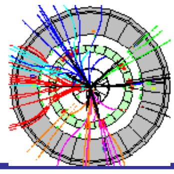


Colliders & accelerator applications:

- different collider types & their limits
- Large Hadron Collider
- beam-beam effects
- electron cloud
- LHC dipoles & protection
- stochastic & electron cooling
- muon collider
- linear colliders
- ILC & CLIC
- FCC
- applied accelerators

Gradient–focusing created at MURA (US,1956): beams focused sufficiently for head-on collisions (”colliders”).

- first 2–ring electron–electron colliders (one beam clockwise in one ring & another beam anticlockwise in seperate ring; collisions at crossing point of both rings): VEPP-I (Russia)1965 & Stanford-Princeton (US) 1966.
- same 2–ring scheme adopted for first large proton–(anti)proton ring 30 GeV + 30 GeV, ISR at CERN 1971.
- 1960’s: single ring collider with electrons & positrons going opposite directions in same guide field. Example: PETRA@DESY (Germany) 1978, PEP@SLAC (US) 1980,Tristan@KEK (Japan) 1987 & LEP@CERN 1989.
- apply single ring to protons & antiprotons (”pbar”) but pbars much more difficult to produce than positrons ($\sim 10^6$ protons $\rightarrow$ 1 pbar) + pbars accumulated during hours. ”Cooling” to compress antiprotons to bunches $\Rightarrow$ S$p\bar{p}$S@CERN 1981; Tevatron@Fermilab (US) 1987: E_{cm} (~ 2 TeV) large but luminosity limited by # of pbar’s.
- next quest for higher energy: Large Hadron Collider (LHC) at CERN, 2–ring proton –proton collider with max. E_{cm} = 14 TeV; first collisions autumn 2009.
- HERA at DESY 1990: a new collider type: 2–ring electron/positron–proton collider with $E_{e\pm}$ = 30 GeV & E_p = 920 GeV

(E.Wilson)

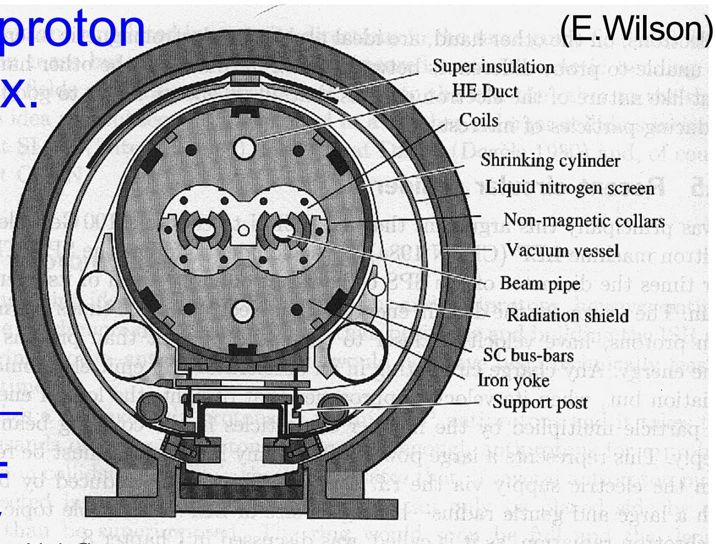
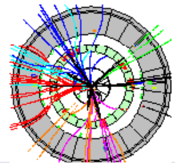
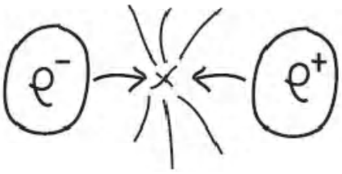


Fig. 11.1 Cross section of the LHC twin-bore dipole magnet in its cryostat.

Different collider types



Electrons (and positrons) are (so far) point like particles: no internal structu



The energy of the collider, namely two times the energy of the beam colliding is totally transferred into the collision

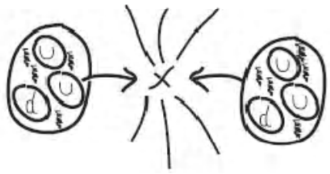
Ecoll= Eb1+ Eb2= 2Eb = 200 GeV (LEP)

Pros: the energy can be precisely tuned to scan for example, a mass region

Precision measurement (LEP)

Cons: above a certain energy is no more convenient to use electron because of too high synchrotron radiation (last lecture)

Protons (and antiprotons) are formed by quarks (uud) kept together by gluons



The energy of each beam is carried by the proton constituents, and it is not the entire proton which collides, but one of his constituent

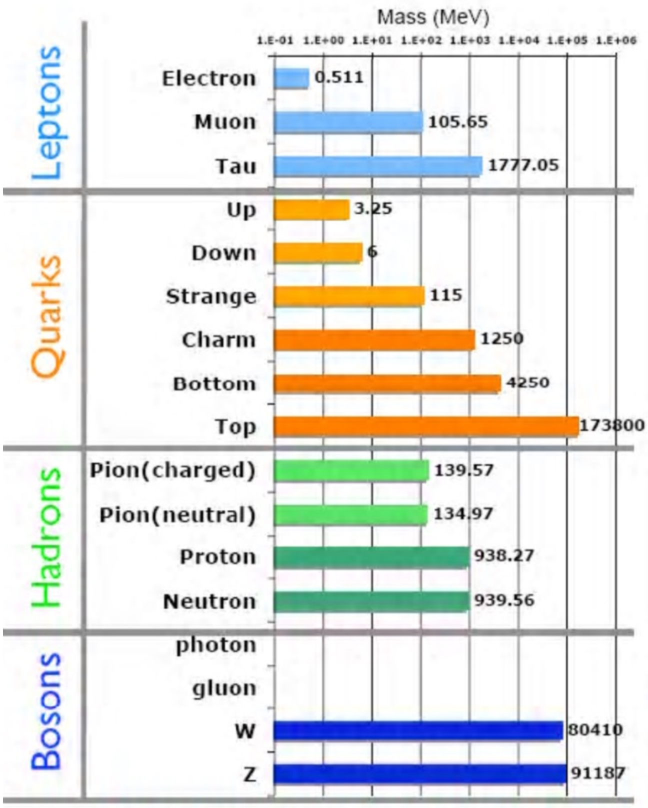
Ecoll < 2Eb

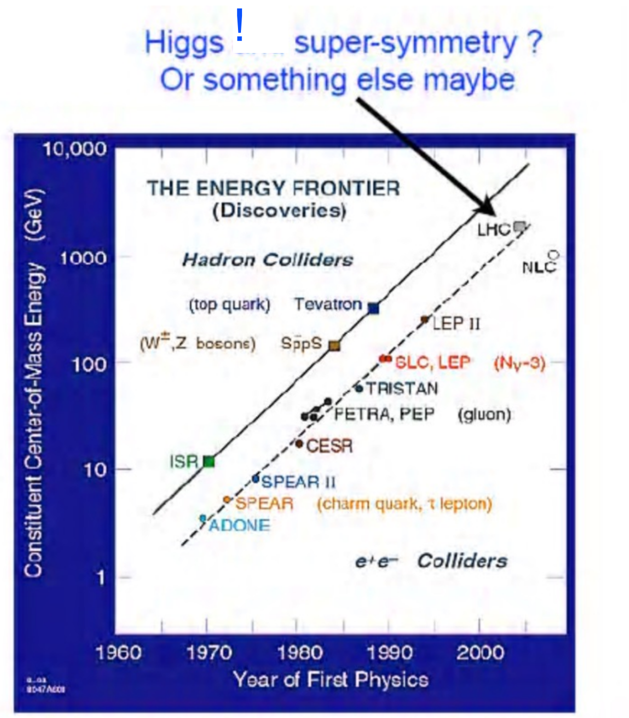
Pros: with a single energy possible to scan different processes at different energies

Discovery machine (LHC)

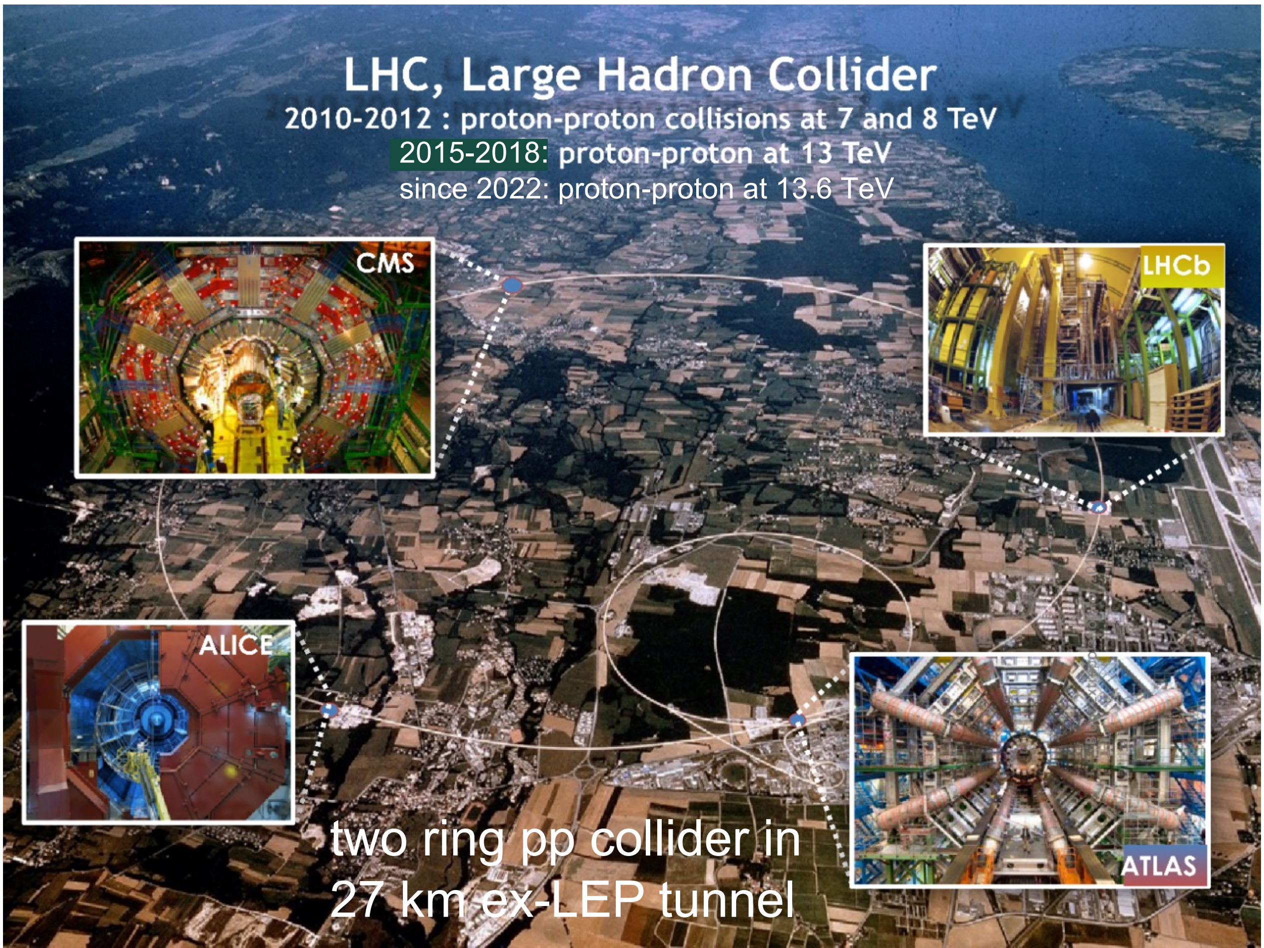
Cons: the energy available for the collision is lower than the accelerator energy

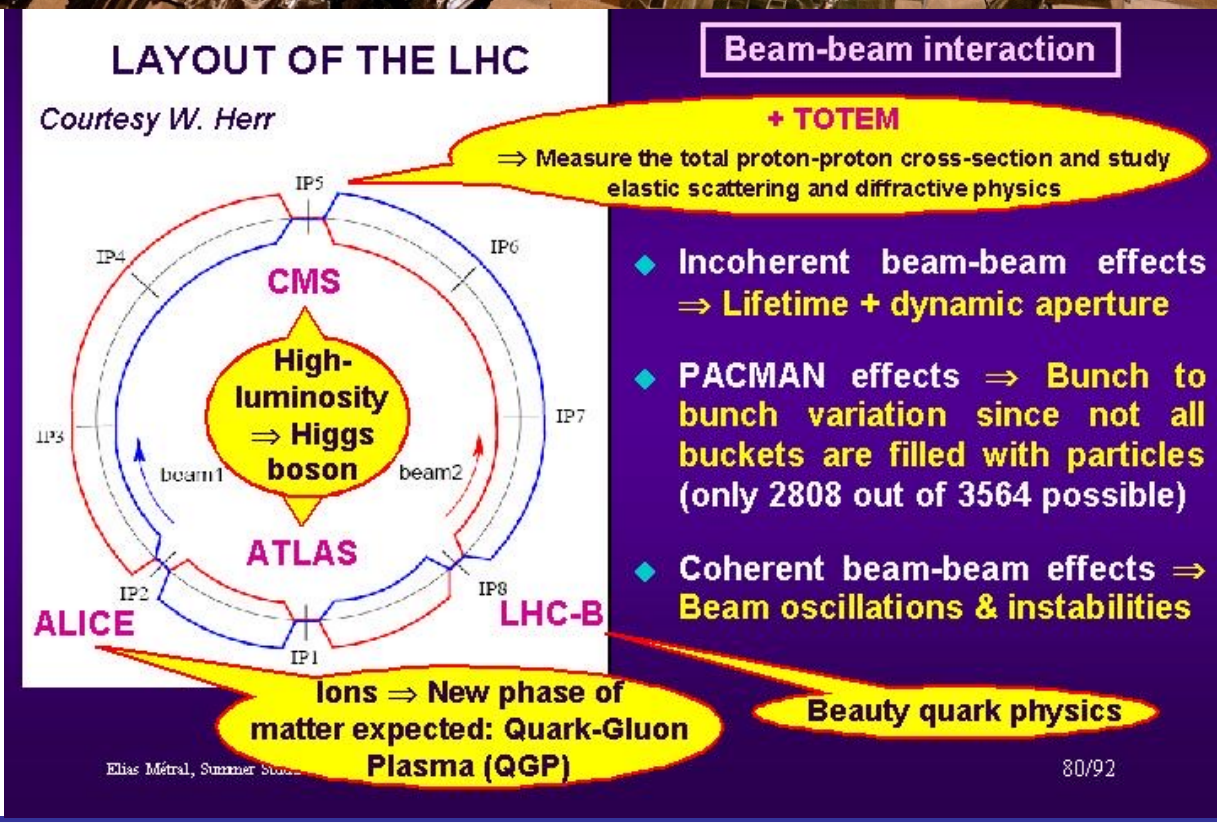
L. Evans - EDMS document 941351



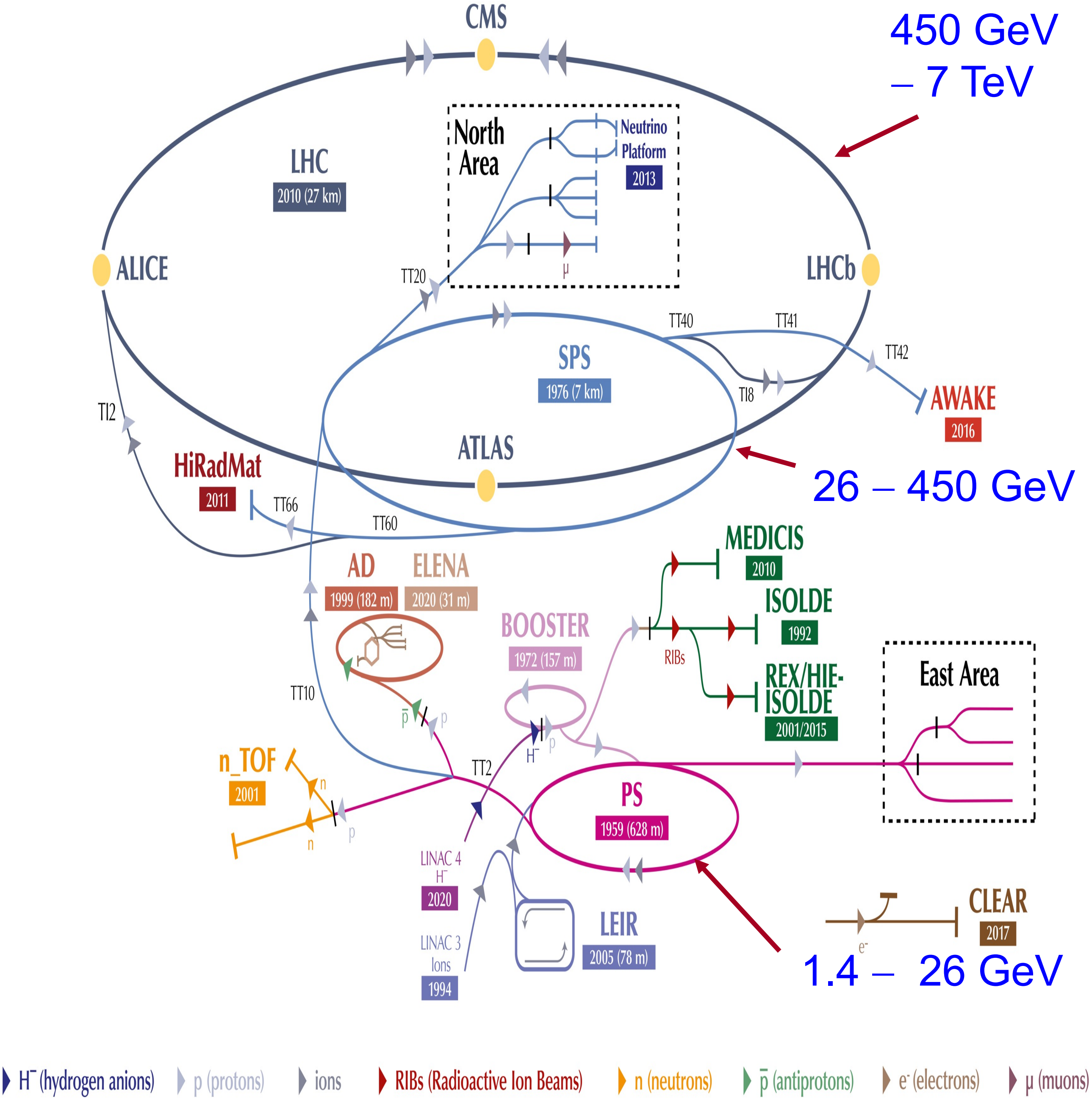


Behind the history plot is hidden the technological development required for each step


LHC, Large Hadron Collider
2010-2012 : proton-proton collisions at 7 and 8 TeV
2015-2018: proton-proton at 13 TeV
since 2022: proton-proton at 13.6 TeV
CMS
LHCb
ALICE
ATLAS
two ring pp collider in
27 km ex-LEP tunnel


LAYOUT OF THE LHC
Courtesy W. Herr
IP5
IP4
IP6
IP3
IP7
IP2
IP8
IP1
CMS
High-luminosity ⇒ Higgs boson
beam1
beam2
ATLAS
ALICE
LHC-B
Beam-beam interaction
+ TOTEM
⇒ Measure the total proton-proton cross-section and study elastic scattering and diffractive physics
Incoherent beam-beam effects ⇒ Lifetime + dynamic aperture
PACMAN effects ⇒ Bunch to bunch variation since not all buckets are filled with particles (only 2808 out of 3564 possible)
Coherent beam-beam effects ⇒ Beam oscillations & instabilities
Ions ⇒ New phase of matter expected: Quark-Gluon Plasma (QGP)
Beauty quark physics
80/92

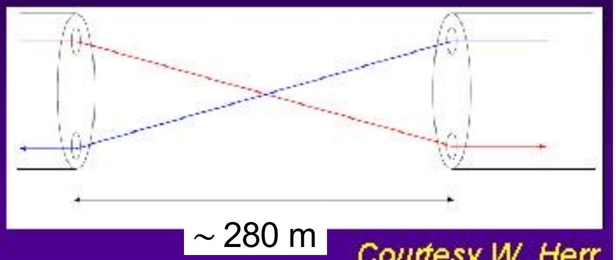
overview of CERN accelerator complex



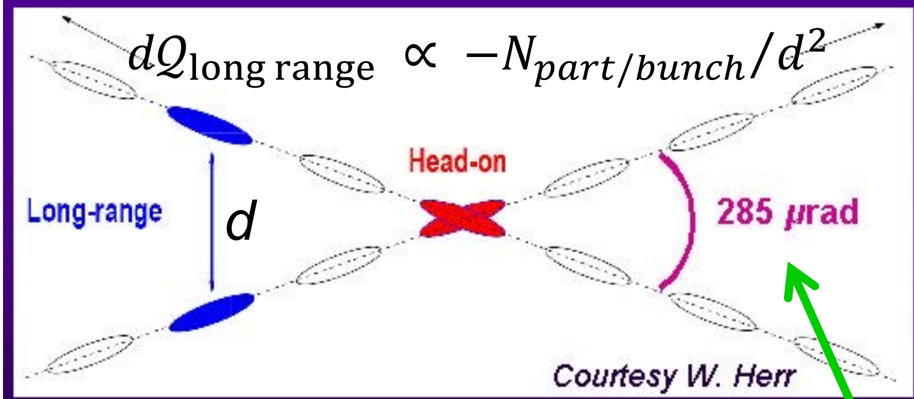
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (24/35)

CROSSING ANGLE ⇒ To avoid unwanted collisions, a crossing angle is needed to separate the 2 beams in the part of the machine where they share a vacuum chamber



Courtesy W. Herr

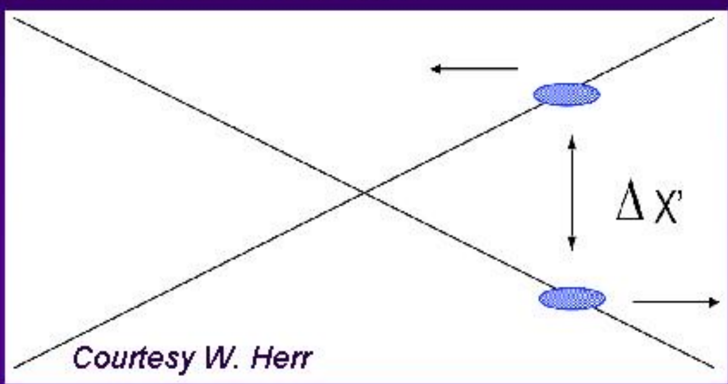


- 30 long-range interactions around each IP ⇒ 120 in total
- Separation: 9 σ

In 2024: 320 μrad with 25 ns bunch spacing

Elias Métral, Summer Student Course, CERN, 6-7-10-11-12/07/06 81/92

- **COHERENT BEAM-BEAM EFFECT**



- A whole bunch sees a (coherent) kick from the other (separated) beam ⇒ Can excite coherent oscillations
- All bunches couple together because each bunch "sees" many opposing bunches ⇒ Many coherent modes possible!

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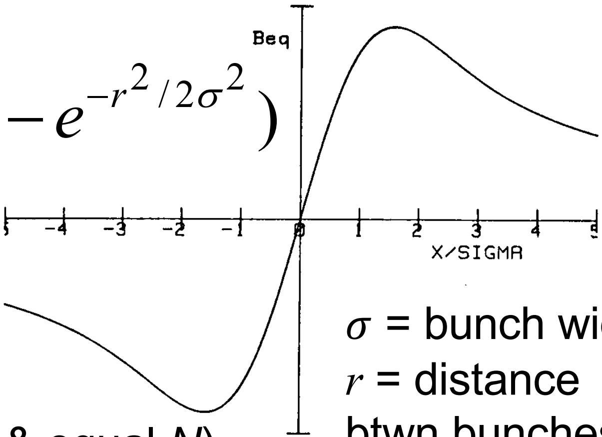
A coherent Coulumb force btwn 2 colliding bunches give (linear) defocusing effect of one bunch on other (like one bunch would see other as an optical lens).

$$F_r(r) = -\frac{N(1+\beta^2)r}{4\pi\varepsilon_0\sigma^2}\left(1-e^{-r^2/2\sigma^2}\right)$$



$$F \propto r/\sigma^2 \quad \text{for} \quad r \ll \sigma$$

$$F \propto 1/r \quad \text{for} \quad r \gg \sigma$$

(formula valid for round beams & equal *N*)

σ = bunch width
r = distance btwn bunches

$\Rightarrow$ change transverse focusing property of accelerator and observed as a spread of the transverse tune Q.

$$dQ = \frac{r_o}{4\pi}\frac{N_{part/bunch}}{\sqrt{\varepsilon_V^*\varepsilon_H^*}}$$

NB! $\partial(dQ)\,/\,\partial E_{cm} \propto 1/E$ but $\partial\sigma_{\text{interest. phys.}}\,/\,\partial E_{cm} \propto 1/E^2$

where r_0 = classical radius of particle

To avoid instabilities Q spread shouldn't be more than one percent for colliding proton beams. For electrons factor 10 more dQ allowed since synchrotron radiation damping protects against slowly growing instabilities.

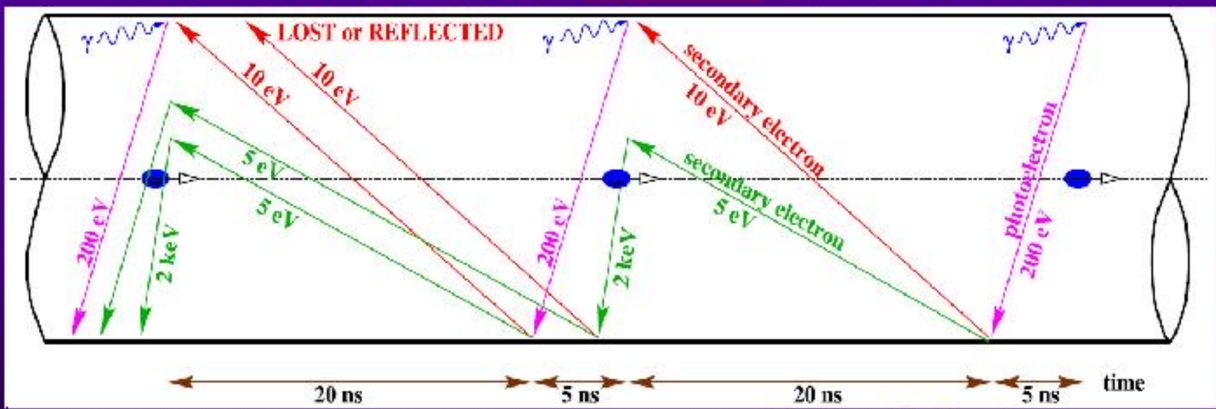
dQ formula essentially contains same variables as luminosity $\mathcal{L}$ formula so difficult to increase $\mathcal{L}$ without increasing dQ. $\mathcal{L}$ increase realized by making β^* as small as possible, # of bunches as large as possible & increase $N_{\text{part/bunch}}$ to limit imposed by instabilities.

LIMITING FACTORS FOR A SYNCHROTRON / COLLIDER
⇒ COLLECTIVE EFFECTS (30/35)

Electron cloud

- **Schematic of electron-cloud build up in the LHC beam pipe during multiple bunch passages, via photo-emission (due to synchrotron radiation) and secondary emission**

The LHC is the 1st proton storage ring for which synchrotron radiation becomes a noticeable effect



Courtesy F. Ruggiero

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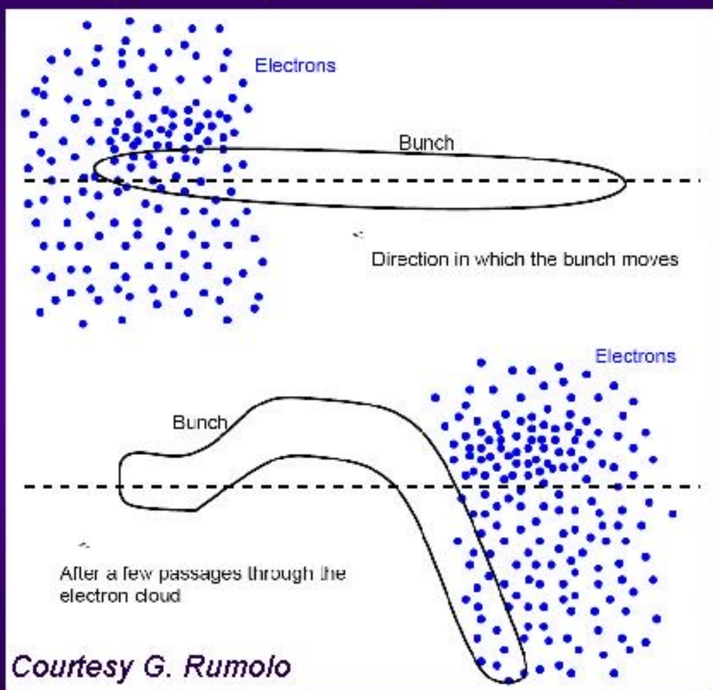
- **Schematic of the single-bunch (coherent) instability induced by an electron cloud**

Increases with reduced bunch spacing & increased bunch intensity → emittance increase & larger beam instability

MOVIE
Single-Bunch Instability From ECloud.mpeg

Courtesy G. Rumolo and F. Zimmermann



Remedy 1: "scrubbing" runs (removing residual gas molecules inside LHC vacuum chamber)

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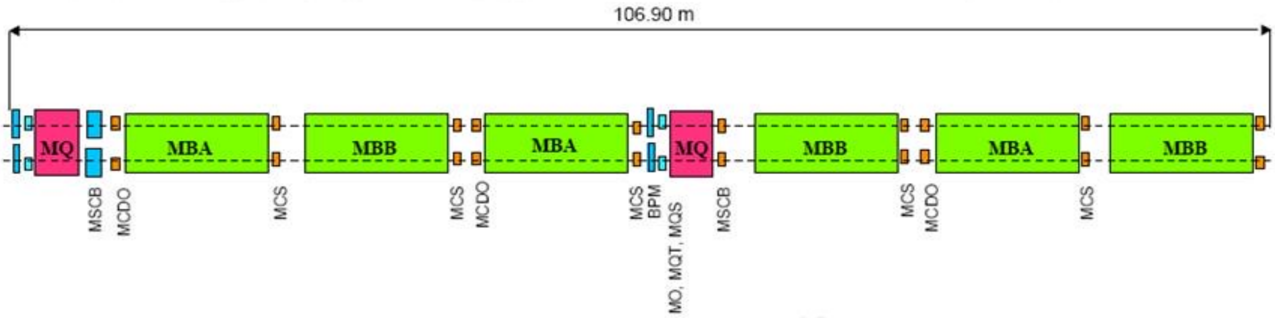
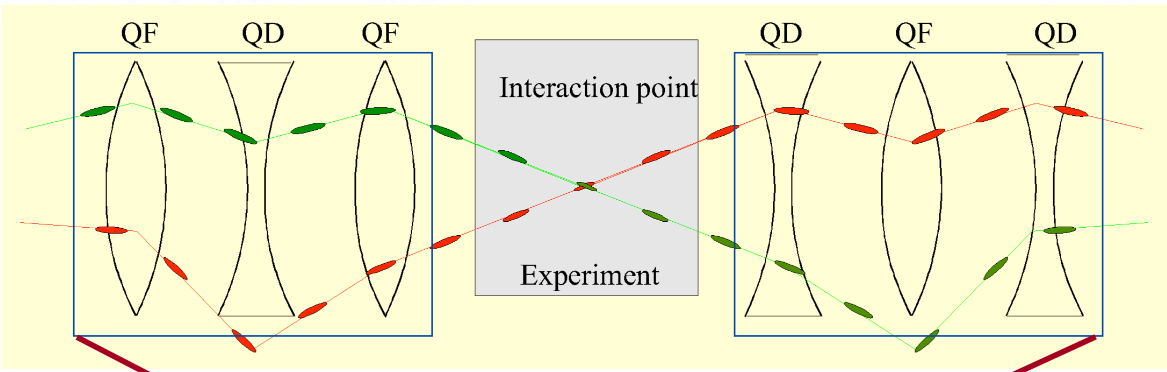
Remedy 2: low electron emittance coating of vacuum chamber inside.

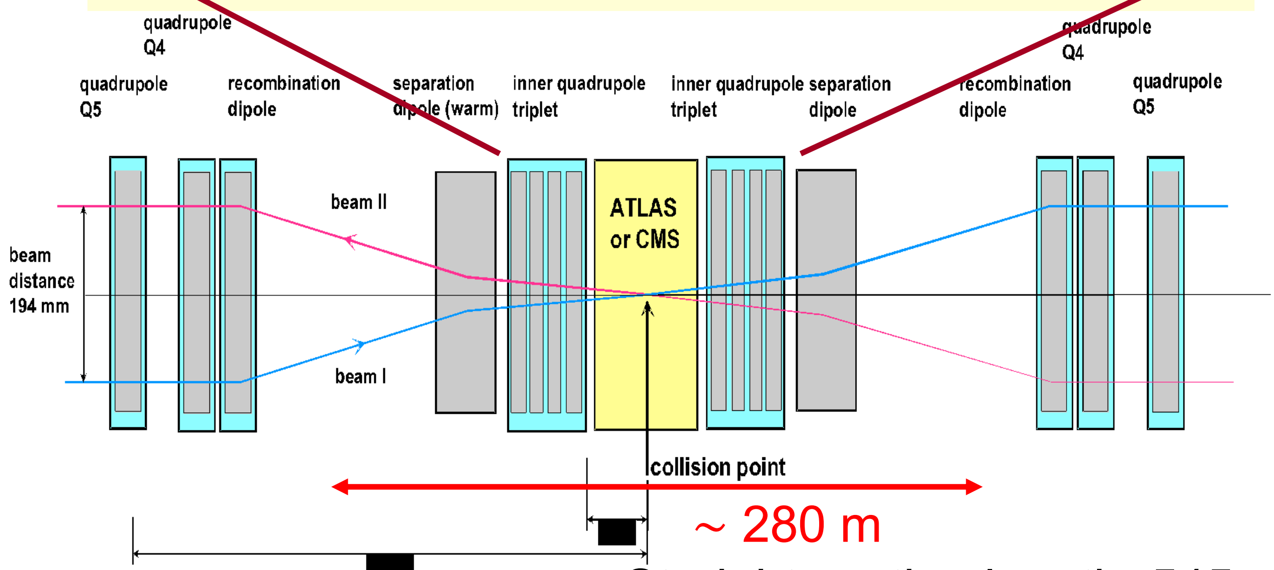


MQ: Lattice Quadrupole
MO: Landau Octupole
MQT: Tuning Quadrupole
MQS: Skew Quadrupole
MSCB: Combined Lattice Sextupole (MS) or skew sextupole (MSS) and Orbit Corrector (MCB)
BPM: Beam position monitor
MBA: Dipole magnet Type A
MBB: Dipole magnet Type B
MCS: Local Sextupole corrector
MCDO: Local combined decapole and octupole corrector

Regular LHC FODO cell

Each LHC arc/octant (2.45 km) contains 23 such FODO cells





~ 280 m

Straight section length: 545 m

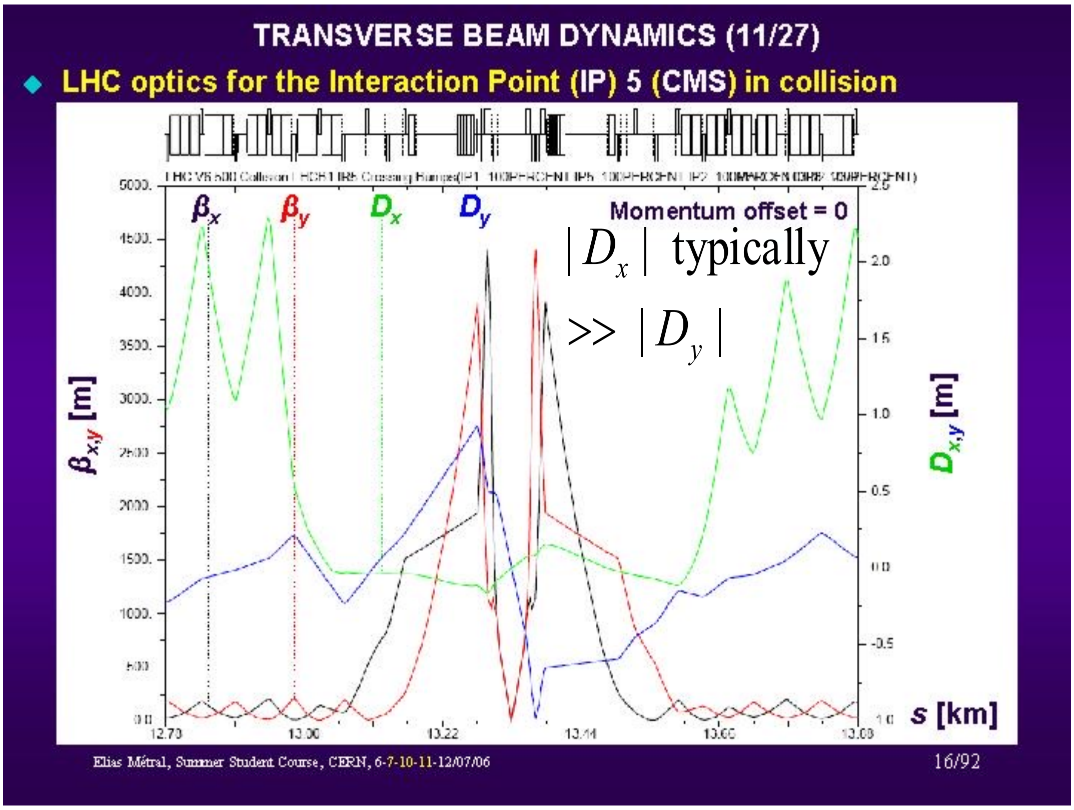
Example for an LHC insertion with ATLAS or CMS

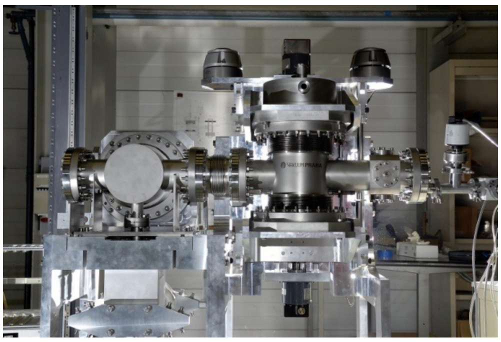
Interaction points (IP)

Particle transport programs for accelerators, like MADX, used to determine ”optical functions” (effective length L^{eff}, magnification v & dispersion D) to estimate displacement of proton from closed orbit at any position s as function of transverse origin (x^*, y^*) and scattering angles (θ_x^*, θ_y^*) at IP & longitudinal momentum loss (ξ = $(p_z - p_{\text{beam}})/p_{\text{beam}}$):

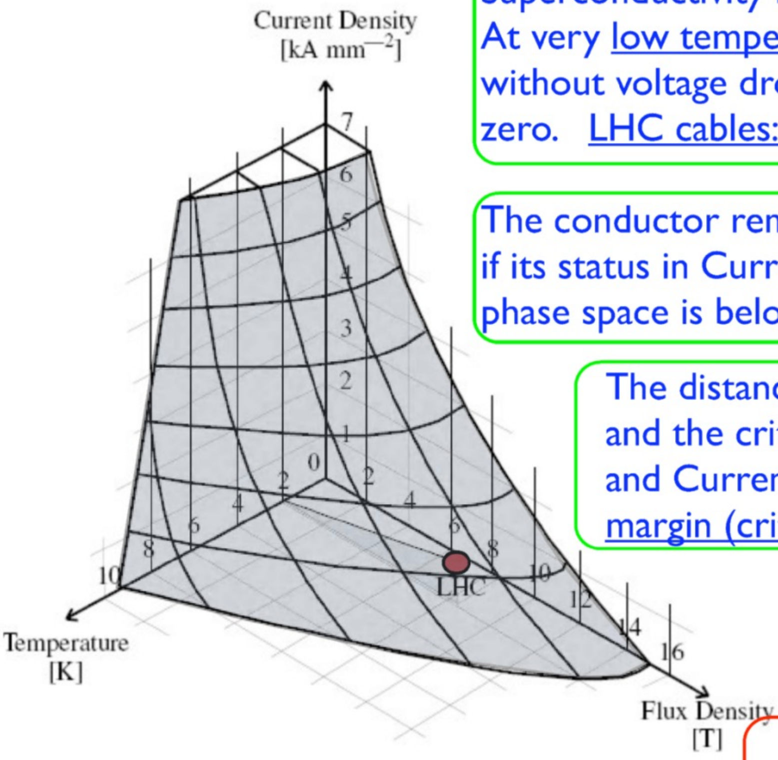
$$x(s) = v_x(s,\xi)\cdot x^* + L_x^{eff}(s,\xi)\cdot\theta_x^* + \xi\cdot D_x(s,\xi)$$

$$y(s) = v_y(s,\xi)\cdot y^* + L_y^{eff}(s,\xi)\cdot\theta_y^* + \xi\cdot D_y(s,\xi)$$





Tool used for predicting acceptance for protons scattered little ($\sim \mu$rads) or lost a bit of momentum ($\xi \sim$ few %) in collision & later measured in ”Roman Pots” far away from IP (> 200 m) close to the outgoing beam.



Superconductivity is a property of some materials. At very low temperature they can carry currents without voltage drop, i.e. their resistivity goes to zero. LHC cables: Nb-Ti working at 1.9 K

The conductor remains Superconductor if its status in Current Density, Temperature, B field phase space is below the Critical Surface

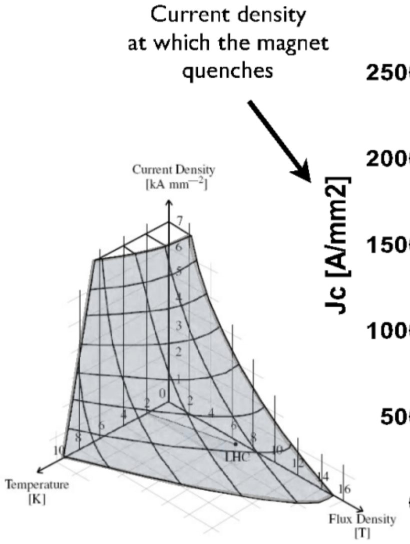
The distance between the working point and the critical surface for a fixed B field and Current Density is the temperature margin (critical temperature)

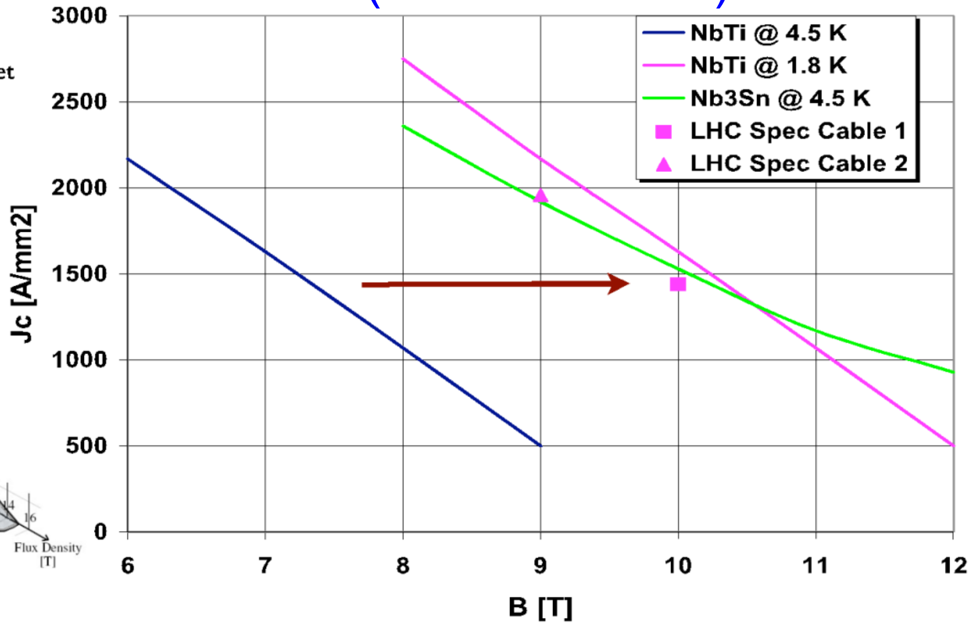
Transition to a normal conducting state is called magnet quench

What can increase the temperature in a magnet ?

e.g. particles hitting the magnet

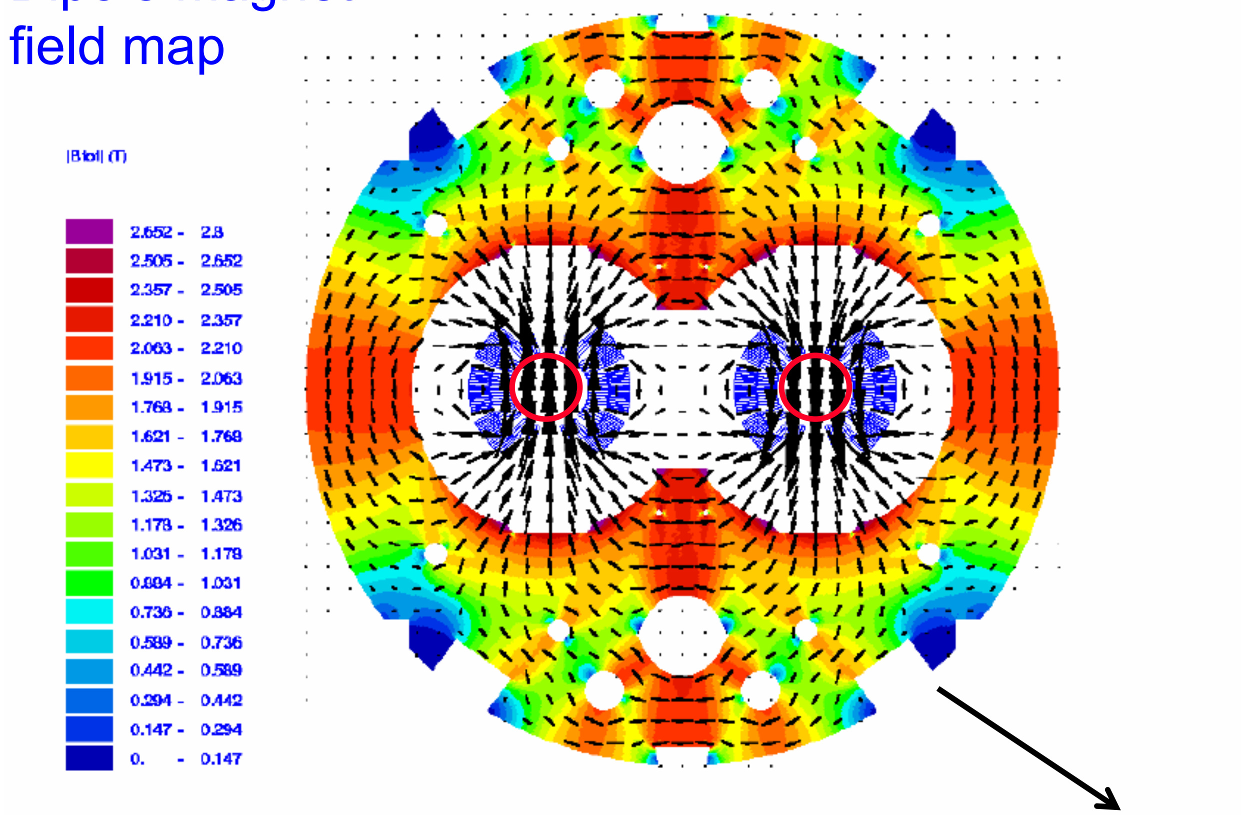
Why 1.9 K in stead of 4.5 K (i.e. HERA-like)?





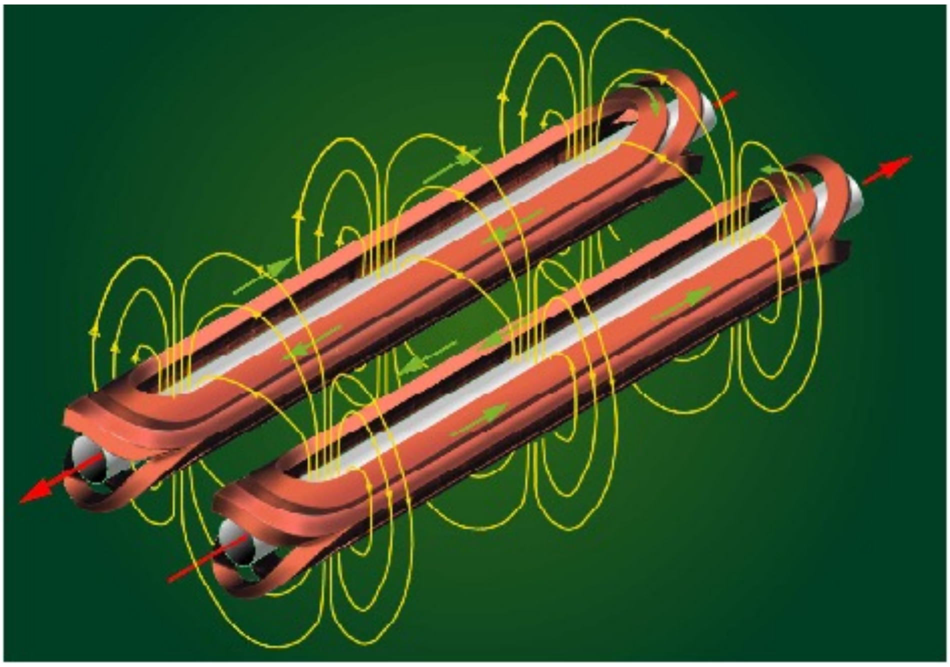
Gain of 3 T lowering the temperature for 4.5 K to 1.9 K.
Gain in dipoles bending strength and hence of MAX energy

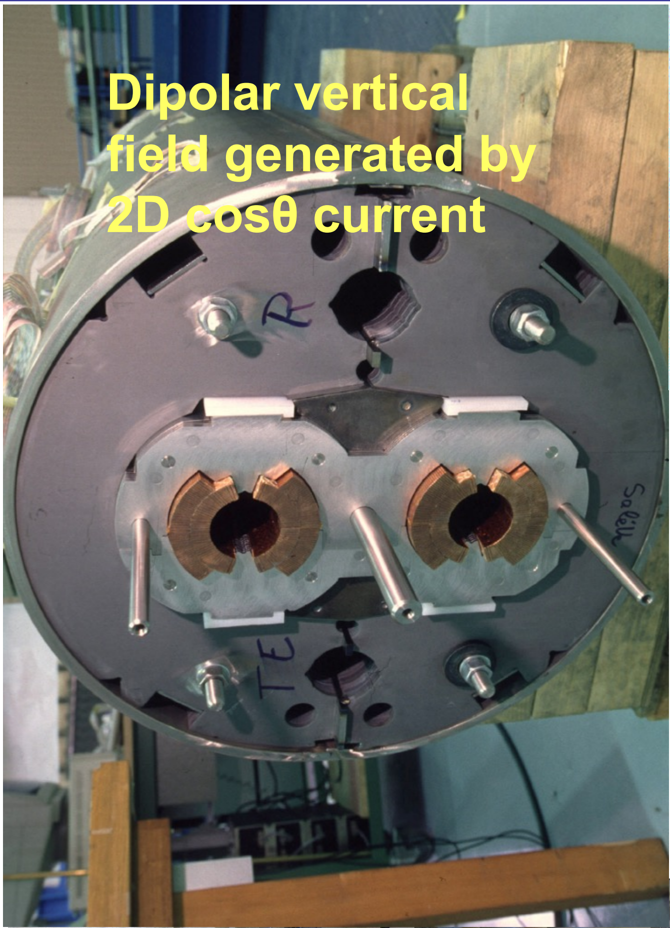
Dipole magnet field map

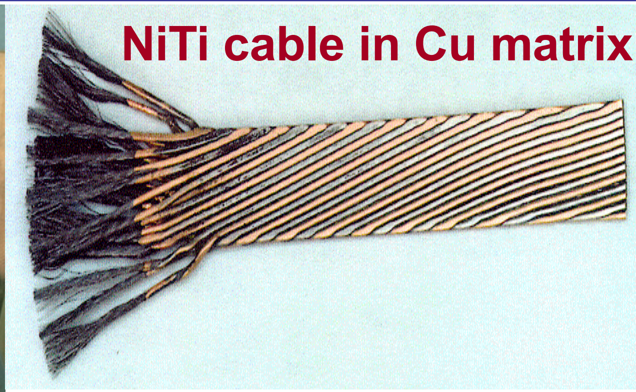


Energy stored in one dipole = 2 $(B^2/\mu_0)\, V_{\text{dipole}} \approx$ 7.6 MJ
Total stored energy in all 1232 LHC dipoles: 9.4 GJ $\leftrightarrow$
Total stored beam energy: $E_{proton} N_{bunch} N_{part/bunch} \approx$ 410 MJ (max. in 2024)

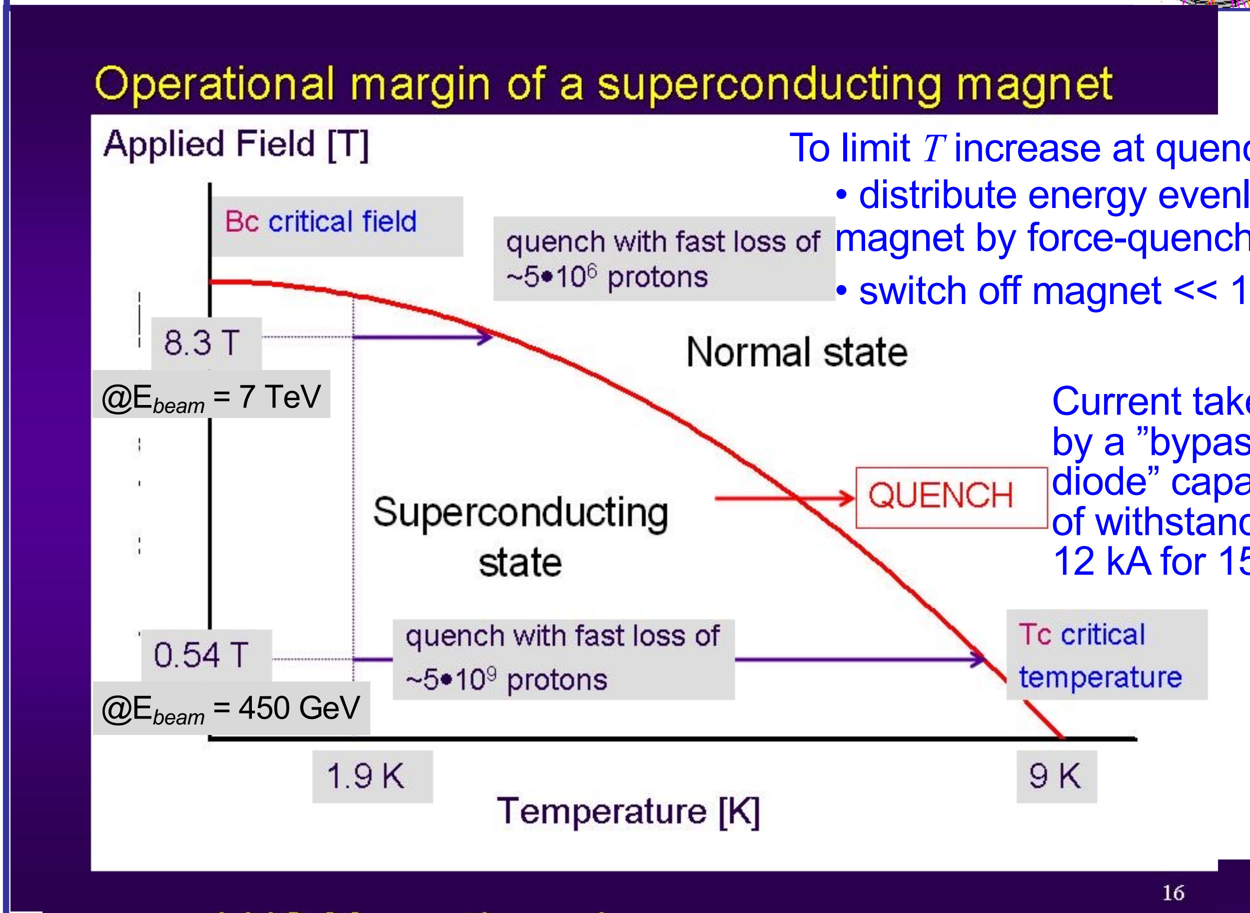
Magnetic field lines in 2-in-1 design







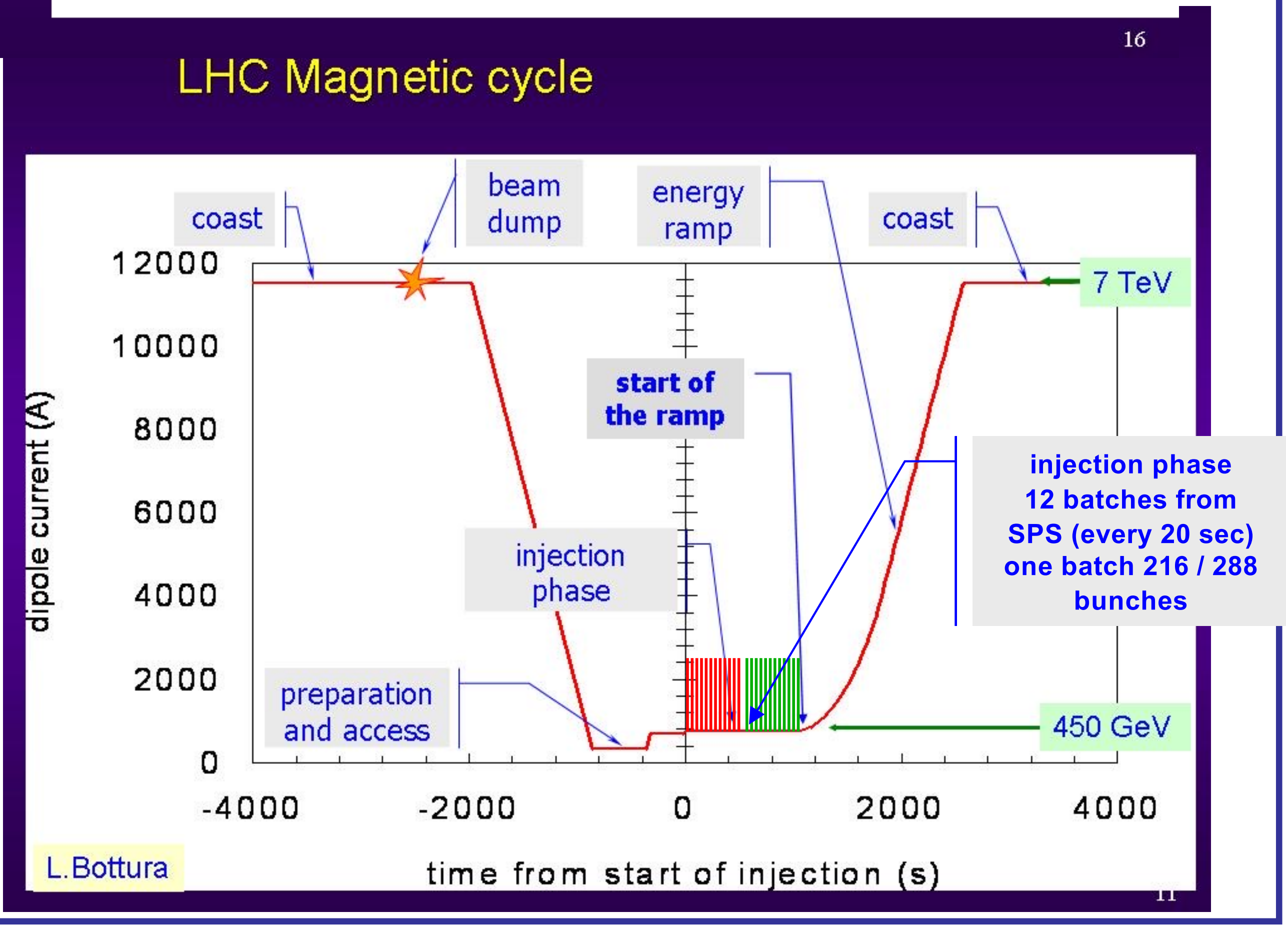
- at 7 TeV: I_{max} = 11850 A; magnetic field = 8.33 T
- weight = 27.5 tons
- length = 15.18 m at room temperature (T), ~10 cm shorter at operating T (1.9 K)
- acceptable loss limit (prevent ΔT > 2 K): 10 mW/cm^3



To limit T increase at quench:

- distribute energy evenly in magnet by force-quenching
- switch off magnet << 1 s

Current taken by a ”bypass diode” capable of withstanding 12 kA for 150 s

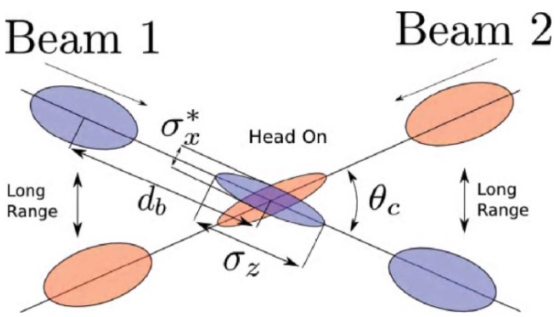


LHC summary

$\mathcal{L}_{peak} \approx 2.1 \cdot 10^{34}$ cm^{-2} s^{-1}

$$\mathcal{L} = \frac{N^2_{\text{part/bunch}}\, f\, N_{\text{bunch}}}{4\pi\sigma^*_x\sigma^*_y} F$$

$$F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2 \cdot \sigma^*}\right)^2}$$



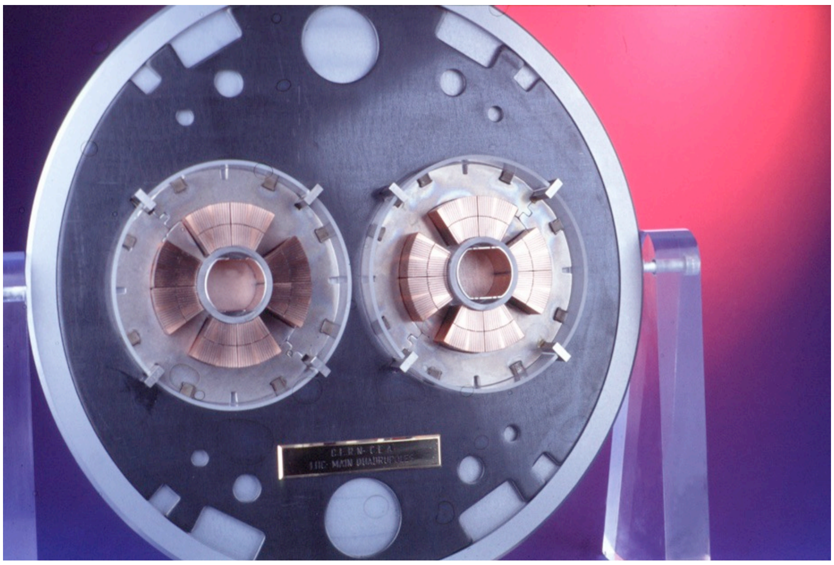
2024 numbers:

Luminosity	
Particle per bunch	$1.4 - 1.6 \cdot 10^{11}$
Bunches	2350
Revolution frequency	11.245 kHz
Crossing rate	40 MHz
Normalised Emittance	2.3 - 2.9 μm rad
β-function at the collision point	0.3 m
RMS beam size @ 7 TeV at the IP1-5	11 μm
Circulating beam current	0.52-0.59 A
Stored energy per beam	410 MJ

LHC luminosity calculator:
https://lpc.web.cern.ch/lumiCalc.html

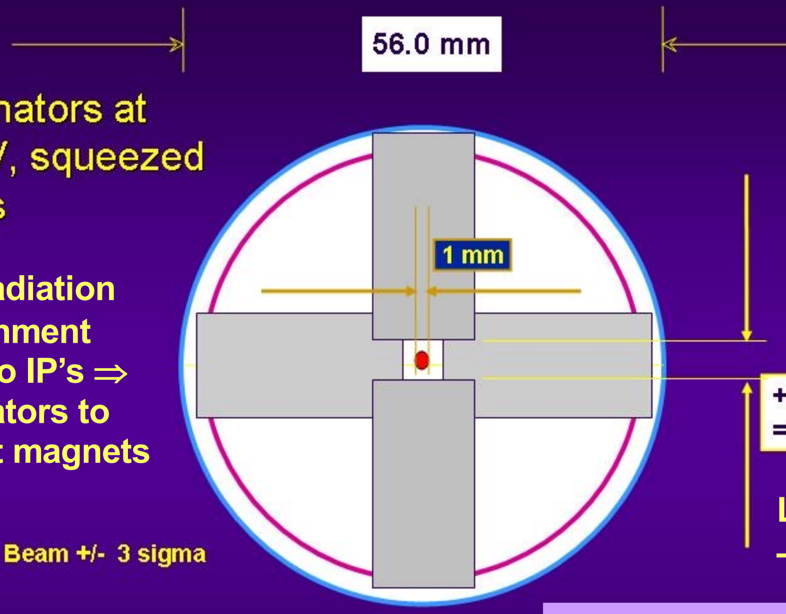
Quadrupoles also two-in-one design

- at 7 TeV: I_{max} = 11850 A; gradient field = 225 T/m
- weight = 6.5 tons; length = 3.1 m



Collimators / beam dump

Collimators at 7 TeV, squeezed optics

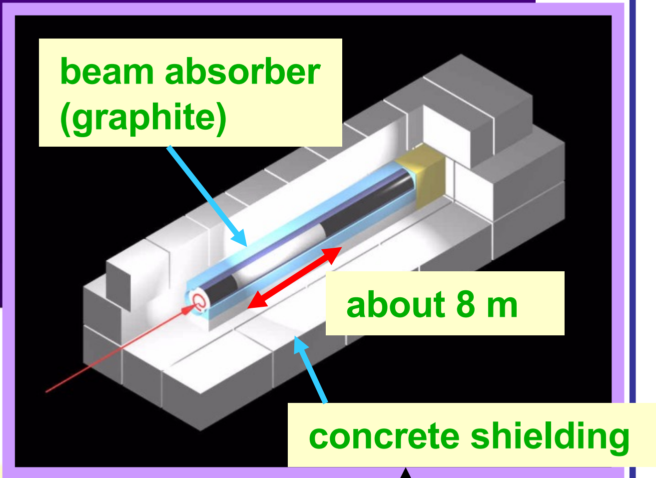


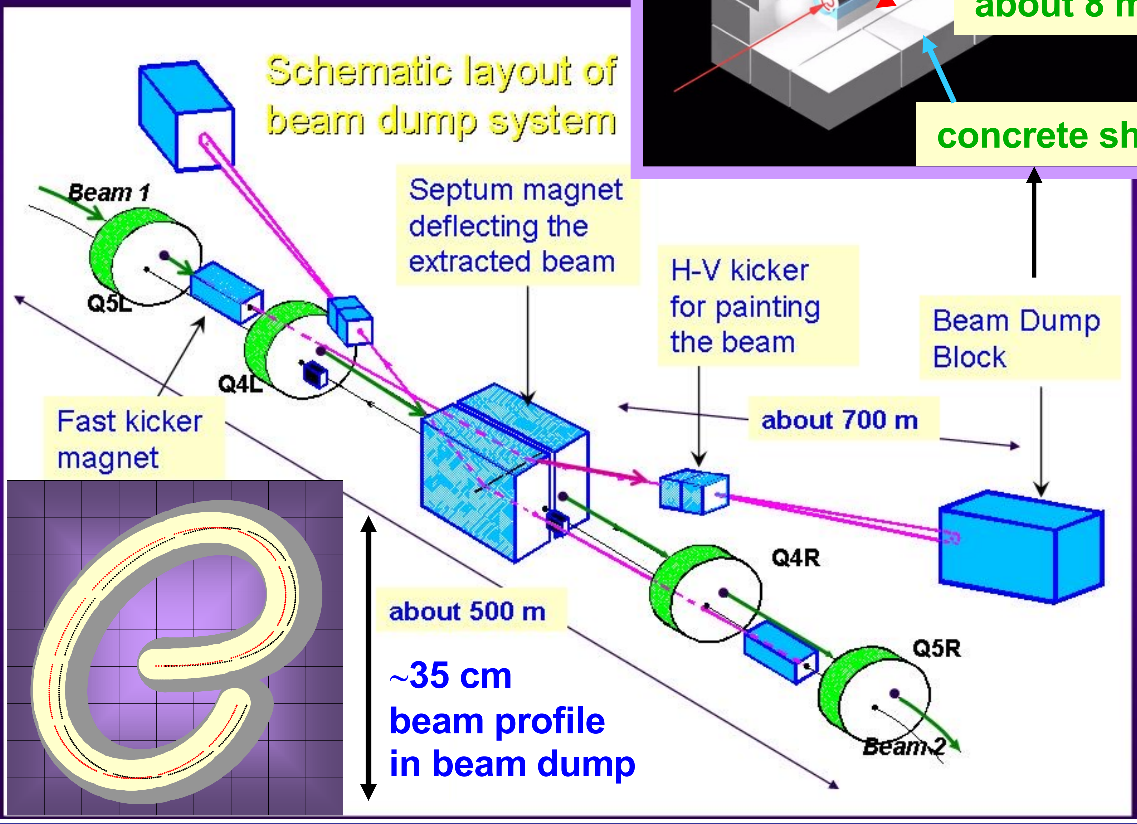
High radiation environment close to IP's ⇒ collimators to protect magnets

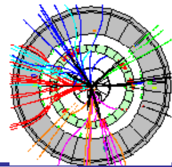
LHC collimators graphite – to limit impedance Z

Example: Setting of collimators at 7 TeV - with luminosity optics

Beam must always touch collimators first !







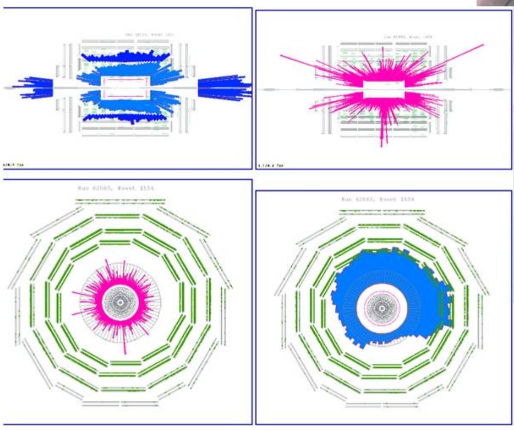
1. start

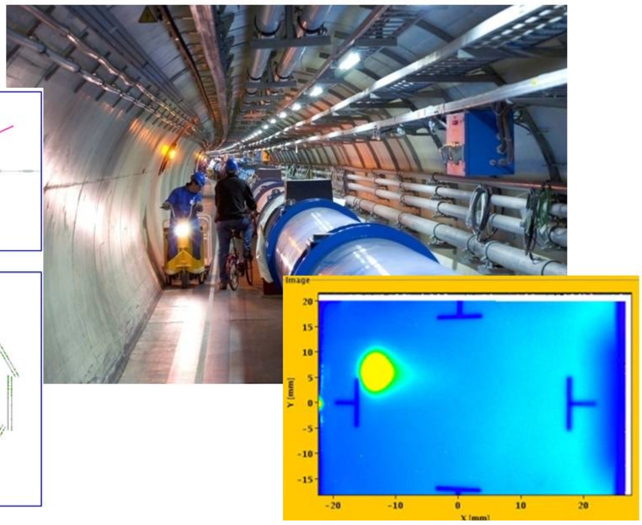
ILTA-SANOMAT

Hiukkaskiihdytin käynnistyi - ei maailmanloppua!

10.09.2008 10:43

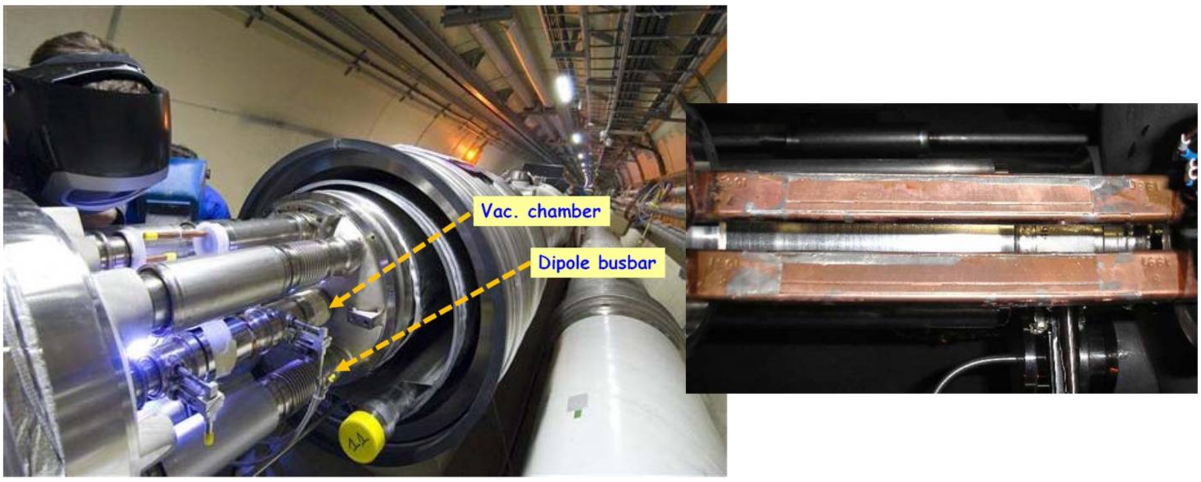
- **LHC start 10.9.2008 – first proton beams around the whole ring in both directions at different times (no collisions)**
- **19.9.2008 – electrical contact broken between two magnets → helium leak, big mechanical damage.**

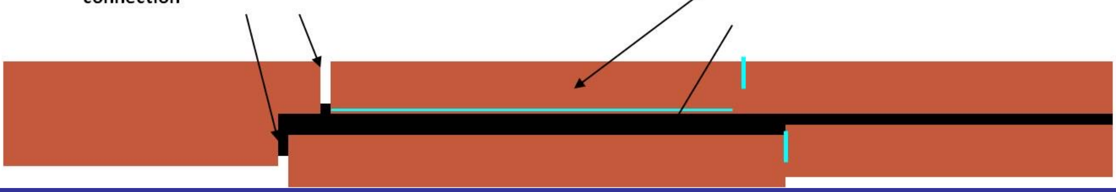




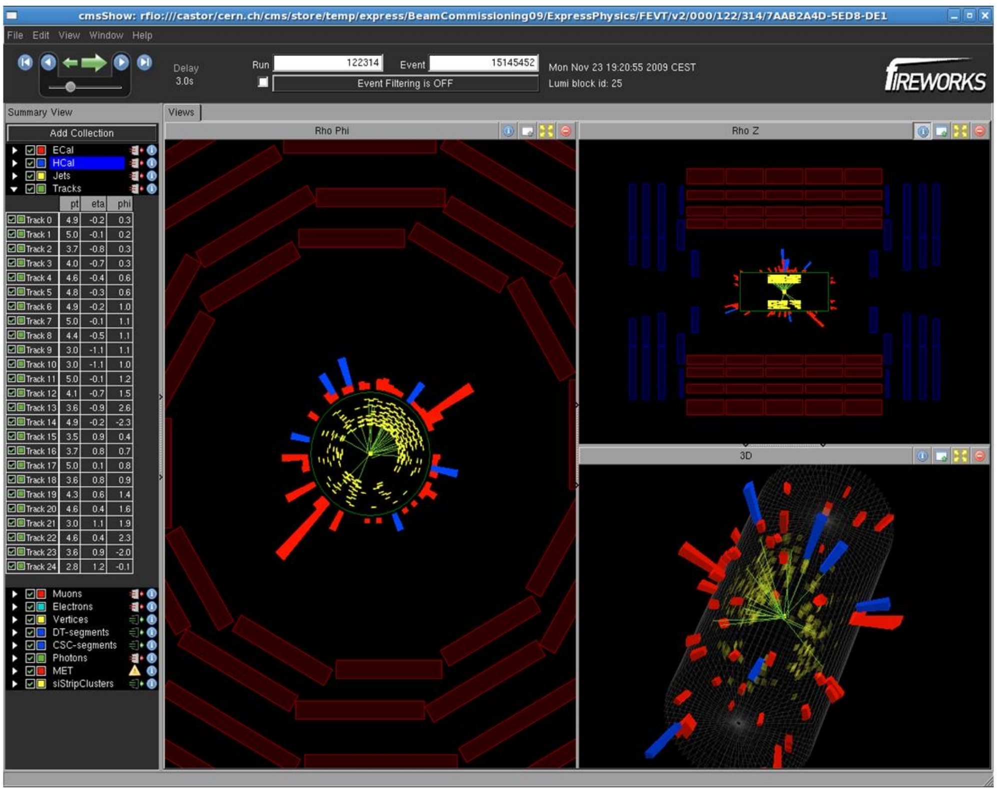
Sector 3-4 indicent 19th September 2008

Failure of busbar splice between one quadrupole and one dipole

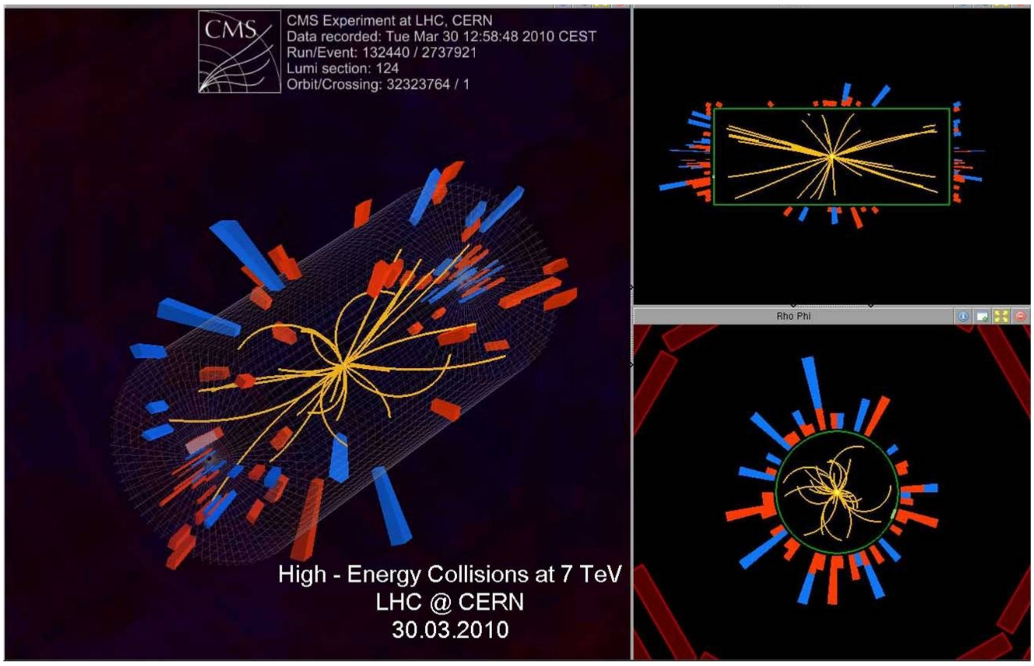




2. start: First proton proton collisions in CMS 23.11.2009



30.03.2010: 7 TeV proton proton collisions in CMS

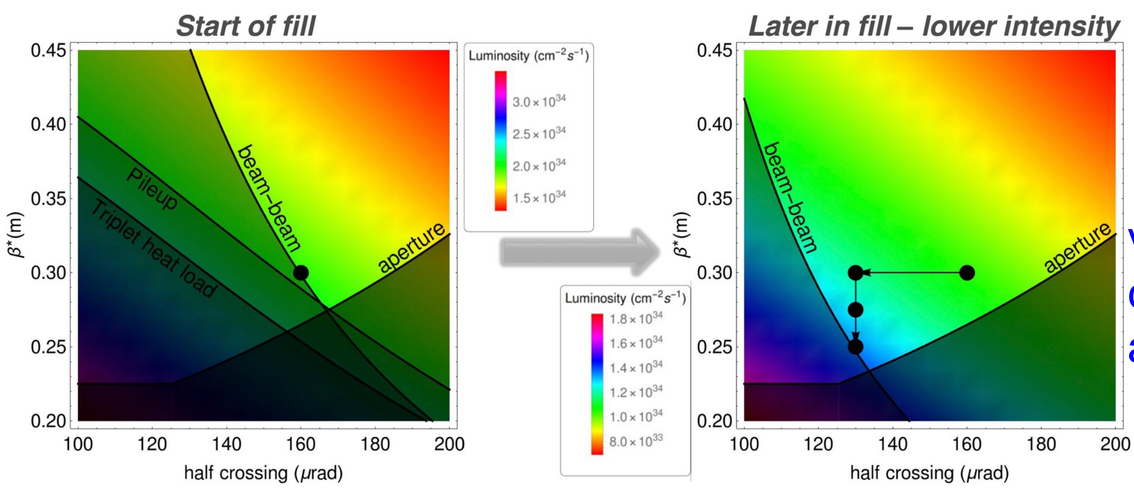


Constant improvement of luminosity by increasing N_{bunch}, $N_{\mathrm{part/bunch}}$ & decreasing β^* and increase of beam energy. Careful optimization of optics & beam parameters to get largest $\mathcal{L}_{\mathrm{integrated}}$. Regularly $\mathcal{L}_{\mathrm{peak}} \approx 2.1 * 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

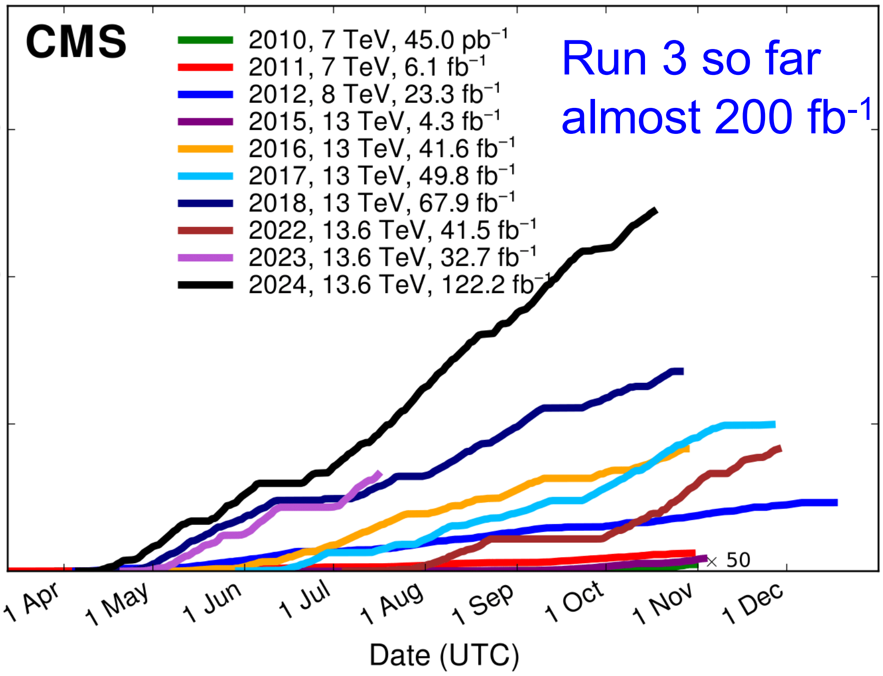
Optimized running scenario (2018)

- Changing both crossing angle and β* through leveling while in stable beams
- Scenario optimized under a number of constraints

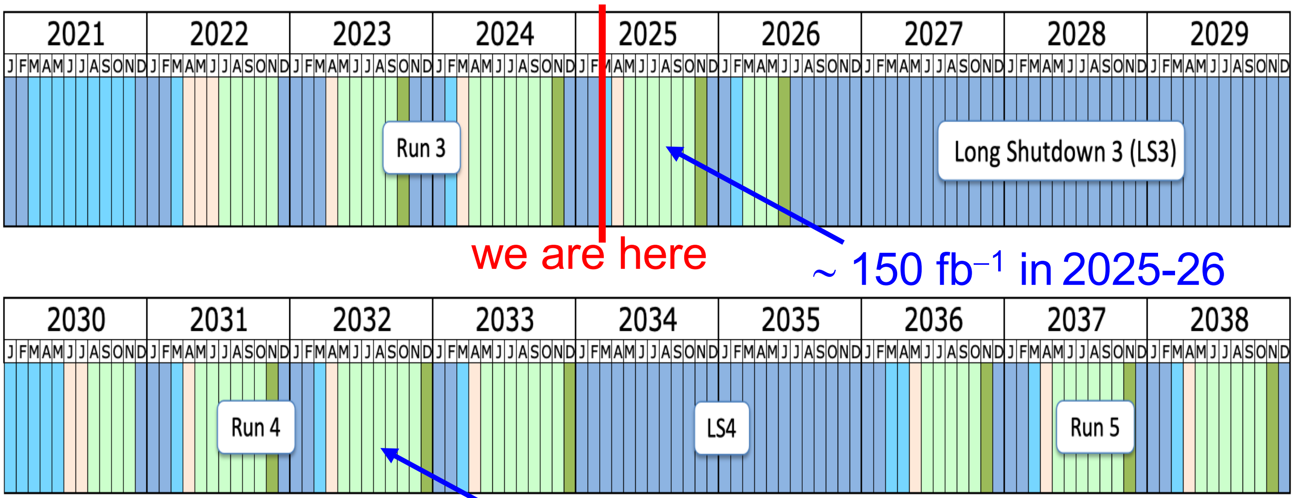
constraints: quadrupole triplet heating, pileup, beam-beam dQ, vacuum chamber aperture

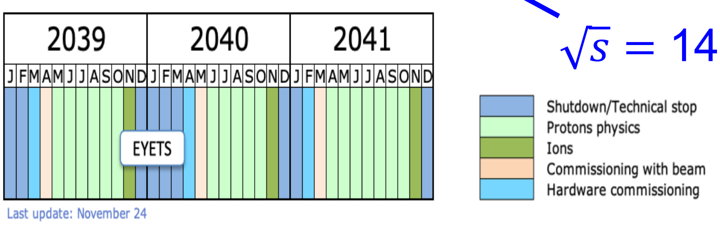


LHC has had Run 1 (2010-12) at $\sqrt{s}$ = 7 and 8 TeV and Run 2 (2015-18) at $\sqrt{s}$ = 13 TeV. Now Run 3 (2022-26) at $\sqrt{s}$ = 13.6 TeV is in full speed.



After Run 3 again a long maintenance period (LS3) to prepare for the next phase, high luminosity LHC (HL-LHC) with increased luminosity by factor ~ 4 in Run 4 (2030 →)



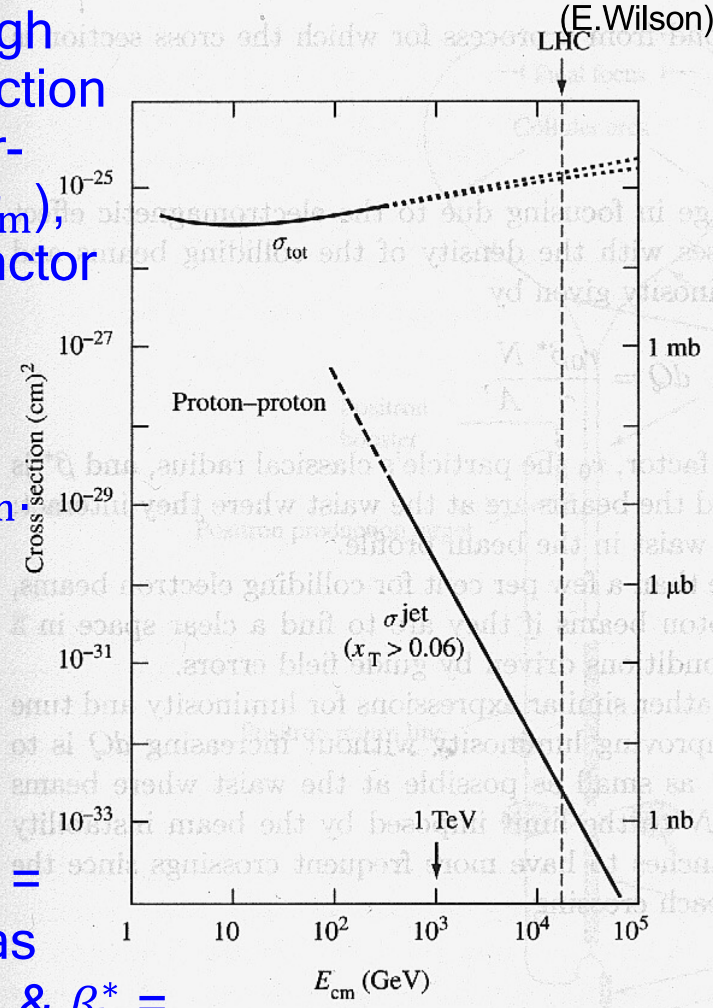


$\sqrt{s}$ = 14 TeV?

$\mathcal{L}_{\text{integrated}}^{2010-2041} \approx 3000$ fb^{-1} ?

Ultimate challenge to high energy colliders: production rate of "interesting" interactions fall as $1/s$ ($\propto E_{\rm cm}^2$), $\Rightarrow$ improve luminosity factor 100 for each factor 10 energy increase i.e. distance at which structures seen $\propto 1/E_{\rm cm}$.

(E.Wilson)



Event rate = $\mathcal{L} \cdot \sigma$

$\mathcal{L} = f_{\rm b} N_{\rm part/bunch}^2 / A$

= luminosity

Strategy for maximal luminosity: beam area A = $4\pi\sigma_x^*\sigma_y^* \propto \beta_{x,y}^*$ as small as possible $\Rightarrow$ minimaze $\beta_{\rm v}^*$ & $\beta_{\rm h}^*$ = vertical/horizontal β at interaction point (IP) & maximize bunch frequency $f_{\rm b}$ (= # of bunches × $f_{\rm rev}$) & $N_{\rm part/bunch}$

Often use more complete formula taking into account large differences in $N_{\rm part/bunch}$ in beam 1 & 2 e.g. $p\bar{p}$ colliders & in emittance of horizontal & vertical planes:

$$L(t) = \sum_{i=1}^{n_{bunch}^{colliding}} \frac{f_{rev} N_{part/bunch\,i}^{beam1}(t) N_{part/bunch\,i}^{beam2}(t)\gamma}{4\pi\sqrt{\varepsilon_{H,i}^*(t)\beta_H^*\varepsilon_{V,i}^*(t)\beta_V^*}} F \;,\; L_{\rm int} = \int L(t)dt$$

where factor F accounts for geometrical reduction due to non-perfect head-on collision & crossing angle at IP.

Threshold for antiproton ("$\bar{p}$") production from fixed target ~ 6 GeV. Usually proton energies ~25 GeV used with ~ 1000 protons needed to produce a $\bar{p}$. Only ~ 1/1000 of produced $\bar{p}$ within collectable angles & momenta ⇒ need intense proton bunches (10^{11-13}) & accumulate over ~10^5 bunches to make a $\bar{p}$ bunch (↔ few hours –1 day). $\bar{p}$'s must be stored in a small storage ring with large aperture & "cooled" not to immediate overflow aperture. Process called "cooling". Needed phase space reduction ~10^9.

Stochastic cooling (van der Meer 1972)

Transverse cooling of single particle. Transverse position measured by fast beam monitor & sent across accelerator to defecting plates correcting orbit by a kick (phase advance ~90°).

Momentum cooling of single particle. Pickup measures revolution frequency. If frequency too high, apply positive voltage on cavity when particle passes. If too low, apply negative voltage on cavity when particle passes.

(E.Wilson)

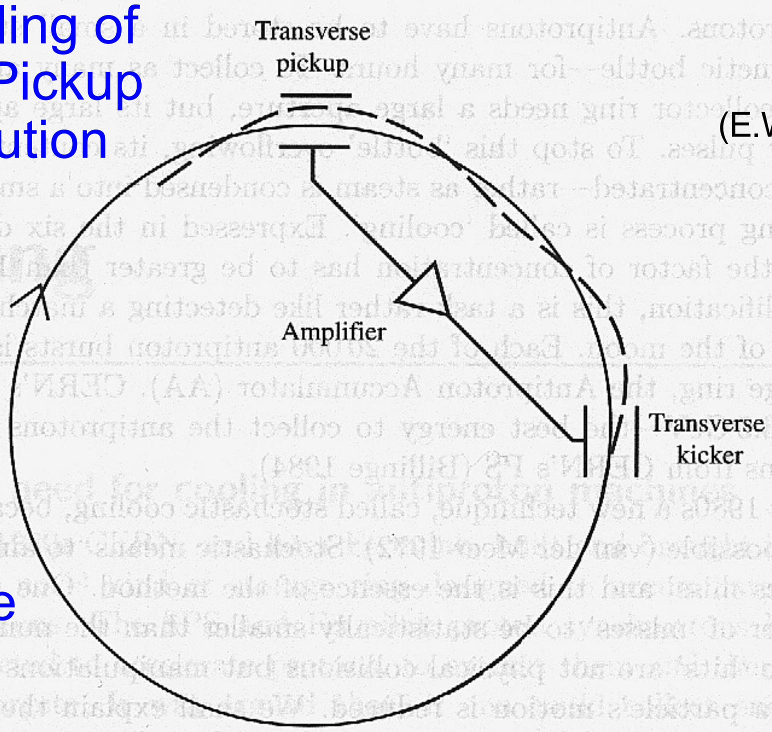
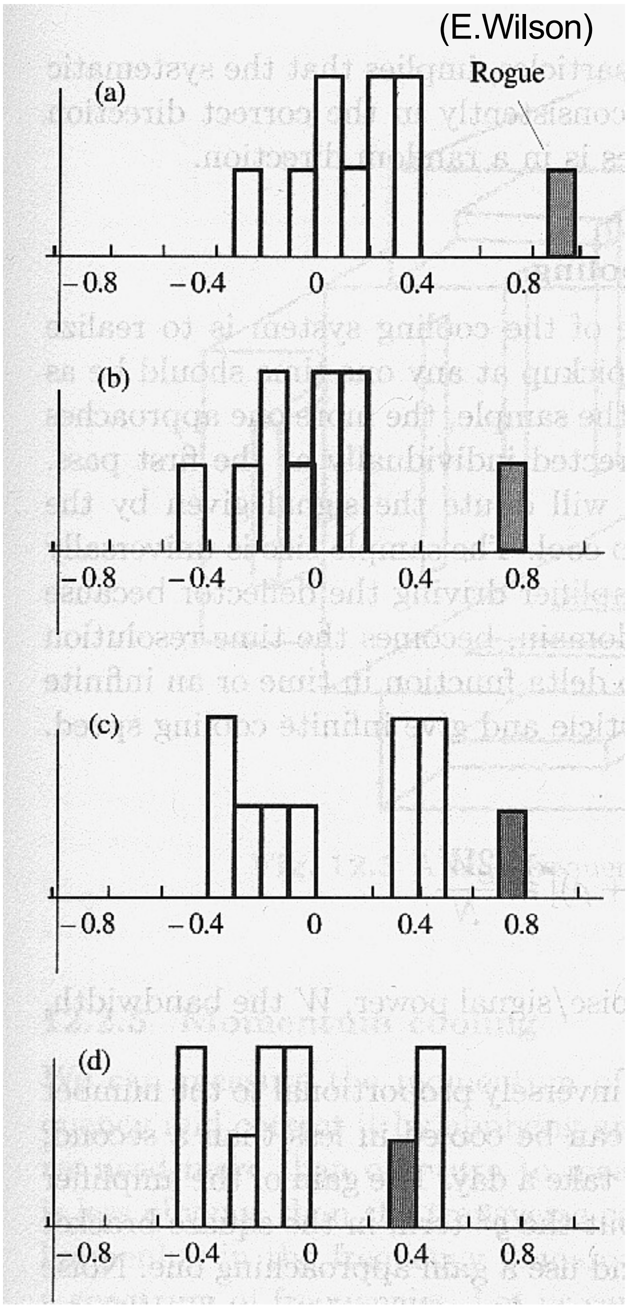


Fig. 12.1 Position pickup signal is amplified and used to deflect the particle.

What happens when one has many particles? Take average & correct according to that. Particles have different momenta & revolution frequency so samples will mix & on average correction for offset particles will go in right direction & for onset particles correction will be random. Key that slip factor η large & that pickup sample time short (# of particles seen by pickup small).



At the pickup:

After kick: rogue nearer center

After 1 turn: particle sample has changed due to mixing & a new correction is applied.

After many turns: now rogue centered after many kicks & mixings.

Electron cooling (Budker 1967)

Idea of electron cooling simple: a bunch of heavier particles, antiprotons/ions, travel through a constantly renewed electron beam with ~ same velocity so that ions transfers their energy to electrons (equipartition of energy). If electron velocity spread small, ion velocity spread becomes even smaller ($\propto$ 1/mass).

(E.Wilson)

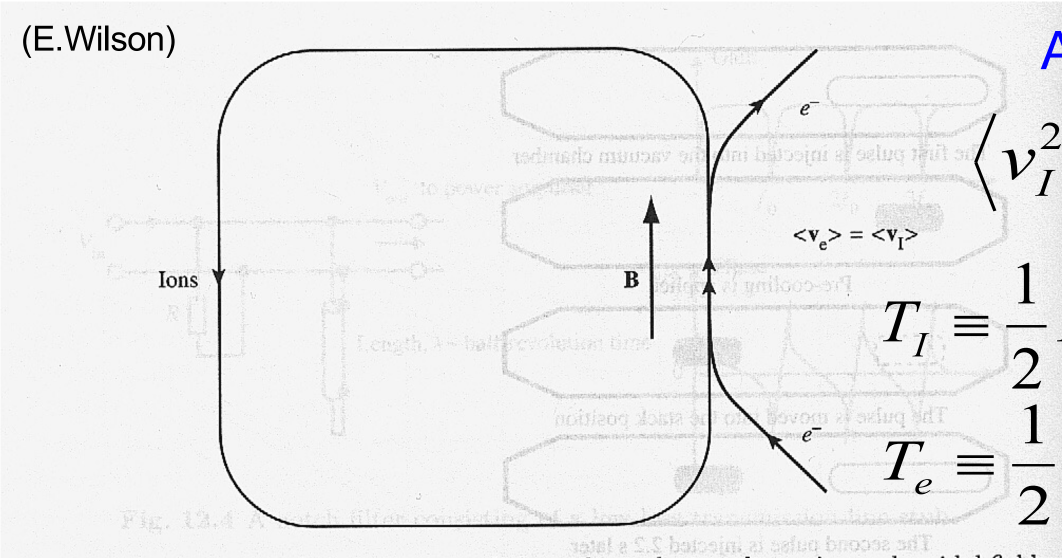


Fig. 12.6 Ions are cooled as they travel through an electron beam in a solenoidal field.

At start:

$$\left\langle v_I^2 \right\rangle \geq \left\langle v_e^2 \right\rangle$$

$$\Rightarrow$$

$$T_I \equiv \frac{1}{2} M_I \left\langle v_I^2 \right\rangle >$$

$$T_e \equiv \frac{1}{2} m_e \left\langle v_e^2 \right\rangle$$

At equilibrium: $T_I \approx T_e \Rightarrow \sigma_v^I = \sqrt{\left\langle v_I^2 \right\rangle} = \sqrt{\frac{m_e}{M_I}} v_e^{rms}$

$$\approx v_e^{rms} / 43\sqrt{A}$$

Electron cooling apparatus. Electron cooling faster than stochastic but needs to be done at a rather low momentum.

(E.Wilson)

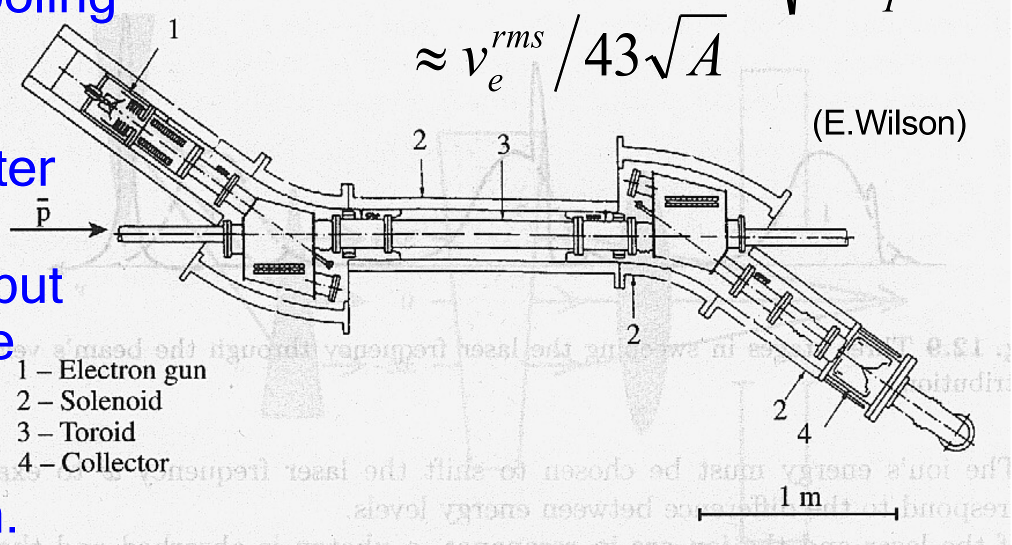


Fig. 12.7 Electron cooling apparatus.

Muon collider of a few TeV a competitive option for a future lepton collider. At those energies muon decay delayed to several tens of ms.
Contrary to electrons, muons not limited by synchrotron radiation.

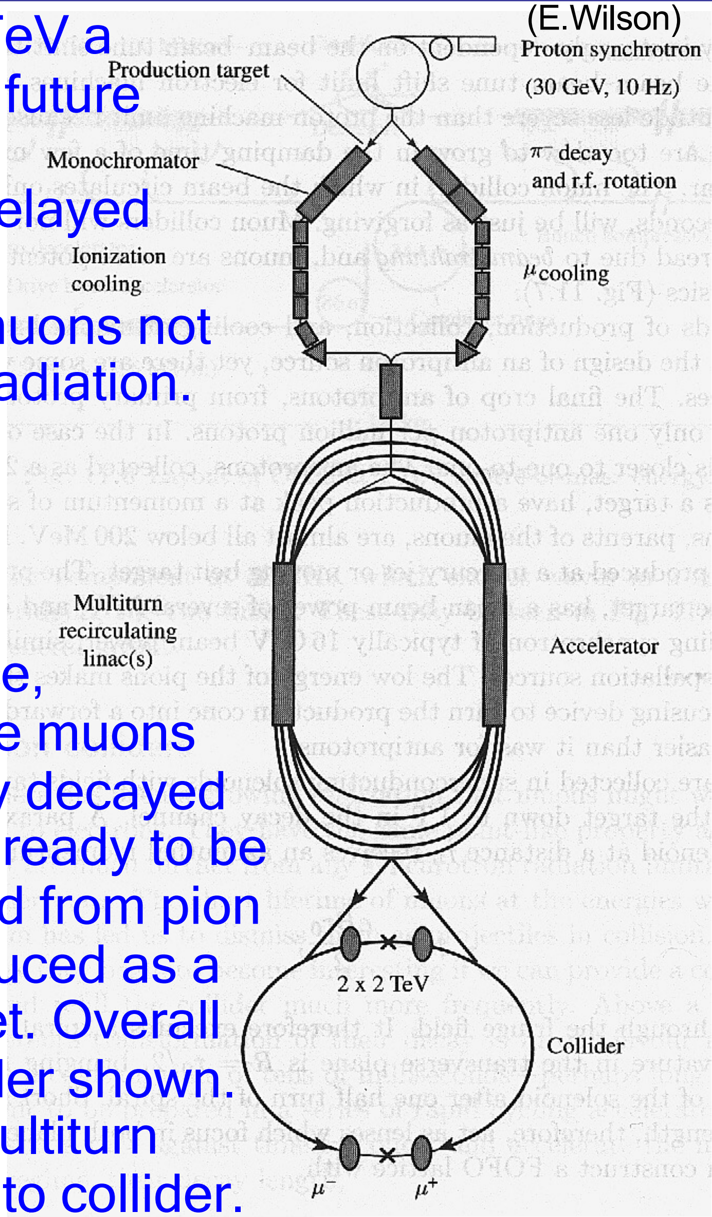
$$\tau_\mu[\mathrm{ms}] = 20.8\,p[\mathrm{TeV/c}]$$

muon decay length:

$$\lambda_\mu[\mathrm{km}] = 6233\,p[\mathrm{TeV/c}]$$

Key is to be fast: produce, cool, accelerate & collide muons before decay. Once they decayed have another bunch set ready to be injected. Muons obtained from pion decay in flight, lots produced as a proton beam hits a target. Overall scheme of a muon collider shown. Muons accelerated in multiturn linacs before injection into collider.

(E.Wilson)



(E.Wilson)

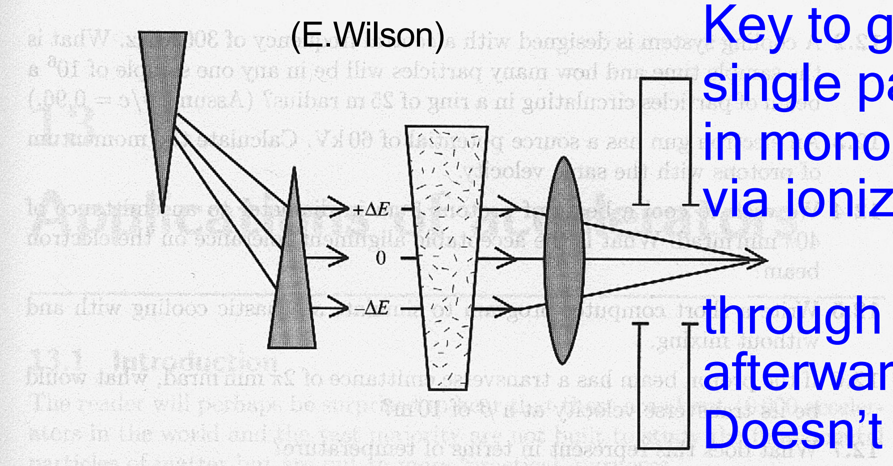
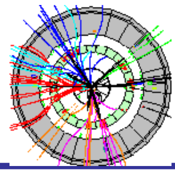


Fig. 12.10 Ionization cooling of a dispersed beam at an absorbing wedge followed by re-acceleration.

Key to good luminosity: single pass cooling;rough in monochromator & finer via ionization cooling, i.e. making beam go through thin absorbers & afterwards accelerate it. Doesn't work for hadrons or electrons.

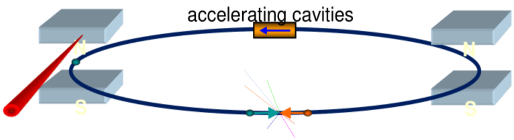


Circular vs linear collider

Circular Collider

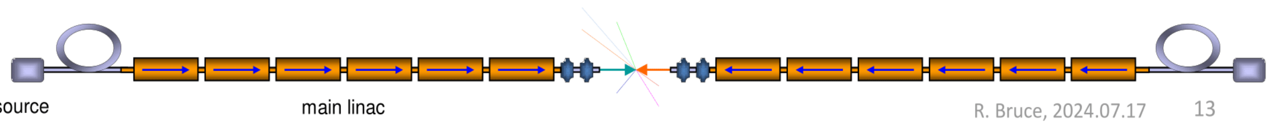
- multi-pass => Accelerate beam in many turns, let beam collide many times
- many magnets, few accelerating cavities
- Bending of beam trajectory => synchrotron radiation losses important for light particles

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



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



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Increasing beam energy

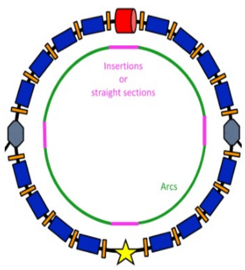
Circular Collider

- 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 F. Asvesta)

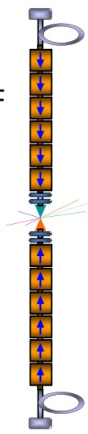


For protons:

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

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

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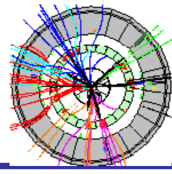


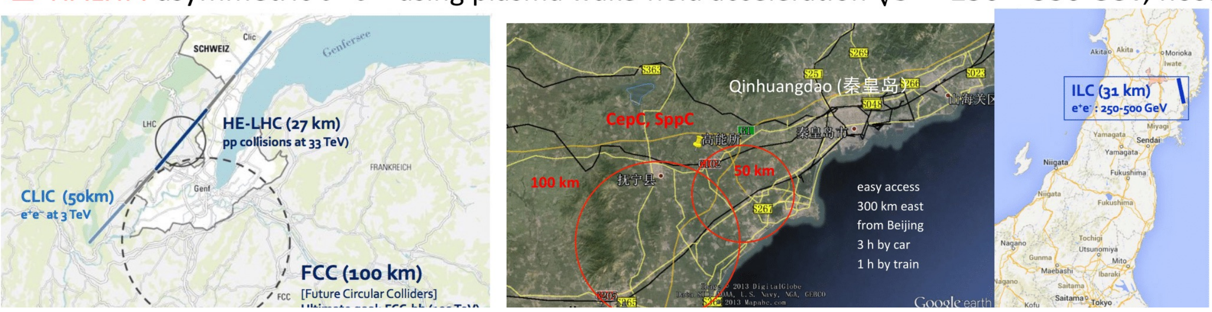
Next high energy frontier machine candidates

Circular colliders:

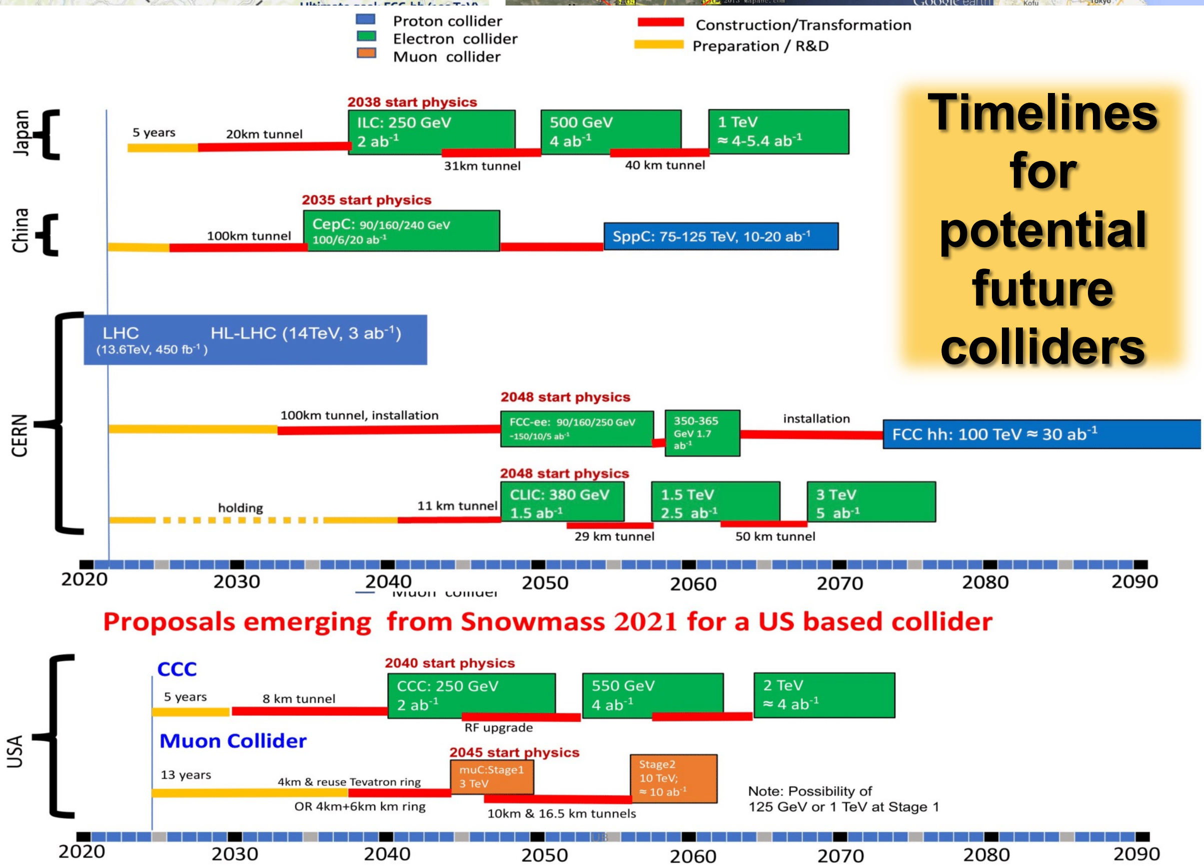
- FCC (Future Circular Collider), CERN hosts
  - FCC-hh: $\sqrt{s}$ = 80 - 115 TeV proton-proton collider, ion operation possible
  - FCC-ee: First step $\sqrt{s}$ = 90 – 365 GeV e^+e^- collider
- CEPC (Circular Electron-Positron Collider): e^+e^- $\sqrt{s}$ = 90 – 360 GeV, China hosts
- SppC (Super proton-proton Collider): proton-proton $\sqrt{s}$ = 75 - 125 TeV, China hosts
- Muon collider: $\mu^+\mu^-$ $\sqrt{s}$ = 3 - 10 TeV, US hosts

Linear colliders:

- ILC (International Linear Collider): e^+e^- $\sqrt{s}$ = 250 – 500 GeV, Japan hosts
- CLIC (Compact Linear Collider): $e^+e^-$$\sqrt{s}$ = 250 GeV - 3 TeV, CERN hosts
- CCC (Cool copper collider): $e^+e^-$$\sqrt{s}$ = 250 GeV - 2 TeV, US hosts
- HALHF: asymmetric e^+e^- using plasma wake-field acceleration $\sqrt{s}$ = 250 – 550 GeV, host?

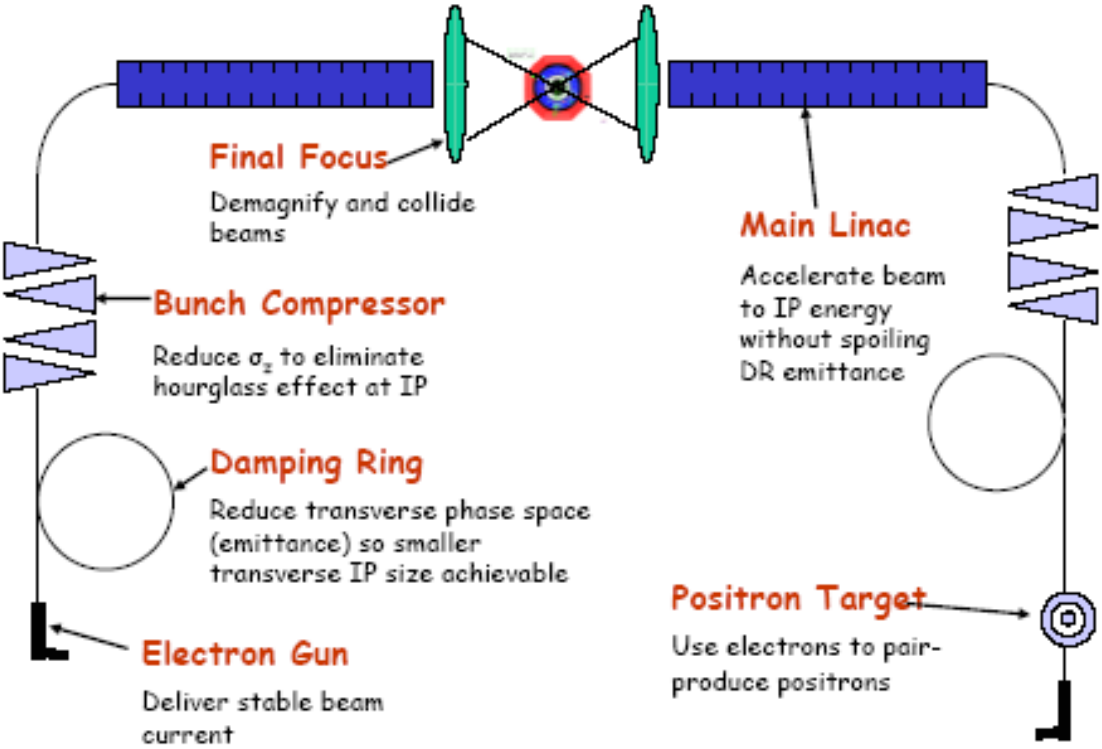


Timelines for potential future colliders



Circular electron-positron colliders near their limits with LEP due to synchrotron radiation.Possible road forward is **a linear collider**, where e^- from one linac collide with e^+ (target produced by e^- beam) from another linac head-on.

Generic linear collider:



Contrary to circular colliders in a linear collider a fresh batch of particles accelerated for each encounter ⇒ continuously renewed beam power, high RF system efficiency & large voltage gradients in accelerating cavities to reduce linac lengths (< ~20 km) ⇒ high-frequency linac structures to minimize stored energy & maximize accelerating gradient ⇒ much smaller accelerating cavities ⇒ more sensitive to instabilities.

Moreover develop RF power sources at frequencies far beyond those used for modern telecommunication.

Linear collider luminosity: $\mathcal{L} = \frac{N^2_{\text{part/bunch}}\, f_{\text{rep}}\, N_{\text{bunch/train}}}{4\pi\sigma^*_x\sigma^*_y} F_{LC}$

where f_{rep} repetition frequency (of bunch trains) & F_{LC} geometrical beam–beam enhancement factor ~ 2. To limit power consumption f_{rep} = few – 100 Hz (↔ LEP: ~ 44 kHz) ⇒ sufficient high L requires nm size beams !! (LC: $\sigma_x\sigma_y \approx$ (60–500) × (1–5) nm² ↔ LEP: $\sigma_x\sigma_y \approx$ 130 × 6 μm²)

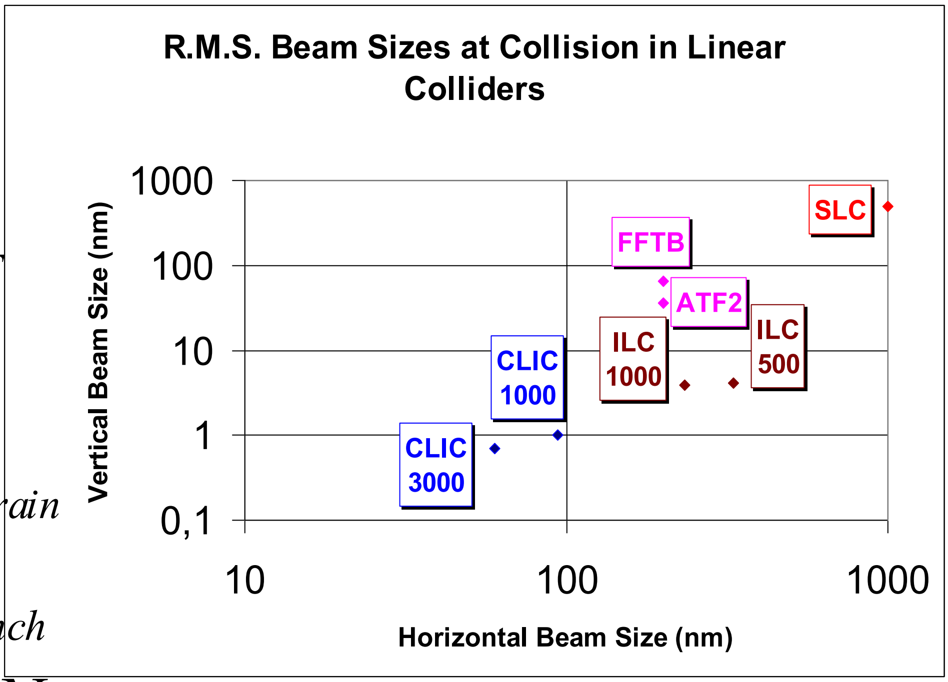
beam–beam effects:

–strong self-focusing in electric field of opposing bunch.

–strong photon emission (”beamstrahlung”) ⇒ smearing of collision energy, reduced by very flat beams ($\sigma_x \gg \sigma_y$).

beam power:

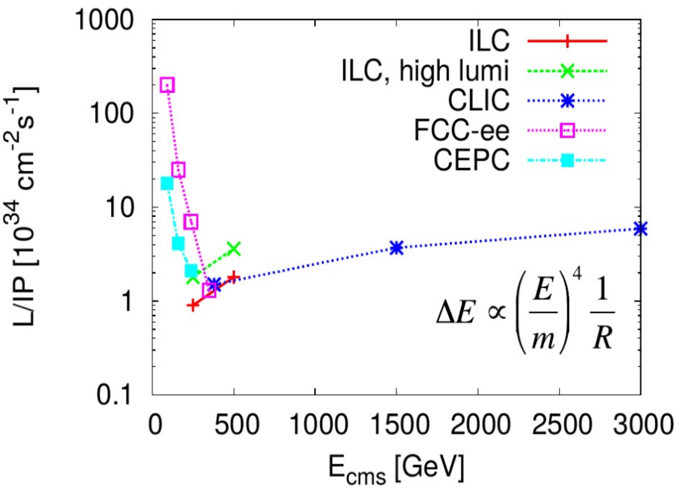
$$P_{beam} = P_{plug}\,\varepsilon_{plug\to RF} \cdot \varepsilon_{RF\to beam} = f_{rep}\, n_{bunch/train} \cdot E_{cm} N_{part/bunch}$$



$$\Rightarrow L = \frac{P_{beam} N_{part/bunch}}{4\pi\sigma_x\sigma_y E_{cm}} F_{LC} \Rightarrow$$ luminosity & energy limited by available power & efficiency to feed electrical power to beam. Electrical power at most a few hundred MW. $\varepsilon_{\text{plug}\to\text{RF}} \approx$ 30 – 40 % & $\varepsilon_{\text{RF}\to\text{beam}} \approx$ 20 – 60 % (CLIC 2–beam scheme ~ 95 %).

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 radiation



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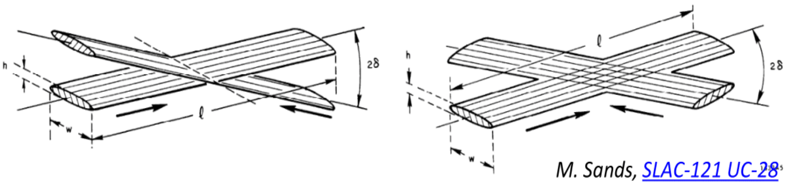
Flat beams in lepton colliders

- Naturally smaller vertical beam size from radiation damping
  - Often true also for linear colliders due to horizontal bending in damping rings, transfer lines etc.
- 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
- To avoid energy spread and keep luminosity high: collide "flat" beams, with much smaller beam size in one plane



M. Sands, SLAC-121 UC-28

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

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

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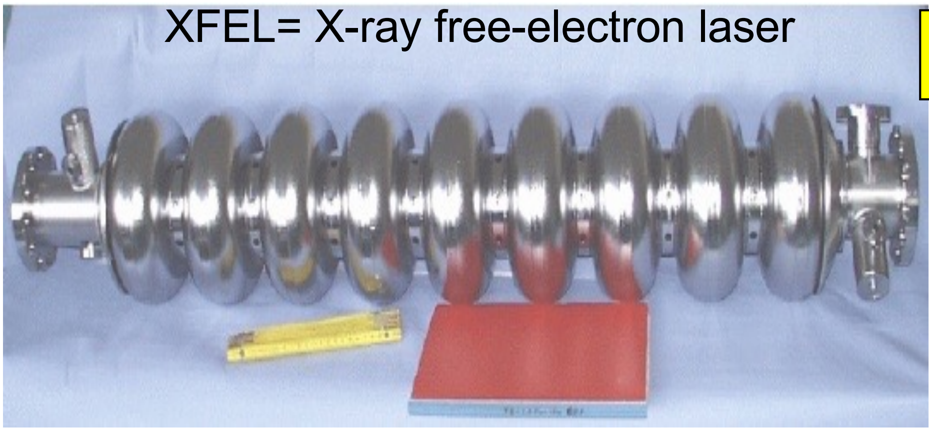
International Linear Collider (ILC) core technology: 1.3 GHz superconducting RF cavity also used for European XFEL (currently in operation). Cavities installed in a cryo-stat cooled at 2 K & operated at gradient 31.5 MV/m.



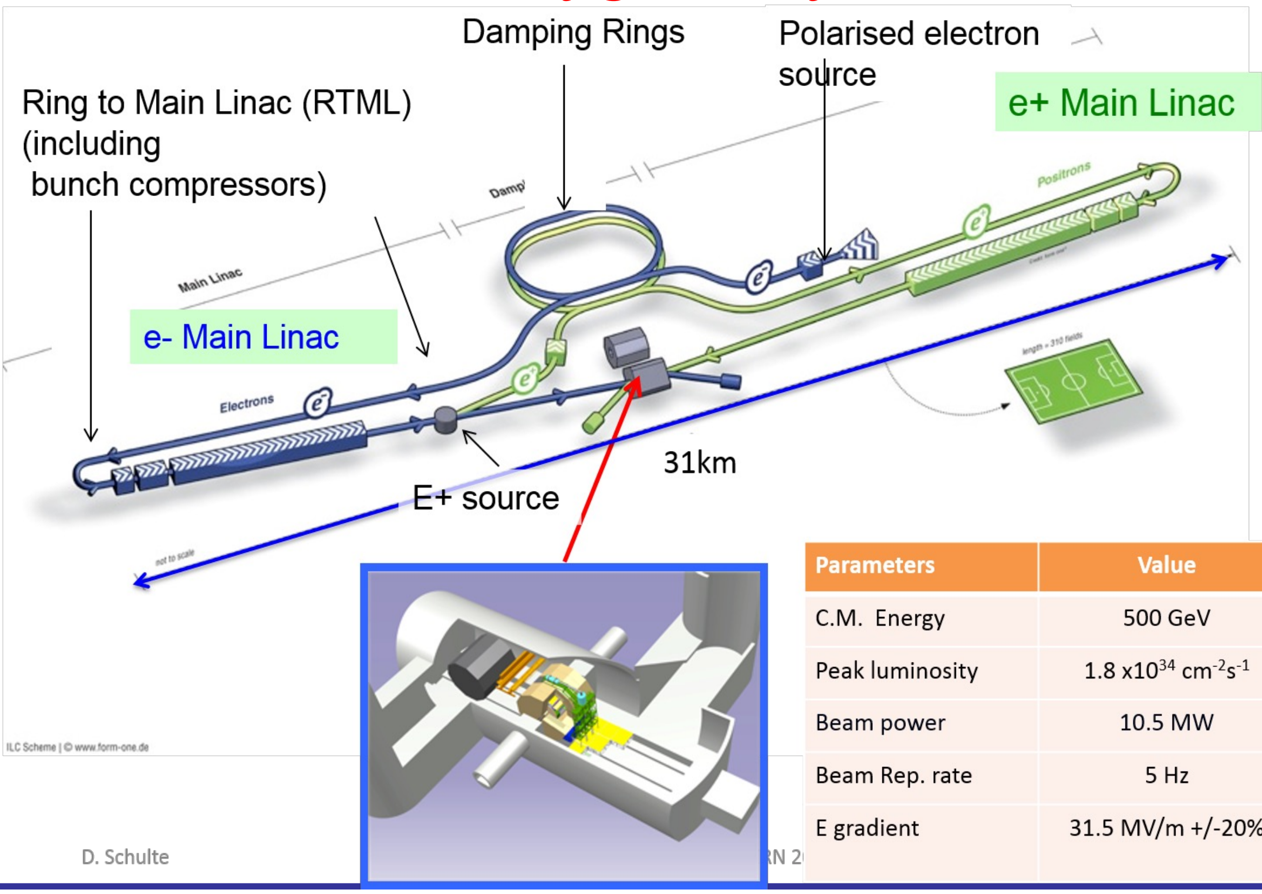
8000 cavities

Technology ready for construction

web-site https://ilchome.web.cern.ch

More info: https://www.nature.com/articles/s42254-019-0044-4

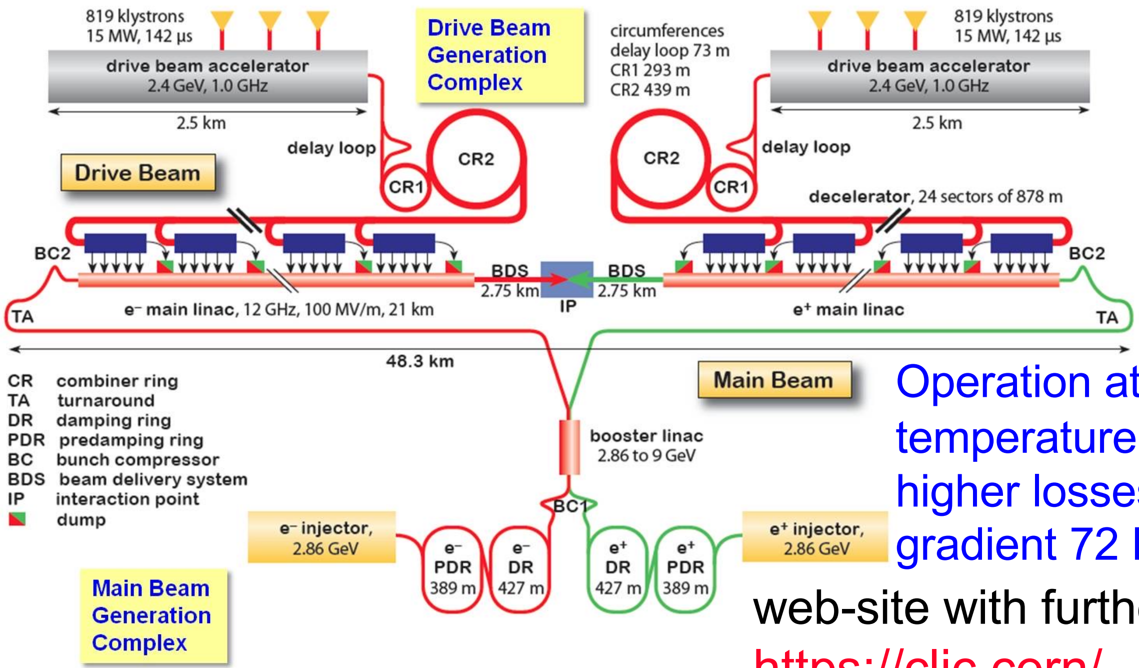
ILC Baseline Configuration for 500 GeV



Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Beam power	10.5 MW
Beam Rep. rate	5 Hz
E gradient	31.5 MV/m +/-20%

Compact Linear Collider (CLIC) Layout at 3 TeV

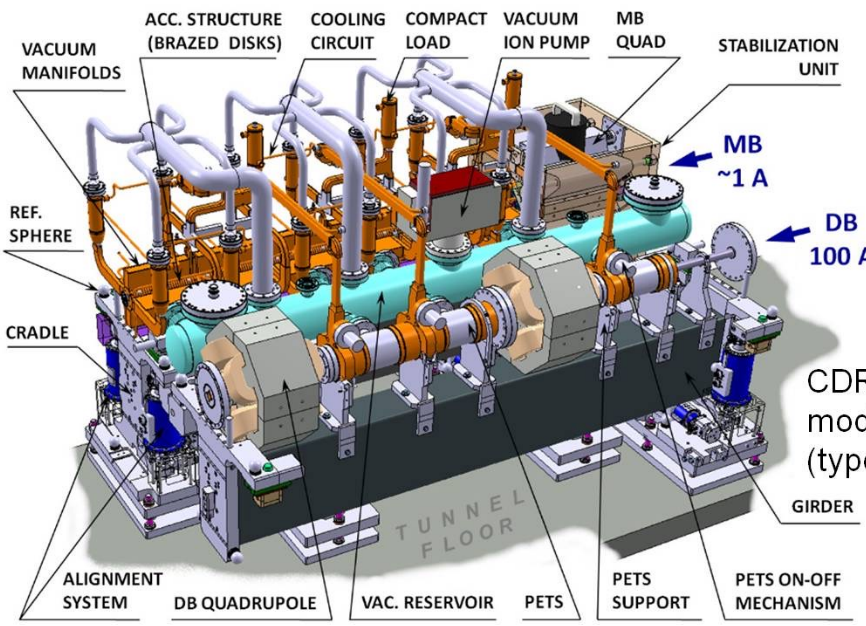
More info: https://www.nature.com/articles/s41567-020-0834-8



Operation at room temperature, despite higher losses higher gradient 72 MeV/m

web-site with further info: https://clic.cern/

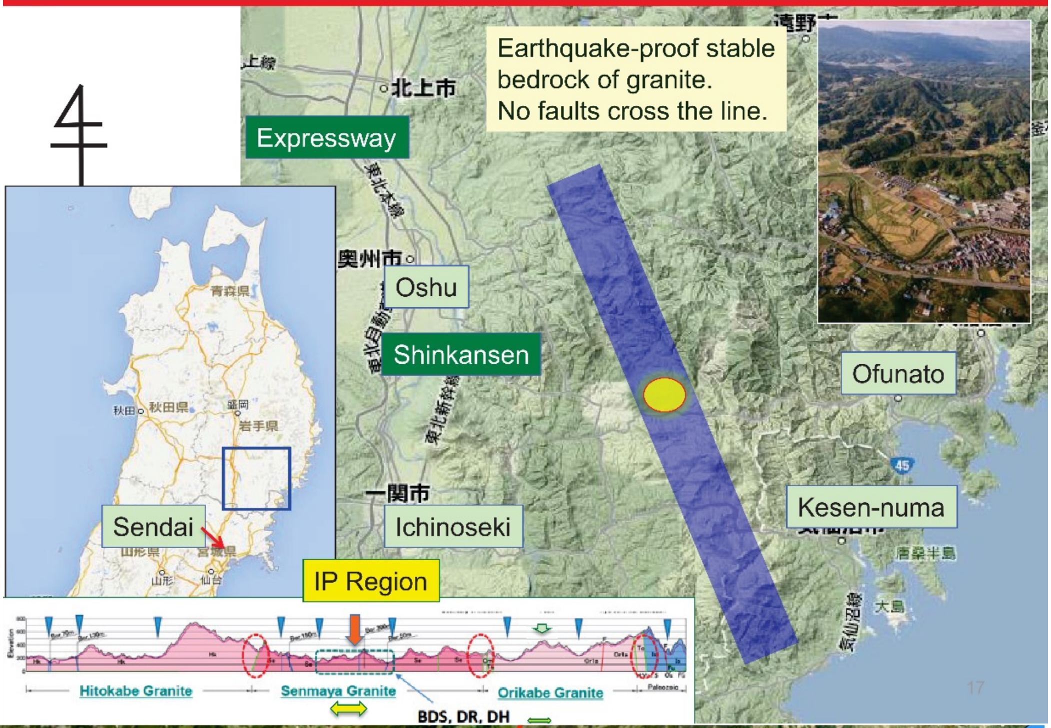
Key feature: 2-beam acceleration scheme; drive beam (DB) deccelerated to produce RF for main beam (MB) ≈ "transformer" (high current & low field → low current & high field)

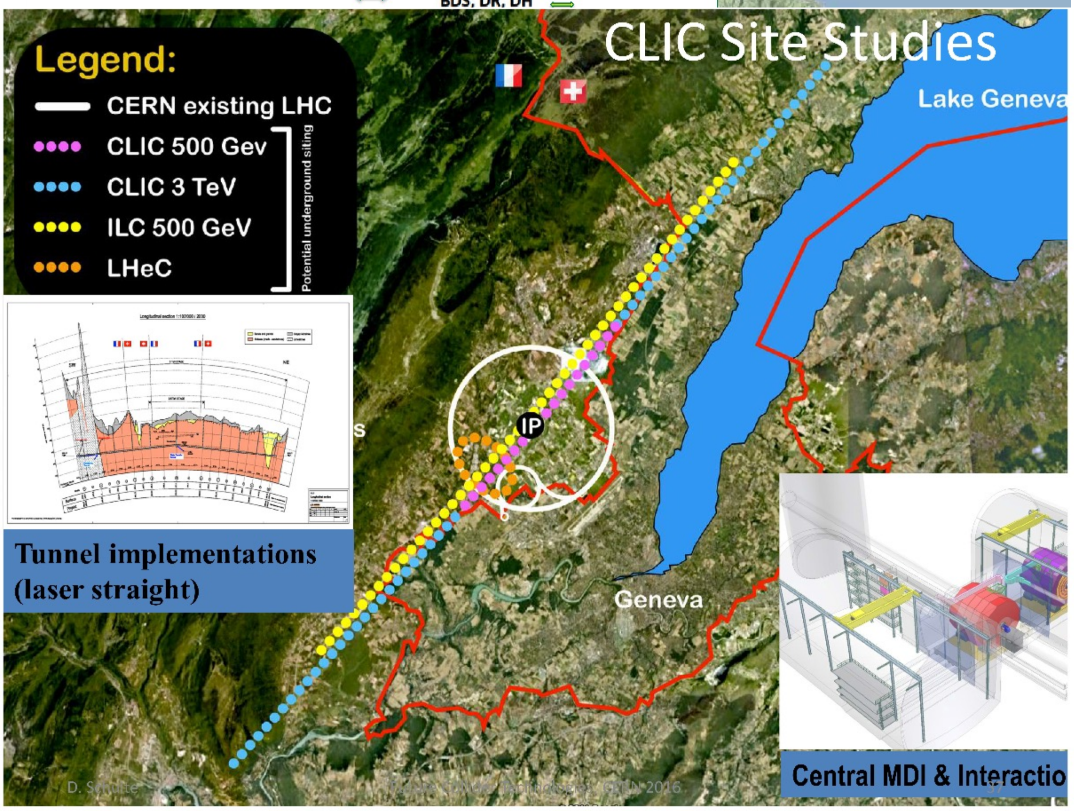


thermal power during operation ~7 kW/module

CDR CLIC two-beam module configuration (type 1)

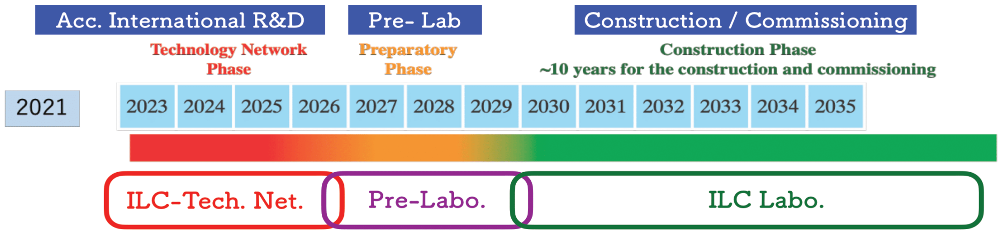
ILC Site Candidate Location in Japan: Kitakami





Compromise between the two technologies operating at ~80 K: “Cool Copper Collider” (C^3) developed in US

Time line for the ILC project



[Step-1] International Dialog w/ partners: to achieve a consensus of **Global Project**

- Importance of the project, Interest in Participation, ... among potential partners
- Guideline for Sharing Cost, Responsibility, Site Decision, ... etc. at the government level

[Step-2] based on [Step-1], international discussion to agree on **Realization of ILC**

International Physicists/Government discuss and decide the shape and site of ILC **as Global Project**

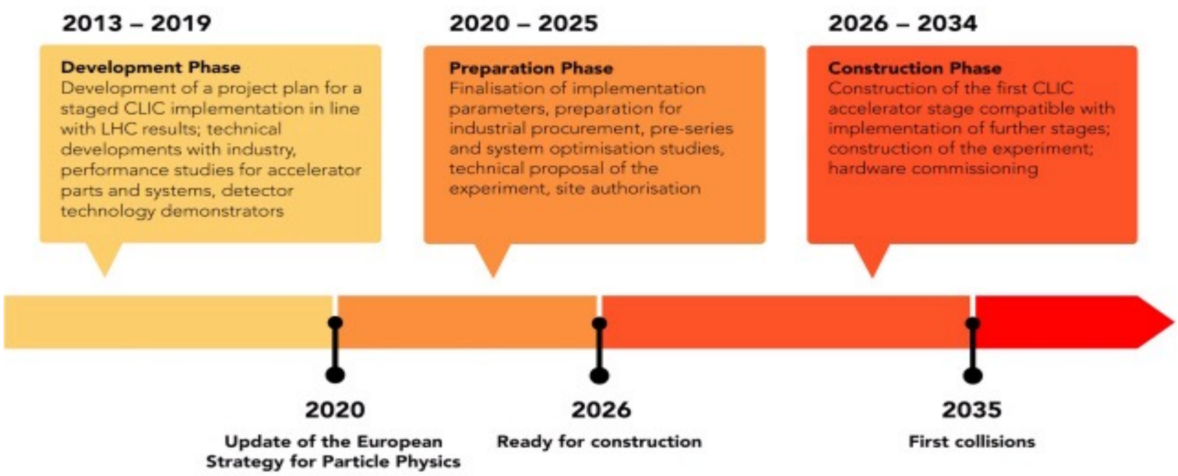
(a) e.g. ILC250 w/ one IP: quick start: lower cost, smaller footprint, ... (JAHEP Idea)

(b) e.g. other type of ILC, e.g. 2IP, starting from higher energy, etc.

(c) ...

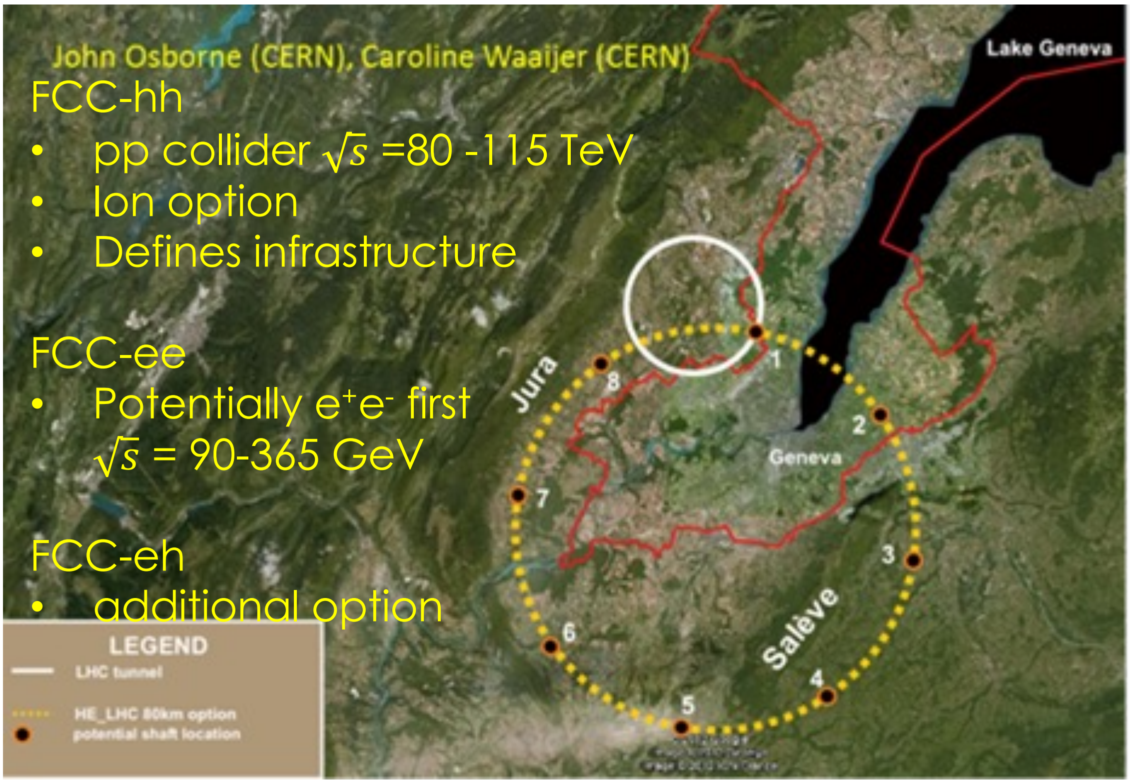
[Step-3] Once [2] starts → **Pre-Lab may be conceived, Further discussions/decisions for starting construction of ILC**

CLIC project time-line



No European decision yet: preparation phase postponed, currently continued CLIC technical development & optimization

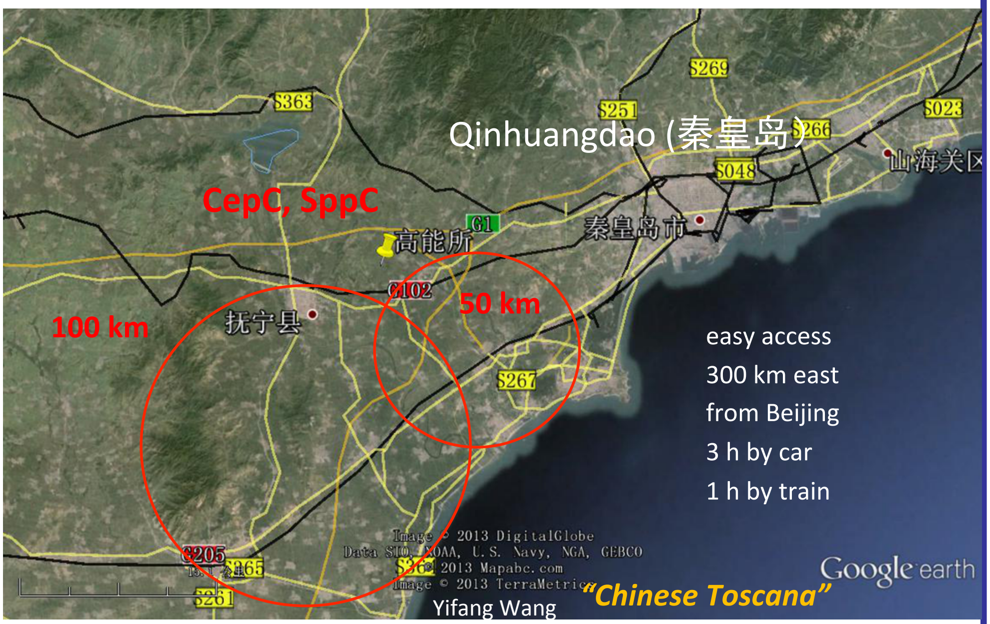
At CERN: FCC (Future Circular Collider):



In China: CEPC / SppC (Circular Electron Positron Collider, Super proton-proton Collider)

CEPC
- e^+e^- collider $\sqrt{s}$ = 90-360 GeV
- focus Higgs

SppC
- Hadron collider to later be installed in same tunnel
- $\sqrt{s}$ = 75-125 TeV



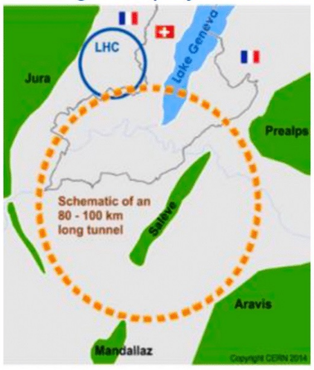
FCC program spanning until end of centary

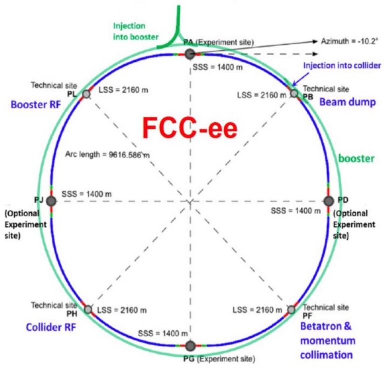
FCC integrated program

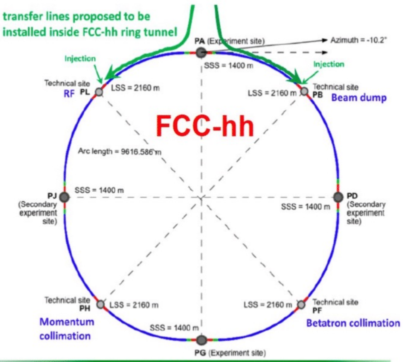
FUTURE CIRCULAR COLLIDER

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders (e.g. model-independent measurements of the Higgs couplings at FCC-hh thanks to input from FCC-ee; and FCC-hh as "energy upgrade" of FCC-ee)
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC







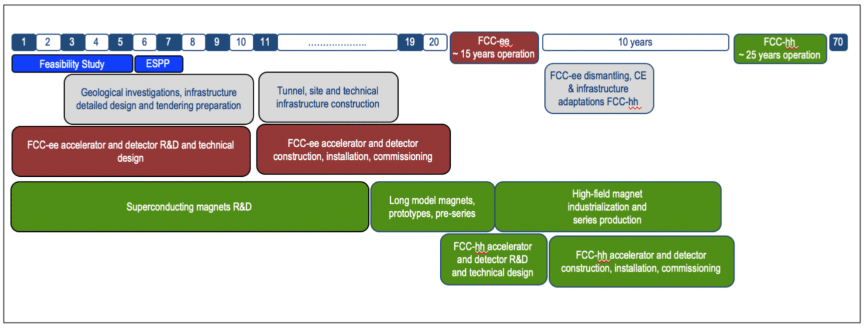
2020 - 2046 | 2048 - 2063 | 2074 -

FCC Feasibility Study Mid-Term Status
Michael Benedikt
RC, 2 February 2024

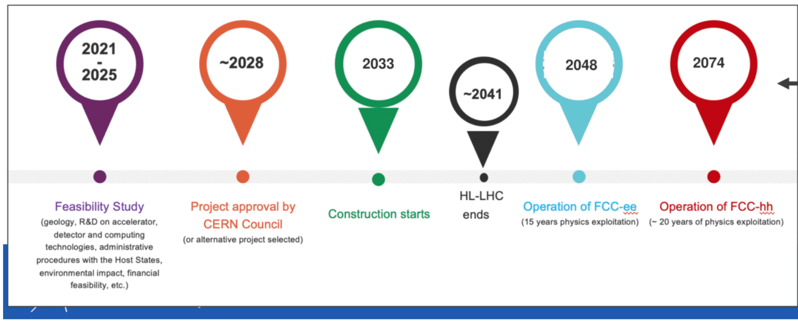
FCC decision ~2028 ⟹ an FCC-ee by 2048

FCC integrated program - timeline

FUTURE CIRCULAR COLLIDER

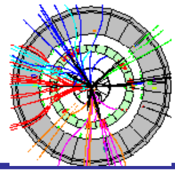


Note: FCC Conceptual Design Study started in 2014 leading to CDR in 2018



"Realistic" schedule taking into account:
- past experience in building colliders at CERN
- approval timeline: ESPP, Council decision
- that HL-LHC will run until 2041

Can be accelerated if more resources available



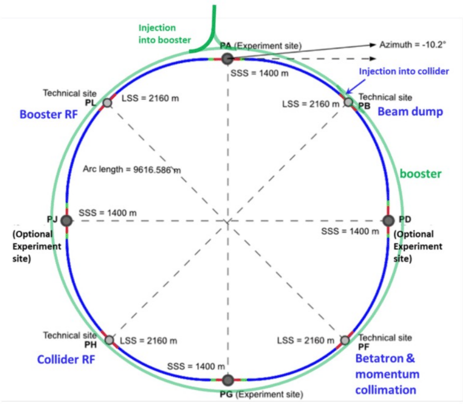
Optimized FCC: a 90.7 km tunnel ring

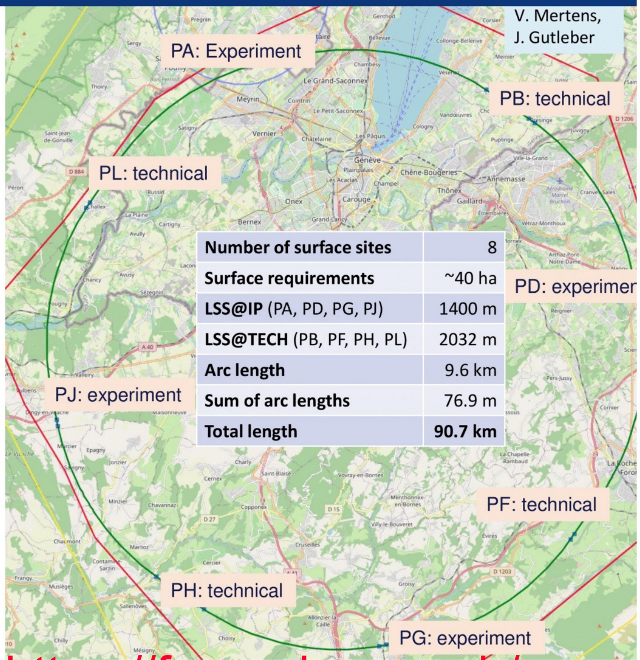
FUTURE CIRCULAR COLLIDER — Optimized placement and layout for feasibility study

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

"Avoid-reduce-compensate" principle of EU and French regulations

Overall lowest-risk baseline: 90.7 km ring, 8 surface points,
Whole project now adapted to this placement





Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

web-site with future info: https://fcc.web.cern.ch/

FCC-ee: > 10 x precision of LEP & HL-LHC

FUTURE CIRCULAR COLLIDER — FCC-ee: main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

Design and parameter dominated by the choice to allow for 50 MW synchrotron radiation per beam.

- x 10-50 improvements on all EW observables
- up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

F. Gianotti

FCC-hh: direct discoveries up to ~ 40 TeV

FCC-hh parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	81 - 115	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity $[10^{11}]$	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity $[10^{34}\ cm^{-2}s^{-1}]$	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP $[fb^{-1}]$	20000	3000	300

With FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies

Formidable challenges:
- ❑ high-field superconducting magnets: 14 - 20 T
- ❑ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ❑ stored beam energy: ~ 9 GJ → machine protection
- ❑ pile-up in the detectors: ~1000 events/xing
- ❑ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:
- ❑ Direct discovery potential up to ~ 40 TeV
- ❑ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ❑ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, $\mu\mu$)
- ❑ Final word about WIMP dark matter

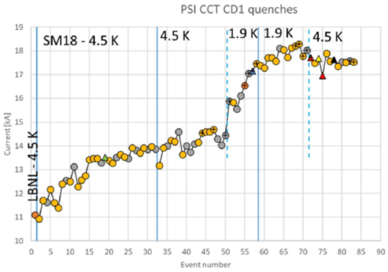
F. Gianott

More info: https://www.nature.com/articles/s41567-020-0856-2

FCC-hh: biggest challenge — high-field magnets

high-field magnets for FCC-hh: Nb_3Sn & HTS R&D

PSI Nb3Sn CCT «CD1» main test carried out in 2022/23



It trained *A LOT*. It reached 100% of maximum field at 4.5 K. No conductor degradation occurred from handling, assembly, powering, or thermal cycling.

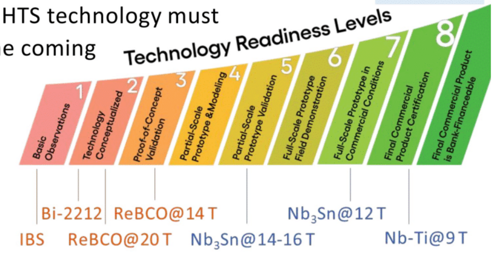
Stress-management works, CD1 is a robust magnet.

B. Auchmann

Rough estimates

Bottom line: HTS technology must catch over the coming 10 years in TRL to LTS

B. Auchmann

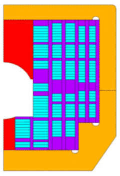


Next: FCC-hh SM-CC Demonstrator

Goal: demonstrate robust and cost-efficient Nb3Sn technology for next ESPPU.

Novel concept: Stress-managed and asymmetric common coils.

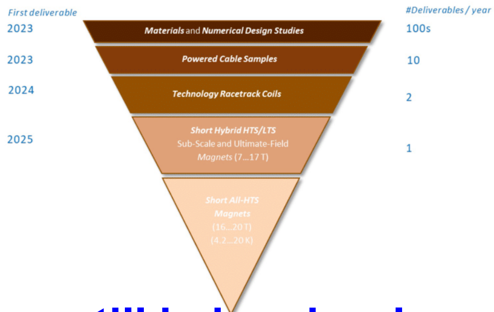
D. Araujo



Stainless steel shell
Iron yoke
Coil collar
Former
Non-magnetic poles
Nb_3Sn conductor

B_0 target of 14 T, at T_{op}: 4.2 K
Eng margin of 10%
B_0 short sample @ 1.9 K: 16 T

HTS Innovation Funnel for HFM



Technology still being developed

FCC: already a global endevour

FUTURE CIRCULAR COLLIDER

Status of FCC global collaboration

The CERN Council reviewed the work undertaken in a fruitful meeting on 2 February 2024. It congratulated and thanked all the teams involved in the study for the excellent and significant work done so far and for the impressive progress, and looks forward to receiving the final report in 2025.

FCC Feasibility Study: Aim is to increase further the collaboration, on all aspects, in particular, on Accelerator and Particle/Experiments/Detectors (PED).

How much does the fun cost & how pays?

FCC-ee cost and funding

FCC-ee construction cost up to operation at ZH : ~ 15 BCHF

F. Gianotti

Does not include upgrade to ttbar operation (~ 1.5 BCHF)

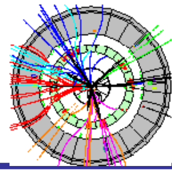
Includes:
- ❑ Civil engineering (tunnel, experimental caverns, surface sites, etc.)
- ❑ FCC-ee collider and injectors
- ❑ Technical infrastructure
- ❑ Other infrastructure (roads, power lines, land, etc.)
- ❑ 4 detectors

Updated cost assessment made in 2023, reviewed by dedicated Cost Review Panel of experts (chair N. Holtkamp), which concluded:
- ❑ cost estimates are appropriate for this stage of the study
- ❑ uncertainty estimates are realistic; most items are class 4 (- 30% to + 50%) or class 3 (-20% to +30%). Aim at class 3 for all main items at the end of the Feasibility Study

Note: **care should be taken when comparing with other proposed future colliders, whose cost estimates are in most cases not so detailed and complete, and have not been re-assessed recently** (high inflation over past years!)

Funding
CERN Budget can cover more than half of the cost. Contributions expected from non-Member States with interested communities (e.g. US) and from Member States (beyond their contributions to CERN Budget).
Other contributions may come from the European Commission and private donors.

Preliminary funding model (including construction and operation expenses) and funding scenarios studied
→ will be further developed in the coming year based on discussions in Council and with potential partners.

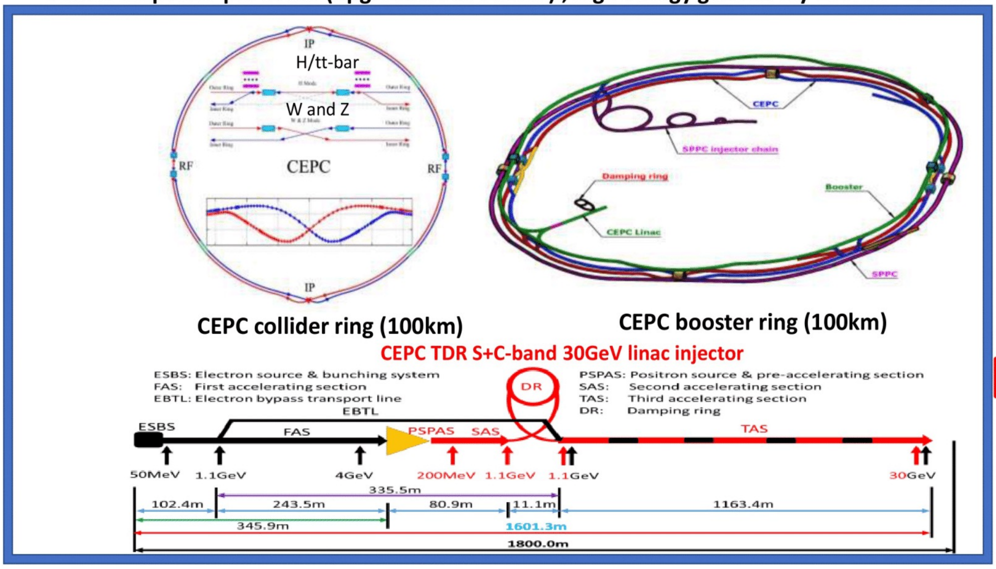


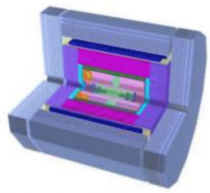
Circular Eelectron Positron Collider (CEPC)

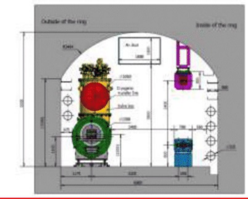
Main competitor: CEPC & SppC in China

CEPC Higgs Factory and SppC Layout in EDR

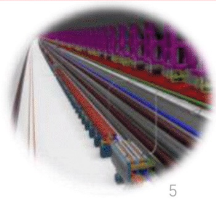
CEPC as a Higgs Factory： H, W, Z, upgradable to ttbar, followed by a SppC (a Hadron collider) ~125TeV
30MW SR power per beam (upgradable to 50MW) , high energy gamma ray 100Kev~100MeV







CEPC/SppC in the same tunnel



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CEPC focuses on Higgs

CEPC Operation Plan and Goals in TDR

Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. per IP ($10^{34}cm^{-2}s^{-1}$)	Integrated Lumi. per year (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H*	240	10	50	8.3	2.2	21.6	4.3×10^6
			30	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30	115**	30	60	2.5×10^{12}
W	160	1	50	26.7	6.9	6.9	2.1×10^8
			30	16	4.2	4.2	1.3×10^8
$t\bar{t}$	360	5	50	0.8	0.2	1.0	0.6×10^6
			30	0.5	0.13	0.65	0.4×10^6

* Higgs is the top priority. The CEPC will commence its operation with a focus on Higgs.
** Detector solenoid field is 2 Tesla during Z operation, 3Tesla for all other energies.
*** Calculated using 3,600 hours per year for data collection.

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Circular Eelectron Positron Collider (CEPC)

CEPC included in China's next 5 year plan?

CEPC Engineering Design Report (EDR) Goal

2012.9	2015.3	2018.11	2023.10	2025	2027	15th five year plan
CEPC proposed	Pre-CDR	CDR	TDR	CEPC Proposal CEPC Detector reference design	EDR	Start of construction

CEPC EDR Phase General Goal: 2024-2027

After completion CEPC accelerator TDR in 2023, CEPC accelerator will enter into the Engineering Design Report (EDR) phase (2024-2027), which is also the preparation phase with the aim for CEPC proposal to be presented to and selected by Chinese government around 2025 for the construction start during the "15th five year plan (2026-2030)" (for example, around 2027) and completion around 2035 (the end of the 16th five year plan).

CEPC EDR includes accelerator and detector (TDRrd)
CEPC detector TDR reference design (rd) will be released by June 30, 2025

CEPC Accelerator EDR goals, scope and the working plan (preliminary) of 35 WGs summarized in a documents of 20 pages, EDR progress be reviewed by IARC in Sept. 18-20, 2024

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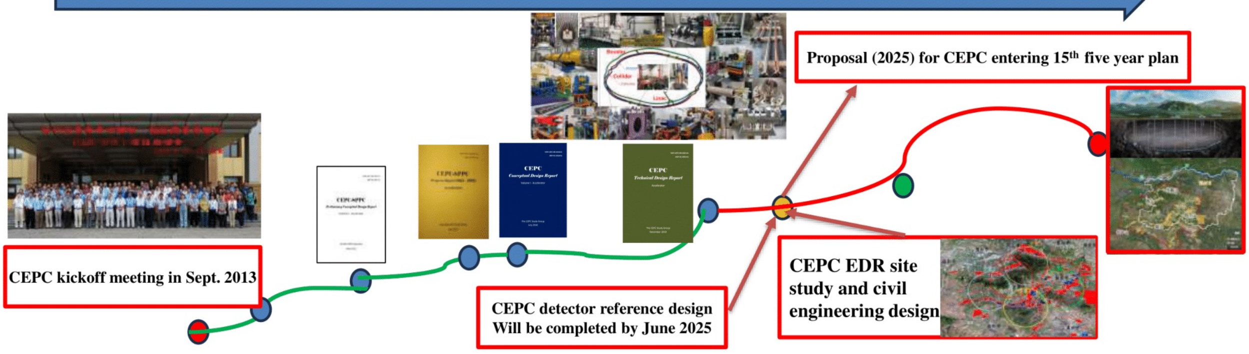
Cost estimate: 36.4 B RMB
(of which accelerator: 19 B)

1 RMB ≈ 0.13 € so ~5 B €

CEPC ready by 2035 (> 10 years before FCC-ee)?

CEPC Evolution Milestones and Timeline

Year	2012	2013	2015	2017	2018	2023	2025	2027	2030	2035



2012.9	2013.9	2015.3	2017.4	2018.11	2023.12	2024	~	2027		~2035
CEPC proposed		Pre-CDR	Progress report	CDR	TDR			EDR	start of construction	Completion

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CEPC: becoming an international endevour?

CEPC International Collaboration

CEPC attracts significant International participation and collaborations

Accelerator TDR report: 1114 authors from 278 institutes (including 159 International Institutes, 38 countries) arXiv: 2312.14363

- More than 20 MoUs have been signed with international institutions and universities
- CEPC International Workshop since 2014
- EU-US versions of CEPC WS since 2018
- Annual working month at HKUST-IAS (mini workshops and HEP conference) since 2015

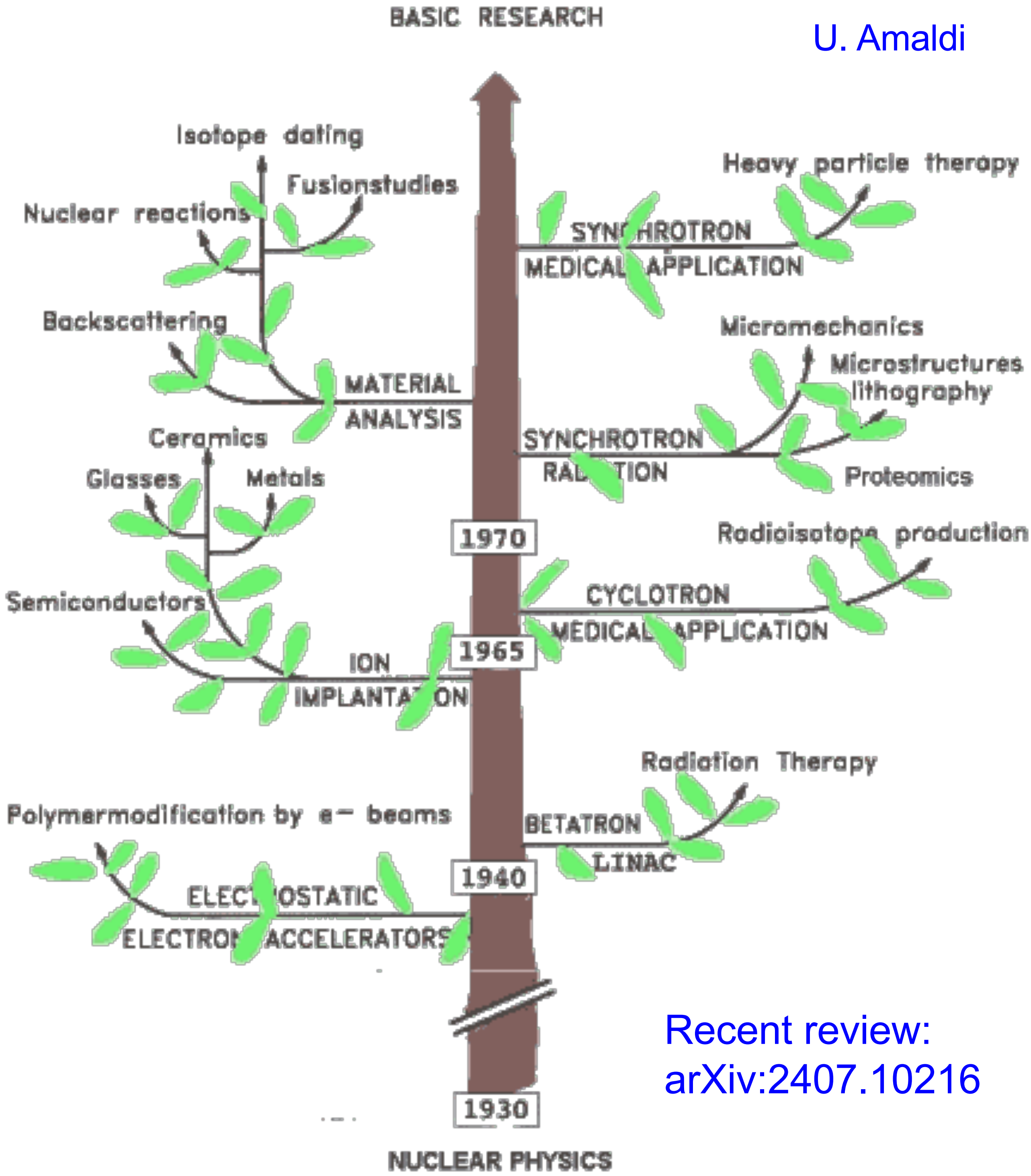
Timeline for the update of the European Strategy for Particle Physics

Third update of 2006 strategy: 2013, 2020

- **End September 2024** – Council appointment of the members of the **PPG** and decision on the venue for the **Open Symposium**
- **December 2024** – Council decision on the venue for the **ESG Strategy Drafting Session**
- **31 March 2025** – **Deadline** for the submission of main input from the community
- **26 May 2025** – **Deadline** for the submission of additional national input in advance of the **Open Symposium**
- **23-27 June 2025** – **Open Symposium**
- **End September 2025** – Submission of the "Briefing Book" to the **ESG**
- **14 November 2025** – **Deadline** for the submission of final national input in advance of the **ESG Strategy Drafting Session**
- **1-5 December 2025** – **ESG Strategy Drafting Session**
- **End January 2026** – Submission of the draft strategy document to the Council
- **March and June 2026** – Discussion of the draft strategy document by the Council and **updating of the Strategy**

More details on ESPP web page: https://europeanstrategyupdate.web.cern.ch/

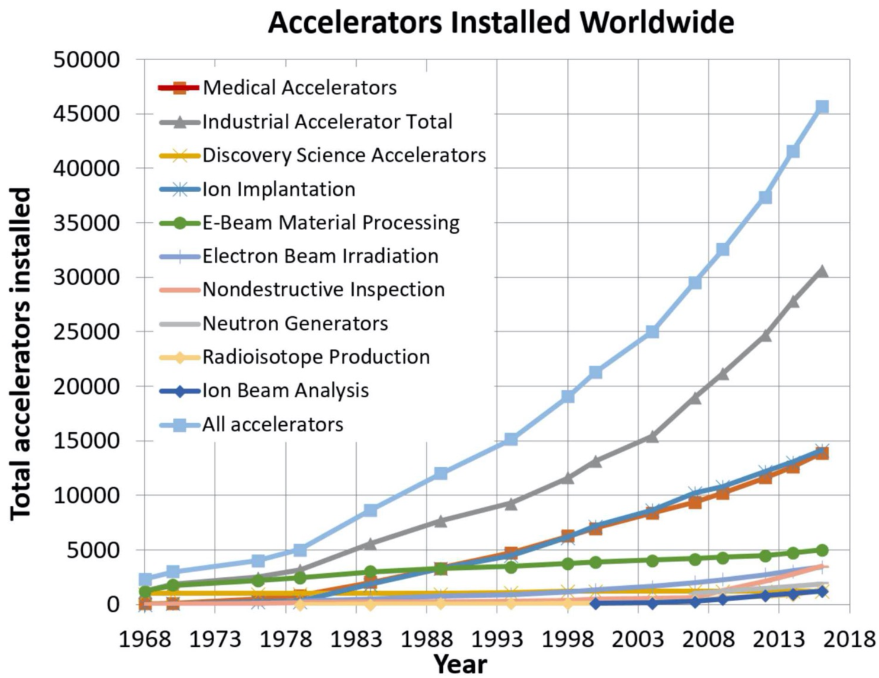
Accelerators have very wide applications – started from needs in basic research on fundamental constituents.



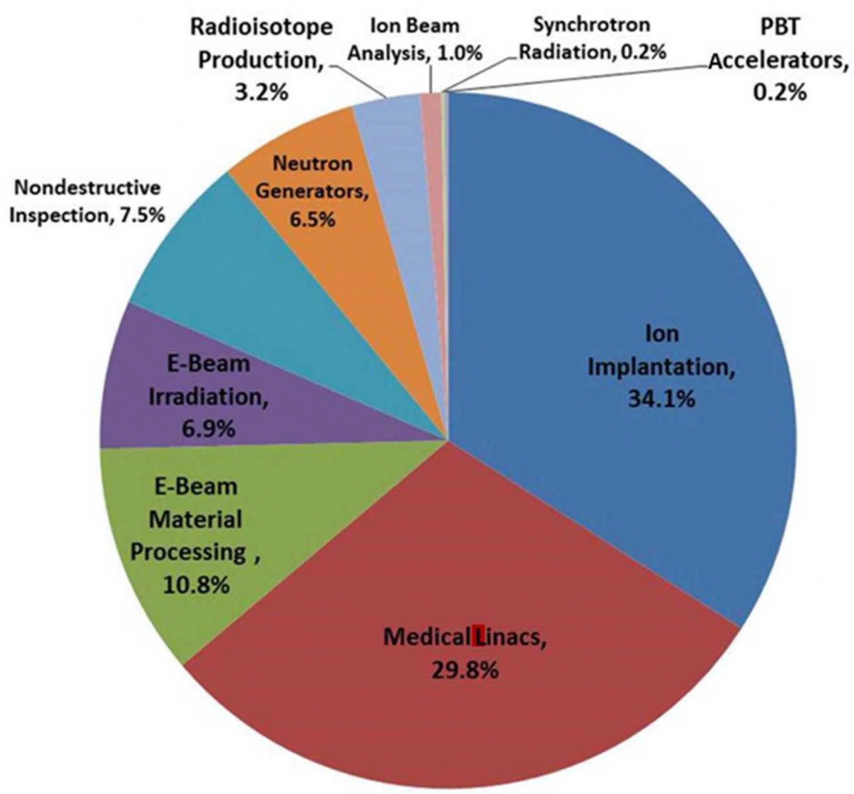
U. Amaldi

Recent review:
arXiv:2407.10216

Particle accelerators – world wide



Commercial & industrial applications:



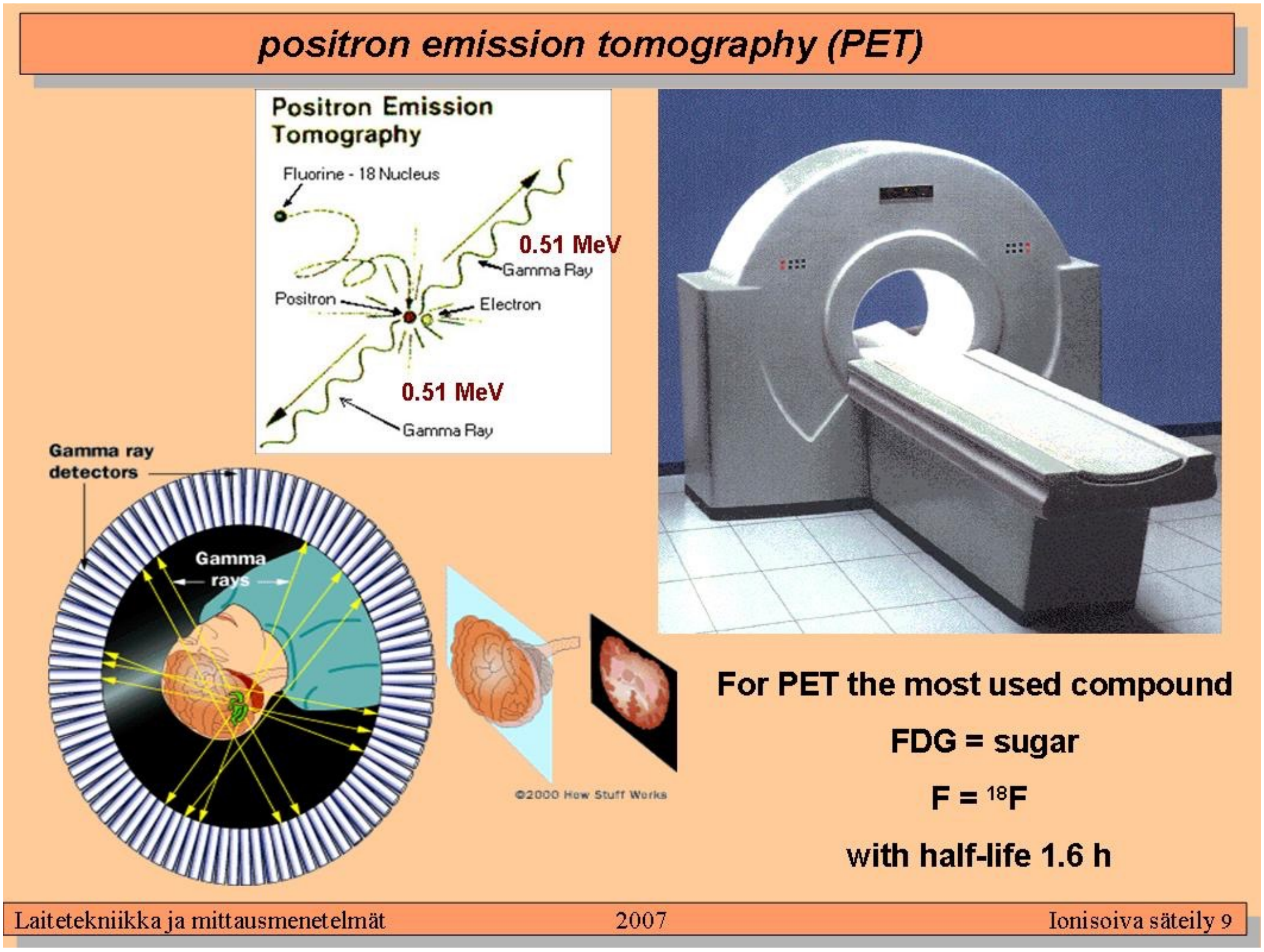
PBT = proton beam theraphy

From B.L. Doyle et al., Sandia Nat. Lab. report 2018-5903B medicine:

• isotope production for tomography (”imaging”); mainly cyclotrons producing isotopes of ^{18}F for positron emission tomography (PET)

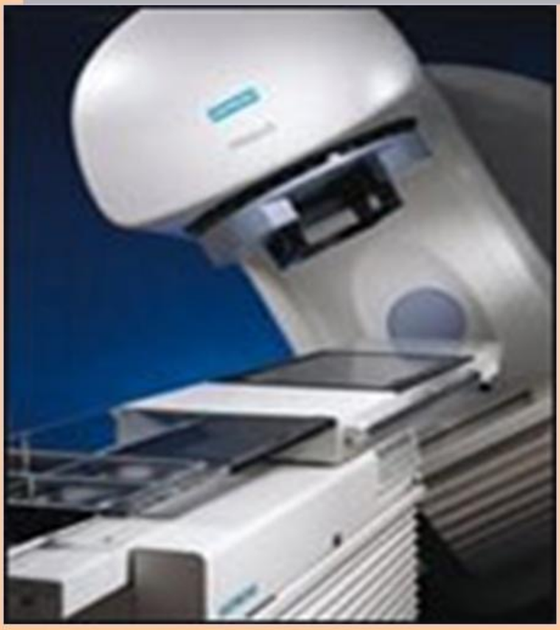
• radiotheraphy – treatment of cancer tumours; mainly electron linacs producing x-rays. Easy to make intensive x-ray beams that can be well focused

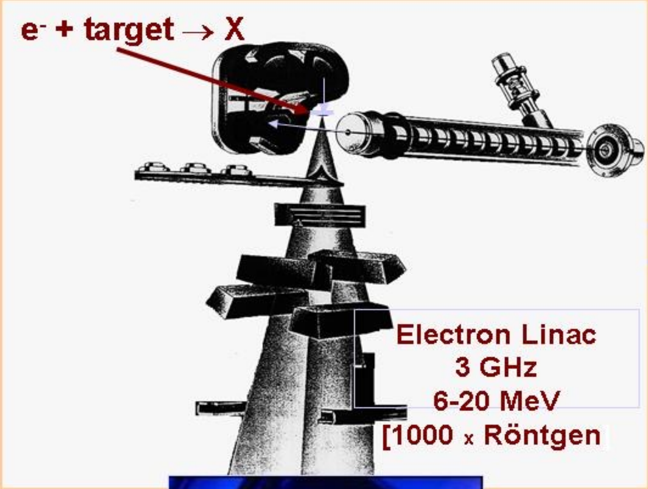
• proton/ion theraphy – treatment of cancer tumours deep in body (especially brain) or small tumours in sensitive organs (i.e. eyes). Better energy deposition profile than x-rays & able to make nm tumour surgery



Cancer therapy

x-rays in radiotherapy: linacs



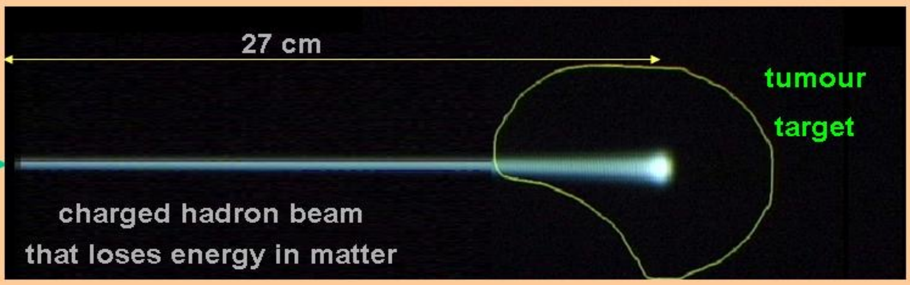


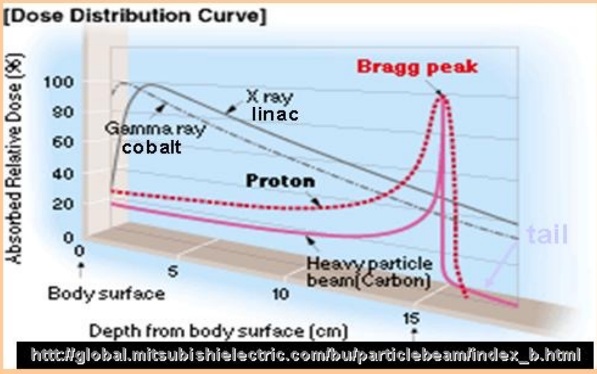
energy deposition of charged hadrons

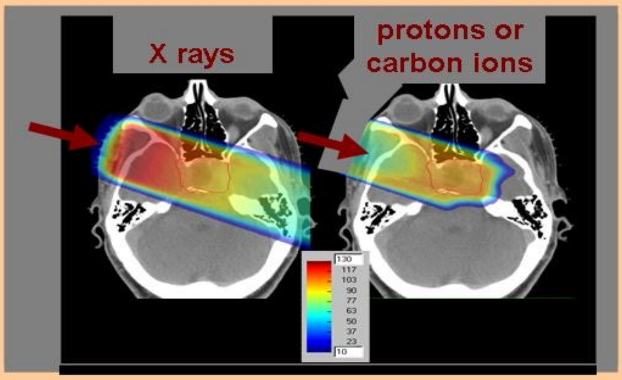
200 MeV protons

4800 MeV carbon ions

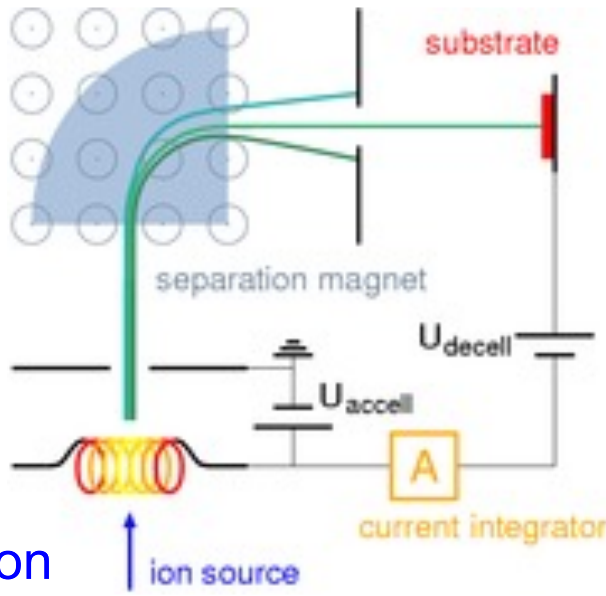
which control radioresistant tumours

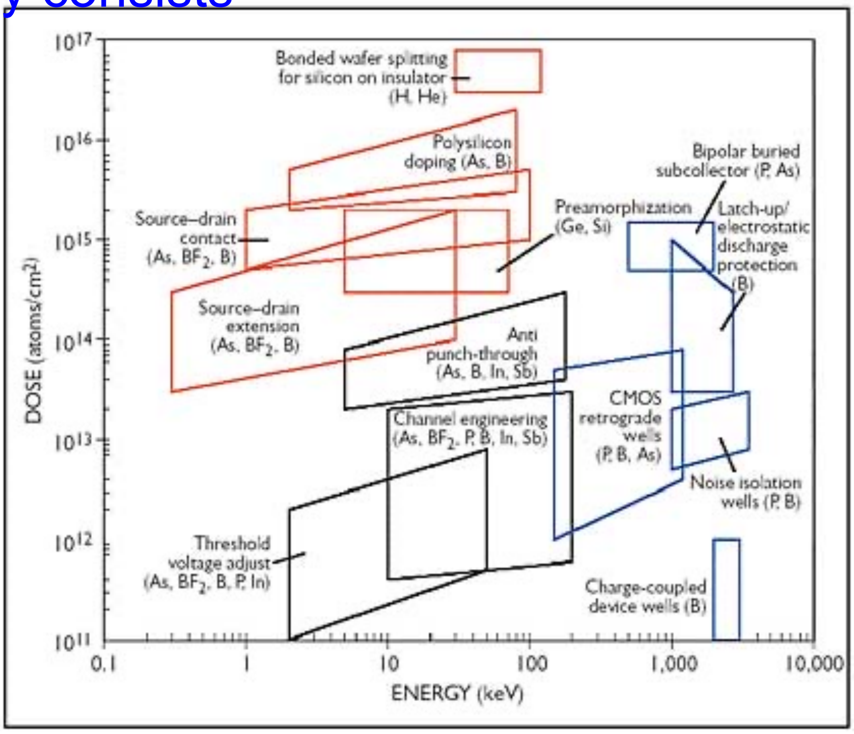






• **Ion implantation**: Ion implantation involves irradiation of solids by beams of energetic ions emanating from particle accelerators. Typical energies employed on the order of 100 keV. Typical depths of penetration on the order of several 1000 angstroms, depending on energy, ion type & target material. In ion implantation, virtually any atomic species can be embedded to any solid. Semiconductors like silicon can alter conductivity by introducing small quantity of dopant atoms like boron, arsenic and phosphorus. Important to accurately control number of implanted dopants & to place them at desired depth. Ion implantation equipment typically consists of an ion source, an accelerator & a target chamber. Ions of desired element produced & accelerated to a high energy. Magnet selects desired beam & directs it towards the material to be implanted.

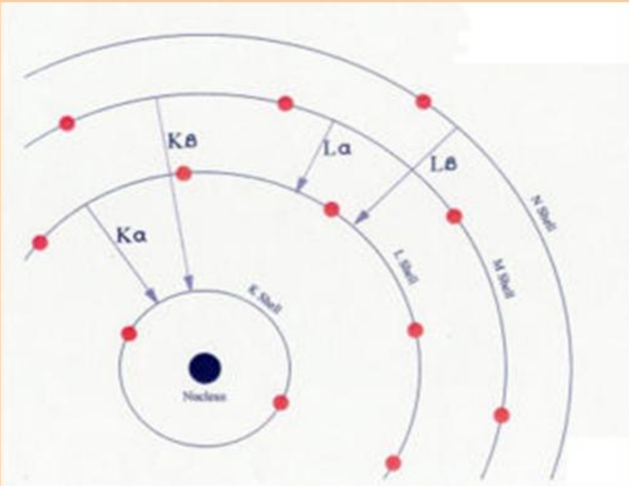


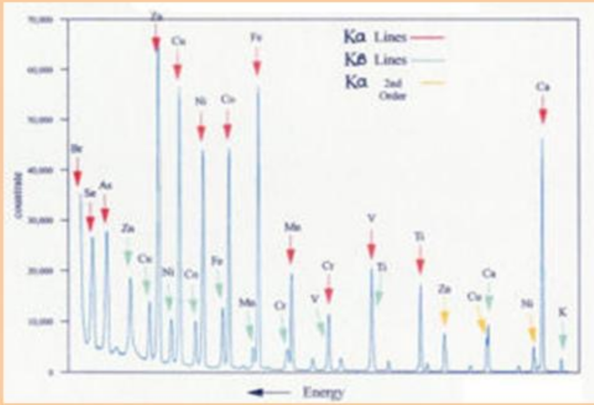


Element analysis

element analysis (alkuaine analyysi)

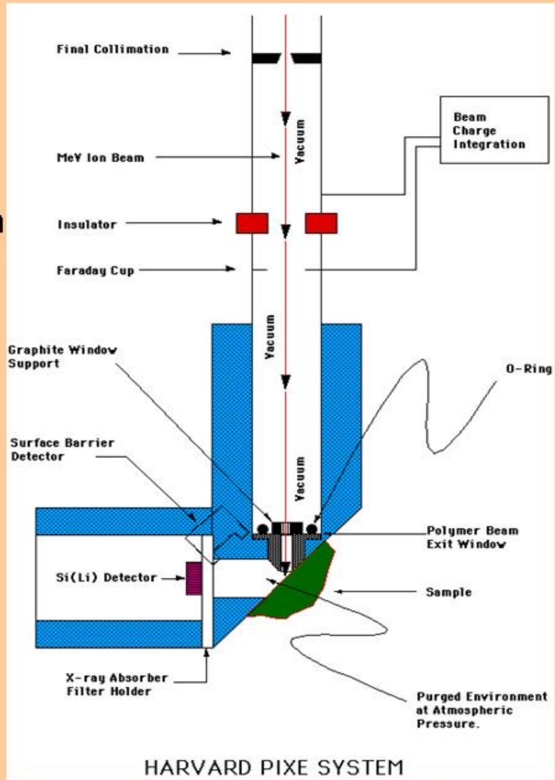
X-rays provides two excellent methods of element analysis: X-ray fluoresence & proton induced x-ray emission (PIXE). X-ray fluoresence = excitation of atoms by X-rays, standard analytical tool in materials industry. elements identified by their characteristic spectral lines (Kα, Kβ, Lα ...)

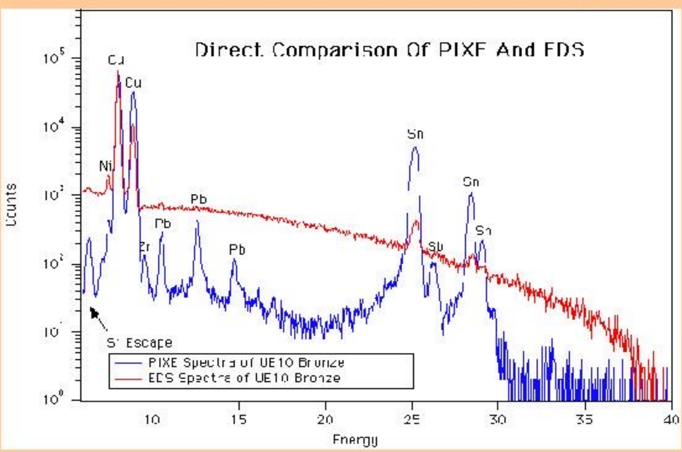




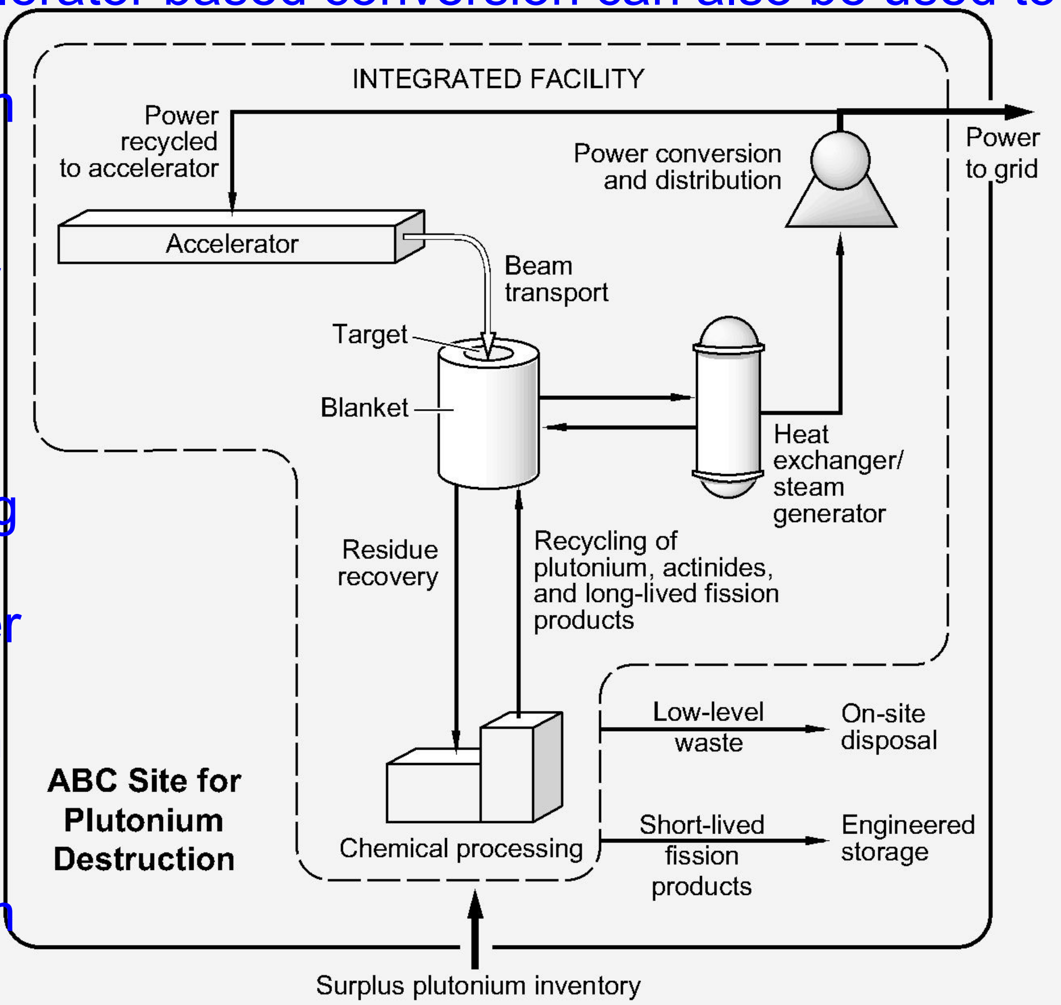
proton induced x-ray emission (PIXE).

a proton beam from an accelerator excites atoms to emit characteristics x-rays. proton beam better than electron beam (used in EDS, energy dispersive X-ray analysis) since protons slow down less rapidly in material than electrons & induce much less bremsstrahlung



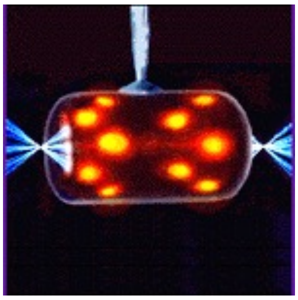


Transmutation of nuclear waste: Nuclear waste from nuclear reactors is stored in storage pools, but nowadays storage pools start to be filled completely & radioactive materials in waste have half-life period of million years. As alternative to deep underground repository, a new concept ADTT (Accelerator Driven Transmutation Technology) to dispose spent nuclear fuel is being developed. Aim: reduce half-life period of radioactive waste to a few centuries. Conceptual basis is to use neutrons to transmute radioactive elements such as Plutonium and Neptunium to products with lower half-life. Accelerator based conversion can also be used to destroy plutonium from weapons & reactor fuel sources by producing products with lower half-life. Can burn up to 98 % of plutonium -239 & 90% of neptunium-237 from explosive material.

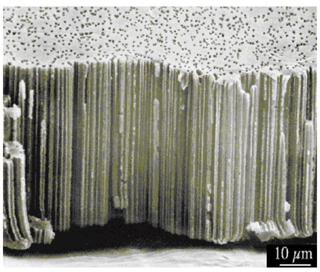


Applications of accelerators outside HEP

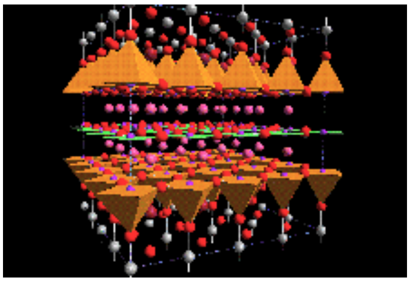
- Synchrotron Light
  5'-exonuclease from
  bacteriophage T5.



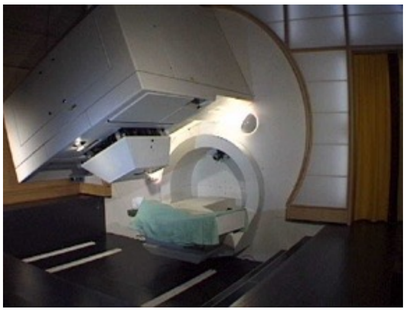
- Heavy ion fusion
  Laser beam simulation



- Ion beams
  Etched ion tracks in
  polymer foil.



- Spallation Neutron diffraction
  Structure of HighTc
  Superconductor



- Proton therapy
  Gantry

- Surface treatment
- Sterilisation
- Polymerisation
- Nuclear waste handling
- ...