Future High-Energy Collider Projects

Part 1

Roderik Bruce

Introductory remarks

- This lecture is based on a collection of materials from many colleagues that I would like to acknowledge:
  - W. Bartmann, M. Benedict, M. Boscolo, H. Burkhardt, R. Corsini, B. Dalena, O. Etisken, F. Gianotti, M. Giovannozzi, B. Harer, B. Holzer, J. Jowett, R. Kersevan, A. Lechner, M. Lamont, J. Pfingstner, T. Pieloni, M. Rakic, S. Redaelli, D. Schulte, L. Rossi, R. Ruber, M. Schaumann, J. Wenninger, F. Zimmermann
  - In particular, a lot of material comes from D. Schulte – thanks! – who in turn used material from S. Stapnes, L. Rossi, Ralph Assmann, J-P. Delahaye, L. Linssen, S. Doebert, A. Grudiev, F. Tecker, W. Wuensch, S. Poss, J. Strube, J. Wenninger, M. Benedikt, F. Zimmermann, B. Holzer, R. Kersevan, Ph. Lebrun

- This is an accelerator lecture. For particle physics, e.g. physics goals etc., please see physics lectures

- I will build on concepts introduced in other lectures:
  - Michaela Schaumann: **Particle Accelerators and Beam Dynamics**
  - Daniel Schoerling: **Accelerator Technology Challenges (Part 1: Magnet Superconductivity)**
  - Anton Lechner: **Accelerator Technology Challenges (Part 3: Accelerator Operation and Design Challenges)**

- Focus on machines studied at CERN

Outline

First lecture

- Introduction
  - Considerations for collider design: particle type, energy, circular/linear…
  - Limitations for future colliders
  - European strategy for particle physics
- ILC (International Linear Collider)
- CLIC (Compact Linear Collider)

Second lecture

- HL-LHC (High-Luminosity Large Hadron Collider)
- FCC-hh (Future Circular collider, hadrons)
- FCC-ee (Future Circular collider, e+e-)
- CEPC/SppC (Chinese Electron-Positron Collider / Super proton-proton Collider)

Linear: ILC, CLIC

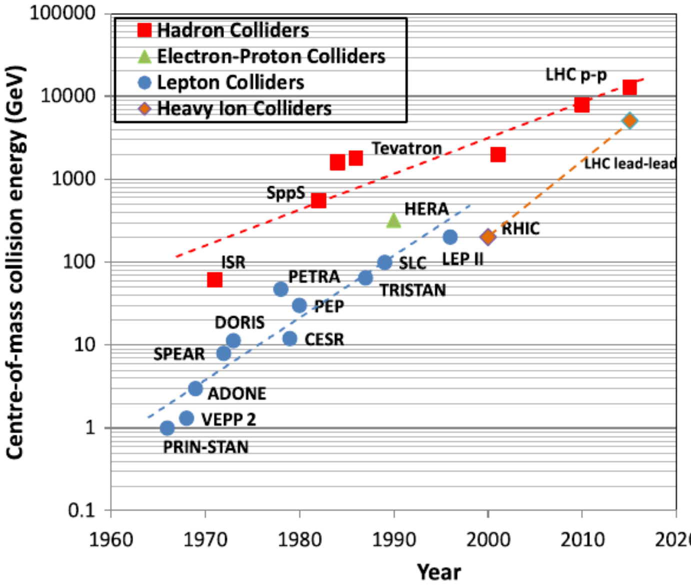
Circular: HL-LHC, FCC-hh, FCC-ee, CEPC/SppC

Particle colliders

- Particle colliders have been instrumental for scientific discoveries in high energy physics for more than half a century
  - Key for establishing the standard model in particle physics

- Technological innovation made it possible to increase energy at a much faster pace than the costs

- LHC has the highest energy among colliders built so far
  - Circular collider, designed to collide 7 TeV protons and heavy ions



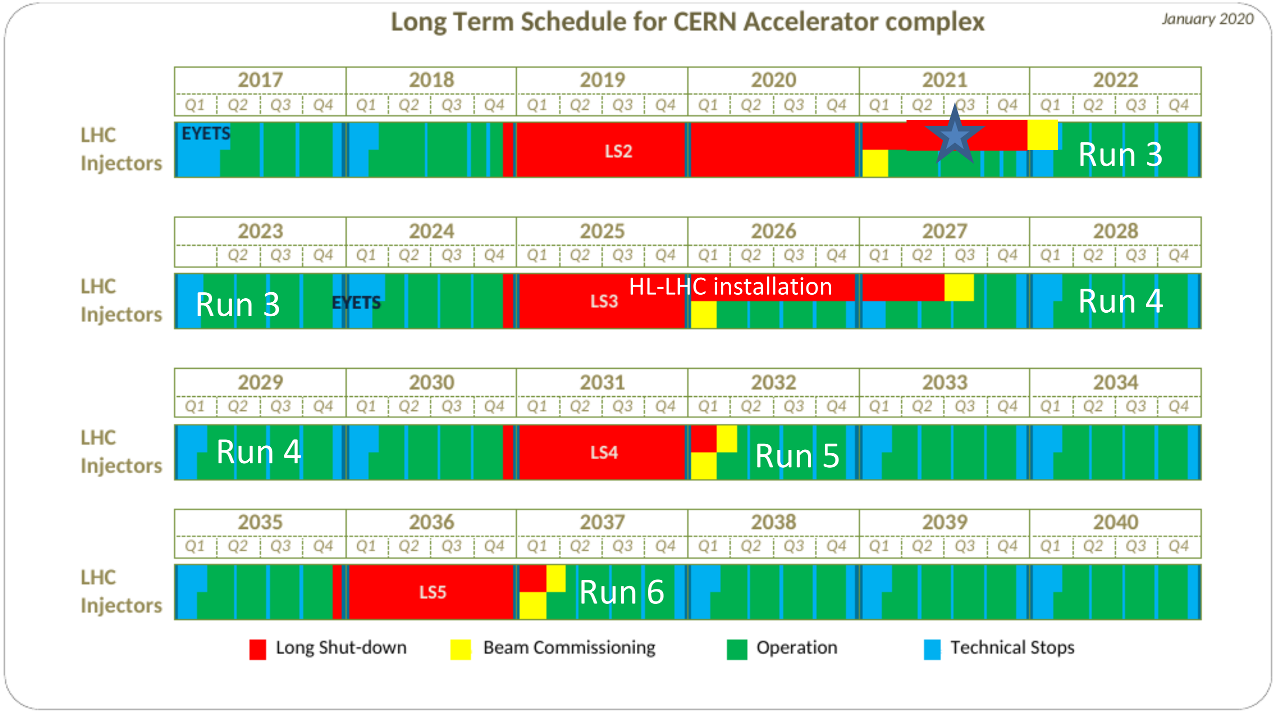
"Livingstone plot" of collider energy vs time (source)

LHC timeline

- Present LHC will operate for a few more years
- High-Luminosity LHC (HL-LHC) upgrades foreseen for next long shutdown
- HL-LHC planned to operate until ~2035-2040
- What happens next?
  - Nobody knows, but there are many ideas on the table
- It took ~25 years to design and build the LHC, so need to start thinking now about future options

Tentative schedule, ***could well change***

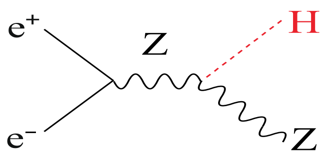
(source https://edms.cern.ch/document/2311633/1.0, updated with LS2 extension)



3 main complementary ways to search for (and study) new physics at accelerators

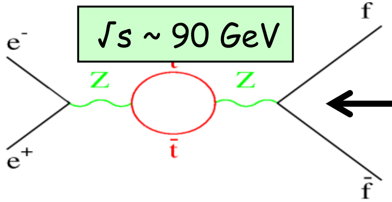
Direct — production of a given (new or known) particle

e.g.: Higgs production at future e^+e^- linear/circular colliders at $\sqrt{s}$ ~ 250 GeV through the HZ process
→ **need high E and high L**

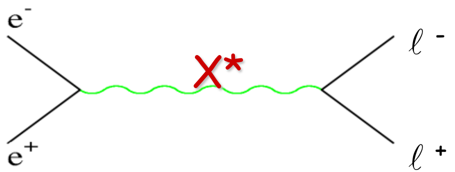


Indirect — precise measurements of known processes

→ look for (tiny) deviations from SM expectation from quantum effects (loops, virtual particles)
→ sensitivities to E-scales $\Lambda \gg \sqrt{s}$ → **need high E and high L**



E.g. top mass predicted by LEP1 and SLC in 1993: m_{top} = 177 ± 10 GeV; first direct evidence at Tevatron in 1994: m_{top} = 174 ± 16 GeV

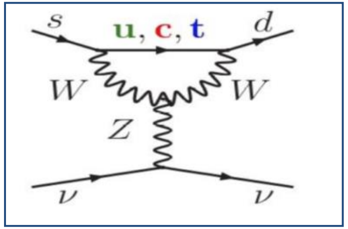


Main focus

Rare processes — suppressed in SM → could be enhanced by New Physics

e.g. neutrino interactions, rare decay modes → **need intense beams and/or ultra-sensitive (massive) detectors ("intensity frontier")**

E.g. $K^+ \to \pi^+\nu\nu$ decay (NA62 experiment)
Proceeds via loops → suppressed in the SM : BR~ 10^{-10}
Can be enhanced by new particles running in the loop.
Theoretically very clean.



Slide from F. Gianotti

Considerations for new colliders

- So, we want high energy and high luminosity
  - When we say high luminosity, we implicitly mean high event rate
  - Reminder: The luminosity directly determines the event rate

- How do we get there? Several choices to be made:
  - What to collide: lepton vs hadron
  - How to collide:
    - fixed target or colliding beams
    - linear vs circular collider
  - Acceleration technology
    - DC, RF, wakefield…
  - Magnet technology
    - Superconducting (what conductor?), normal conducting → see lecture D. Schoerling
  - Acceptable cost of construction, power consumption, site

- Think about various limitations to energy and luminosity and how to overcome them

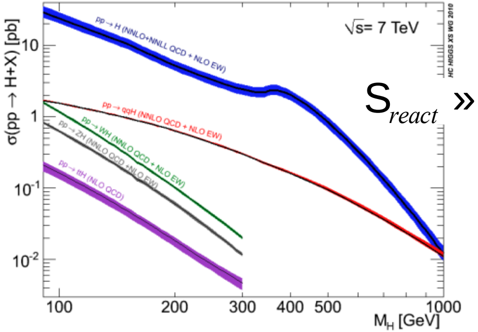
$$\boxed{\frac{dR}{dt} = L \times \sigma_p}$$

Event rate

Luminosity (determined by and collider design: can be influenced)

Cross section (given by physics, cannot be influenced)

Higgs cross section:

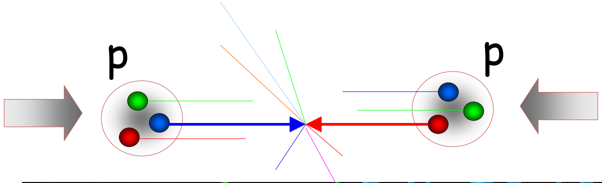


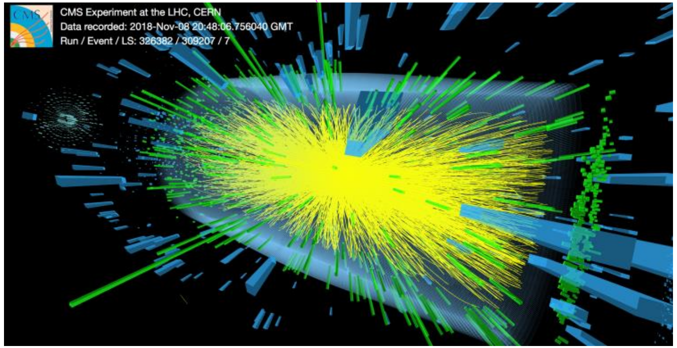
S_{react} »$1pb$

Leptons vs hadrons

Hadrons (protons or ions)

- Mix of quarks, anti-quarks and gluons:
  - variety of processes
  - not all nucleon energy available in collision
  - Energy spread between partons – spread in collision energy
  - huge QCD background
- Can typically achieve highest collision energy
- Good for discoveries at the frontier of new physics

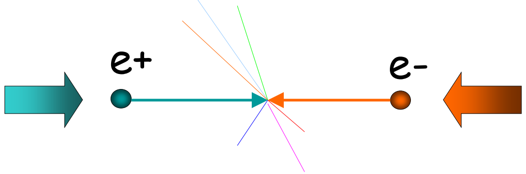




LHC Pb-Pb collision, CMS

Leptons (electrons, positrons, maybe muons)

- Elementary particles colliding - very well defined centre-of-mass energy
- Low background
- Good for high-precision measurements
- Higher energy loss from synchrotron radiation influences accelerator design → see next slides

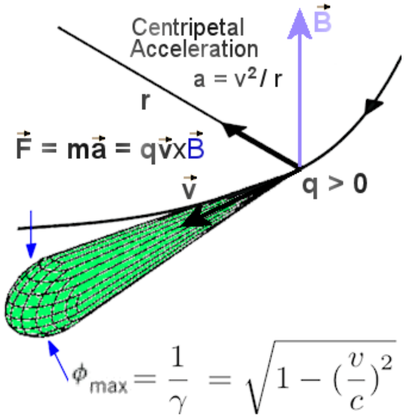


LEP II e+e- collision, DELPHI

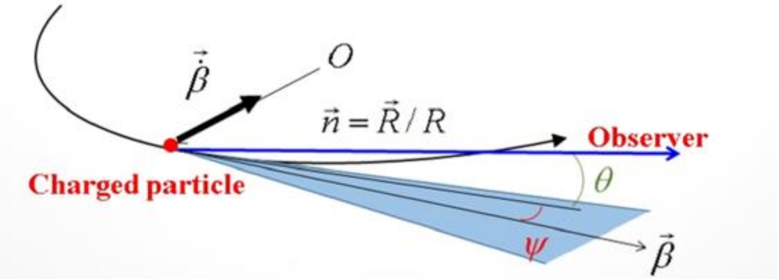
Synchrotron radiation

- Classical electrodynamics: an accelerating charge radiates
  - Radiation carries off energy, which is taken away from the kinetic energy
  - Radiated energy needs to be replenished by accelerating RF cavities => could lead to very high power consumption
  - Radiated photons impact on vacuum chamber => causes heating, maybe even damage for high power loads

Imposes limitations on collider design



- For a relativistic charged particle, radiation is forward – it sweeps around like a locomotive's headlight as the particle moves



Radiated power

- For full derivation, see e.g. Jackson, Classical electrodynamics, chapter 14

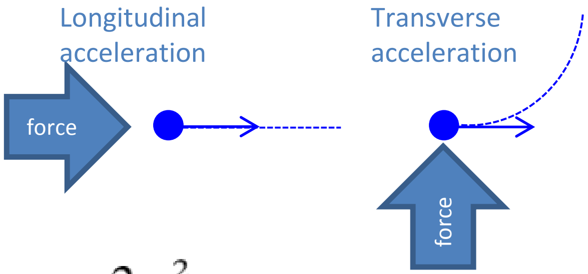
- *Very* short summary
  - Write down electric and magnetic fields of moving point charge (at relativistic speed)
  - Power radiated is given by integral of Poynting vector over closed surface around charge, let R→∞ (only 1/R terms in fields contribute)
  - Integrate …. don't be in a hurry

- Result:
  - Energy loss is negligible for longitudinal acceleration, except for extreme (unphysical) gradients
  - For transverse acceleration (as in circular colliders), energy loss could be significant - 4^{th} power dependence on energy and mass
  - Effect is much more limiting for light particles, such as electrons/positrons
    - Electrons are 2000 times lighter than protons!

$$\mathbf{B} = [\mathbf{n} \times \mathbf{E}]_{\mathrm{ret}}$$

$$\mathbf{E}(\mathbf{x}, t) = e\left[\frac{\mathbf{n}-\boldsymbol{\beta}}{\gamma^2(1-\boldsymbol{\beta}\cdot\mathbf{n})^3R^2}\right]_{\mathrm{ret}} + \frac{e}{c}\left[\frac{\mathbf{n}\times\{(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}\}}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3R}\right]_{\mathrm{ret}}$$

$$P(r) = \oint \mathbf{S}\cdot d\mathbf{a} = \frac{1}{\mu_0}\oint(\mathbf{E}\times\mathbf{B})\cdot d\mathbf{a}$$



$$P = \frac{2}{3}\frac{e^2c}{\rho^2}\beta^4\gamma^4$$ … meaning… $$\boxed{\Delta E \propto \left(\frac{E}{m}\right)^4\frac{1}{R}}$$

Radiation damping

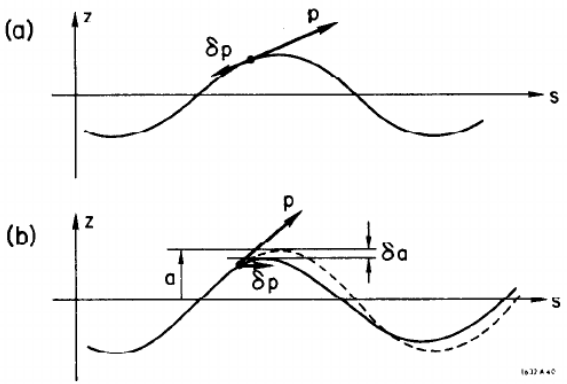


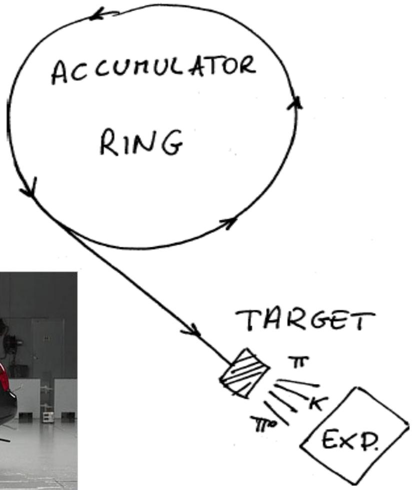
FIG. 40--Effect of an energy change on the vertical betatron oscillations: (a) for radiation loss, (b) for rf acceleration.

M. Sands, SLAC-121 UC-28

- Emitted photons along betatron trajectory – (almost) no change in angle of particle
- Energy losses compensated by RF, giving purely longitudinal momentum kick
  - Increases longitudinal momentum and not transverse => decrease in angle
  - Smaller betatron amplitudes => smaller emittance, "radiation damping"
    - Remember: emittance determines phase space area occupied by beam (lecture M. Schaumann)
- On the other hand: photon emission gives small random energy (and very small angle) change => blowup, "quantum excitation"
- Equilibrium between radiation damping and quantum excitation exists: equilibrium emittance
  - Time needed for the beam to reach the equilibrium emittance: "Damping time"
  - Equilibrium emittance is typically smaller in vertical than horizontal plane => "flat" lepton beams

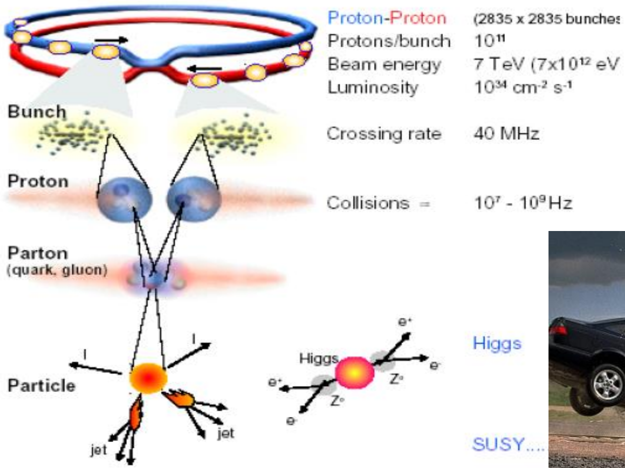
Collider vs fixed target experiments

- Fixed Target



$$E_{CM} = \sqrt{2\left(E_{beam}mc^2 + m^2c^4\right)}$$

- Collider



$$<< \qquad E_{CM} = 2\left(E_{beam} + mc^2\right)$$

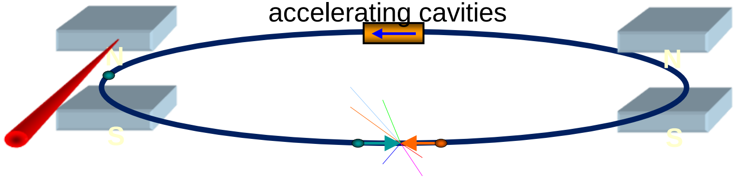
To achieve the highest possible centre-of-mass energy, need a collider
(see lecture M. Schaumann)

Circular vs linear collider

Circular Collider

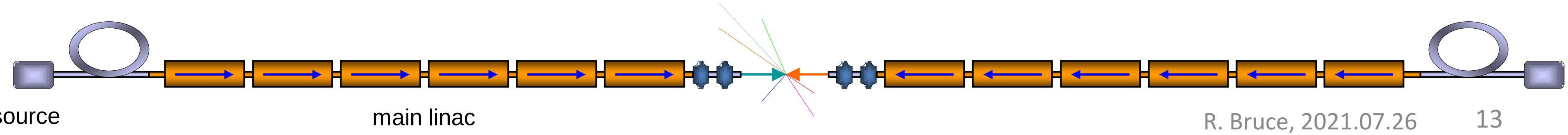
- multi-pass => Accelerate beam in many turns, let beam collide many times
- many magnets, few accelerating cavities
- Bending of beam trajectory => synchrotron radiation losses

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



Linear Collider

- single pass => need to be very efficient
- few magnets, many accelerating cavities
- Not limited by synchrotron radiation – promising choice for reaching highest lepton energies



Increasing beam energy

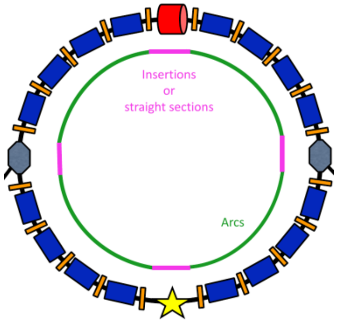
Circular Collider

- Hadron beams: energy limited by ability of to keep particle on circular orbit
  - Maximum achievable dipole field (superconductor technology)
  - Radius of ring (cost, site)
- Lepton beams: radiation losses
  - RF power consumption
  - Disposal of radiated power
  - Radius of ring (cost, site)

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

$$\frac{p}{q} = B\,\rho$$

$B\,\rho$ = Beam rigidity
(see lecture M. Schaumann)

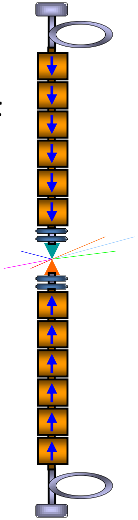


For protons:

$$E_{beam}[TeV] \approx 0.3 \times B[T] \times R[km]$$

Linear Collider

- Energy depends on
  - Accelerating gradient (RF technology)
    - Plasma wakefield acceleration promises large advancement, but not yet mature to produce required beam quality
  - Length (cost, site)



$$E_{cm} \approx L_{linac} G_{acc}$$

To push energy boundary: improve technology (B-fields, RF gradient) or build a larger machine

Increasing luminosity

Reminder: luminosity depends on beams and optics (see lecture M. Schaumann)

Expression for round beams:

$$\frac{dR}{dt} = L \times \sigma_p$$

Higher intensity

Increase number of bunches

Increase bunch intensity

$$L = \frac{kN^2 f \gamma}{4\pi \beta^* \varepsilon} \cdot F$$

Increase F: shorter bunches, smaller crossing angle

$$\frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma_x} \frac{\phi}{2})^2}}$$

Smaller β*

Smaller emittance

Smaller beam size

In addition:

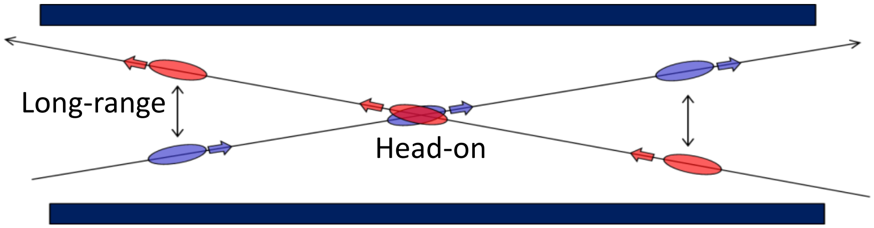
- Potential limitations on luminosity from losses and showers from the collisions (see lecture A. Lechner).

Elliptic beams: $L \propto \frac{kN^2 f \gamma}{4\pi \sigma_x^* \sigma_y^*} F$

Some limitations on intensity and beam size

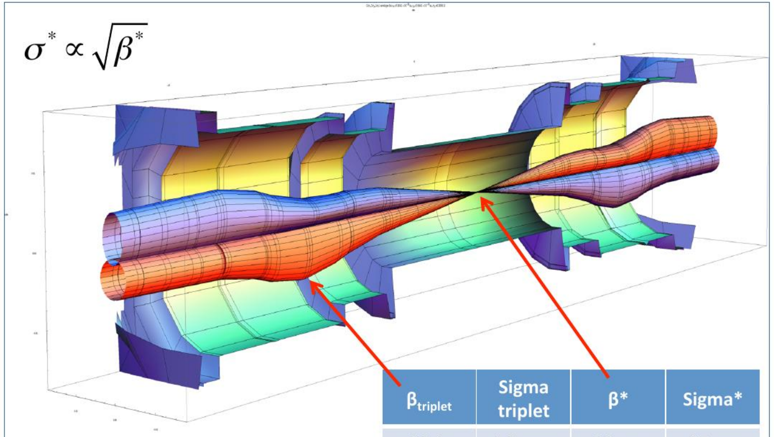
(not exhaustive list)

- Intensity
  - Limitations in beam production scheme
  - Collective effects and instabilities, e.g. space charge, impedance effects, beam-beam effects
  - Beam-beam effects (detrimental non-linear electromagnetic field acting on opposing beam)
  - In circular lepton machines, limitations on RF power (compensate synchrotron radiation losses)
  - Detrimental effects of beam losses



remember from lecture by M. Schaumann: $\beta(s) = \beta^* + \frac{s^2}{\beta^*}$

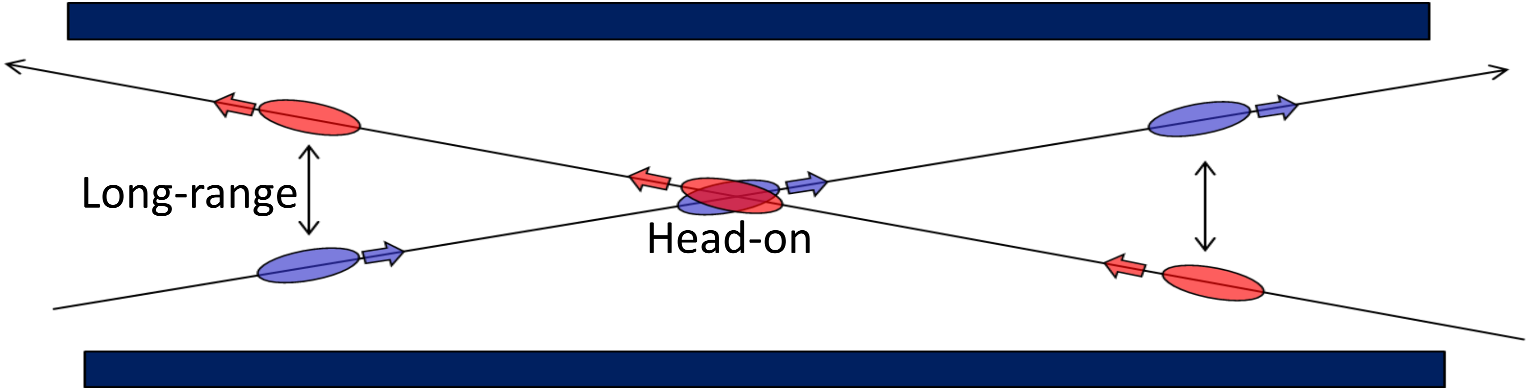
- Beam size
  - β* limited by magnet focusing strength and aperture in final focus quadrupoles
  - Emittance: limitations in beam production, larger risk for instabilities, blowup (intra-beam scattering); not easy to reduce emittance of existing beam, need dedicated cooling etc
    - Lepton machines: equilibrium emittance determined by accelerator lattice
    - Can use damping rings to shrink emittance
  - Beam-beam effects



$\beta_{triplet}$	Sigma triplet	β*	Sigma*
~4.5 km	1.5 mm	55 cm	17 um

Image courtesy John Jowett

Geometric reduction factor



$$L = \frac{kN^2 f \gamma}{4\pi \beta^* \varepsilon} \cdot F$$

$$\frac{1}{\sqrt{1 + \left(\frac{\sigma_s}{\sigma_x} \frac{\phi}{2}\right)^2}}$$

- Bunches must collide with an angle, "crossing angle" – otherwise we get unwanted collisions outside interaction point
  - Crossing angle need to be large enough so that bunches are not perturbed by electromagnetic field at parasitic encounters (long-range beam-beam effect)

- Fewer collisions when overlap is not perfect – geometric reduction factor
  - Depends on crossing angle, bunch length, and transverse size

Considerations for future collider choices

D. Schulte

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

European strategy for particle physics

- Common strategy worked out in Europe to guide future decision-making in field: "European strategy for particle physics"
  - endorsed by the CERN council

- Based on bottom-up approach:
  - physics community is invited to submit proposals for near-term, mid-term and longer-term projects → community discussion in open symposium, Physics briefing book
  - Based on this input, the European Strategy Group formulates the strategy
    - consists of scientific delegates from CERN Member States, Associate Member States, directors of major European laboratories, representatives of various European organizations, some invitees from outside the European Community

- Initiated in 2006, updated in 2013 and 2020, next update foreseen in 2026/2027

2020 update: Key takeaway messages

Some recommendations in European strategy

Some points relevant to future high-energy colliders - see full document here

- [about LHC] "The successful completion of the high-luminosity upgrade …. should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC …. should be exploited. "

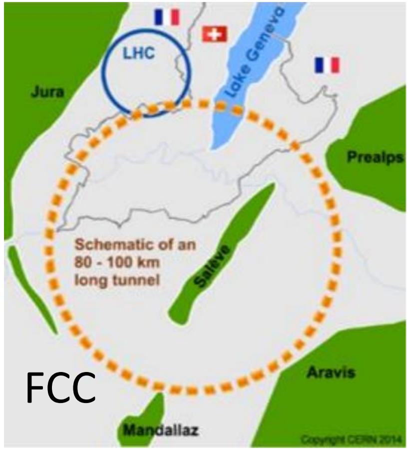
- "An electron-positron Higgs factory is the highest-priority next collider"

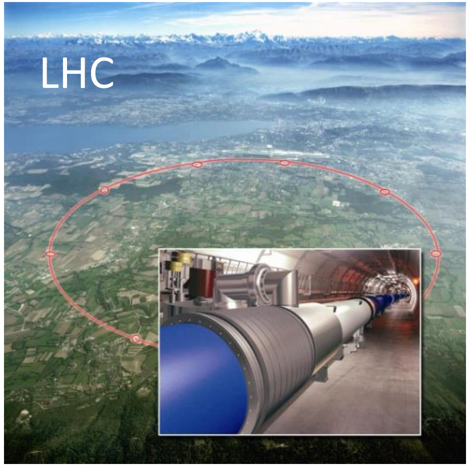
- "Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. "

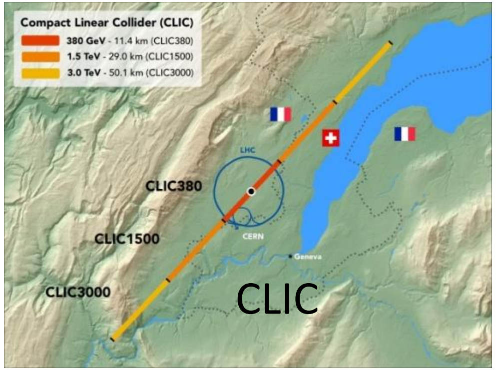
- "The particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors"

High-energy colliders studied at CERN

- **HL-LHC**: luminosity upgrade of the LHC.
  - Approved and financed - production and installation of upgrades already in full swing
  - 14TeV pp CMS and heavy ions as in LHC, 27 km
- **Future Circular Collider (FCC)** in different stages
  - Conceptual design report released
  - Circular e+e- collider in 100 km tunnel, up to 365 GeV CMS: FCC-ee
  - Re-use tunnel for 100 km hadron collider, 100 TeV pp CMS: FCC-hh
  - 2-step approach inspired by successful LEP – LHC programs at CERN
  - Alternative approaches:
    - energy upgrade of the LHC using stronger magnets: High-Energy LHC (HE-LHC)
    - Hadron-electron collisions at the FCC: FCC-he
    - Lower-field version of FCC-hh
- **Compact Linear Collider (CLIC)**
  - Linear e+e- collider, conceptual design report released
  - Up to ~50 km and 3 TeV CMS energy
- Other projects that are being studied
  - Muon collider
  - LHeC (hadron-electron collisions at the LHC)

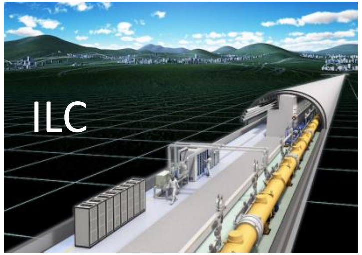




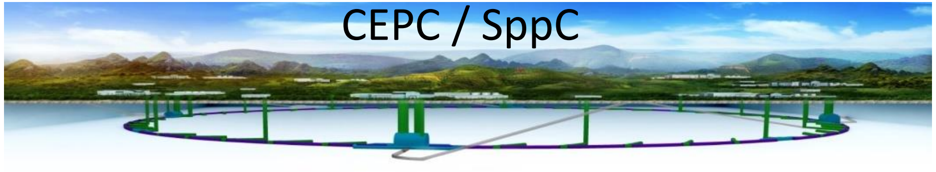


Initiatives in the rest of the world

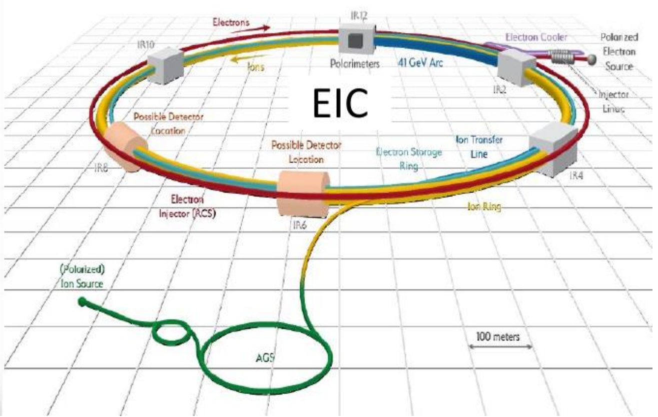
- **International Linear Collider (ILC)**
  - Linear e+e- collider, technical design report released – mature design
  - up to 500 GeV CMS, 31 km
  - Potentially hosted by Japan – waiting for political decisions



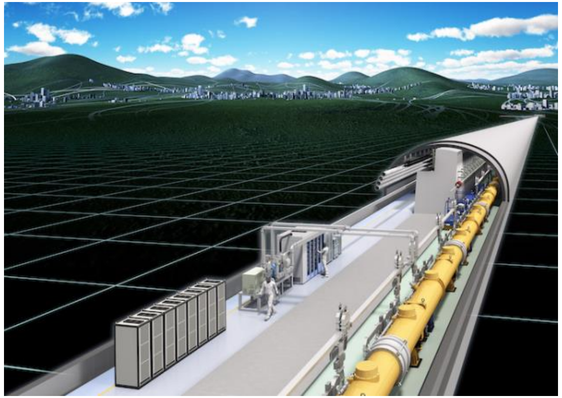
- **Chinese initiative for circular collider**
  - First: e+e- collider (CEPC), up to 240 GeV CMS energy, 100 km ring
  - followed by a 100 km hadron collider (SppC), 75 TeV CMS energy (proposals for extensions to ~150 TeV)



- **Electron-Ion Collider (EIC)** to be built at Brookhaven, US
  - Circular, up to 140 GeV CMS energy, ~3.4 km
  - Range of ions: p-U
  - Use existing RHIC with some upgrades for ions
  - New electron storage ring and injector
  - Project approved, announced timeline to completion of ~10-15 years

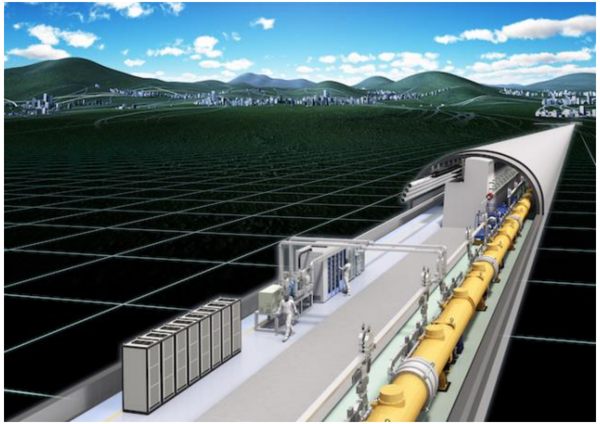


ILC



ILC basics

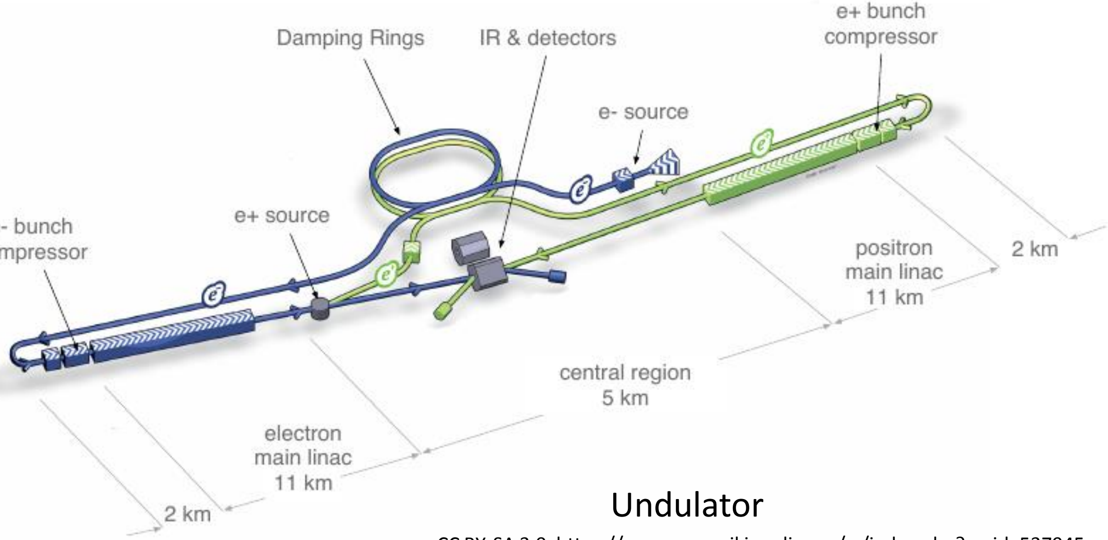
- International Linear Collider: e+e- collider, aiming at 100-250 GeV beam energy (up to 500 GeV centre of mass)
  - Extendable to 1 TeV (requires doubling the length)
- Foreseen length at 500 GeV CMS energy of 31 km
- Possibly to be built in Japan – waiting for political decisions and agreements on funding



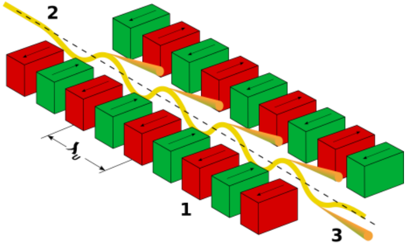
ILC layout and concept

- First, create e- (photocathode DC gun)
- Accelerate, send to circulate in 3.2 km damping ring
  - Shrinking emittance under radiation damping
- e- sent to main linac, accelerate
- To create e+: Electrons pass undulator – magnets with many periodic bends
  - Radiated photons impact on Ti-alloy target, creating e+e- pairs.
  - Capture e+, accelerate, send to damping ring
- Send e+ to main linac, accelerate
- Collide e+e- inside detector

From ILC design report



Undulator



ILC main parameters

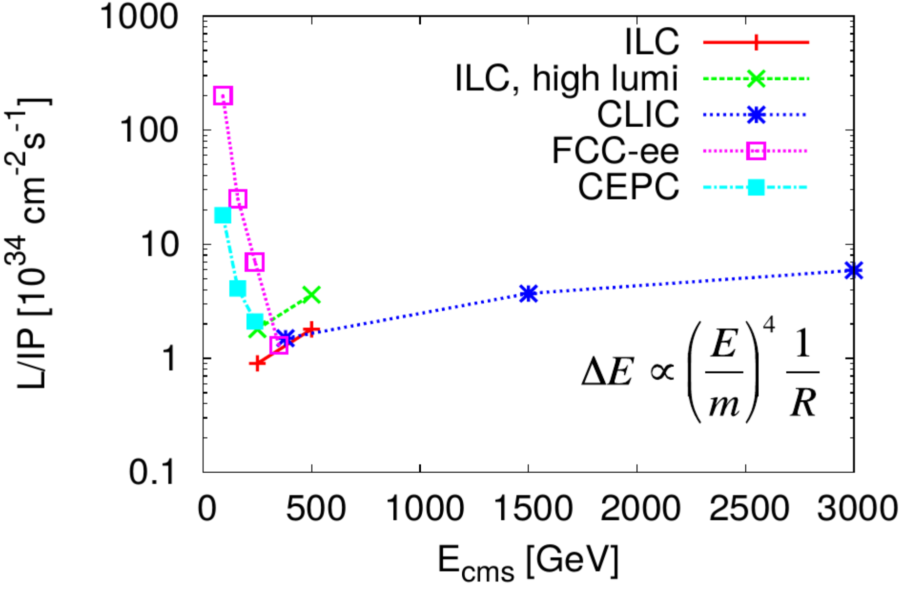
From ILC design report

			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
								A	B
Centre-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	10	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	554	554	366	366	366
Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	G_a	MV m^{-1}	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	P_{beam}	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	122	121	163	129	204	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	μm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	β_y^*	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	729.0	683.5	474	729	474	481	335
IP RMS veritcal beam size	σ_y^*	nm	7.7	5.9	5.9	7.7	5.9	2.8	2.7
Luminosity	L	$\times 10^{34}$ cm^{-2}s^{-1}	0.75	1.0	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		0.97%	1.9%	4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	62.4	93.6	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	46.5	115.0	344.1	46.5	344.1	1338.0	3441.0

Luminosity comparison

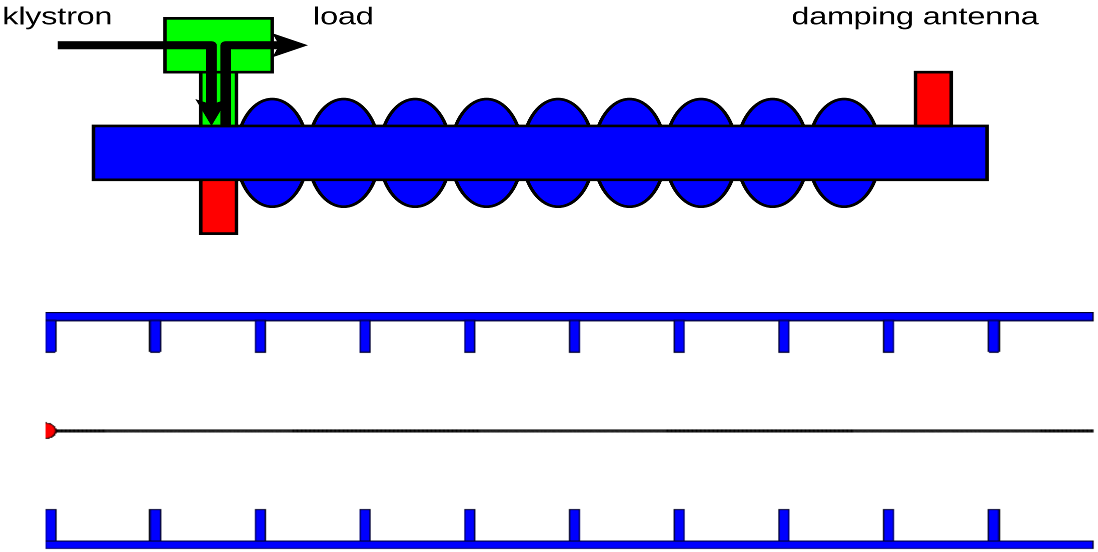
- Comparing luminosity between different future lepton colliders
  - Circular and linear

- At high energies, linear lepton colliders can achieve higher luminosity than circular ones
  - Intensity in circular colliders limited by synchrotron raditaion



ILC Cavities

- Superconducting cavity (Ni at 2 K)
- RF frequency is 1.3 GHz, 23 cm wavelength
- Length is 9 cells = 4.5 wavelengths = 1 m

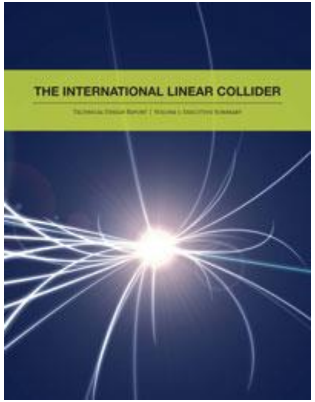


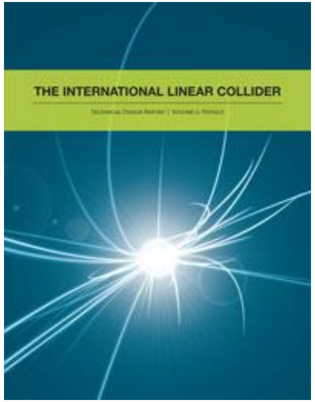
D. Schulte

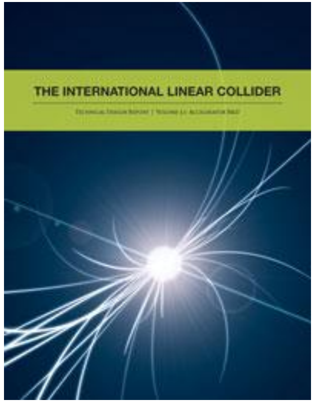
- Standing wave structure, achieving gradients of 31.5 MV/m
- Theoretical field limit around 50-60 MV/m
  - In reality, reaching about 30-40 MV/m with imperfections
- Need about 8000 cavities

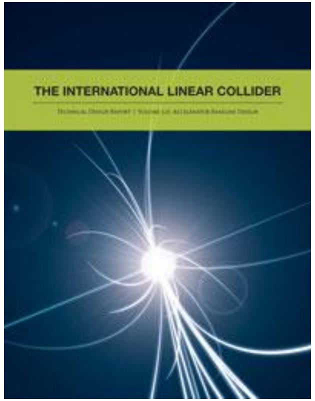
Further documentation

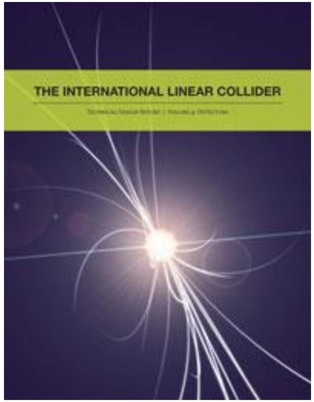
- [ILC technical design report]



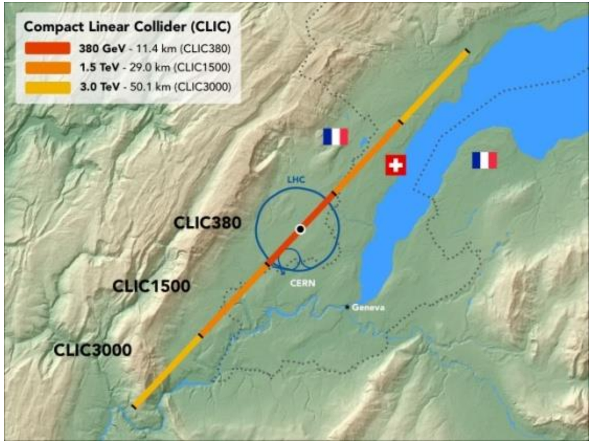








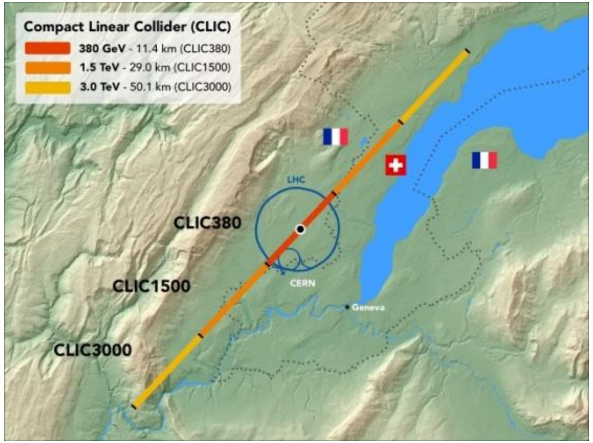
CLIC

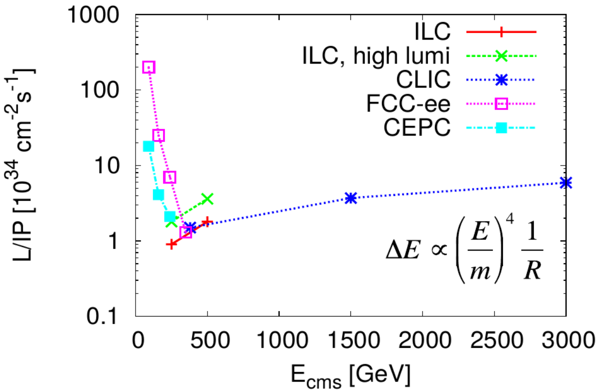


Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva

CLIC basics

- Linear e+e- collider, to be built in stages of increasing centre-of-mass energy:
  - 380 GeV – 3 TeV
  - Length between ~11 km and ~50 km
- Aiming at highest lepton energies
- 30 MW of beam power at 3TeV



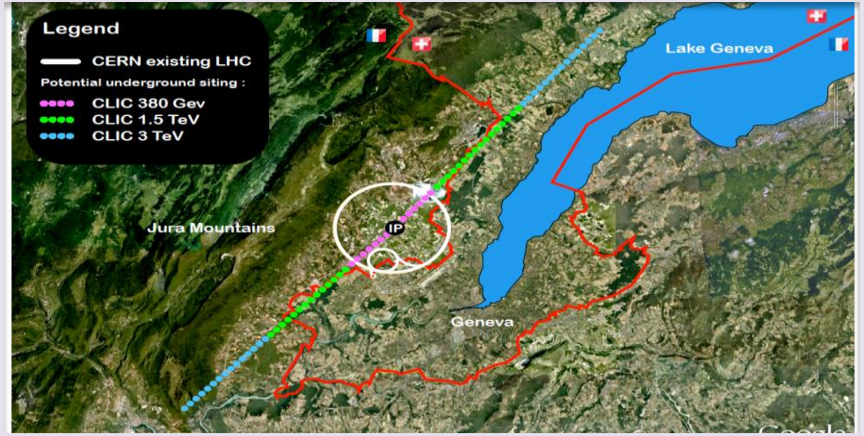


CLIC Staged Scenario

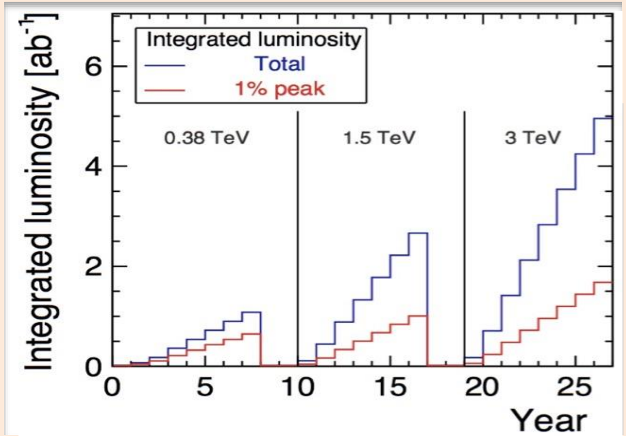
3 stages foreseen:

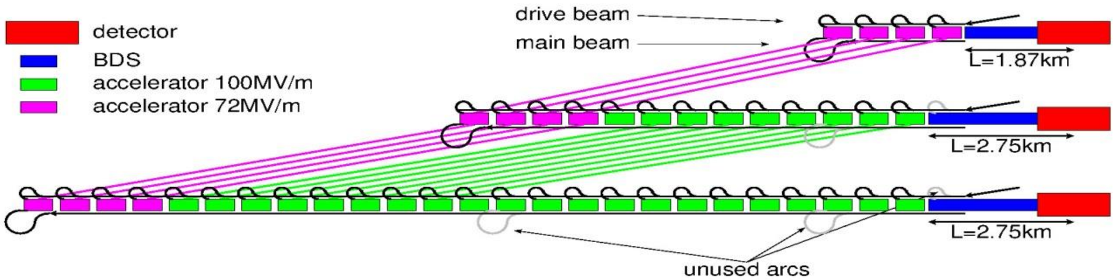
Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{int}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0
2	1.5	2.5
3	3.0	5.0

Central complex on Prevessin site



Luminosity evolution





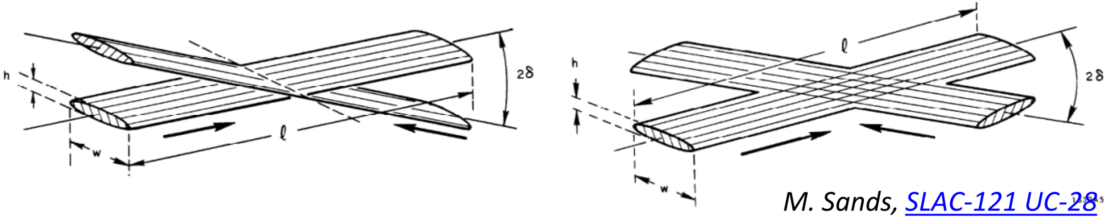
CLIC parameters

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

D. Schulte

Flat beams in lepton colliders

- Naturally smaller vertical beam size from radiation damping
  - Often true also for linear colliders due to horizontal bending in damping rings, transfer lines etc.



M. Sands, SLAC-121 UC-28

- Beam-beam effect
  - Focusing of e+e- beams due to each others' fields => higher luminosity
  - Bending of particles => synchrotron radiation, "beamstrahlung" => unwanted energy spread in collisions

Luminosity depends on product of beam sizes: $L \propto \dfrac{N^2}{\sigma_x^* \sigma_y^*}$

average number of photons per collision depends on sum of beam sizes:

$$n_\gamma \approx \frac{12}{\pi^{3/2}} \frac{\alpha r_e N_b}{\sigma_x^* + \sigma_y^*} \approx \frac{12}{\pi^{3/2}} \frac{\alpha r_e N_b}{\sigma_x^*}$$

M.A. Valdivia García et al., doi:10.18429/JACoW-IPAC2019-MOPMP035

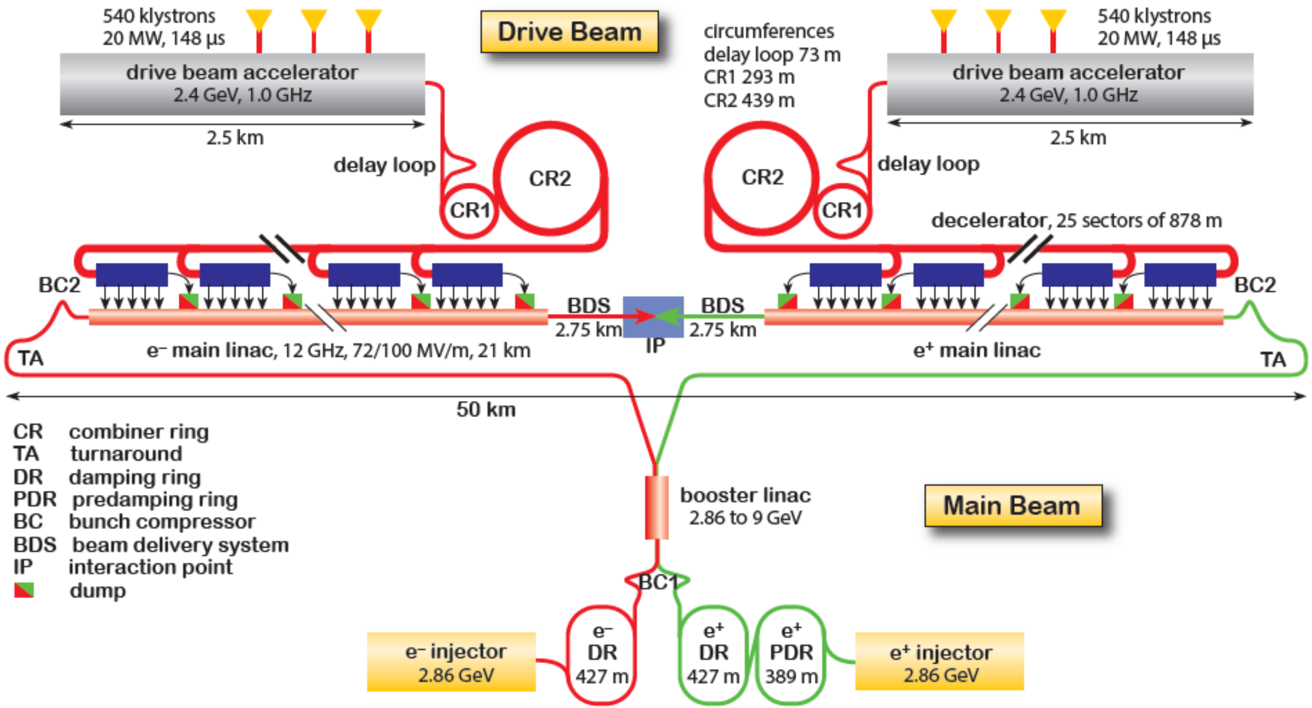
- To avoid energy spread and keep luminosity high: collide "flat" beams, with much smaller beam size in one plane

CLIC layout

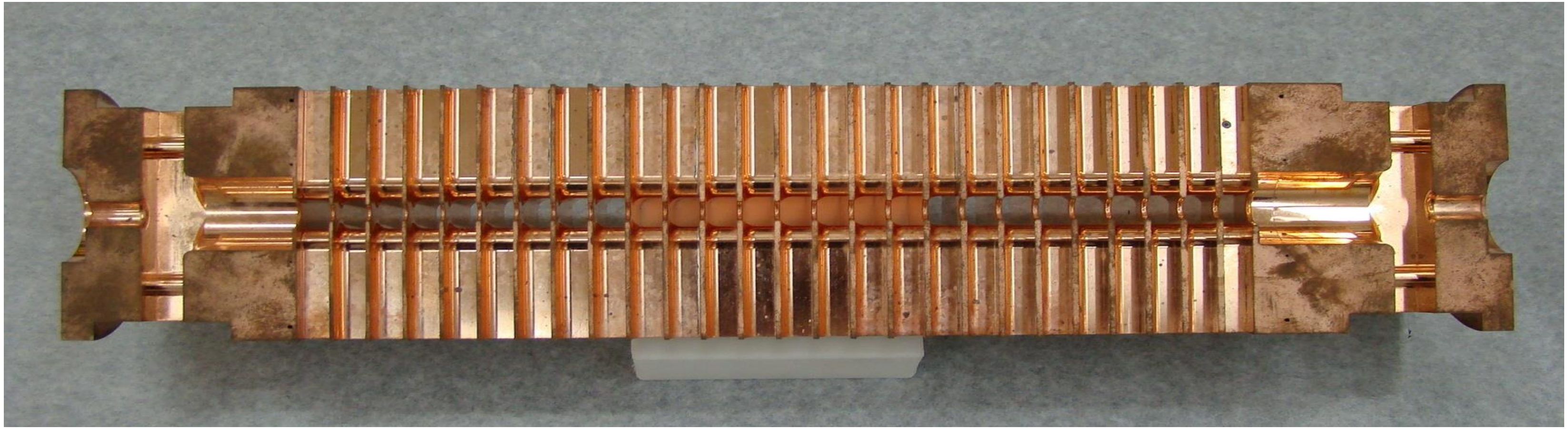
- Concept:
  beam generation
  → pre-acceleration
  → damping rings
  → booster linac
  → main linacs
  →collisions

- CLIC aims at gradients of 100 MV/m, 20 times higher than the LHC
  - Compare 30 MV/m at ILC

- Different acceleration concept in main LINAC from ILC :
  - drive-beam acceleration, with RF power taken from another e- beam



CLIC cavities



D. Schulte

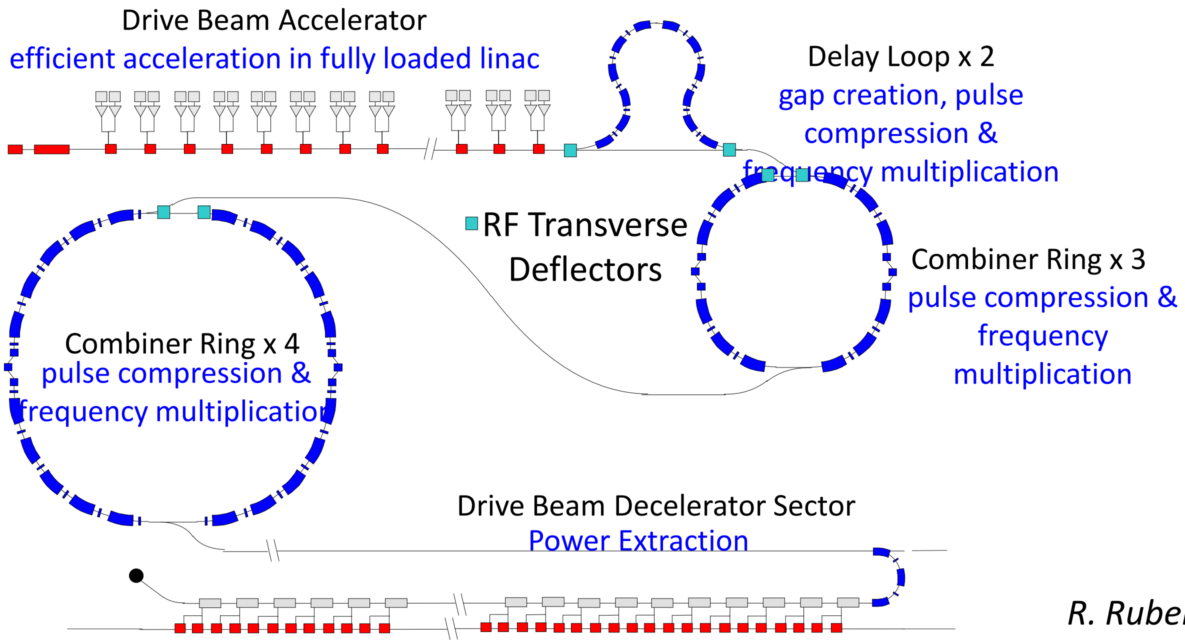
- To reach 100 MV/m: different type of cavity from ILC
- 12 GHz, 23 cm long, normal conducting
  - ⇒ Much worse conductor than SC, but allows reaching higher fields
  - ⇒ Problem: power is very rapidly lost in the walls
  - ⇒ Need to put in very intense and short RF pulses timed to the passage of the beam

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

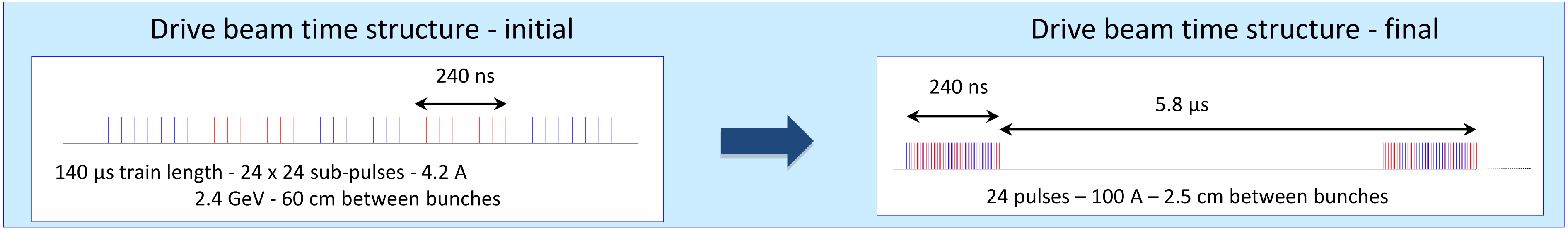
Average RF power about 3 kW/m
About 1 kW/m into beam

Drive beam acceleration

- To produce very rapid pulses: use two-beam acceleration scheme
- A very long beam pulse at 4A, 140 us produced in LINAC
- Use combiner rings to decrease bunch spacing of drive beam => produce very short and intense 100 A pulse
- Send to decelerating structure



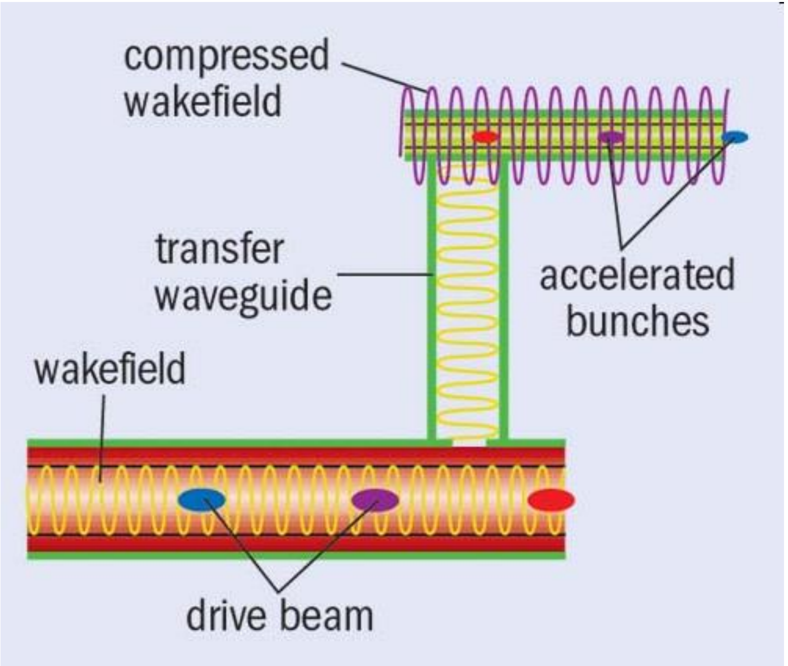
R. Ruber

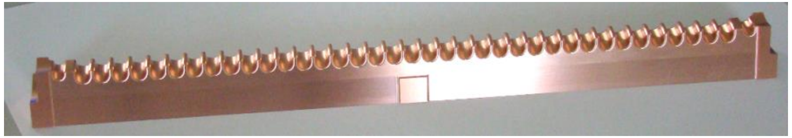


Two-beam acceleration scheme

- The high-current drive beam is decelerated in special power extraction structures (PETS)

- Generated EM field can be transferred in RF waveguides to the other beam => power is used to accelerate the main beam

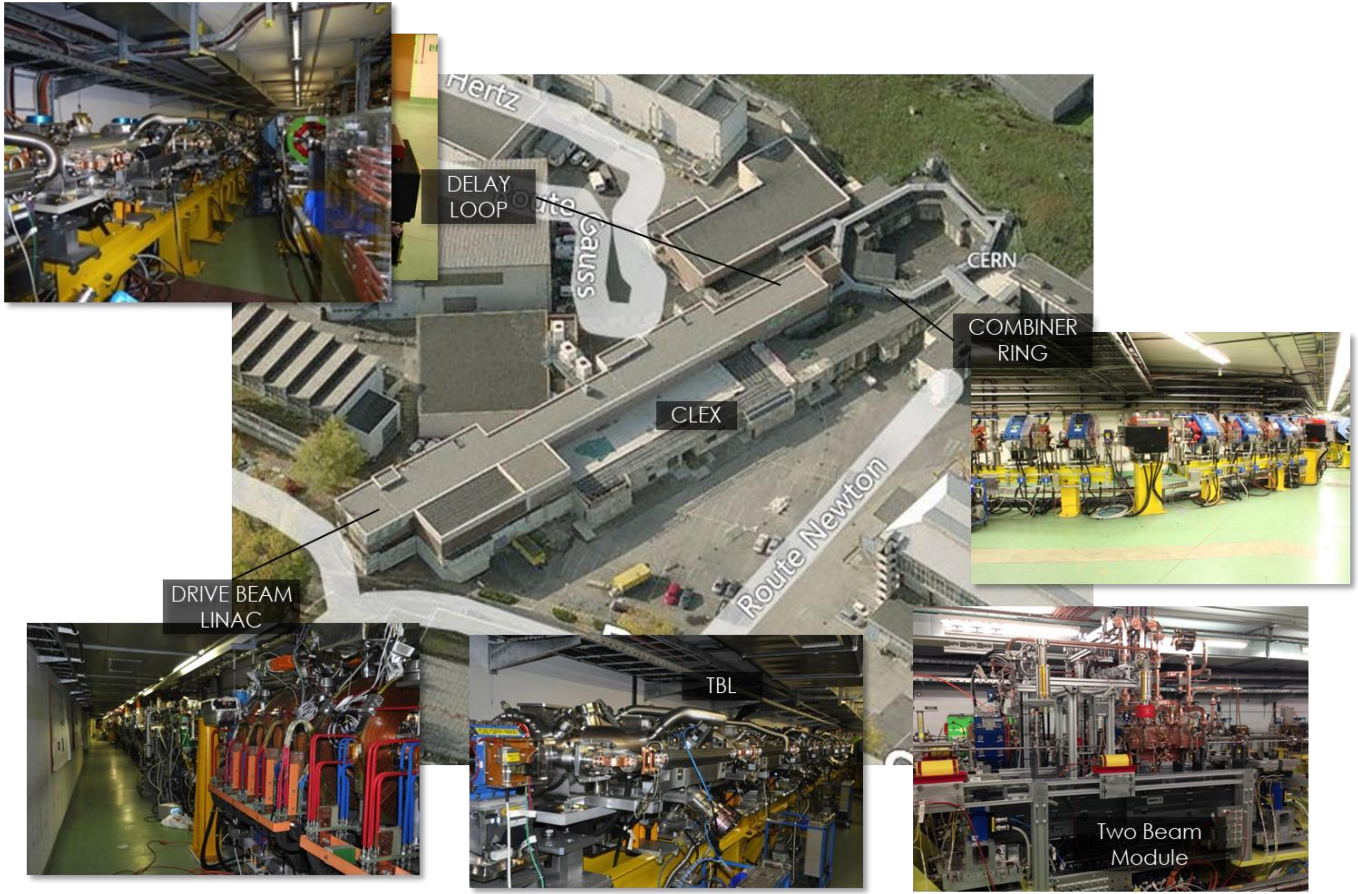




CLIC Test Facility (CTF3)

- Experimental tests carried out in test facility at CERN to demonstrate drive beam concept

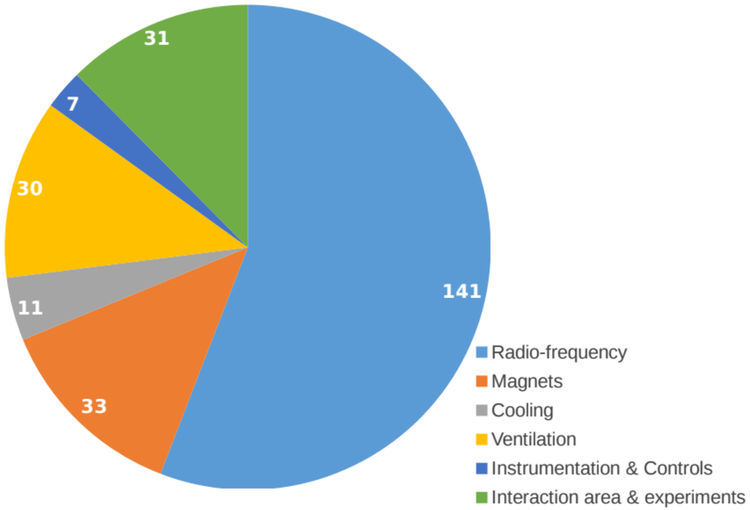
- Accelerating gradient of >100 MV/m achieved



CLIC power consumption

- Power and energy consumption at 380 GeV is well within the existing parameters and installations at CERN
- At 1.5 TeV: power will surpass the current CERN usage (2017) by ~30%
- At 3 TeV the energy consumption will be a factor two of the current CERN usage (2017)
- Development work ongoing to further improve energy efficiency

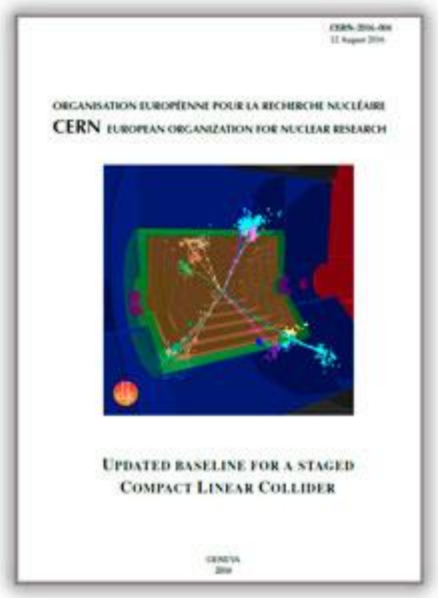
Estimated power consumption of CLIC in MW at 380 GeV (total: 252 MW)



https://clic.cern

CLIC reference documents

- More information:
  - Conceptual design report (2012)
  - Updated CLIC baseline document (2016)



Outline

First lecture

- Introduction
  - Considerations for collider design: particle type, energy, circular/linear…
  - Limitations for future colliders
  - European strategy for particle physics
- ILC (International Linear Collider)
- CLIC (Compact Linear Collider)

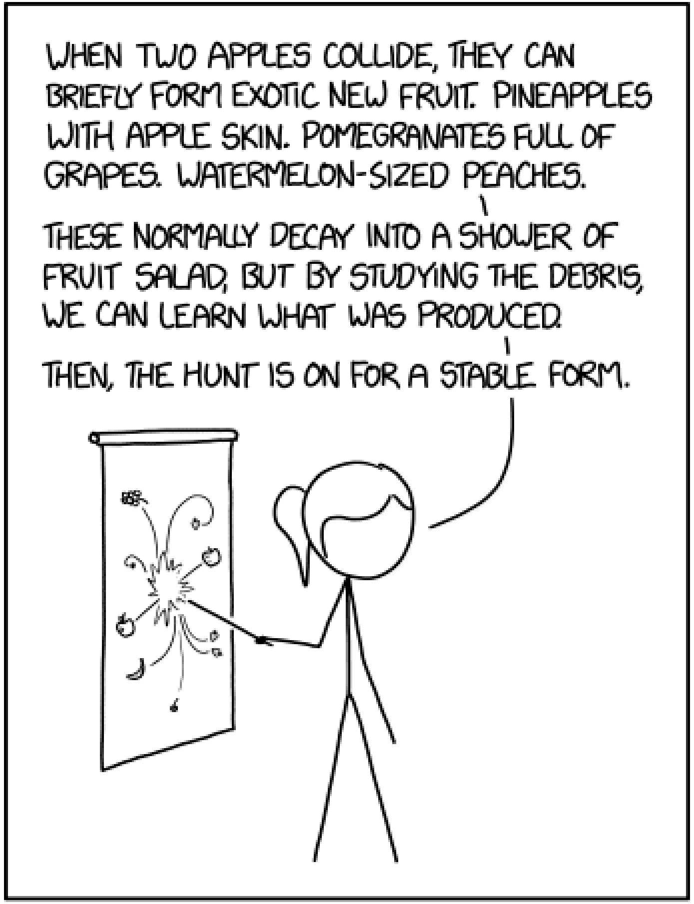
Linear

Second lecture

- HL-LHC (High-Luminosity Large Hadron Collider)
- FCC-hh (Future Circular collider, hadrons)
- FCC-ee (Future Circular collider, e+e-)
- CEPC/SppC (Chinese Electron-Positron Collider / Super proton-proton Collider)

Circular

Coffee break – some fruit?



HOW NEW TYPES OF FRUIT ARE DEVELOPED

Source: https://xkcd.com/1949/