Teilchenbeschleuniger

die grössten wissenschaftlichen Instrumente

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Contents

- **Energy Gain,   E / B field.   Units**
- **Types of accelerators :   Ring, Collider, Linac, e+e−, pp ; Cosmic**
- **Components: Source, Magnets, resonant Cavities**
- **Basic machine optics**
- **Energy and Luminosity**
- **Synchrotron Radiation, Vacuum**

- **Examples from CERN with LHC**
- **Plans and ideas for future high energy accelerators**
- **Accelerator applications and R&D**
- **Discussion, questions**

General, introductory refs. and books on Accelerators :

E. D. Courant and H. S. Snyder, *Theory of the Alternating-Gradient Synchrotron*, pdf

M. Sands, *Physics of Electron Storage Rings*, SLAC Report No. 121;   Wiedemann, *Particle Accelerator Physics* Bd. I,II

S.Y. Lee, *Accelerator Physics*, World Scientific; M. Conte, W. MacKay, *Physics of Particle Accelerators*, World Scientific

CERN CAS yellow reports ;   K. Wille, *The physics of particle accelerators,* Oxford University Press, 1996

Accelerators for Particle Physics, H. Burkhardt, in Handbook of Particle Detection and Imaging, Ed. C. Grupen, Oct. 2011

The **L**arge **H**adron **C**ollider : O. Brüning, H. Burkhardt, S. Myers, 10.1016/j.ppnp.2012.03.001, CERN-ATS-2012-064

Accelerators and Colliders, Landolt-Börnstein New Series I/21C, Springer 2013

Accelerators at the Energy Frontier

Livingston plot

Exponential growth of E_{cm} in time

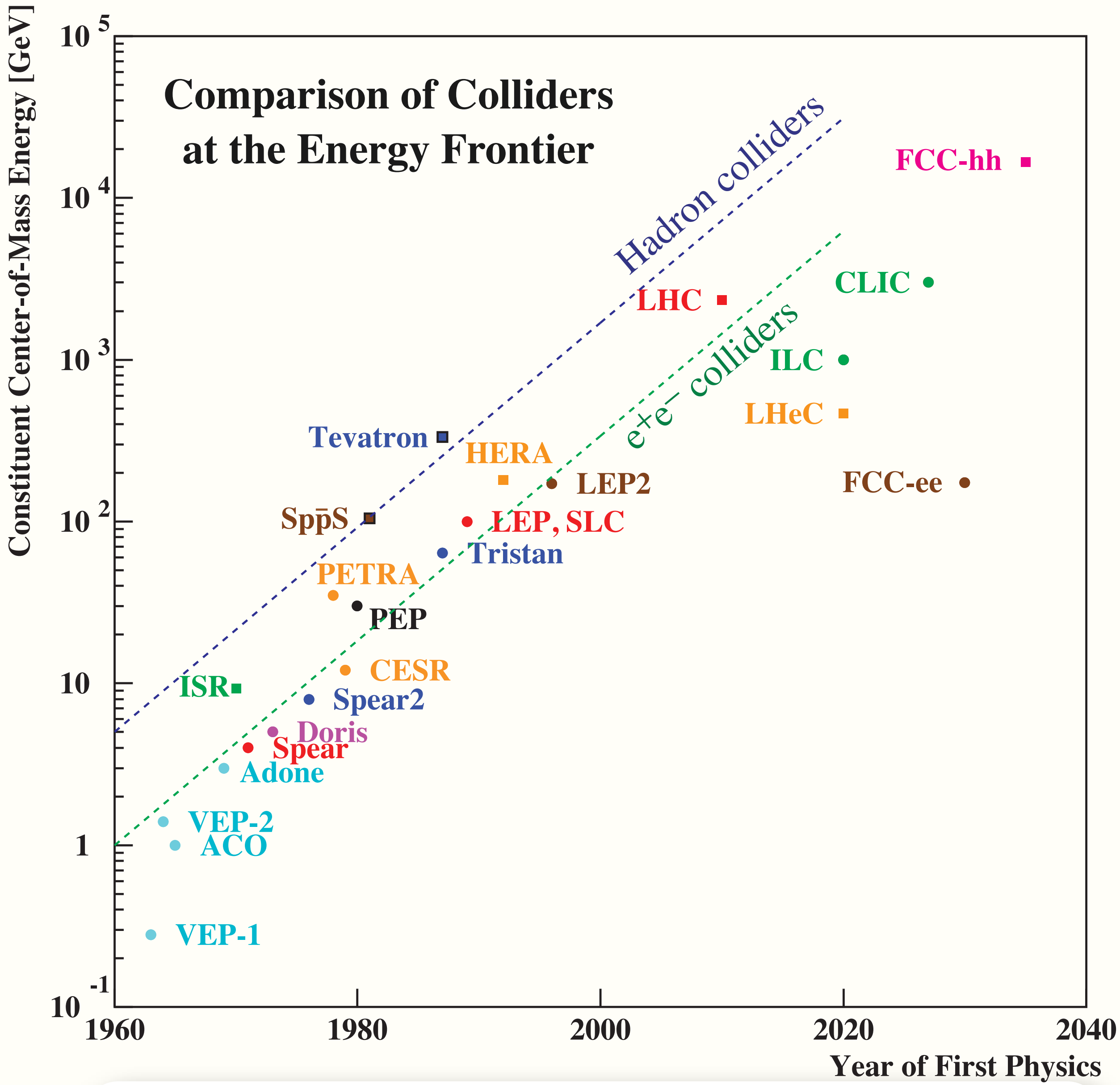
Starting in 60's with e^+e^- at about 1GeV

Factor 4 every 10 y

pp, $p\bar{p}$: E_{cm} / 6 still 5 × above e^+e^- at same time

pp, $p\bar{p}$: discovery
e^+e^- : precision
both required machines

+ ep : hadron structure, QCD
HERA, LHeC

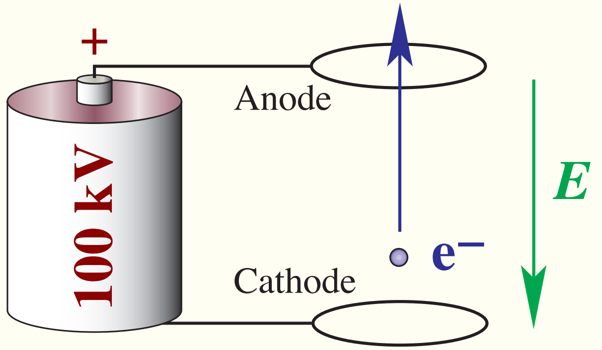


LHC big step --- Higgs discovery

we already look well beyond

Basic concepts and units

Electric field :
Acceleration
or rather
Energy gain
100 keV



Electric charge **e**
and electric field **E**

Special relativity, Lorentz transformation

$$E = \gamma m c^2 \qquad p = \beta \gamma m c \qquad \beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$m_e \approx 0.511$ MeV/c^2 $m_p \approx 938$ MeV/c^2 $e \approx 1.602\times10^{-19}$ C

For $E = 10$ GeV :
Electron $\beta = 0.999\,999\,9987$ $\gamma = 19569.5$
Proton $\beta = 0.995\,588\,4973$ $\gamma = 10.6579$

Unit conversion

$$\frac{e^2}{4\pi\epsilon_0} = \alpha\hbar c = r_{\text{part}}\, m_{\text{part}}\, c^2$$
$$= 1.43996 \times 10^{-18}\ \text{GeV m}$$

$$\hbar c = 197.327 \times 10^{-18}\ \text{GeV m}$$

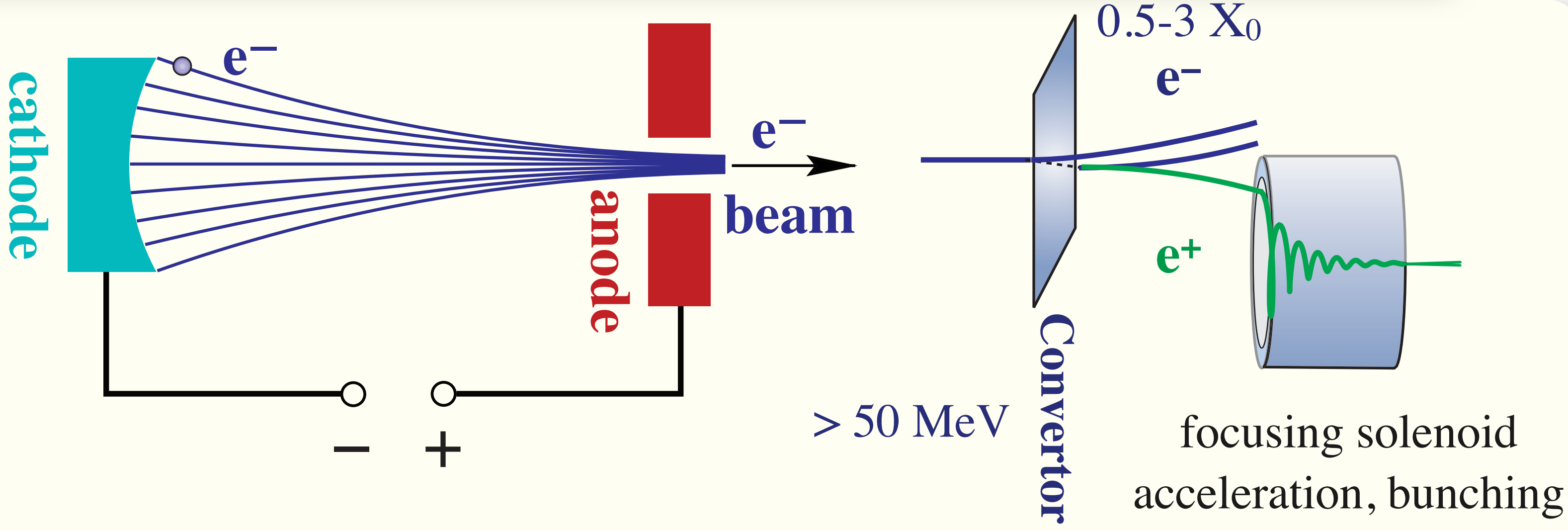
$$(\hbar c)^2 = 3.8938 \times 10^{-32}\ \text{GeV}^2\ \text{m}^2$$
$$= 3.8938 \times 10^{5}\ \text{GeV}^2\ \text{nb}$$

for precise numbers see PDG

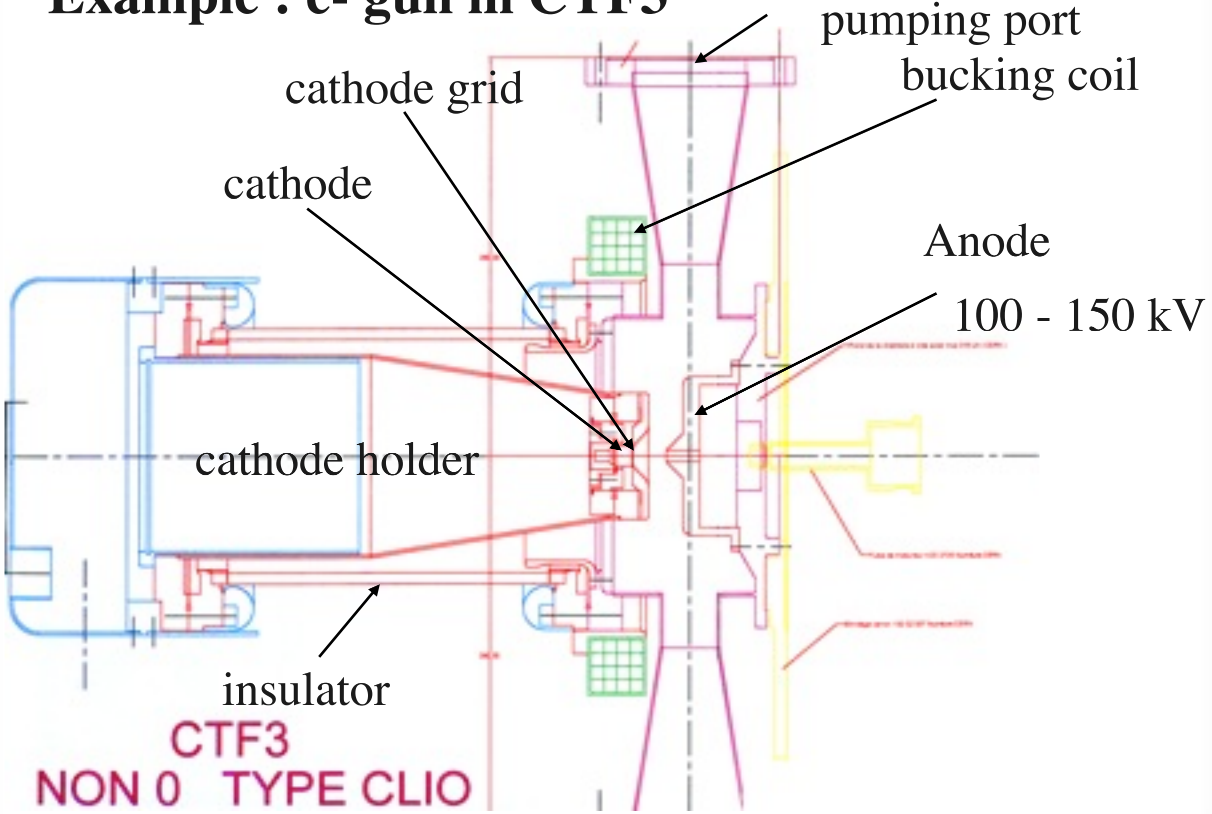
giga G = 10^9 tera T = 10^{12} peta P = 10^{15} exa E = 10^{18} zetta Z = 10^{21} yotta Y = 10^{24}

Particle sources

Thermionic electron source principle same as cathode ray tube



Example : e- gun in CTF3



challenges :

high intensity

polarized e⁻ sources

damping rings for minimum emittance

undulator polarized e⁺ sources

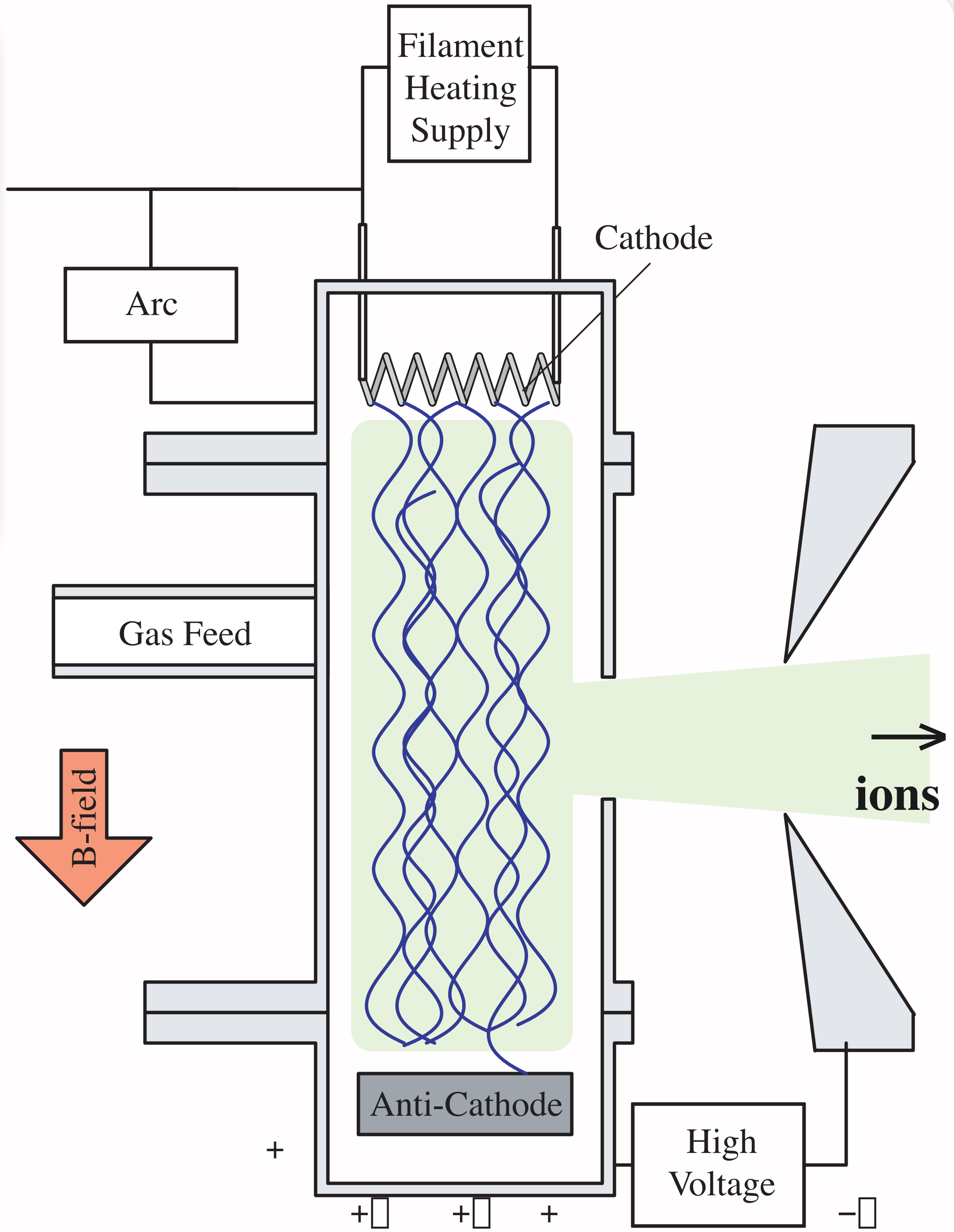
Proton and ion sources

Various methods exist to produce
p (H$^+$), H$^-$ (p with 2 e$^-$) and heavy ions -
heavier atoms, most electrons removed

Typically involves : **low pressure heated gas**
ionized gas / plasma, inject H$_2$ to get protons,
or surface sputtering
and electric and magnetic fields
to keep the electrons

CERN p-source and 50 MeV Linac

special techniques
H– injection
Radio**F**requency
Quadrupole

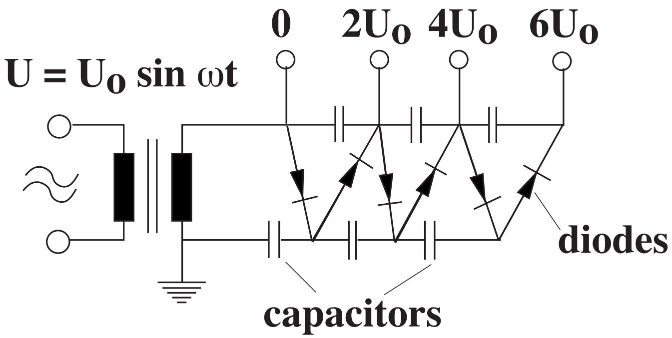


Linear Acceleration with Electrostatic Field

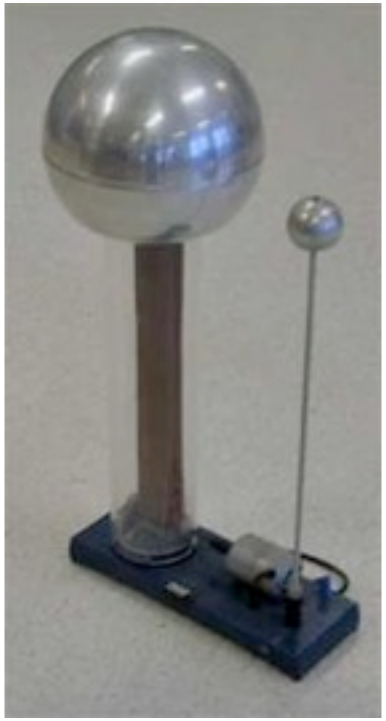
allows for DC, 100 % duty factor

limited by HV-breakdown ~ 1 MV / m

Cockcroft Walton
voltage multiplier

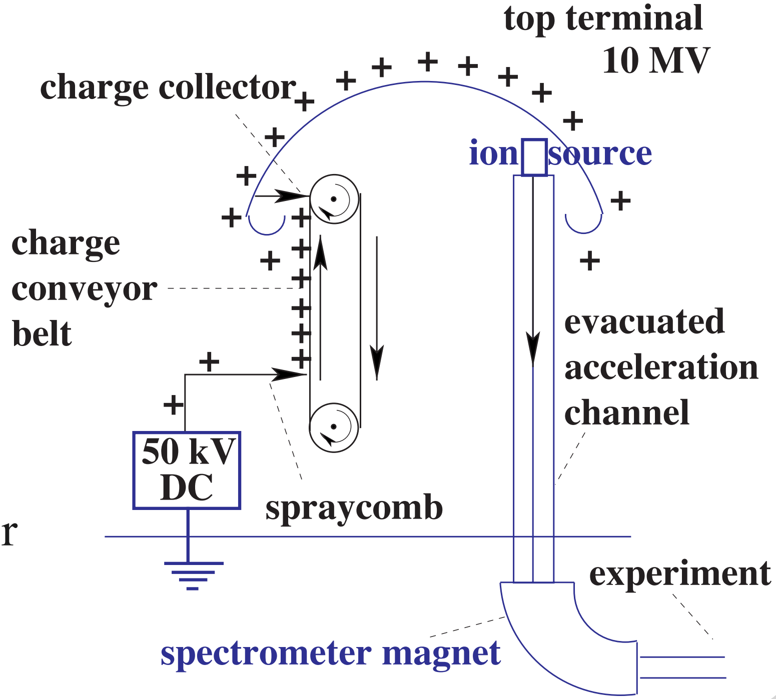


800 kV
proton pre-injector
used at
CERN
until 1993



Van de Graaff generator
static electricity from belts

Oak Ridge Tandem Van de Graaff generator
reached 25.5 MV using pressurised SF_6



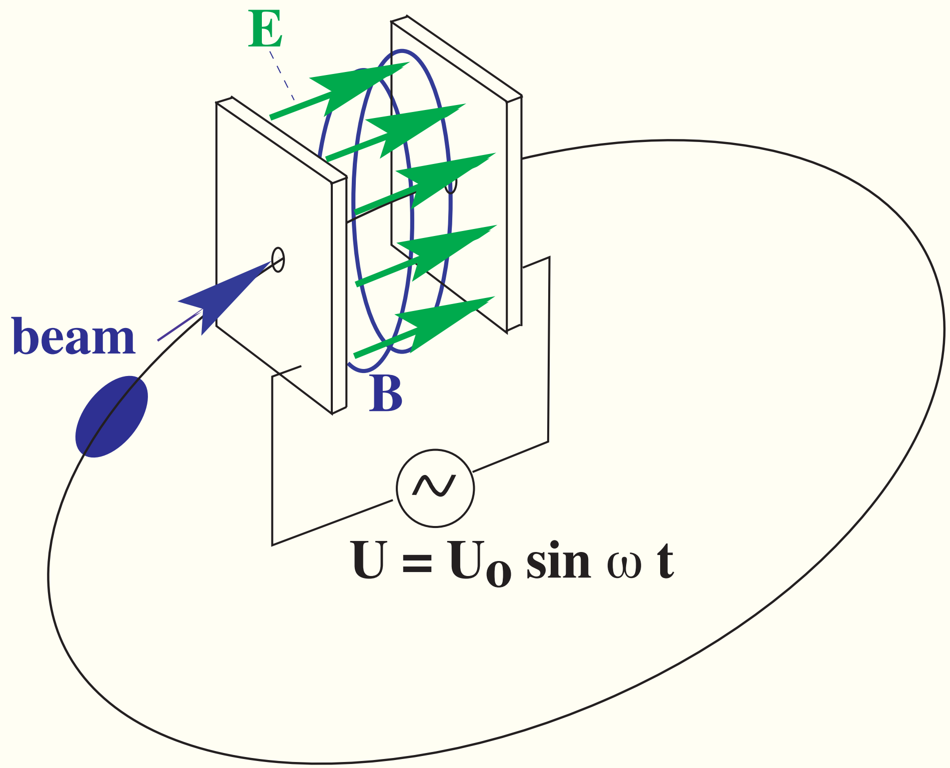
Time Varying Fields

Radio-frequency or short RF acceleration

- **allows for multiple passages**
- **bunched beams, reduced duty cycle**
- **higher RF frequencies allow for higher acceleration gradients**

no time for breakdown / flashover

LEP , SC	**8 MV / m at 352 MHz**
Tesla / ILC, SC	**31.5 MV / m at 1.3 GHz**
CLIC	**100 MV / m at 12 GHz**



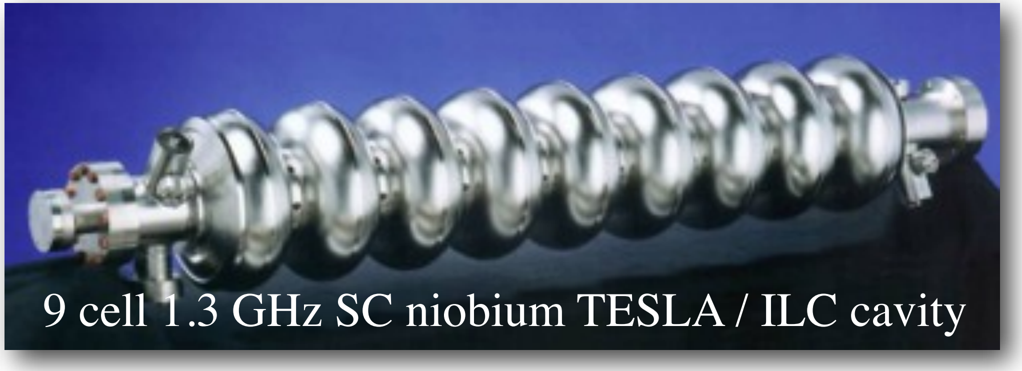
$U = U_0 \sin \omega t$

little gain above 12 GHz

SC limit ~ 50 MV/m, reached for single cell

surface gradients higher then acceleration gradients, smooth structures

high f : shorter bunches - collective effects (peak current)
and alignment more difficult
less energy stored in structure



9 cell 1.3 GHz SC niobium TESLA / ILC cavity

Basic parameters, Lorentz Force

$$\mathbf{F} = q\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

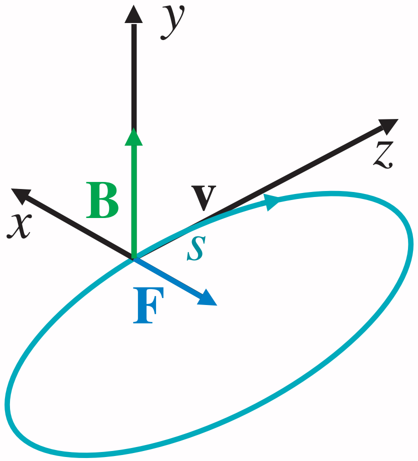
charge q, normally $q = e$; $q = Z\,e$ for ions

- Electric field **E** provides the acceleration or rather energy gain
- The magnetic field **B** keeps the particles on their path

Circular motion for

$\mathbf{E} = 0$

$\mathbf{v} \perp \mathbf{B}$



ρ is the radius of curvature for motion perpendicular to the static magnetic field. Often called

- gyromagnetic or Larmor radius in astroparticle physics
- bending radius for accelerators

$B\rho$ known as magnetic rigidity, units Tm

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

for $q = e$ numerically

$B\,[\mathrm{T}] = p\,[\mathrm{GeV/c}]\quad 3.336\ \mathrm{m} / \rho$

high energy, $v = c$ "$p = E$"

$E < E_H = q\,B\,\rho$ Hillas criterion

LHC

- **Momentum $p =$ 7 TeV/c**
- **LHC bending radius $\rho = 2804$ m**
- **Bending field B = 8.33 Tesla**
- **magnets at 1.9 K, super-fluid He**

Astroparticle

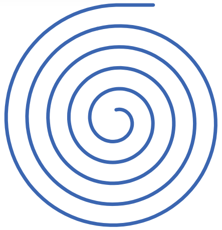
units $10^{-4}\mathrm{T} = 1\mathrm{Gauss}$; a.u. $= 1.5\times10^{11}$m

Solar system $B = 10\,\mu\mathrm{G}$ $E = 5$ TeV $\rho = 11$ a.u.

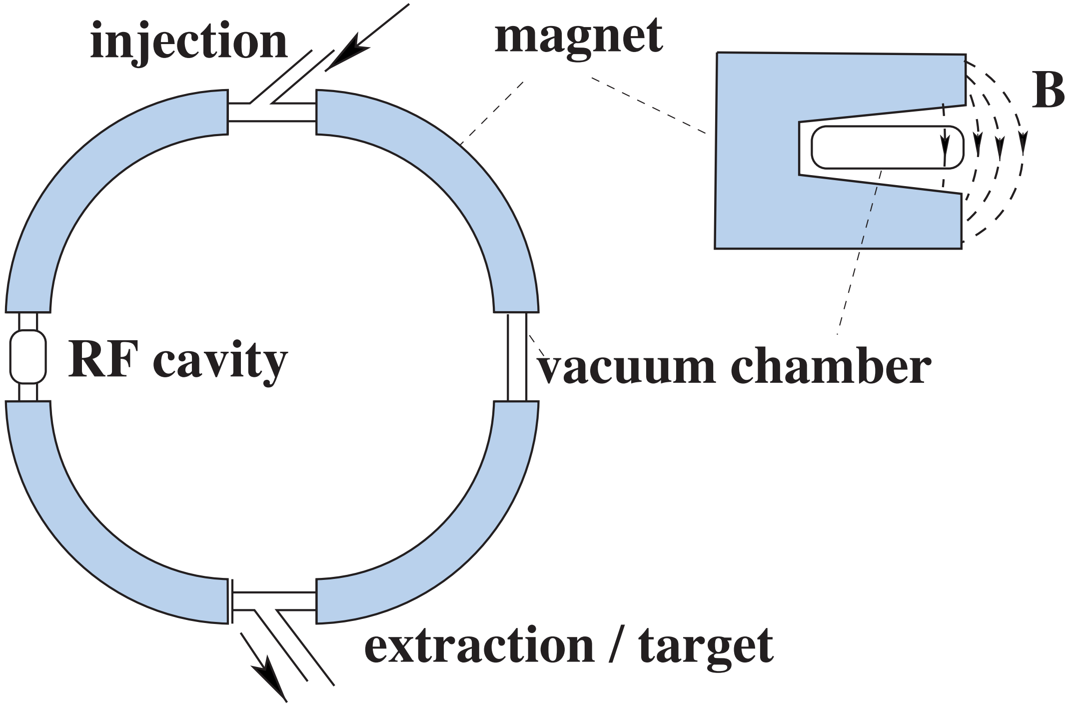
Intergalactic $B = 1\,\mathrm{nG}$ $E = 5$ PeV (knee)

$\rho = 1.7\times10^{19}$m (4 % of galaxy-radius)

Circular Accelerator



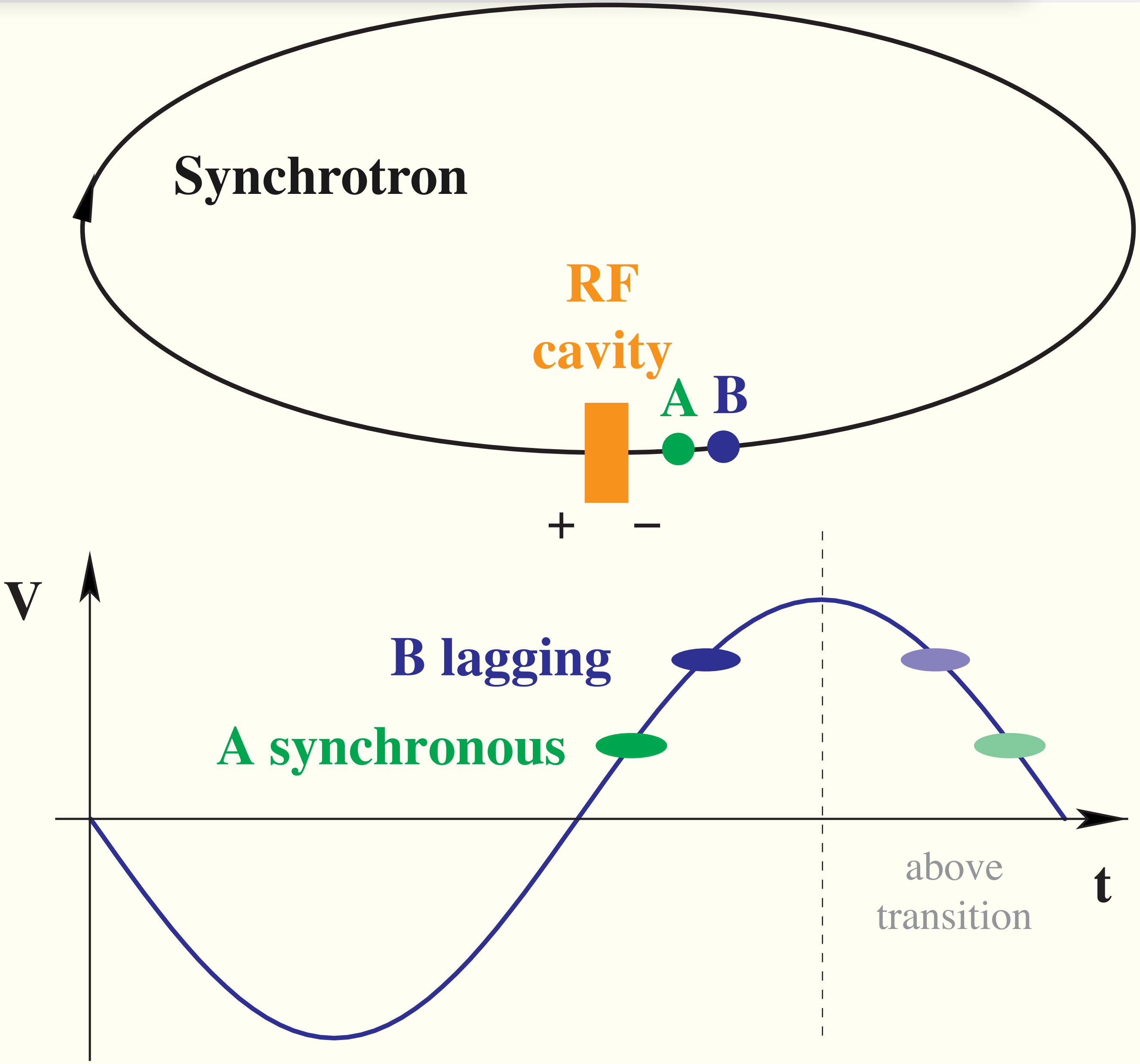
- **Cyclotron : constant rf-frequency. Magnetic field radius ϱ increases with energy. Used for smaller machines**
- **Synchrotron : ϱ = const. B increased with energy. RF-frequency adjusted slightly ($\beta = 0.999$ .. 1.0).** Most HEP and all CERN ring accelerators PS, SPS, LEP, LHC of this type. Principle same for e, p, heavy-ion – PS, SPS – accelerate(d) all of these, in some cases switching within seconds



Phase stability I

acceleration,
ramping up in energy :

- allow for enough RF-voltage
- ramp up magnets
- particle adjust themselves in radius and phase to gain on average the right amount of energy



LHC nominal RF parameters
Voltage at injection   8 MV
top energy 16 MV

Revolution frequency $f_{rf} = h\, f_{rev}$ $h = 35\,640$ $f_{rf} = 400.7896$ MHz $L = 26658.864$ m

Circumference $L = v / f_{rev} = \beta c / f_{rev}$ $f_{rev} = 11.2455$ kHz   1 turn in 88.92446 µs

Magnets and Power Consumption

Why super conducting magnets ?

$$P = R\, I^2$$

LEP

B = 0.1 T LEP2 ~ 100 GeV

(half) **cells with each three 11.55 m long dipole magnets**

I = 4500 A together R = 1 mΩ P = 20 kW / cell

488 cells P = 10 MW

if we would have kept the same magnets for the LHC

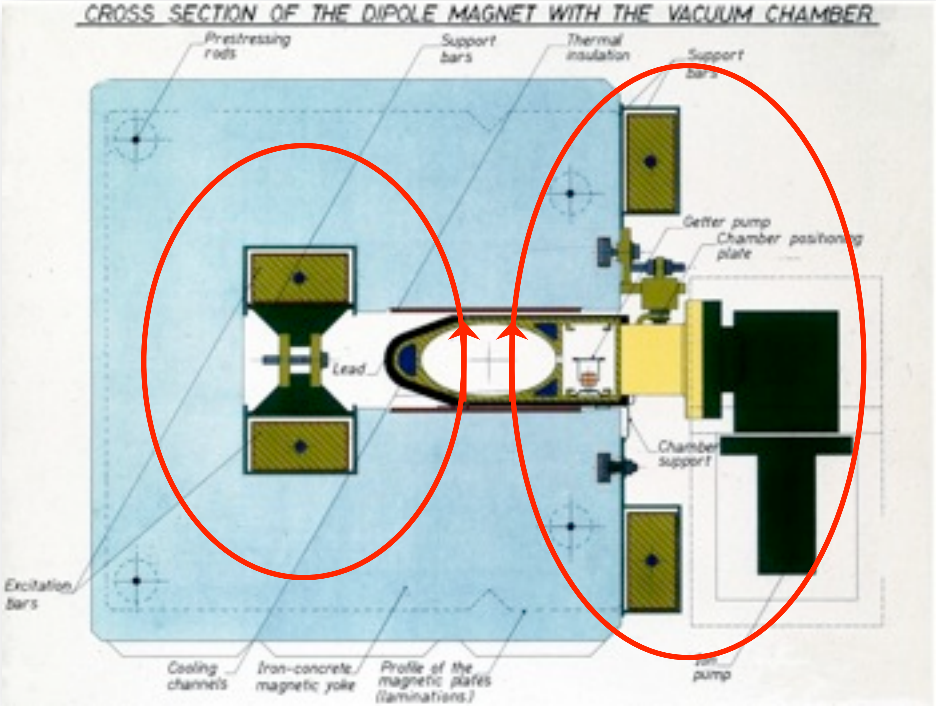
LHC B ∝ I B = 8.38 T

would need now I = 280 kA with LEP magnets R = 1 mΩ

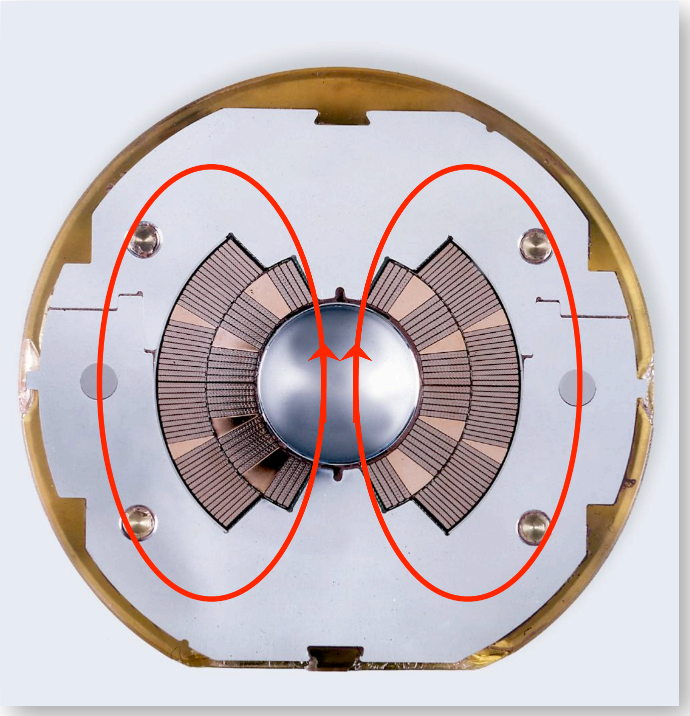
P = 78 MW / cell × 488 cells total power P = 38 GW

Magnet technology

warm

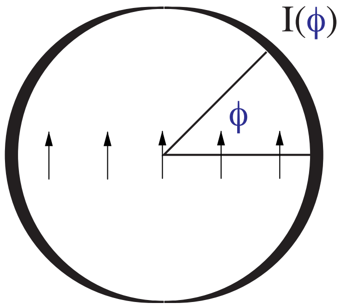


cold



Dipole current distribution

$I(\Phi) = I_0 \cos(\phi)$

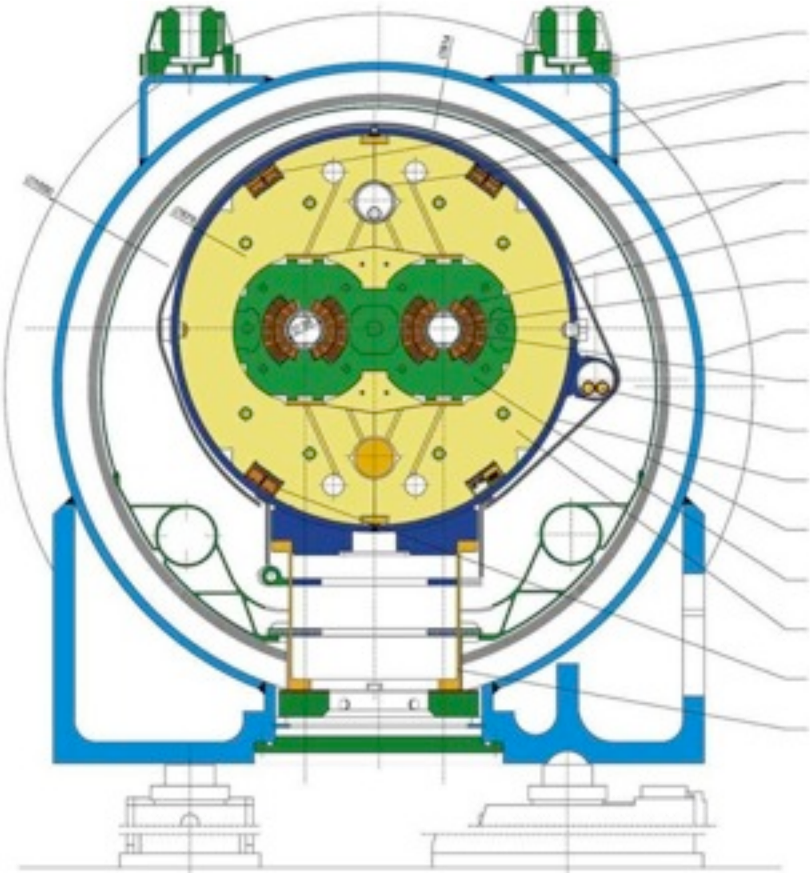


- field quality given by pole face geometry
- field amplified by Ferromagnetic material
- hysteresis and saturation ~ 2 T
- Ohmic losses for high magnet currents

- field quality given by coil geometry
- requires cooling to cryogenic temperatures
- persistent currents and snap back
- risk of magnet quenches

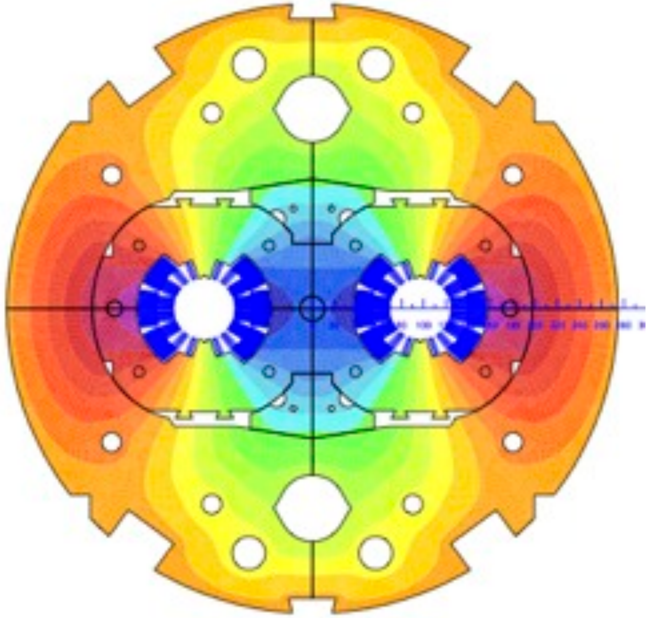
LHC dipole magnet

2-in-1 dipole magnet, 8.33 T field, 15 m long, mass 30 ton



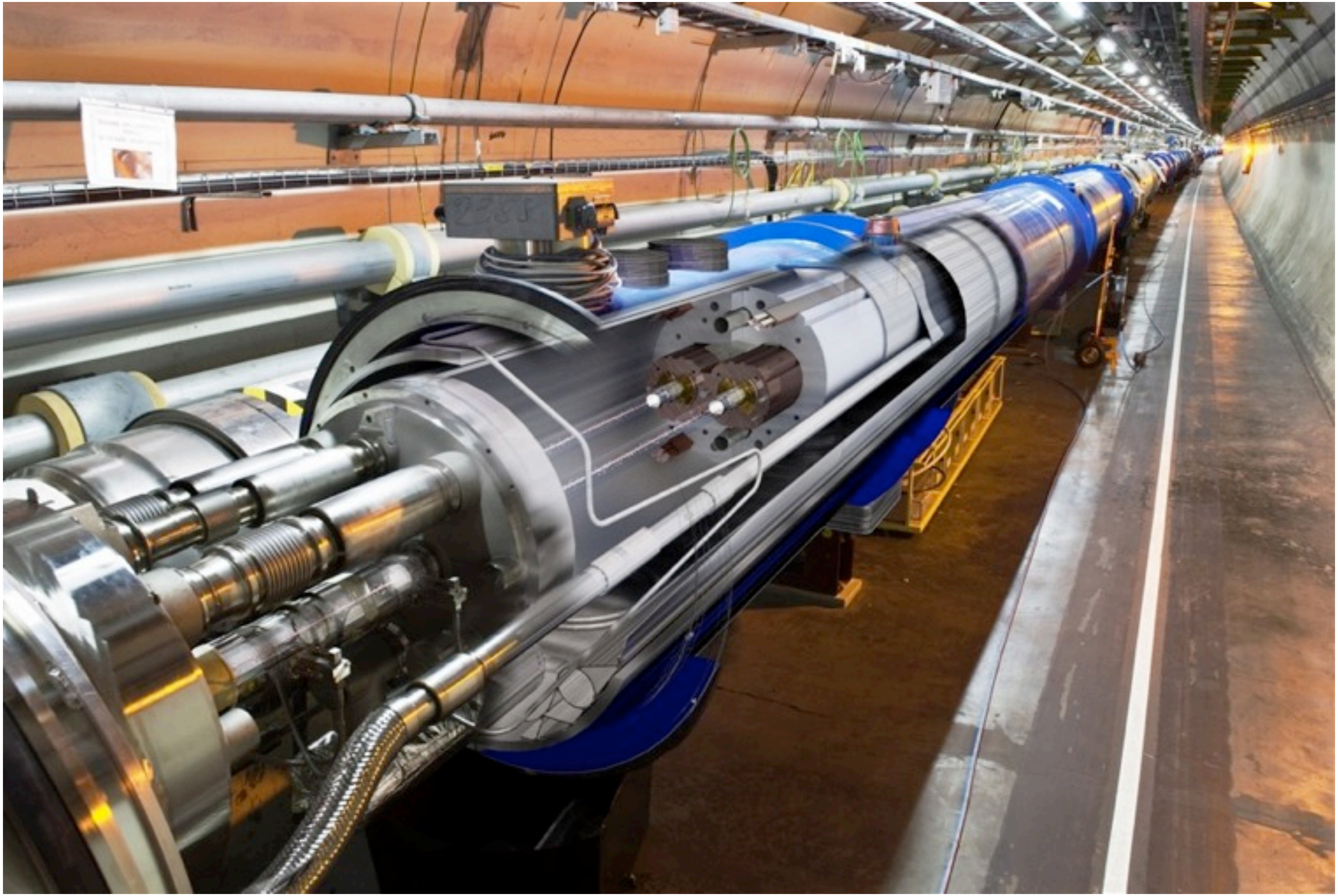
alignment target
main quadrupole bus-bars
heat exchange pipe
superinsulation
superconducting coils
beam pipe
vacuum vessel
beam screen
auxiliary bus bars
shrinking cylinder / He I-vessel
thermal shield (55 to 75 K)
non-magnetic collars
iron yoke (cold mass, 1.9 K)
dipole bus-bars
support post

LHC dipole magnet cross-section

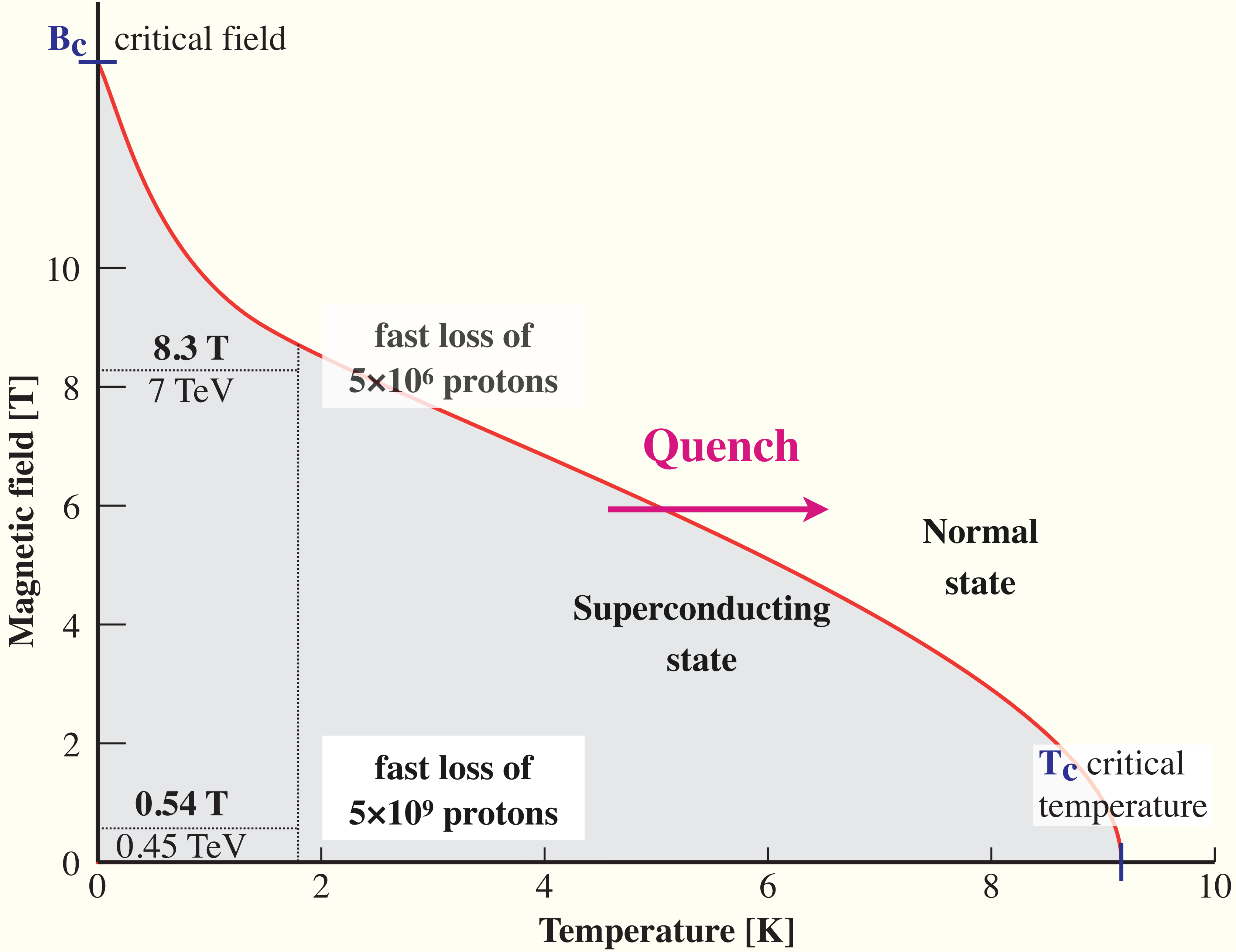


current distribution

LHC magnets installed in the tunnel



Operational margin of a superconducting LHC dipole



Fixed Target vs Collider

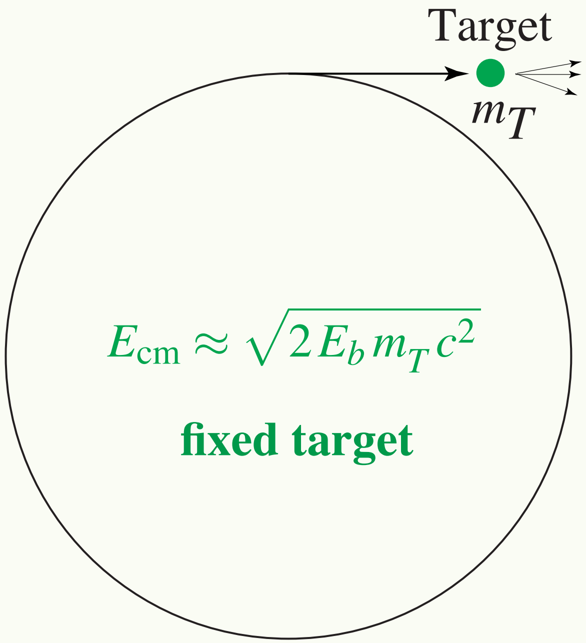
Fixed target, high energy collisions :

Energy “lost” as kinetic energy

High Energy e+e− and very high energy pp gain a lot from colliders

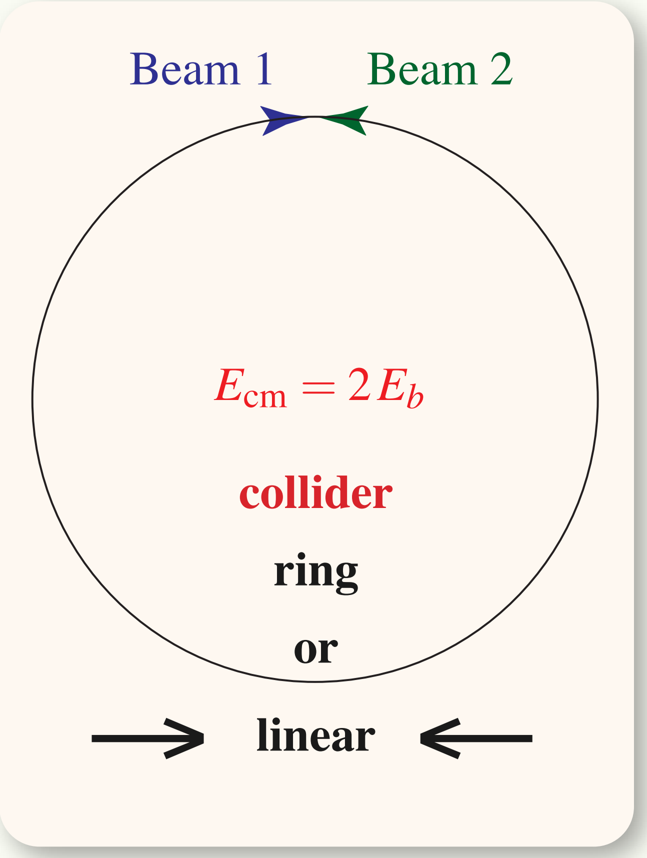
Gain for LHC is by ×122

(14 TeV / 114.6 GeV)



$$E_{\rm cm} \approx \sqrt{2\,E_b\,m_T\,c^2}$$

fixed target



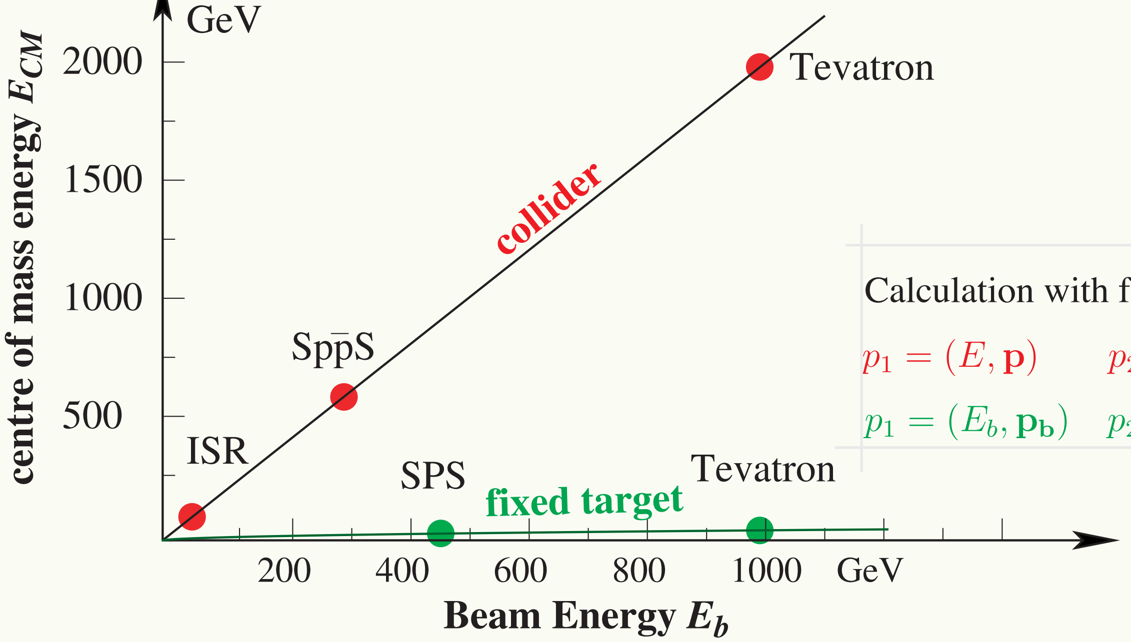
$$E_{\rm cm} = 2\,E_b$$

collider

ring

or

linear



Calculation with four vectors for c = 1 $\quad E_{CM} = \sqrt{s} \quad s = (p_1 + p_2)^2$

$p_1 = (E, \mathbf{p}) \quad p_2 = (E, -\mathbf{p}) \quad s = 2m^2 + 2E^2 + 2p^2 = 4E^2$ collider

$p_1 = (E_b, \mathbf{p_b}) \quad p_2 = (m_T, \mathbf{0}) \quad s = m_b^2 + m_T^2 + 2m_T E_b$ fixed target

Primary cosmic ray spectrum

E spectrum falls as $\mathbf{E^{-2.7}}$
to knee at E ≈ 5e15 eV
= 5×10^{6} GeV
~1 particle/m^2 and year
origin galactic

above ~ $\mathbf{E^{-3}}$

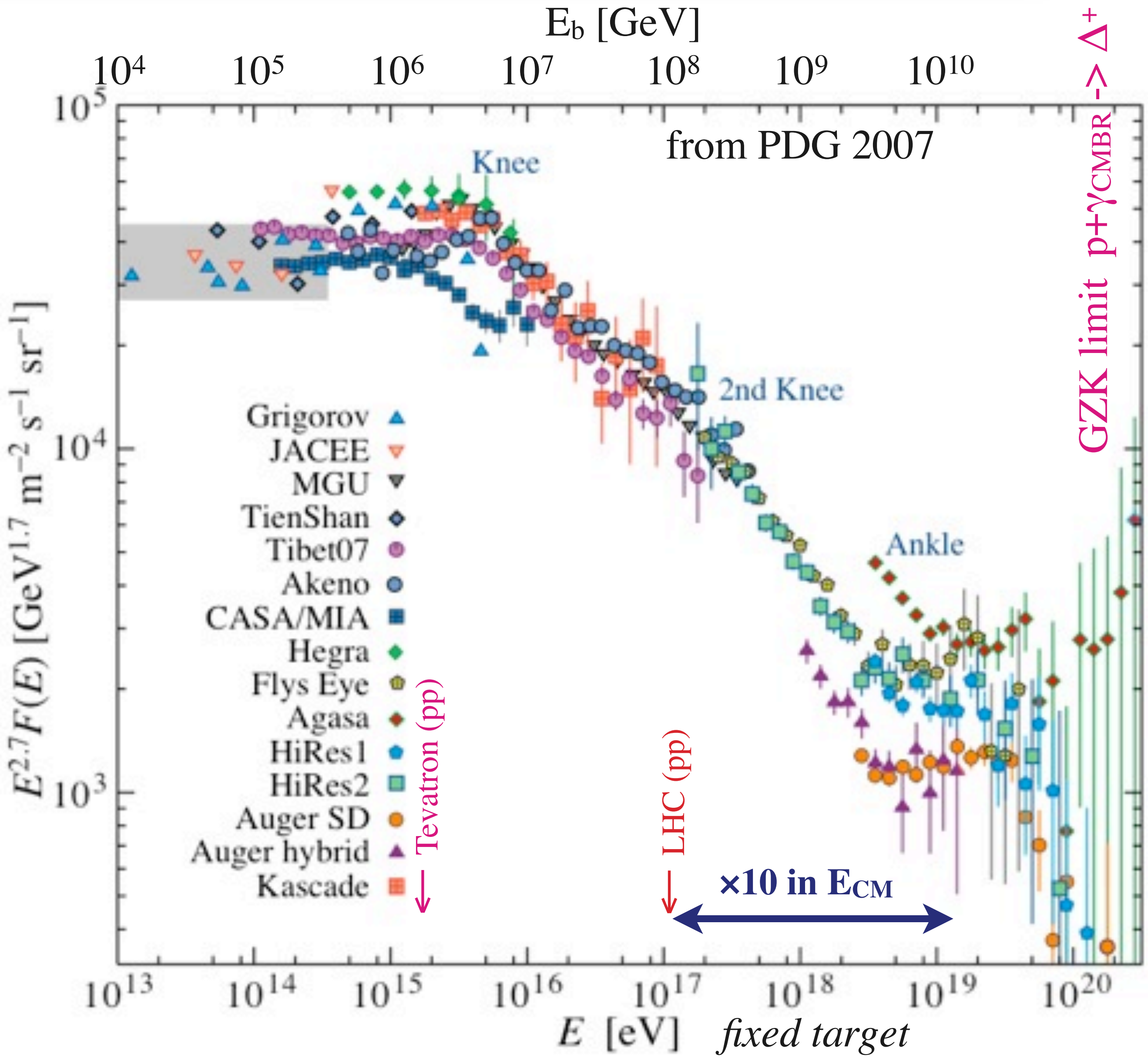
back to $\mathbf{E^{-2.7}}$ at very
highest energies

conversion to $\mathbf{E}_{cm}$

E_b [eV]	E_{cm} [TeV]
10^{13}	0.137
10^{15}	1.370
10^{17}	13.70
10^{19}	137.0
10^{21}	1370.

≈ LHC pp

← LHC ions

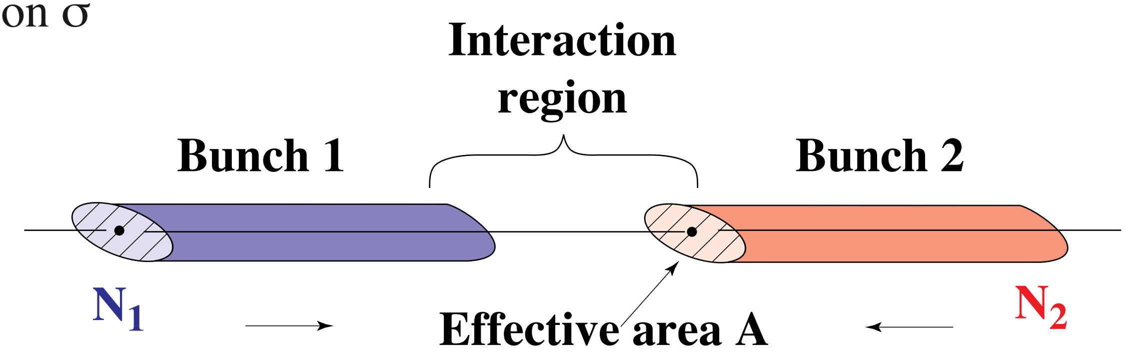


Nature has much larger and more powerful **cosmic accelerators** then we can ever built.
With colliders we can get to these collision energies in clean laboratory conditions.
The LHC already gets us to within 1-2 orders of magnitude of the very highest cosmic rays.

Luminosity and collision rates

Event rate for process with cross section σ

$$\dot{n} = \mathcal{L}\sigma$$



Luminosity from bunch crossings at frequency $f = f_{rev}\, n_b$

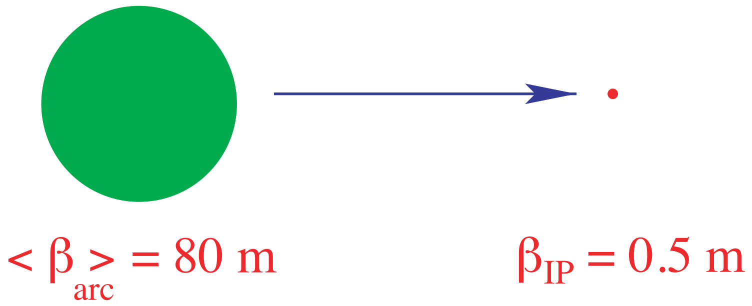
$$\mathcal{L} = \frac{N_1 N_2 f}{A}$$

for Gaussian bunches with rms sizes $\sigma_x\ \sigma_y$ **A** $= 4\,\pi\,\sigma_x\,\sigma_y$

High **Luminosity** : N↑ collide many particles, A↓ squeezed in small bunches

LHC 1.15×10^{11} protons, n_b = 2808 (f↑ crossings at 25 ns intervals)

Beams squeezed using strong large aperture quadrupoles around the interaction points from ~ 0.2 mm to $\sigma_x = \sigma_y = 17\ \mu\text{m}$



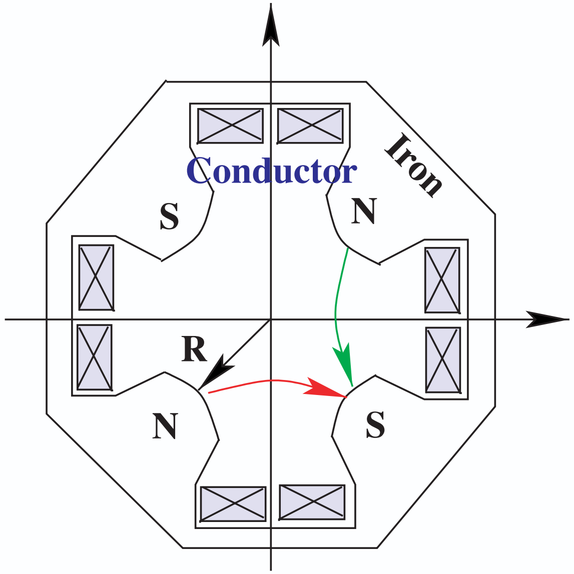
Rare new processes, like Higgs production can have very small cross section, like 1fb = 10^{-39}cm^2 . LHC designed for very high Luminosity **$L = 10^{34}$ cm^{-2}s^{-1}**

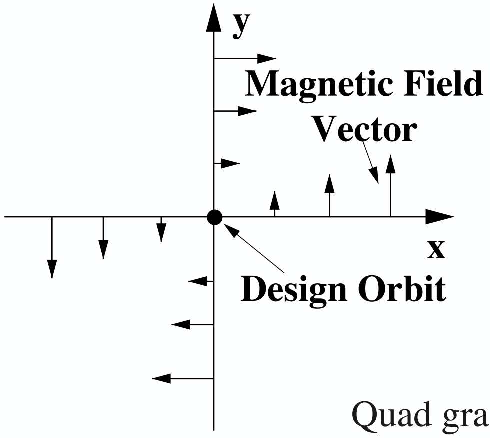
Event rate for such rare processes : ~ 1 new particle every 28h.

Instead pp $\sigma_{tot} \approx 0.1$ barn 30 / crossing

Alternate gradient focusing

Quadrupole lens focusing in x, defocusing in y or vice versa





$B_x = k\,y$

$B_y = k\,x$

$B_z = 0$

$\nabla \times \boldsymbol{B} = \boldsymbol{0}$

$\mathbf{F} = e\,(\mathbf{v} \times \mathbf{B})$

here

$\mathbf{F} = e\,(0, 0, v) \times (B_x, B_y, 0)$

$\quad = e\,(-v\,B_y,\ +v\,B_x,\ 0)$

Quad gradients in the LHC

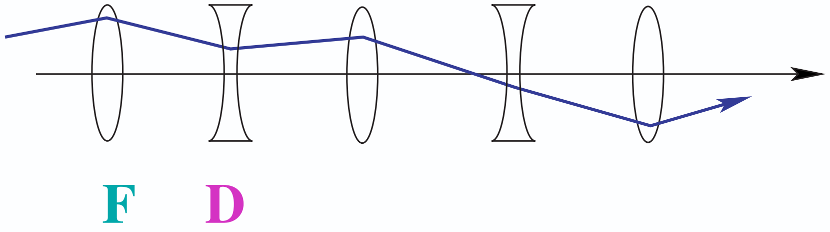
$K = 1/B\varrho\ \ \partial B_y/\partial x \approx 200$ T/m

Combine F D

Defocusing when at small amplitude

Overall focusing

alternate gradient focusing



Normal (light) optics :

Focal length of two lenses at distance D

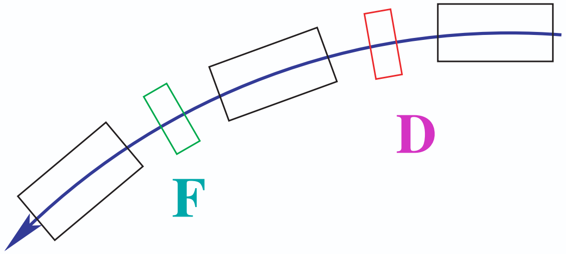
$1/f = 1/f_1 + 1/f_2 - D/f_1 f_2$

is overall focusing

with $1/f = D/f^2$

for $f = f_1 = -f_2$

together with bending magnets FODO lattice



N. C. Christofilos, unpublished manuscript in 1950 and patent

Courant, Snyder in 1952, Phys. Rev. 88, pp 1190 - 1196 + longer review in Annals of Physics 3 (1958)

Betatron motion

Equation of motion of particles in a ring (with bending fields) **and quadrupoles** (field gradients $\propto \partial B/\partial r$)

In both transverse planes, here written with x for x, y : known as Mathieu-Hill equation

$$x''(s) + k(s)\,x(s) = 0,$$

derived in 1801 to describe planetary motion

Generalised oscillator equation with position dependent, periodic restoring force $k(L+s) = k(s)$ given by the quadrupole gradients (+ the small weakly focusing bending term in the ring plane)

Solution :

$$x(s) = \sqrt{\epsilon\,\beta(s)}\,\cos(\mu(s)+\phi)$$

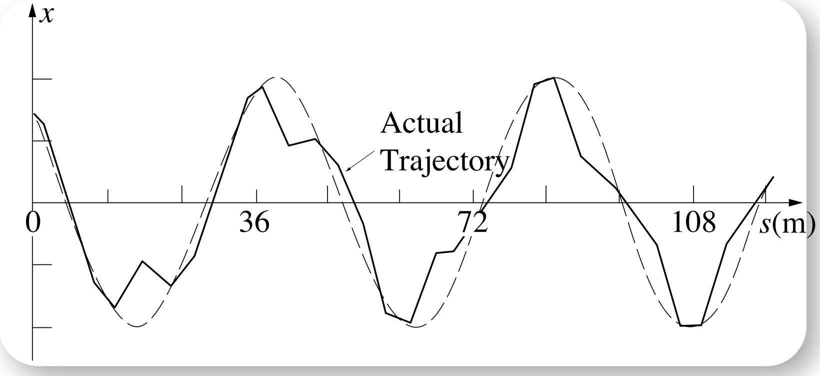
Phase advance

Lyapunov-Floquet Transformation

$$\mu(s) = \int_0^s \frac{ds}{\beta(s)}$$

Tune # of betatron oscillations

$$Q = \mu\,/\,2\pi$$



motion $x/\sqrt{\beta}$ *plotted with phase advance normalised coordinates - becomes simple cos*

$\boldsymbol{\beta(s)}$ **beta function**, describes the focusing properties of the magnetic lattice

$\boldsymbol{\varepsilon}$ invariant, together with $\beta(s)$ amplitude. "single particle emittance"

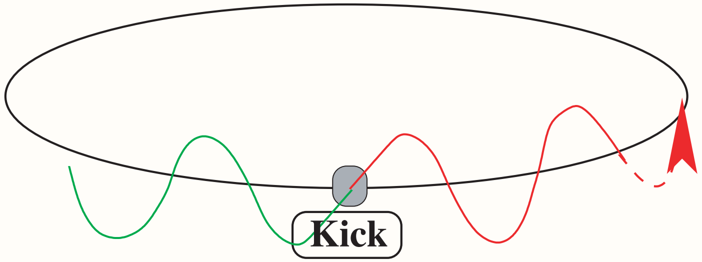
Motion conveniently described in phase space (x, x') where $x' = p_x / p$

and linear optics elements as matrices ; with simple case for M, applies for IP to IP

$$\begin{pmatrix} x(s) \\ x'(s) \end{pmatrix} = \mathbf{M} \begin{pmatrix} x(s_0) \\ x'(s_0) \end{pmatrix} \qquad \mathbf{M} = \begin{pmatrix} \cos 2\pi Q & \beta \sin 2\pi Q \\ -\frac{1}{\beta}\sin 2\pi Q & \cos 2\pi Q \end{pmatrix}$$

Accelerator design : starts with magnet lattice based on linear beam optics ; MAD program

Orbit stability and tune

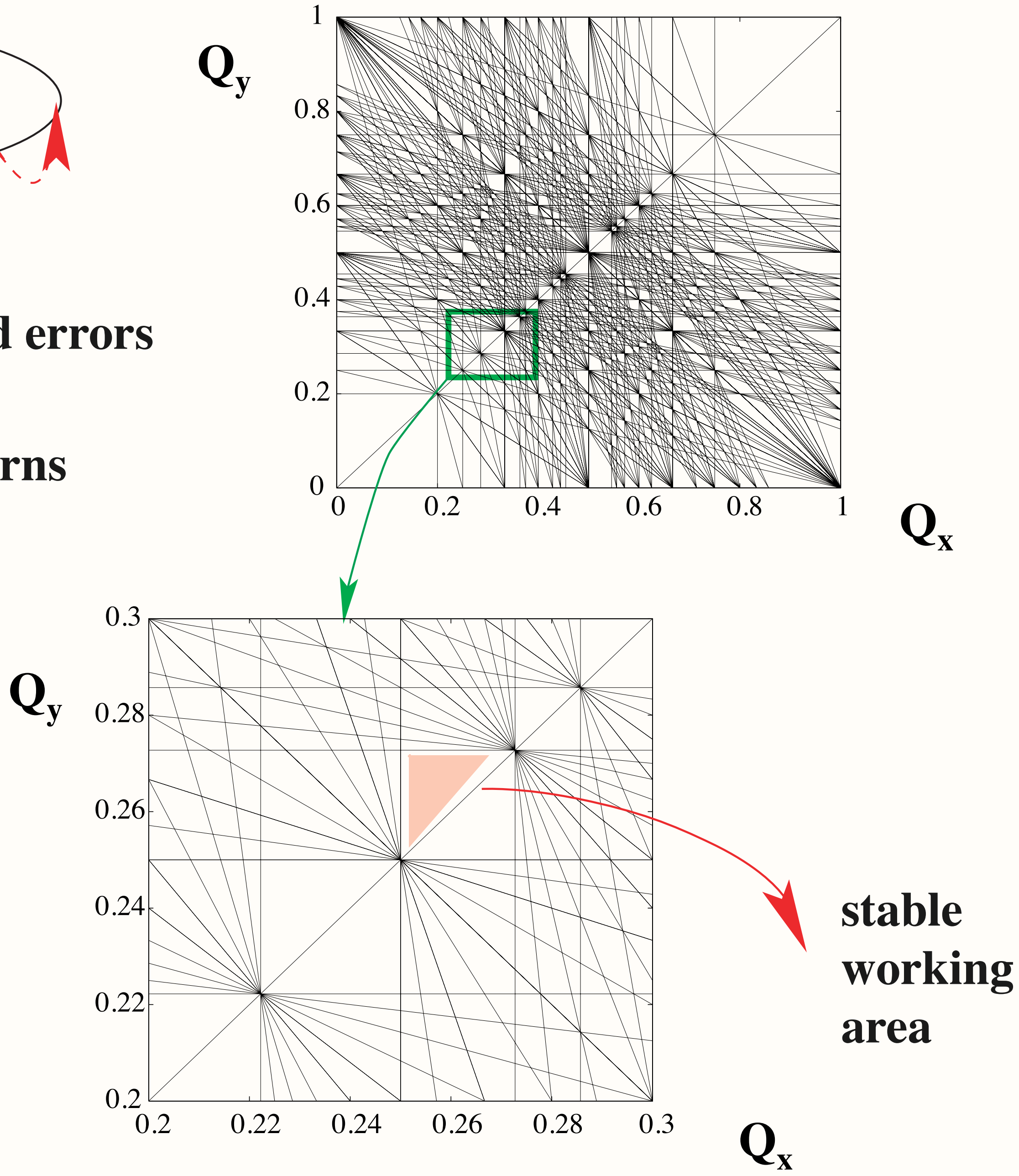


Misalignments and dipole field errors

→ orbit perturbations

would add up on successive turns

for integer tune Q = N



Higher order field errors,

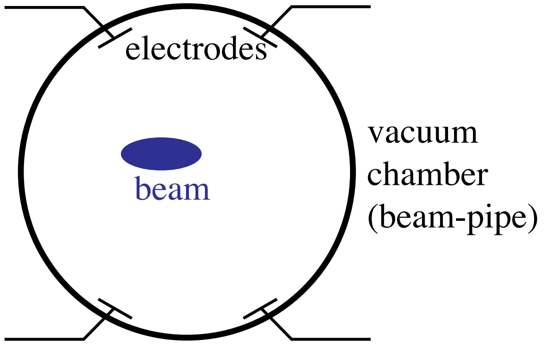
Quad., Sext. perturbations.

Avoid simple fractional tunes

$nQ_x + m\,Q_y + m\,Q_s = \text{int.}$

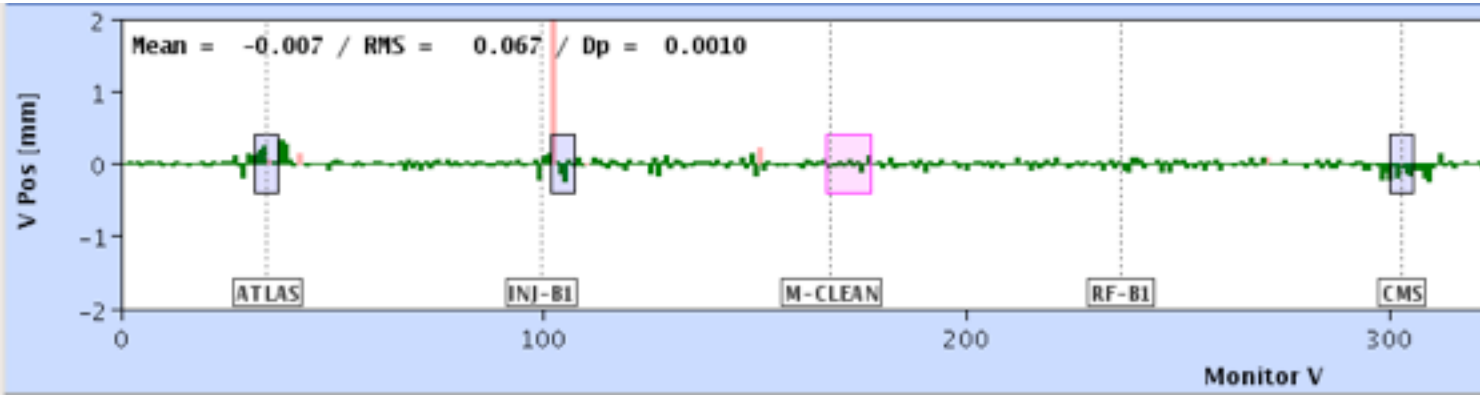
Minimise field and alignment errors

Orbit, tune measurement and peak beam current



Beam Pickup Monitor

vertical **orbit, June 2011, 1st half of LHC shown**



$\langle I_b \rangle$ average ring
and
$\hat{I}$ local peak
current

$$\hat{I} = \frac{\langle I_b \rangle L}{\sqrt{2\pi}\,\sigma_z}$$

Typical numbers, for a single bunch $\langle I_b \rangle = n\, e\, f_{rev}$

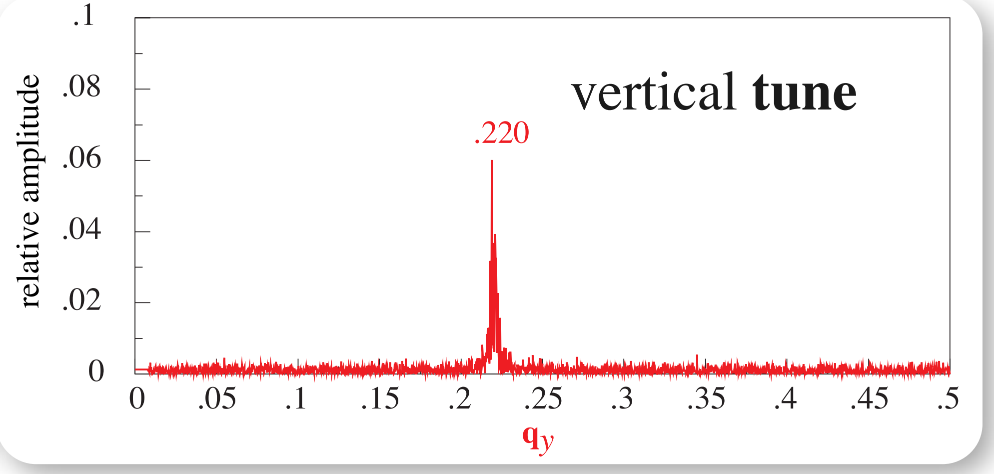
LEP $n = 4\times10^{11}$ $\langle I_b \rangle = 0.72$ mA $\sigma_z = 2$ cm $\hat{I} = 960$ A

LHC $n = 1.15\times10^{11}$ $\langle I_b \rangle = 0.21$ mA $\sigma_z = 7.55$ cm $\hat{I} = 73.2$ A

$f_{rev} = 11245$ kHz, $L = 26658.9$ m

Bunch peak currents are many Amperes !
Strong signals, used to monitor beam position and oscillations

Also source of undesirable effects :
wake fields, heating, instabilities



Transverse beam size and emittance

consider : beam of many particles on stable orbit and
simple case : dispersion and slope $\beta' = 0$ by default at IP - relevant for experiments

beam size, r.m.s. $$\sigma(s) = \sqrt{\varepsilon\beta(s)}$$

beam divergence, r.m.s. $$\theta(s) = \sqrt{\varepsilon/\beta(s)}$$

product $$\varepsilon = \sigma(s)\theta(s)$$

β - function : local machine quantity - focusing of lattice
Emittance ε : beam quantity - the average action

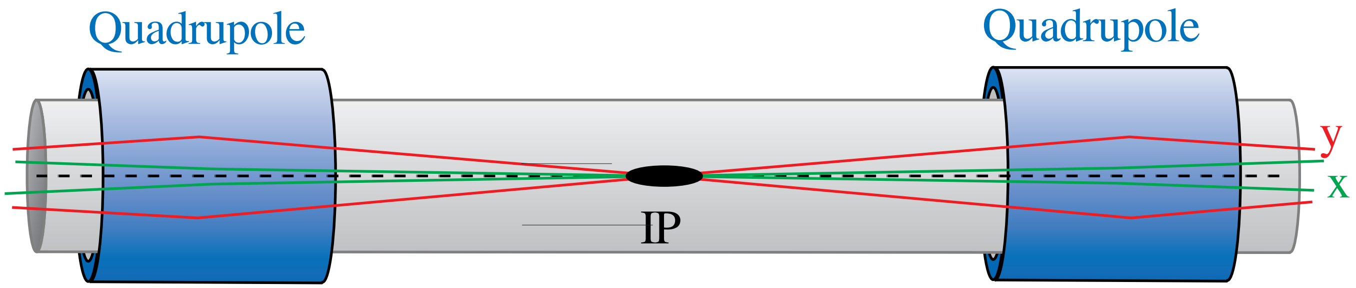
related to phase space density or kind of beam temperature

given by initial conditions (injected beam)

or equilibrium of quantum excitation and damping - 2nd lecture

in ideal machine : x, y, z motion uncoupled, 3 emittances ε_x, ε_y, ε_z

IP: squeeze β to a minimum, called β* ⇒ maximum of divergence, needs aperture



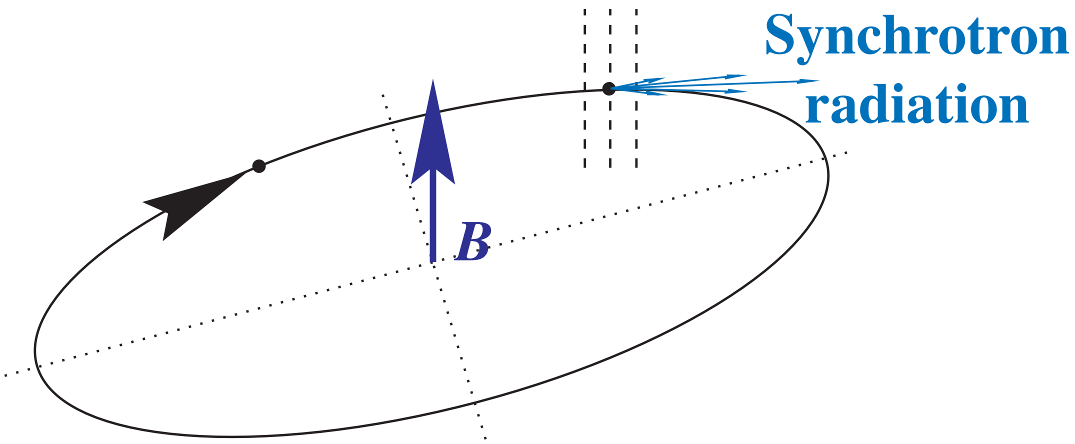
LHC $\varepsilon_N = \varepsilon\,\beta\gamma = 3.75\ \mu\text{m}$, at top $E_b = 7$ TeV: $\varepsilon = 0.503$ nm, $\beta^* = 0.55$ m, $\sigma^* = 16.63\ \mu\text{m}$, $\theta^* = 30\ \mu\text{rad}$

Standard Synchrotron Radiation

$$E_c = \frac{3}{2}\frac{\hbar c\gamma^3}{\rho} = 2.96\times 10^{-7}\mathrm{eV\,m}\,\frac{\gamma^3}{\rho}$$

$$U_0 = \frac{e^2}{3\varepsilon_0}\frac{\gamma^4}{\rho} \approx 6.0317\cdot 10^{-9}\ \mathrm{eV\ m}\ \frac{\gamma^4}{\rho}$$

$$P_b = \frac{U_0 I_b}{e}$$



		E GeV	γ	ϱ m	U_0 MeV	E_c keV	τ_d s	N 10^{12}	I mA	P_b MW	B T
RHIC	**Au**	**A×100**	**107.4**	**242.8**	**21×10^{-6}**	**1.5×10^{-6}**	**4.9×10^{6}**	**0.06**	**60**	**1.3×10^{-12}**	**3.42**
LHC	**p**	**7000**	**7460.5**	**2804**	**0.0067**	**0.044**	**61729**	**646**	**1163**	**0.0072**	**8.33**
LEP1	**e**	**45.6**	**89237**	**3026**	**126**	**69.5**	**23×10^{-3}**	**2.22**	**4**	**0.5**	**0.05**
LEP2	**e**	**104.5**	**204501**	**3026**	**3490**	**836**	**1.9×10^{-3}**	**2.8**	**5**	**18**	**0.115**

Same beam energy E and radius ϱ : electron instead of proton $U_0 \sim \gamma^4$: $(m_p/m_e)^4 = 1.13\times10^{13}$

Electrons, E >> 100 GeV needs linear collider (ILC / CLIC)

Damping time E / U_0 turns or $\tau_d = t_{rev}\, E / U_0$ revolution time LEP/LHC $t_{rev} = 88.9\ \mu s$

Gold ions Au^{79+} A=197 $<E_\gamma> = 8/(15\sqrt{3})\, E_c$ $8/(15\sqrt{3}) \approx 0.308$

Synchrotron light monitor

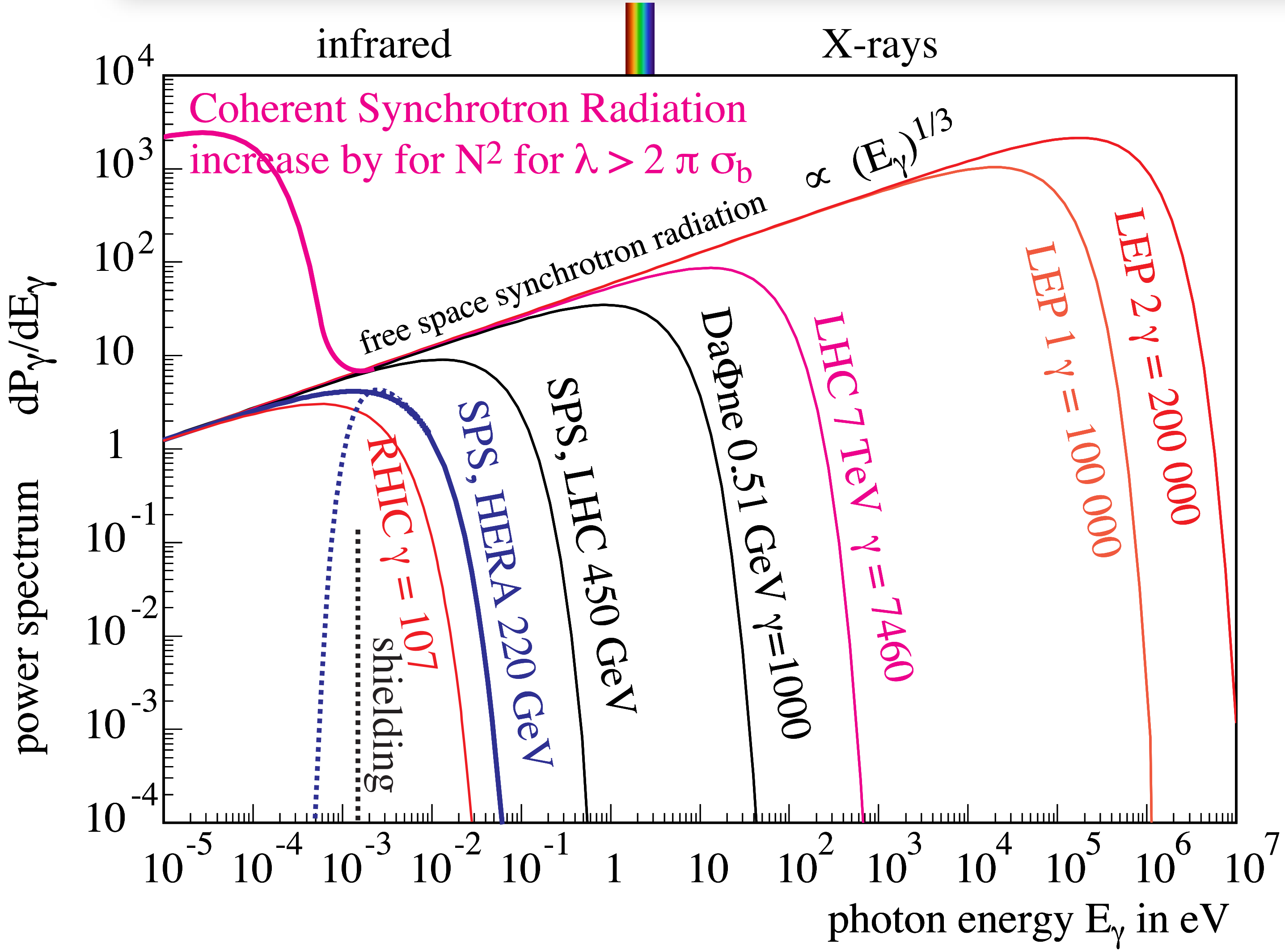
Picture from LEP. Typical transverse rms beam size 0.15 mm vertical 1.5 mm horiz.

SR-Telescope BEUV A 831 QS18.L8 Particle Electron

	Last Sample	Over 10 Samples
Std.Dev.X	0.899	0.897 ± 0.003
Std.Dev.Y	0.621	0.622 ± 0.004

Mirror, small slit, telescope and camera : beams continuously visible.
Now also used for protons in the LHC.

Power Spectrum, Free space, Cutoff and CSR



$$\frac{f_{\mathrm{cutoff}}}{f_{\mathrm{rev}}} = \sqrt{\frac{2}{3}}\left(\frac{\pi\rho}{h}\right)^{3/2}$$

ϱ bending radius

h chamber height

cutoff relevant

for $\gamma \approx 100$

12 orders of magnitude in E_γ and λ

10^{-5} eV $\lambda = 0.124$ m

10^{+7} eV $\lambda = 124$ fm

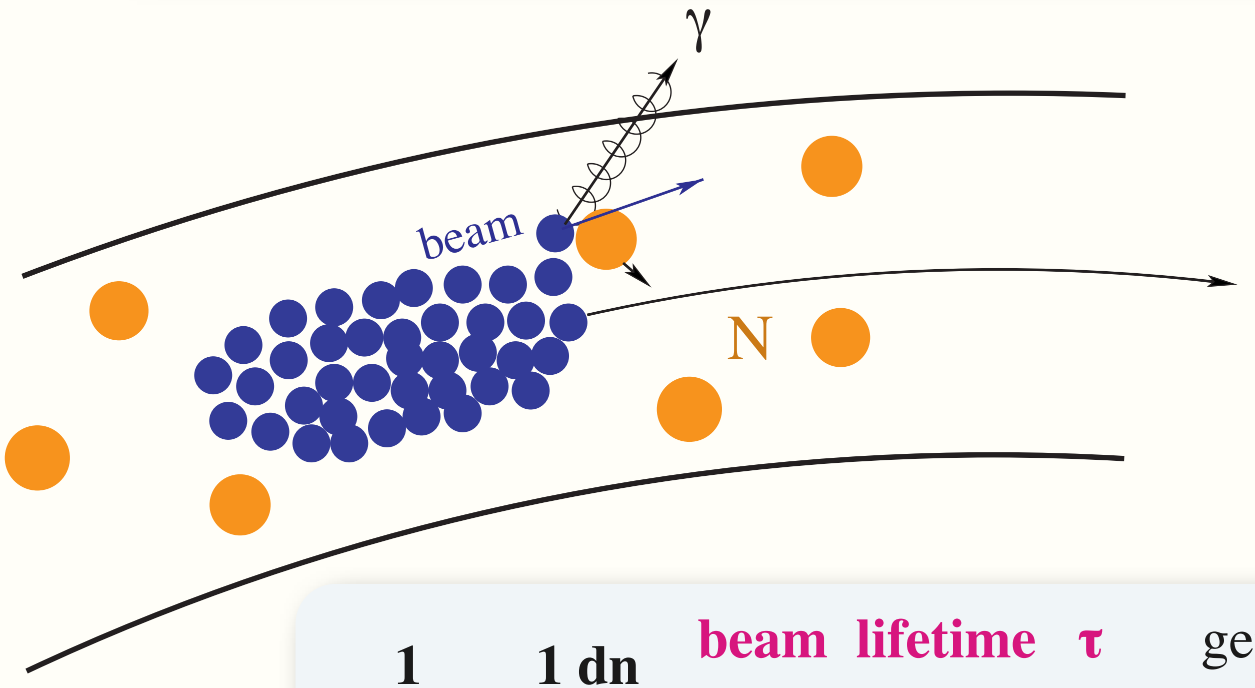
Effects which can modify the low energy, long wavelength spectrum :

i) Coherent Synchrotron Radiation CSR **increases radiation and loss**

ii) Boundary conditions - cutoff by conducting chamber **decreases radiation and loss**

Energy Loss of Gold Ions in RHIC, EPAC 2008

Vacuum, beam Gas - lifetime



Beam blow up, core + halo
Background to experiments
loss, radiation, beam and Luminosity lifetime

Minimize effect :
Good vacuum
O(nTorr or 10^{-9} mb)
Collimation

$$\frac{1}{\tau} = -\frac{1}{n}\frac{dn}{dt}$$

beam lifetime τ general expression
average time between collisions leading to beam loss
inverse normalised loss rate

$$p = 1\,\text{ntorr} = 1.33 \times 10^{-7}\,\text{Pa}$$

$$\rho_m = \frac{p}{kT} = 3.26 \times 10^{13}\text{molecules / m}^3$$

$$\text{typical cross section } \sigma = 6\,\text{barn} = 6 \times 10^{-28}\text{m}^2$$

$$\text{collision probability } P_{\text{coll}} = \sigma\,\rho_m = 1.96 \times 10^{-14}/\,\text{m}$$

$$\tau = \frac{1}{P_{\text{coll}}\,c} = 1.7 \times 10^5\,\text{s} = 47\,\text{hours} \qquad \text{for } v \approx c$$