Toni Baroncelli Experimental High Energy Physics at Colliders 2021

Z ➙ ee Candidate
[September 2010]

Display of a proton-proton collision event recorded by ATLAS on 3 June 2015, with the first LHC stable beams at a collision energy of 13 TeV. Tracks reconstructed by the tracking detector are shown as light blue lines, and hits in the layers of the silicon tracking detector are shown as colored filled circles. The four inner layers are part of the silicon pixel detector and the four outer layers are part of the silicon strip detector. The layer closest to the beam, called IBL, is new for Run 2. In the view in the bottom right it is seen that this event has multiple pp collisions. The total number of reconstructed collision vertices is 17 but they are not all resolvable on the scale of this picture.

Toni Baroncelli
INFN RomaTRE

Originally inspired by Hans-Christian Schultz-Coulon   *but also Material from many different sources*
Kirchhoff-Institut für Physik

Introduction & Motivation

The LHC and its Experiments
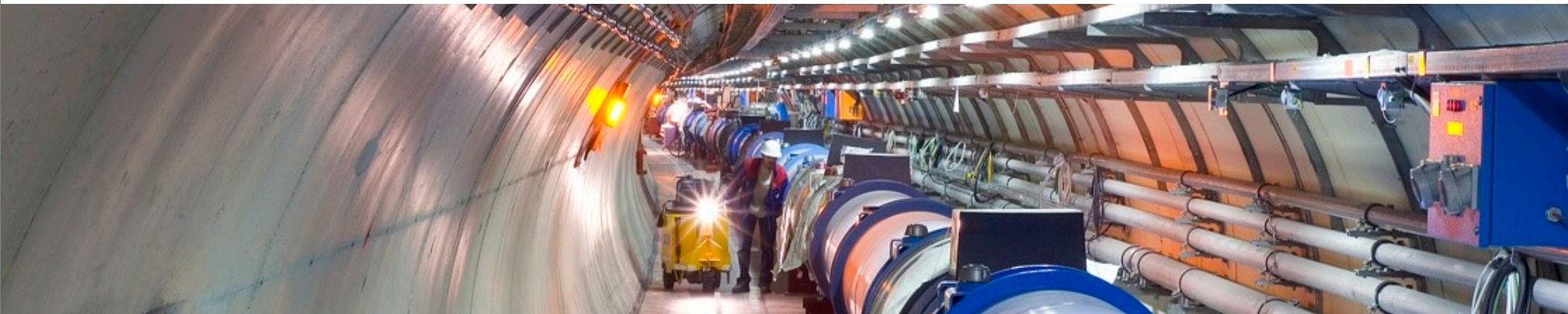
LHC: motivations

• Higgs mechanism via **EW symmetry breaking**? **Check couplings!**

• **Supersymmetry**, extension of the SM, realised in nature, implying that all known particles have supersymmetric partners?

• **Extra dimensions**, as predicted by various models based on string theory, and can we detect them?

• **dark matter** that appears to account for 27% of the mass-energy of the universe?
• What about **dark energy**?

Other open questions that may be explored using high-energy particle collisions:

• Why is the **gravity** force so many orders of magnitude weaker than the other three fundamental forces?
• Why are there apparent violations of the symmetry between **matter and antimatter**?

• What are the nature and properties of **quark-gluon plasma**, thought to have existed in the early universe ?
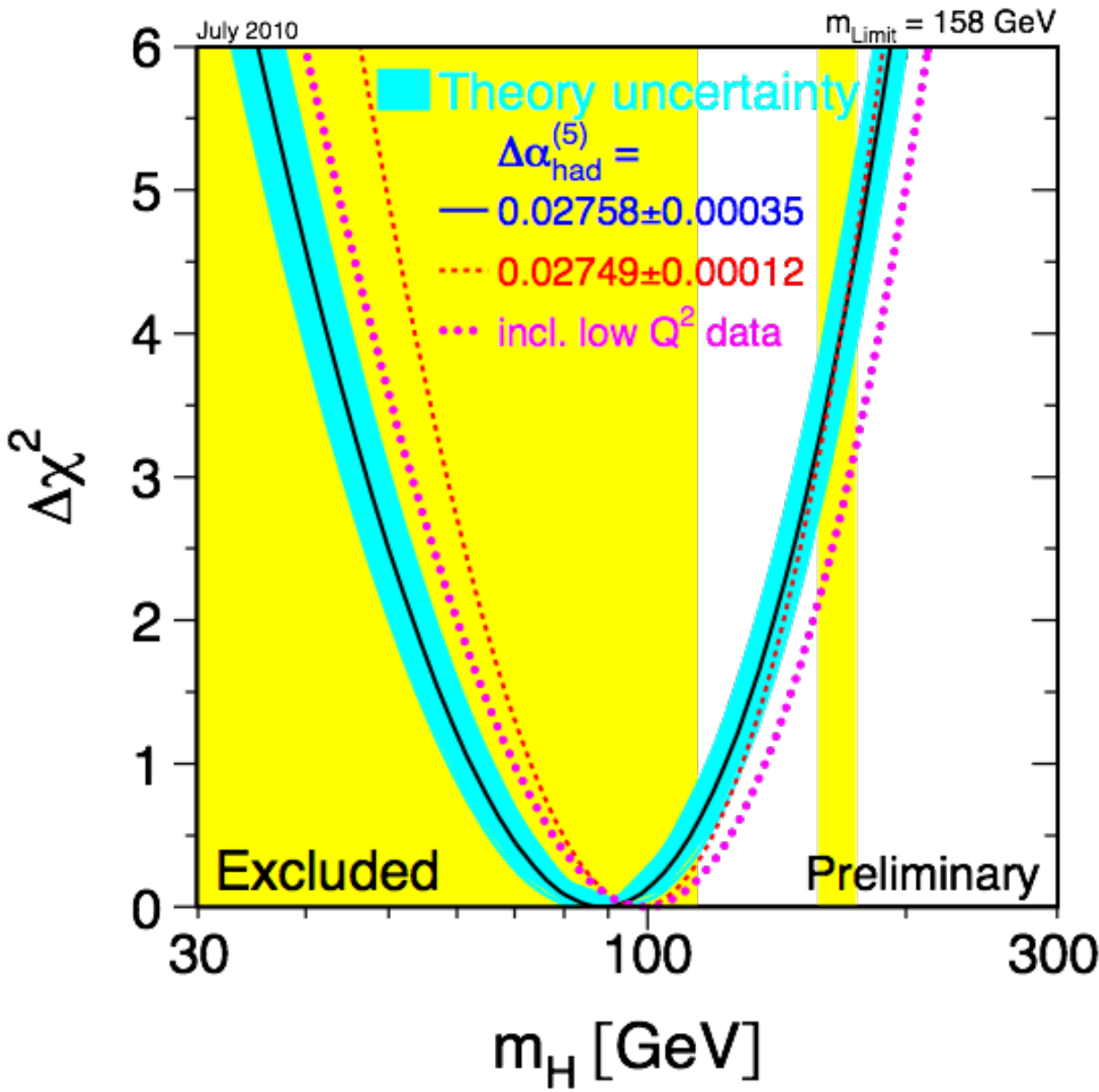
EW-Fits:

$M_H = 89$ 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

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EW-Fits:

$$M_H = 89\ ^{+35}_{-26}\,\text{GeV}$$
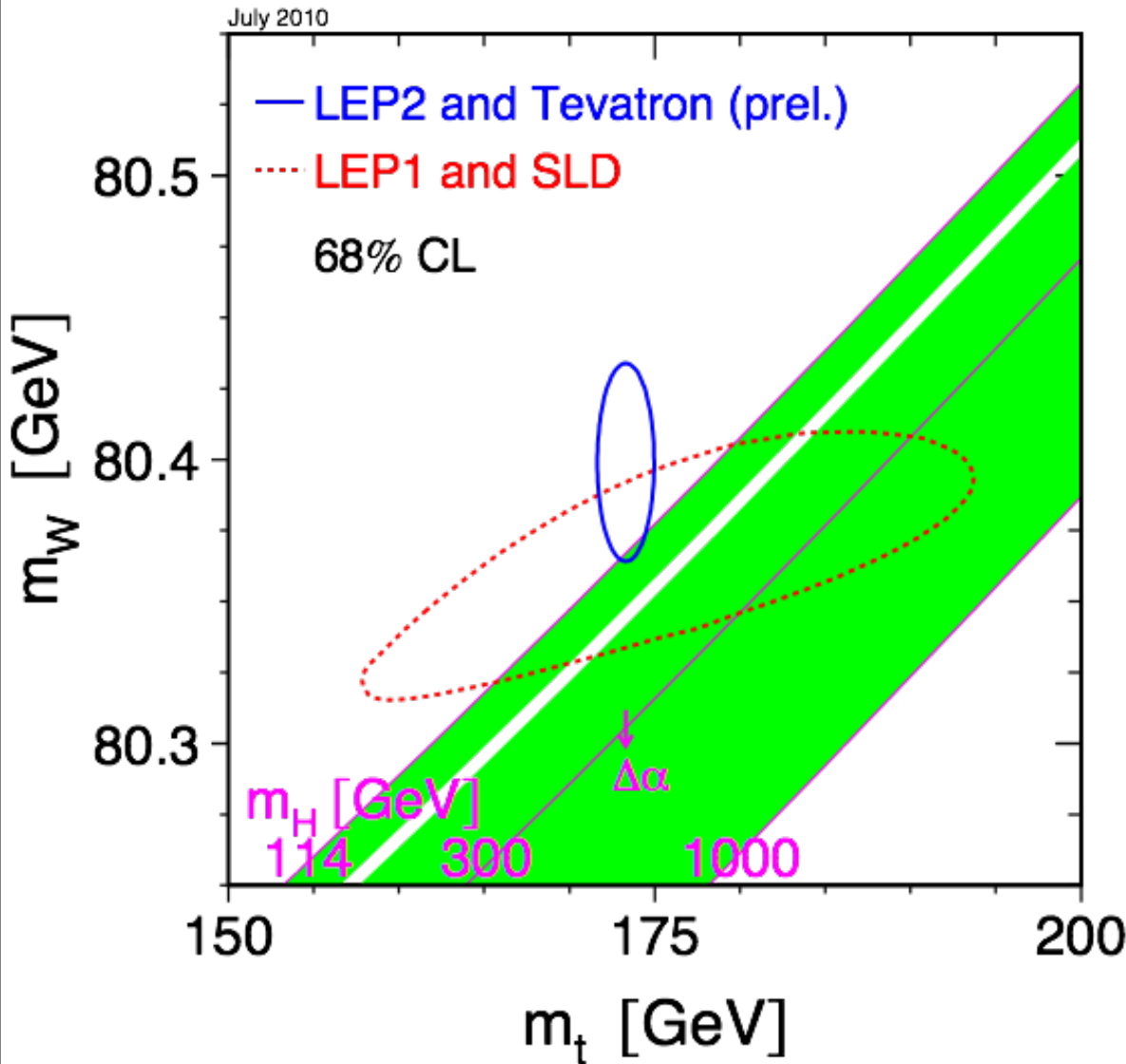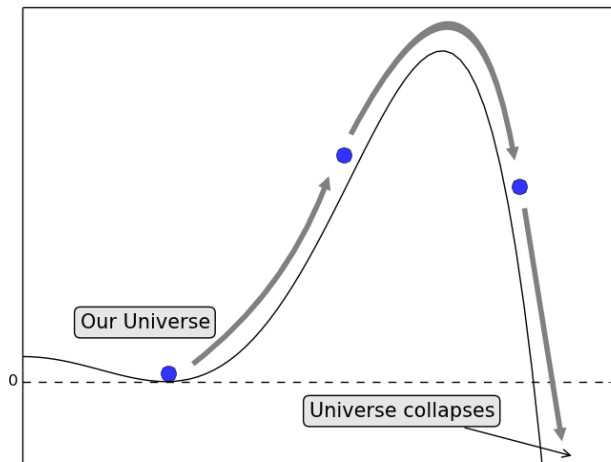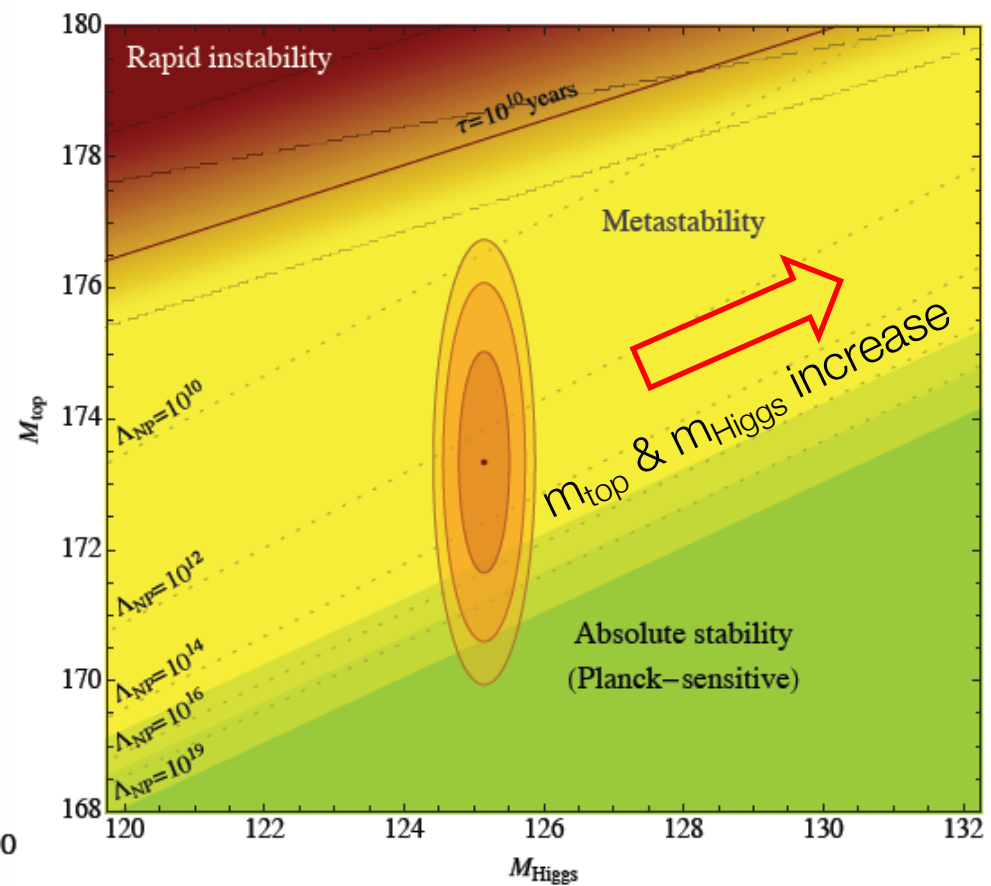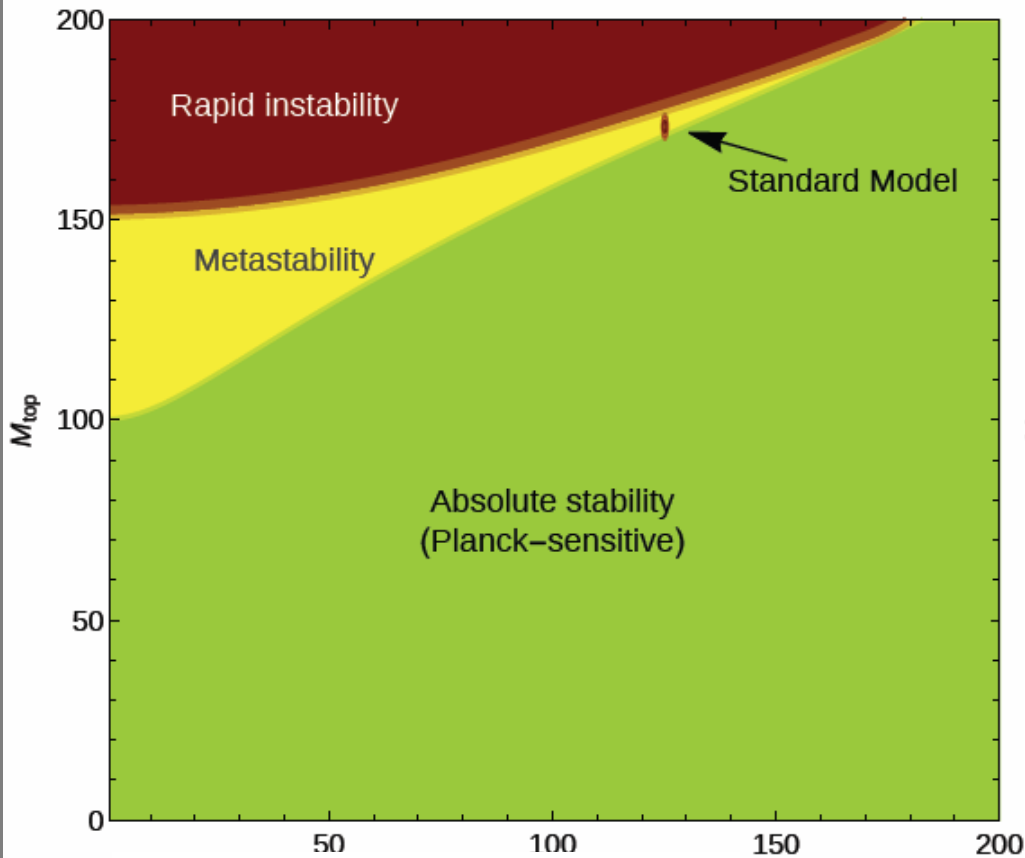
$$M_H < 158\ \text{GeV} \text{ @ 95\% CL}$$

From direct search at LEP:

$$M_H > 114\ \text{GeV} \text{ @ 95\% CL}$$

From direct search at Tevatron:

$$158 < M_H < 175\ \text{GeV} \text{ @ 95\% CL}$$

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

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

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m_{top} = 173.2 ± 0.9 GeV

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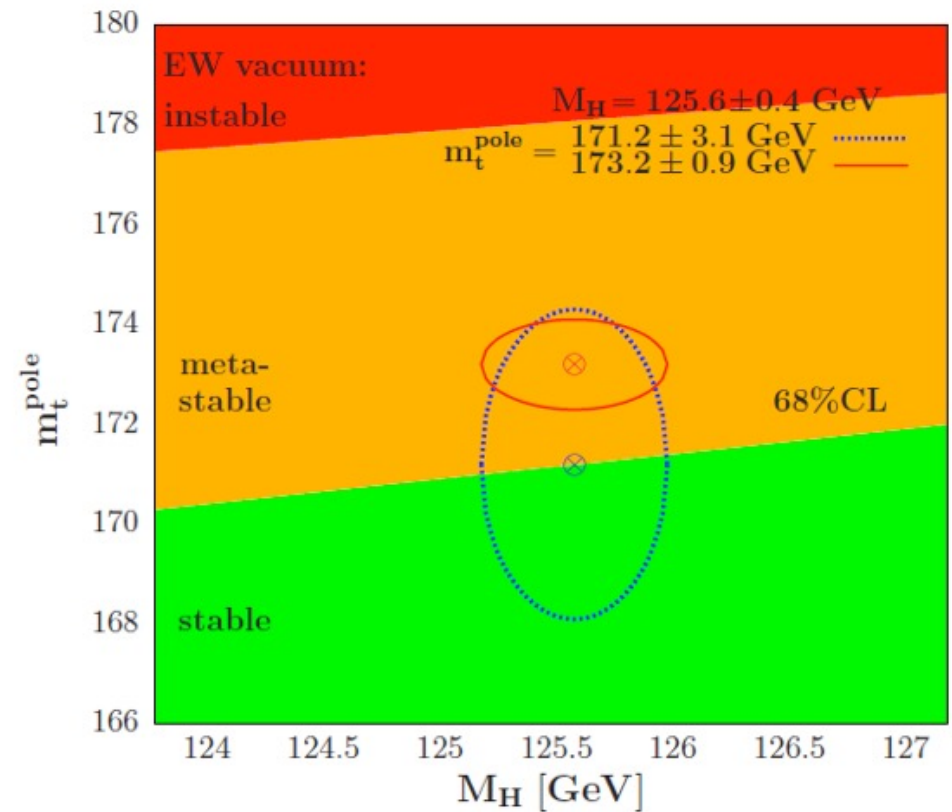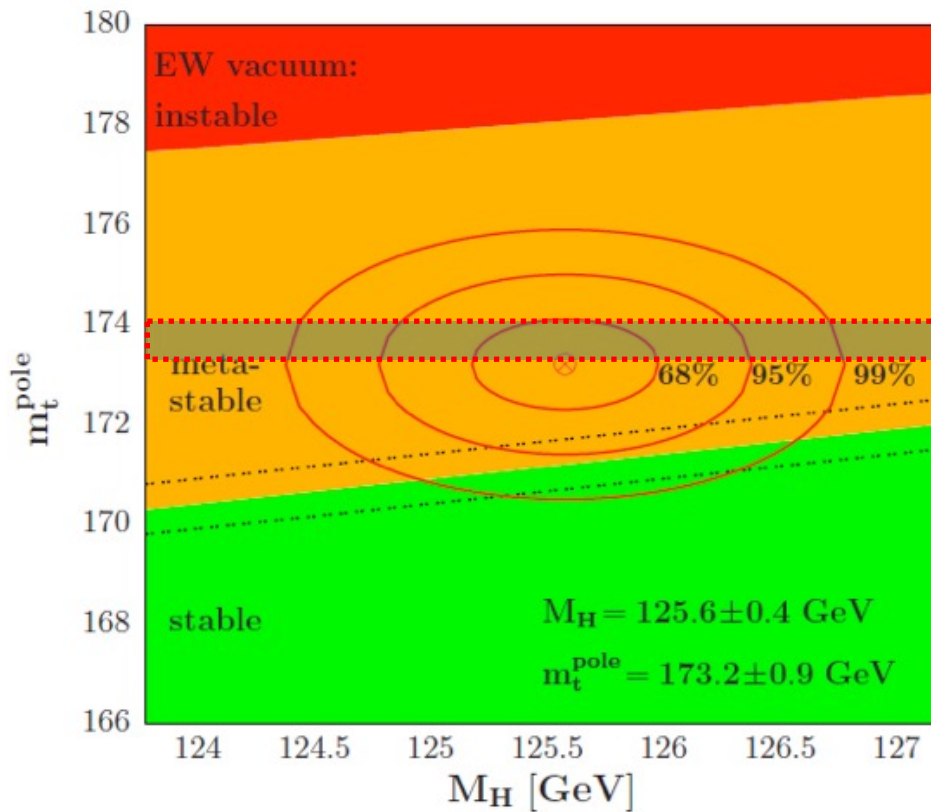
The ellipses in the [M_H,m_{tpole}] plane with the inputs M_H=125 +/-0.4 GeV and α_s=0.1187 are confronted with the areas in which the SM vacuum is absolutely stable, metastable and unstable up to the Planck scale. Left plot m_{tpole} is identified with the Tevatron measured top mass m_t=173.2+/-0.9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

Very complex topologies!
(very different from e⁺e⁻ collisions)

- Hard interaction: qq, gg, qg fusion

- Initial and final state radiation (ISR,FSR)

- Secondary interaction
  ["underlying event"]
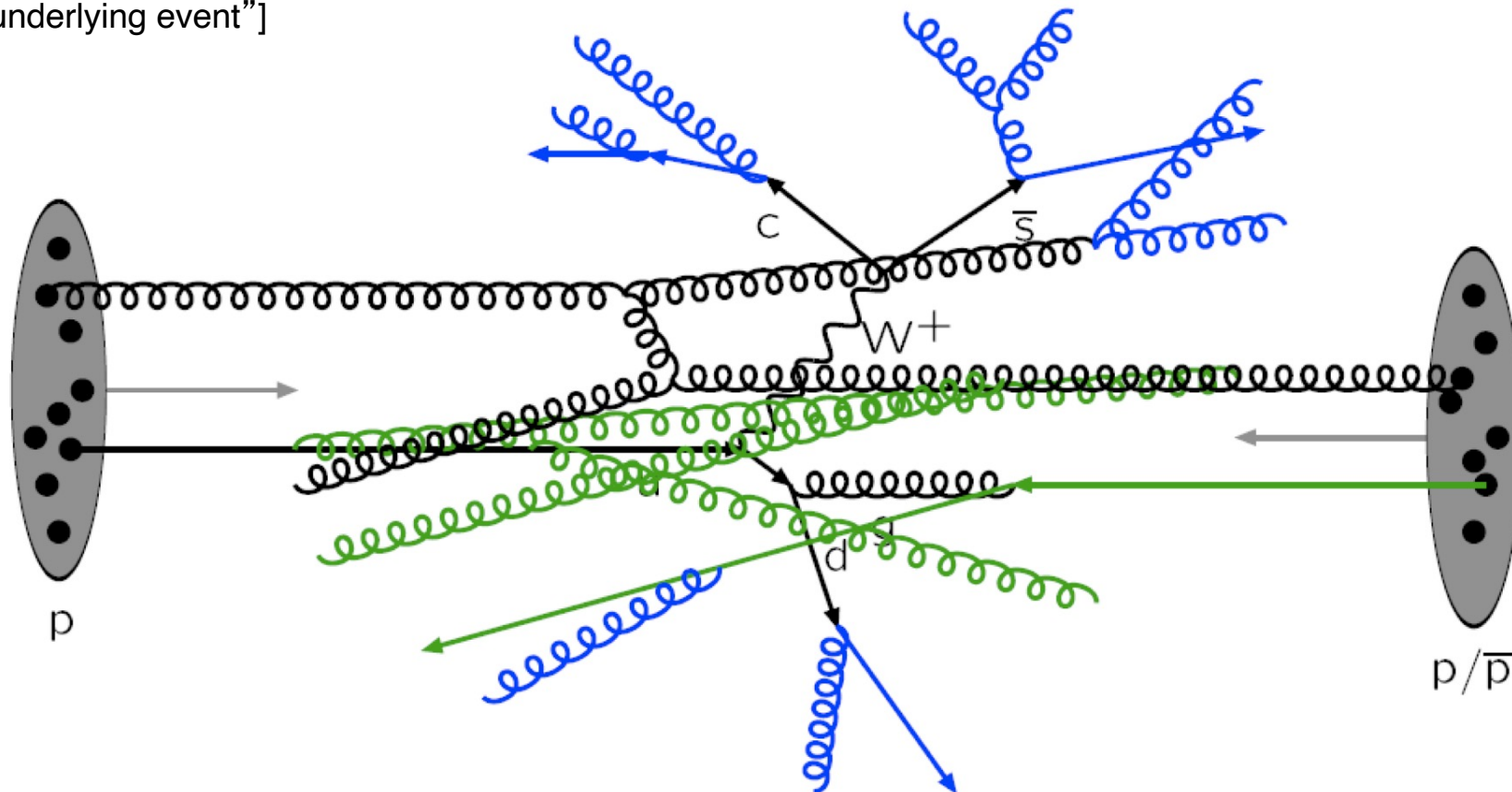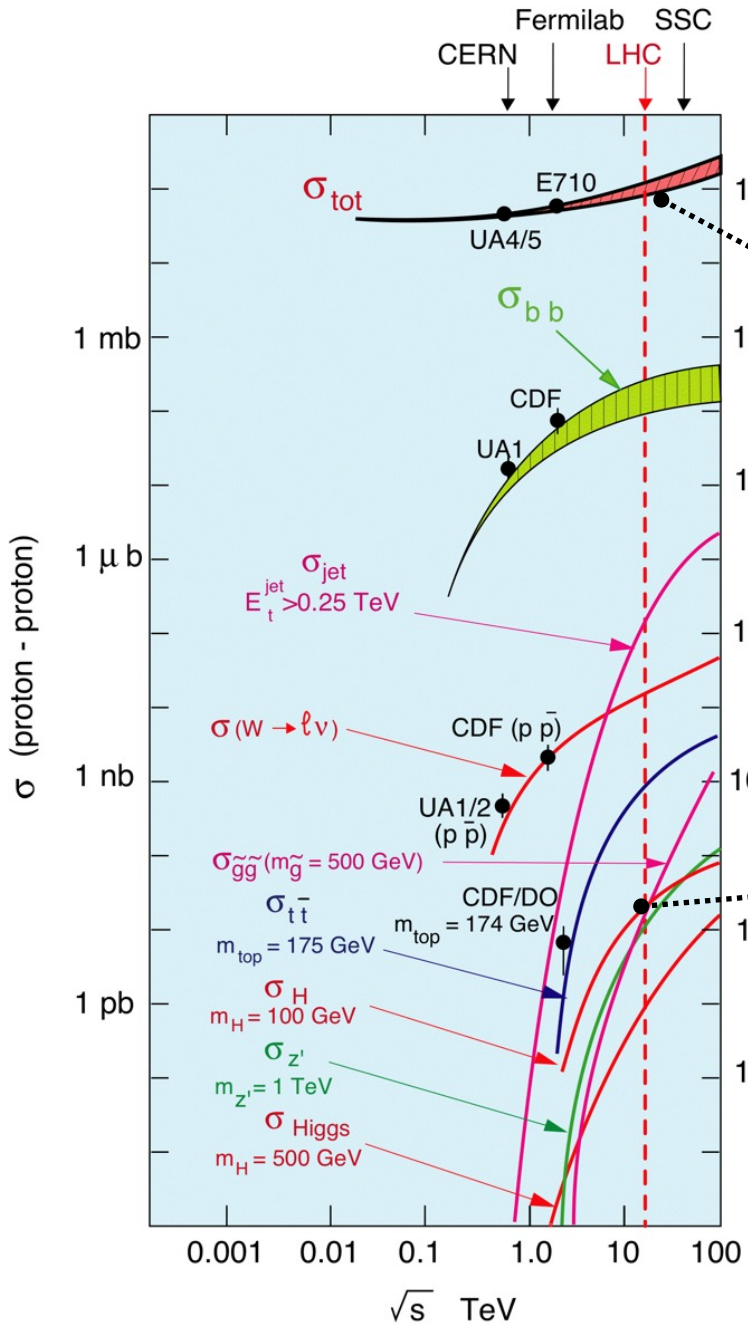
10⁹ Events/sec

10^9 Events/sec

[1 Mbyte/Event]

~ 10^{10} reduction needed

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 !

Fast selection of interesting Events
Number of necessary decisions: 40 million/sec
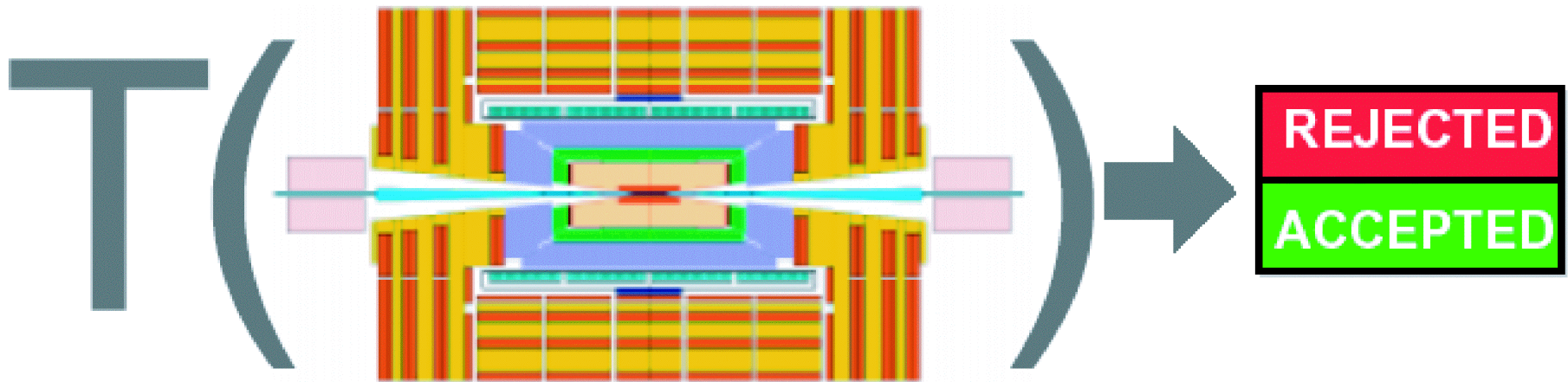
Function T(…) is highly complex
Detector data not directly available

Stepwise decision

→ Trigger Levels
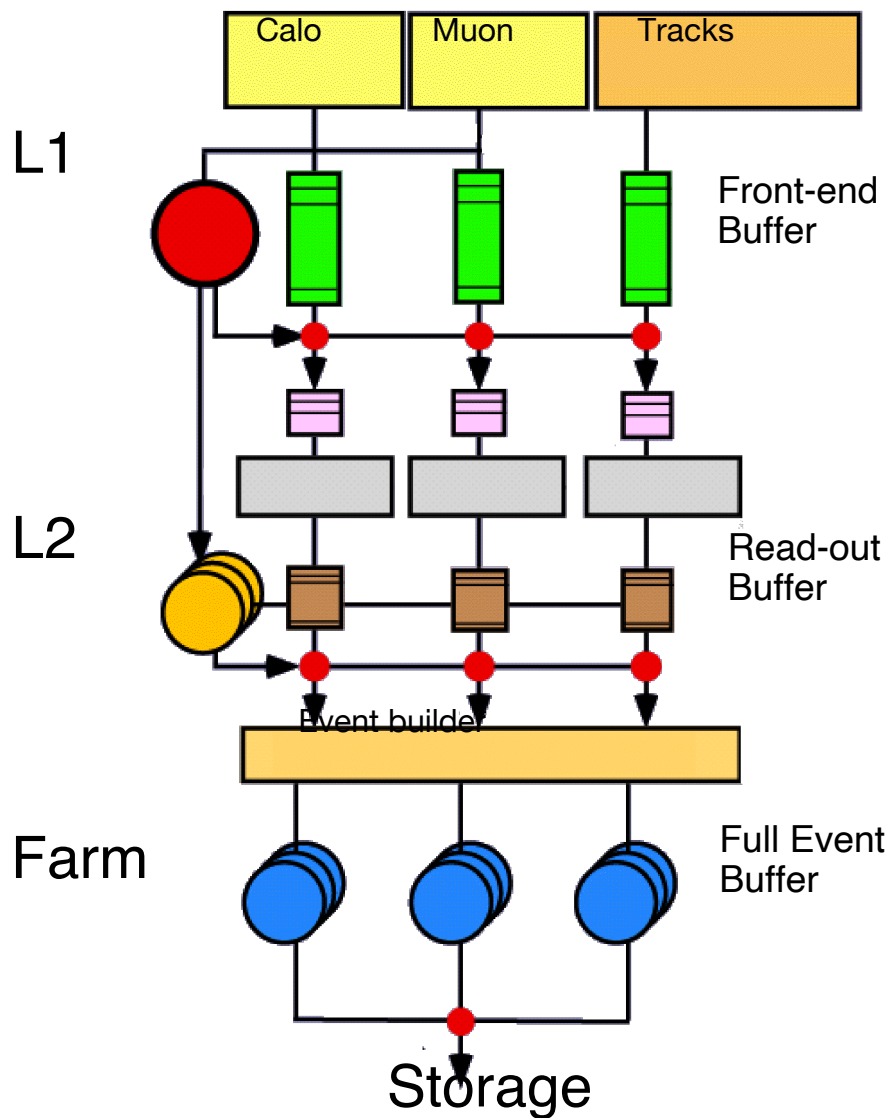
Experiments
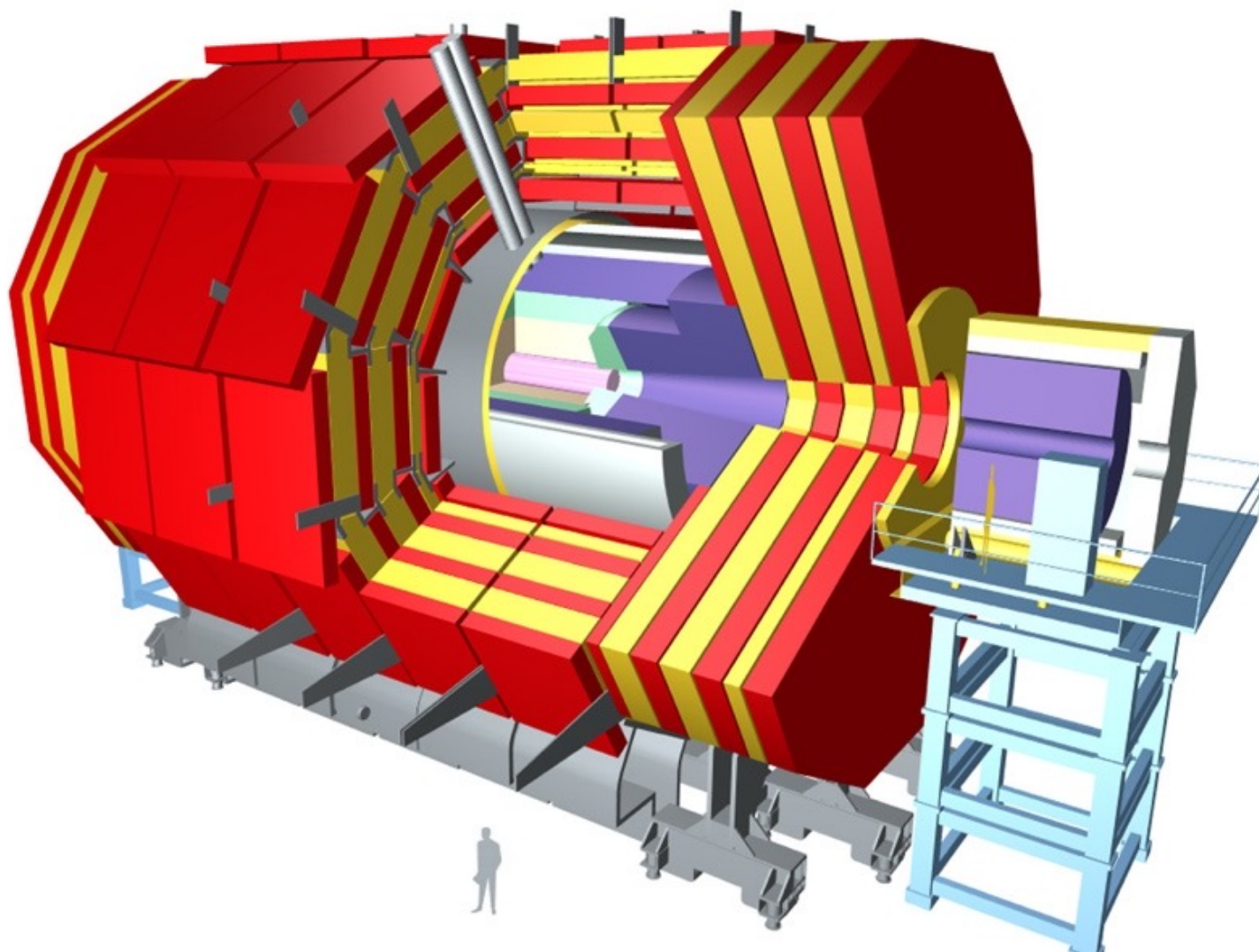
The LHC and its Experiments

ATLAS: A Toroidal LHC ApparatuS
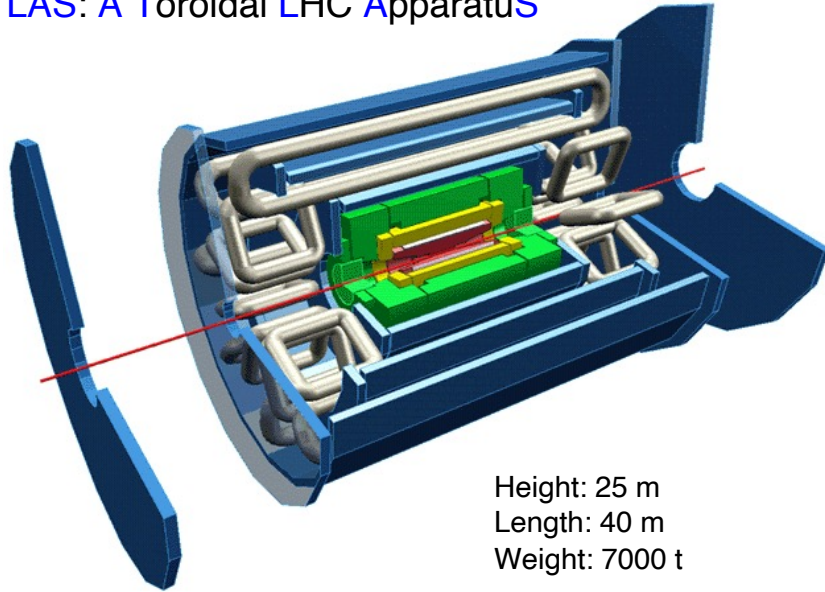
Height: 25 m
Length: 40 m
Weight: 7000 t

CMS: Compact Muon Solenoid
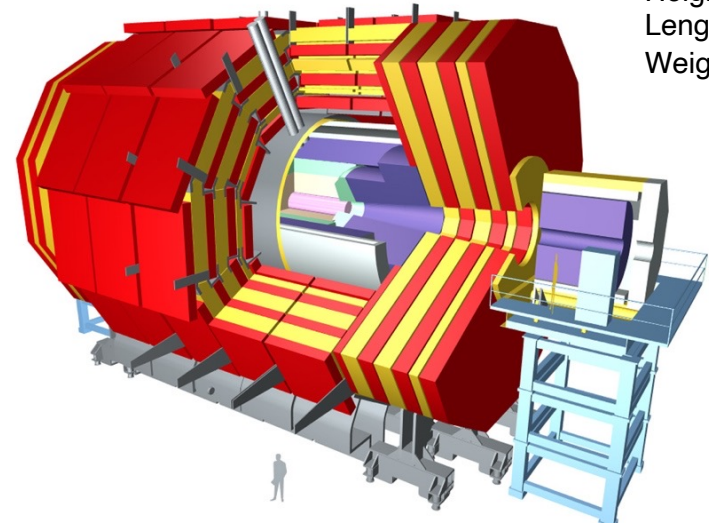
Height: 15 m
Length: 22 m
Weight: 12500 t

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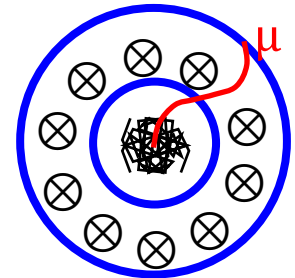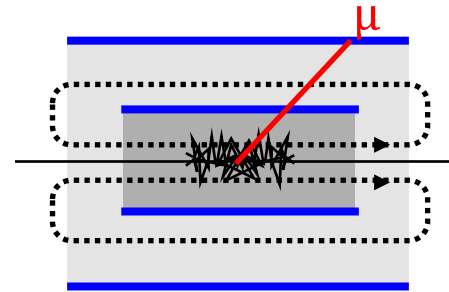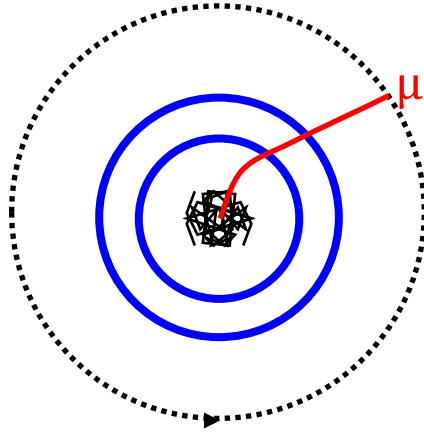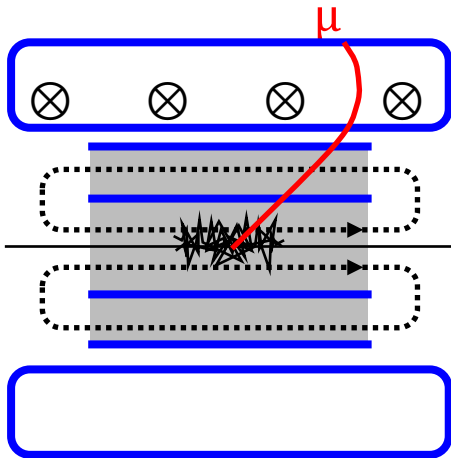
The basic design criteria of the detector included the following points:

1. Excellent electromagnetic calorimetry for **electron and photon identification** and measurements, complemented by full-coverage hadronic calorimetry for accurate jet and ETmiss measurements;

2. High-precision **muon momentum measurements**, with the capability of accurate measurements at the highest collision rates using the external muon spectrometer alone;

3. Efficient **charged particle tracking at high luminosity** for high transverse momentum (p_T) lepton-momentum measurements, electron and photon identification, τ-lepton and heavy-flavour identification, and full event reconstruction capability at lower luminosity;

4. **Large acceptance in pseudorapidity (η)** with almost full azimuthal angle (φ) coverage everywhere. The azimuthal angle is measured around the beam axis z, whereas pseudorapidity relates to the polar angle (θ) where θ is the angle from the z direction, $η = -\ln(\tan\frac{θ}{2})$.

5. **Triggering and measurements of particles at low-p_T thresholds**, providing high efficiencies for most physics processes of interest at the LHC.

The main active detector components of the ATLAS detector, from the beam line towards the outside. The total readout channels for each component is given, as well as its pseudorapidity coverage.

| Detector component	Position	Channels (total)	η - coverage [Collapse]
Tracking			
Pixel B-layer (IBL, added for Run 2)	1 cylindrical barrel layer	6 million	±2.5
	Average radius 33 mm		
Pixel	3 cylindrical barrel layers	80.4 million	±2.5
	3 end-cap disks on each side		
	Radial envelope 45.5 - 242 mm		
SCT strips	4 cylindrical barrel layers	6.3 million	±2.5
	9 end-cap disks on each side		
	Radial envelope 251 - 610 mm		
TRT	73 barrel straw planes	351,000	±2.0
	80 end-cap straw planes		
	Radial envelope 554 - 1106 mm		
Calorimetry			
EM presampler	Barrel	7,808	±1.52
	End-caps	1,536	1.5 < |η| < 1.8
EM calorimeter	3 depth samples barrel	101,760	±1.48
	3 depth layers end-caps	62,208	1.375 < |η| < 3.2
Hadronic tile calorimeter	3 depth samples barrel	5,760	±1.0
	3 depth samples extended barrel	4,092	0.8 < |η| < 1.7
LAr hadronic end-caps	4 depth layers	5,632	1.5 < |η| < 3.2
LAr forward hadronic calorimeter	3 depth layers	3,524	3.1 < |η| < 4.9
Muon spectrometer			
MDT precision tracking	3 multi-layer stations	354,000	±2.7
CSC precision tracking	1 innermost station end-caps	31,000	2.0 < |η| < 2.7
RPC trigger chambers	2 multi-layer stations barrel	373,000	±1.05
TGC trigger chambers	2 multi-layer stations end-cap	318,000	1.05 < |η| < 2.4

Upgrades! → Detector evolves with time

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)

44m

25m

Tile calorimeters

LAr hadronic end-cap and
forward calorimeters

Pixel detector

LAr electromagnetic calorimeters

Toroid magnets

Solenoid magnet

Transition radiation tracker

Muon chambers

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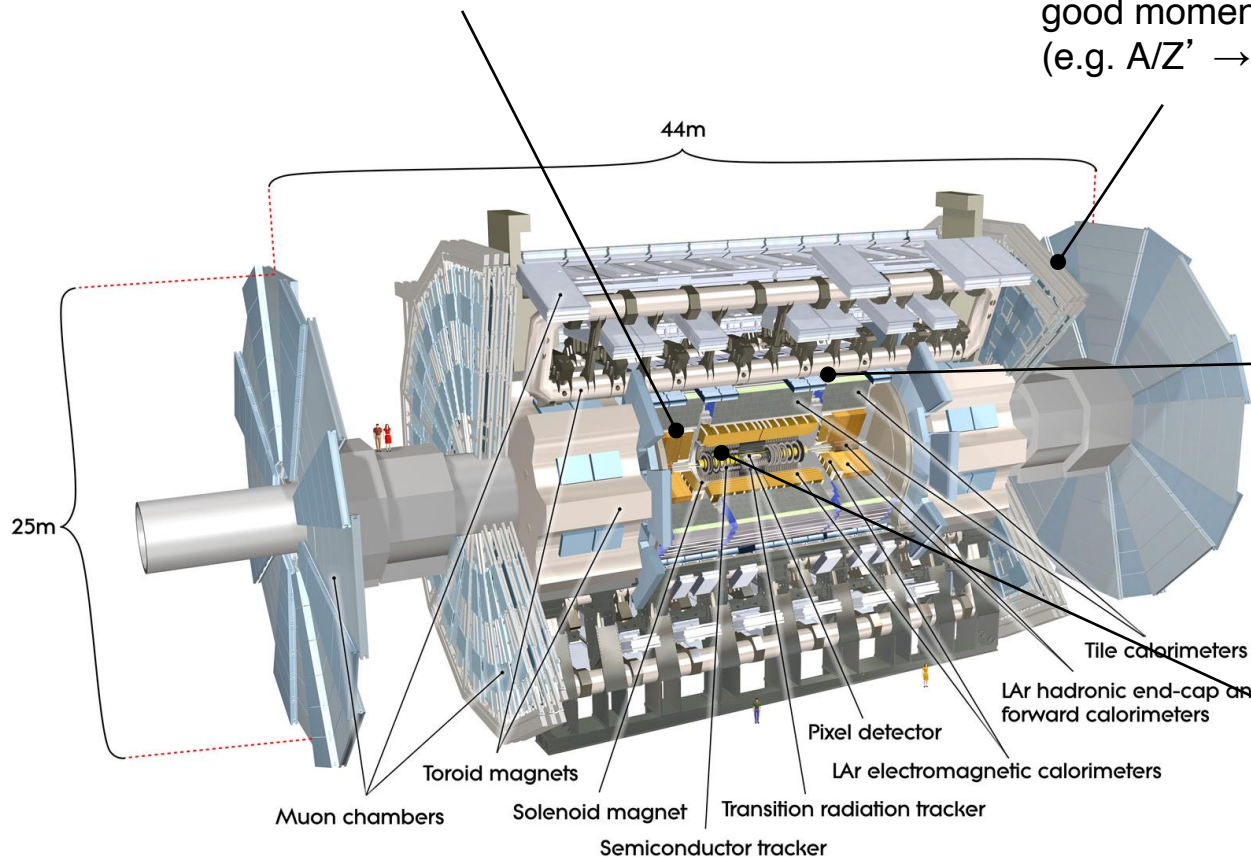
Inner Detector:
Si Pixel & strips; TRT
$\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$
good impact parameter res., i.e.
$\sigma(d_0) \approx 15$ μm @ 20 GeV
(e.g. H → bb)

Magnets:

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

Reminder: the E_{CM} of scattering objects (two partons carrying an unknown fraction x_1 and x_2 of proton momentum) is not known.
→ the CM moves in the longitudinal plane.
However the CM has ~$p_T=0$

Indicative resolutions of the ATLAS detector components. The units for energy E and transverse momentum p_T are in GeV. The symbol $\oplus$ means adding both parts in quadrature.

Detector component	Resolution
Tracking	$\sigma_{p_T}/p_T = 0.05\% \, p_T \oplus 1\%$
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$
Hadronic calorimetry (jets)	
barrel and end-caps	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$
Muon spectrometer	$\sigma_{p_T}/p_T = 10\%$ at $p_T = 1\,\text{TeV}$

$p_T \uparrow \sigma_{PT} \uparrow$

$E \uparrow \sigma_E \downarrow$

$E \uparrow \sigma_E \downarrow$

$p_T \uparrow \sigma_{PT} \uparrow$

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]

TRACKER
CRYSTAL ECAL

PRESHOWER

RETURN YOKE

SUPERCONDUCTING
MAGNET

HCAL

FEET

FORWARD
CALORIMETER

MUON CHAMBERS

Magnet:
    Solenoid: 4 T

Key:
— Muon
— Electron
— Charged Hadron (e.g. Pion)
‑‑‑ Neutral Hadron (e.g. Neutron)
‑‑‑ Photon

0m 1m 2m 3m 4m 5m 6m 7m

4T

2T

Silicon Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Superconducting Solenoid

Iron return yoke interspersed with Muon chambers

Transverse slice through CMS

D.Barney, CERN, February 2004

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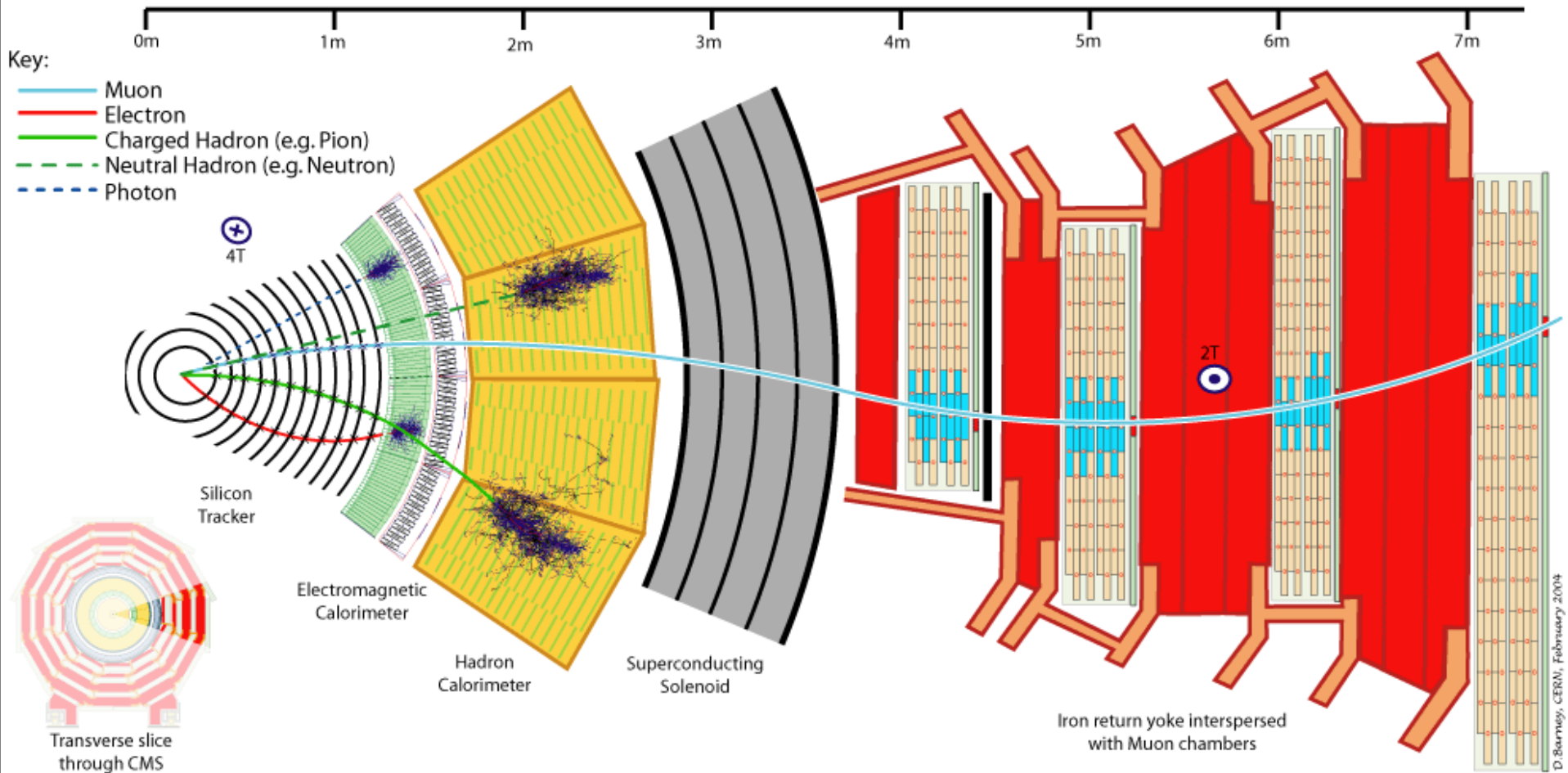
ATLAS vs CMS

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

Accelerators

The LHC and its Experiments

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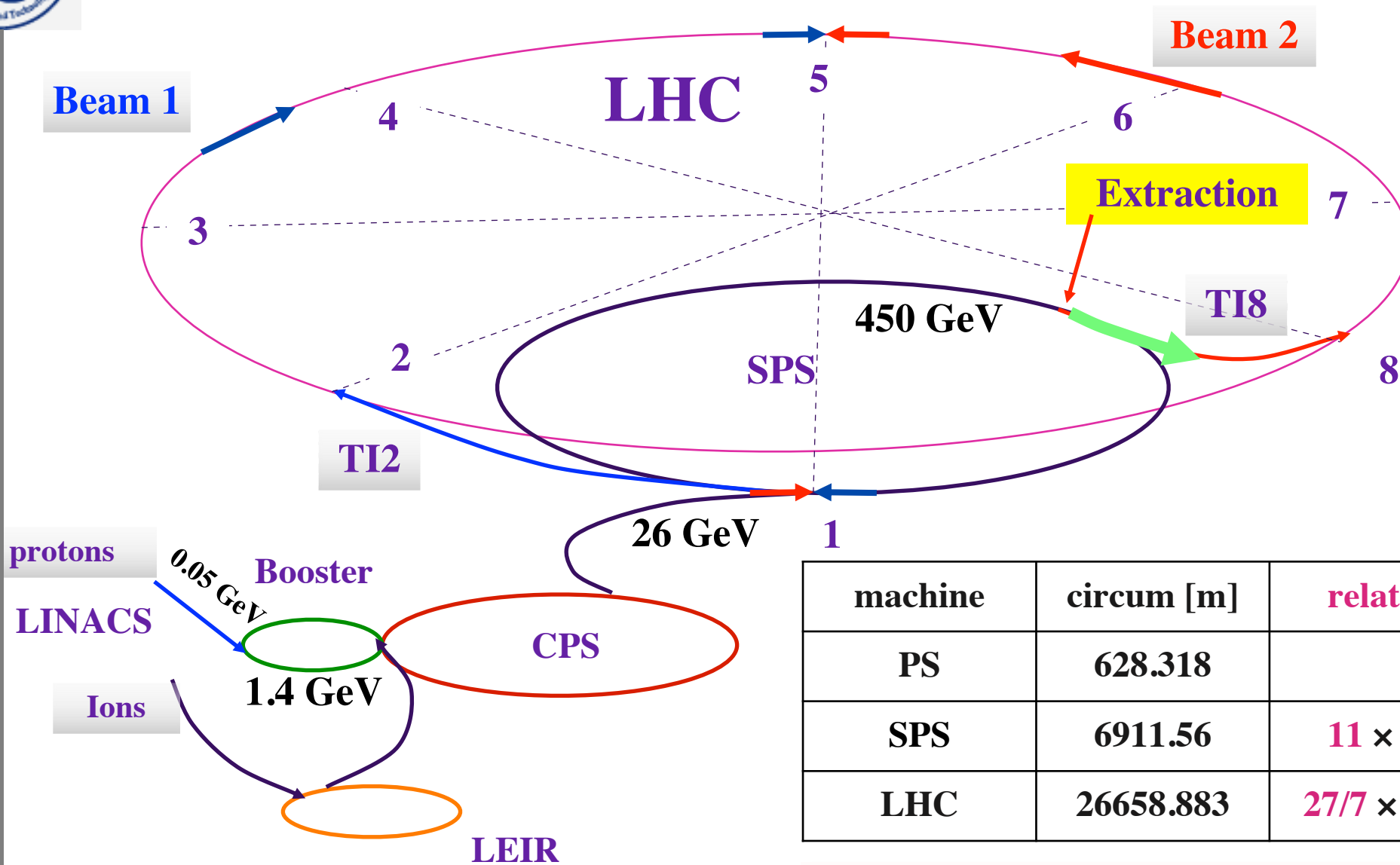
machine	circum [m]	relative
PS	628.318	
SPS	6911.56	11 × PS
LHC	26658.883	27/7 × SPS

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

24

IR1=P1=IP1

Proton-Proton

Bunch

Proton

Parton
(quark, gluon)

l

l

jet

jet
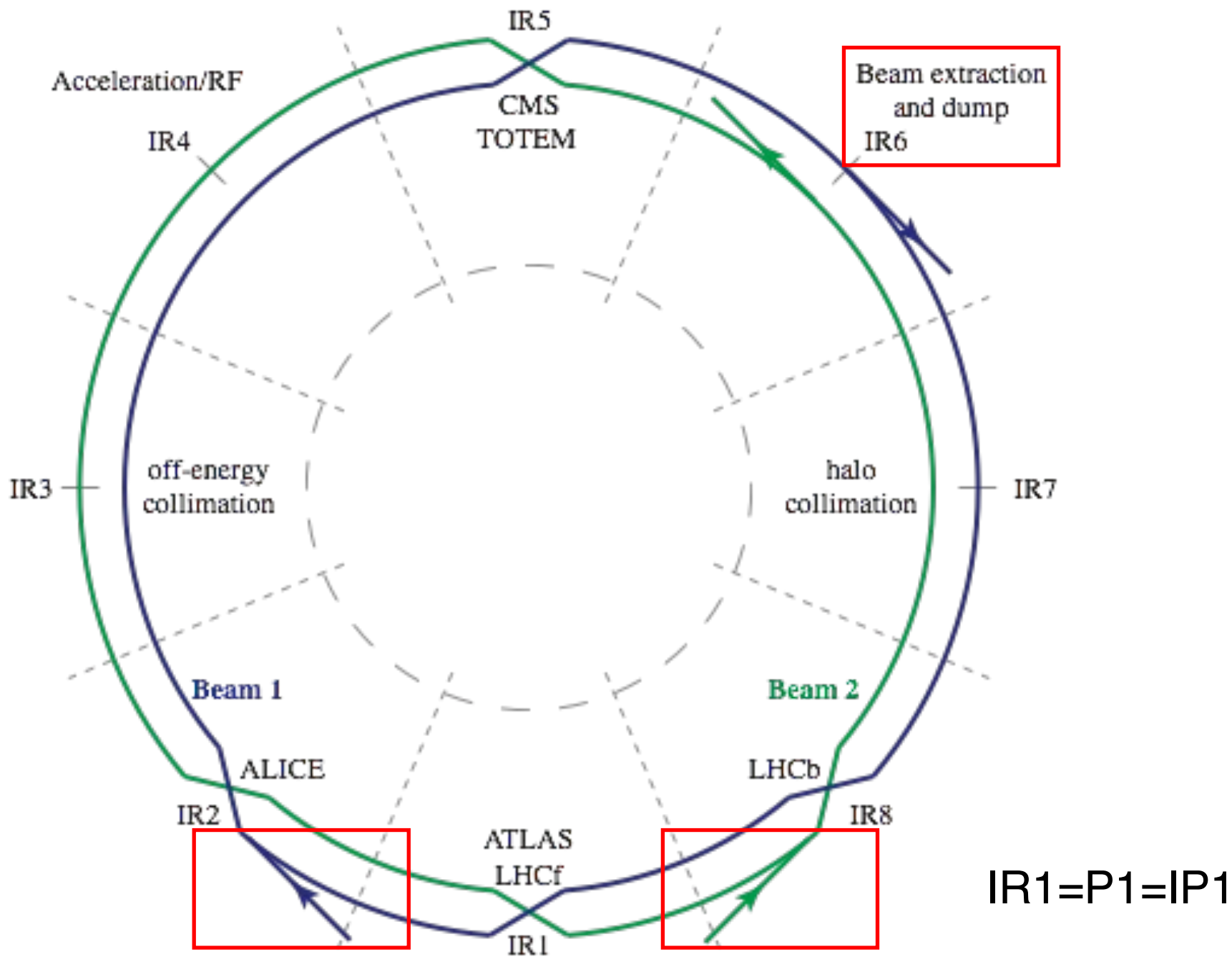
Physics
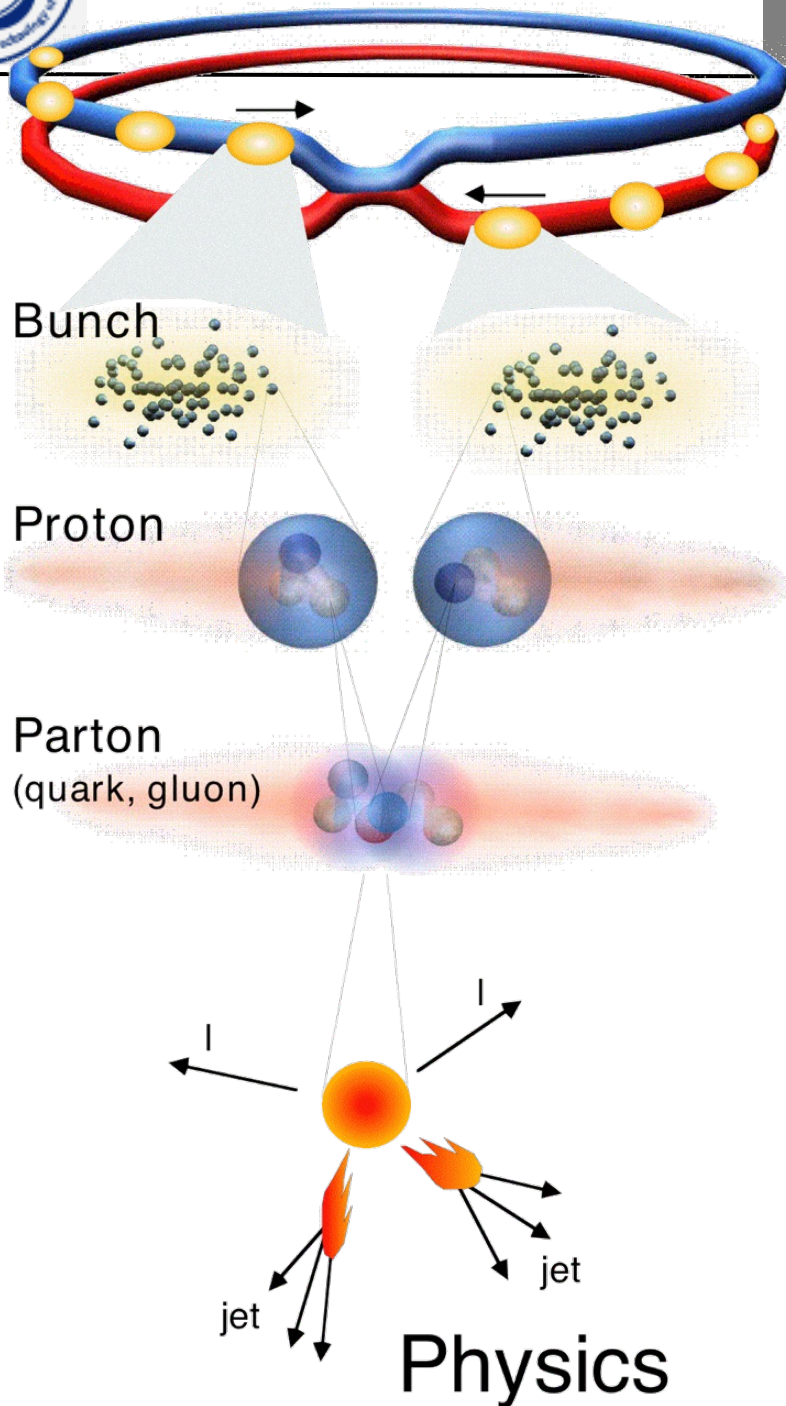
total number of bunches (some empty) 3564x3564

2835 x 2835 proton bunches
distance: 7.5 m [25 ns]

(1.7^*) 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

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Fundamental relation

$$N = L \cdot \sigma$$

X-Sec →Physics.

Number of Events → Experiment

Integrated Luminosity (function of Machine)

$$\rightarrow \sigma = N/L$$

ATLAS Online Luminosity $\sqrt{s}$ = 13 TeV
- LHC Stable Beams

Peak Lumi: 13.8×10^{33} cm^{-2} s^{-1}

Peak Luminosity per Fill [10^{33} cm^{-2} s^{-1}]

2/17 calibration

Day in 2016

ATLAS Online Luminosity $\sqrt{s}$ = 13 TeV
- LHC Stable Beams

Peak Lumi: 20.9×10^{33} cm^{-2} s^{-1}

Peak Luminosity per Fill [10^{33} cm^{-2} s^{-1}]

2/18 calibration

Day in 2017

ATLAS Online Luminosity $\sqrt{s}$ = 13 TeV
- LHC Stable Beams

Peak Lumi: 21.4×10^{33} cm^{-2} s^{-1}

Initial 2018 calibration

Day in 2018

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β^* indicates longitudinal size of the bunch

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} $\int L\, dt$ = 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} $\int L\, dt$ = 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} $\int L\, dt$ = 23.3 fb^{-1} 1380 bunches

2013 **2014 shutdown,** magnet interconnections

2015 2×6.5 TeV, β^*= 0.6 m, L_{peak} = 0.5×10^{34} cm^{-2}s^{-1} $\int L\, dt$ = 4.2 fb^{-1} 2232 bunches

2016 2×6.5 TeV, β^*= 0.4 m, L_{peak} = 1.4×10^{34} cm^{-2}s^{-1} $\int L\, dt$ = 35.6 fb^{-1} 2208 bunches

2017 2×6.5 TeV, β^*= 0.3 m, L_{peak} = 2.1×10^{34} cm^{-2}s^{-1} $\int L\, dt$ = 50.4 fb^{-1} 2544 bunches

2018 $\int L\, dt = 60\ fb^{-1}$ 2556 bunches

	LHC design	achieved
Momentum at collision, TeV/c	7	6.5
Luminosity, cm^{-2}s^{-1}	1.0E+34	2.1E+34
Dipole field at top energy, T	8.33	8.33
Number of bunches, each beam	3564	2544
Particles / bunch	1.15E+11	1.7E+11
Typical beam size in ring, μm	200 – 300	~300
Beam size at IP, μm	17	16

Not all bunches collide!

72 BUNCHES
25 ns DISTANT

8 MISSING BUNCHES

38 MISSING BUNCHES

39 MISSING BUNCHES

119 MISSING BUNCHES

1   2   3   4

88.924 μs

'e' indicates 'empty'

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

Bunch 0

Bunch 3563
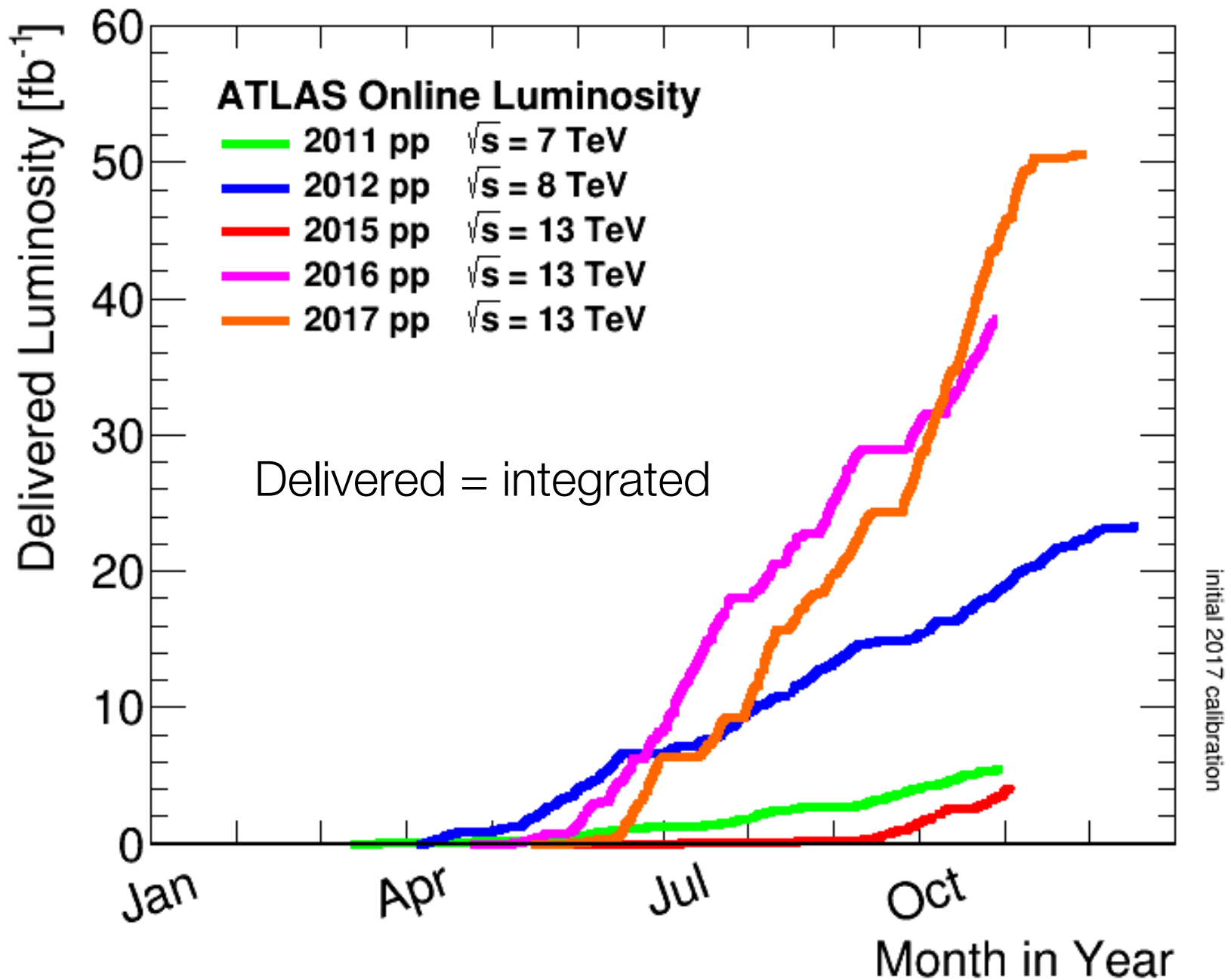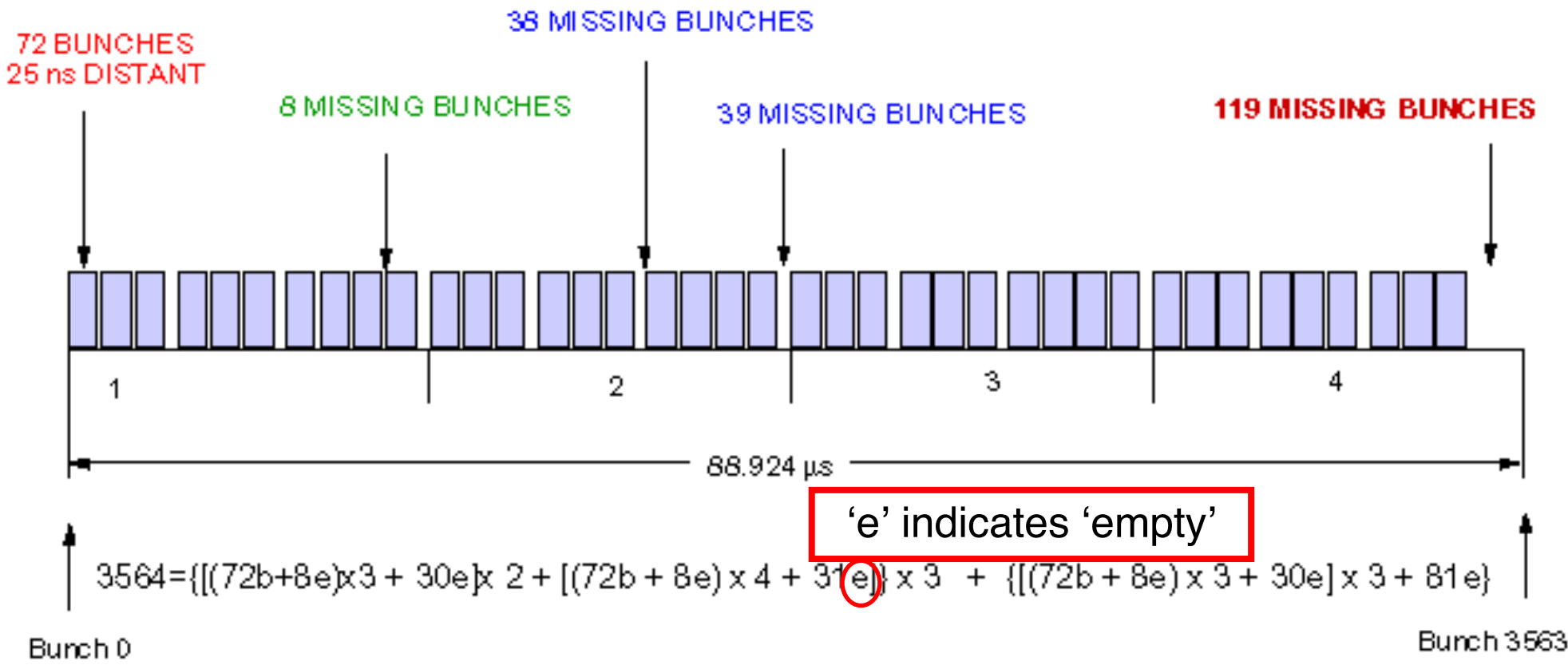
Filled bunches = 2808 = {   [(72b)x3]x2 + [(72b)x4]   }x3+{   [(72b)x3]x3 }

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LHC (1-Ring) = 88.924 μs

3-batch   4-batch

τ_3

SPS = 7/27 LHC

τ_4

τ_5

Filling Scheme

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

τ_2

PS = 1/11 SPS

τ_1

72 bunches
25ns spacing

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

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Luminosity (LHCb) << Luminosity(ATLAS, CMS, ALICE)

Beam 2

Beam 1

Point 5
CMS

LHC
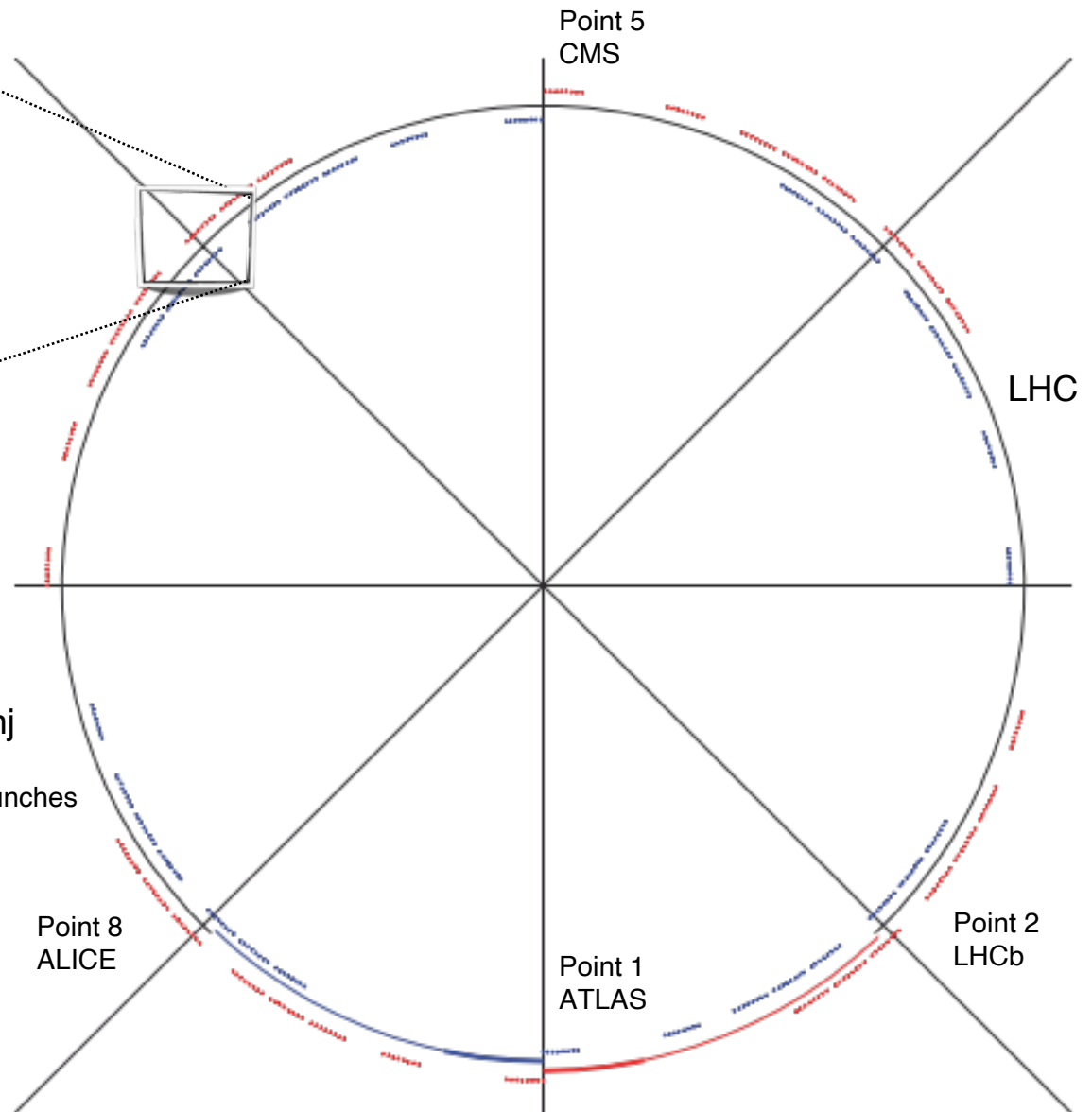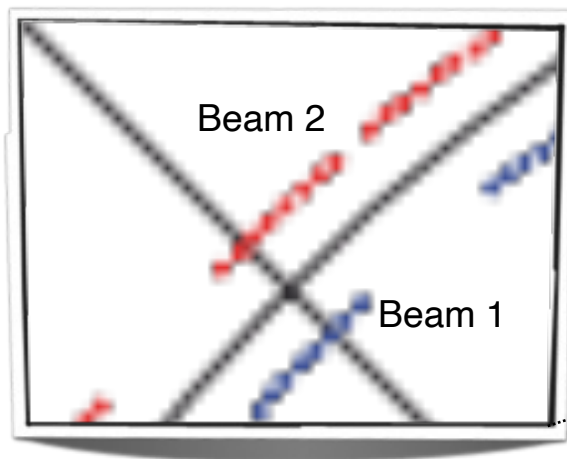
Present Bunch Structure:
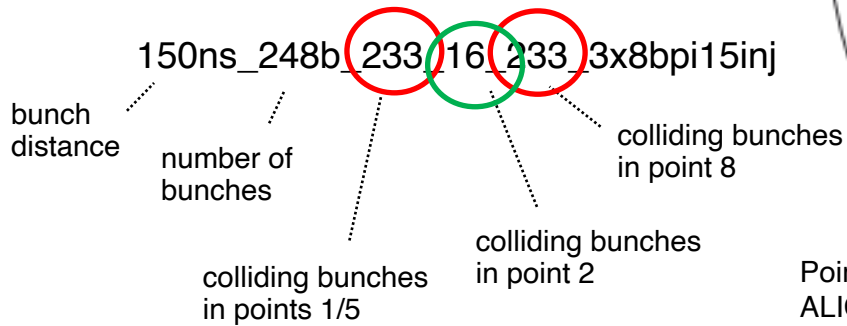
150ns_248b_233_16_233_3x8bpi15inj

bunch
distance

number of
bunches

colliding bunches
in points 1/5

colliding bunches
in point 2

colliding bunches
in point 8

Point 8
ALICE

Point 1
ATLAS

Point 2
LHCb

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- Injection probe beam

- Injection

- Ramp

- Squeeze

- Adjust

- Stable Beams

| 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 |

FBCT Intensity and Beam Energy — Updated: 20:52:35

Injection   Accelerating

⟵ ~1 hour ⟶

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

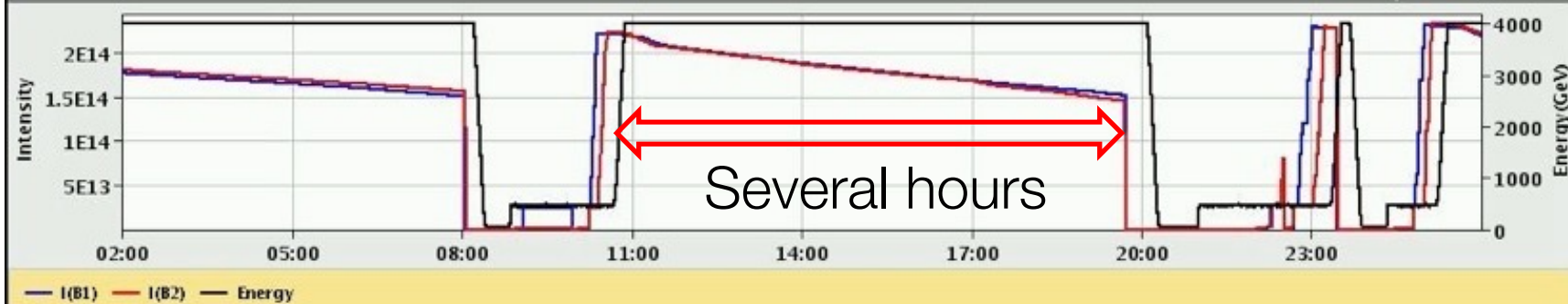LHC Operation in CCC : 77600, 70480 | PM Status B1 ENABLED | PM Status B2 ENABLED

peak Luminosity $7.8 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$

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Present LHC Status

ATLAS Online Luminosity

- LHC Stable Beams
- ATLAS Recorded

23 August, 2010
LHC Fill 1298
$\sqrt{s} = 7$ TeV

Total Delivered: 280 nb^{-1}
Total Recorded: 273 nb^{-1}

Luminosity [10^{-31} cm^{-2} s^{-1}]

CEST Time
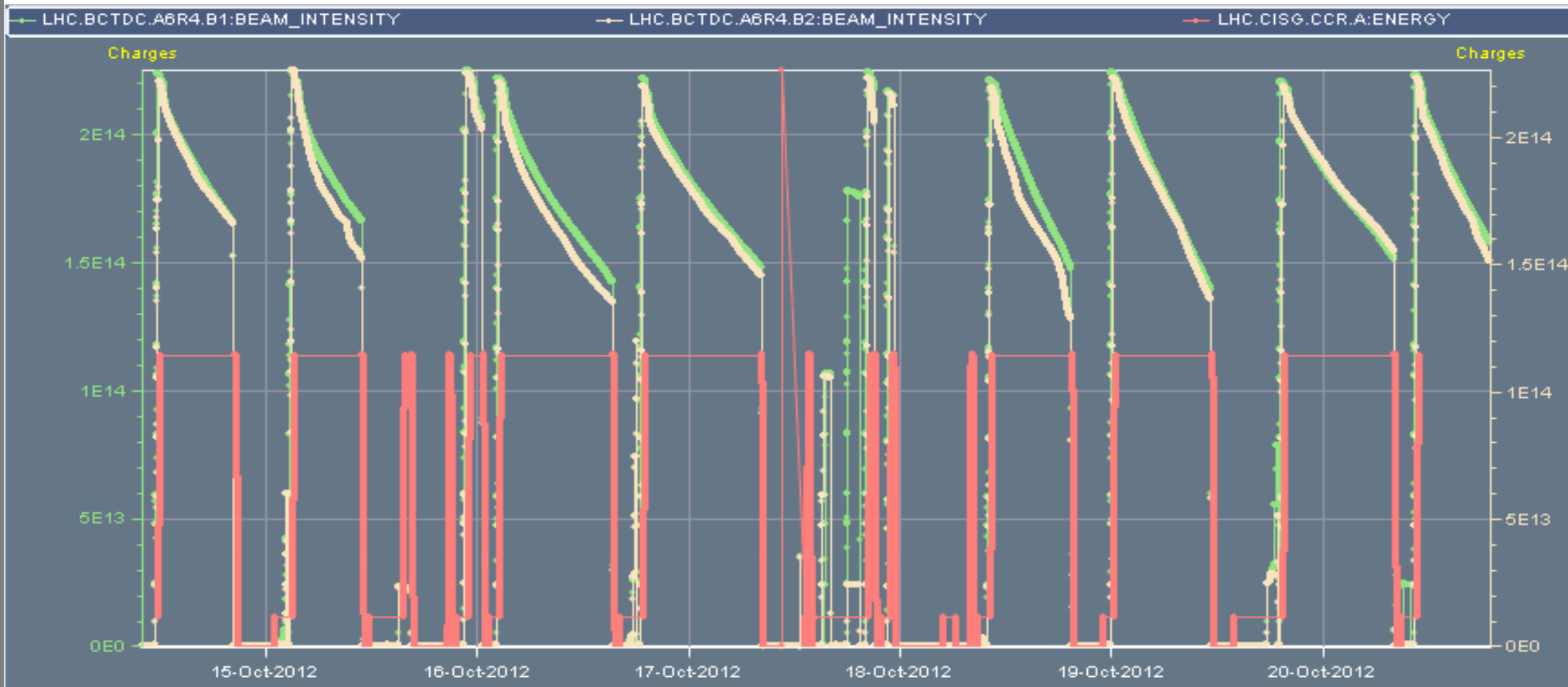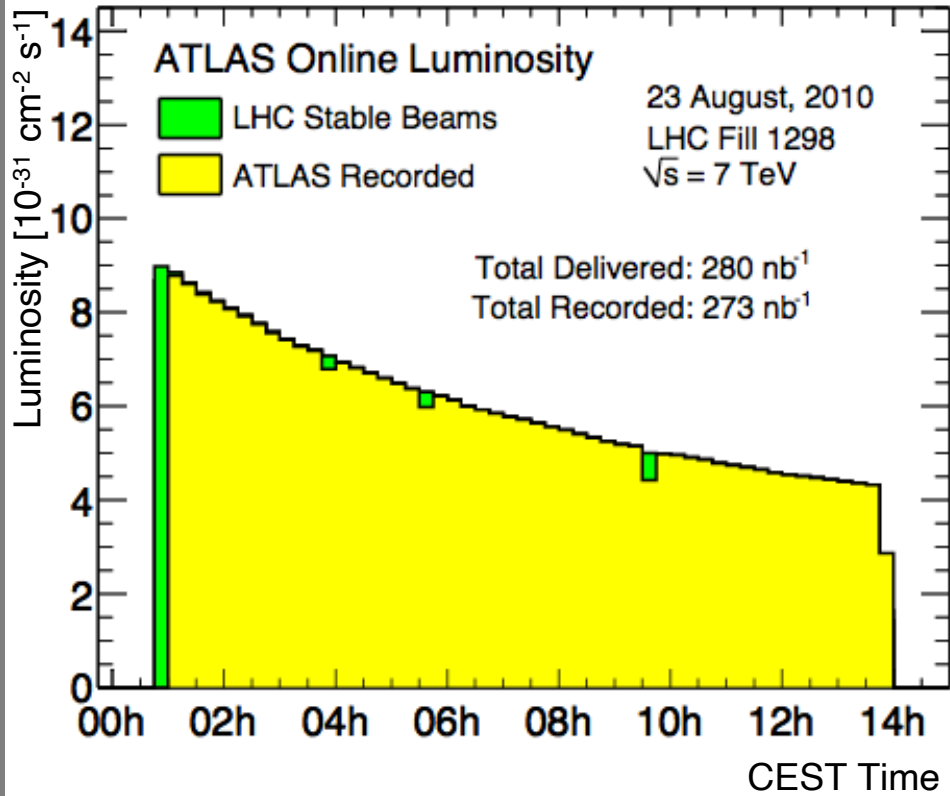
LHC Fill
[August 2010]

Delivered and Recorded
Luminosity

ATLAS Online Luminosity $\sqrt{s} = 7$ TeV

- LHC Delivered
- ATLAS Recorded

Total Delivered: 12.75 pb^{-1}
Total Recorded: 11.5 pb^{-1}

Total Integrated Luminosity [pb^{-1}]

Days 2010
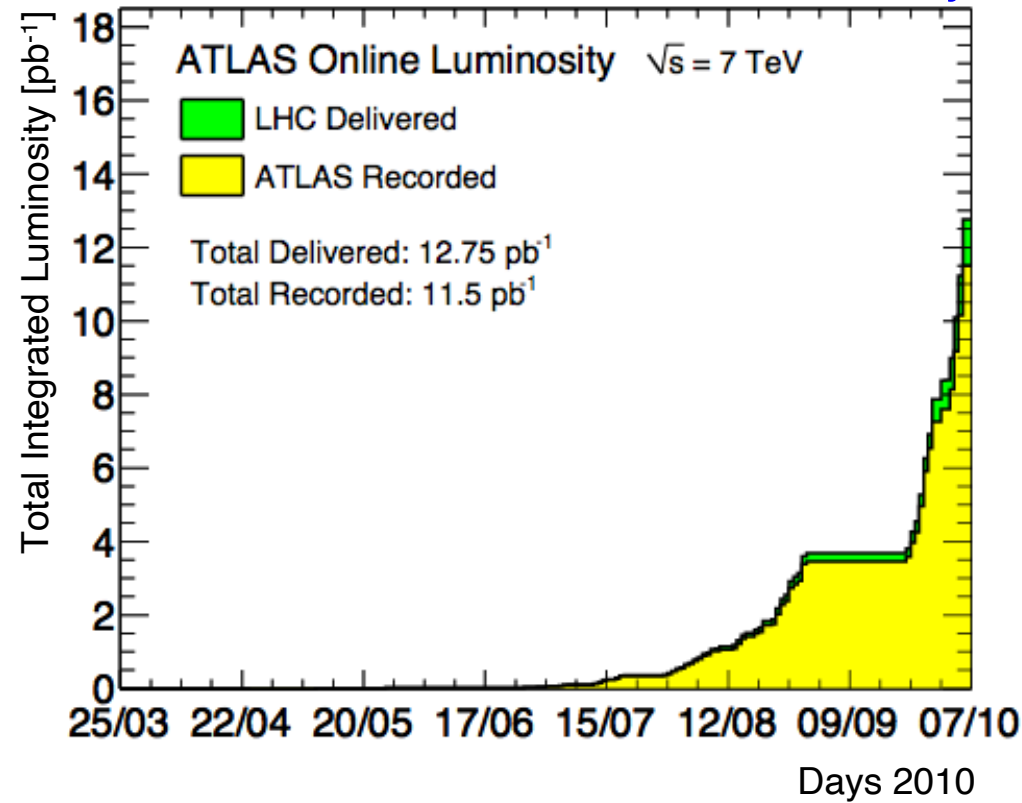
$$N = L \cdot \sigma$$

Number of Events

Integrated Luminosity

X-Sec.

Introduction to Accelerators

Helmut Burkhardt, CERN

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**
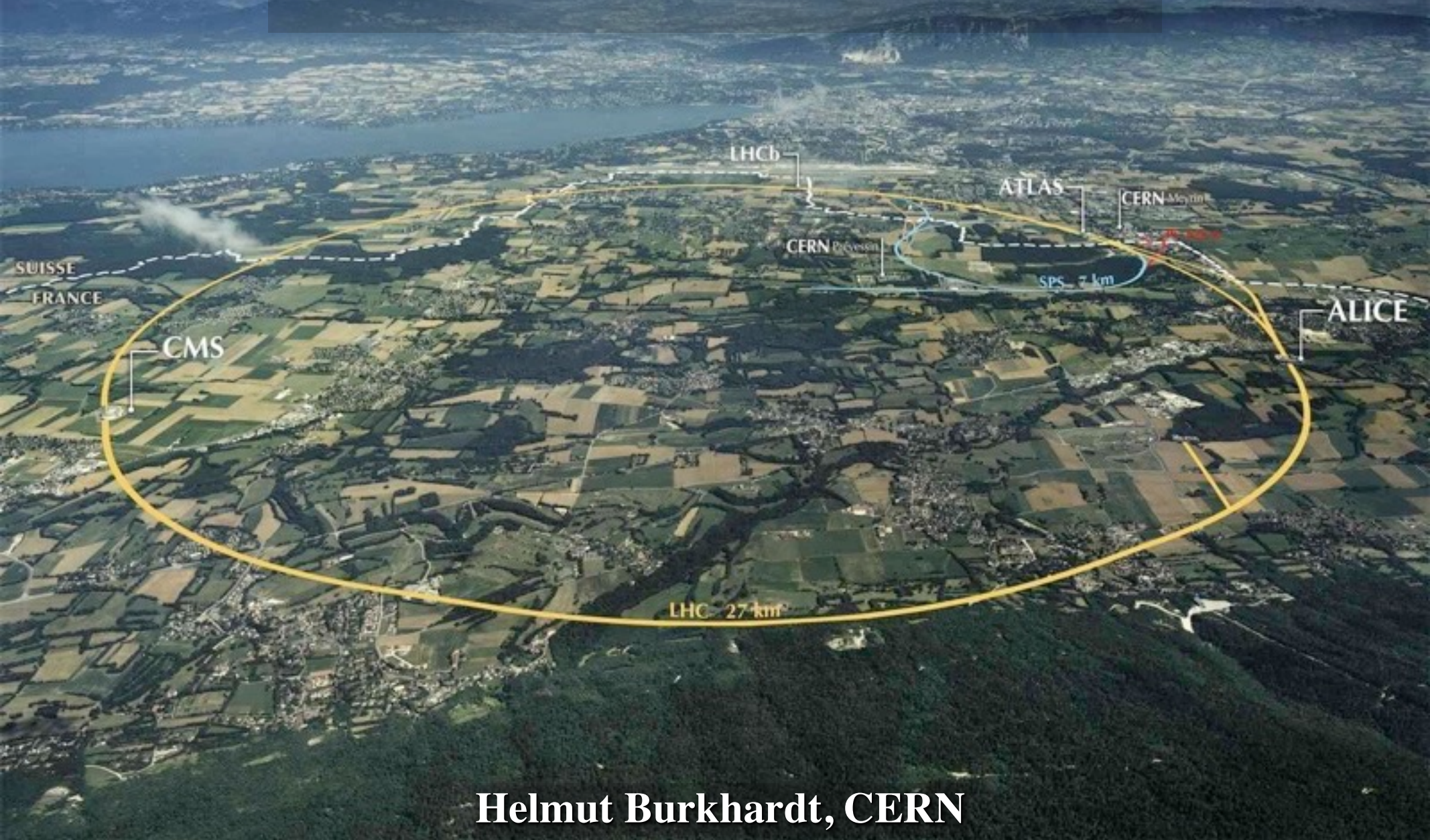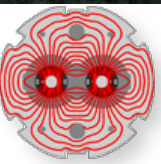- **Energy and Luminosity**
- **Synchrotron Radiation**
- **Limitations, current and future challenges**

- **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

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, pp̄ : E_{cm} / 6
still **5 × above e⁺e⁻** at
same time

pp, pp̄ : discovery
e⁺e⁻ : precision
both required machines

+ **ep** : hadron structure, QCD
HERA, LHeC

LHC

Comparison of Colliders
at the Energy Frontier
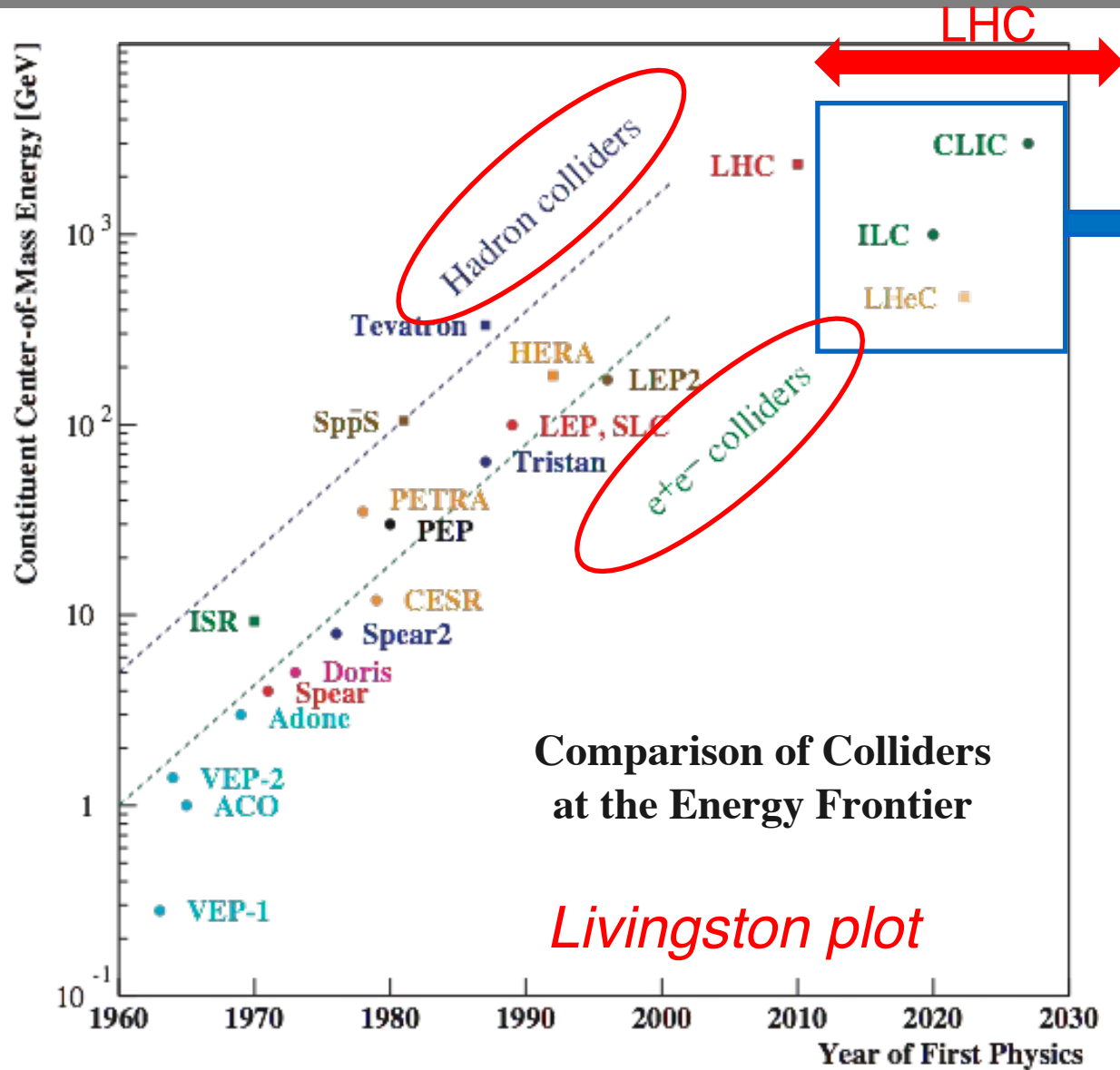
Livingston plot

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

Toni Baroncelli Experimental High Energy Physics at Colliders 2021
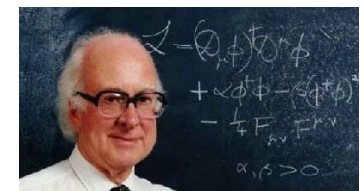
🟩 **Living**ston Plot:

Accelerator energy:
Energy reach has increased exponentially over the last 40 years

➔ Slow-down after 2000 (LHC and ILC)

➔ Indication for limit of existing technologies!!

Electric field :
Acceleration
or rather
Energy gain
100 keV

100 kV

+

Anode

E

Cathode

e^-

Electric charge **e**
and electric field
E

Special relativity, Lorentz transformation

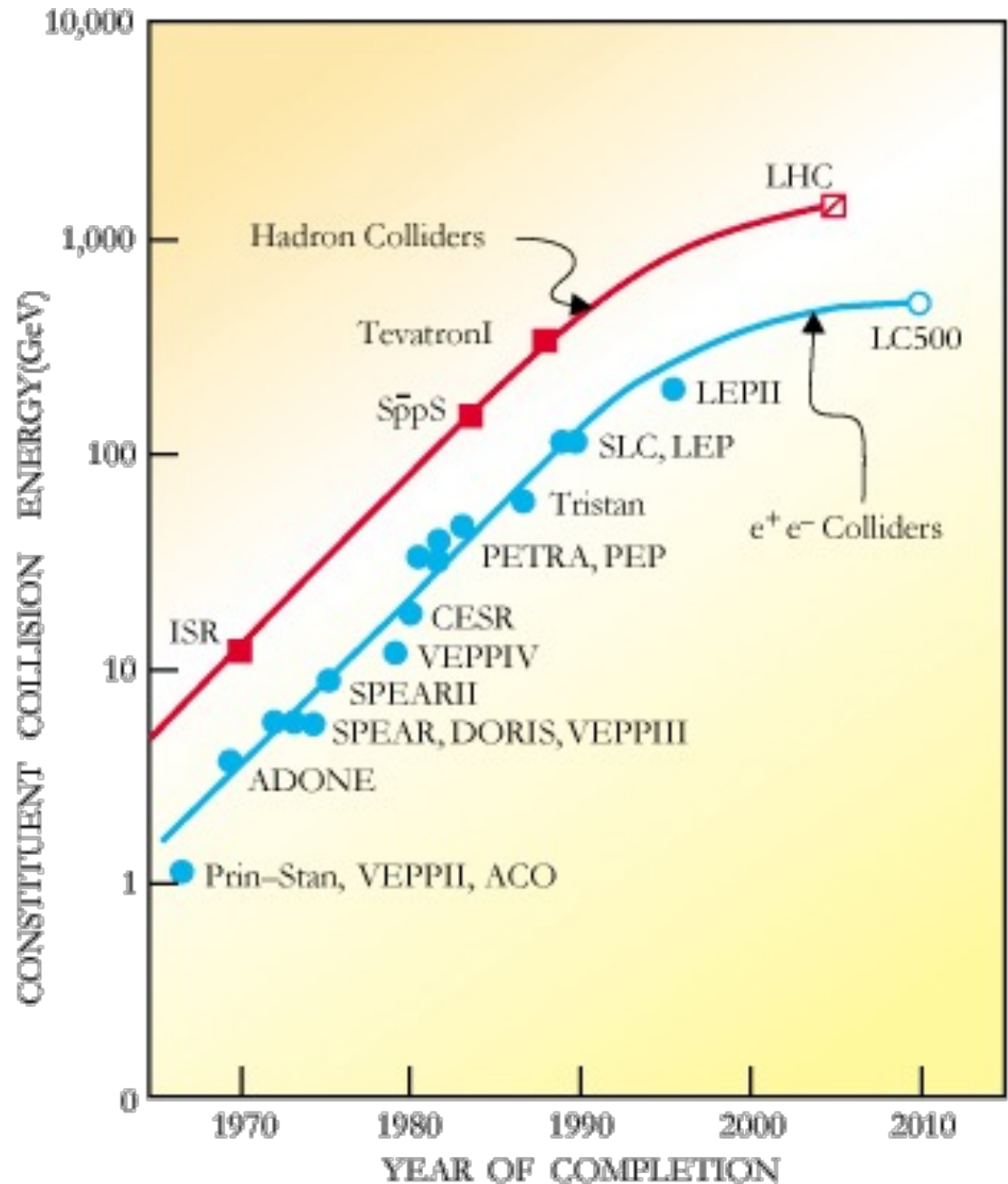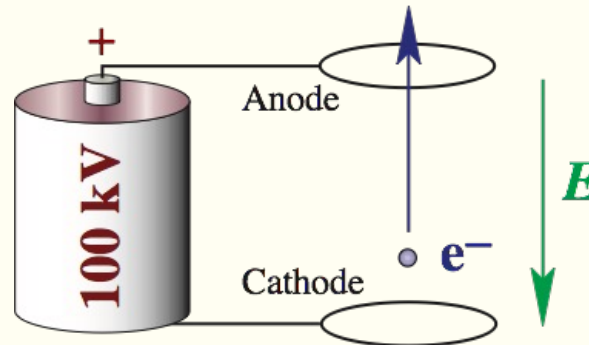$$E = \gamma m c^2 \qquad p = \beta \gamma m c \qquad \beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$m_e \approx 0.511 \text{ MeV/c}^2$ $m_p \approx 938 \text{ MeV/c}^2$ $e \approx 1.602 \times 10^{-19}$
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

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

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

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

for precise numbers see [PDG](#)

---

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

Particle sources

Thermionic electron source principle same as cathode ray tube (significant for temperatures ~ 700 C)

cathode

anode

e^-

e^- beam

$-$ $+$

0.5-3 X_0

e^-

e^+

Convertor

> 50 MeV

focusing solenoid acceleration, bunching

Example : e- gun in CTF3

Vacuum→ pumping port

bucking coil

cathode grid

cathode

Anode

100 - 150 kV

cathode holder

insulator
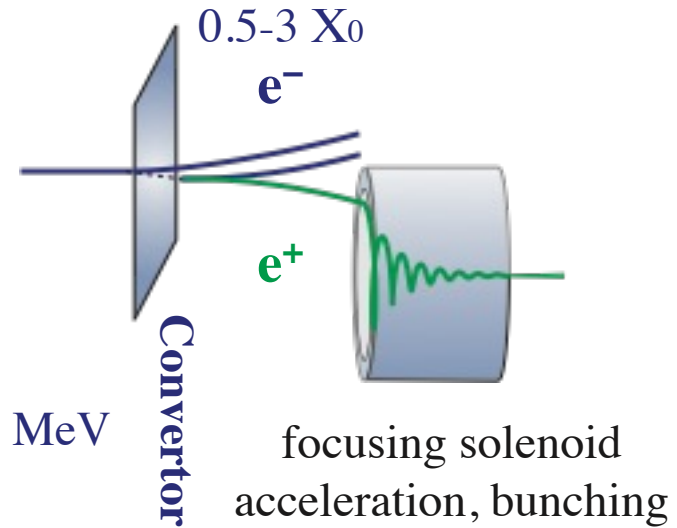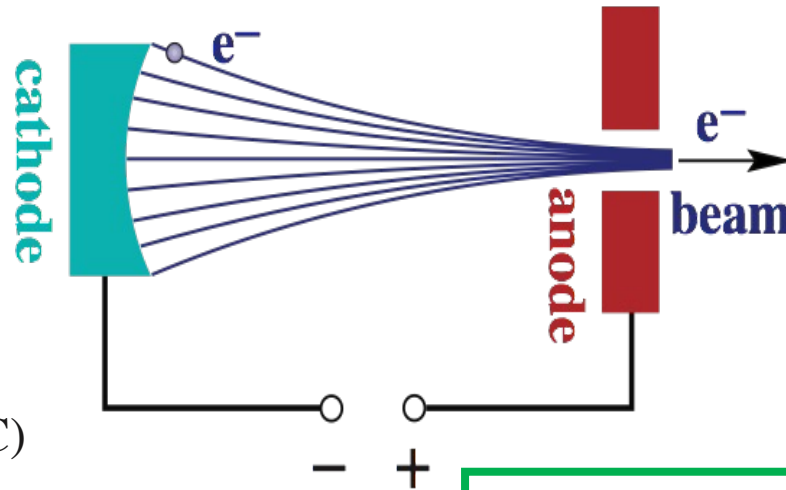
CTF3
NON 0   TYPE CLIO
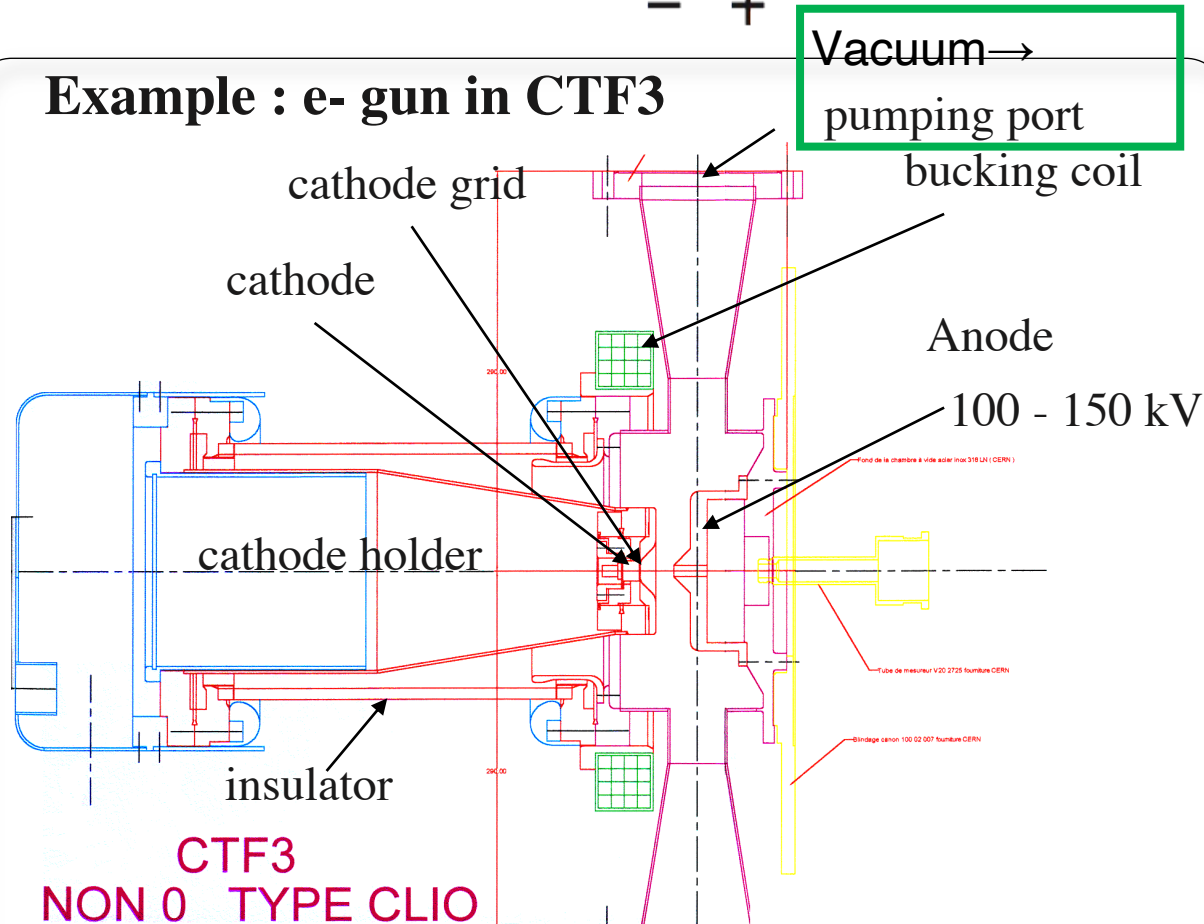
challenges :

high intensity

polarized e^- sources

damping rings for minimum emittance

undulator polarized e^+ sources

42

U_W

② Wehnelt cylinder

-200/-300 V

$\vec{E}_A$

Hot cathode ①

~small area emission

U_H

③ Anode +30 KV

$\vec{v}$

$\ominus$

U_A

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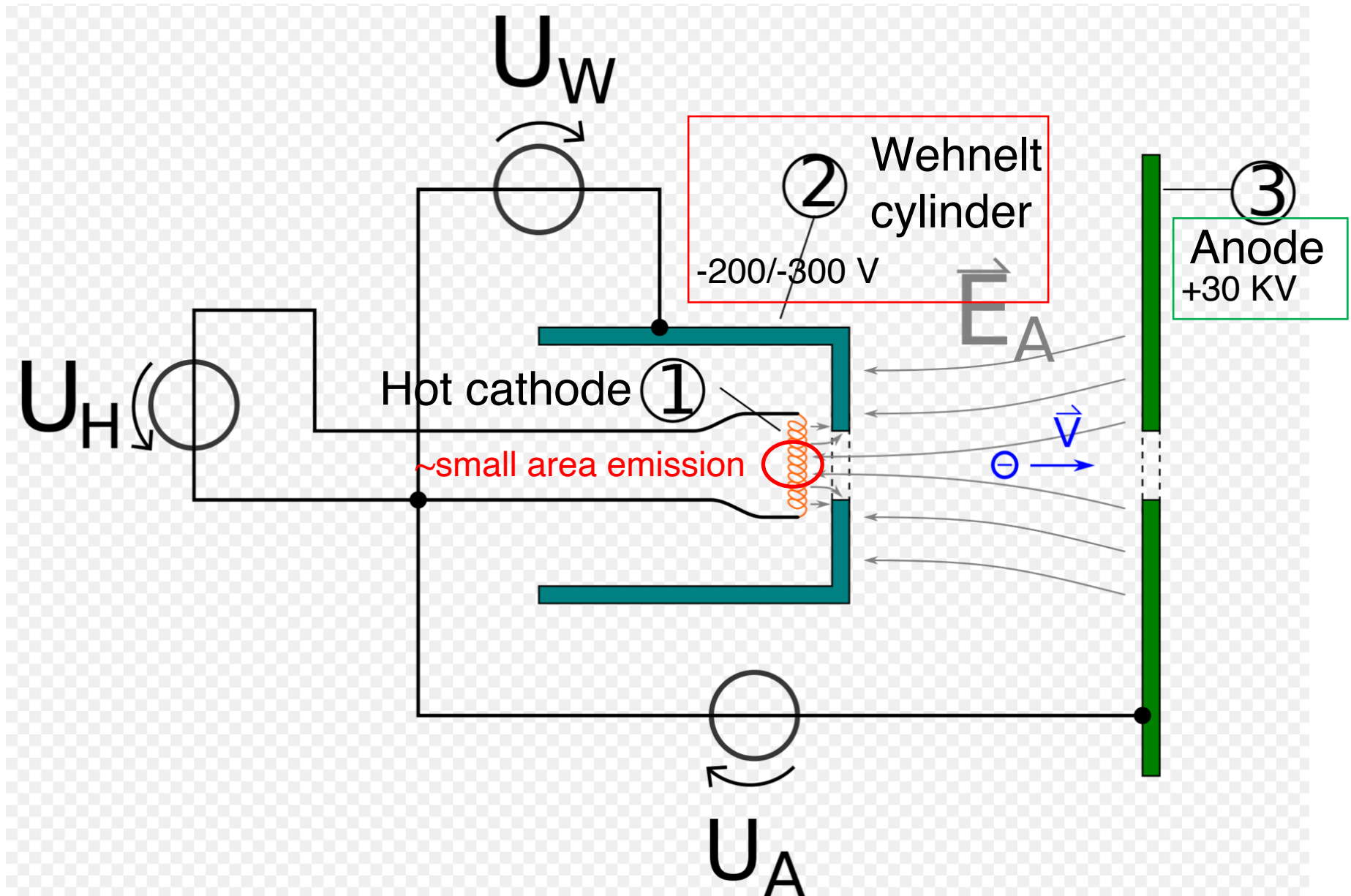
A Wehnelt cap has the shape of a topless, hollow cylinder. The bottom side of the cylinder has an aperture (through hole) located at its center, with a diameter that typically ranges from 200 to 1200 μm. The bottom face of the cylinder is often made from platinum or tantalum foil.

Operation

A Wehnelt acts as a control grid and it also serves as a convergent electrostatic lens. An electron emitter is positioned directly above the Wehnelt aperture, and an anode is located below the Wehnelt. The anode is biased to a high positive voltage (typically +1 to +30 kV) relative to the emitter so as to accelerate electrons from the emitter towards the anode, thus creating an electron beam that passes through the Wehnelt aperture. The Wehnelt is biased to a negative voltage (typically –200V to –300V) relative to the emitter, which is usually a tungsten filament or Lanthanum hexaboride (LaB$_6$) hot cathode with a "V" shaped (or otherwise pointed) tip. This bias voltage creates a repulsive electrostatic field that suppresses emission of electrons from most areas of the cathode.

The emitter tip is positioned near the Wehnelt aperture so that, when appropriate bias voltage is applied to the Wehnelt, a small region of the tip has a net electric field (due to both anode attraction and Wehnelt repulsion) that allows emission from only that area of the tip. The Wehnelt bias voltage determines the tip's emission area, which in turn determines both the beam current and effective size of the beam's electron source.

As the Wehnelt bias voltage increases, the tip's emitting area (and along with it, the beam diameter and beam current) will decrease until it becomes so small that the beam is "pinched" off. In normal operation, the bias is typically set slightly more positive than the pinch bias, and determined by a balance between desired beam quality and beam current.

The Wehnelt bias controls beam focusing as well as the effective size of the electron source, which is essential for creating an electron beam that is to be focussed into a very small spot (for scanning electron microscopy) or a very parallel beam (for diffraction). Although a smaller source can be imaged to a smaller spot, or a more parallel beam, one obvious trade off is a smaller total beam current.

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

intermediate electrode

anode

Hydrogen gas inlet

electrons

cathode

plasma

ion jet
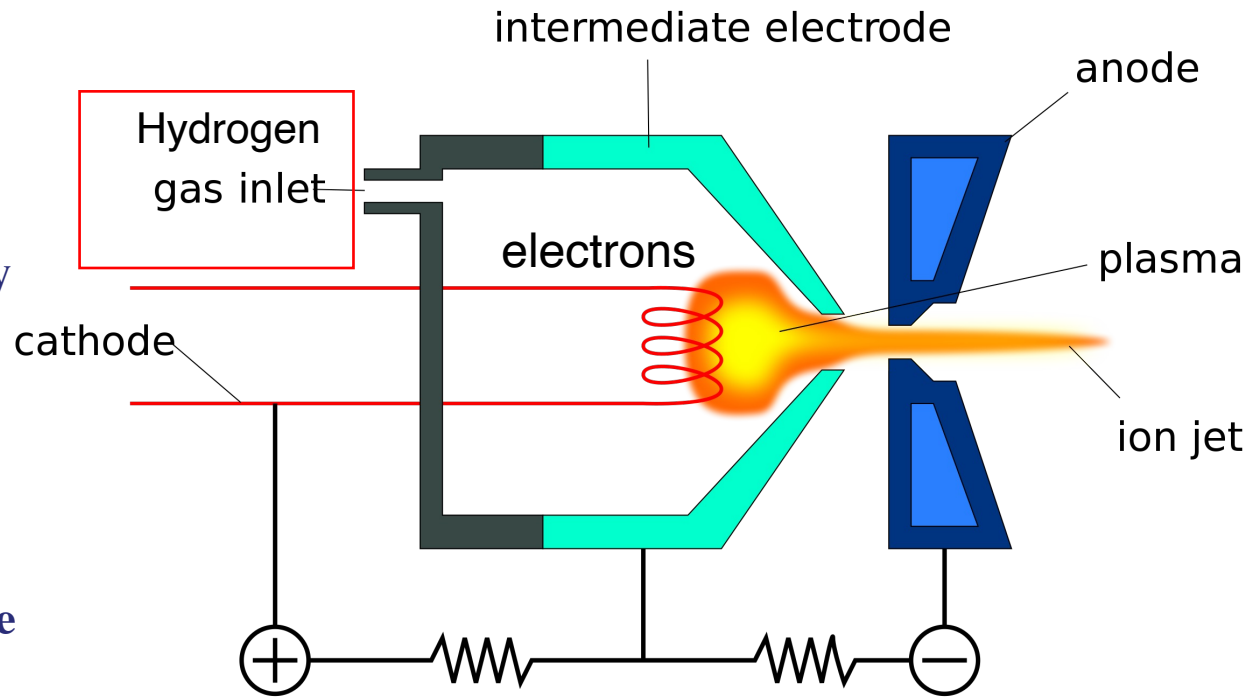
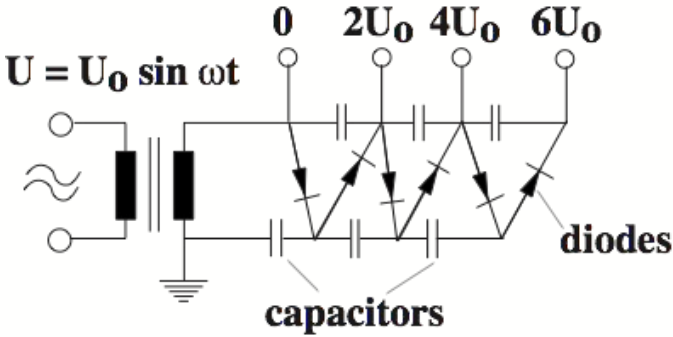**CERN p-source and 50 MeV Linac**

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Linear Acceleration with Electrostatic Field

allows for DC, 100 % duty factor

limited by HV-breakdown ~ 1 MV / m
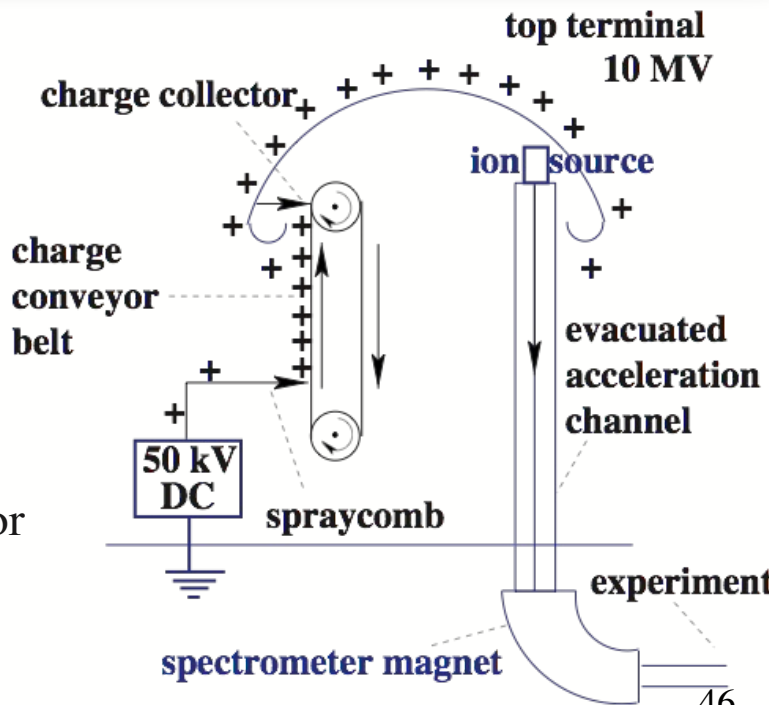
Cockcroft Walton
voltage multiplier

$U = U_0 \sin \omega t$

0    $2U_0$ $4U_0$ $6U_0$

diodes

capacitors

800 kV
proton pre-
injector
used at
CERN
until 1993

10305890
© CERN / Science & Society Picture Library
Viewed by Guest on 6/30/2006

Van de Graaff generator
static electricity from belts

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

top terminal
10 MV

charge collector

ion source

charge
conveyor
belt

50 kV
DC

spraycomb

evacuated
acceleration
channel

experiment

spectrometer magnet

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Time Varying Fields

Radio-Frequency or short RF acceleration

- **allows for multiple passages**

- **bunched beams, reduced duty cycle**

- **higher RF frequencies allow for higher acceleration gradients**

no time for breakdown / flashover

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

$$U = U_o \sin \omega t$$

little gain above 12 GHz

SC limit ~ 50 MV/m, reached for single cell surface gradients higher then acceleration gradients, smooth structures

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

9 cell 1.3 GHz SC niobium TESLA / ILC cavity
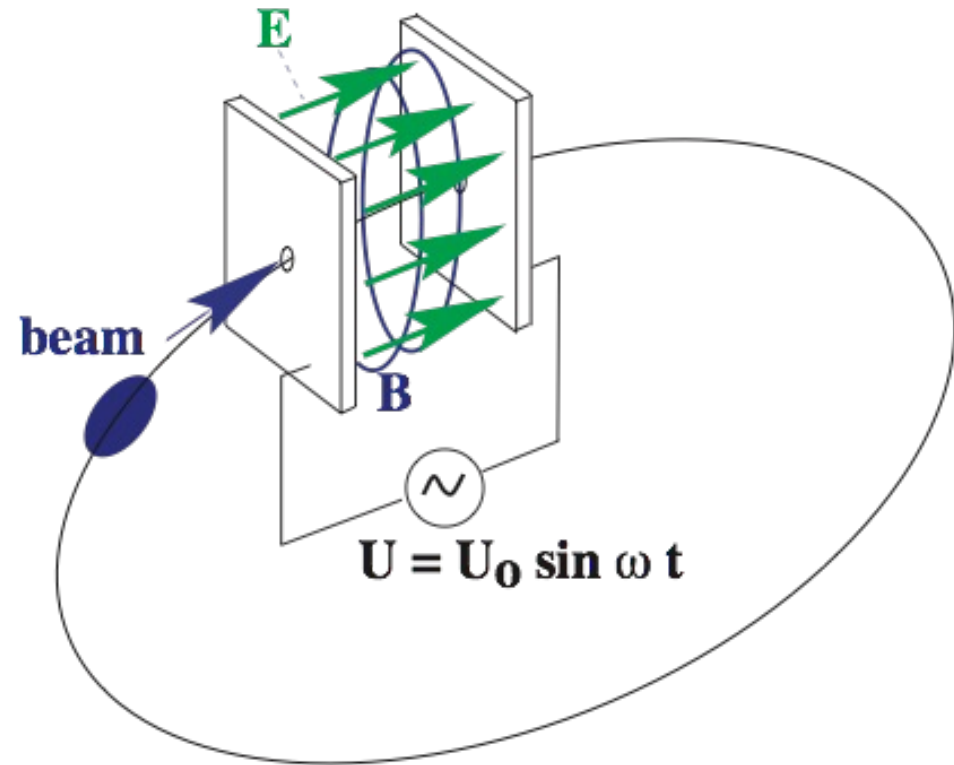
Basic parameters, Lorentz Force

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

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

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

ρ is the radius of curvature for motion perpendicular to the static magnetic field. Often called
- gyromagnetic or Larmor radius in astroparticle physics
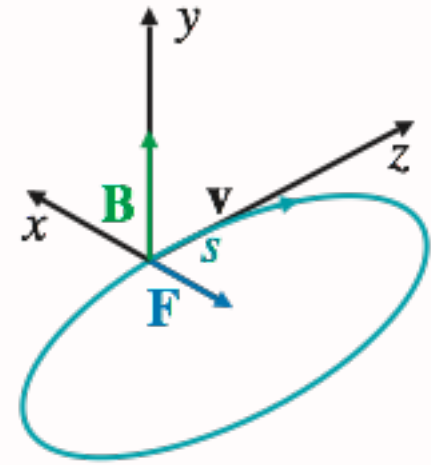- bending radius for accelerators

Bρ known as magnetic rigidity, units Tm

Circular motion for
$$\mathbf{E} = 0$$
$$\mathbf{v} \perp \mathbf{B}$$

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

for q = e numerically

B [T] = p [GeV/c]   3.336 m / ρ

high energy, v = c "p = E"

E < Eн = q B ρ 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}T = 1 Gauss ; a.u. = 1.5×10^{11} m

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

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

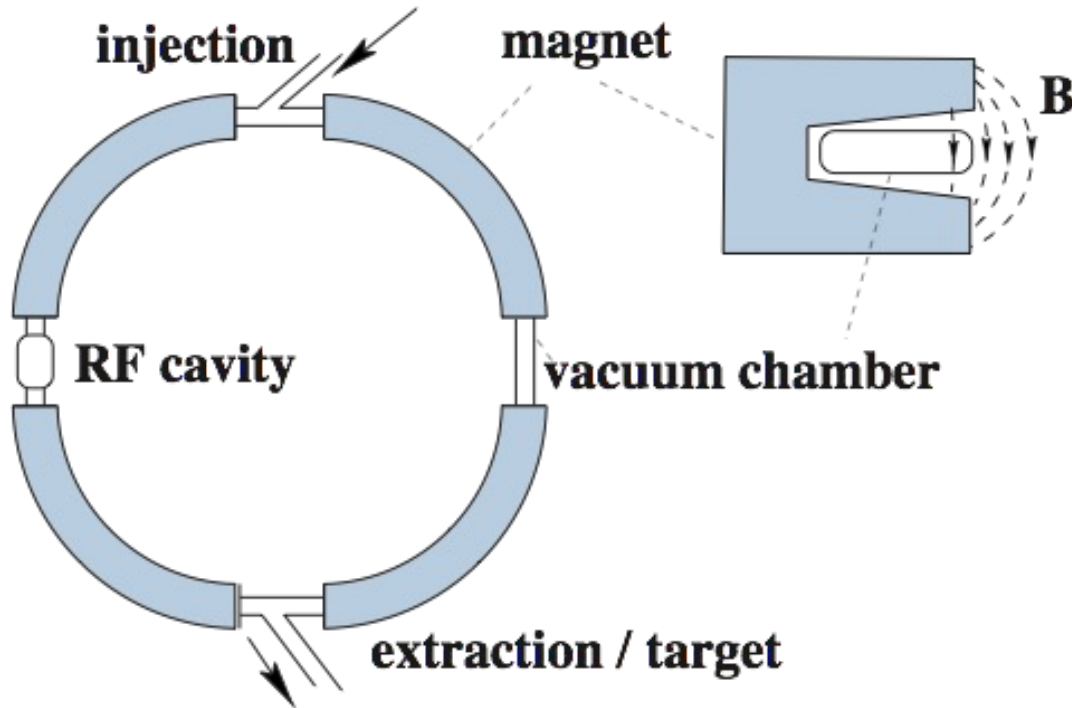ρ = 1.7×10^{19} m (4 % of galaxy-radius)

A sketch of an historical Cyclotron
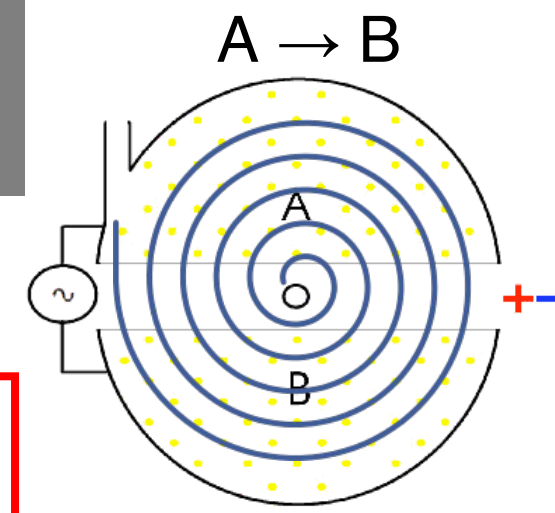
- **Cyclotron : constant rf-frequency. Magnetic field radius ϱ increases with energy. Used for smaller machines**
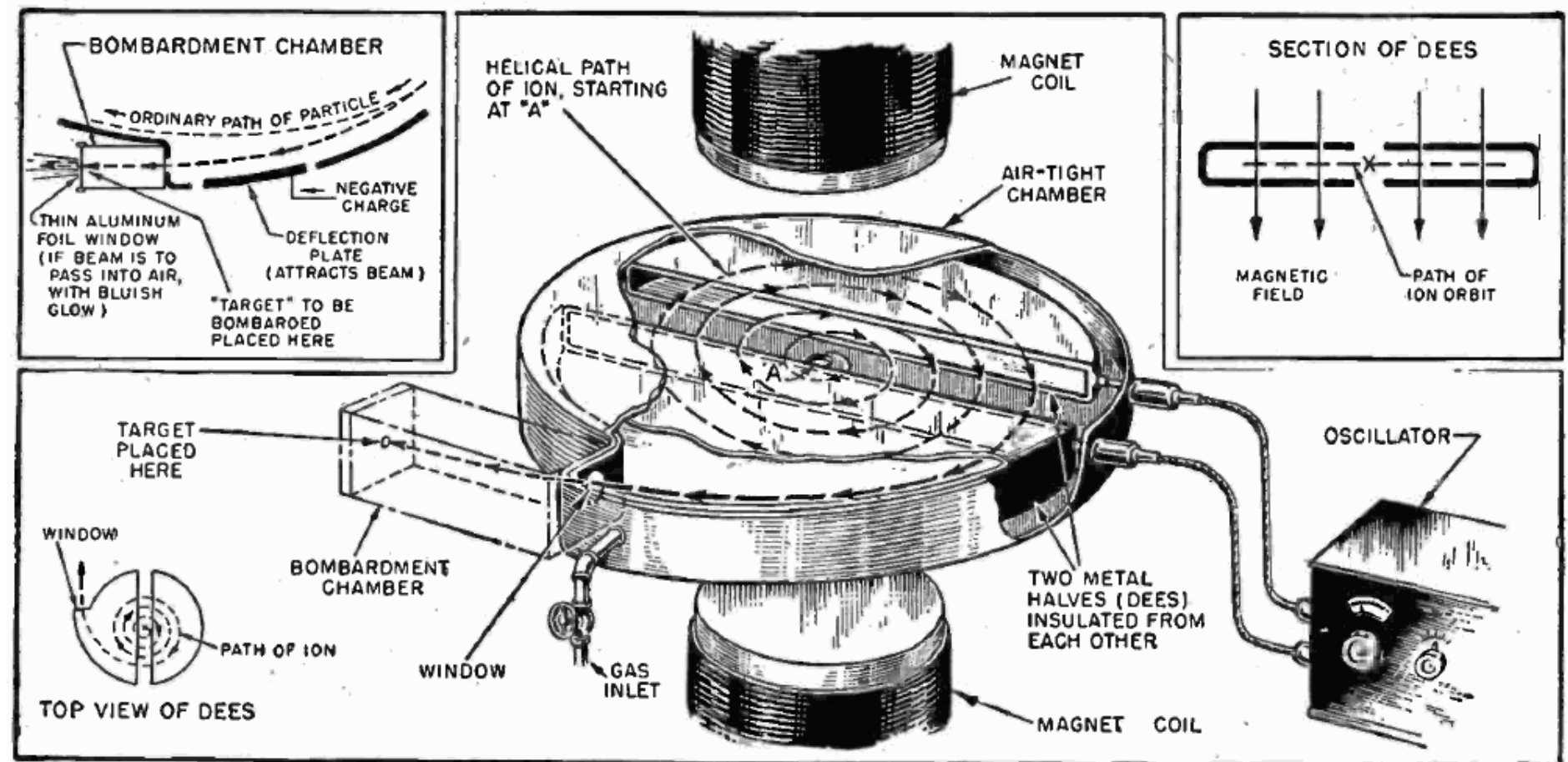
Circular Accelerator

$$B[T] = p \left[\frac{GeV}{c}\right] \cdot 3.336 \frac{m}{\rho}$$

$$\rho \propto p$$

- **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

Synchrotron

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

RF cavity

A B

+ –

B lagging

A synchronous

above transition

V

t
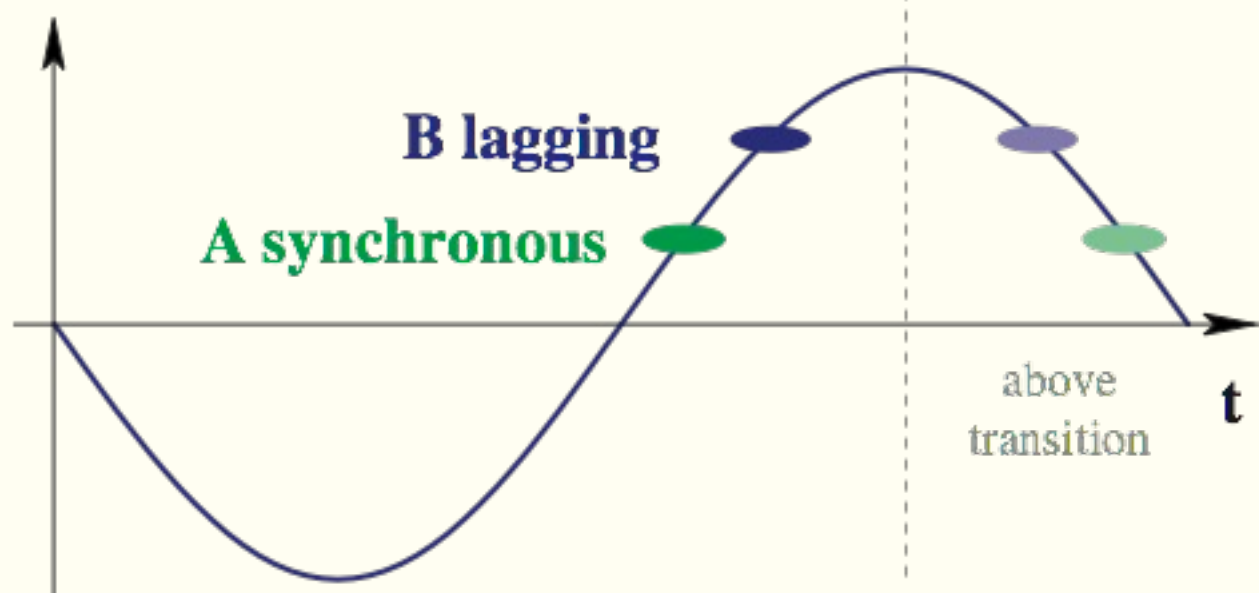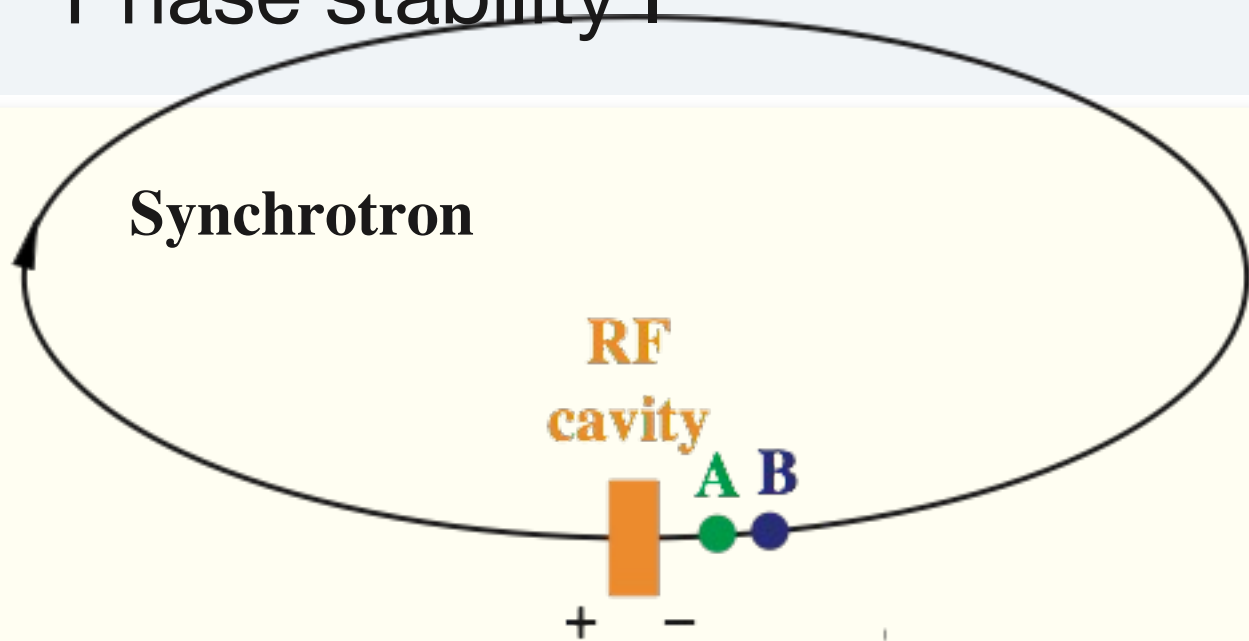
LHC nominal RF parameters
Voltage at injection   8 MV
          top energy 16 MV
Revolution frequency f_{rf} = h f_{rev} h = 35 640 f_{rf} = 400.7896 MHz L = 26658.864 m
Circumference   L = v / f_{rev} = β c / f_{rev} f_{rev} = 11.2455 kHz   1 turn in   88.92446 µs

Magnets and Power Consumption

Why super conducting magnets ?

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

LEP

$Lep = e^+e^-$ *machine*

B = 0.1 T   LEP2 ~ 100 GeV

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

I = 4.5 kA   together   R = 1 mΩ   P = 20 kW / cell

488 cells   **P = 10 MW**

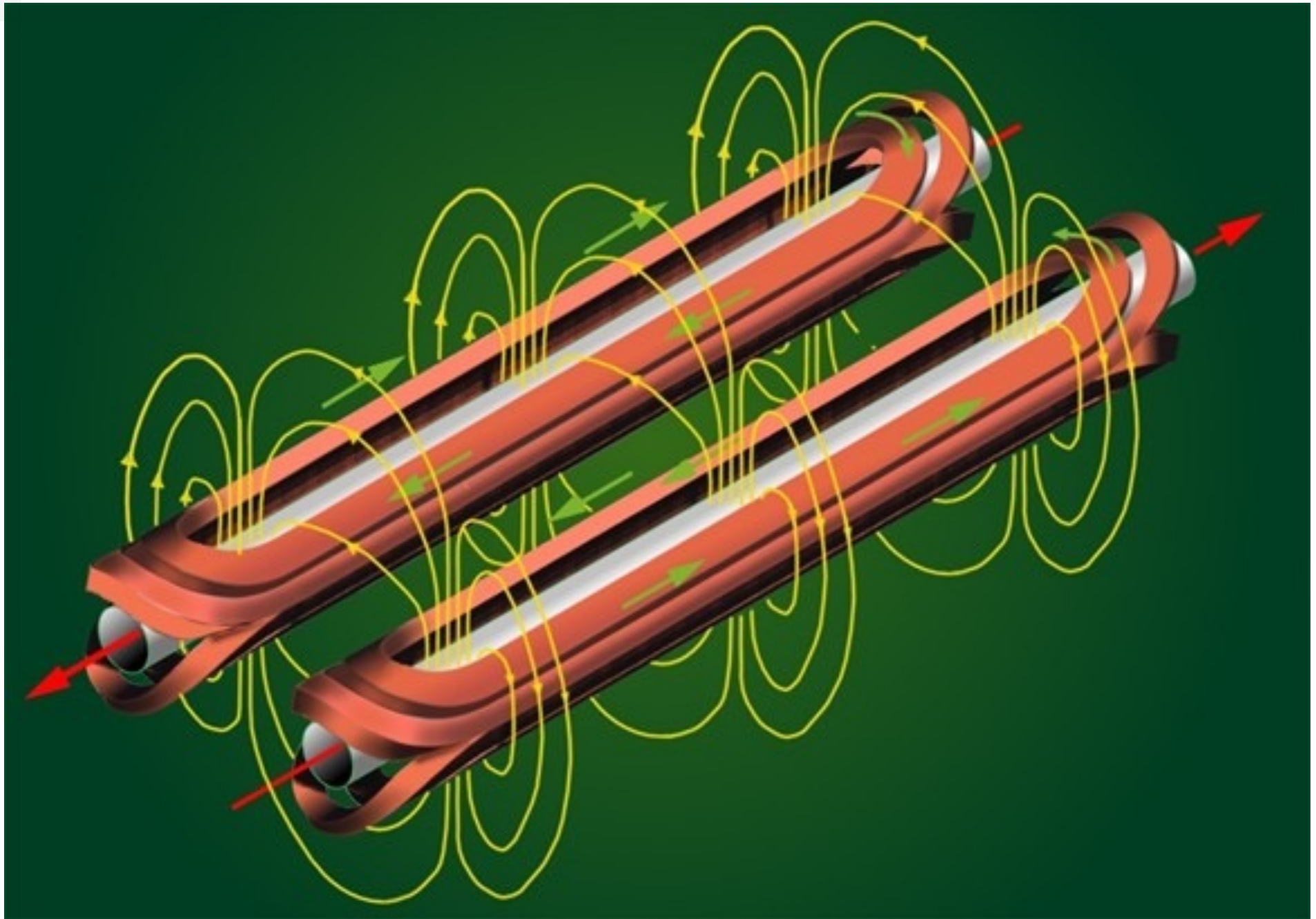**if we would have kept the same magnets for the LHC**

LHC   B ∝ I   B = 8.38 T

$LHC = pp$ *machine*

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

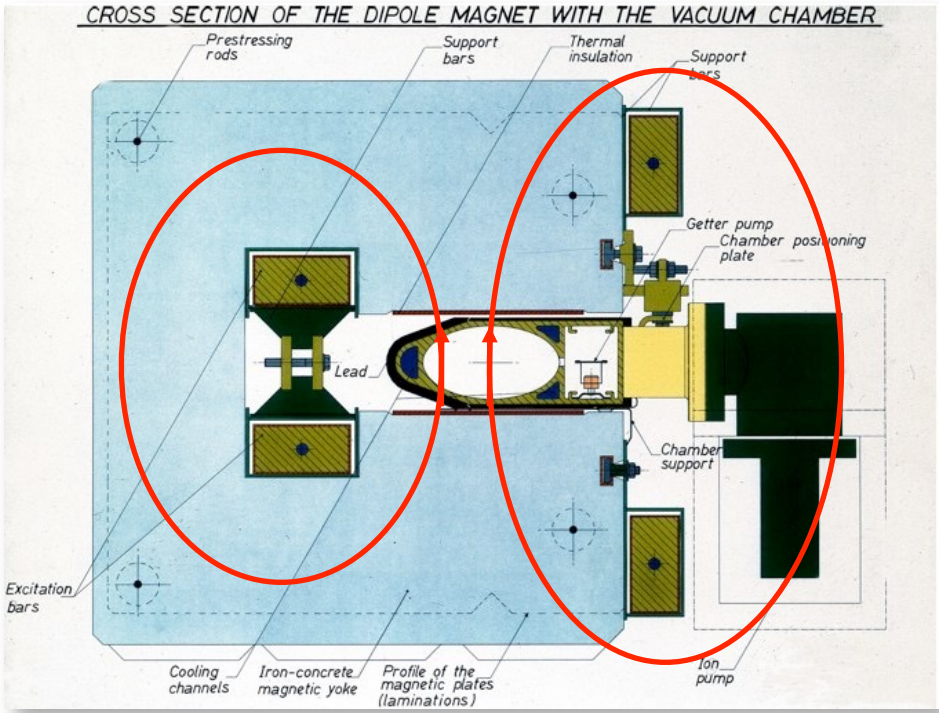**P = 78 MW / cell   × 488 cells   total power P = 38 GW**
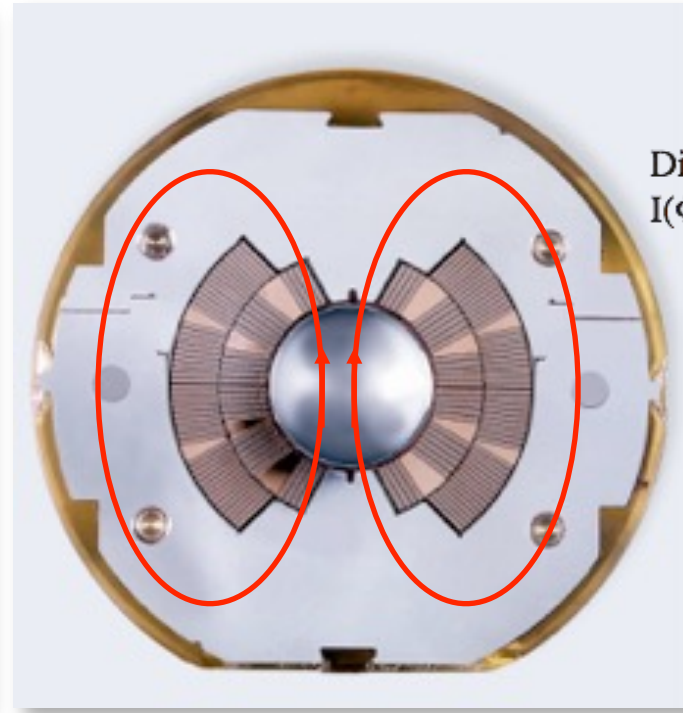
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LHC dipoles

Magnet technology

warm

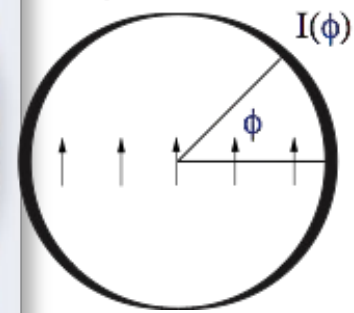**cold**


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

2-in-1 dipole magnet, 8.33 T field, 15 m long, mass 30 ton
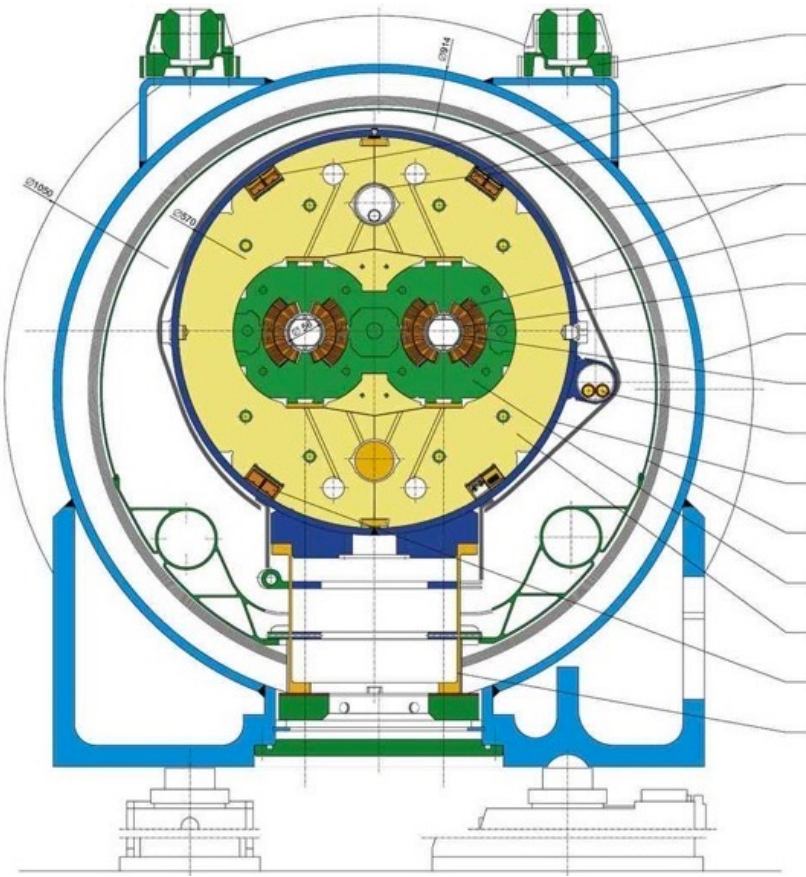
alignment target
main quadrupole bus-bars
heat exchange pipe
superinsulation
superconducting coils
beam pipe
vacuum vessel
beam screen
auxiliary bus bars
shrinking cylinder / He I-vessel
thermal shield (55 to 75 K)
non-magnetic collars
iron yoke (cold mass, 1.9 K)
dipole bus-bars
support post
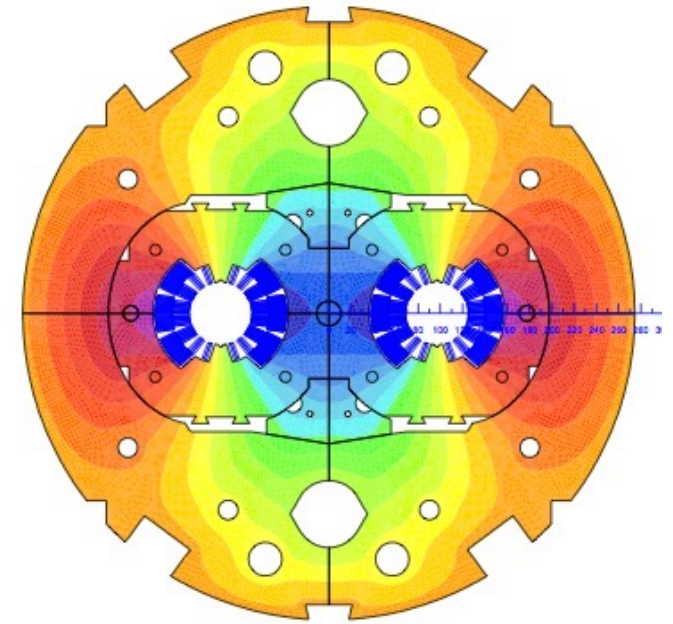
current distribution

LHC dipole magnet cross-section

Toni Baroncelli Experimental High Energy Physics at Colliders 2021

Toni Baroncelli Experimental High Energy Physics at Colliders 2021

Toni Baroncelli Experimental High Energy Physics at Colliders 2021
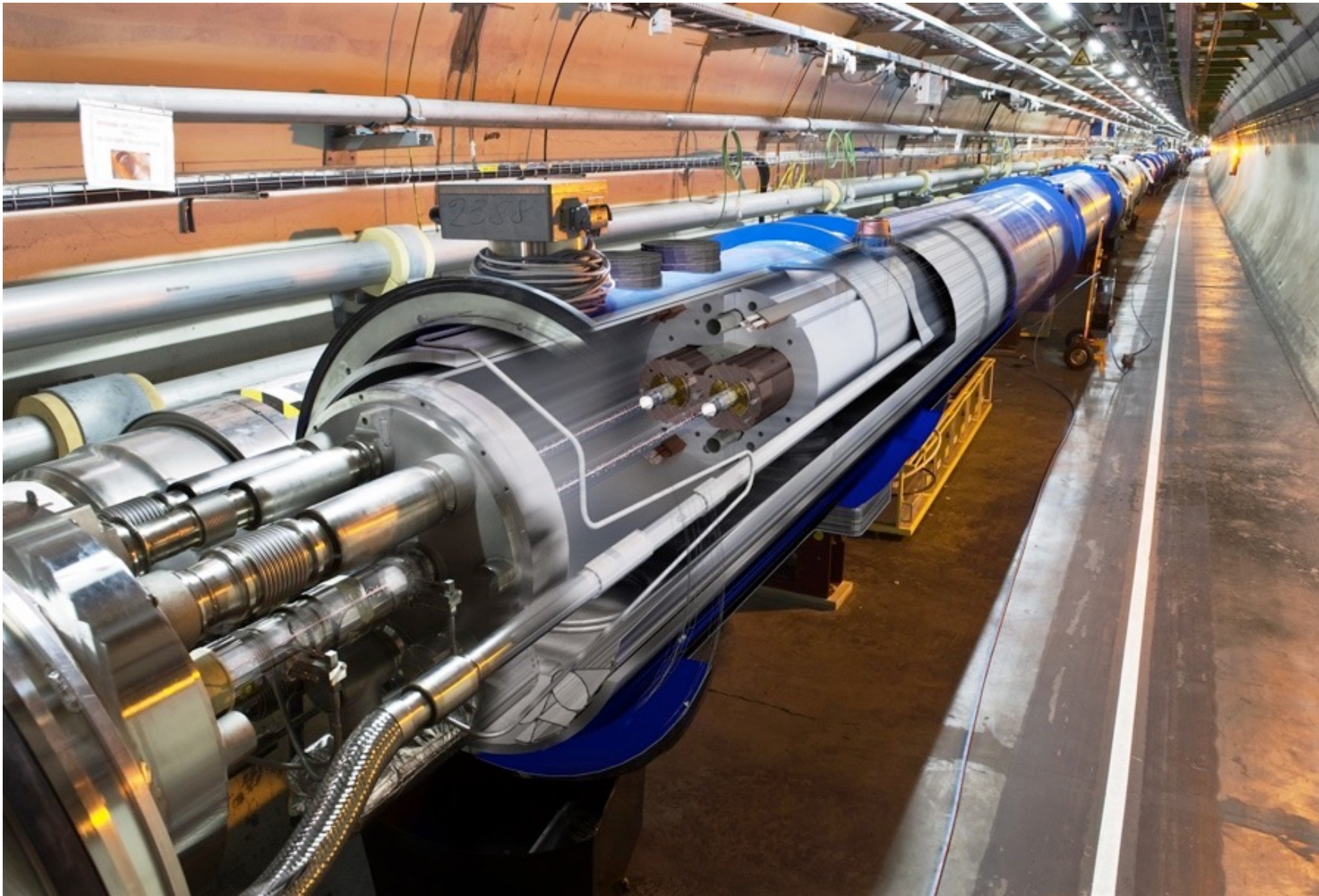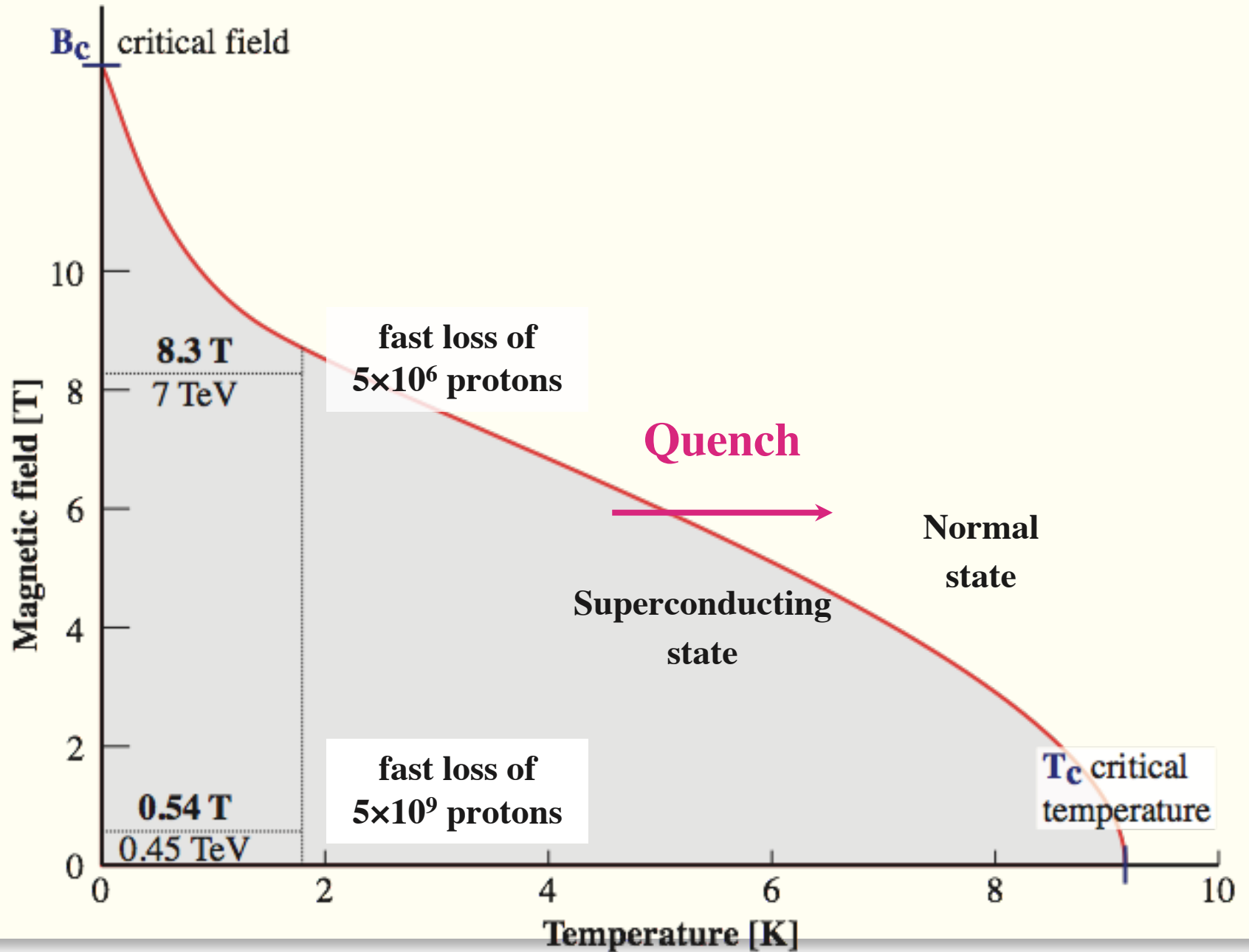
Fixed target, high energy collisions :

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)

Target

m_T

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

fixed target

Beam 1   Beam 2

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

collider

ring

or

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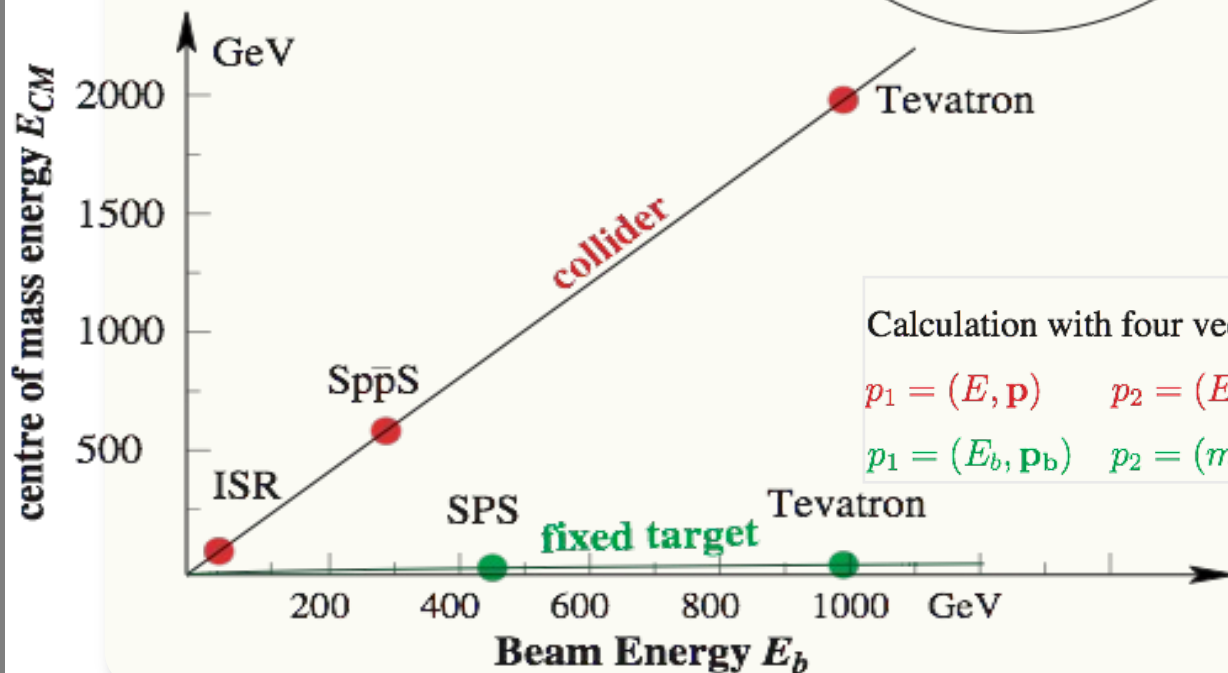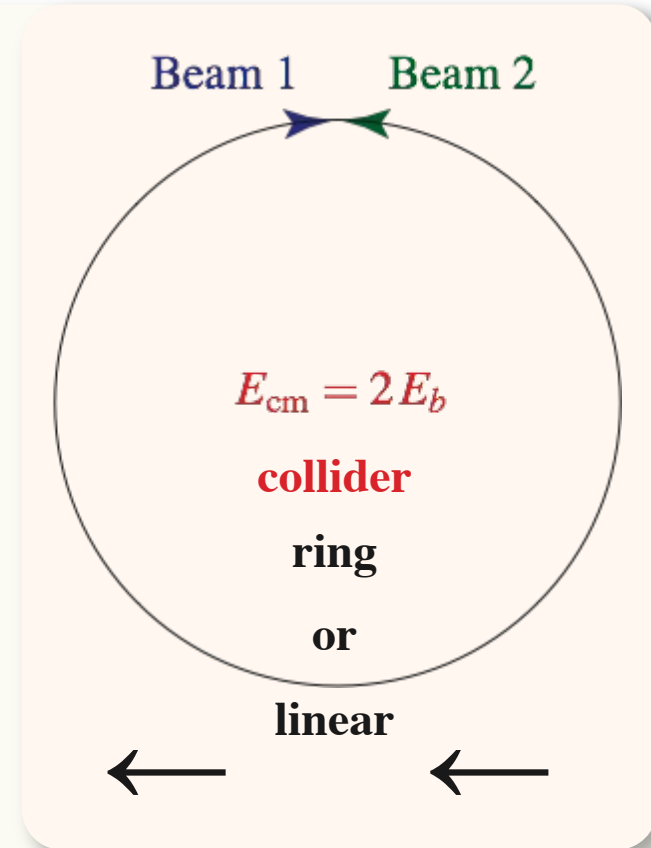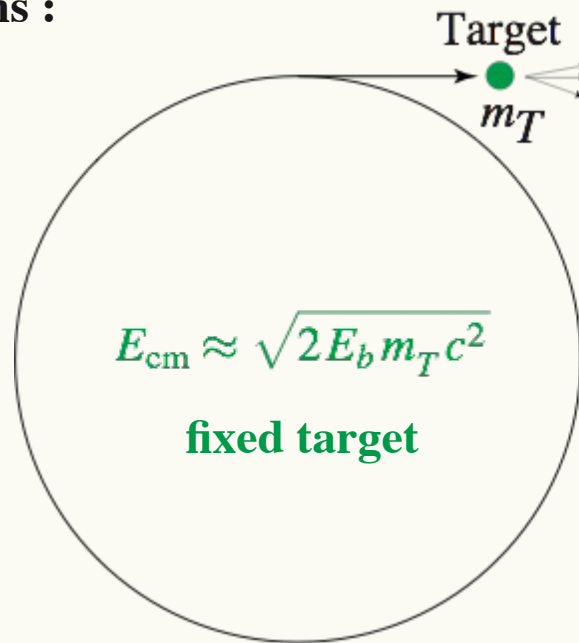
Calculation with four vectors for c = 1 $E_{\rm CM} = \sqrt{s}$ $s = (p_1 + p_2)^2$

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

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

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Primary cosmic ray spectrum

E spectrum falls as **E$^{-2.7}$**
to knee at E ≈ 5e^{15} eV
= 5×10^6 GeV
~1 particle/(m^2 year)

origin galactic

above ~ **E^{-3}**

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

conversion to **E$_{cm}$**

E$_b$ [eV]	E$_{cm}$ [TeV]	
10^{13}	0.137	
10^{15}	1.370	
10^{17}	13.70	≈ LHC pp
10^{19}	137.0	← LHC ions
10^{21}	1370.	
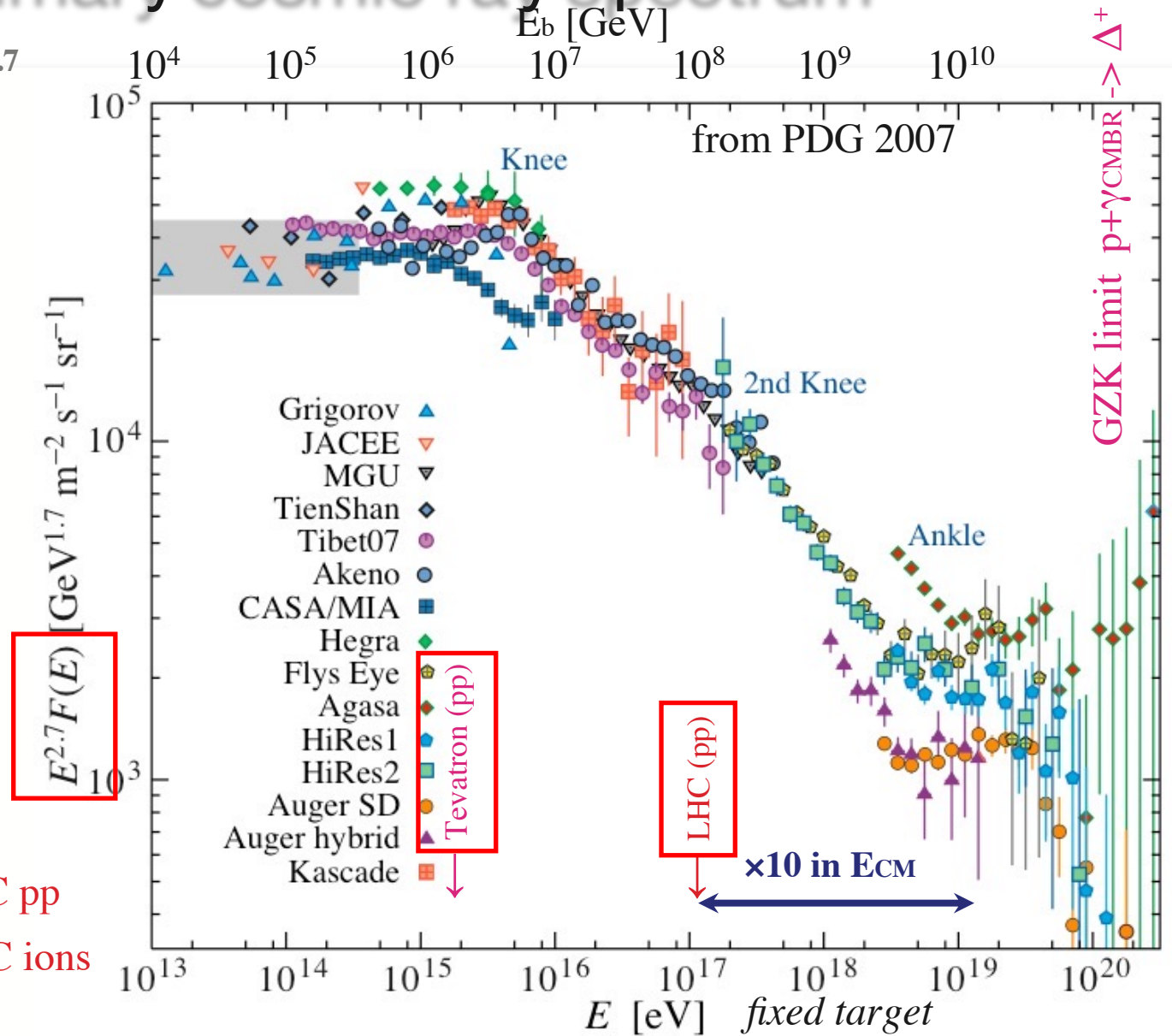
Nature has much larger and more powerful **cosmic accelerators** then we can ever built.
With colliders we can get to these collision energies in clean laboratory conditions.
The LHC already gets us to within 1-2 orders of magnitude of the very highest cosmic rays.

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Event rate for process with cross section σ

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

Luminosity from bunch

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

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

Interaction region

Bunch 1

N_1

Effective area A

Bunch 2

N_2

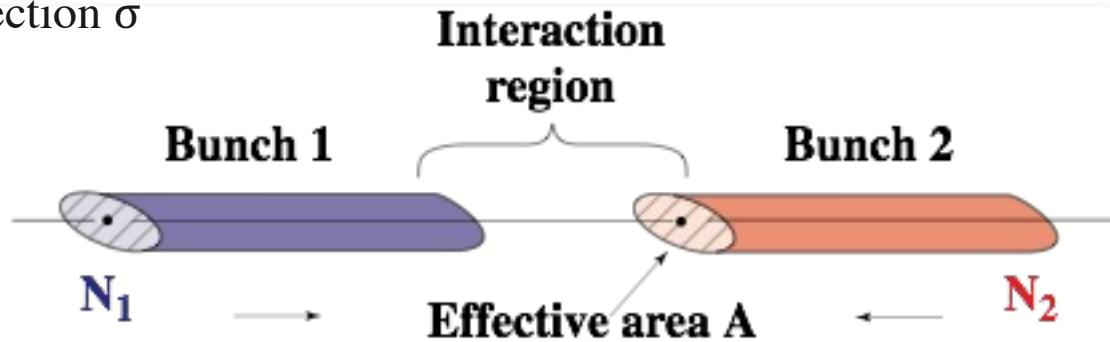for Gaussian bunches with rms sizes $\sigma_x\,\sigma_y$ $A = 4\,\pi\,\sigma_x\,\sigma_y$

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

$< \beta >_{arc} = 80$ m $\beta_{IP} = 0.5$ m

Rare new processes, like Higgs production can have very small cross section,
like $1 fb = 10^{-39} cm^2$.   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

$F = e\,(\,v \times B\,)$
here
$F = e\,(0, 0, v) \times (\,B_x,\ B_y, 0)$
$\quad = e\,(\,-\,v\,B_y,\ +\,v\,B_x,\ 0)$

Combine F D
Defocusing when at small amplitude
Overall 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 $f = f_1 = -f_2$

Conductor
Iron
S N
S R N
N S
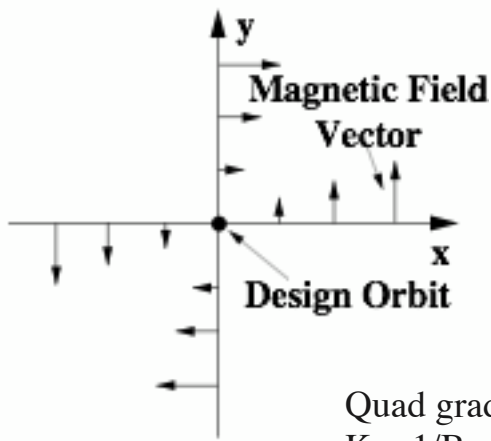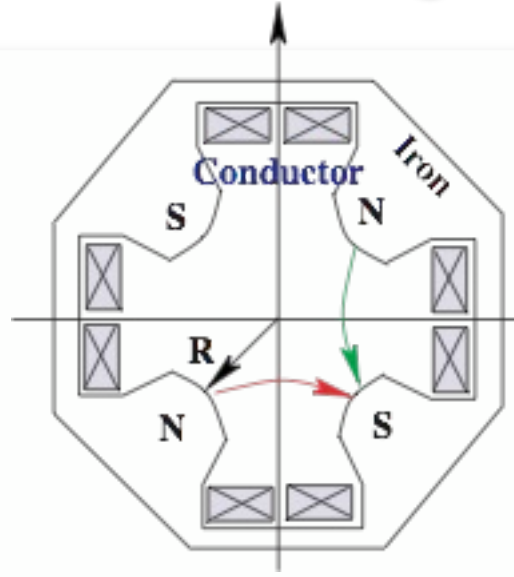
$B_x = k\,y$
$B_y = k\,x$
$B_z = 0$

$\nabla \times B = 0$

Quad gradients in the LHC
$K = 1/B\varrho\ \ \partial B_y /\partial x \approx 200$ T/m

alternate gradient focusing

F   D
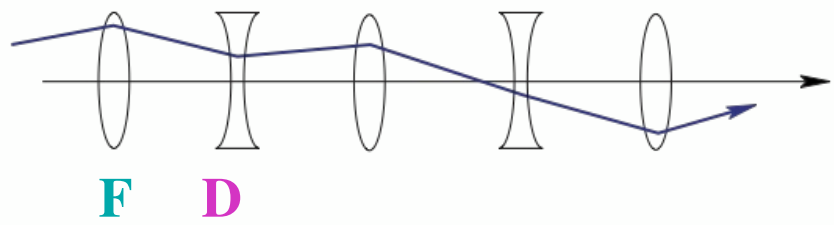
together with bending magnets FODO lattice

D

F
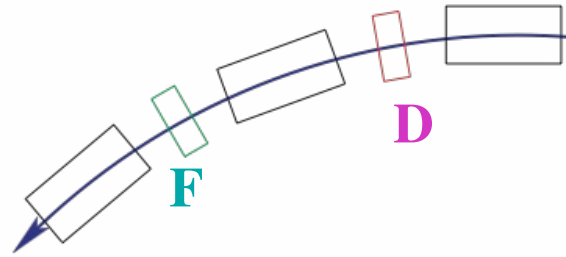
N. C. Christofilos, unpublished manuscript in 1950 and patent
Courant, Snyder in 1952, Phys. Rev. 88, pp 1190 - 1196 + longer review in Annals of Physics 3 (1958)

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

Actual Trajectory

Phase advance
Lyapunov-Floquet Transformation

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

Tune # of betatron oscillations

$$Q = \mu / 2\pi$$
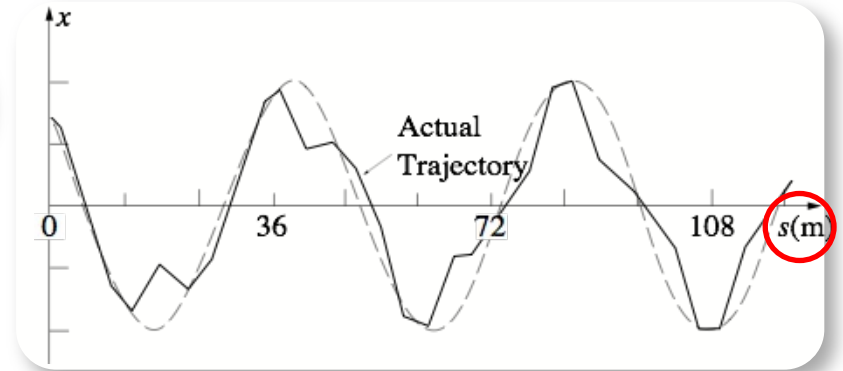
motion x/√β *plotted with phase advance normalised coordinates - becomes simple cos*

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

ε 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

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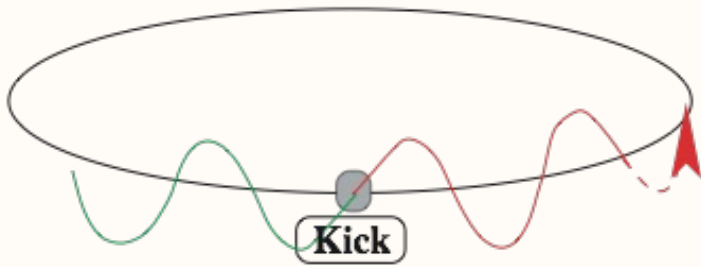
Misalignments and dipole field errors

→ **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 = $ int.**

**Minimise field and alignment
errors**

Q_y

Q_x

Q_y

Q_x

**stable
working
area**

electrodes

vacuum chamber (beam-pipe

beam

Beam Pickup Monitor

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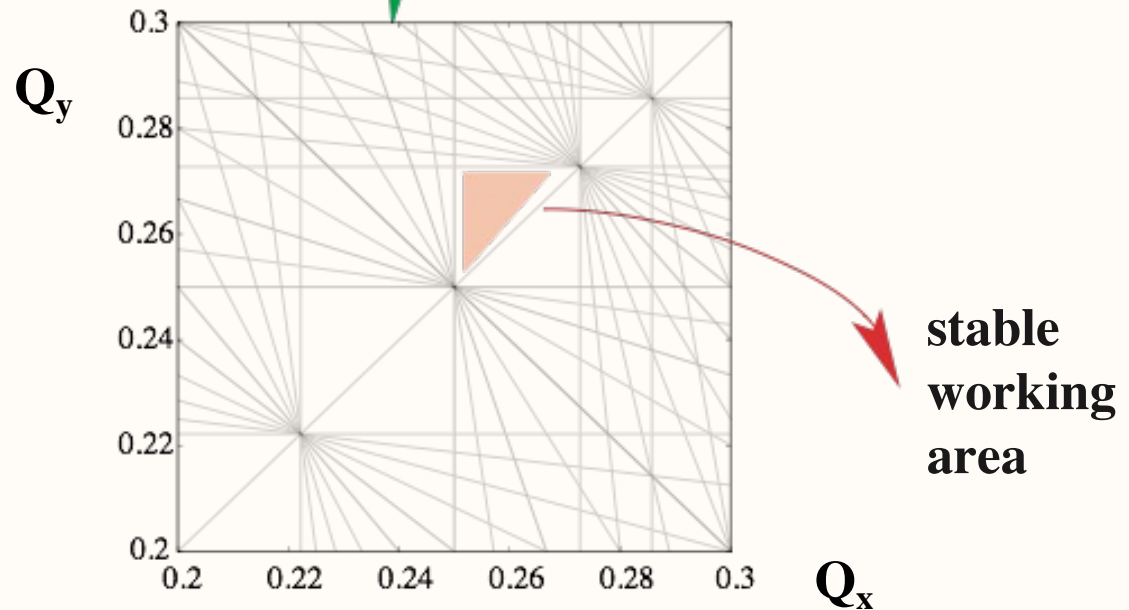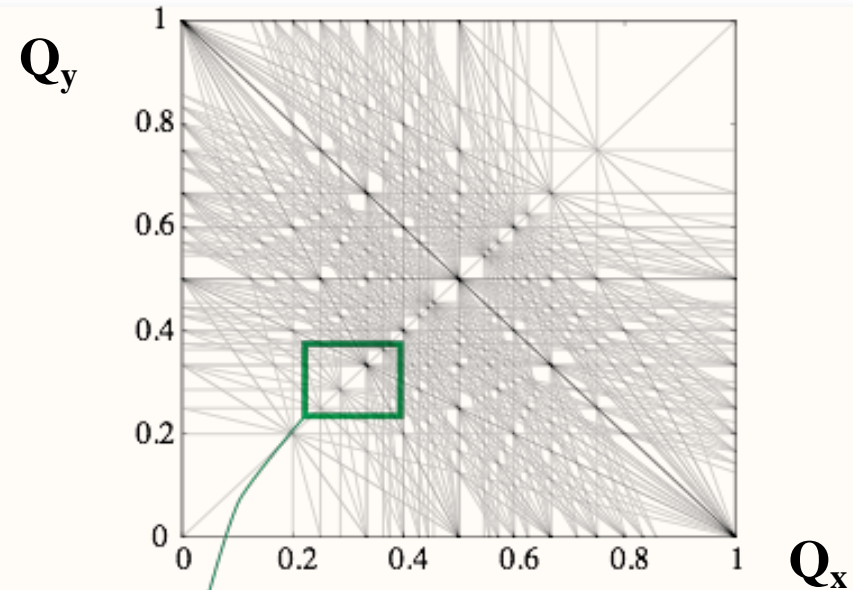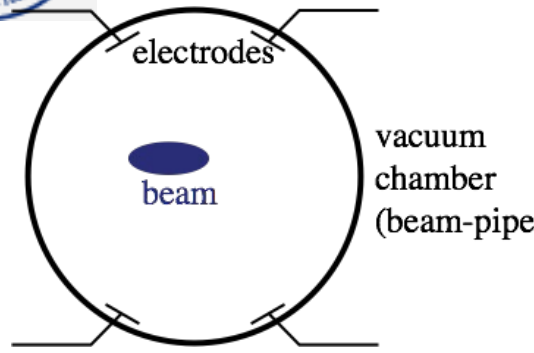

Mean = -0.007 / RMS = 0.067 / Dp = 0.0010

V Pos [mm]

ATLAS   INJ-B1   M-CLEAN   RF-B1   CMS

Monitor V
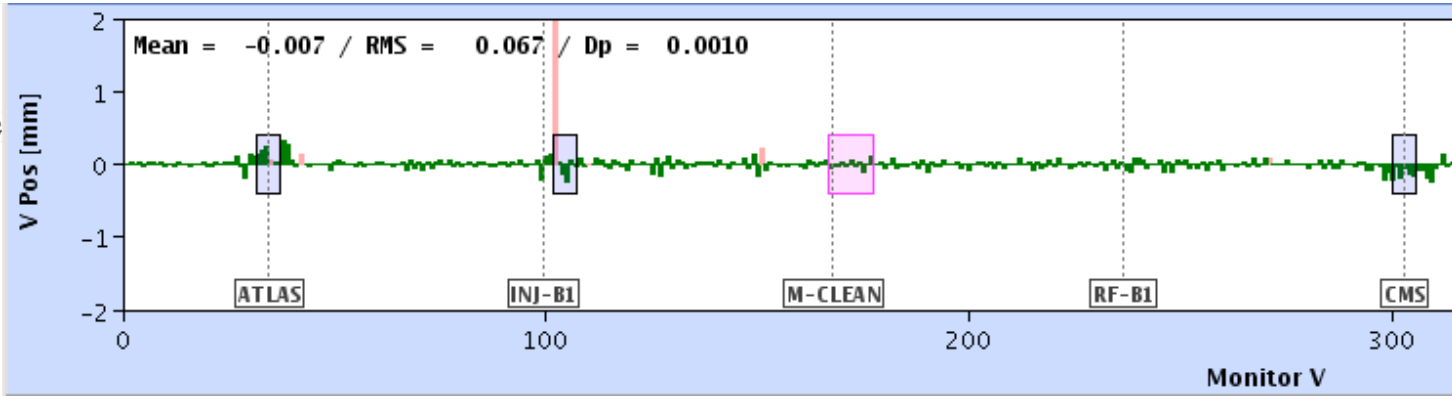
$\langle I_b \rangle$ average ring and

$\hat{I}$ 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 = 4×10^{11} $\langle I_b \rangle = 0.72$ mA $\sigma_z = 2$ cm $\hat{I} = 960$ A

LHC n = 1.15×10^{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

vertical **tune**

.220

relative amplitude

q_y

64
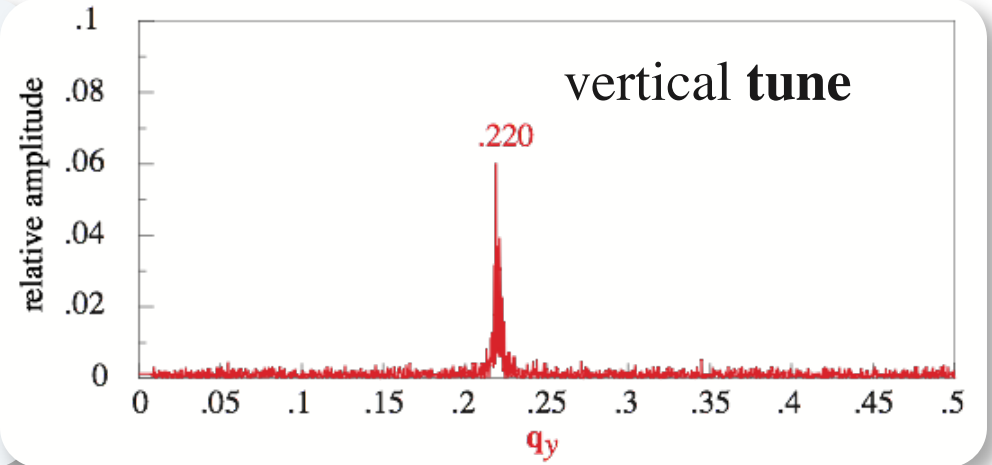
consider : **beam of many particles on stable orbit** and

simple case : **dispersion and slope β′ = 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 $\varepsilon_x, \varepsilon_y, \varepsilon_z$

IP: squeeze β to a minimum, called β* ⇒ maximum of divergence, needs aperture
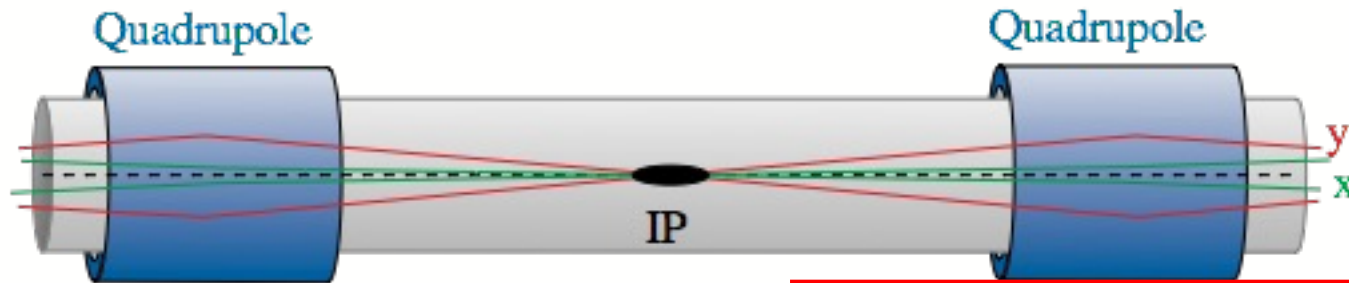
LHC $\varepsilon_N = \varepsilon \beta\gamma = 3.75$ μm, at top $E_b = 7$ TeV: $\varepsilon = 0.503$ nm, $\beta^* = 0.55$ m, $\sigma^* = 16.63$ μm, $\theta^* = 30$ μrad

Standard Synchrotron Radiation

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

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

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

Synchrotron radiation

$\boxed{\gamma \propto 1/m_0}$

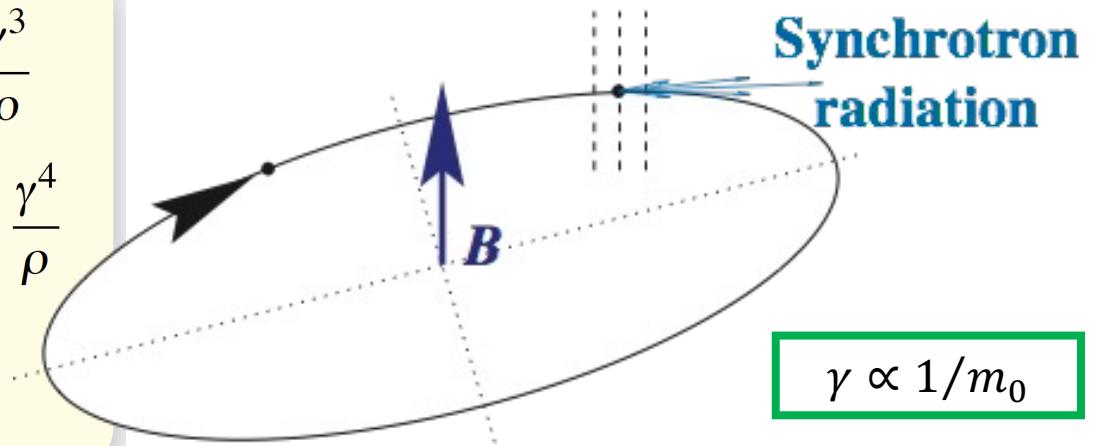|		E GeV	γ	ϱ m	U_0 MeV	E_c keV	τ_d s	N 10^{12}	I mA	P_b MW	B T
RHIC	Au	A×100	107.4	242.8	21×10⁻⁶	1.5×10⁻⁶	4.9×10⁶	0.06	60	1.3×10⁻¹²	3.42
LHC	p	7000	7460.5	2804	0.0067	0.044	61729	646	1163	0.0072	8.33
LEP1	e	45.6	89237	3026	126	69.5	23×10⁻³	2.22	4	0.5	0.05
LEP2	e	104.5	204501	3026	3490	836	1.9×10⁻³	2.8	5	18	0.115

Same beam energy E and radius ϱ : electron instead of proton $\boxed{U_0 \sim \gamma^4 \;:\; (m_p/m_e)^4 = 1.13 \times 10^{13}}$

Electrons, $E \gg 100$ GeV needs linear collider (ILC / CLIC)

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

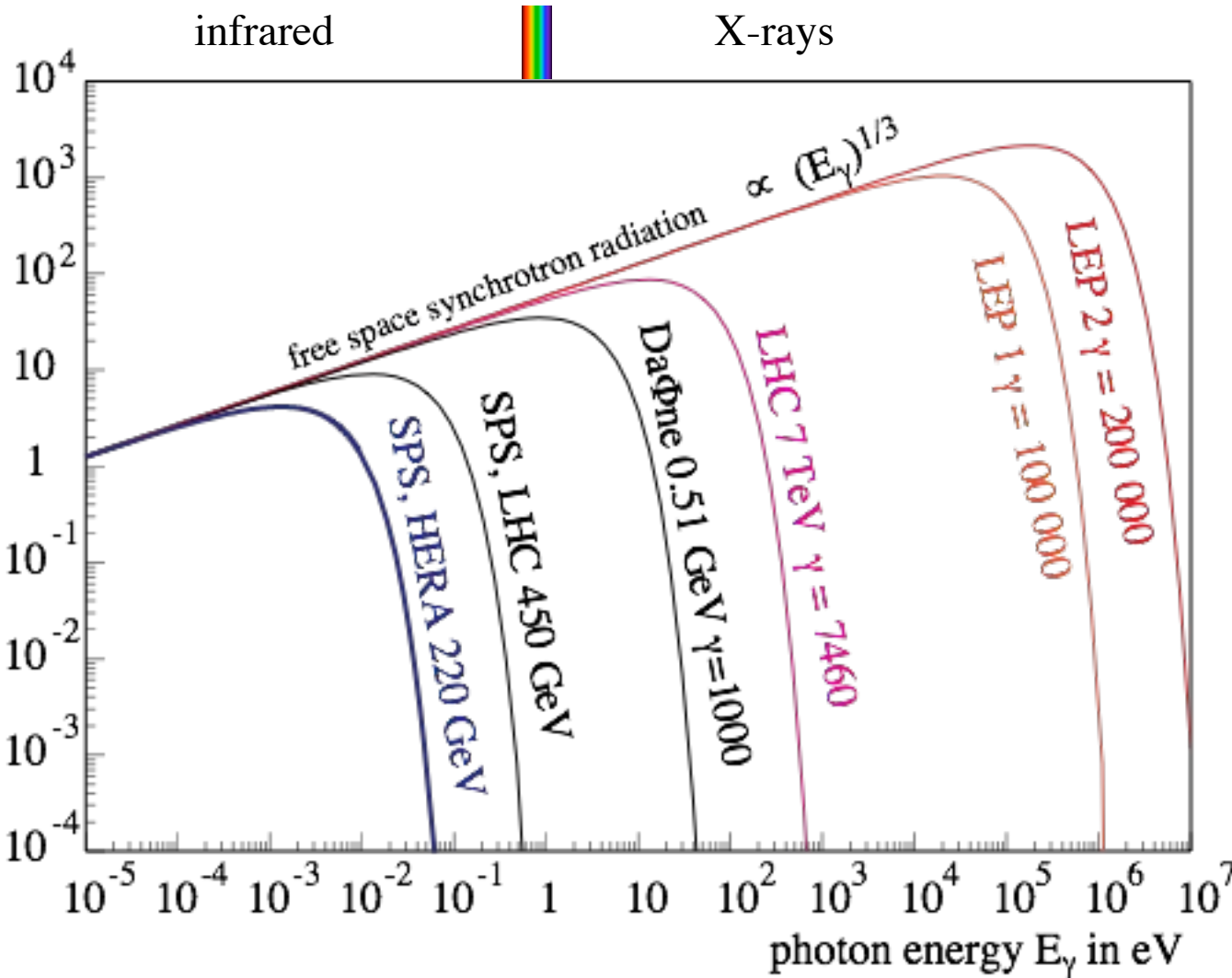**Gold ions Au^{79+} A=197 $\langle E_\gamma \rangle = 8/(15\sqrt{3})\,E_c$ $8/(15\sqrt{3}) \approx 0.308$**

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

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

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

ρ bending radius
h chamber height
cutoff relevant
for γ ≈ 100

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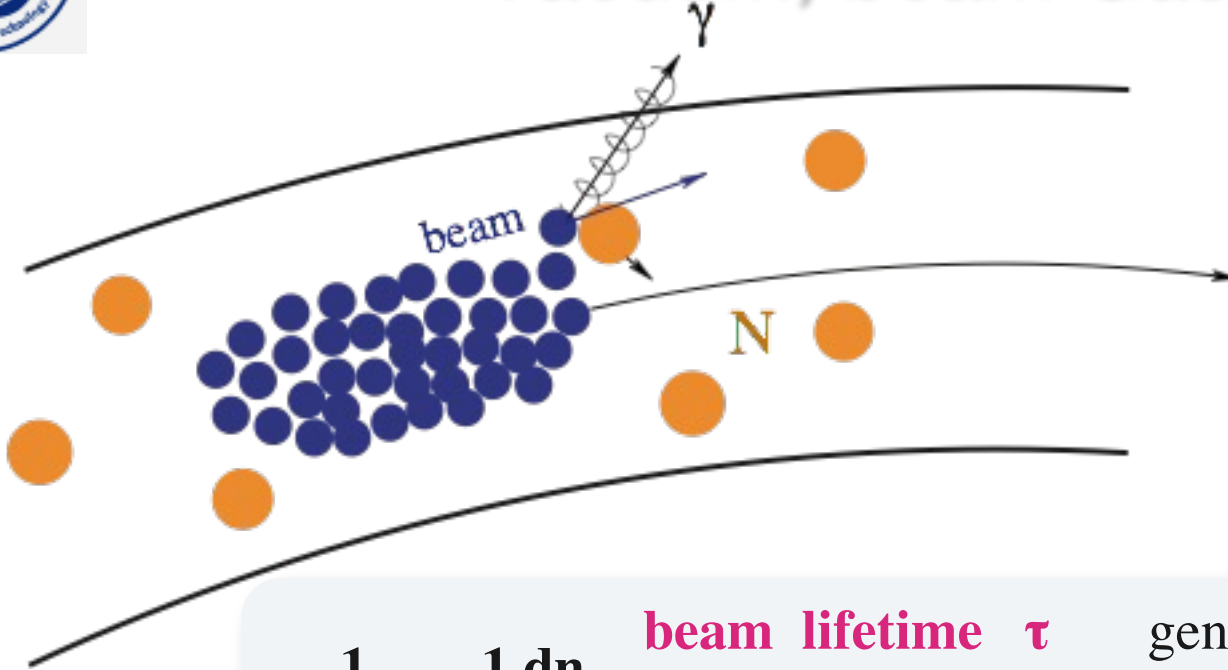10^{+7} eV   λ = 124 fm

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

γ

beam

N

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

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

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

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

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

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

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

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

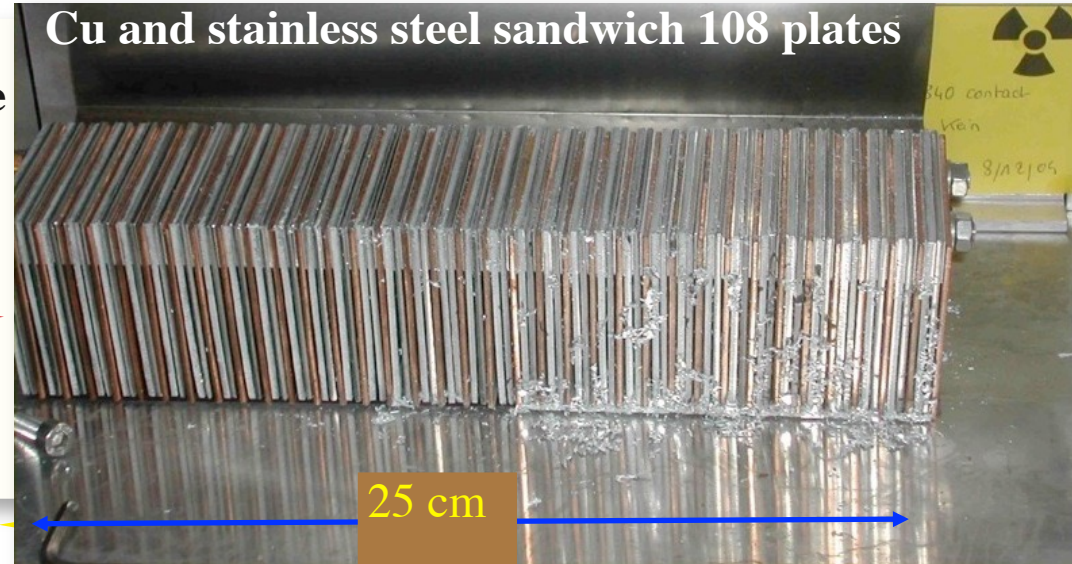$$\tau = \frac{1}{P_{\text{coll}}\,c} = 1.7 \times 10^5\,\text{s} = 47\,\text{hours} \qquad \text{for}\ v \approx c$$

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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

Cu and stainless steel sandwich 108 plates

25 cm

6 cm

$2 \cdot 10^{12}$ $4 \cdot 10^{12}$ $8 \cdot 10^{12}$ $6 \cdot 10^{12}$

SPS results confirmed :

8×10^{12} clear damage

2×10^{12} below damage limit
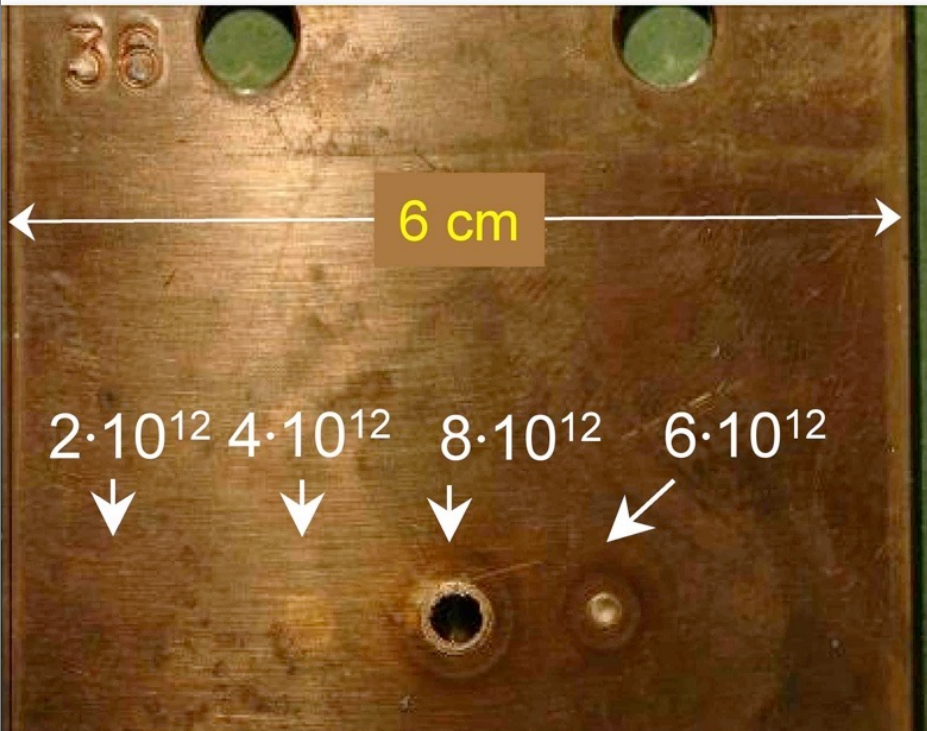
for details see V. Kain et al., PAC 2005 RPPE018

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
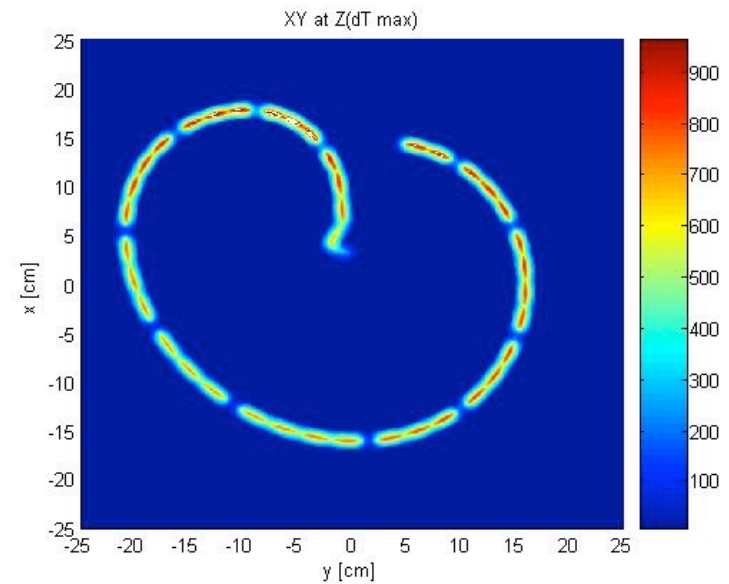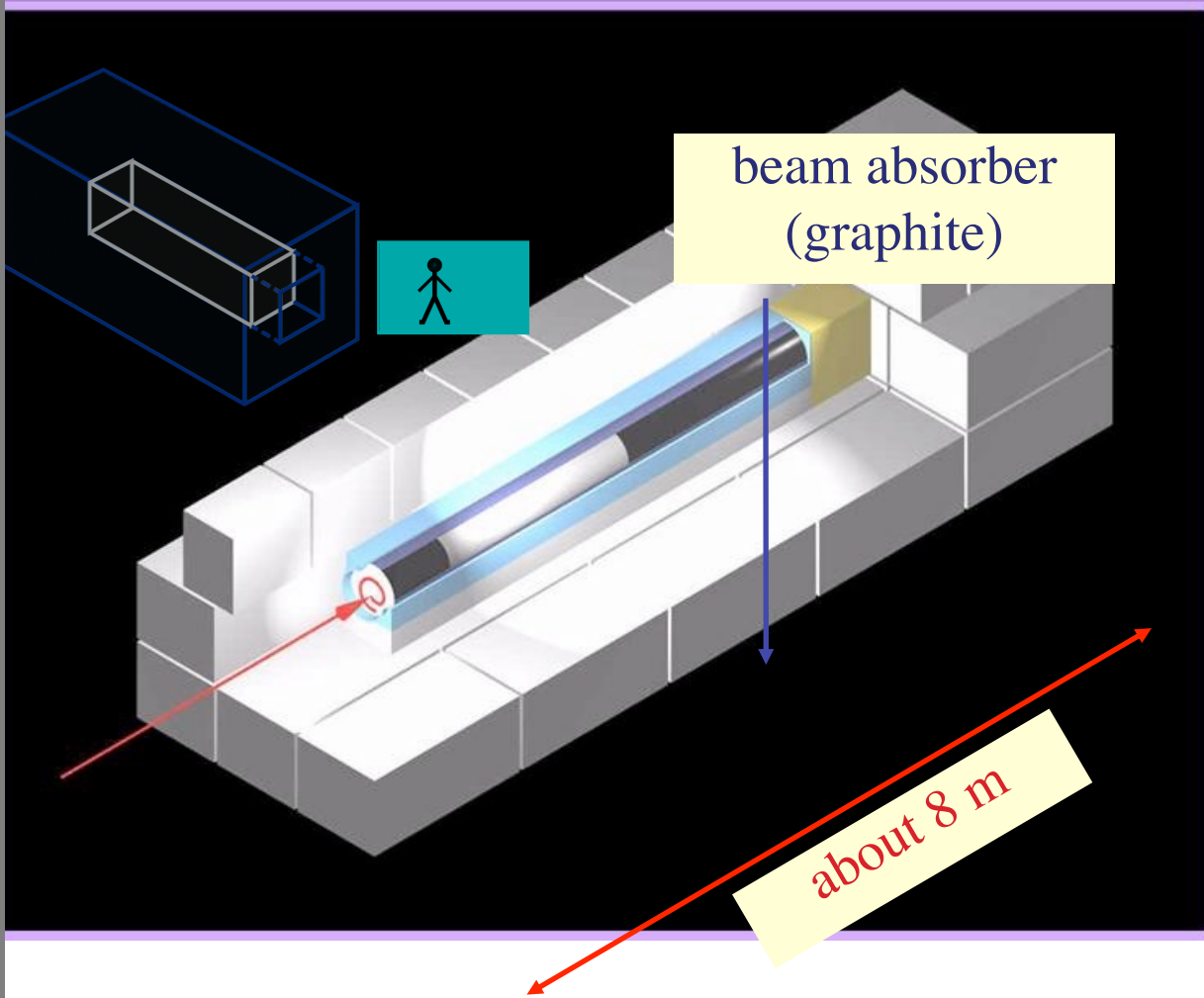
70

beam absorber (graphite)

about 8 m

XY at Z(dT max)

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Beam 1

Q5L

Q4L

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

Q4R

Q5R

Beam 2

72
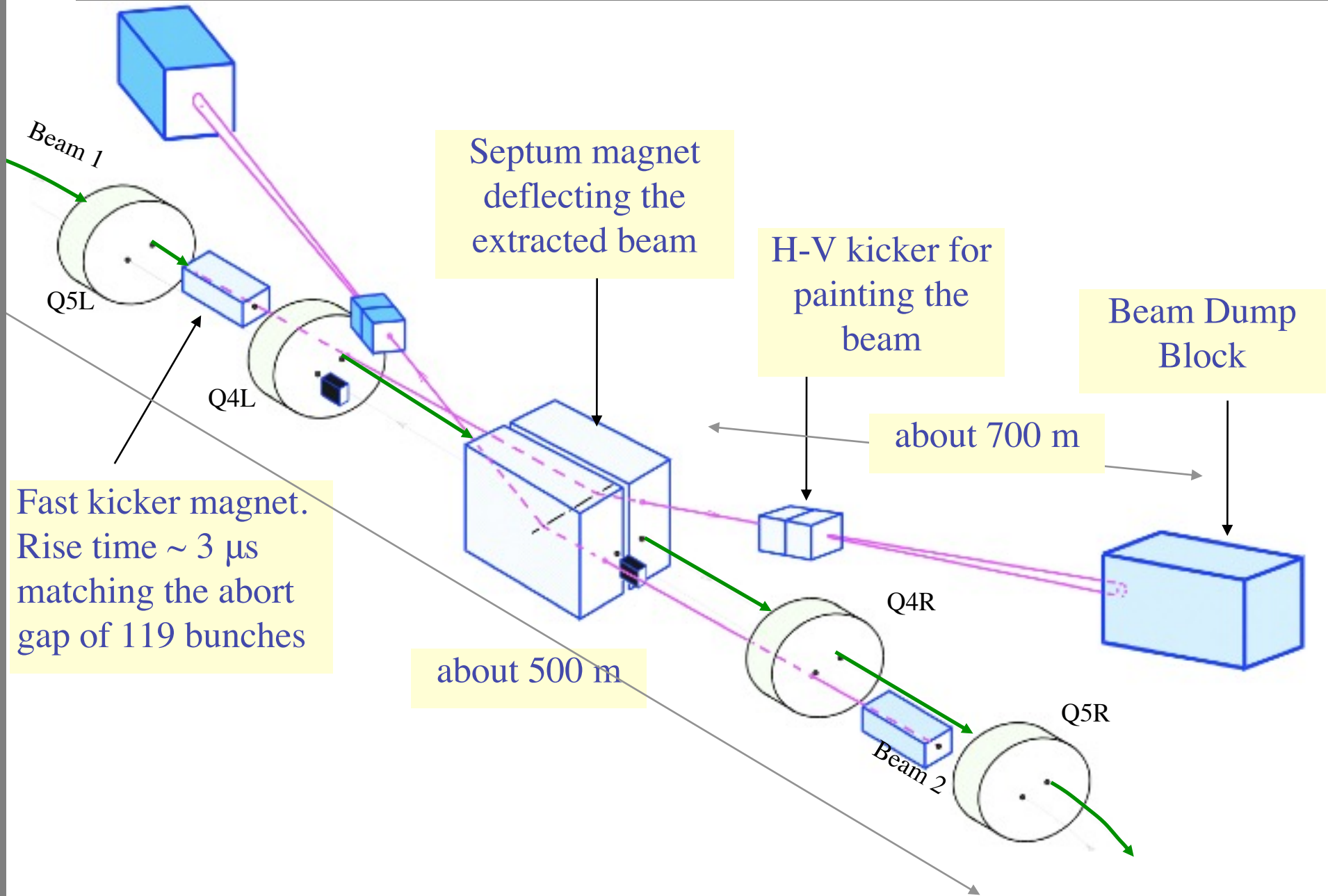
- **absolute luminosity normalization**

- **low, well understood backgrounds**

- **precision optics for ATLAS-ALFA and TOTEM**

$\beta^* = 1000$ m, Oct.'12

VdM scan

IP1 H

IP1 V
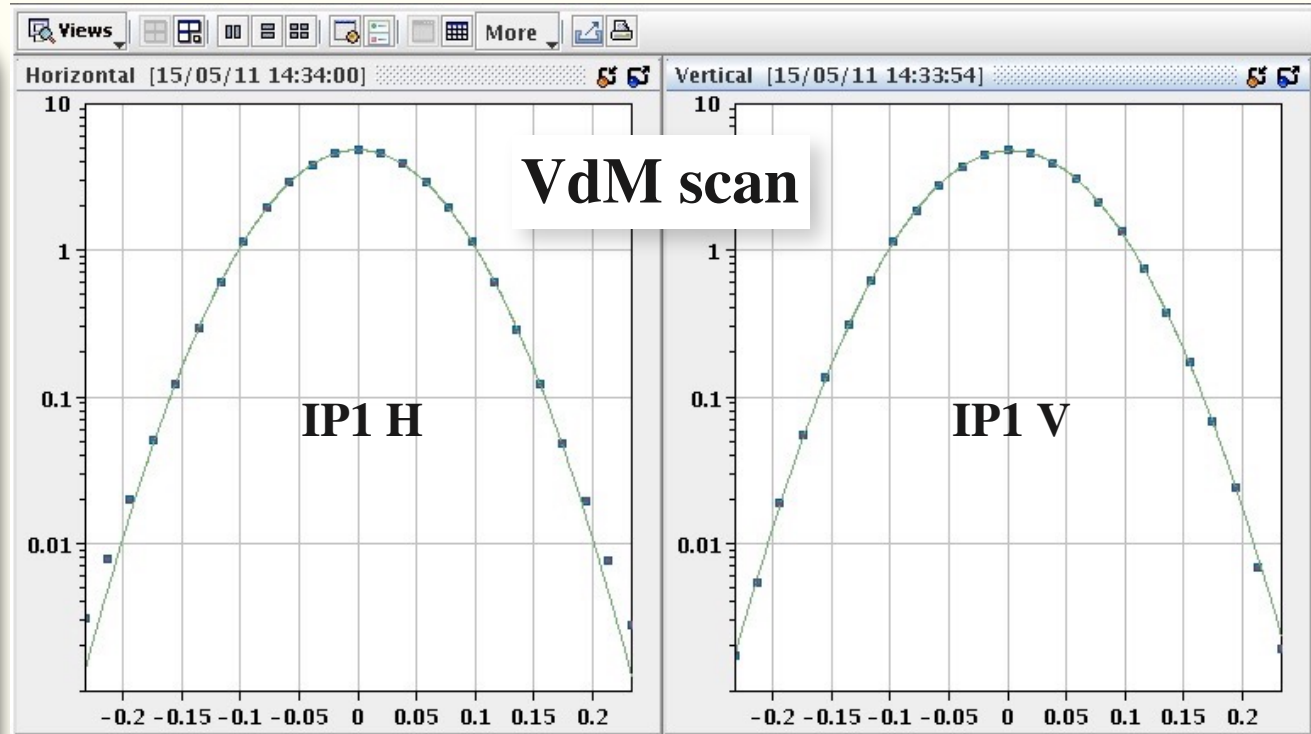
precise measurement of the luminous region + beam intensity --> absolute luminosity and cross section calibration

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

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The LHC is still a rather young machine
Operation planning + upgrade studies (HL-LHC) extend to ~ 2030
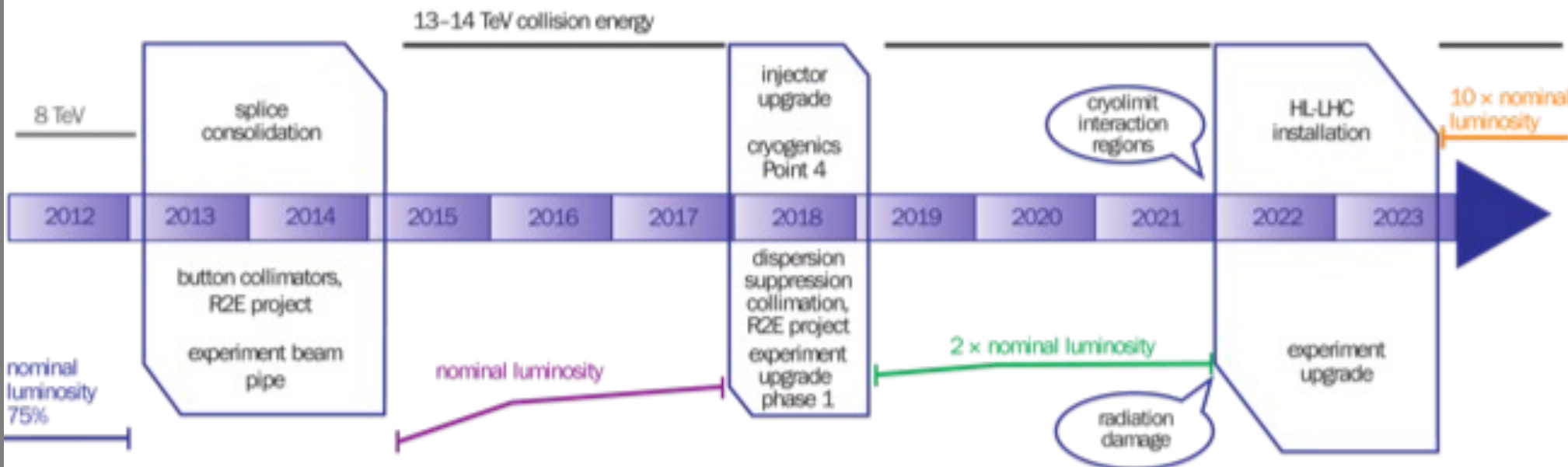
Further ideas already exist (HE-LHC, LHeC, TLEP)
We also study other machines, and in particular CLIC ➔

CLIC

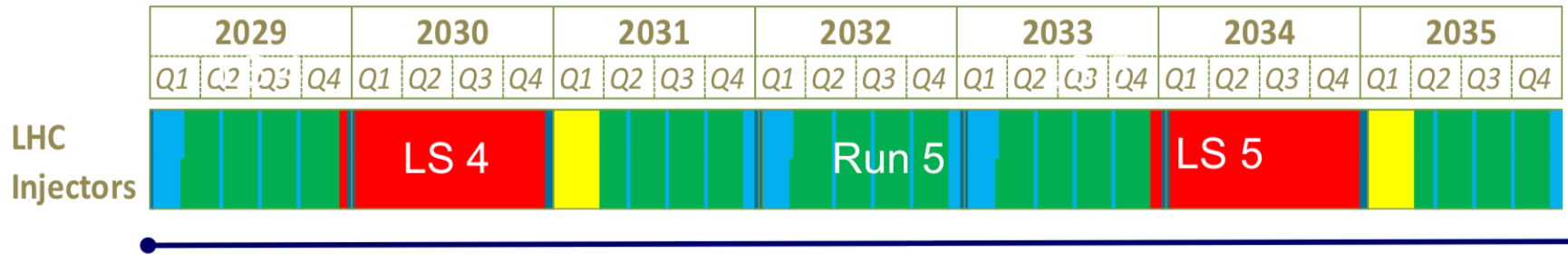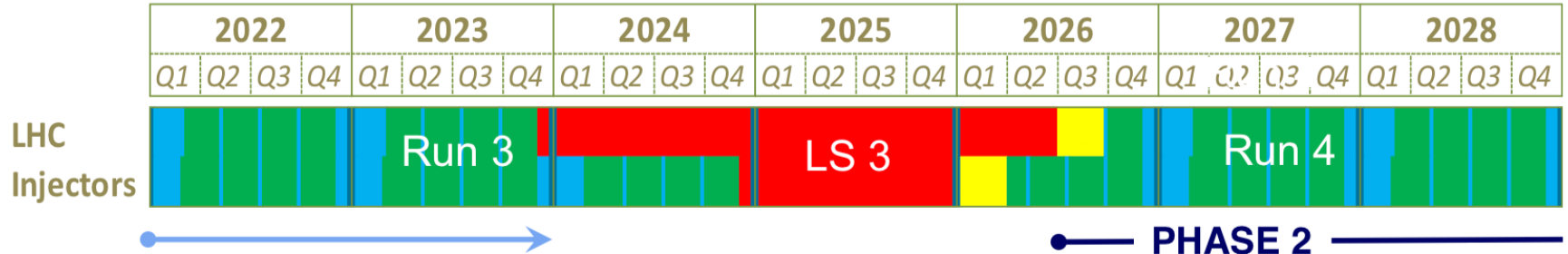819 klystrons
15 MW, 142 μs

drive beam accelerator
2.4 GeV, 1.0 GHz

2.5 km

circumferences
delay loop 73 m
CR1 293 m
CR2 439 m

819 klystrons
15 MW, 142 μs

drive beam accelerator
2.4 GeV, 1.0 GHz

2.5 km

delay loop

Drive Beam

CR2

CR1

CR2

CR1

delay loop

decelerator, 24 sectors of 878 m

BC2

BDS
2.75 km

BDS
2.75 km

BC2

TA

e⁻ main linac, 12 GHz, 100 MW/m, 21 km

IP

e⁺ main linac

TA

48.3 km

Main Beam

CR   combiner ring
TA   turnaround
DR   damping ring
PDR   predamping ring
BC   bunch compressor
BDS   beam delivery system
IP   interaction point
■   dump

booster linac
2.86 to 9 GeV

BC1

e⁻ injector,
2.86 GeV

e⁻
PDR
389 m

e⁻
DR
427 m

e⁺
DR
427 m

e⁺
PDR
389 m

e⁺ injector,
2.86 GeV
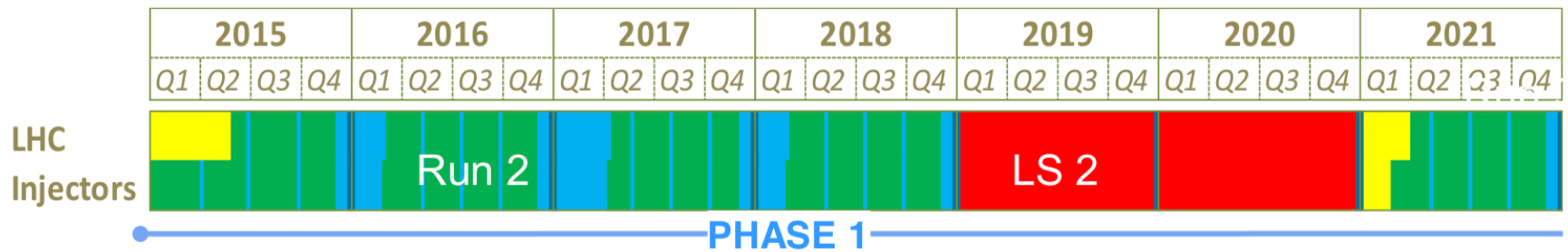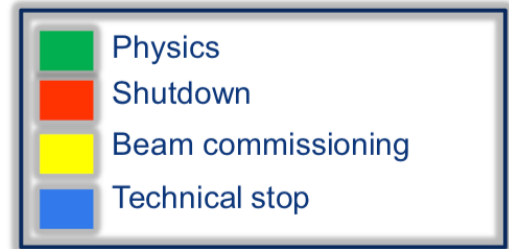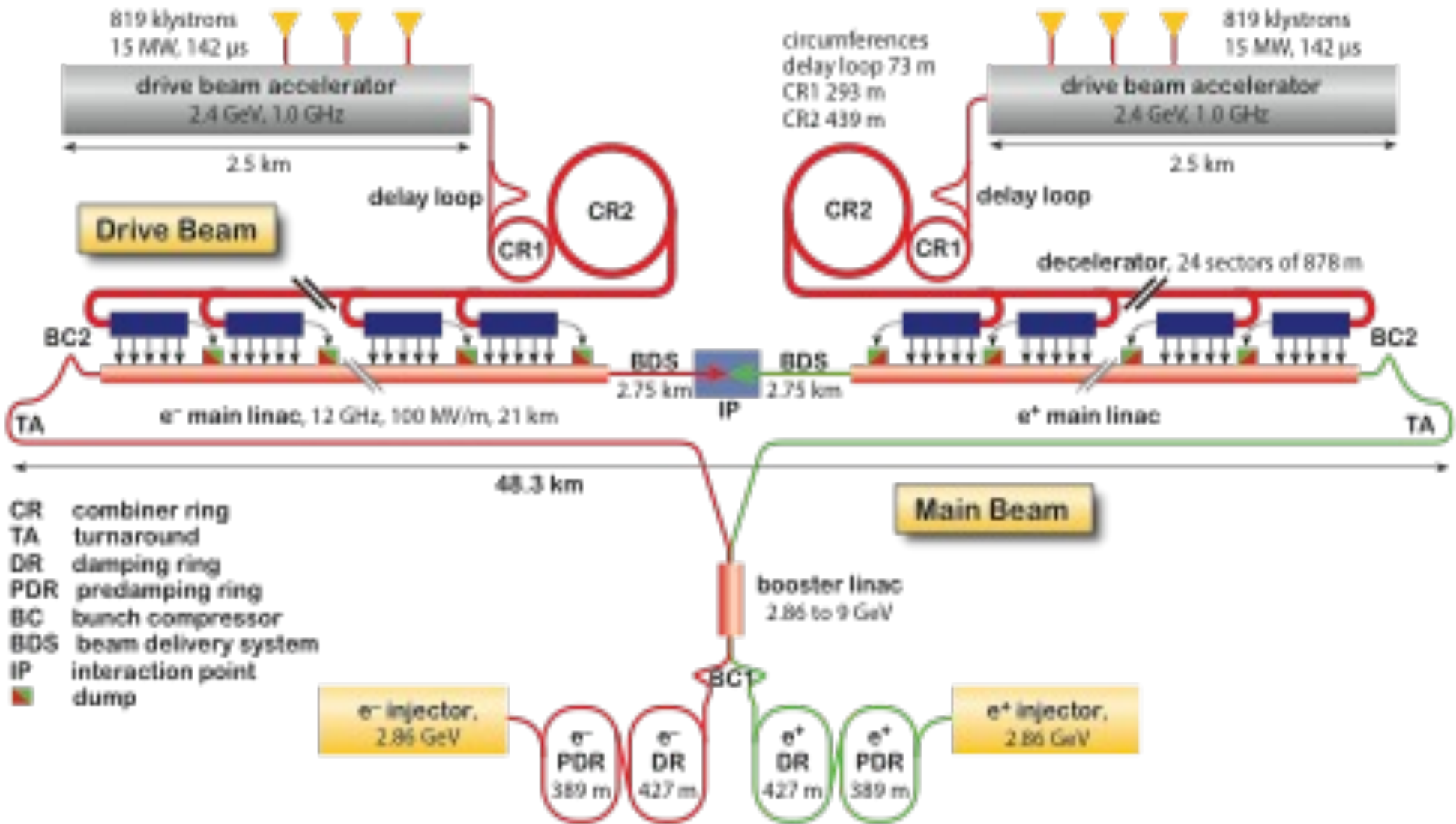
Overview of the CLIC layout at $\sqrt{s} = 3$ TeV

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

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- **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**

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Reserve

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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.

$\mathbf{v}\|\dot{\mathbf{v}}$

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

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

CDR just finalized
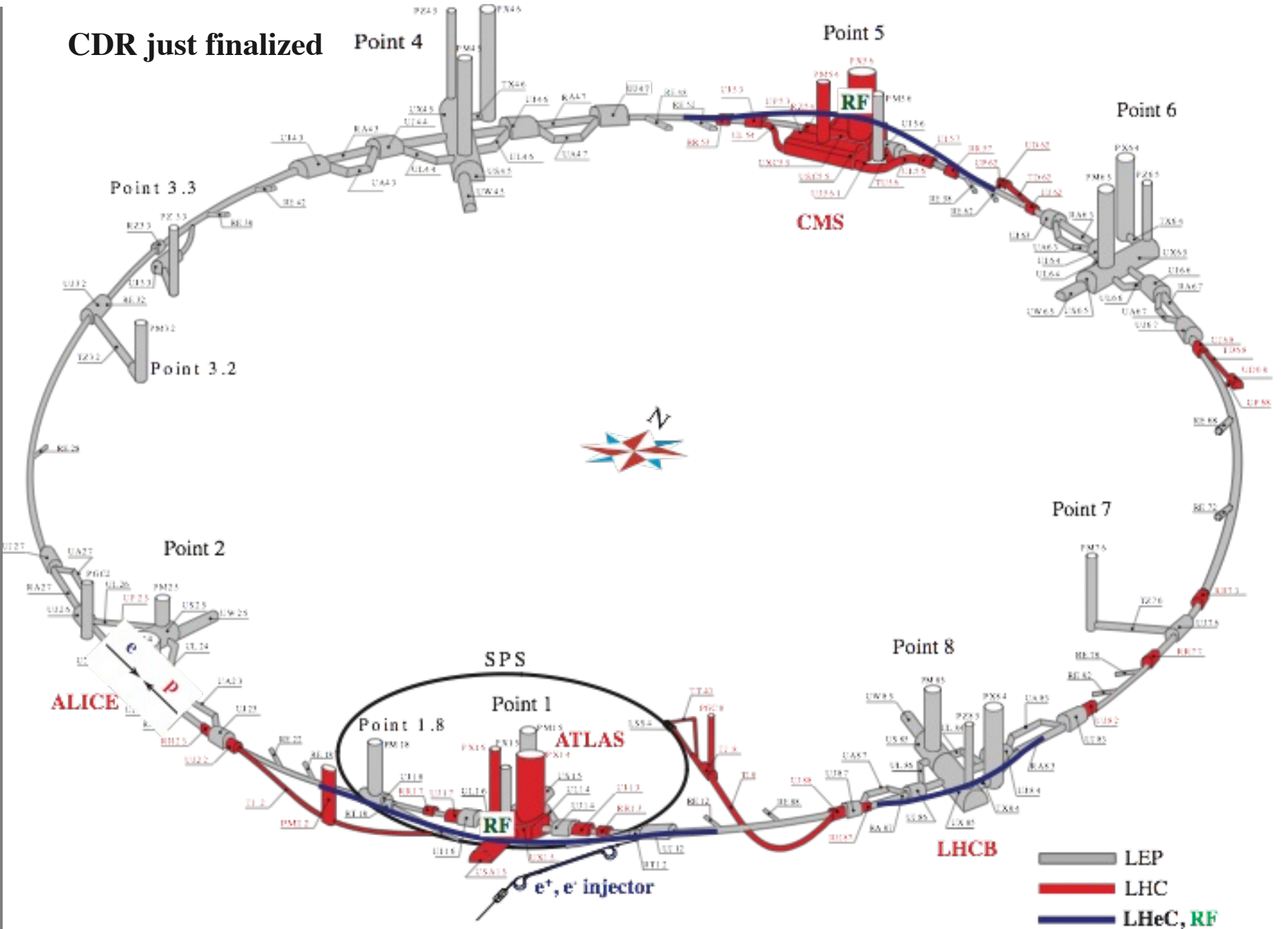
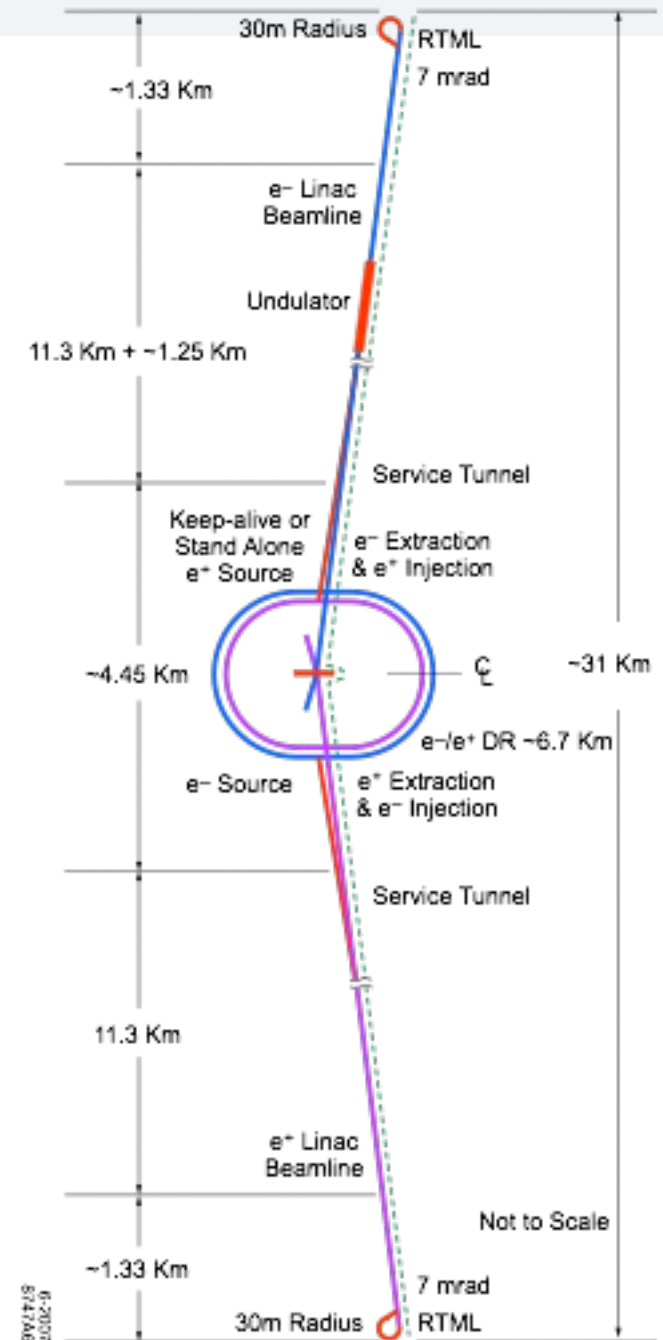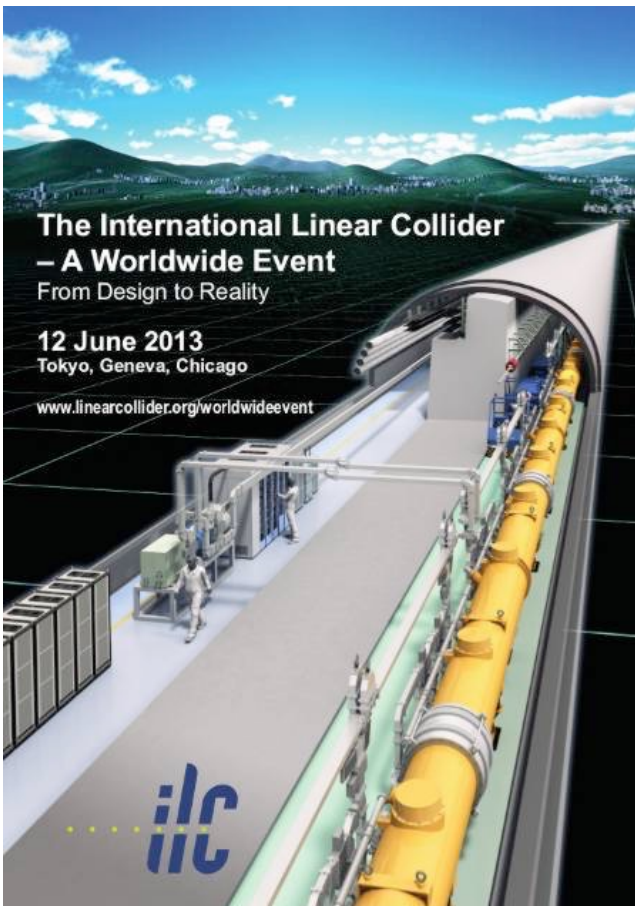**ILC TDR Handover**, 12 June 2013

- **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

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

QUAD

QUAD

Power Extraction Structure

12 GHz – 140 MW

PET

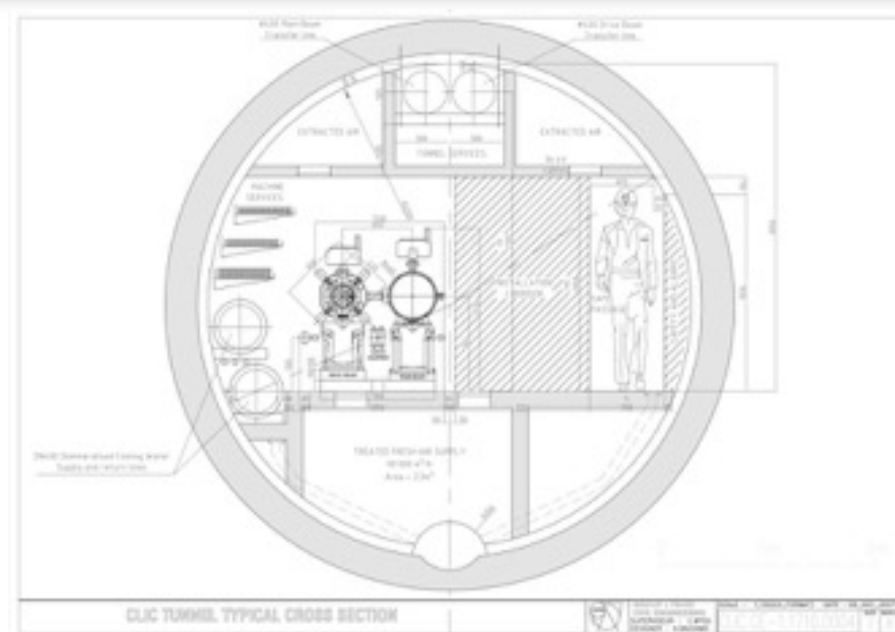ACCELERATING
STRUCTURES

BPM
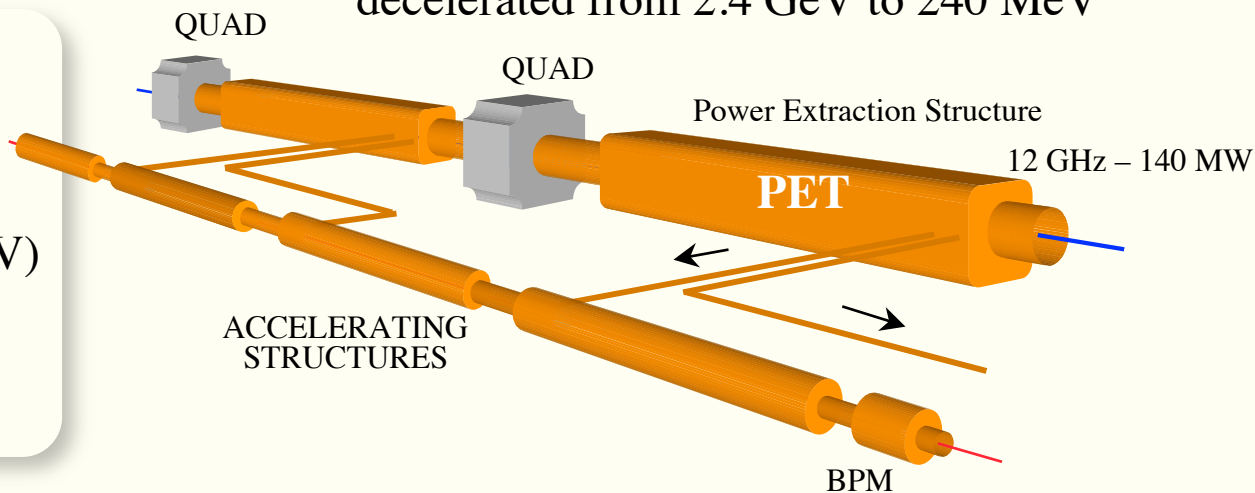
Two Beam Scheme

Drive Beam supplies RF power
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

warm (not superconducting) RF

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

COOLING CIRCUITS

ACCELER. STRUCTURE
(BRAZED DISKS)

VACUUM MANIFOLDS

RF DISTRIBUTION

BEAM
INSTRUMENTATION

DER

CRADLES

GNMENT
TEM

NTERCONNECTIONS

PETS (MINI-TANK)

PETS (OCTANTS)

CLIC TUNNEL TYPICAL CROSS SECTION
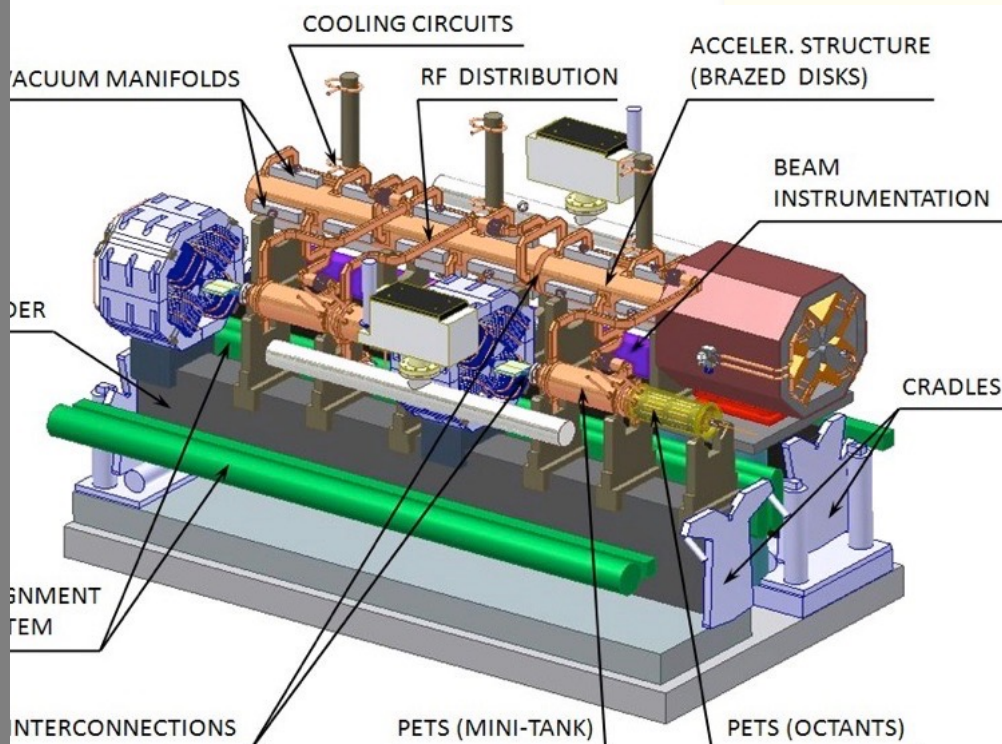
	ILC: Superconducting RF **500 GeV**	CLIC: normal conducting copper RF **3 TeV**
accelerating gradient:	**31.5 MV/m** 35 MV/m target	**100 MV/m**
RF Peak power:	**0.37 MW/m , 1.6 ms, 5 Hz**	**275 MW/m, 240 ns, 50 Hz**
RF average power:	2.9 kW/m	3.7 kW/m
total length:	31 km	48.4 km
site power :	230 MW	392 MW

Beam structure:

	ILC	CLIC
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**

EPS 2009 G.Geschonke, CERN

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 feed-boxes