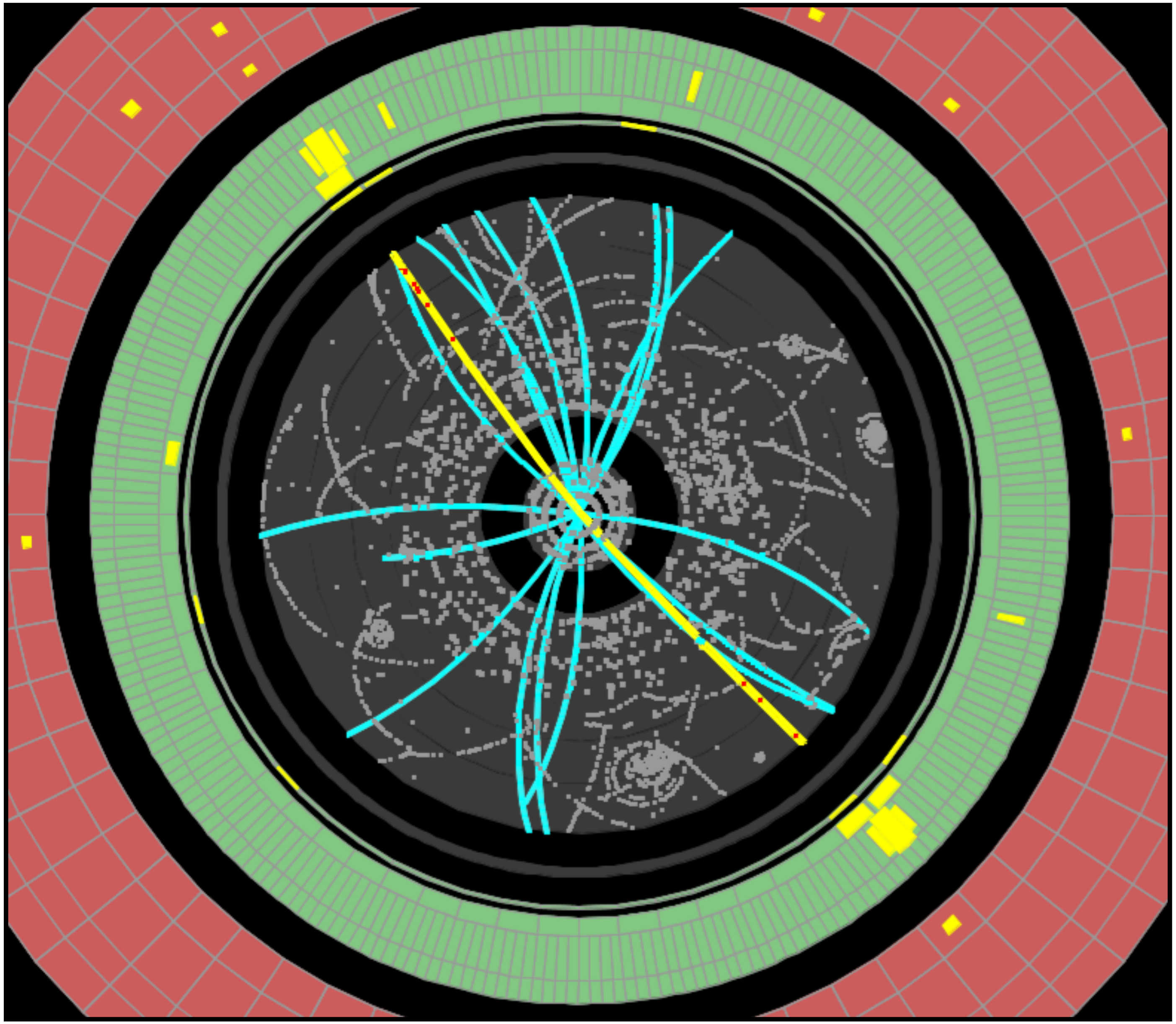
Experimental High Energy Physics at Colliders
Lecture 1: Experiments & Accelerators



Z ➛ ee Candidate
[September 2010]

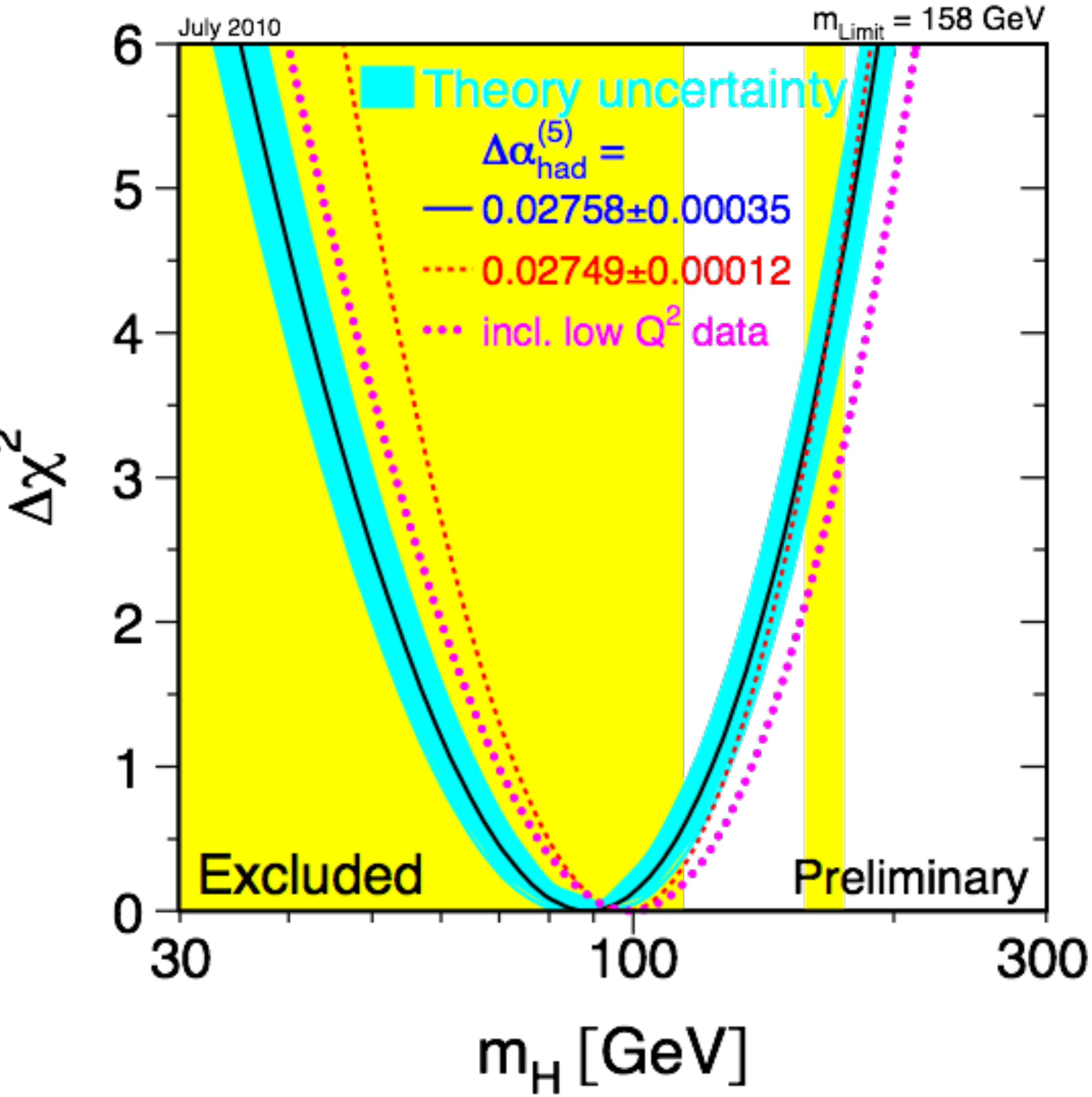
Toni Baroncelli
INFN RomaTRE

Hans-Christian Schultz-Coulon
Kirchhoff-Institut für Physik

Introduction & Motivation

The LHC and its Experiments

Our Knowledge about the Higgs before its discovery



EW-Fits:

$M_H = 89$ GeV

$M_H < 158$ GeV @ 95% CL

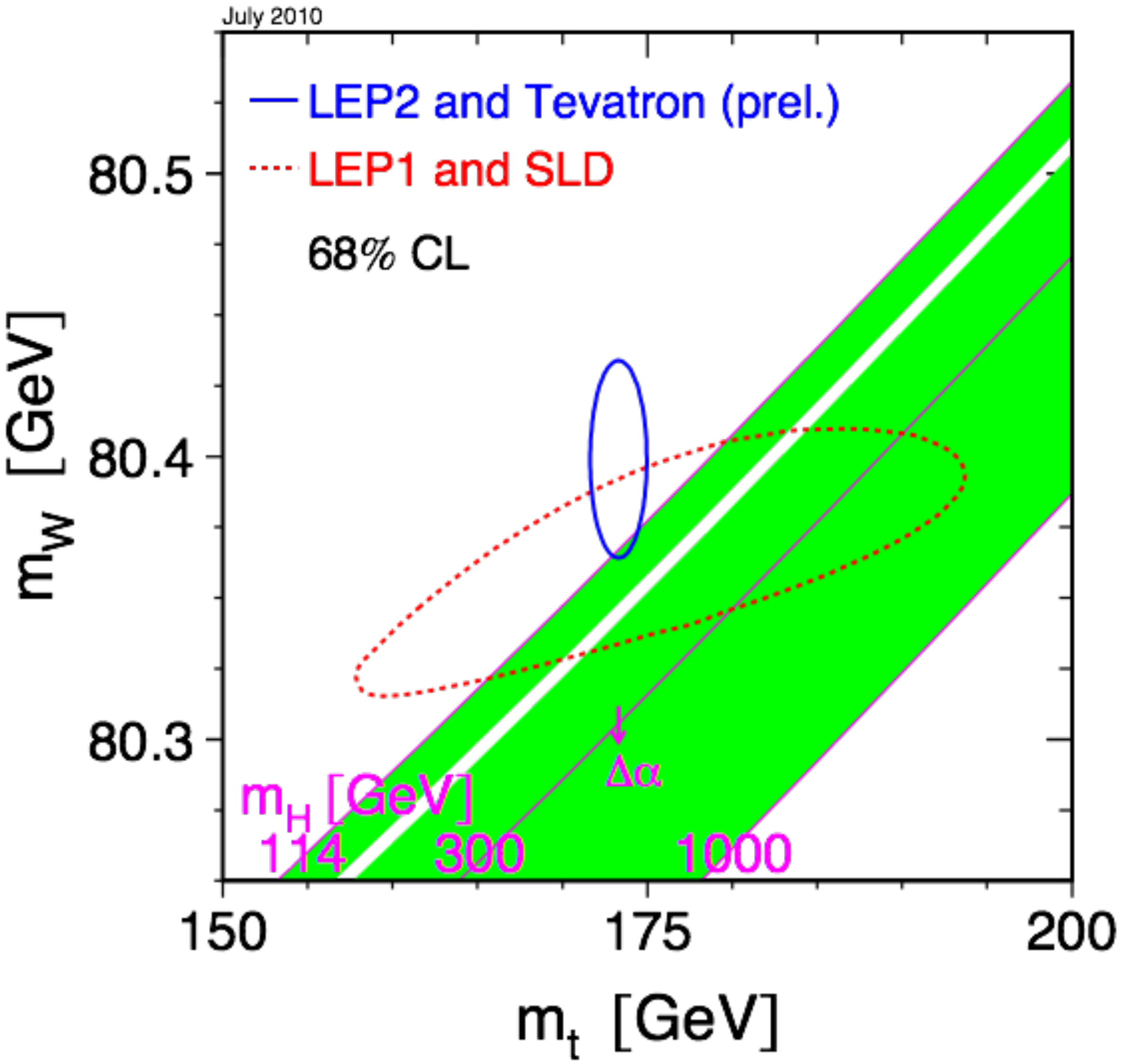
From direct search at LEP:

$M_H > 114$ GeV @ 95% CL

From direct search at Tevatron:

$158 < M_H < 175$ GeV @ 95% CL

Our Knowledge about the Higgs before its discovery



EW-Fits:

$M_H = 89^{+35}_{-26}$ GeV

$M_H < 158$ GeV @ 95% CL

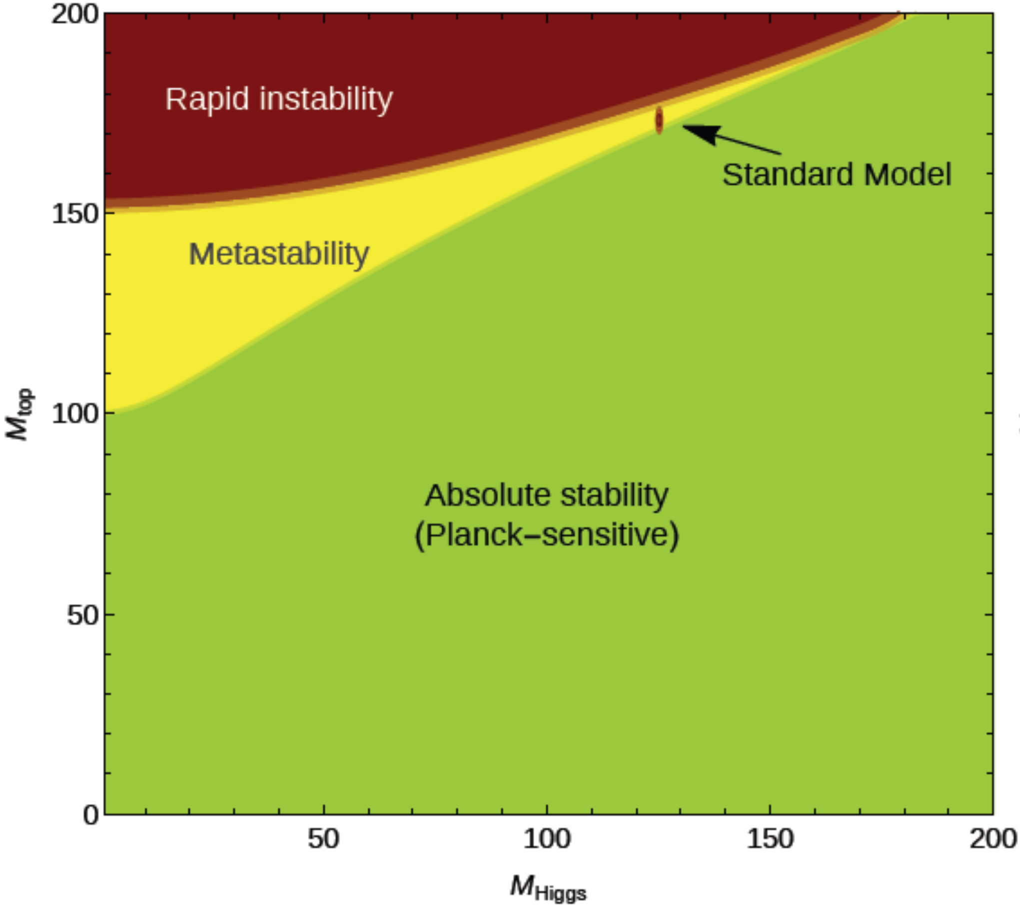
From direct search at LEP:

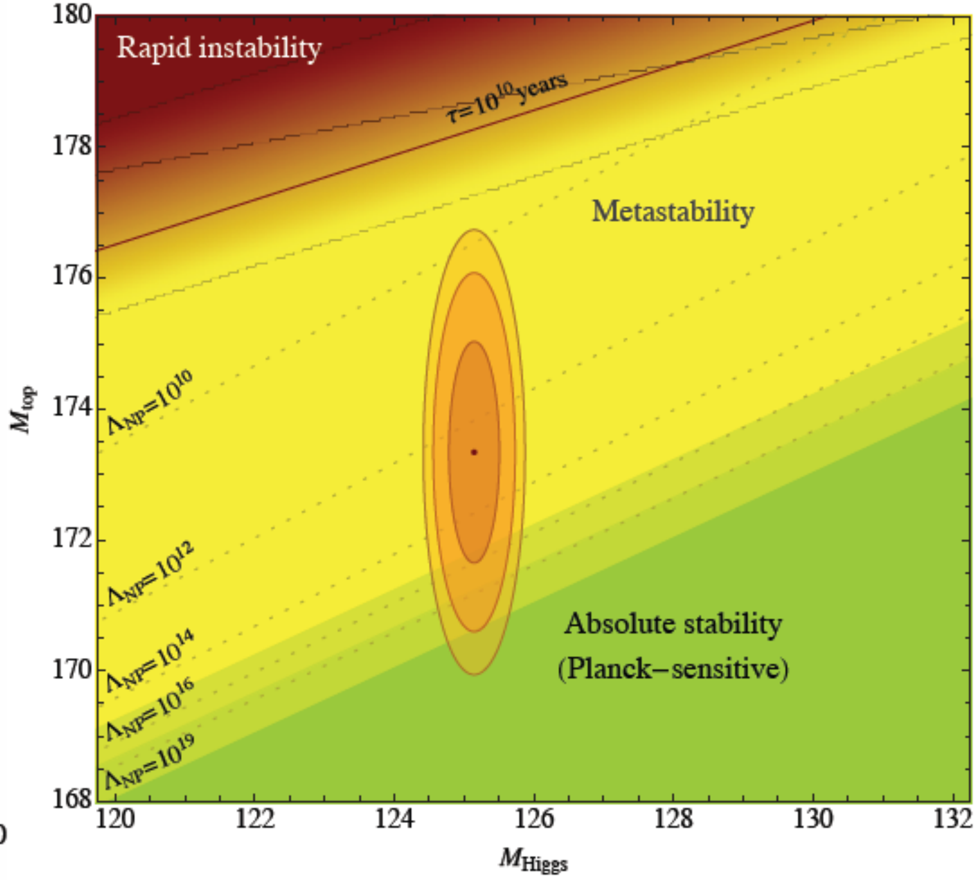
$M_H > 114$ GeV @ 95% CL

From direct search at Tevatron:

$158 < M_H < 175$ GeV @ 95% CL

After the Higgs discovery: m_{top} vs m_{Higgs} and stability of the Universe

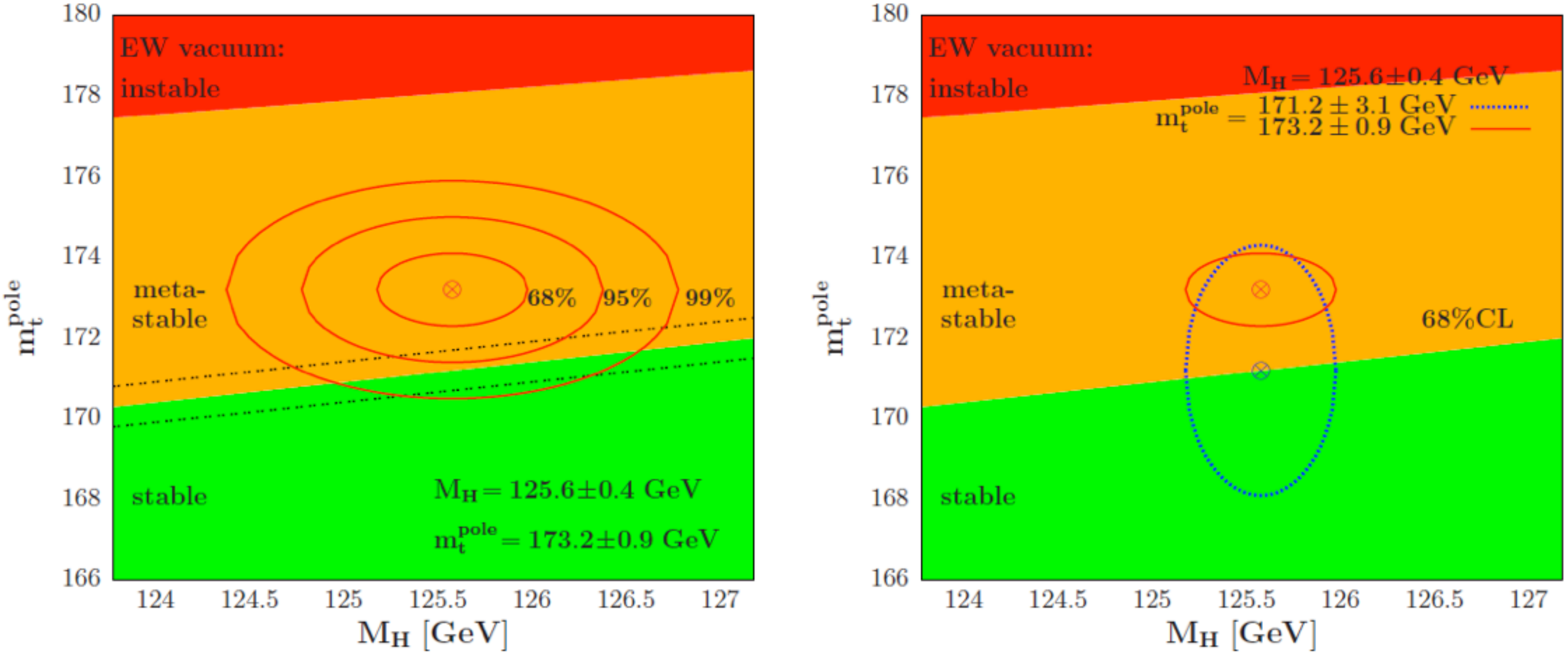




$$m_h^{\text{pole}} = (125.14 \pm 0.23)\ \text{GeV}$$

$$m_t^{\text{pole}} = (173.34 \pm 1.12)\ \text{GeV}$$

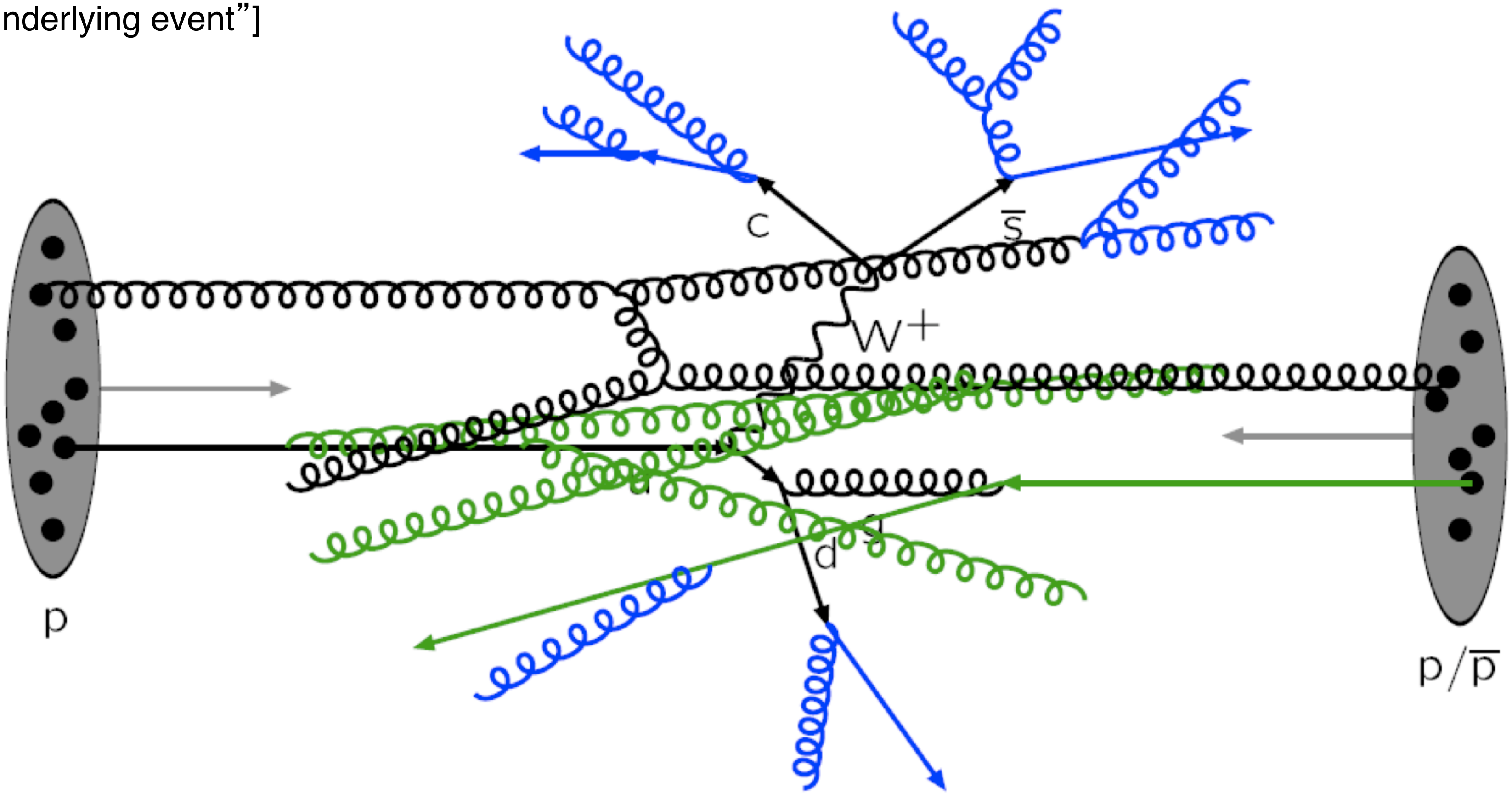
After the Higgs discovery: m_{top} vs m_{Higgs} and stability of the Universe



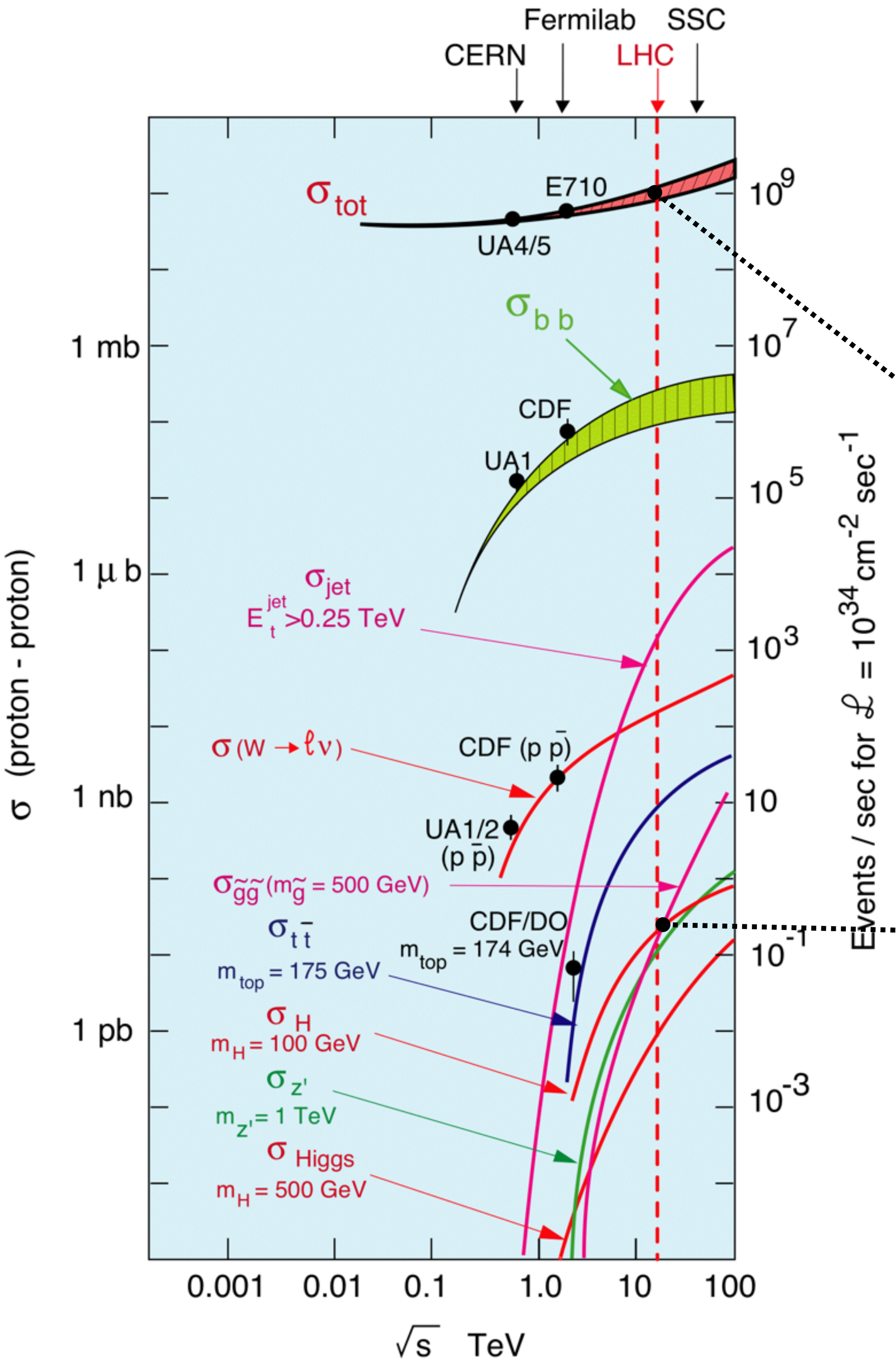
The ellipses in the [MH,mtpole] plane with the inputs MH=125 +/-0.4 GeV and α_s=0.1187 are confronted with the areas in which the SM vacuum is absolutely stable, metastable and unstable up to the Planck scale. Left plot mtpole is identified with the Tevetron measured top mass mt=173.2+/-0.9 GeV, Right: mtpole is taken as the as the one measured at the Tevatron mt=171.2+/-3.1GeV extracted for the ttbar production cross section

Proton-Proton Scattering @ LHC

- Hard interaction: qq, gg, qg fusion
- Initial and final state radiation (ISR,FSR)
- Secondary interaction
  [“underlying event”]



Needle in a Haystack



10^9 Events/sec

[1 Mbyte/Event]

~ 10^{10}

Efficient
rate reduction needed

[Storage rate: 100 Hz]

10 Events/min

[$m_H \approx 100$ GeV]

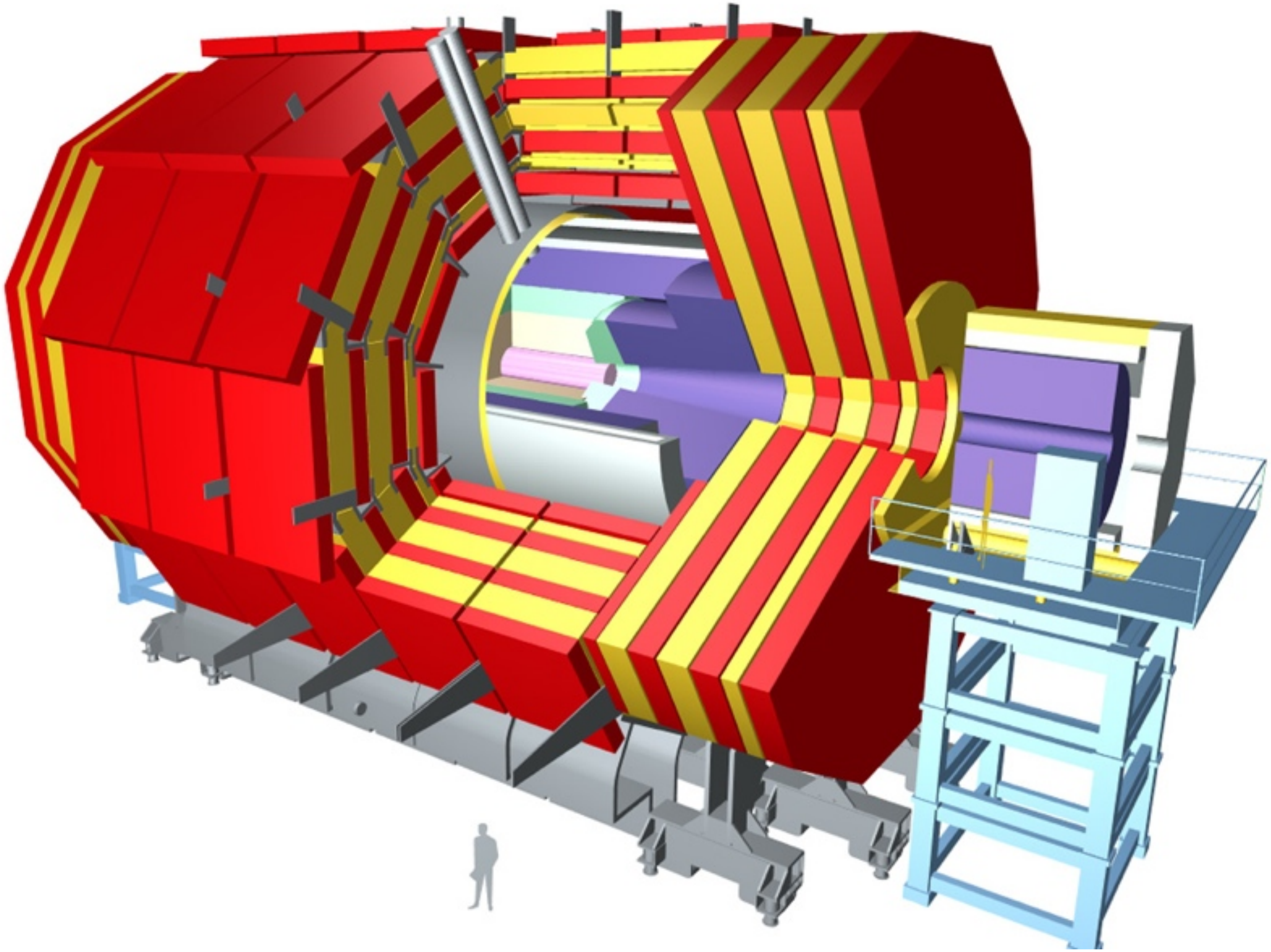
with 0.2% H → γγ
1.5% H → ZZ

Trigger !

Experiments

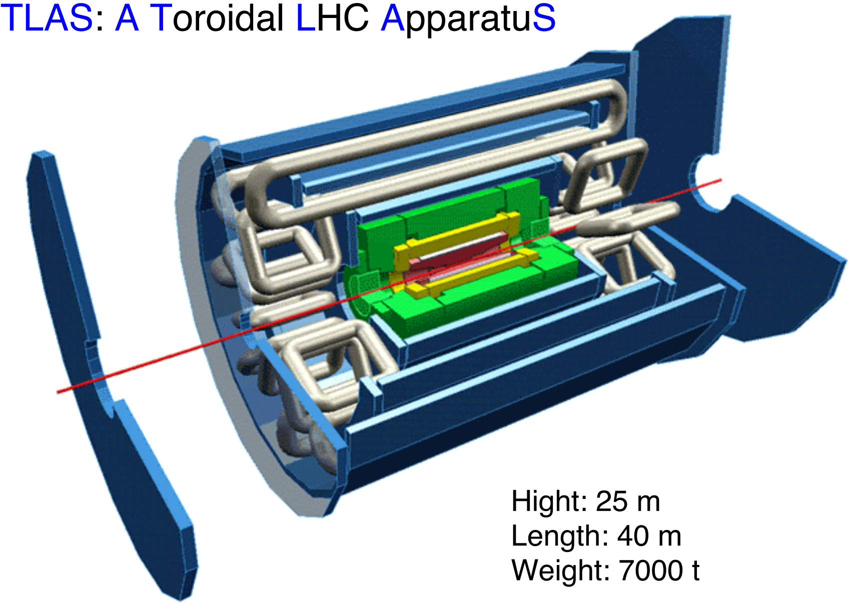
The LHC and its Experiments

LHC Detectors, mostly ATLAS & CMS



Basic Design Concepts

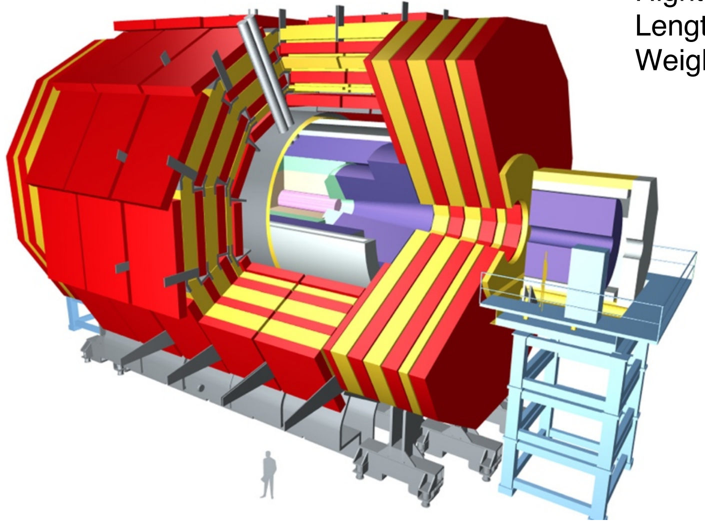
ATLAS: A Toroidal LHC ApparatuS

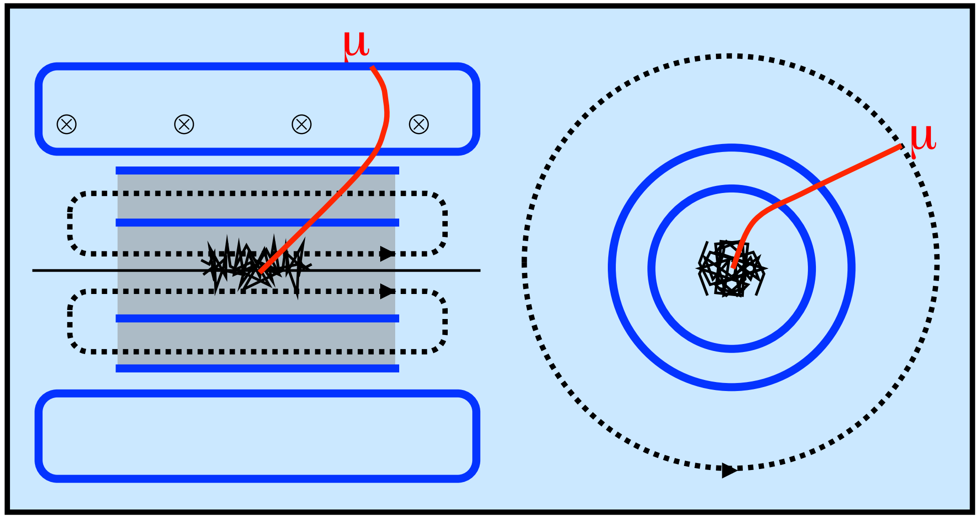


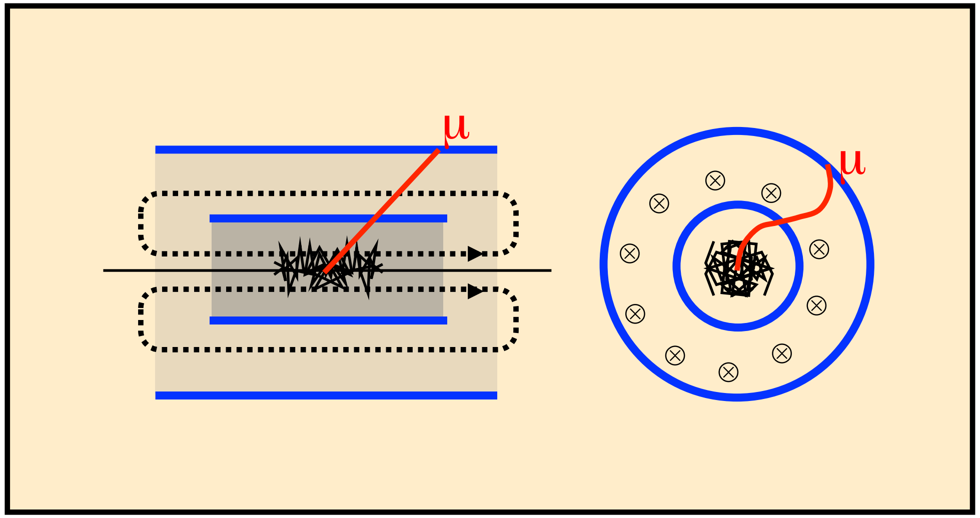
Hight: 25 m
Length: 40 m
Weight: 7000 t

CMS: Compact Muon Solenoid

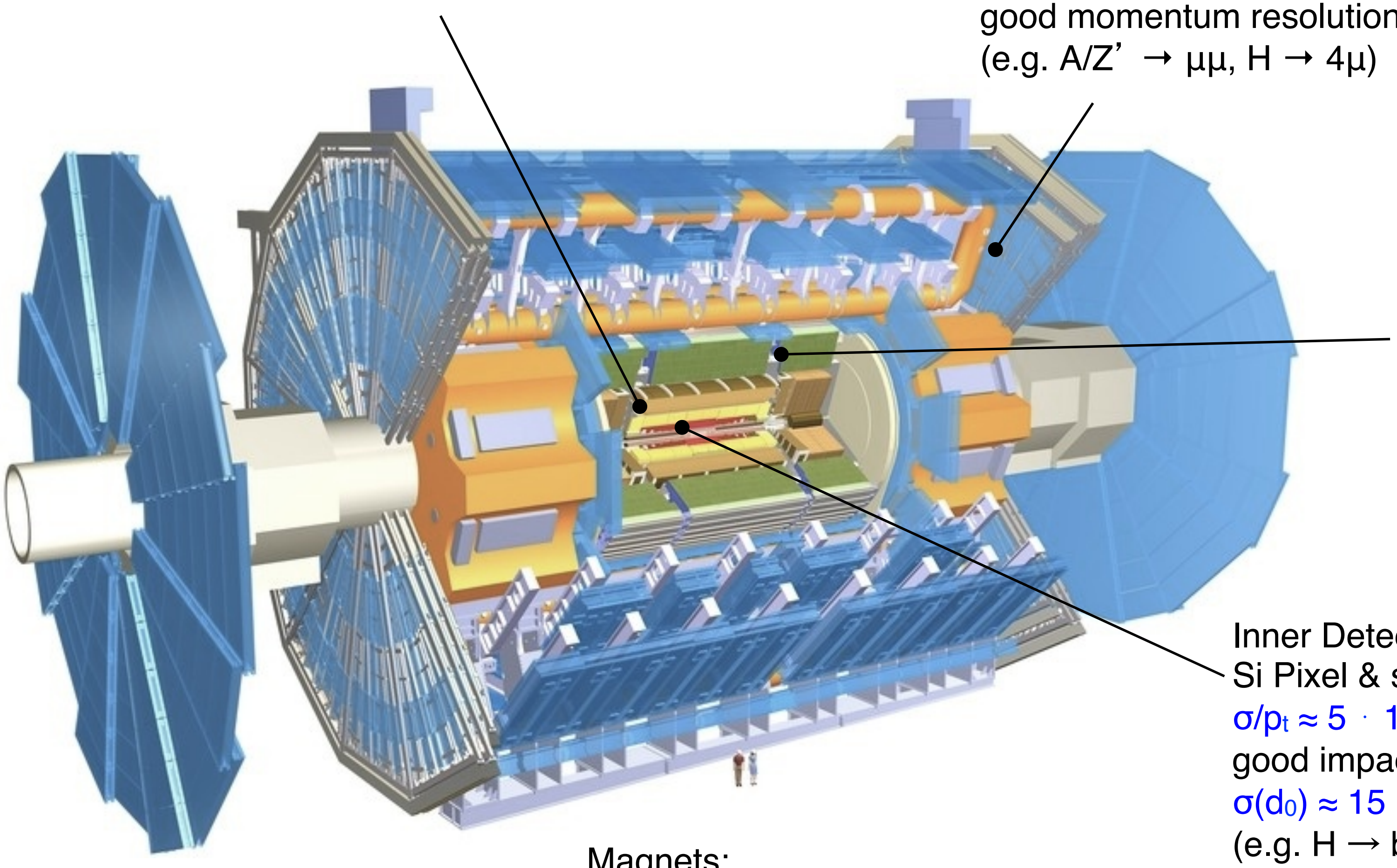
Hight: 15 m
Length: 22 m
Weight: 12500 t







The ATLAS Detector



EM Calorimeters: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$
excellent e/γ identification
good energy resolution (e.g. for H → γγ)

Precision Muon Spectrometer: $\sigma/p_t \approx 10\%$ @ 1 TeV
fast trigger response
good momentum resolution
(e.g. A/Z' → μμ, H → 4μ)

Hadron Calorimeter:
$\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$
good jet resolution
good missing E_T resolution
(e.g. H → ττ)

Inner Detector:
Si Pixel & strips; TRT
$\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$
good impact parameter res., i.e.
$\sigma(d_0) \approx 15\ \mu m$ @ 20 GeV
(e.g. H → bb)

Magnets:
Solenoid (inner detector): 2 T
Toroid (muon spectrometer): 0.5 T

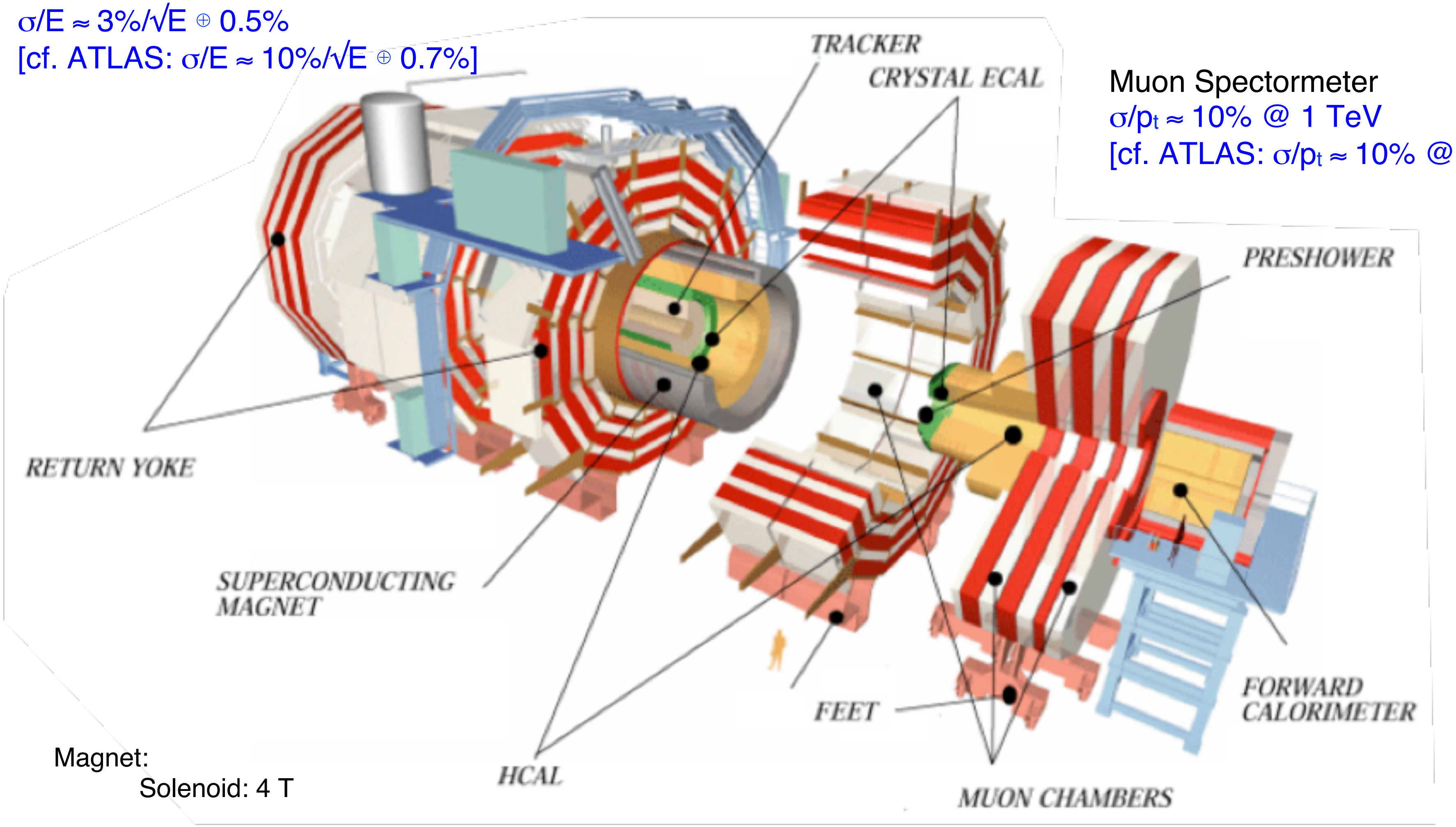
The CMS Detector

Inner Detector:
$\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$
[cf. ATLAS $\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$]

Hadron Calorimeter:
$\sigma/E \approx 100\%/\sqrt{E} \oplus 5\%$
[cf. ATLAS: $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$]

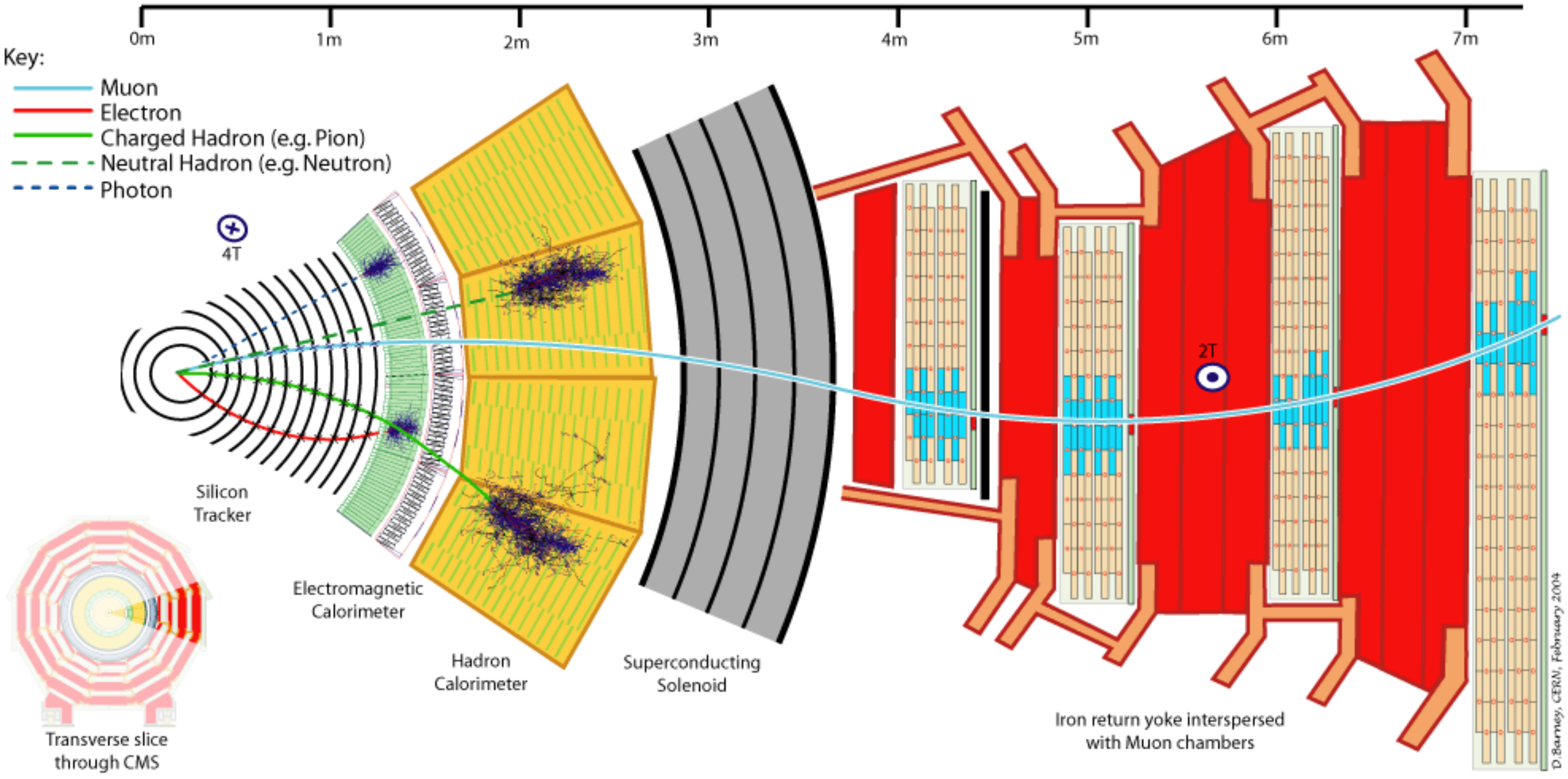
EM Calorimeters:
$\sigma/E \approx 3\%/\sqrt{E} \oplus 0.5\%$
[cf. ATLAS: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$]

Muon Spectormeter
$\sigma/p_t \approx 10\%$ @ 1 TeV
[cf. ATLAS: $\sigma/p_t \approx 10\%$ @ 1 TeV]



Magnet:
Solenoid: 4 T

The CMS Detector - 2

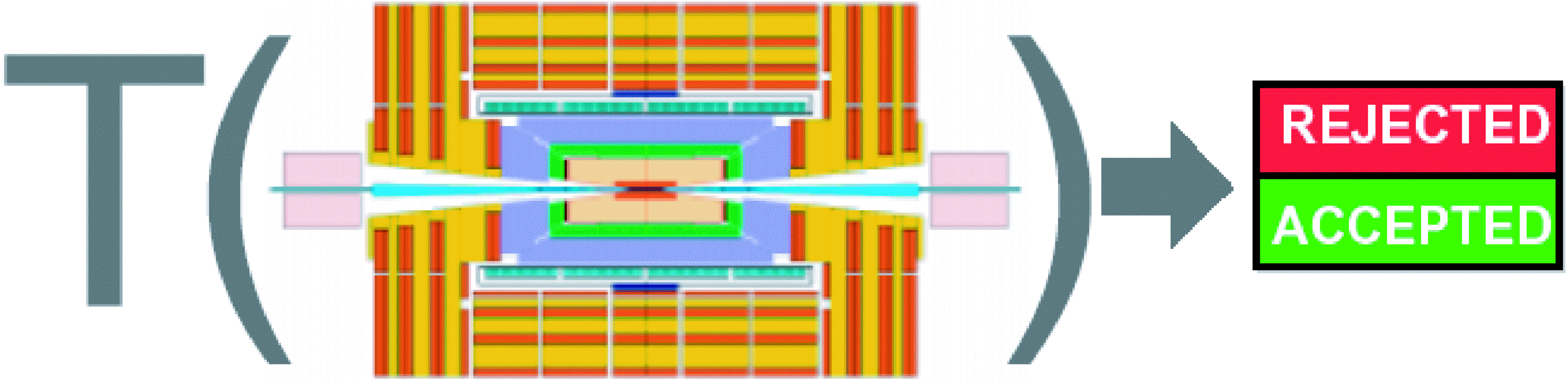


ATLAS vs CMS

ATLAS		CMS
Silicon pixels; Silicon strips; Transition Radiation Tracker; 2 T magnetic field	Inner Detector	Silicon pixels, Silicon strips, 4 T magnetic field
Lead plates as absorbers; active medium: liquid argon; outside solenoid	Electrom. Calorimeter	Lead tungsten ($PbWO_4$) crystals; both absorber and scintillator; inside solenoid
Central region: Iron absorber with plastic scintillating tiles; Endcaps: copper and tungsten absorber with liquid argon	Hadronic Calorimeter	Stainless steel and copper with plastic scintillating tiles
Large air-core toroid magnet; muon chambers: drift tubes and resistive plate chambers; 0.5 T magnetic field	Muon Chambers	Magnetic field from return yoke (solenoid field: 4 T); muon chambers: drift tubes and resistive plate chambers

Challenge 1: Fast Trigger System

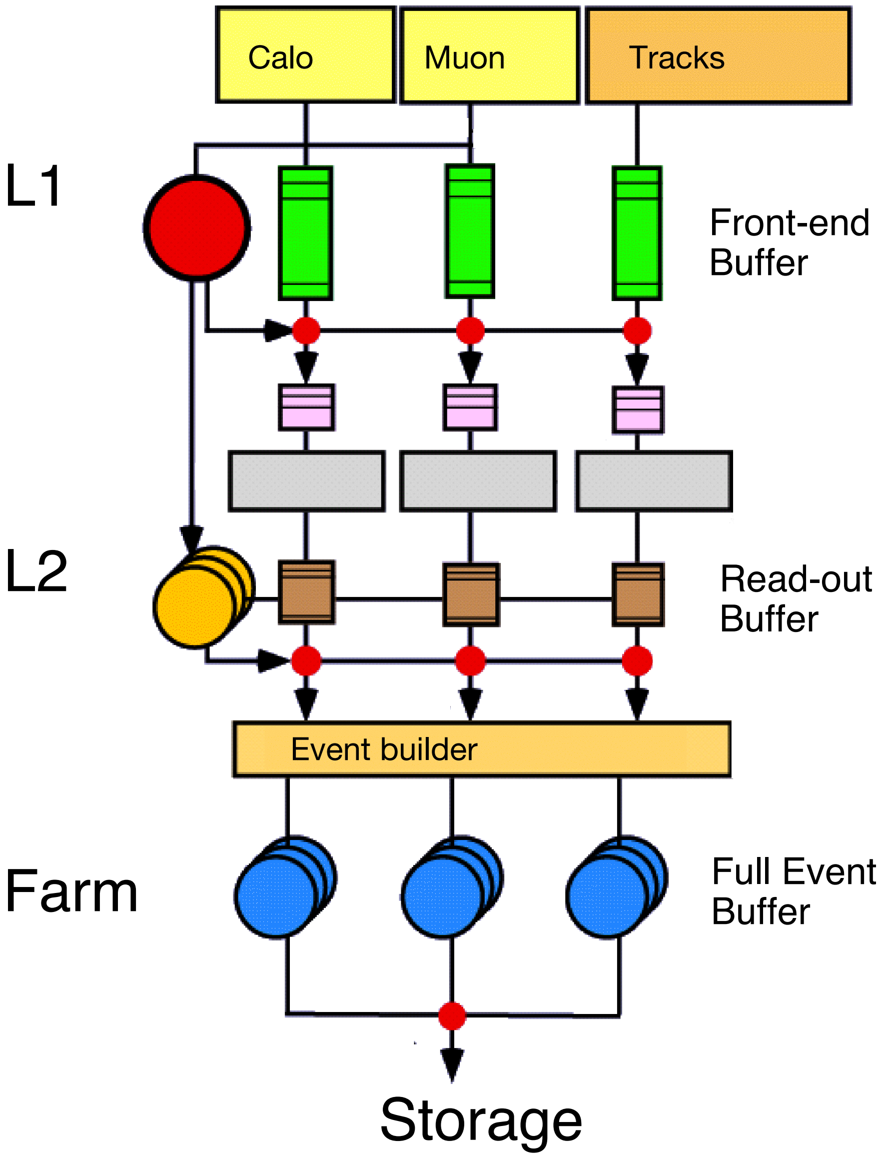
Fast selection of interesting Events
Number of necessary decisions: 40 million/sec



Function T(…) is highly complex
Detector data not directly available ➥ Stepwise decision

→ Trigger Levels

Challenge 1: Fast Trigger System



40 MHz

LEVEL-1 TRIGGER

- Hardware-Trigger [FPGAs & ASICs]
- Information from calorimeters & muon systems; low granularity
- 2 μs latency [2.5 μs pipelines]

~75 kHz

LEVEL-2 TRIGGER

- Regions-of-Interest
- In principle full information of all subdetectors; high granularity
- Decision time: O(10 ms)

~2 kHz

EVENT FILTER

- Complete detector information
- Full event reconstruction
- Decision time: O(1 s)

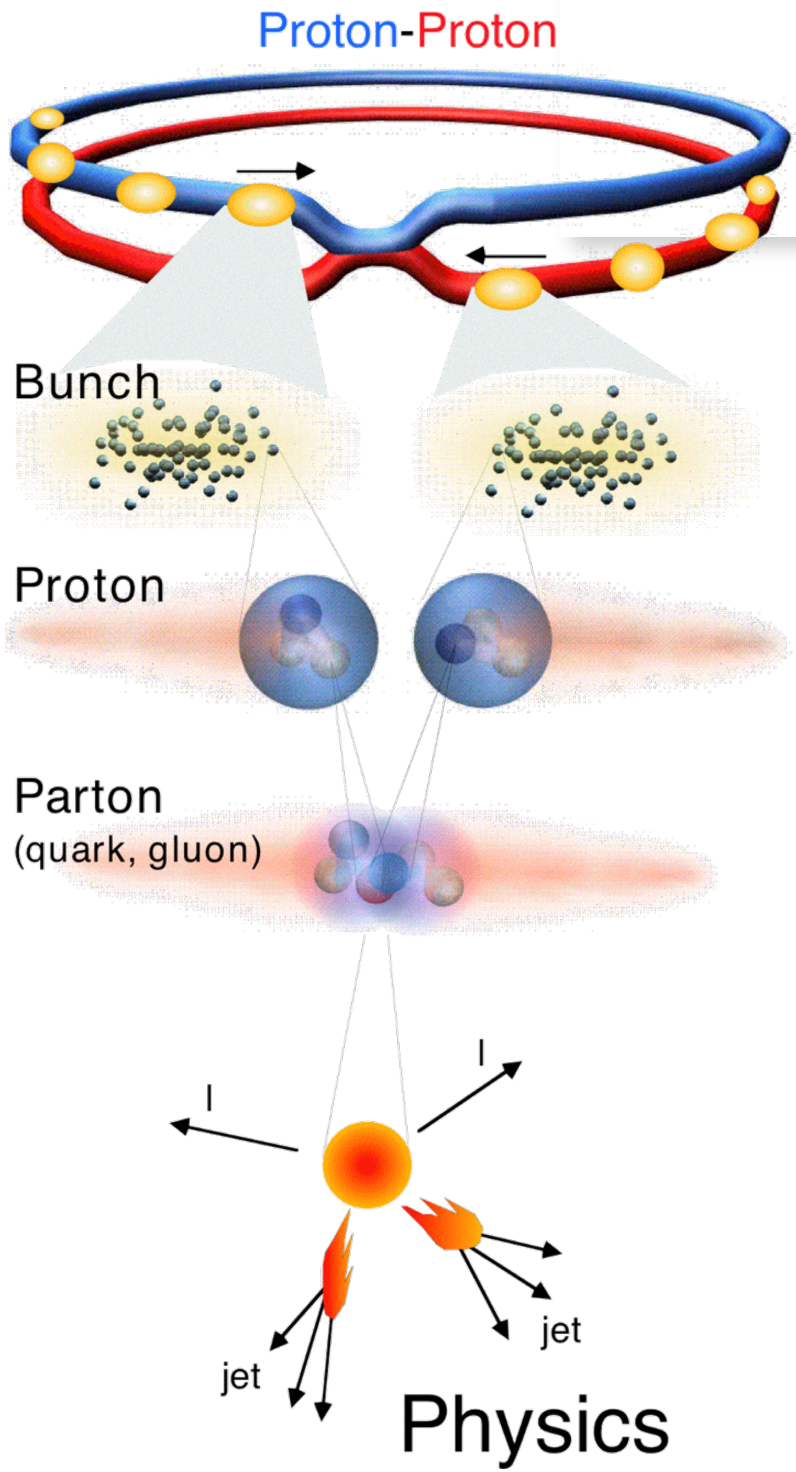
~ 200 Hz

Accelerators

The LHC and its Experiments

The Large Hadron Collider

Some numbers
(relevant for ATLAS & CMS)



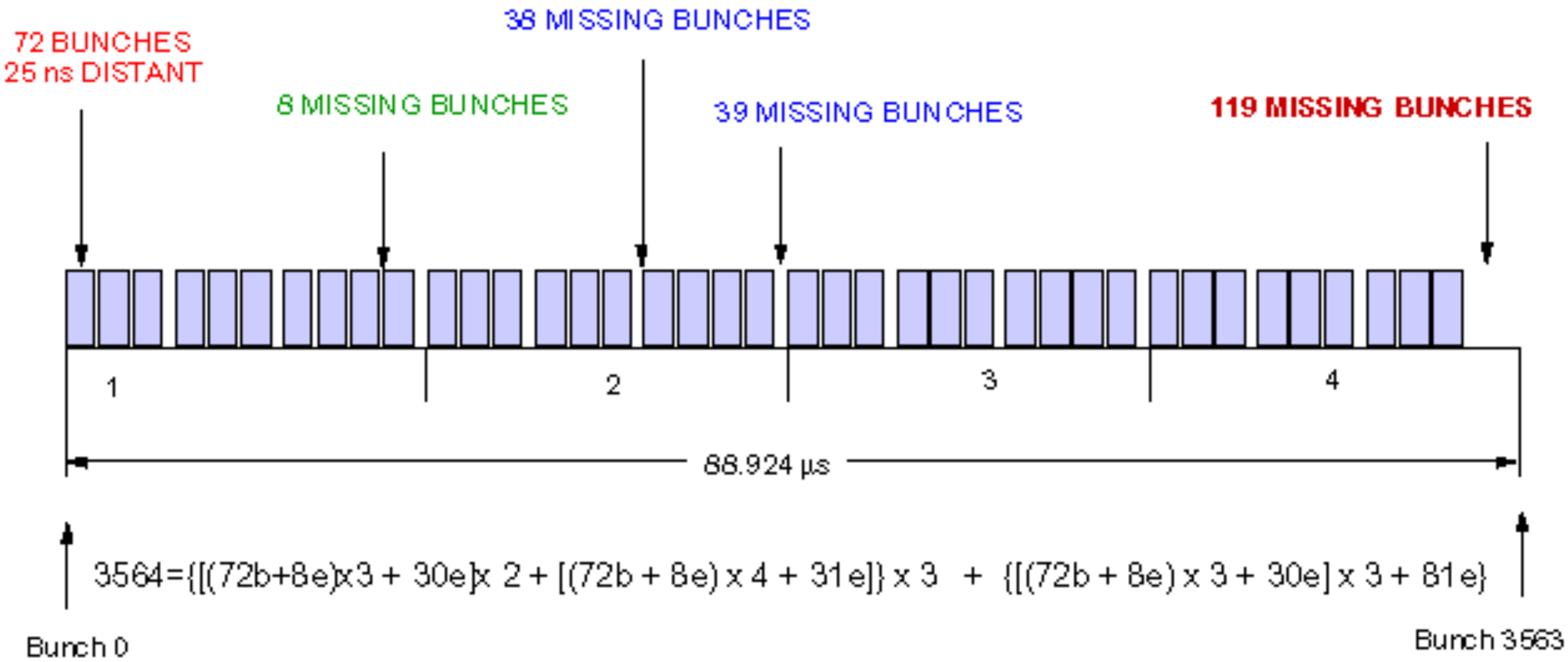
2 3564x3564 proton bunches
distance: 7.5 m [25 ns]

10^{11} protons/bunch
bunch crossing rate: 40 MHz

10^{9} pp-collisions/sec
[i.e.: 23 pp-interactions/bunch crossing.]

Dominant Interactions:
gluon-gluon, quark-quark and quark-gluon scattering

LHC Nominal Bunch Structure



72 BUNCHES
25 ns DISTANT

8 MISSING BUNCHES

38 MISSING BUNCHES

39 MISSING BUNCHES

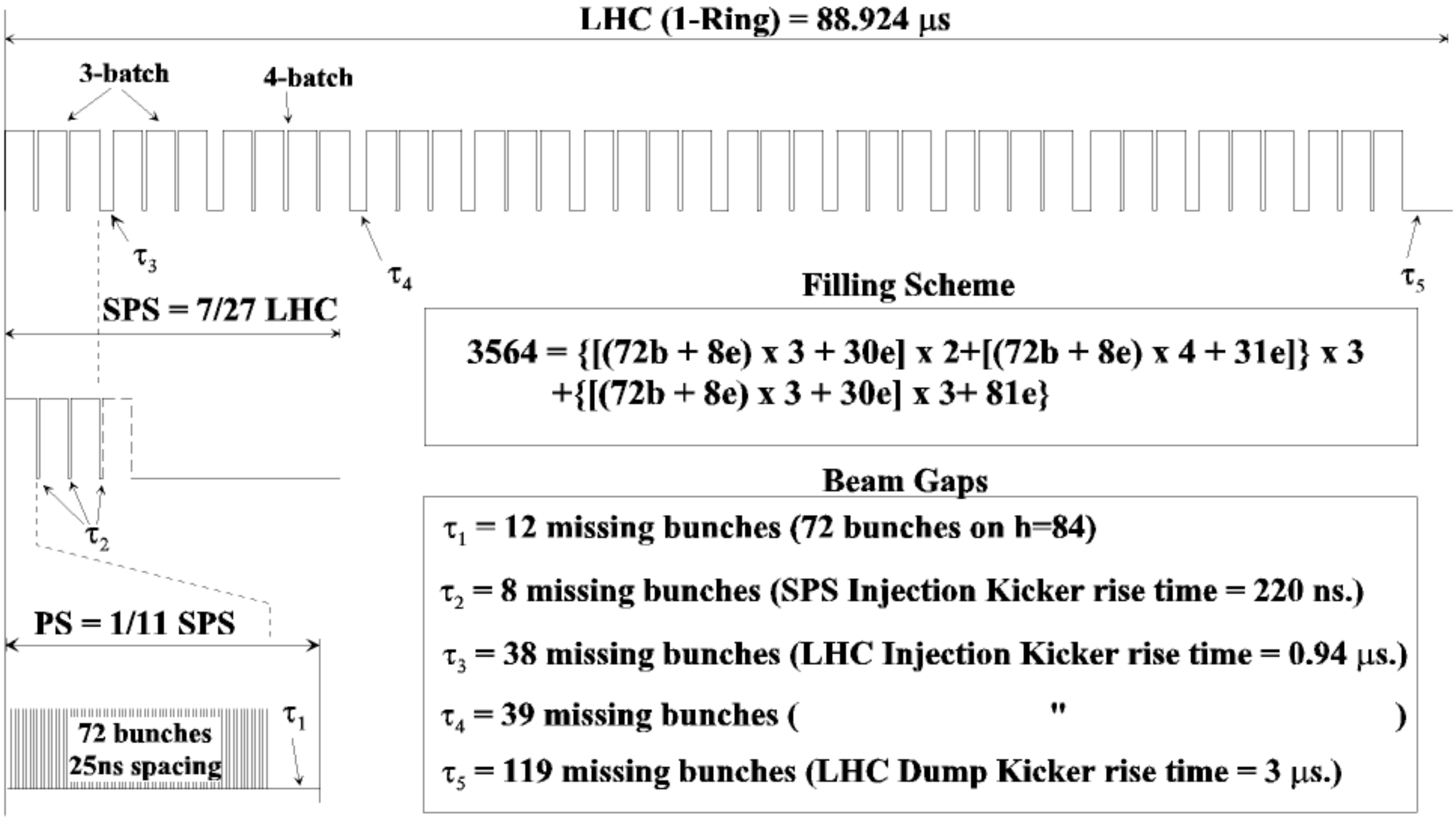
119 MISSING BUNCHES

$$3564=\{[(72b+8e)\times 3+30e]\times 2+[(72b+8e)\times 4+31e]\}\times 3+\{[(72b+8e)\times 3+30e]\times 3+81e\}$$

Bunch 0

Bunch 3563

Bunch structures in LHC, SPS and PS



Filling Scheme

3564 = {[(72b + 8e) x 3 + 30e] x 2+[(72b + 8e) x 4 + 31e]} x 3
+{[(72b + 8e) x 3 + 30e] x 3+ 81e}

Beam Gaps

τ_1 = 12 missing bunches (72 bunches on h=84)

τ_2 = 8 missing bunches (SPS Injection Kicker rise time = 220 ns.)

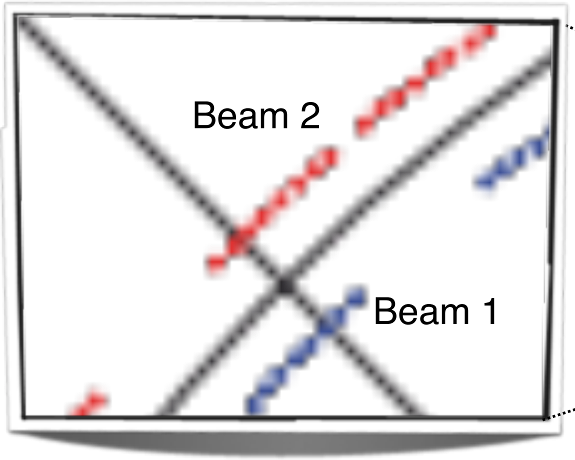
τ_3 = 38 missing bunches (LHC Injection Kicker rise time = 0.94 μs.)

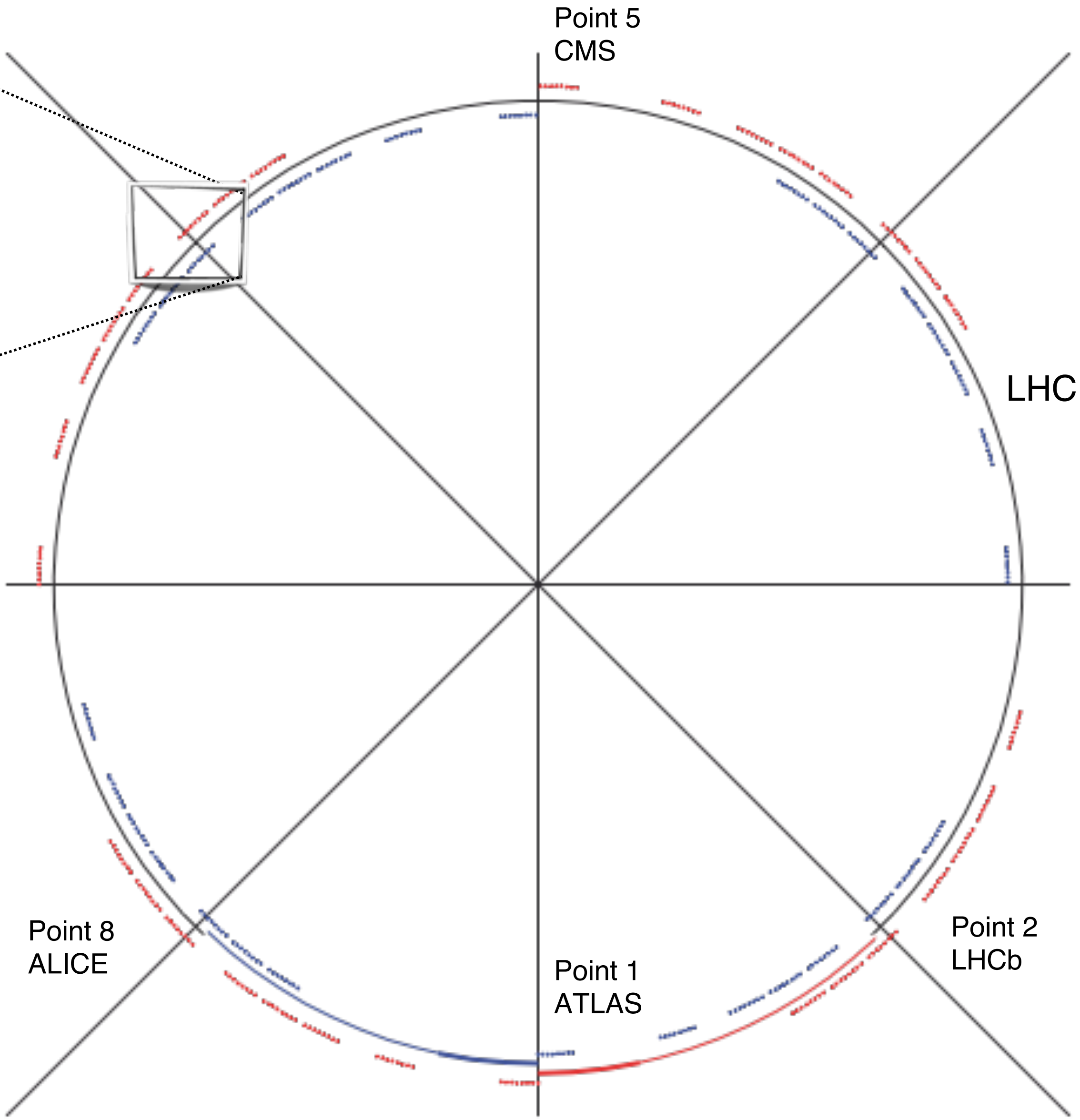
τ_4 = 39 missing bunches (")

τ_5 = 119 missing bunches (LHC Dump Kicker rise time = 3 μs.)

P. Collier 12/6/2000

Present LHC Status





Present Bunch Structure:

150ns_248b_233_16_233_3x8bpi15inj

bunch distance

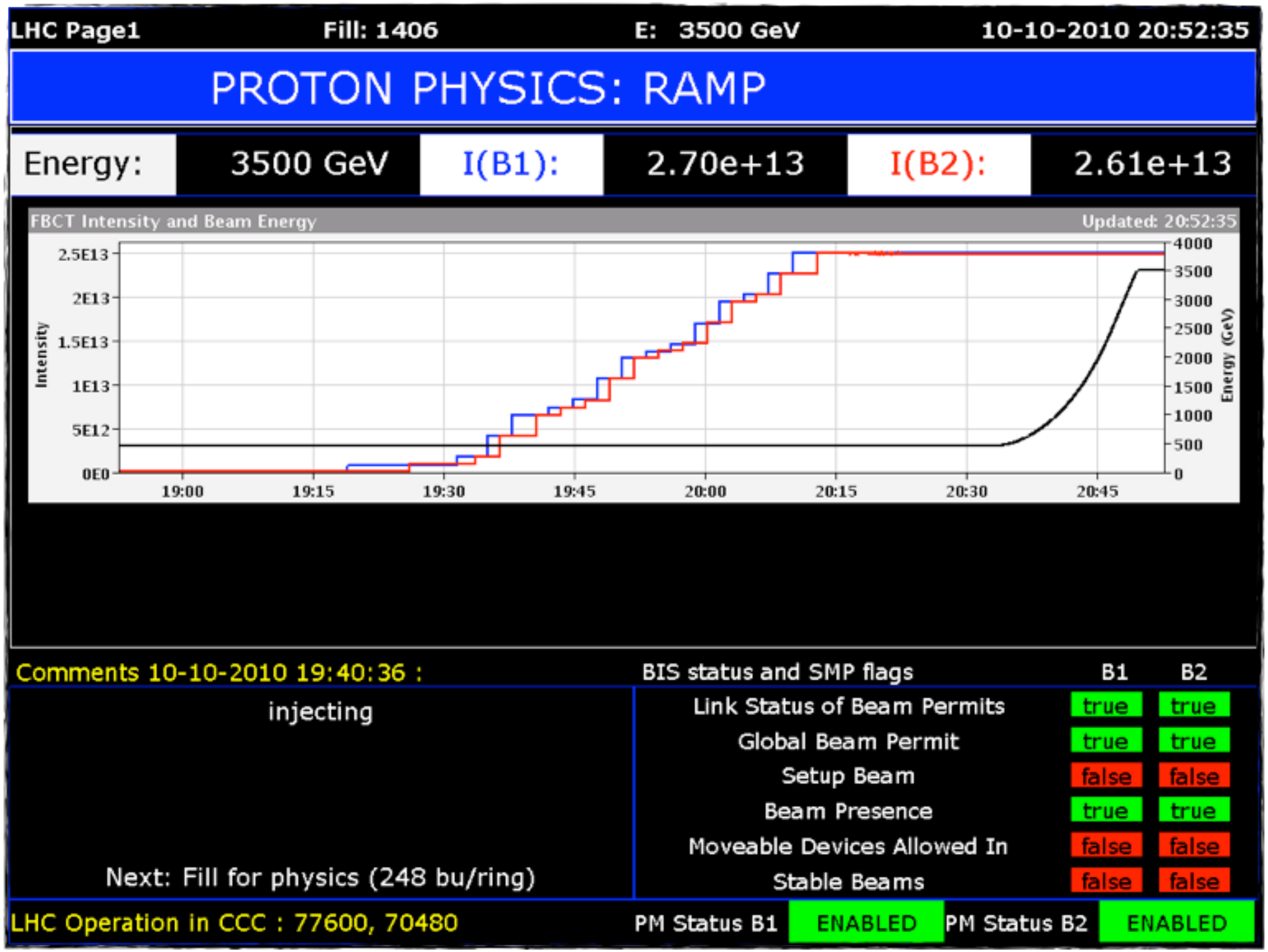
number of bunches

colliding bunches in points 1/5

colliding bunches in point 2

colliding bunches in point 8

LHC in Operation



LHC Page1 Fill: 1406 E: 3500 GeV 10-10-2010 20:52:35

PROTON PHYSICS: RAMP

Energy: 3500 GeV I(B1): 2.70e+13 I(B2): 2.61e+13

Comments 10-10-2010 19:40:36 :

injecting

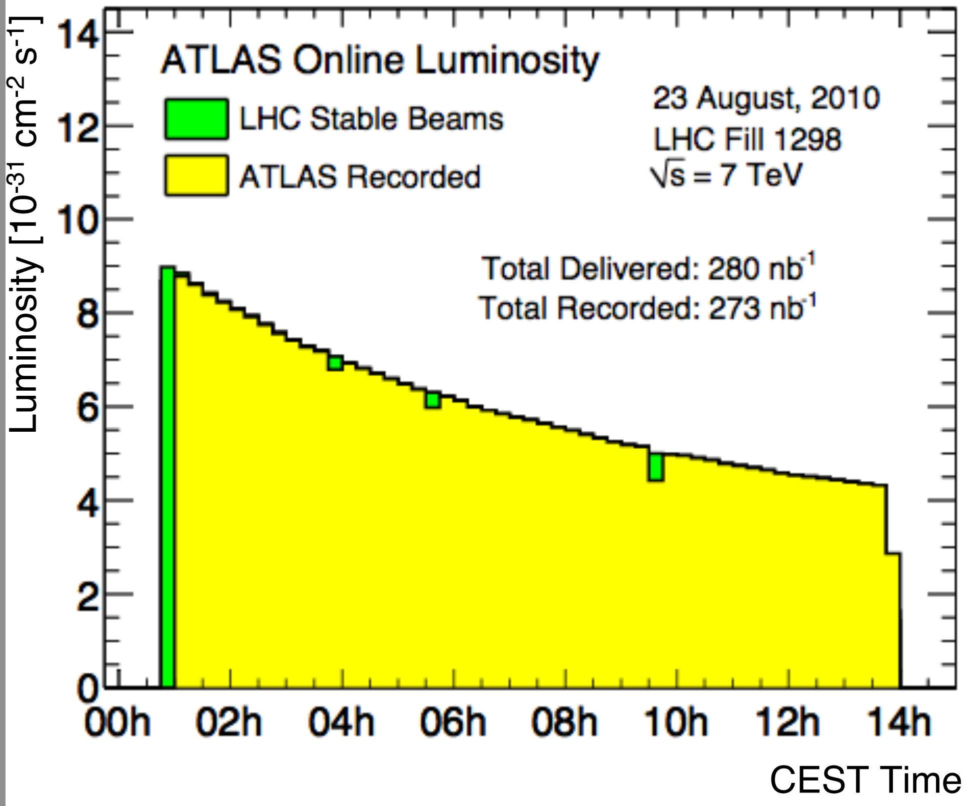
Next: Fill for physics (248 bu/ring)

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

LHC Operation in CCC : 77600, 70480

PM Status B1 ENABLED PM Status B2 ENABLED

Present LHC Status



LHC Fill
[August 2010]

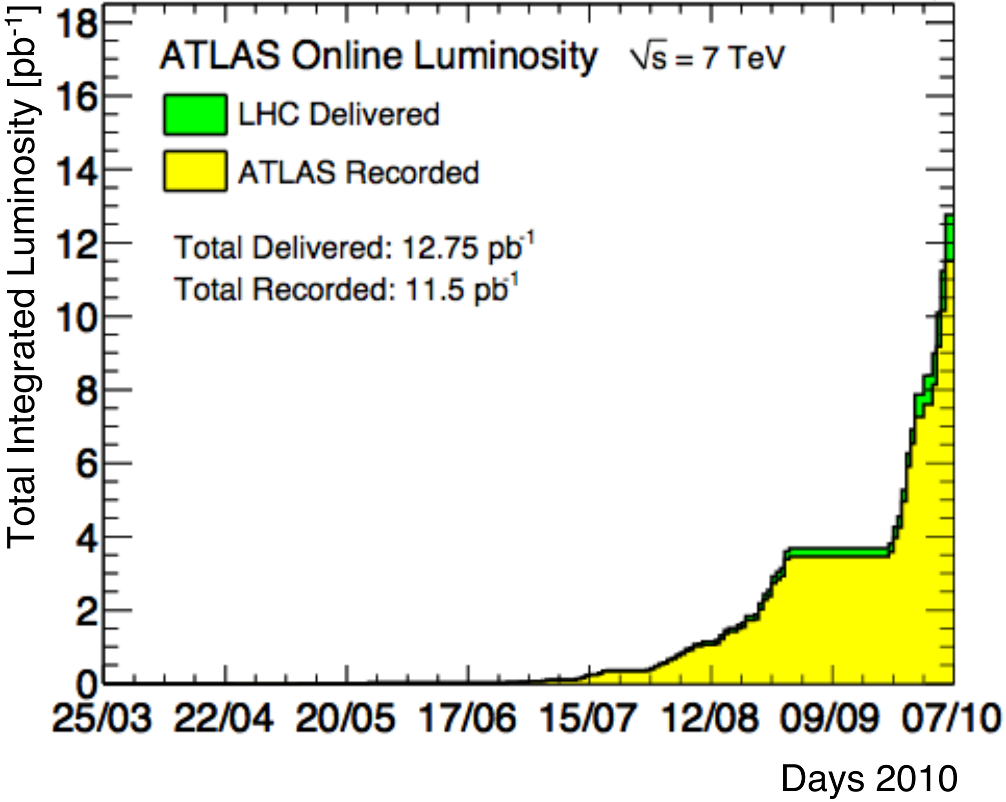
$$N = L \cdot \sigma$$

Number of
Events

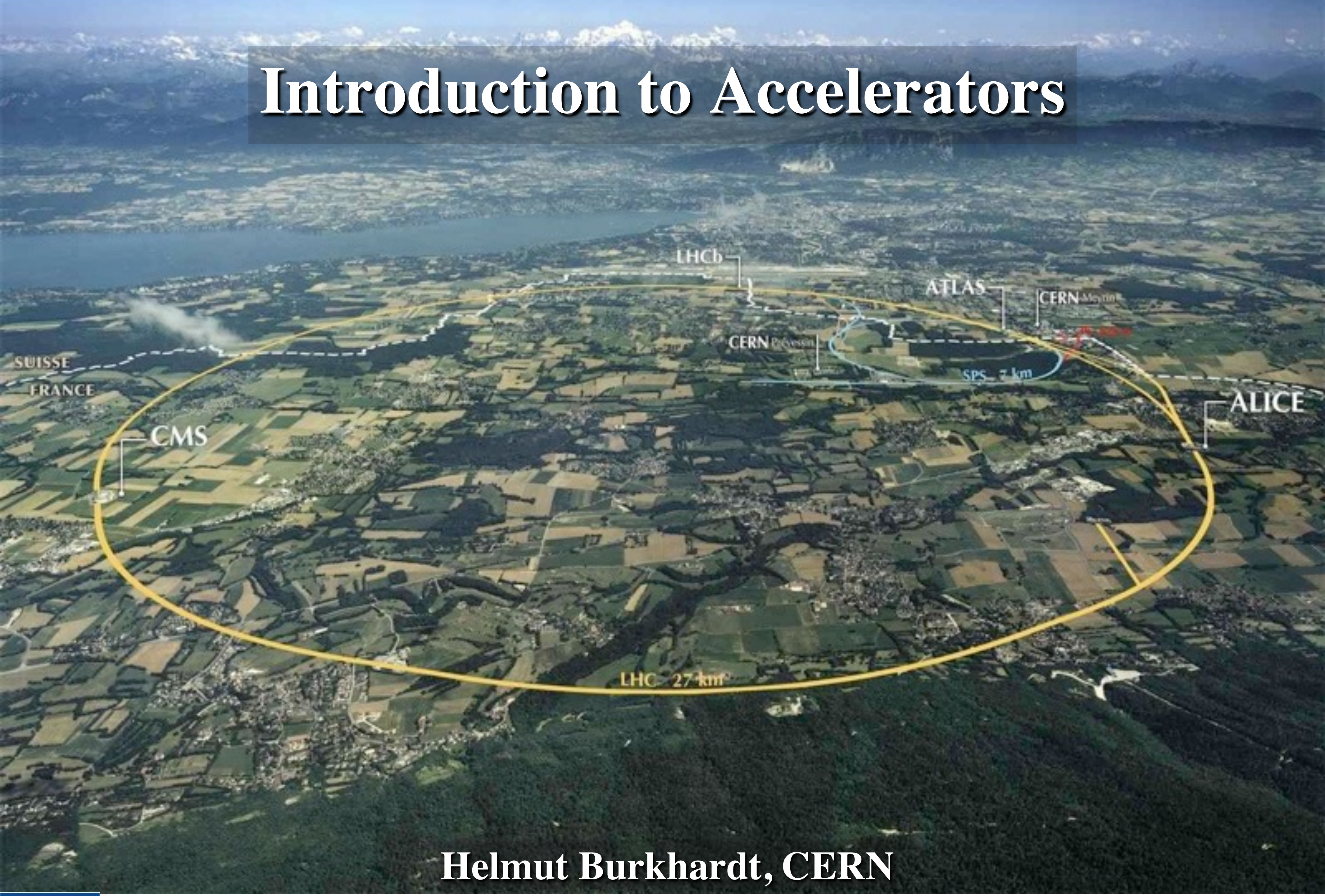
Integrated
Luminosity

X-Sec.

Delivered and Recorded
Luminosity



Introduction to Accelerators



Helmut Burkhardt, CERN

ISEF 2013 24 June 2013

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; 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

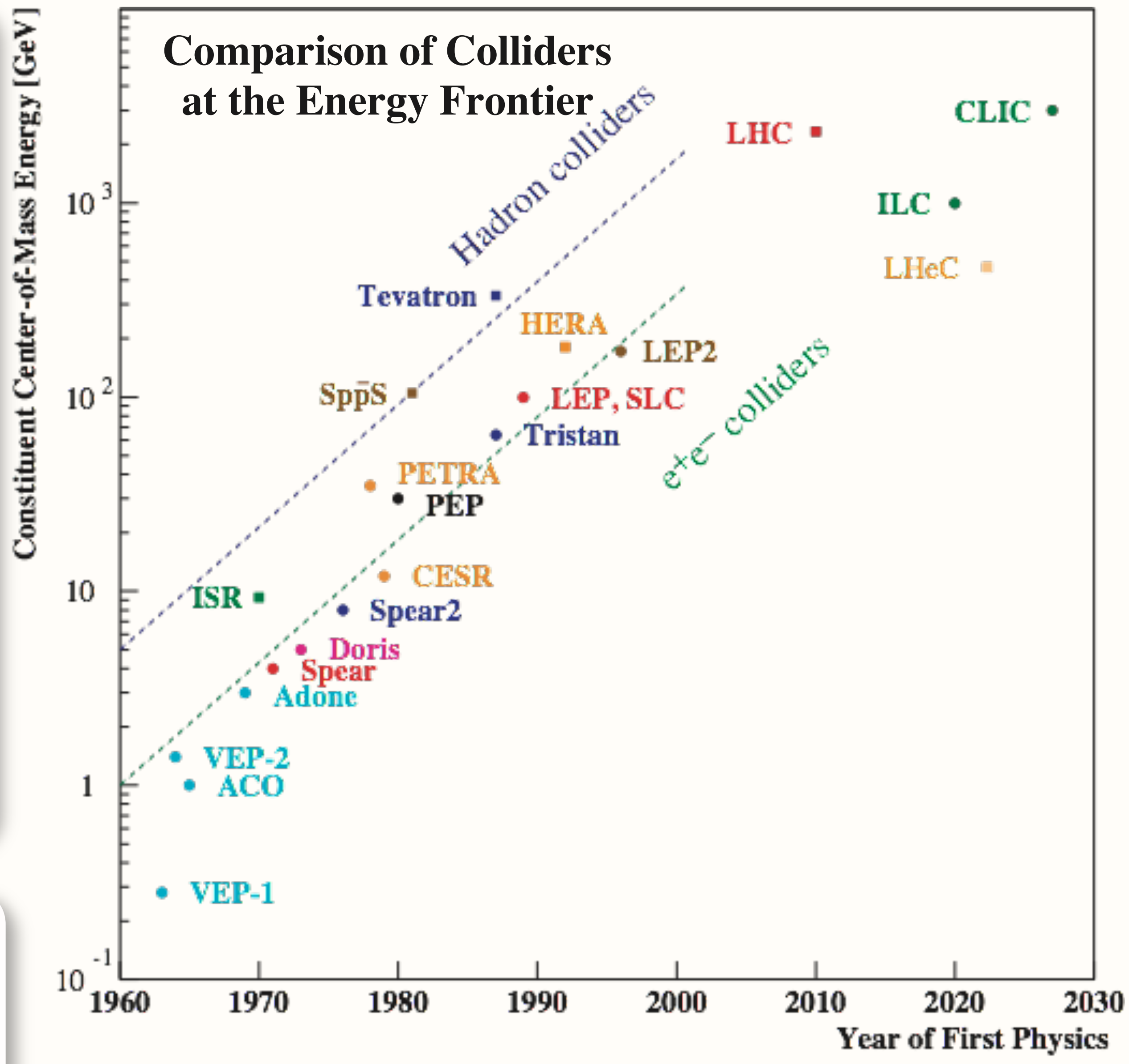
Livingston plot

Exponential growth of E_{cm} in time

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

Factor 4 every 10 y

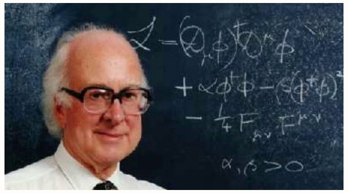
pp, $p\bar{p}$: E_{cm} / 6 still 5 × above e^+e^- at same time



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

+ ep : hadron structure, QCD
HERA, LHeC

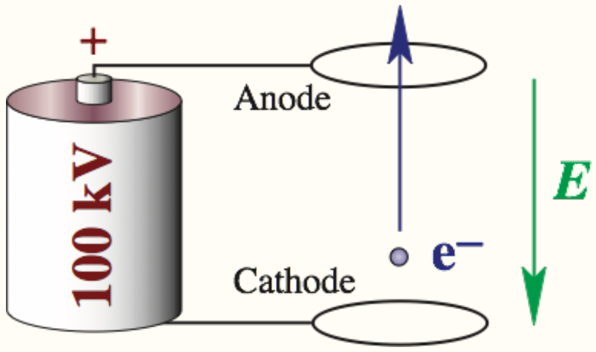
The LHC is a major step forward
Discovery machine : Higgs ...



Helmut Burkhardt: Introduction to accelerators June 2013

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 β = 0.999 999 9987 γ = 19569.5

Proton β = 0.995 588 4973 γ = 10.6579

Unit conversion

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

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

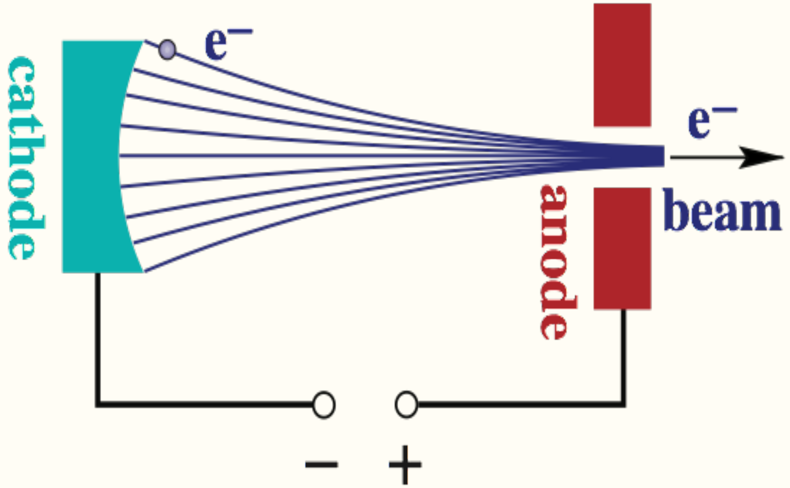
$$(\hbar c)^2 = 3.8938 \times 10^{-32}\,\text{GeV}^2\,\text{m}^2$$
$$= 3.8938 \times 10^{5}\,\text{GeV}^2\,\text{nb}$$

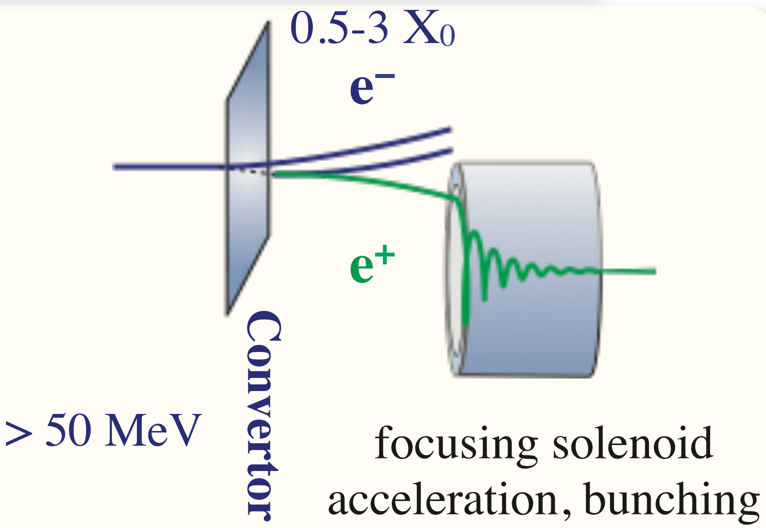
for precise numbers see PDG

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

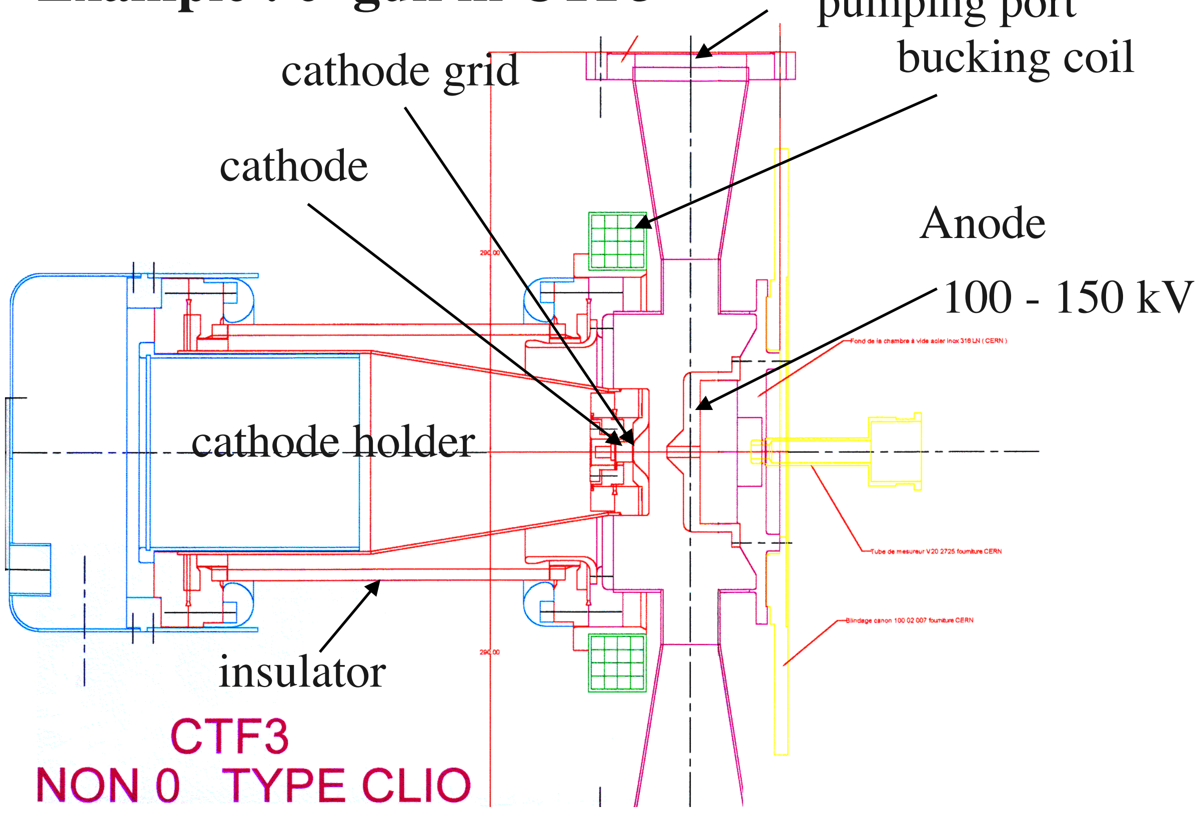
Particle sources

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

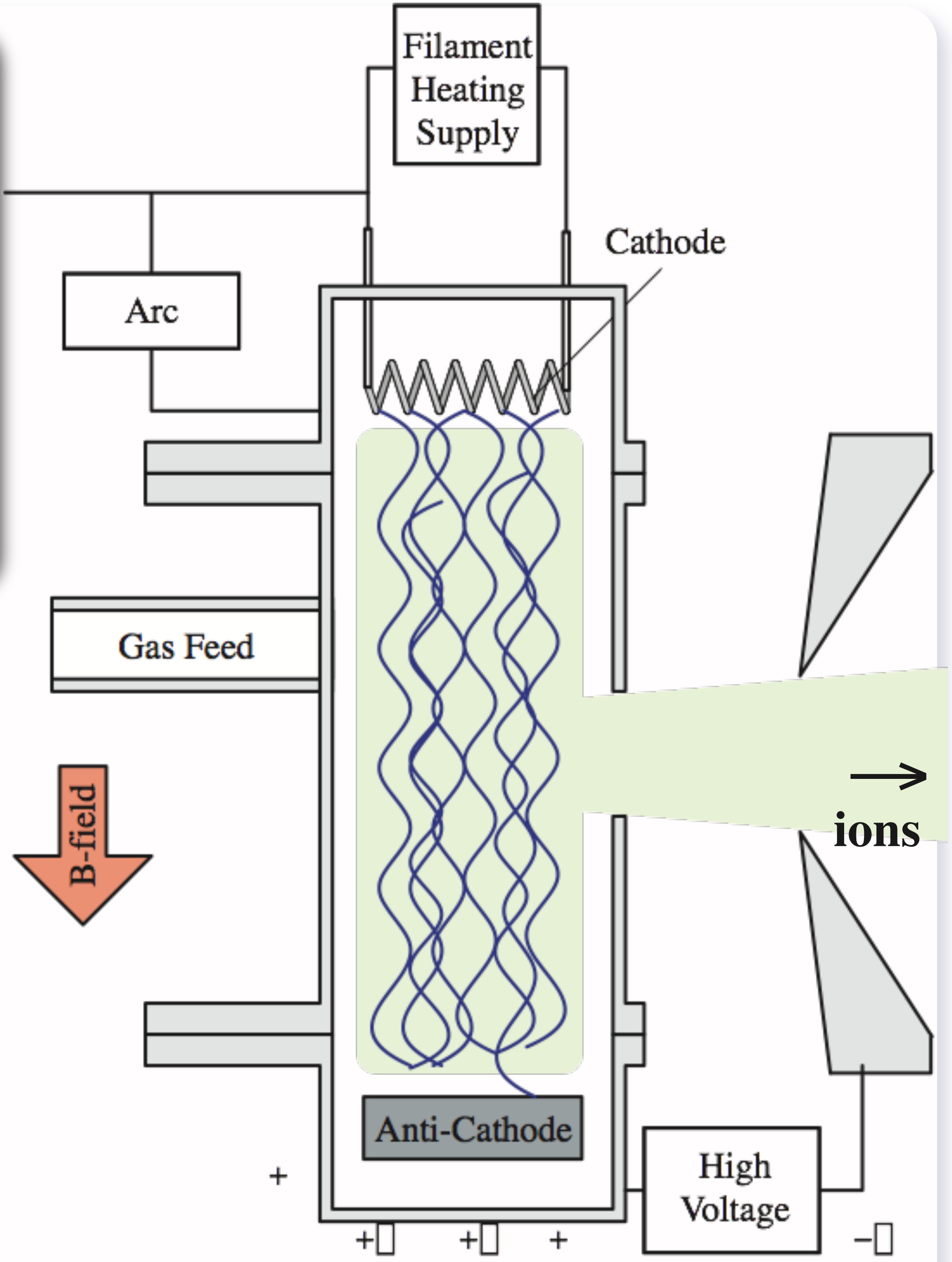
Proton and ion sources

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

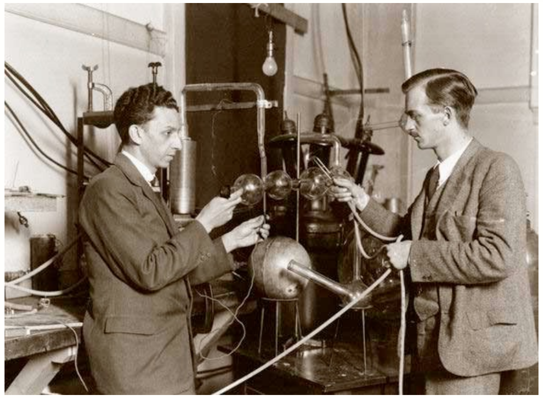
Typically involves : **low pressure heated gas**
ionized gas / plasma, inject H_2 to get protons,
or surface sputtering
and electric and magnetic fields
to keep the electrons

CERN p-source and 50 MeV Linac

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

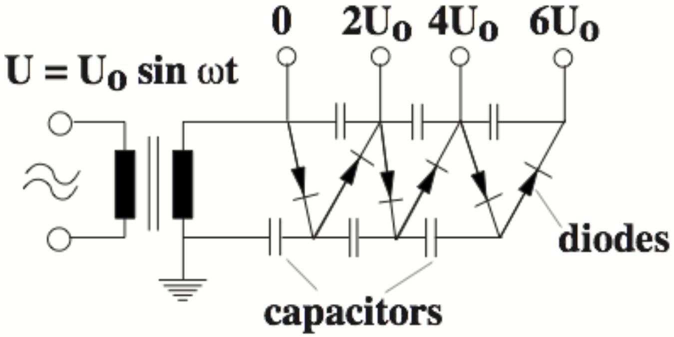


Linear Acceleration with Electrostatic Field

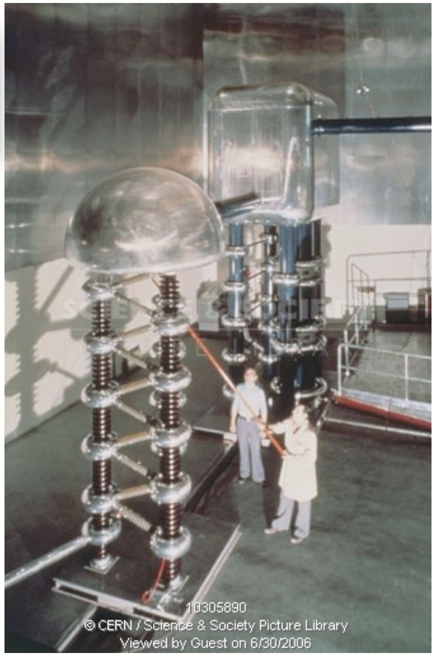


allows for DC, 100 % duty factor

limited by HV-breakdown ~ 1 MV / m



800 kV
proton pre-injector
used at
CERN
until 1993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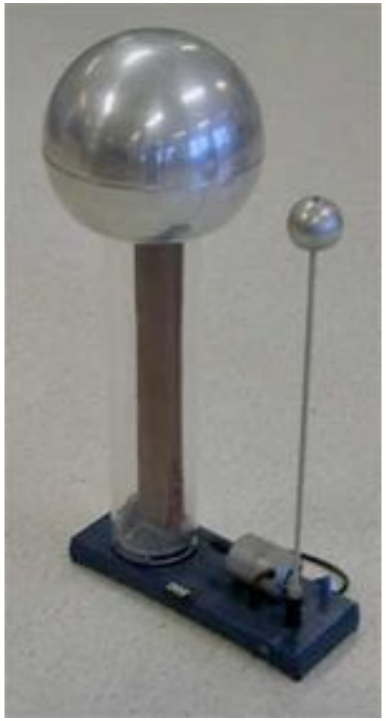
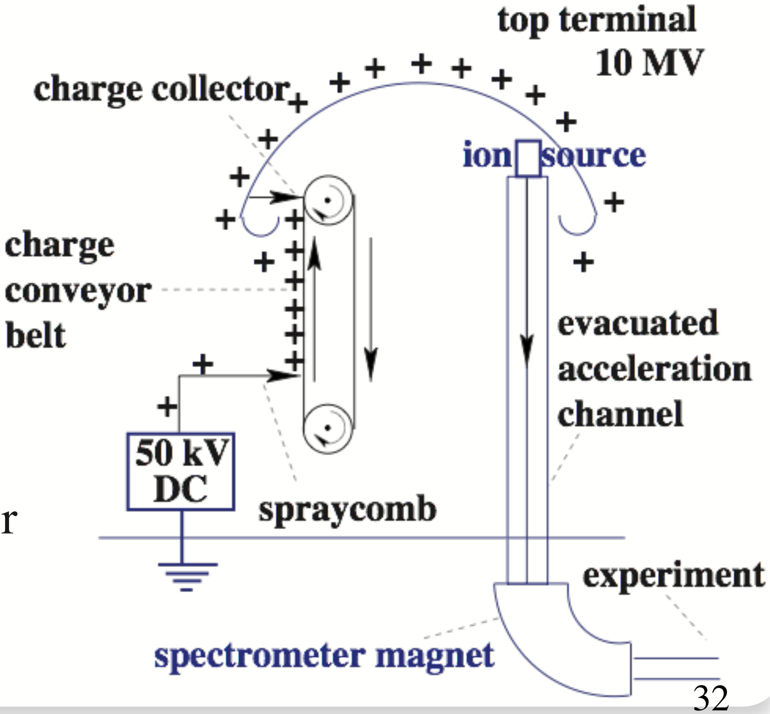
Cockcroft Walton
voltage multiplier



Van de Graaff generator
static electricity from belts

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



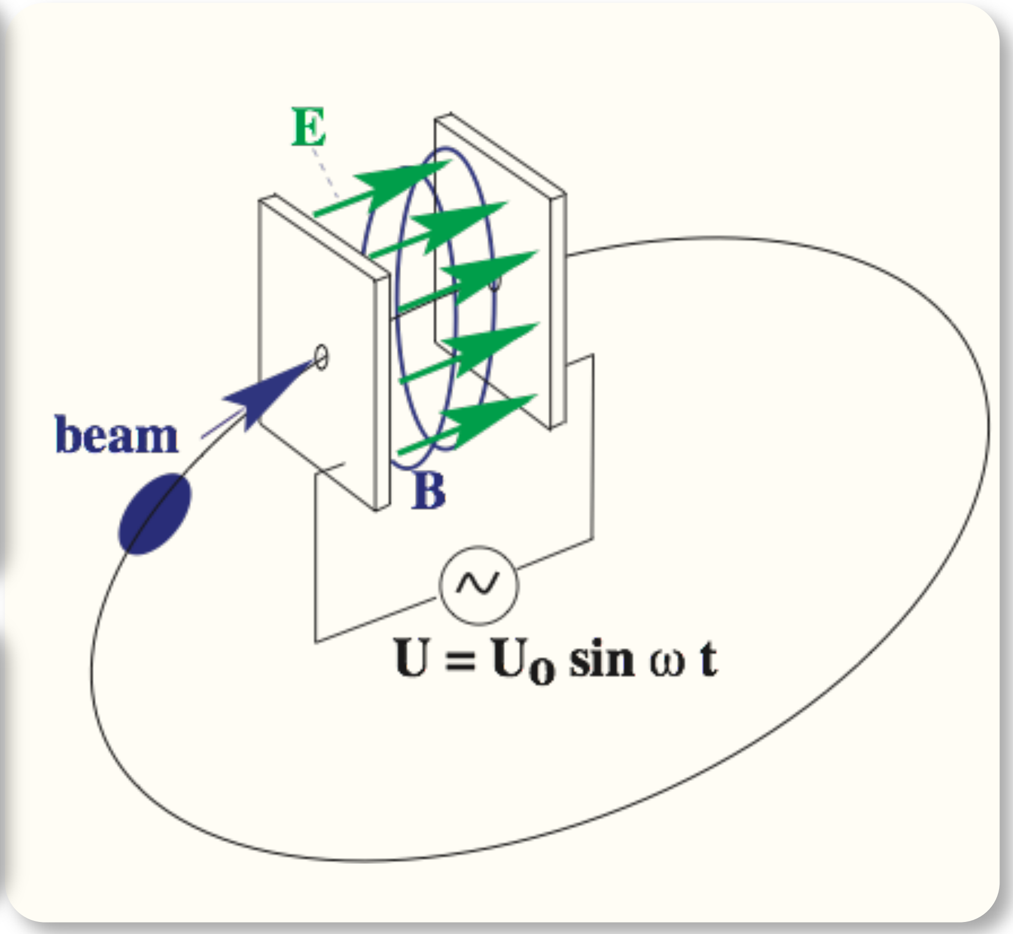
Time Varying Fields

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

Helmut Burkhardt: Introduction to accelerators June 2013

Basic parameters, Lorentz Force

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

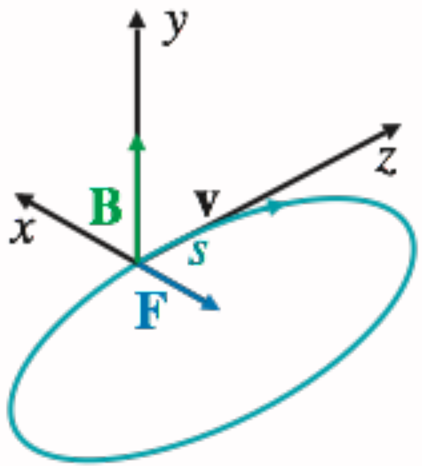
charge q, normally $q = e$; $q = Z\,e$ for ions

- 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

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

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. = 1.5×10^{11} m

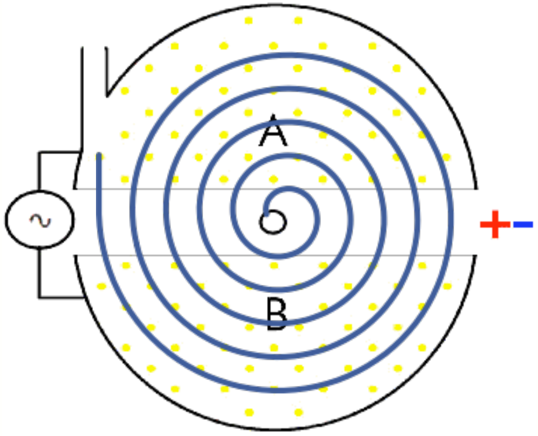
Solar system B = 10 μG E = 5 TeV ρ = 11 a.u.

Intergalactic B = 1 nG E = 5 PeV (knee)

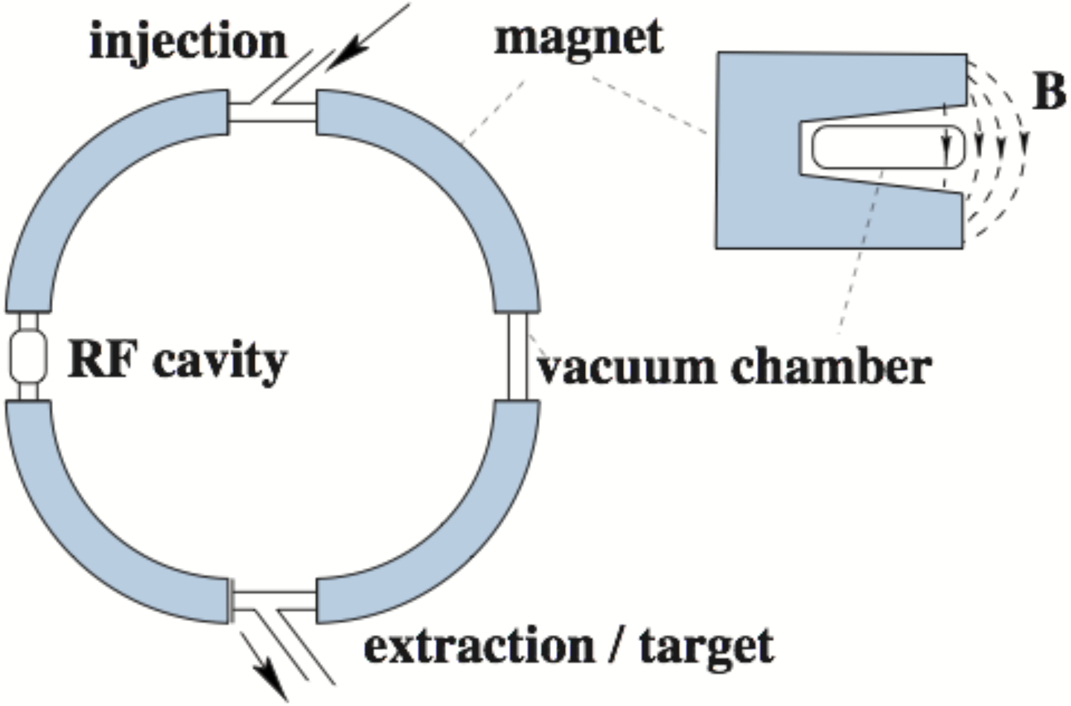
ρ = 1.7×10^{19} m (4 % of galaxy-radius)

Circular Accelerator

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



Cyclotron

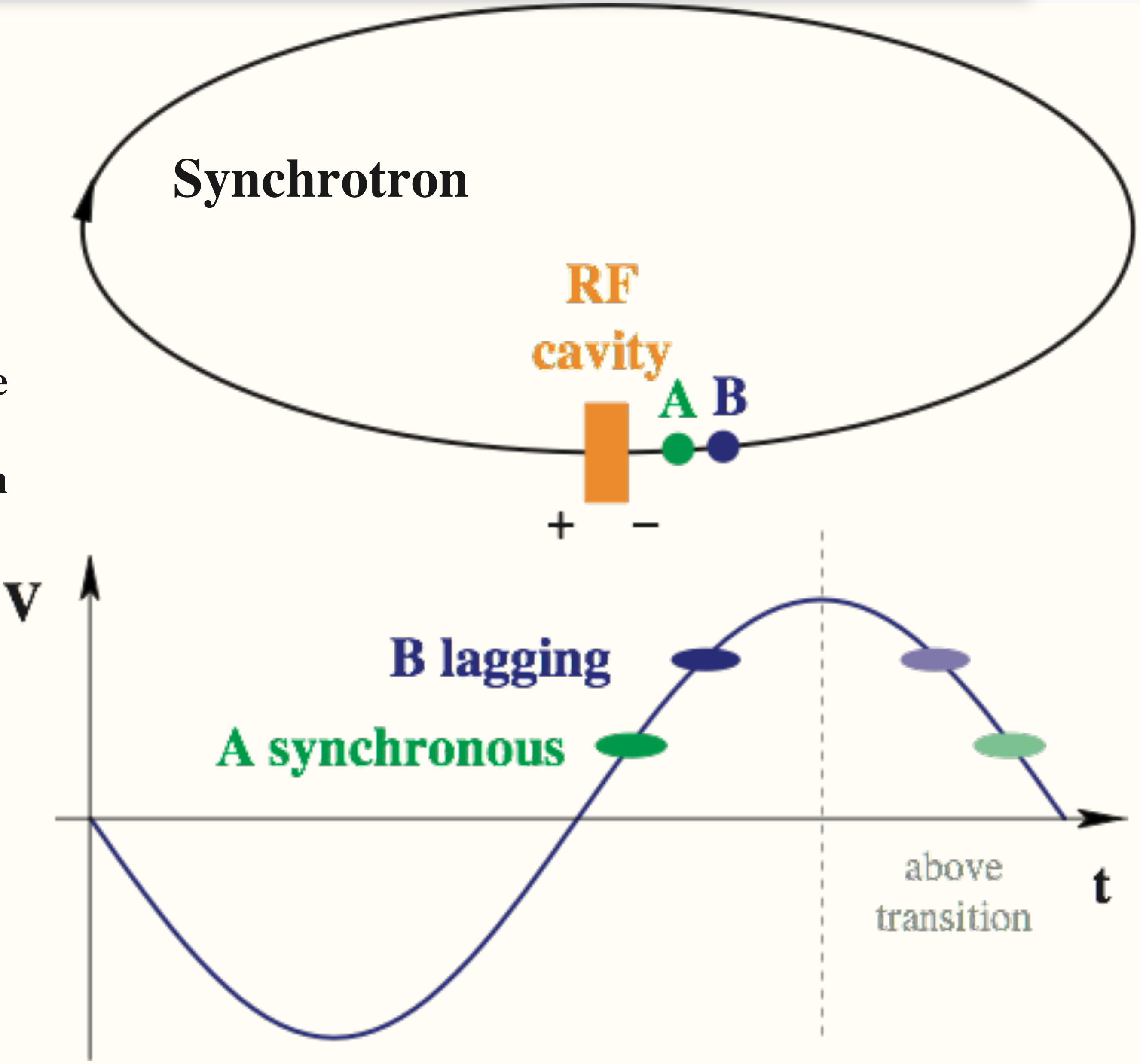


- **Synchrotron : ϱ = const. B increased with energy. RF-frequency adjusted slightly (β = 0.999 .. 1.0).** Most HEP and all CERN ring accelerators PS, SPS, LEP, LHC of this type. Principle same for e, p, heavy-ion – PS, SPS – accelerate(d) all of these, in some cases switching within seconds

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

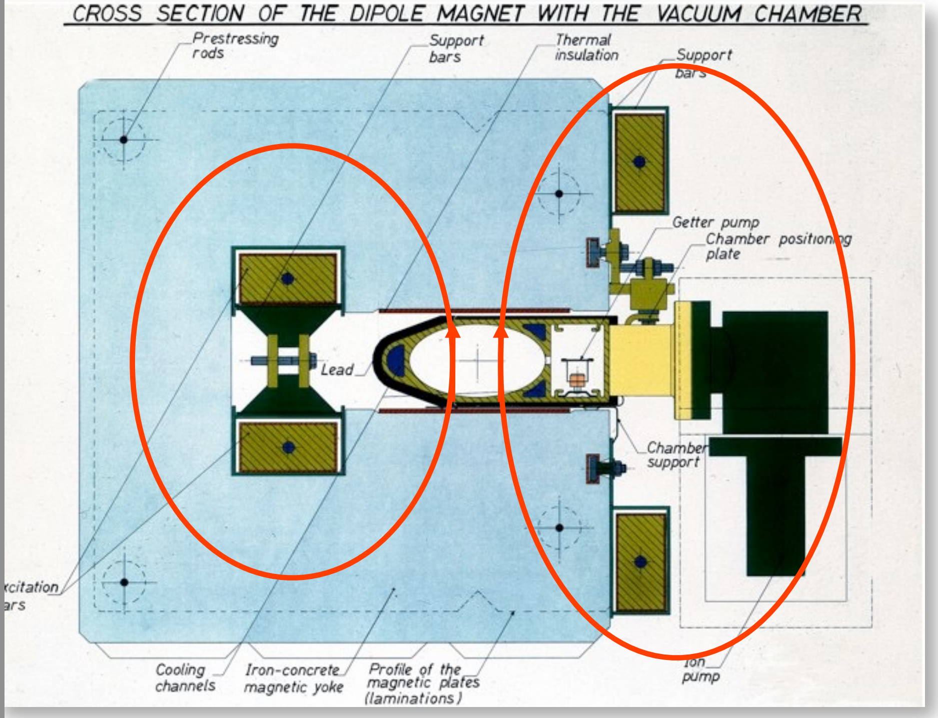
LHC $B \propto I$ B = 8.38 T

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

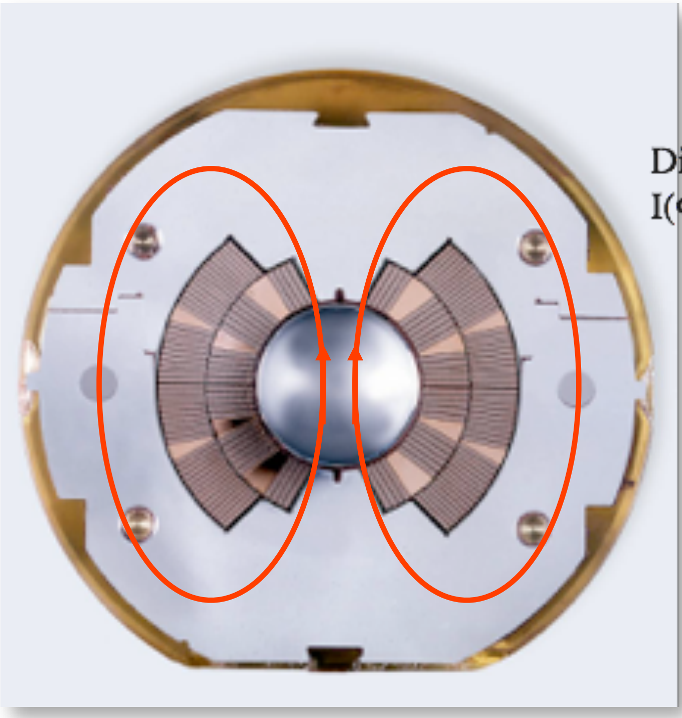
P = 78 MW / cell × 488 cells total power P = 38 GW

Magnet technology

warm

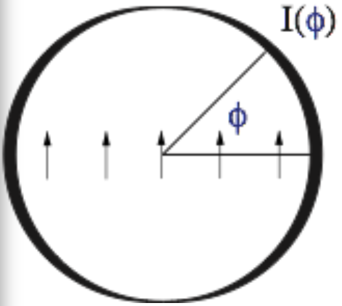


cold



Dipole current distribution

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

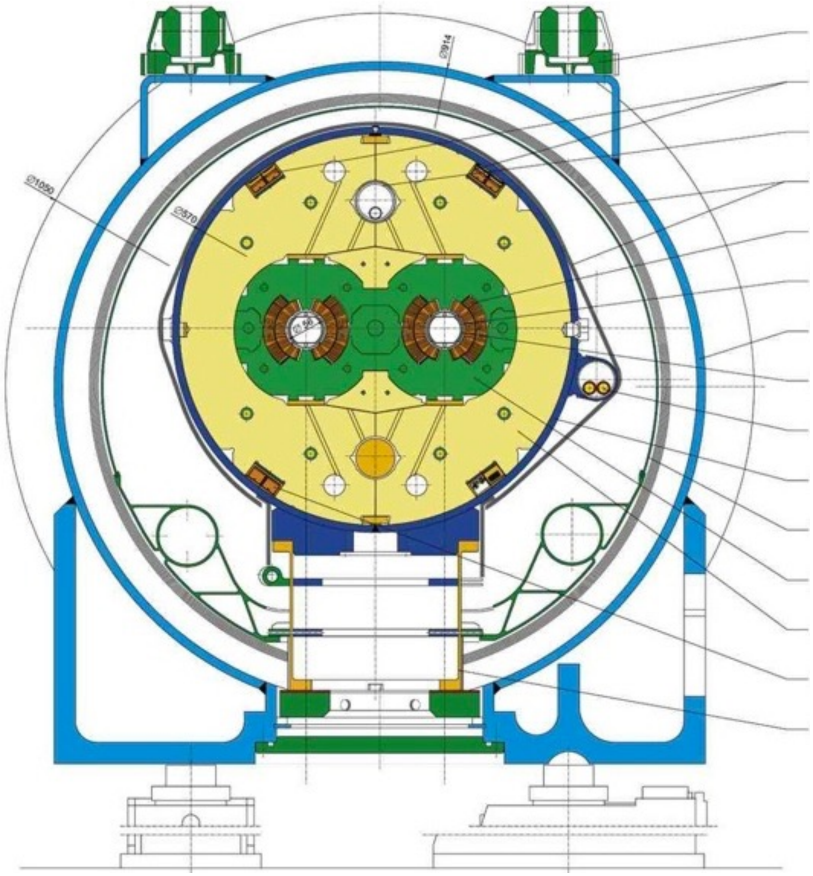


- field quality given by pole face geometry
- field amplified by Ferromagnetic material
- hysteresis and saturation ~ 2 T
- Ohmic losses for high magnet currents

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

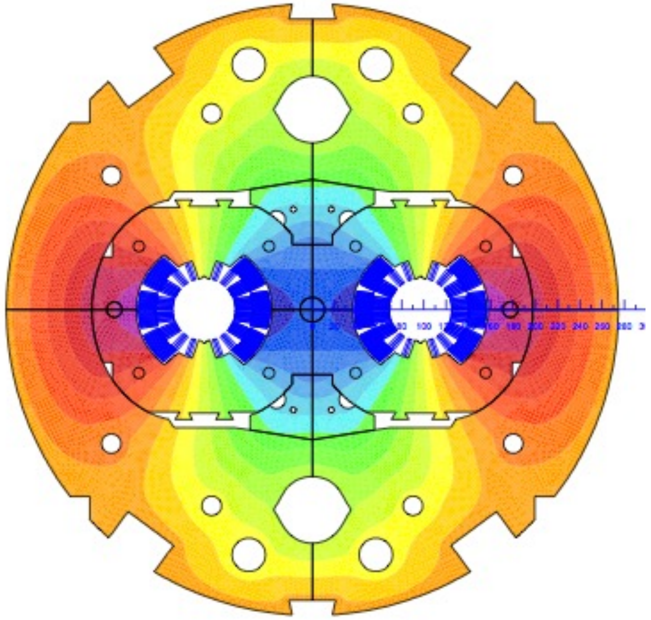
LHC dipole magnet

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



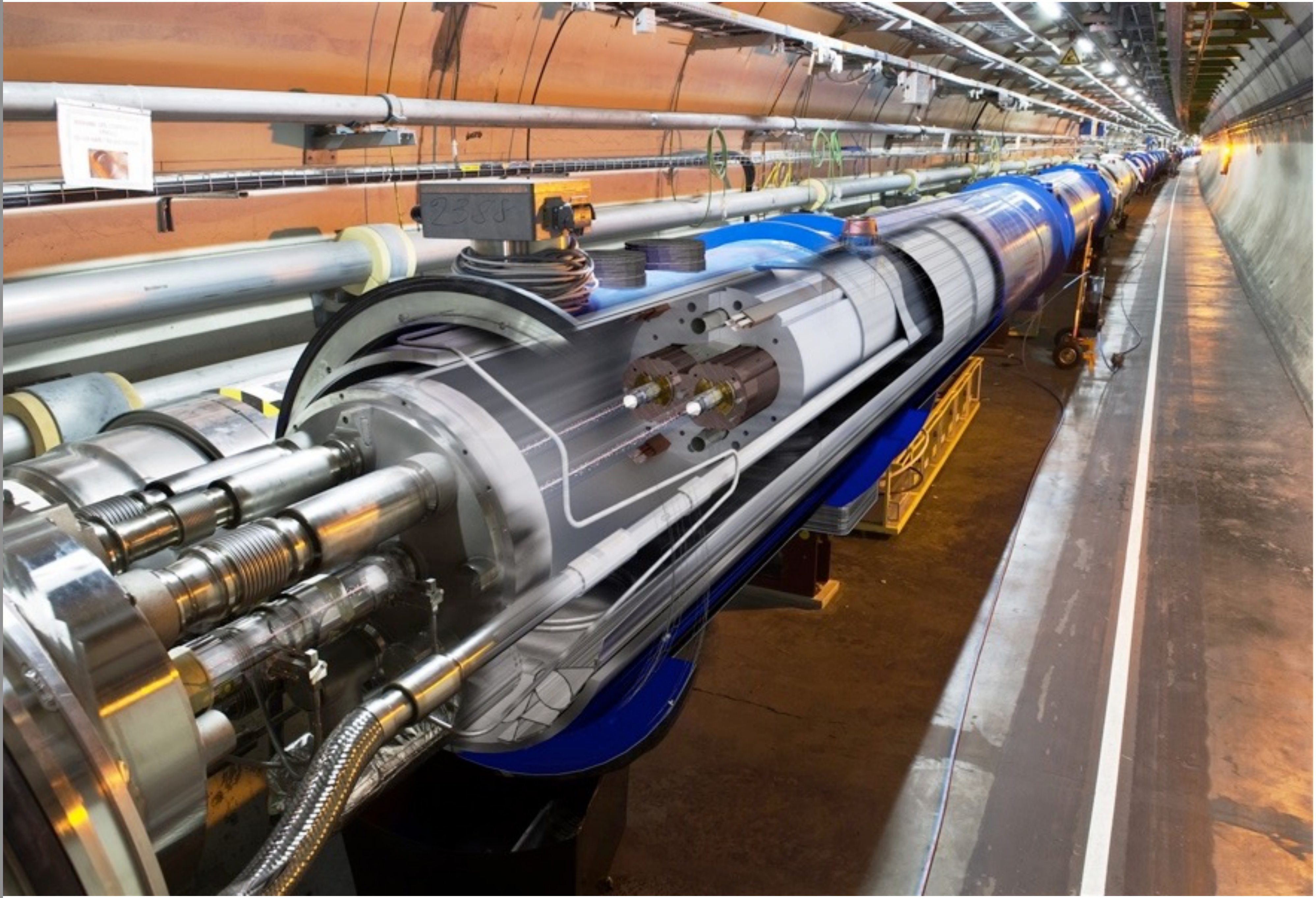
alignment target
main quadrupole bus-bars
heat exchange pipe
superinsulation
superconducting coils
beam pipe
vacuum vessel
beam screen
auxiliary bus bars
shrinking cylinder / He I-vessel
thermal shield (55 to 75 K)
non-magnetic collars
iron yoke (cold mass, 1.9 K)
dipole bus-bars
support post

LHC dipole magnet cross-section

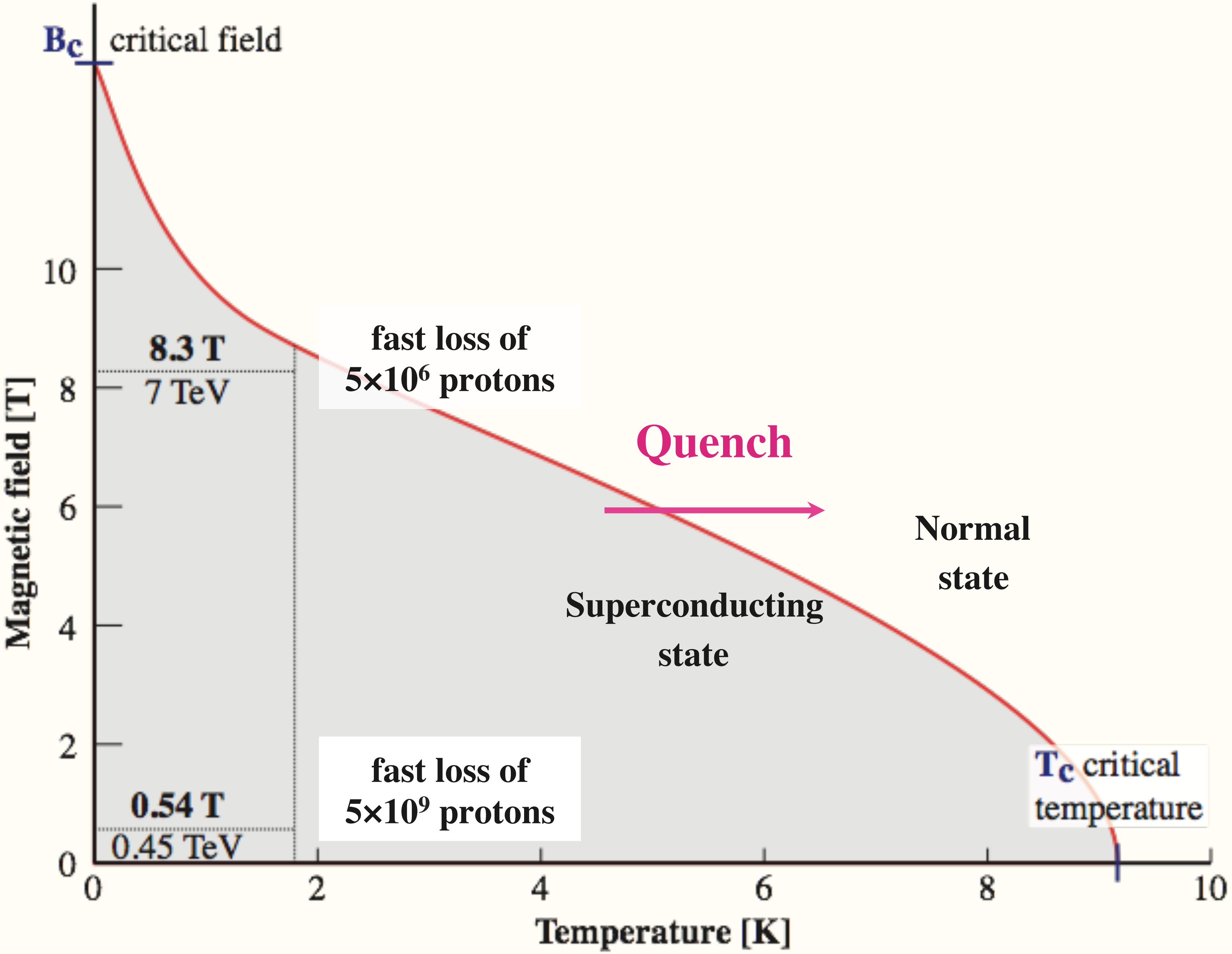


current distribution

LHC magnets installed in the tunnel



Operational margin of a superconducting LHC dipole



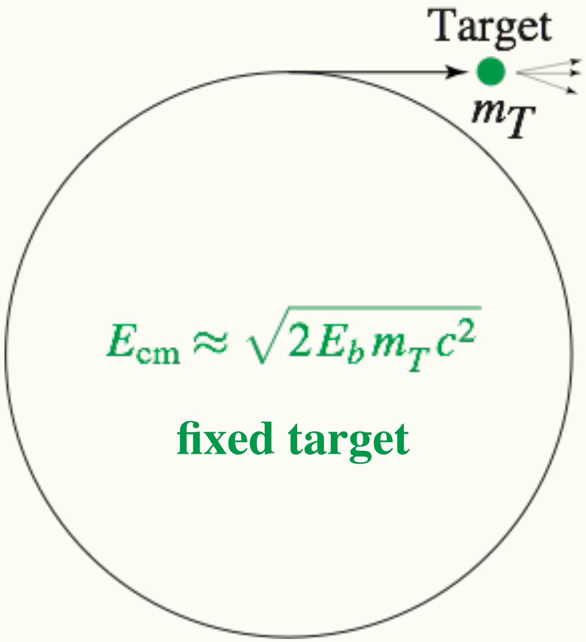
Fixed Target vs Collider

Fixed target, high energy collisions :

Energy “lost” as kinetic energy

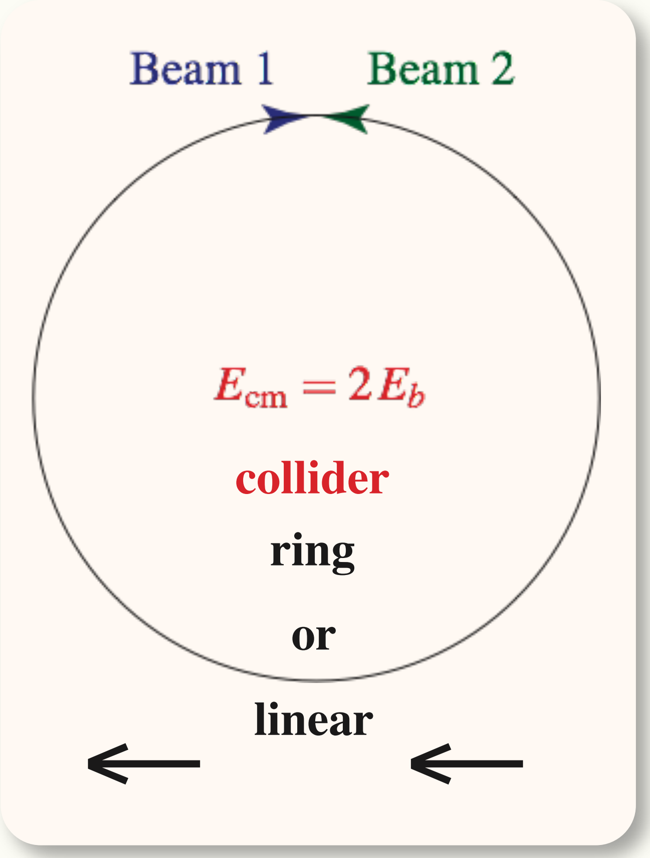
High Energy e+e− and
very high energy pp gain
a lot from colliders

Gain for LHC is by ×122
(14 TeV / 114.6 GeV)



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

fixed target



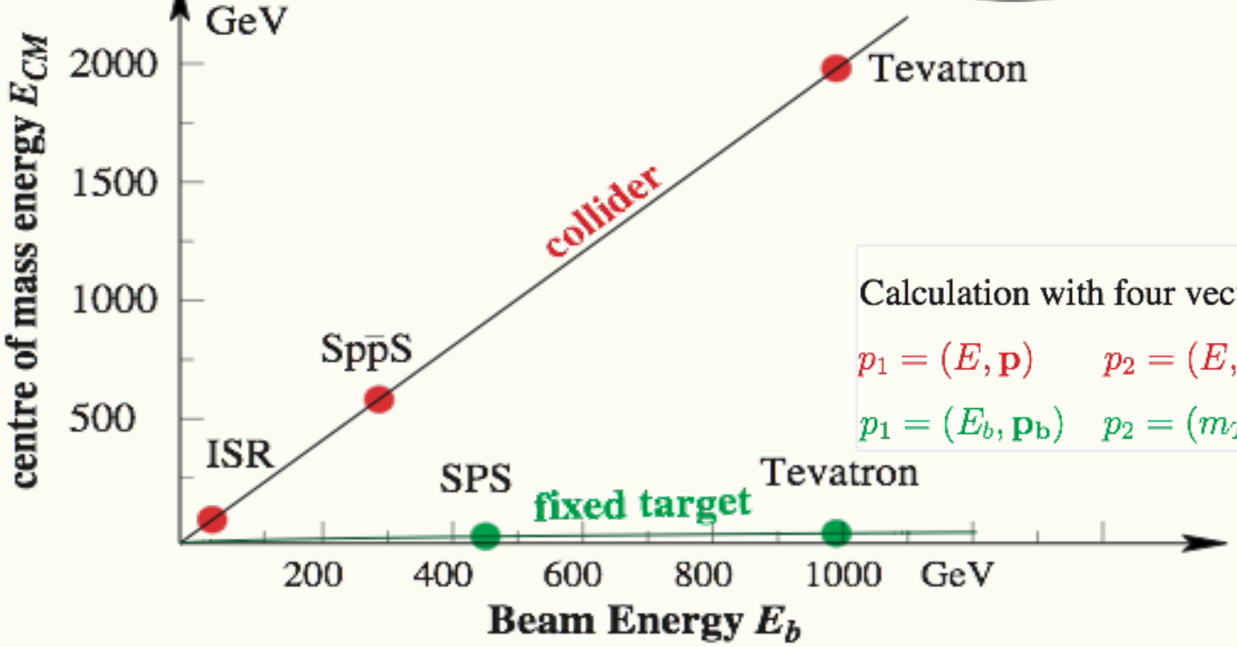
$E_{\mathrm{cm}} = 2E_b$

collider

ring

or

linear



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

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

$p_1 = (E_b, \mathbf{p_b}) \quad p_2 = (m_T, 0) \quad s = m_b^2 + m_T^2 + 2m_T E_b$ 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 ~ $\mathbf{E^{-3}}$

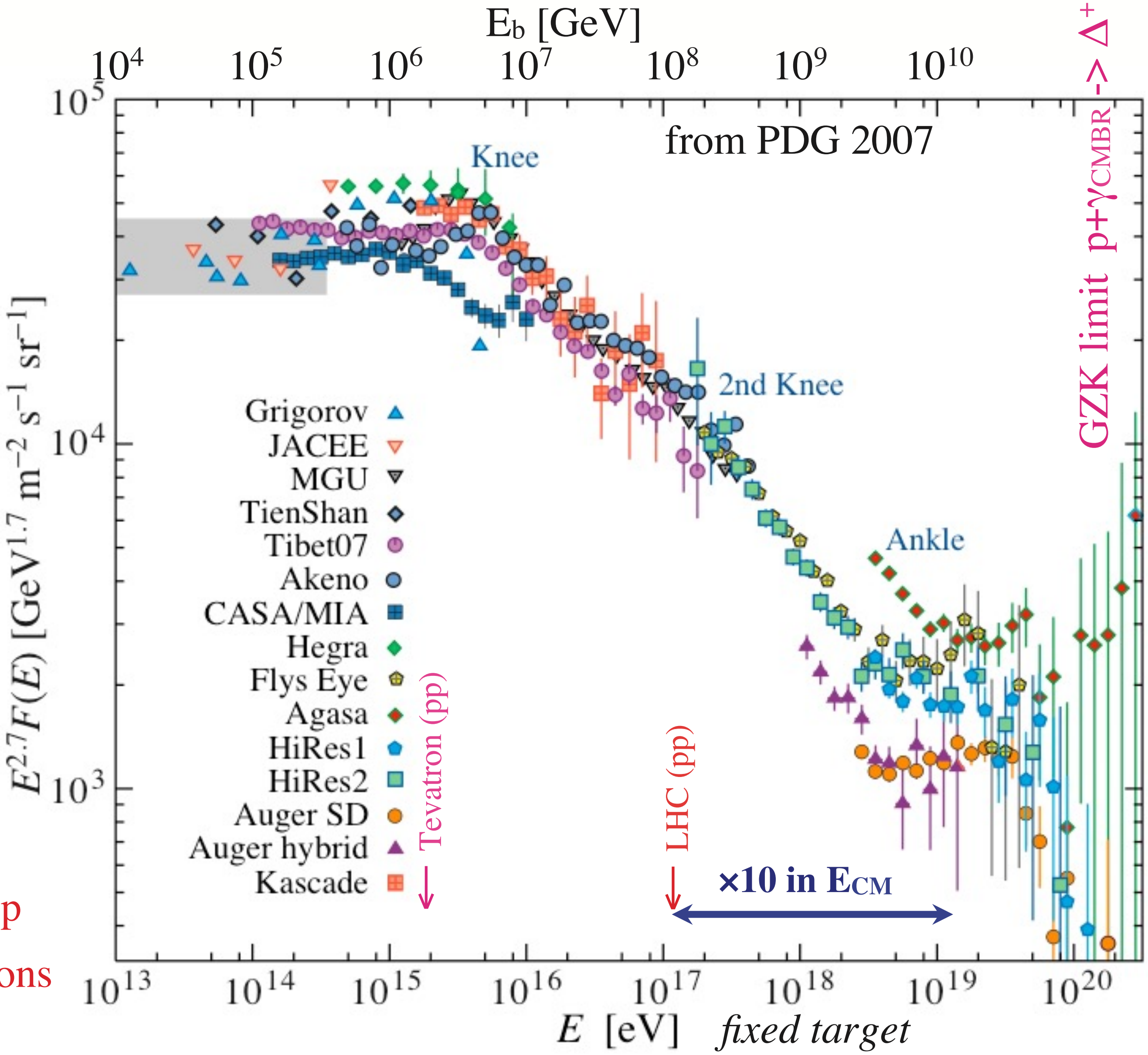
back to $\mathbf{E^{-2.7}}$ at very
highest energies

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.

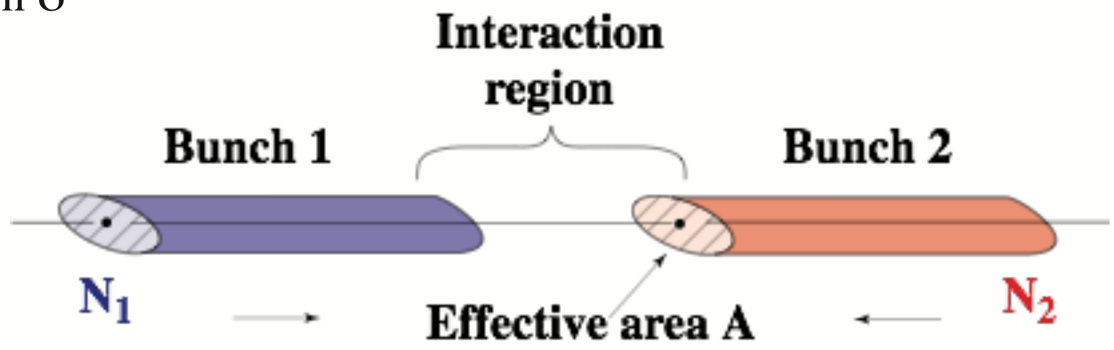
Luminosity and collision rates

Event rate for process with cross section σ

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

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

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

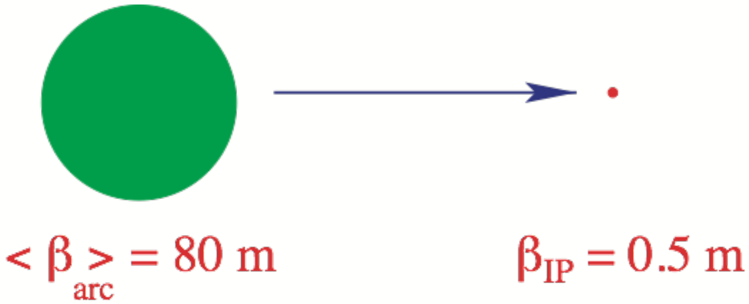


for Gaussian bunches with rms sizes $\sigma_x\ \sigma_y$ **A** $= 4\,\pi\,\sigma_x\,\sigma_y$

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 $\sigma_x = \sigma_y = 17\ \mu\text{m}$



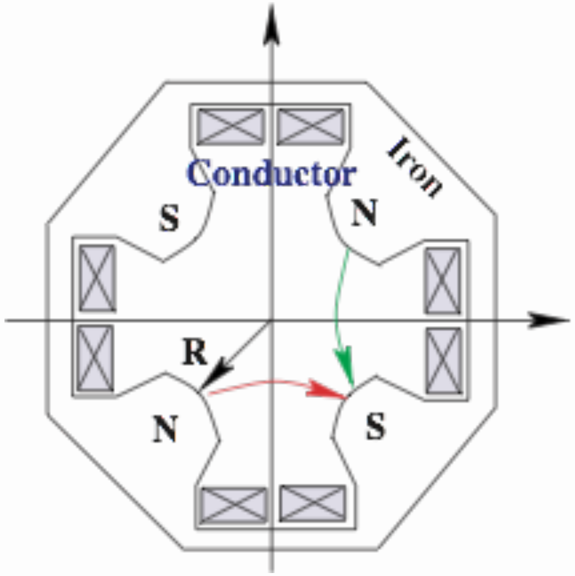
Rare new processes, like Higgs production can have very small cross section, like $1\text{fb} = 10^{-39}\text{cm}^2$. LHC designed for very high Luminosity **$L = 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$**

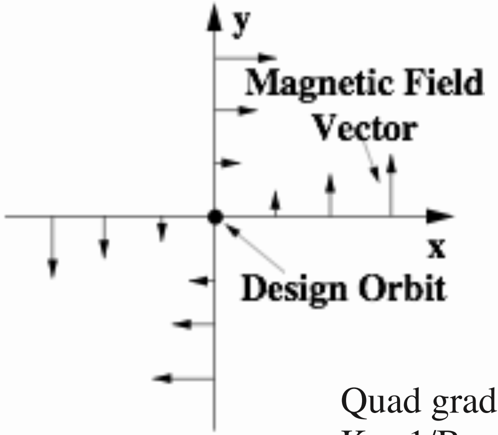
Event rate for such rare processes : ~ 1 new particle every 28h.

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

Alternate gradient focusing

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





$B_x = k\,y$
$B_y = k\,x$
$B_z = 0$

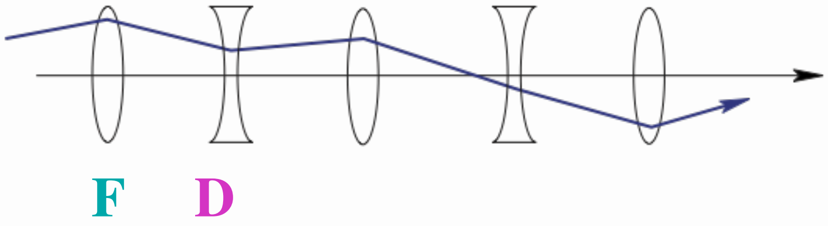
$\nabla \times \boldsymbol{B} = \boldsymbol{0}$

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

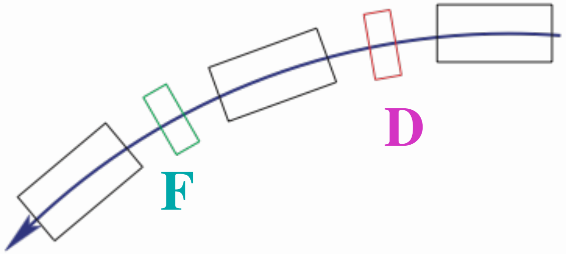
Combine F D
Defocusing when at small amplitude
Overall focusing

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)

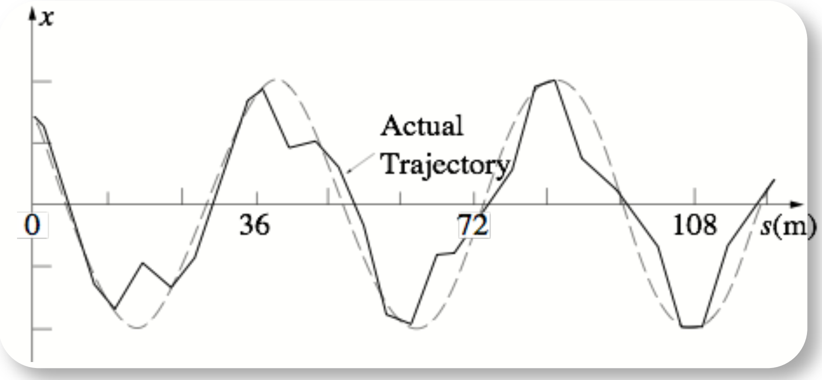
Solution : $x(s) = \sqrt{\epsilon \beta(s)}\, \cos(\mu(s) + \phi)$

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

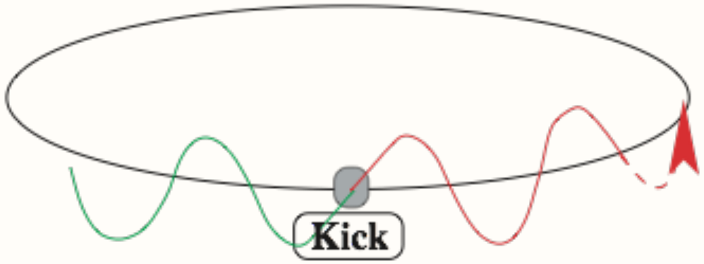
$\boldsymbol{\varepsilon}$ invariant, together with $\beta(s)$ amplitude. “single particle emittance”

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

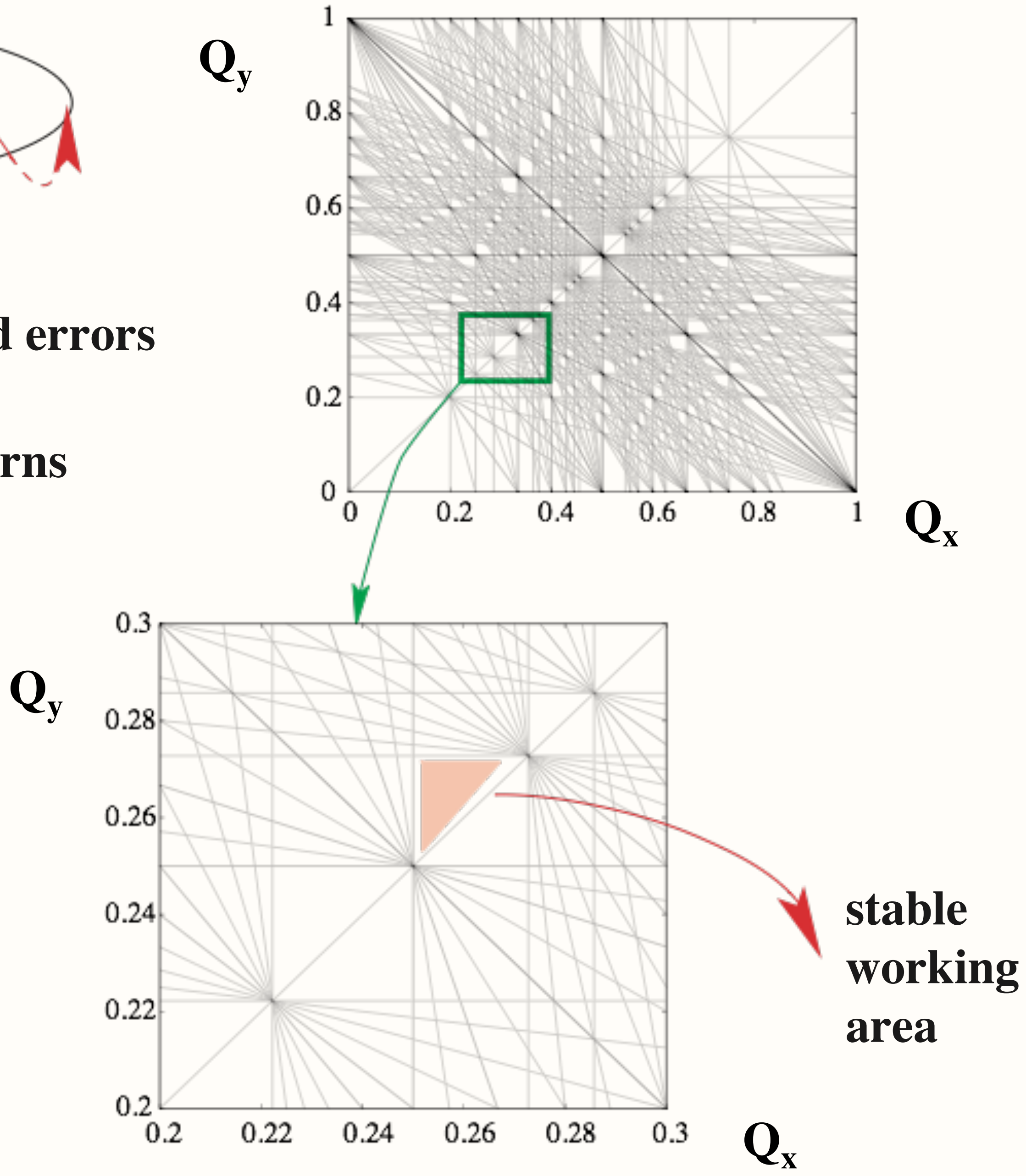
Orbit stability and tune



Misalignments and dipole field errors

→ **orbit perturbations**

would add up on successive turns for integer tune Q = N



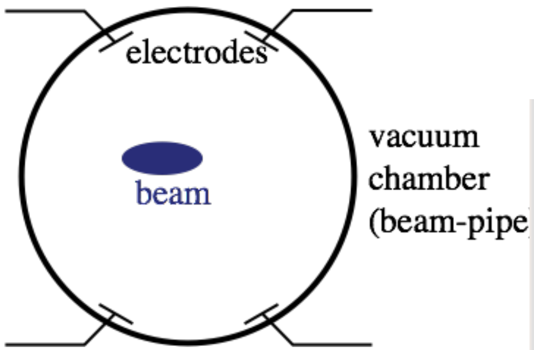
stable working area

Higher order field errors, Quad., Sext. perturbations. Avoid simple fractional tunes

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

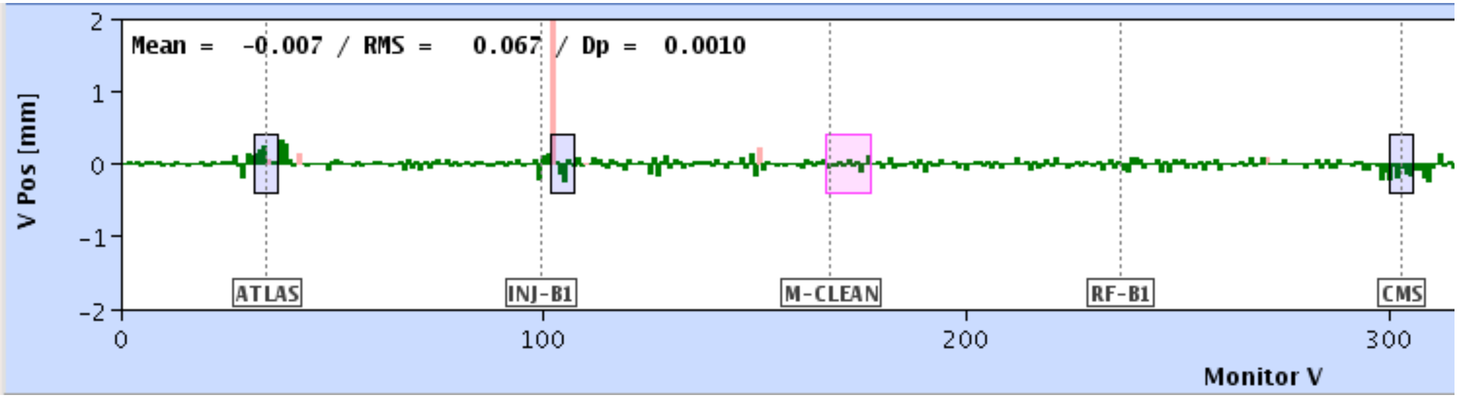
Minimise field and alignment errors

Orbit, tune measurement and peak beam current



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

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



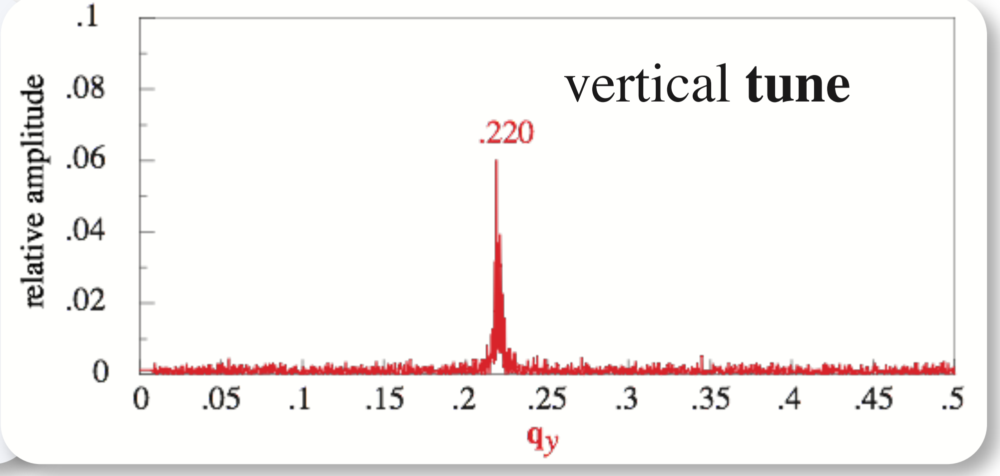
$\langle I_b \rangle$ average ring
and
$\hat{I}$ local peak
current

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

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

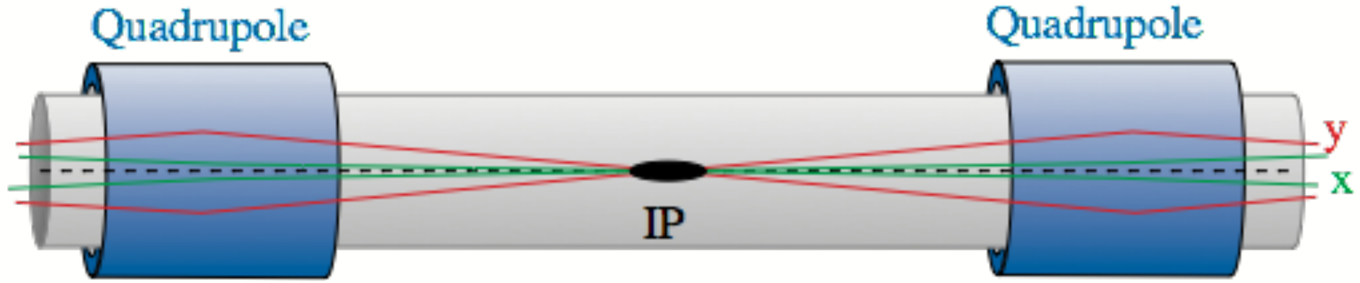
beam size, r.m.s. $$\sigma(s) = \sqrt{\varepsilon\beta(s)}$$

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



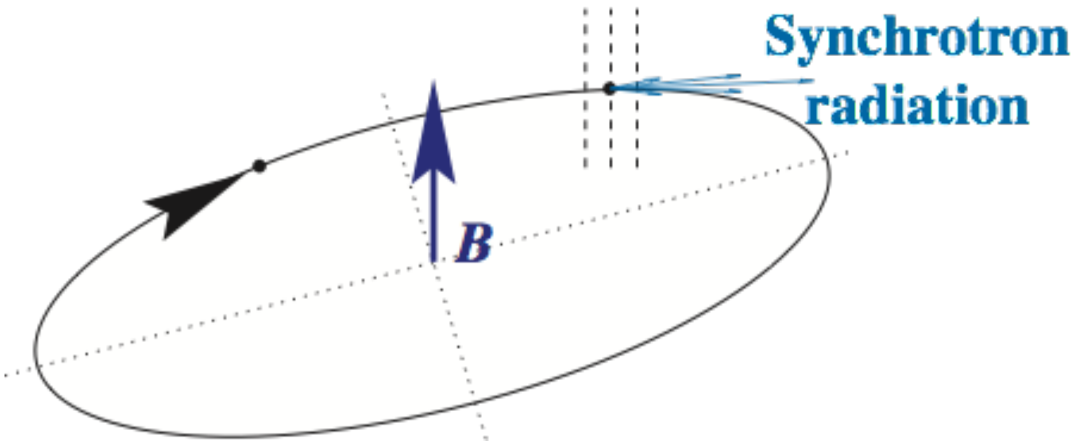
LHC $\varepsilon_N = \varepsilon\,\beta\gamma = 3.75\ \mu$m, at top $E_b = 7$ TeV: $\varepsilon = 0.503$ nm, $\beta^* = 0.55$ m, $\sigma^* = 16.63\ \mu$m, $\theta^* = 30\ \mu$rad

Standard Synchrotron Radiation

$$E_c = \frac{3}{2}\frac{\hbar c\gamma^3}{\rho} = 2.96\times10^{-7}\,\mathrm{eV\,m}\,\frac{\gamma^3}{\rho}$$

$$U_0 = \frac{e^2}{3\varepsilon_0}\frac{\gamma^4}{\rho} \approx 6.0317\cdot10^{-9}\,\mathrm{eV\ m}\ \frac{\gamma^4}{\rho}$$

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



		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 $U_0 \sim \gamma^4$: $(m_p/m_e)^4 = 1.13 \times 10^{13}$

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 $\langle E_\gamma \rangle = 8/(15\sqrt{3})\ E_c$ $8/(15\sqrt{3}) \approx 0.308$

Synchrotron light monitor

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

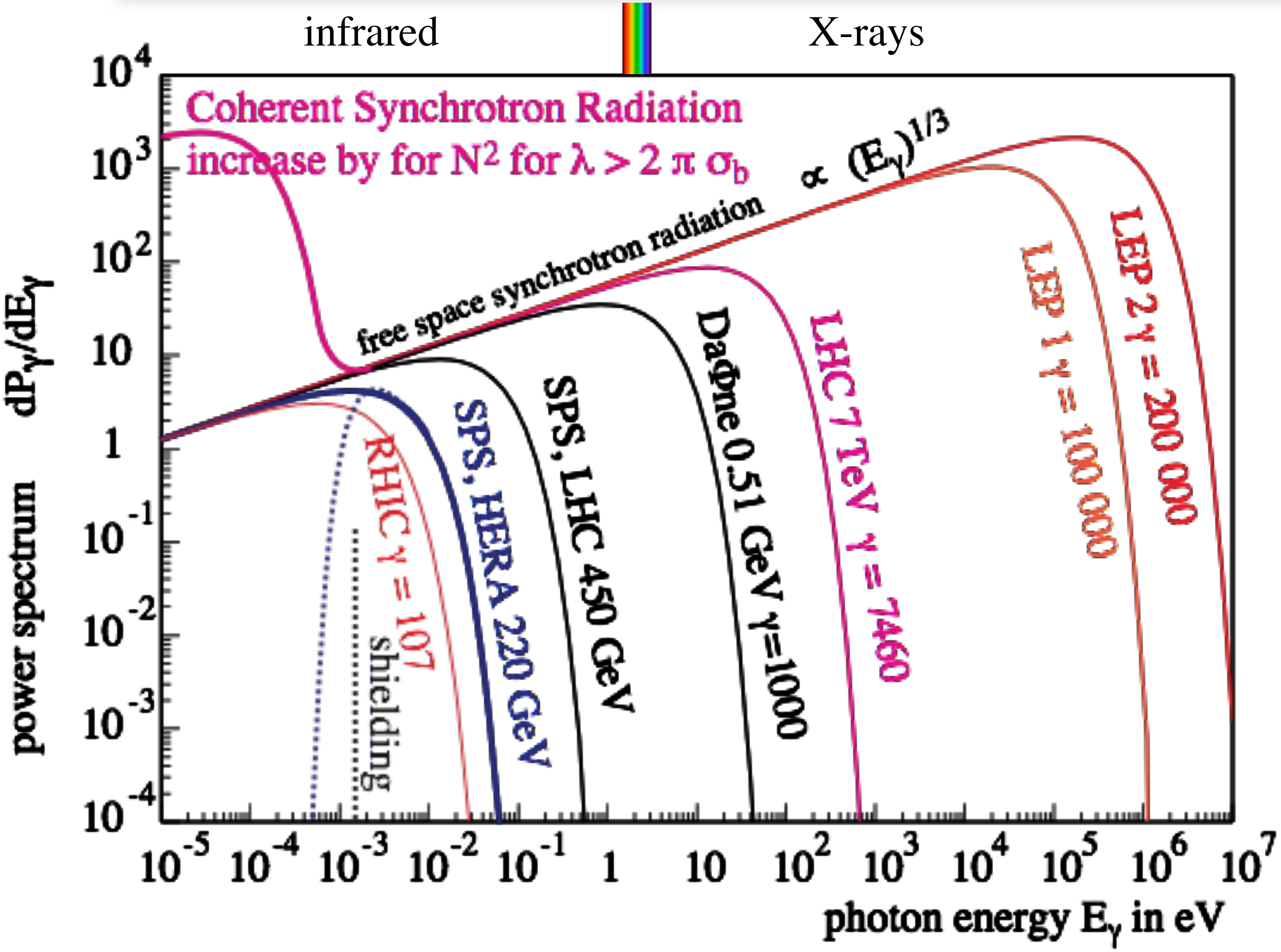
SR-Telescope BEUV A 831 QS18.L8 Particle Electron

	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 $\lambda = 0.124$ m

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

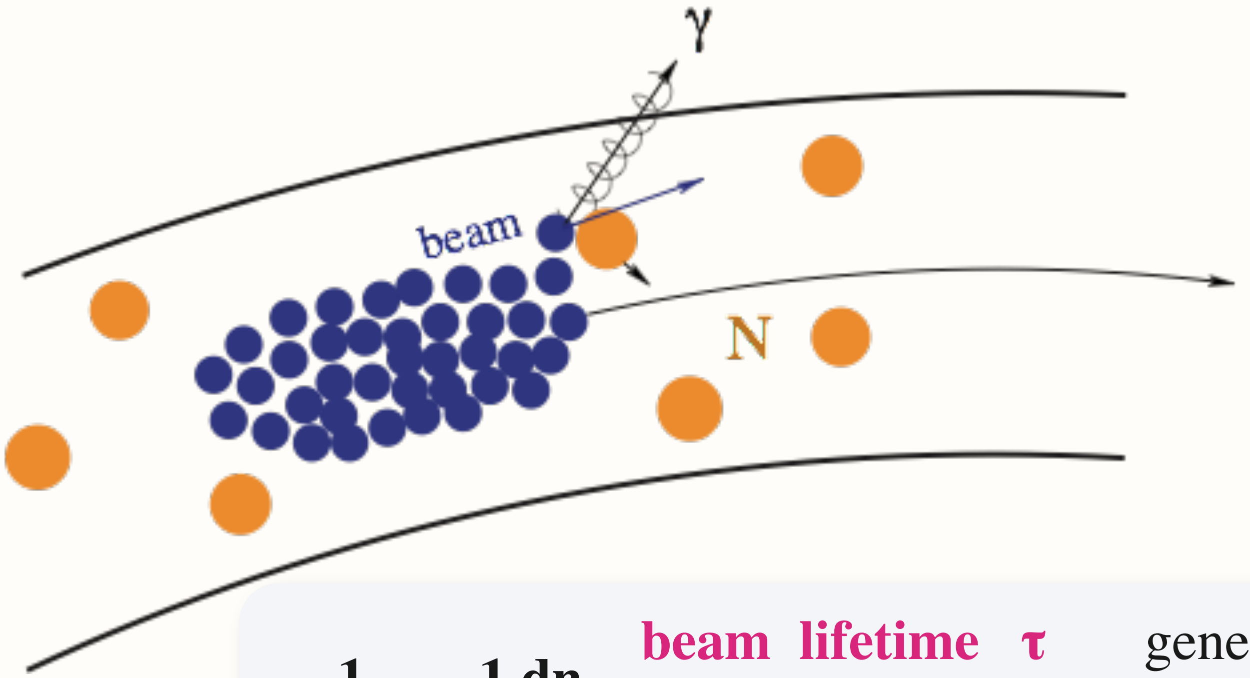
Effects which can modify the low energy, long wavelength spectrum :

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

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

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

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

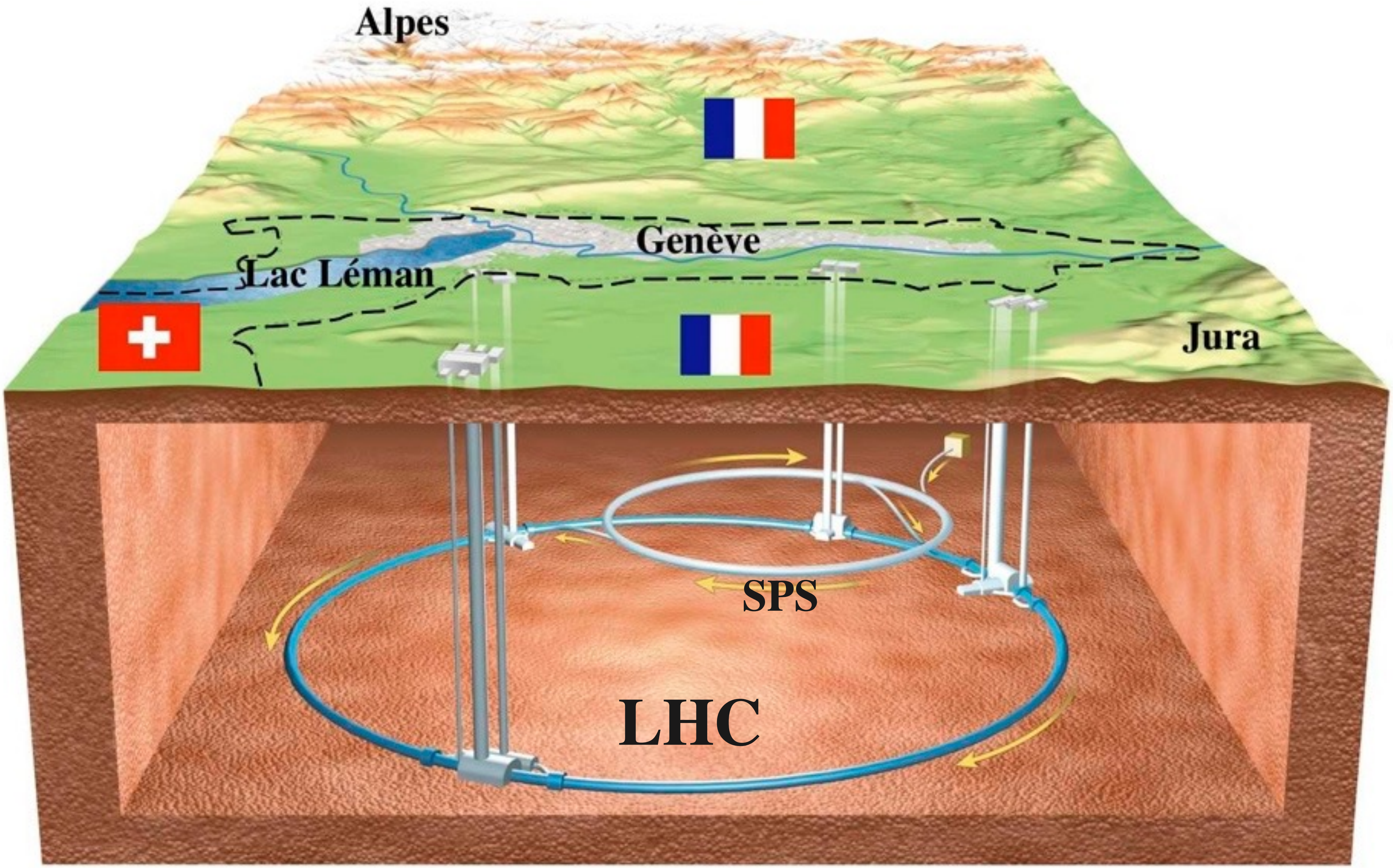
$$\rho_m = \frac{p}{kT} = 3.26 \times 10^{13}\mathrm{molecules\,/\,m^3}$$

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

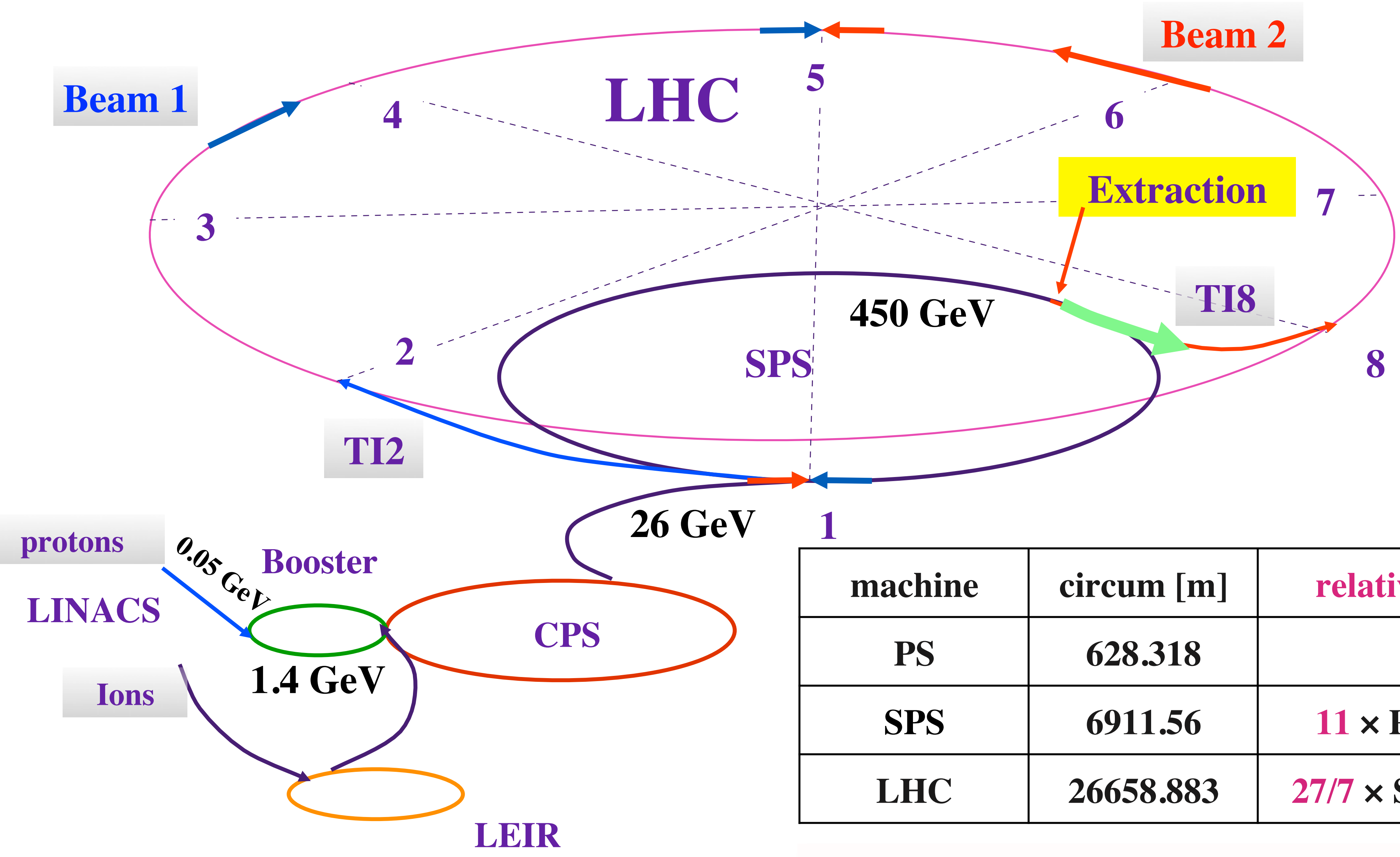
$$\text{collision probability } P_{\mathrm{coll}} = \sigma\,\rho_m = 1.96 \times 10^{-14}/\,\mathrm{m}$$

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

Examples from CERN with the LHC



The CERN accelerator complex : injectors and transfer

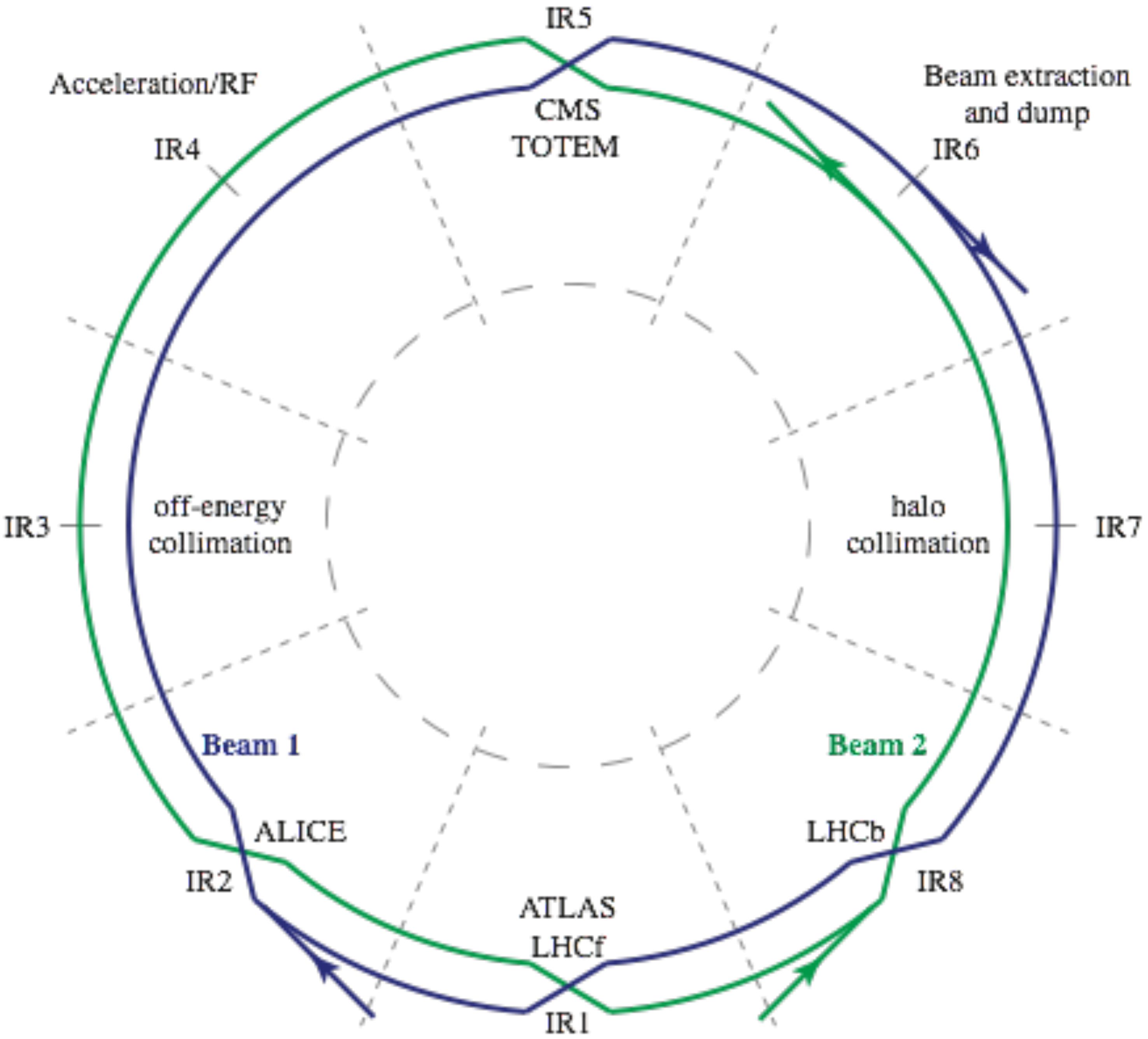


machine	circum [m]	relative
PS	628.318	
SPS	6911.56	11 × PS
LHC	26658.883	27/7 × SPS

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 2x3.5 TeV, β*= 3.5 m, **L_{peak} = 0.2×10^{33} cm^{-2}s^{-1} ∫ L dt = 0.044 fb^{-1}** 368 bunches

2011 2×3.5 TeV, β*= 1.0 m, **L_{peak} = 3.5×10^{33} cm^{-2}s^{-1} ∫ L dt = 6.1 fb^{-1}** 1380 bunches

2012 2×4.0 TeV, β*= 0.6 m, **L_{peak} = 7.7×10^{33} cm^{-2}s^{-1} ∫ L dt = 23.3 fb^{-1}** 1380 bunches

2013 Pb-p run, shutdown, magnet interconnects, restart in 2015 at **2×6.5 TeV,** increase #bunches

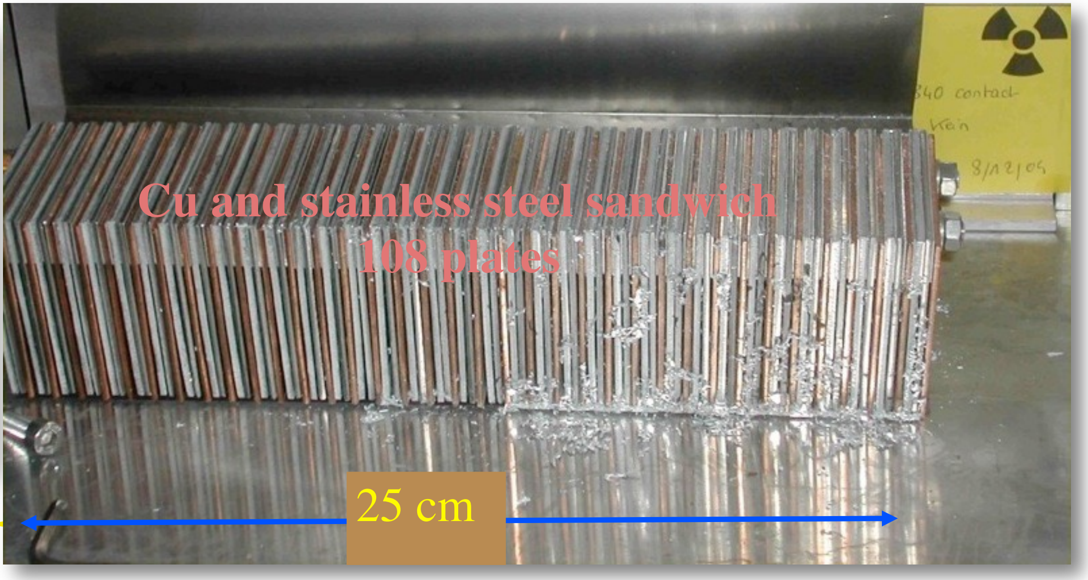
	LHC design	**achieved**
Momentum at collision, TeV/c	**7**	**4**
Luminosity, cm^{-2}s^{-1}	**1.0E+34**	**7.7E+33**
Dipole field at top energy, T	**8.33**	**4.8**
Number of bunches, each beam	**2808**	**1380**
Particles / bunch	**1.15E+11**	**1.7E+11**
Typical beam size in ring, µm	**200 – 300**	**~300**
Beam size at IP, µm	**17**	**20**

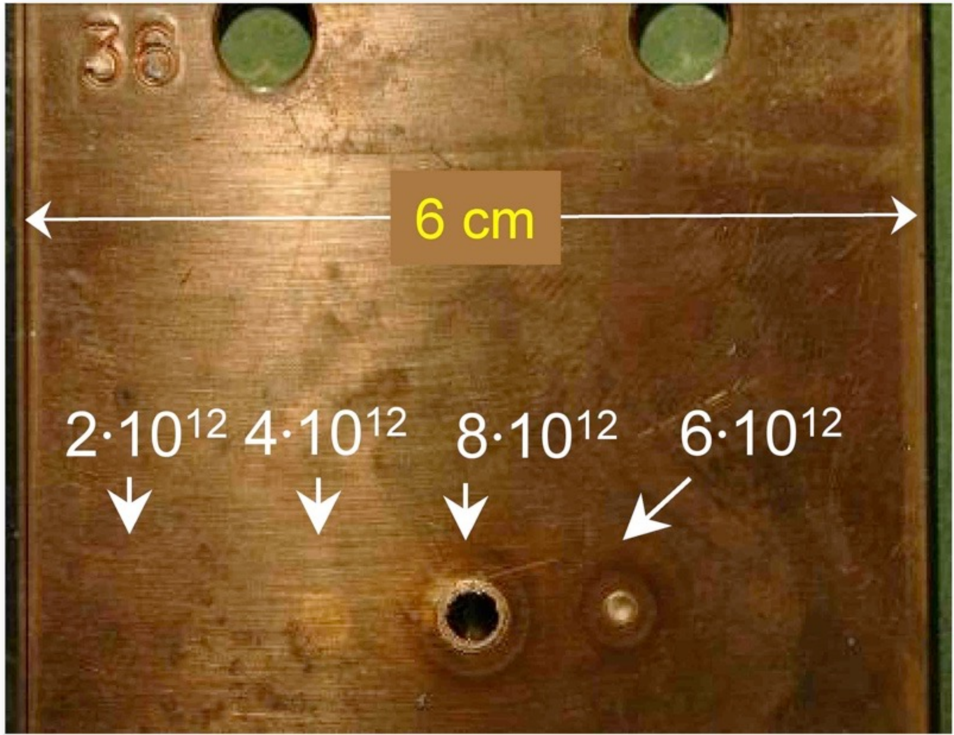
Damage potential : confirmed in controlled SPS experiment

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 :

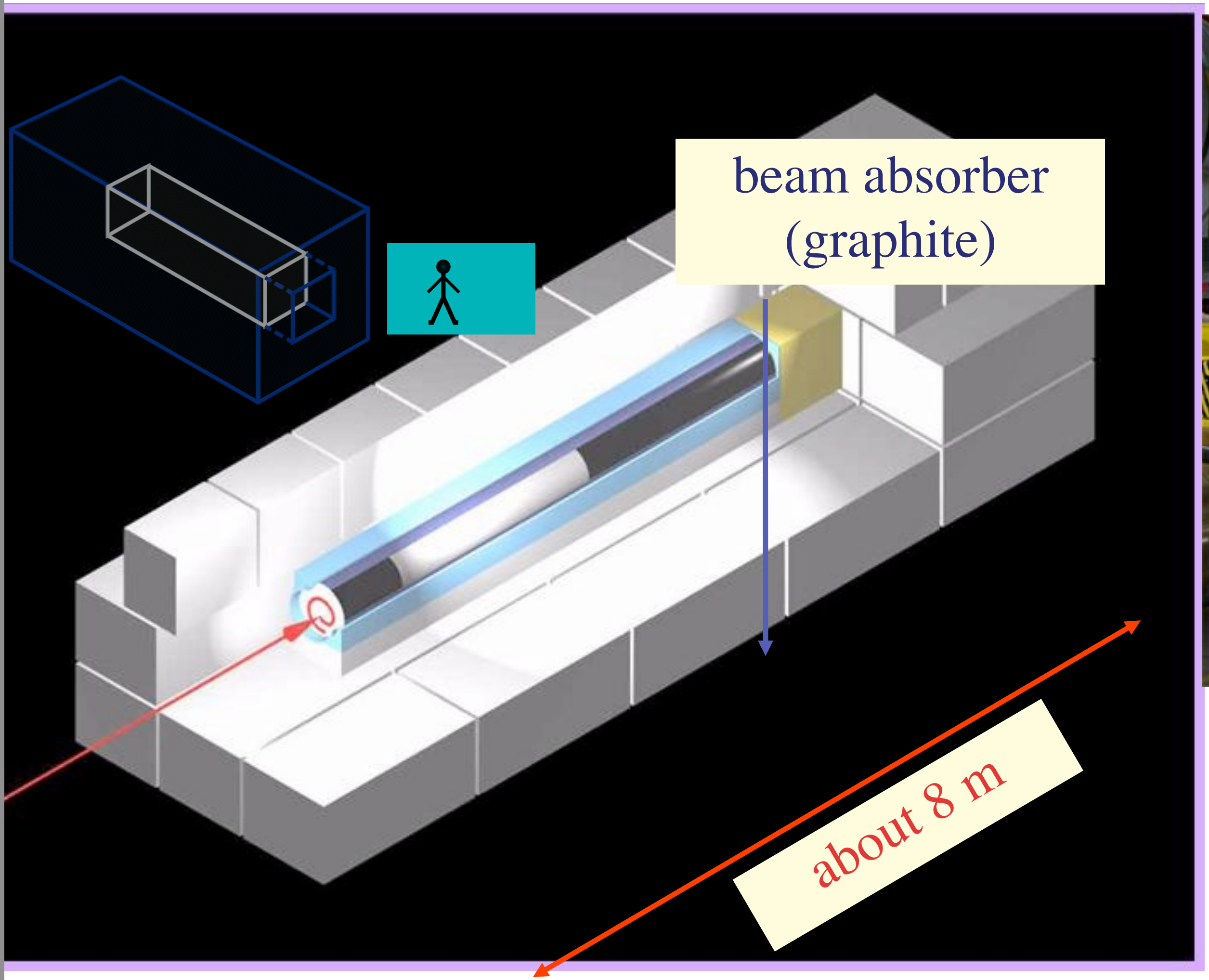
8×10^{12} clear damage

2×10^{12} below damage limit

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

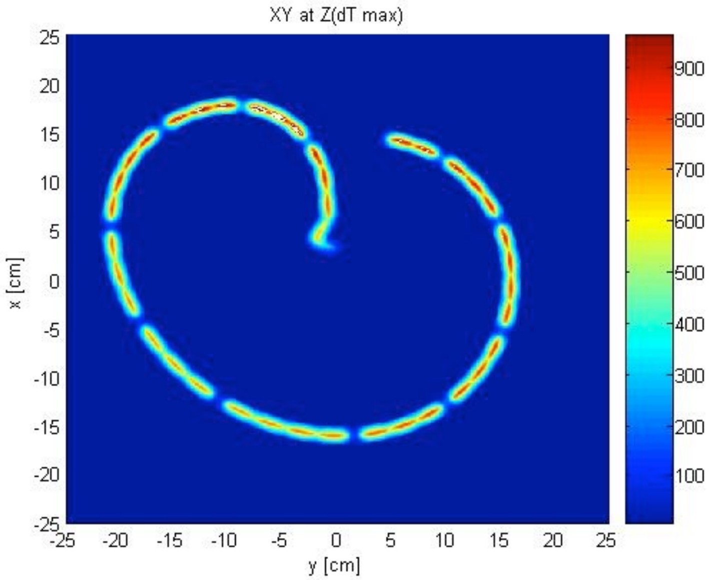
For comparison, the LHC nominal at 7 TeV :
$2808 \times 1.15 \times 10^{11} = 3.2 \times 10^{14}$ p/beam
at $< \sigma_{x/y} > \approx 0.2$ mm
over 3 orders of magnitude above damage level for perpendicular impact

Dumping the LHC beam



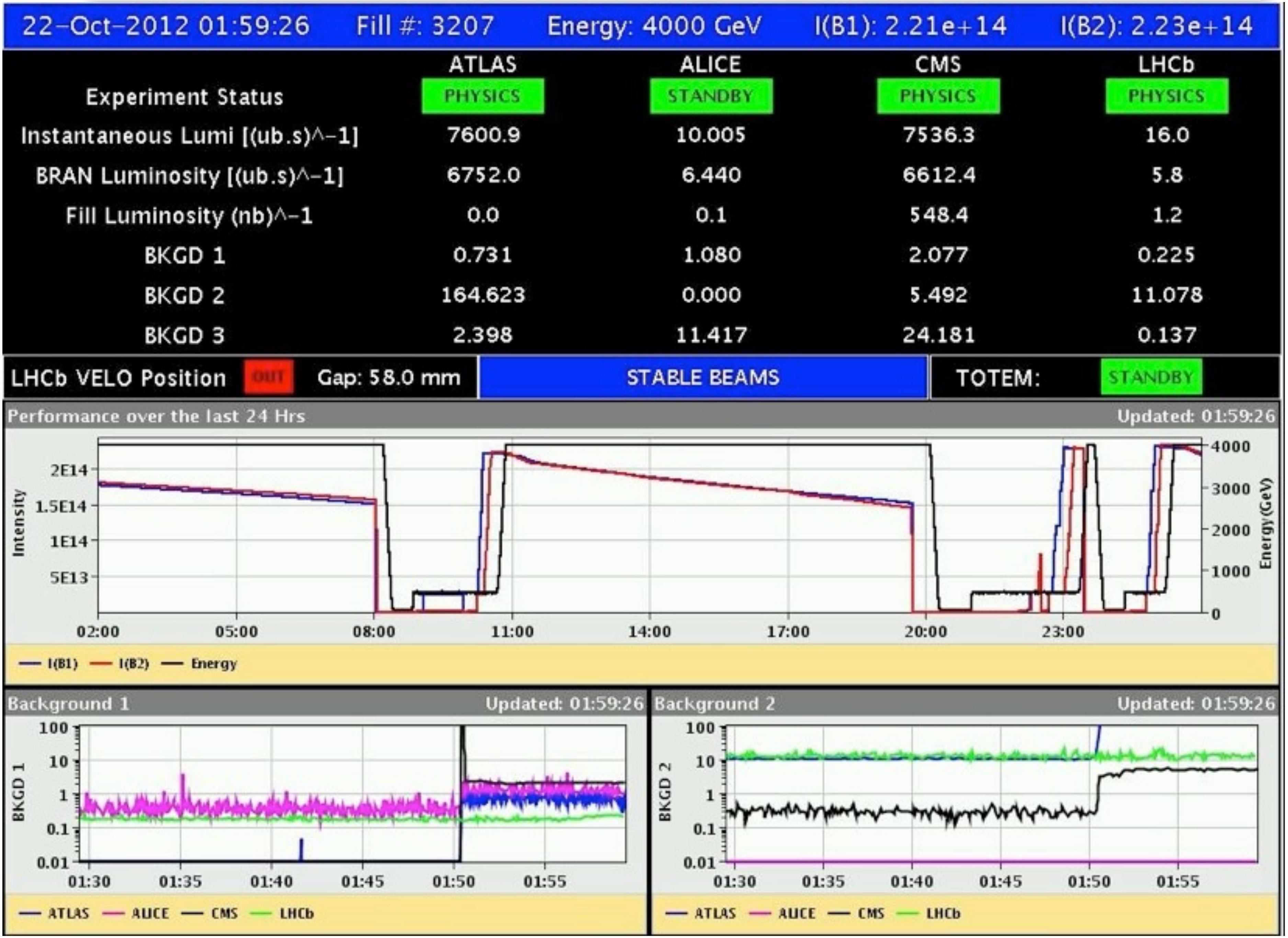
beam absorber (graphite)

about 8 m



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

LHC 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

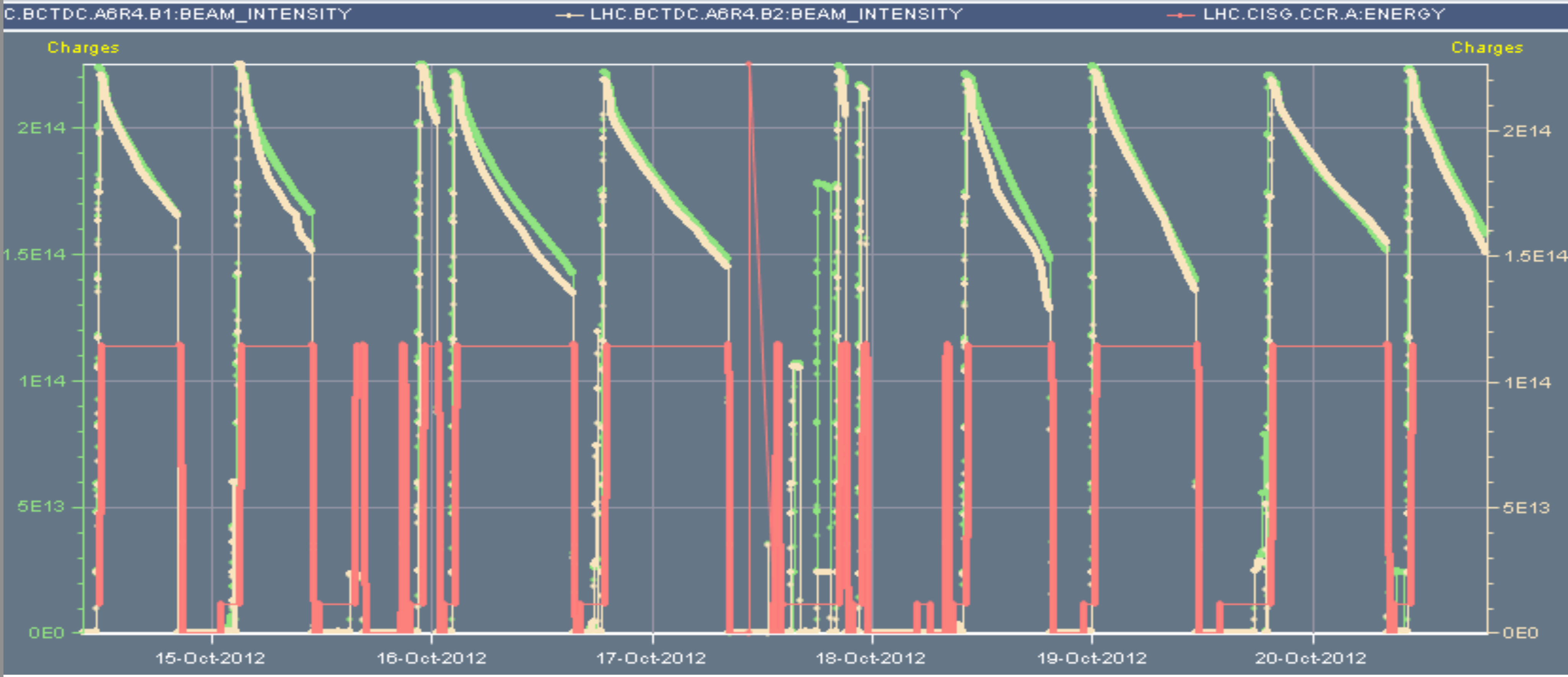
Performance over the last 24 Hrs Updated: 01:59:26

Background 1 Updated: 01:59:26

Background 2 Updated: 01:59:26

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

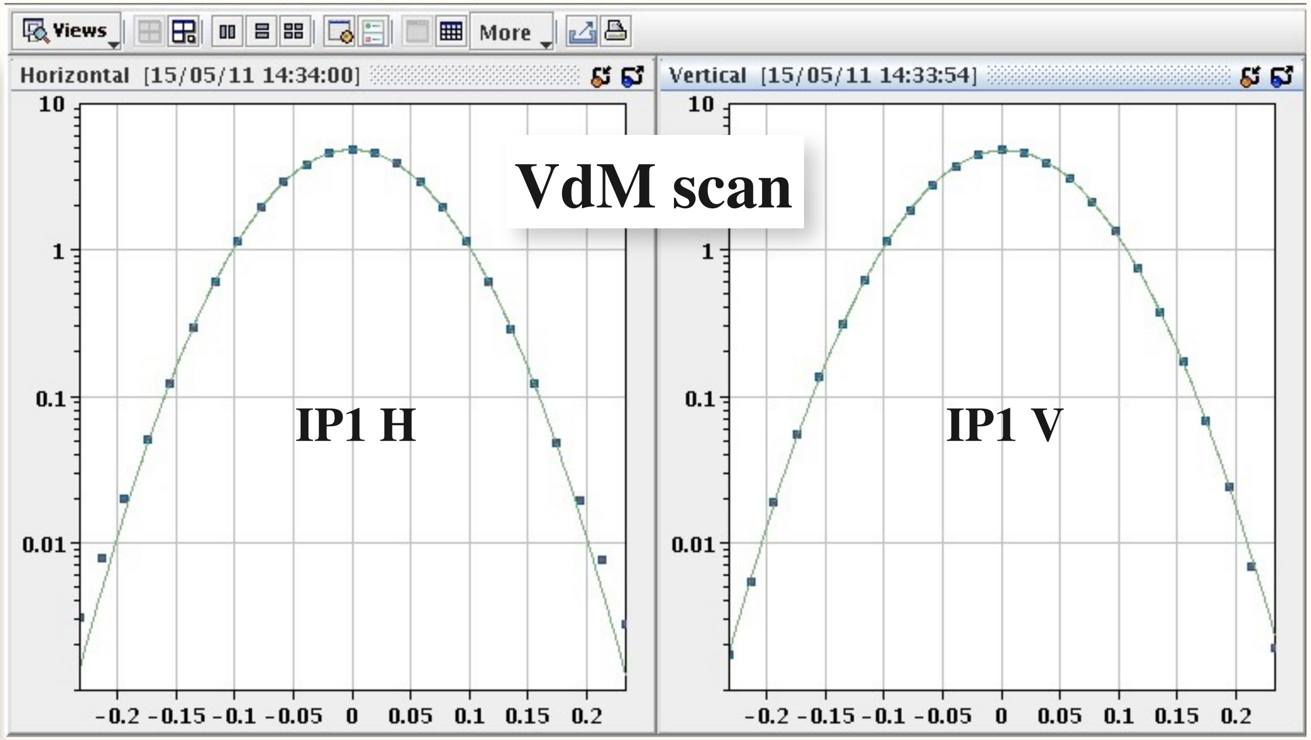
LHC typical week, Oct. ‘12, 1.2 pb-1



Precision front - high quality of LHC beams

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

β* = 1000 m, Oct.’12



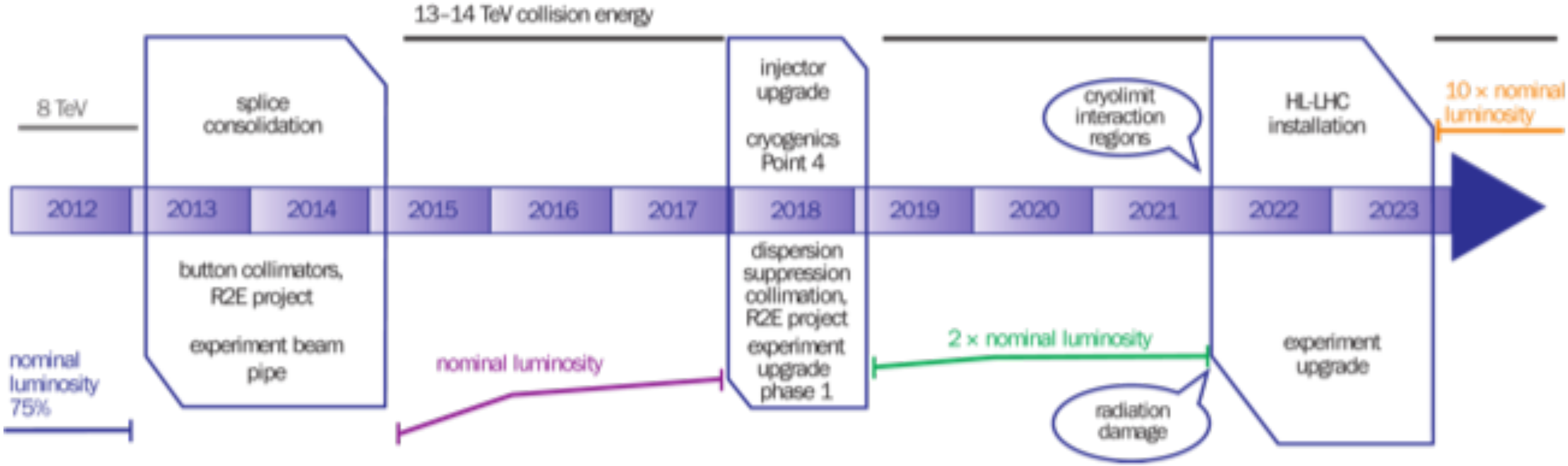
VdM scan

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

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

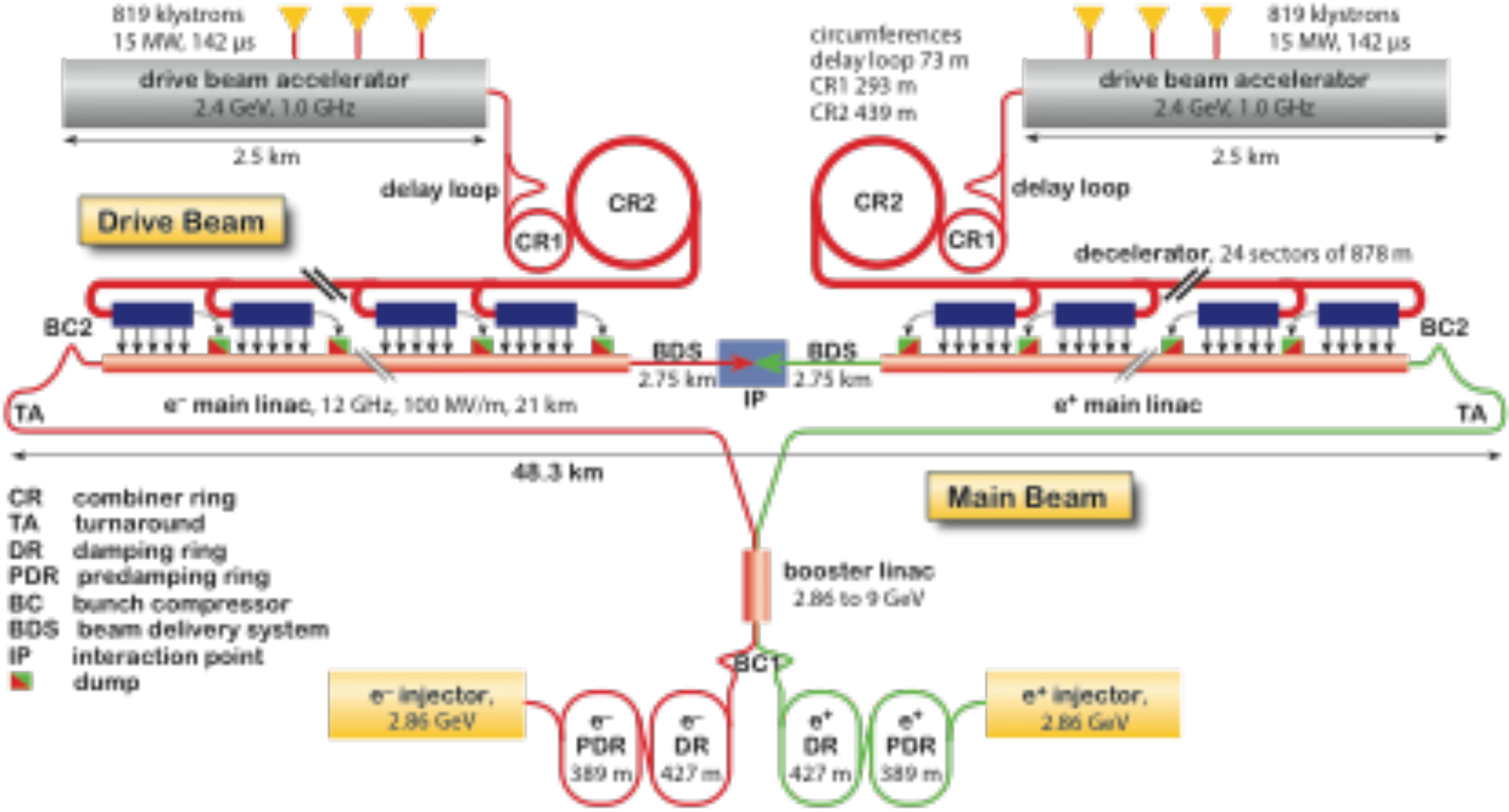
HL-LHC Timeline

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



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

CLIC



Overview of the CLIC layout at $\sqrt{s} = 3$ TeV

The machine requires only one drive beam complex for stages 1 and 2.

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)

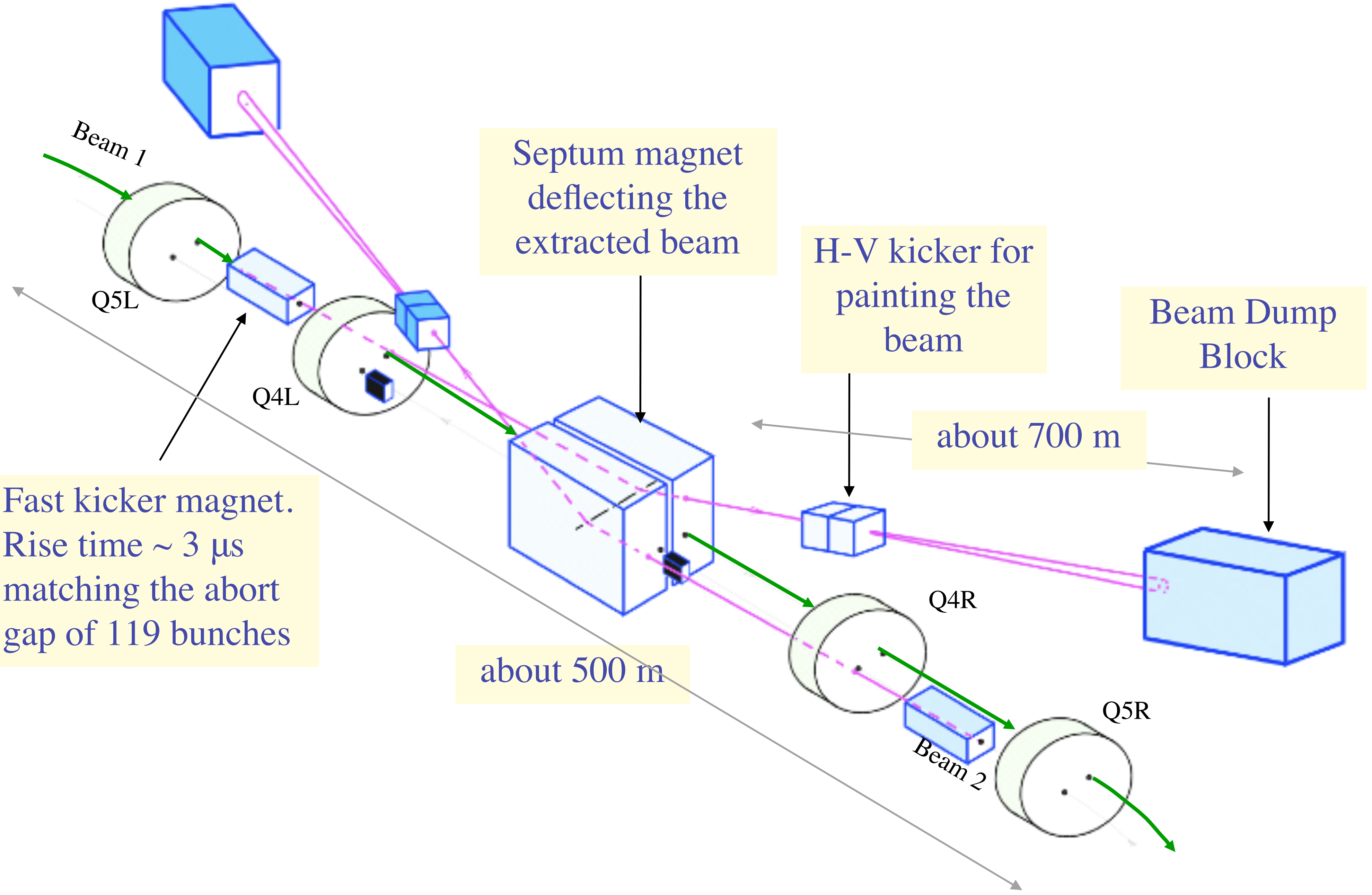
Yearly international accelerator conferences IPAC, last one in May'13 in Shanghai

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

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

relativistic Lamor formula

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

$\mathrm{v}\perp\dot{\mathrm{v}}$

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

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

$\mathrm{v}\parallel\dot{\mathrm{v}}$

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

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

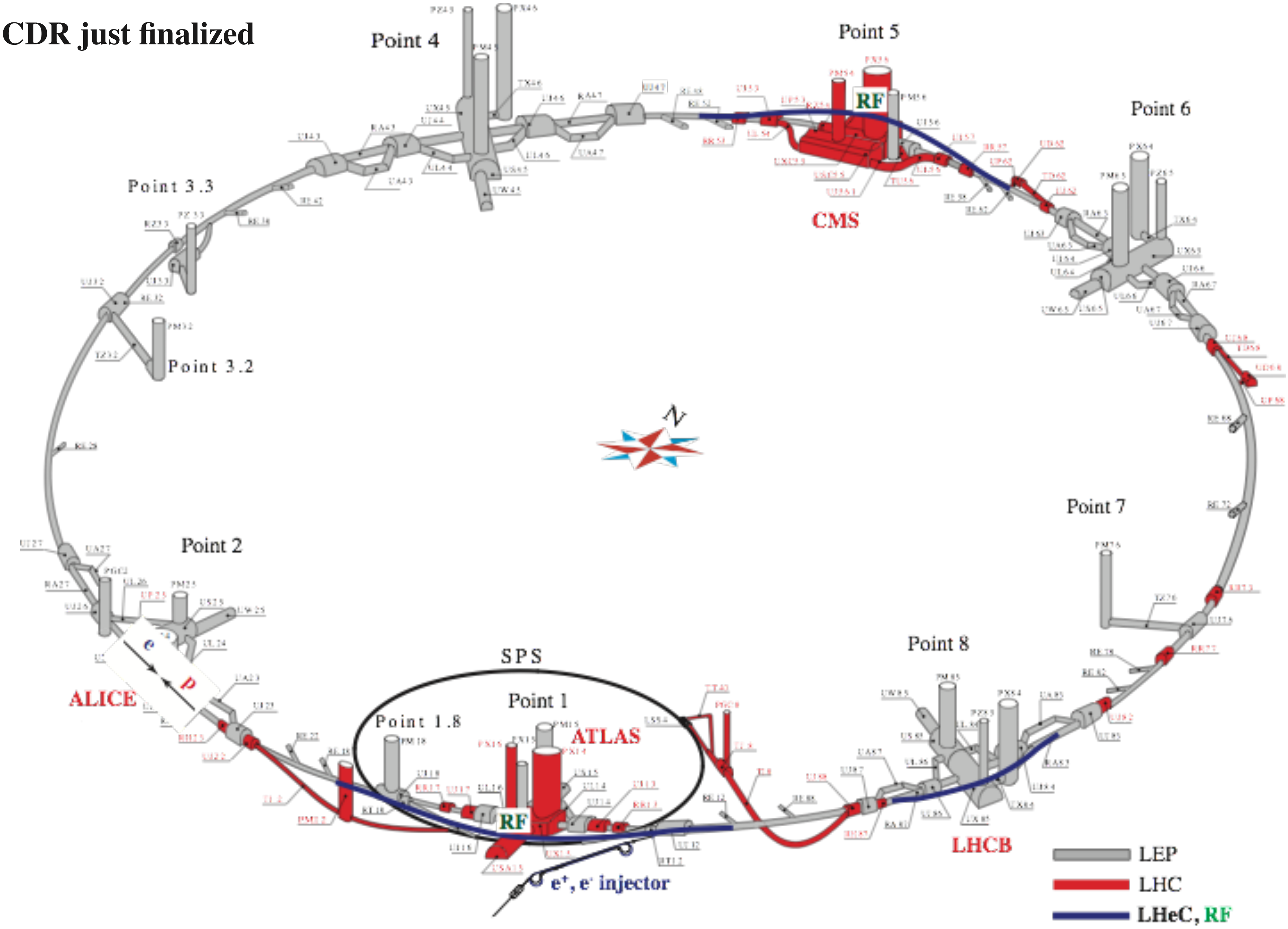
Parallel acceleration, E-field, Linac case cancellation, $1/\gamma^2$

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

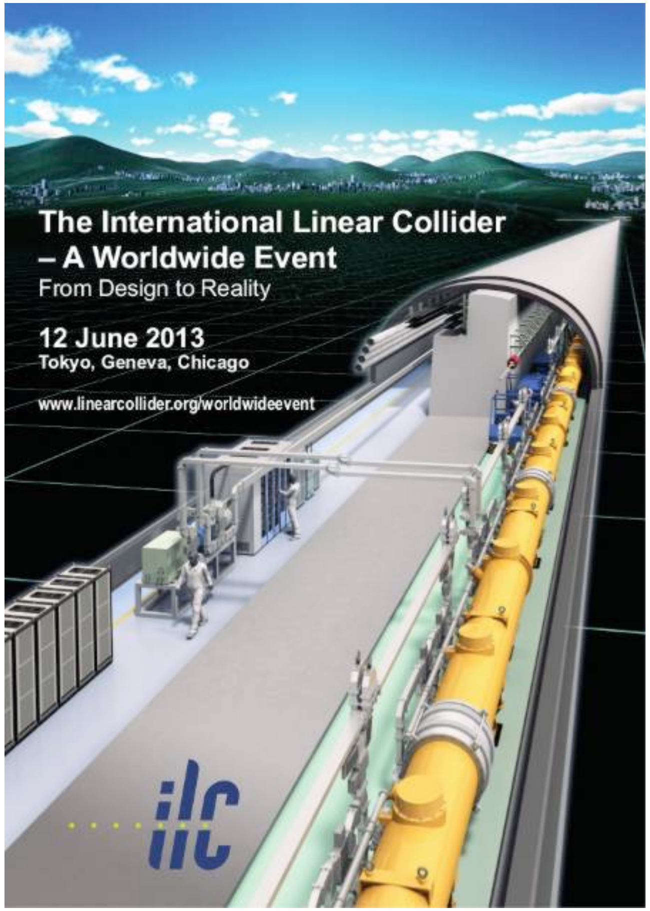
CDR just finalized



ILC

ILC TDR Handover, 12 June 2013

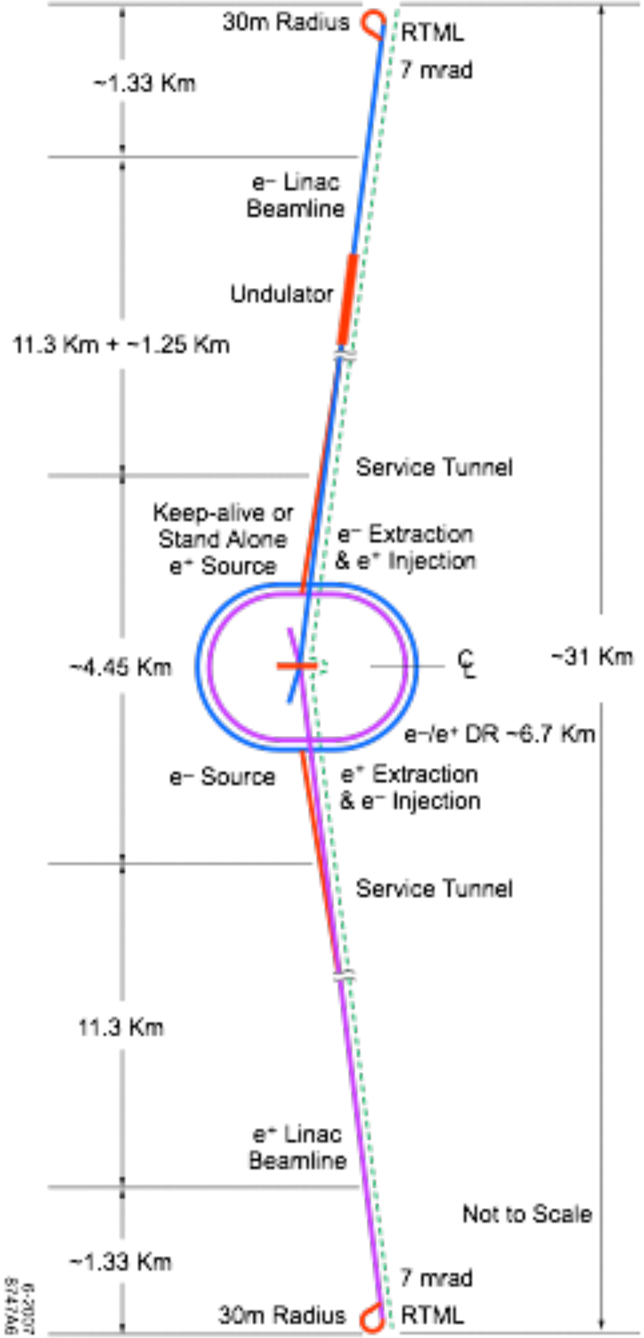
- 200-500 GeV centre-of-mass, 31 km long
- Luminosity: 2×10^{34} cm^{-2}s^{-1}
- Based on accelerating gradient of 31.5 MV/m 1.3 GHz superconducting RF



The International Linear Collider
– A Worldwide Event
From Design to Reality

12 June 2013
Tokyo, Geneva, Chicago

www.linearcollider.org/worldwideevent



CLIC Compact Linear Collider

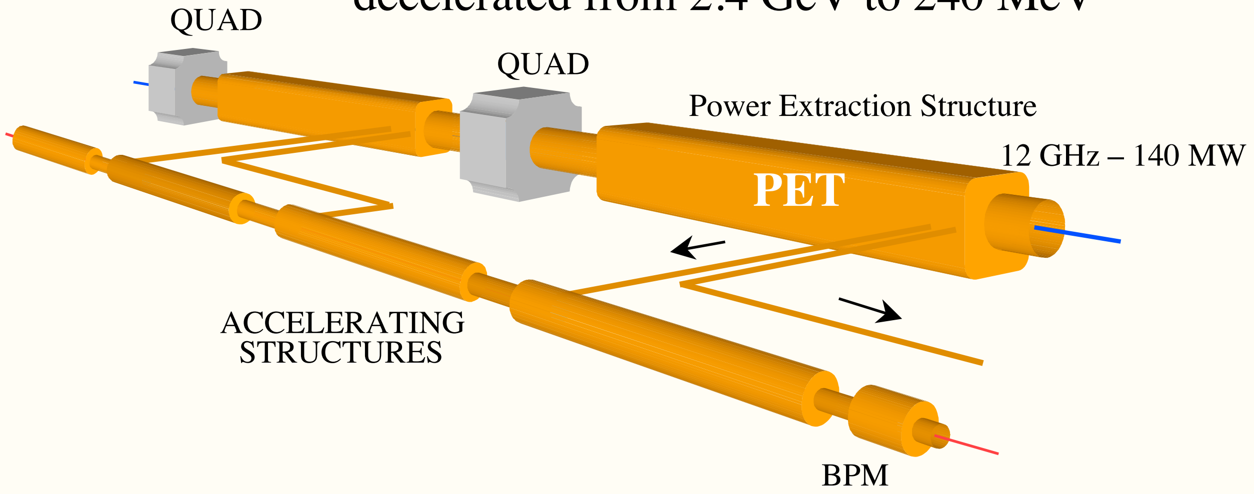
Two Beam Scheme

Drive Beam supplies RF power

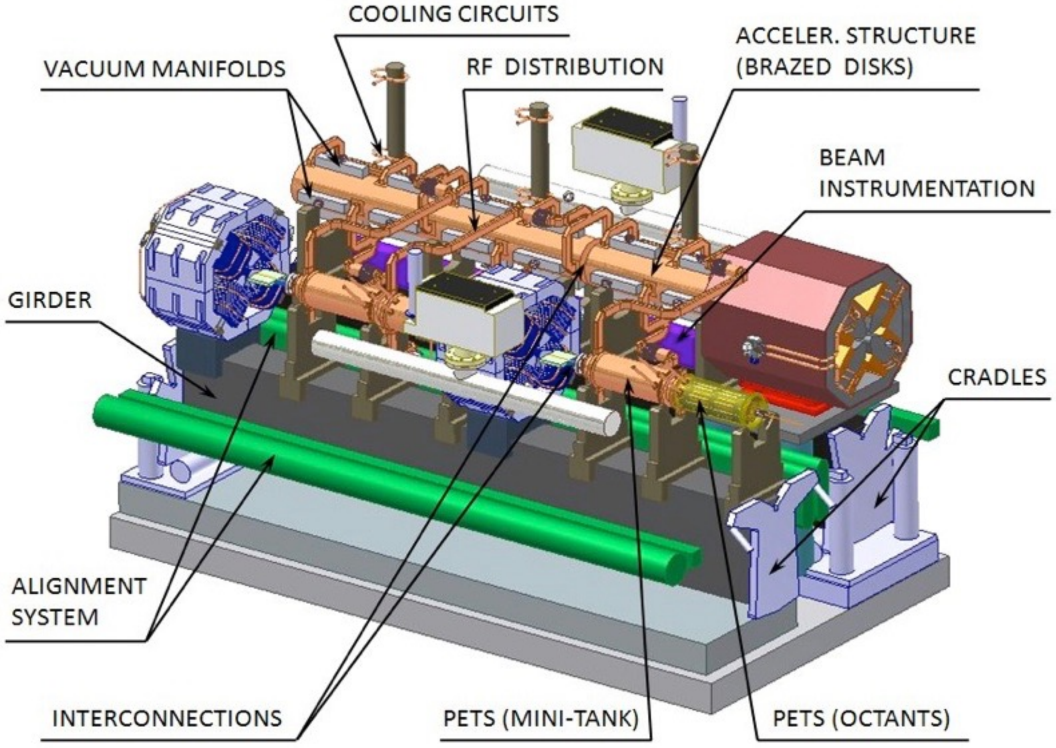
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

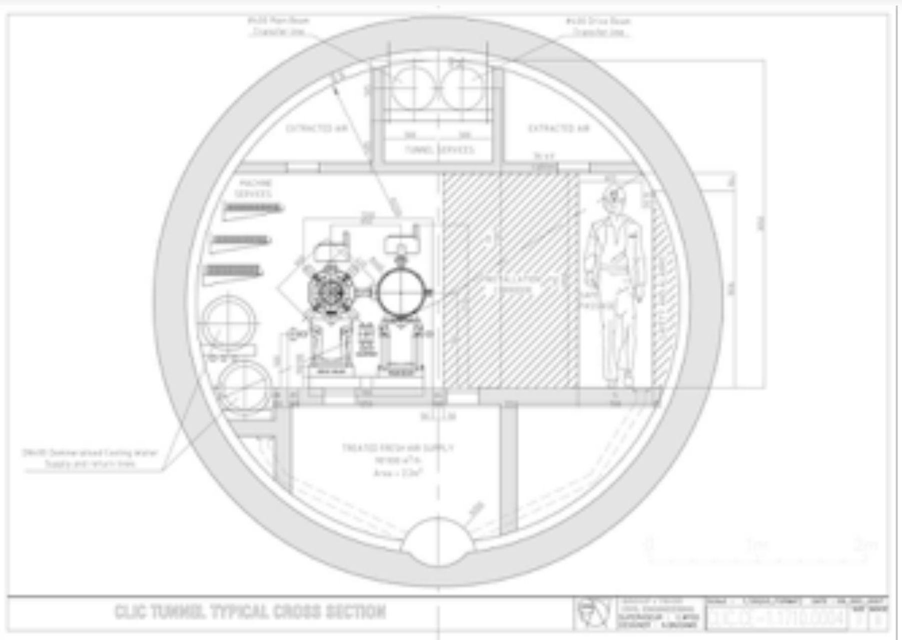
warm (not superconducting) RF

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

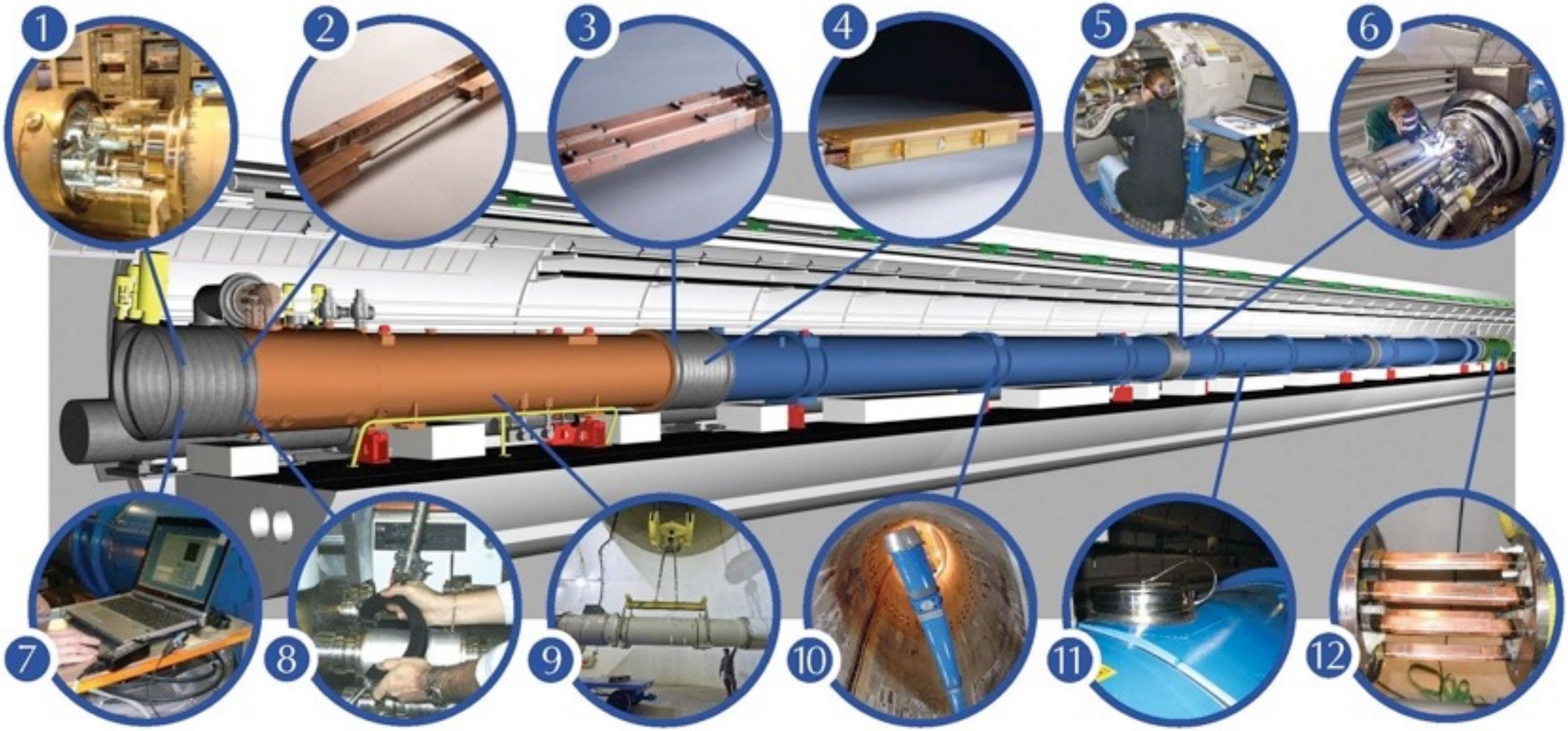




ILC and CLIC parameters

	ILC: Superconducting RF **500 GeV**	CLIC: normal conducting copper RF **3 TeV**
accelerating gradient:	**31.5 MV/m** 35 MV/m target	**100 MV/m**
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**

The main 2013-14 LHC consolidations



1695 Openings and final reclosures of the interconnections

Complete reconstruction of 1500 of these splices

Consolidation of the 10170 13kA splices, installing 27 000 shunts

Installation of 5000 consolidated electrical insulation systems

300 000 electrical resistance measurements

10170 orbital welding of stainless steel lines

18 000 electrical Quality Assurance tests

10170 leak tightness tests

4 quadrupole magnets to be replaced

15 dipole magnets to be replaced

Installation of 612 pressure relief devices to bring the total to 1344

Consolidation of the 13 kA circuits in the 16 main electrical feedboxes