Particle Colliders

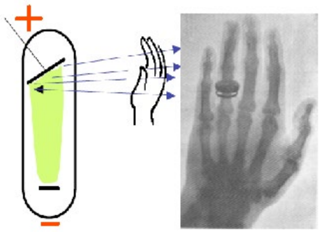
Laboratory for Particle Accelerator Physics

[includes material by D.Schulte, CERN]

EPFL

History …

1895 **W.C. Röntgen** discovers X-ray production in discharge tubes when sufficiently high voltage is applied.



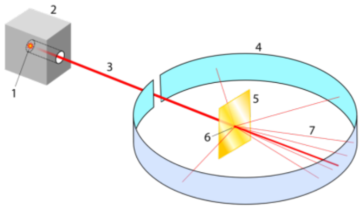
1896 **A.H. Bequerel** discovers radioactivity (of U), further studied by **Pierre** and **Marie Curie** .

1897 **F. Braun** builds cathodic ray tube

1897 **J.J. Thompson** measures the ratio *q/m* of cathodic rays :they are **electrons**

1900 **E. Rutherford** finds there are different species of radioactive products :

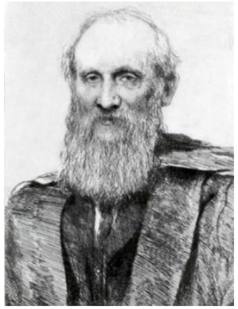
- He nuclei
- electrons
- neutral (e.m.) radiation



1909 **E. Rutherford** performs scattering experiment using α-particles on gold foil

Lord Kelvin, 1900: Address to the British Association for the Advancement of Science

There is nothing new to be discovered in physics now, All that remains is more and more precise measurement.



examples of the unknown (1900): structure of atoms and nuclei, energy production in sun, forces other than gravitation & electromagnetic

incredible journey since 1900, many nobel prices related to accelerators

Year	Name	Accelerator-Science Contribution to Nobel Prize-Winning Research
1939	Ernest O. Lawrence	Lawrence invented the cyclotron at the University of Californian at Berkeley in 1929 [12].
1951	John D. Cockcroft and Ernest T.S. Walton	Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13].
1952	Felix Bloch	Bloch used a cyclotron at the Crocker Radiation Laboratory at the University of California at Berkeley in his discovery of the magnetic moment of the neutron in 1940 [14].
1957	Tsung-Dao Lee and Chen Ning Yang	Lee and Yang analyzed data on K mesons (θ and τ) from Bevatron experiments at the Lawrence Radiation Laboratory in 1955 [15], which supported their idea in 1956 that parity is not conserved in weak interactions [16].
1959	Emilio G. Segrè and Owen Chamberlain	Segrè and Chamberlain discovered the antiproton in 1955 using the Bevatron at the Lawrence Radiation Laboratory [17].
1960	Donald A. Glaser	Glaser tested his first experimental six-inch bubble chamber in 1955 with high-energy protons produced by the Brookhaven Cosmotron [18].
1961	Robert Hofstadter	Hofstadter carried out electron-scattering experiments on carbon-12 and oxygen-16 in 1959 using the SLAC linac and thereby made discoveries on the structure of nucleons [19].
1963	Maria Goeppert Mayer	Goeppert Mayer analyzed experiments using neutron beams produced by the University of Chicago cyclotron in 1947 to measure the nuclear binding energies of krypton and xenon [20], which led to her discoveries on high magic numbers in 1948 [21].
1967	Hans A. Bethe	Bethe analyzed nuclear reactions involving accelerated protons and other nuclei whereby he discovered in 1939 how energy is produced in stars [22].
1968	Luis W. Alvarez	Alvarez discovered a large number of resonance states using his fifteen-inch hydrogen bubble chamber and high-energy proton beams from the Bevatron at the Lawrence Radiation Laboratory [23].
1976	Burton Richter and Samuel C.C. Ting	Richter discovered the J/Ψ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the J/Ψ particle independently in 1974 using the Brookhaven Alternating Gradient Synchrotron [25].
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg	Glashow, Salam, and Weinberg cited experiments on the bombardment of nuclei with neutrinos at CERN in 1973 [26] as confirmation of their prediction of weak neutral currents [27].
1980	James W. Cronin and Val L. Fitch	Cronin and Fitch concluded in 1964 that CP (charge-parity) symmetry is violated in the decay of neutral K mesons based upon their experiments using the Brookhaven Alternating Gradient Synchrotron [28].
1981	Kai M. Siegbahn	Siegbahn invented a weak-focusing principle for betatrons in 1944 with which he made significant improvements in high-resolution electron spectroscopy [29].
1983	William A. Fowler	Fowler collaborated on and analyzed accelerator-based experiments in 1958 [30], which he used to support his hypothesis on stellar-fusion processes in 1957 [31].
1984	Carlo Rubbia and Simon van der Meer	Rubbia led a team of physicists who observed the intermediate vector bosons W and Z in 1983 using CERN's proton-antiproton collider [32], and van der Meer developed much of the instrumentation needed for these experiments [33].
1986	Ernst Ruska	Ruska built the first electron microscope in 1933 based upon a magnetic optical system that provided large magnification [34].
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger	Lederman, Schwartz, and Steinberger discovered the muon neutrino in 1962 using Brookhaven's Alternating Gradient Synchrotron [35].
1989	Wolfgang Paul	Paul's idea in the early 1950s of building ion traps grew out of accelerator physics [36].
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor	Friedman, Kendall, and Taylor's experiments in 1974 on deep inelastic scattering of electrons on protons and bound neutrons used the SLAC linac [37].
1992	Georges Charpak	Charpak's development of multiwire proportional chambers in 1970 were made possible by accelerator-based testing at CERN [38].
1995	Martin L. Perl	Perl discovered the tau lepton in 1975 using Stanford's SPEAR collider [39].
2004	David J. Gross, Frank Wilczek, and H. David Politzer	Gross, Wilczek, and Politzer discovered asymptotic freedom in the theory of strong interactions in 1973 based upon results from the SLAC linac on electron-proton scattering [40].
2008	Makoto Kobayashi and Toshihide Maskawa	Kobayashi and Maskawa's theory of quark mixing in 1973 was confirmed by results from the KEKB accelerator at KEK (High Energy Accelerator Research Organization) in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II (Positron Electron Project II) at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42].

2013: François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at **CERN's Large Hadron Collider**"

Colliding Beams

1943

R. Wideroe .. *"…I had thus come upon **a simple method for improving the exploitation of particle energies available .. for nuclear reactions**. As with cars* (collisions)*, when a target particle (at rest) is bombarded, a considerable portion of the kinetic energy* (of the incident particle) *is used to hurl it (or the reaction products) away.*
*Only a relatively small portion of the accelerated particle's energy is used to actually to split or destroy the colliding particles. However, **when the collision is frontal, most of the available kinetic energy can be exploited**.*

For nuclear particles, relativistic mechanics must be applied, and .. the effect .. be even greater ".

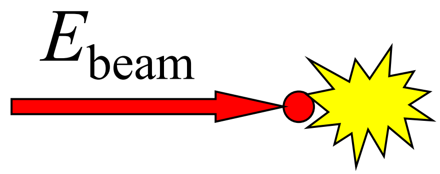
In addition :

*"… If it were possible to **store the particles in rings for longer periods**, and if these 'stored' particles were **made to run in opposite directions**, the result would be one opportunity for collision at each revolution.*
Because the accelerated particles would move very quickly they would make many thousand revolutions per second and one could expect to obtain a collision rate that would be sufficient for many interesting experiments."

Fixed target vs collisions

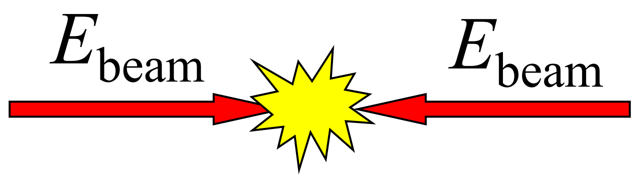
What energy is available in collisions (center-of-mass energy)?

fixed target geometry:



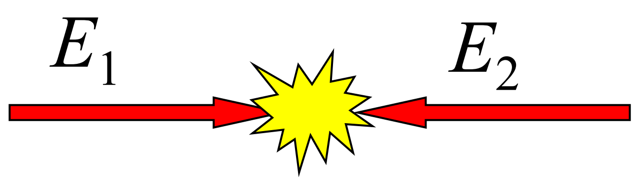
$$E_{\text{cm}} = \sqrt{2mc^2} \cdot \sqrt{E_{\text{beam}}}$$

Colliding beams:



$$E_{\text{cm}} = 2 \cdot E_{\text{beam}}$$

unequal energy:



$$E_{\text{cm}} = 2 \cdot \sqrt{E_1 E_2}$$

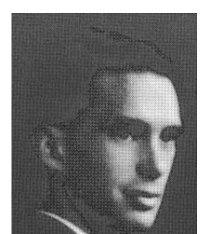
example HERA collider Hamburg/Germany:
27.5 GeV electrons against 920 GeV protons,
E_{cm} = 318 GeV
$\rightarrow$ exploring the structure of the proton

[see Wiedemann 1.4.4]

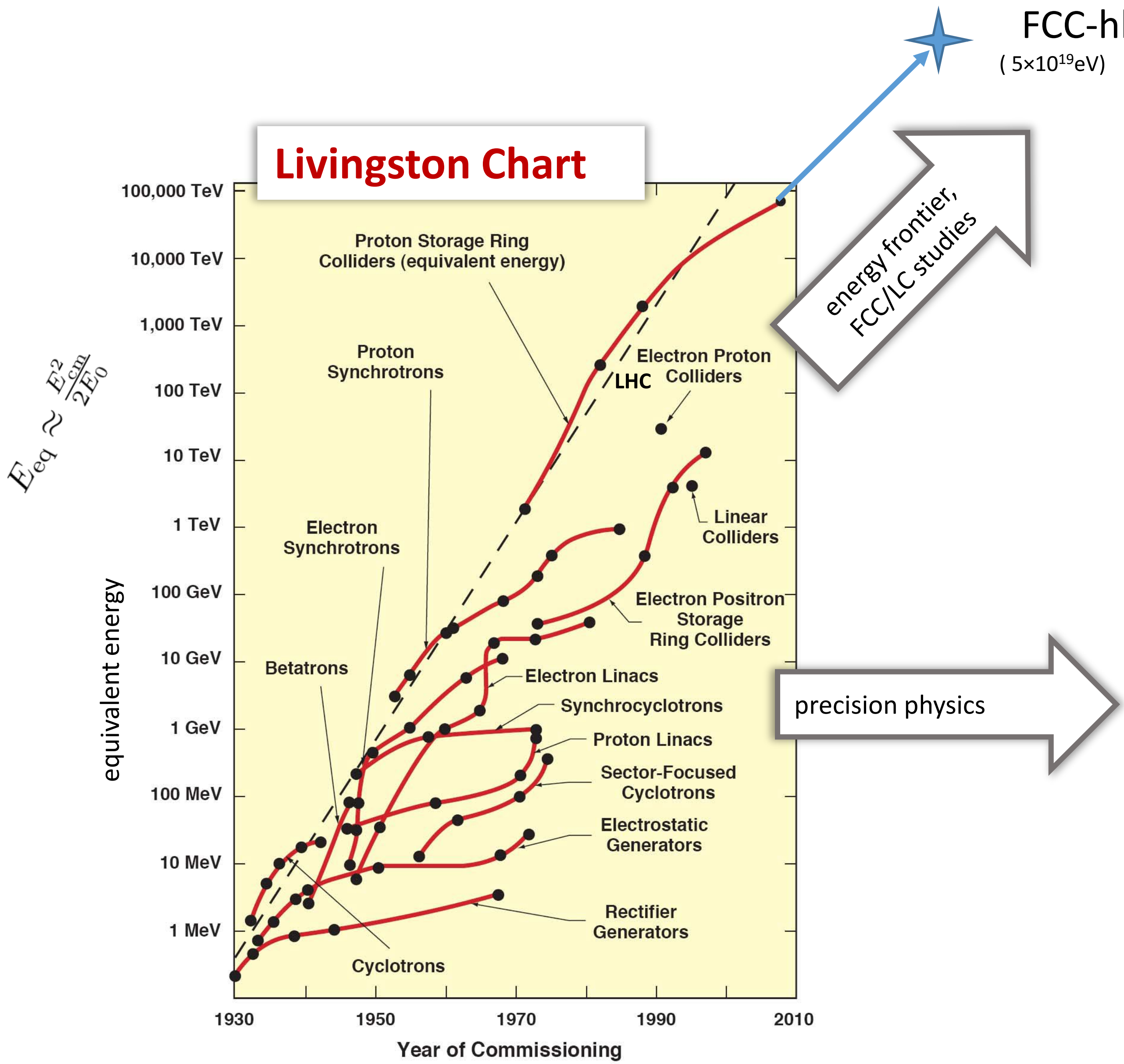
First Collider

Anello di Accumulazione AdA B. Touschek 1960

the first collider facility AdA was built 1960 in Frascati by Bruno Touschek



Branches of Accelerators for Particle Physics



particle colliders

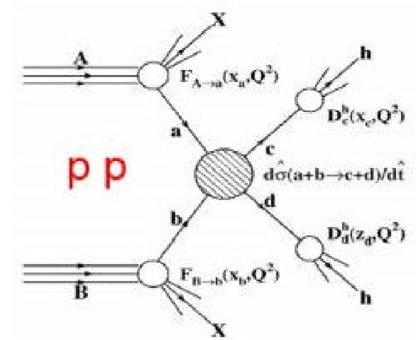
high intensity beams →

muon, neutrino sources, UCNs etc.

Collider Choices

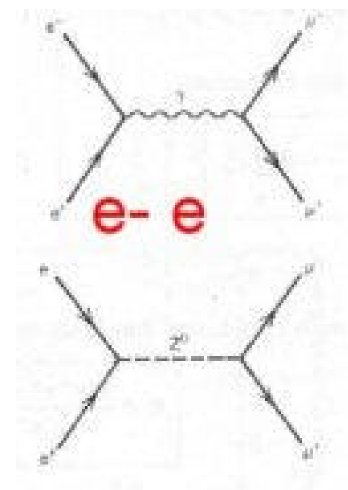
Hadron collisions: compound particles

- Protons or ions
- Mix of quarks, anti-quarks and gluons: variety of processes
- Parton energy spread
- QCD processes large background sources
- Hadron collisions $\Rightarrow$ can typically achieve higher collision energies



Lepton collisions: elementary particles

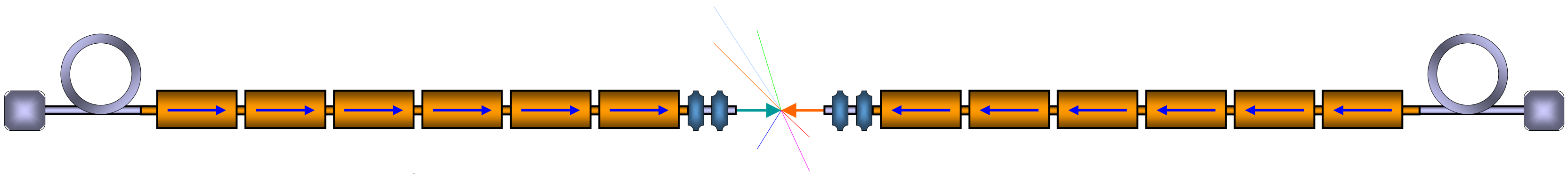
- Electrons, positrons and probably muons
- Collision process known
- Well defined energy
- Less background
- Lepton collisions $\Rightarrow$ precision measurements



Photons also possible

D. Schulte

Solutions for Leptons



use a linear collider

- no synchrotron radiation
- But
  - must accelerate beams rapidly
  - collide only once

hence challenges

- High accelerating gradient
- Small beams at collision

use a ring collider

- strong synchrotron radiation

$$\Delta E \propto \left(\frac{E}{m_0}\right)^4 \frac{1}{R}$$

Or use heavier particles
Muons are 200 times heavier than electrons
But they have a short lifetime (2μs)

Considerations for Colliders

Physics goals

- discoveries vs. precision measurements, addressing specific open questions $\rightarrow$ choice of particles to collide

Physics reach

- center of mass energy (size/cost, choice of technology)
- event rate and sensitivity (Luminosity, backgrounds)

Practical aspects

- cost (size, technology)
- conceptual maturity (complexity etc.)
- operation time
- energy consumption and environmental compatibility

Examples of Collider Variants

Ring Collider

Leptons
PETRA (DESY/DE)
LEP (CERN)
PEP-II (SLAC/US)
KEK-BII (KEK/JP)
FCC-ee (CERN)
CEPC (China)

Hadron/Lepton
HERA (DESY/DE)
EIC (BNL/US)
FCC-eh (CERN)

Hadron
TEVATRON (Fermilab/US)
RHIC (BNL/US)
LHC (CERN)
FCC-hh (CERN)
SppC (China)

Linear Collider

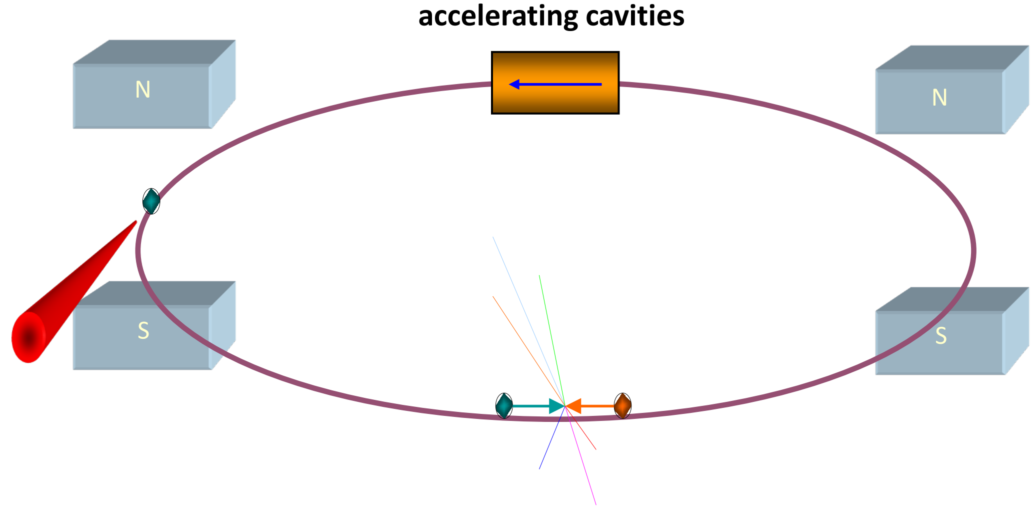
Leptons
SLC (SLAC/US)
ILC (int./Japan)
CLIC (CERN)

Muon Collider

Studies
MAP (US)
LEMMA (int./IT)
MICE exp. (UK)

past facility
operating facility
approved project
concept study

The Energy Limit for Rings



Hadron colliders are circular
Maximum energy defined magnetic field and size

Required radius R of the ring is given by

$$R \propto \frac{E}{B}$$

→ magnetic field B of bending dipoles as strong as possible

convenient:

- accelerate beam in many turns
- let beam collide many times

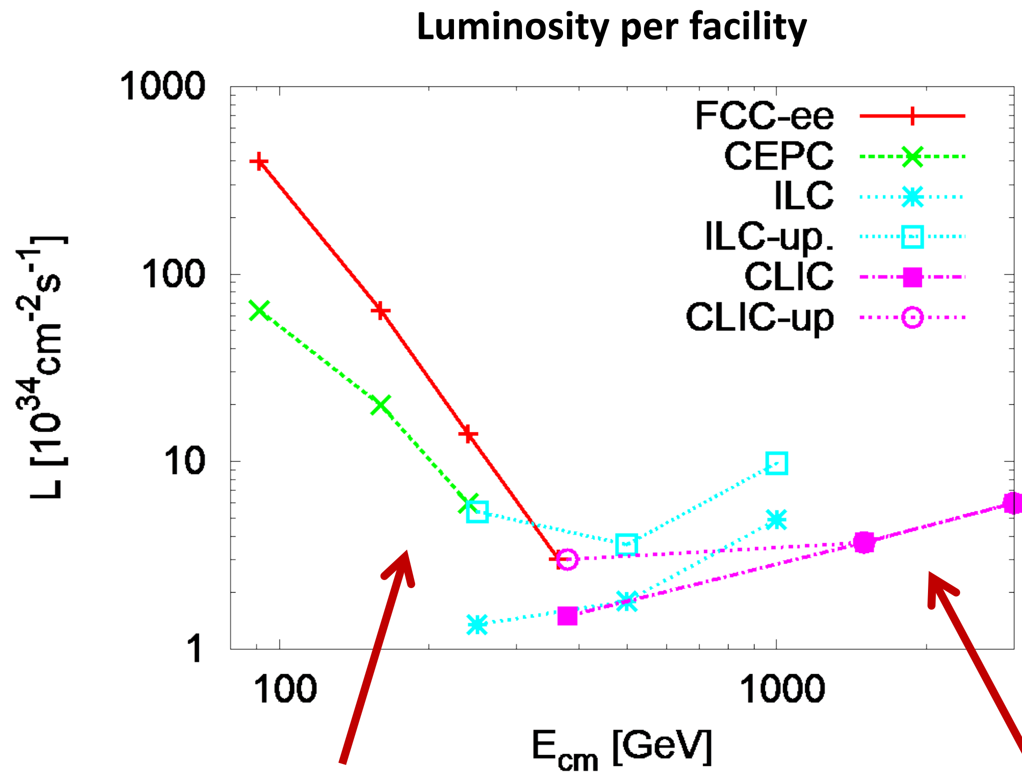
Electron-Positron Colliders have been mostly circular so far (one exception)

Energy (and luminosity) are limited by synchrotron radiation

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

Electrons are 1800 times lighter than protons
→ LEP2 lost 2.75GeV/turn for E=105GeV

Electron-positron Luminosity



$$L \propto P_{\mathrm{synrad}}/E_{\mathrm{cm}}^4$$

$$L \propto P_{\mathrm{RF}} E_{\mathrm{cm}}$$

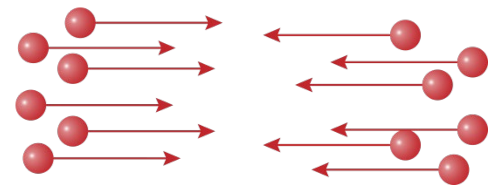
At low energies **circular colliders** look good
$\rightarrow$ Reduction at high energy due to synchrotron radiation

At high energies **linear colliders** excel
$\rightarrow$ Luminosity per beam power roughly constant

Next: Selected Physics Aspects of Colliders

- luminosity
- beam-beam interaction

Luminosity for Research



Luminosity relates event rate for a specific type of event with its cross section.

$$\dot{N}_{\text{event}} = L \cdot \sigma_{\text{event}}$$

physics property [1barn = 10^{-24} cm^2]

collider property [cm^{-2} s^{-1}]

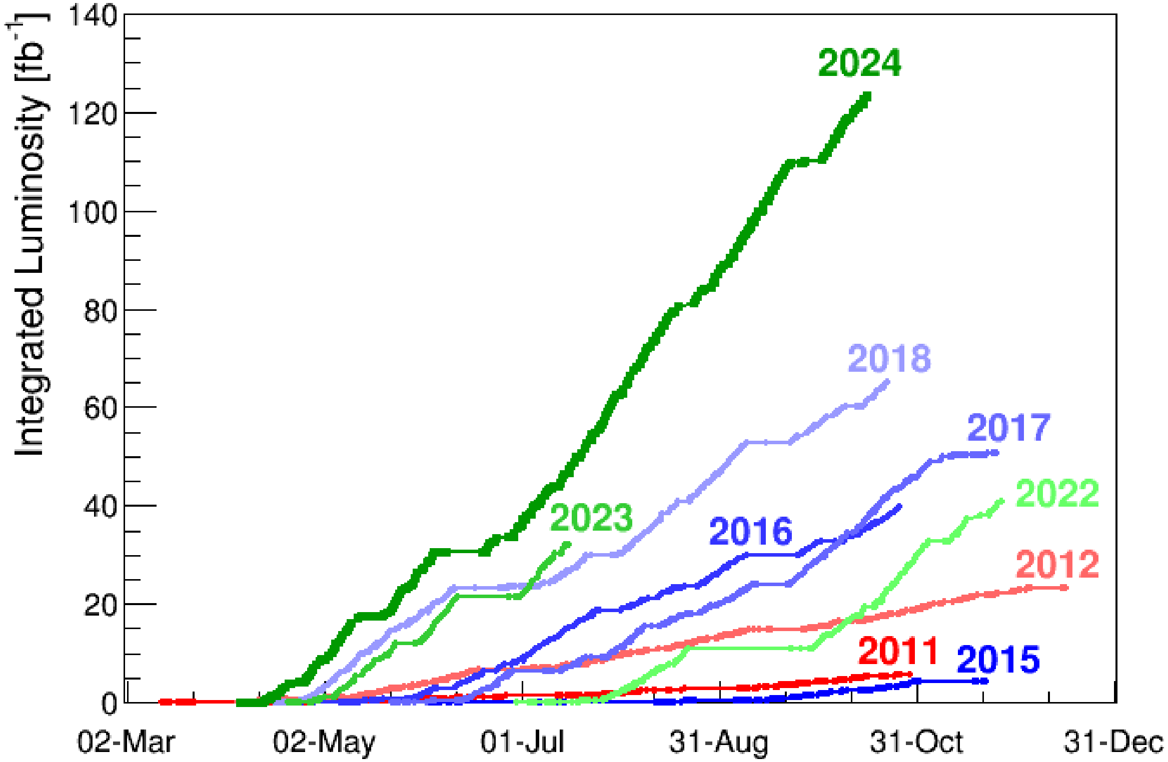
a related and common unit is integrated luminosity (e.g. for one run or one year):

$$N_{\text{event}} = \sigma_{\text{event}} \int L(t)\, dt$$

e.g.: [fb^{-1}] = “inverse femto-barn”

for example LHC run I: 30 fb^{-1}

Example LHC Operation, integrated Luminosity over the year

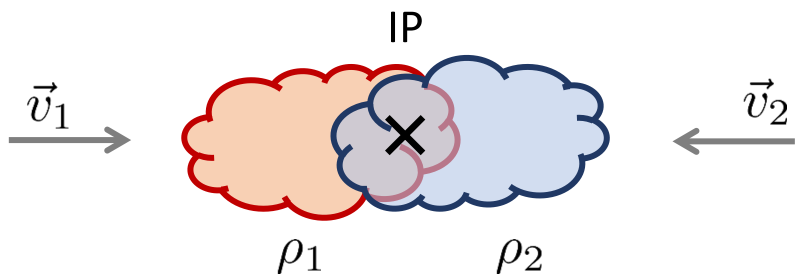


→ very significant improvements over time

→ integrated luminosity unit: 1/area or “inverse femto-barns”

→ Total cross section pp collisions: **100 mb** – huge number of uninteresting events

Luminosity from Machine Parameters



instantaneous event rate from overlapping bunch distributions:

$$\dot{N}_{\mathrm{bc}}(t) = |\vec{v}_1 - \vec{v}_2| \; \sigma_{\mathrm{event}} \int \rho_1(\vec{r},t)\rho_2(\vec{r},t)\, d^3r$$

event rate during bunch crossing

$K \approx 2c$

cross section

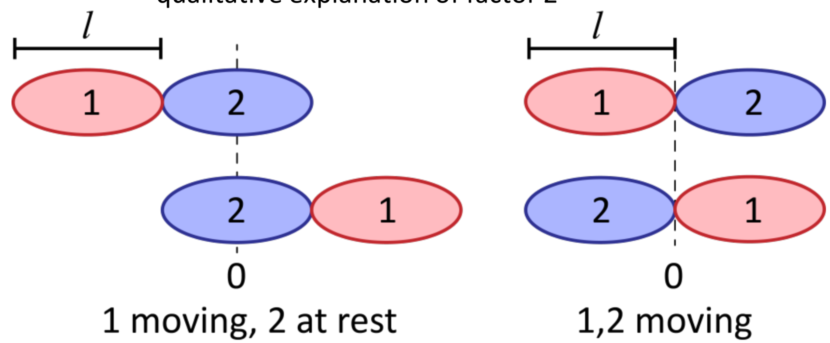
with crossing angle: $K = \sqrt{(\vec{v}_1 - \vec{v}_2)^2 - \vec{v}_1 \times \vec{v}_2}$

Luminosity per Bunch Crossing

$$\dot{N}_{\rm bc}(t) = 2c\;\sigma_{\rm event}\int \rho_1(\vec{r},t)\rho_2(\vec{r},t)\,d^3r$$

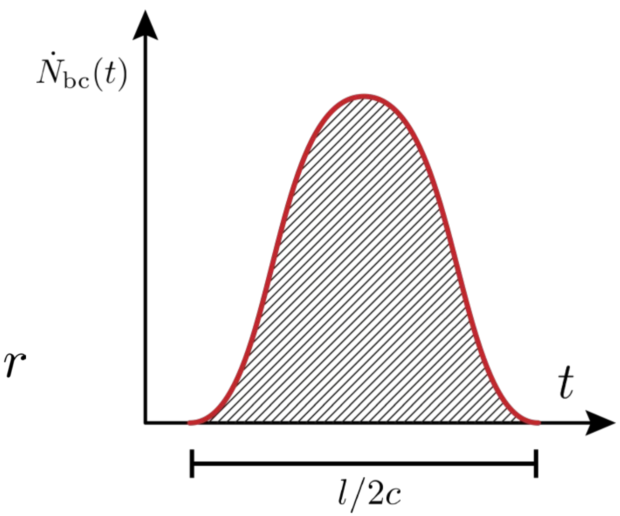
half interaction time
with opposite motion

qualitative explanation of factor 2



events for one bunch crossing:

$$N_{\rm bc} = \int \dot{N}_{\rm bc}(t)\,dt$$
$$= 2c\,\sigma_{\rm event}\iint \rho_1(\vec{r}+\vec{v}_1 t)\rho_2(\vec{r}-\vec{v}_2 t)\,dt\,d^3r$$



Total Luminosity

$$\dot{N}_{\text{event}} = n_b \, f_{\text{rev}} \, N_{\text{bc}} = \mathcal{L} \, \sigma_{\text{event}}$$

revolution frequency

bunches per turn

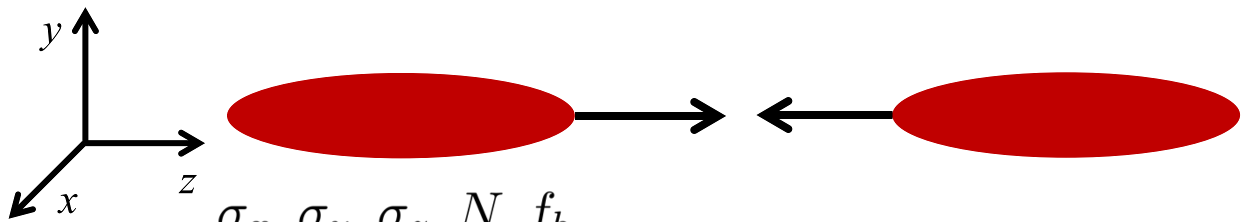
recipe for computing luminosity:

$$\mathcal{L} = 2c \, n_b f_{\text{rev}} \iint \rho_1(\vec{r} + \vec{v}_1 t) \rho_2(\vec{r} - \vec{v}_2 t) \, dt \, d^3 r$$

Gaussian beams:

$$\rho_{1,2}(\vec{r}, t) = \frac{N_{1,2}}{(2\pi)^{\frac{3}{2}} \sigma_x \sigma_y \sigma_z} \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{(z \pm v_{1,2} t)^2}{2\sigma_z^2} \right)$$

Luminosity for Gaussian Beams



$$\sigma_x, \sigma_y, \sigma_z, N, f_b$$

intensity (beam power)

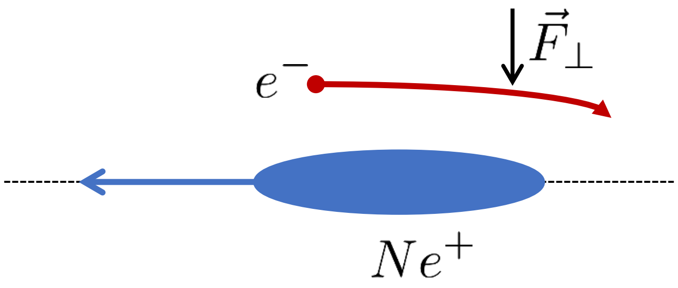
luminosity for equal Gaussian beams:

$$\mathcal{L} = \frac{f_{\mathrm{rev}} n_b N_1 N_2}{4\pi \sigma_x \sigma_y}$$

size (beam quality, focusing)

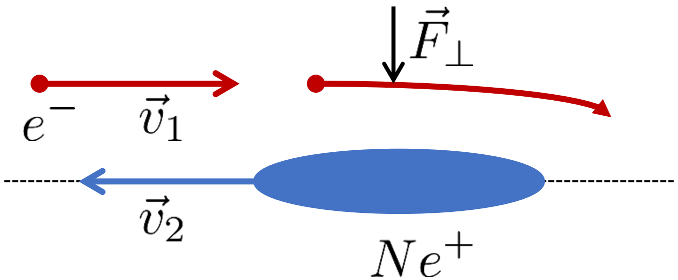
colliders use „low beta insertions“ to focus beams at the collision point

Beam-Beam Force



- strong force focuses in both planes
- quadrupole like, causes tune shift
- nonlinear force causes tune spread
- extreme forces in linear collider

Computing the Beam-Beam Force



$$\vec{F}_\perp = -e(\vec{E}_\perp + \vec{v}_1 \times \vec{B}_\perp)$$
$$= -e(1 + \beta_1\beta_2)\vec{E}_\perp$$
$$\approx -2e\vec{E}_\perp$$

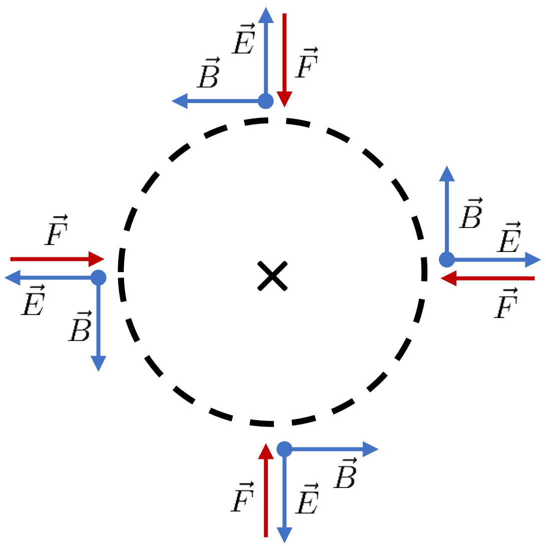
related Lorentz transformations of fields and bunch length:

$$\vec{E}_{||} = \vec{E}^*_{||}, \quad \vec{E}_\perp = \gamma\vec{E}^*_\perp$$

$$\vec{B}_{||} = 0, \quad \vec{B}_\perp = \frac{\gamma}{c^2}\vec{v}_2 \times \vec{E}^*_\perp$$

$$l = \frac{1}{\gamma}l^*$$

Orientation of the Beam-Beam Force



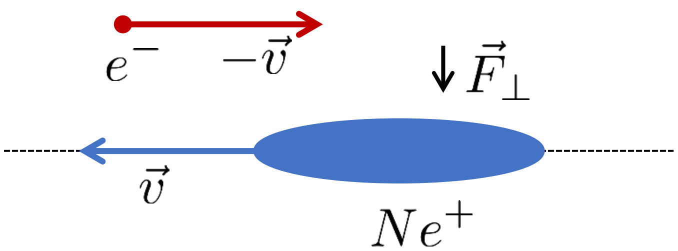
Beam-beam force for an electron in the field of an opposing positron bunch

Unlike quadrupoles this force is focusing in both planes which can be explained by the presence of the opposing beam:

$$\mathrm{rot}\vec{B} = \mu_0 \vec{j} \neq 0$$

Related: Why do bunches not blow up during normal beam transport?

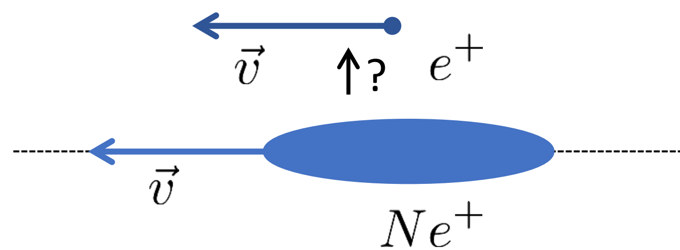
Beam-beam:



$$\vec{F}_\perp = -e\,(\vec{E}_\perp + \vec{v}\times\vec{B}_\perp)$$
$$= -e\,(1+\beta^2)\vec{E}_\perp$$
$$\approx -2e\vec{E}_\perp$$

Force doubles.

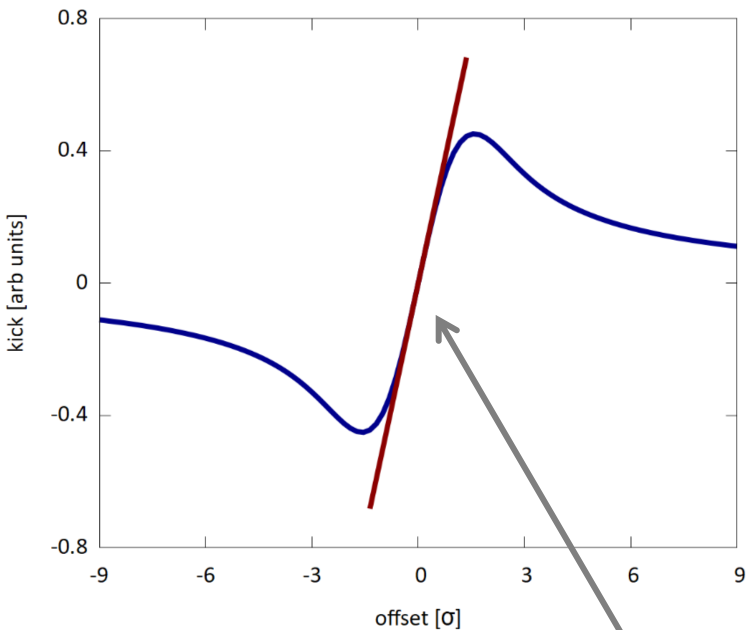
Co-moving positron:



$$\vec{F}_\perp = e\,(\vec{E}_\perp - \vec{v}\times\vec{B}_\perp)$$
$$= e\,(1-\beta^2)\vec{E}_\perp$$
$$= \frac{e}{\gamma^2}\vec{E}_\perp$$

Force cancels nearly.

Beam-Beam Force for Round Beams (see Appendix, by integration over distribution)



beam-beam kick:

$$\Delta r' = -\frac{2Nr_e}{\gamma}\frac{1-e^{-\frac{r^2}{2\sigma_r^2}}}{r}$$

$$\approx (KL)\cdot r = -\frac{Nr_e}{\gamma\sigma_r^2}\cdot r$$

near center similar to quadrupole

Beam-Beam parameter and tune shift (ring)

compute tune shift in same way as quadrupole error:

$$\Delta Q = \frac{1}{4\pi} \oint \beta(s) \Delta K(s) ds = \frac{\beta^*}{4\pi} \frac{N r_e}{\gamma \sigma_r^2}$$

define tune shift parameter ξ.

for round beams:

$$\xi = \frac{\beta^*}{4\pi} \cdot \frac{d(\Delta r')}{dr} = \frac{\beta^*}{4\pi} \frac{N r_e}{\gamma \sigma_r^2}$$

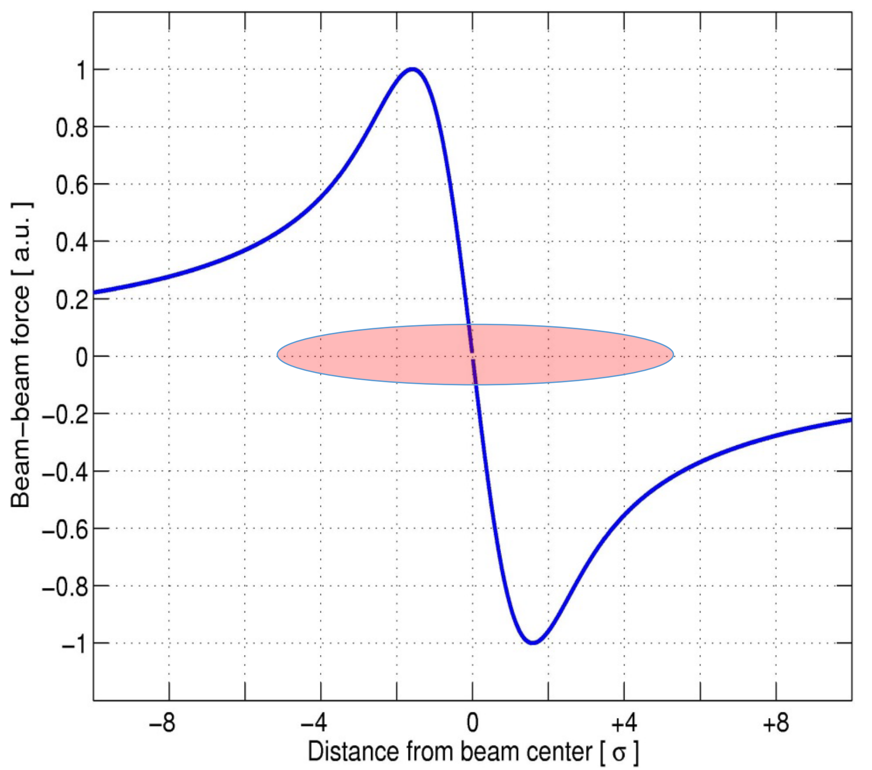
for non-round beams:

$$\xi_{x,y} = \frac{\beta^*_{x,y}}{4\pi} \frac{N r_e}{\gamma \sigma_{x,y}(\sigma_x + \sigma_y)}$$

Examples of Tune Shift

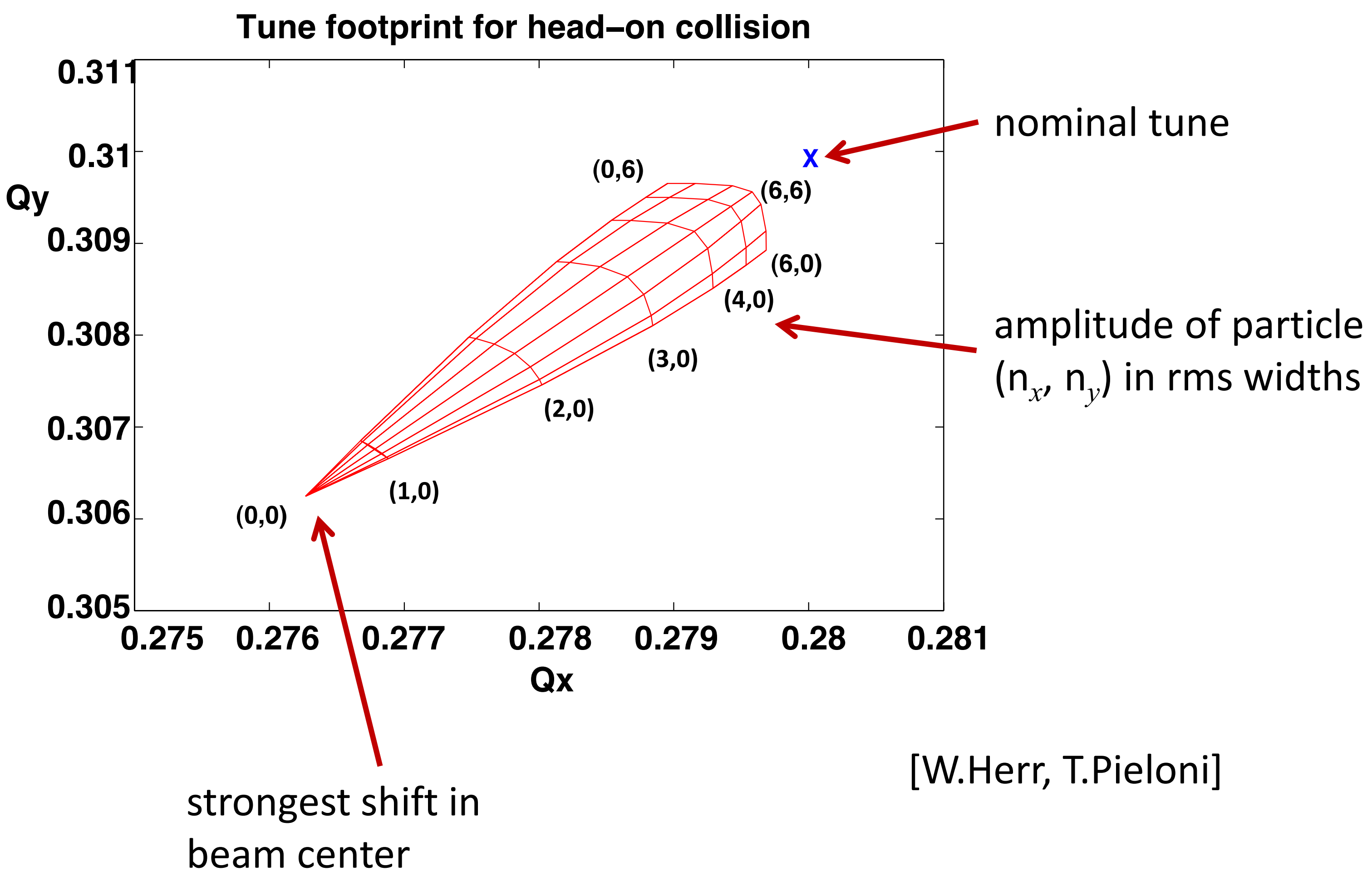
Parameters	LEP (e^+e^-)	LHC(pp)	LHC 2012
Intensity $N_{p,e}$/bunch	$4\ 10^{11}$	$1.15\ 10^{11}$	$1.7\ 10^{11}$
Energy GeV	100	7000	4000
Beam size H	160-200 μm	16.6 μm	18 μm
Beam size V	2-4 μm	16.6 μm	18 μm
$\beta_{x,y}^*$ m	1.25-0.05	0.55-0.55	0.6-0.6
Crossing angle μrad	0	285	290
ξ_{bb}	**0.07**	**0.0037**	**0.009**

Beam Particles are spread across the Beam-Beam Force Distribution of the opposing Beam



particles experience a range of beam-beam forces
→ results in tune spread

Tune Footprint (- Distribution)



[W.Herr, T.Pieloni]

Next: Ring Colliders

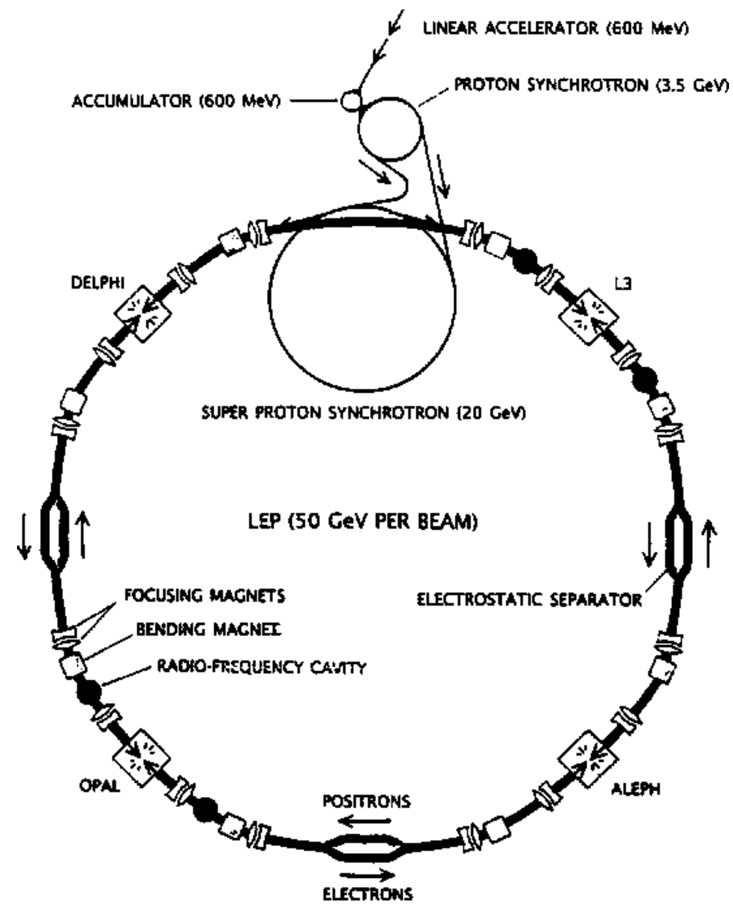
- Collider Examples
- Magnet Technology
- Beam power & Collimation

Ring Colliders

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

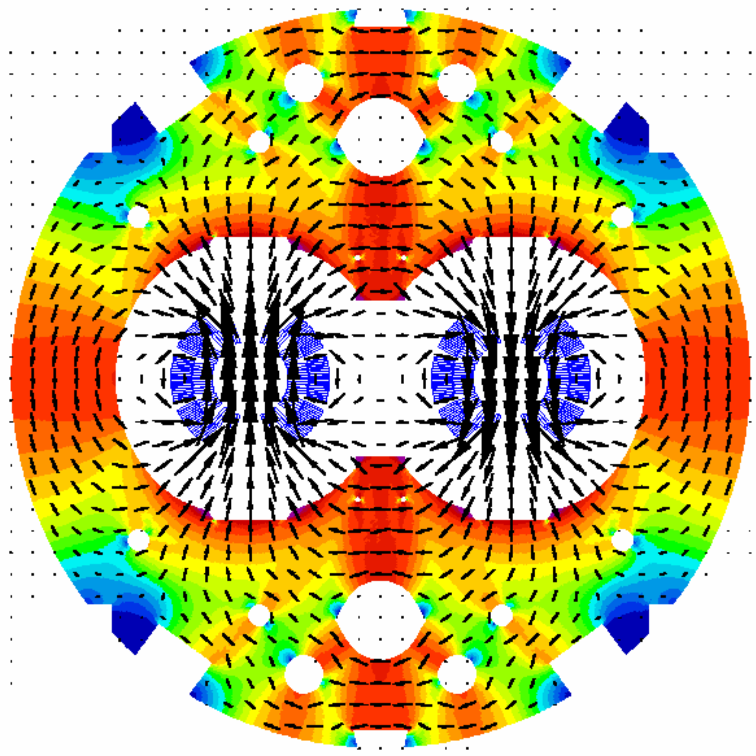
Highest particle speed in any accelerator



Next: Hadron Collider Technologies

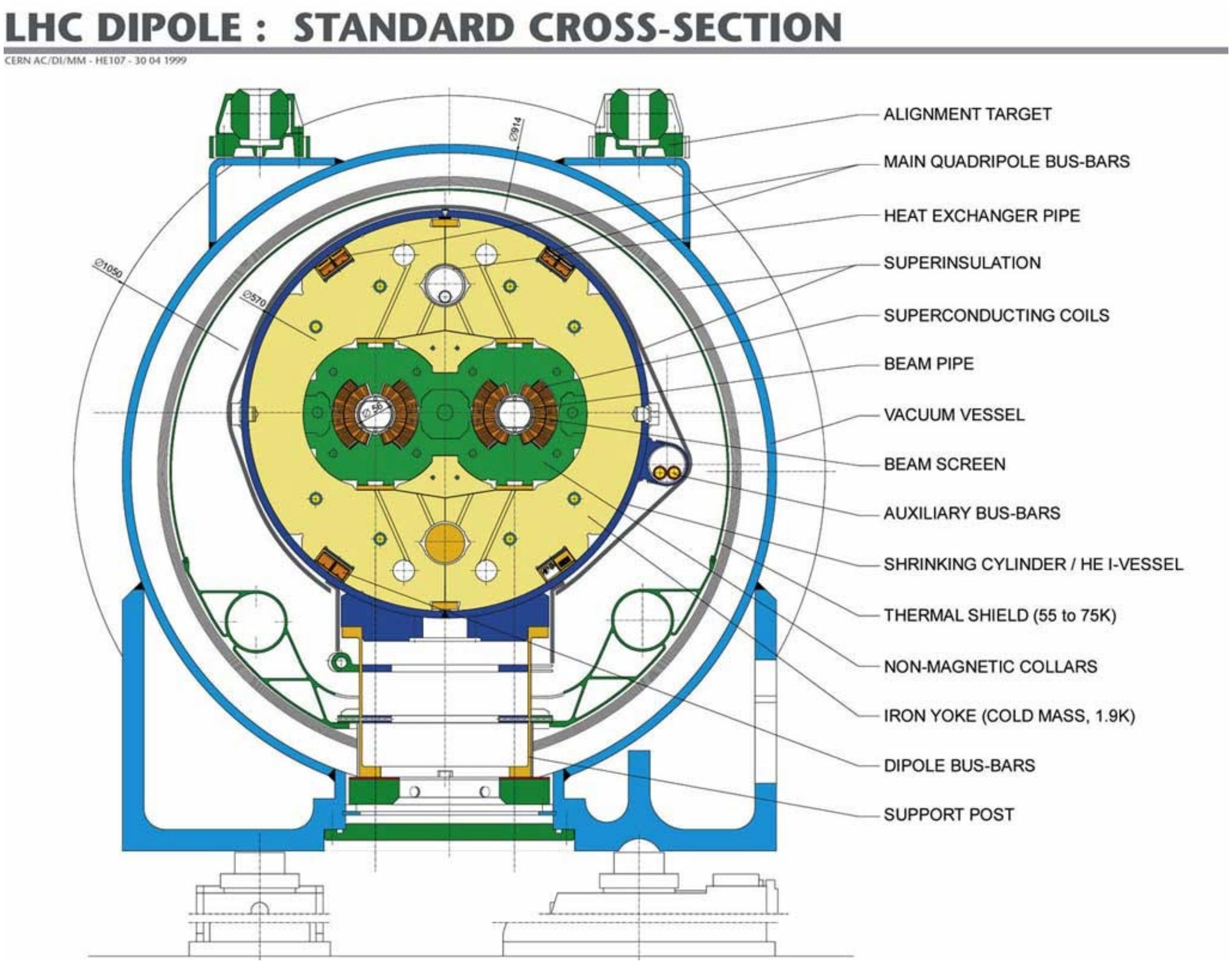
- Superconducting magnets
- Energy & Collimation

LHC two-in-one dipole magnets



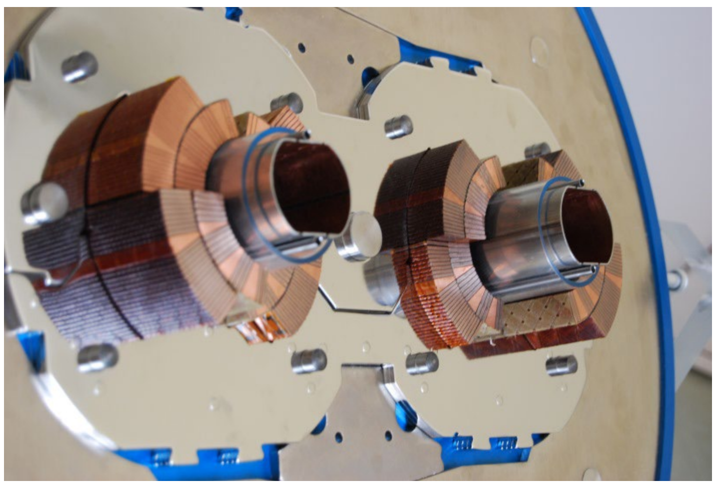
→ economic solution to fit two beams in one cryostat
→ tunnel diameter 3.8 m (comparably small, originally for LEP)

LHC Dipole cross section

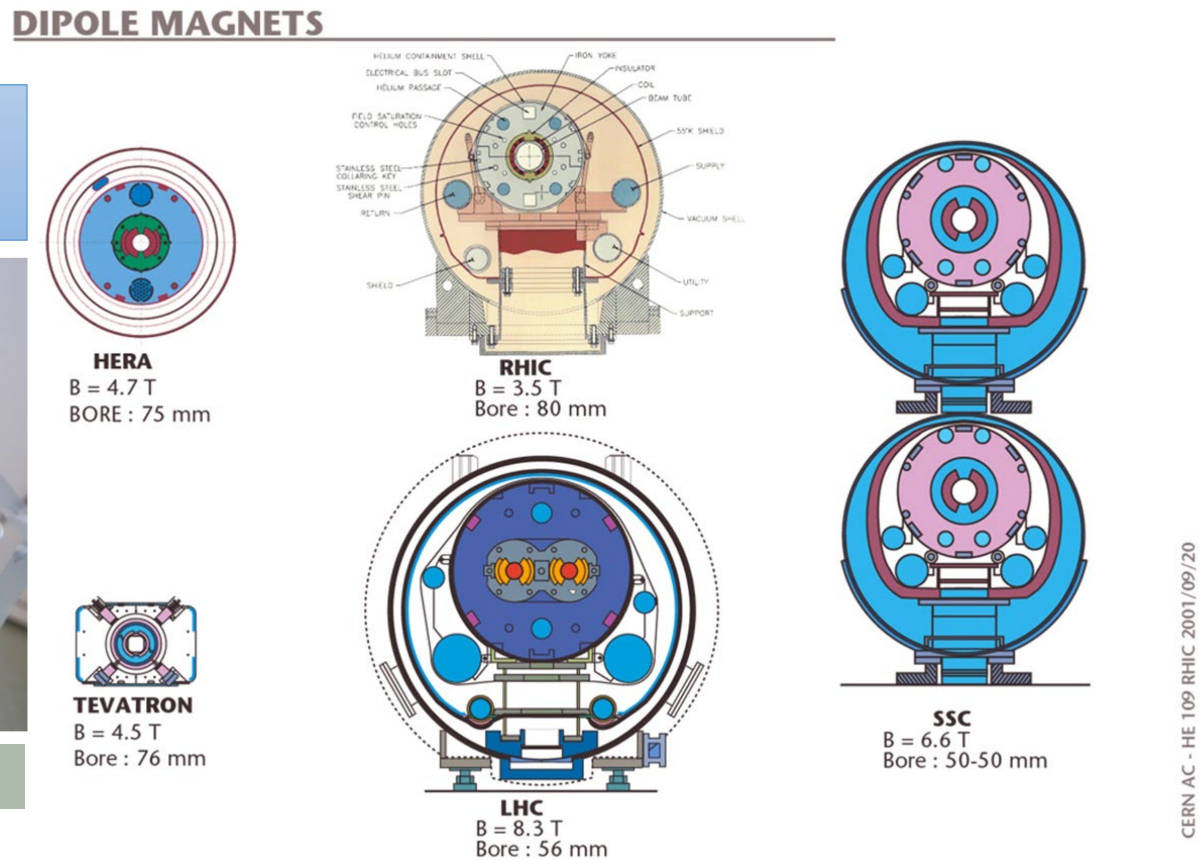


Hadron Collider Magnets: Hall of fame

LHC has been the summit of > 40 y developements with SC Nb-Ti magnets. Magnet design soon converged to Cosϑ

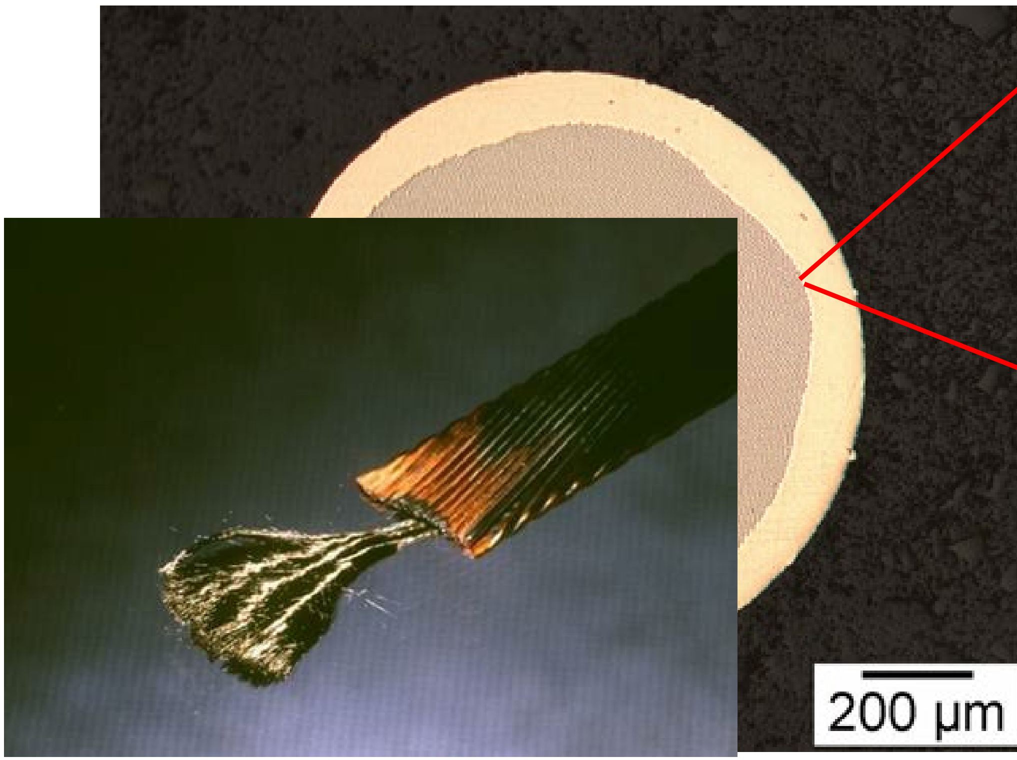


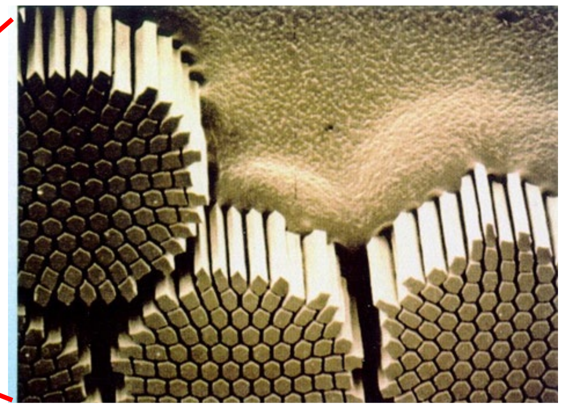
LHC Dipole Cross section: Cosϑ layout



[L.Rossi, 2019]

The key factor: superconductor (but not the only factor!)



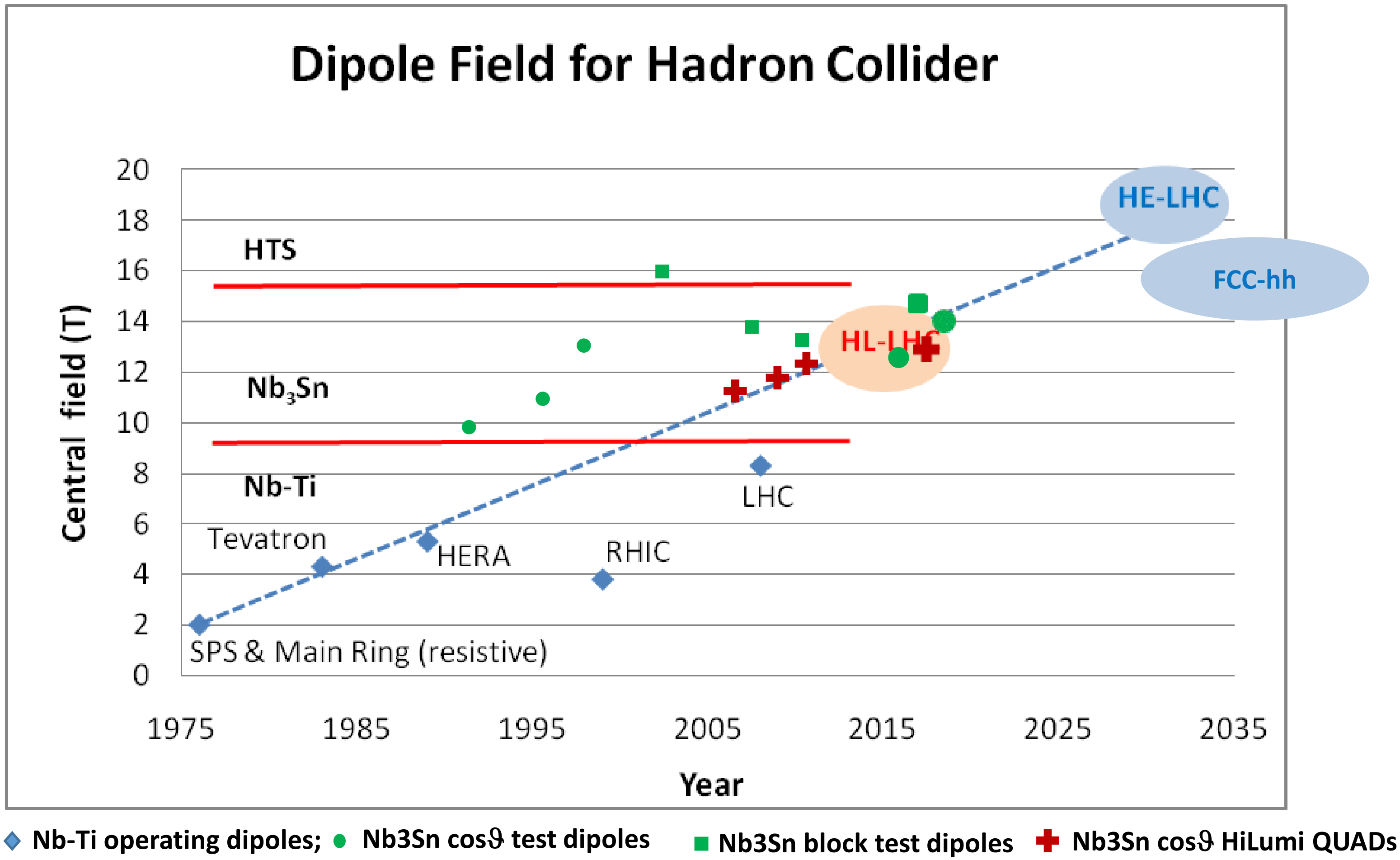


Developing SC is the key in SC accelerators. LHC is indebted to SSC

The perfection of LHC superconductor is such that we basically «forget» the SC effects and is the base of the repeatibility and optimal performance of the collider

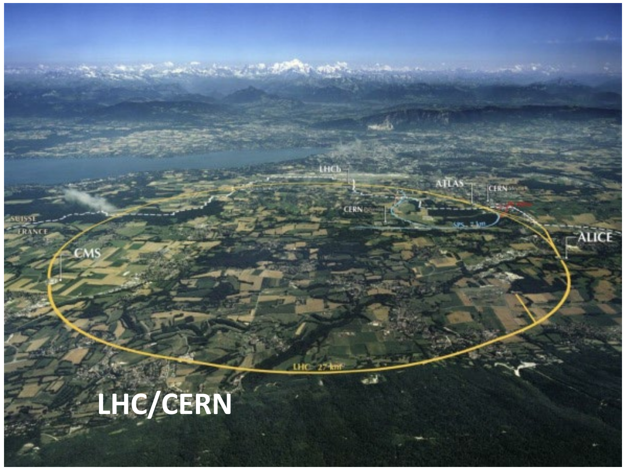
[L.Rossi, 2019]

Overview Magnetic Fields for Colliders



[L.Rossi, 2019]

Energetic Beams in Proton Colliders



collimation + beam abort systems are essential for handling huge energy

- minimizing probability of quench / destruction (beam abort)
- yet allowing operational robustness (collimation)
- **available aperture = collimation reserve + luminosity performance !**

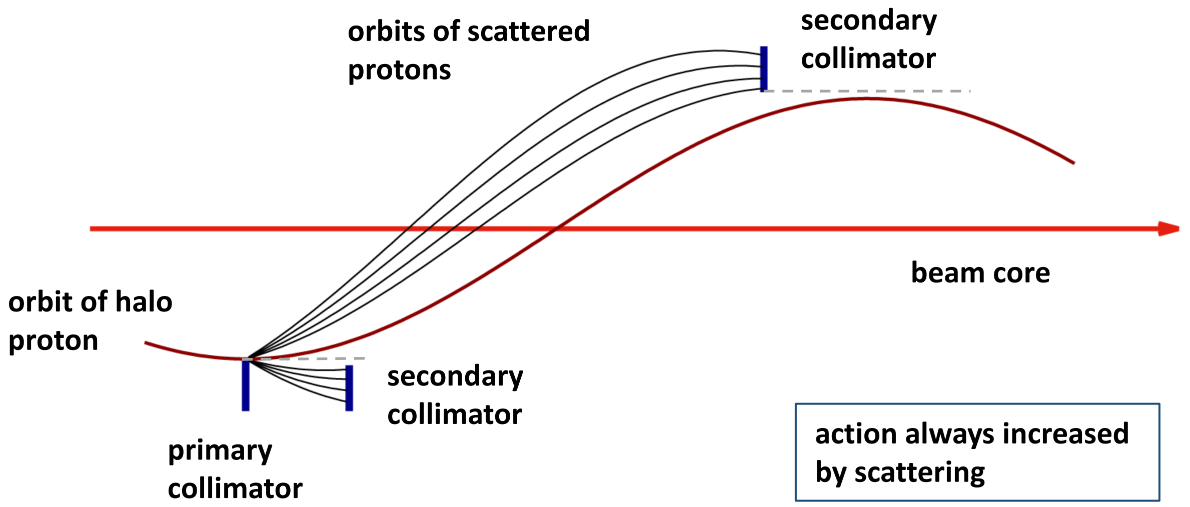
	kinetic energy	tot beam energy	tolerated loss power
HERA-p	0,92 TeV	1,9 MJ	50kW / minutes
LHC	7 TeV	360 MJ	500kW / 10 sec
FCC	50 TeV	8.400 MJ	11MW / seconds

can melt 12 tons of Cu

Quench:
ca 30mW/cm^3

Collimation – multidisciplinary R&D fields:
beam dynamics, impedance, radiation transport, efficient / yet safe tuning strategies, advanced materials, thermomechanical problems

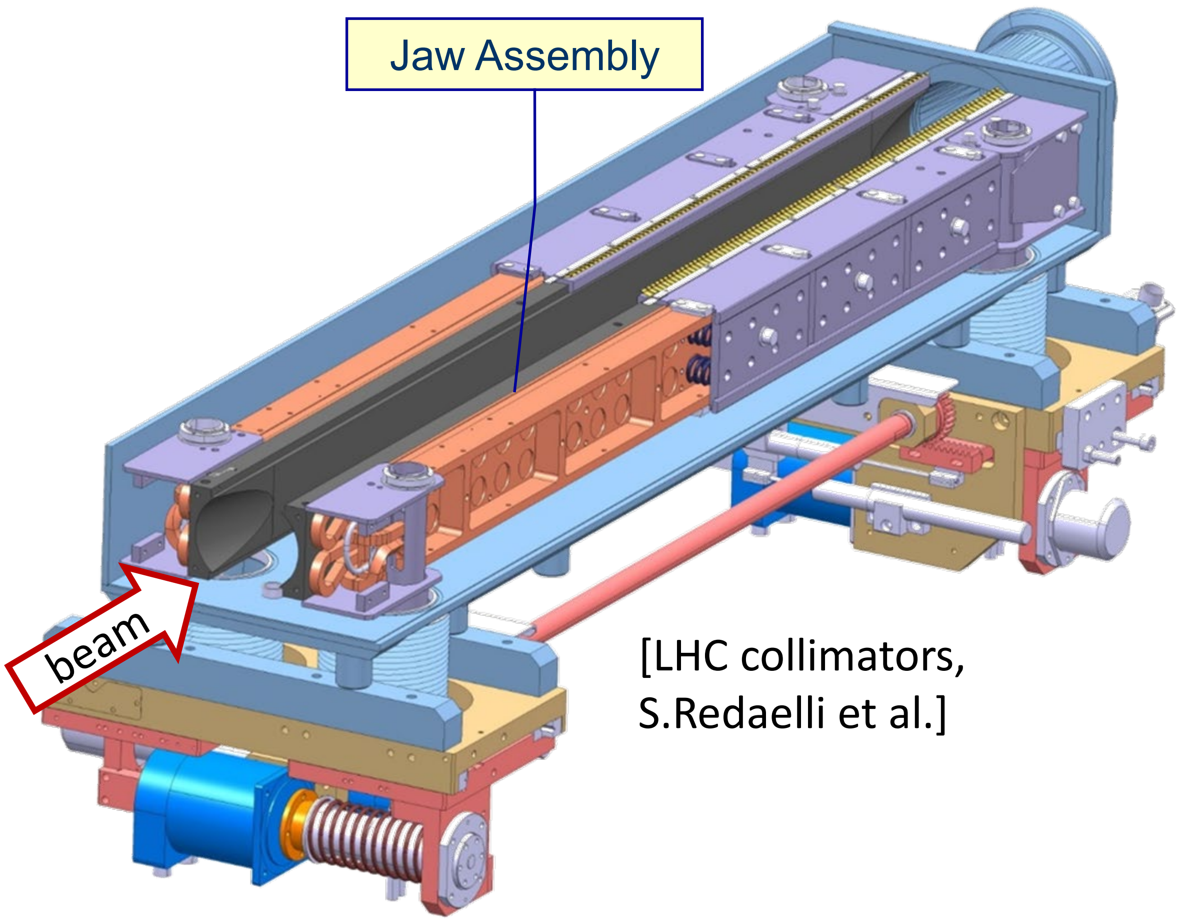
Two Stage Collimation



multiphysics challenges for collimation system:

- Beam dynamics: halo diffusion & impact parameter
- Beam dynamics: scattering & multi stage collimation
- Beam material interaction, thermo-mechanics
- Wakefields/Impedance
- in practice also tertiary collimators, LHC: ≈100 jaws

Collimator Unit



[LHC collimators, S.Redaelli et al.]

halo removal efficiency:

- jaw straightness
- precision adjustment
- reproducibility

robustness:

- thermomechanical stab.
- thermal deformation
- efficient cooling

minimal beam impact

- resistive wall wakefields
- geometric wakefields
- vacuum

The Future: Study of 80-100 km tunnel in Geneva area - design driven by pp requirements

FCC-hh hadron collider with 100 TeV proton cms energy

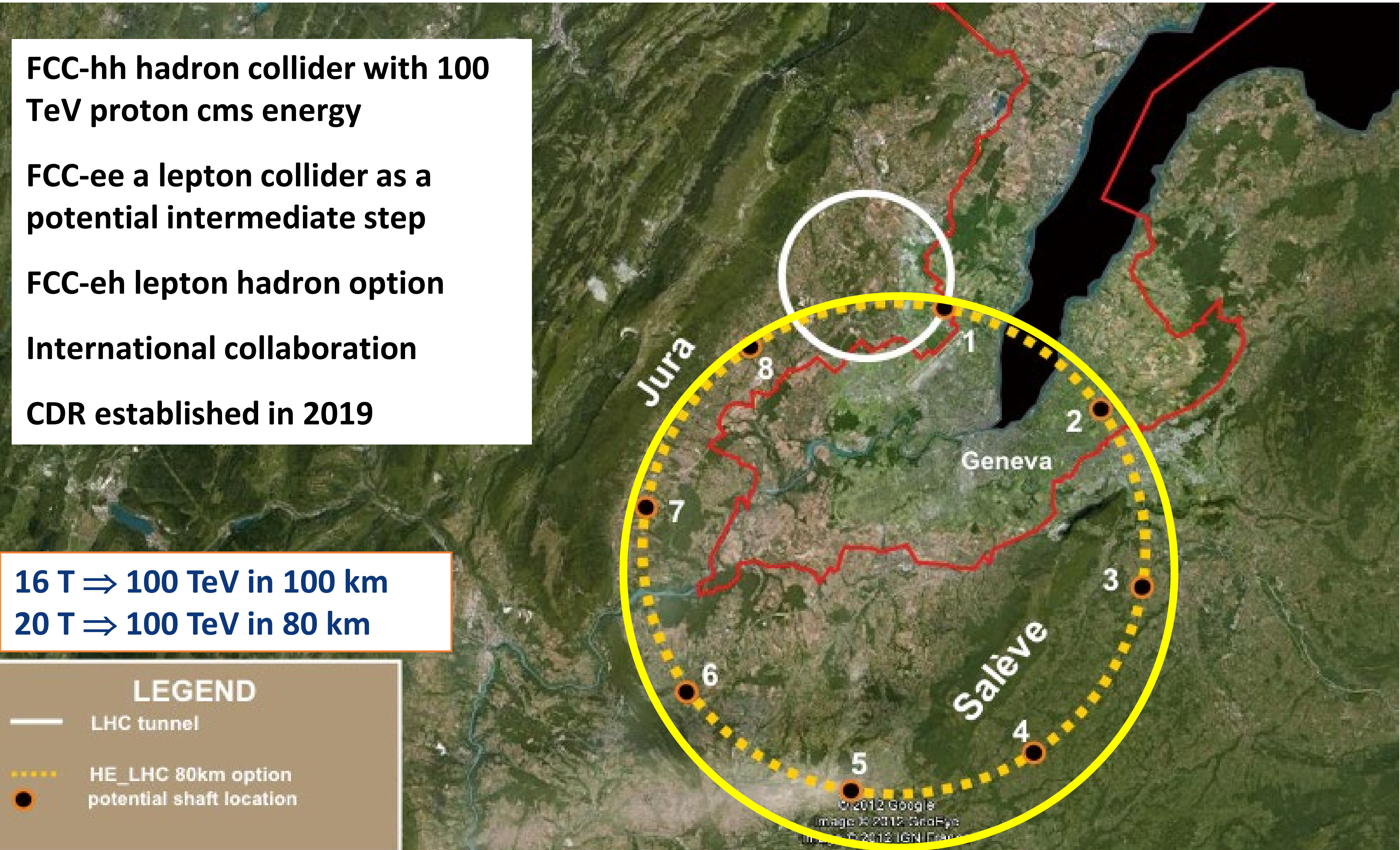
FCC-ee a lepton collider as a potential intermediate step

FCC-eh lepton hadron option

International collaboration

CDR established in 2019

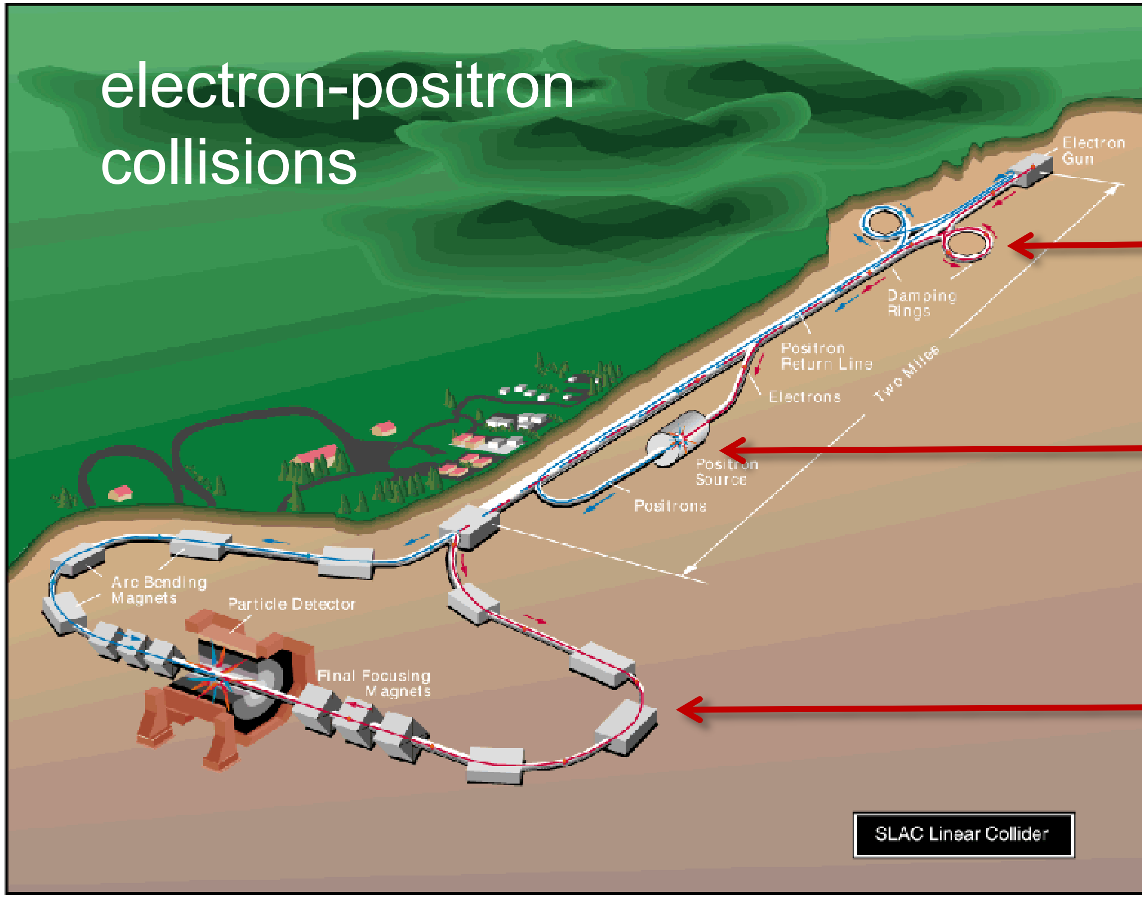
16 T ⇒ 100 TeV in 100 km
20 T ⇒ 100 TeV in 80 km



Next: Linear Collider

- Stanford LC, CLIC, ILC
- parameters and disruption during collissions
- accelerating structure technology

Stanford Linear Collider (SLC, till 1997)



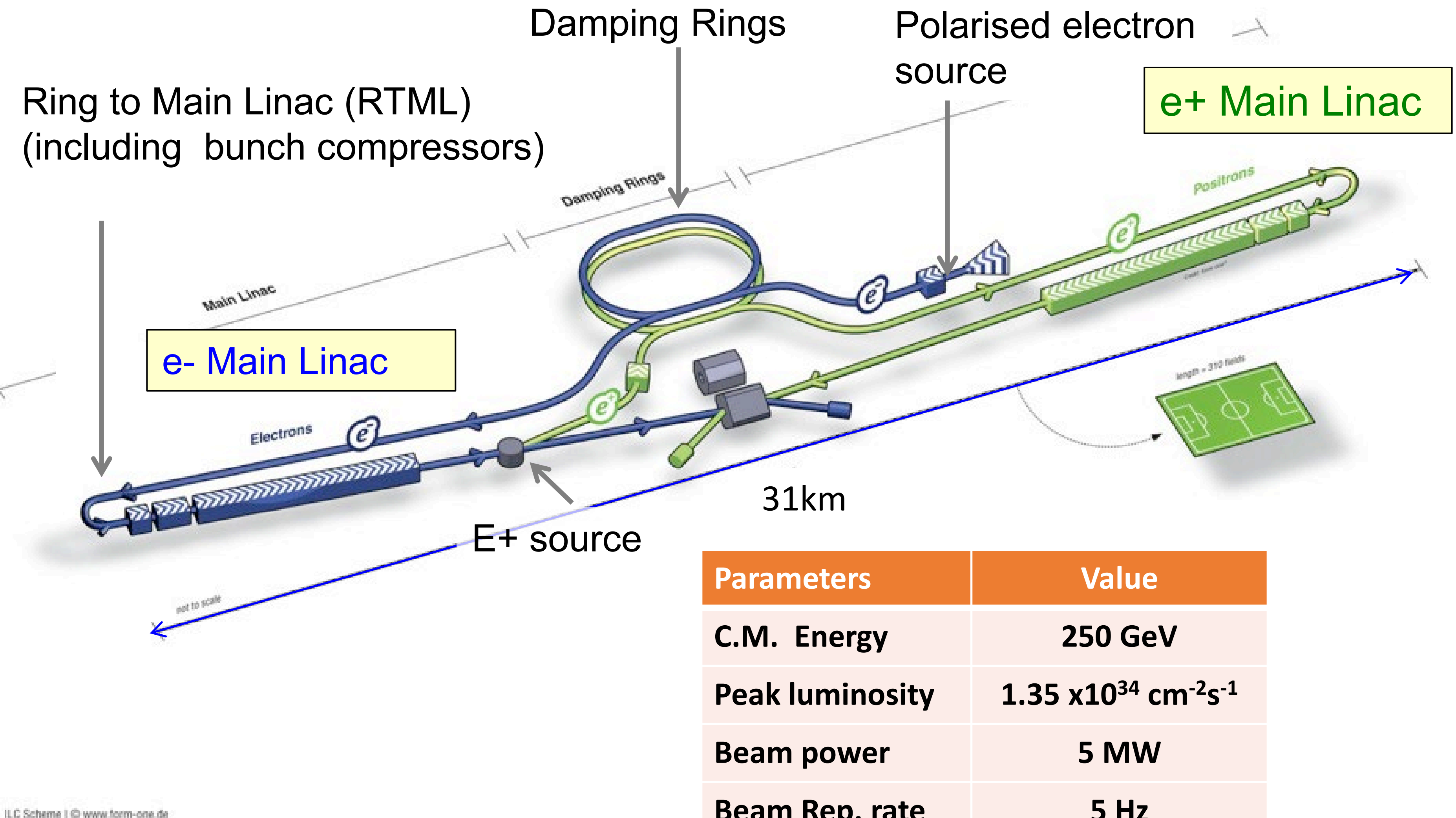
damping rings, low emittance particularly for positrons

positron source

arcs allow using the same linac for e+/e- but: disadvantages in beam dynamics

only linear collider in world, Stanford / USA
Linac: 3km length
2x50GeV e^+/e^- collisions, polarised!

modern version: ILC

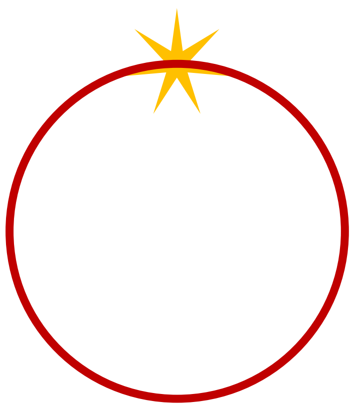


Parameters	Value
C.M. Energy	250 GeV
Peak luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Beam power	5 MW
Beam Rep. rate	5 Hz
E gradient	31.5 MV/m +/-20%

Ring Collider vs. Linear Collider

Ring Collider
beams circulate

Linear Collider
beams collide once



	FCC-ee 365GeV	**CLIC** 380GeV
σ_x [nm]	38‘000	150
σ_y [nm]	68	3
σ_z [μm]	2‘500	70
N [10^9]	230	5,2
f_b [kHz]	144	17,6

- beam reused
- synchrotron radiation dominated
- equilibrium beamsize $\rightarrow$ collision parameters limited

- beam used only once
- no synchrotron radiation
- ambitious collision parameters possible (no ring dynamics)

LC: Luminosity and Parameter Drivers

re-write normal luminosity formula:

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

H_D = luminosity enhancement factor from beam-beam (additional focusing)

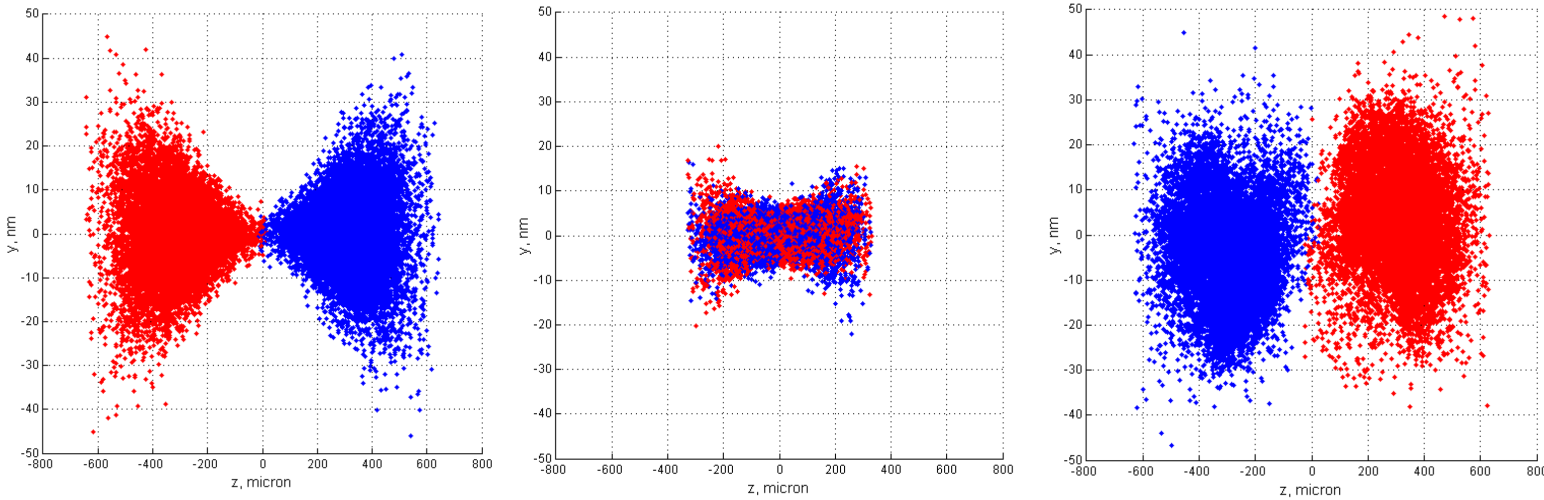
$$\mathcal{L} \propto H_D \, \frac{N}{\sigma_x} \, n_b f_r N \, \frac{1}{\sigma_y}$$

Luminosity spectrum

Beam power

Beam Quality (+bunch length)

Linear Collider: Beam-Beam enhancement Factor



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

H_D – beam-beam enhancement factor

[D.Schulte]

Linear Collider – Beam Strahlung

Bunches are squeezed strongly to maximise luminosity

↓

Electron magnetic fields are very strong

↓

Beam particles travel on curved trajectories

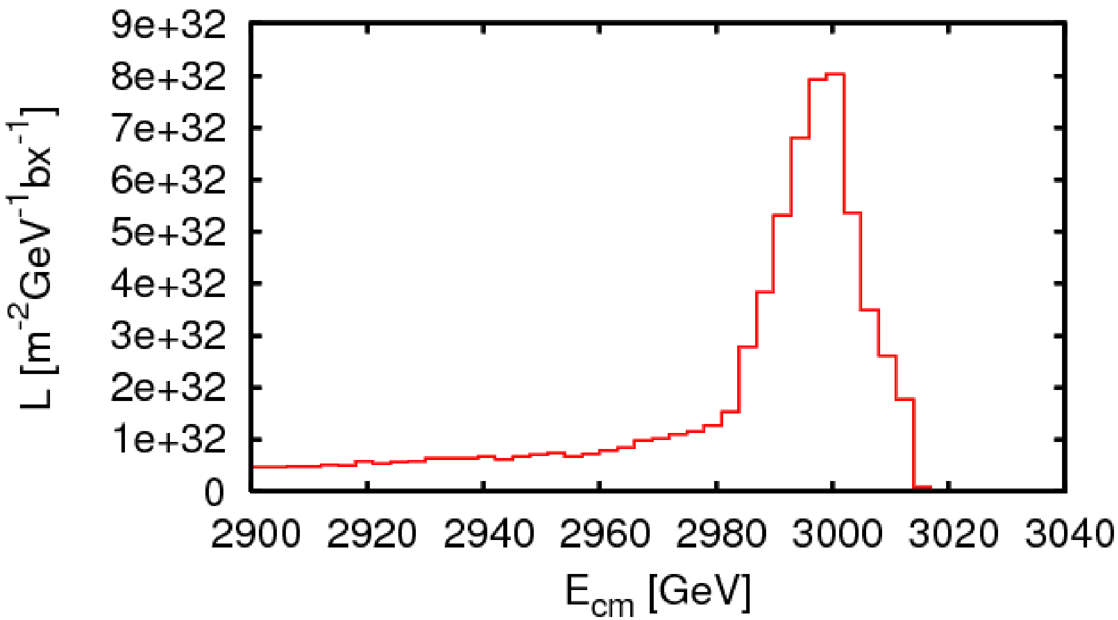
↓

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

↓

They collide with less than nominal energy

example: CLIC collision energy

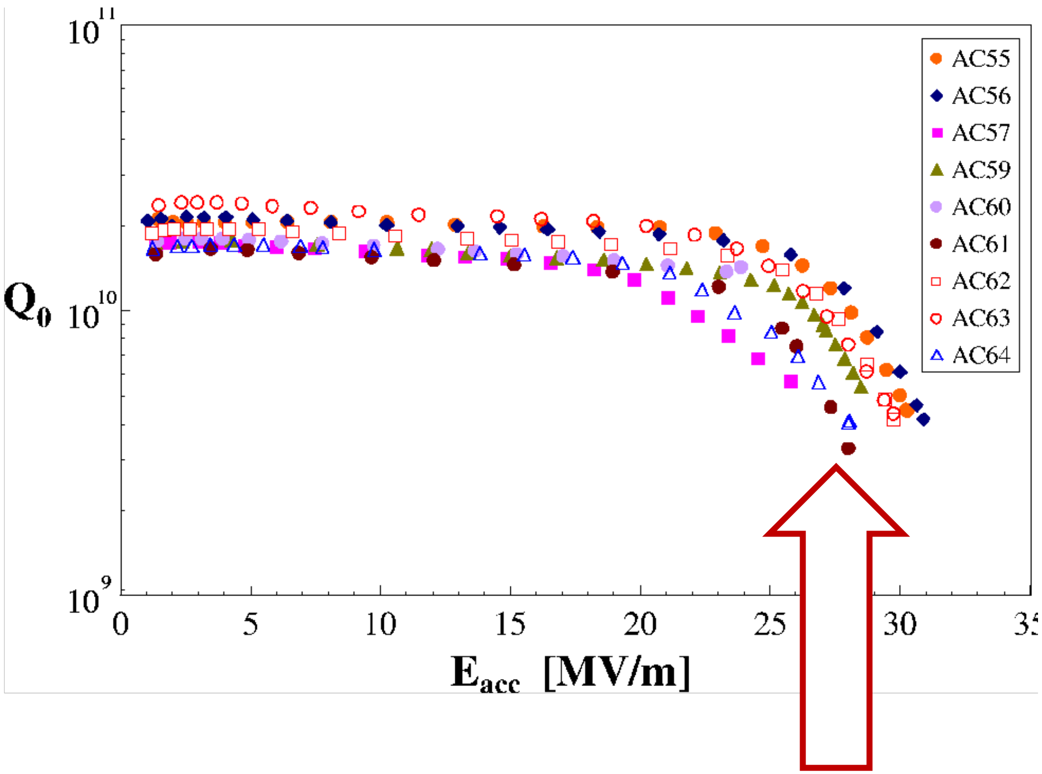


Beamstrahlung is minimized with flat beams, i.e. $\sigma_x \gg \sigma_y$

Next: Linear Collider Technology

- superconducting and room temperature cavities

ILC: Superconducting Cavities



todays state of the art

if a church bell had the same low damping:

$$Q_0 = 2 \times 10^{10}$$

$$f = 500\mathrm{Hz} \rightarrow \tau = 2\mathrm{y}$$

Cryostat and note on cryogenics

Cavities have small losses

$$P_{\mathrm{loss}} \propto \frac{V^2}{Q_0}$$

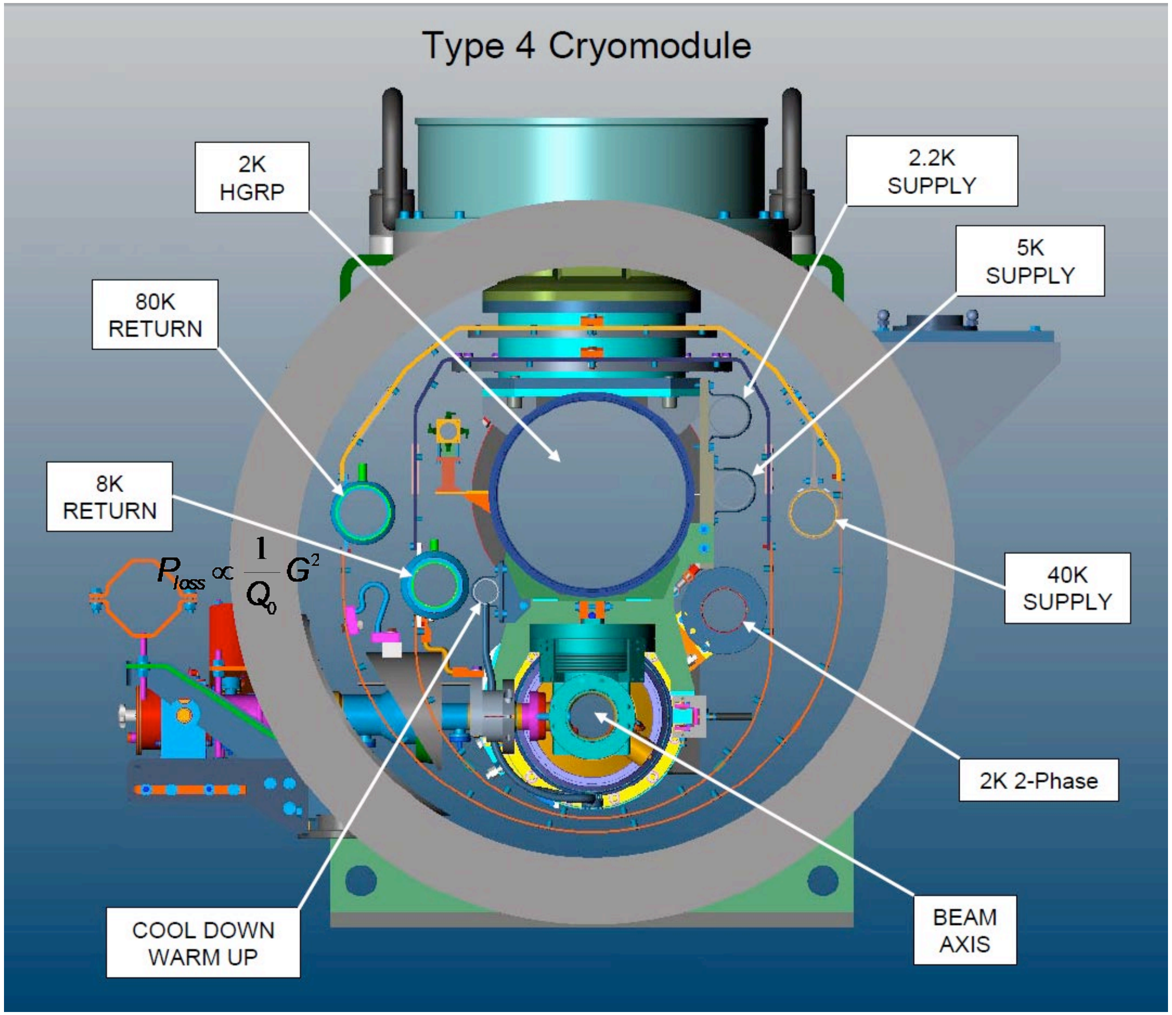
About 1W/m

But cooling costly at low temperatures

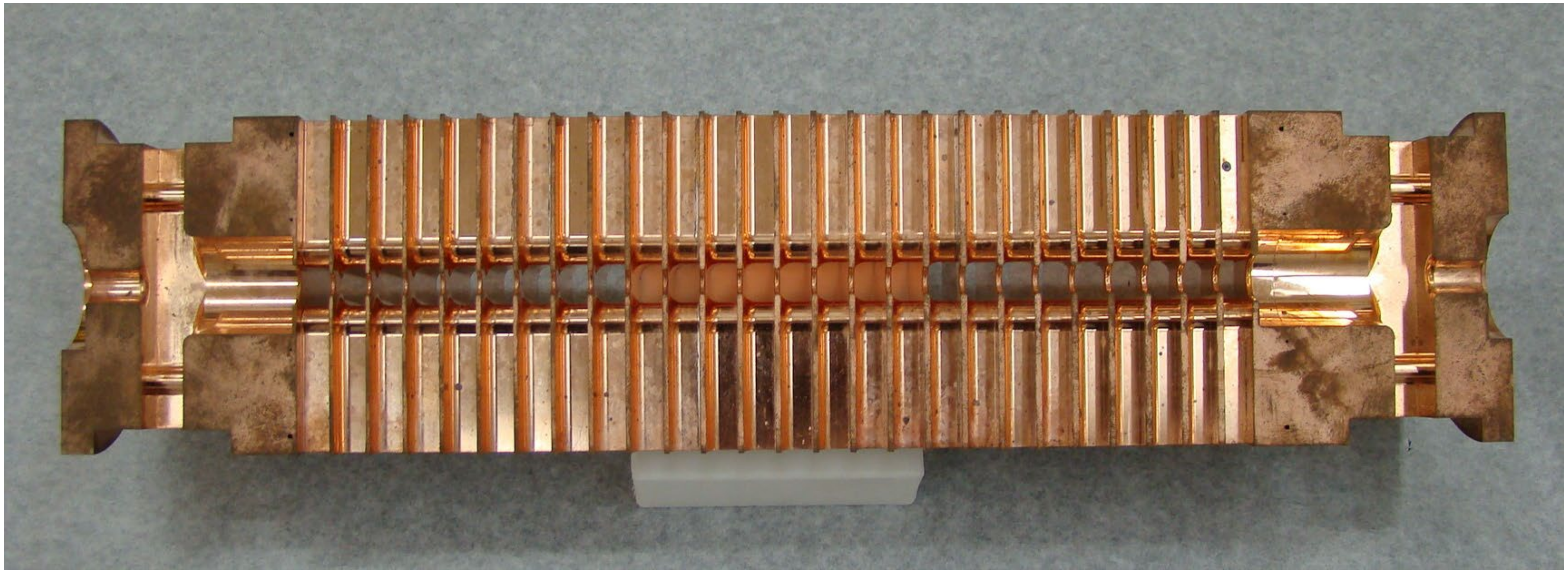
Carnot Efficiency:

$$P_{\mathrm{cryo}} \approx 700 \times P_{\mathrm{loss}}$$

The typical heat load of 1 W/m
$\Rightarrow$ about 1 kW/m for cryogenics



CLIC Accelerating Structure (room temperature)



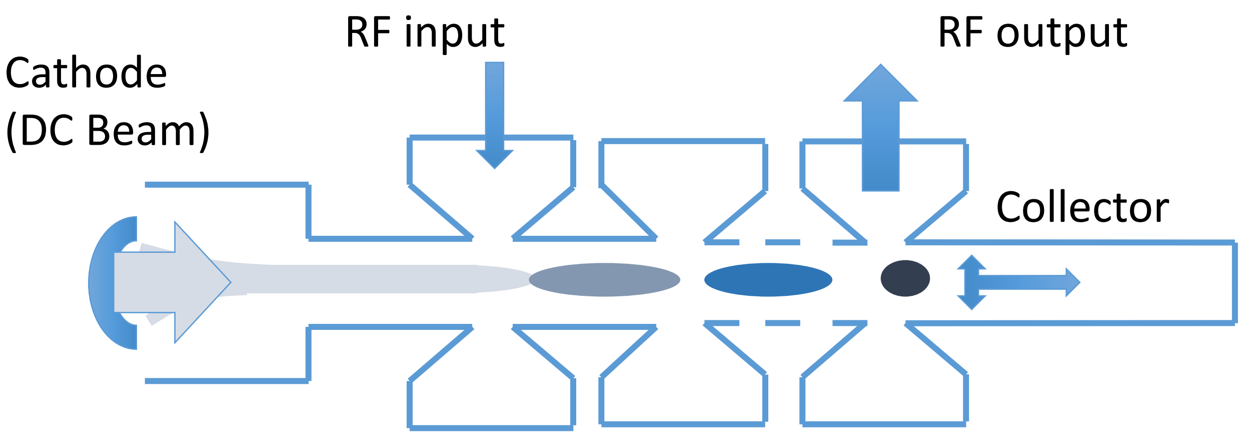
12 GHz, 23 cm long, **normal conducting**
Loaded gradient **100 MV/m**
→ Allows to reach higher energies
→ 140,000 structures at 3 TeV
→ **Power during pulse 8.5 x 10^6 MW (3000 x ILC)**

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

≈ 1 kW/m into beam

Klystron = RF Source - Principle

- DC beam passes through input
- Electron beam is velocity modulated, bunches formed
- Output cavity is excited by bunches, power extracted

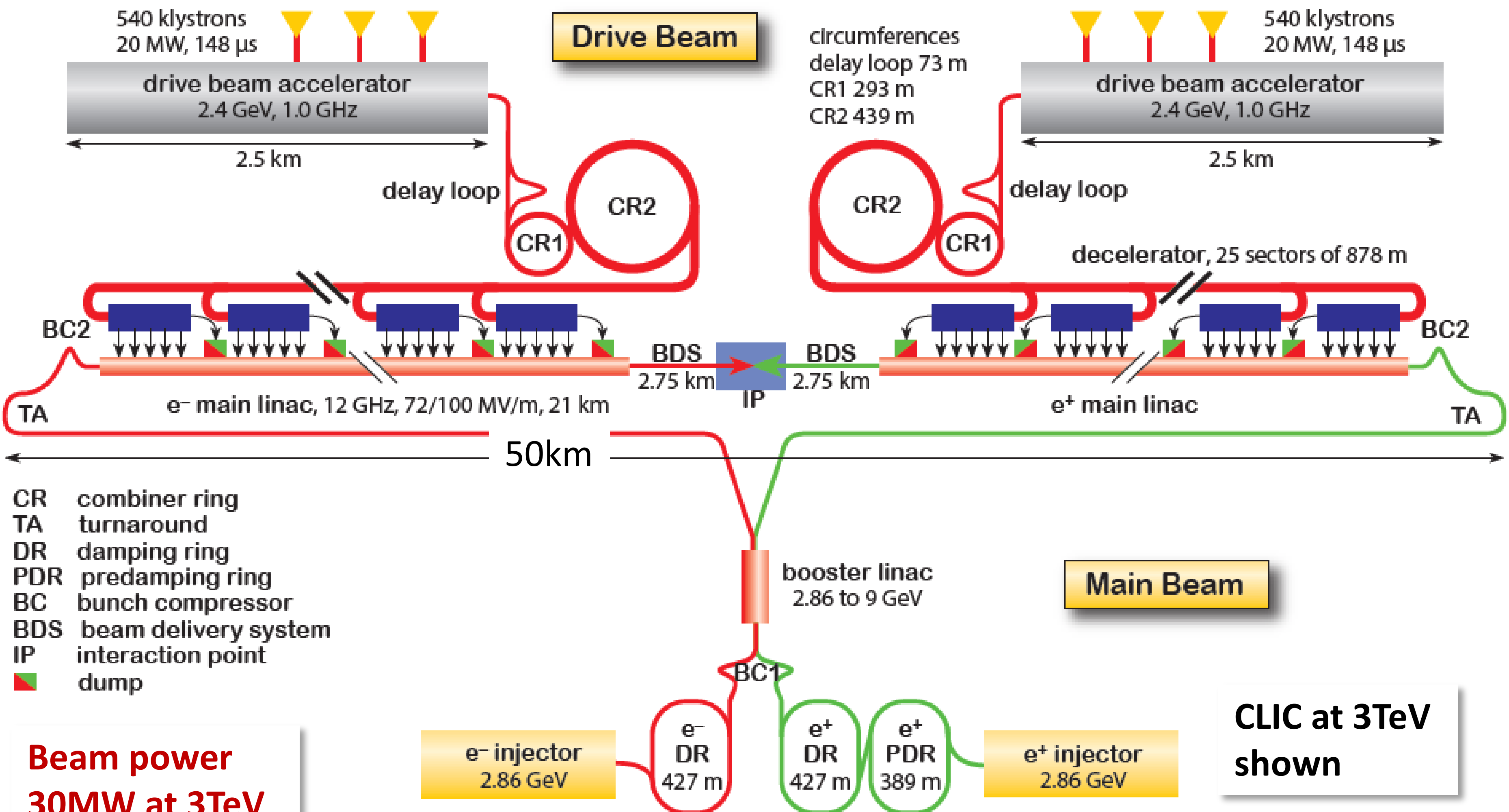


[C.Marchand, CEA]

CLIC Idea: Drive Beam Linac like a series of klystrons in a row

→ simplifies concept and improves efficiency

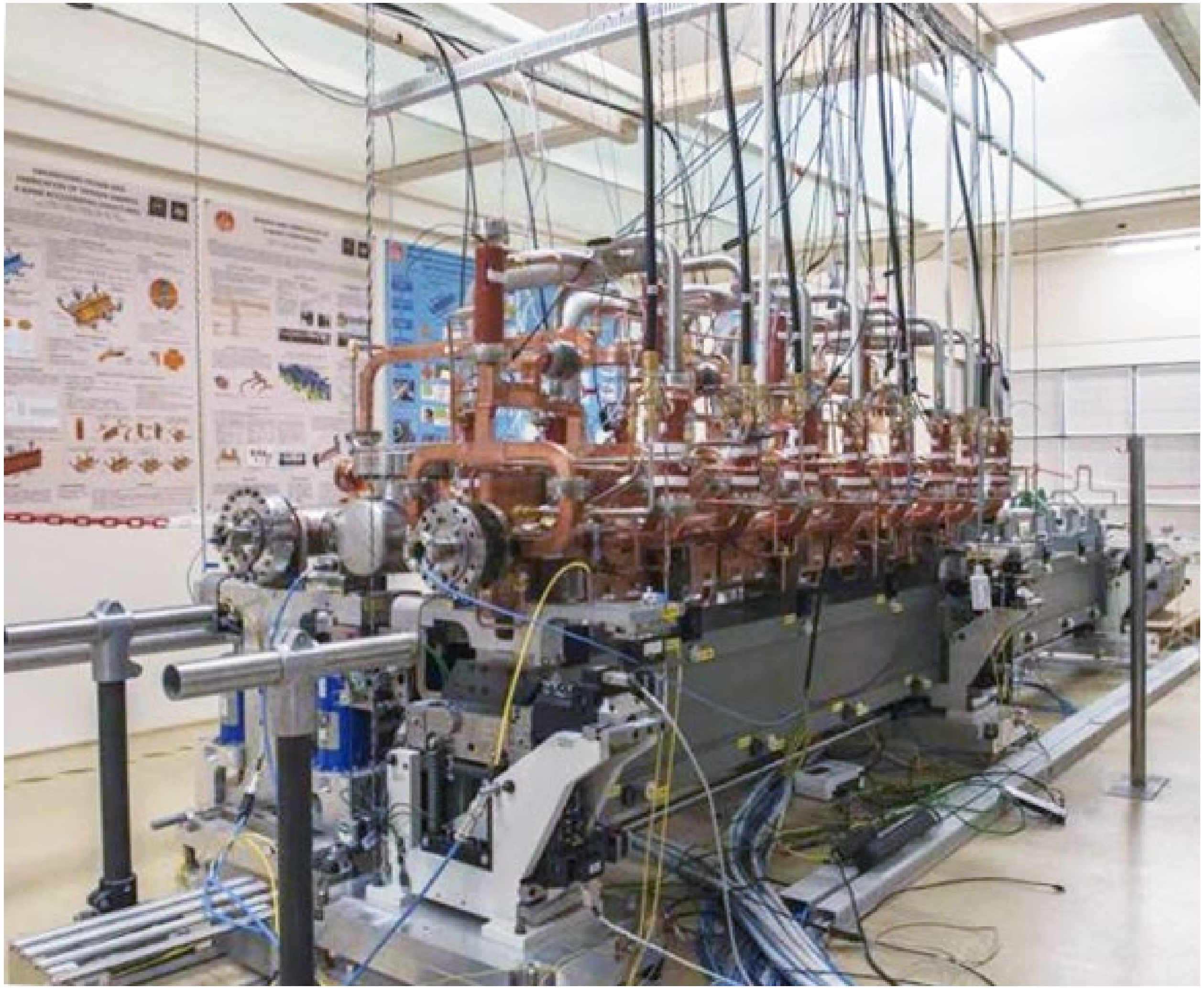
CLIC: The Basis



Beam power 30MW at 3TeV

CLIC at 3TeV shown

CLIC Two-beam Module



80 % filling with accelerating structures
11 km for 380 GeV cms, 50 km for 3 TeV

Summary Colliders and Overview Collider Studies

	Leptons	Hadrons
Ring Collider	×	×
Linear Collider	×	

EPFL

Proposed HEP Projects and Grid Power

		ECM [TeV]	L / IP [10^{34}cm^{-2}s^{-1}]	P_{Grid} [MW]	power driving effects
ring collider	FCC-ee (Z)	0.091	230	**259**	SR Power: 50MW/beam
ring collider	FCC-ee (t)	0.365	1.5	**359**	SR power: 50MW/beam
ring collider	FCC-hh	100	30	**580**	SR power: 2.4MW/beam @ 50K, cryogenics
linear	ILC	1	4.9	**300**	beam power: 13.6 MW/beam, cryogenics
linear	CLIC	3	5.9	**582**	beam power: 14 MW/beam
Muons	muon coll.	6	12	**270**	mu decay, 1.6MW/drive beam, cycling magnets, but scaling advantages, least developed

$$P_{\mathrm{SR}} \propto \left(\frac{E}{E_0}\right)^4 \frac{1}{R}$$

$$L_{\mathrm{lc}} \propto H_D \sqrt{\frac{\delta_E}{\varepsilon_{x,n}}} P_{\mathrm{beam}}$$

$$L_\mu \propto B \frac{N_0}{\varepsilon_{xy,n}} \gamma P_{\mathrm{beam}}$$

Significant energy cost: 4TWh ~ 200M€, and sustainability concerns.
$\rightarrow$ need more R&D towards efficient concepts & technology, energy management

Summary Colliders

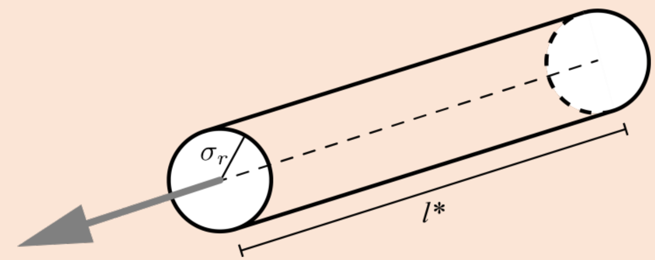
- **colliding beams against each other** is more effective than fixed target scattering, and **colliders have been a driving force behind accelerator development**
- **lepton collisions allow precision measurements** as compared to hadron collisions (constituents)
- **energy reach and luminosity** are key parameters of colliders

- lepton ring colliders are **limited by SR losses**, e.g. 50MW losses for FCC-ee
- linear colliders have no synchrotron radiation but as **single pass machines** achieving sufficient luminosity is challenging
- the energy of hadron ring colliders is limited by the available **magnetic field strength** in the range of 8…16Tesla, and by size/cost

Appendix: Computing the Field of a Moving Bunch

solve electrostatic problem in moving frame*,
then transform to lab frame

charge density and field in moving frame:

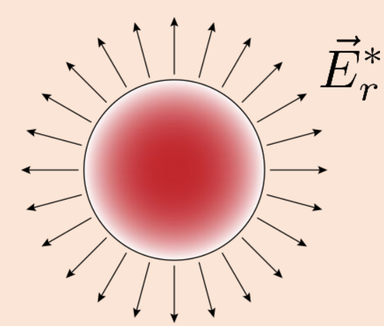


$$\rho^*(r) = \frac{Ne}{2\pi\sigma_r^2 l^*} e^{-\frac{r^2}{2\sigma_r^2}} \qquad \iint \vec{E}^*\, d\vec{A} = \frac{q}{\varepsilon_0}$$

in the moving frame l^* is much larger than σ_r

compute surface integral of E and
relate to enclosed charge q:

$$2\pi r l^* E_r^* = l^* \int_0^{2\pi} d\varphi \int_0^r r' dr' \rho^*(r')$$



results in radial field, lab frame:

$$E_r = \gamma E_r^* = \frac{Ne}{2\pi l \varepsilon_0} \frac{1 - e^{-\frac{r^2}{2\sigma_r^2}}}{r}$$

Appendix: Beam-Beam Force for Round Beams

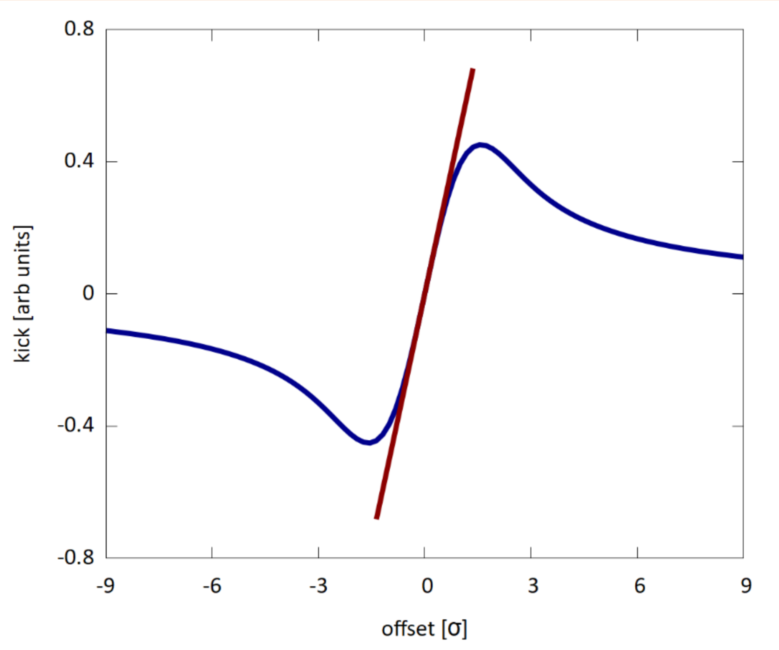
$$\Delta p_\perp = F_\perp \, \Delta t = -2eE_\perp \frac{l}{2c}, \;\; \Delta r' = \Delta p_\perp / p_0$$

beam-beam kick:

$$\Delta r' = -\frac{2Nr_e}{\gamma} \frac{1 - e^{-\frac{r^2}{2\sigma_r^2}}}{r}$$

$$\approx (KL) \cdot r = -\frac{Nr_e}{\gamma \sigma_r^2} \cdot r$$

similar to quadrupole



$$r_e = \frac{e^2}{4\pi\varepsilon_0 m_0 c^2} = 2.82 \times 10^{-15} \text{ m}$$