800	800
Current	mA	5	9	9	9

Energy stability over 3hrs with 4.5mA

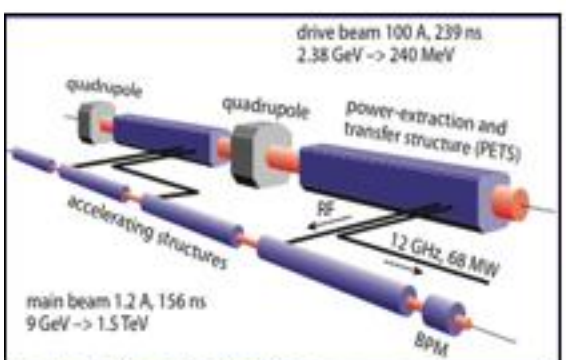


The CLIC Layout

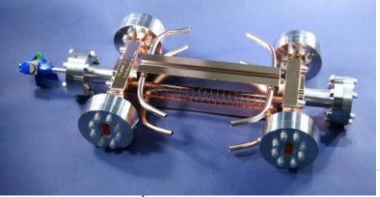


Feasibility issues studied:

Drive beam generation
Beam driven RF power generation
Accelerating Structures
Two Beam Acceleration
Ultra low emittances and beam sizes
Alignment
Vertical stabilization
Operation and Machine Protection System

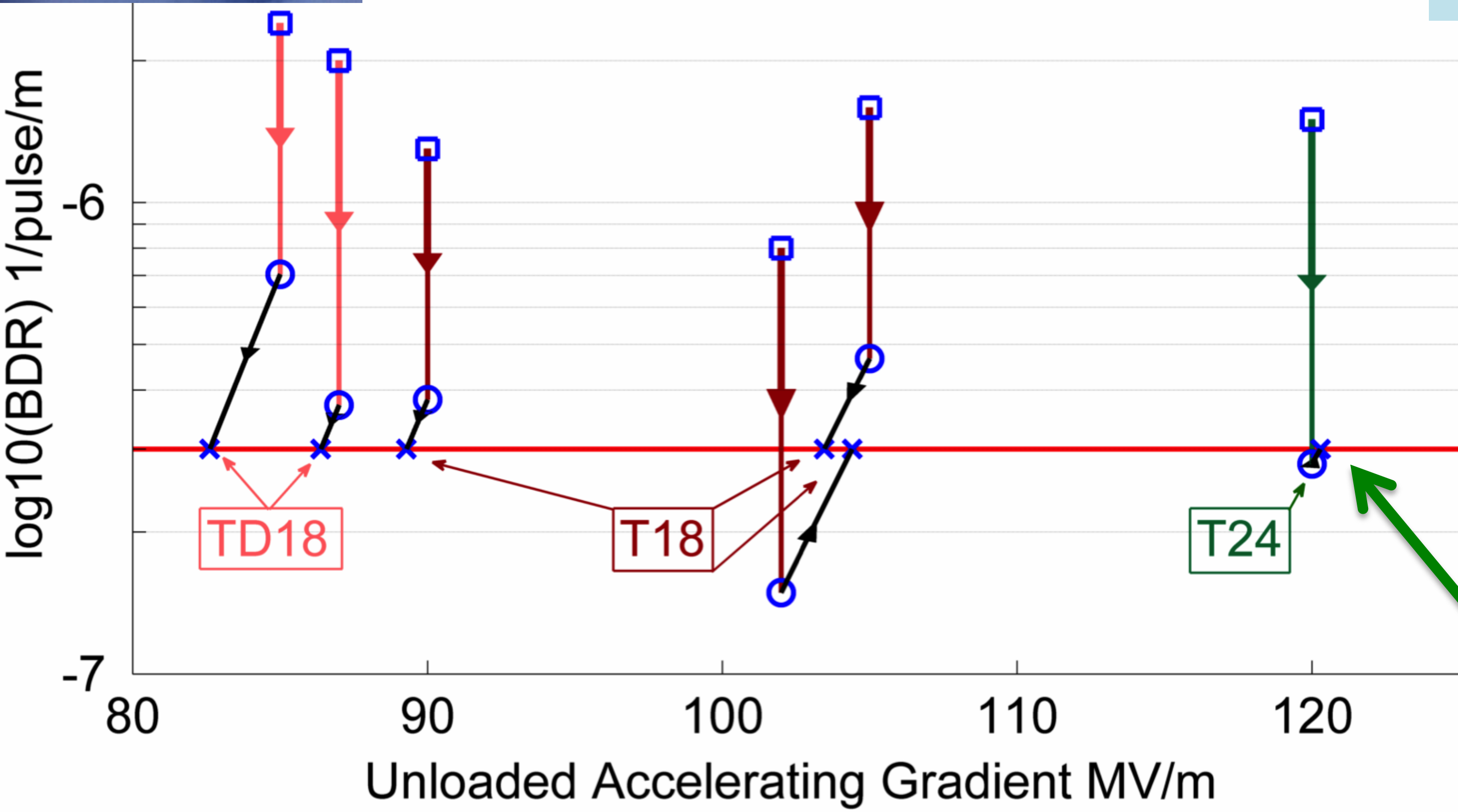


parameter	unit	CLIC	CTF3
accelerated current	A	4.2	3.5
combined current	A	101	28
final energy	MeV	2400	≈ 120
accelerated pulse length	μs	140	1.2
final pulse length	ns	240	140
acceleration frequency	GHz	1	3
final bunch frequency	GHz	12	12



Achieved Gradient

Tests at KEK and SLAC



Measurements scaled according to:

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

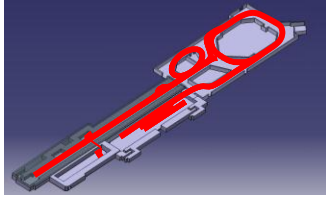
Require breakdown probability 1% per pulse i.e. ≤ $3\times10^{-7}m^{-1}pulse^{-1}$

Same input power as 100MV/m loaded

CLIC RF team
N. Shipman

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

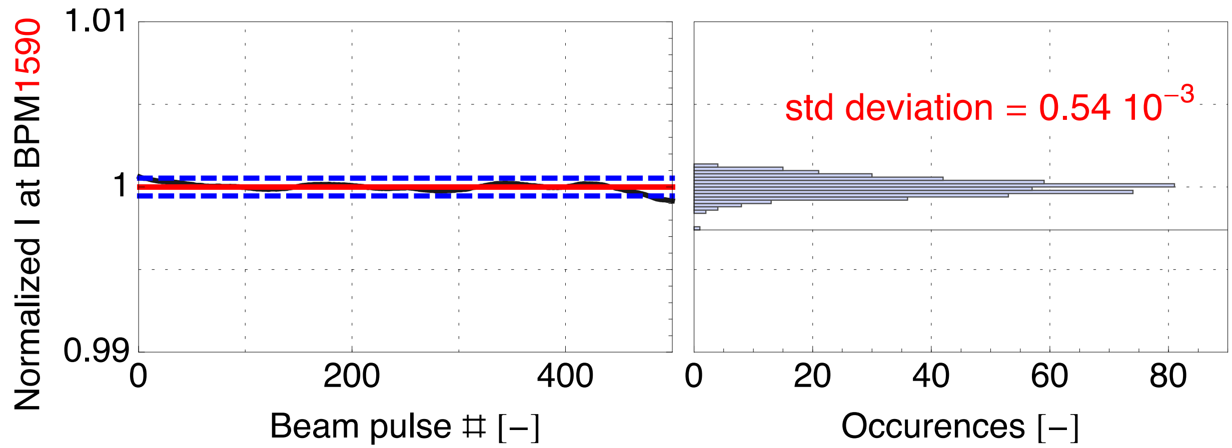
TD24: September 15th @ KEK
mid-November @ SLAC
Soon @ CERN



CTF3 results

Pulse charge measured at end of the linac

After factor 8 combination
~ 1% jitter



CTF3 specific issues need to Be addressed and limits identified

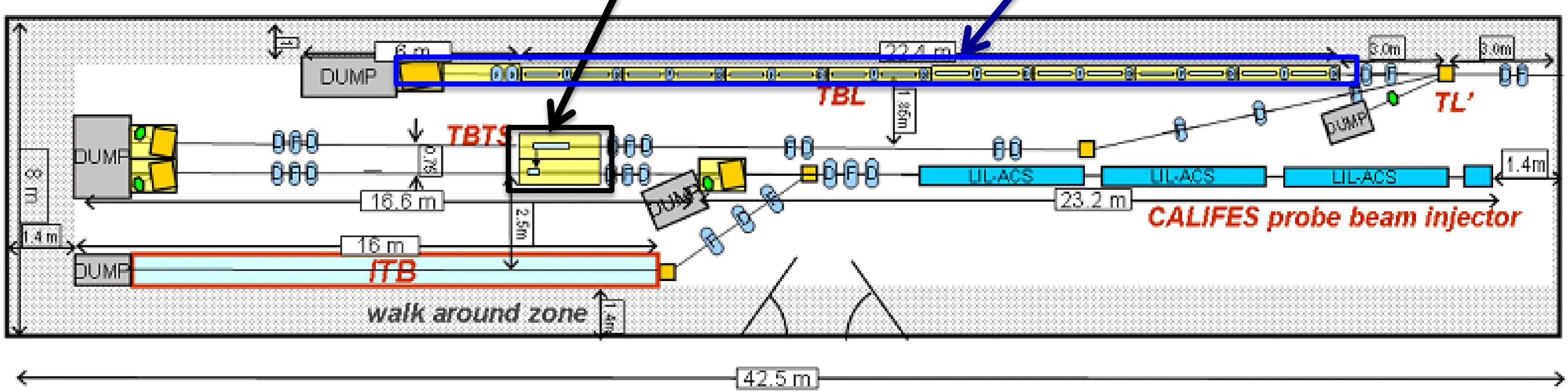
- RF pulse compression
- Beam energy in combiner ring is 5% of that in CLIC
- Geometric emittance 20 times larger
- Instrumentation …

TBTS (two-beam test stand)

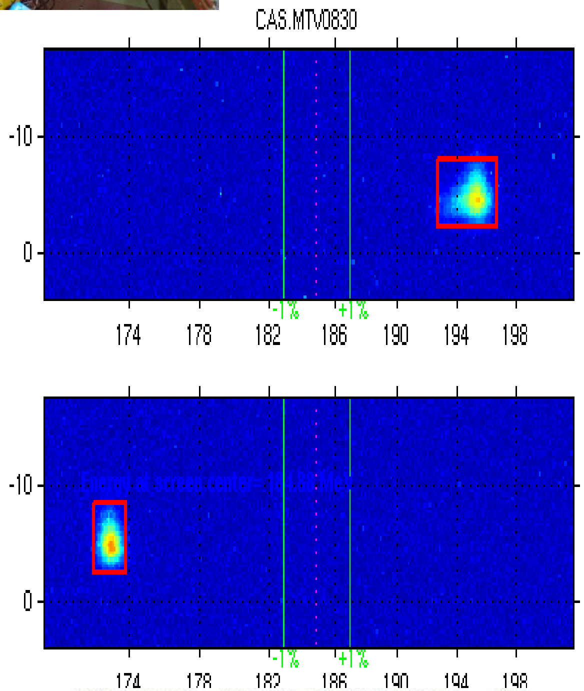
- power transfer to main beam
- module design

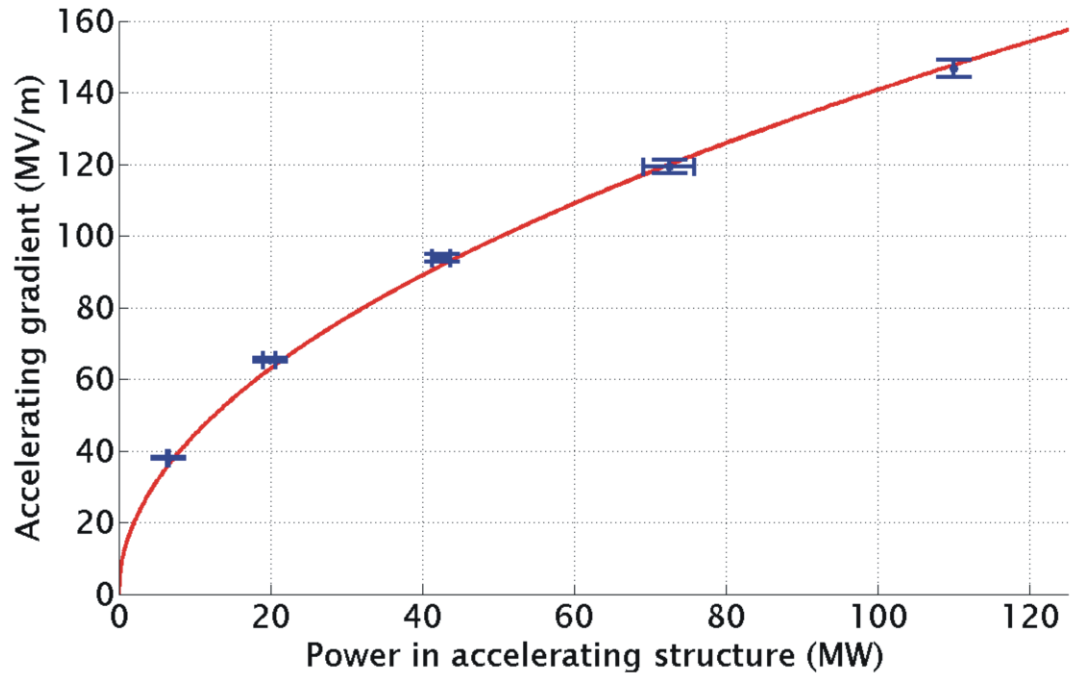
TBL (test beam line)

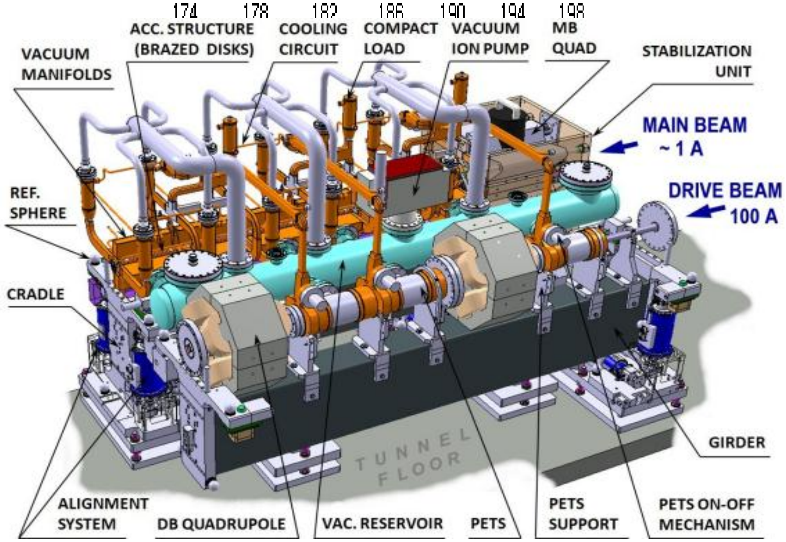
- drive beam stability during deceleration



TBTS: Two Beam Acceleration





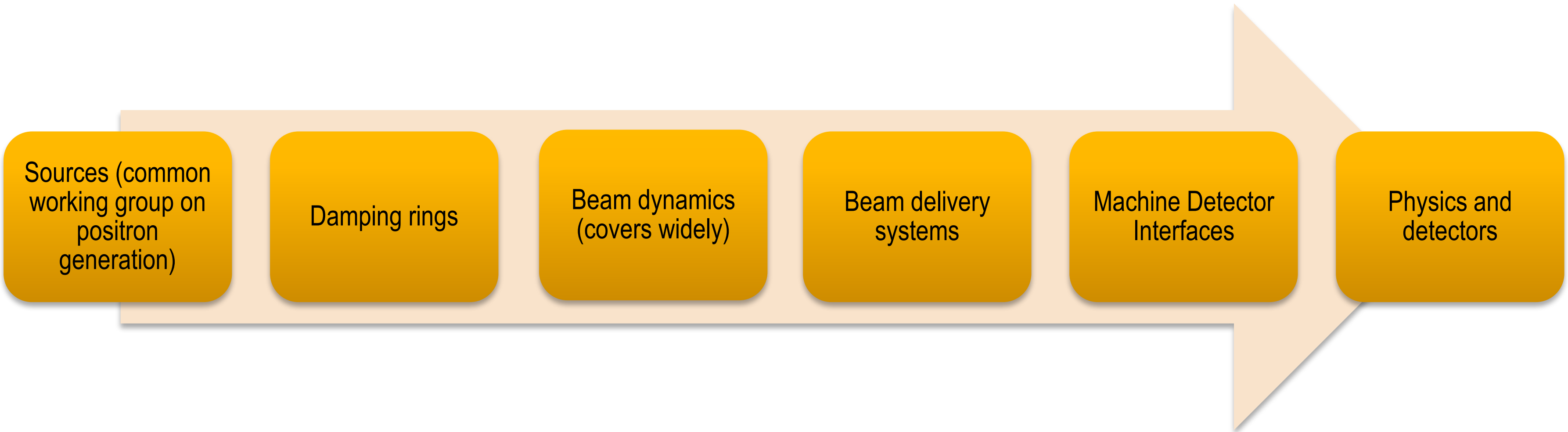


Maximum gradient 145 MV/m

Consistency between
- produced power
- drive beam current
- test beam acceleration

LC common studies

Many common problems and solutions even though the basic core acceleration methods differ, and the parameters to be achieved by the systems below differ – in some cases leading to different solutions

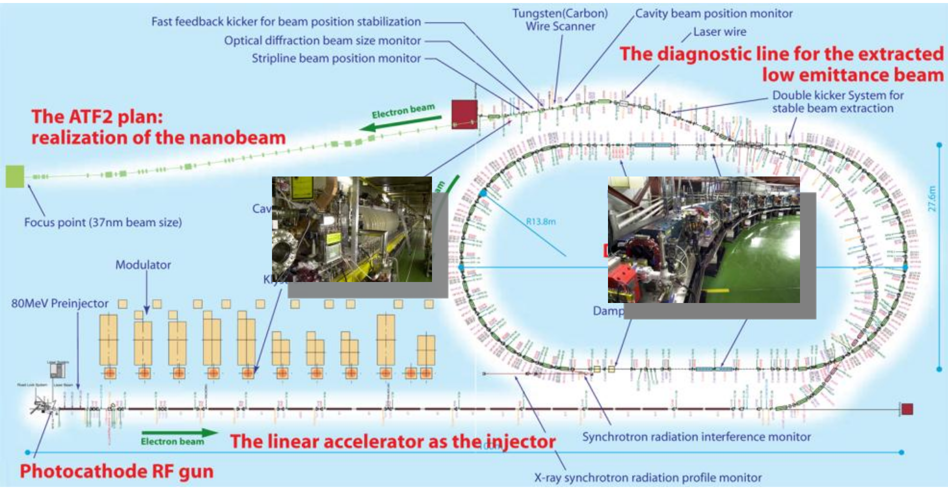


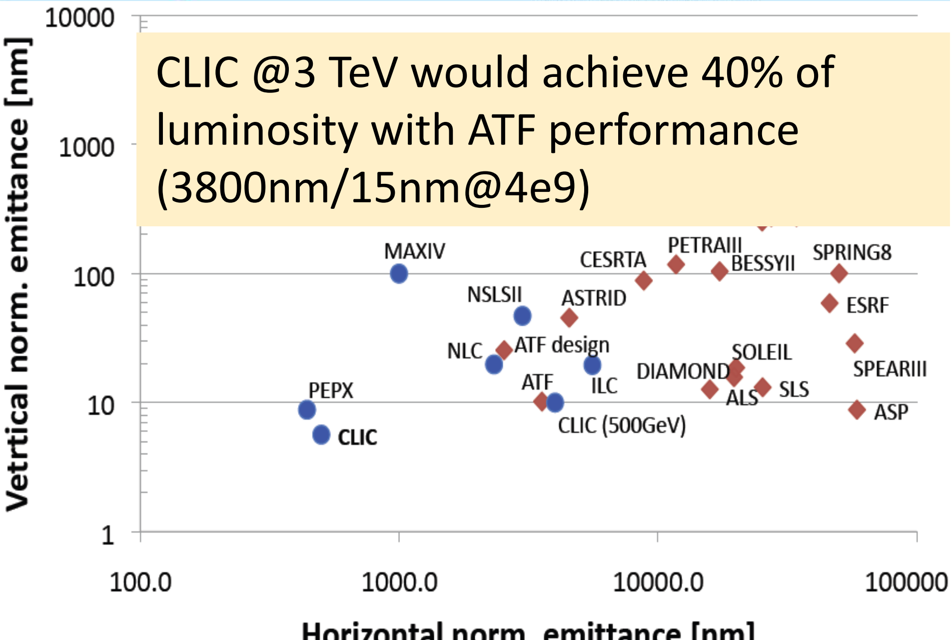
In addition common working groups on: Cost and Schedule, Civil Engineering and Conventional Facilities – and a General Issues Working Group

Will illustrate some of these items too ..

Importance of Generic Test Facilities on Linear Colliders Common Issues

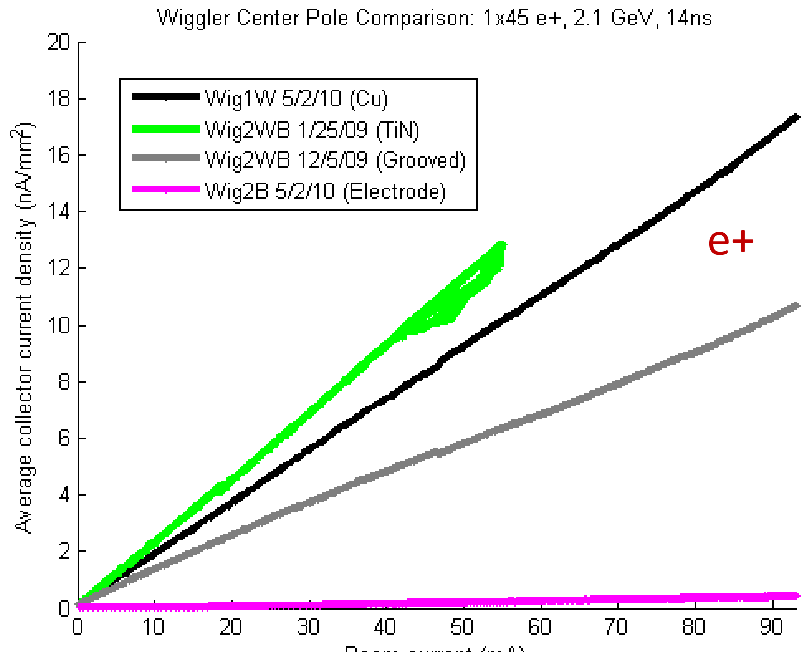
ATF/KEK: ultra low emittance and nanometer beam sizes

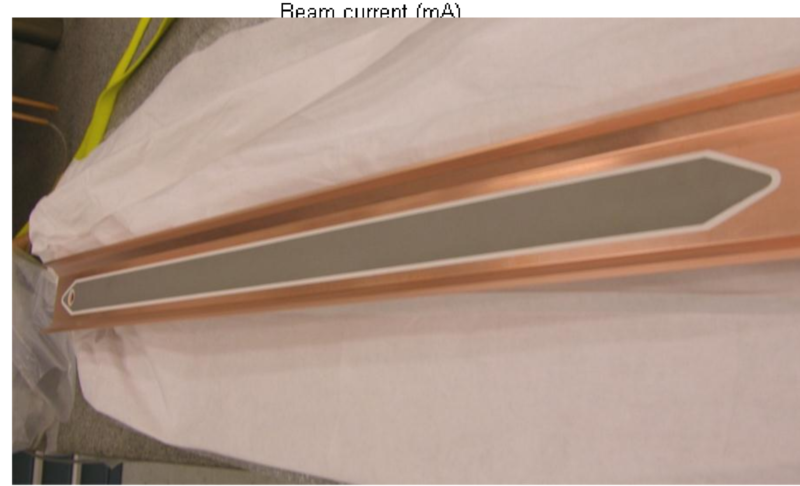




CLIC @3 TeV would achieve 40% of luminosity with ATF performance (3800nm/15nm@4e9)

CESR-TA/Cornell: Electron cloud



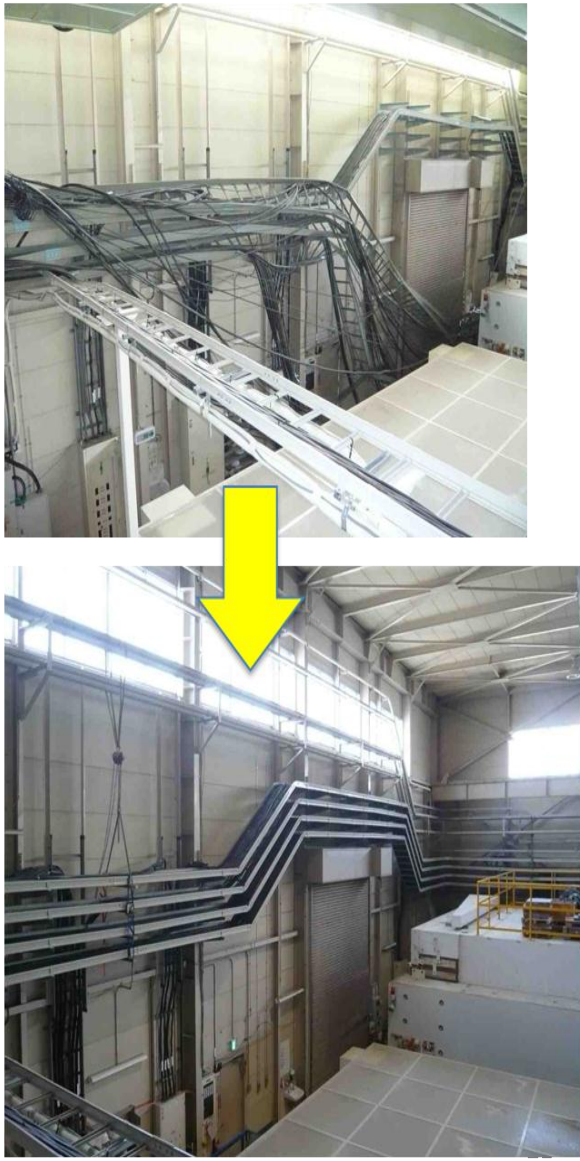


Importance of Generic Test Facilities on Linear Colliders Common Issues

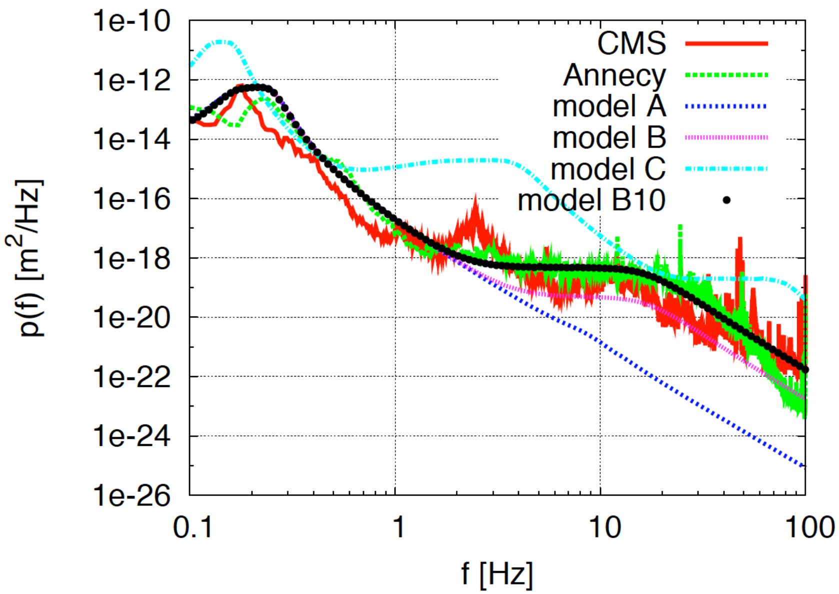
The fast recovery of all the ATF accelerator systems after the Great Eastern Japan Earthquake on 11 March 2011 has been remarkable. Given the scale of the damage incurred, its speed exceeded the most optimistic expectations.

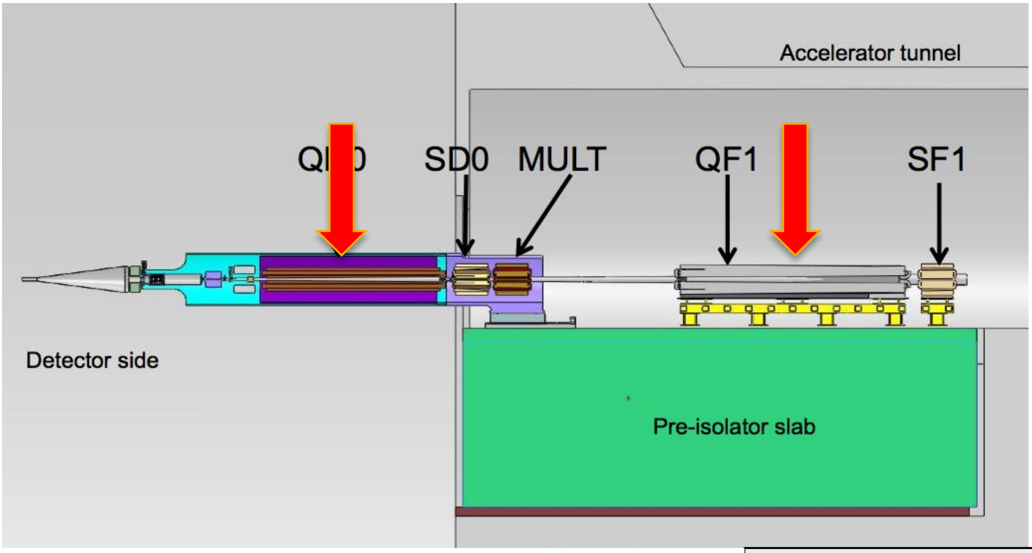
In response to delays incurred from the earthquake it is decided **to extend the approved ATF/ATF2 operation until March 2014**

The **proposed ATF plan for the period 2014-2018 included important activities for further LC studies (input both from ILC and CLICC)**

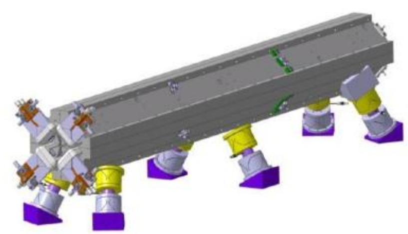


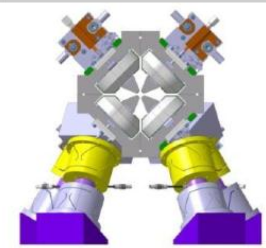
Ground Motion and Its Mitigation



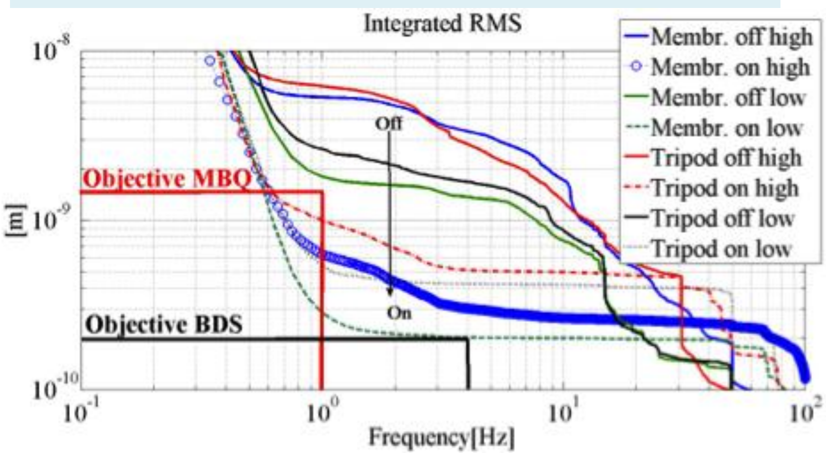


A. Gaddi et al.





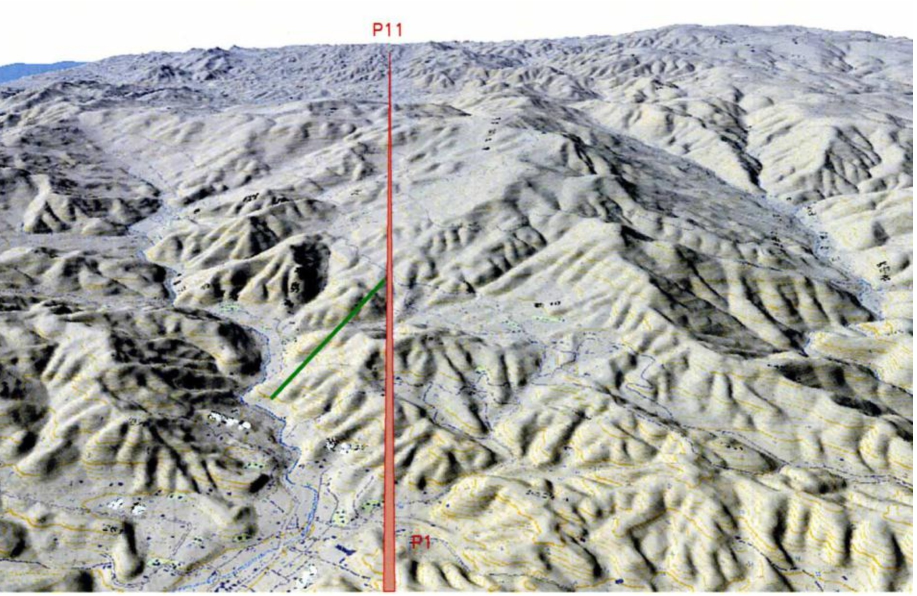
Natural ground motion: typical quadrupole jitter tolerance O(1nm) in main linac and O(0.1nm) in final



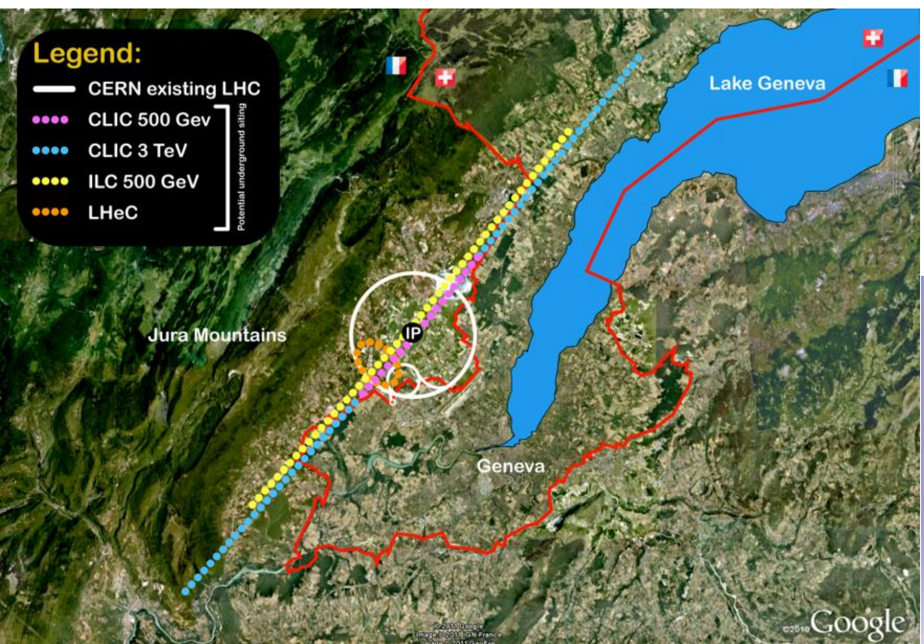
Luminosity achieved/lost [%]

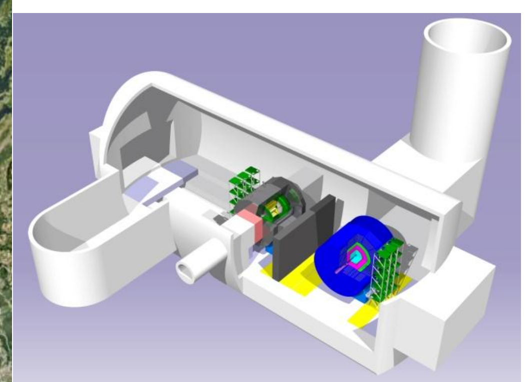
	A	B10
No stab.	119%/2%	53%/68%
Current stab.	116%/5%	108%/13%
Future stab.		118%/3%

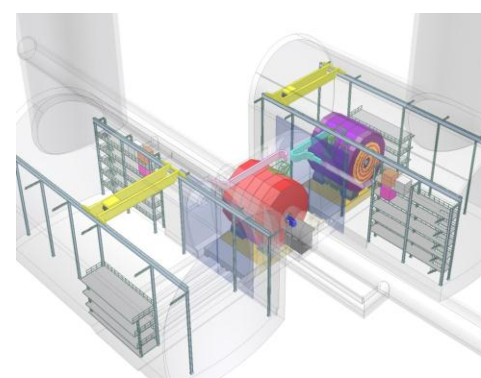
Site-Dependent Study going on



Mountain area tunnel design in Japan



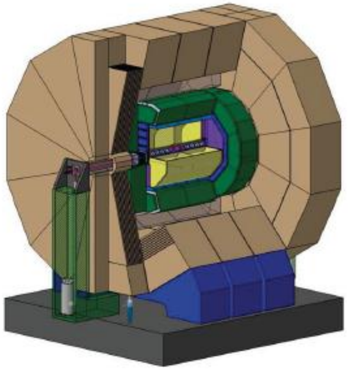




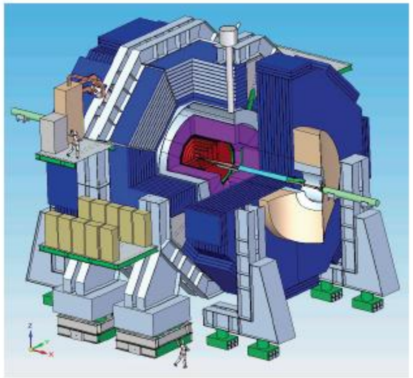
Detector/Physics

- Detector requirements for CLIC and ILC are similar - but some adaptions are needed
- Differences
  - Time structure (0.5 ns vs. 738 ns)
  - Higher background due to; higher energy – general, Smaller bunch spacing – machine specific
  - Other parameters are slightly modified
    - Crossing angle of 20 mradian at CLIC, ILC: 14 mradian
  - Larger beam pipe radius in CLIC (30mm)
  - Denser and deeper calorimetry needed
- However, the detector concepts studies for ILD and SiD and R&D efforts are in most cases relevant for any flavour of the machine

- In general the detectors are very highly granular solenoid based detectors, with very powerful inner trackers and calorimeters optimized for energy flow measurements
- The requirements for granularity, material, power, time-resolution are very challenging



ILD



SiD

TDRs and CDRs

TDR and DBD (end 2012):

- RDR reports in 2007: http://www.linearcollider.org/about/Publications/Reference-Design-Report
- Two volumes by end 2012 for the ILC machine
- Part I: Technical Design Phase R&D
  - Introduction
  - SCRF technology
  - Beam test facilities
  - Accelerator Systems R&D
  - Post TDR R&D
  - Conclusions
- Part II: The ILC Baseline Design
  - Introduction and Overview
  - General parameters and layout
  - SCRF Main Linacs
  - Polarised electron source
  - Positron source
  - Damping ring
  - RTML
  - BDS and MDI
  - Conventional Facilities, Siting and Global Systems
  - The TeV Upgrade Option
  - Scope of post TDR engineering (technical risk assessment)
  - Project Implementation Planning
  - Cost and Schedule
  - Conclusions

- DBD (Detailed Baseline Design) outline for detector March 2012
- Physics scope - March/April 2012?

CDRs (end 2011, volume three mid 2012):

- Vol 1: The CLIC accelerator and site facilities (H.Schmickler)
  - 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 ranges
- Vol 2: The CLIC physics and detectors (L.Linssen)
- Vol 3: CLIC study summary (S.Stapnes)
  - 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)
- Timescales:
  - By end 2011: aim to have Vol 1 and 2 completed
  - Spring/mid 2012: Vol 3 ready for the European Strategy Open Meeting

Main information page:
http://clic-study.org/accelerator/CLIC-ConceptDesignRep.php

Accelerator http://project-clic-cdr.web.cern.ch/project-CLIC-CDR/
- About 90% of the contributions received
- About 60% of the contributions received as final, for the Editorial Board to address

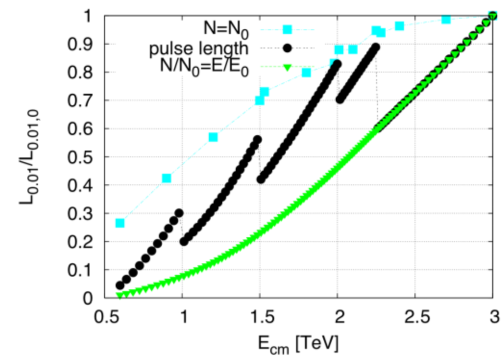
Physics and Detectors
http://lcd.web.cern.ch/LCD/CDR/CDR.html#Overview
- See talk later this afternoon

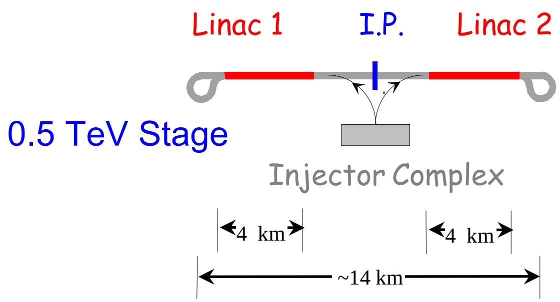
A link providing the opportunity to subscribe as a signatory for the CLIC CDR can be found on the main information page

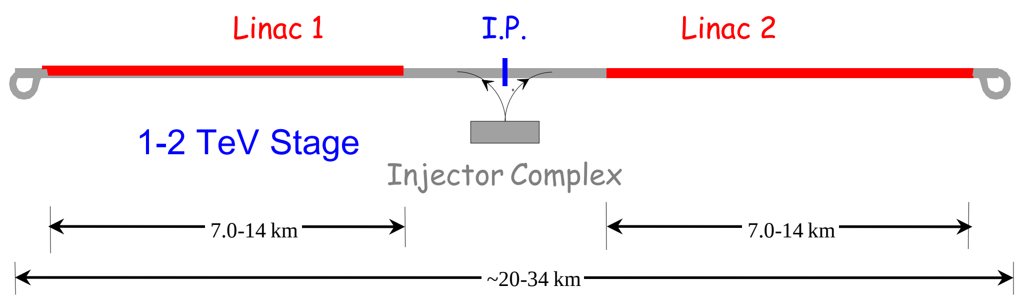
CLIC energy staging

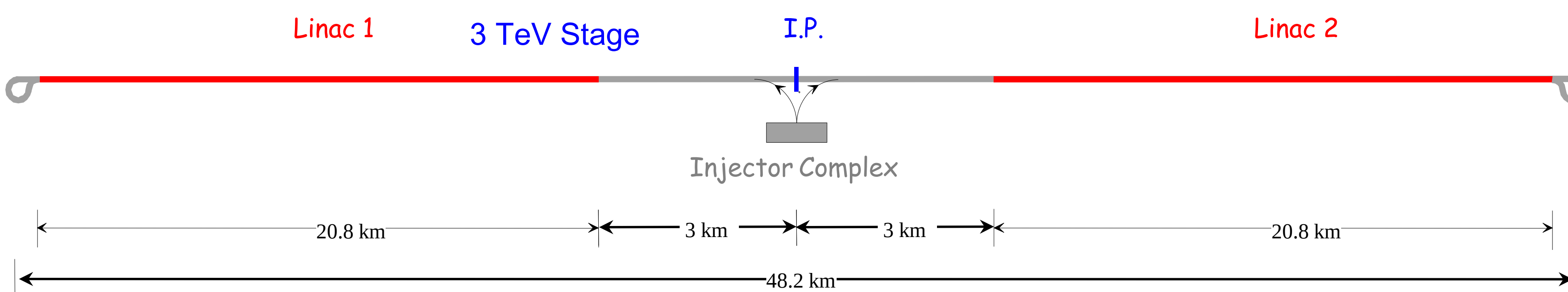
CLIC two-beam scheme compatible with energy staging to provide the optimal machine for a large energy range

Lower energy machine can run most of the time during the construction of the next stage. Physics results will determine the energies of the stages



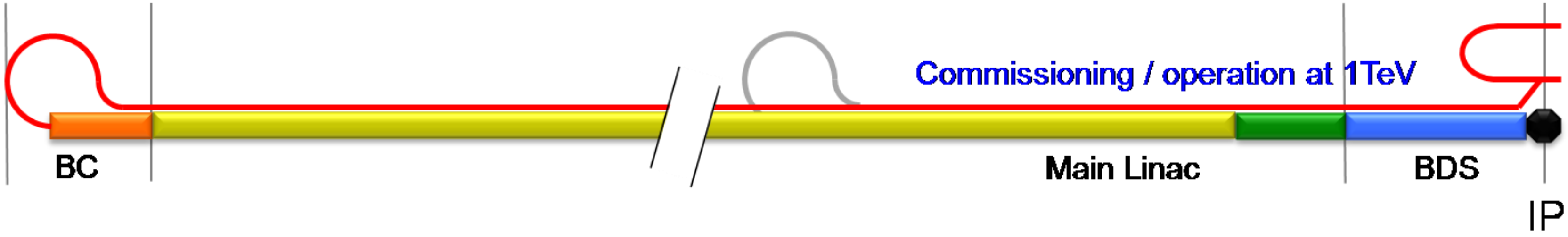






ILC 1TeV Upgrade

- Extending the energy reach
- Scenario
  - 2x250GeV Linac addition at upstream
  - Move turn-around and bunch compressor
  - Undulator at the same location
  - Cost effective design (higher gradient)
- Strawman parameter set
  - Assume operating gradient 45MV/m, $Q_0 > 2 \times 10^{10}$
  - Max site power < 300MW



Energy flexibility

- Currently there is quite some effort to understand better how to build and operate LC at several energies: ILC extended to 1 TeV in a second stage and CLIC at three stages 500 (or lower) GeV, 1-2 TeV intermediate, and then a final stage at ~3 TeV.
- Not trivial at all:
  - Benefits of running close to thresholds versus at highest energy, and distribution of luminosities as function of energy ?
  - From a light Higgs threshold (~200 GeV) to (multi-)TeV, in several stages ?
  - What are the integrated luminosities needed and what it is the flexibility needed within a stage
    - Interested in looking in more detail for at least one model in order to make sure the machine implementation plan can cope with whatever will be needed
    - Complementarity with LHC a key, taking into account where LHC will be in 15-20 years
  - What are reasonable commissioning and luminosity ramp up times ?
    - LHC will need 3 years to get to 50 fb^{-1} and collects ~50 fb-1/year at 10^{34} (roughly) – can an LC do better ?
  - How would we in practice do the tunneling and productions/installation of parts in a multistage approach
    - Cheapest (overall) to do in one go but we don't know final energy needed, and it is likely that we can make significant technical process before we get to next stage
    - Timescales for getting into operation, and getting from one stage to another

- Answers are possible but must be found based on all available information at the time the project is launched

CLIC 2012-16

European Strategy
for Particle Physics
@ CERN Council

Final CLIC CDR and
feasibility established

	2010	2011	2012	2013	2014	2015	2016	2017	....
Feasibility issues (Accelerator&Detector)									
Conceptual design & preliminary cost estimation									
Engineering, industrialisation & cost optimisation									?
Project Preparation									
Project Implementation									?

After 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 accoun 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 with validation facilities

The CLIC International Collaboration

CLIC multi-lateral collaboration - 41 institutes from 21 countries

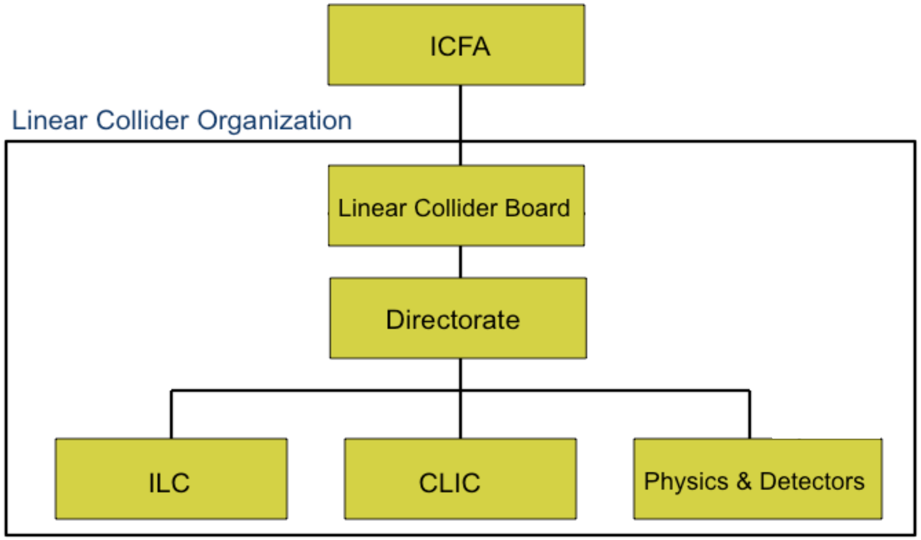
ACAS (Australia)
Aarhus University (Denmark)
Ankara University (Turkey)
Argonne National Laboratory (USA)
Athens University (Greece)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
ETHZurich (Switzerland)
FNAL (USA)
Gazi Universities (Turkey)
Helsinki Institute of Physics (Finland)
IAP (Russia)
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. Univ. 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)

ILC post 2012

- Completion of TDR at end of 2012
  - GDE mission will be completed
    - Some works (TDR review and final printing) still needed (~half year?)
  - New organization expected to start in early 2013
    - Smooth transition required
    - Being discussed in ICFA/ILCSC (→ J.Bagger's talk)
    - Will take some time to start to function
    - Political issues (governance/siting) will become important
- What to do post 2012 for technology?
  - Remaining R&D
  - Facility operation
    - DESY-FLASH, KEK-STF2, FNAL-NML
    - ATF/ATF2
  - Engineering design
  - Industrialization and cost reduction of SCRF components
  - Development of technology for energy upgrade

Linear Collider Organization post 2012

- Mumbai ILCSC meeting resulted in a proposal for an overall LC organization
- Challenges now in implementation of the parts/boxes, and developing further the connections between them



Main messages

- Physics potential of a LC formidable - but LHC results and guidance very much needed
- Technical progress good with the ILC technologies and tests-setups maturing, and CLIC technologies moving from feasibility studies towards implementation studies and optimizations in next phase
- Increased focus on energy flexibility and staged implementation, as well as system testing
- Common work in a large number of areas and also common use of facilities – common working groups and workshops (for both accelerators, detector/physics and site studies)
  - Moving towards a common LC organisation post 2012
- CDRs for CLIC underway, and ILC TDR/DBDs by end 2012

Most slides extracted for talks at the Linear Collider Workshop in Granada last week:
http://www.ugr.es/~lcws11/

Many thanks and apologies for omissions (many) and mistakes (hopefully fewer)