Introduzione agli acceleratori di particelle

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Material from presentations by:
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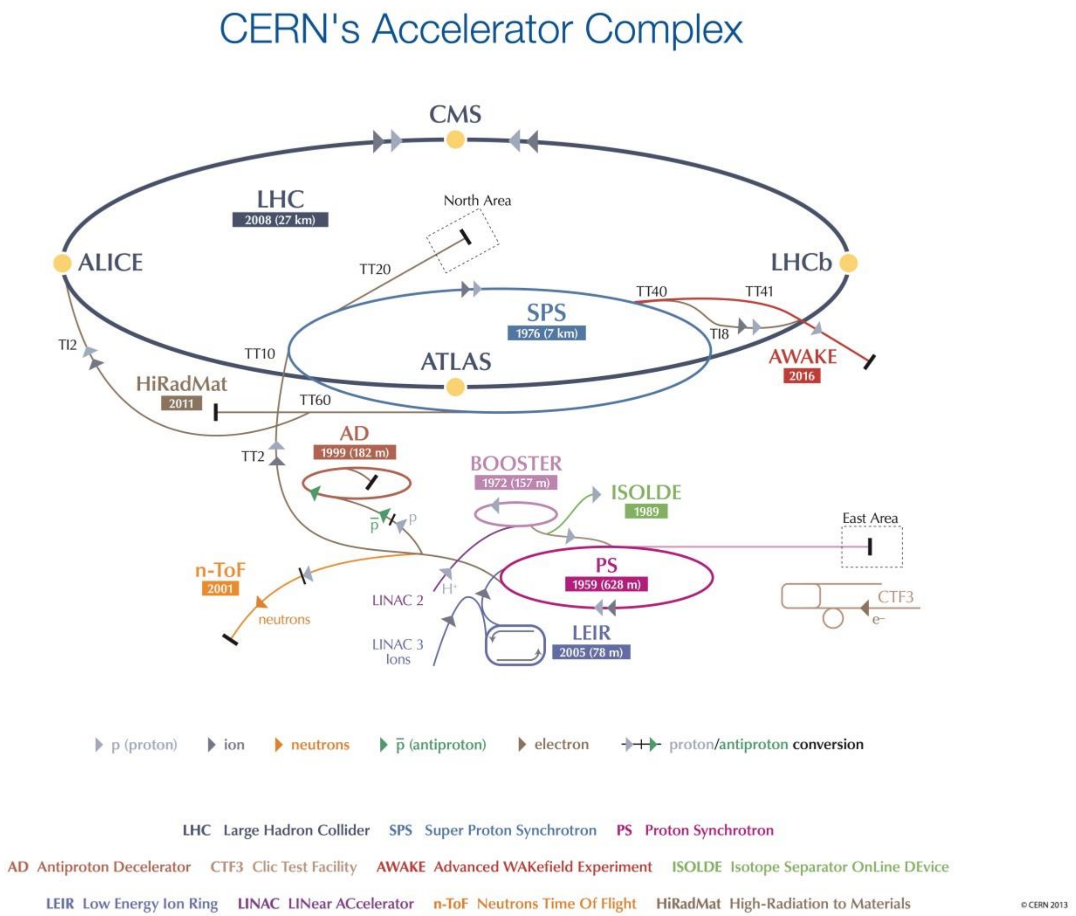
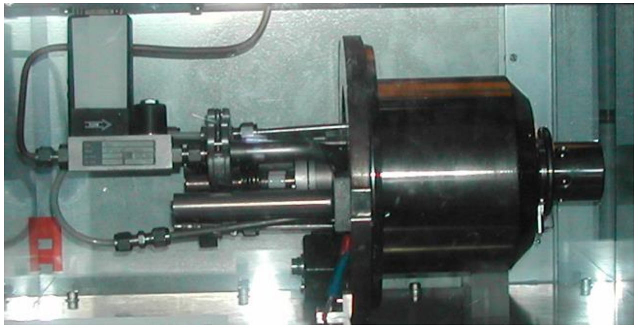
CERN Accelerators

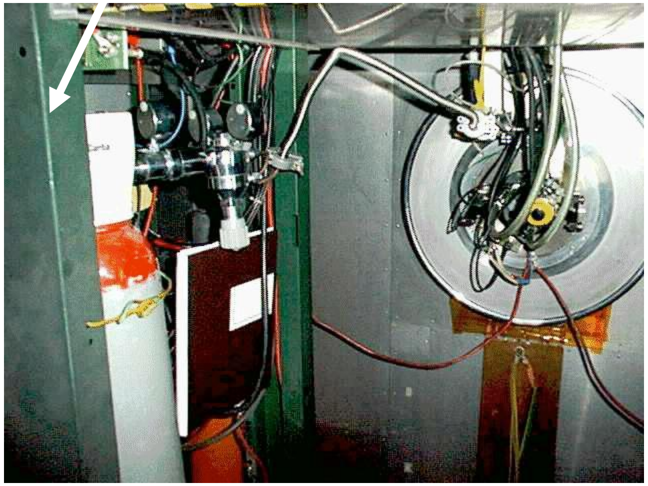


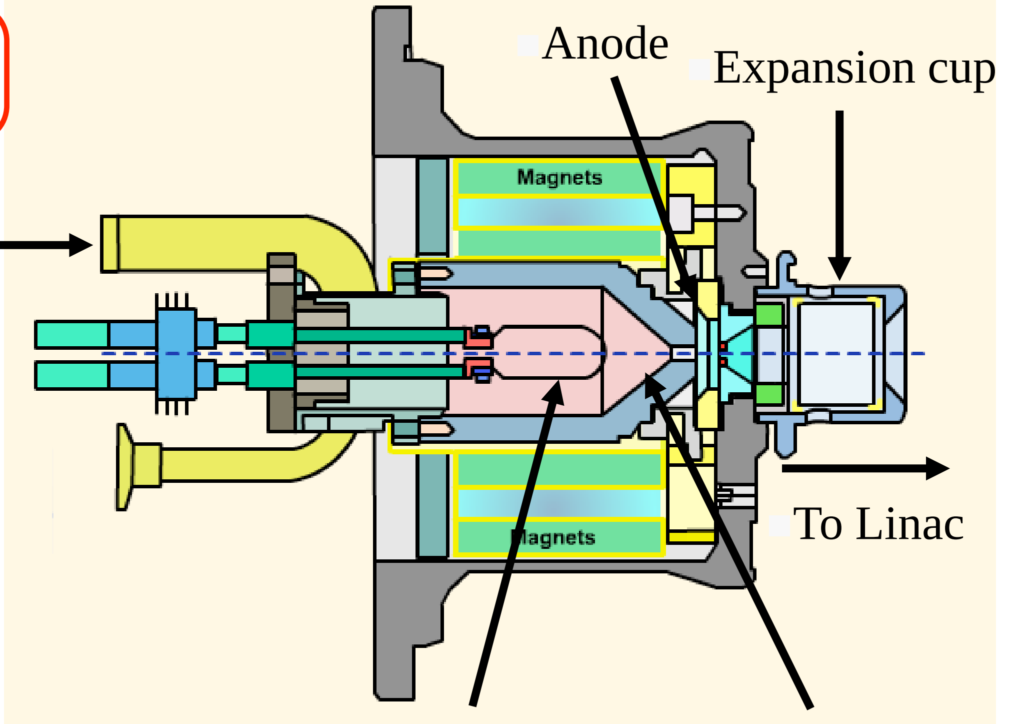
How to get protons: duoplasmatron source

Protons are produced by the ionization of H_2 plasma enhanced by an electron beam



Hydrogen supply (one lasts for 6 months)





H_2 inlet

Anode

Expansion cup

To Linac

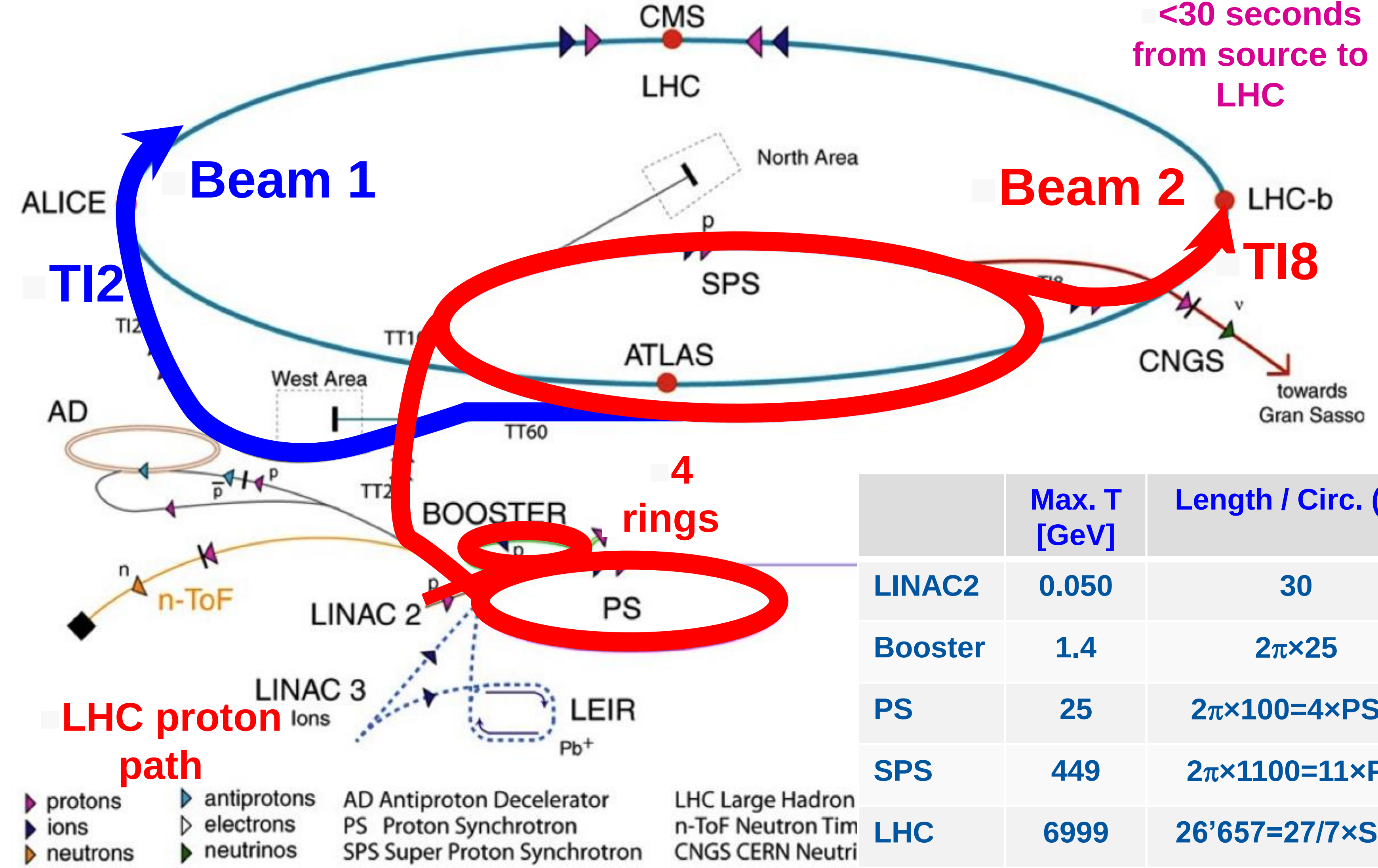
Electron cathode

Plasma chamber

Proton exiting from the about 1 mm^2 hole have a speed of 1.4 % of the speed of light, v ≈4000 km/s

The SPACE SHUTTLE goes only up to 8 km/s

LHC accelerator complex



<30 seconds from source to LHC

Beam 1

Beam 2

TI2

TI8

4 rings

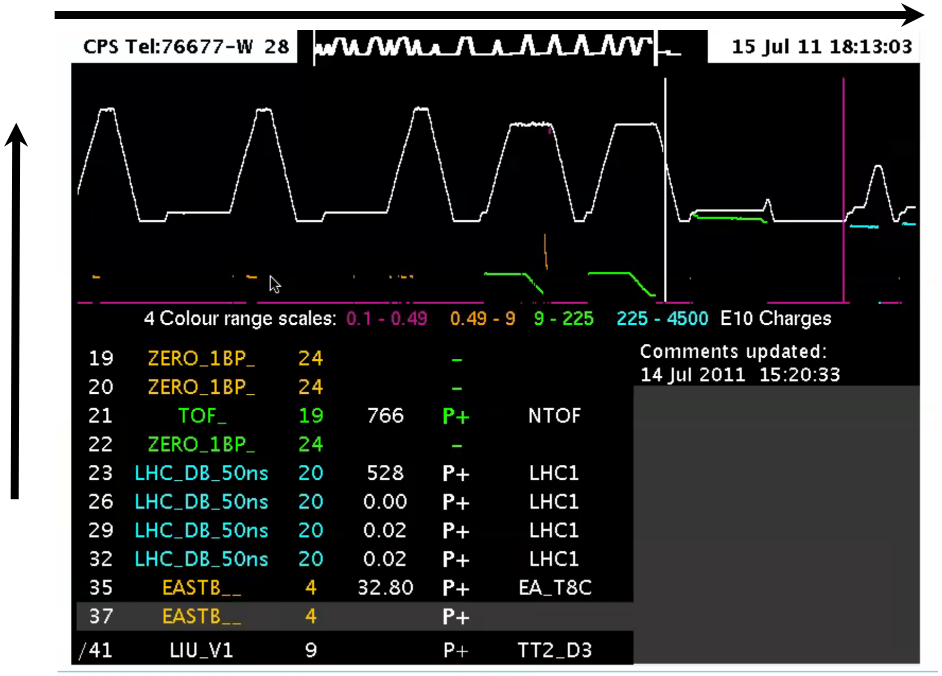
LHC proton path

	Max. T [GeV]	Length / Circ. (m)
LINAC2	0.050	30
Booster	1.4	2π×25
PS	25	2π×100=4×PSB
SPS	449	2π×1100=11×PS
LHC	6999	26’657=27/7×SPS

An example of cycling machine: the CERN-PS

time

B(t) or E(t)



CPS Tel:76677-W 28

15 Jul 11 18:13:03

4 Colour range scales: 0.1 - 0.49 0.49 - 9 9 - 225 225 - 4500 E10 Charges

Comments updated:
14 Jul 2011 15:20:33

19	ZERO_1BP_	24		–	
20	ZERO_1BP_	24		–	
21	TOF_	19	766	P+	NTOF
22	ZERO_1BP_	24		–	
23	LHC_DB_50ns	20	528	P+	LHC1
26	LHC_DB_50ns	20	0.00	P+	LHC1
29	LHC_DB_50ns	20	0.02	P+	LHC1
32	LHC_DB_50ns	20	0.02	P+	LHC1
35	EASTB__	4	32.80	P+	EA_T8C
37	EASTB__	4		P+	
/41	LIU_V1	9		P+	TT2_D3

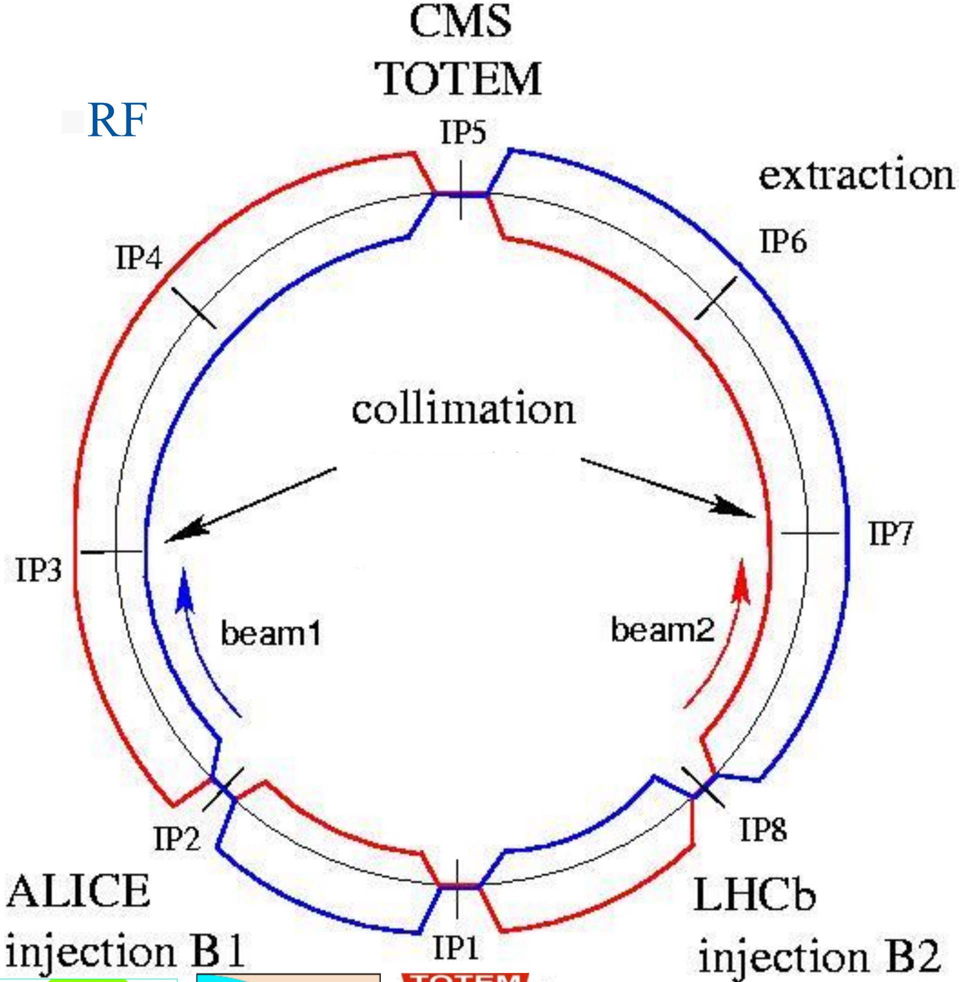
by E.Matli

$$\frac{dB}{dt} = 24\,G/ms$$

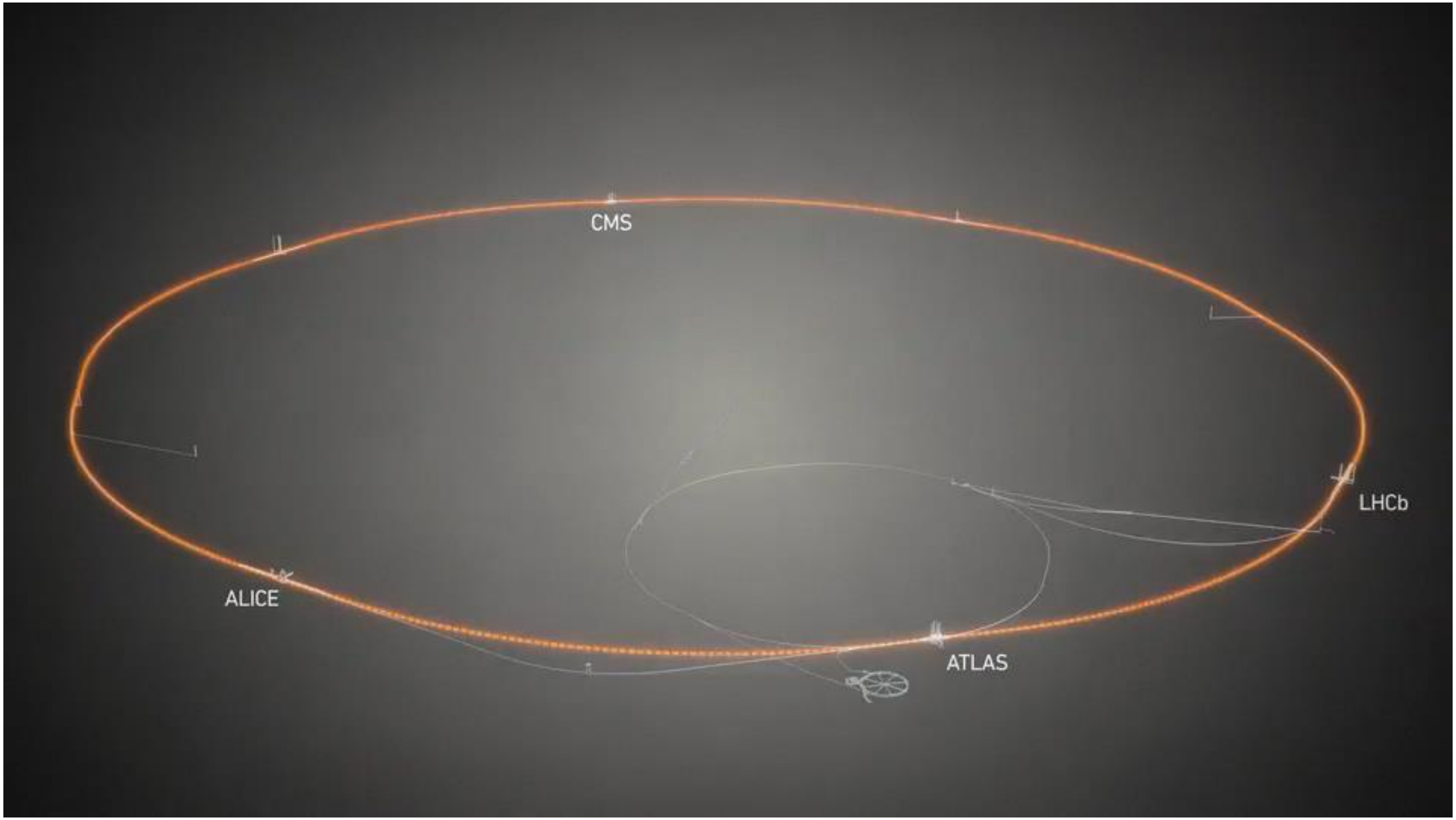
- **PS is a slow synchrotron: pulses every 1.2 s (or multiples)**
- PS radius: 100 m
- Injection: B = 1013 G (0.1013 T) E = 1.4 GeV
- Extraction (max): 12000 G (1.2T) E ~ 26 GeV

LHC layout and parameters

- Total length 26.57 km, in the former LEP tunnel.
- 8 arcs (sectors), ~2.8 km each.
- 8 long straight sections (700 m each).
- beams cross in 4 points.
- 2-in-1 magnet design with separate vacuum chambers → *p-p* (or ion/ion or p/ion) collisions.



The LHC



Why a collider?

Two particles have equal rest mass m_0.

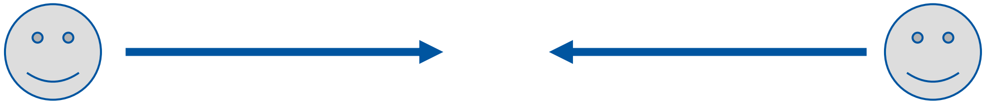
The Centre of Mass Energy

$E_{CM} = c\sqrt{(\boldsymbol{P}_1 + \boldsymbol{P}_2)^2}$ is invariant and it represent the energy available for the generation of the collision products.

- $|\mathbf{P}|c = \sqrt{E^2 - \mathbf{p}^2c^2} = m_0c^2$ is invariant.

- $P_1c=(E, \mathbf{pc})$ $P_2c=(m_0c^2,\mathbf{0})$

Fixed Target: one particle at rest, total energy is E.



- $P_1c=(E, \mathbf{pc})$ $P_2c=(E,\mathbf{-pc})$

Collider: Particles with opposite momenta

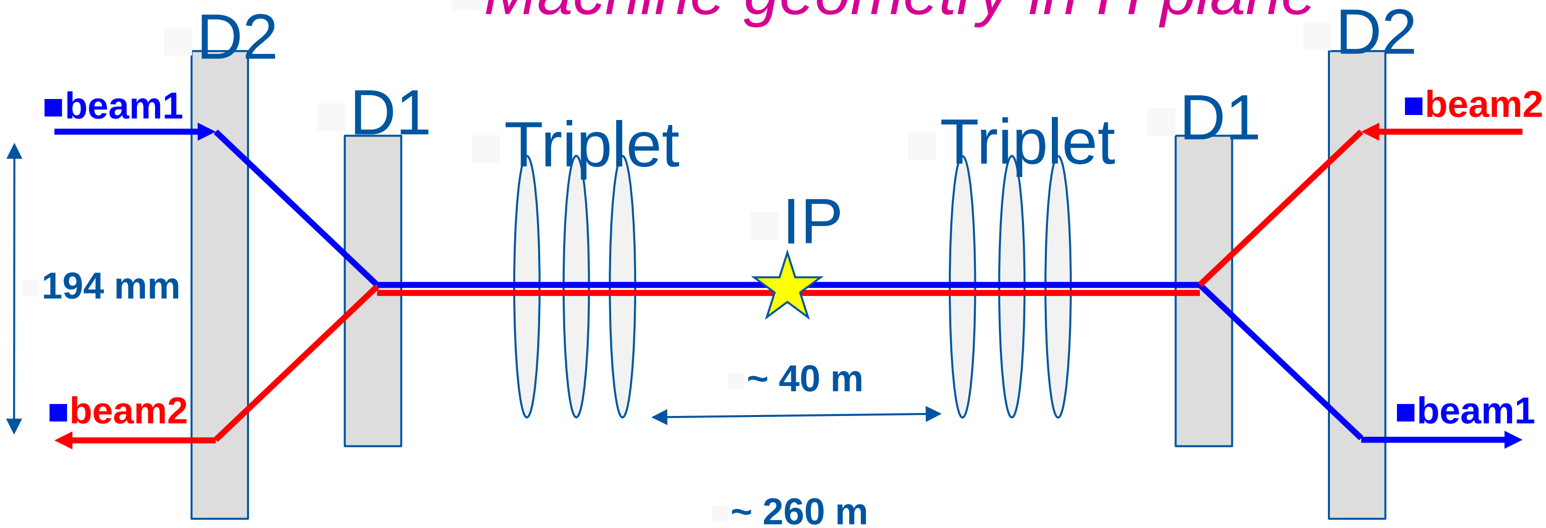
- **Fixed Target:** $E_{CM} = \sqrt{2m_0c^2(m_0c^2 + E)}$
- **Collider:** $E_{CM} = 2E$

In order to get a CoM energy of 100GeV we need a beam of 5328 GeV for a fixed target experiment or two colliding beams of 50 GeV each!!!

Interaction regions geometry

- ❑ In the IRs, the beams are first combined into a single common vacuum chamber and then re-separated in the horizontal plane,
  - ❑ The beams move from inner to outer bore (or vice-versa),
- ❑ The triplet quadrupoles are used to focus the beam at the IP.

Machine geometry in H plane



D1,D2 :

separation/recombination dipoles

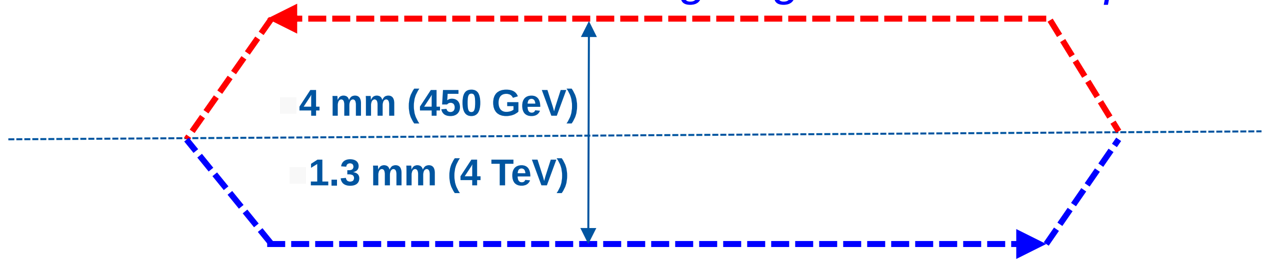
Common vacuum chamber

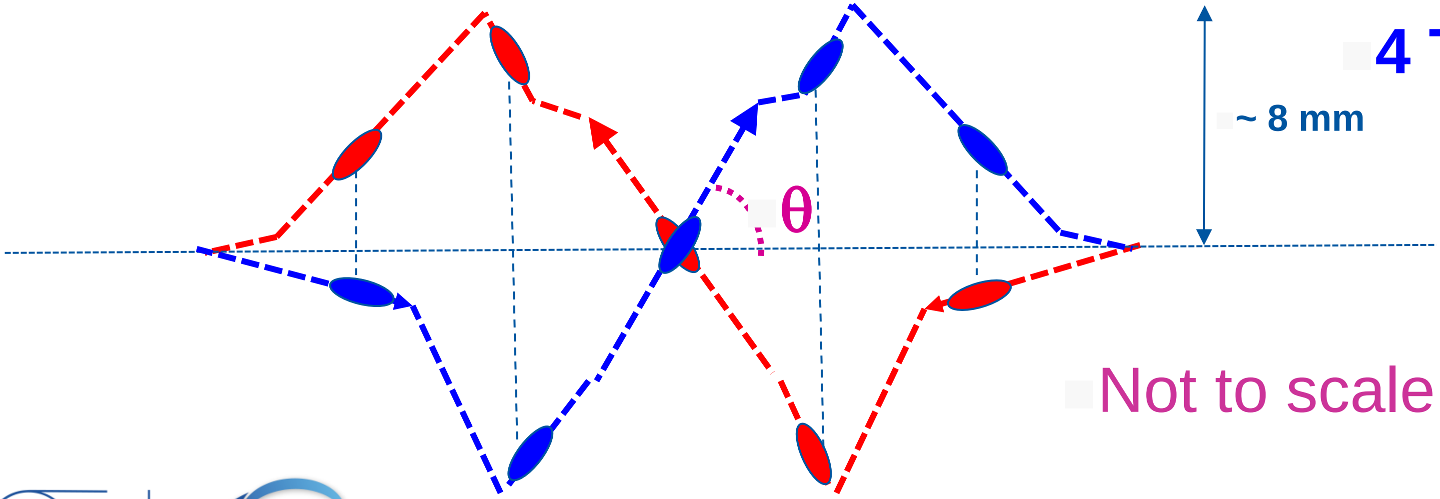
Separation and crossing

Because of the tight bunch spacing and to prevent undesired parasitic collisions in the region where the beams circulate in the common vacuum chamber:

- *Parallel separation in one plane (mostly effective at the IP), which is collapsed to 0 when the beams are colliding,*
- *Crossing angle in the other plane.*

	α (μrad)
ATLAS	**-145 / ver.**
ALICE	**145 / ver.**
CMS	**145 / hor**
LHCb	**90 / ver**

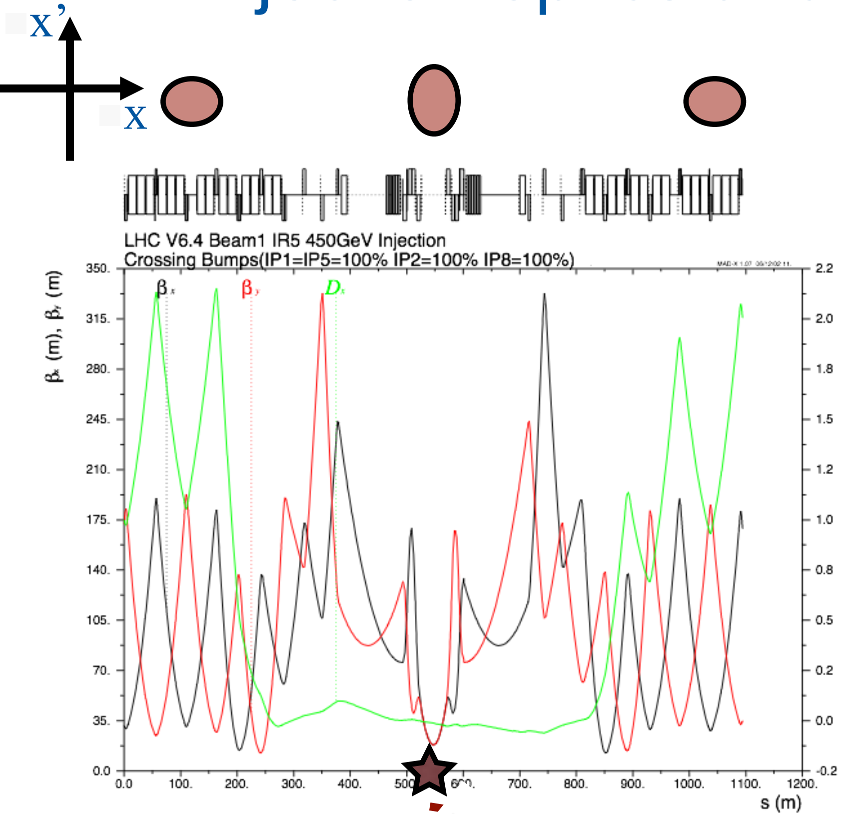


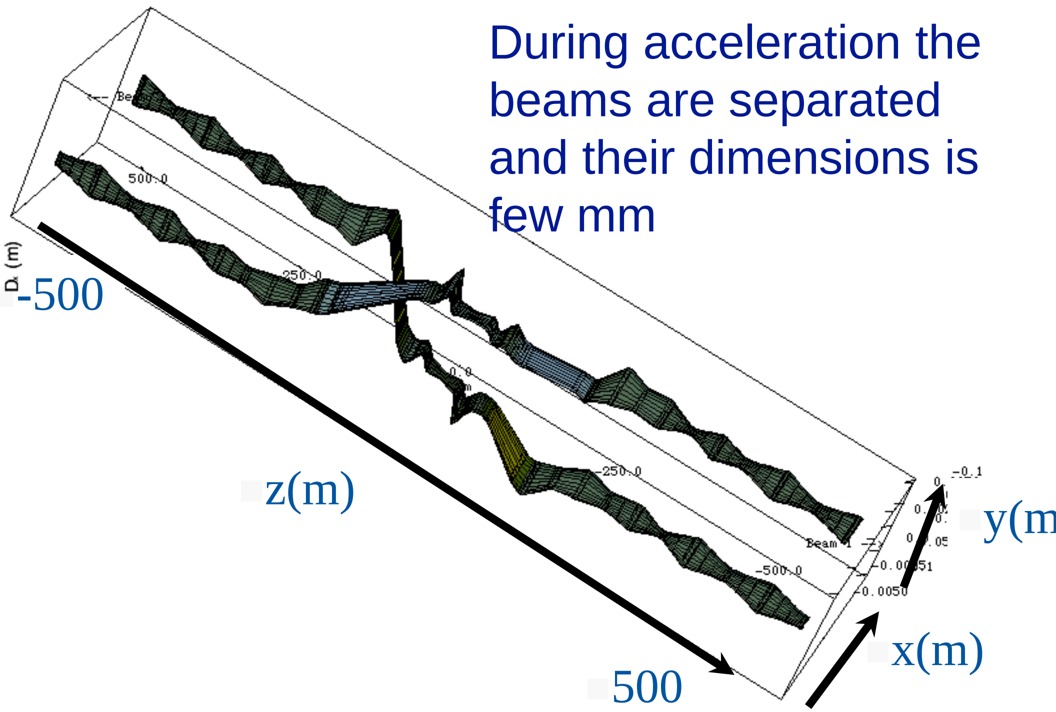


4 TeV / 2012 !

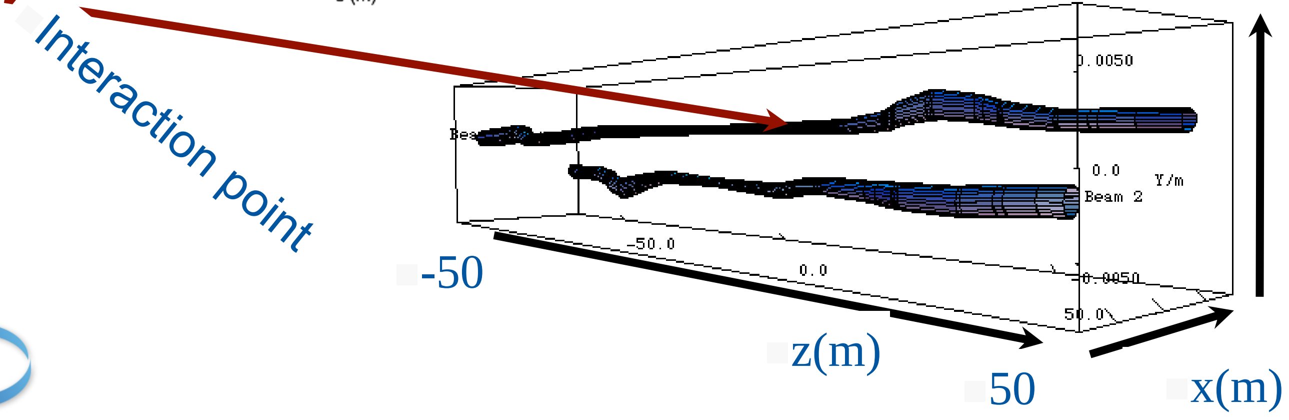
Not to scale !

Injection optics and during acceleration IP5(CMS)

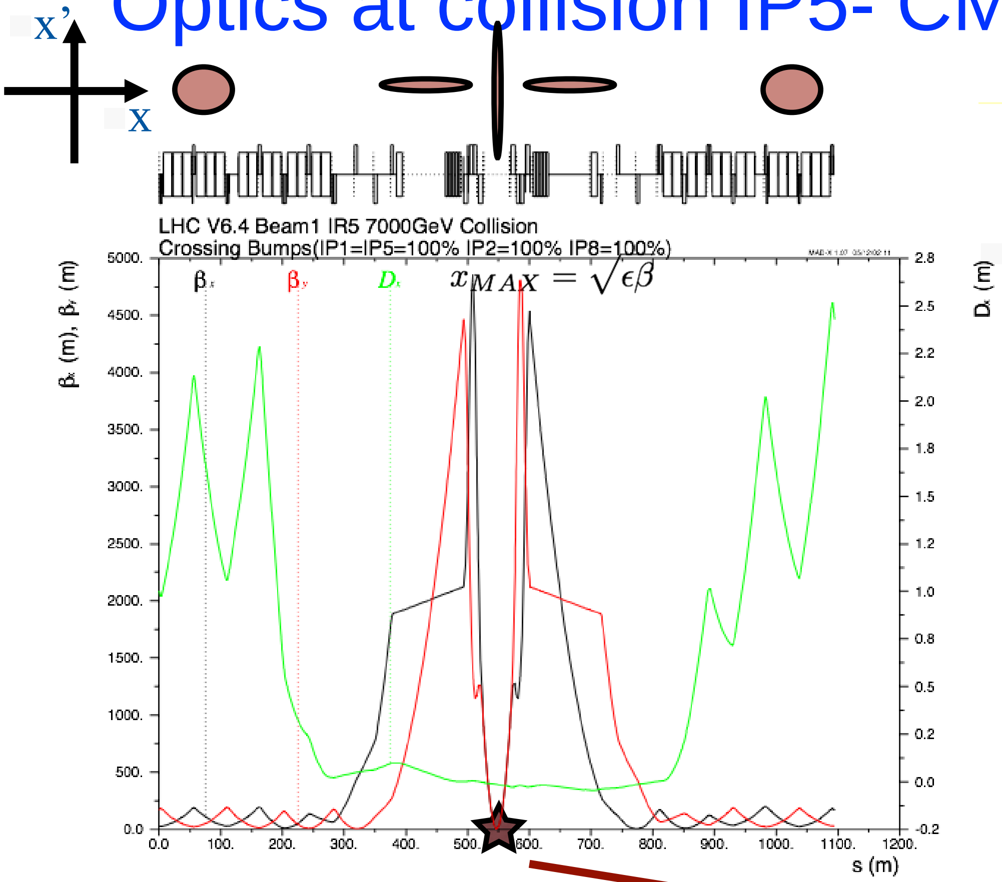


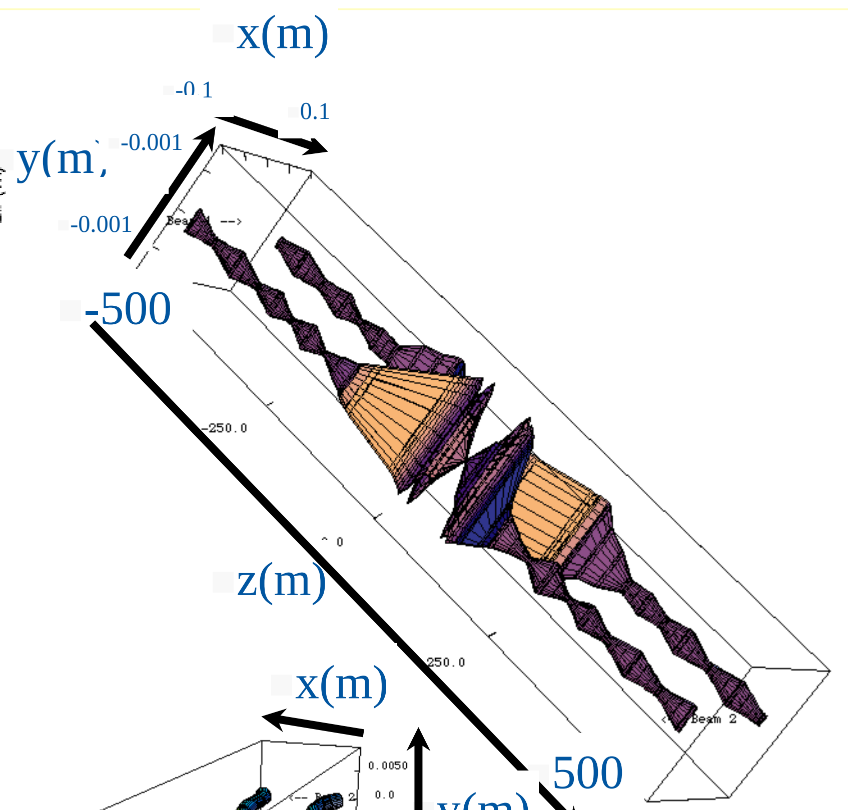


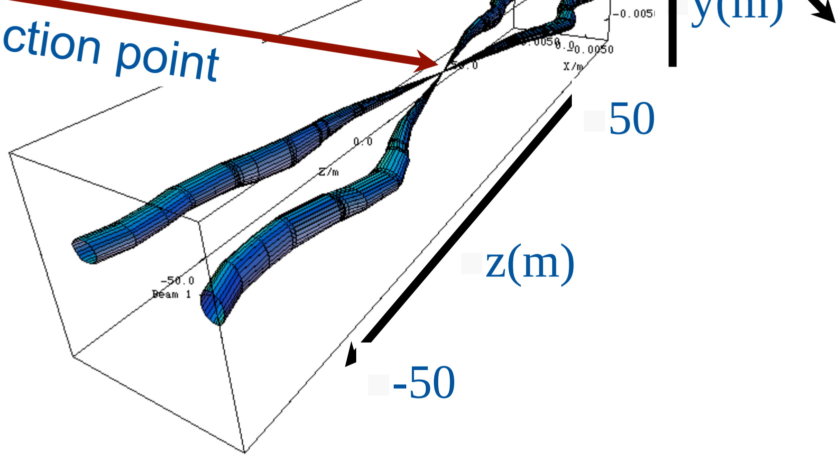
During acceleration the beams are separated and their dimensions is few mm



Optics at collision IP5- CMS





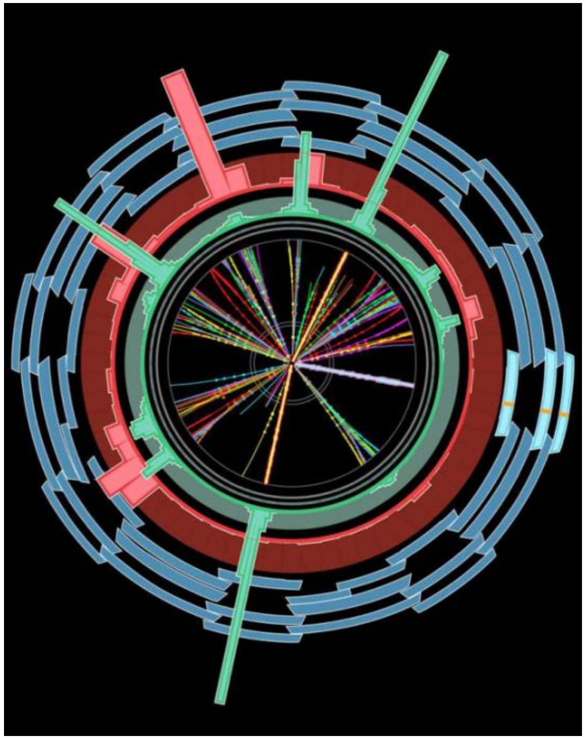


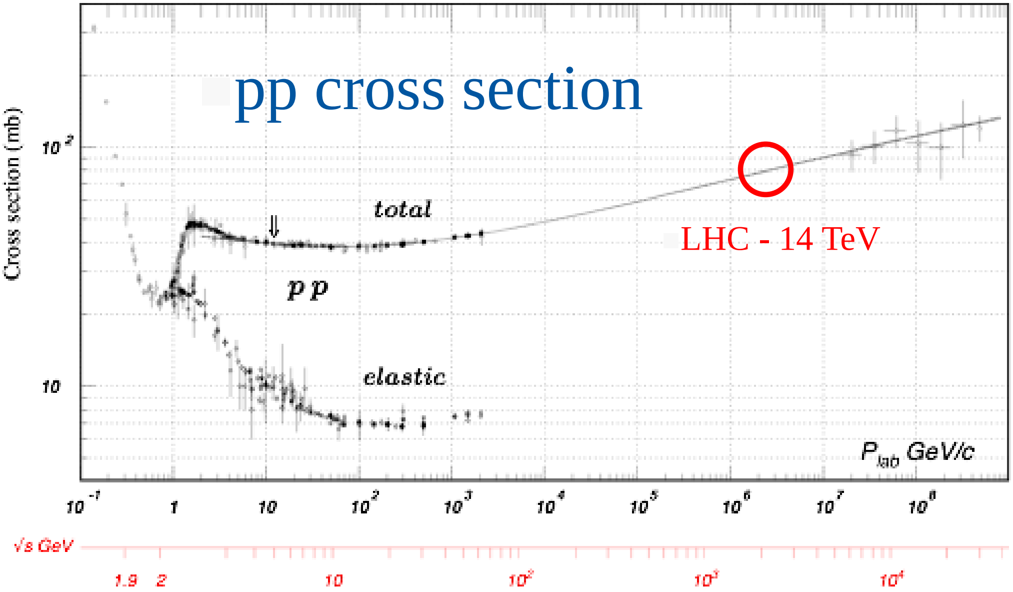
Interaction point

At collision the beams are "squeezed" down to few microns at the interaction point

More luminosity

$$\frac{dN_{event}}{dt} = L\sigma_{event}$$





Luminosity

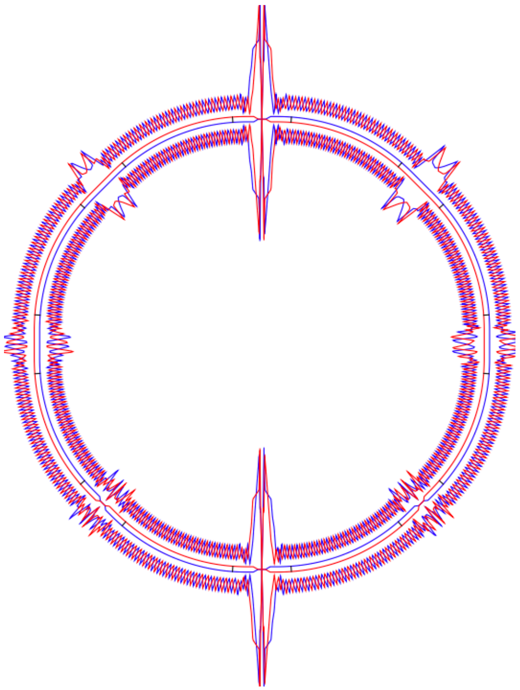
$$L = \frac{kN_b^{\,2} f}{4\pi\sigma_x^*\sigma_y^*} F = \frac{kN_b^{\,2} f\gamma}{4\pi\beta^*\varepsilon^*} F$$

$$\sigma_x^*\sigma_y^* = \frac{\beta^*\varepsilon^*}{\gamma}$$ *(Round beams)*

- *γ = E/m, f is the revolution frequency (11.25 kHz) defined by the circumference (v~c!!)*
- *k is the number of colliding bunch pairs,*
- *N_b is the bunch population,*
- *σ is the beam size at IP*
- *ε^* is the normalized emittance*
- *β^* the betatron (envelope) function at the IP*
- *F is a reduction factor due to the crossing-angle*

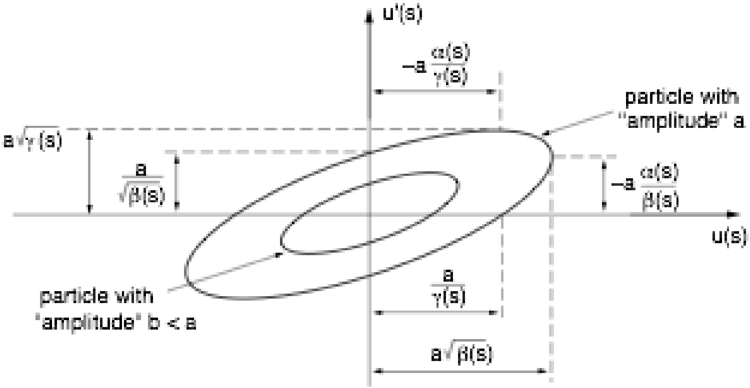
Beam size

$$\sigma = \sqrt{\beta\varepsilon}$$



- β = optical function defined at each point of the machine by strength of the quadrupoles. β* is the value of the β function at the IP which is a focal point for the machine optics.
- ε = emittance: phase space area. As we move around the machine the shape of the phase space ellipse will change as β(s) but the area of the ellipse (πε) does not change (Liouville). ε shrinks naturally as we go up in energy (p_s increases, p_t doesn't) normalized emittance ε*:

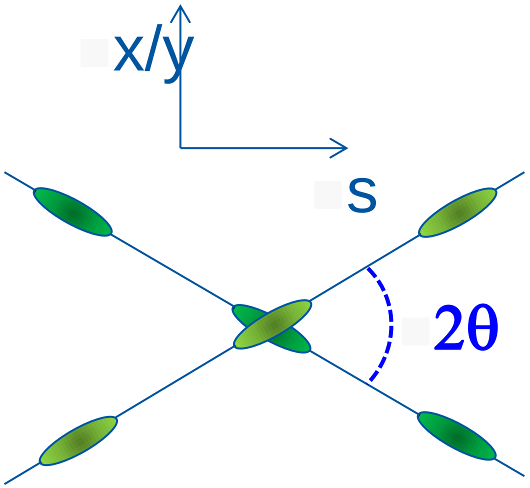
$$\varepsilon^* = \varepsilon\beta\gamma$$



- Ideally constant across the injector chain essentially defined at the proton source!!

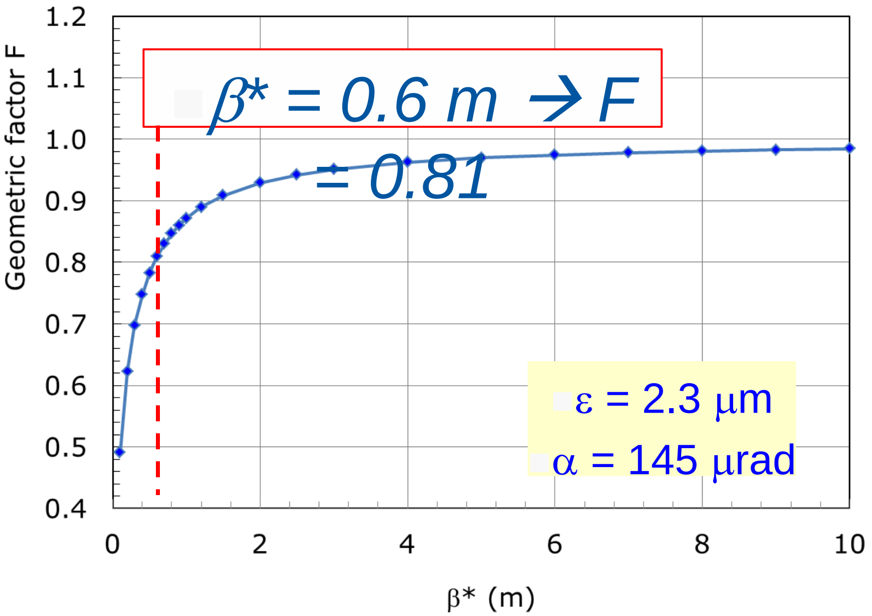
Crossing angle

- Drawbacks:
  - Due to the small beam size the luminosity geometric reduction factor due to bunch length σ_s and crossing angle becomes significant for low β*



$$F = \frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_{x/y}}\tan\theta\right)^2}}$$

  - Reduction of the aperture
  - Long range beam-beam interactions
  - and others (e.g. synchro-betatron resonances,…)



β* = 0.6 m → F = 0.81

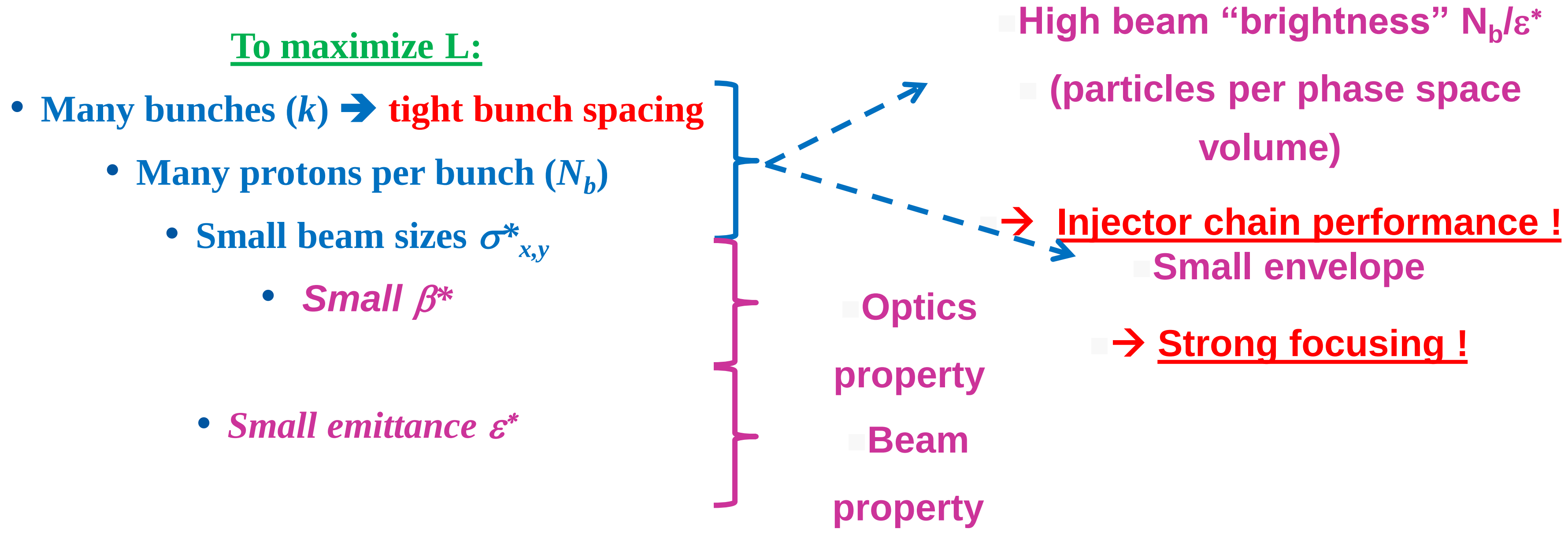
ε = 2.3 μm

α = 145 μrad

Luminosity

$$L = \frac{k N_b^{2} f}{4\pi \sigma_x^{*} \sigma_y^{*}} F = \frac{k N_b^{2} f \gamma}{4\pi \beta^{*} \varepsilon^{*}} F$$

$$\sigma_x^{*} \sigma_y^{*} = \frac{\beta^{*} \varepsilon^{*}}{\gamma}$$



To maximize L:

- **Many bunches (*k*) ➔ tight bunch spacing**
  - **Many protons per bunch (N_b)**
    - **Small beam sizes $\sigma^*_{x,y}$**
      - ***Small β^****
    - ***Small emittance ε^****

High beam “brightness” N_b/ε^*

(particles per phase space volume)

→ Injector chain performance !

Small envelope

→ Strong focusing !

Optics property

Beam property

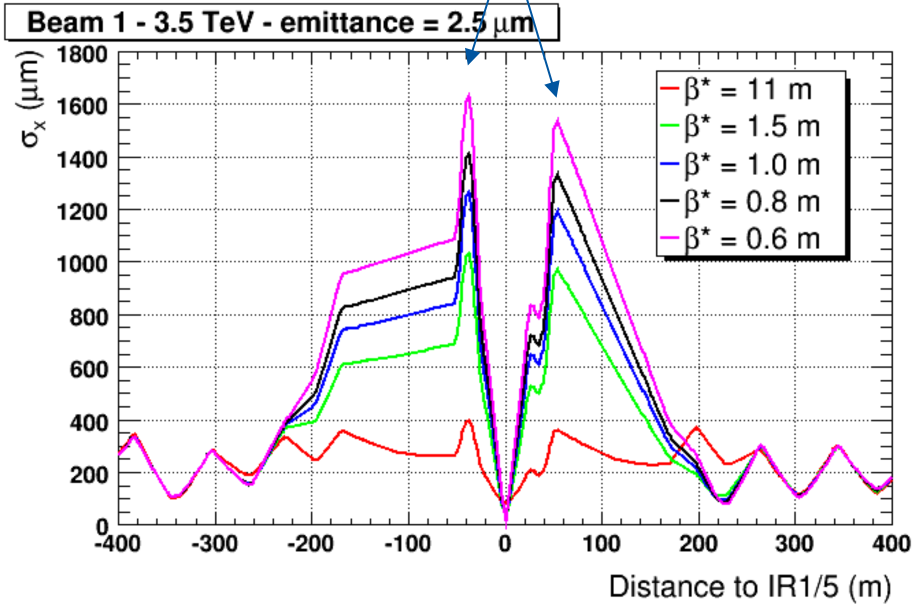
What limits β*?

Limits on β*

In the high luminosity IRs, the triplet quadrupoles define the *machine aperture limit* for squeezed beams, β* is constrained by:

$$\sigma_{triplet} \propto \sqrt{\frac{\varepsilon}{\beta^{*}\gamma}}$$

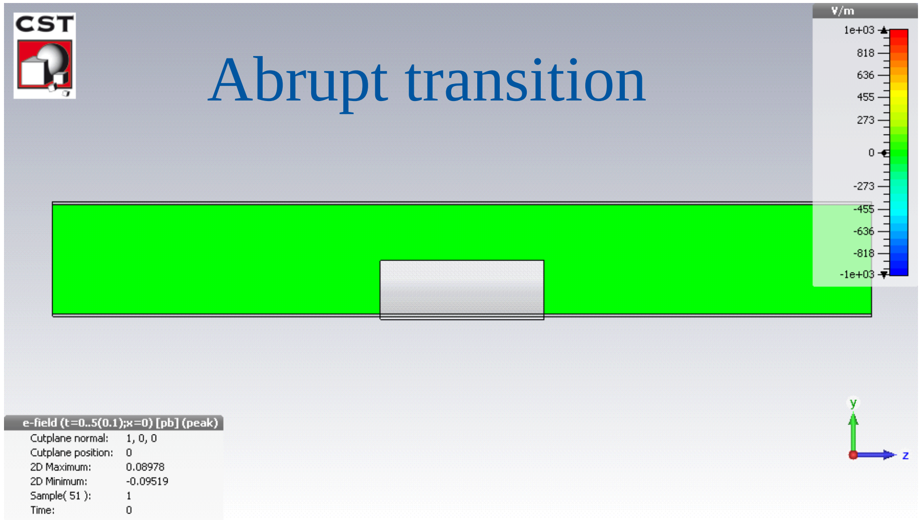
- *the beam envelope*
- *the **crossing angle***



What limits the number and population of the bunches?

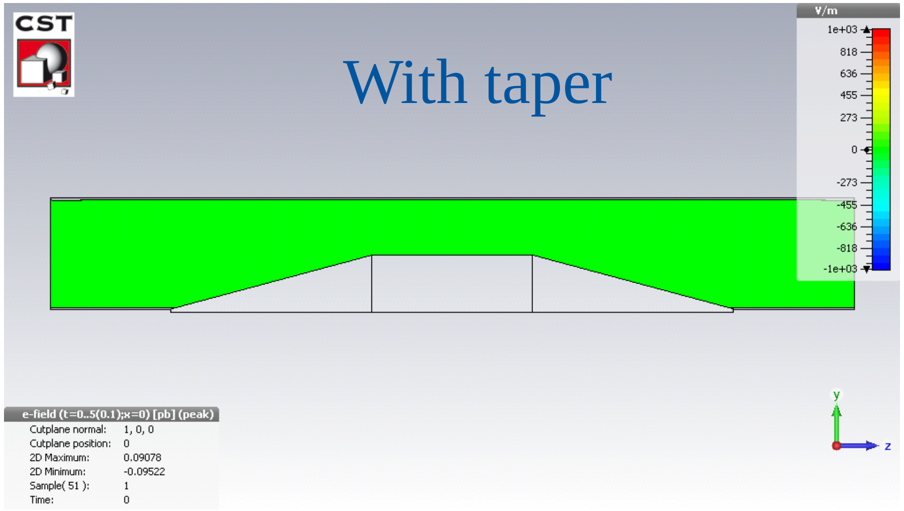
Wake fields and Impedances

- Intense bunches generate electromagnetic (EM) fields when passing inside a structure (e.g. Carbon collimators – opening of ~1 mm!!!)
- → results in an EM force, called wake field in time domain, beam-coupling impedance in frequency domain.



Abrupt transition

e-field (t=0..5(0.1);x=0) [pb] (peak)
Cutplane normal: 1, 0, 0
Cutplane position: 0
2D Maximum: 0.08978
2D Minimum: -0.09519
Sample(51): 1
Time: 0



With taper

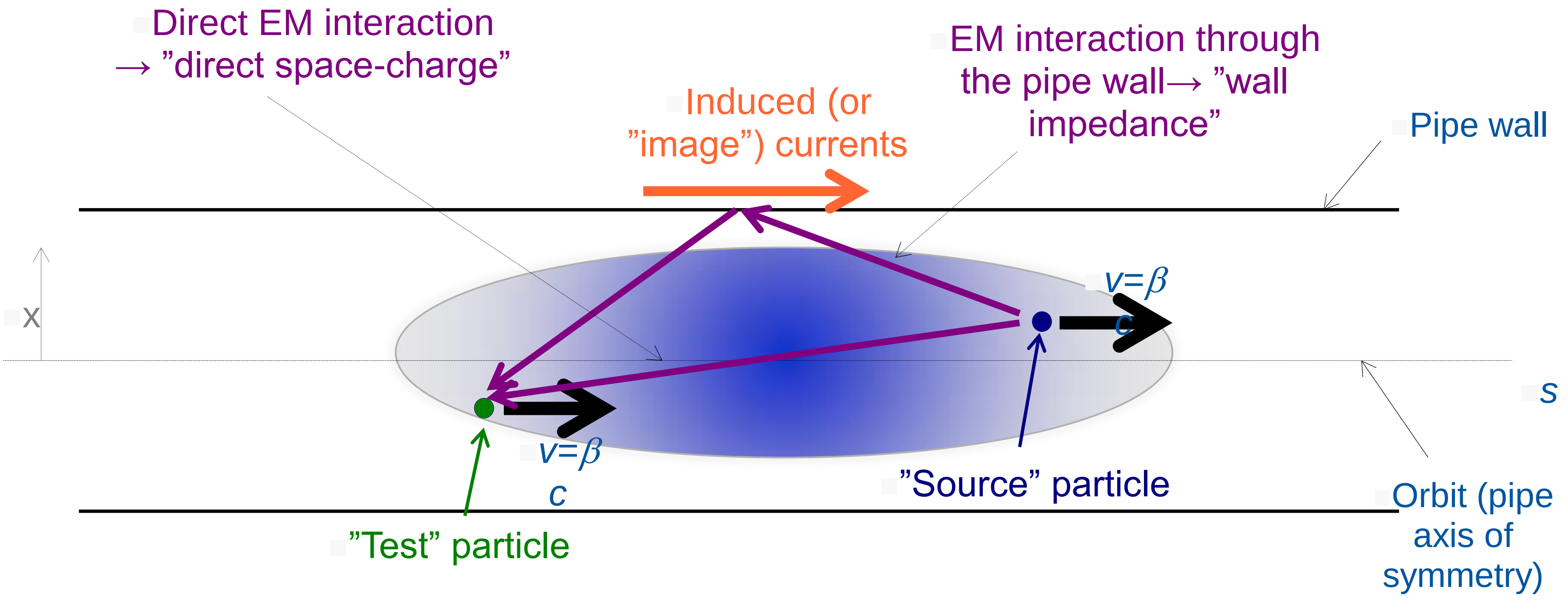
e-field (t=0..5(0.1);x=0) [pb] (peak)
Cutplane normal: 1, 0, 0
Cutplane position: 0
2D Maximum: 0.09078
2D Minimum: -0.09522
Sample(51): 1
Time: 0

- Avoid the abrupt transition for the beam fields at the location of the beam passage (taper)
- Reduce the resistivity of the material

B. Salvant

Wake fields and instabilities

- Wake fiels can couple the head and tail of a bunch



Direct EM interaction
→ ”direct space-charge”

Induced (or
”image”) currents

EM interaction through
the pipe wall→ ”wall
impedance”

Pipe wall

x

$v=\beta c$

s

$v=\beta c$

”Source” particle

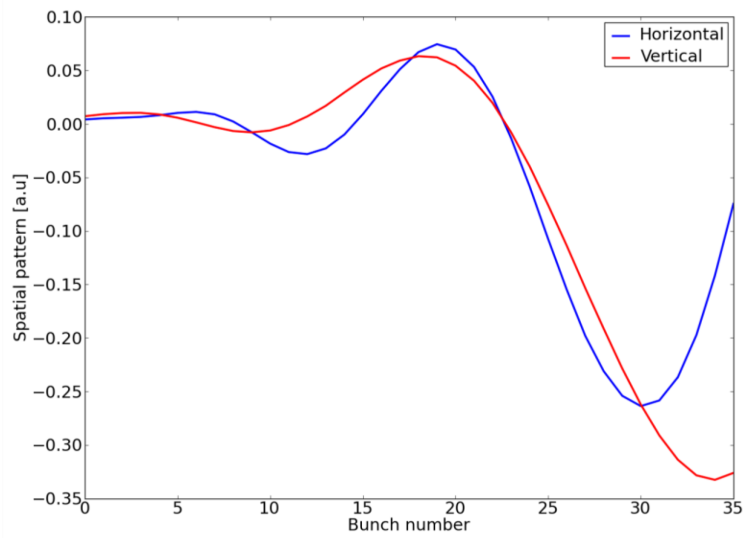
”Test” particle

Orbit (pipe
axis of
symmetry)

Wake fields and Instabilities

- Many bunches (up to 2800 with 25 ns spacing)

- Bunches can interact together (or even the head of each bunch can interact with the tail of the bunch) and in some cases begin to oscillate.
- Example with 36 bunches in the LHC: oscillation pattern along the bunch train (simulation result):



→ Coupled-bunch instabilities

N. Mounet

Beam instabilities

- In 2012 instabilities have become more critical due to higher bunch intensity and tighter collimators settings. The LHC is one of the few machines where instabilities are more critical at high energy.
- Interplay between impedance (mostly due to collimators) and two-beams phenomena (mostly beam-beam)
- Cures:
  - Transverse feedback ('damper') that measures the oscillations and sends corrective deflections,
  - Non-linear magnetic fields (sextupoles, octupoles, beam-beam) that produce a frequency spread among particles – kill coherent motion

Beam-beam effects

Strong non linear fields when counter-rotating beams are sharing vacuum chamber.

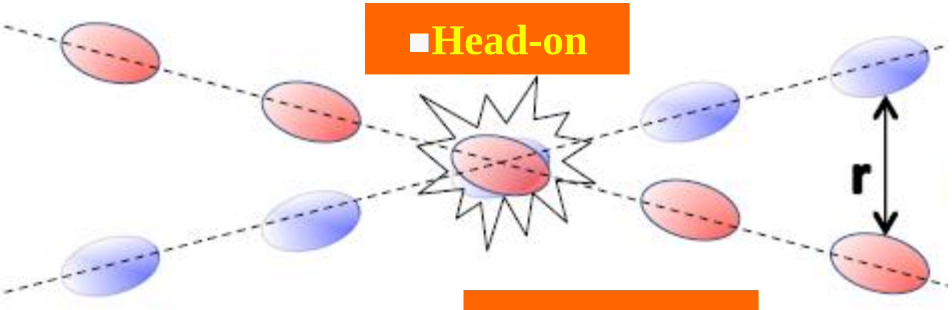
➔ spread in betatronic frequencies ➔ risk of overlapping resonances driven by magnetic errors

Minimize magnetic errors ➔ Paid off for the LHC

Devise correction schemes and sorting ➔ Paid off for the LHC

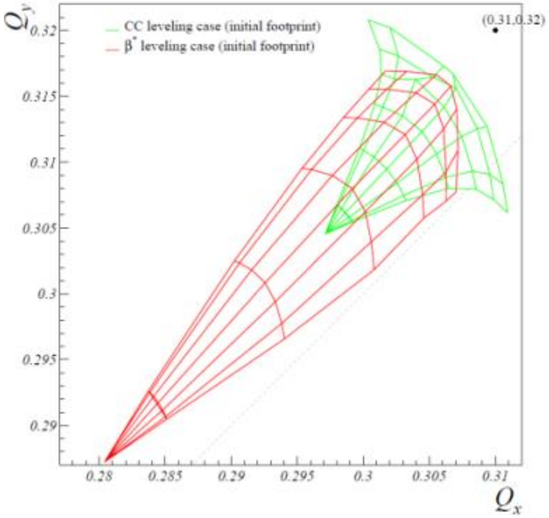
Initially expected to have limit at $\Delta Q_{BB} \sim 0.005$/IP

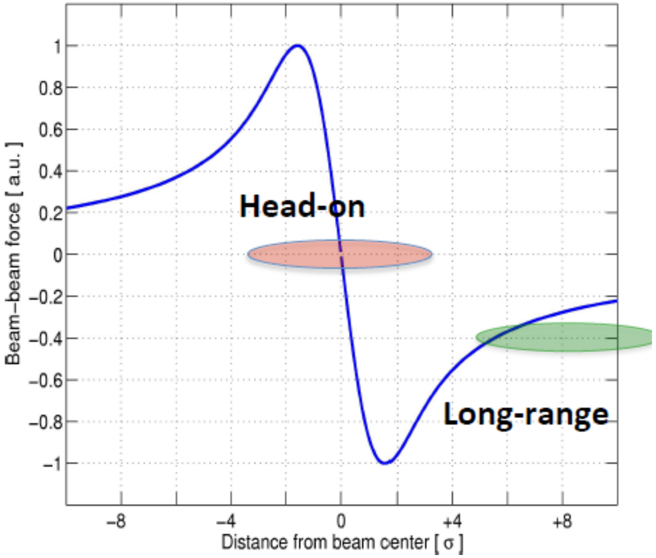
- Long-range
- Head-on



- T. Pieloni

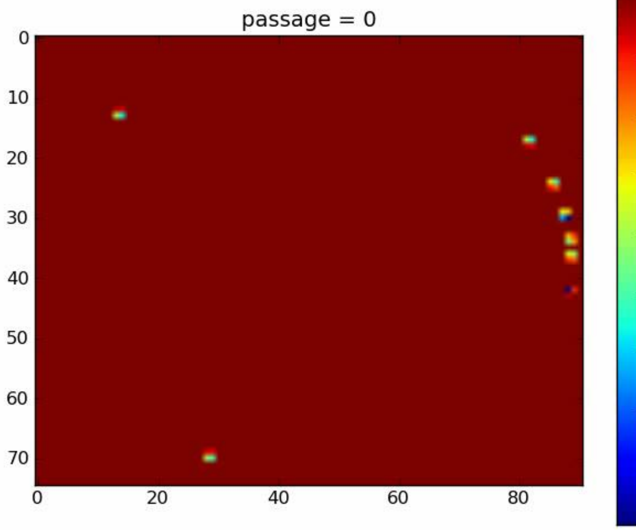
- $\Delta Q_{bb} \propto N_b$



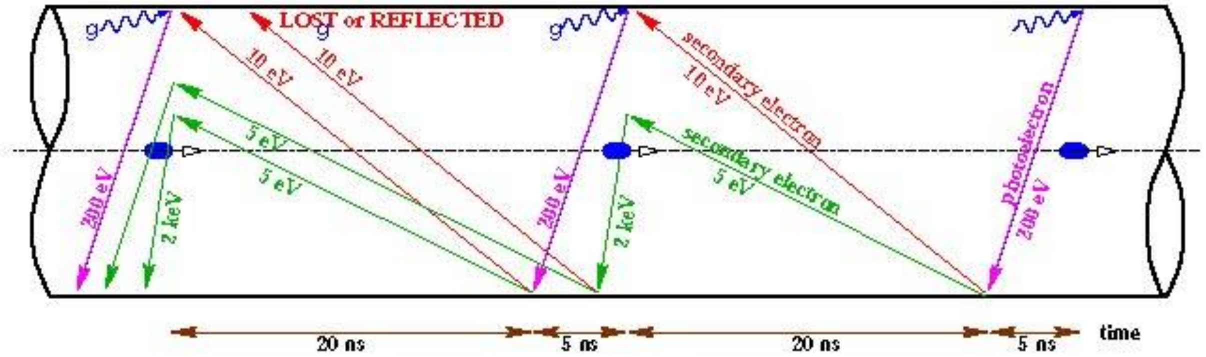


- S. Fartoukh

G. Iadarola, G. Rumolo



Electron cloud effects



■F. Ruggiero

Secondary emission yield [SEY]

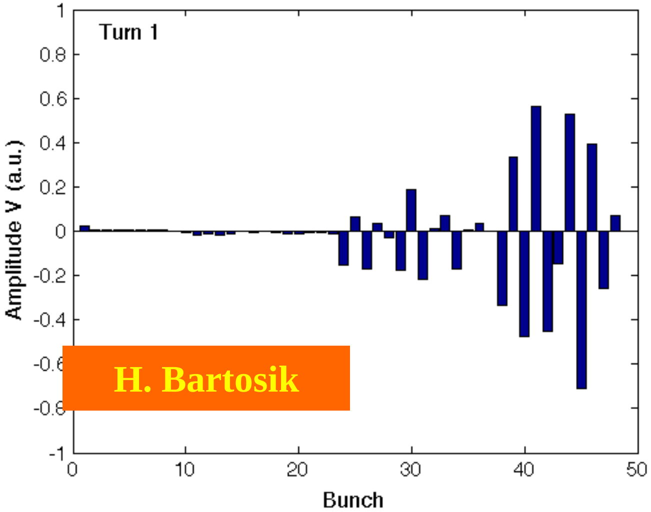
SEY>SEY$_{th}$ ➔ avalanche effect (multipacting)

SEY$_{th}$ depends on bunch spacing and population

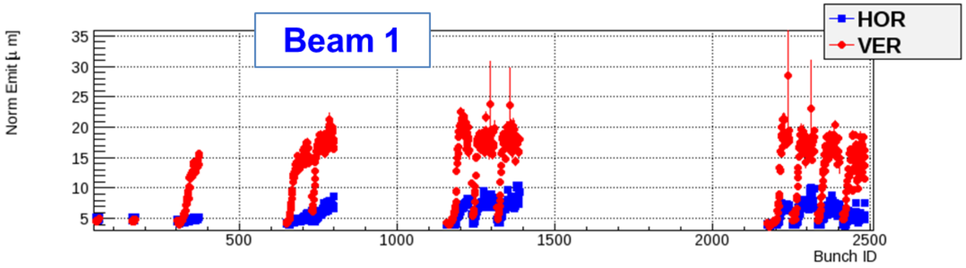
- Electron cloud effects occur both in the warm and cold regions, their intensity increases rapidly for shorter bunch spacing. Observed as soon as we started to inject bunch trains (150 ➔ 75 ➔ 50 ➔ 25 ns spacing):
  - Vacuum pressure rise (interlock levels, beam losses…)
  - Single-bunch and multi-bunch instabilities ➔ beam size growth
  - Incoherent beam size growth
  - Heat load on the cryogenics

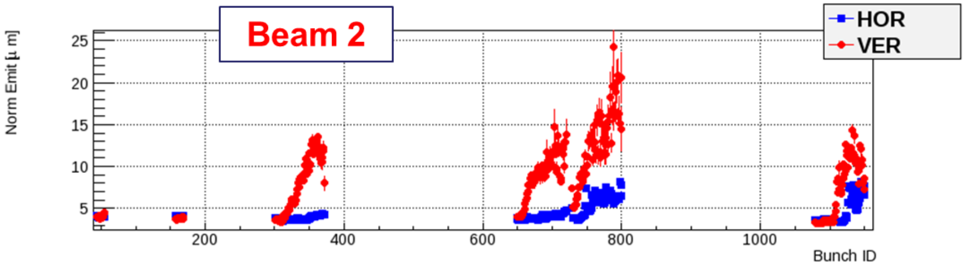
Electron cloud effects

- Fields induced by electrons act like wake fields (more complex) that couple different bunches along the train and head&tail of each bunch and have similar adverse effects on beam stability as impedances.
- As a result of that emittance blow-up and beam losses



H. Bartosik





Cures for electron cloud effects

- At the time of the construction of the LHC:
  - NEG coating ➔ would require activation to >200 ºC ➔ impractical
  - Conditioning by beam-induced electron bombardment (“scrubbing”) leading to a progressive reduction of the SEY as a function of the accumulated electron dose ➔ tested in the laboratory (on Cu surfaces) and in the SPS (Stainless Steel vacuum chambers) ➔ Chosen strategy for the LHC operation with bunch trains – but it takes time!! (in particular for 25 ns operation)

- More recently a-C coating has been successfully tested in the SPS showing SEY as low as 1.1 ➔ possible implementation for HL-LHC (interaction regions)

YEARS / ANS CERN

The technology of LHC

LHC: Some Challenges

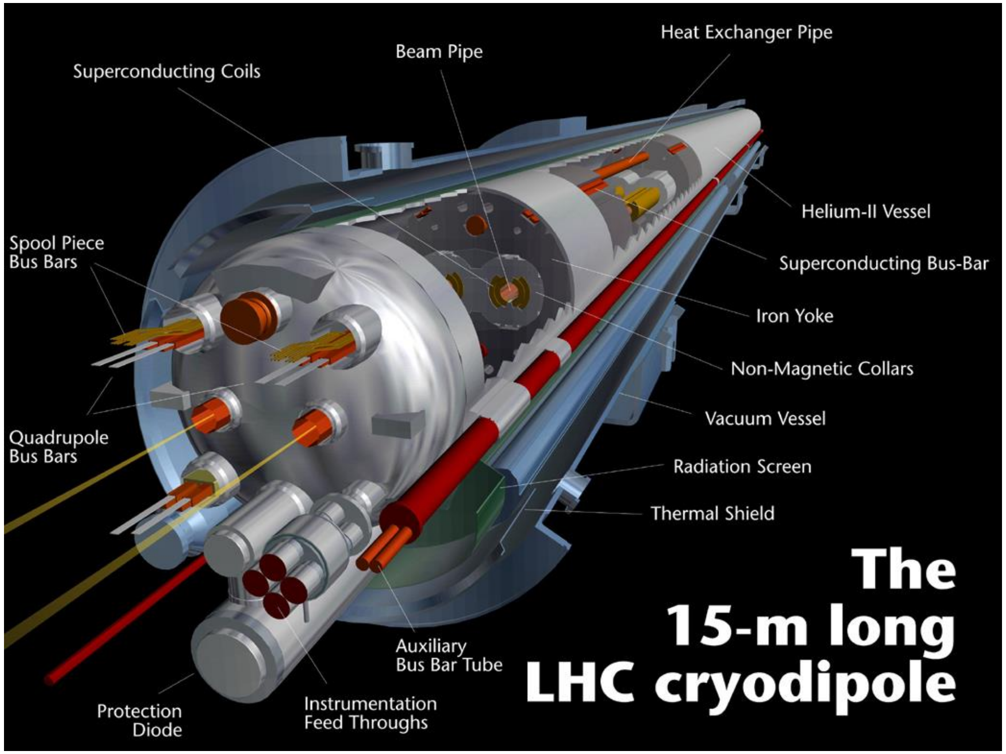
Circumference (km)	26.7	100-150m underground
Number of Dipoles	1232	Cable Nb-Ti, cold mass 37 million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K)	1.9	Superconducting magnets needed for the high magnetic field. Super-fluid helium
Current in dipole sc coils (A)	13000	Results from the high magnetic field. 1ppm resolution
Beam Intensity (A)	0.5	$2.2.10^{-6}$ loss causes quench
Beam Stored Energy (MJ)	362	Results from high beam energy and high beam current.. 1MJ melts 2kg Cu
Magnet Stored Energy (MJ)/octant	1100	Results from the high magnetic field
Sector Powering Circuit	8	1612 different electrical circuits

LHC dipole magnet

1232 dipole magnets.

B field 8.3 T (11.8 kA) @ 1.9 K (super-fluid Helium) – after incident operated up to ~4.7 T ➔ interconnect consolidation during Long Shut-down 2013-2014

2 magnets-in-one design : two beam tubes with an opening of 56 mm.

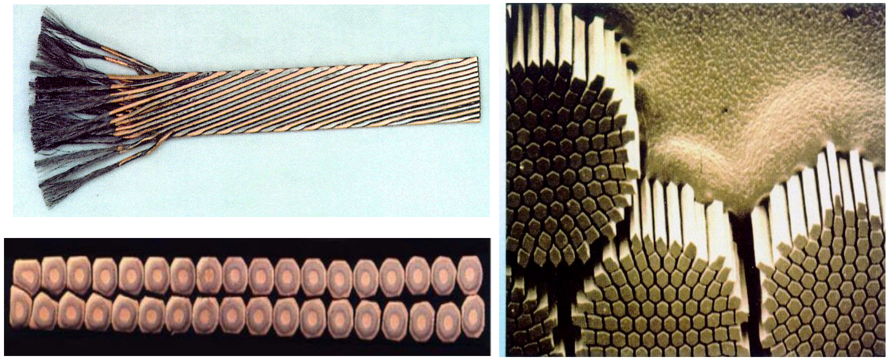


Operating challenges:

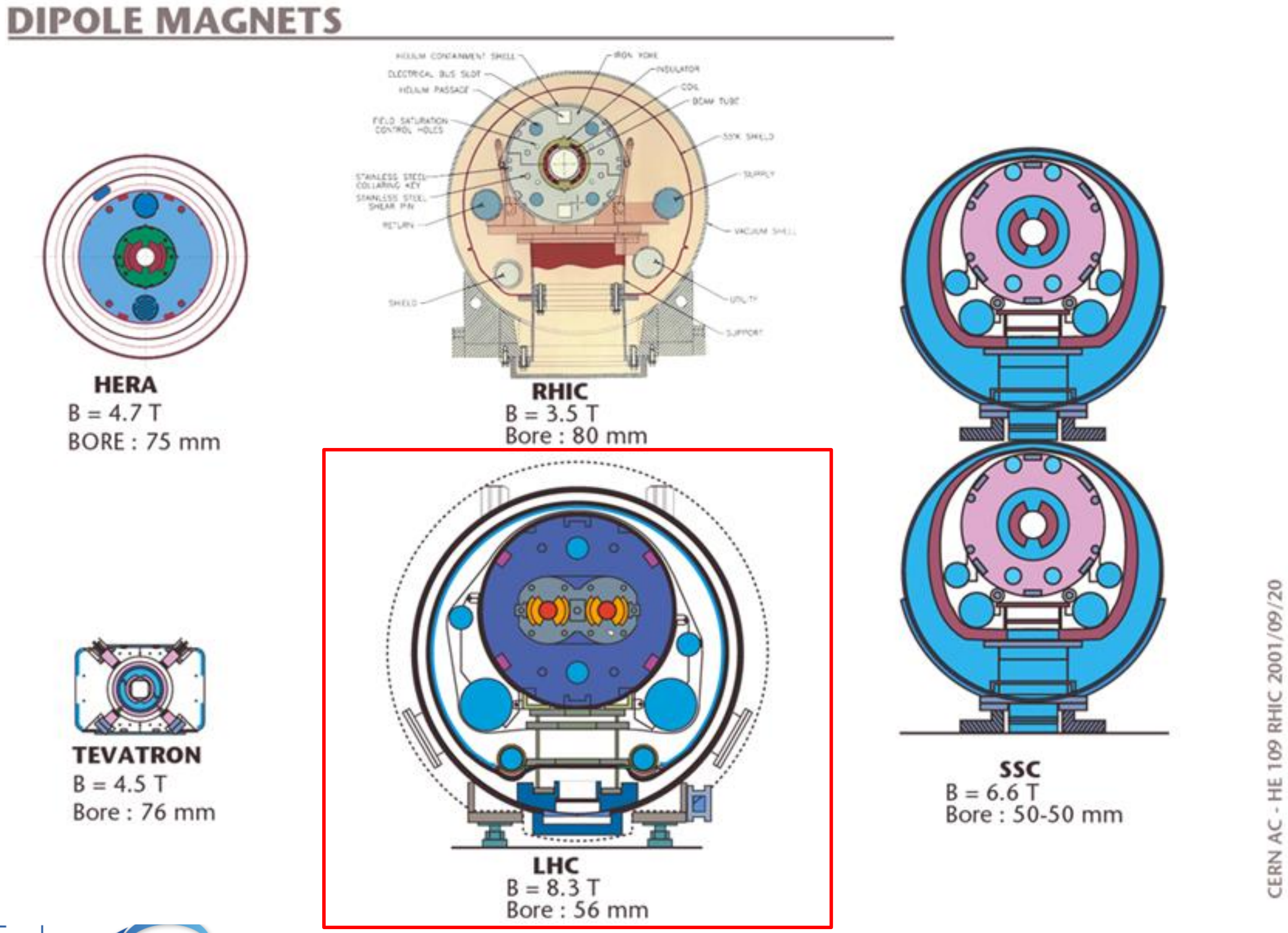
- *Dynamic field changes at injection.*
- *Very low quench levels (~ mJ/cm^3)*

Magnets

- SC magnets:
  - field generated by a suitable distribution of current, properly arranged around the beam aperture:
    - ➔ tight constraints in coil position: 0.1 mm inaccuracy in the coil position can give rise to important field error that would affect beam quality and lifetime
    - ➔ stability within few μm needed to avoid cable movement that could lead to transition to normal conducting state
  - SC magnet technology relies heavily on the ability to produce technical SC materials in the form of high current cables.

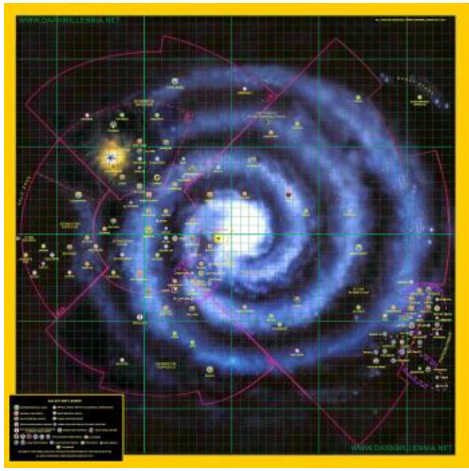


SC Dipoles from Recent Colliders

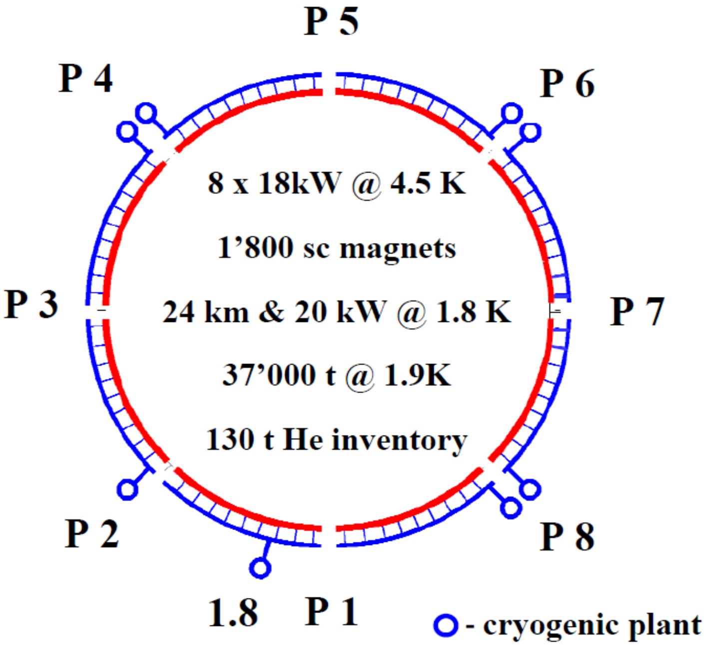


One of the coldest places in the universe…

- Superconducting magnets with a field of 8.3 Tesla are cooled by superfluid helium at 1.9 K (corresponds to -271 ^{0}C) along 20 km



- Large cooling plants for magnet cooling at 1.9 K, 4.5 K and higher temperatures



Protection of Superconducting Magnets

- A superconductor is such only when it operates below its critical surface. Once in normal conducting state, e.g., because of a sudden temperature increase caused by internal mechanical energy release or a beam loss, the superconductor generates resistive power, causing a thermal runaway "quench".

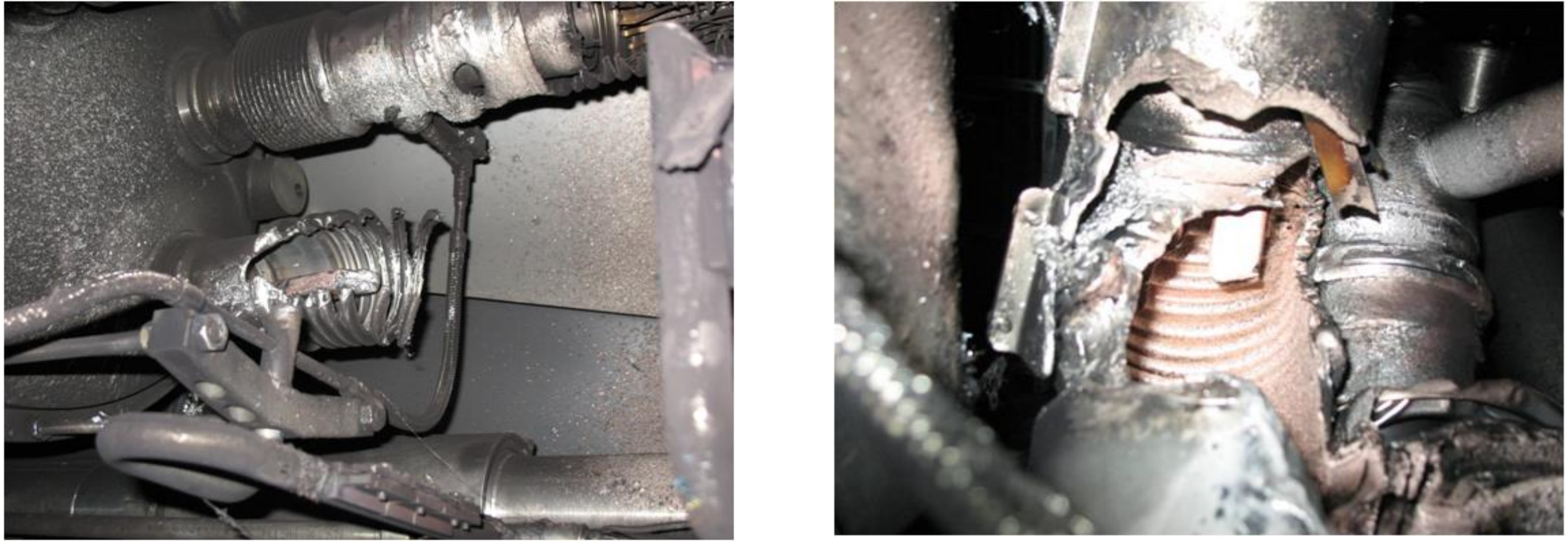
- SC accelerator magnets, tend to have large stored magnetic energy. (LHC → 10 GJ).

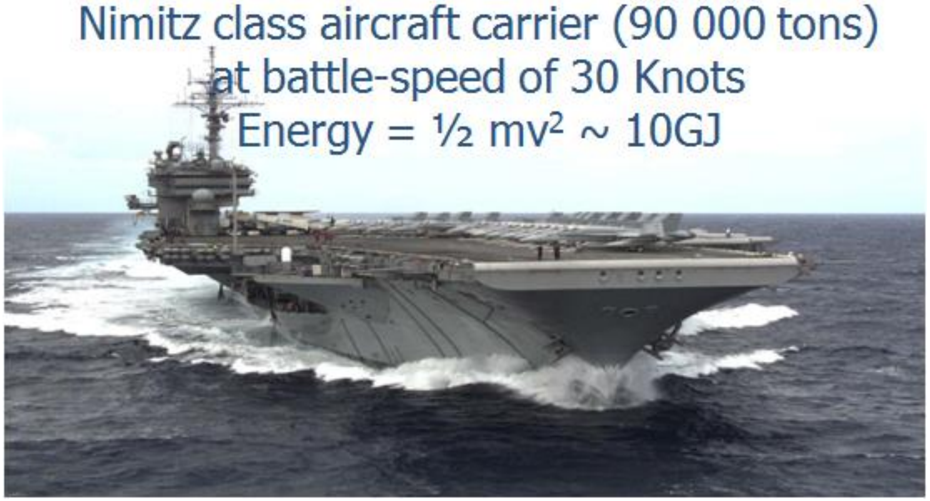
- Local dissipation of energy has the potential to lead to material damage and loss of electrical insulation

  → SC magnets must be protected against quench by detecting any irreversible resistive transition (quench detection electronics) and discharging the magnet

  → very precise measurement of the resistance across the SC coils (< mV resolution in a very EM noisy environment!)

Protection of Superconducting Magnets





Nimitz class aircraft carrier (90 000 tons)
at battle-speed of 30 Knots
Energy = ½ mv^2 ~ 10GJ

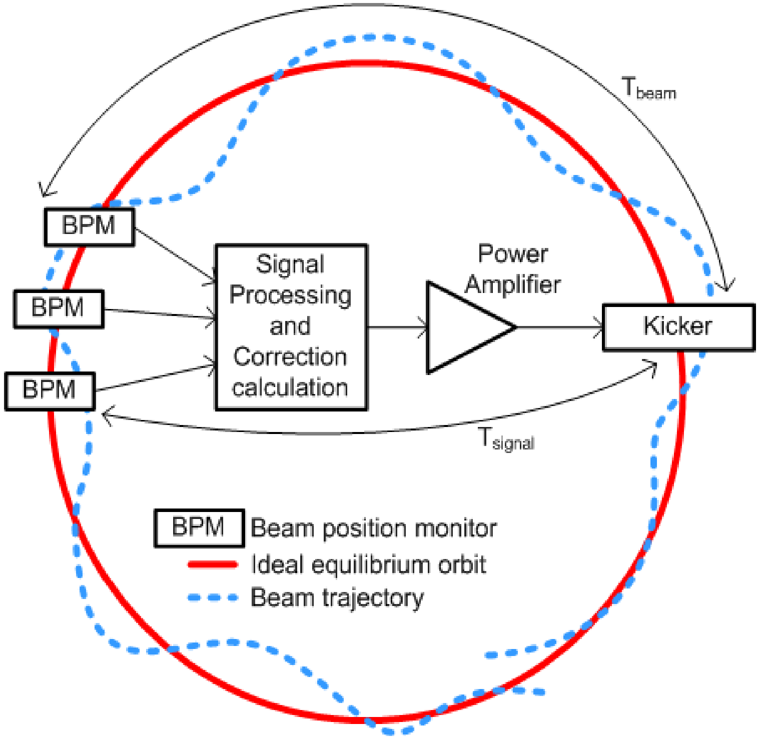
RF systems

- 8 Superconducting cavities/beam delivering an accelerating field of 5.5 MV/m and a total accelerating voltage per turn of 16 MV
- Fine synchronization of the drive signals and loops to the 10^{-12} s level

LHC 400MHz Klystron Installation

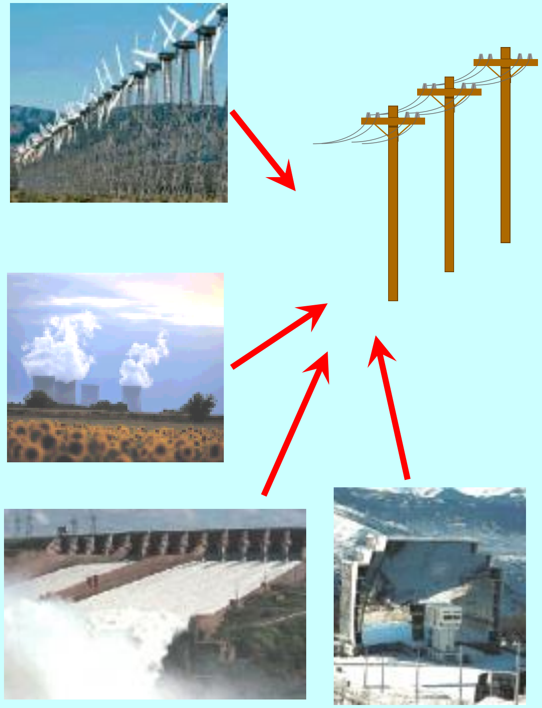
LHC 400MHz SC cavities

RF systems

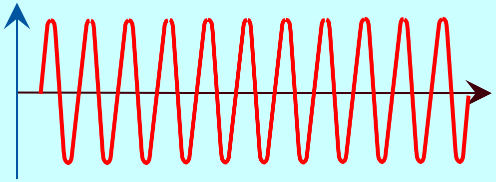


- LHC Transverse Feedback system: bunch-by-bunch/turn-by-turn measurement and correction of the trajectory of individual bunches
- 20 MHz bandwidth.
- ±7.5 kV maximum voltage on two electrodes spaced by 50 mm

Power converters



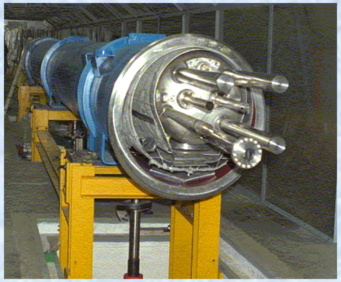
50 or 60 Hz ; AC



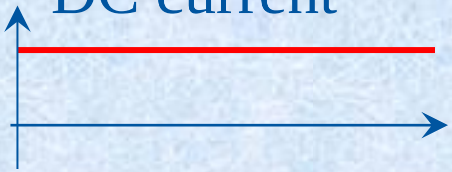
Power converter

The task of a power converter is

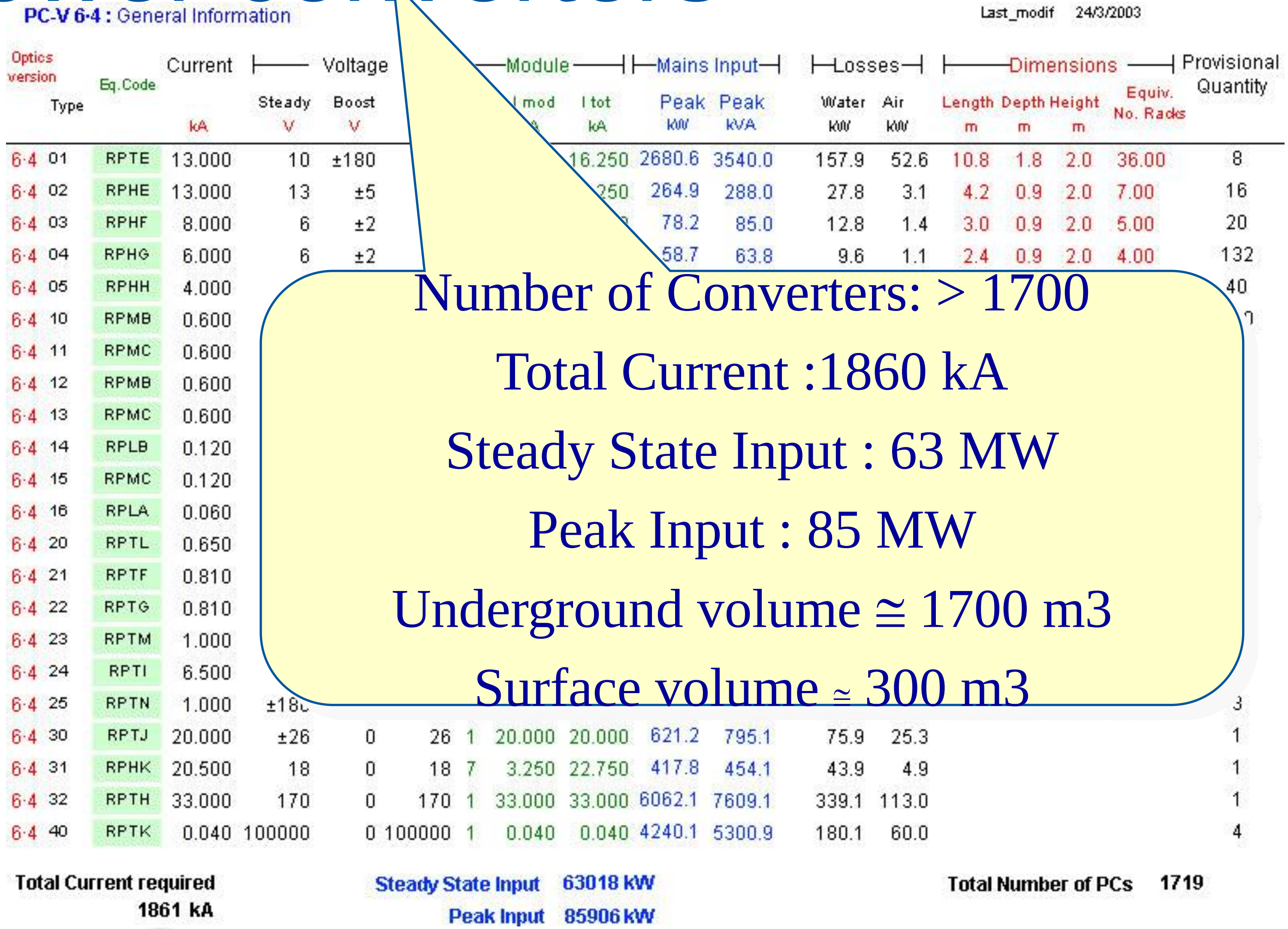
to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for accelerator equipment powering



DC current



Power converters



PC-V 6·4 : General Information

Last_modif 24/3/2003

Optics version	Type	Eq.Code	Current kA	Voltage Steady V	Voltage Boost V			Module I mod	Module I tot kA	Mains Input Peak kW	Mains Input Peak kVA	Losses Water kW	Losses Air kW	Dimensions Length m	Dimensions Depth m	Dimensions Height m	Dimensions Equiv. No. Racks	Provisional Quantity
6·4	01	RPTE	13.000	10	±180				16.250	2680.6	3540.0	157.9	52.6	10.8	1.8	2.0	36.00	8
6·4	02	RPHE	13.000	13	±5				250	264.9	288.0	27.8	3.1	4.2	0.9	2.0	7.00	16
6·4	03	RPHF	8.000	6	±2					78.2	85.0	12.8	1.4	3.0	0.9	2.0	5.00	20
6·4	04	RPHG	6.000	6	±2					58.7	63.8	9.6	1.1	2.4	0.9	2.0	4.00	132
6·4	05	RPHH	4.000															40
6·4	10	RPMB	0.600															
6·4	11	RPMC	0.600															
6·4	12	RPMB	0.600															
6·4	13	RPMC	0.600															
6·4	14	RPLB	0.120															
6·4	15	RPMC	0.120															
6·4	16	RPLA	0.060															
6·4	20	RPTL	0.650															
6·4	21	RPTF	0.810															
6·4	22	RPTG	0.810															
6·4	23	RPTM	1.000															
6·4	24	RPTI	6.500															
6·4	25	RPTN	1.000	±18														3
6·4	30	RPTJ	20.000	±26	0	26	1	20.000	20.000	621.2	795.1	75.9	25.3					1
6·4	31	RPHK	20.500	18	0	18	7	3.250	22.750	417.8	454.1	43.9	4.9					1
6·4	32	RPTH	33.000	170	0	170	1	33.000	33.000	6062.1	7609.1	339.1	113.0					1
6·4	40	RPTK	0.040	100000	0	100000	1	0.040	0.040	4240.1	5300.9	180.1	60.0					4

Total Current required **1861 kA**

Steady State Input **63018 kW**

Peak Input **85906 kW**

Total Number of PCs **1719**

Number of Converters: > 1700

Total Current :1860 kA

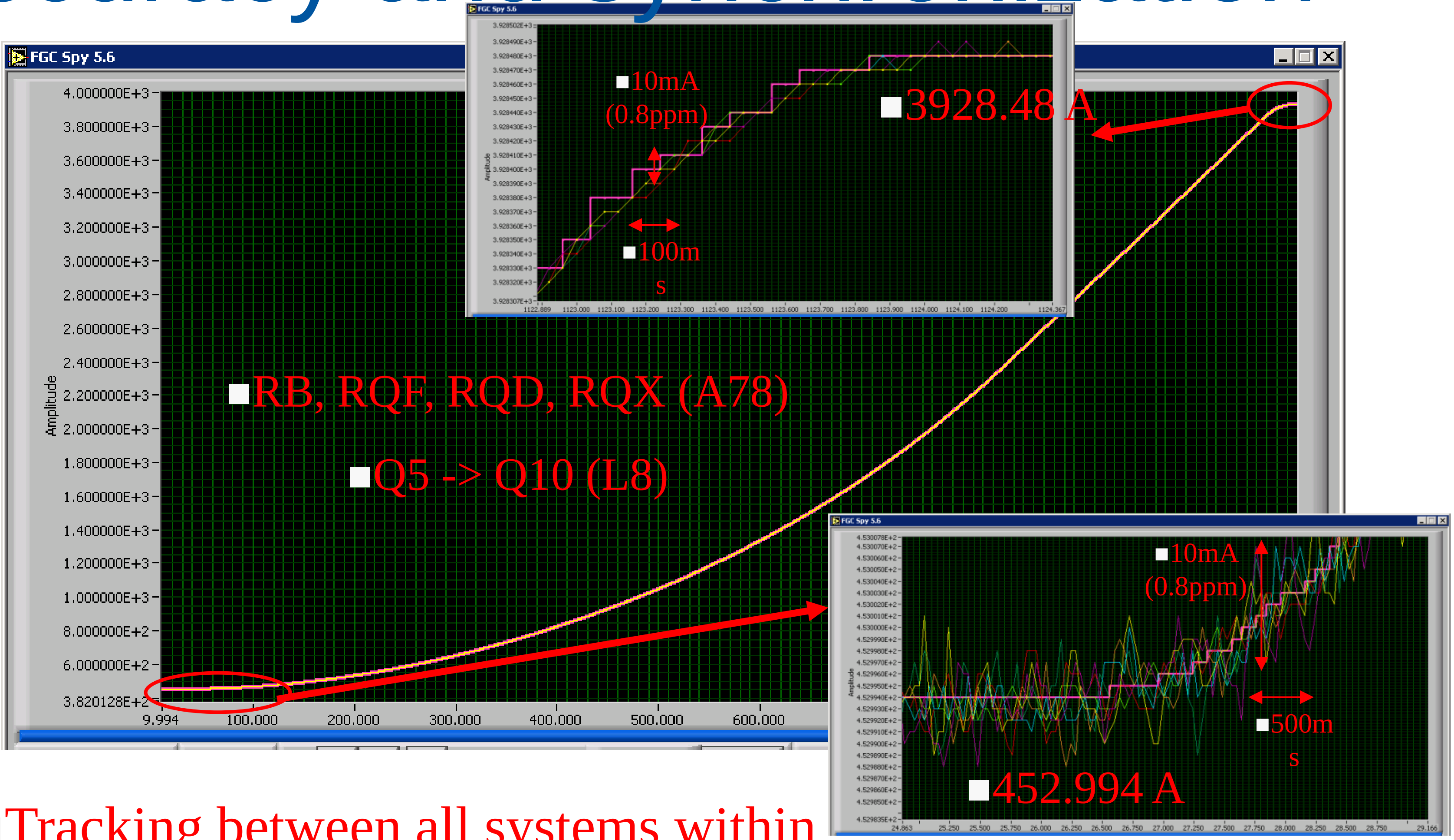
Steady State Input : 63 MW

Peak Input : 85 MW

Underground volume ≅ 1700 m3

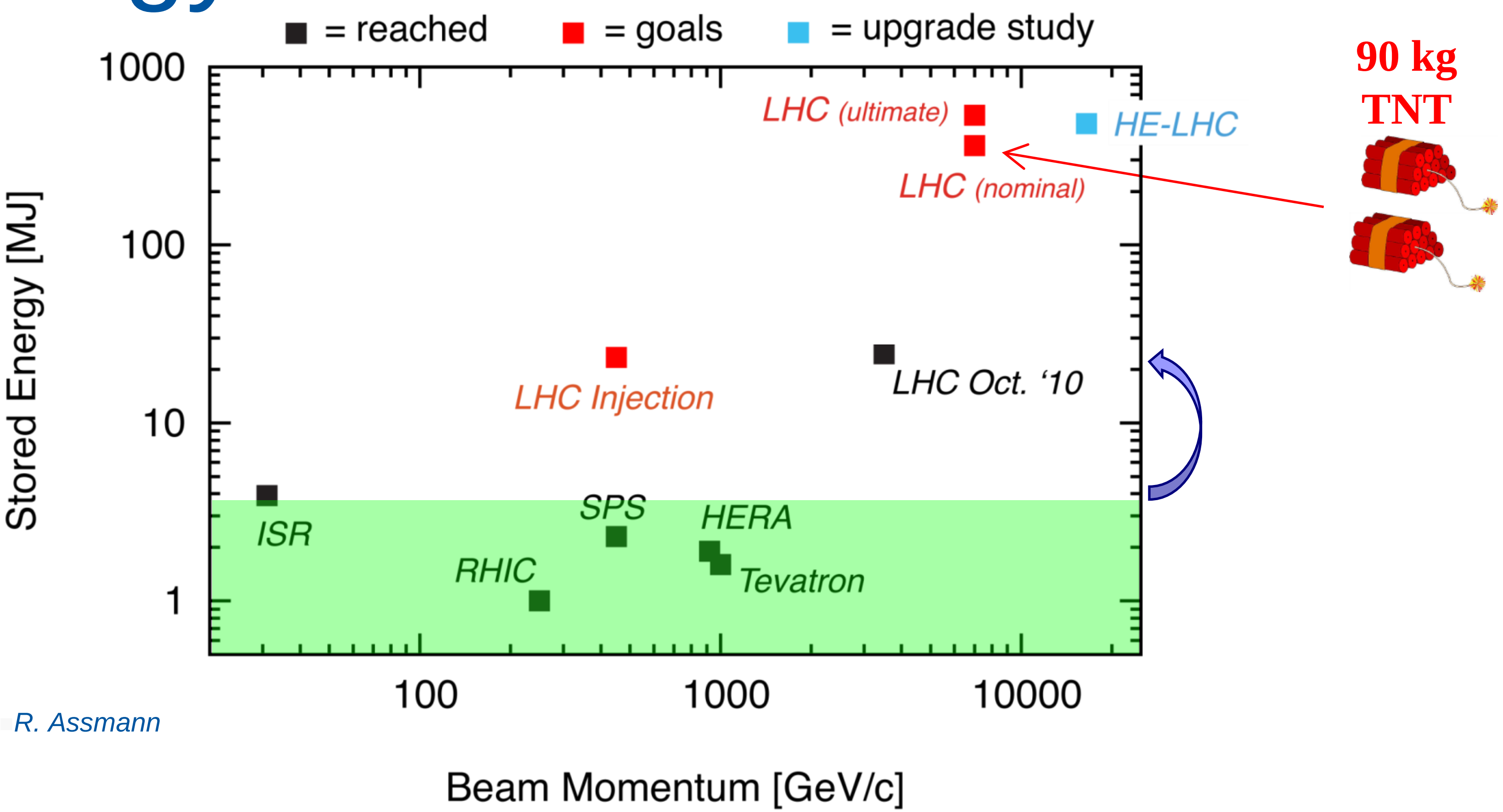
Surface volume ≃ 300 m3

Accuracy and synchronization



Tracking between all systems within measurement noise

Energy stored in one beam



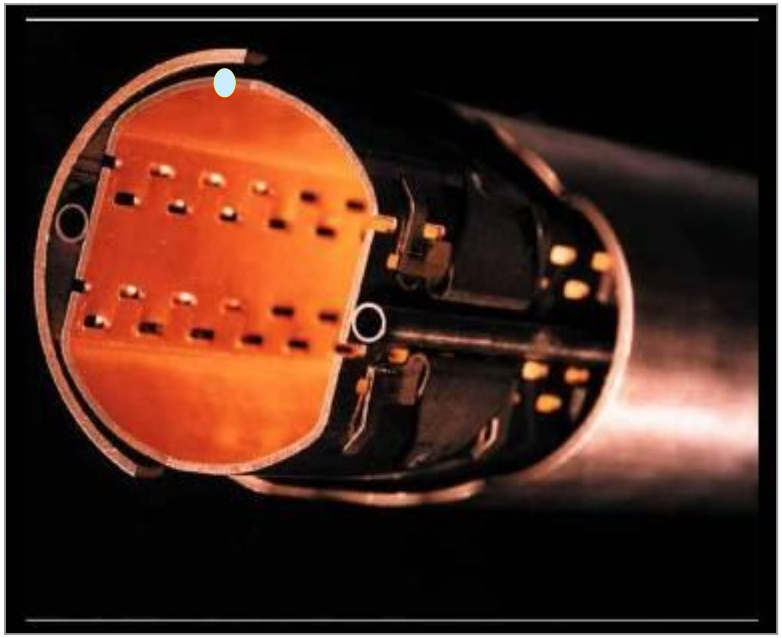
R. Assmann

Energy stored in one beam

- 300000000000000 (=$3 \cdot 10^{14}$) protons in each beam
- Kinetic Energy of 200 m Train at 155 km/h ≈ 360 Million Joule
- Stored energy per beam is 360 Million Joule

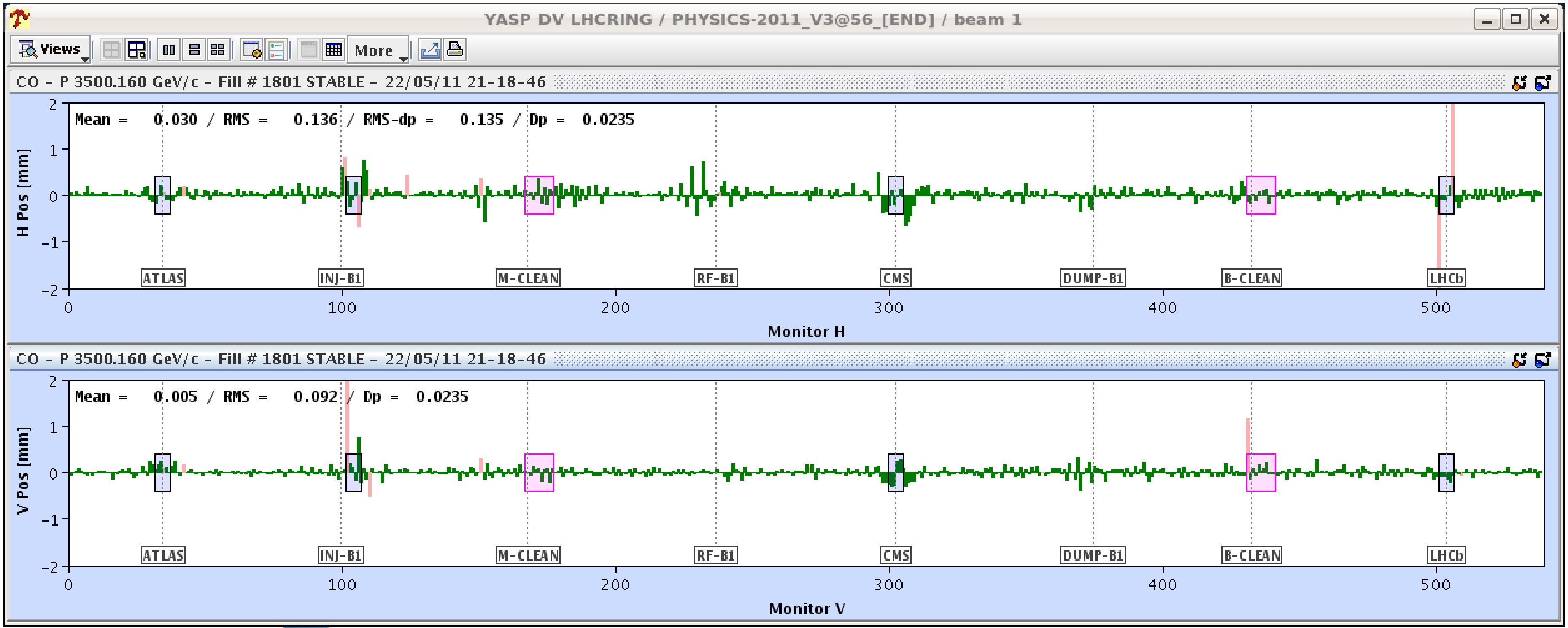
Risk of damage from beam

- Beams with the energy of a fast speed train are running through the beam tube with the speed of light
- 10000 magnets keep the beams in the center of the beam tube
- In case of magnet failure, the beams hit the accelerator equipment in a very short time, 1/1000 of a second
- This must **never happen**.



LHC Beam Position Monitors

- Very precise orbit measurement is necessary to safely operate the machine. Precision are of the order of ~100 μm all around the 27 km of the ring. Total of **1182** BPMs for the LHC and its Transfer Lines



YASP DV LHCRING / PHYSICS-2011_V3@56_[END] / beam 1

CO - P 3500.160 GeV/c - Fill # 1801 STABLE - 22/05/11 21-18-46

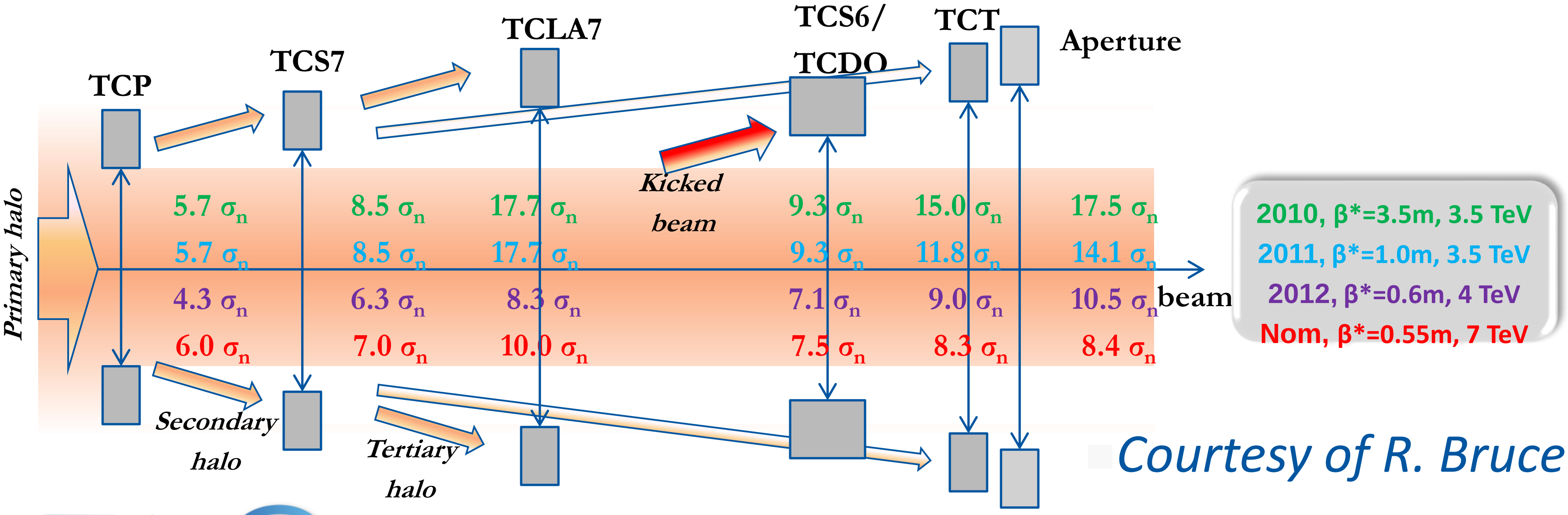
```
Mean =    0.030  / RMS =    0.136  / RMS-dp =    0.135  / Dp =   0.0235
```

CO - P 3500.160 GeV/c - Fill # 1801 STABLE - 22/05/11 21-18-46

```
Mean =    0.005  / RMS =    0.092  / Dp =   0.0235
```

Collimation system

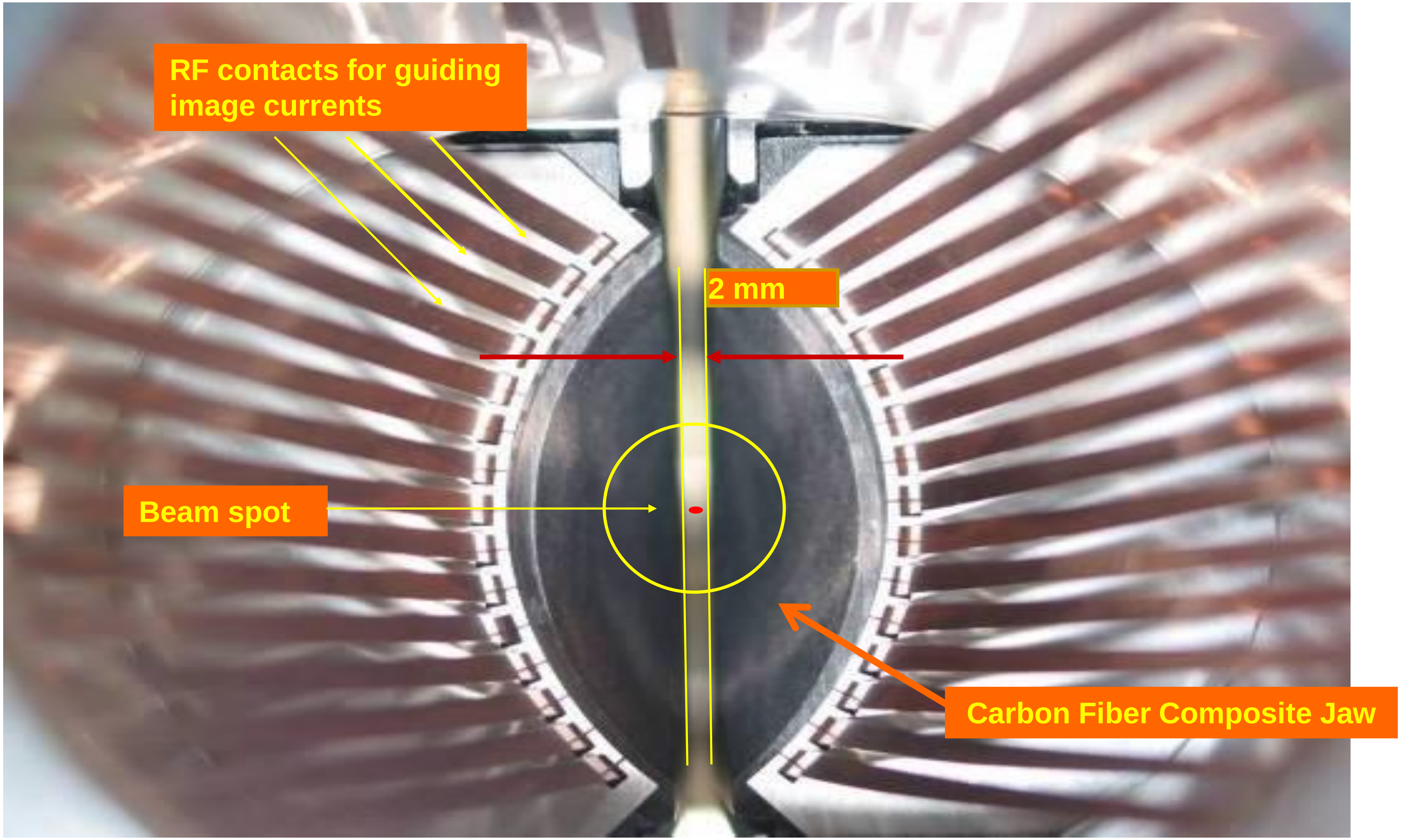
- Complex and high performance multi-stage collimation system.
- Collimation hierarchy has to be respected in order to achieve satisfactory protection and cleaning.
- Lower β* implies tighter collimator settings as well as alignment, beam sizes and orbit well within tolerance. We could do it only after having gained experience in orbit and optics controls and thanks to the small emittance delivered by the injectors.
- Smaller β* implies tighter collimator settings



	TCP	TCS7	TCLA7	TCS6/TCDQ	TCT	Aperture
2010, β*=3.5m, 3.5 TeV	5.7 σ_n	8.5 σ_n	17.7 σ_n	9.3 σ_n	15.0 σ_n	17.5 σ_n
2011, β*=1.0m, 3.5 TeV	5.7 σ_n	8.5 σ_n	17.7 σ_n	9.3 σ_n	11.8 σ_n	14.1 σ_n
2012, β*=0.6m, 4 TeV	4.3 σ_n	6.3 σ_n	8.3 σ_n	7.1 σ_n	9.0 σ_n	10.5 σ_n
Nom, β*=0.55m, 7 TeV	6.0 σ_n	7.0 σ_n	10.0 σ_n	7.5 σ_n	8.3 σ_n	8.4 σ_n

Courtesy of R. Bruce

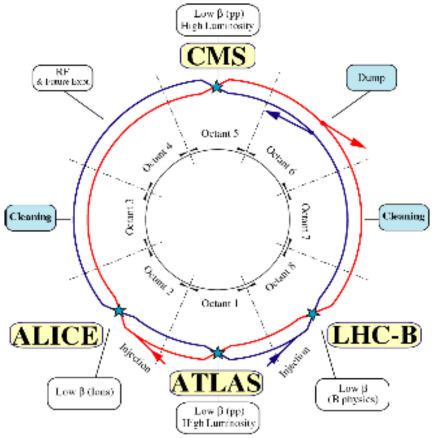
Collimators

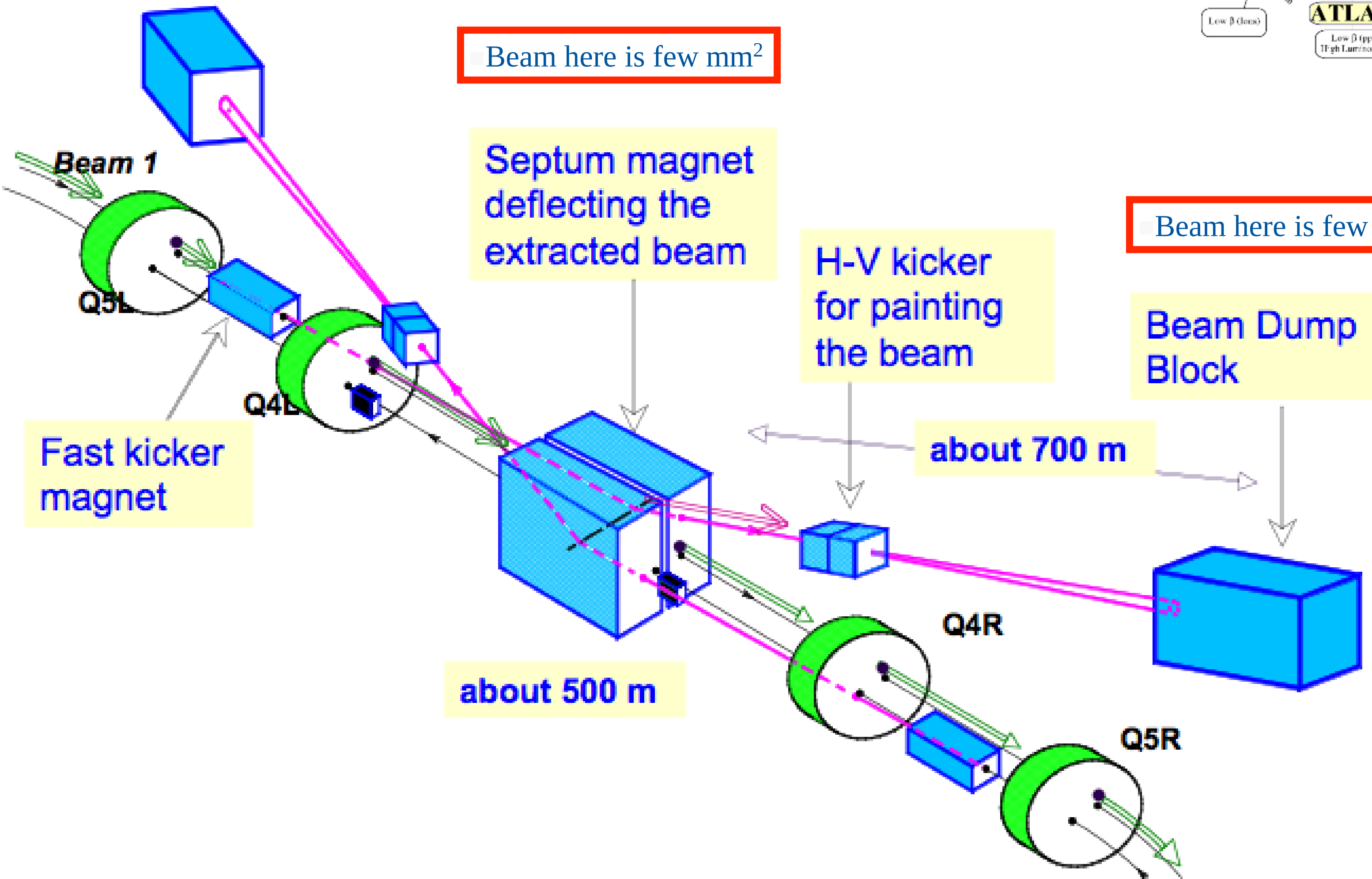


Beam extraction, emergency or not...

At the end of every "fill", when too low luminosity, or when BLM system triggers, both beams extracted on an external beam dump, in one turn.

Beam dump built to absorbe full power at full energy.





Beam here is few mm^2

Septum magnet deflecting the extracted beam

H-V kicker for painting the beam

Beam here is few cm^2

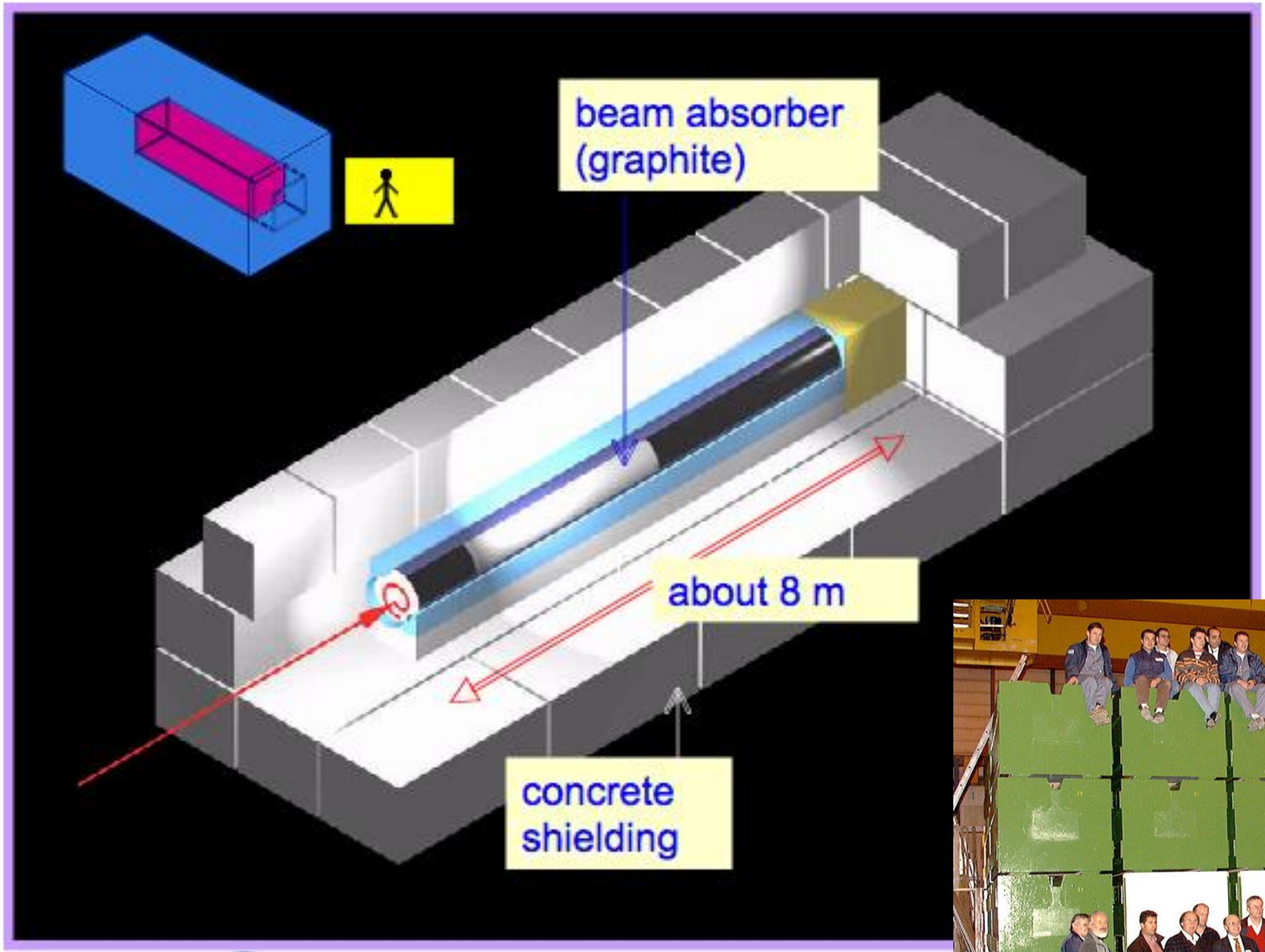
Beam Dump Block

about 700 m

Fast kicker magnet

about 500 m

Scheme of one of the beam absorbers

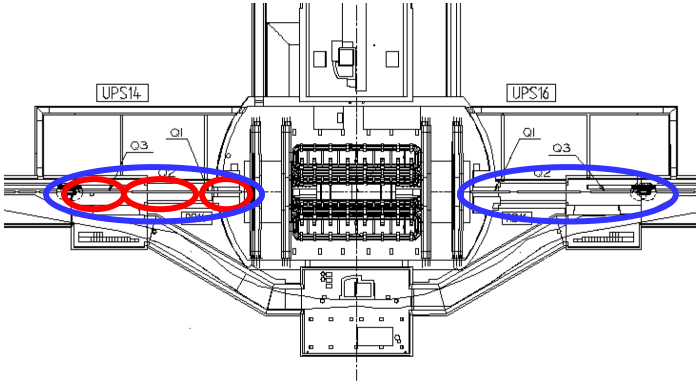


Survey and Alignment

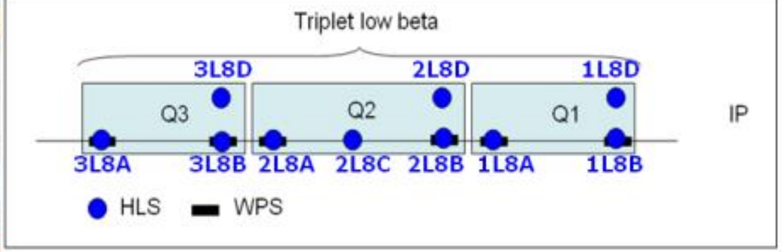
- Very tight tolerances in absolute and relative accuracy for the positioning of the accelerator components imposed by:
  - beam dynamics (e.g. quadrupole magnet misalignments give rise to trajectory distortion of the circulating beam
  - mechanical and geometrical issues influencing the aperture available for the circulating beam.

- Position, orientation, shape and the size of all major accelerator components must be measured to accuracies not needed in any other domain. In order to position a component, a reference system (frame) must be defined, and transferred to the accelerator tunnel.

Survey and Alignment

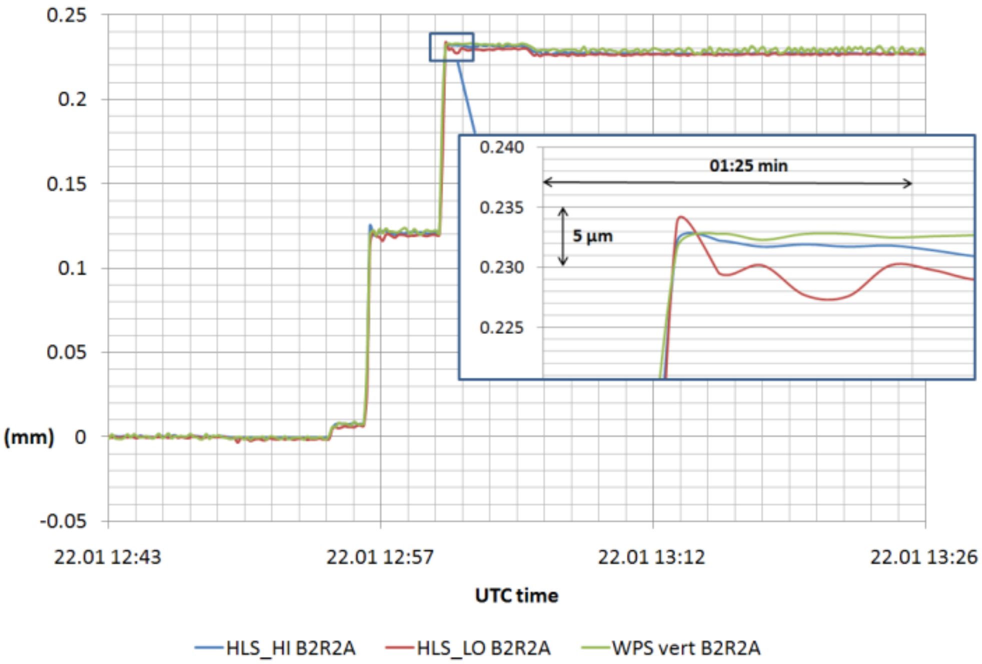


- VERY TIGHT TOLERANCES:
- Relative alignment Left/Right (~50 m distance): ±0.5 mm (3 σ)
- Stability of the positioning of a quadrupole inside its triplet: few tens microns



Survey and Alignment

Case of a remote displacement: resolution of the sensors



- Displacement of 220 μm monitored within 5 μm
- Hydrostatic Levelling System (HLS) based on communicating vessels principle
- Wire Positioning System (WPS) based on stretched Carbon wire

Accelerators in the world

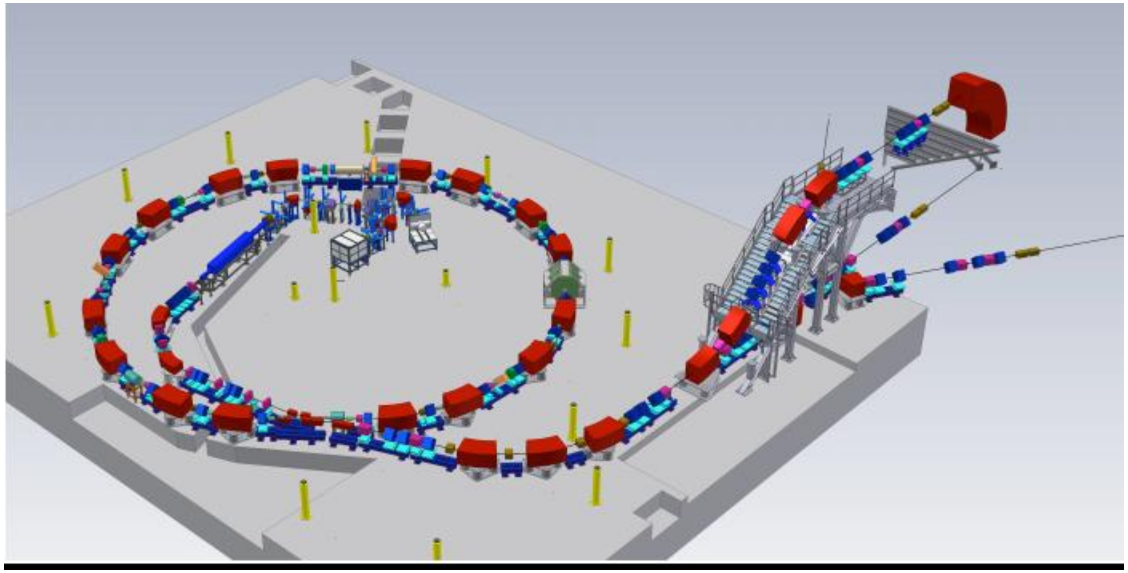
- Accelerator for research are a small fraction of the overall number: more than 30000 now

Accelerators for Everyday's life

- Particle accelerators are also used in many different applications such as material analysis and modification and spectrometry especially in environmental science
- About half of the world's 15,000 accelerators are used as ion implanters, for surface modification and for sterilization and polymerization
- The ionization arising when charged particles are stopped in matter is often utilized for example in radiation surgery and therapy of cancer. At hospitals about 5,000 electron accelerators are used for this purpose.
- Accelerators also produce radioactive elements that are used as tracers in medicine, biology and material science
- In material science, ion and electron accelerators are used to produce neutrons and photons over a wide range of energies. Well-defined beams of photons are for example increasingly used for lithography in order to fabricate the very small structures required in electronics.

Accelerators for Everyday's life

- Not far from here (Pavia – south of Milan) an accelerator is operating in a Hospital (CNAO) to allow cancer therapy with proton and ion beams (hadron-therapy) providing one of the most advanced tools in radiation therapy.



- CERN has contributed to design of this machine and some of its components

Medical applications

CNAO = Centro Nazionale di Adroterapia at Pavia

Edificio del sincrotrone

Edificio ospedaliero

Insegnanti italiani - UA - 9.9.13

TERA

34

Medical applications

Il sincrotrone

Insegnanti italiani - UA - 9.9.13

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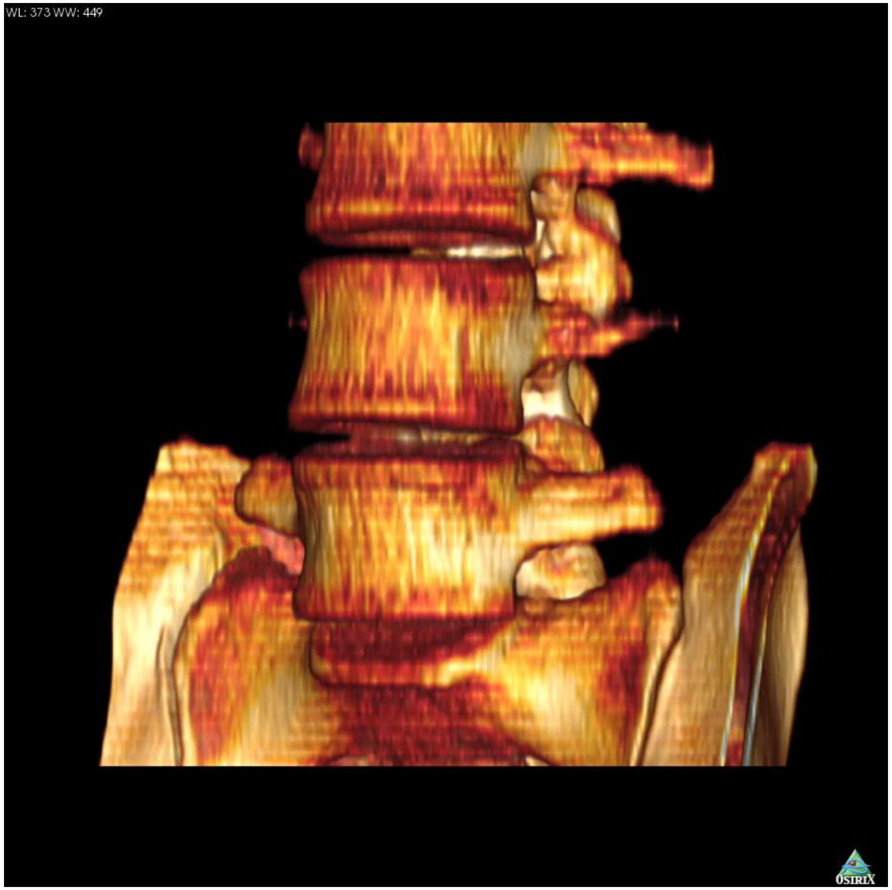
Medical Applications

Heidelberg Ion Therapy Facility (HIT)

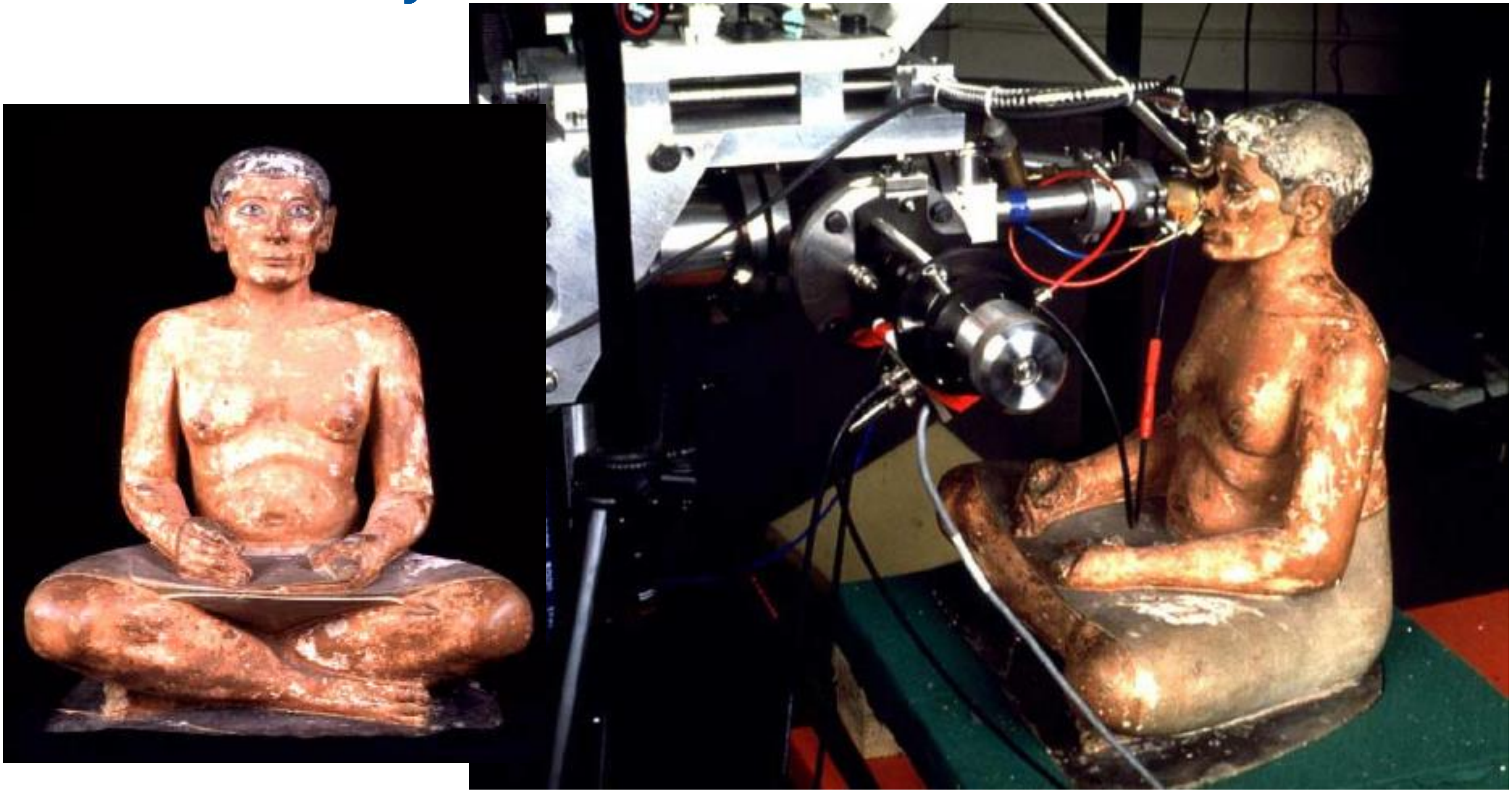
Medical imagery



- A CT (computerized tomography) scanner, or CAT (computerized axial tomography).
- x-ray machine plus detector, both rotating around the patient

http://www.clermontradiology.com/ct_scan.html

Application of Louvre Tandem: composition of scribe eyes

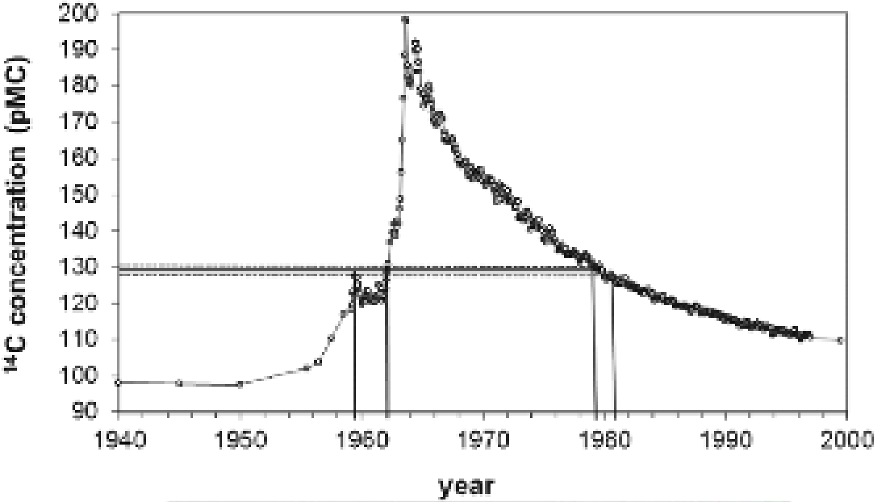


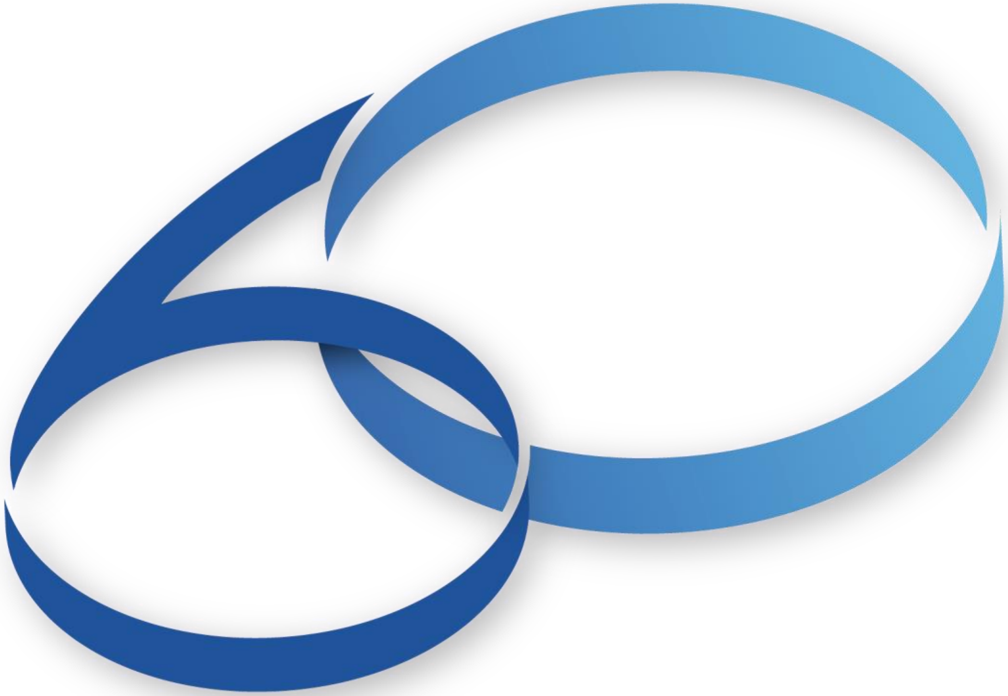
http://accelconf.web.cern.ch/AccelConf/e02/TALKS/FRYGB001.pdf

Discovering forgeries of modern art by the ^{14}C Bomb Peak

Contraste de formes, Fernard Leger (?)
Peggy Guggenheim Collection, Venice.

Accelerator Mass Spectrometry (AMS) to measure rare isotopes abundance with 3MV Tandetron accelerator of INFN-LABEC in Florence.





YEARS / ANS **CERN**