Introduction to Accelerators

Helmut Burkhardt, CERN

HST Course, July 2006

Outline (2 + discussion lecture)

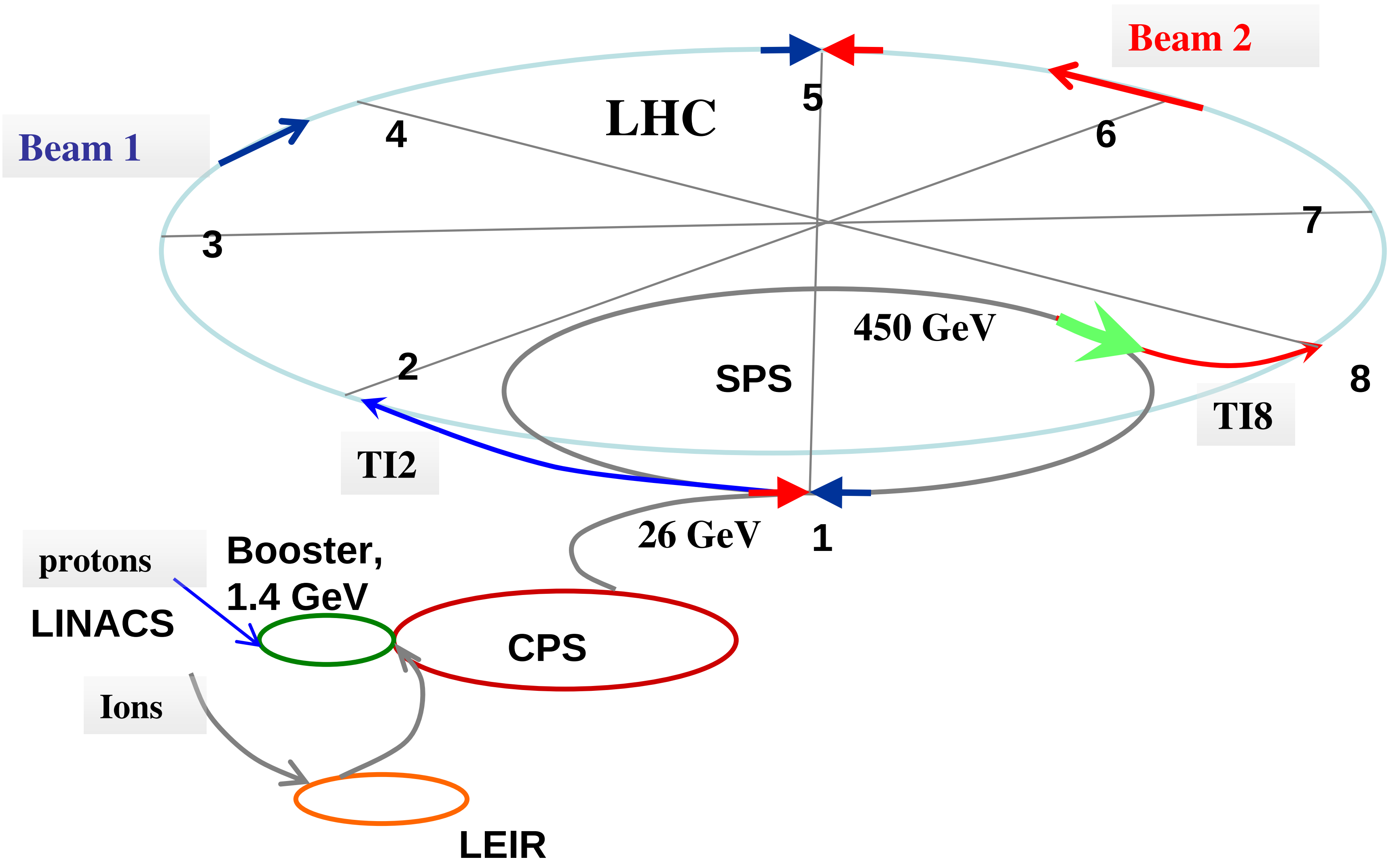
- Concepts: Energy Gain, E / B field. Units
- Types of accelerators. Linac, Ring, Collider
- Components: Source, Magnets, resonant Cavities
- Energy and Luminosity
- Synchrotron Radiation
- Electron vs Proton Colliders
- LEP, LHC, ILC

Both : Principles and examples of real bits and pieces with figures and number from CERN machines

Current and future challenges.

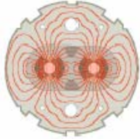
Acknowledgement : thanks to many of my CERN colleagues. In particular Oliver Brüning (HST previous years), Richard Scrivens (Sources), Werner Herr,…

The CERN accelerator complex: injectors and transfer




LEP Beam pipe
vacuum channel
131 mm x 70 mm beam channel
cooling channel
Single cell 1.3 GHz Tesla test cavity
LHC dipole magnet cross section
LHC cable NbTi

About Me



Helmut.Burkhardt@cern.ch http://hbu.home.cern.ch/hbu/Welcome.html

1978-1982 DESY/Hamburg, 1978 summer student at CERN
PhD Oct. 1982 in Exp. Physics at Hamburg University, study of e+e- coll. 14 - 35 GeV
Since then at CERN, as Fellow and Siegen Univ. PostDoc. Working on SPS proton fixed target experiments (protons 450 GeV)
μ likesign analysis ν - CDHS, NA31 direct CP violation experiment (HEPP-EPS price 2005)
ℵ Aleph-Experiment @ LEP 1985-1900 with Luminosity / Background monitors.

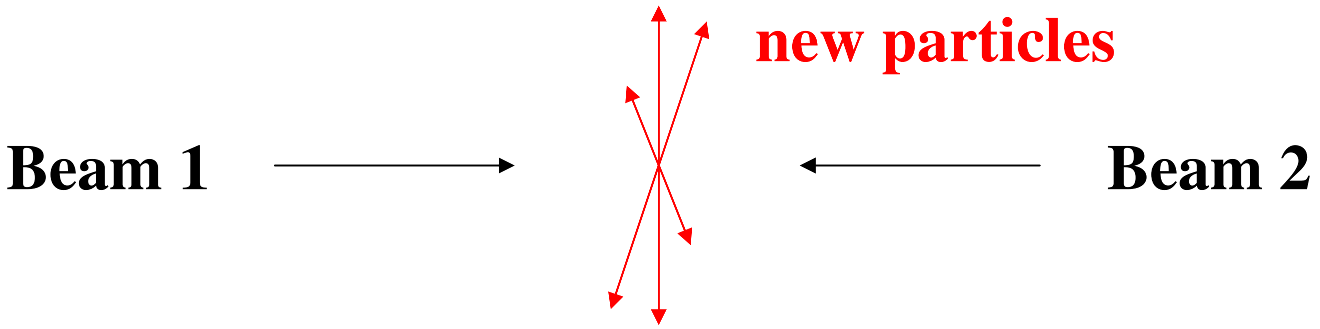
CERN-Staff (1990) :
1990 - SPS / LEP operation as "Engineer In Charge"
1995 - SPS / LEP machine coordination. LEP e+e-, 90 - 209 GeV
1999 - now :
Senior Accelerator Physicist in Accelerator Physics Group (AB/ABP)
Studies, improvements and upgrade of present (SPS) and design and commissioning of new/ future machines :
LHC 14 TeV pp, SPS-LHC transfer lines, ELFE study, ECFA-TESLA study, EuroTeV-ILC study 0.5 -1 TeV e+e- , CLIC study 3 TeV e+e-

Motivation

The progress of our understanding of fundamental particles and forces is very closely linked to the progress in accelerators.

What do I need to discover a new particle, like the Higgs ?

An accelerator which provides enough Energy and collisions (Luminosity)



new particles

Beam 1

Beam 2

LEP (e+e- collider @ CERN, 1990-2000) :

E = 90 - 209 GeV, ideal to study Z and W+W-.

e+e- --> H Z $m_Z \bullet 91$ GeV Leaves at best 209 - 91 GeV = 118 GeV.

Higgs not found in direct search at LEP. Implies $m_H > 114$ GeV

LHC will provide collisions at 14 TeV (7 TeV + 7 TeV protons) from 2008 on and directly produce Higgs and / or other new particles previously out of reach.

Progress in Accelerators : The Energy Frontier

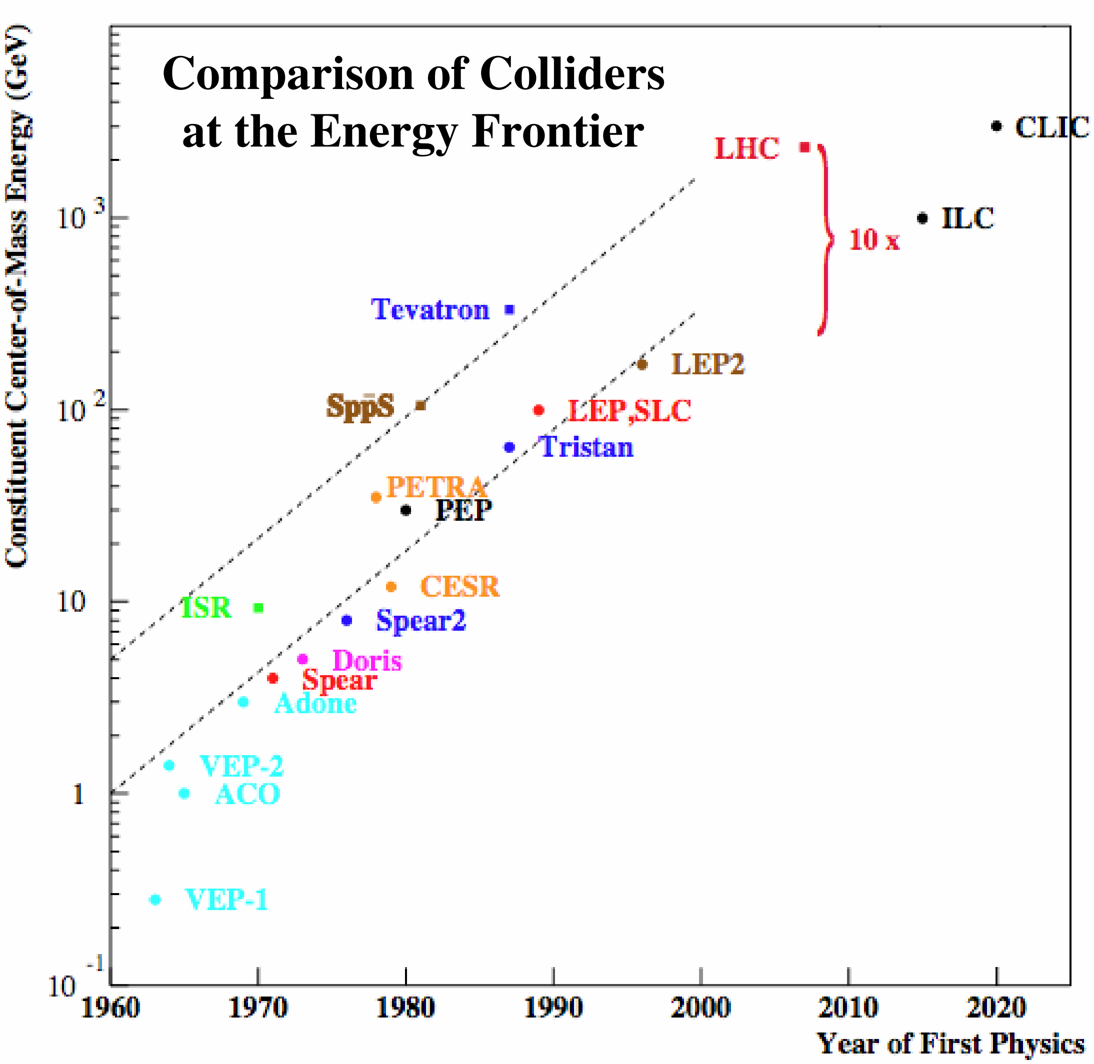
My current
version of the
Livingston Plot

Exponential growth
of E_{cms} in time

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

Factor 4 every 10 y

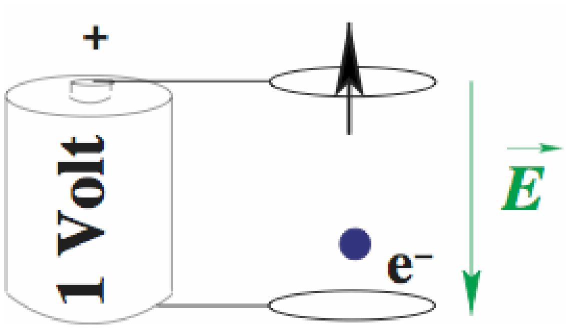
pp, $p\bar{p}$: E_{cms} / 6
5 x above
e^+e^- at same time
discovery machines.



Accelerator R&D was originally and still is to a large extent) driven by particle physics. Impressive progress.
Besides top energy: increase in intensity (number of particles), reliability, cost effectiveness.
Accelerators widely used as synchrotron light sources, for medicine (diagnosis and treatments),…

Concepts and Units

Electric E field:
Acceleration
or rather
Energy gain
of 1 eV



Electric charge e
and electric field **E**

$$1\,\text{eV} \approx 1.60 \times 10^{-19}\,\text{J} \qquad 1\,\text{GeV} = 10^{9}\,\text{eV} \qquad 1\,\text{TeV} = 10^{12}\,\text{eV}$$

$$m_e \approx 0.511\,\text{MeV}/c^2 = 9.11 \times 10^{-31}\,\text{kg} \qquad m_p \approx 938\,\text{MeV}/c^2 = 1.67 \times 10^{-27}\,\text{kg}$$

for precise numbers see http://pdg.lbl.gov/2005/reviews/consrpp.pdf

Einstein's special relativity, Lorentz transformation

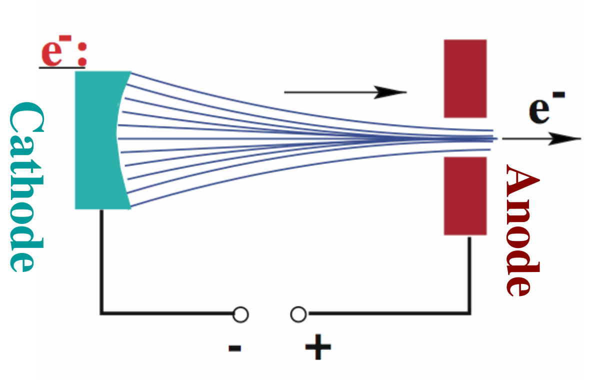
$$E = \gamma m c^2 \qquad p = \beta \gamma m c \qquad \beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

Comparison for 10 GeV total energy

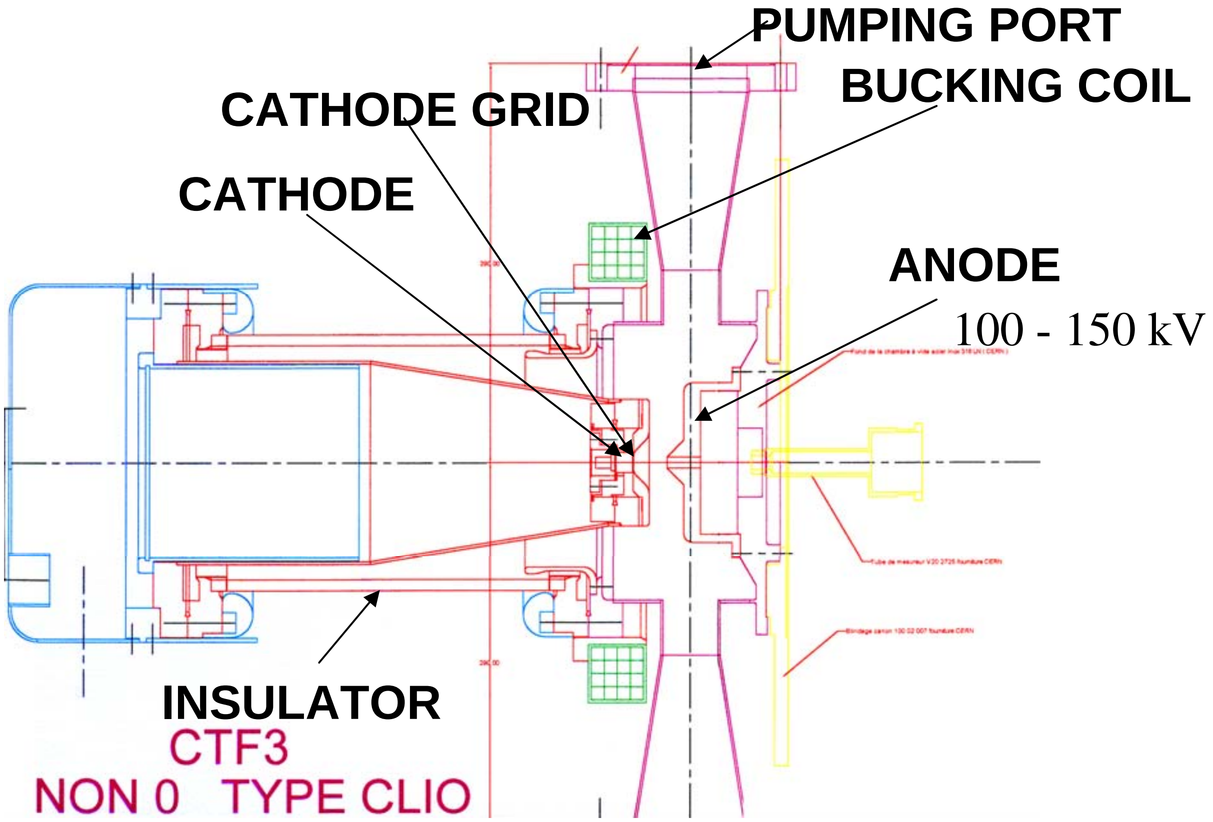
Electron	$\beta = 0.999\,999\,9987$	$\gamma = 19569.5$
Proton	$\beta = 0.995\,588\,4973$	$\gamma = 10.6579$

Particle sources

Thermionic electron source principle
(Cathode ray tube)



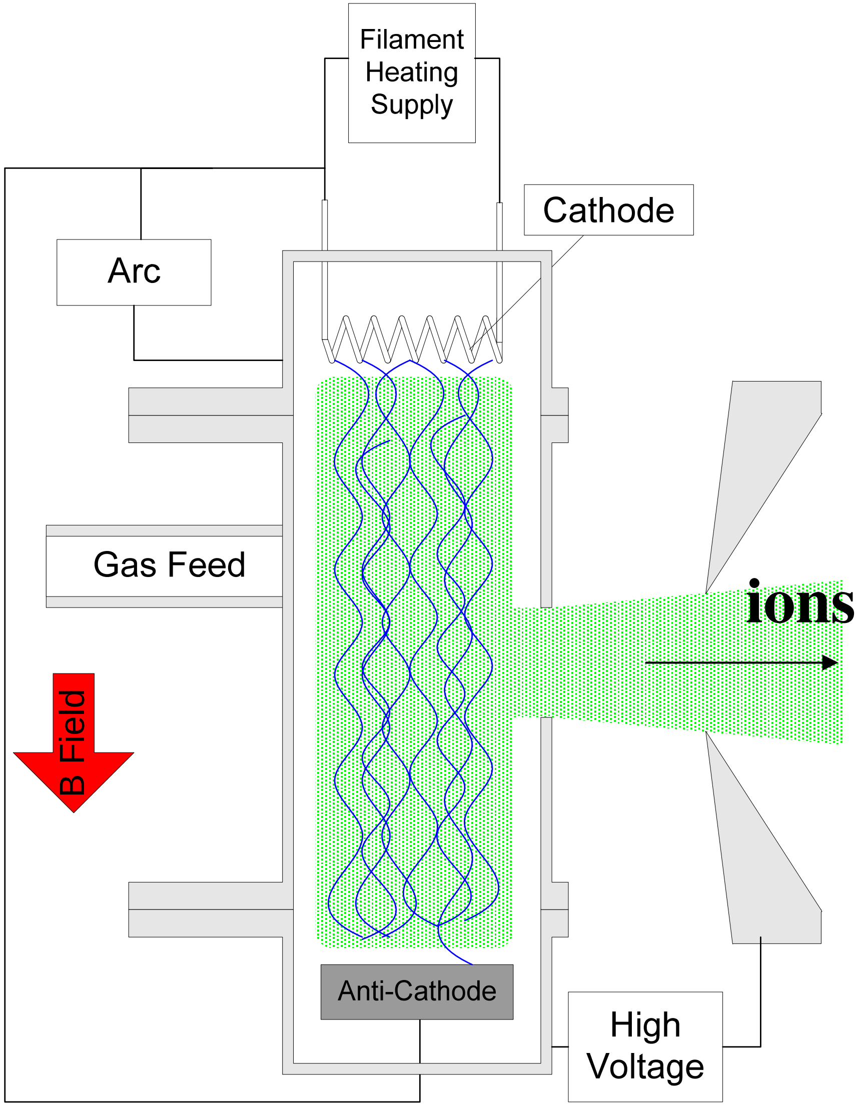
Example :
e-gun
in CTF3



Proton and ion sources

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

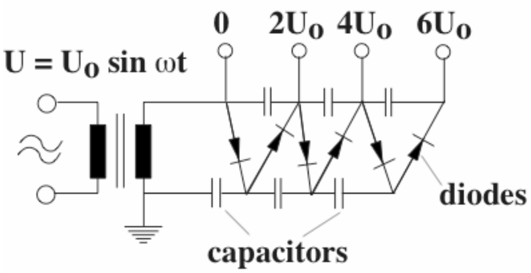
Typically involves :
low pressure heated gas
(ionized gas / plasma,
inject H_2 to get protons),
or surface sputtering,
electric and magnetic fields **(keep the electrons)**



Linear Acceleration with Electrostatic Field

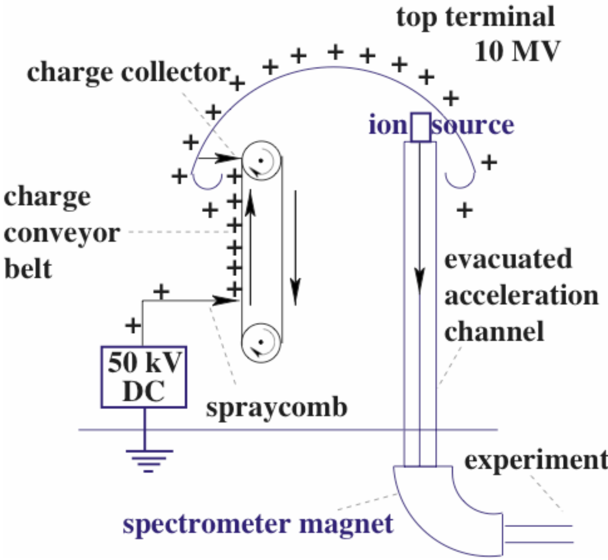
limited by HV-breakdown ~ 1 MV / m

Cockcroft Walton
voltage multiplier



800 kV proton pre-injector used at CERN until 1993

Van de Graaff generator
static electricity from belts

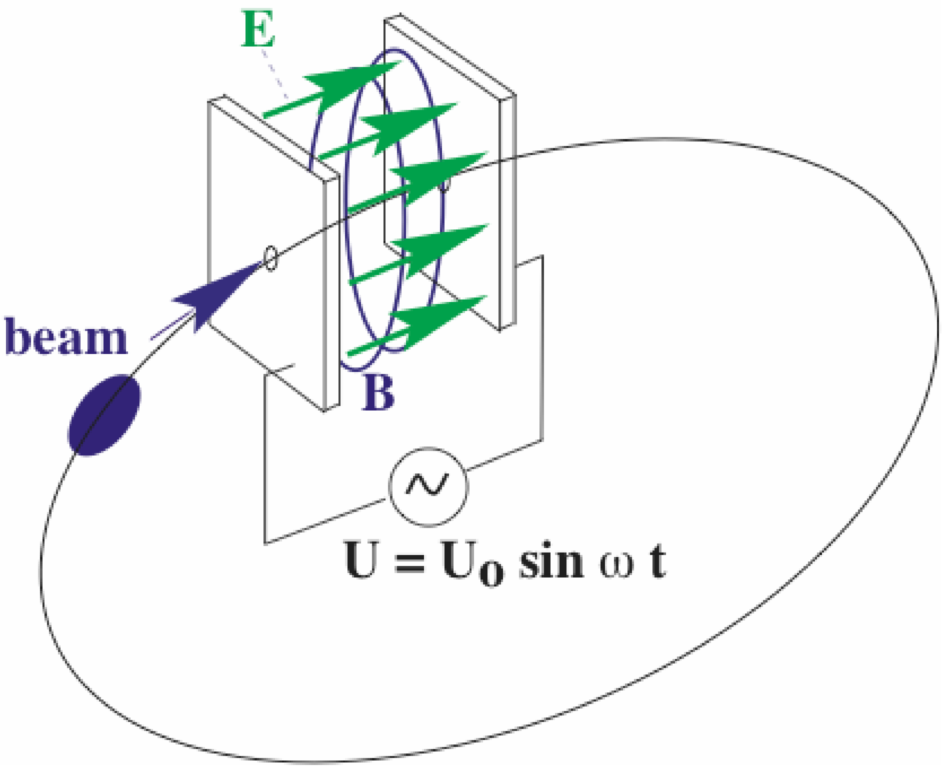


Oak Ridge Tandem Van de Graaff generator reached 25.5 MV using pressurised SF_6

Time Varying Fields

Radiofrequency or short RF acceleration

allow for multiple passages



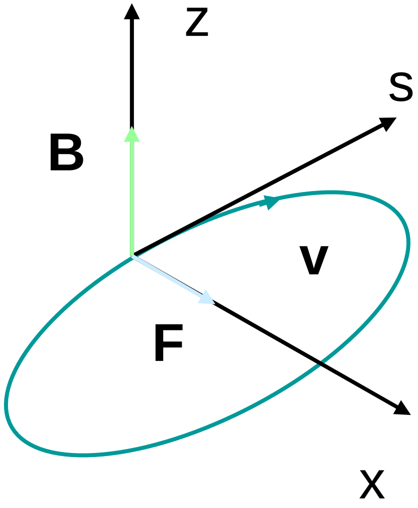
higher RF frequencies also allow for higher acceleration gradients no time for breakdown - flashover

LEP	8 MV / m at 352 MHz
Tesla / ILC	30 MV / m at 1.3 GHz
CLIC	150 MV / m at 30 GHz

Lorentz Force

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

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



Simple case - circular motion :

$$\mathbf{E} = 0 \qquad \mathbf{v} \perp \mathbf{B}$$

Example LHC:

- **Momentum p = 7000 GeV/c**
- **LHC bending radius ρ = 2804 m**
- **Bending field B = 8.33 Tesla**
- **Provided by superconducting magnets cooled with He to 1.9 K**

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

For q = e numerically

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

Circular Accelerator

- **Cyclotron : constant rf-frequency and magnetic field radius ρ increases with energy. Used for smaller machines**

- **Synchrotron : ρ = const. B increased with energy.**
  rf-frequency adjusted slightly ($\beta = 0.999..\ 1.0$)
  The CERN ring accelerators PS, SPS, LEP - LHC are of this type

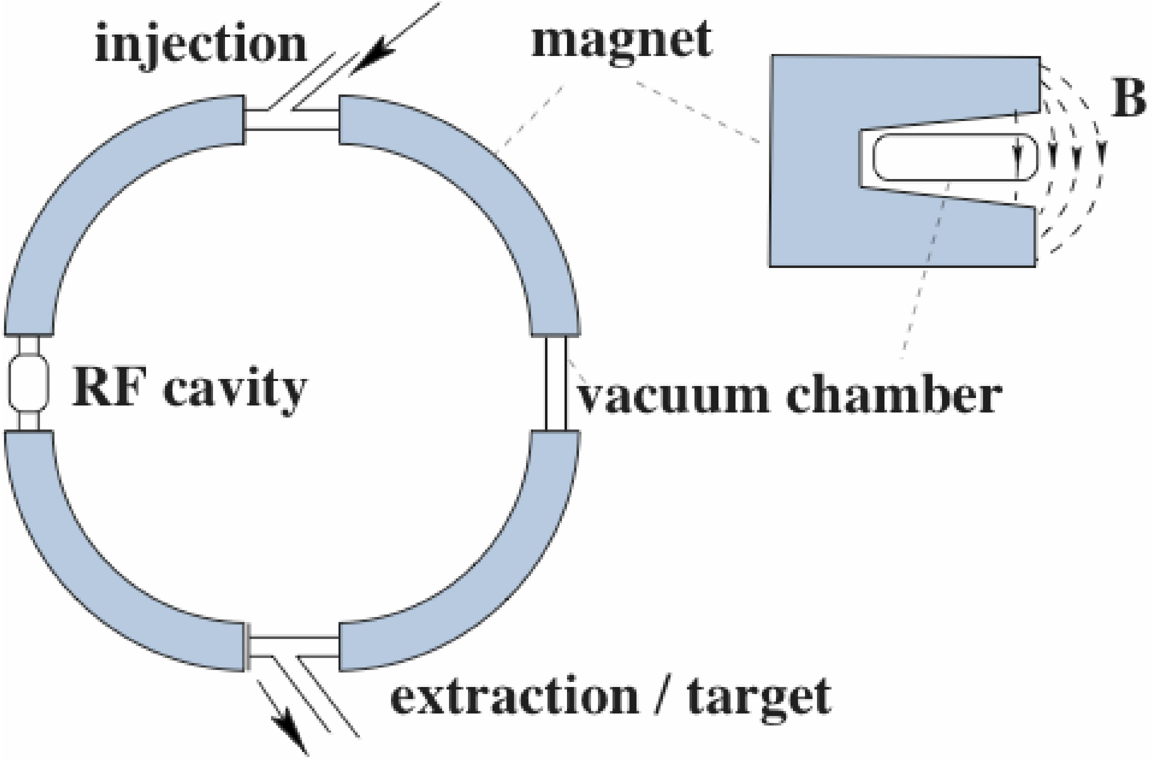
p [GeV/c] = B [T] ρ / 3.336 m

LHC:

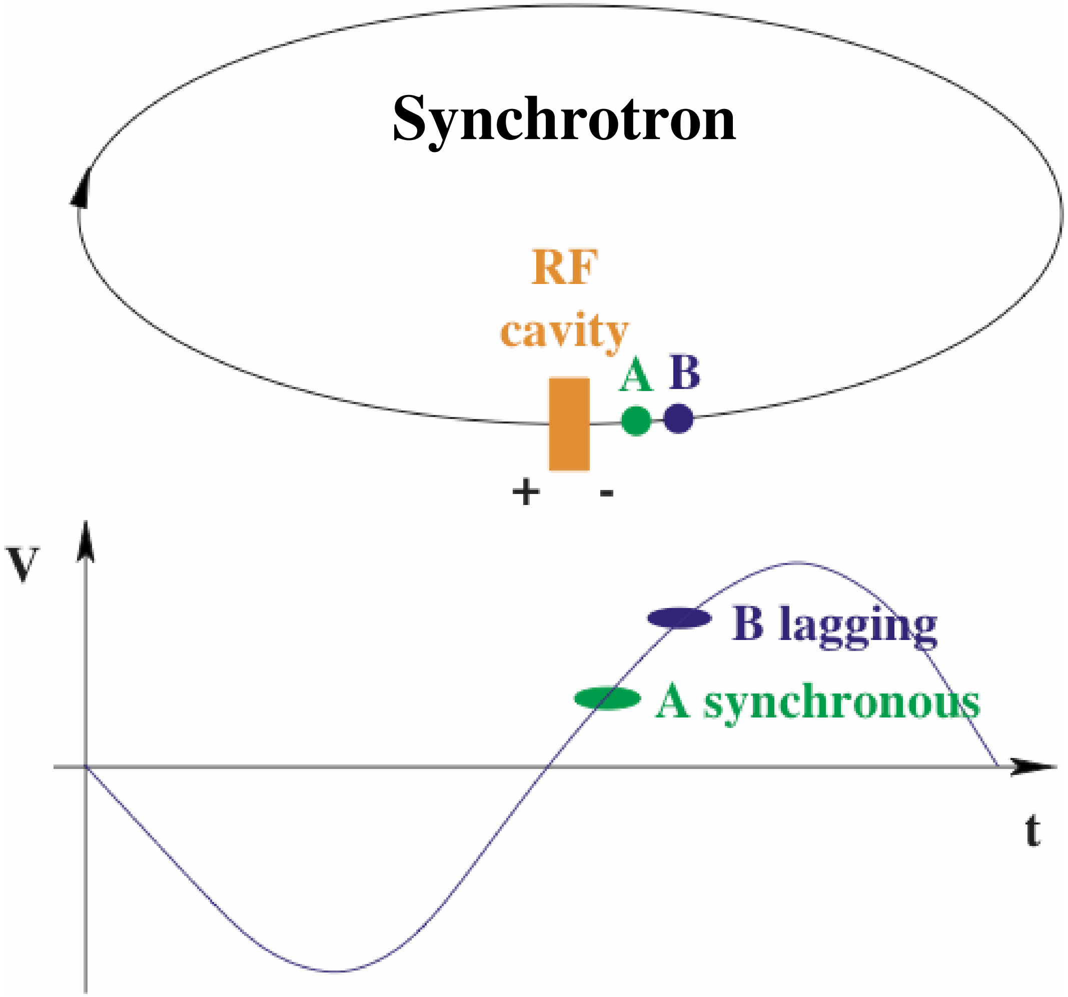
$B = 8.33$ T

$\rho = 2804$ m

$p = 7$ TeV / c



Phase stability I



Revolution frequency $f_{rev} = h\, f_{rf}$ LEP h=31320 $f_{rf} = 352.209$ MHz L = 26658.9 m

Circumference $L = v / f_{rev} = \beta\, c / f_{rev}$ $f_{rev} = 11.2455$ kHz 1 turn in 88.9244 µs

Magnets and Power Consumption

$$P = R I^2$$

LEP

$B = 0.1$ T

$I = 4500$ A $R = 1$ mΩ $P = 20$ kW / magnet

ca. 500 magnets → $P = 10$ MW

LHC $B \propto I$

$B = 8.38$ T

$I = 280$ kA $R = 1$ mΩ $P = 78$ MW / magnet

ca. 500 magnets $P = 39$ GW

Use superconducting technology !

Synchrotron Radiation

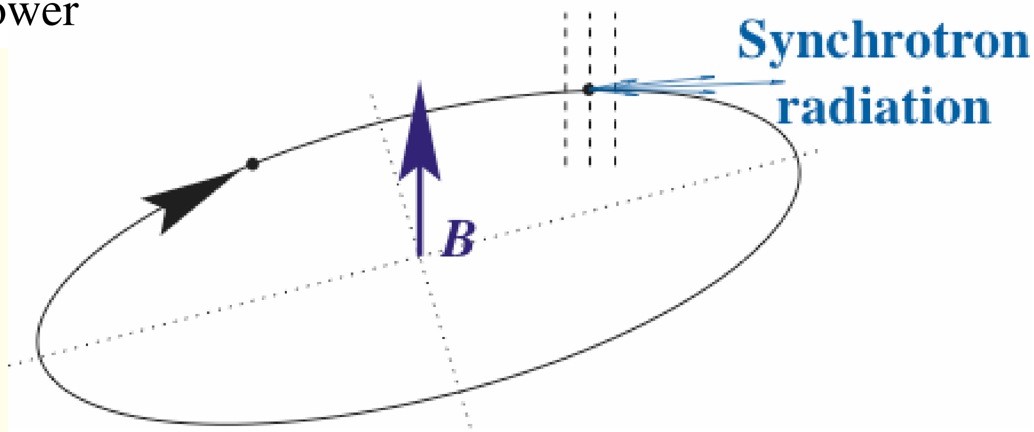
Generally : any accelerated charge emits radiation
Significant for highly relativistic particles $\gamma > 1000$ on curved path

Critical energy, energy loss / turn and Power

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

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

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

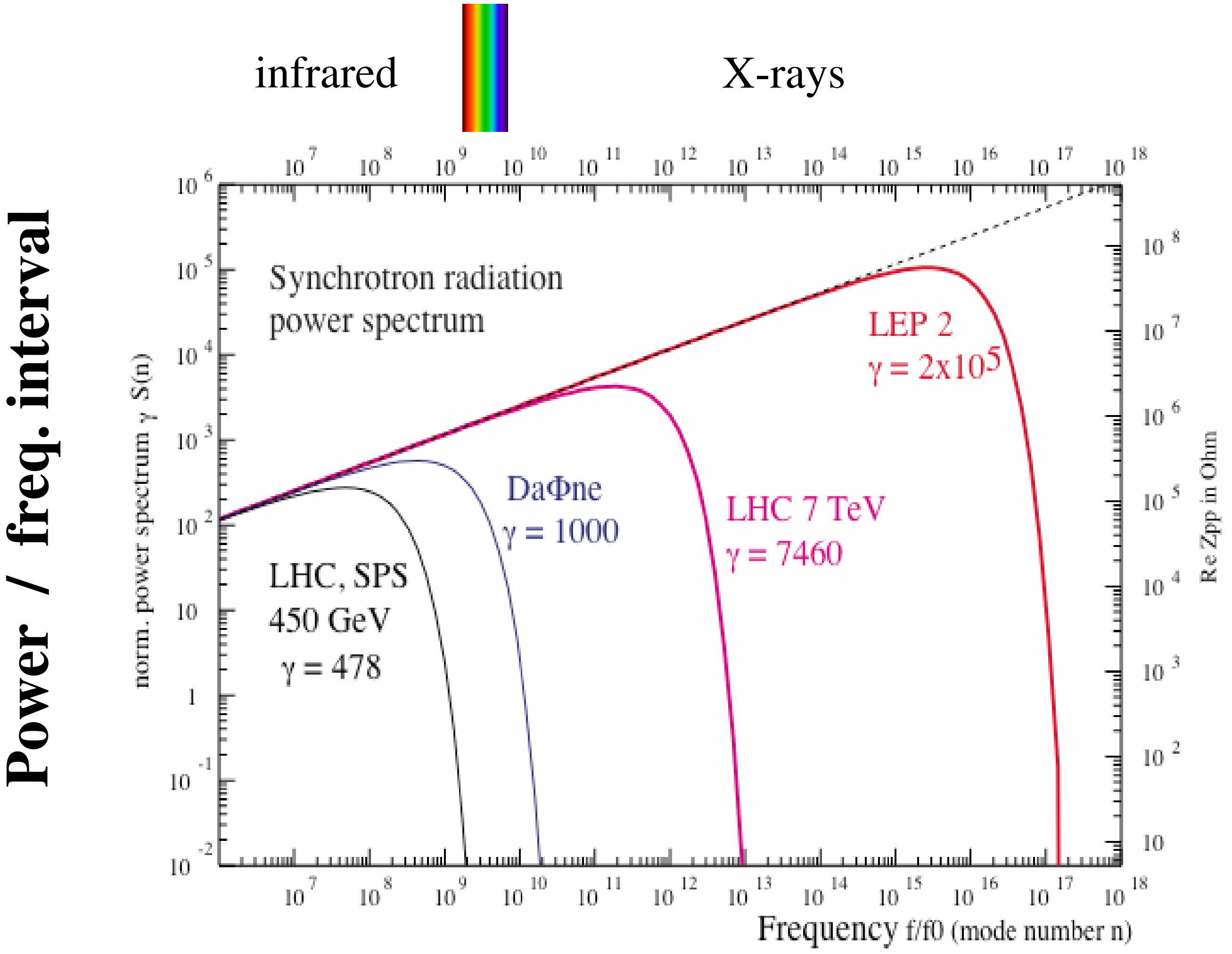


LEP : E_{bmax} = 104.5 GeV γ = 204501 ρ = 3026 m E_c = 836 keV
U_0 = 3.49 GeV total beam current I_b = 5 mA P_b = 18 MW
Limited by Energy Loss in Synchrotron Radiation / superconducting RF system
Magnetic field “only” 0.115 T
Much higher beam energy: needs linear collider (ILC / CLIC) or
LHC with p instead of e γ^4 : $(m_p/m_e)^4 = 1.13 \times 10^{13}$
E_b = 7 TeV, γ = 7460, U_0 = 6.7 keV/turn, E_c = 44 eV I_b = 1.07 A P_b = 7.2 kW

LEP / LHC syn.rad. comparison

	E GeV	ρ m	γ	E_c keV	U_0 MeV	N 10^{12}	I mA	P_b MW	B T
LEP1	45.6	3026	89237	69.5	126	2.22	4	0.5	0.05
LEP2	104.5	3026	204501	836	3490	2.8	5	18	0.115
LHC	7000	2804	7460.5	0.044	0.0067	646	1163	0.0072	8.33

Synchrotron radiation spectrum

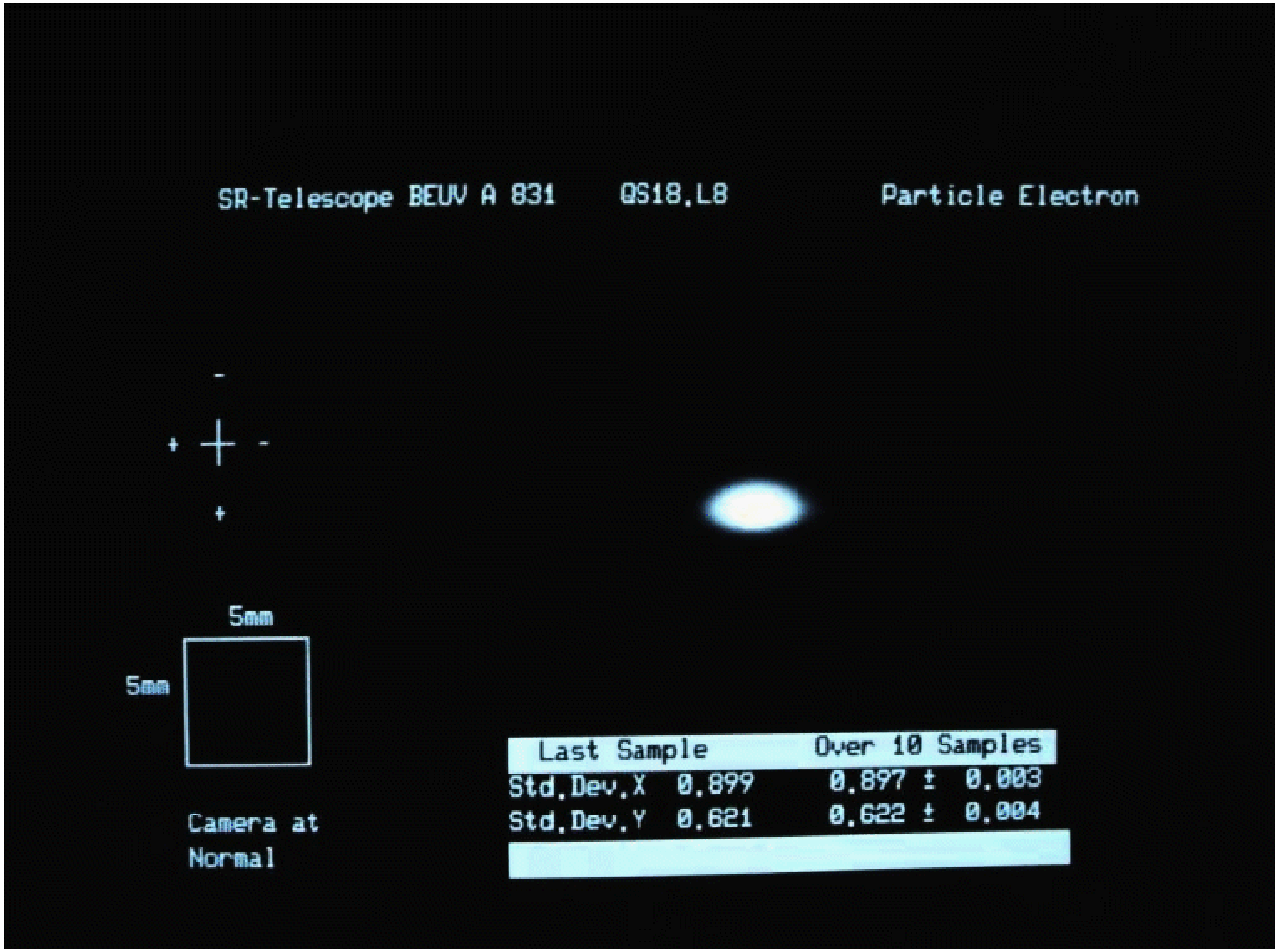


The long dipole synchrotron radiation spectrum is very broad. Half of the power is radiated above the critical energy.

With increasing E_b, γ the spectrum gets extended to higher energies / frequencies.

Synchrotron light monitor

Here a picture
from LEP.
Typical
transverse
rms beam size
0.15 mm vertical
1.5 mm horiz.

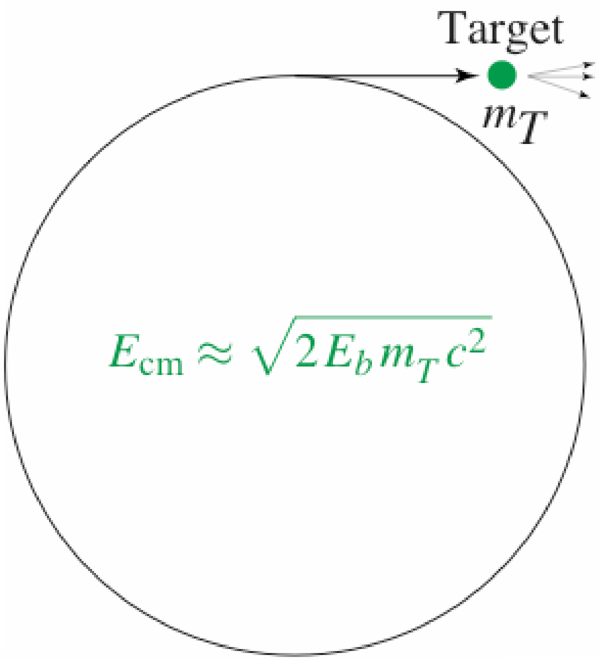


```
SR-Telescope BEUV A 831      QS18.L8            Particle Electron

Camera at
Normal

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

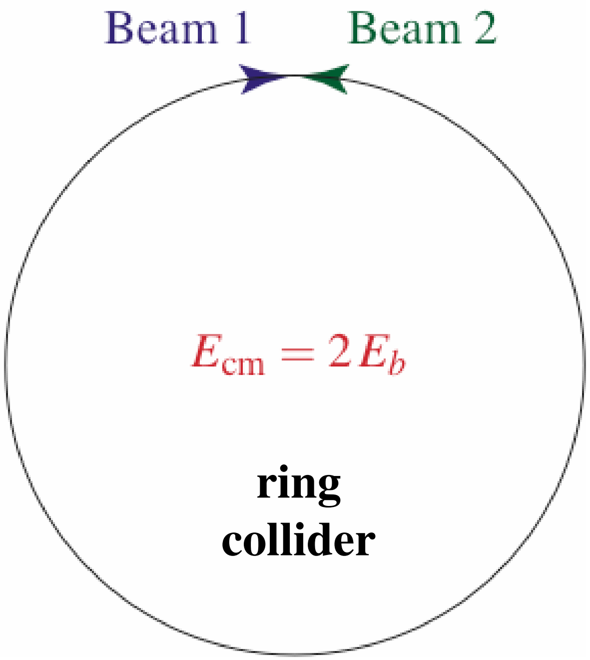
Mirror, telescope and camera : beams continuously visible.
Will also be used for protons in the LHC.

Fixed Target vs Collider

Fixed target, high energy collisions : Energy “lost” as kinetic energy

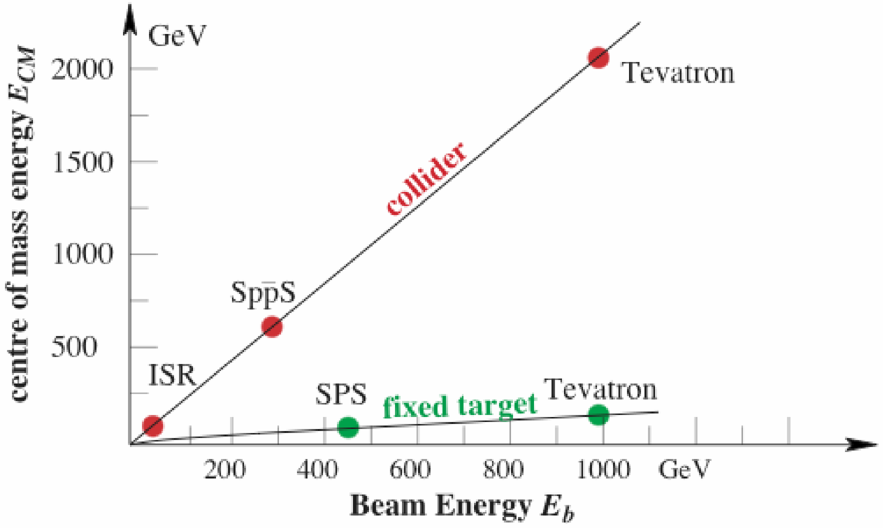


$$E_{\rm cm} \approx \sqrt{2\,E_b\,m_T\,c^2}$$



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

ring collider



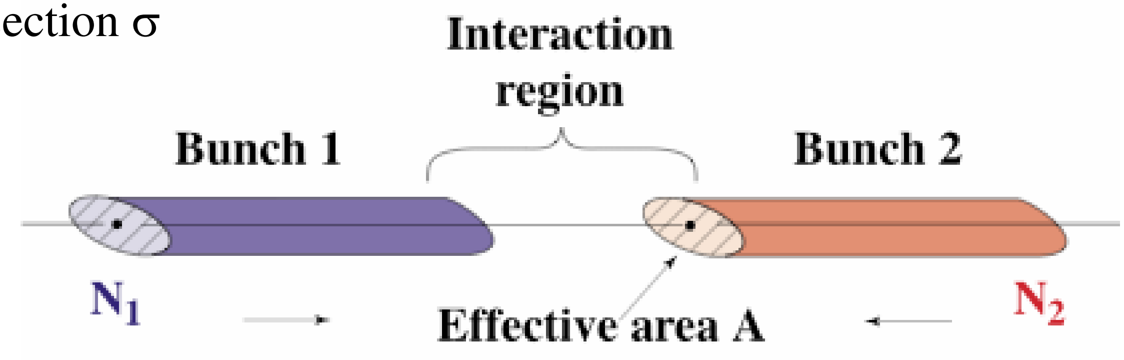
linear collider

High Energy e+e- and very high energy pp : needs colliders

Luminosity

Event rate for process with cross section σ

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



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

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

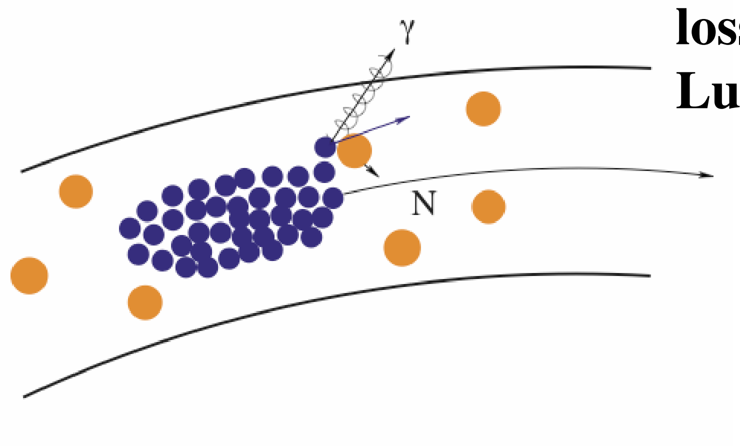
For Gaussian bunches with rms sizes $\sigma_x\ \sigma_y$ **A** $= 4\,\pi\,\sigma_x\,\sigma_y$

High **L** : collide many particles, squeezed in small bunches
LHC 1.15 x 10^{11} protons, $n_b = 2808$ (crossings at 25 ns intervals),
Beams squeezed using strong large aperture quadrupoles around the interaction points from ~ 0.2 mm to $\sigma_x = \sigma_y = 17\ \mu m$

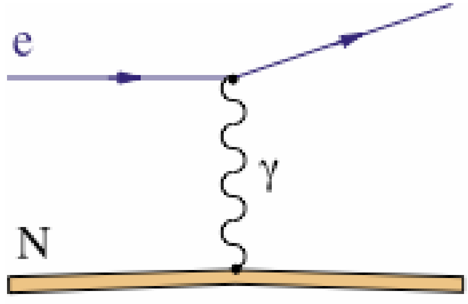
Rare new processes, like Higgs production can have very small cross section, like 1fb = $10^{-39}cm^2$. LHC designed for very high Luminosity $L = 10^{34}\ cm^{-2}s^{-1}$
Event rate for such rare processes : ~ 1 new particle every 28h. Instead pp 20 / crossing

Vacuum, Beam Gas interaction

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



Minimize :
Good vacuum
Collimation



elastic Mott (Coulomb) Scattering

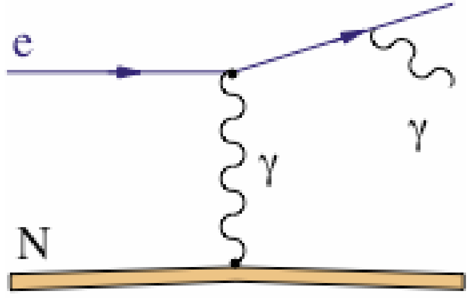
$$\rho_m = 1\,\mathrm{ntorr} = 1.33 \times 10^{-7}\,\mathrm{Pa}$$

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

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

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

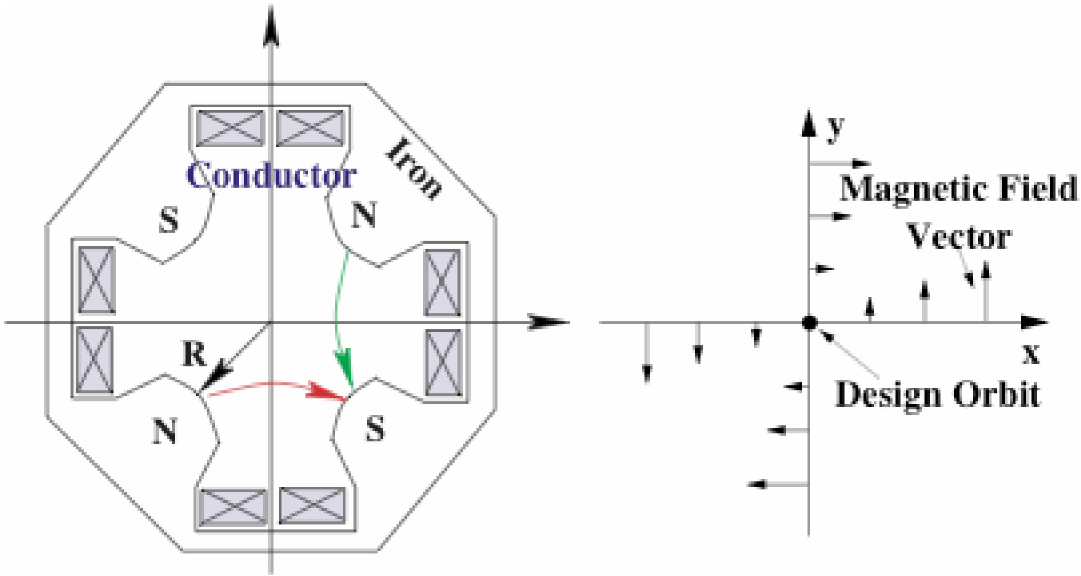
$$\text{for } v \approx c \quad 1 \text{ collision every } \frac{1}{P_{\mathrm{coll}}\,c} = 1.7 \times 10^{5}\,\mathrm{s} = 47\,\mathrm{hours}$$



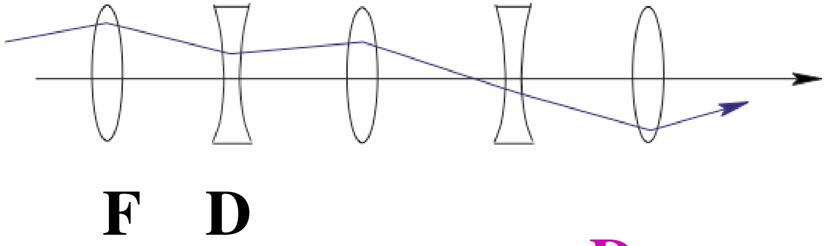
Bremsstrahlung

Quadrupole focusing

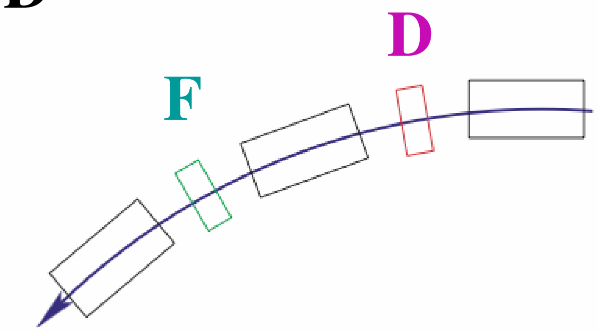
Lens
focusing in x
defocusing in y
or vice versa



alternate gradient focusing



FODO



Betatron Oscillations, β-Function and Tune

Here somewhat qualitatively. Formally: solve equation of motion : “Hill’s” equation.

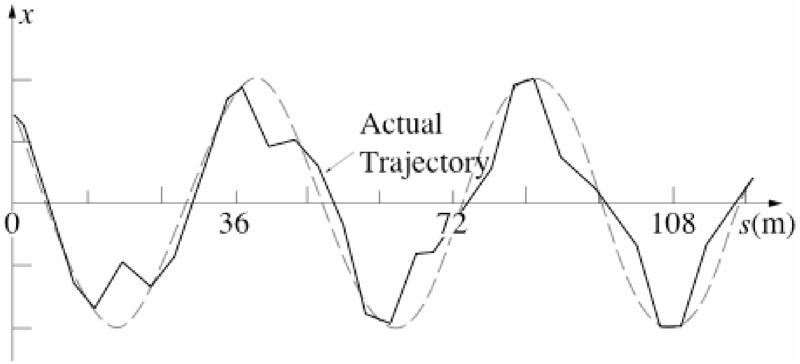
Courant and H. S. Snyder, 1957, Annals of Physics 281, 360

Particle trajectories:

Solution with betatron oscillations

around a stable orbit.

Tune **Q = number of betatron oscillations**

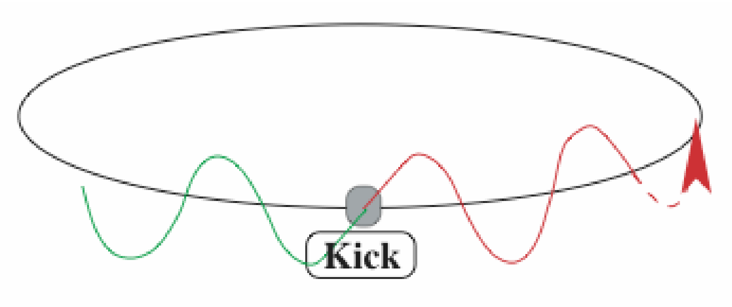


Magnets as lattice elements, to first order described by a linear transformation : Matrix multiplication with particle vector

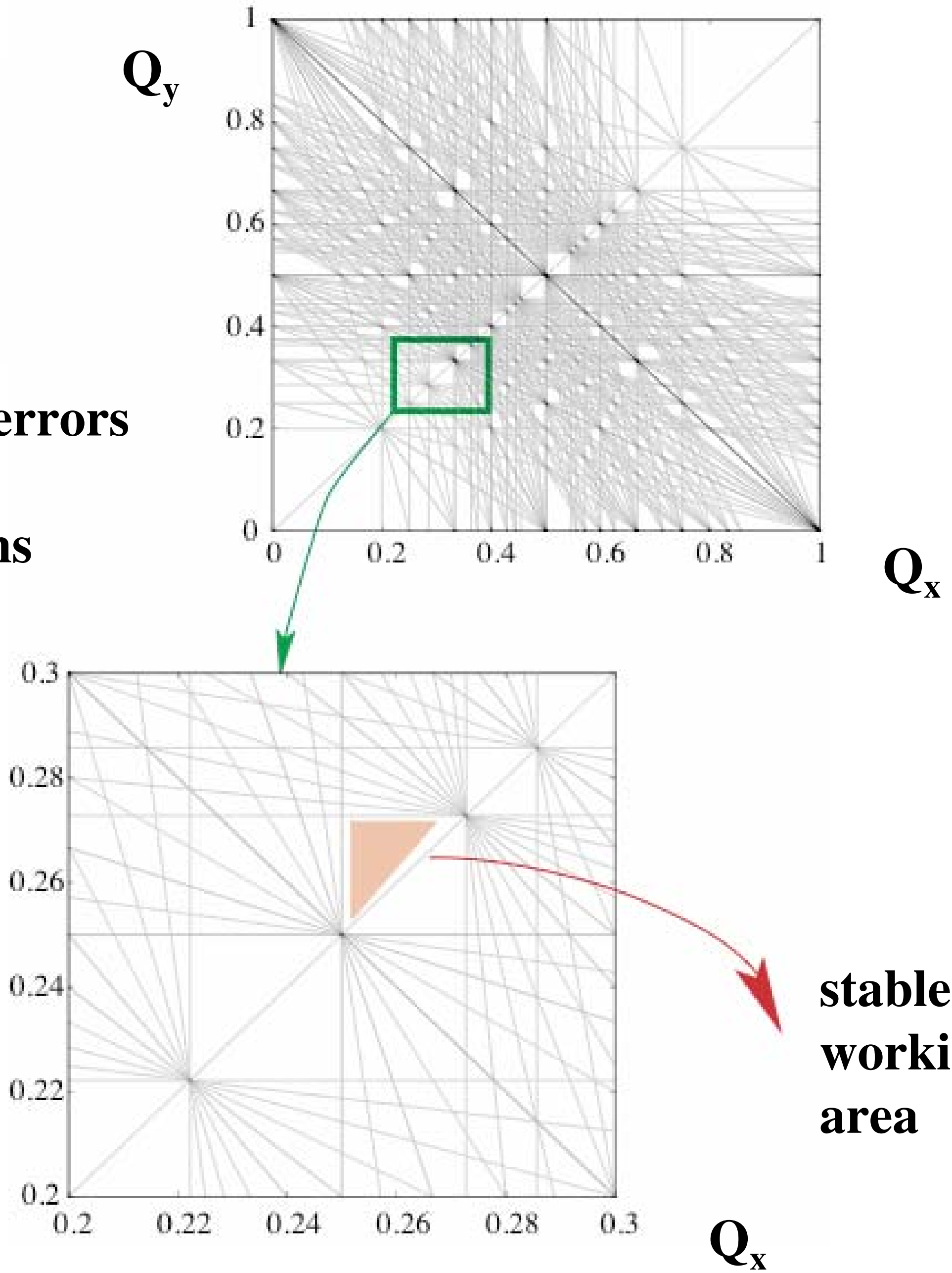
$$\begin{pmatrix} x(s) \\ x'(s) \end{pmatrix} = \mathbf{M} \begin{pmatrix} x(s_0) \\ x'(s_0) \end{pmatrix}$$

simple example, IP - IP $\mathbf{M} = \begin{pmatrix} \cos 2\pi Q & \beta \sin 2\pi Q \\ -\frac{1}{\beta} \sin 2\pi Q & \cos 2\pi Q \end{pmatrix}$

Orbit stability and tune



Misalignments and dipole field errors
→ orbit perturbations
would add up on successive turns
for integer tune Q = N

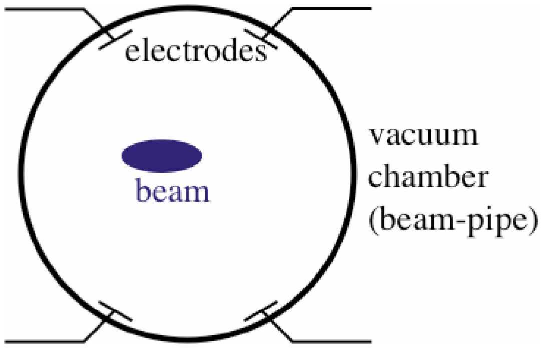


stable working area

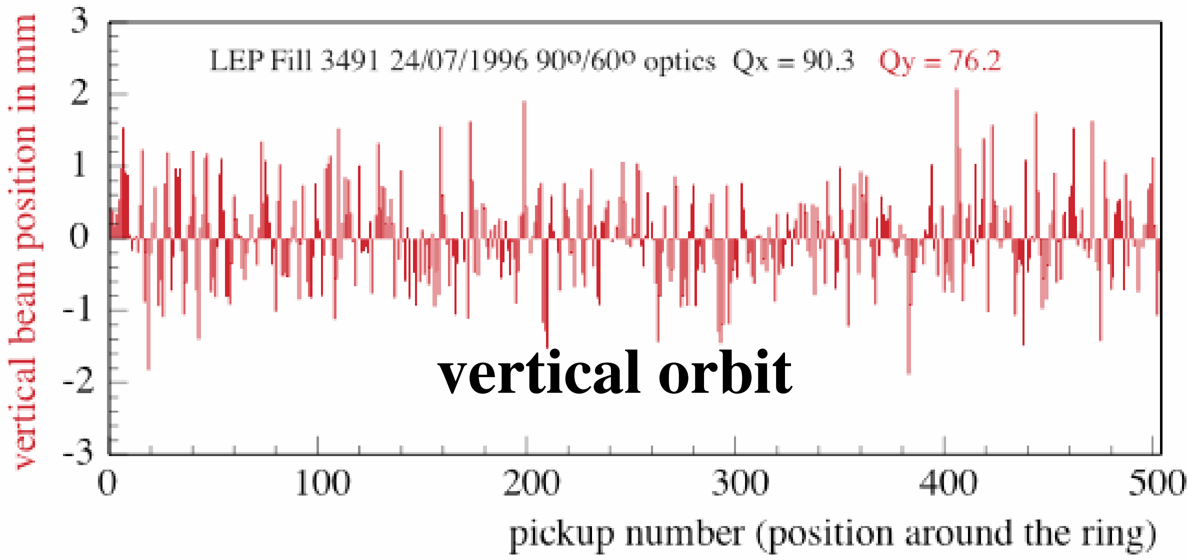
Higher order field errors,
Quad., Sext. Perturbations.
Avoid simple fractional tunes
$nQ_x + m\ Q_y + m\ Q_s = \text{int.}$

Minimise field and alignment errors

Orbit and Tune measurement, Peak current



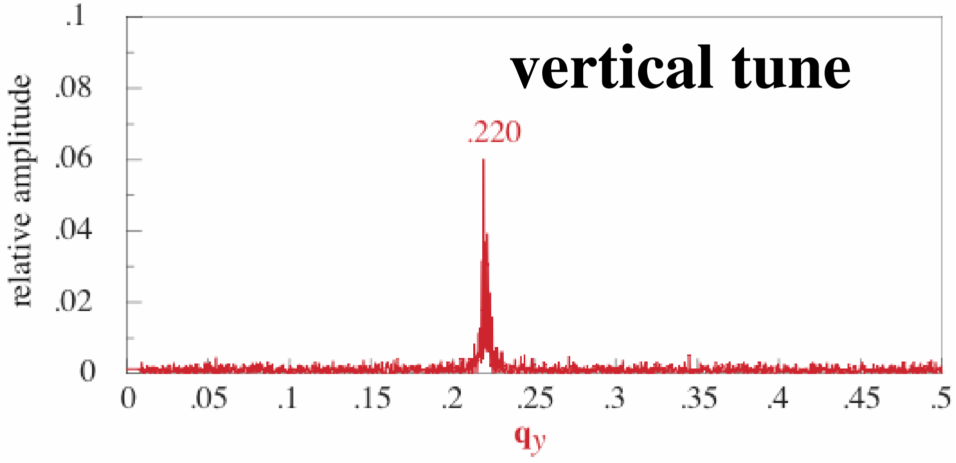
Beam **P**ickup **M**onitor



$$\langle I_b \rangle = n\, e\, f_{\mathrm{rev}} \qquad\qquad I = \frac{\langle I_b \rangle L}{\sqrt{2\pi}\,\sigma_z}$$

LEP $n = 4 \times 10^{11}$ $\langle I_b \rangle = 0.72\,\mathrm{mA}$ $\sigma_z = 2\,\mathrm{cm}$ $I = 960\,A$

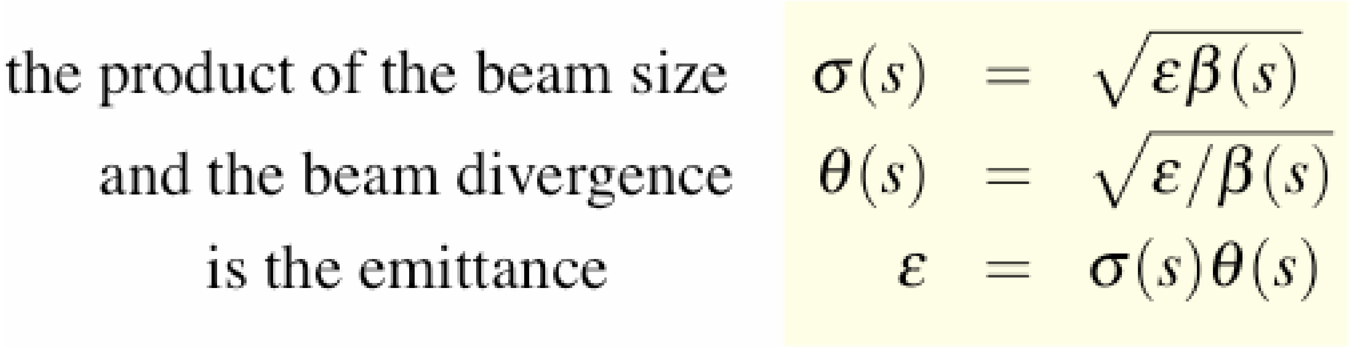
LHC $n = 1.15 \times 10^{11}$ $\langle I_b \rangle = 0.21\,\mathrm{mA}$ $\sigma_z = 7.55\,\mathrm{cm}$ $I = 73.2\,A$



LEP/LHC f_{rev} = 11245 kHz, L = 26658.9 m

Bunch peak currents are many Amperes !
“Easy” to measure. Unwanted effects :
wake fields, heating, ~ instabilities

Transverse Beam Size and Emittance



the product of the beam size $\sigma(s) = \sqrt{\varepsilon\beta(s)}$

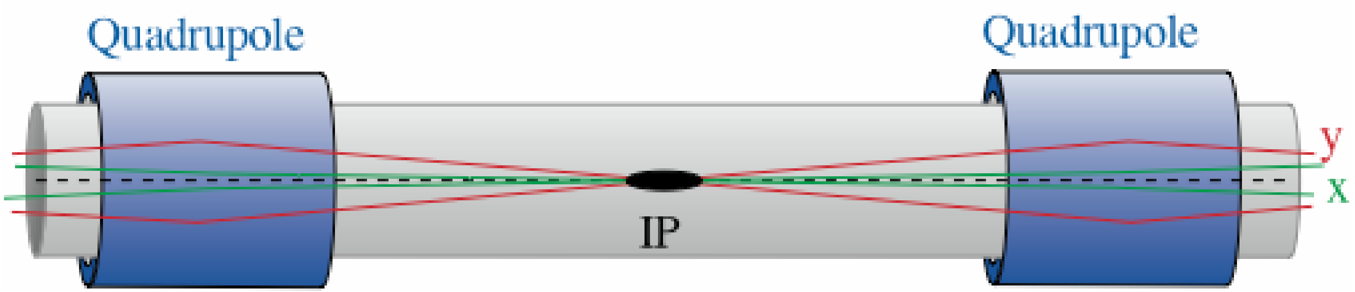
and the beam divergence $\theta(s) = \sqrt{\varepsilon/\beta(s)}$

is the emittance $\varepsilon = \sigma(s)\theta(s)$

The emittance ε is a constant for the machine (phase space density or kind of temperature)

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

IP: squeeze β to a minimal β* ==> maximum of divergence, aperture



Emittance

e+ e- ring : equilibrium emittance from synchrotron radiation quantum excitation and energy loss / rf-acceleration damping

Distance between synchrotron photon emissions

$$\lambda = \frac{\lambda_B}{B_\perp} \qquad \text{where} \quad \lambda_B = \frac{2\sqrt{3}}{5}\frac{mc}{\alpha e} = 0.16183\,\mathrm{Tm}$$

horizontal emittance :

$$\varepsilon_x = c_q \gamma^2 \frac{I_5}{I_2 J_x} \qquad \sim 30\,\mathrm{nm} \ \text{for LEP2}$$

vertical emittance < 1 nm
naturally flat large x, small y beams

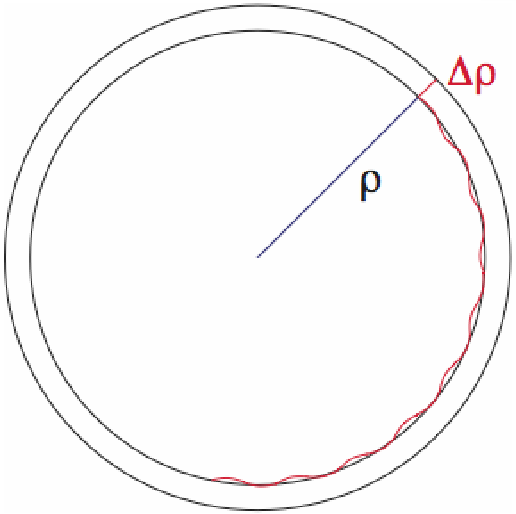
Linac, proton-ring (synchrotron radiation small) :

constant normalised emittance $\varepsilon_N = \beta\gamma\,\varepsilon$ 3.75 μm for LHC

geometrical emittance decreases in acceleration $\varepsilon = \dfrac{\varepsilon_N}{\beta\gamma}$ 7.8 → 0.5 from 0.45 to 7 TeV

Emittance given by injectors. For protons and ions typically round, $\varepsilon_x = \varepsilon_y$

Momentum compaction and transition



High energy : β • 1 revolution time constant
“no more acceleration” in velocity, v • c.
On the contrary. Higher momentum particles on longer path, slower in revolution : above transition.

$\Delta p / p = 10^{-3}$ should remain within the machine, say $\Delta\rho < 1$ mm. For large machines LEP/LHC we have $\rho = 3$ km. This implies strong momentum focusing
LHC : $\alpha_c = 3.4 \times 10^{-4}$

Also implies :
Large machines are very sensitive.
Very small circumference changes produce noticeable momentum changes.
tidal effects $\Delta L/L \sim 10^{-8}$ visible in LEP.

High (integer) tunes Q ~ 100
Still adjust fractional part to 10^{-3}
Need for precise magnet control ~ 10^{-5}

momentum compaction factor $\alpha_c = \frac{\Delta L}{L} \Big/ \frac{\Delta p}{p} \approx \frac{1}{Q^2}$

travelling time T and path length $L = vT = \beta c T$

relativistic change of velocity with momentum $\frac{dv}{dp} = \frac{1}{\gamma^2}\frac{v}{p}$

$$\frac{dT}{dp} = \frac{T}{p}\left(\alpha_c - \frac{1}{\gamma^2}\right) \qquad \frac{\Delta T}{T} = \underbrace{\left(\alpha_c - \frac{1}{\gamma^2}\right)}_{\eta}\frac{\Delta p}{p}$$

SPS $Q = 26.2$ $\alpha_c = 1.92 \times 10^{-3}$

transition when $\eta = 0 : \frac{1}{\gamma_{\text{tr}}^2} = \alpha_c$ SPS : $\gamma_{\text{tr}} = 22.83$

Bunch length and Damping

negligible synchrotron radiation :

rf- only needed to keep particles bunched and accelerate, which

Ramping usually very slow - of order seconds or minutes

$> 10^5$ turns, gain per turn small < MeV

Bunches can fill a large fraction of an rf-bucket

LHC $f_{rf} = 400$ MHz $\lambda_{rf} = 75$ cm $\sigma_z = 11$ cm (450 GeV)

in case of strong synchrotron radiation (e-rings):

Major loss U_o each turn, LEP2 : 3.5 GeV,

"all energy lost" in $E_b / U_o = 104.5$ GeV / 3.49 GeV = 30 turns or 3 ms - damping time

Major continuous "acceleration" from RF to compensate for loss.

Bunch length small faction of λ_{rf}.

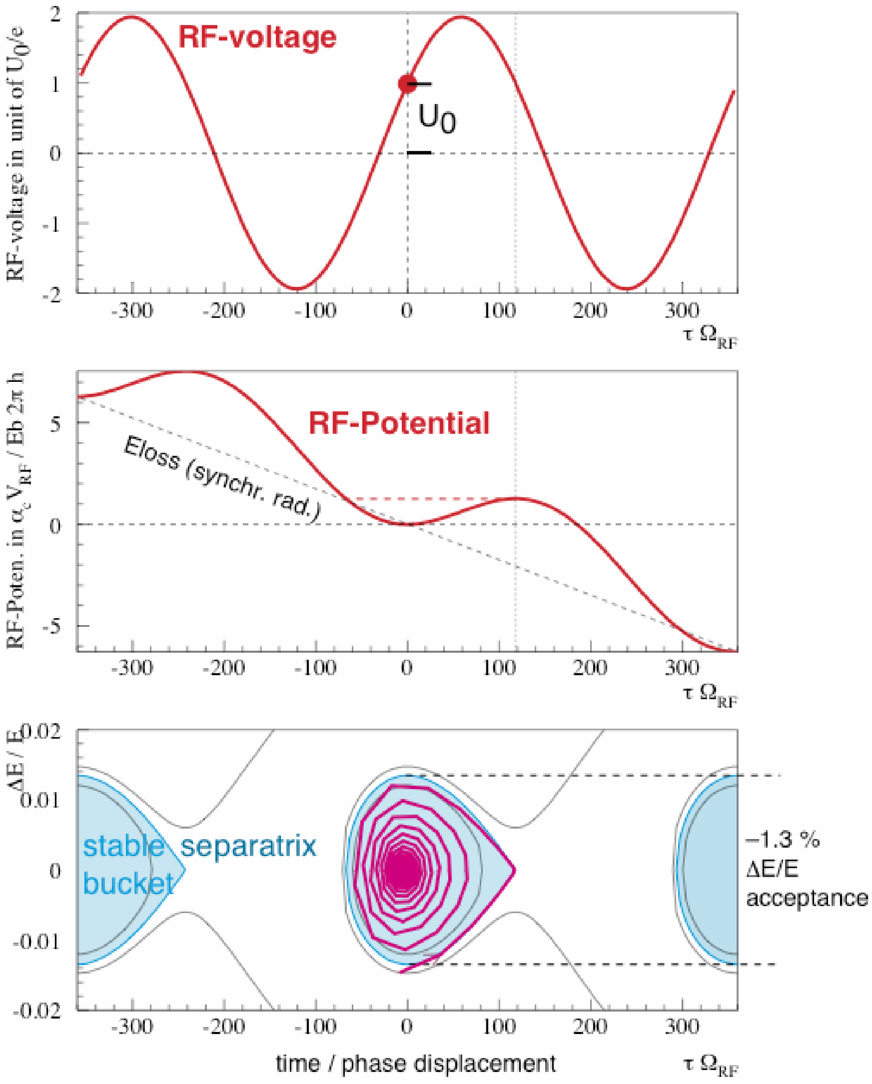
LEP $f_{rf} = 352$ MHz, $\lambda_{rf} = 85$ cm, $\sigma_z = 1$ cm

rf-bucket, energy acceptance, e-ring

RF : more than U_o needed
for good energy aperture

relative energy spread
$\sigma_e \sim 1.5\ 10^{-3}$ for e-rings, LEP
Tails refilled by quantum fluctuations
Needs good rf-acceptance > 6.5 σ_e

Large acceptance and damping :
Allows for injection with
accumulation.



good quantum lifetime: provide enough rf-voltage such that loss by quantum fluctuations very improbable $\Delta E/E > 6.5\ \sigma_e$

LHC Filling capture with animation

Filling: > 9 min (2 x 12 inj. x 21.6 sec.)

Off-energy particles remain in the machine
Slowly fill the abort gap
- cleaning foreseen (using the transverse damper), latest removed during start of ramp in the momentum cleaning section

LHC momentum collimation at $3\text{x}10^{-3}$

RF-frequency 400 MHz
RF-bucket length λ = 0.75 m or 2.5 ns
RF-acceptance (bucket- 1/2 height) ~ 10^{-3}
$\sigma_e = 3 \text{ x } 10^{-4}$ LHC 450 GeV

Energy deviation

QuickTime™ and a
H.264 decompressor
are needed to see this picture.

longitudinal coordinate, s or t

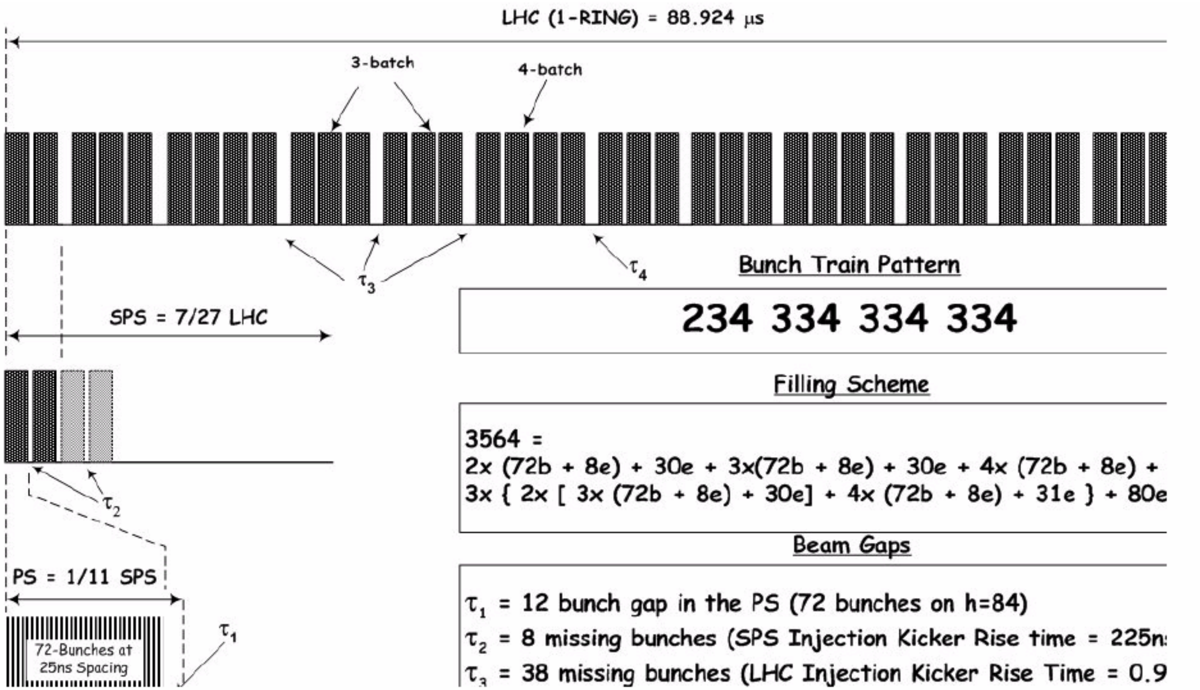
Shown here: simulation of injection
with $3\text{x}10^{-4}$ energy offset

Simulation details 6dim phase space program BeamTrack written in C++ with interface to Higz by H.Burkhardt 8/2003 - 2/2006.
Here 5000 particles, 100 turns. 3 sec CPU on iMac G5 2.1 GHz. using ps -> pdf -> quicktime movie conversion

Filling pattern - bunches, buckets, …

f_{RF} = 400 MHz
λ_{RF} = 0.75 m or 2.5 ns
35 640 RF buckets
Bunches spaced by
25 ns or 10 buckets
Inject batches of
2, 3 or 4 x 72 bunches
39x72=2808 bunches in LHC
Leave a 119 bunch
abort gap free ~ 3 μs

A full turn is 88.9 μs



Bunch Train Pattern

234 334 334 334

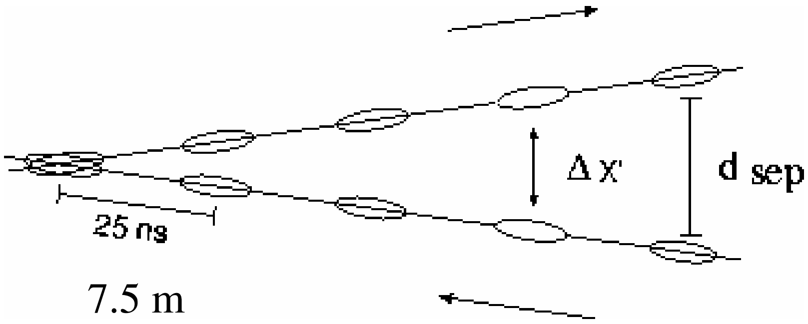
Filling Scheme

3564 =
2x (72b + 8e) + 30e + 3x(72b + 8e) + 30e + 4x (72b + 8e) +
3x { 2x [3x (72b + 8e) + 30e] + 4x (72b + 8e) + 31e } + 80e

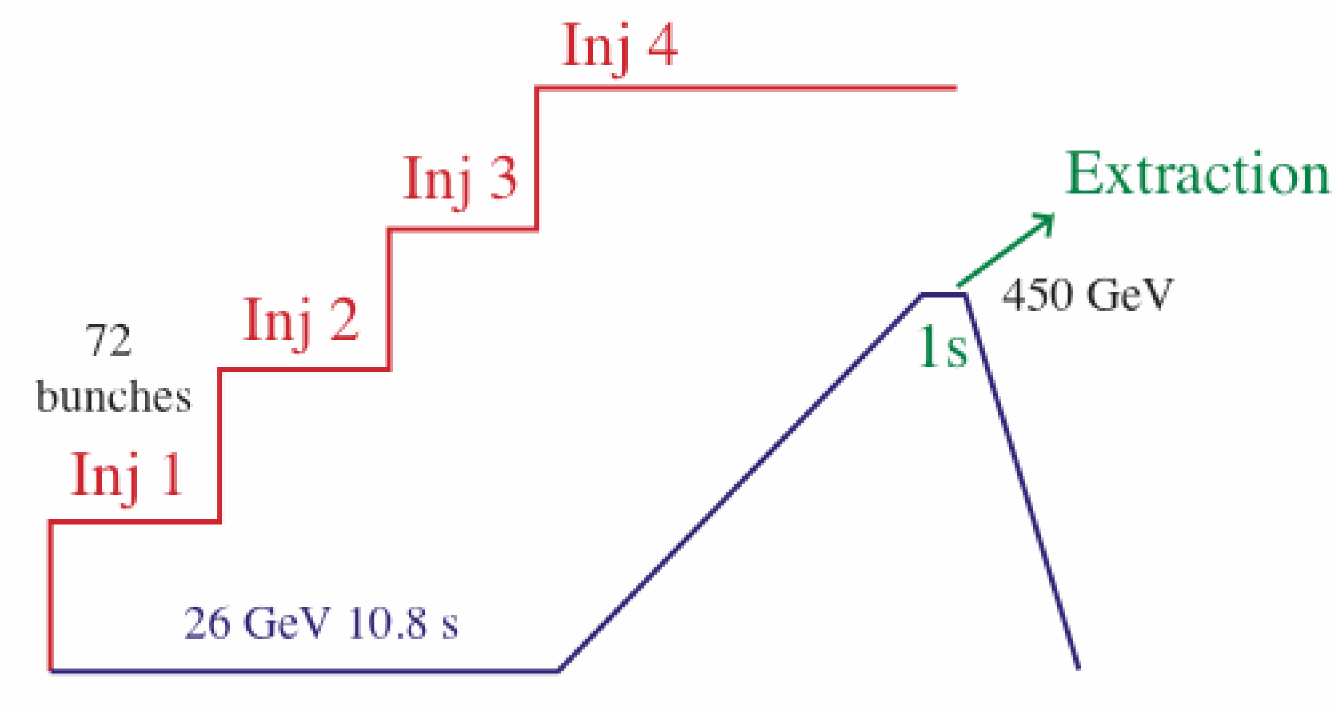
Beam Gaps

τ_1 = 12 bunch gap in the PS (72 bunches on h=84)
τ_2 = 8 missing bunches (SPS Injection Kicker Rise time = 225n
τ_3 = 38 missing bunches (LHC Injection Kicker Rise Time = 0.9

Crossing angle needed for > 156 bunches
to avoid encounters closer than ~ 6 σ
Angle needed depends on β*
Nominal angle ±150 μrad

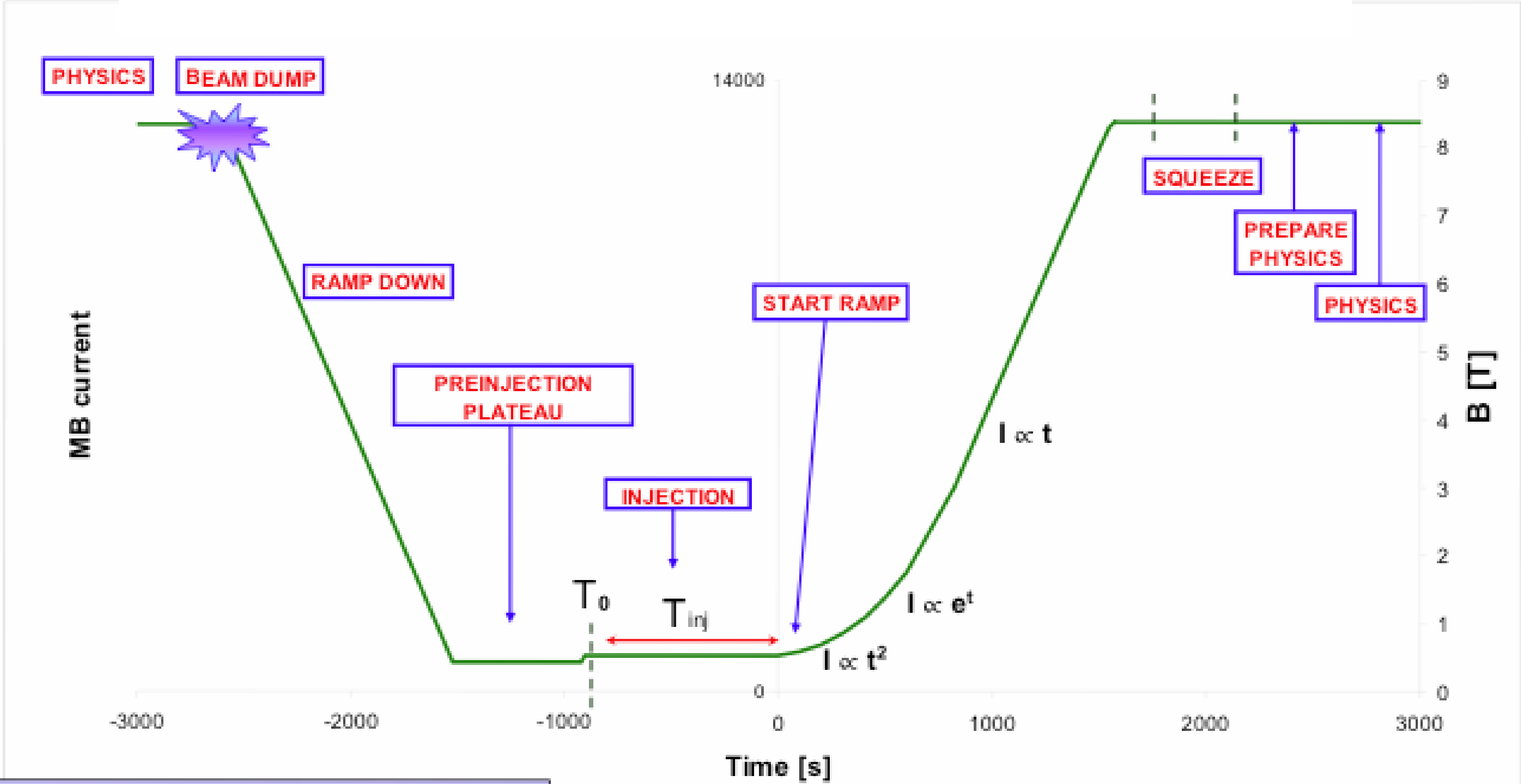


SPS cycle for LHC injection



SPS proton cycle for LHC injection, total 21.8 s

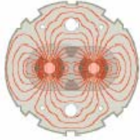
LHC cycle



Injection plateau	0
alpha	5.92105E-06
current rate end snapback	0.6
current at injection	760
current variation during snapback	20
parabolic segment duration	405.333
current at end exp	4110.000
b at end exp	3.000
current to field scaling factor	1370.000
max current rate	10.000
current rate end parablolic	3.648
exp time constant inverse	2.433E-03

Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs

Ramp



Major LHC challenges

Centre-of-mass energy of 7 TeV in given (ex LEP) tunnel

- **Magnetic field of 8.33 T with superconducting magnets**
- **Helium cooling at 1.9 K**
- **Large amount of energy stored in magnets**
- **"Two accelerators" in one tunnel with opposite magnetic dipole field and ambitious beam parameters pushed for very high of luminosity of 10^{34} cm^{-2} s^{-1}**
- **Many bunches with large amount of energy stored in beams**

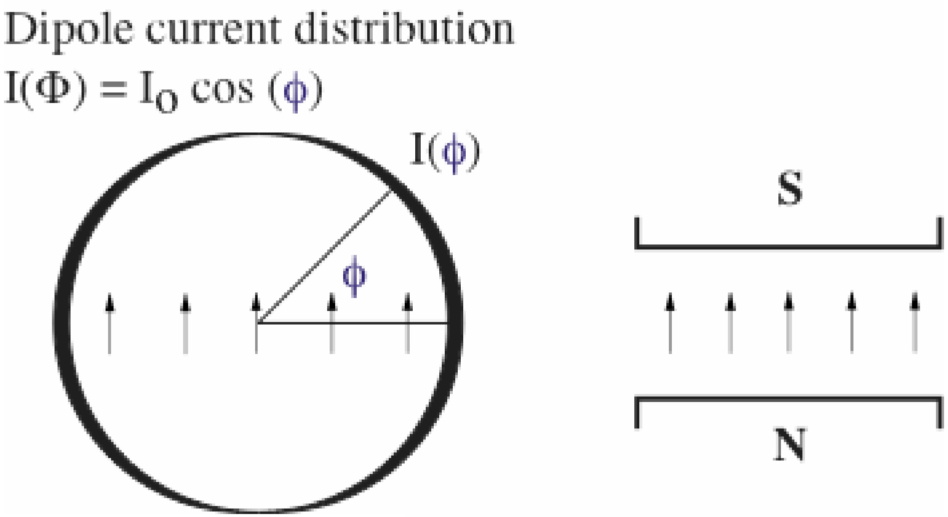
Complexity and Reliability

- **Unprecedented complexity with 10000 magnets powered in 1700 electrical circuits, complex active and passive protection systems,….**

- **Emittance conservation** $\varepsilon_N = \beta\,\gamma\,\varepsilon$ const., related to phase space density conservation, Liouville
  in absence of major energy exchange in synchrotron radiation / rf damping clean, perfectly matched injection, ramp, squeeze, minimize any blow up from: rf, kicking beam, frequent orbit changes, vibration, feedback, noise,..
- **Dynamic effects - persistent current decay and snapback**
- **Non-linear fields (resonances, diffusion, dynamic aperture, non-linear beam dynamics** (.. chaos) **)**

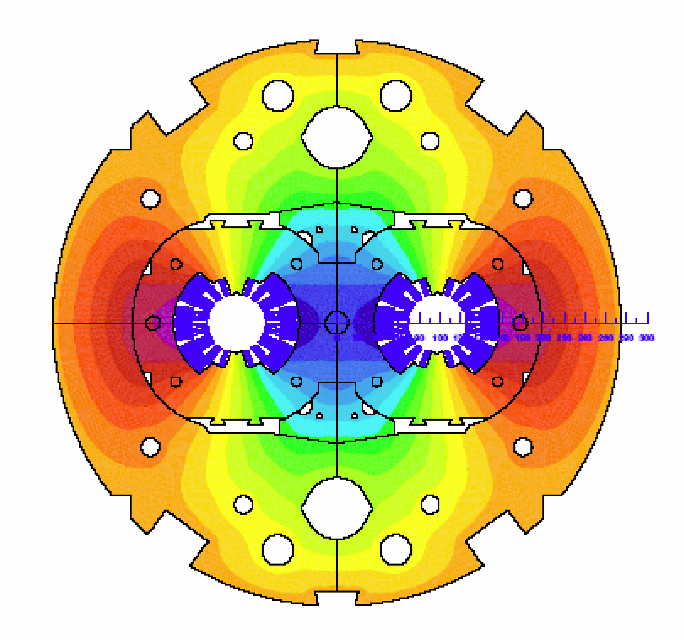
LHC dipole magnet

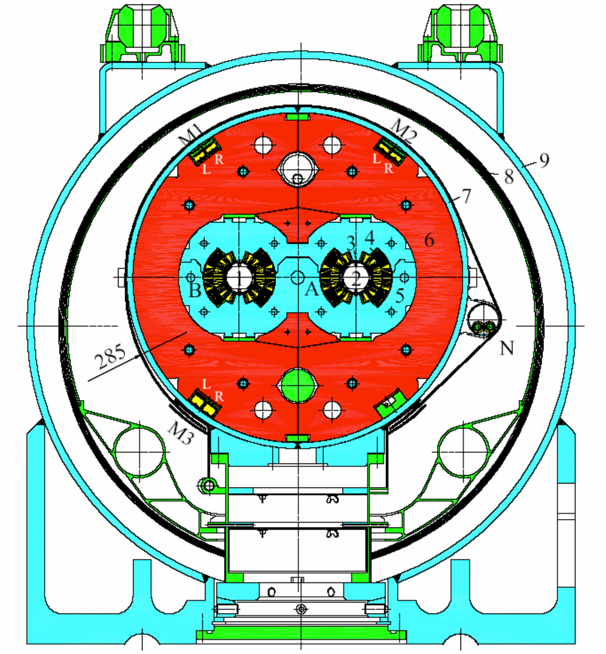
field from current distribution


Dipole current distribution

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

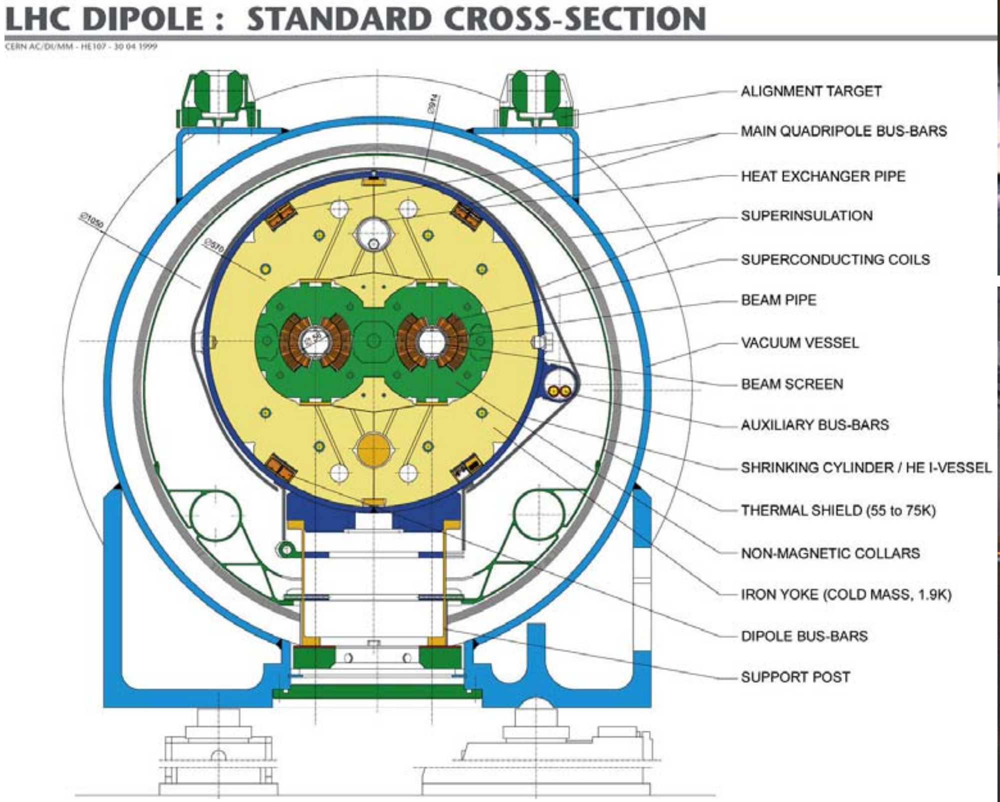
LHC dipole

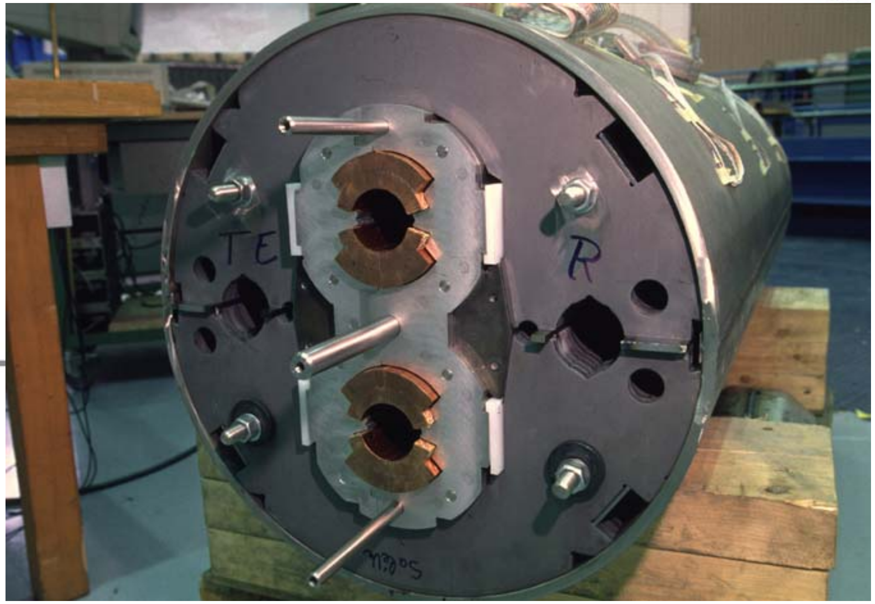




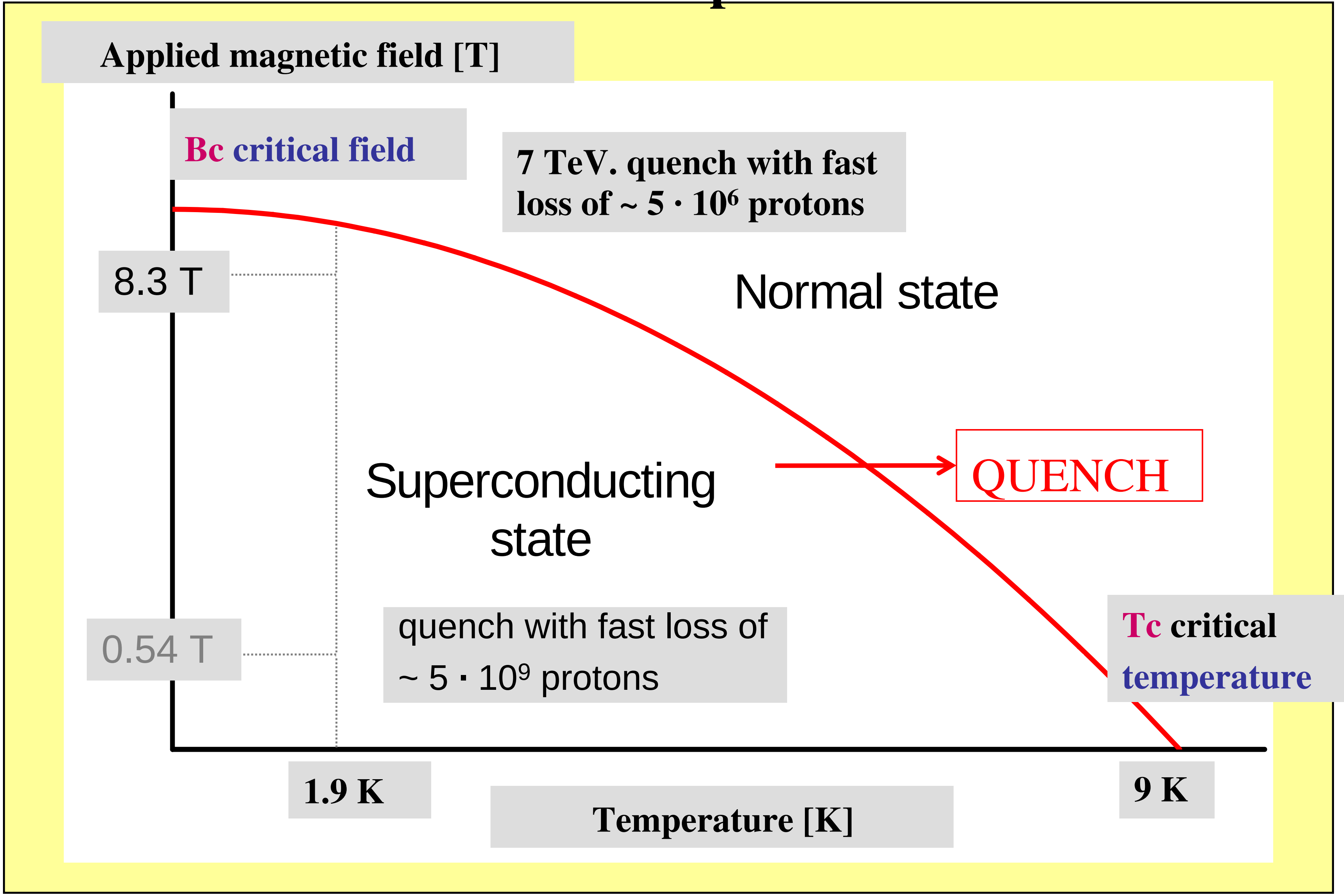
LHC dipole magnet

2-in-1 dipole magnet design
8.4 T, 15 m long, 30 Ton





Operational margin of a superconducting LHC dipole



Applied magnetic field [T]

Bc critical field

7 TeV. quench with fast loss of ~ 5 · 10^6 protons

8.3 T

Normal state

Superconducting state

QUENCH

0.54 T

quench with fast loss of ~ 5 · 10^9 protons

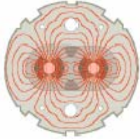
Tc critical temperature

1.9 K

Temperature [K]

9 K

LHC beam parameters at 7 TeV



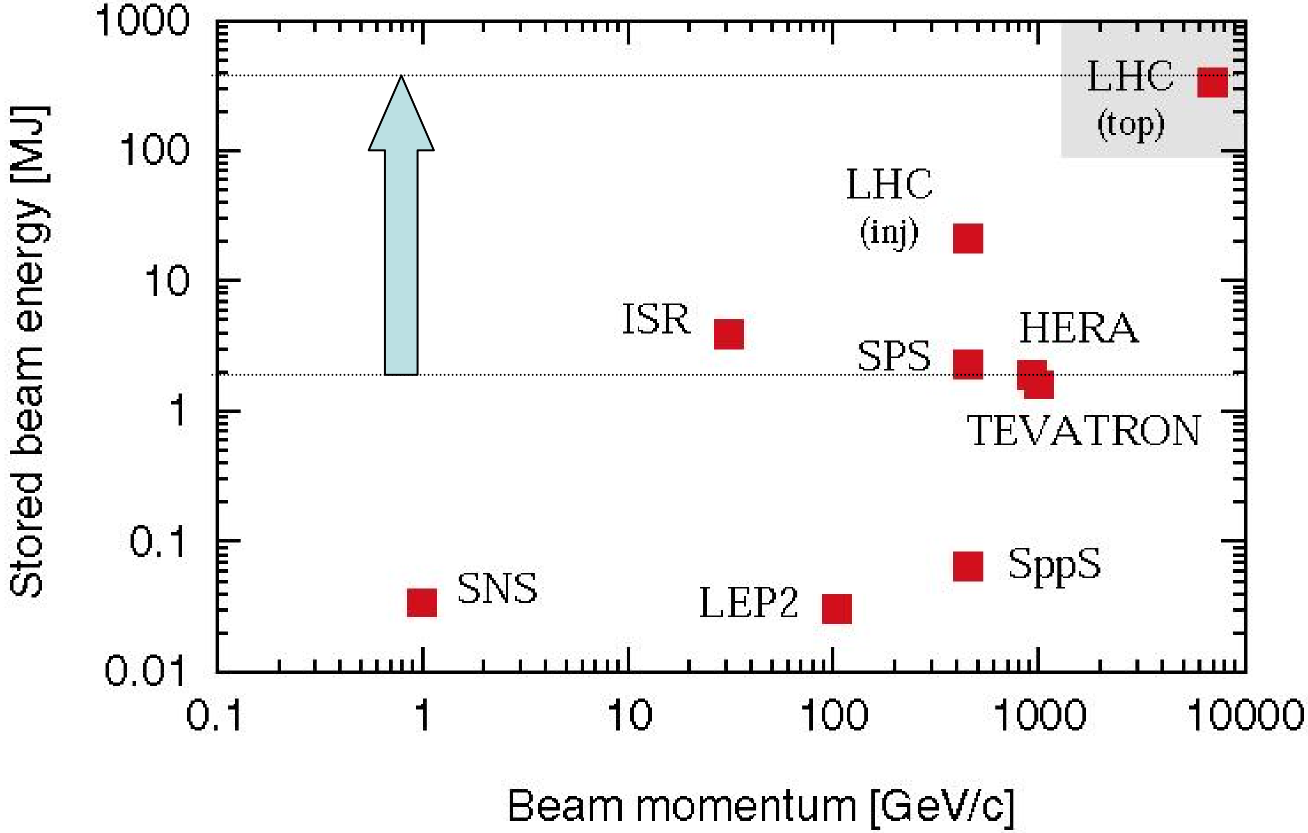
	LHC		LEP2	
Momentum at collision	**7**	**TeV/c**	0.1	TeV/c
Luminosity	**10^{34}**	**$cm^{-2}s^{-1}$**	~ 10^{32}	$cm^{-2}s^{-1}$
Dipole field at 7 TeV	**8.33**	**Tesla**	0.11	T
Number of bunches	**2808**		4	
Protons per bunch	**$1.15 \cdot 10^{11}$**		$4.2 \cdot 10^{11}$	e^+, e^-
Typical beam size (ring)	**200-300**	**µm**	1800/140	µm (H/V)
Beam size at IP	**16**	**µm**	200/3	µm (H/V)

- **Energy stored in the magnet system: 10 GJoule** — Airbus A380 560t at 700 km/h
- **Energy stored in one (of 8) dipole circuit: 1.1 GJ**
- **Energy stored in one beam: 362 MJ** — 17t plane
- **Energy to heat and melt one kg of copper: 0.7 MJ**

the LEP2 total stored beam energy was about 0.03 MJ

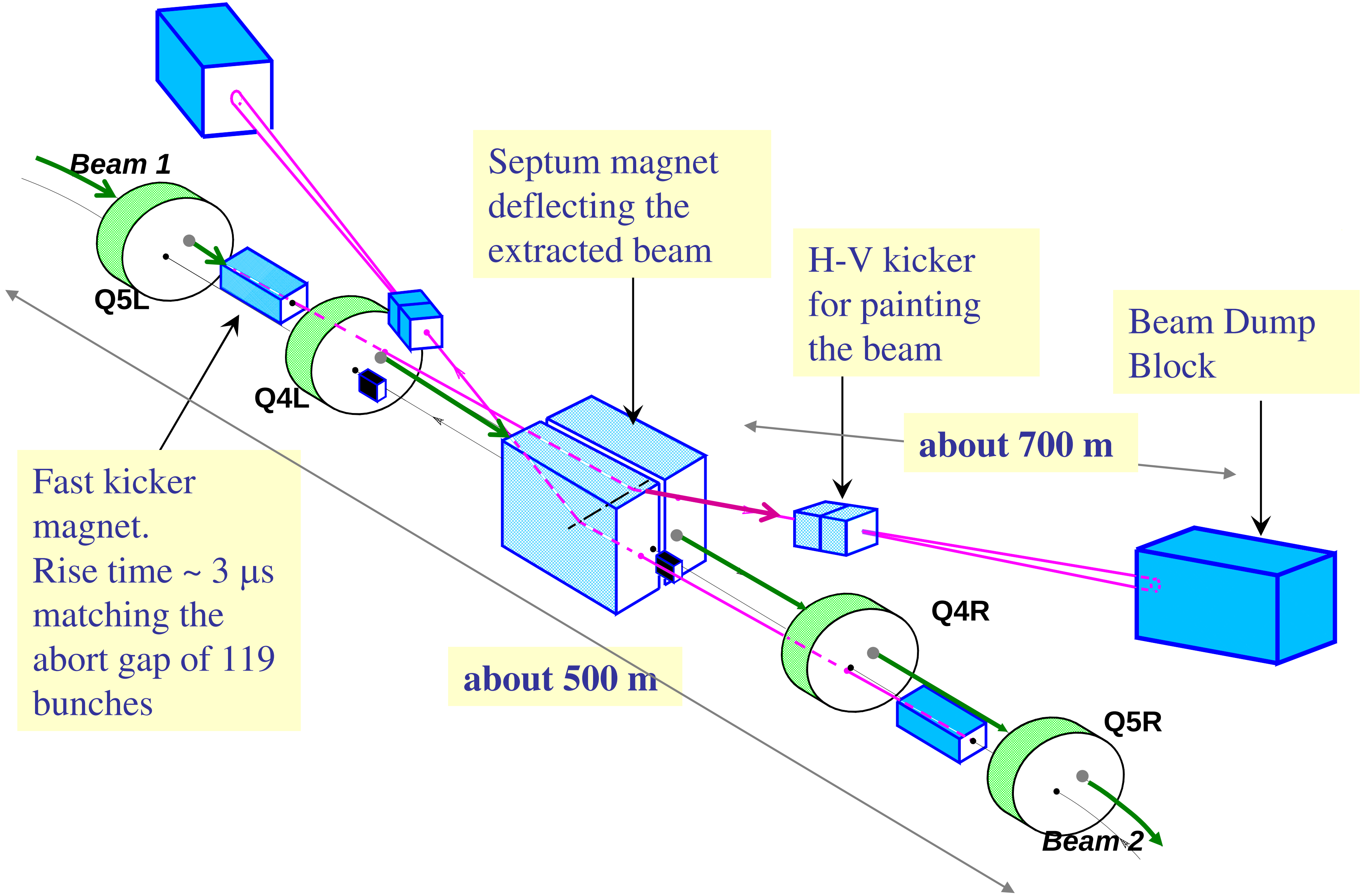
The total stored energy of the LHC beams

Nominal LHC design: 3 x 10^{14} protons accelerated to 7 TeV circulating at 11 kHz in a SC ring



LHC: > 100 x higher stored energy and small beam size: ~ 3 orders of magnitude in energy density and damage potential. Active protection (beam loss monitors, interlocks) and collimation for machine and experiments essential.
Only the specially designed beam dump can safely absorb this energy.

Schematic layout of beam dump system in IR6



Septum magnet deflecting the extracted beam

H-V kicker for painting the beam

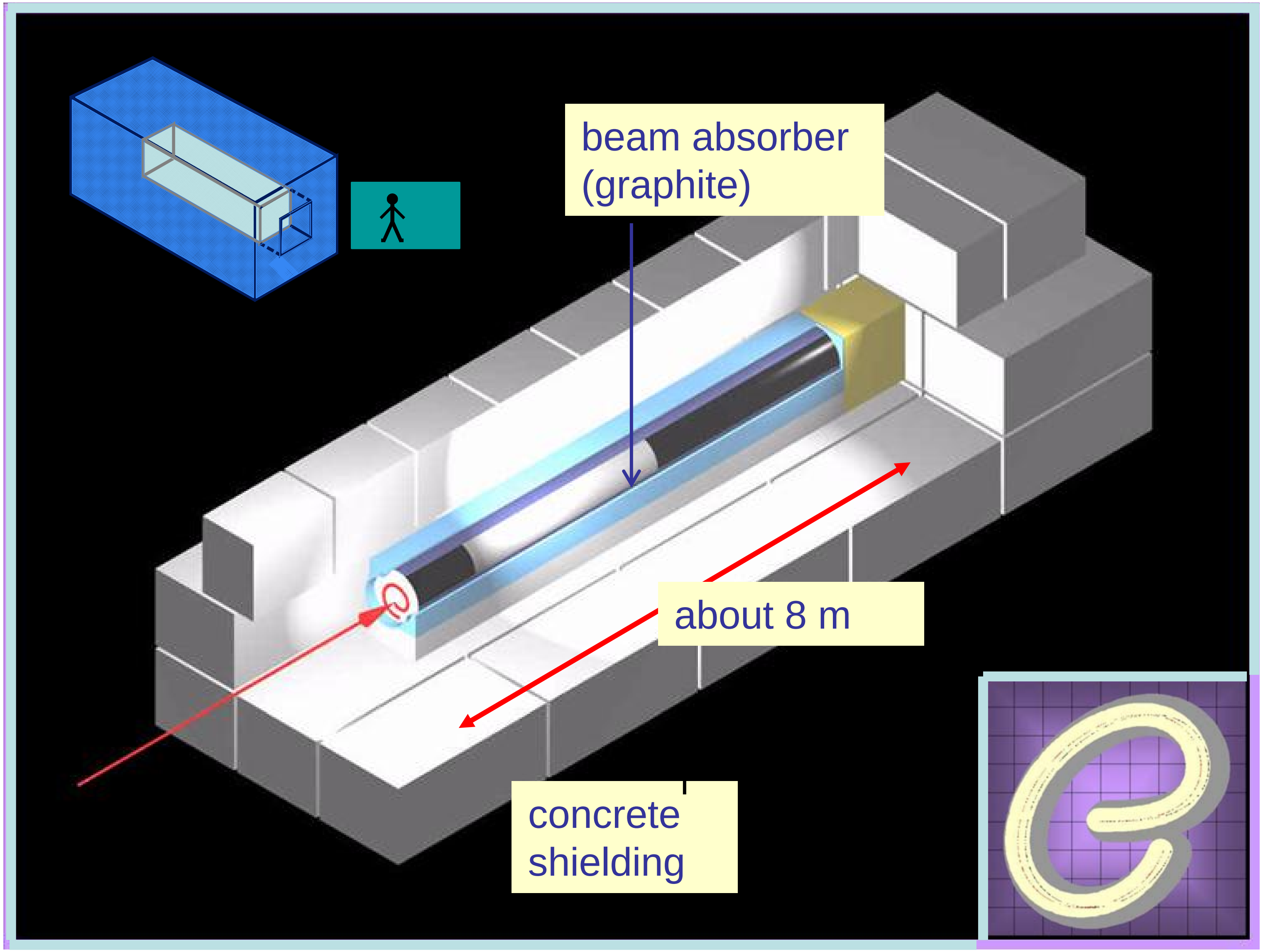
Beam Dump Block

about 700 m

Fast kicker magnet.
Rise time ~ 3 μs matching the abort gap of 119 bunches

about 500 m

Dumping the LHC beam



beam absorber (graphite)

about 8 m

concrete shielding

about 35 cm

Protection and Beam Energy

A small fraction of beam sufficient for damage

Very efficient protection systems throughout the cycle are required

A tiny fraction (~10^{-4} at inj. 10^{-7} at 7 TeV) of the beam is sufficient to quench a magnet

Very efficient beam cleaning is required

- Sophisticated beam cleaning with about 50 collimators, each with two jaws + various specialized (injection...), in total about 100 collimators and beam absorbers
- Collimators are close to the beam (full gap as small as 2.2 mm, for 7 TeV with fully squeezed beams), such that particles get lost on collimators first !

The LHC insertions

Two warm LHC insertions dedicated to cleaning:

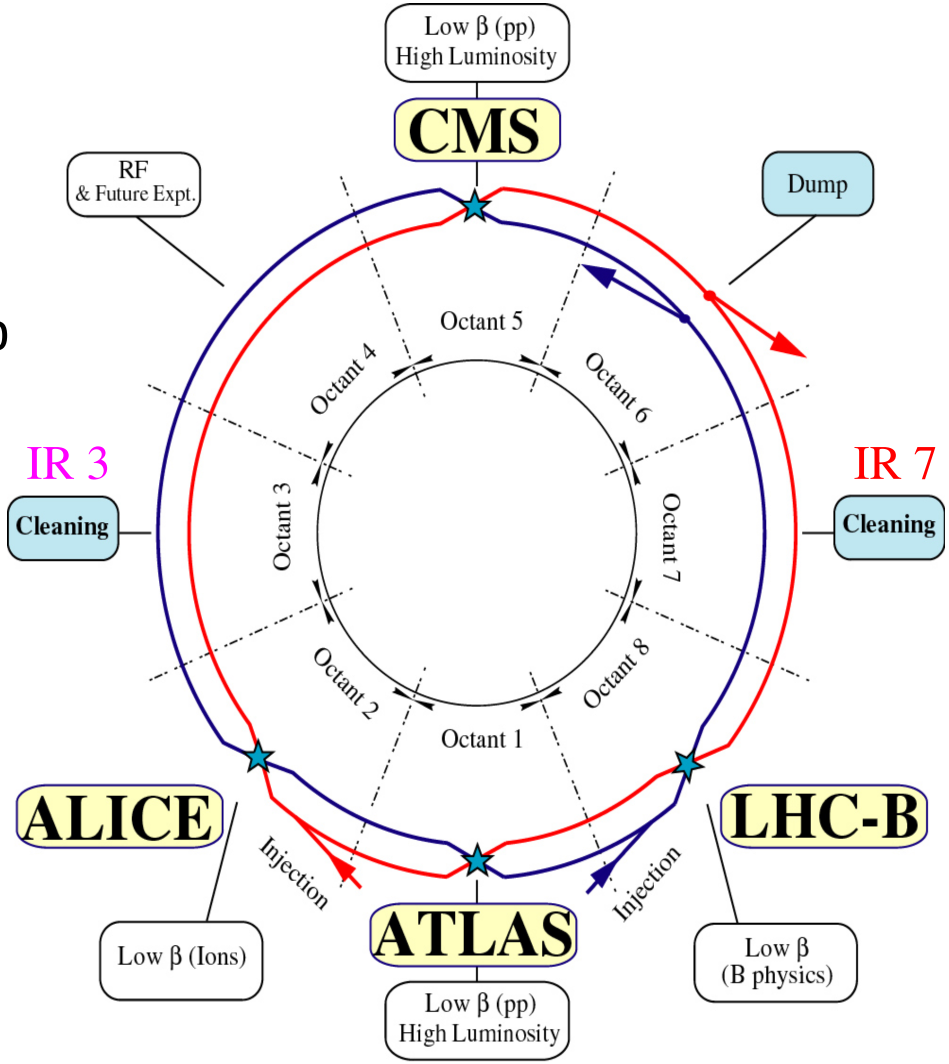
IR3 Momentum cleaning

IR7 Betatron cleaning

Collimators for injection, dump and in experimental insertions IR1, IR2, IR5, IR8.

Beam Dump in IR6.

Four large experiments : two multipurpose high L and two dedicated Heavy Ion (ALICE) and B-physics (LHC-B) experiments.



In addition: CMS/Totem σ_{tot}, Atlas high β, LHCf, …

Short outlook into the longer term future

High energy machines need many years to plan and build

about 25 years for the LHC : 1982 (well before LEP start) **- 2007**

Developments on the longer term future (for Φ > 2015) have in fact already been going on for several years.

On the high energy frontier mainly :

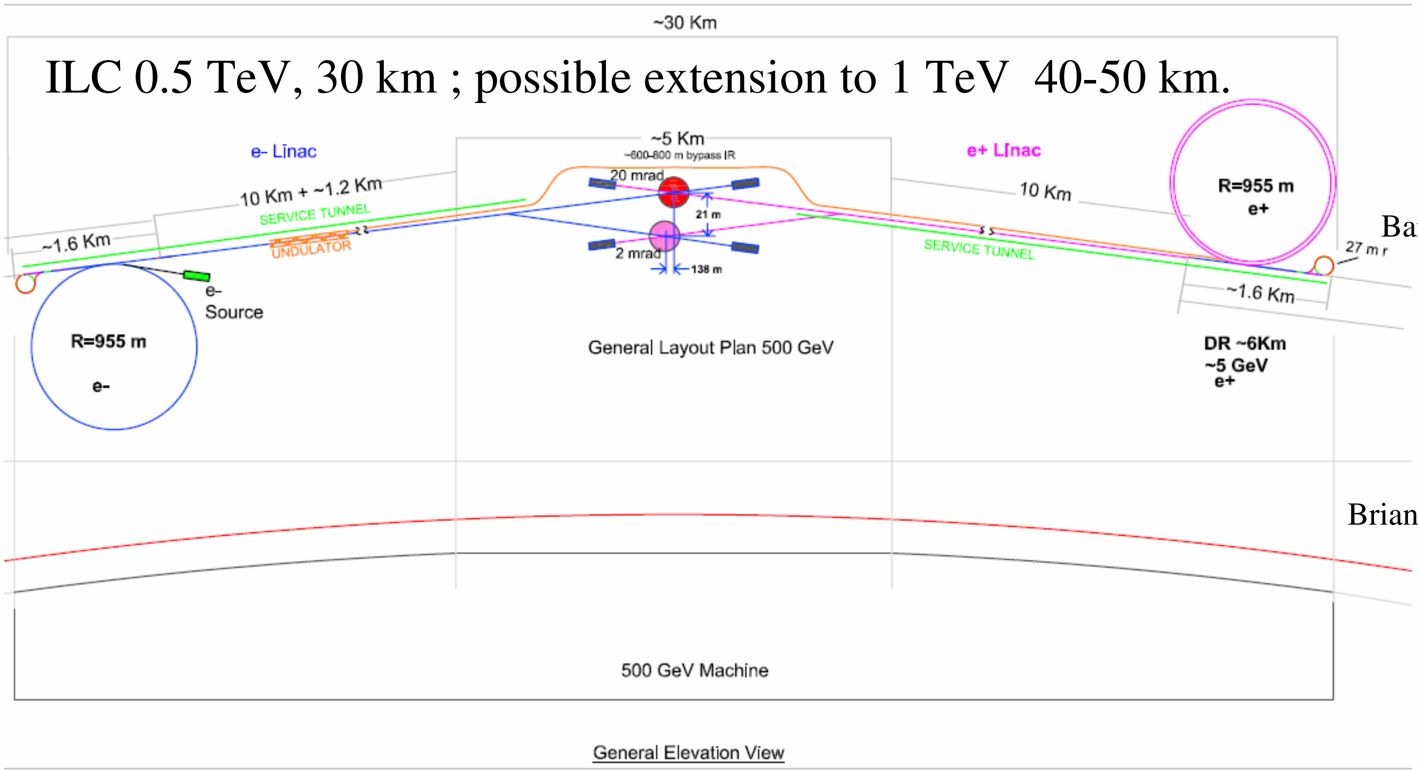
- **E_{cms}= .2 -.5 TeV** (with possible 1 TeV extension) **e^+e^- collider ILC**
- **Multi (3-5) TeV e^+e^- collider: CLIC**
- **LHC upgrade**

ILC International Linear Collider

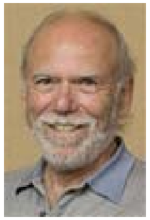
www.linearcollider.org/cms/

GDE Global Design Effort

interactions.org/linearcollider/gde/



ILC 0.5 TeV, 30 km ; possible extension to 1 TeV 40-50 km.



Barry Barish, GDE Director

Brian Foster, Director for Europe

J.P. Delahaye, Deputy Director,
and CLIC project leader

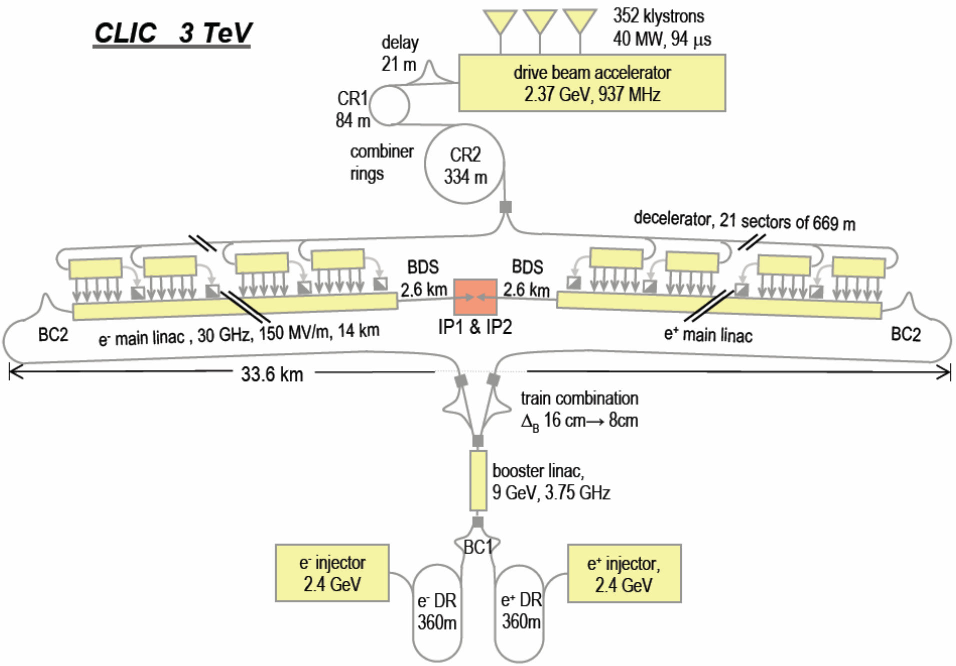
Acceleration using superconducting (Tesla) RF, Nb, 1.3 GHz

This year : Baseline Configuration Document http://www.linearcollider.org/wiki/doku.php?id=bcd:bcd_home

Aim for decision in 2010. 1 US/FNAL**, 1 Asian/**KEK**, 2 Europ.** CERN, DESY **site studies**

Multi-TeV collider study : CLIC

http://clic-study.web.cern.ch/CLIC-Study/
http://ctf3.home.cern.ch/ctf3/CTFindex.htm



CLIC layout for E_{cms} = 3 TeV

- High acceleration gradient (150 MV/m)
  - "Compact" collider - overall length < 40 km
  - Normal conducting accelerating structures
  - High acceleration frequency (30 GHz)
- Two-Beam Acceleration Scheme
  - Capable to reach high frequency
  - Cost-effective & efficient (~ 10% overall)
  - Simple tunnel, no active elements
- Central injector complex
  - "Modular" design, can be built in stages

Very interesting and ambitious R&D - new accel. concept, innovative instruments..
Current aim : demonstrate feasibility (CTF3) + detailed conceptual design by 2010

LHC upgrade

LHC is designed for very high luminosity and energy.
A further upgrade is very difficult but probably feasible
Many years of R&D efforts needed.
First studies already started.
Mainly along two lines :

Higher luminosity (2 - 9 x 10^{34}) : SLHC

$\beta^*/2$, 1.7 x 10^{11} p / bunch, more bunches (5161 @ 12.5 ns) …
new IR, larger crossing angle, also **very challenging** for the experiments; could be done in steps, timescale ~ 10y from LHC start

Doubling the Energy : DLHC timescale ~ 2020 ?

new 15 T dipoles (NbTi(Ta) or Nb_3Sn cable instead of currently NbTi)
there are ideas to even triple the energy (Peter McIntyre et al.)
with 25 T dipoles, inner windings Bi-2212, outer Nb_3Sn

Answers to Questions

Synchrotron Light Image of the Beam :
In reply to the question how a spot-like image is obtained :
U-shaped mirror + small slit to select radiation centre of bending magnet optimised at diffraction limit
for details see : http://accelconf.web.cern.ch/AccelConf/d99/papers/CT08.pdf

What is a beam :
the particles moving in a controlled way in the evacuated "beam" pipe

What is a bunch :
group of beam-particles "captured" within one rf-wavelength

Why underground :
environmental / economic
cosmic rays no problem - relatively small rate and easily identified / rejected by detectors

Movies, pictures :
http://user.web.cern.ch/user/Communication/MediaPublicCorner/MediaPublicCorner.html