Teilchenbeschleuniger

die grössten wissenschaftlichen Instrumente

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Contents

- **Concepts: 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**
- **Limitations, current and future challenges**

- **Mixed with examples - mostly from CERN machines and in particular the LHC**

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; Conte, 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 at the Energy Frontier

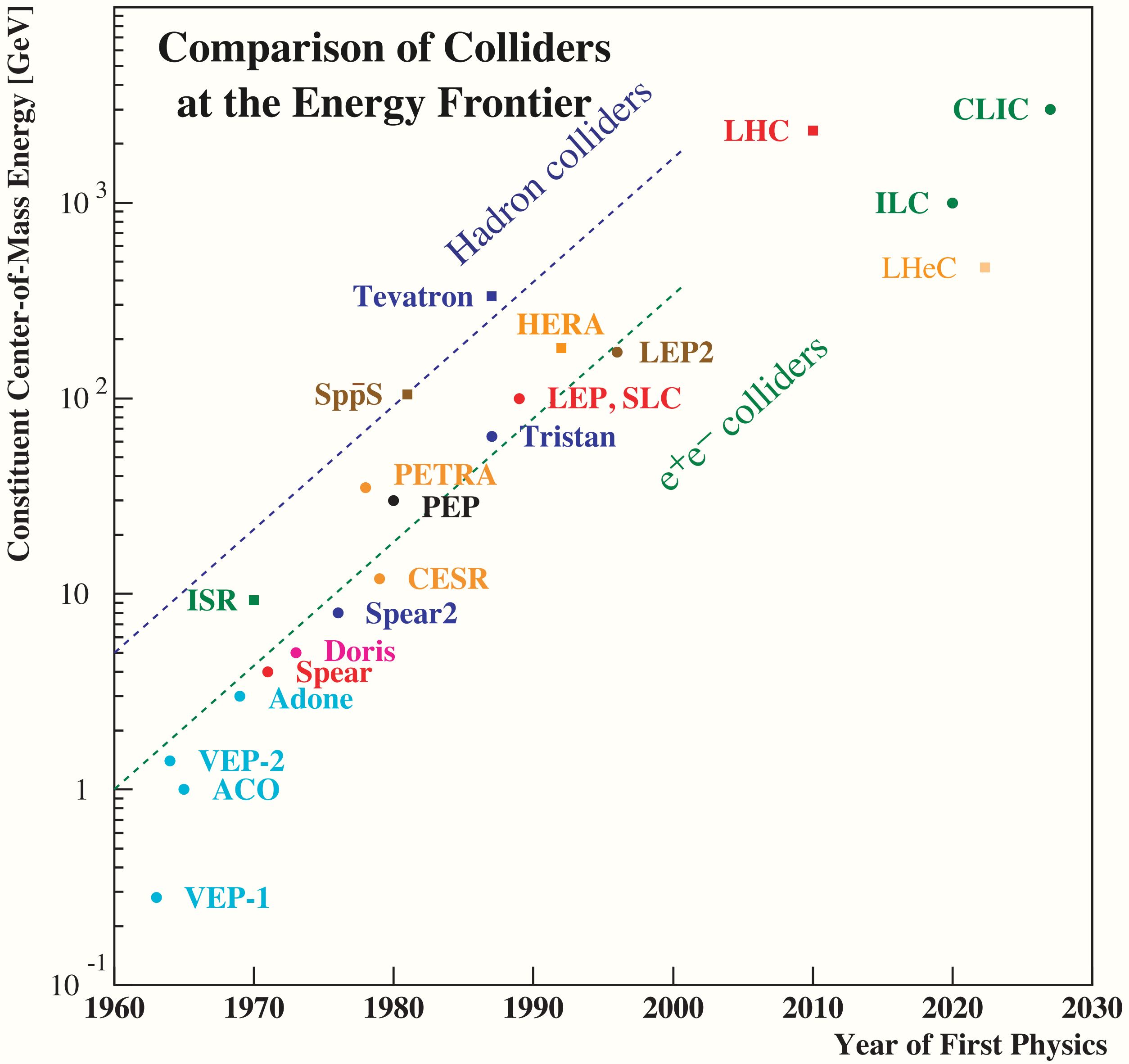
Livingston plot

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



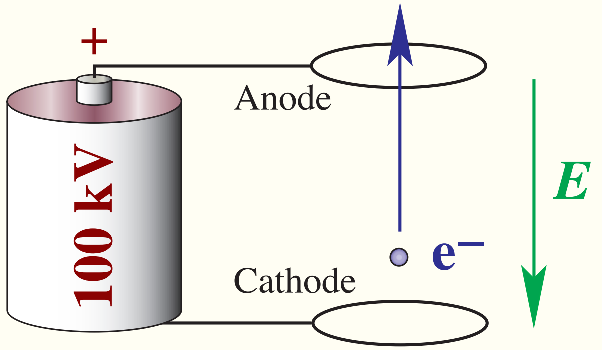
pp, p$\bar{p}$: discovery
e^+e^- : precision
both required machines

+ ep : hadron structure, QCD
HERA, LHeC

The LHC is a major step forward
Discovery machine : Higgs ...

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 $\approx 1.602 \times 10^{-19}$ 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

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

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

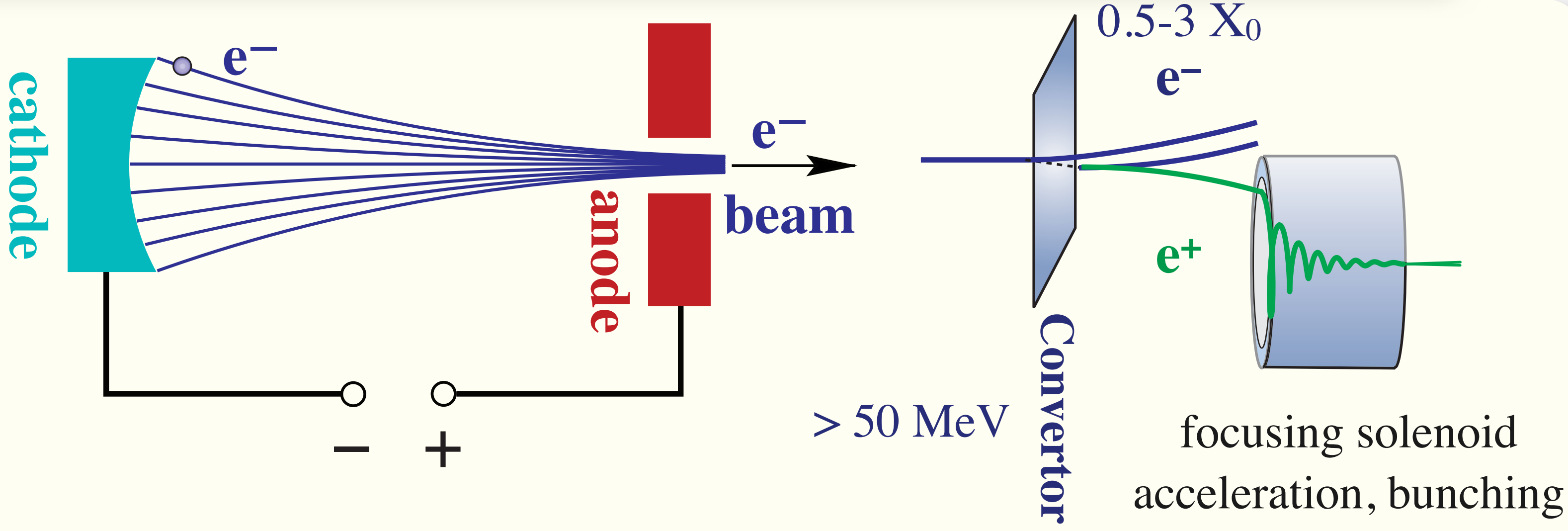
$$(\hbar c)^2 = 3.8938 \times 10^{-32}\ \mathrm{GeV^2\ m^2} = 3.8938 \times 10^{5}\ \mathrm{GeV^2\ nb}$$

for precise numbers see PDG

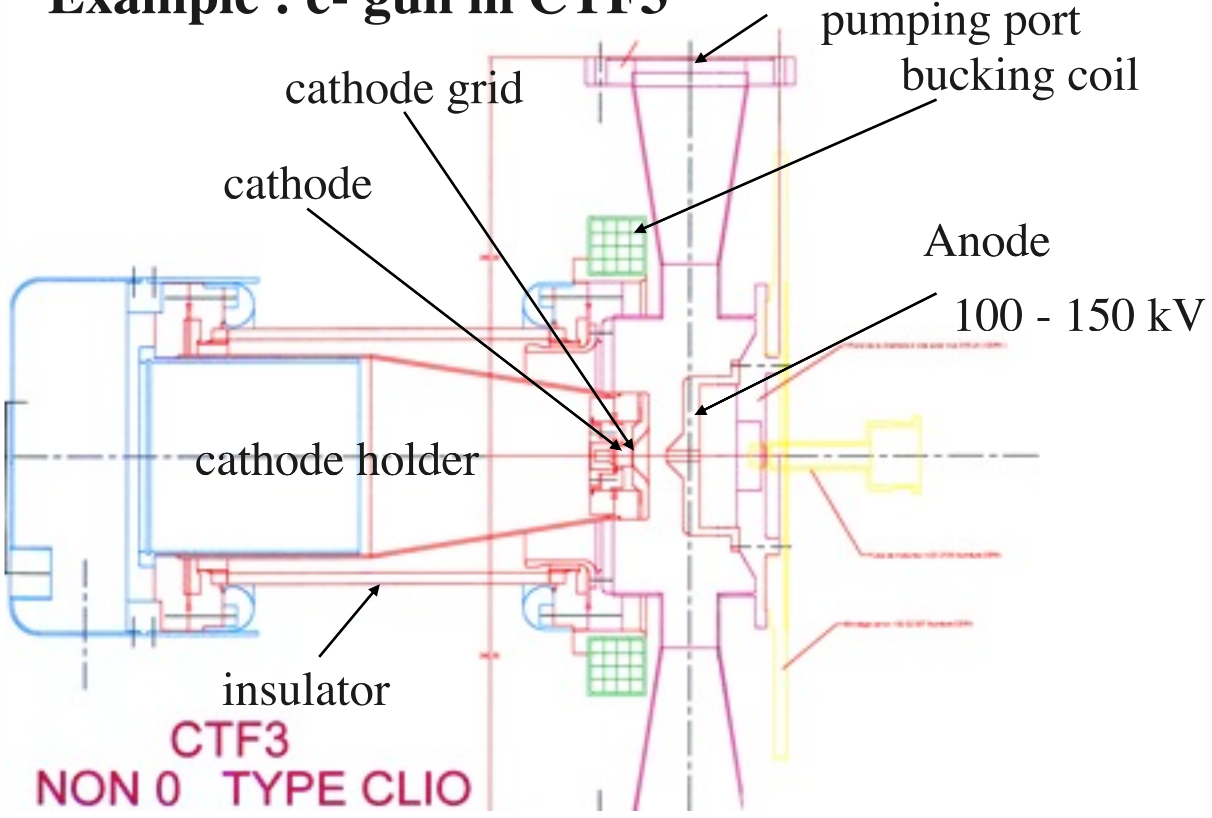
giga G = 10^9 tera T = 10^{12} peta P = 10^{15} exa E = 10^{18} zetta Z = 10^{21} yotta Y = 10^{24}

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

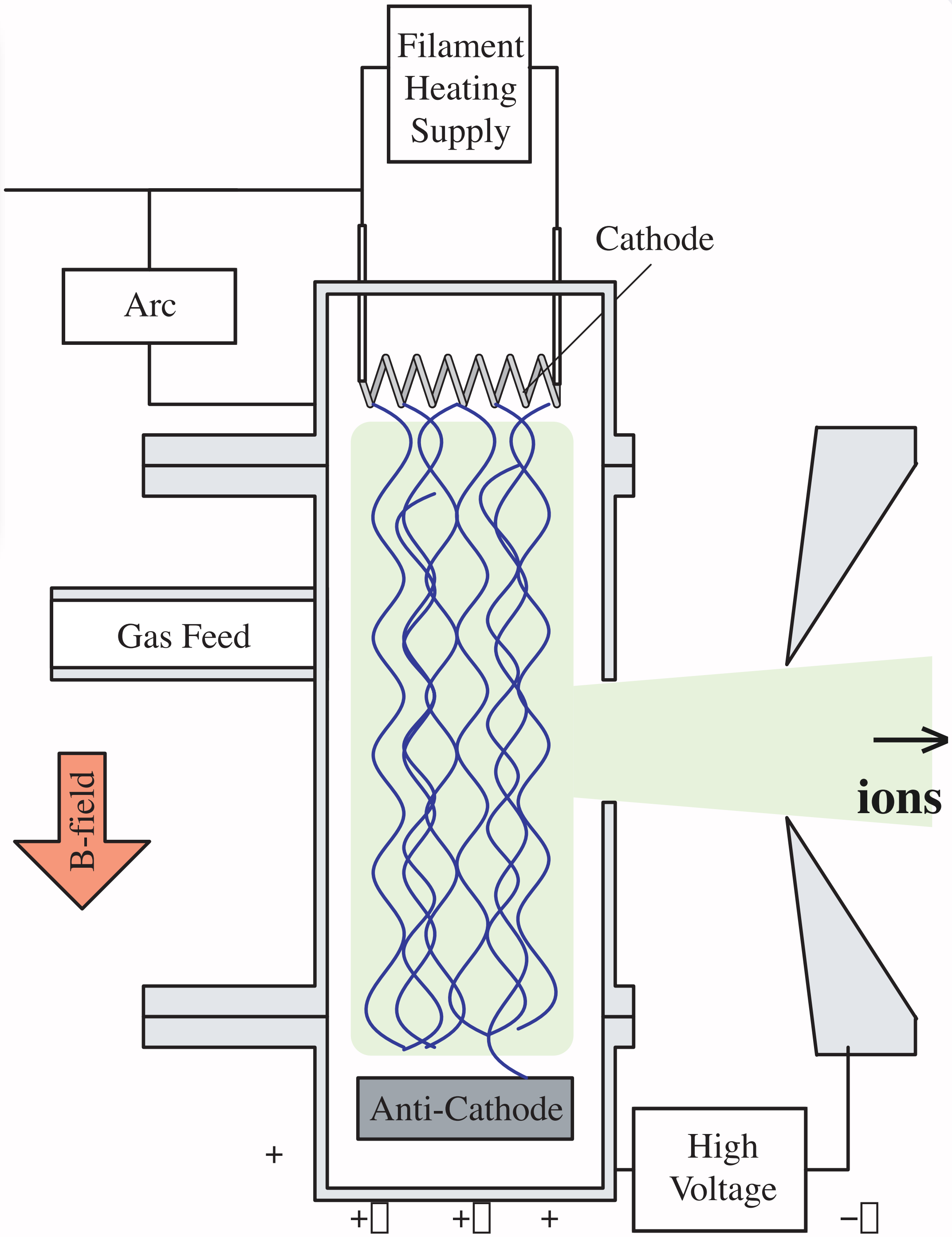
Proton and ion sources

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

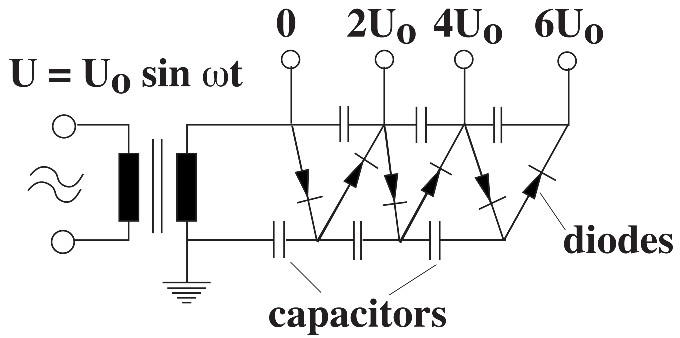


Linear Acceleration with Electrostatic Field

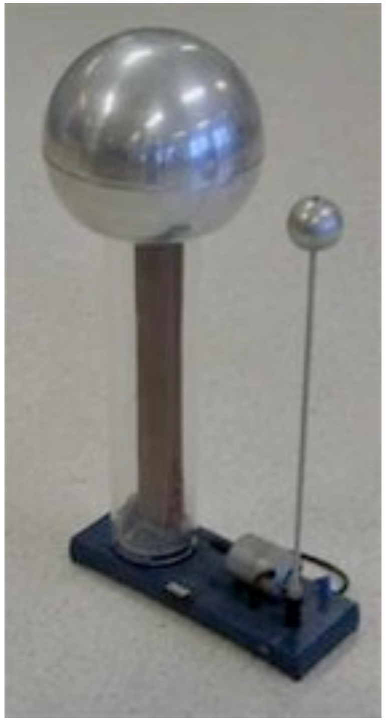
allows for DC, 100 % duty factor

limited by HV-breakdown ~ 1 MV / m

Cockcroft Walton
voltage multiplier

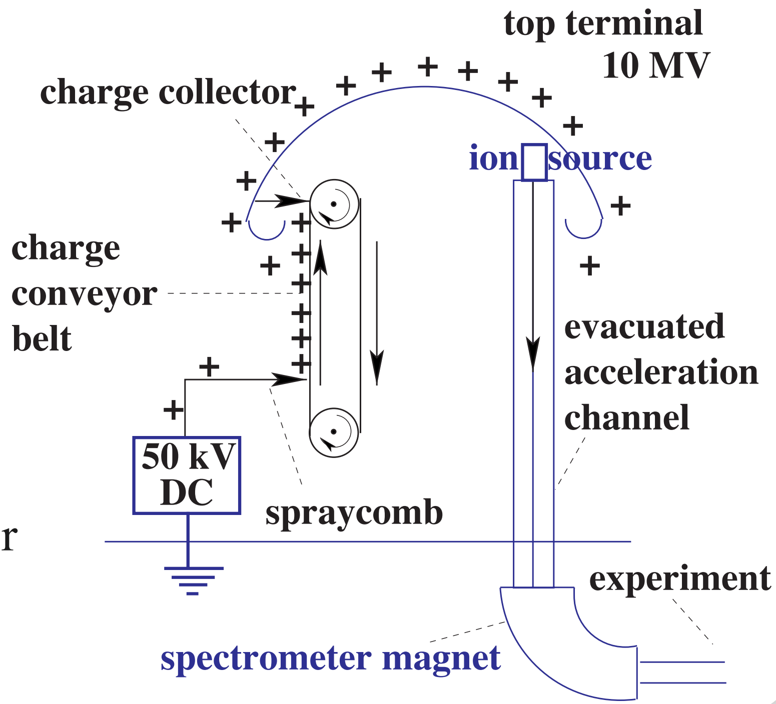


800 kV
proton pre-injector
used at
CERN
until 1993



Van de Graaff generator
static electricity from belts

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



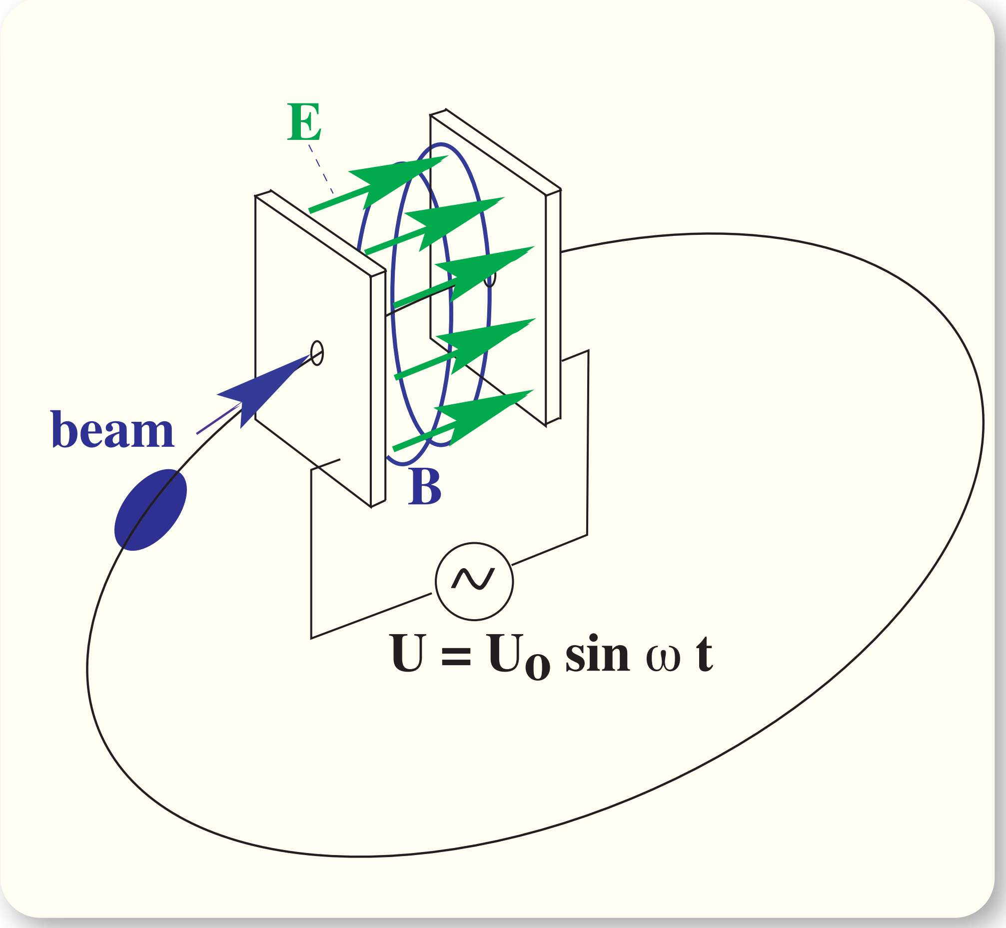
Time Varying Fields

Radio-frequency or short RF acceleration

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

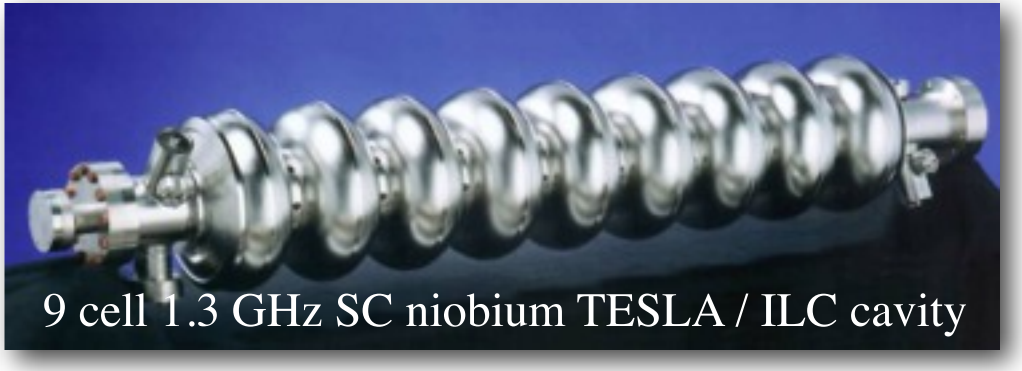
no time for breakdown / flashover

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**



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

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

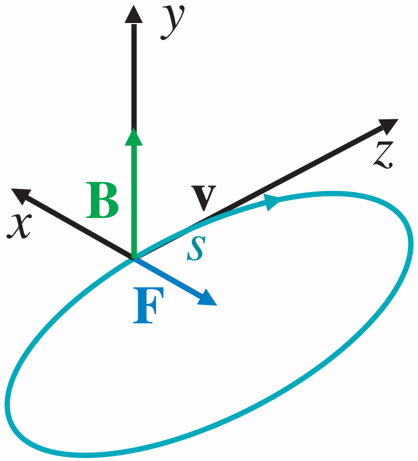
charge q, normally $q = e$; $q = Z\,e$ for ions

- 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

Bρ 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 ρ = 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. $= 1.5\times10^{11}\,\mathrm{m}$

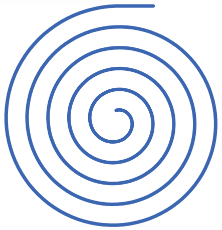
Solar system $B = 10\,\mu\mathrm{G}$ $E = 5$ TeV $\rho = 11$ a.u.

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

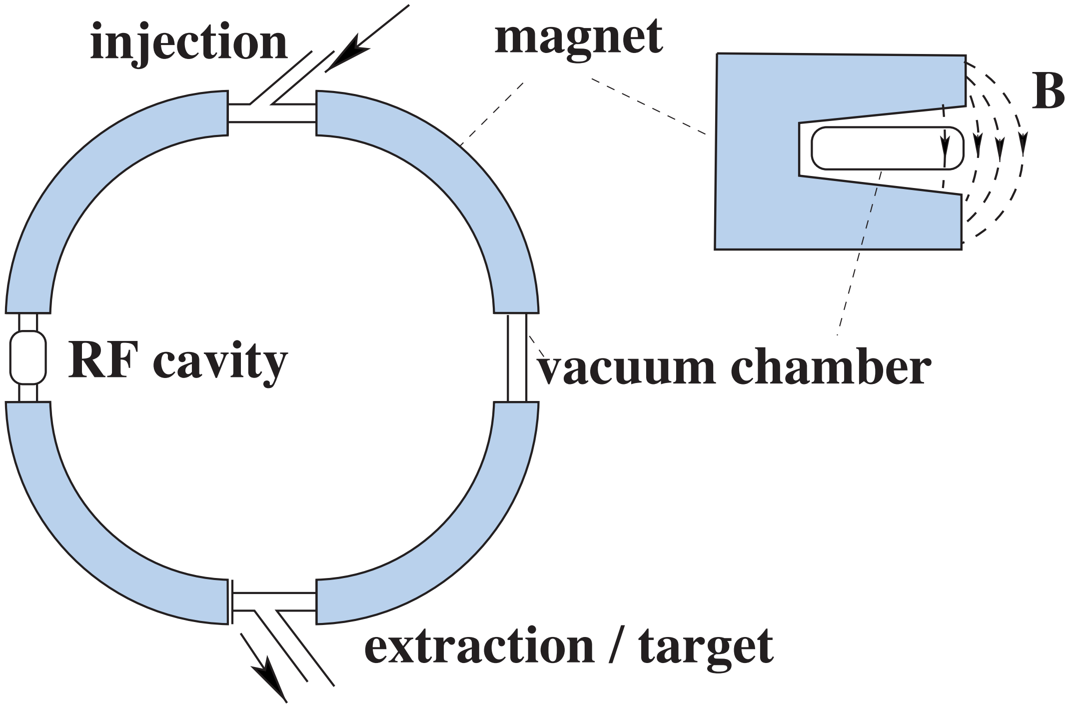
$\rho = 1.7\times10^{19}\,\mathrm{m}$ (4 % of galaxy-radius)

Circular Accelerator

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



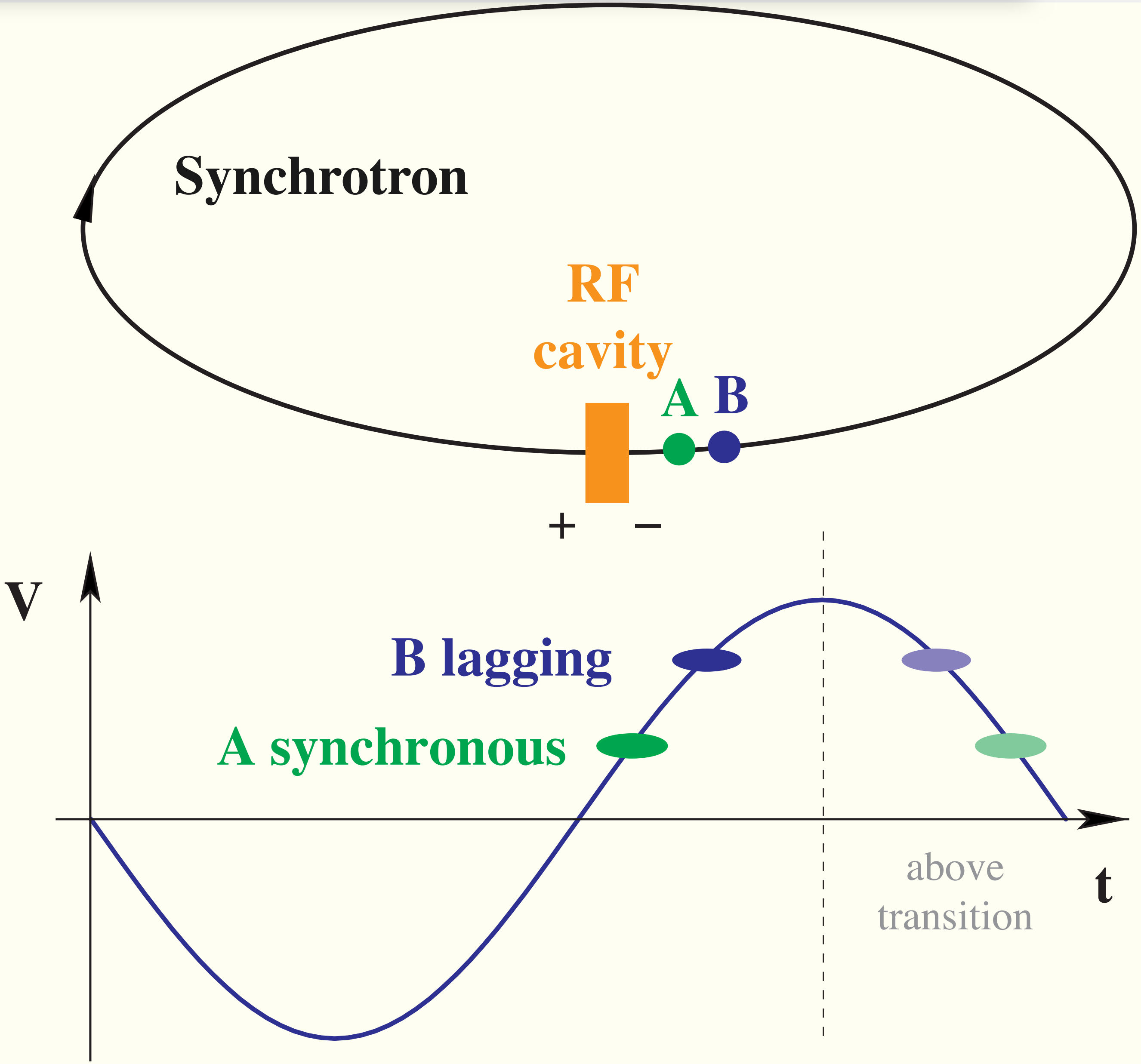
- **Synchrotron : ϱ = const. B increased with energy. RF-frequency adjusted slightly ($\beta = 0.999$ .. 1.0).** Most HEP and all CERN ring accelerators PS, SPS, LEP, LHC of this type. Principle same for e, p, heavy-ion – PS, SPS – accelerate(d) all of these, in some cases switching within seconds



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

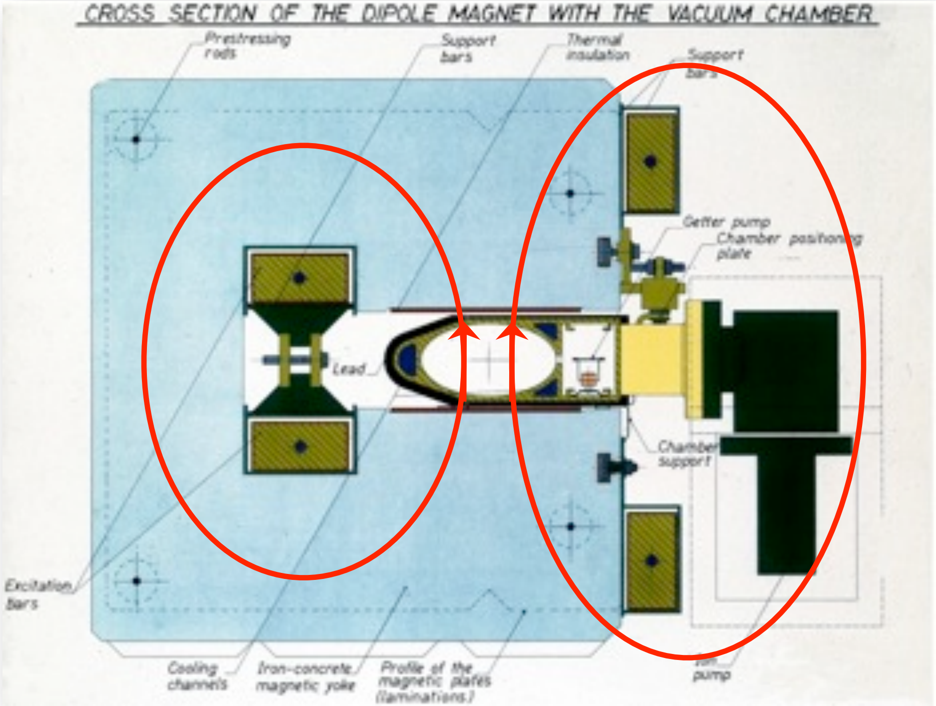
LHC B ∝ I B = 8.38 T

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

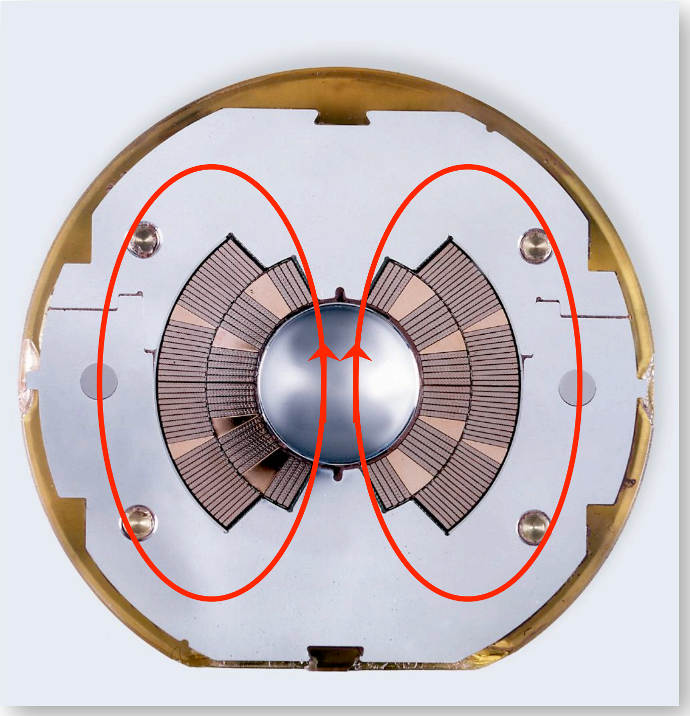
P = 78 MW / cell × 488 cells total power P = 38 GW

Magnet technology

warm

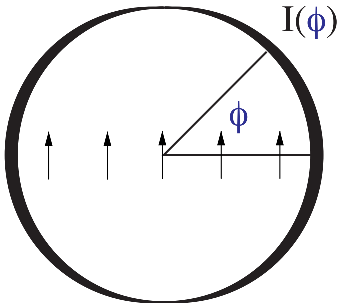


cold



Dipole current distribution

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

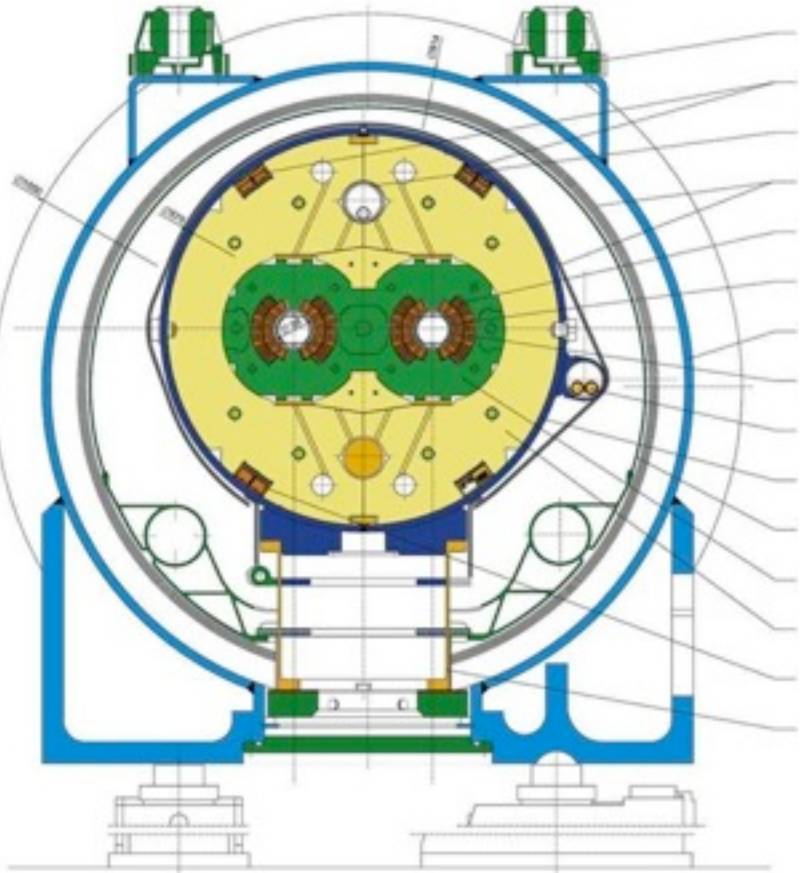


- field quality given by pole face geometry
- field amplified by Ferromagnetic material
- hysteresis and saturation ~ 2 T
- Ohmic losses for high magnet currents

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

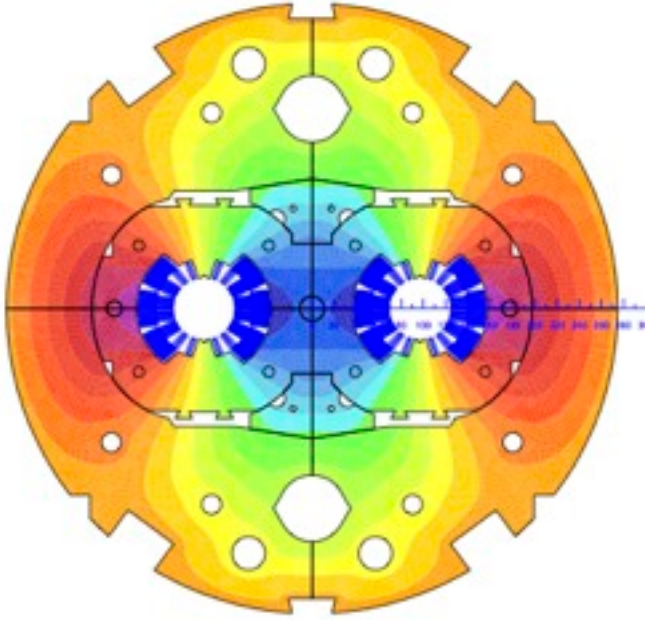
LHC dipole magnet

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



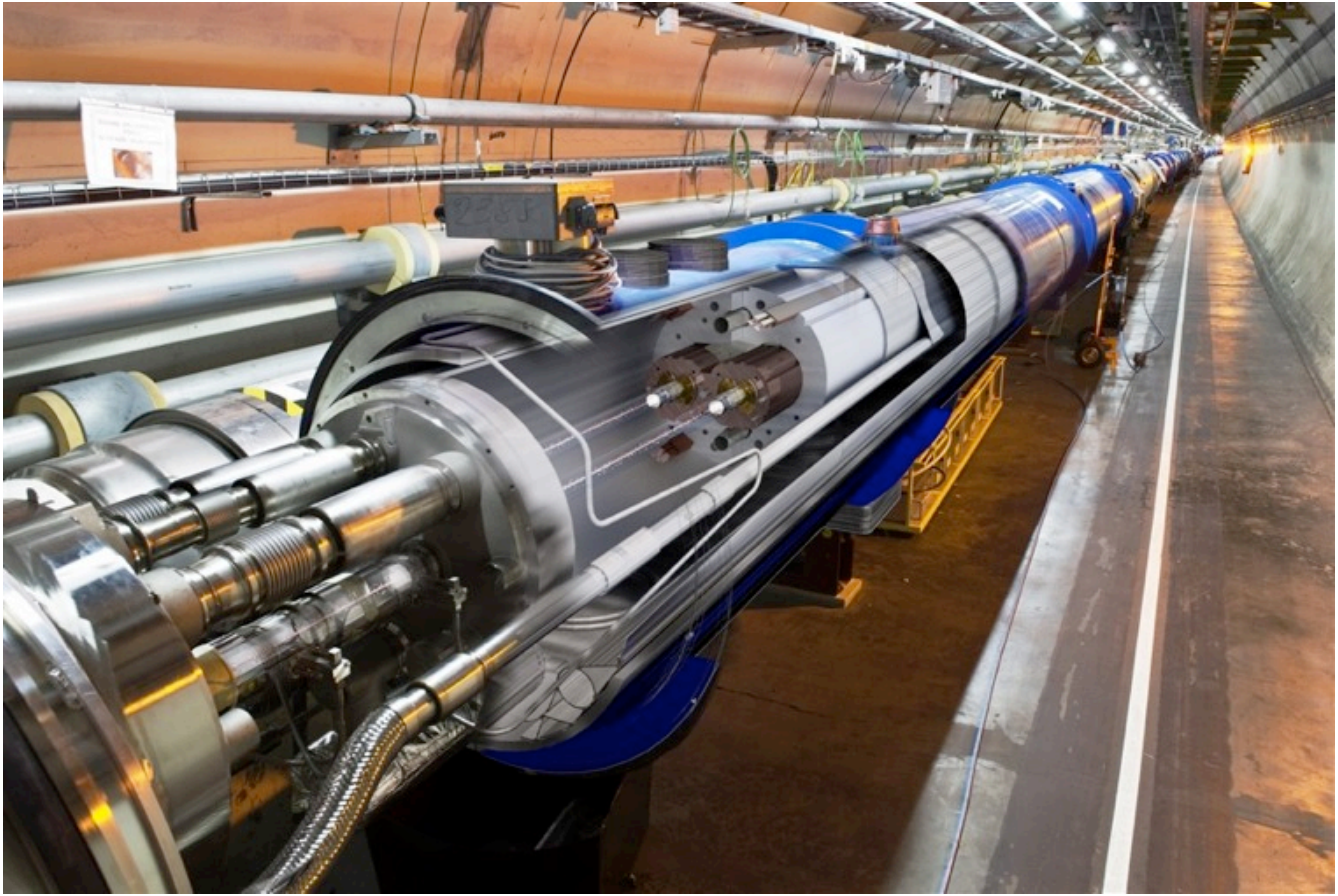
alignment target
main quadrupole bus-bars
heat exchange pipe
superinsulation
superconducting coils
beam pipe
vacuum vessel
beam screen
auxiliary bus bars
shrinking cylinder / He I-vessel
thermal shield (55 to 75 K)
non-magnetic collars
iron yoke (cold mass, 1.9 K)
dipole bus-bars
support post

LHC dipole magnet cross-section

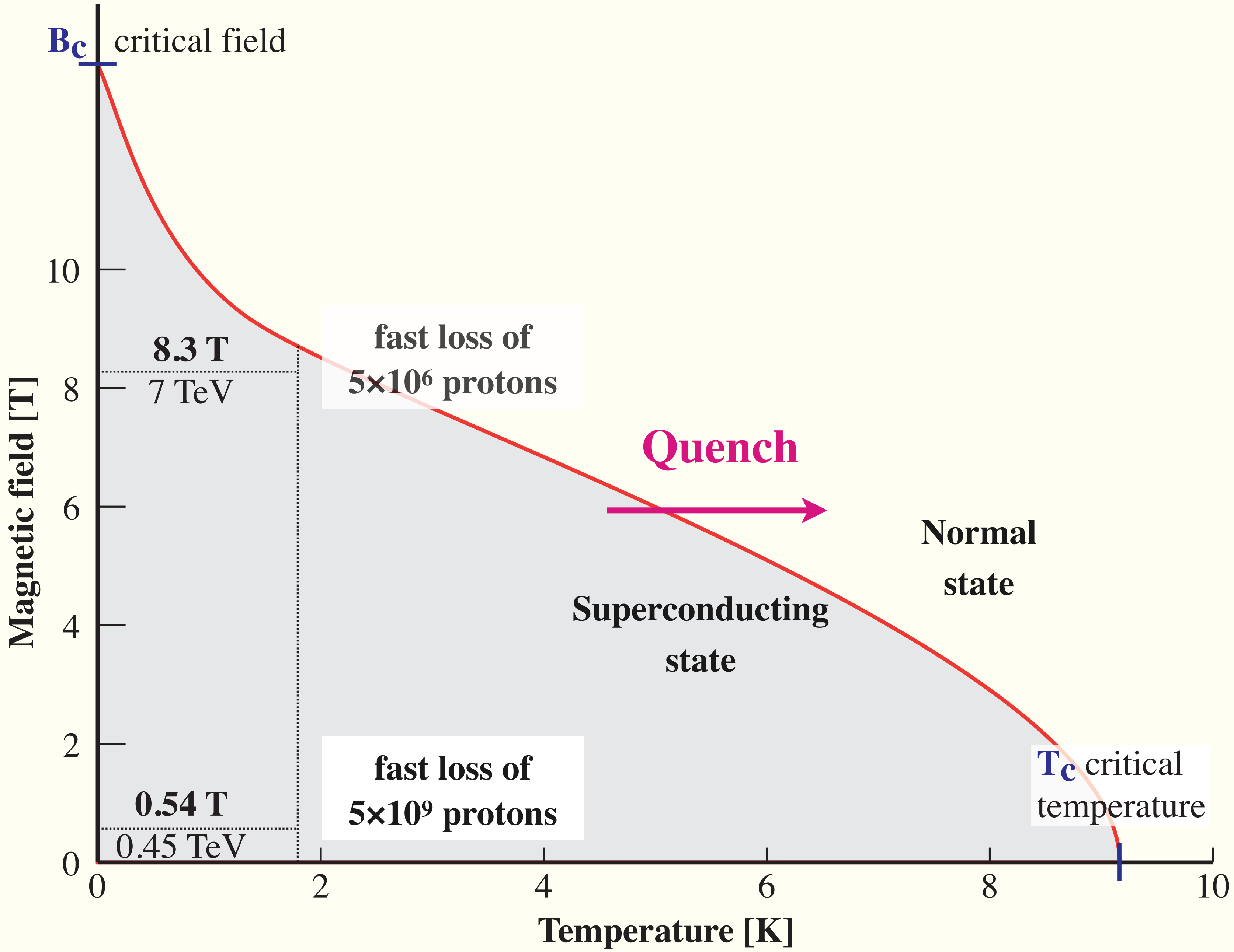


current distribution

LHC magnets installed in the tunnel



Operational margin of a superconducting LHC dipole



Fixed Target vs Collider

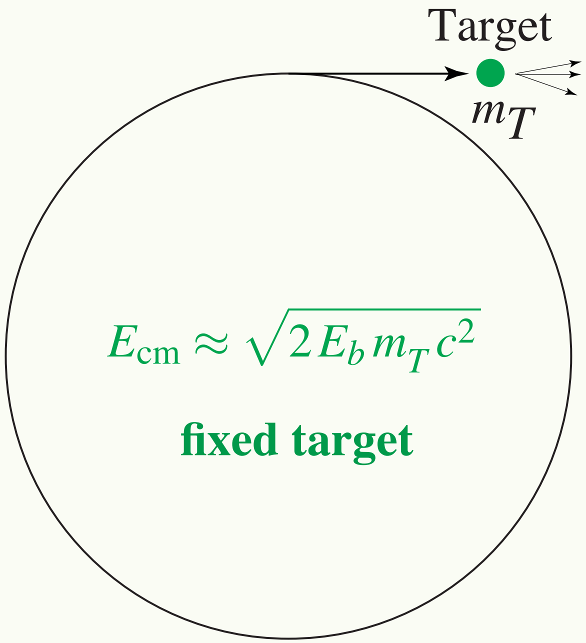
Fixed target, high energy collisions :

Energy “lost” as kinetic energy

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

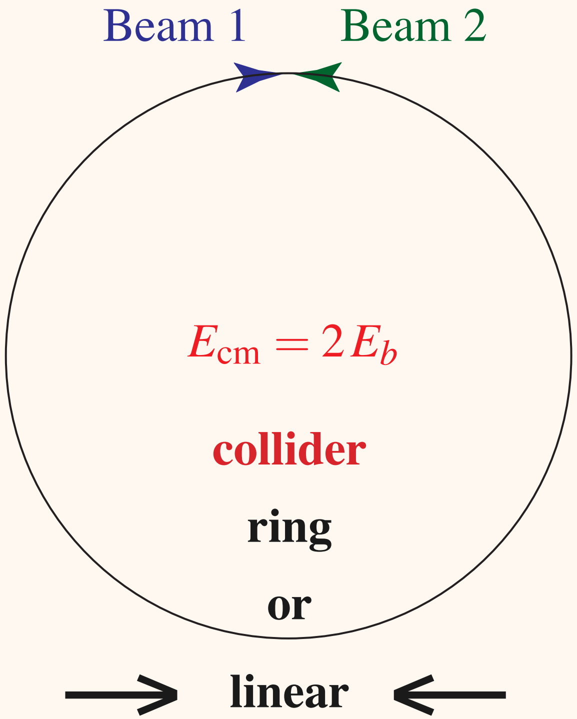
Gain for LHC is by ×122

(14 TeV / 114.6 GeV)



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

fixed target



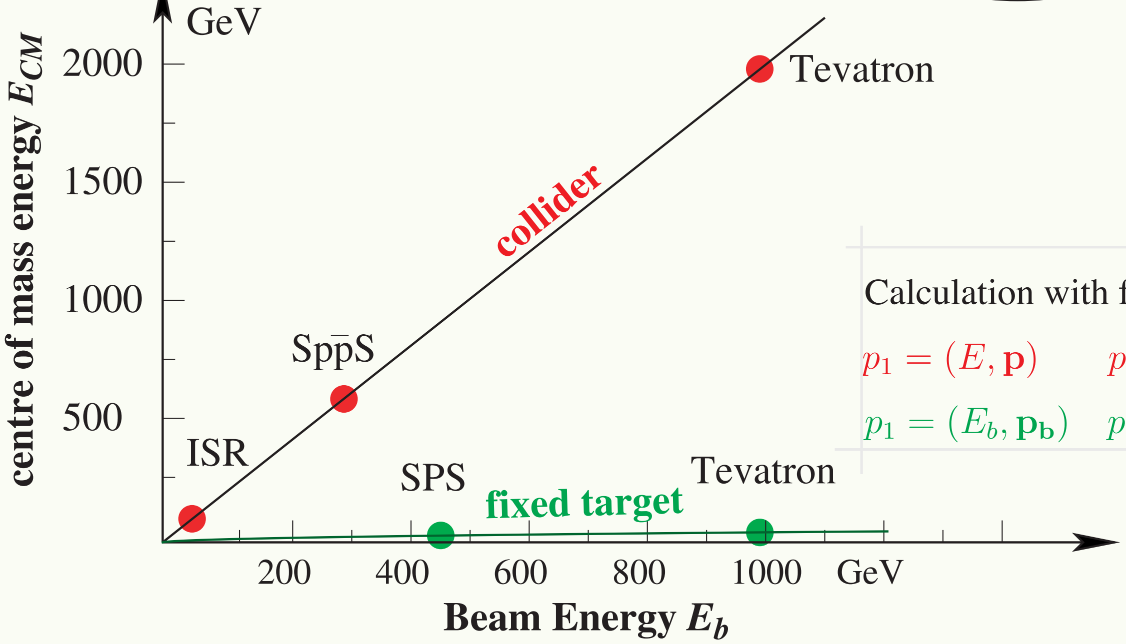
$$E_{\rm cm} = 2\,E_b$$

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

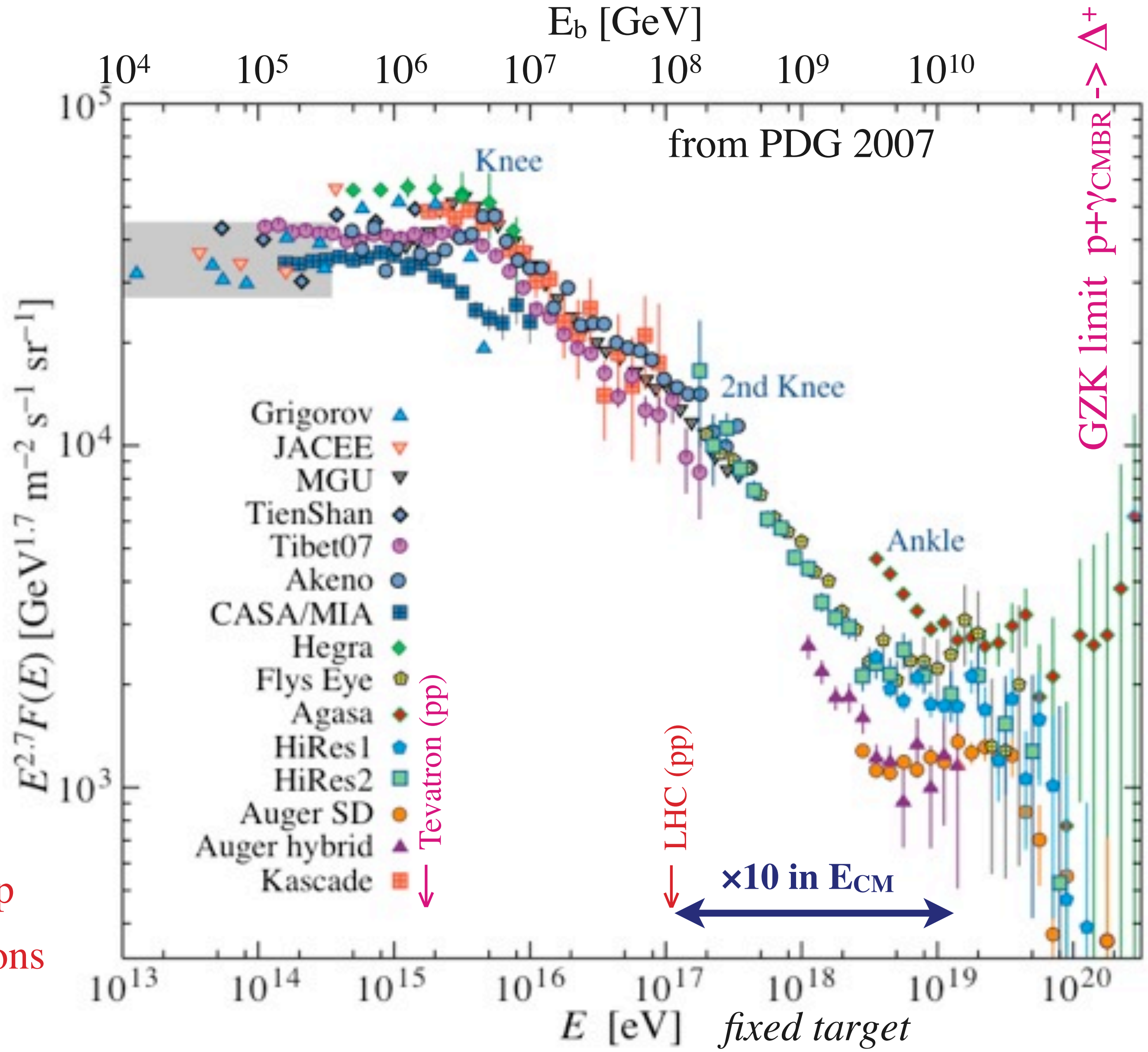
$p_1 = (E_b, \mathbf{p_b}) \quad p_2 = (m_T, \mathbf{0}) \quad s = m_b^2 + m_T^2 + 2m_T E_b$ fixed target

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.

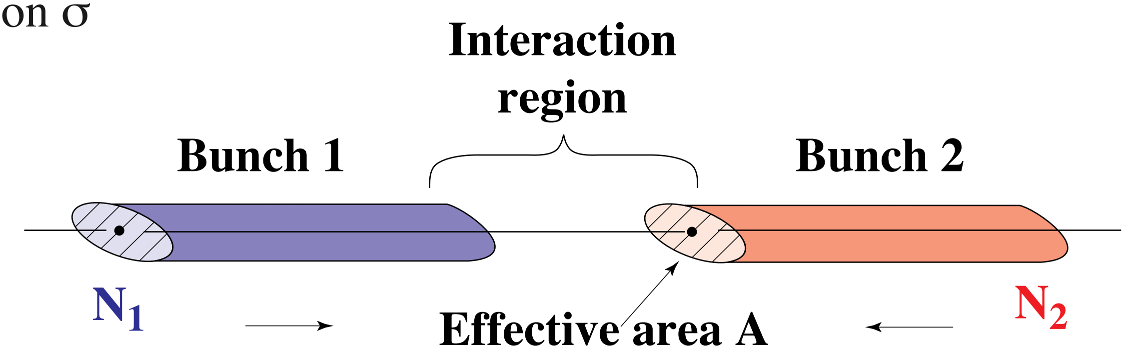
Luminosity and collision rates

Event rate for process with cross section σ

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

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

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

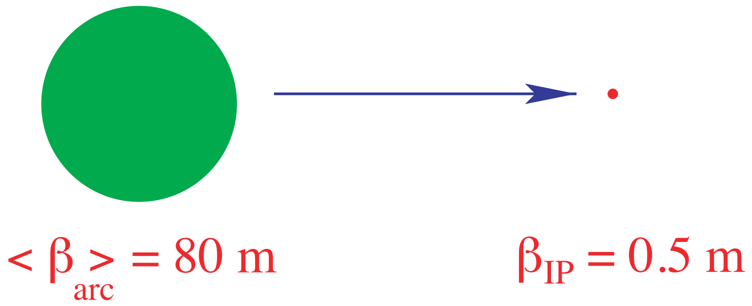


for Gaussian bunches with rms sizes $\sigma_x\ \sigma_y$ **A** $= 4\,\pi\,\sigma_x\,\sigma_y$

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 $\sigma_x = \sigma_y = 17\ \mu m$



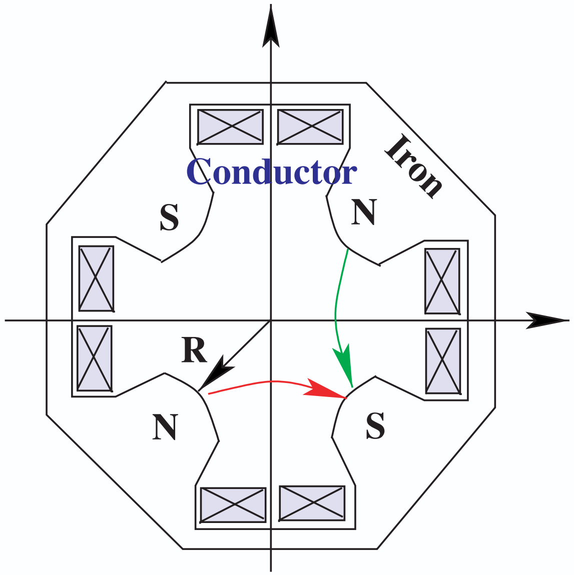
Rare new processes, like Higgs production can have very small cross section, like 1fb = 10^{-39}cm^2 . LHC designed for very high Luminosity $\mathbf{L = 10^{34}\ cm^{-2}s^{-1}}$

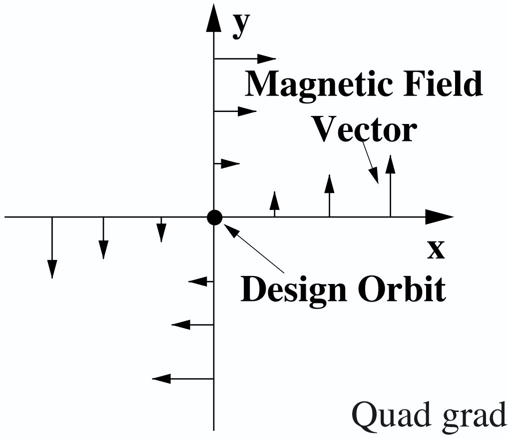
Event rate for such rare processes : ~ 1 new particle every 28h.

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

Alternate gradient focusing

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





$B_x = k\,y$

$B_y = k\,x$

$B_z = 0$

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

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

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

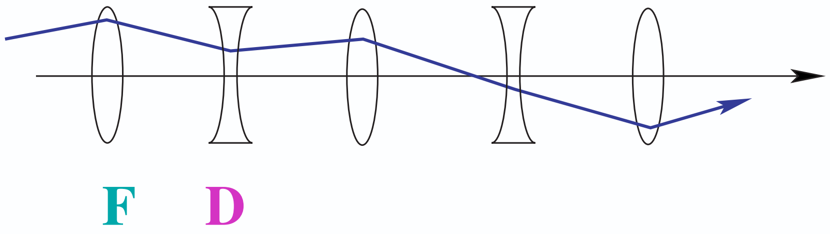
Combine F D

Defocusing when at

small amplitude

Overall focusing

alternate gradient focusing



Normal (light) optics :

Focal length of two lenses

at distance D

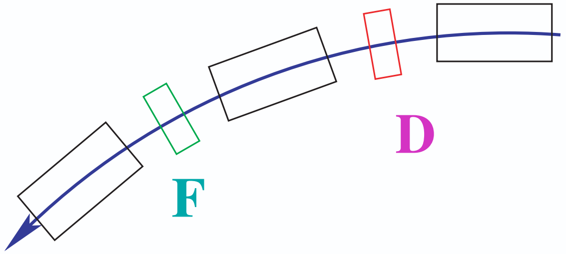
$1/f = 1/f_1 + 1/f_2 - D/f_1f_2$

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 ∝∂B/∂r)

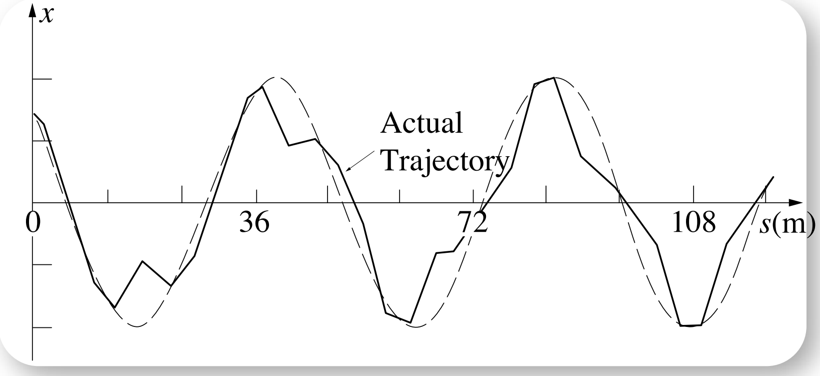
In both transverse planes, here written with x for x, y : known as Mathieu-Hill equation

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

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



motion x/√β *plotted with phase advance*
normalised coordinates - becomes simple cos

Phase advance

Lyapunov-Floquet Transformation

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

Tune # of betatron oscillations

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

β(s) **beta function**, describes the focusing properties of the magnetic lattice

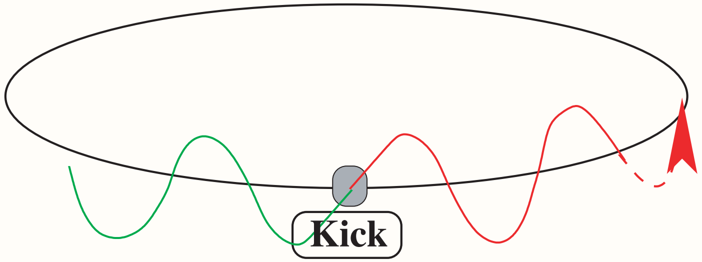
ε invariant, together with *β(s)* amplitude. "single particle emittance"

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

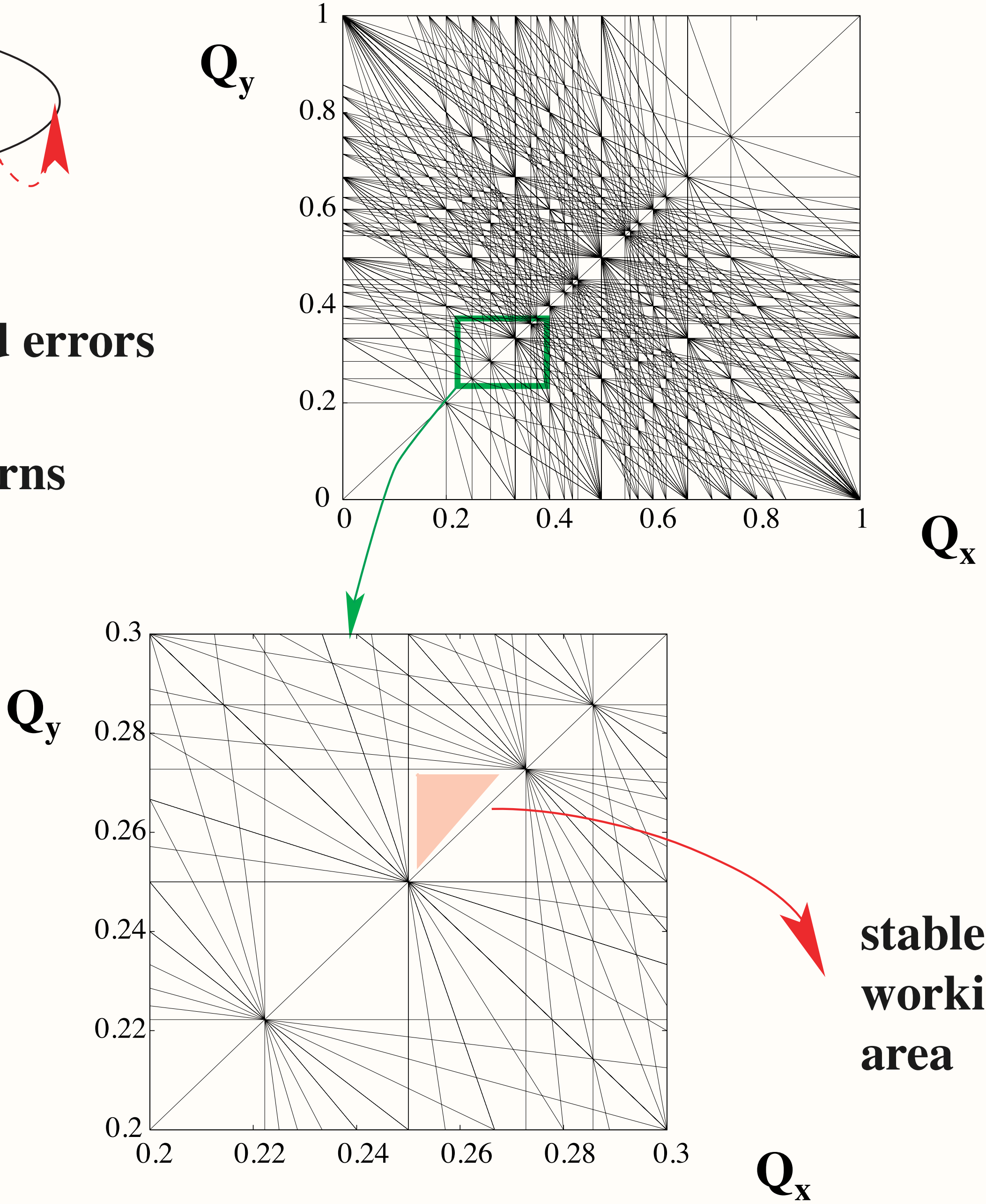
Higher order field errors,

Quad., Sext. perturbations.

Avoid simple fractional tunes

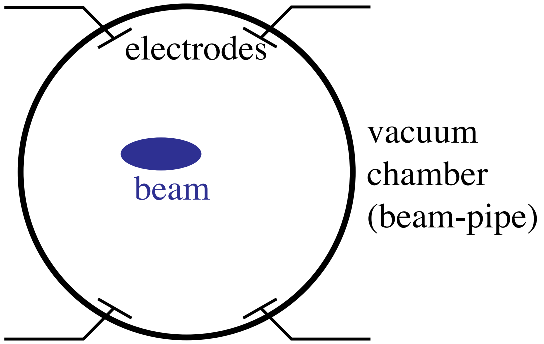
$nQ_x + m\ Q_y + m\ Q_s = \text{int.}$

Minimise field and alignment errors



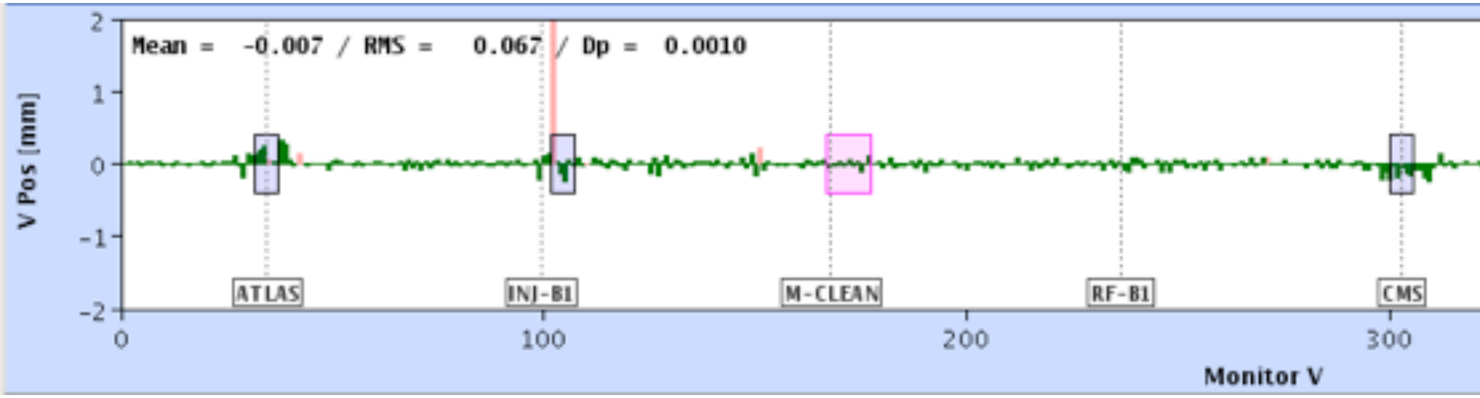
stable working area

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 $\langle I_b \rangle = n\,e\,f_{rev}$

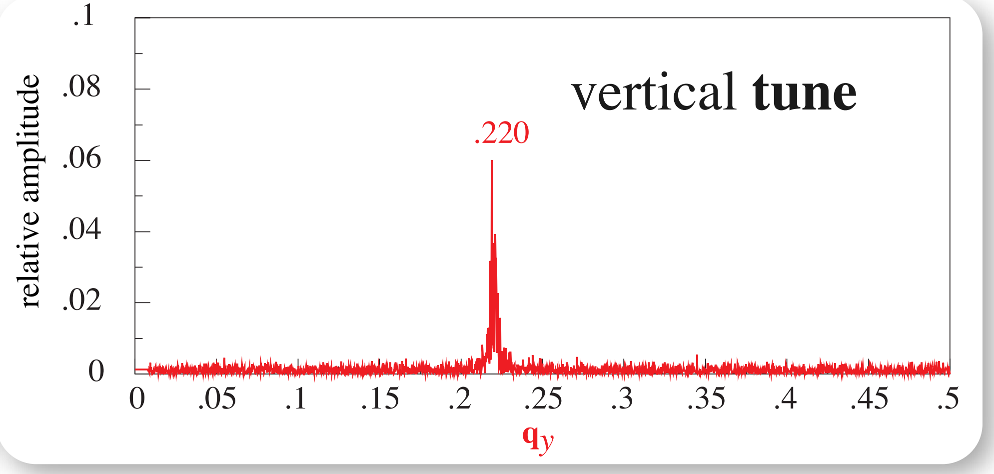
LEP $n = 4\times10^{11}$ $\langle I_b \rangle = 0.72$ mA $\sigma_z = 2$ cm $\hat{I} = 960$ A

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

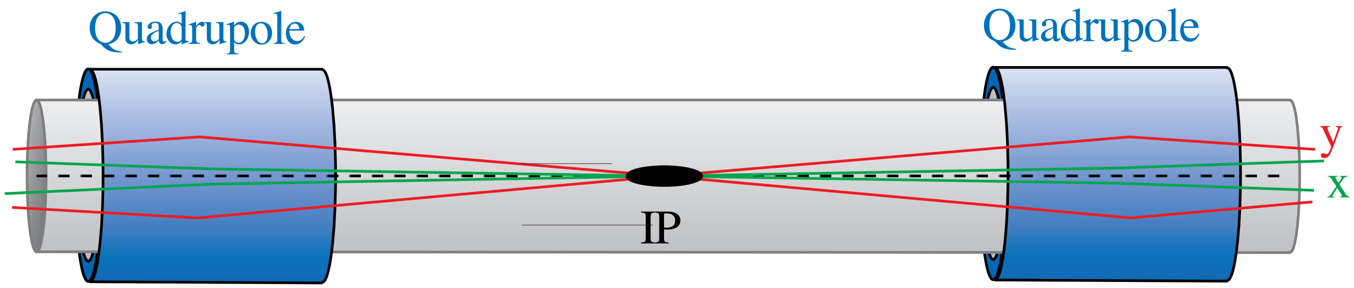
beam size, r.m.s. $\sigma(s) = \sqrt{\varepsilon\beta(s)}$

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



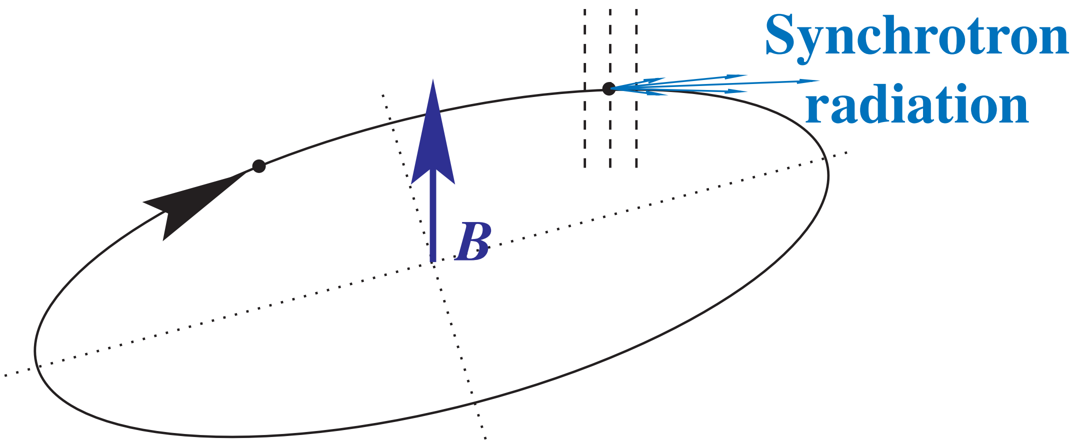
LHC $\varepsilon_N = \varepsilon\,\beta\gamma = 3.75\ \mu\mathrm{m}$, at top $E_b = 7$ TeV: $\varepsilon = 0.503$ nm, $\beta^* = 0.55$ m, $\sigma^* = 16.63\ \mu\mathrm{m}$, $\theta^* = 30\ \mu\mathrm{rad}$

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.

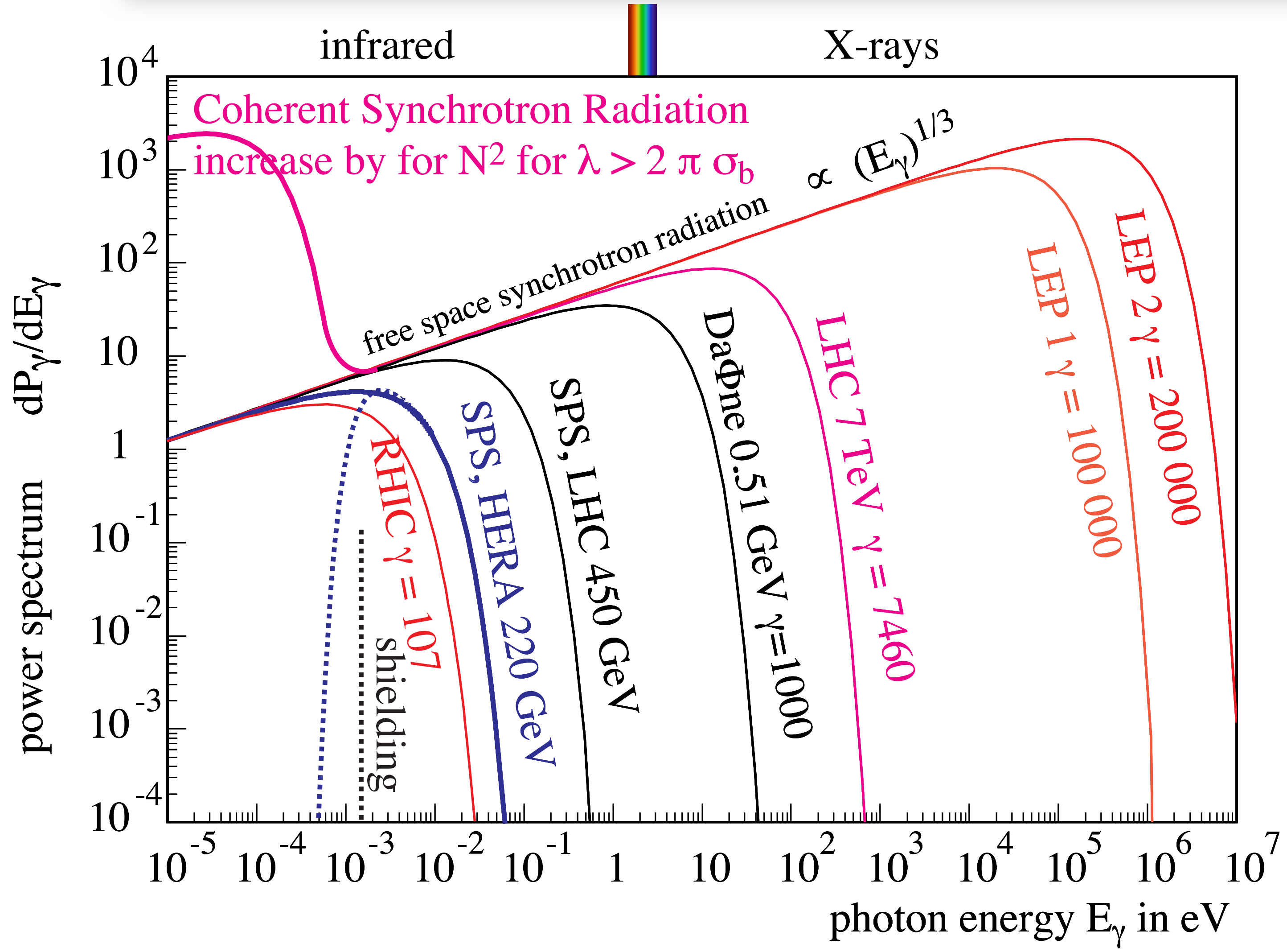

SR-Telescope BEUV A 831 QS18.L8 Particle Electron

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

Camera at
Normal

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

Power Spectrum, Free space, Cutoff and CSR



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

ϱ bending radius

h chamber height

cutoff relevant

for $\gamma \approx 100$

12 orders of magnitude
in E_γ and λ
10^{-5} eV λ = 0.124 m
10^{+7} eV λ = 124 fm

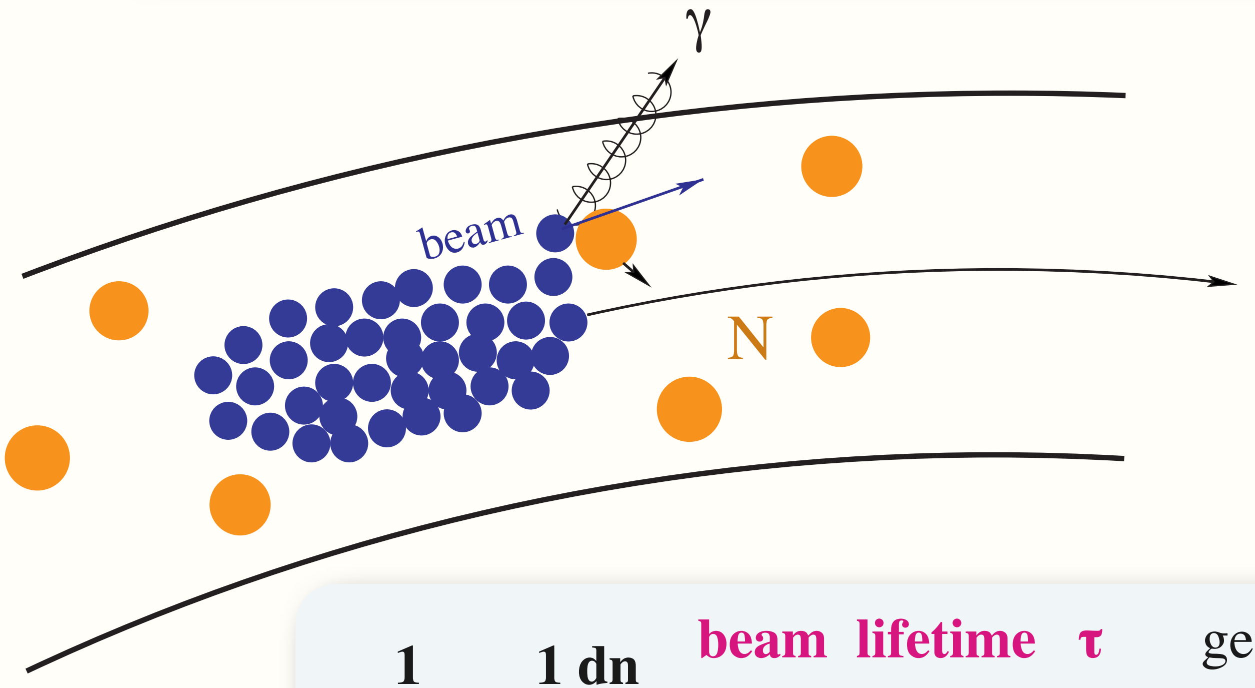
Effects which can modify the low energy, long wavelength spectrum :

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

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

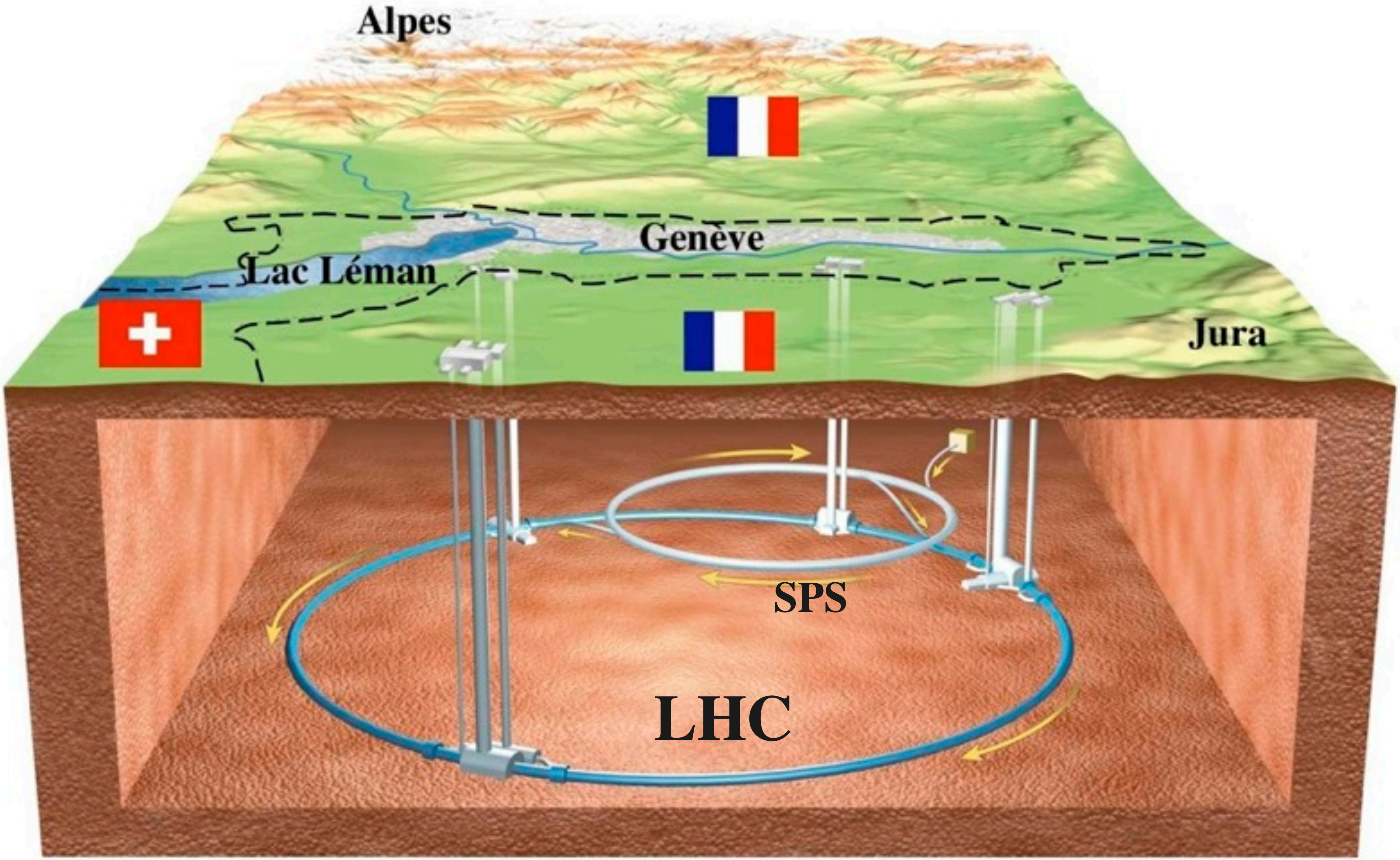
$$\rho_m = \frac{p}{kT} = 3.26 \times 10^{13}\text{molecules / m}^3$$

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

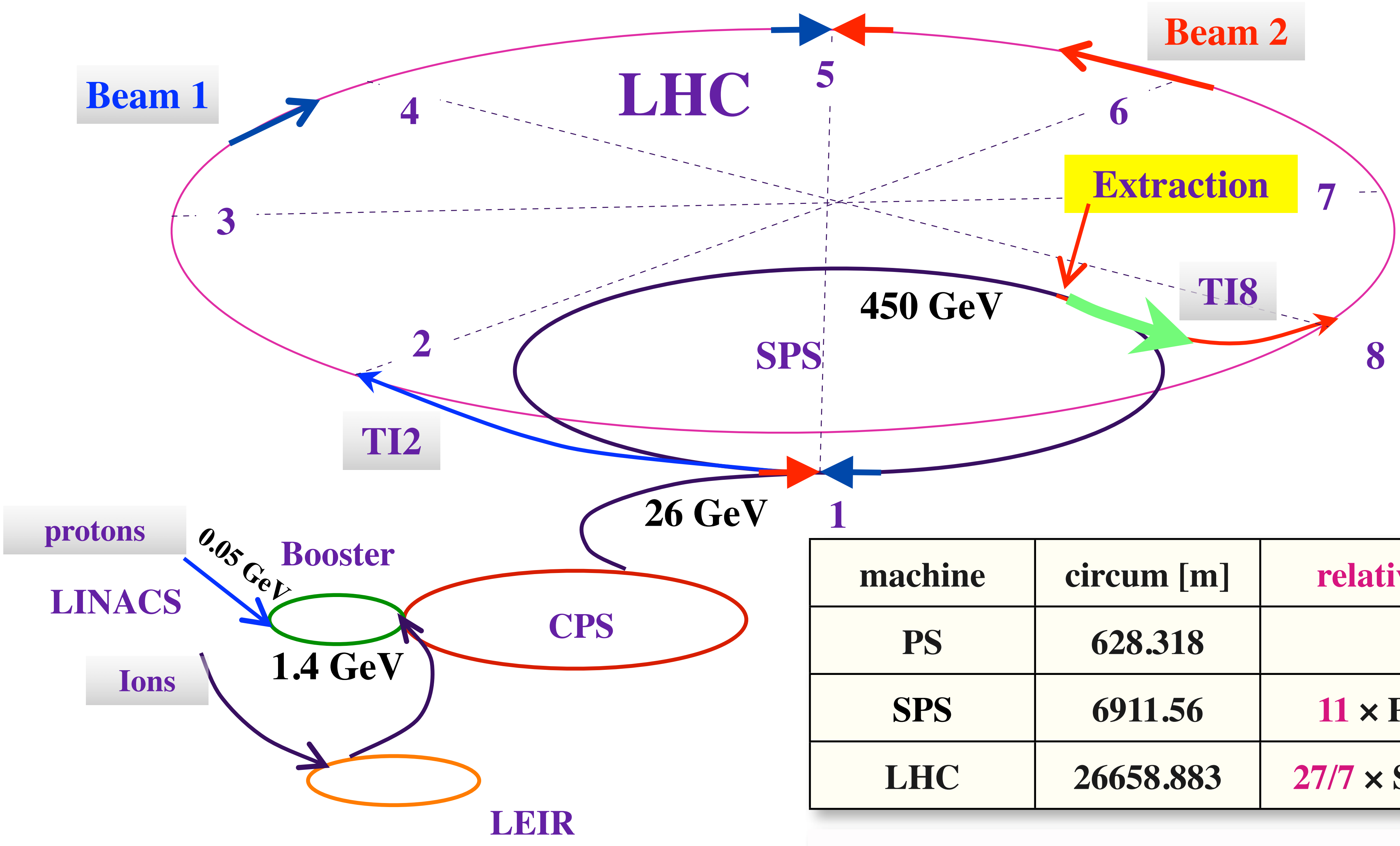
collision probability $P_{\text{coll}} = \sigma\,\rho_m = 1.96 \times 10^{-14}/\,\text{m}$

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

Examples from CERN with the LHC



The CERN accelerator complex : injectors and transfer



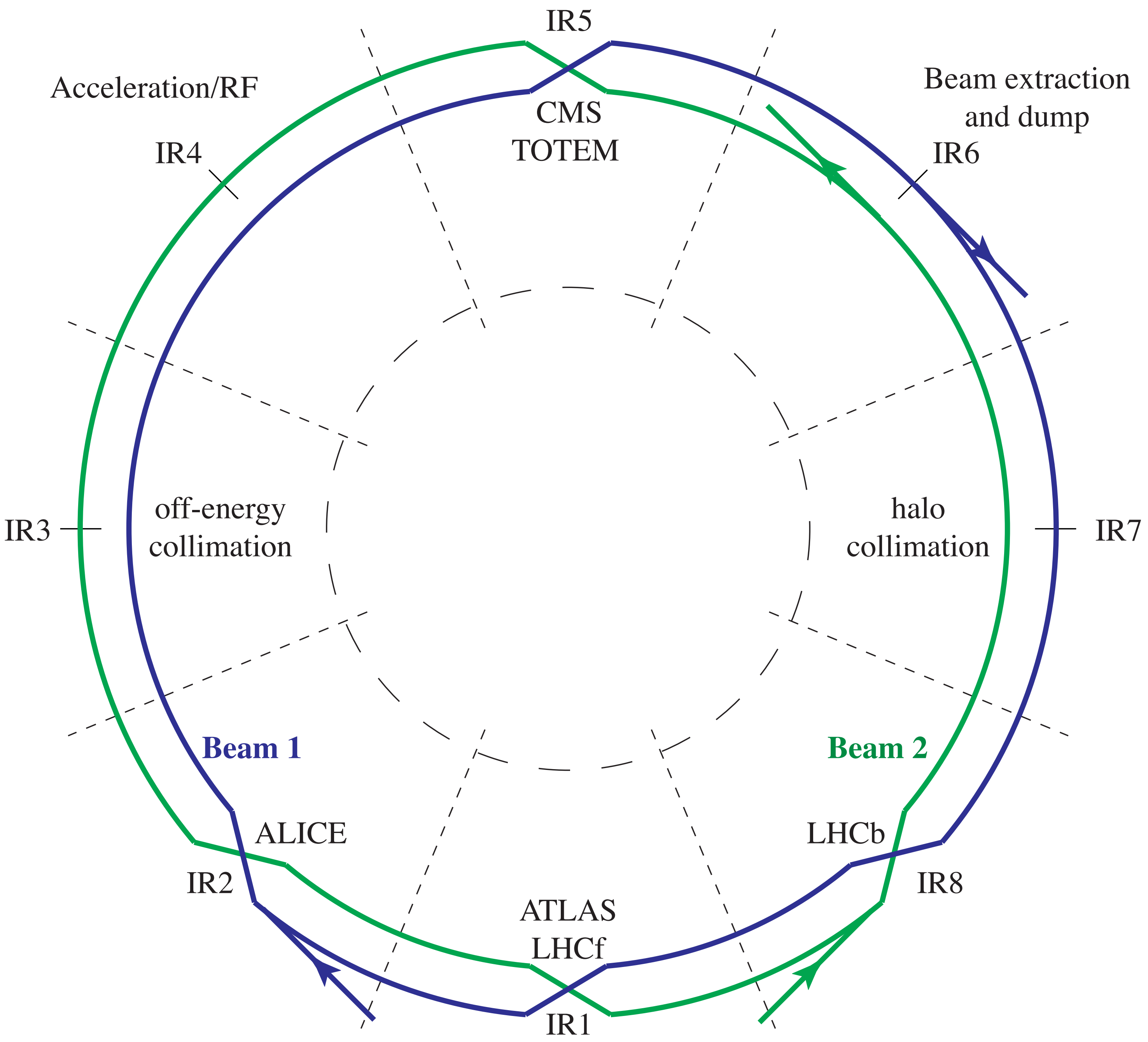
machine	circum [m]	relative
PS	628.318	
SPS	6911.56	11 × PS
LHC	26658.883	27/7 × SPS

simple rational fractions for synchronization based on a single frequency generator at injection

Beam size of protons decreases with energy : area $\sigma^2 \propto 1 / E$

Beam size largest at injection, using the full aperture

Layout of the LHC



10 September 2008

10:30	**beam 1**	**3 turns**
15:00	**beam 2**	**3 turns**
22:00	**beam 2**	**several 100 turns**

LHC status

- **main LHC challenge : damage potential --- increase safely (slowly) the intensity**
- **enormous stored energy :** nominal is 10 GJ in magnets, 362 MJ in beam; 0.7 MJ melts 1kg Cu
- currently 3.3 GJ in magnets, 130 MJ in beam

LHC :

2009 first collisions, mostly at injection energy 2x450 GeV

2010 commissioning and first year of operation with collisions at high energy 2x3.5 TeV

368 bunches, Luminosity L_{peak} = **0.2×10^{33} cm^{-2}s^{-1}** **∫ L dt = 0.048 fb^{-1}**

2011 2×3.5 TeV, β*= 1 m, L_{peak} = **3.5×10^{33} cm^{-2}s^{-1}** **∫ L dt = 5.3 fb^{-1}**

2012 2×4.0 TeV, β*= 0.6m, L_{peak} = **6.7×10^{33} cm^{-2}s^{-1}** **∫ L dt = 6.6 fb^{-1}** already

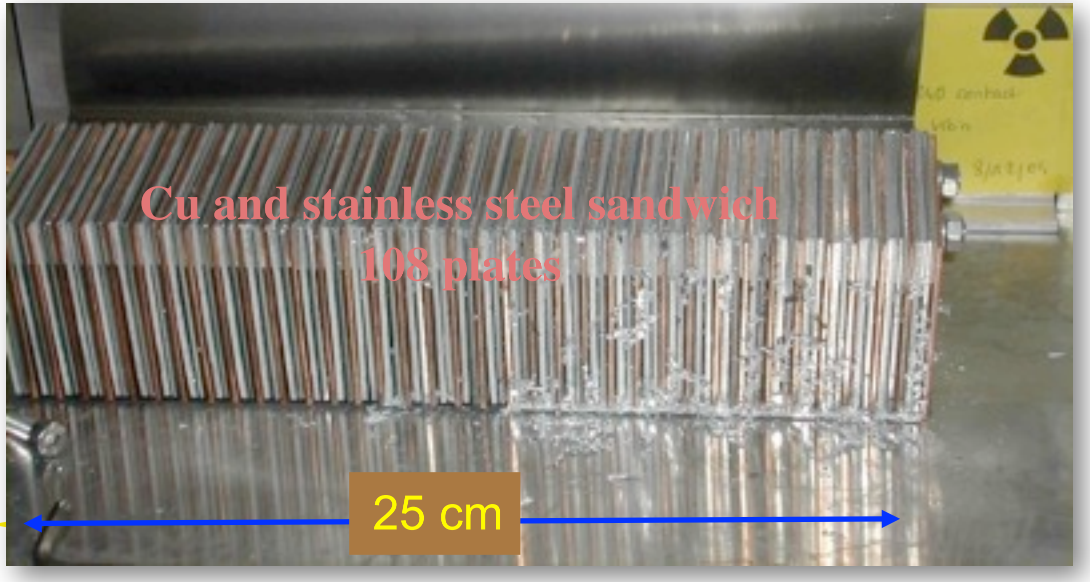
	LHC design	**now**
Momentum at collision, TeV/c	**7**	**4**
Luminosity, cm^{-2}s^{-1}	**1.0E+34**	**6.8E+33**
Dipole field at top energy, T	**8.33**	**4.8**
Number of bunches, each beam	**2808**	**1380**
Particles / bunch	**1.15E+11**	**1.50E+11**
Typical beam size in ring, µm	**200 – 300**	**~300**
Beam size at IP, µm	**17**	**20**

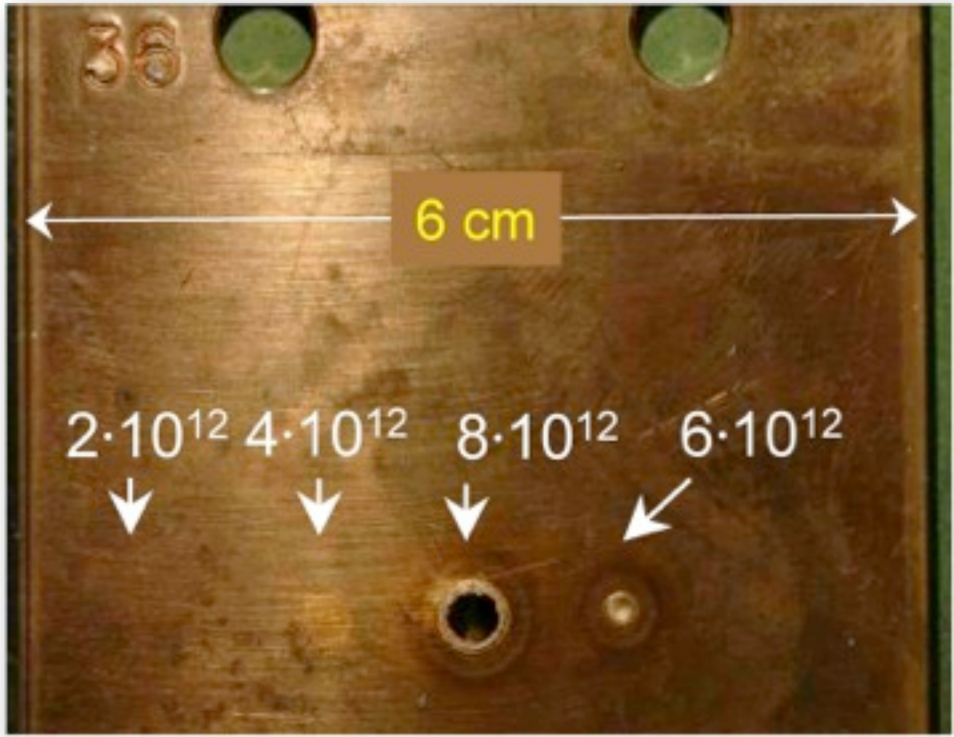
Damage potential : confirmed in controlled SPS experiment

controlled experiment with beam extracted from SPS at 450 GeV in a single turn, with perpendicular impact on Cu + stainless steel target

450 GeV protons →

r.m.s. beam sizes $\sigma_{x/y} \approx 1$ mm





SPS results confirmed :

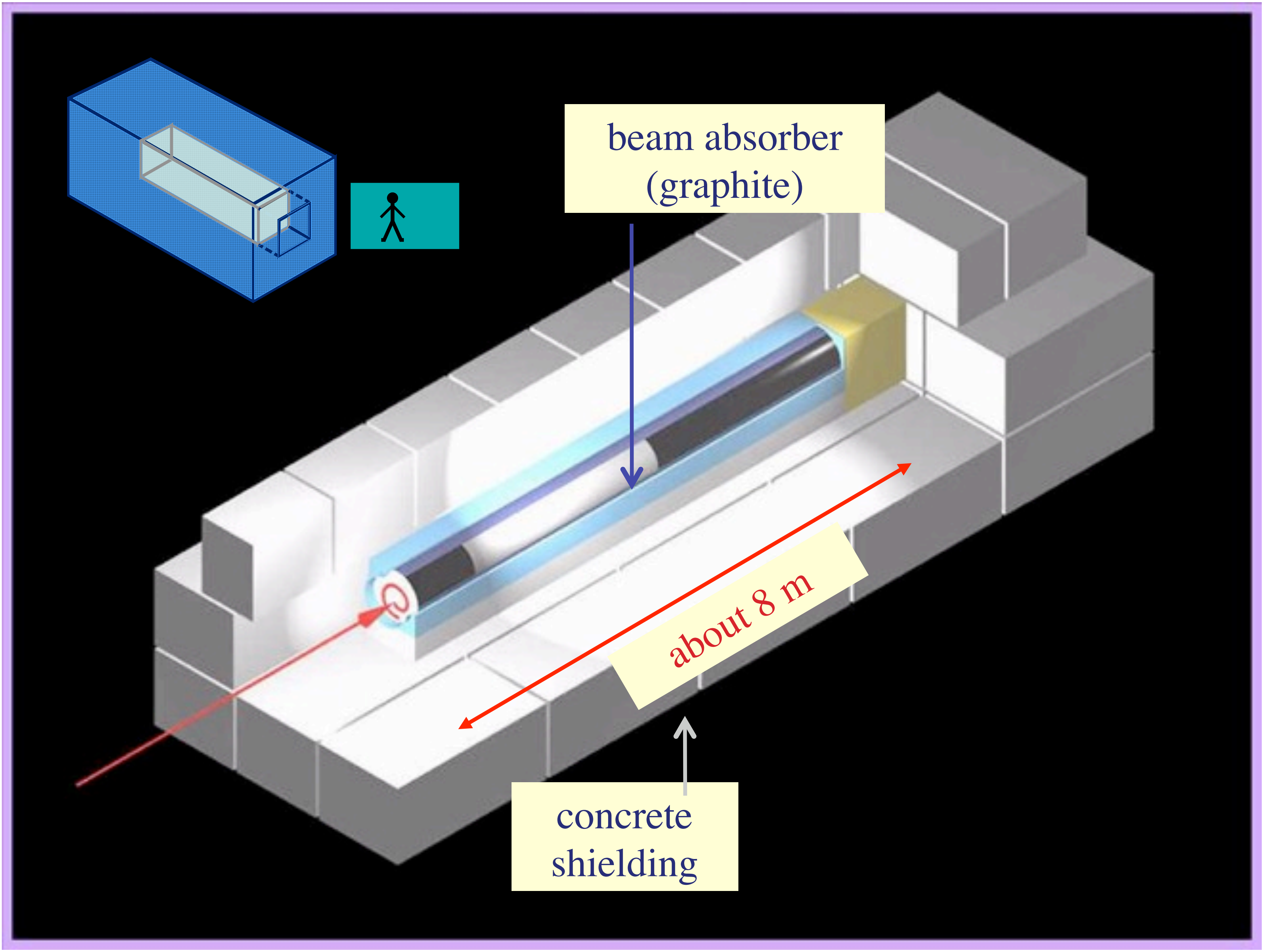
8×10^{12} clear damage

2×10^{12} below damage limit

for details see V. Kain et al., PAC 2005 RPPE018

For comparison, the LHC nominal at 7 TeV :
$2808 \times 1.15\times10^{11} = 3.2\times10^{14}$ p/beam
at $< \sigma_{x/y} > \approx 0.2$ mm
over 3 orders of magnitude above damage level for perpendicular impact

Dumping the LHC beam



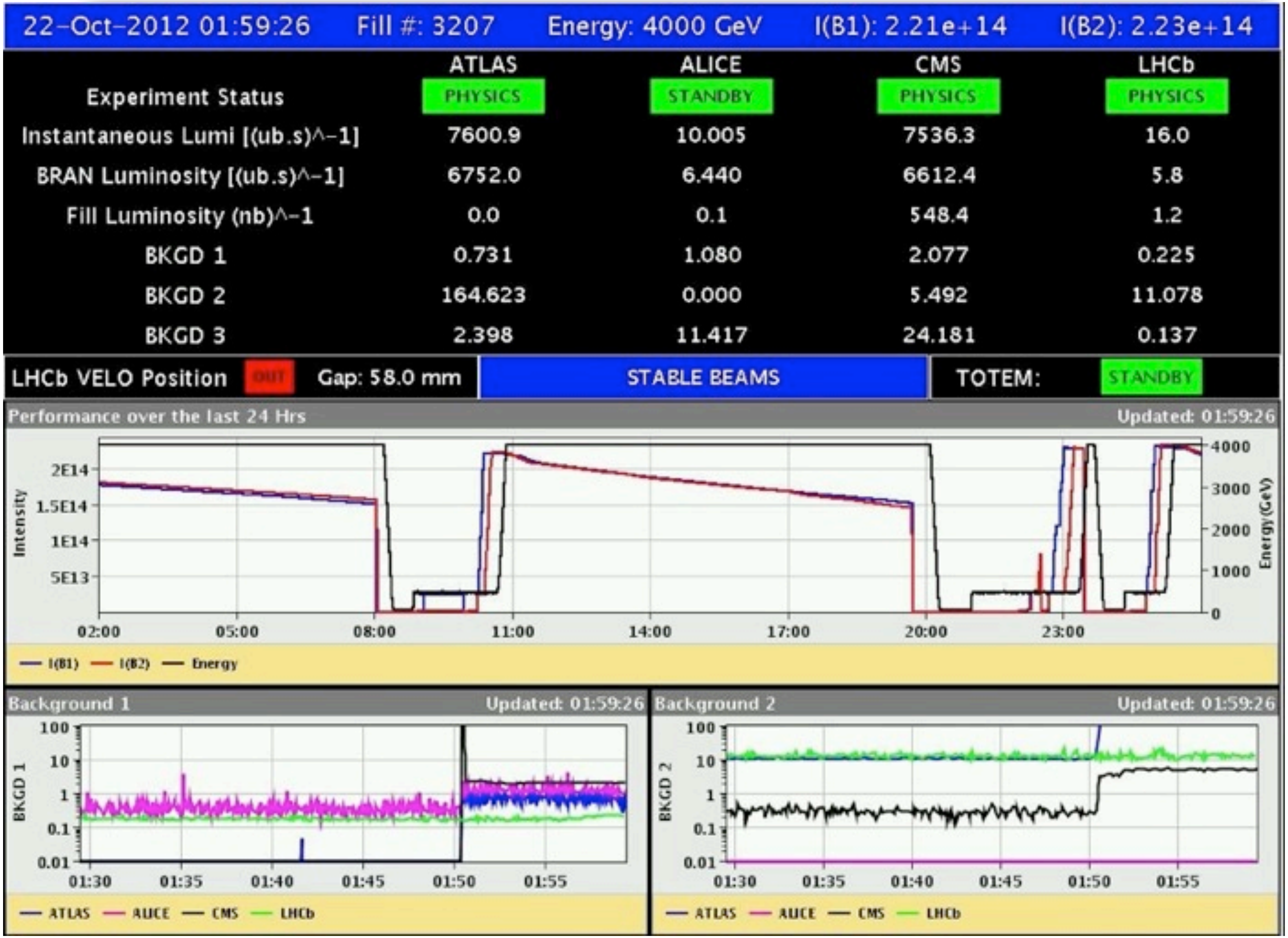
beam absorber (graphite)

about 8 m

concrete shielding

First high energy 3.5TeV+3.5TeV collisions, 30 March 2010

LHC currently running very well



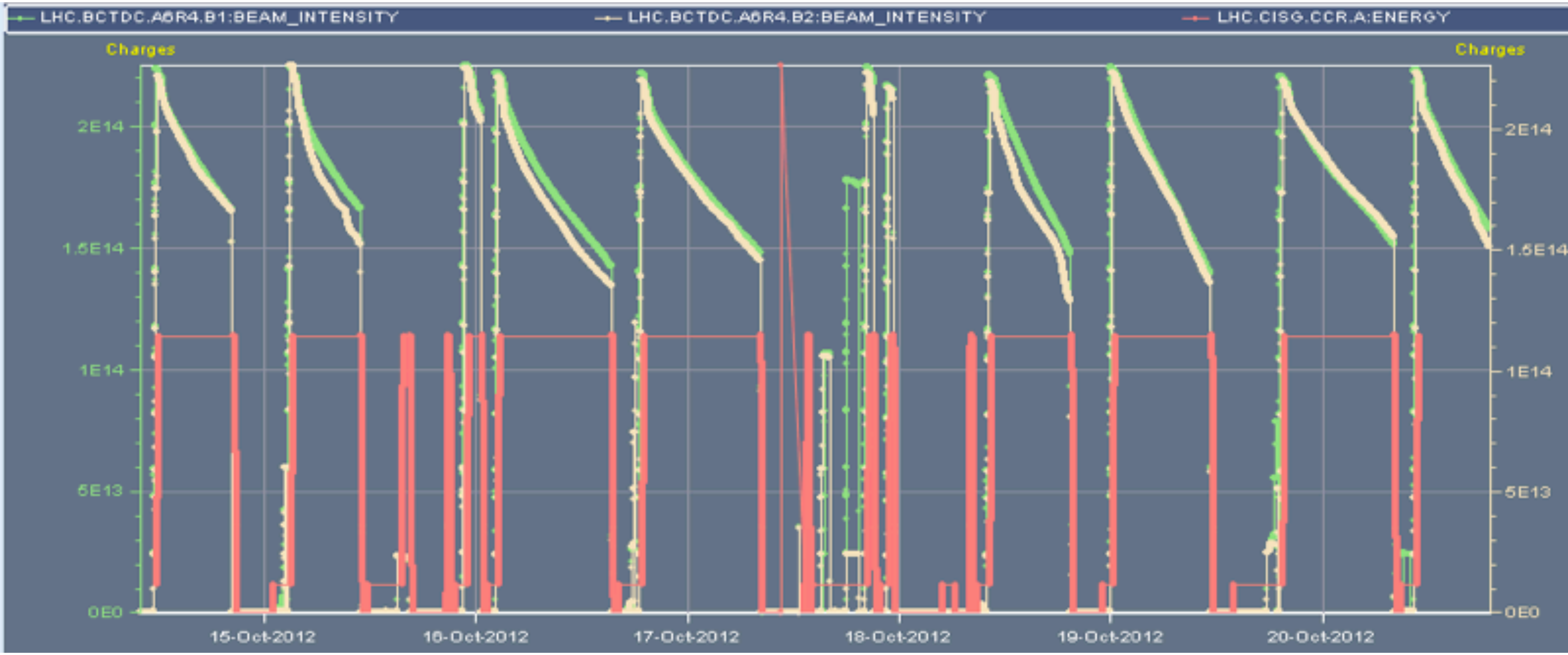
22-Oct-2012 01:59:26 Fill #: 3207 Energy: 4000 GeV I(B1): 2.21e+14 I(B2): 2.23e+14

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	STANDBY	PHYSICS	PHYSICS
Instantaneous Lumi [(ub.s)^-1]	7600.9	10.005	7536.3	16.0
BRAN Luminosity [(ub.s)^-1]	6752.0	6.440	6612.4	5.8
Fill Luminosity (nb)^-1	0.0	0.1	548.4	1.2
BKGD 1	0.731	1.080	2.077	0.225
BKGD 2	164.623	0.000	5.492	11.078
BKGD 3	2.398	11.417	24.181	0.137

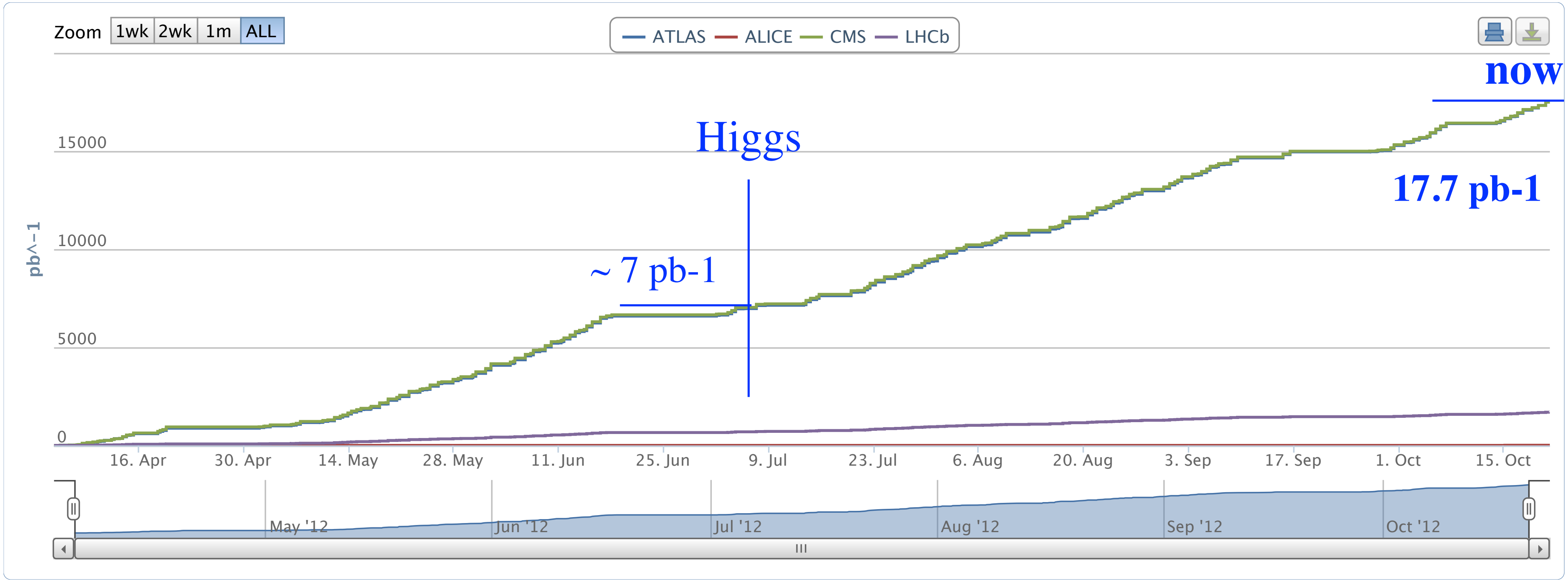
LHCb VELO Position OUT Gap: 58.0 mm STABLE BEAMS TOTEM: STANDBY

peak Luminosity 7.8 ×10^{33}cm^{-2}s^{-1}

LHC last week, 1.2 pb-1



Integrated Luminosity or # collisions produced



now

Higgs

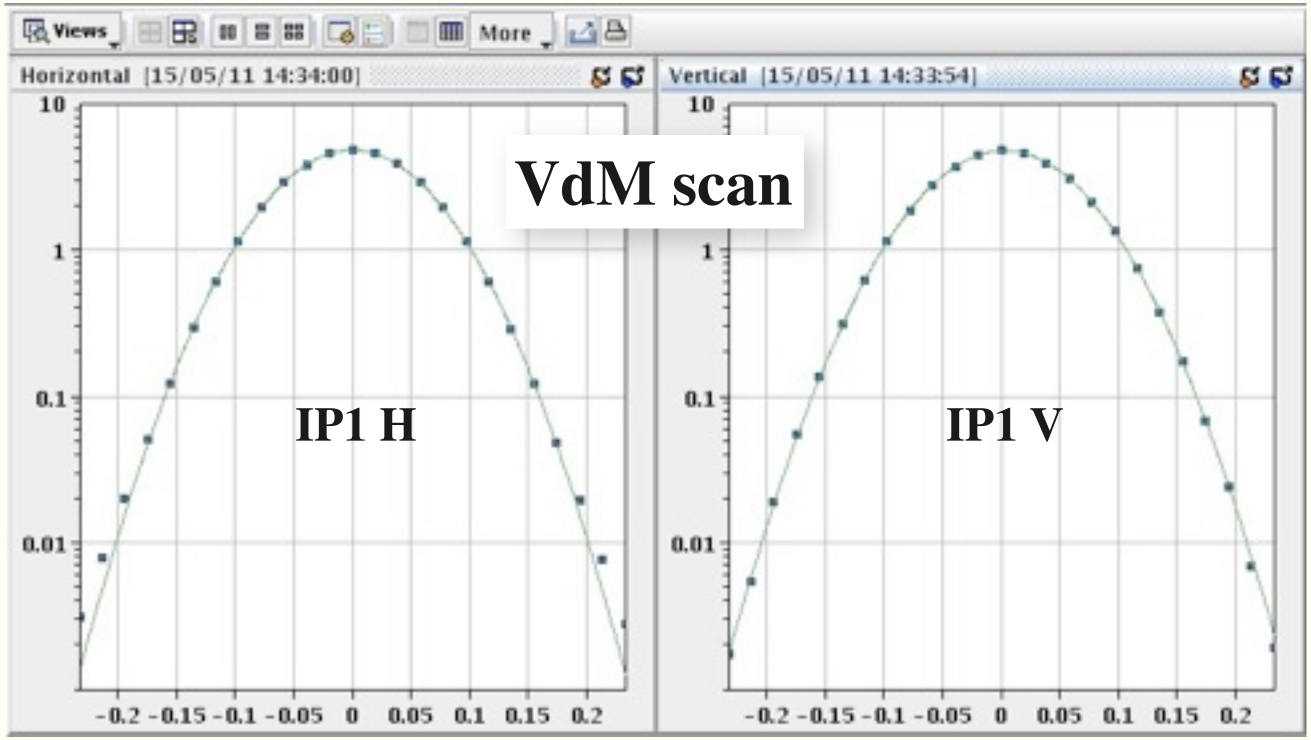
~ 7 pb-1

17.7 pb-1

Precision front - high quality of LHC beams

- absolute luminosity normalization
- low, well understood backgrounds
- precision optics for ATLAS-ALFA and TOTEM

  β* = 1000 m run this Wednesday

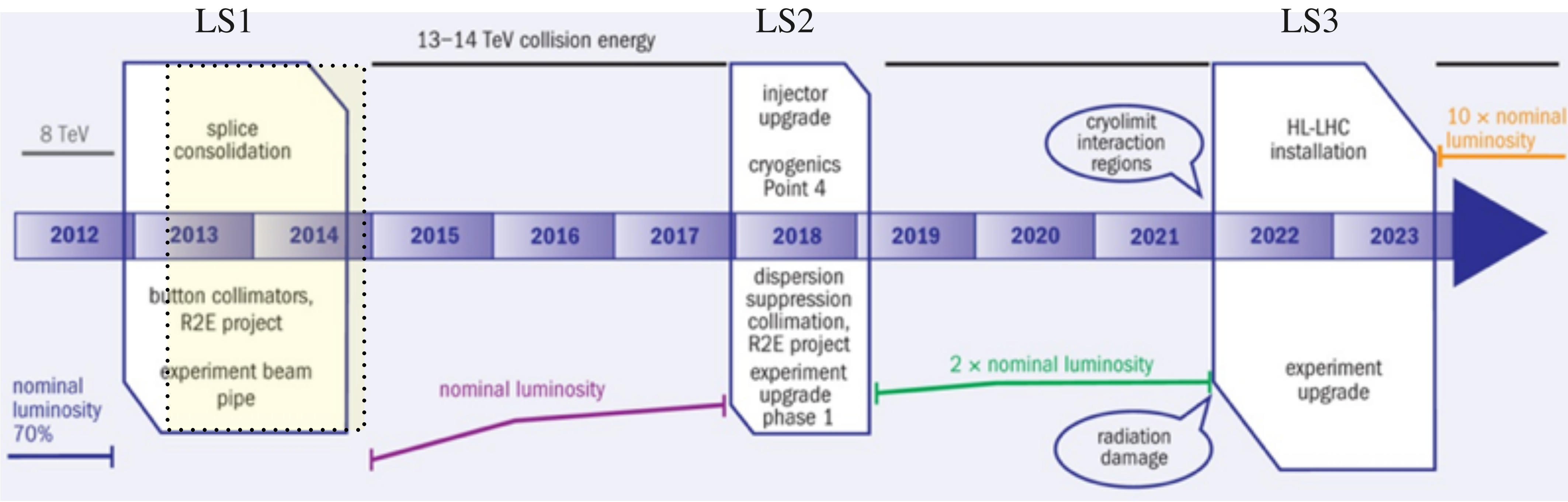


precise measurement of the luminous region + beam intensity --> absolute luminosity and cross section calibration

currently ~ 3 % level (Tevatron had ~ 15 %)

HL-LHC Timeline

The LHC is still a rather young machine
Operation planning + upgrade studies (HL-LHC) extend to ~ 2030



Further ideas already exist (HE-LHC, LHeC)
We also study other machines, and in particular CLIC ➜

CLIC Compact Linear Collider

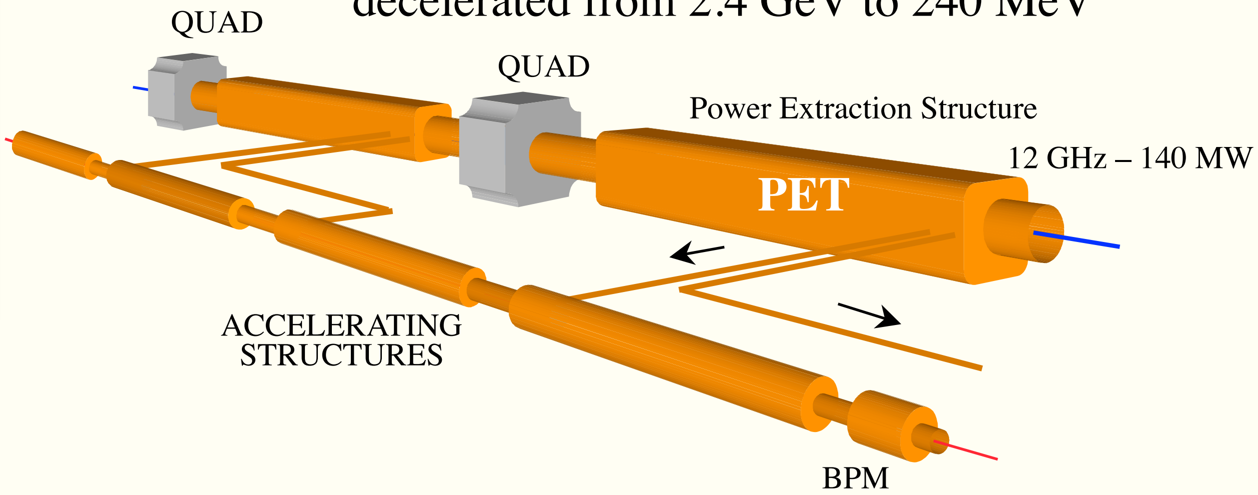
Two Beam Scheme

Drive Beam supplies RF power

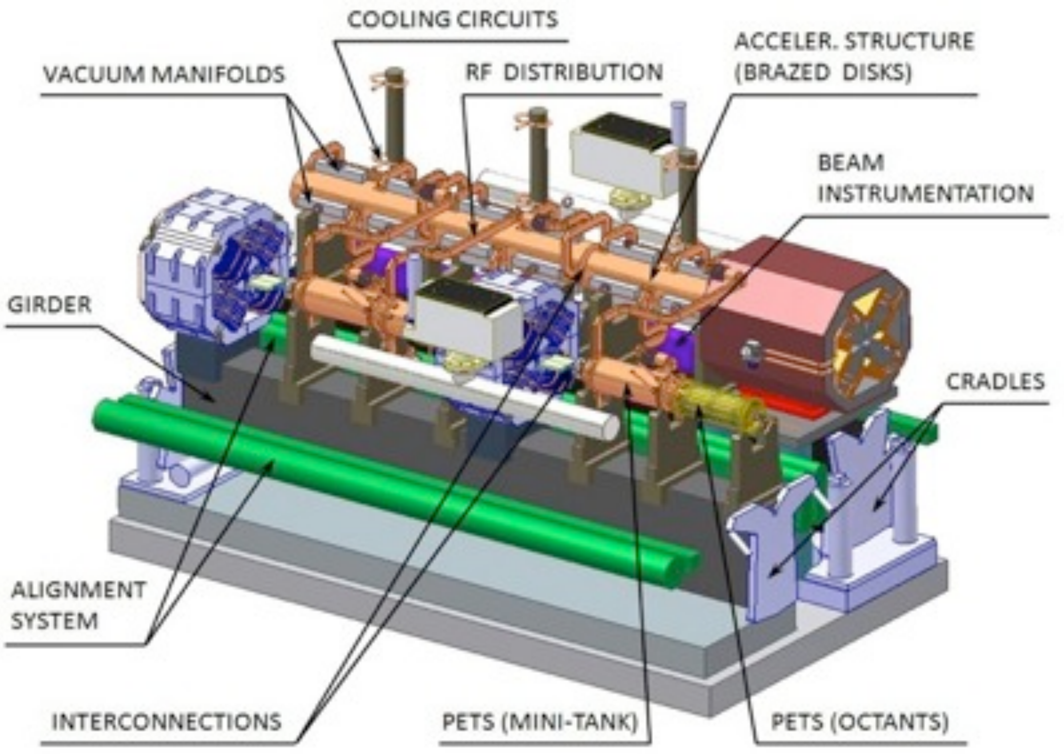
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

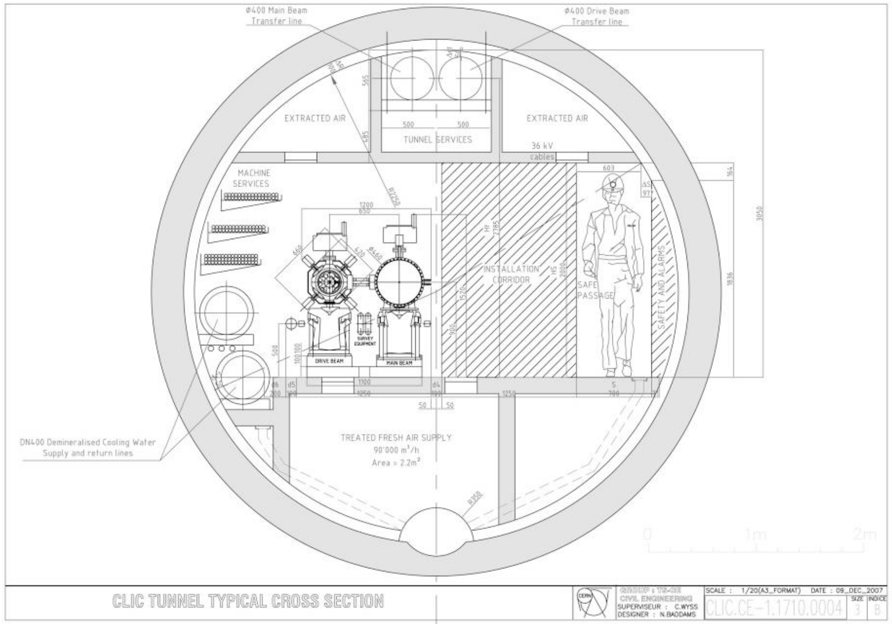
warm (not superconducting) RF

Drive beam - 100 A, 240 ns
decelerated from 2.4 GeV to 240 MeV

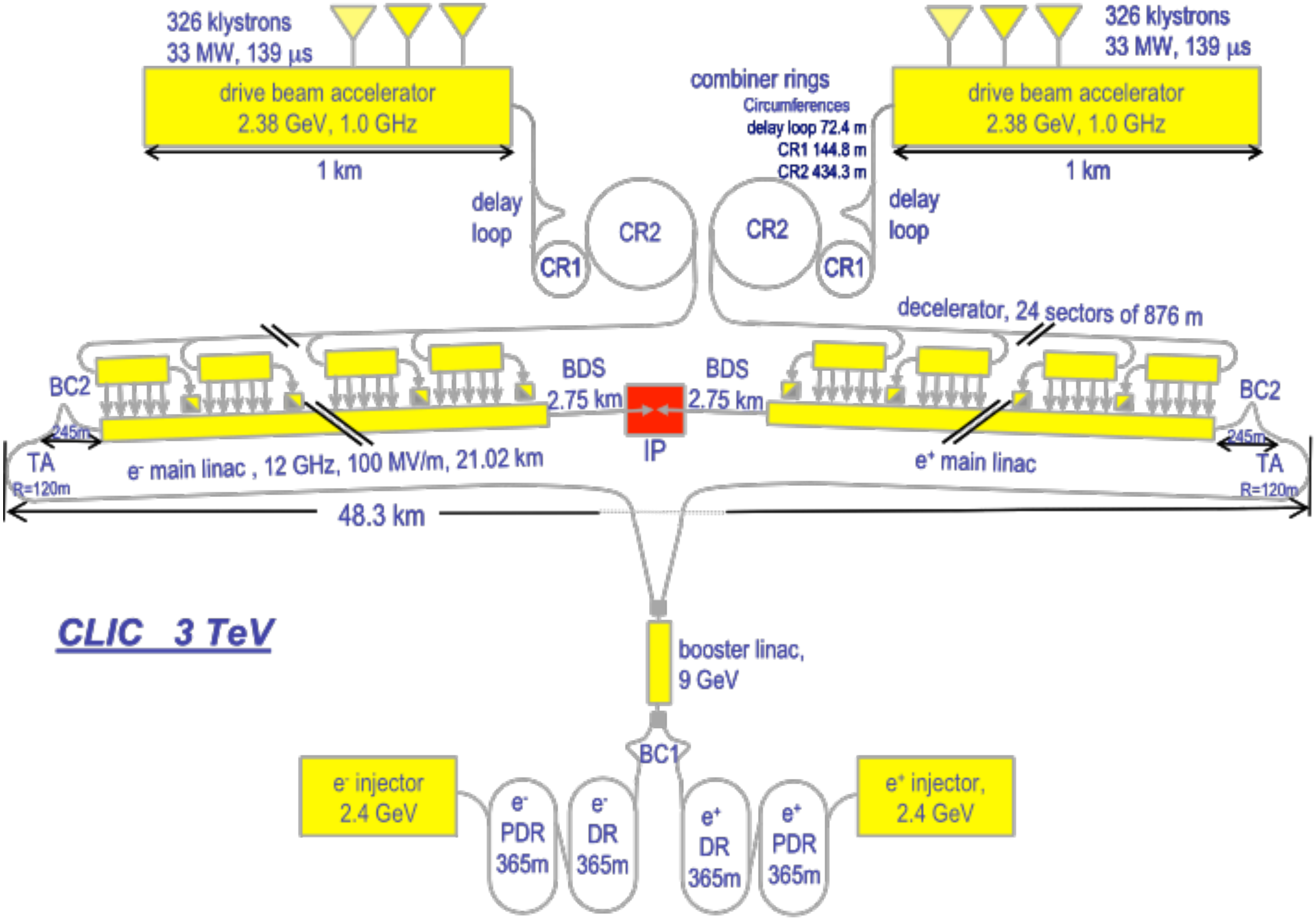


Main beam - 1.2 A, 156 ns bunch trains
accelerated from 9 GeV to 1.5 TeV





CLIC, full layout, not to scale



Accelerator applications and R&D (last slide)

- **The largest flag-ship accelerator is the LHC here at CERN**
- **By now many more accelerators outside particle physics**
  #Accelerators in the world : O (30 000) mostly smaller for medical and industrial applications
- **Broad range of particle accelerator types and applications**

Large research facilities for :
Synchrotron light, UV, X-Ray (electron accelerators)
High intensity proton accelerators + neutron spallation sources
condensed matter, material science and biology research,
accelerator driven subcritical fission (energy production & radioactive waste incineration)

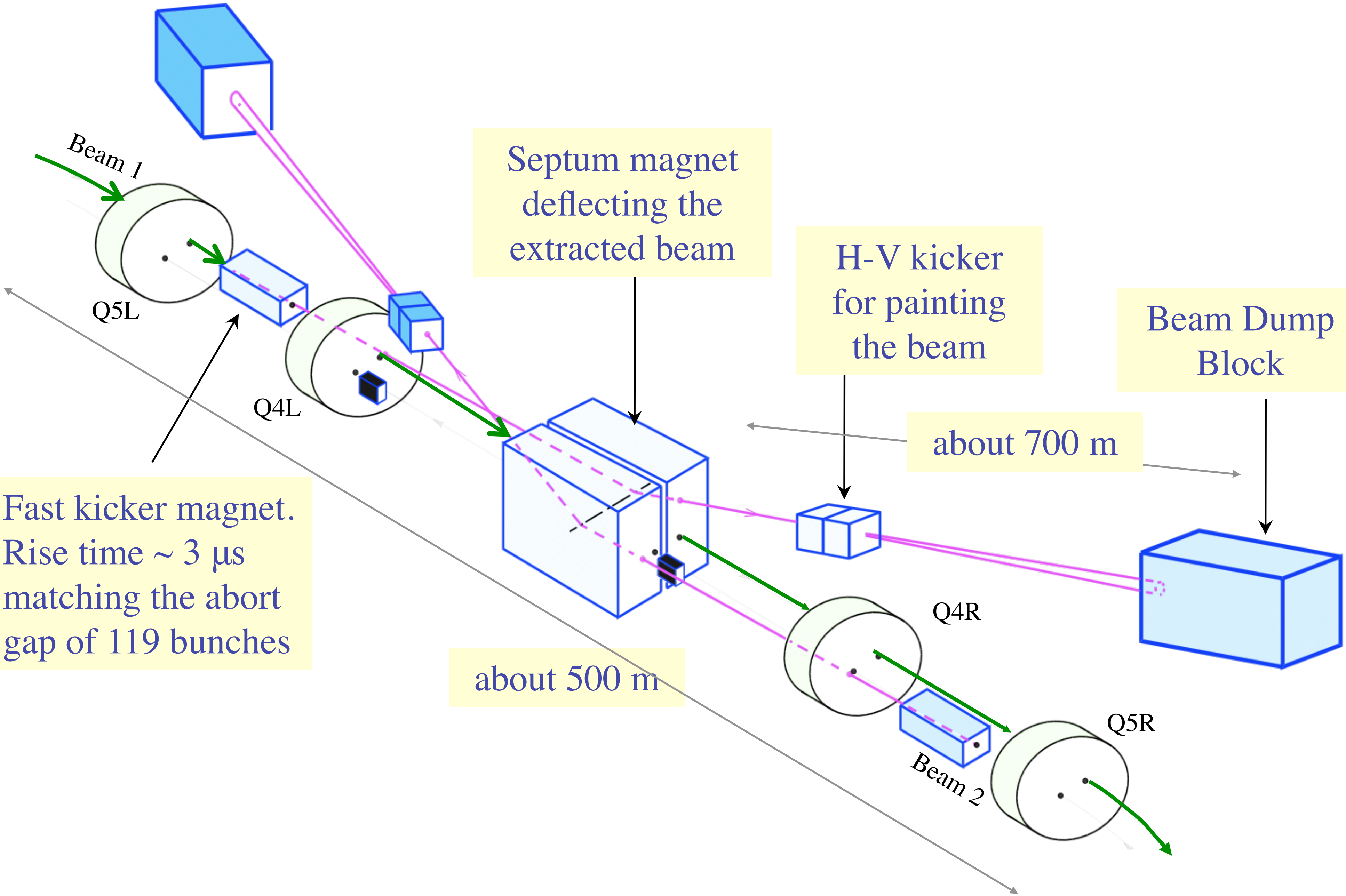
Recent snap-shot : IPAC'12, from this years accelerator conference in May New Orleans

Some of the hot-subjects and keywords :

- **Free electrons lasers FEL, X-FEL, Laser induced coherent SR**
- **Advanced LINACS -- including recirculation and energy recovery ERL**
- **New acceleration techniques :**
  - **Dieletric, LASER, Plasma driven**

Reserve

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

Radiation of an accelerated Charge

General concept - power radiated by an accelerated charge. Relativistic version of Lamor's formula, derived by Lienard in 1898, before relativity was known.

Photon spectrum : J. Schwinger Phys. Rev. 75 (1949) pp. 1912-1925

Here written with formulas in SI units. More info + references in my paper on MC generation of SynRad CERN-OPEN-2007-018

power radiated by an accelerated charge

$$P = \frac{e^2\gamma^2}{6\pi\epsilon_0 m^2 c^3}\left[\left(\frac{d\mathbf{p}}{dt}\right)^2 - \beta^2\left(\frac{dp}{dt}\right)^2\right]$$

relativistic Lamor formula

results in a major energy loss for a ring at high γ

$\mathbf{v} \perp \dot{\mathbf{v}}$

$$\left(\frac{d\mathbf{p}}{dt}\right)^2 - \beta^2\underbrace{\left(\frac{dp}{dt}\right)^2}_{0} = \dot{\mathbf{p}}^2 \qquad P = \frac{e^2}{6\pi\epsilon_0 m^2 c^3}\,\gamma^2\,\dot{\mathbf{p}}^2$$

Perpendicular acceleration, B-field (or $E_\perp$ field). Motion in circular machine.

$\mathbf{v} \parallel \dot{\mathbf{v}}$

$$\left(\frac{d\mathbf{p}}{dt}\right)^2 = \left(\frac{dp}{dt}\right)^2 \qquad \left(\frac{d\mathbf{p}}{dt}\right)^2 - \beta^2\left(\frac{dp}{dt}\right)^2 = \dot{p}^2(1-\beta^2) = \frac{\dot{p}^2}{\gamma^2}$$

Parallel acceleration, E-field, Linac case cancellation, $1/\gamma^2$

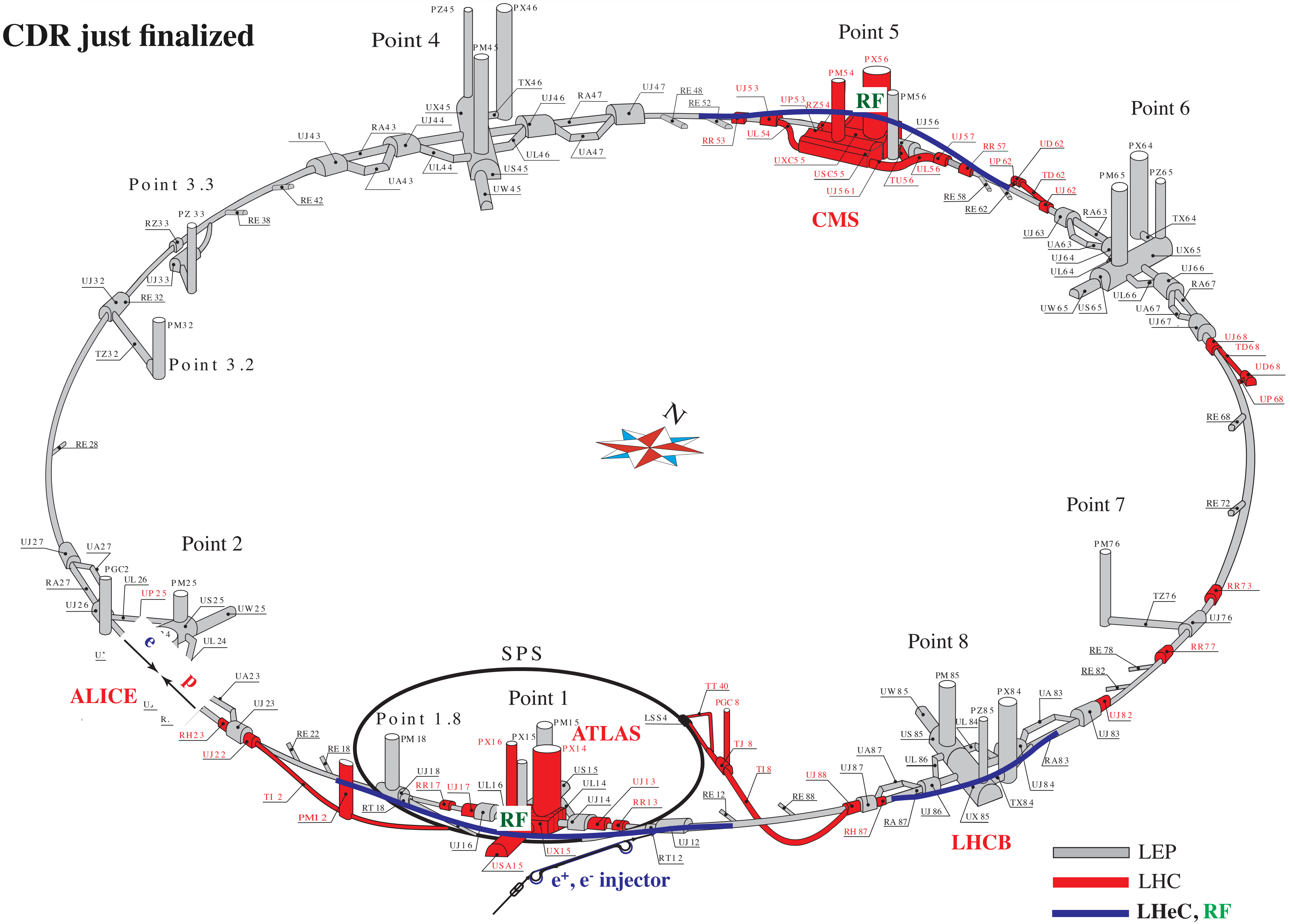
$$P = \frac{e^2}{6\pi\epsilon_0 m^2 c^3}\,\dot{p}^2$$

The energy loss for linear acceleration is very small.

Example: CLIC gradient 100 MV/m. Loss is 11 keV/s or only 0.4 eV for a 1 TeV 10 km Linac

LHeC

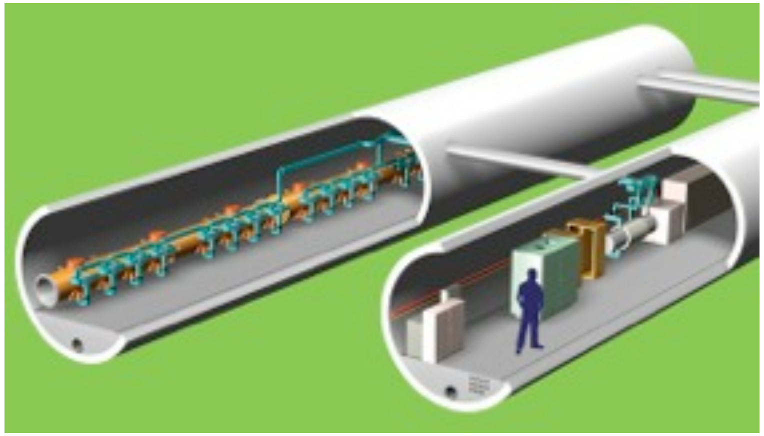
CDR just finalized



ILC

ILC Reference Design Report, August 2007

- **200-500 GeV centre-of-mass, 31 km long**
- **Luminosity: 2×10^{34} cm^{-2}s^{-1}**
- **Based on accelerating gradient of 31.5 MV/m 1.3 GHz superconducting RF**



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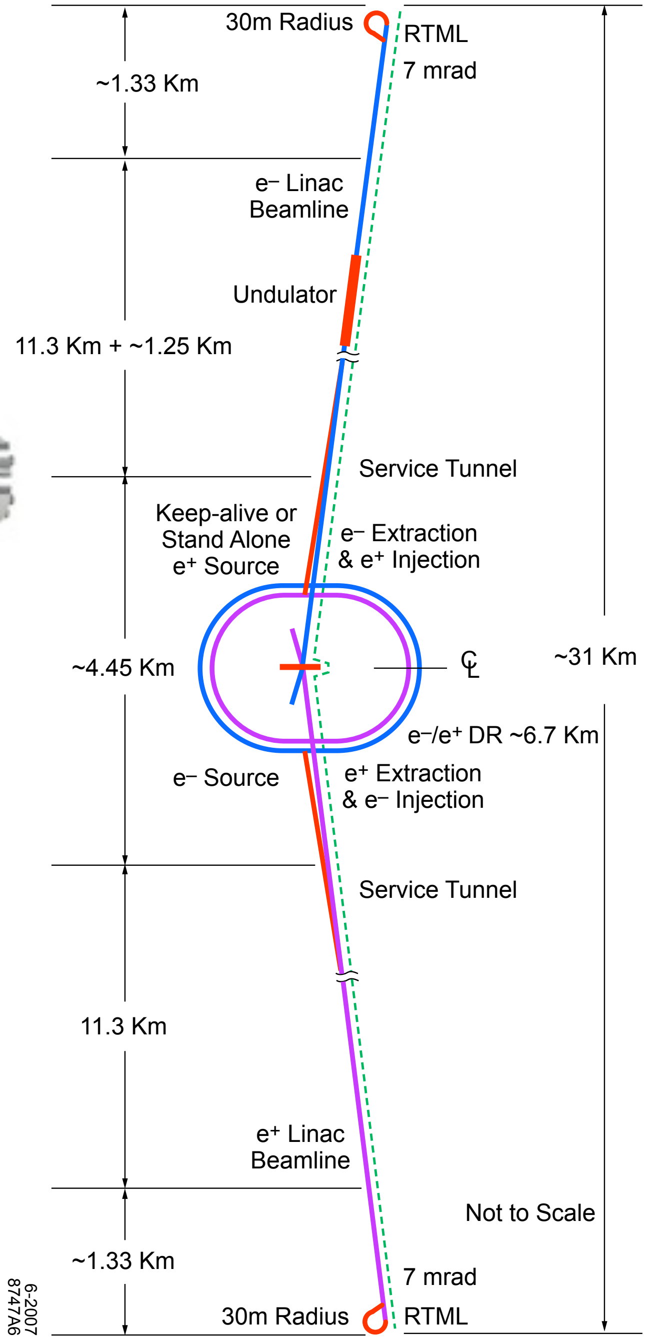


CLIC Compact Linear Collider

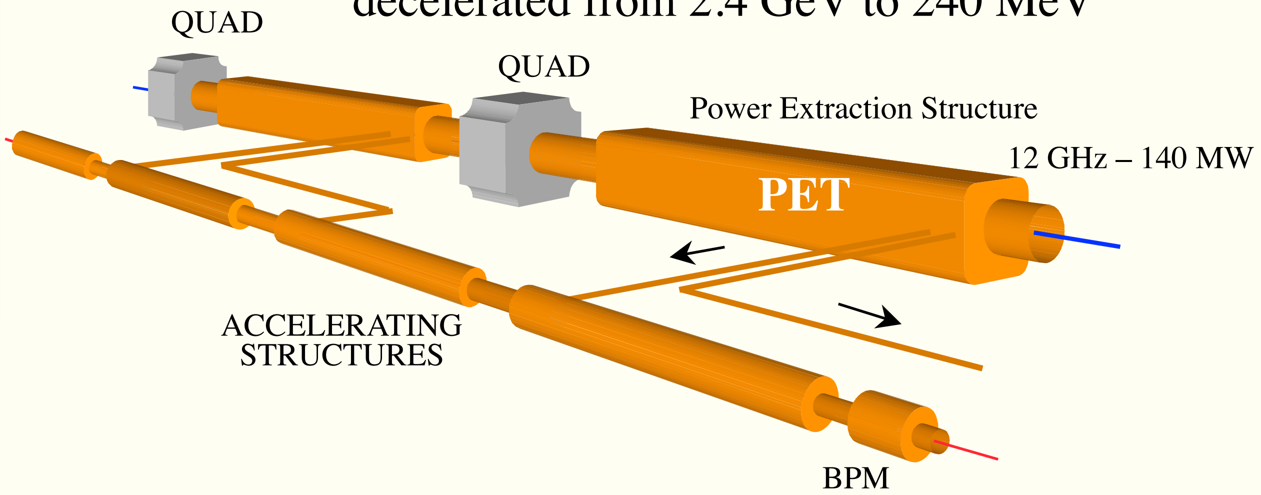
Two Beam Scheme

Drive Beam supplies RF power

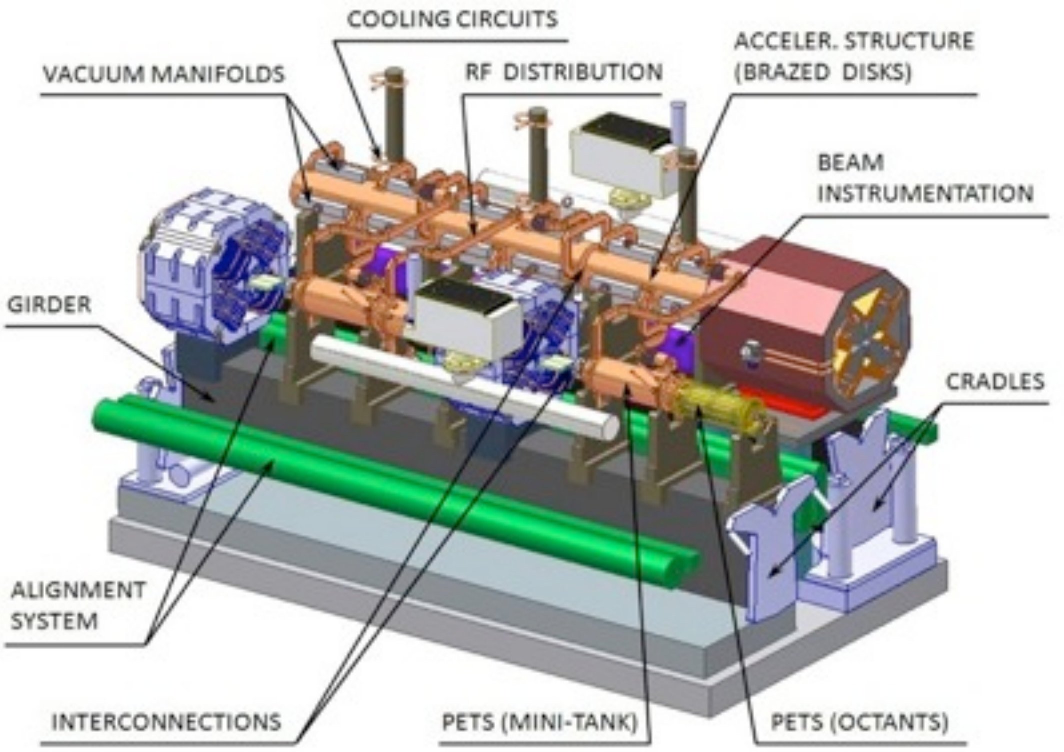
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

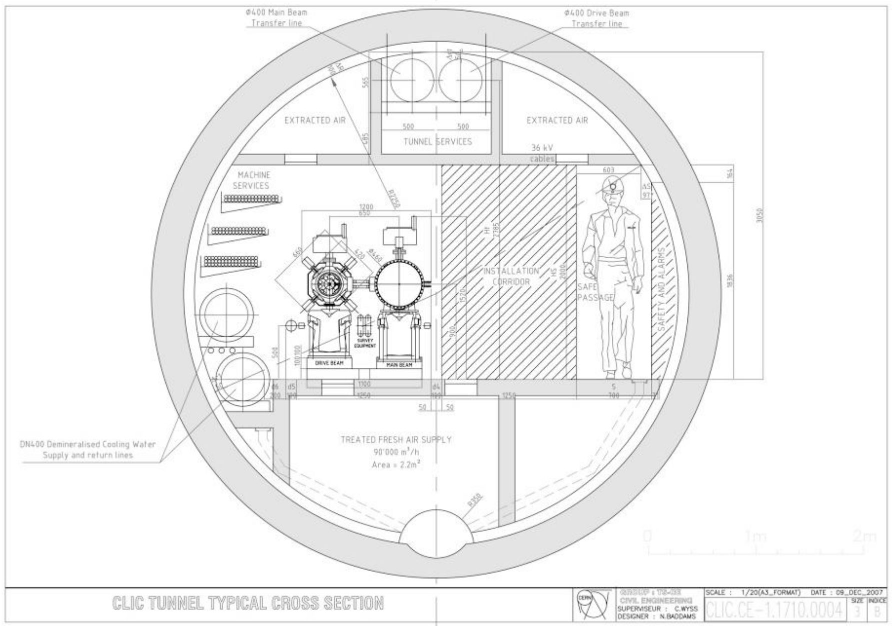
warm (not superconducting) RF

Drive beam - 100 A, 240 ns
decelerated from 2.4 GeV to 240 MeV

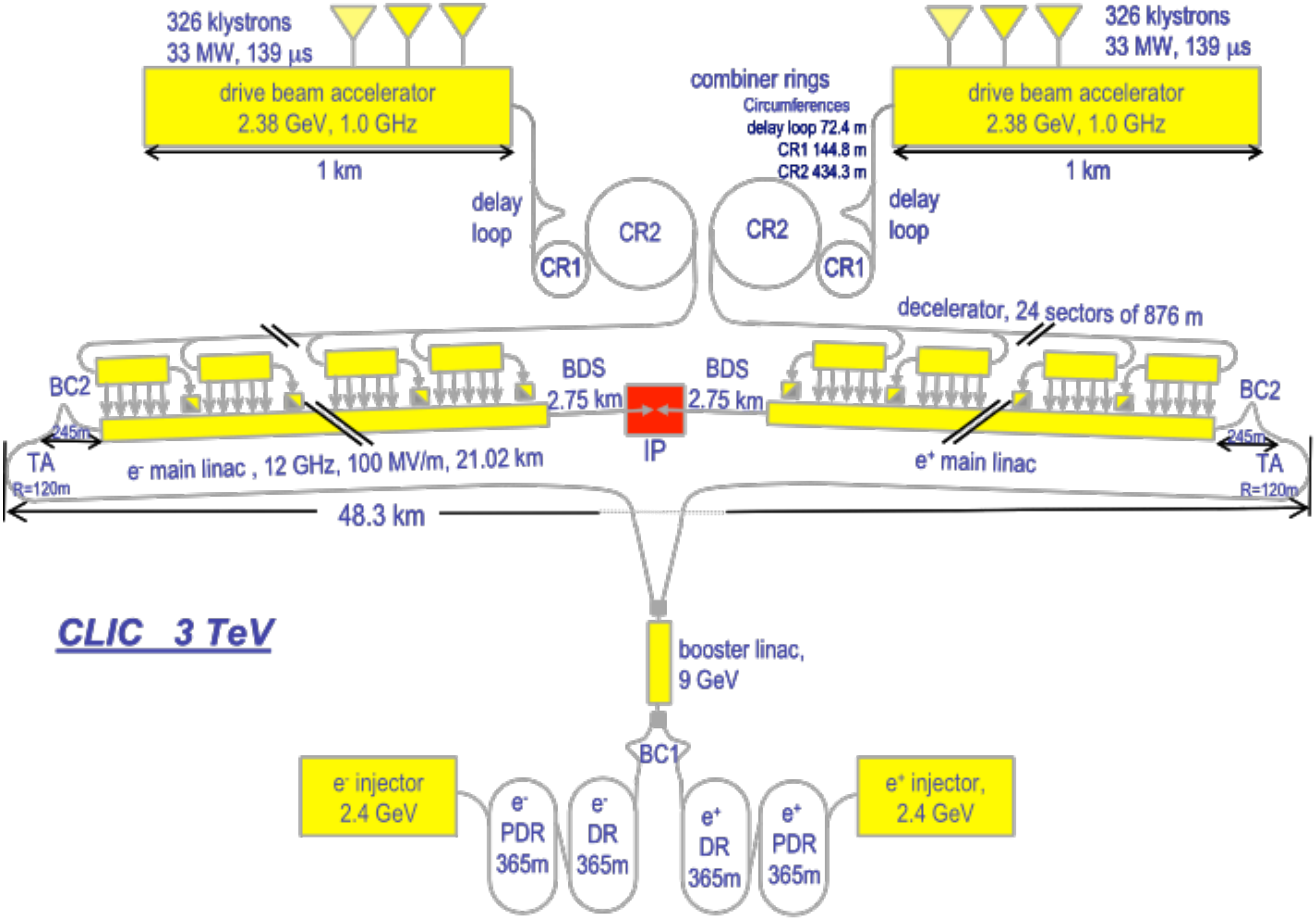


Main beam - 1.2 A, 156 ns bunch trains
accelerated from 9 GeV to 1.5 TeV





CLIC, full layout, not to scale



ILC and CLIC parameters

	ILC: Superconducting RF	CLIC: normal conducting copper RF
	500 GeV	**3 TeV**
accelerating gradient:	**31.5 MV/m**	**100 MV/m**
	35 MV/m target	
RF Peak power:	**0.37 MW/m , 1.6 ms, 5 Hz**	**275 MW/m, 240 ns, 50 Hz**
RF average power:	2.9 kW/m	3.7 kW/m
total length:	31 km	48.4 km
site power :	230 MW	392 MW
	Beam structure:	
particles per bunch:	**20×10^9**	**3.7×10^9**
2625 bunches / pulse of	0.96 ms	312 bunches / pulse of 156 ns
bunch spacing	**369 ns**	**0.5 ns**