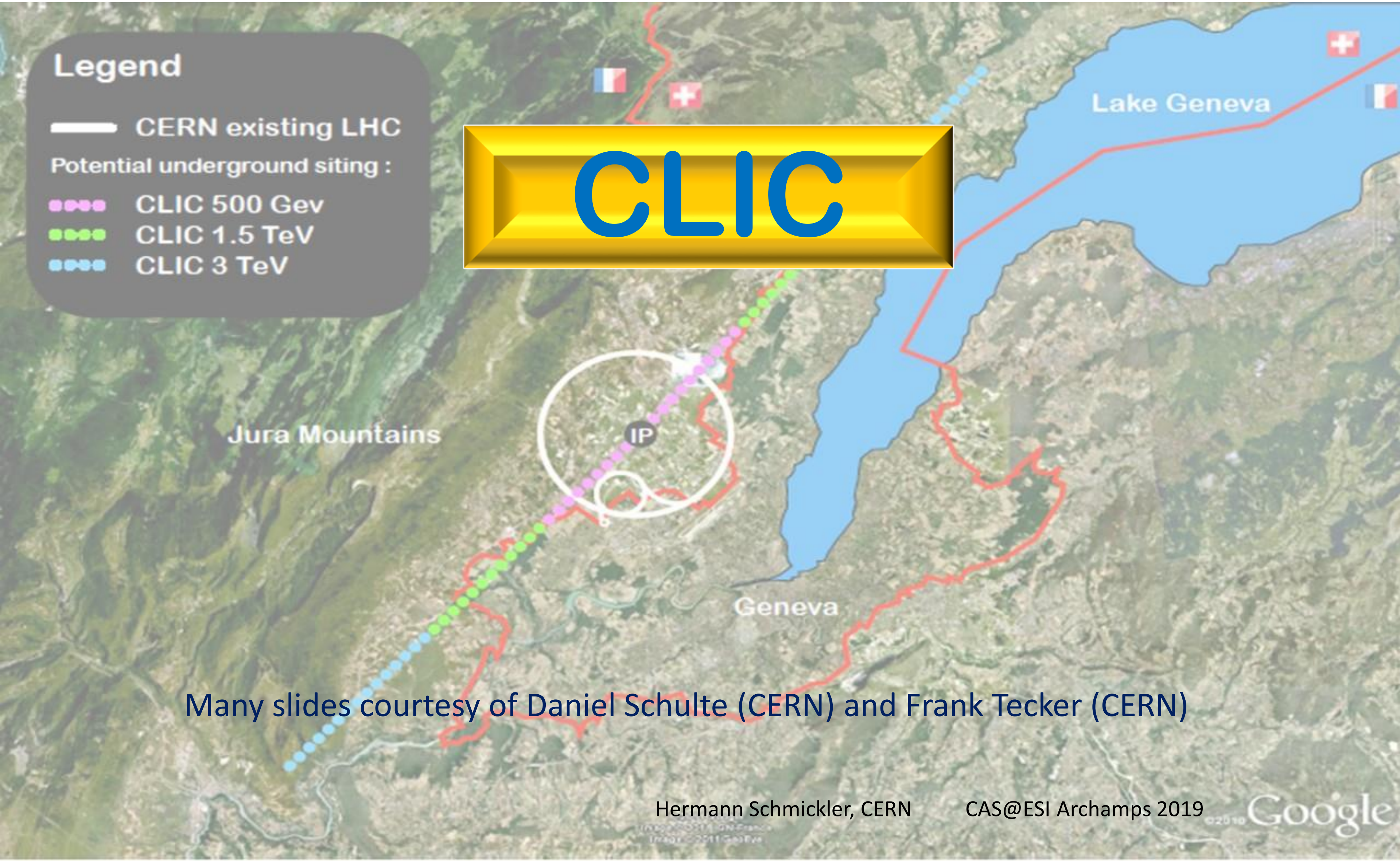
CLIC



Many slides courtesy of Daniel Schulte (CERN) and Frank Tecker (CERN)

Outline

- Overview future (and past) high energy colliders
- CLIC := Compact Linear (e+e-) Collider
  - Why e+e-? → precision physics
  - Why linear? → no synchrotron radiation
  - how compact? → 100 MV/m with NC RF
- Basic Parameters of CLIC…Comparison with ILC
- Focus on two aspects:
  - Nanometer Size Beams at IP: Why and how?
  - RF Powering through a second particle beam: Why and how?

Past/Existing High Energy Frontier Colliders

Only referring to the highest energy

Lepton colliders:

- LEP (Large Electron Positron Colliders)
  - Z_0 factory at 90GeV electron-positron cms energy
  - W^+W^- factory at 160GeV
  - Maximum 209 GeV cms energy for higgs search
    (bad luck: e+e- → Z^0H needs about 250 GeV)
  - Closed in the year 2000

- SLC (Standford Linear Collider)
  - Z_0 factory at 90GeV electron-positron cms energy

Hadron colliders
- LHC (Large Hadron Collider):
  - Proton-proton with 13TeV
  - Ion-ion operation

Considered Future High Energy Frontier Colliders

Circular colliders:

- FCC (Future Circular Collider)
  - FCC-hh: 100TeV proton-proton cms energy, ion operation possible
  - FCC-ee: Potential intermediate step 90-350 GeV lepton collider
  - FCC-he: Lepton-hadron option
- CEPC / SppC (Circular Electron-positron Collider/Super Proton-proton Collider)
  - CepC : e^+e^- 240GeV cms
  - SppC : pp 70TeV cms

Linear colliders

- ILC (International Linear Collider): e^+e^-, 500 GeV cms energy, Japan considers hosting project
- CLIC (Compact Linear Collider): e^+e^-, 380GeV-3TeV cms energy, CERN hosts collaboration

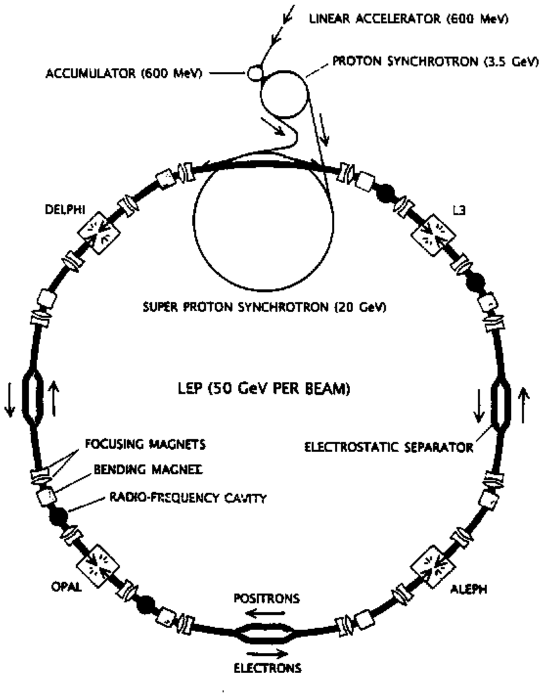
Others

- Muon collider, has been supported mainly in the US but effort has stopped
- Plasma wakefield acceleration in linear collider…not yet ready
- Photon-photon collider
- LHeC

LEP (at CERN)

27km circumference
Electron-positron collider
4 experiments: ALEPH, DELPHI, L3, OPAL
CMS energy: 90GeV (LEP I) - 209GeV (LEP II)
Peak Luminosity: $10^{32}cm^{-2}s^{-1}$
Operation: 1989-2000

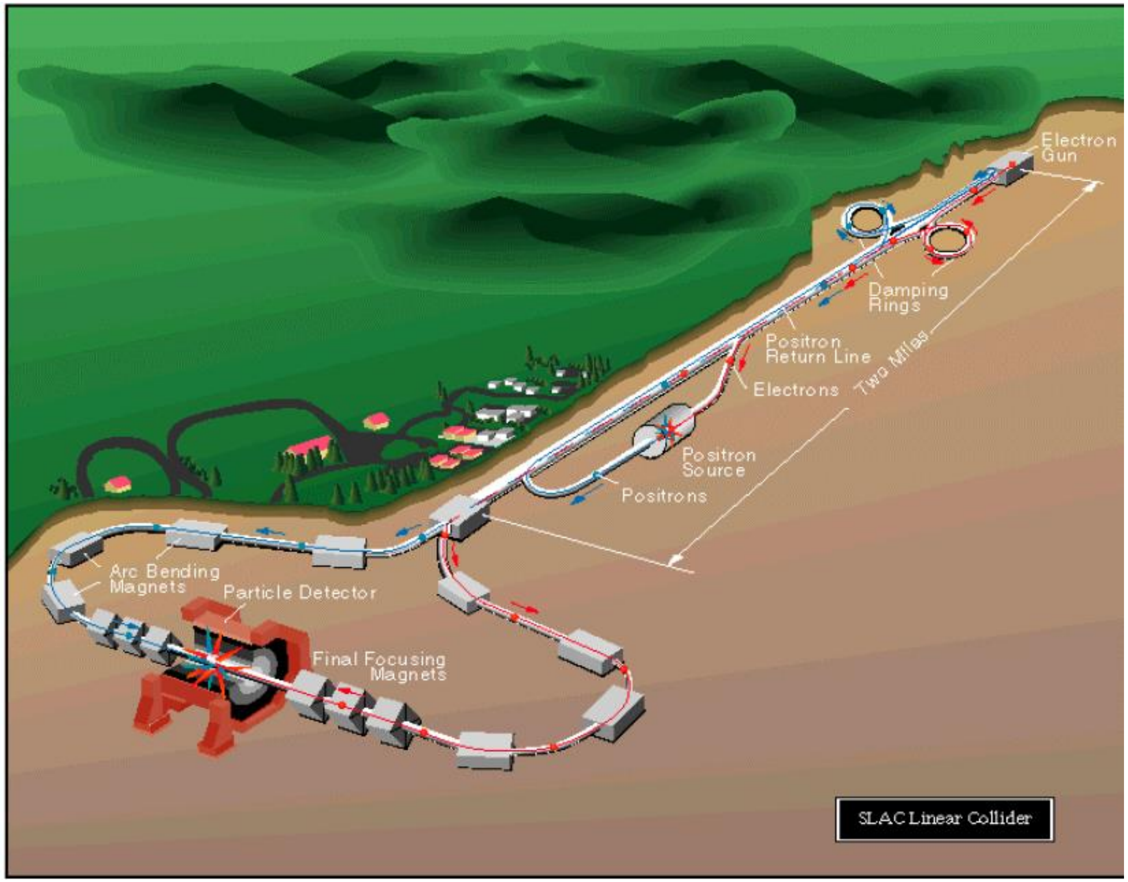
Highest particle speed in any accelerator



SLC (at SLAC)

Electron-positron linear collider
2 experiments: first MARK II, then SLD
CMS energy: 92GeV
Peak Luminosity: $2x10^{30}cm^{-2}s^{-1}$
Operation: 1989-1998

The only linear collider sofar



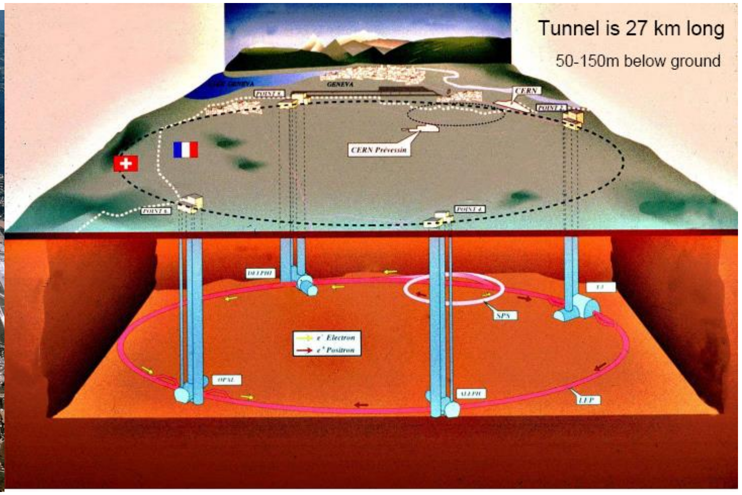
The LHC (at CERN)

27km circumference (well, the LEP tunnel)

4 main experiments

Nominal CMS energy: 14TeV
Peak Luminosity: $10^{34}cm^{-2}s^{-1}$
Operation: 2009-today

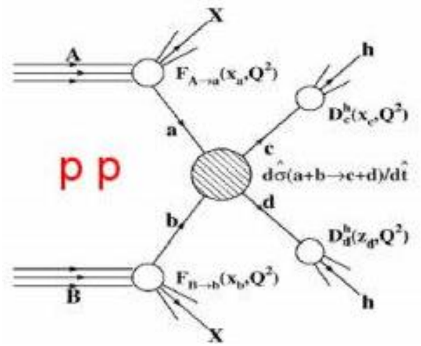
Highest particle energy in any accelerator



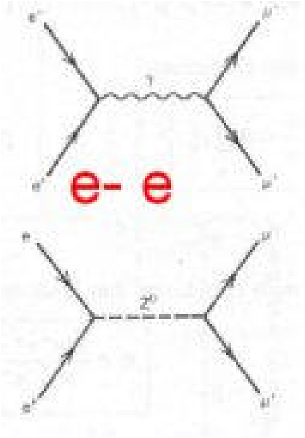
Other Colliders

Collider Choices

- Hadron collisions: compound particles
  - Mix of quarks, anti-quarks and gluons: variety of processes
  - Parton energy spread
  - QCD processes large background sources
    total cross section increases with log s;
    "interesting cross sections" decrease with s
  - Hadron collisions $\Rightarrow$ large discovery range

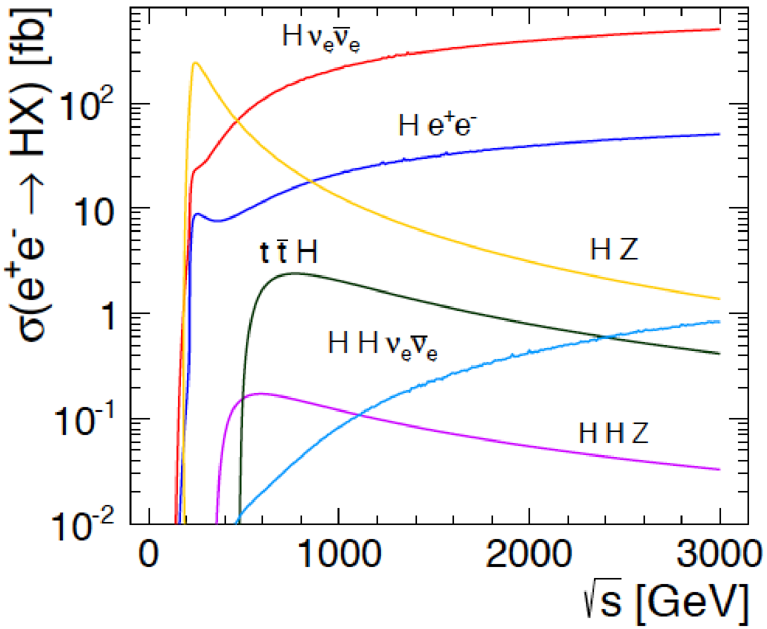


- Lepton collisions: elementary particles
  - Collision process known
  - Well defined energy
  - Other physics background limited
  - Lepton collisions $\Rightarrow$ precision measurements
  - All cross sections decrease with s

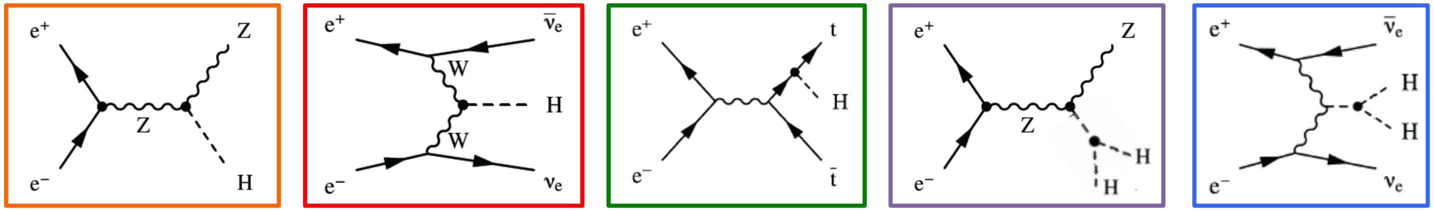


- Lepton-hadron is also possible

Higgs Physics in e+e- Collisions

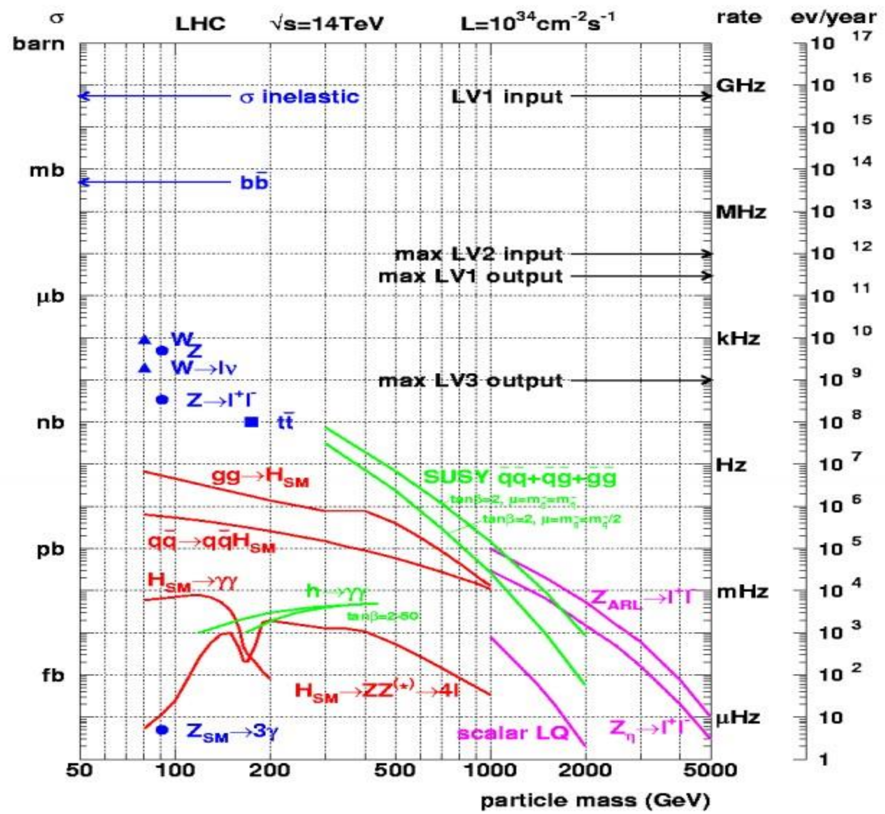


- **Precision Higgs measurements**
- Model-independent
  - Higgs couplings
  - Higgs mass
- Large energy span of linear colliders allows to collect a maximum of information:
  - ILC: 500 GeV (1 TeV)
  - CLIC: ~350 GeV – 3 TeV



The LHC: signals much smaller than "bkg"

- **General event properties**
- **Heavy flavor physics**
- **Standard Model physics**
  - QCD jets
  - EWK physics
  - Top quark
- **Higgs physics**
- **Searches for SUSY**
- **Searches for 'exotica'**



P. Sphicas
The Standard Model and Beyond

CERN Accelerator School
Feb 06, 2016

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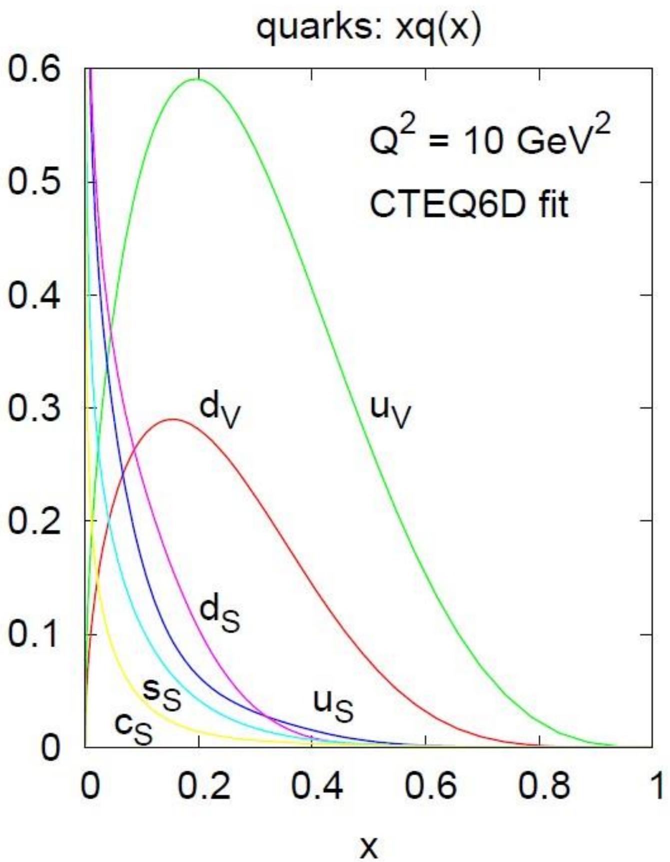
All quarks



These & other methods $\rightarrow$ whole set of quarks & antiquarks

NB: also strange and charm quarks

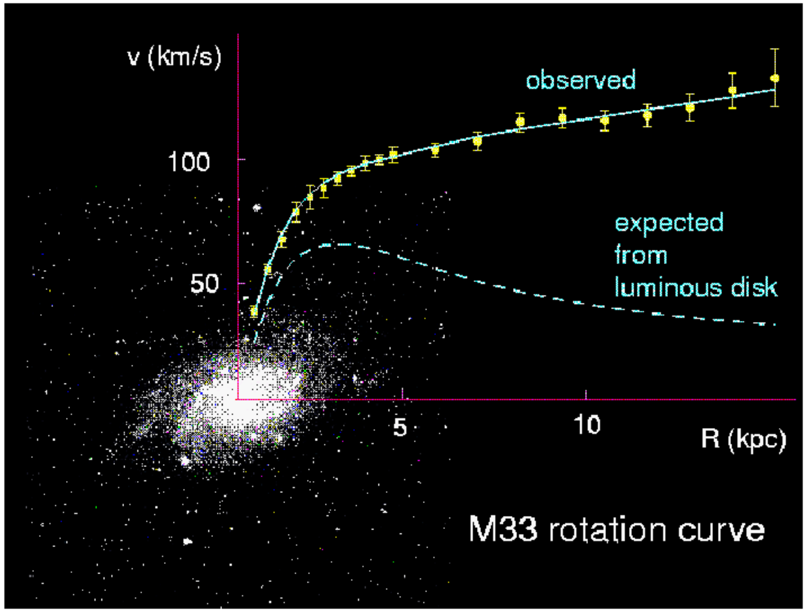
- valence quarks ($u_V = u - \bar{u}$) are *hard*
  $x \rightarrow 1 : xq_V(x) \sim (1-x)^3$
  quark counting rules
  $x \rightarrow 0 : xq_V(x) \sim x^{0.5}$
  Regge theory
- sea quarks ($u_S = 2\bar{u}, \ldots$) fairly *soft* (low-momentum)
  $x \rightarrow 1 : xq_S(x) \sim (1-x)^7$
  $x \rightarrow 0 : xq_S(x) \sim x^{-0.2}$

Physics Beyond the Standard Model (BSM)
Example: Dark Matter

The outer region of galaxies rotate faster than expected from visible matter

Corbelli & Salucci (2000); Bergstrom (2000)

$$v_{circ} = \sqrt{\frac{GM(r)}{r}}$$



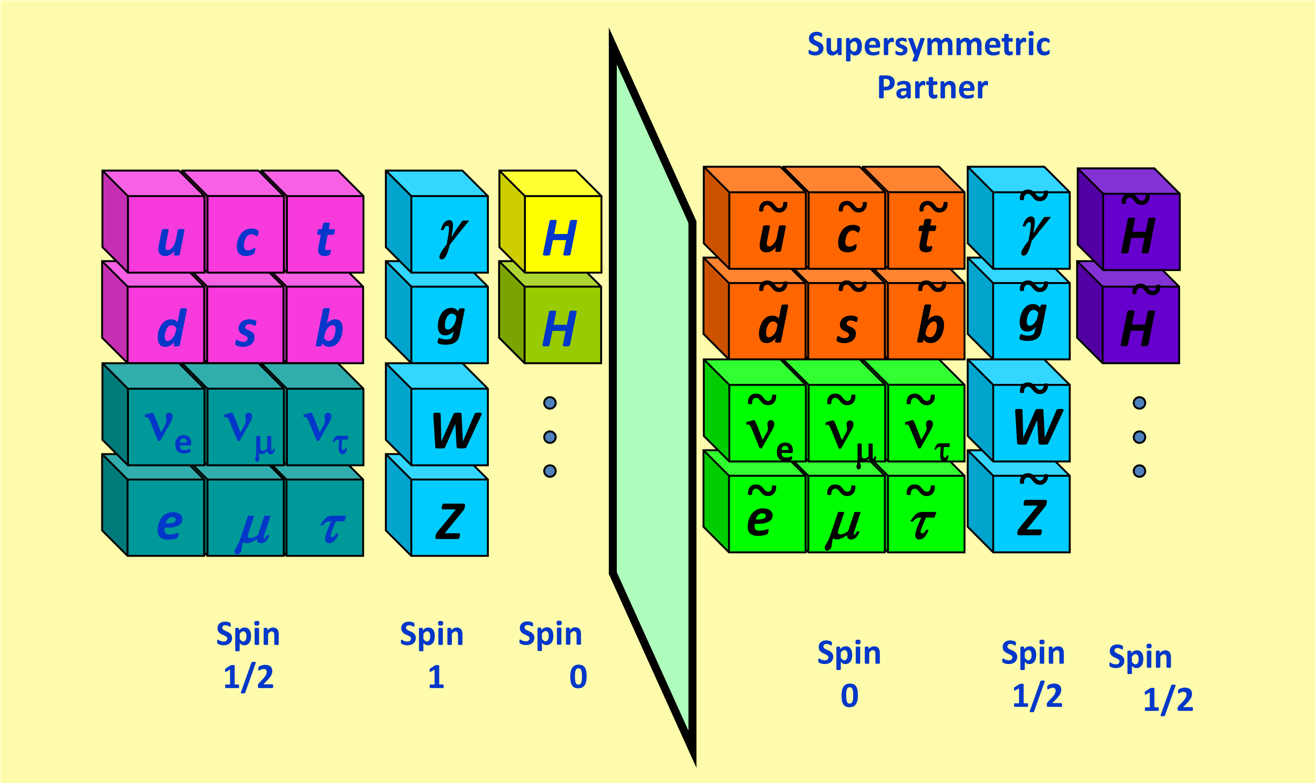
Dark matter would explain this

Other observations exist
- But all through gravity

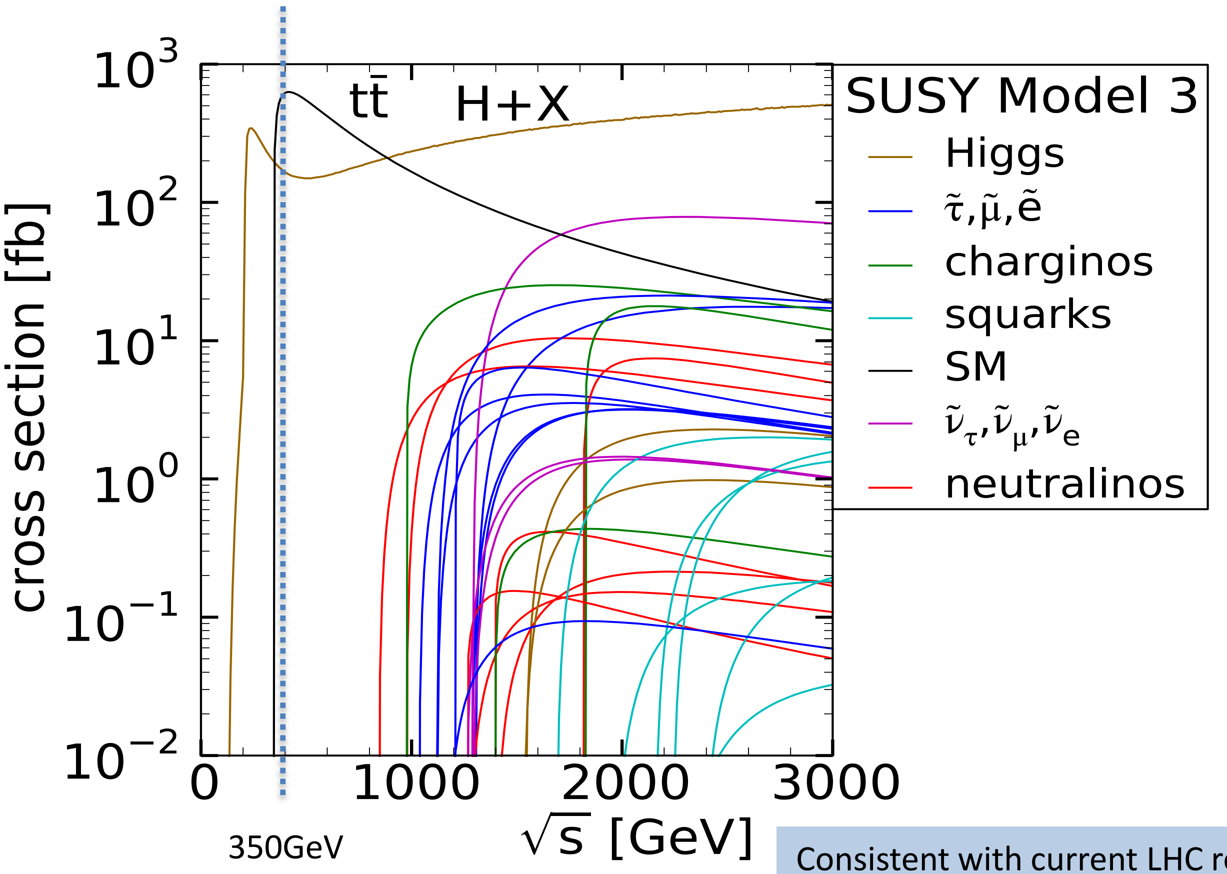
What is it?

One explanation is supersymmetry

Supersymmetry



Example of Potential SUSY Scenario



Consistent with current LHC results

A "real" story from the past ...

Barcelona, 15 March 1493 .....

CristofoRolf Columbus:

Your Majesty, the fleet needs an **upgrade**, we need to go back to the Indies with **10 times** more ships

King Ferdinand and Queen IsAgnieszka:

You discovered the Indies, your theory is right, why do you need more?

CristofoRolf Columbus:

Theorists* say these may not be the **standard Indies**. They calculated the Earth radius, and the standard Indies cannot be so close: these are likely to be ***beyond* the standard Indies** (*moving eastward* ...)

** If the King had listened to theorists to start with, he would have never authorized the mission: everyone would have died of starvation well before reaching the "standard" Indies ...*

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Lepton Collider Options

Three main approaches

- Big LEP-type collider ring
  - FCC-ee, CepC
  - Later a proton collider in the same tunnel
- Linear collider
  - ILC, CLIC
  - The focus of this course
- Muon collider

Ring Collider Energy Limitation

Beam can be used many times

Lepton beam energy is below LHC
-> magnets are not a problem

But synchrotron radiation is:

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

At LEP2 lost 2.75GeV/turn for E=105GeV

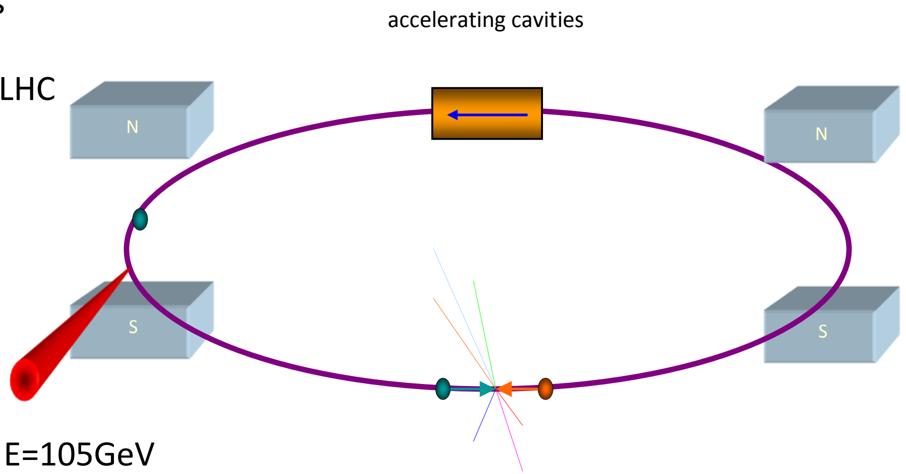
Pay for installed voltage (ΔE) and size (R),
so scale as:

$$R \propto E^2$$

$$\Rightarrow \Delta E \propto E^4 / E^2$$

$$\Rightarrow \Delta E \propto E^2$$

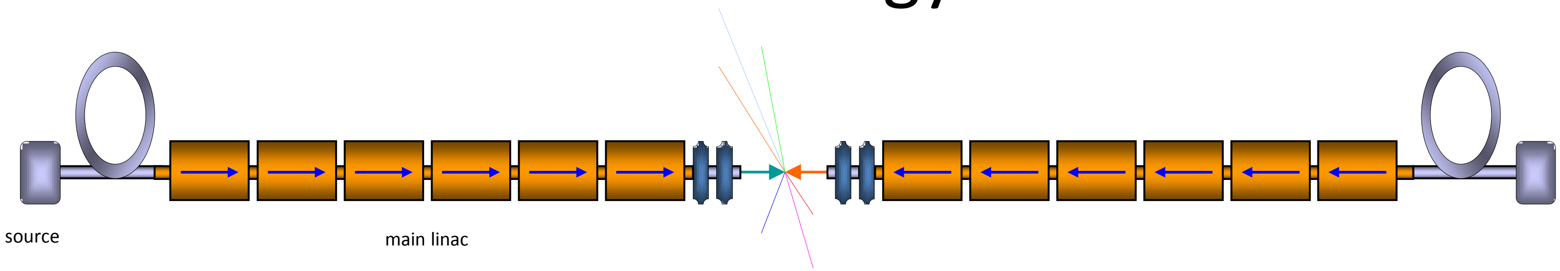
$$\Rightarrow \Delta E \propto R$$



$$C_R = a_R E^2 + b_R$$

-> use heavier particles, e.g. muons
-> or linear collider
(-> or try to push a bit harder on cost)

Linear Collider Energy Limitation



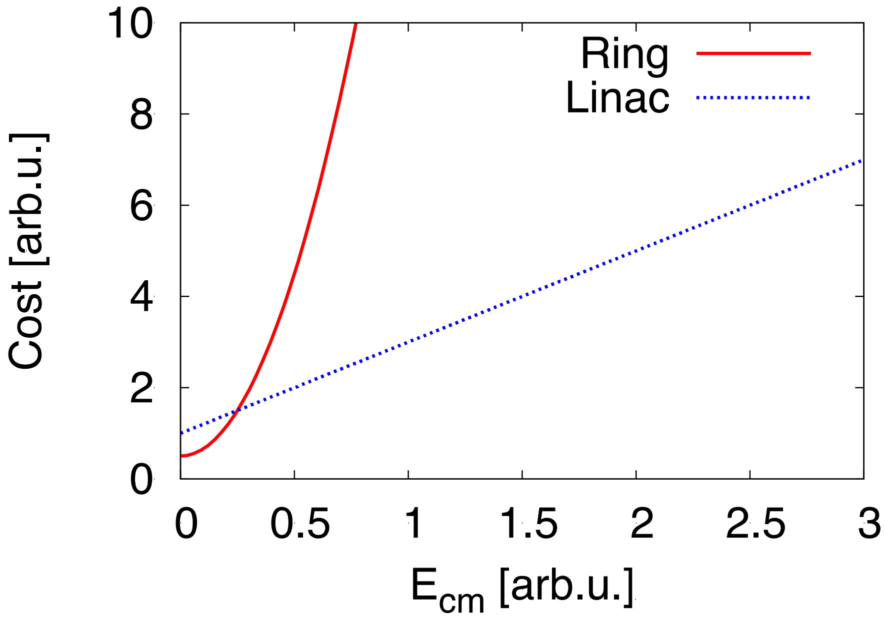
Hardly any synchrotron radiation

Beam can only be used only once
-> strong beam-beam effects

Acceleration gradient is an important issue

$$C_L = a_L E + b_L$$

Simplified Cost Scaling Comparison



Linac:

$$C_L = a_L E + b_L$$

Ring:

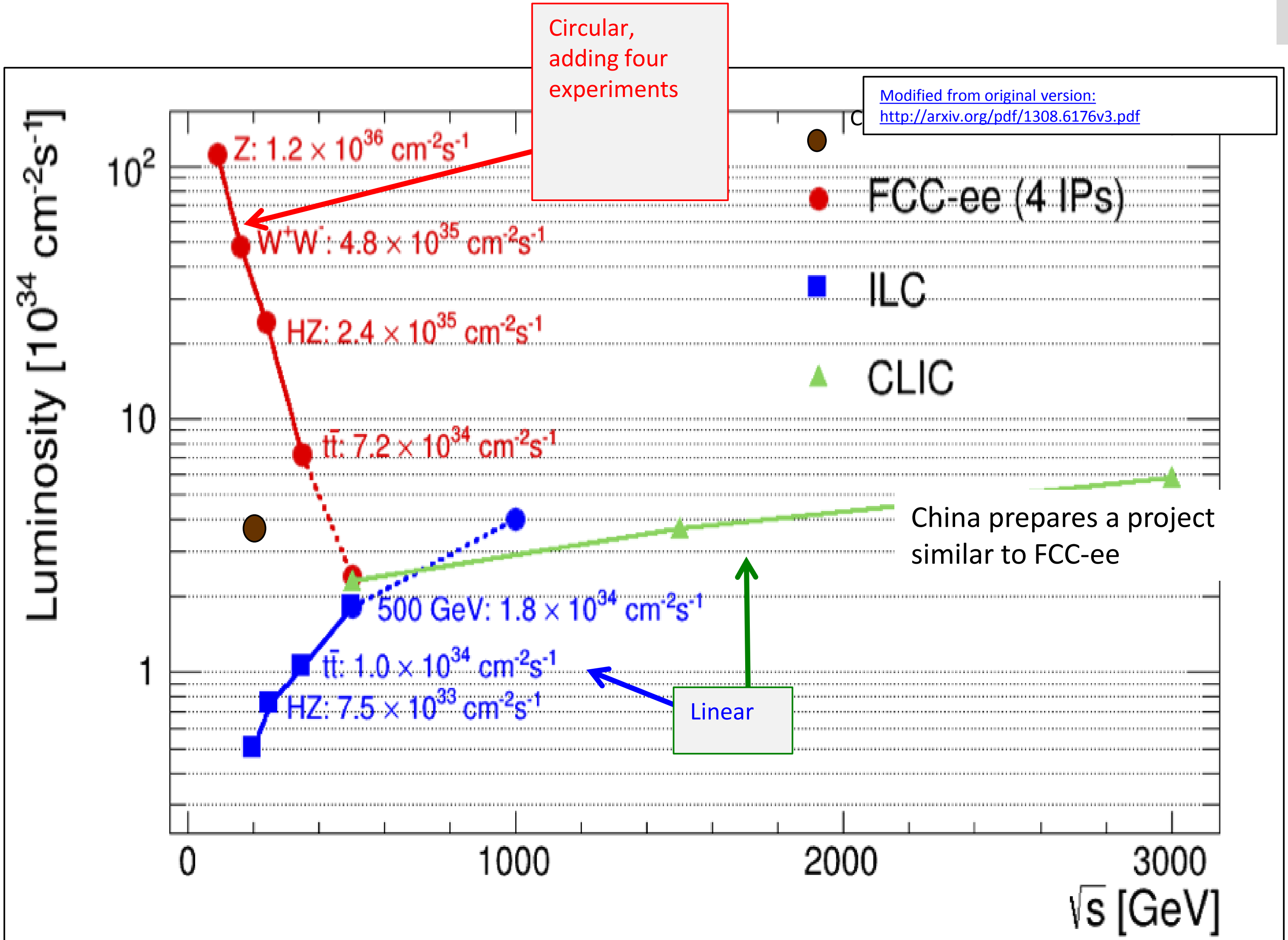
$$C_R = a_R E^2 + b_R$$

Power consumption behaves similar to cost for constant luminosity

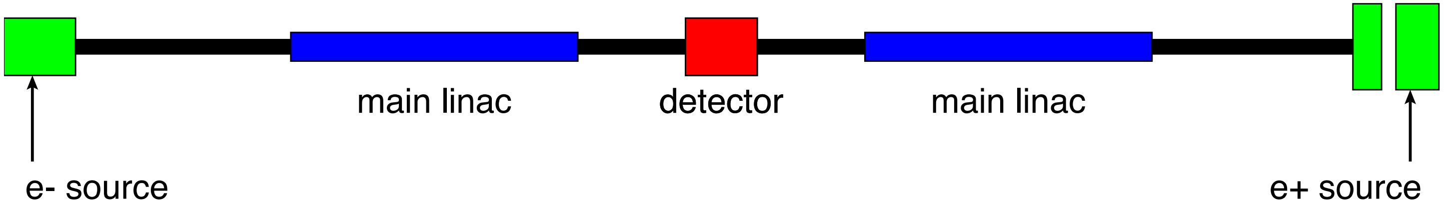
There will always be an energy where linear colliders are better

Circular vs. Linear Colliders

F. Gianotti



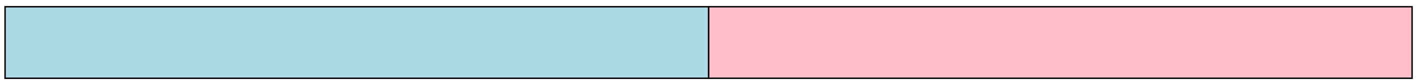
Generic Linear Collider



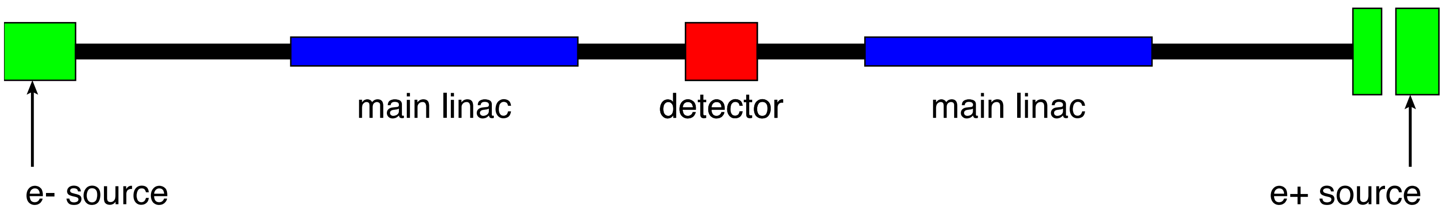
The main linac provides the energy of the beam

Issue 1: the gradient

Generic Linear Collider



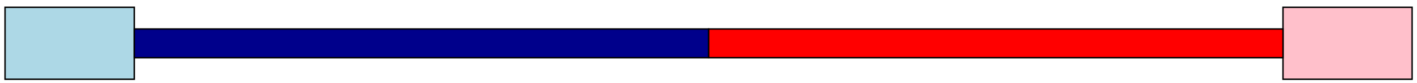
$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r$$



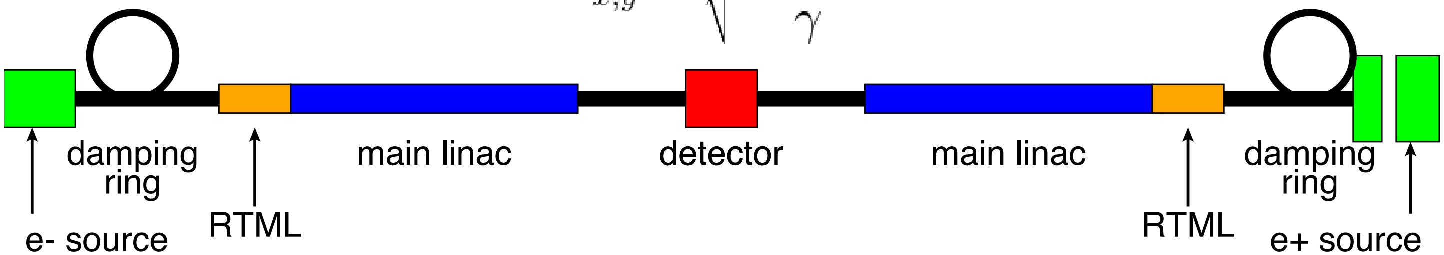
But little luminosity, since beams collider only once

Need very small σ_x and σ_y

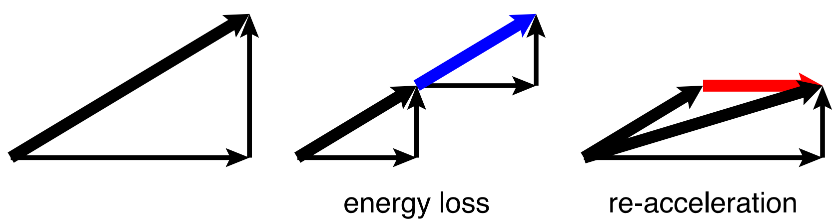
Generic Linear Collider



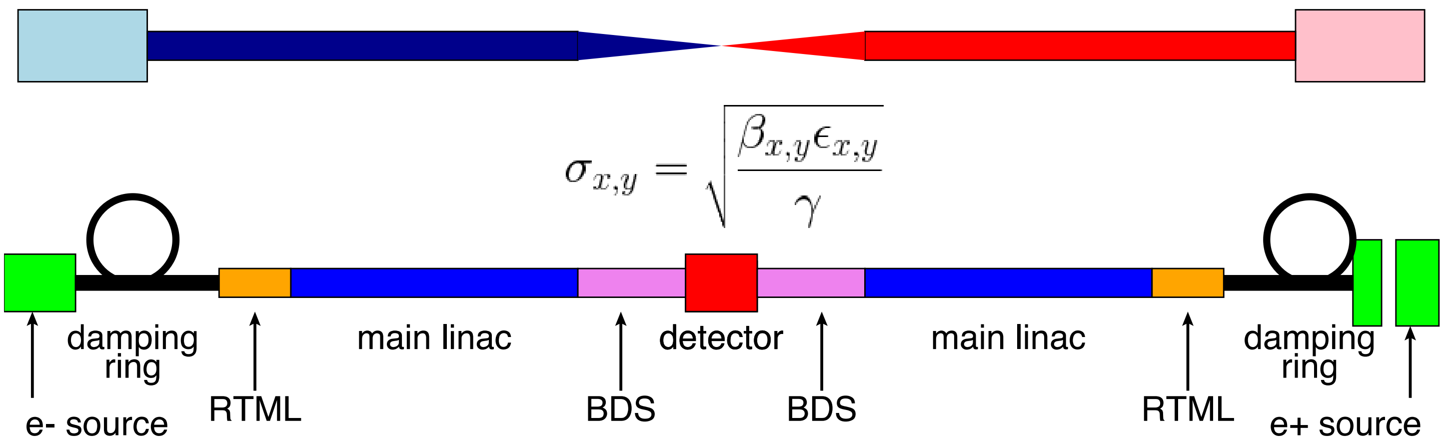
$$\sigma_{x,y} = \sqrt{\frac{\beta_{x,y}\epsilon_{x,y}}{\gamma}}$$



The damping rings reduce the phase space (emittance $\varepsilon_{x,y}$) of the beam
The RTML (ring-to-main linac transport) reduces the bunch length



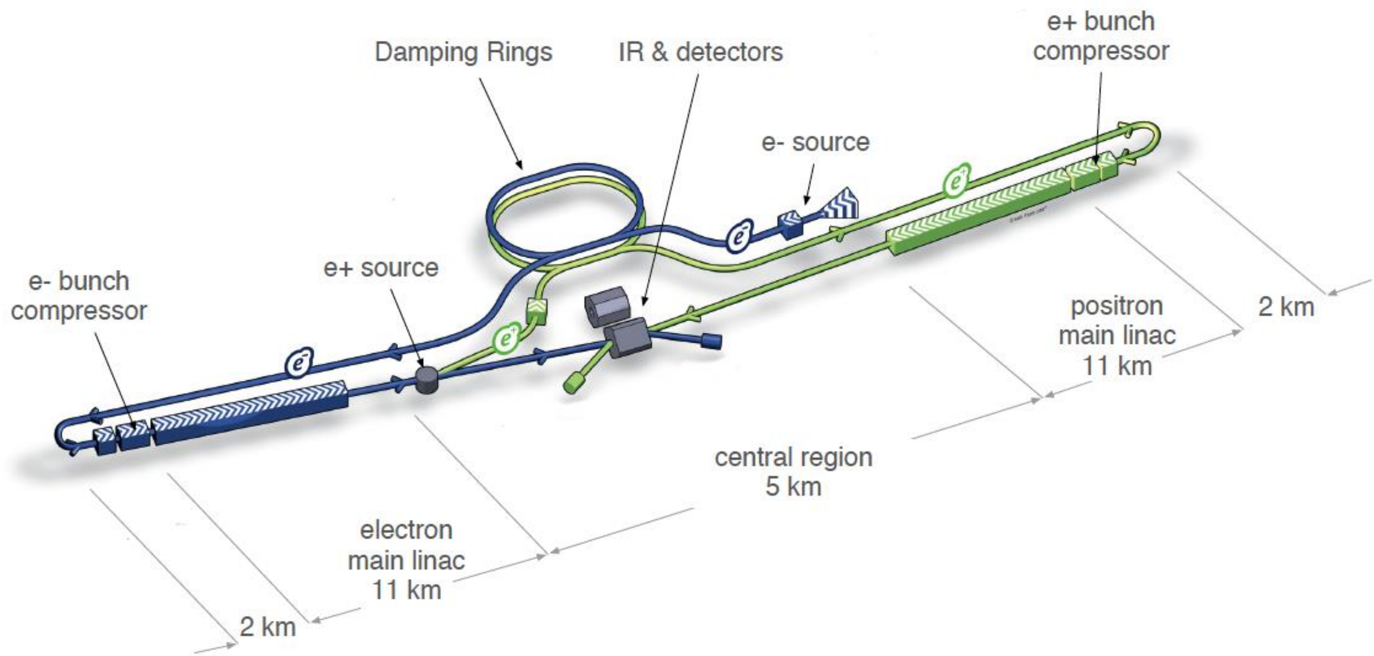
Generic Linear Collider



$$\sigma_{x,y} = \sqrt{\frac{\beta_{x,y}\epsilon_{x,y}}{\gamma}}$$

The beam delivery system (BDS) squeezes the beam as much as possible, i.e. reduces $\beta_{x,y}$

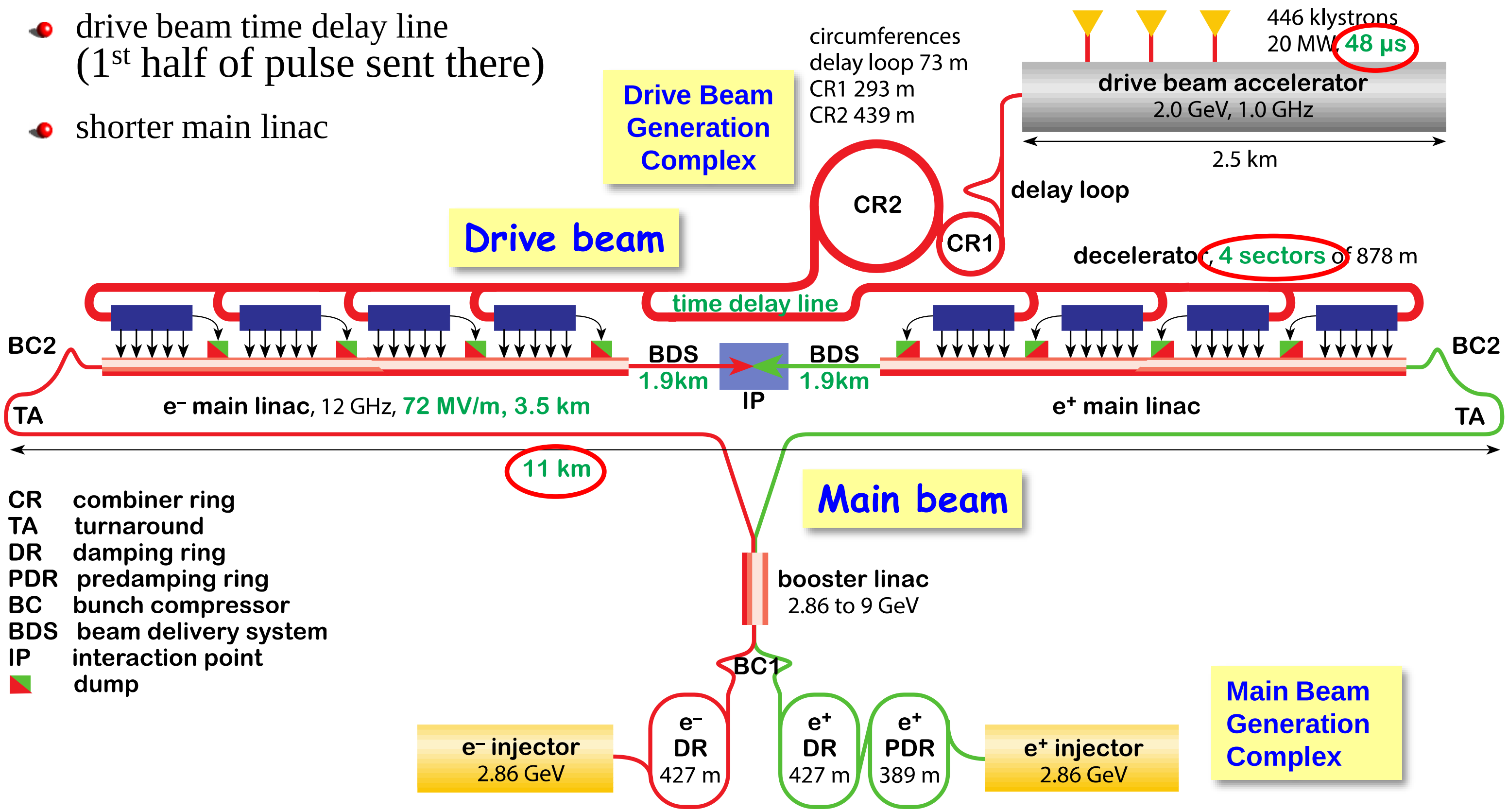
ILC Layout



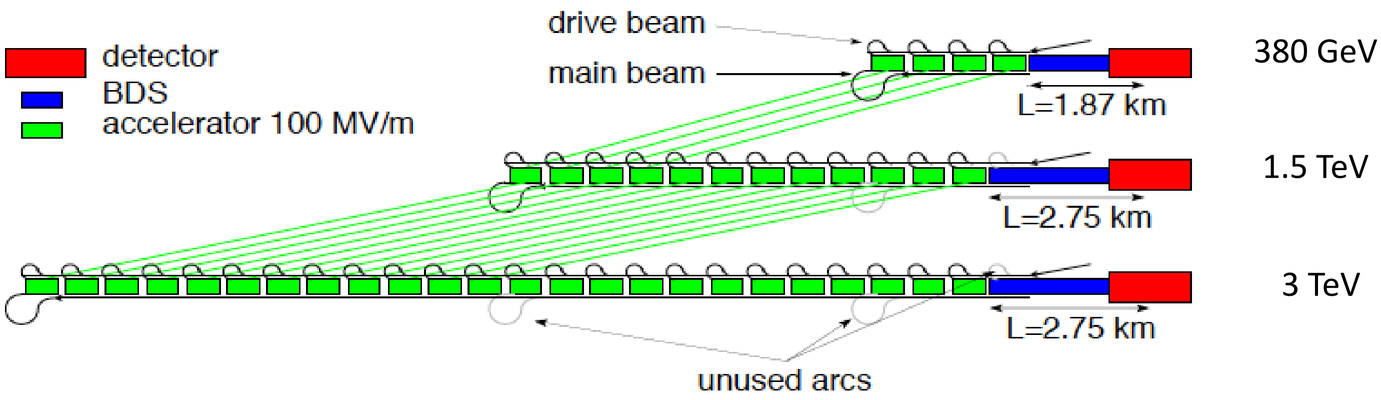
Damping Rings
IR & detectors
e+ bunch
compressor
e- source
e- bunch
compressor
e+ source
positron
main linac
11 km
2 km
central region
5 km
electron
main linac
11 km
2 km

CLIC – layout for 380 GeV

- only one DB complex (with 2x RF pulse length compared to 2 DB complexes)
- drive beam time delay line (1st half of pulse sent there)
- shorter main linac



CLIC Staged Design



Staged design for CLIC to optimise physics and funding profile:

- First stage: E_{cms}=380 GeV, L=1.5x10^{34}cm^{-2}s^{-1}, $L_{0.01}$/L>0.6
- Second stage: E_{cms}=O(1.5 TeV)
- Final stage: E_{cms}=3 TeV, $L_{0.01}$=2x10^{34}cm^{-2}s^{-1}, $L_{0.01}$/L>0.3

Cavity/Accelerating Structure

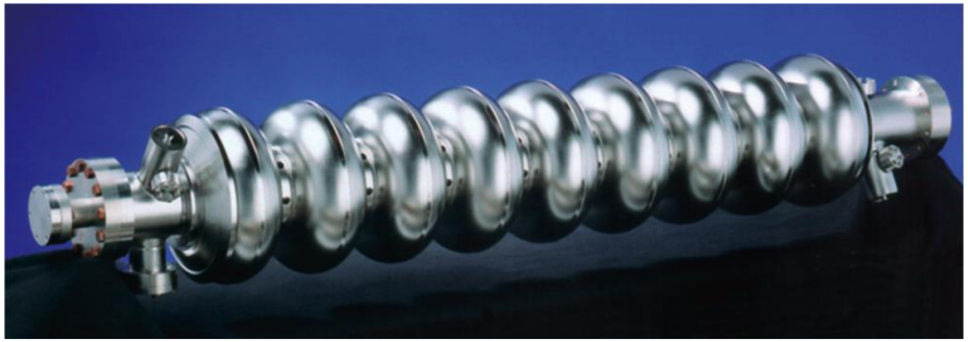
ILC cavity

1.3 GHz, superconducting

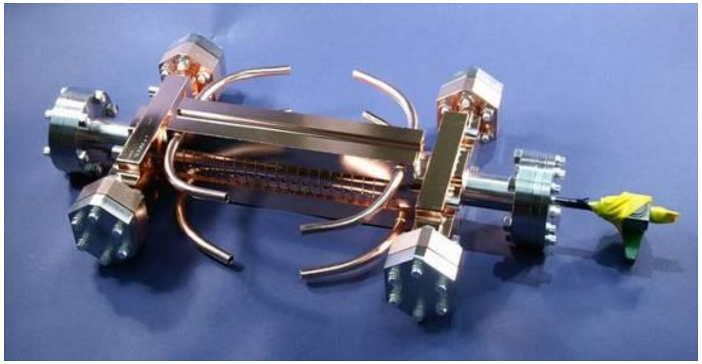
Target effective operational 31.5MV/m

Target gradient 35MV/m

$Q_0 \approx 10^{10}$



CLIC accelerating structure



12 GHz, normal conducting

Target loaded gradient 100MV/m

Target unloaded gradient 120MV/m

$Q_0 \approx 6\ 10^3$

Warm vs Cold RF Collider

- Normal Conducting
- High gradient => short linac ☺
- High rep. rate => ground motion suppression ☺
- Small structures => strong wakefields ☹
- Generation of high peak RF power ☹

- Superconducting
- long pulse => low peak power ☺
- large structure dimensions => low WF ☺
- very long pulse train => feedback within train ☺
- SC structures => high efficiency ☺
- Gradient limited <40 MV/m => longer linac ☹ (SC material limit ~ 55 MV/m)
- Large number of e+ per pulse ☹
- very large DR ☹

ILC and CLIC Main Parameters

Parameter	Symbol [unit]	SLC	ILC	CLIC
Centre of mass energy	E_{cm} [GeV]	92	500	3000
luminosity	L [$10^{34}cm^{-2}s^{-1}$]	0.0003	1.8	6
Luminosity in peak	$L_{0.01}$ [$10^{34}cm^{-2}s^{-1}$]	0.0003	1	2
Gradient	G [MV/m]	20	31.5	100
Particles per bunch	N [10^9]	37	20	3.72
Bunch length	σ_z [μm]	1000	300	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	1700/600	474/5.9	40/1
Vertical emittance	$\varepsilon_{x,y}$ [nm]	3000	35	20
Bunches per pulse	n_b	1	1312	312
Distance between bunches	Δz [mm]	-	554	0.5
Repetition rate	f_r [Hz]	120	5	50

ILC has parameter sets from 250 GeV to 1TeV
CLIC has parameter sets from 250 GeV to 3TeV

Let us look at two main aspects:

- Why does CLIC need so small vertical beam sizes?
  (6 times smaller than ILC)

  → and what does this imply for the technical systems

- Why “two beam acceleration”?
  - usually we have already problems enough with one beam….

Luminosity and Parameter Drivers

Can re-write normal luminosity formula

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

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

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

Need to ensure that we can achieve each parameter

Small (vertical) beam sizes

Also important: BDR – pulse-length gradient scaling

NC RF <-> SC RF

Only Normal conducting RF enables accelerating gradients of 100 MV/m

Large RF Power

In the present CLIC RF structure (23 cm long) some 50 MW peak power are needed to produce a 100 MV/m accelerating field

Pulsed operation

With 50 Hz repetition rate beam pulse is as short as 156 ns; i.e. duty cycle 8 * 10-6!!! Still 300 MW electrical power only for the RF acceleration in case of the 3 TeV accelerator

Highest bunch density

Max. Rf frequency in damping rings:
2 GHz (presently 1 GHz): 312 bunches/pulse
← wake fields in accelerating structure

Max. bunch charge

4 * 10^9 particles/bunch

Flat beams

Flat beams for minimum energy spread in luminosity spectrum; need to get high luminosity **from small vertical beam size**

Like firing bullets to hit in middle …

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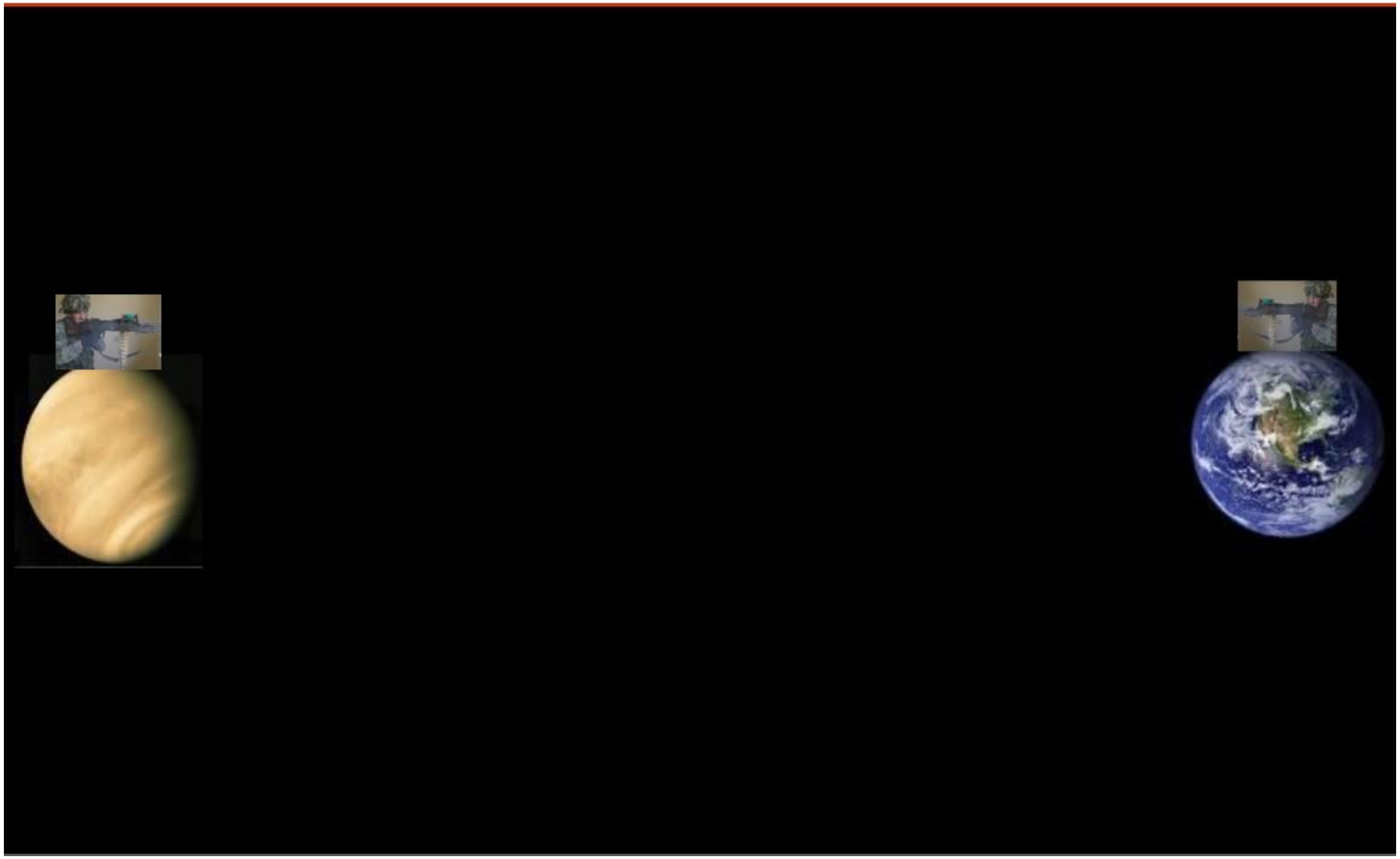
Except that …



Whole list of requirements for colliding small beams

- Generate small vertical emittance in high performance damping rings
- Extract from damping rings with low ripple kickers (10-4)
- Transport beams over 24 km without emittance growth
  - through hundreds of quadrupoles
    → active stabilisation against ground motion
  - through thousands of acceleration cavities
    → 10 um alignment to avoid wakefields
- Beam delivery system with highest gradient quadrupoles
- Feedbacks….feedbacks….feedbacks

Let us look at two main aspects:

- Why does CLIC need so small vertical beam sizes?
  (6 times smaller than ILC)

  → and what does this imply for the technical systems

- Why “two beam acceleration”?
  - usually we have already problems enough with one beam….

→ Mainly a consequence of the very short beam pulse

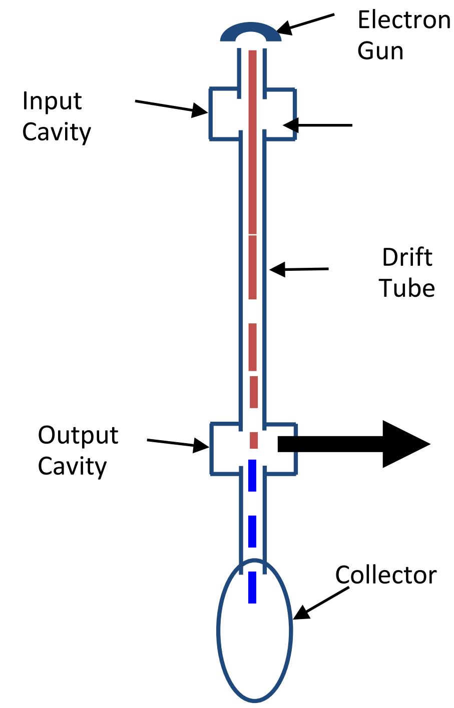
Why not using klystrons as RF powersource?

- Reminder: Klystron
  - narrow-band vacuum-tube amplifier at microwave frequencies (an electron-beam device).
  - low-power signal at the design frequency excites input cavity
  - Velocity modulation becomes time modulation in the drift tube
  - Bunched beam excites output cavity

- We need: - high power for high fields
  - very short pulses (remember: 200 ns!)

- We need also: Many klystrons
  - ILC: 560 10 MW, 1.6 ms
  - NLC: 4000 75 MW, 1.6 µs
  - CLIC: would need many more klystrons with extremely short pulses
  - Avoid another critical set of components: RF pulse compression schemes

- → **Drive beam like beam of a gigantic klystron**



CLIC – layout for 380 GeV

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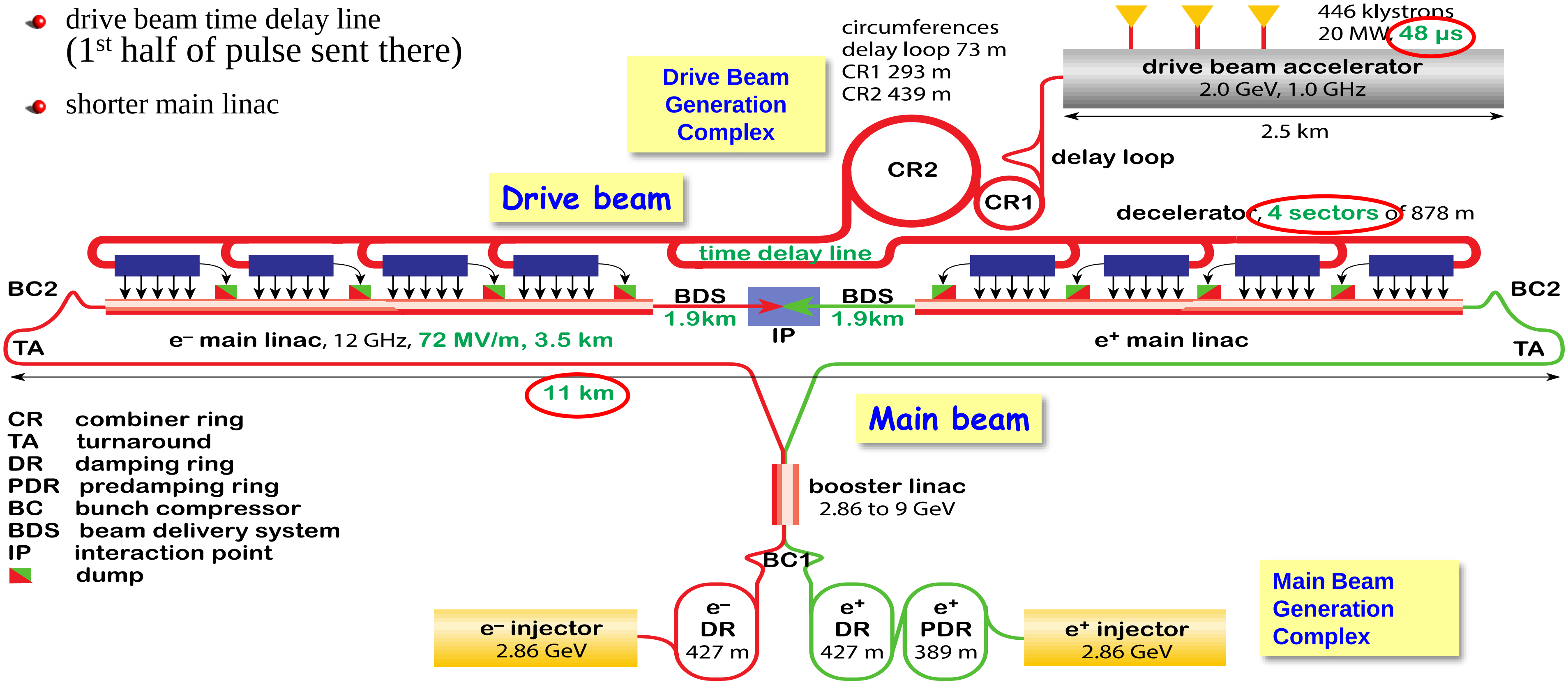
- drive beam time delay line (1st half of pulse sent there)
- shorter main linac

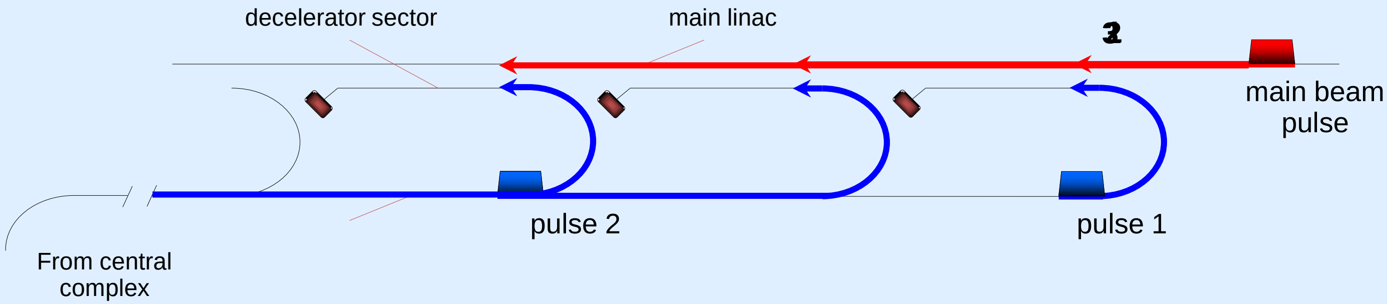


Two-beam acceleration

Counter propagation from central complex

Instead of using a single drive beam pulse for the whole main linac, several (N_S = 24) short drive beam pulses are used

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



R.Corsini

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

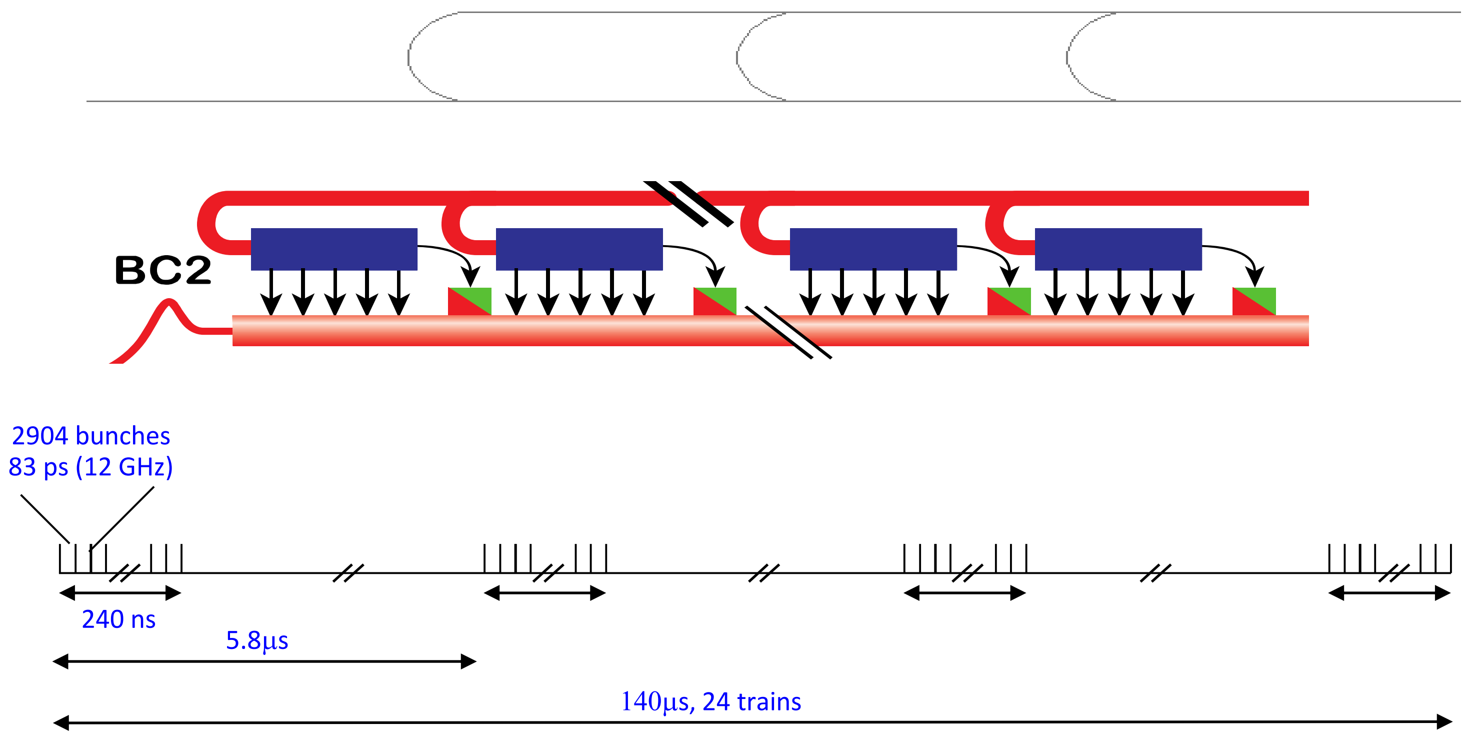
The distance between the pulses is $2\,L_s = 2\,L_{main}/N_S$ (L_{main}= single side linac length)

The initial drive beam pulse length t_{DB} is given by twice the time of flight through one single linac

so $t_{DB} = 2\,L_{main} / c$, 140 µs for the 3 TeV CLIC

This is the required RF pulse length of the drive beam klystrons.

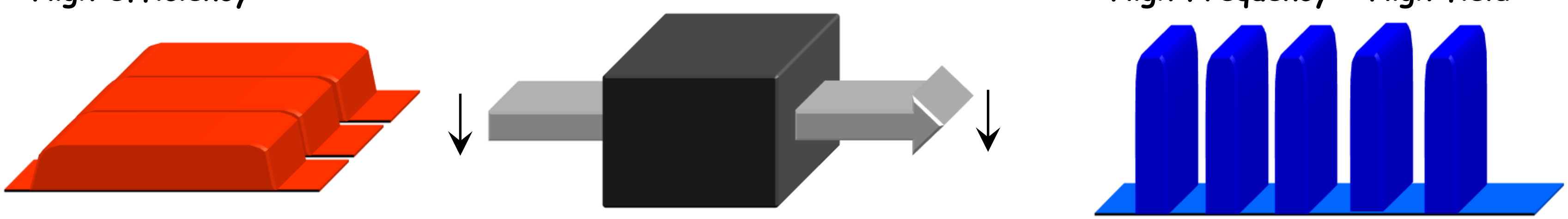
Drive beam time structure



Bunch charge: 8.4 nC, Current in train: 100 A

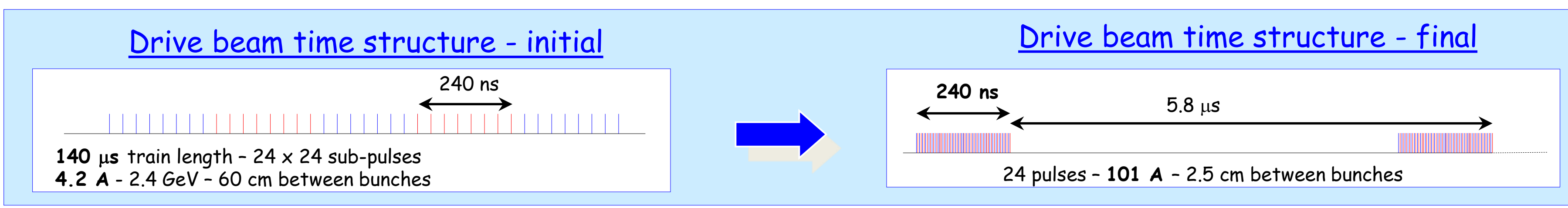
CLIC Drive Beam Scheme

- Very high gradients possible with NC accelerating structures at high RF frequencies (12 GHz)
- Extract required high RF power from an intense e- "drive beam"
- Generate efficiently long beam pulse and compress it (in power + frequency)

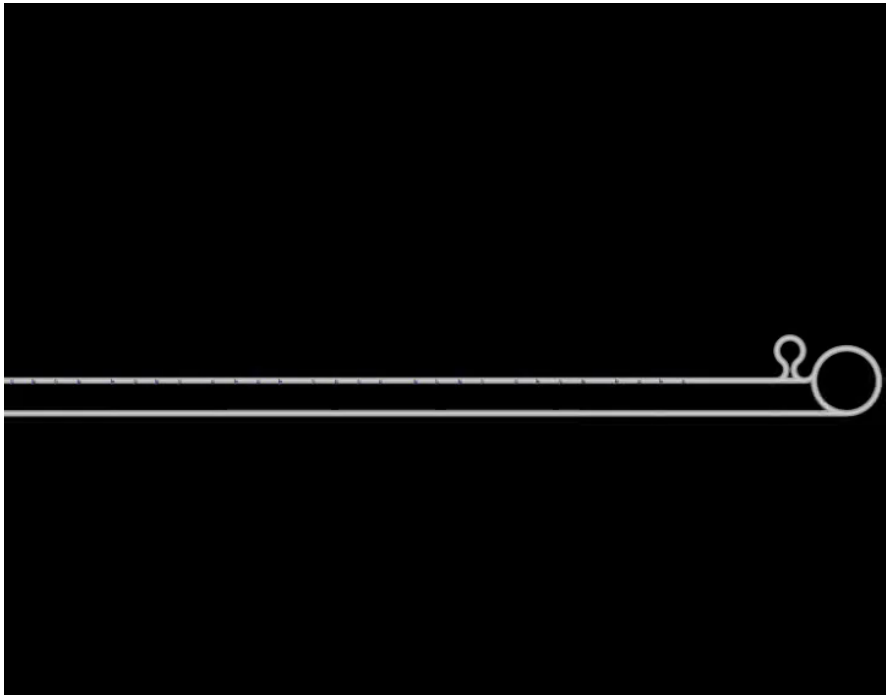


More on drive beam generation

- Again a big transformer:
  → But now in time domain
- Input: Long beam pulse train
  low current
  low bunch frequency
- Output: Short beam pulse trains
  high current
  high bunch frequency
- => high beam power



Lemmings Drive Beam



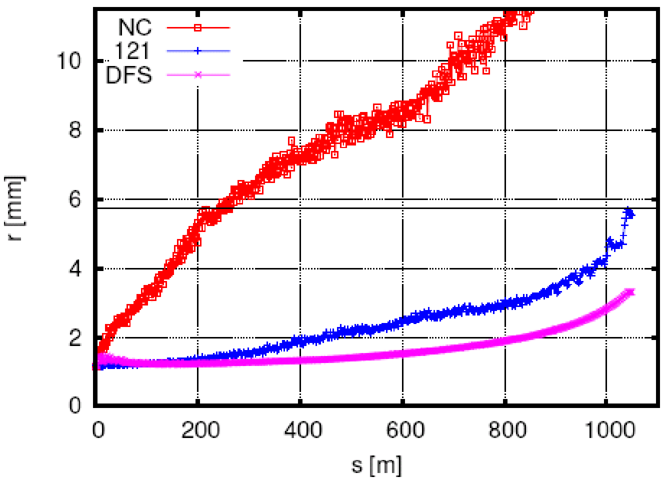
Alexandra
Andersson

H.Schmickler

CLIC decelerator

- Goal: transport particles of all energies through the decelerator sector: in the presence of huge energy spread (90%)
- Tight FODO focusing (large energy acceptance, low beta)
- Lowest energy particles ideally see constant FODO phase-advance μ~90º, higher energy particles see phase-advance varying from μ~90º to μ~10º

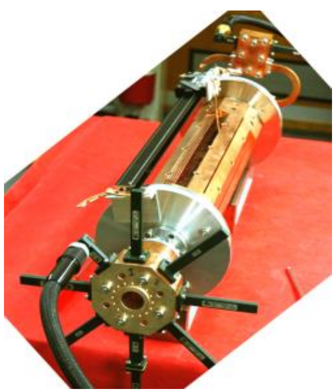
- Good quad alignment needed (20μm)
- Good BPM accuracy (20μm)
- Orbit correction essential
  - 1-to-1 steering to BPM centres
  - DFS (Dispersion Free Steering) gives almost ideal case

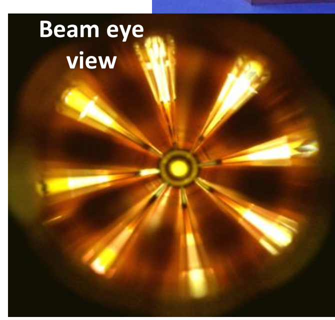


H.Schmickler

Power extraction structure PETS

- must extract efficiently >100 MW power from high current drive beam
- passive microwave device in which bunches of the drive beam interact with the impedance of the periodically loaded waveguide and generate RF power
- periodically corrugated structure with low impedance (big a/λ)
- ON/OFF mechanism





The power produced by the bunched (ω_0) beam in a constant impedance structure:

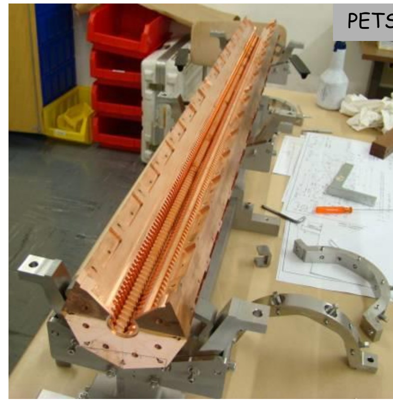
Design input parameters — PETS design

$$P = I^2 L^2 F_b^2 w_0 \frac{R/Q}{4 v_g}$$

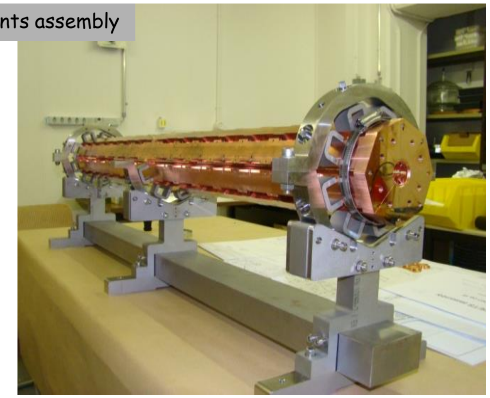
P – RF power, determined by the accelerating structure needs and the module layout.
I – Drive beam current
L – Active length of the PETS
F_b – single bunch form factor (≈ 1)

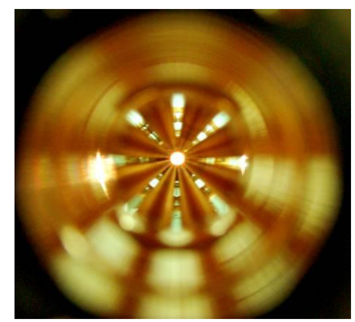
12 GHz PETS assembly

8 bars, as received from VDL



PETS octants assembly



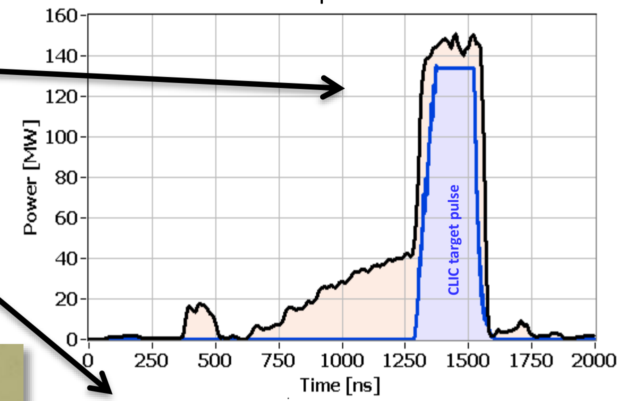


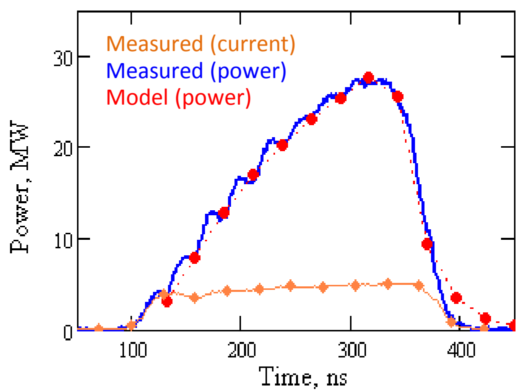
I. Syratchev

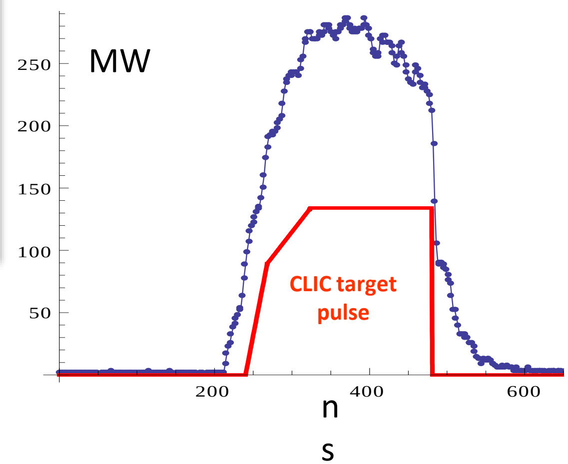
Present PETS status (12 GHz)

- achieved 150 MW @ 266ns in RF driven test at SLAC
- up to >250 MW peak power beam driven at CTF3 (recirculation)
- model well understood

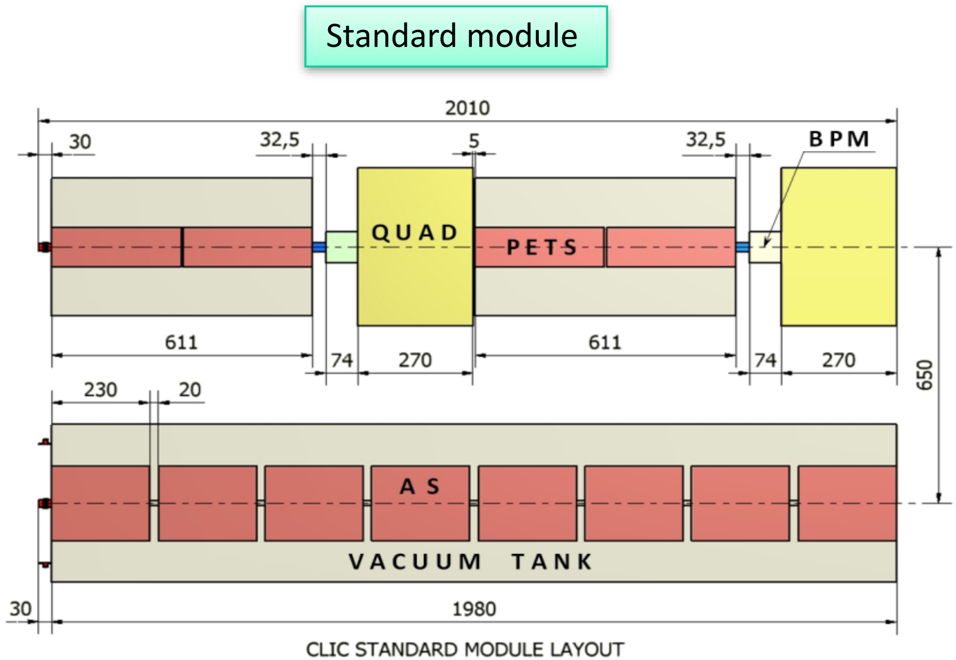
Typical RF pulse shape in ASTA during the last 125h of operation







CLIC two-beam Module layout



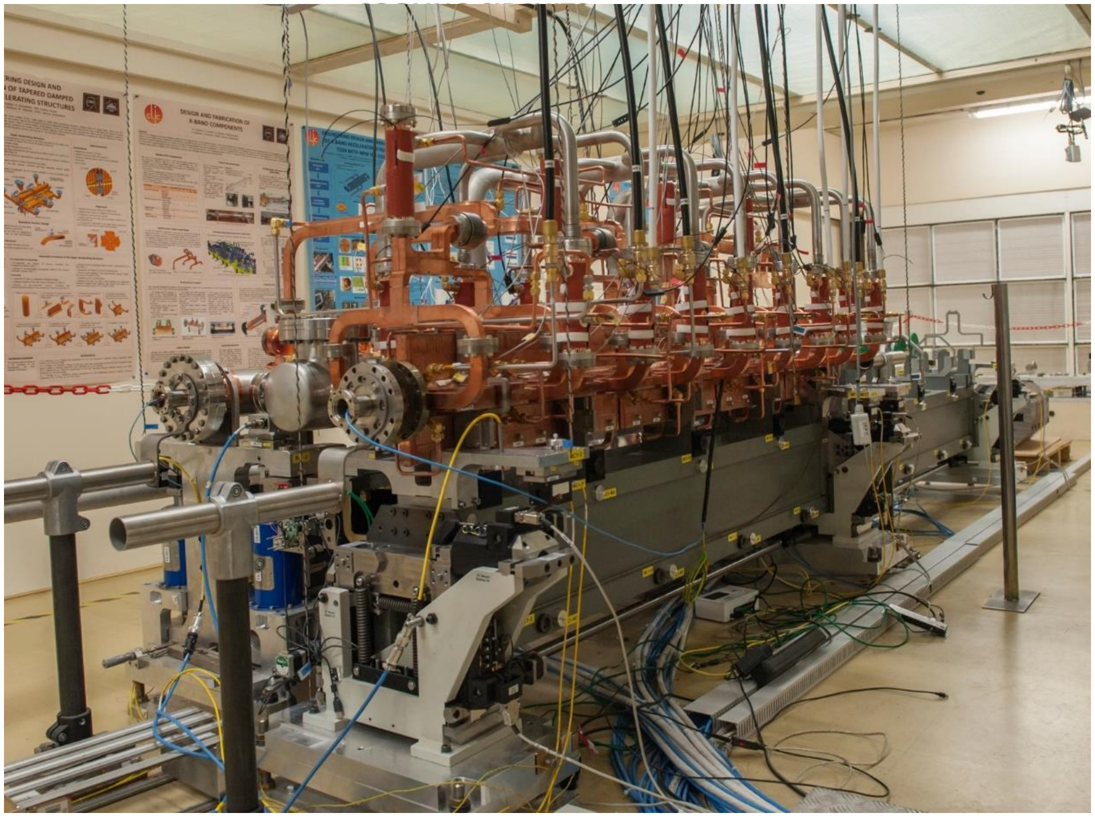
Total per module
8 accelerating structures
8 wakefield monitors

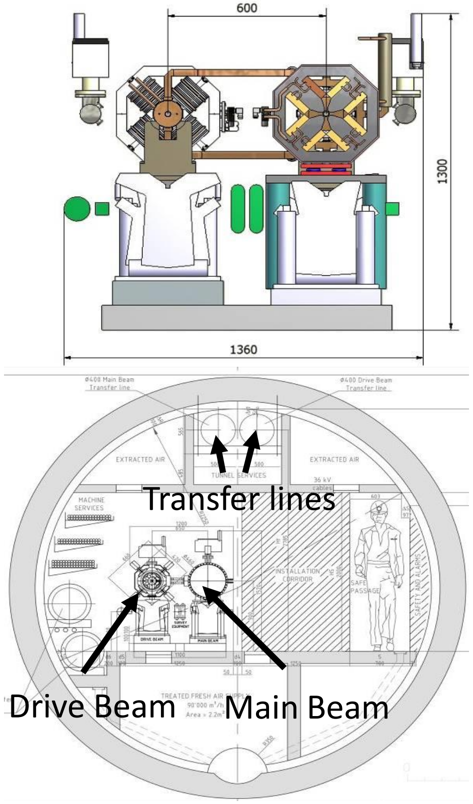
4 PETS
2 DB quadrupoles
2 DB BPM

Total per linac
8374 standard modules

- Other modules have 2,4,6 or 8 acc.structures replaced by a quadrupole (depending on main beam optics)
- Total 10462 modules, 71406 acc. structures, 35703 PETS

CLIC two-beam Module





- Alignment system, beam instrumentation, cooling integrated in design

G.Riddone

CLIC - Future Milestones

2013-18 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.

4-5 year Preparation Phase

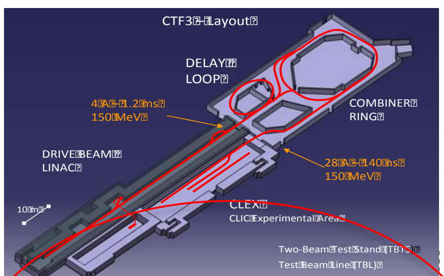
Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

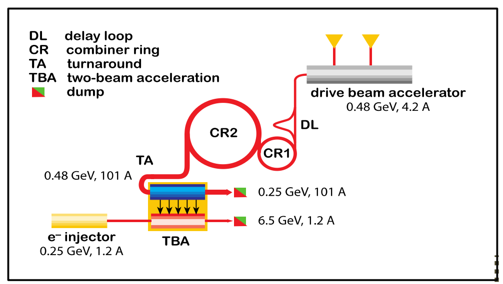
Prepare detailed Technical Proposals for the detector-systems.

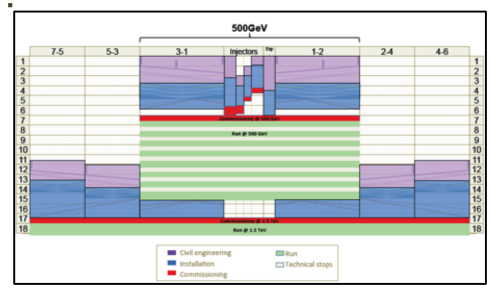
Construction Phase

Stage 1 construction of CLIC, in parallel with detector construction.

Preparation for implementation of further stages.







2018-19 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects as FCC), take decisions about next project(s) at the Energy Frontier.

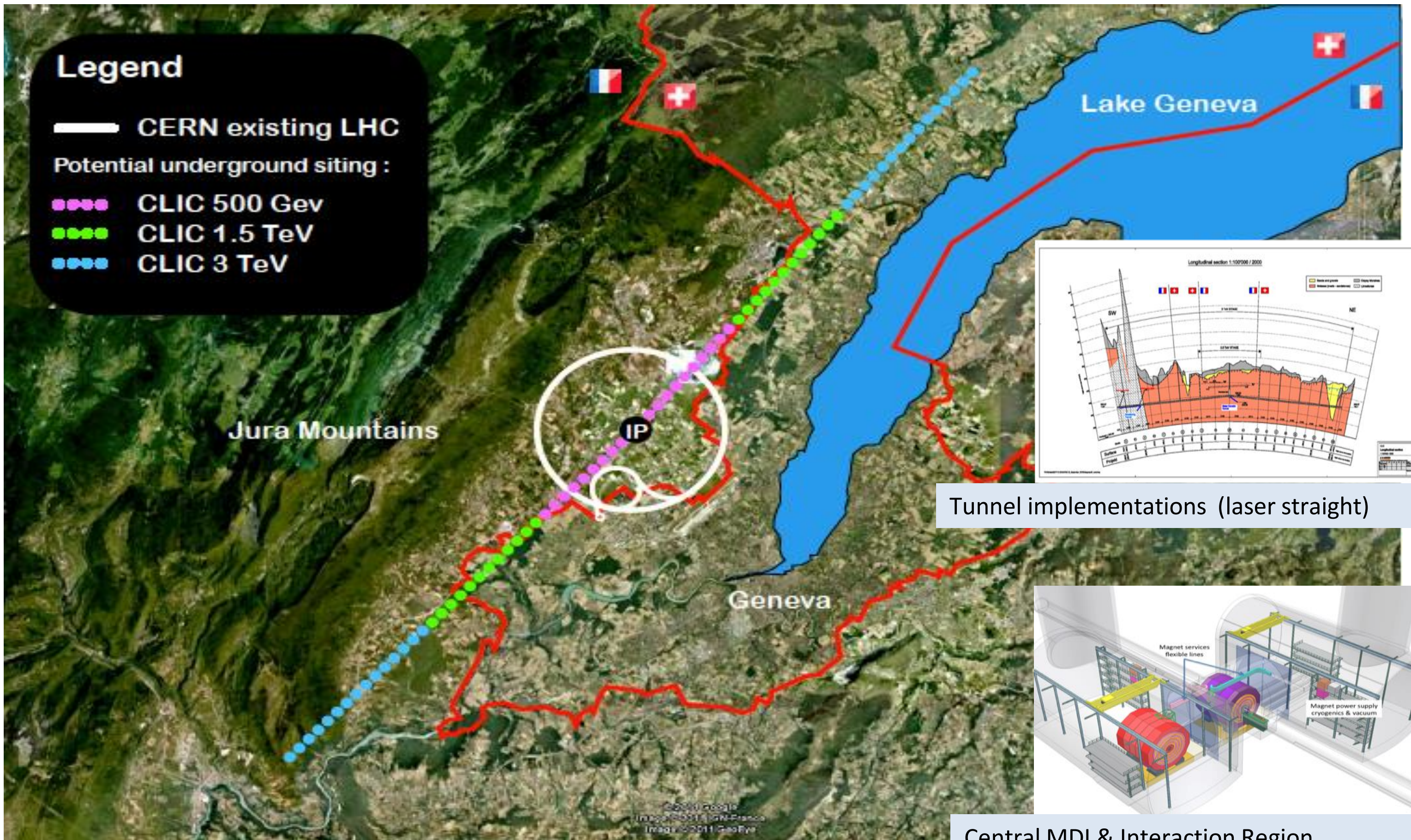
2024-25 Construction Start

Ready for full construction and main tunnel excavation.

Commissioning

Becoming ready for data-taking as the LHC programme reaches completion.

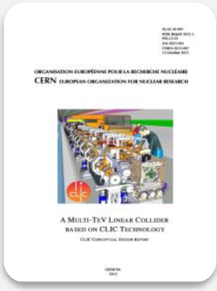
CLIC near CERN



Tunnel implementations (laser straight)

Central MDI & Interaction Region

CLIC Documentation - CDRs

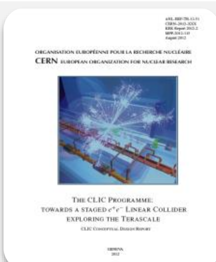


Vol 1: The CLIC accelerator and site facilities (H.Schmickler)

- 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 range
- Complete, presented in SPC in March 2011, in print!

Vol 2: Physics and detectors at CLIC (L.Linssen)

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



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)
- Completed and printed, submitted for the European Strategy Open Meeting in September http://arxiv.org/pdf/1209.2543v1

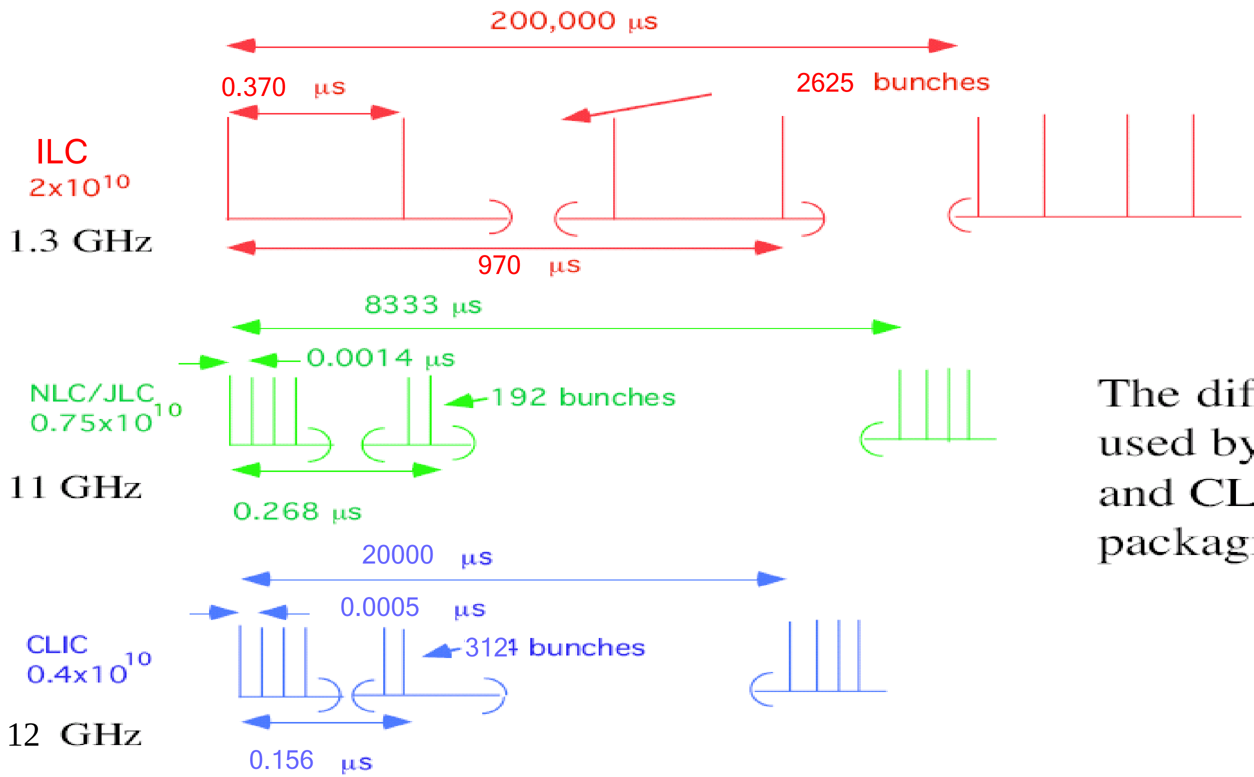
In addition a shorter overview document was submitted as input to the European Strategy update, available at: http://arxiv.org/pdf/1208.1402v1

Slides for detailed explanation
of small vertical emittances

all slides get called from within the talk

Bunch structure

- SC allows long pulse, NC needs short pulse with smaller bunch charge



The different RF technologies used by ILC, NLC/JLC and CLIC require different packaging for the beam power

Beam-beam Effect

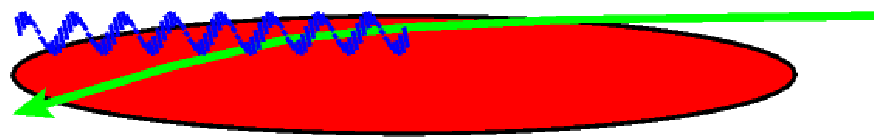
Bunches are squeezed strongly to maximise luminosity

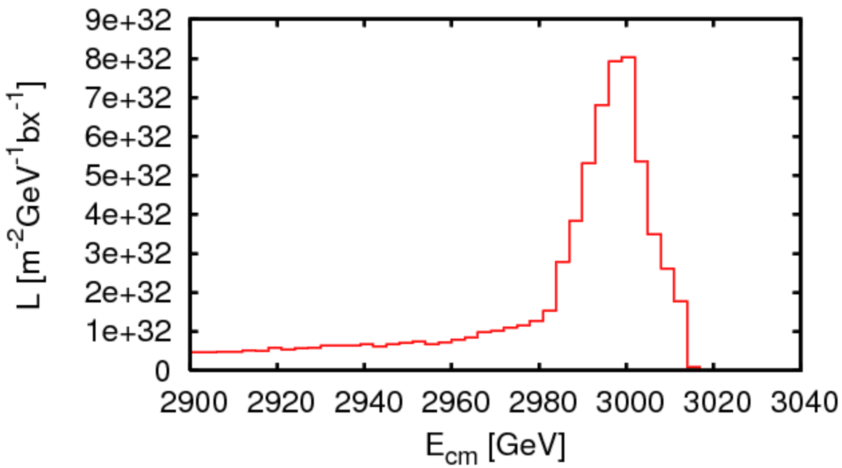
Electron magnetic fields are very strong

Beam particles travel on curved trajectories

They emit photons (O(1)) (beamstrahlung)

They collide with less than nominal energy





Beamstrahlung Optimisation

For low energies (classical regime) number of emitted photons

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

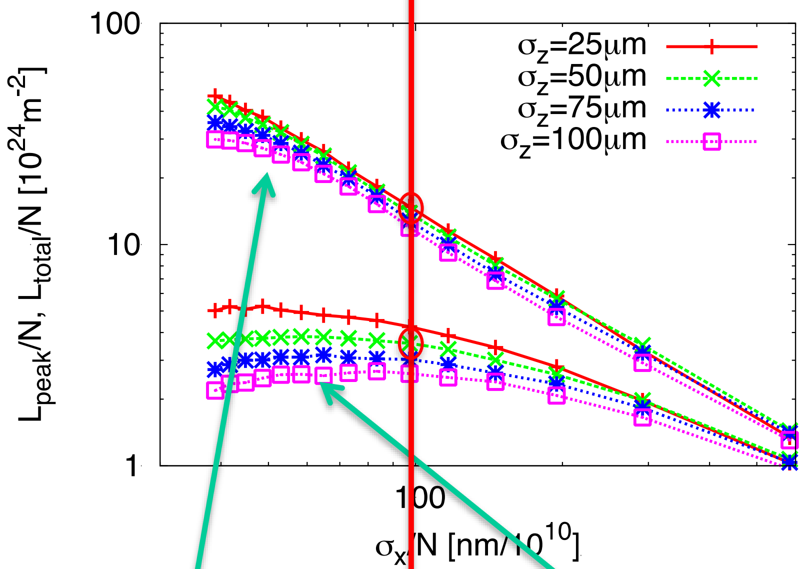
$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

Hence use $\sigma_x \gg \sigma_y$

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

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

For CLIC at 3TeV (quantum regime)



Total lumin grows for smaller beams

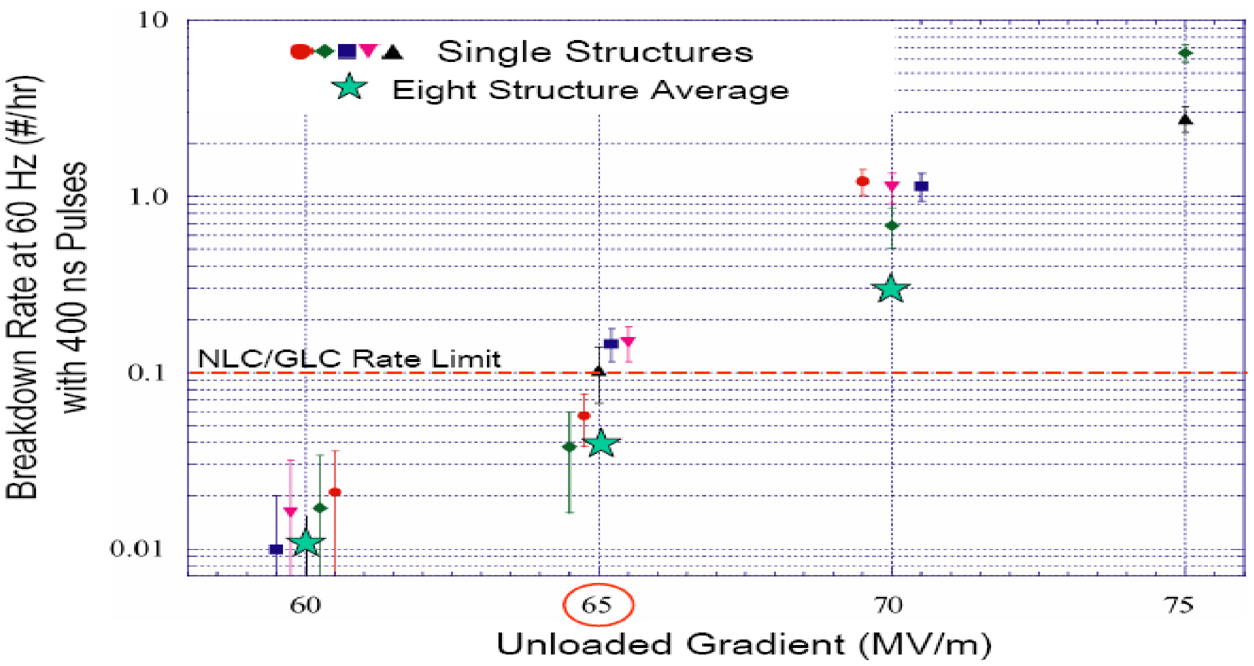
CLIC parameter choice

inosity in peak starts to decrease again

H.Schmickler

Breakdown-rate vs gradient

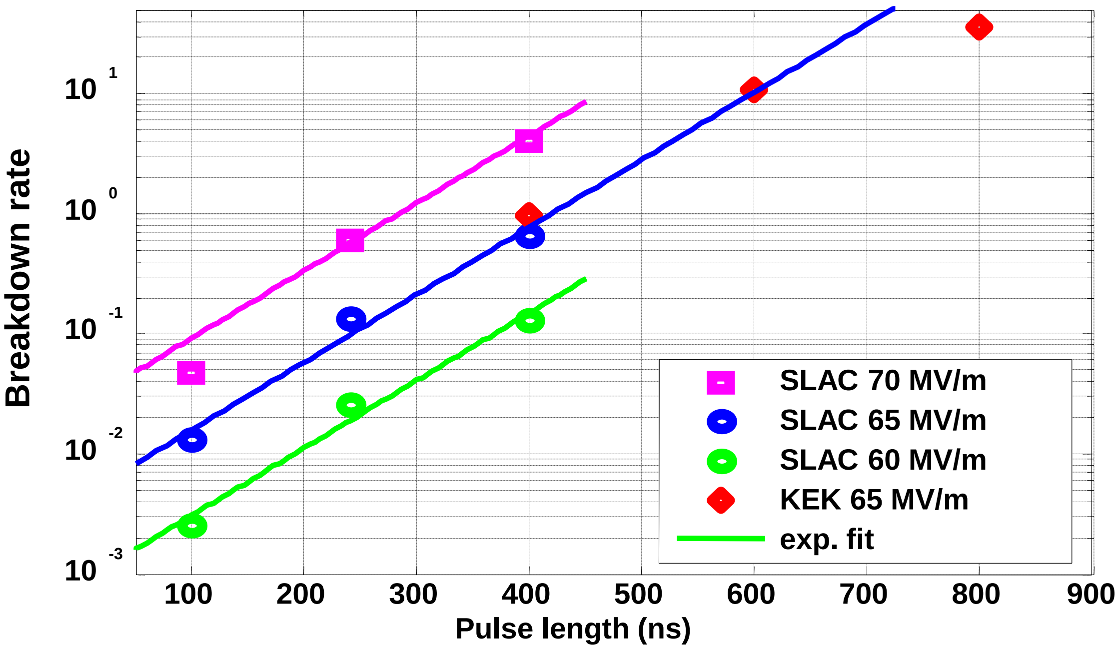
- Higher breakdown rate for higher gradient
- Strong function of the field ($\sim E^{\sim 30}$)
  => small decrease of field lowers BDR significantly



C. Adolphsen /SLAC

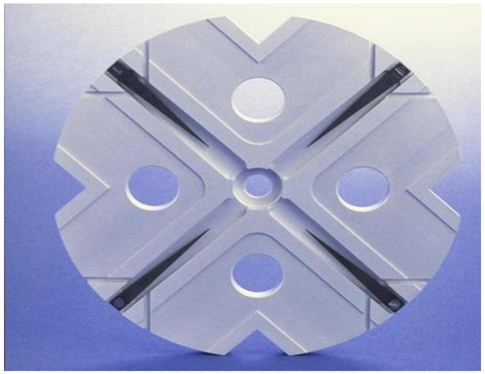
Breakdown-rate vs pulse length

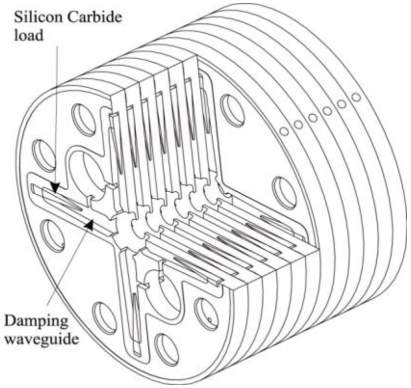
- Higher breakdown rate for longer RF pulses

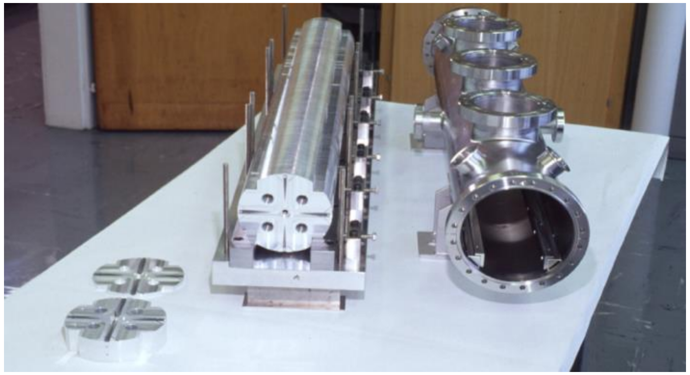


- experimental scaling: BDR ~ $(\text{pulselength})^{6} * (\text{gradient})^{30}$

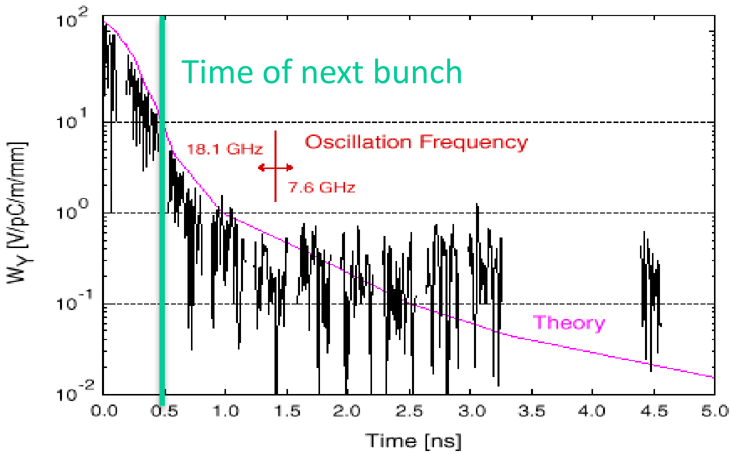
Accelerating structure developments







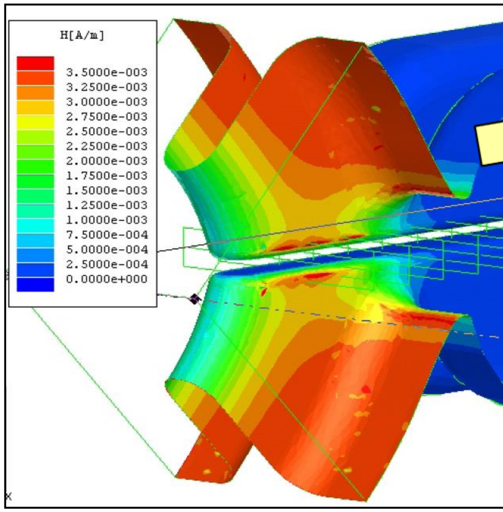
- Structures built from discs
- Each cell damped by 4 radial WGs
- terminated by SiC RF loads
- Higher order modes (HOM) enter WG
- Long-range wakefields efficiently damped

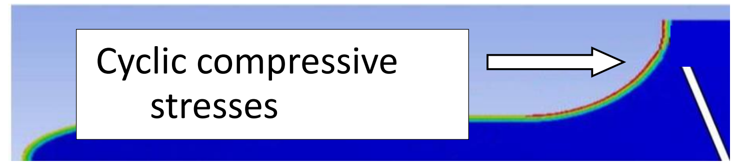


Limitations of NC Gradient E_{acc}

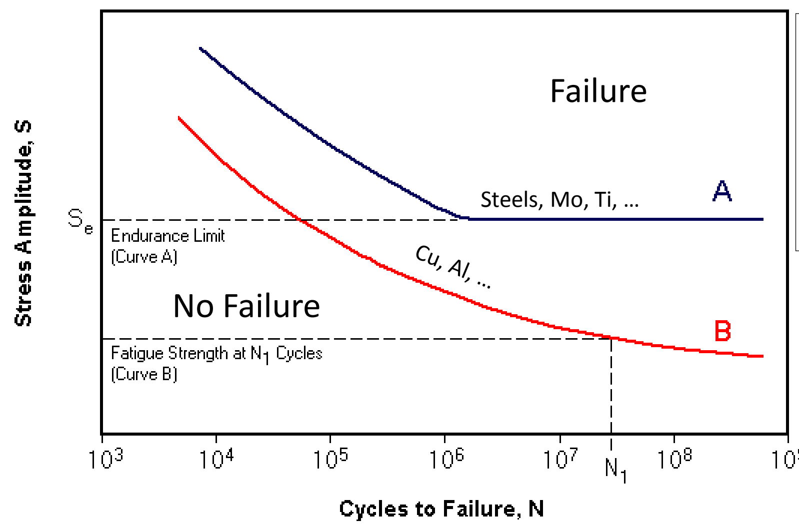
- Surface magnetic field
  - Pulsed surface heating => material fatigue => cracks
- Field emission due to surface electric field
  - RF break downs
  - Break down rate => Operation efficiency
  - Local plasma triggered by field emission => Erosion of surface
  - Dark current capture
    => Efficiency reduction, activation, detector backgrounds
- RF power flow
  - RF power flow and/or iris aperture apparently have a strong impact on achievable E_{acc} and on surface erosion. Mechanism not fully understood

Pulsed surface heating - Fatigue





- Magnetic RF field heats up cavity wall
- Extension causes compressive stress
- Can lead to fatigue



H_{peak}
⇕
ΔT
⇕
σ

- High number of cycles limits to smaller stresses
- 20 years operation => ~10^{10} cycles!
- Limits maximum ΔT and peak magnetic field

Pulsed surface heating

- Pulsed surface heating proportional to
  - Square root of pulse length
  - Square of peak magnetic field
- Field reduced only by geometry, but high field needed for high gradient
- Limits the maximum pulse length => short pulses (~few 100ns)

$$\Delta T = \sqrt{\frac{\mu_0}{2\pi} \frac{\omega t_P}{\sigma \lambda \rho c_H}} \hat{H}^2$$

ΔT temperature rise, σ electric conductivity
λ heat conductivity, ρ mass density
c_H specific heat, t_P pulse length
$\hat{H}$ peak magnetic field

$$\hat{H} = \frac{g_H}{377\,\Omega} E_{acc}$$

g_H geometry factor of structure design
typical value $g_H \approx 1.2$

Numerical values for copper

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

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

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