LHC Physics Centre at CERN - Student lectures
April 7th and 9th, 2010
CERN, Geneva, Switzerland

The operation of the LHC accelerator complex

Part 1

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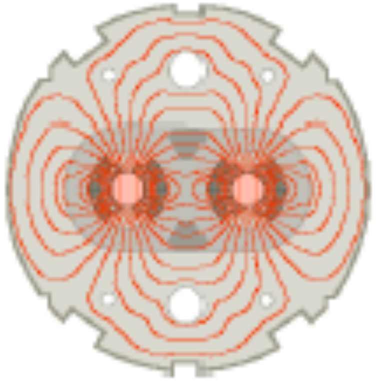
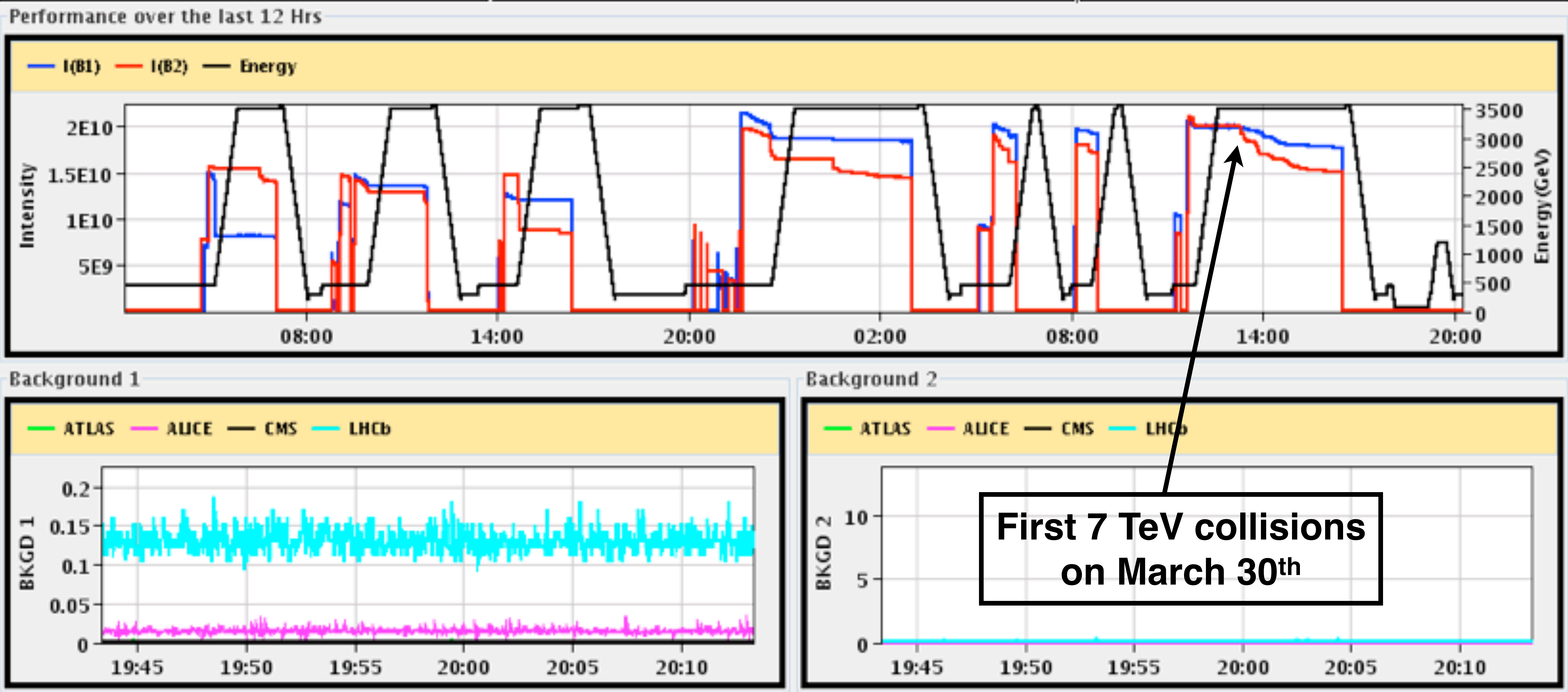
CERN Beams Department
Operations Group



30-Mar-2010 20:14:20 Fill #: 1005 Energy: 297.4 GeV I(B1): 1.55e+08 I(B2): 7.06e+07

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	STANDBY	STANDBY	STANDBY
Instantaneous Luminosity	0.000e+00	0.000e+00	0.000e+00	0.000e+00
BRAN Count Rate	1.559e-01	2.818e-05	2.969e+00	2.732e-07
BKGD 1	0.002	0.013	0.002	0.122
BKGD 2	0.000	0.000	0.002	0.002
BKGD 3	0.000	0.005	0.003	0.040

LHCf STANDBY Count(Hz): 0.000 | LHCb VELO Position OUT Gap: 58.0 mm | TOTEM: STANDBY



What do experiments want?

High energy

B = bending field
ρ = bending radius
p = momentum
e = charge

$$B\rho = \frac{p}{\mathrm{e}}$$

Determined by the maximum field of bending dipoles, B

High luminosity

$$\mathcal{L} = \frac{N^2 n_b f_{\mathrm{rev}}}{4\pi\sigma_x\sigma_y} F$$

N = bunch population
n_b = number of bunches
f_{rev} = revolution frequency
$\sigma_{x,y}$ = colliding beam sizes
F = geometric factor

Depends on machine parameters: charge per bunch (N), num. of bunches (n_b) and transverse beam sizes (σ)

“Thus, to achieve high luminosity, all one has to do is make (lots of) high population bunches of low emittance to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible.” PDG 2005, chapter 25

LHC design parameters

Nominal LHC parameters	
Beam injection energy (TeV)	0.45
Beam energy (TeV)	7.0
Number of particles per bunch	1.15×10^{11}
Number of bunches per beam	2808
Max stored beam energy (MJ)	362
Norm transverse emittance (μm rad)	3.75
Colliding beam size (μm)	16
Bunch length at 7 TeV (cm)	7.55

- How do we produce ~3000 proton bunches of 450 GeV?

- How do we accelerate them to higher energies?

- How do we make small beams?

- What are the implication of these parameters on OP/layout?

- How do we operate the whole LHC complex? With which tools?

- How do we talk to the experiments?

- ...

Outline - 1st lecture

- **Introduction**
- **Recap. of accelerator physics**
  - Basic equations
  - Measurements → tools
- **LHC injector complex**
  - Source and Linac2
  - PS Booster
  - Proton synchrotron
  - Super Proton Synchrotron
- **LHC parameters and layout**
  - Arc and straight sections
  - Machine protection system

Outline - 2st lecture

- **Parameters for 2010-11**
- **LHC operational phases**
  - The LHC cycle
  - Commissioning: baseline / status
- **Operational tools**
  - Page 1's / Fixed displays
  - More applications
- **One shift of LHC operation**
  - How do we operate the LHC

Outline

- Introduction
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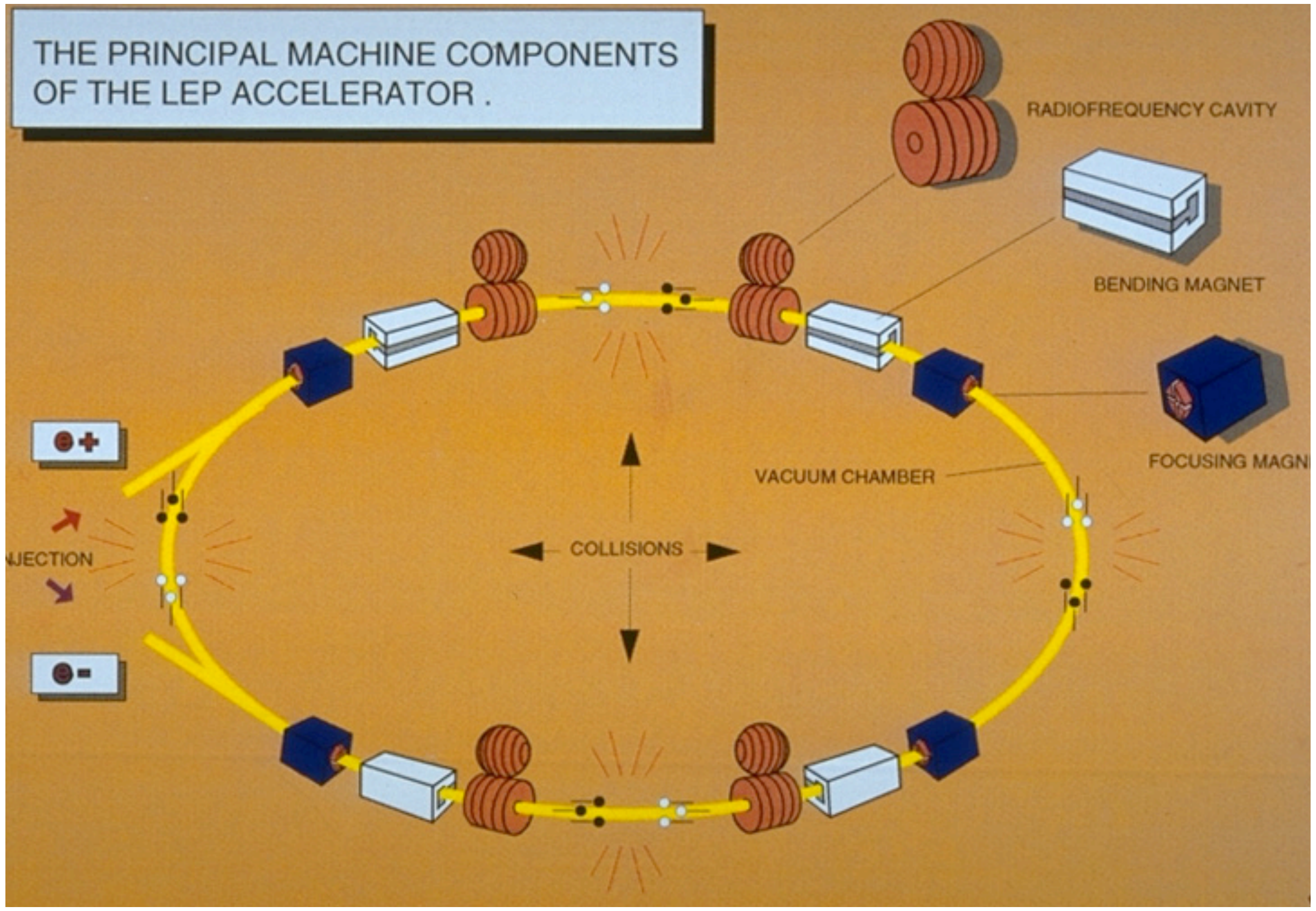
Basic concepts



Charged particles are accelerated, guided and confined by **electromagnetic fields**.

- Bending: Dipole magnets
- Focusing: Quadrupole magnets
- Acceleration: RF cavities

In synchrotrons, they are ramped together synchronously to match beam energy.

- Chromatic aberration:Sextupole magnets

Lorentz force

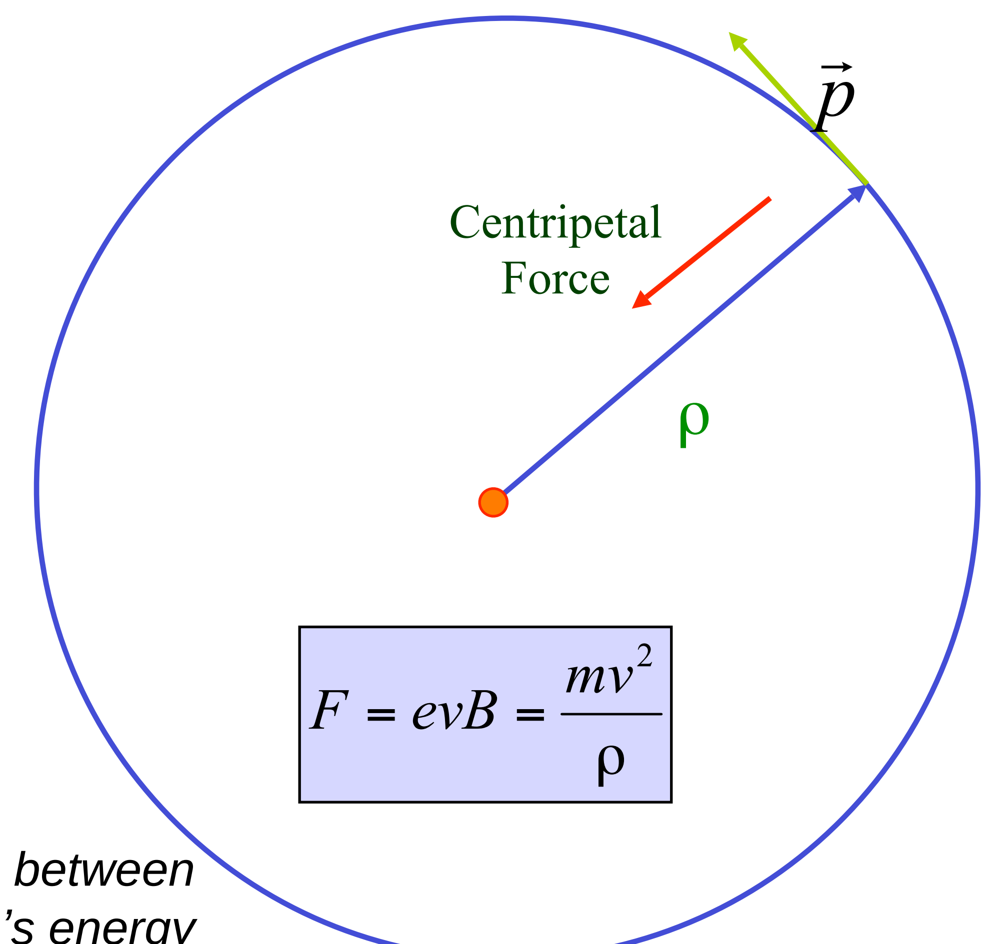
$$\vec{F} = e(\vec{v} \times \vec{B} + \vec{E})$$

Magnetic rigidity

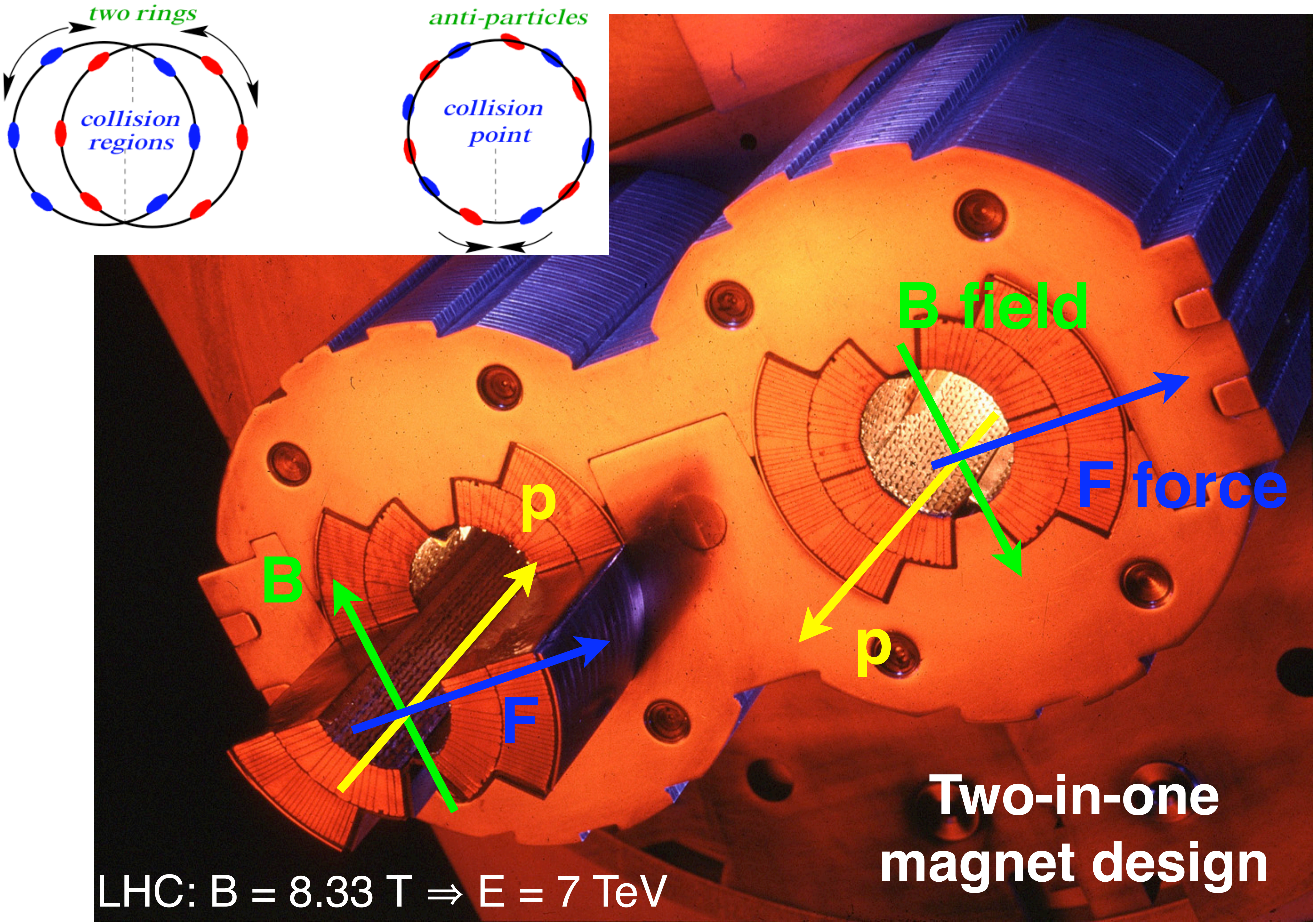
$$B\rho = \frac{mv}{e} = \frac{p}{e}$$

LHC: ρ = 2.8 km given by LEP tunnel!

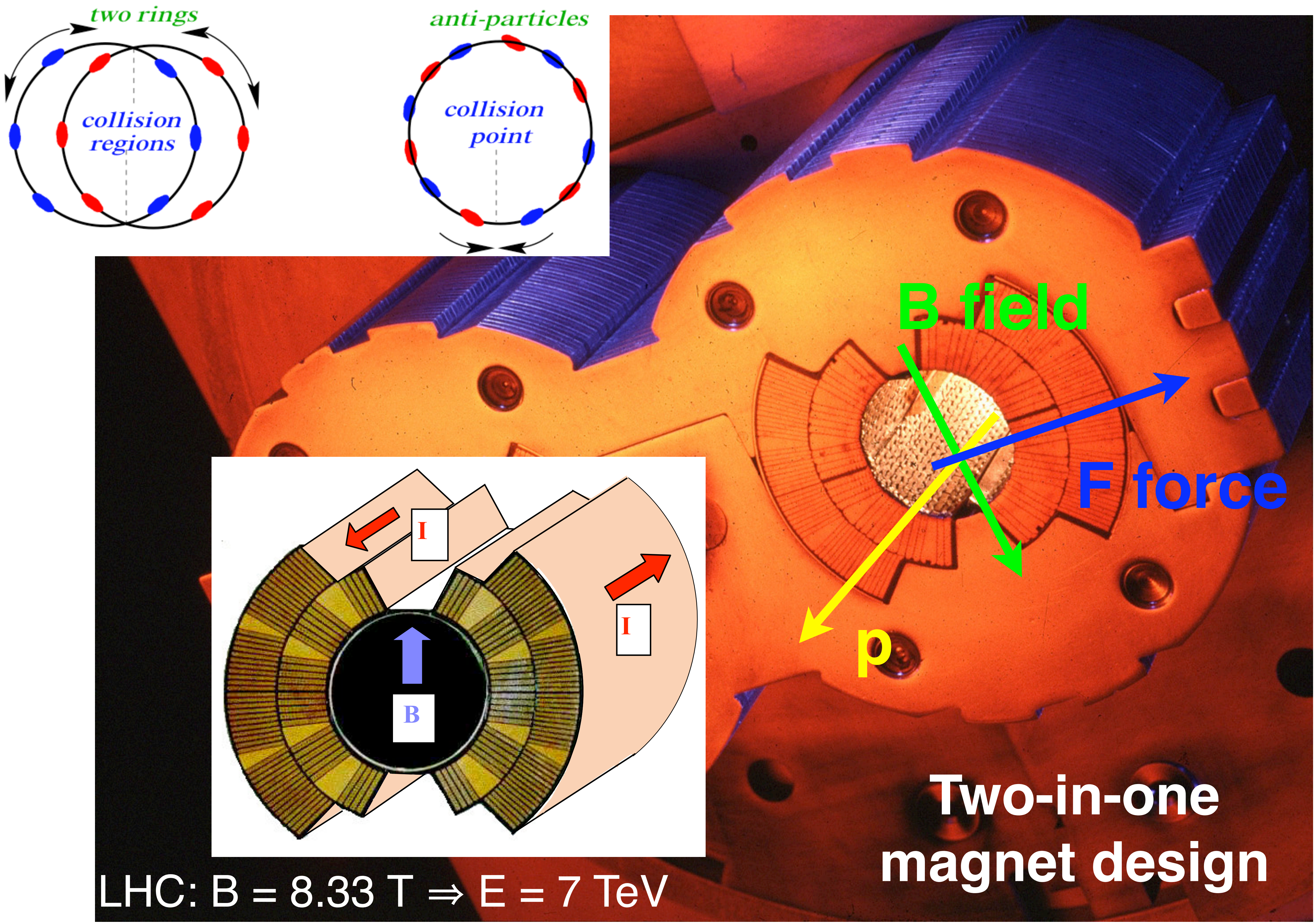
Fixes the relation between magnetic field and particle's energy



Bending


two rings
collision regions
anti-particles
collision point
B field
F force
p
B
p
F
Two-in-one magnet design
LHC: B = 8.33 T ⇒ E = 7 TeV

Bending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I
I
B
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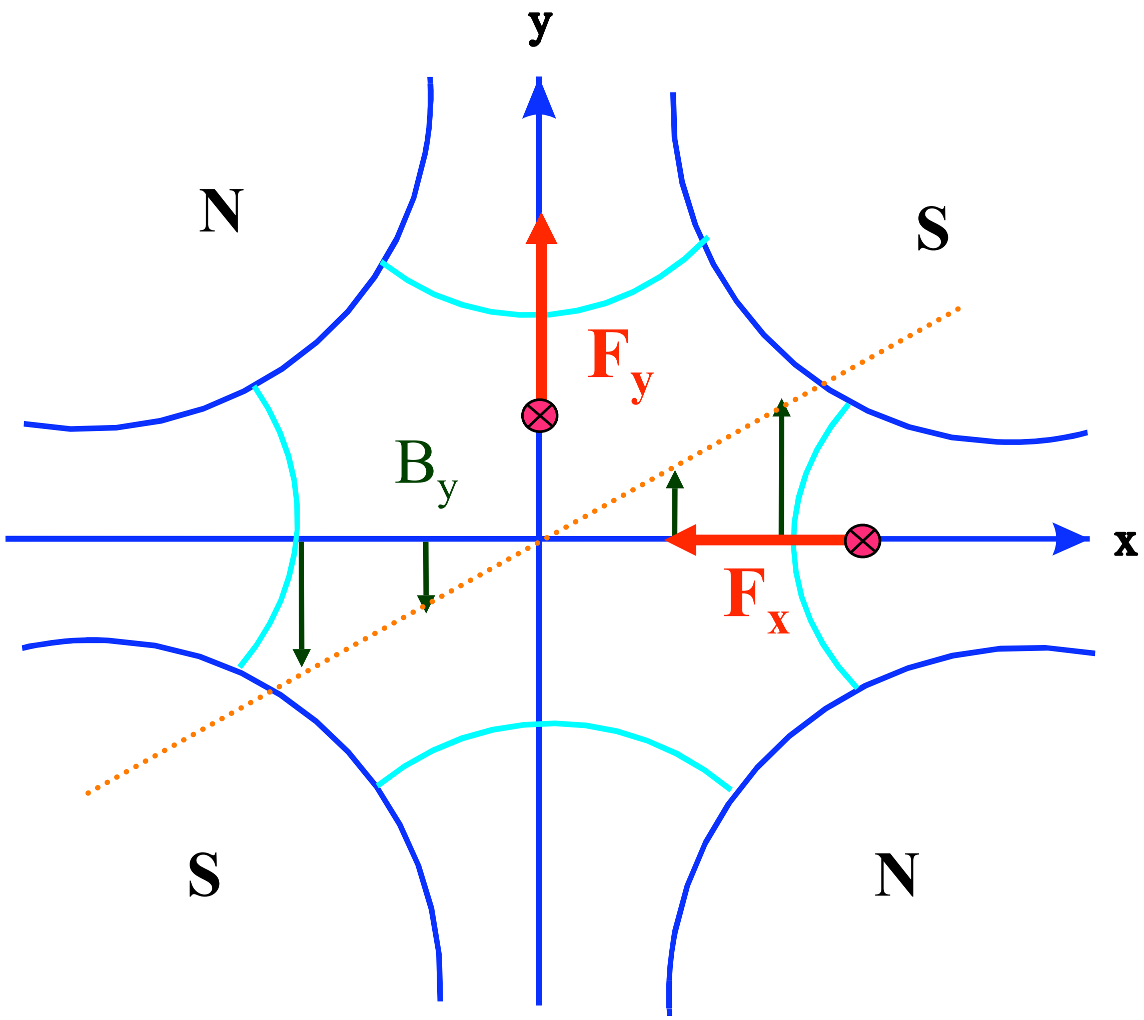
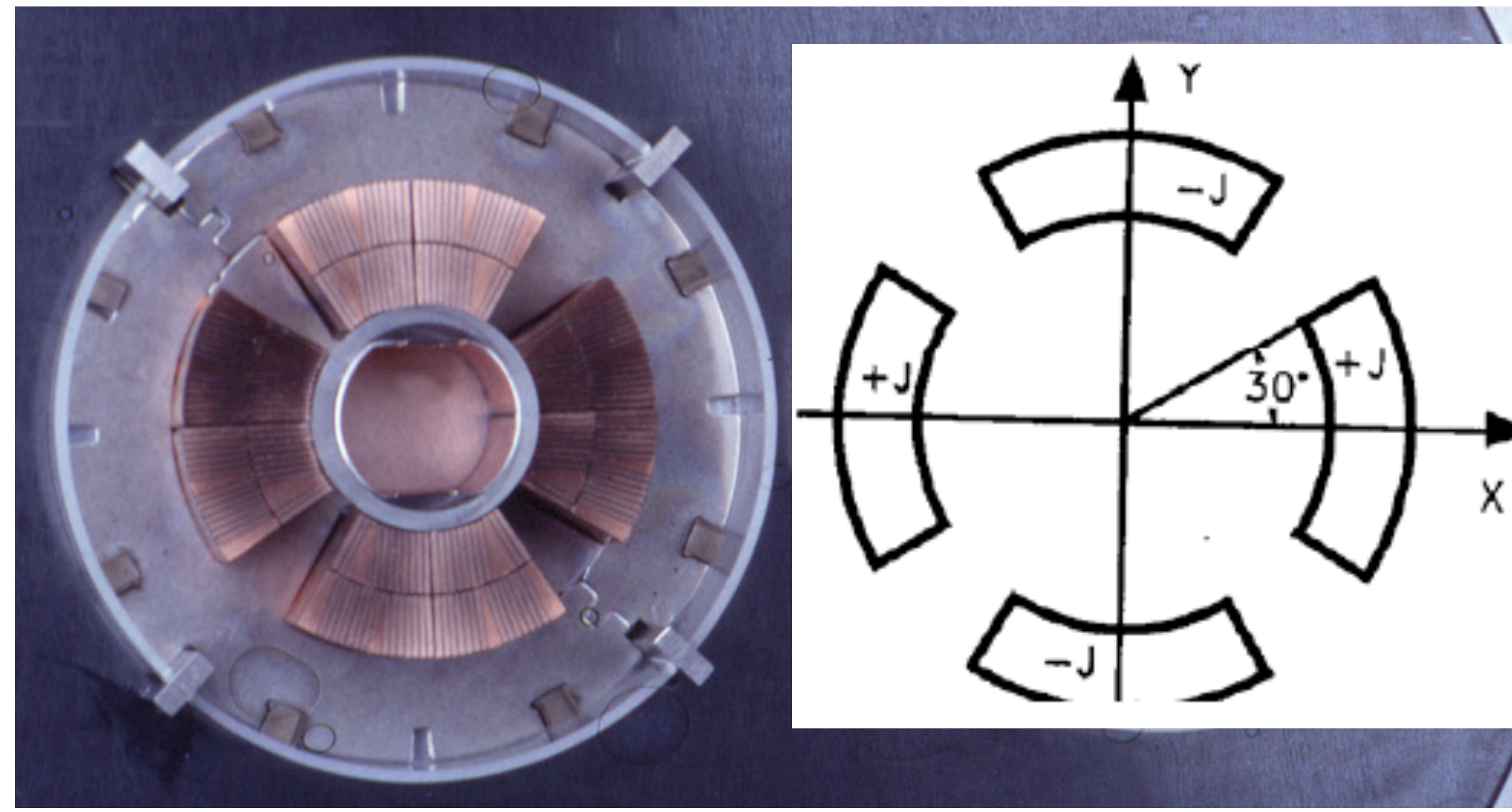
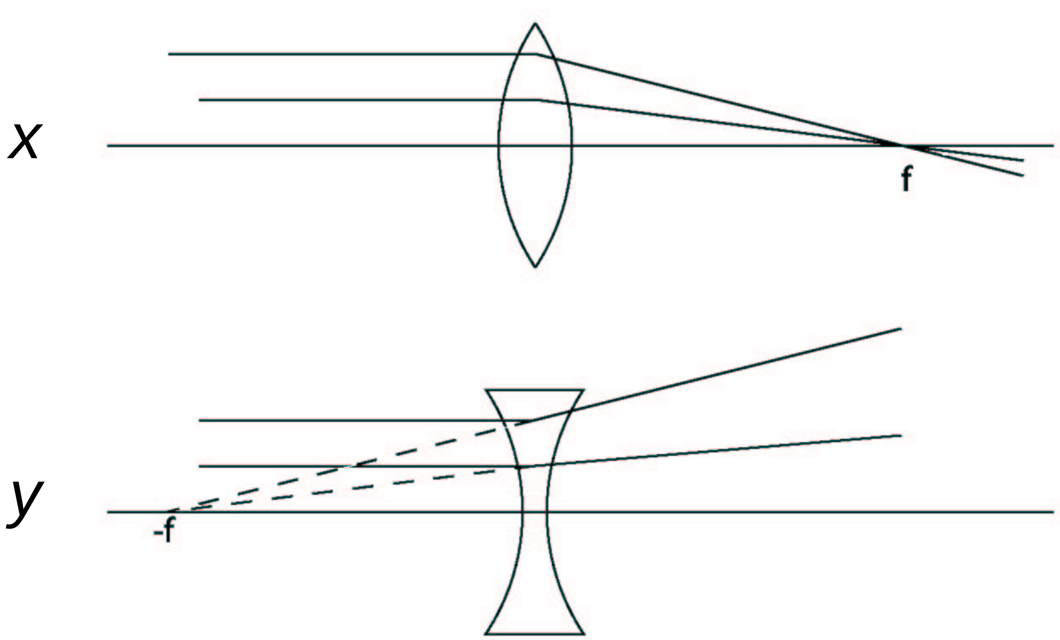
Focusing







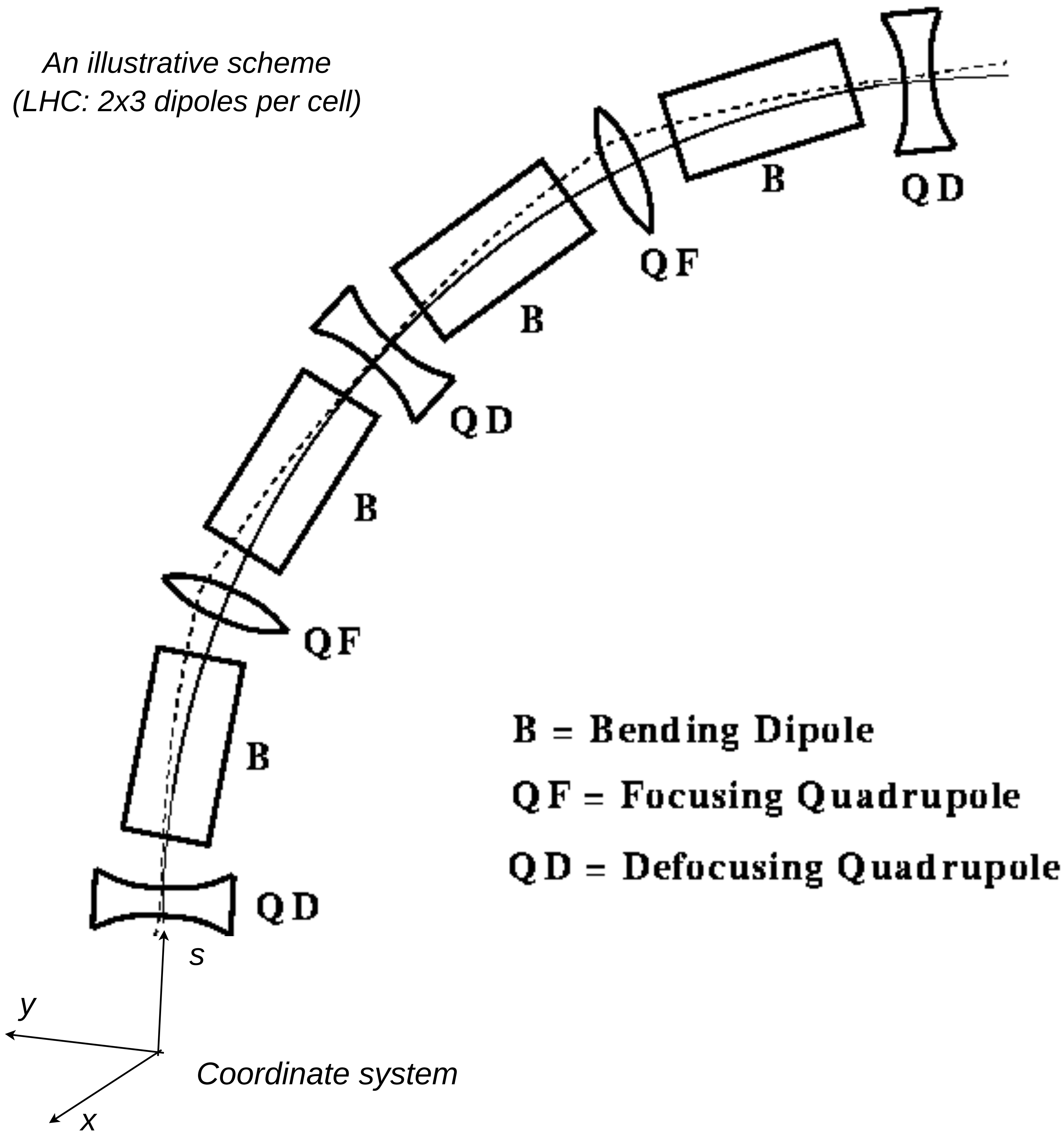
Transverse focusing is achieved with **quadrupole magnets**, which act on the beam like an optical lens.

Linear increase of the magnetic field along the axes (no effect on particles on axis).

Focusing in one plane, **de-focusing** in the other!

Alternating gradient lattice

An illustrative scheme
(LHC: 2x3 dipoles per cell)

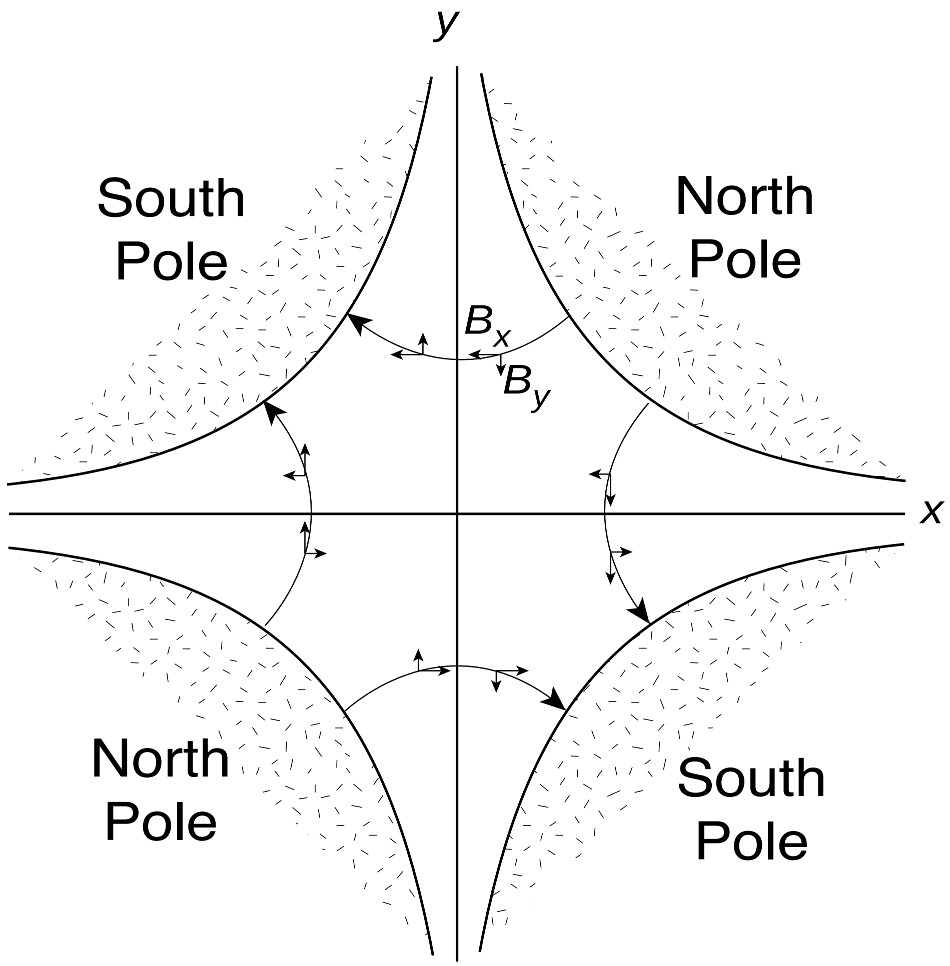


One can find an arrangement of quadrupole magnets that provides net focusing in both planes (“strong focusing”).

Dipole magnets keep the particles on the circular orbit.

Quadrupole magnets focus alternatively in both planes.

Transverse equation of motion



Magnetic field [T] : $$B_y = \frac{\partial B_y}{\partial x} \times x$$

Field gradient [T m-1] : $$g = \frac{\partial B_y}{\partial x}$$

Normalized grad. [m-2] : $$K = \frac{g}{p_0/e} = \frac{1}{f}$$

$$x'' + K(s)x = 0$$

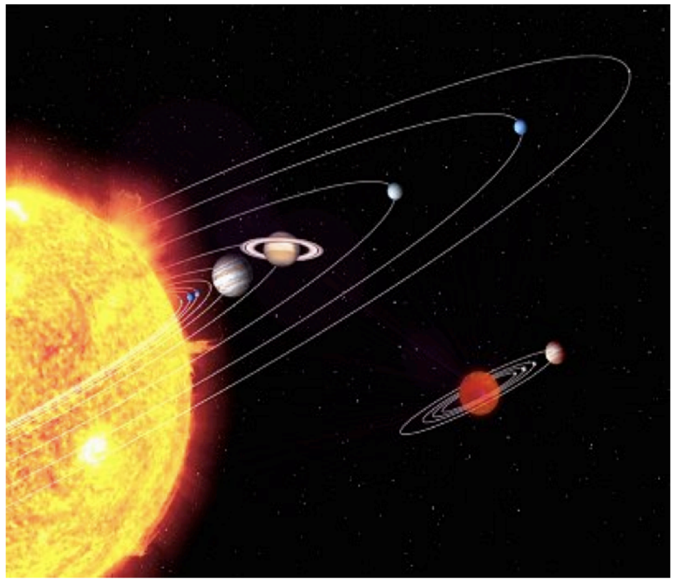
Hill's equation

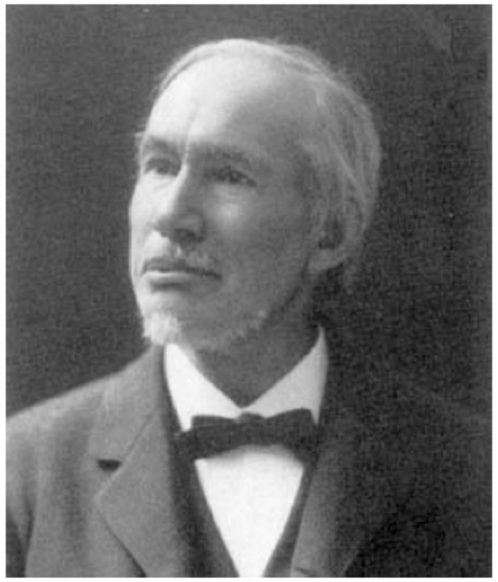
K(s) describes the distribution of focusing strength along the lattice.

Alternating Gradient focusing → pseudo-harmonic oscillator with *s*-dependent spring constant *K(s)*.

The general linear magnet lattice can be parameterized by a 'varying spring constant', *K=K(s)*

Note that dipoles give a "weak focusing" term in the horizontal plane, $K(s) = K(s)+1/\rho^2$





G. Hill, 1838-1914

Betatron motion

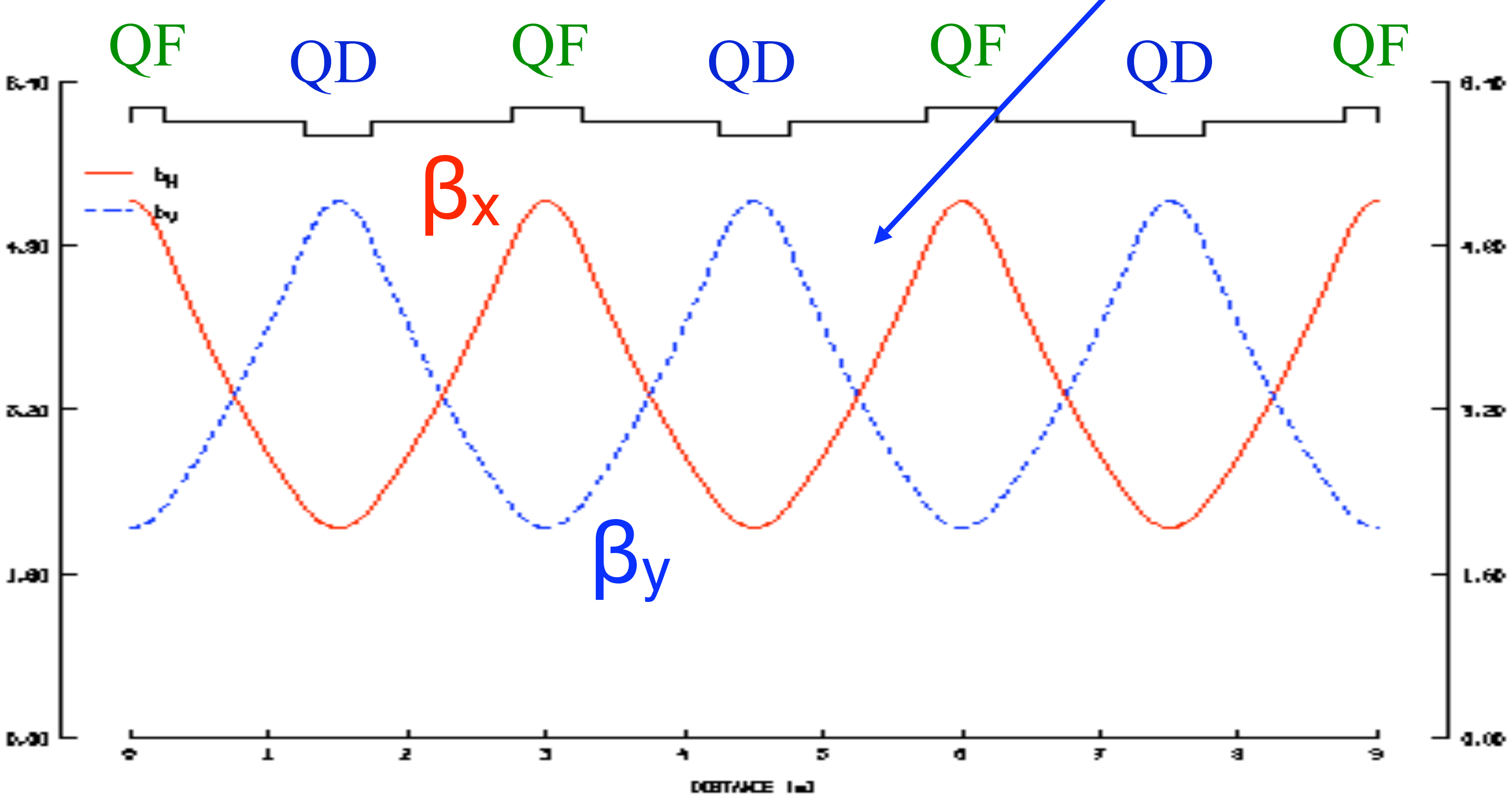
The solution of Hill's equation:

(s is the longitudinal coordinate)

$$x(s) = A\sqrt{\beta_x(s)}\cos[\phi(s) + \phi_0]$$

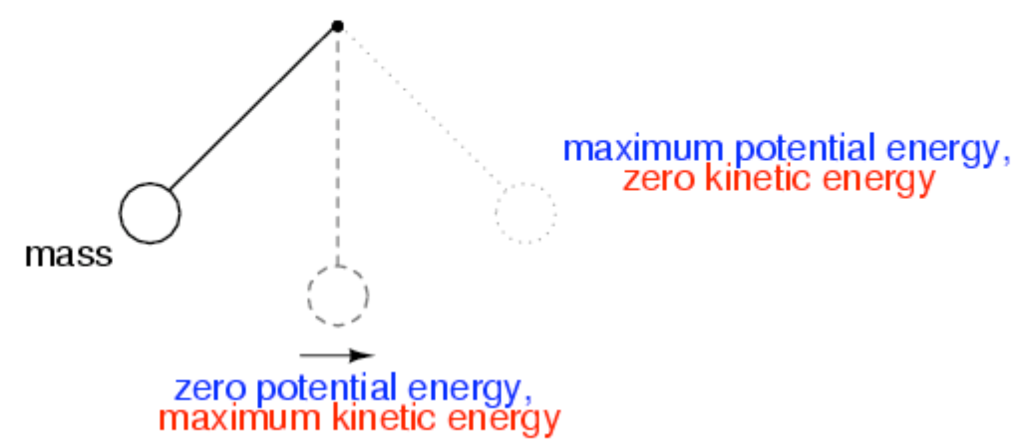
s-dependent amplitude

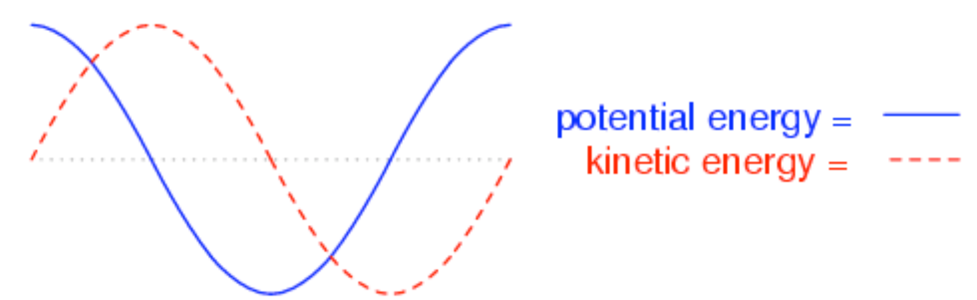
Oscillatory term



Betatron functions in a simple FODO cell

It is analogous to the general solution for simple harmonic motion:

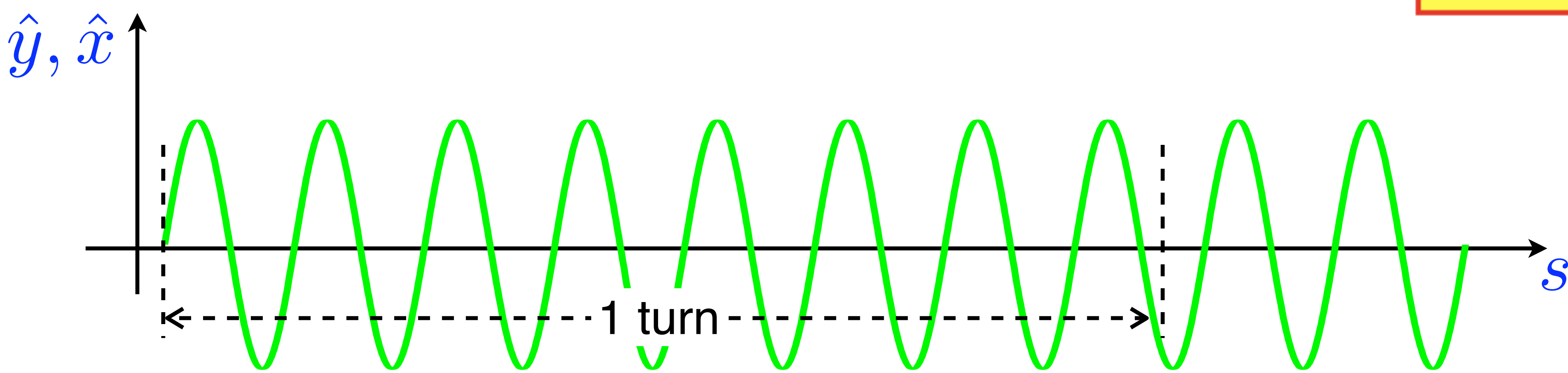




Betatron tune

Betatron phase advance over 1 turn: $\mu = \oint \frac{ds}{\beta(s)}$

Betatron tune: $Q \equiv \frac{1}{2\pi} \oint \frac{ds}{\beta(s)}$

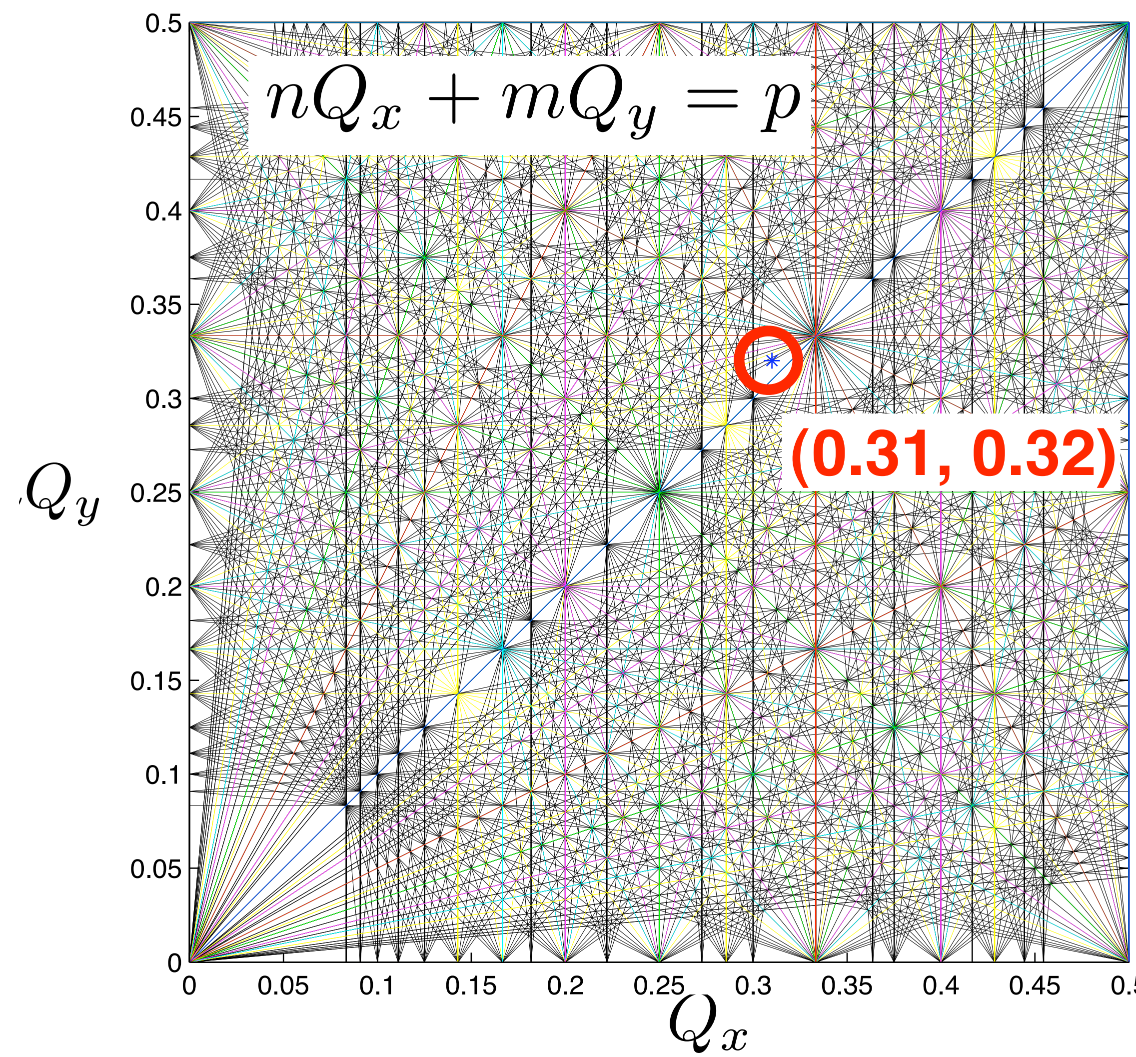


The tune is the **number of betatron oscillations per turn**.

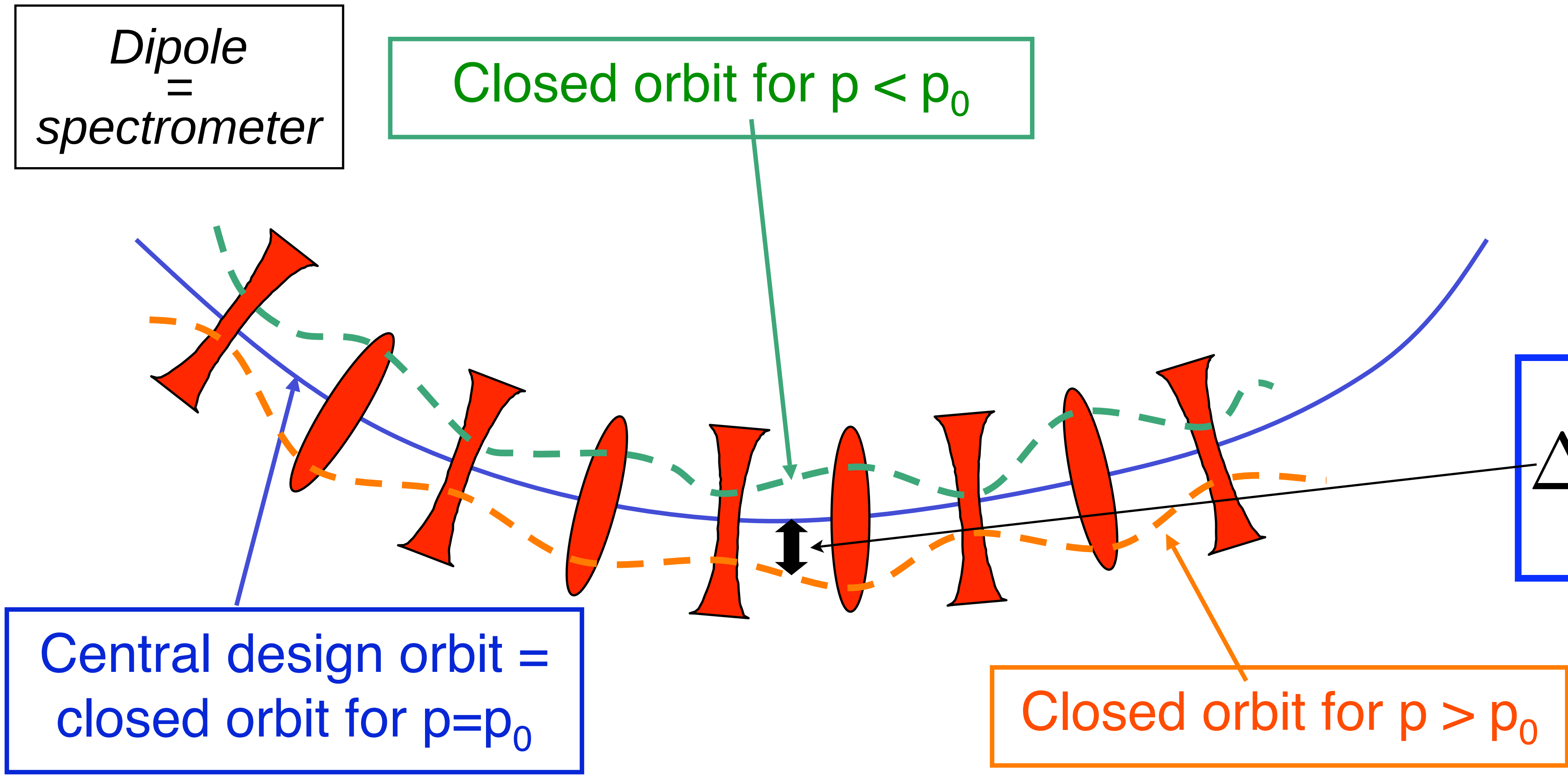
We *normally* only care about the **fractional part** of the tune! 64.31 is 0.31!

The operating tune values (**working point**) must be chosen to avoid resonance.

The tune values must be controlled to within better than 10^{-3}, during all machine phases (ramp, squeeze, ...)



Dispersion



Lattice property

Particle's momentum error

$$\Delta x(s) = D(s) \times \frac{\Delta p}{p}$$

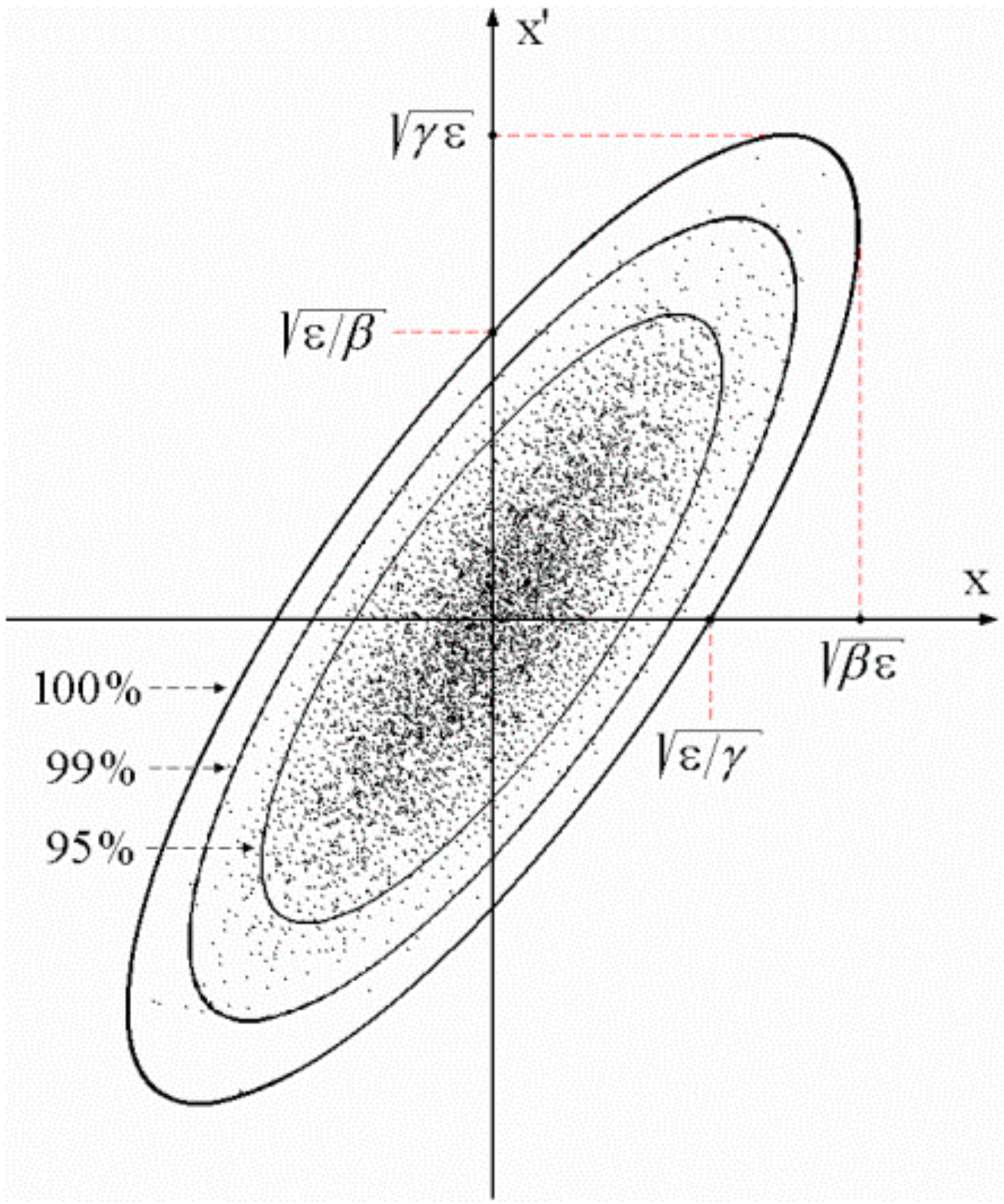
$$x'' + K(s)x = \frac{1}{\rho}\frac{\Delta p}{p_0}$$

Non-homogeneous Hill's equation

$$x(s) = A\sqrt{\beta_x(s)}\cos[\phi(s) + \phi_0] + D(s) \times \frac{\Delta p}{p}$$

D(s) = dispersion function. Periodic in *s*.

Emittance and beam size (i)



Motion of a single particle:

$$x(s) = A\sqrt{\beta_x(s)}\cos[\phi(s)+\phi_0] + D(s) \times \frac{\Delta p}{p}$$

β(s), ϕ(s), D(s) → determined by lattice

A_i, ϕ_i, $\Delta p/p_i$ → define individual trajectories

For an ***ensemble* of particles**:

The **transverse emittance**, **ε**, is the area of the phase-space ellipse.

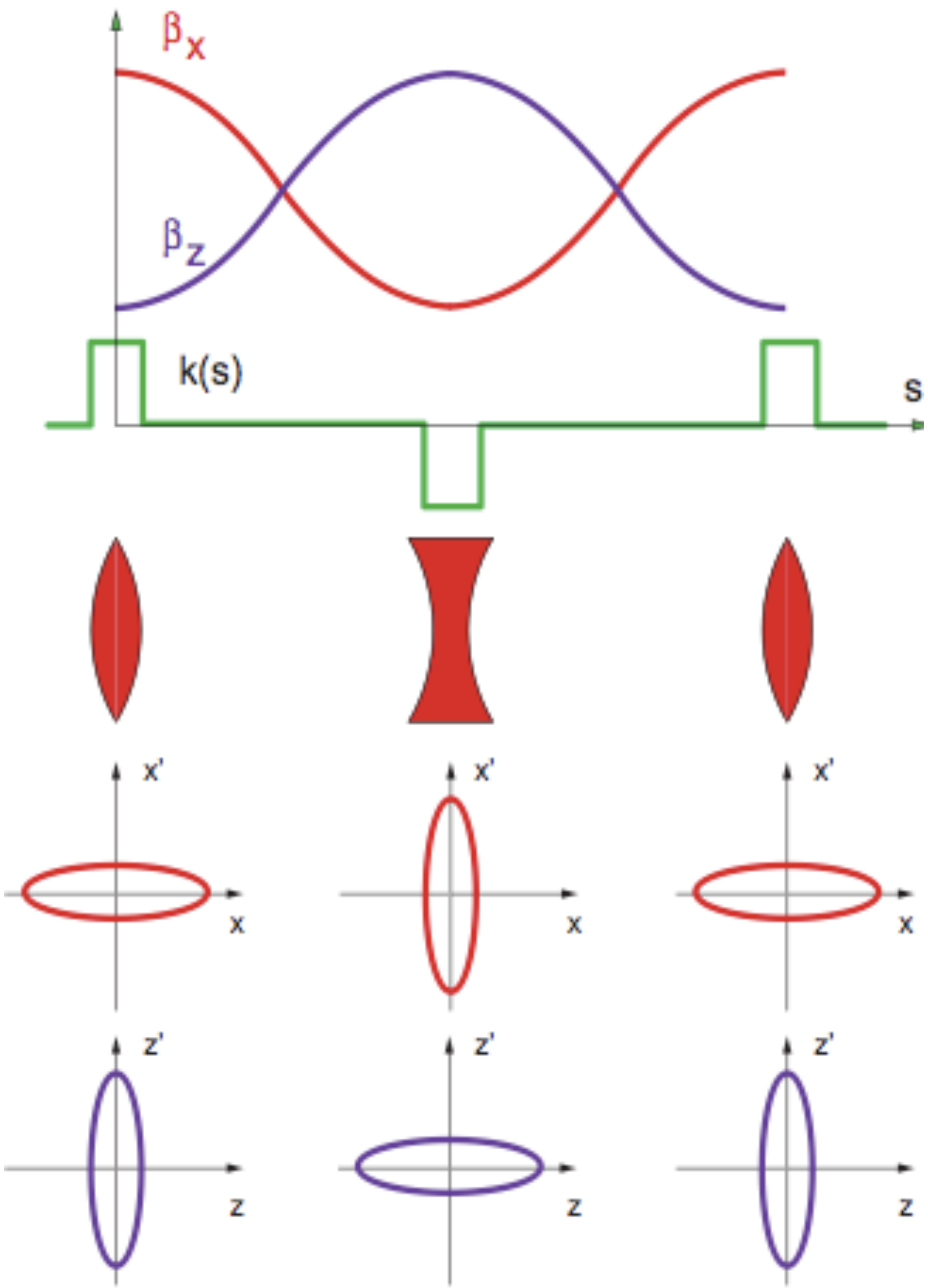
Usually, 95% confidence level given.

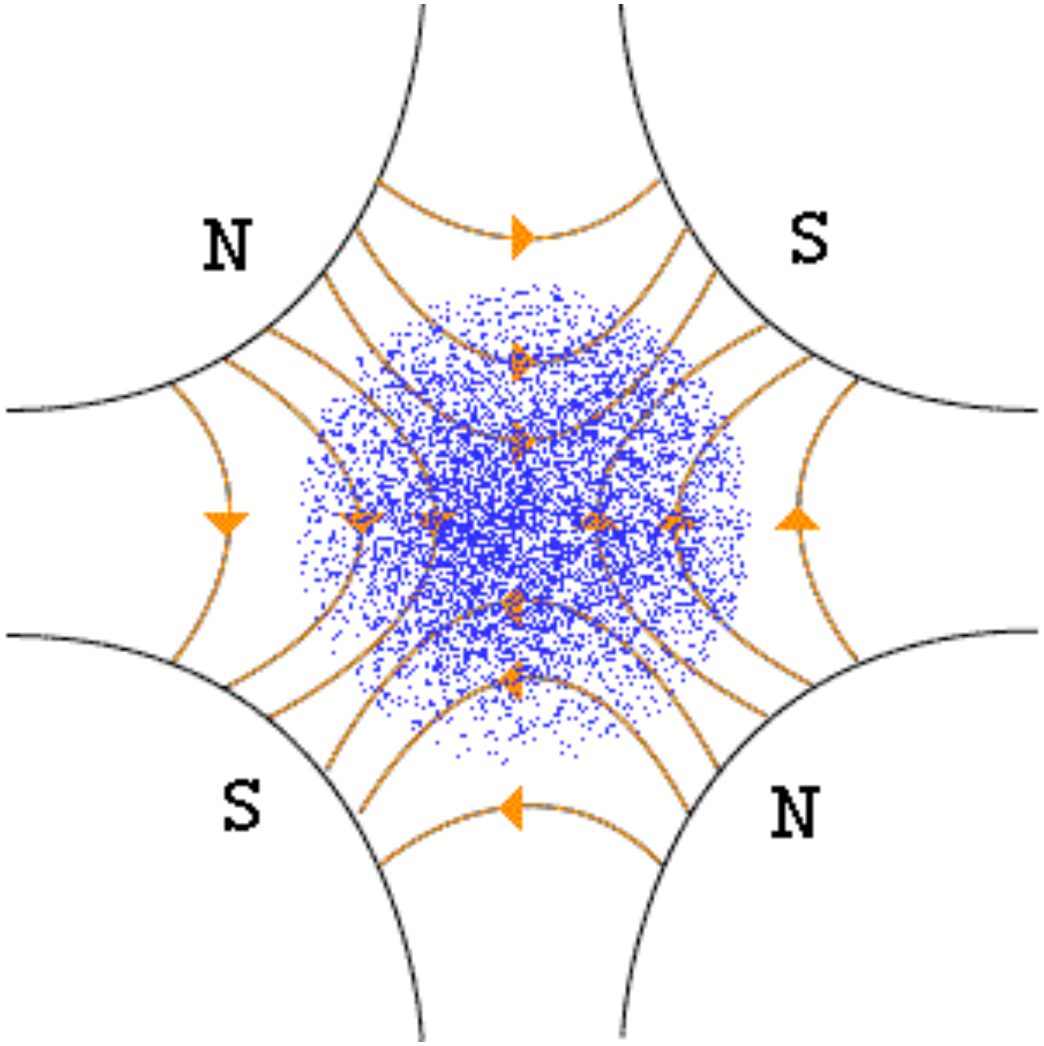
Beam size = projection on *X* (*Y*) axis

Beam size $$\sigma_x(s) = \sqrt{\epsilon\beta_x(s) + [D_x(s)\delta]^2}$$

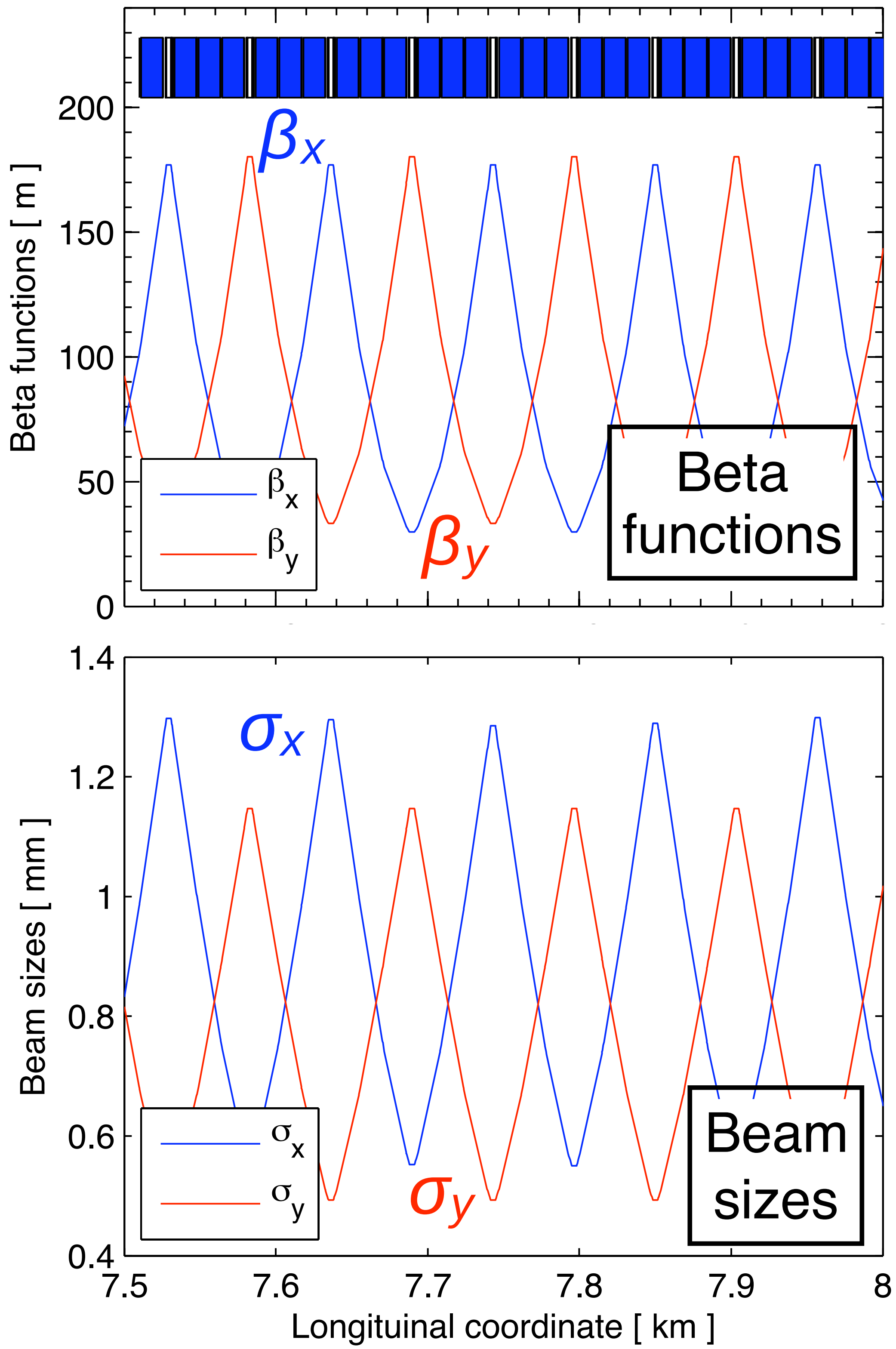
Bunch energy spread $$\delta = \left(\frac{\Delta p}{p}\right)_{\mathrm{rms}}$$

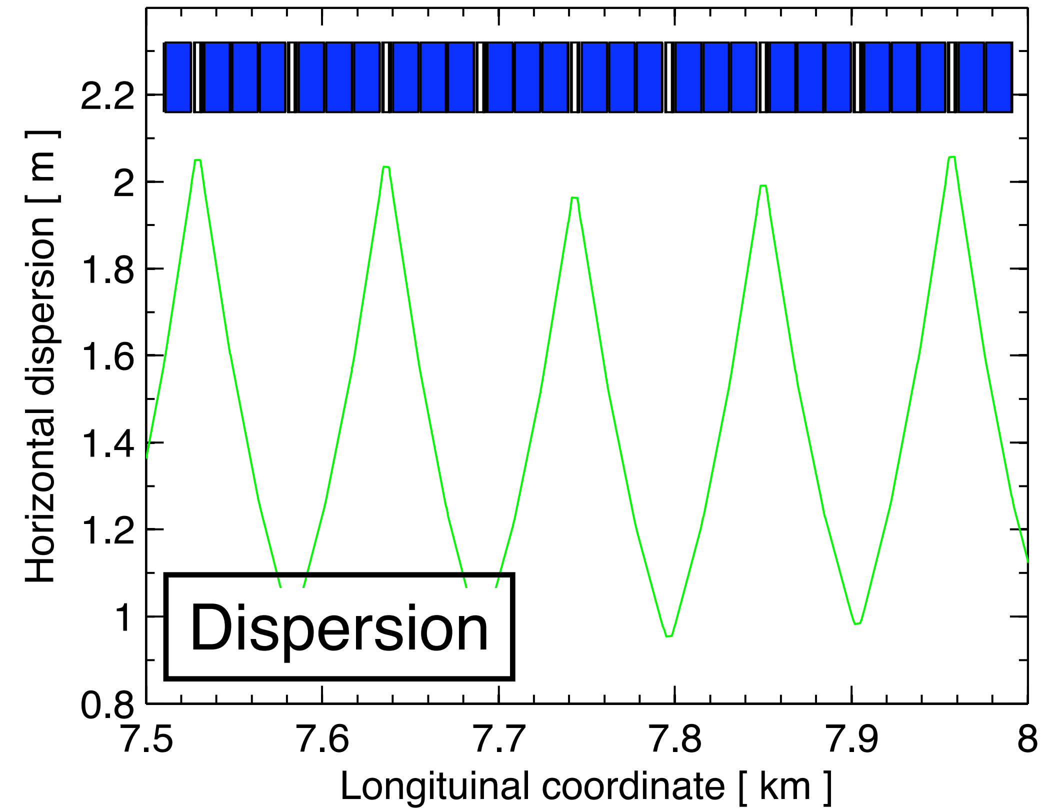
Emittance and beam size (ii)





Example for the LHC arc (450 GeV)





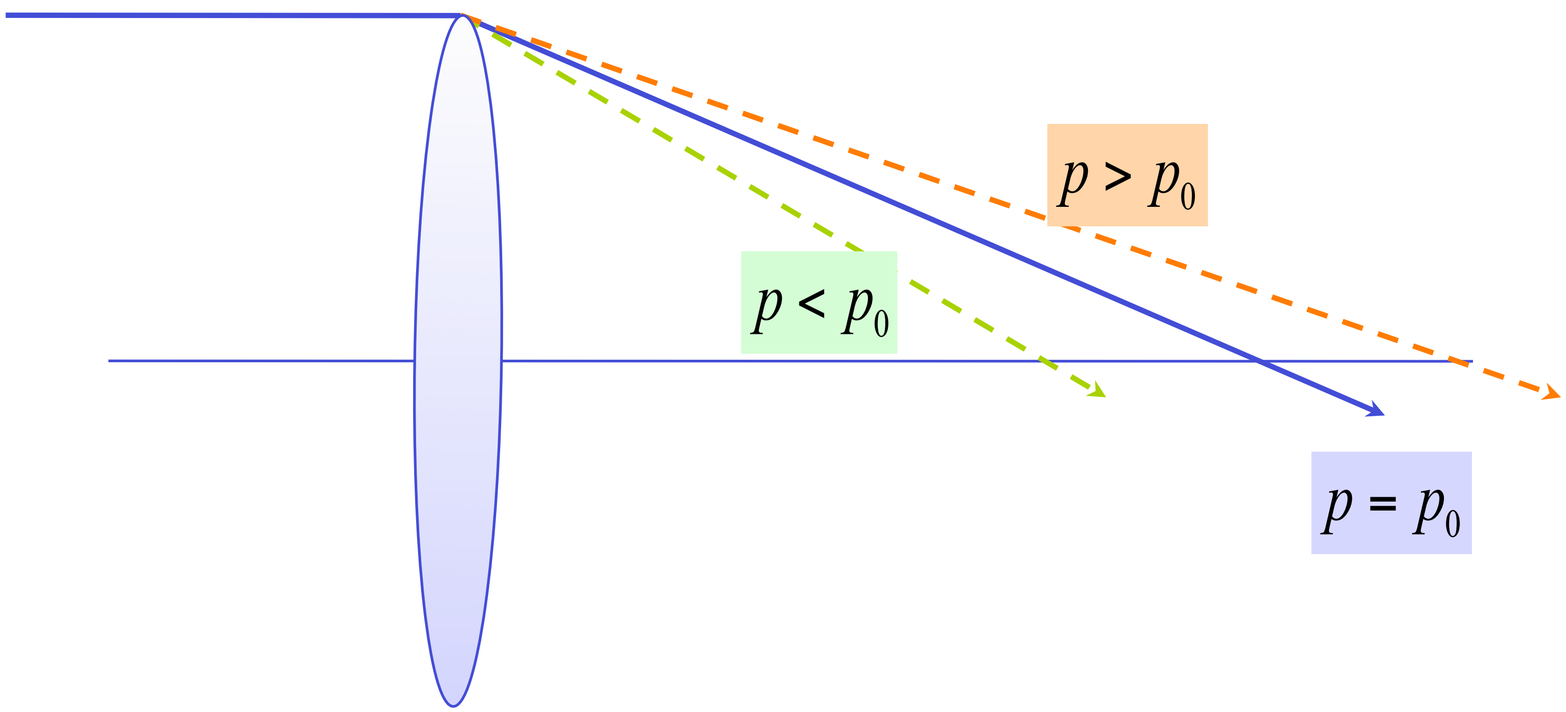
$$\beta_{x,y} = 30 \div 180\mathrm{m}$$

$$\left(\frac{\Delta p}{p}\right)_{\mathrm{rms}} = 3.06 \times 10^{-4}$$

$$D_x^{\mathrm{max}} \approx 2\mathrm{m}$$

... will see later what happens in the interaction points!

Chromaticity



$$Q' = \frac{\Delta Q}{\Delta p / p}$$

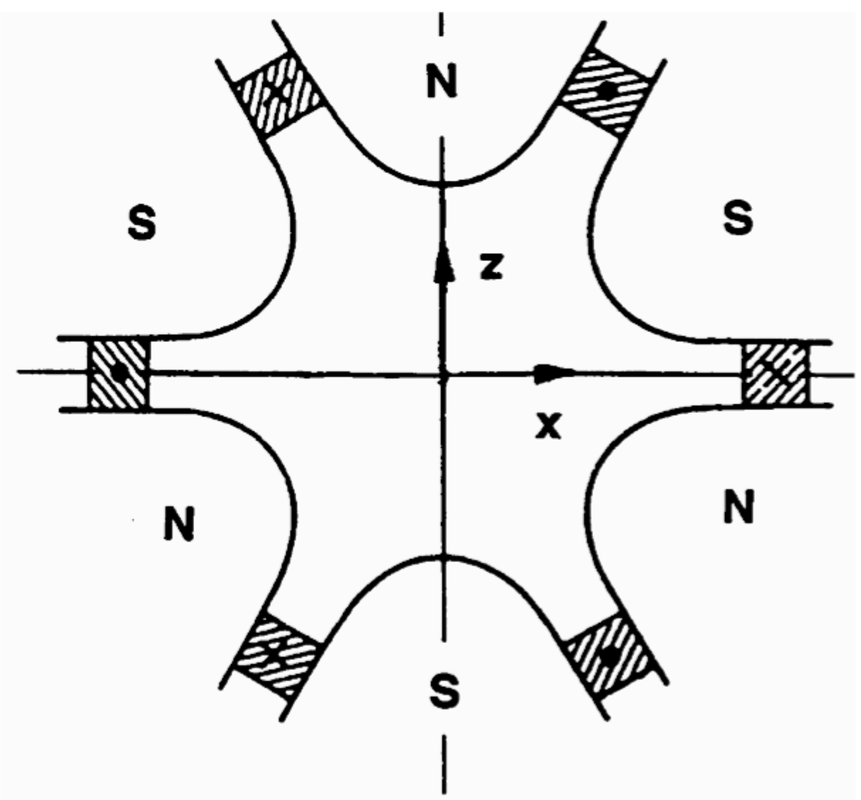
Particles with different energies have different betatron tunes.

<u>Bad</u> for the beam:
- Adds a tune spread
- Instabilities ("head-tail")

Focusing error from momentum errors ~ ***-K Δp/p***

Chromaticity corrections is done with **sextupole magnets**. The field changes as x^2.

LHC:
2 sextupole families per plane per beam for chromaticity correction.



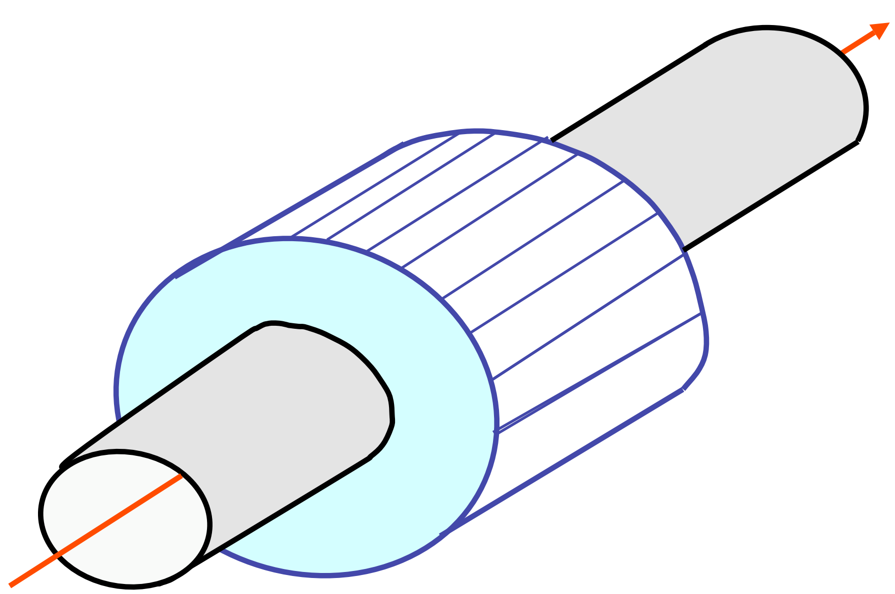
Acceleration

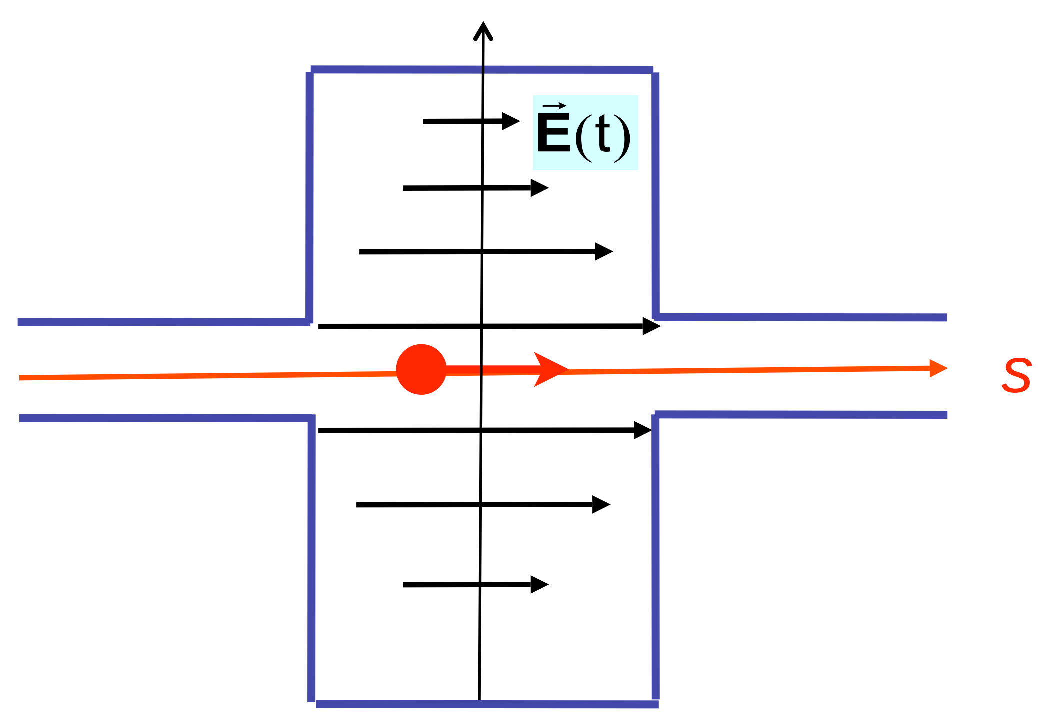
Acceleration is performed with electric fields fed into **Radio-Frequency (RF) cavities**.
RF cavities are basically resonators tuned to a selected frequency.

In circular accelerators, the acceleration is done with small steps at each turn.

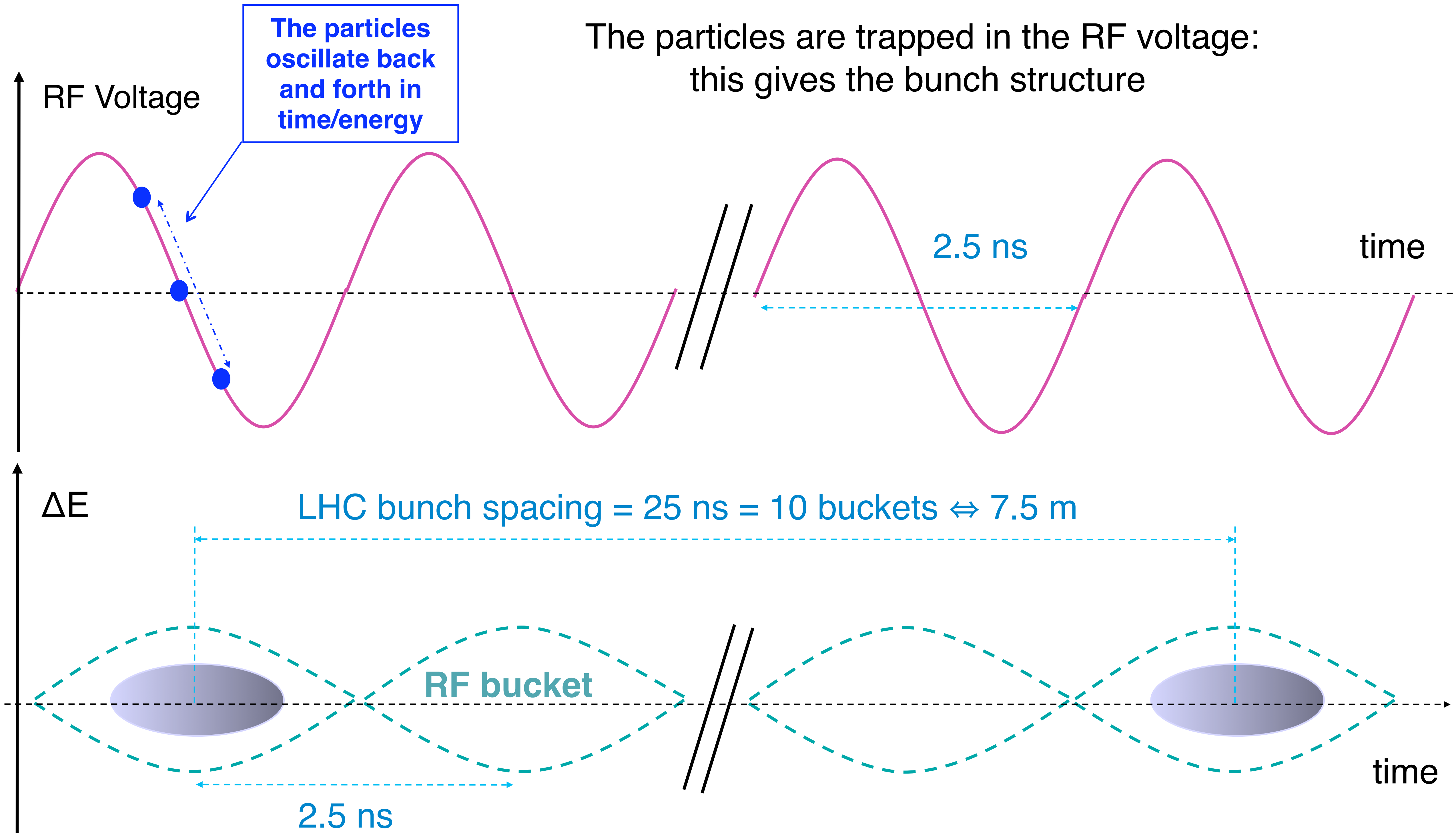
LHC: 8 RF cavities per beam (400 MHz), located in point 4

At the LHC, the acceleration from **450 GeV** to **7 TeV** lasts ~ 20 minutes (nominal!), with an average energy gain of ~ 0.5 MeV on each turn.
[Today, we ramp at a factor 4 less energy gain per turn than nominal!]





Buckets and bunches



	<u>450 GeV</u>	<u>7 TeV</u>
RMS bunch length	11.2 cm	7.6 cm
RMS energy spread	0.031%	0.011%

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- Introduction
- **Recap. of accelerator physics**
    - Basic equations
    - **Measurements → tools**
- LHC injector complex
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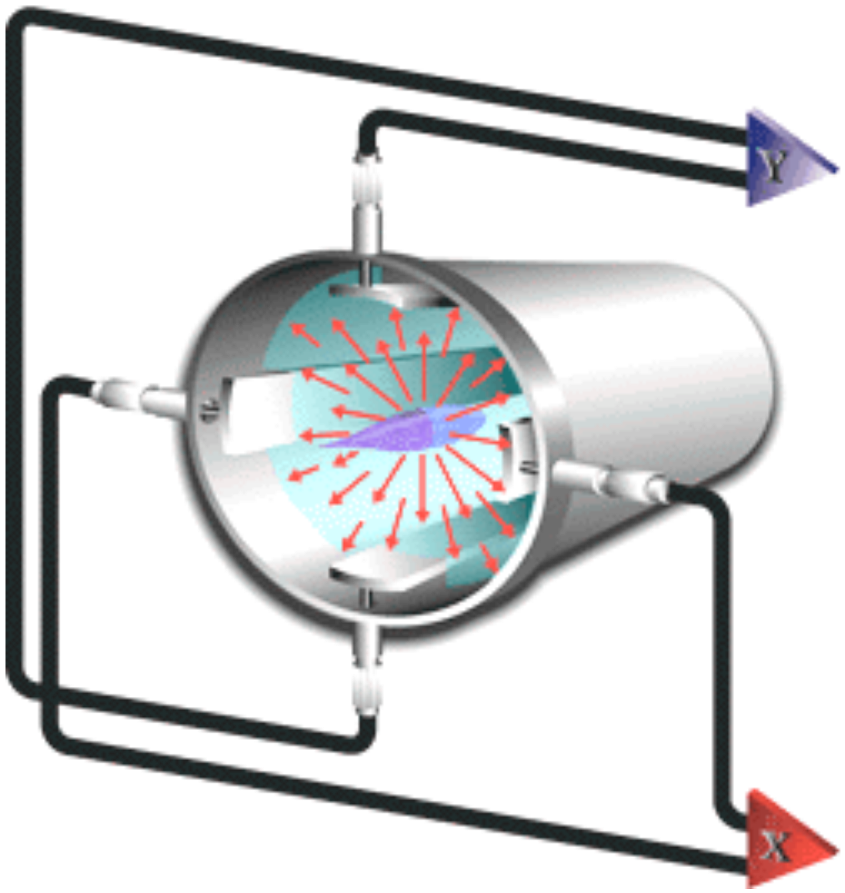
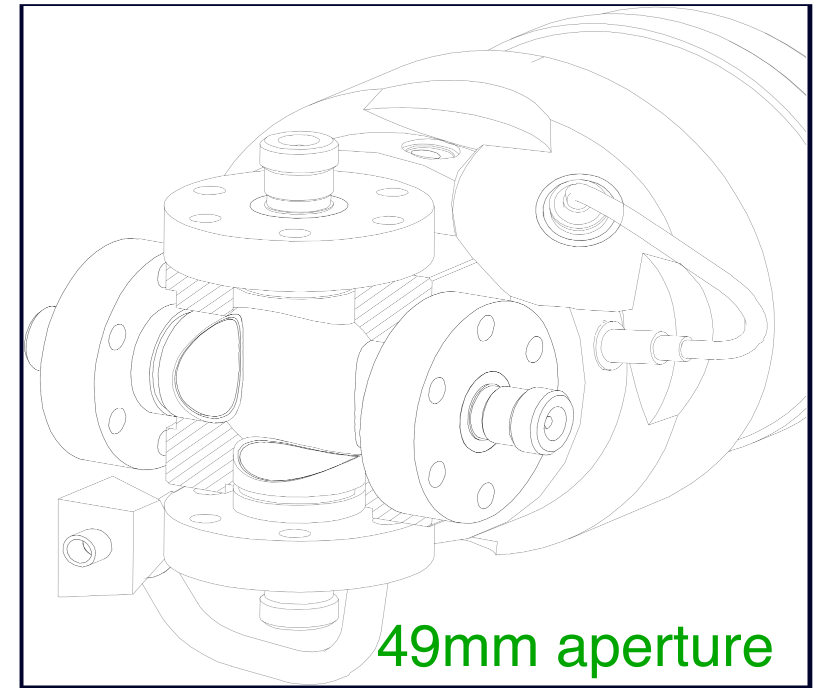
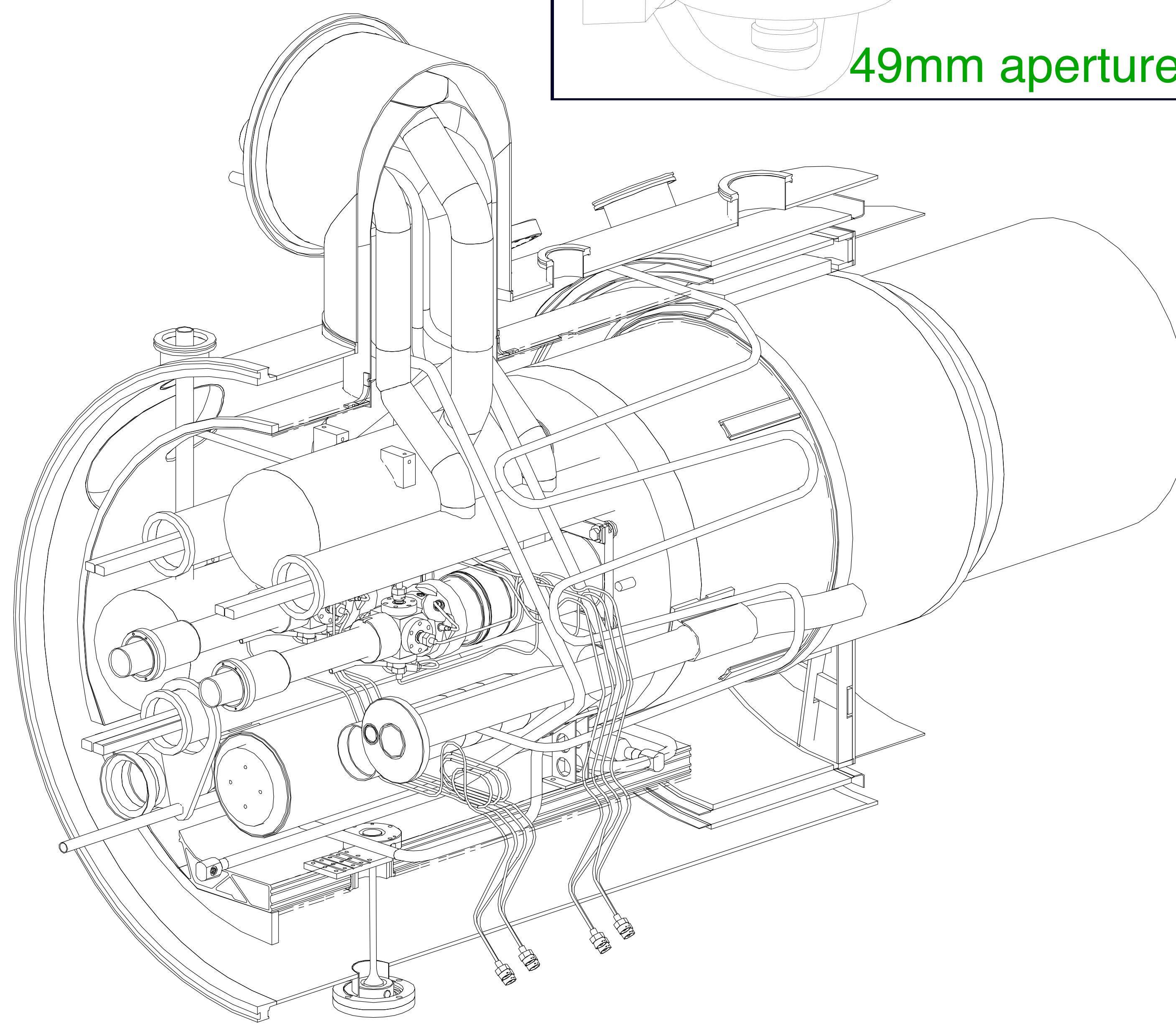
LHC beam position monitors (BPMs)



4 buttons pick-up the e.m. signal induced by the beam. One can infer the transverse position in both planes.





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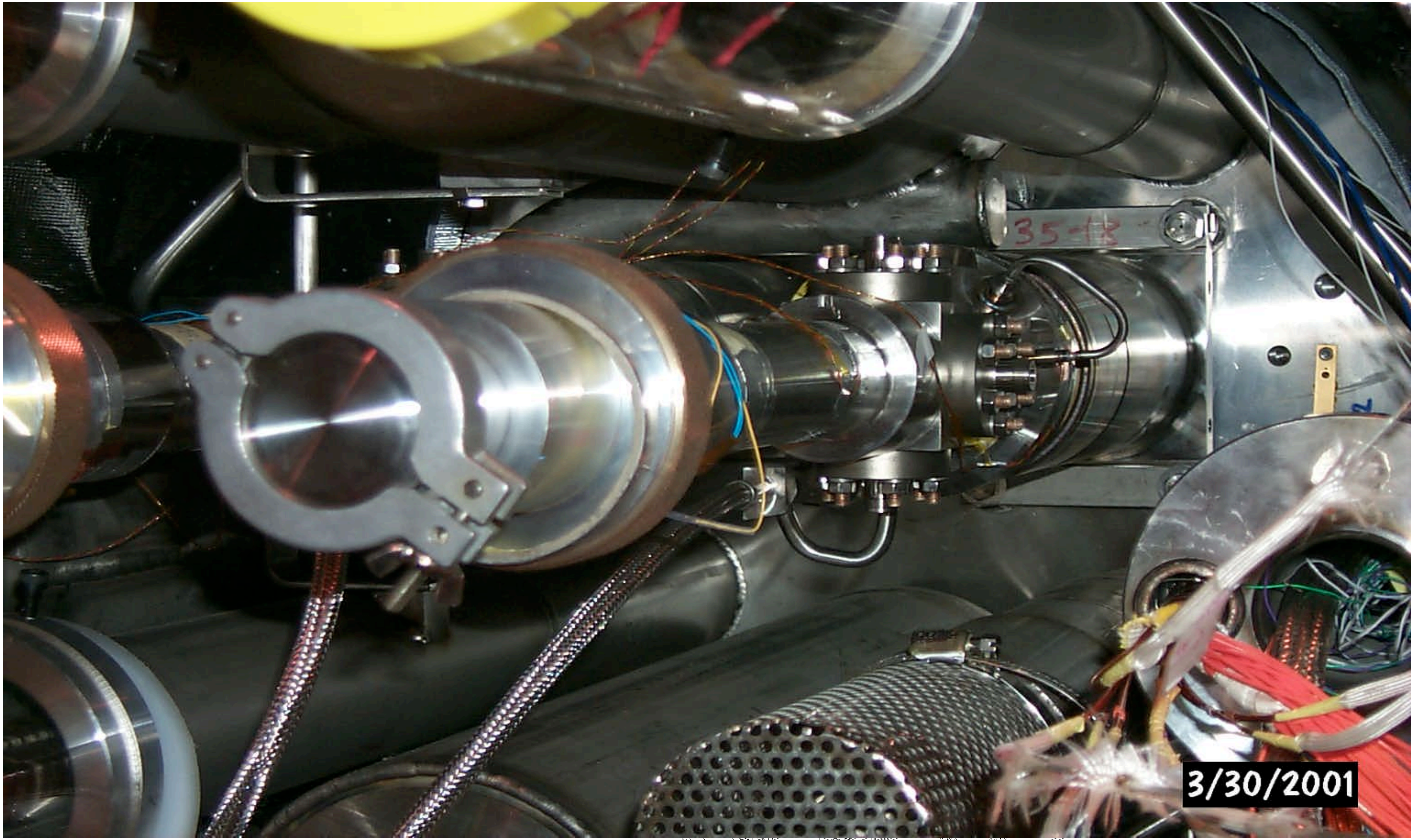
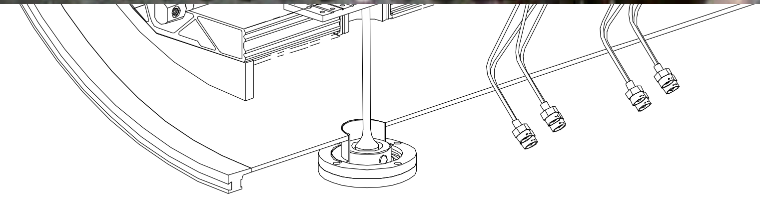
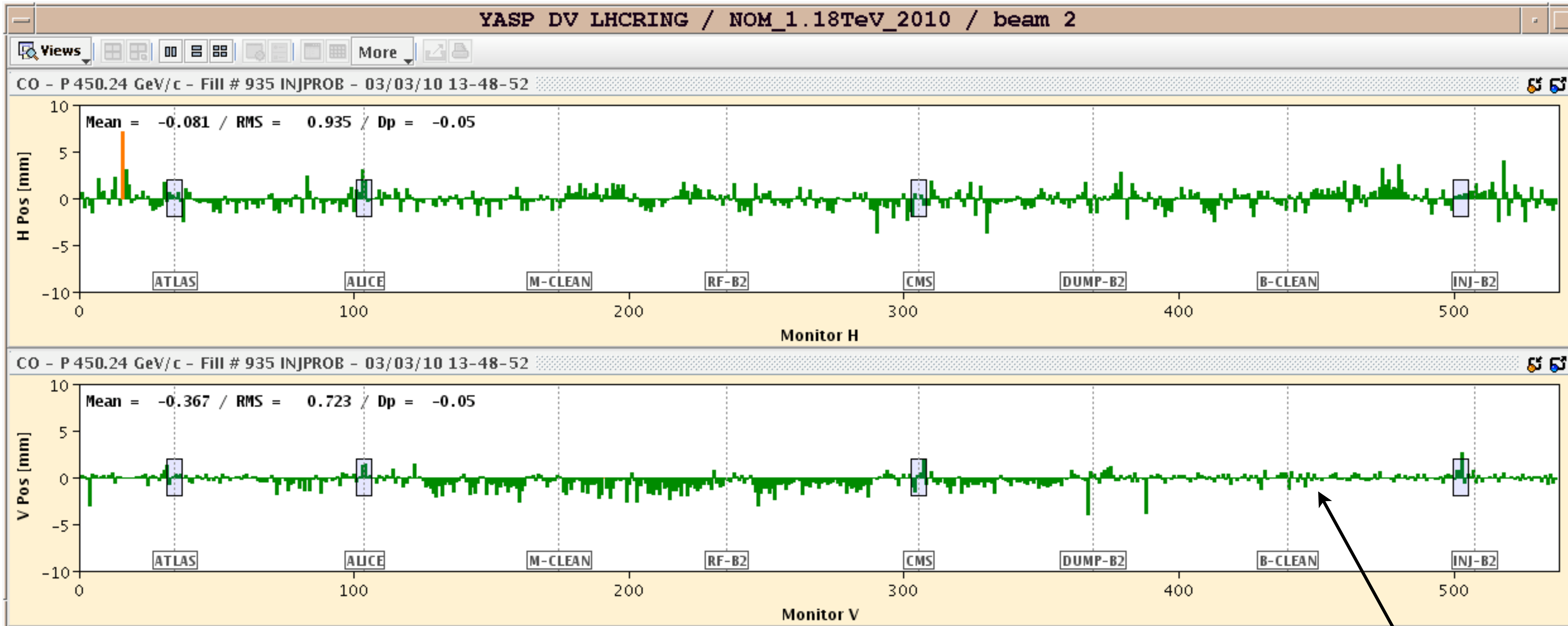
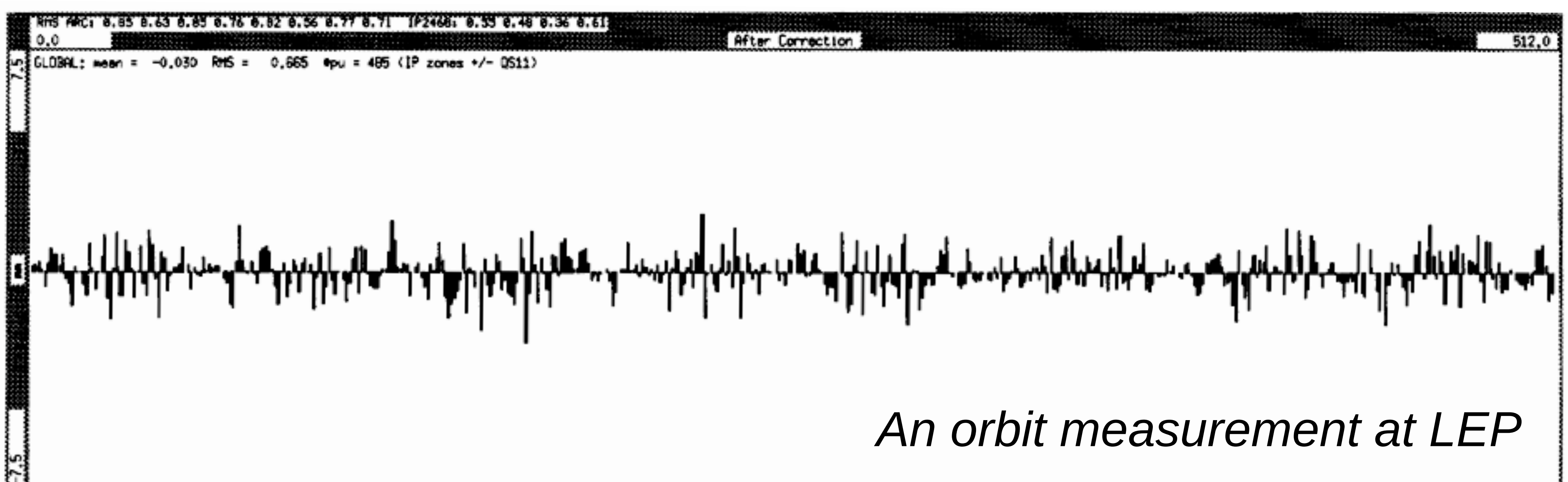




Closed-orbit measurements





An orbit measurement at LEP

> 500 measurements per beam per plane!

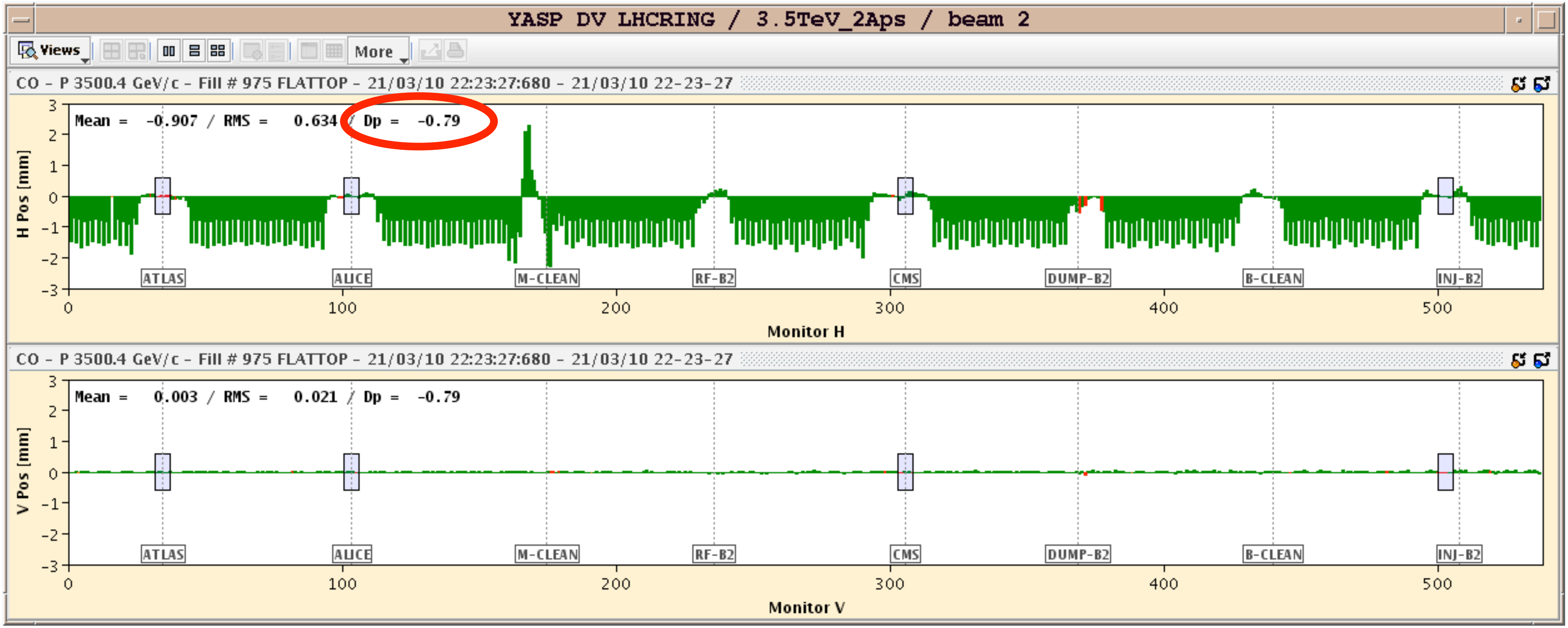
More than 1 per quad!

1 Hz data + turn-by-turn are possible

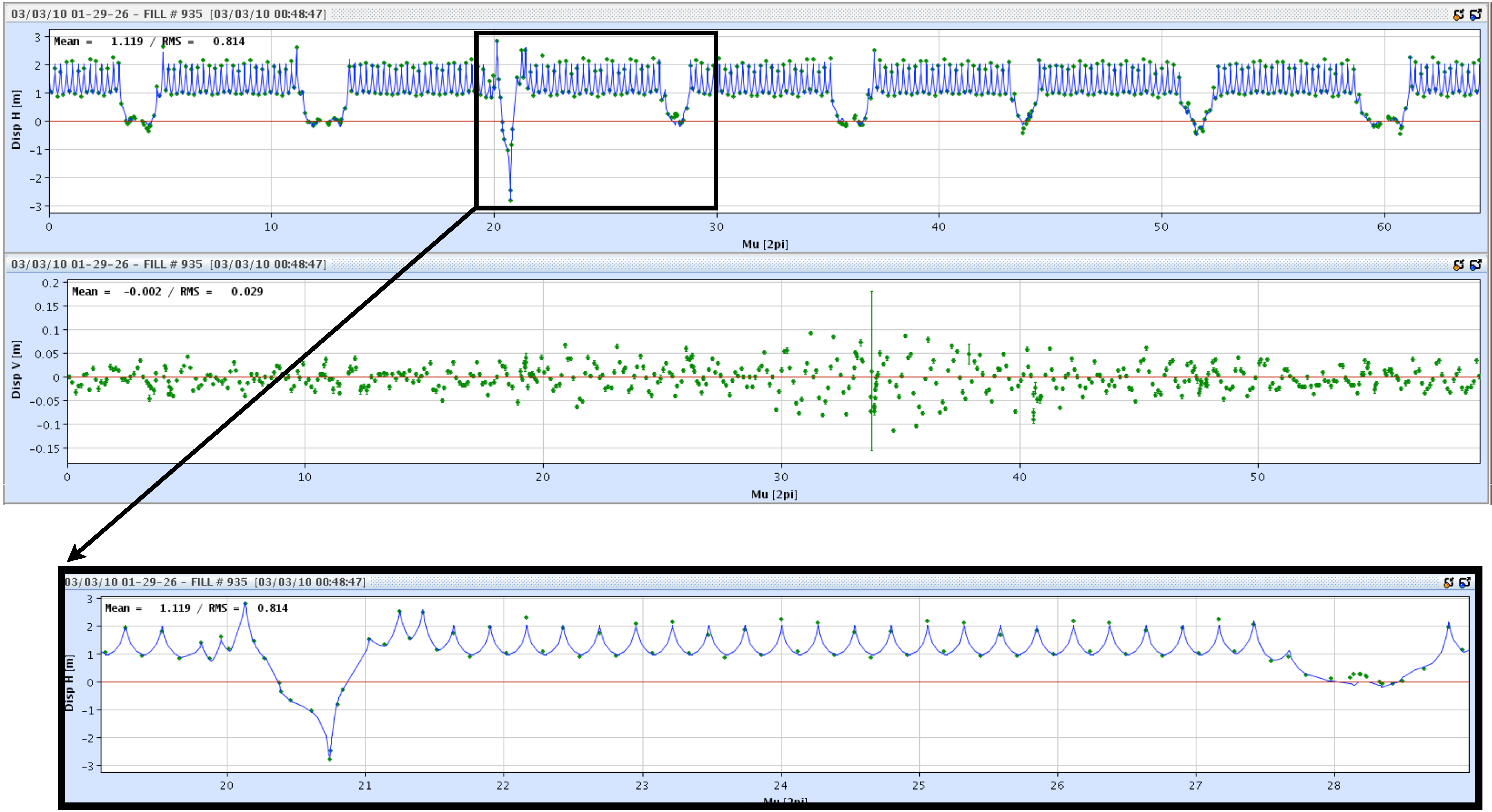
Dispersion measurements (i)

$$\Delta x(s) = D(s) \times \frac{\Delta p}{p}$$

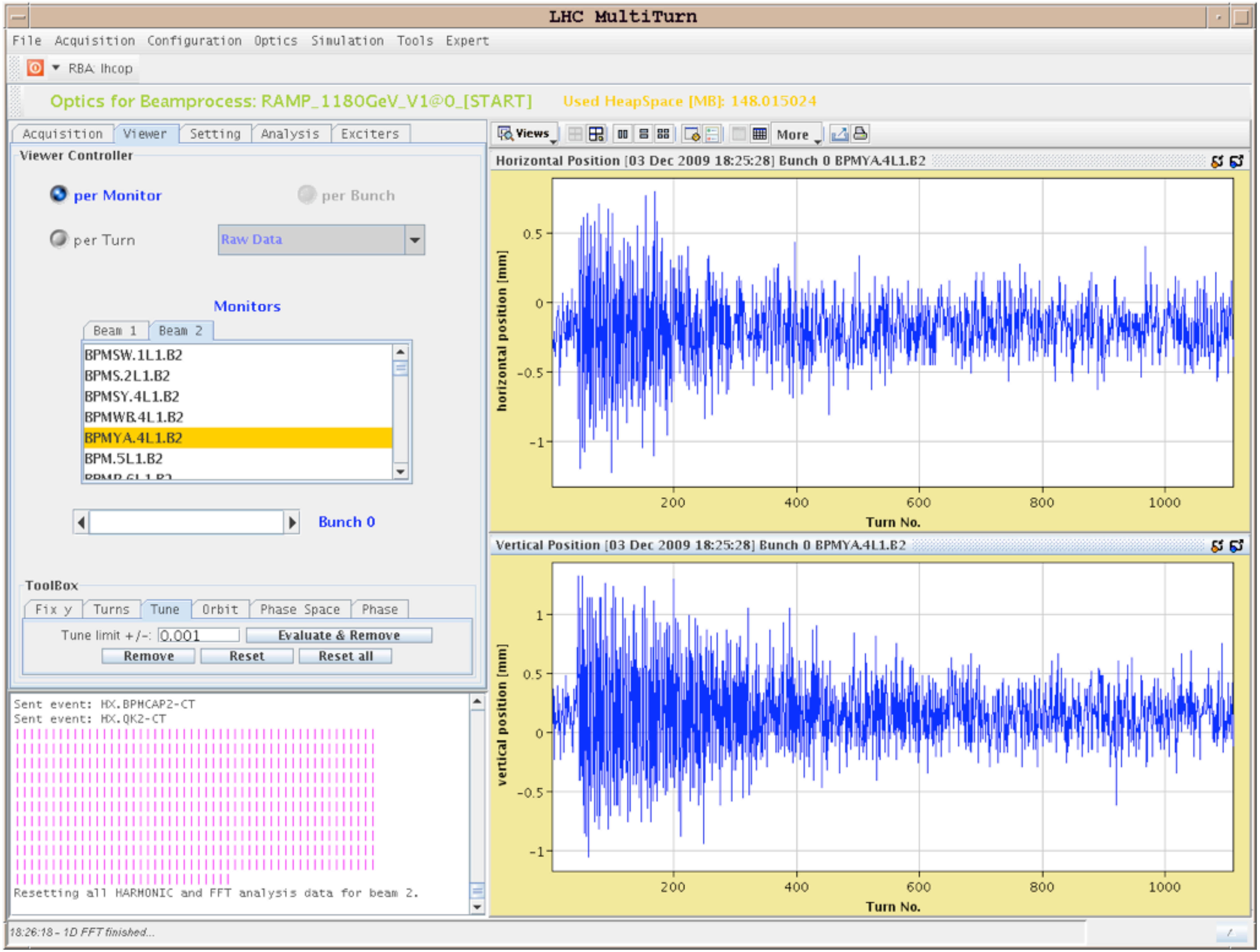
Measure the orbit offset for different beam energies.



Dispersion measurements (ii)

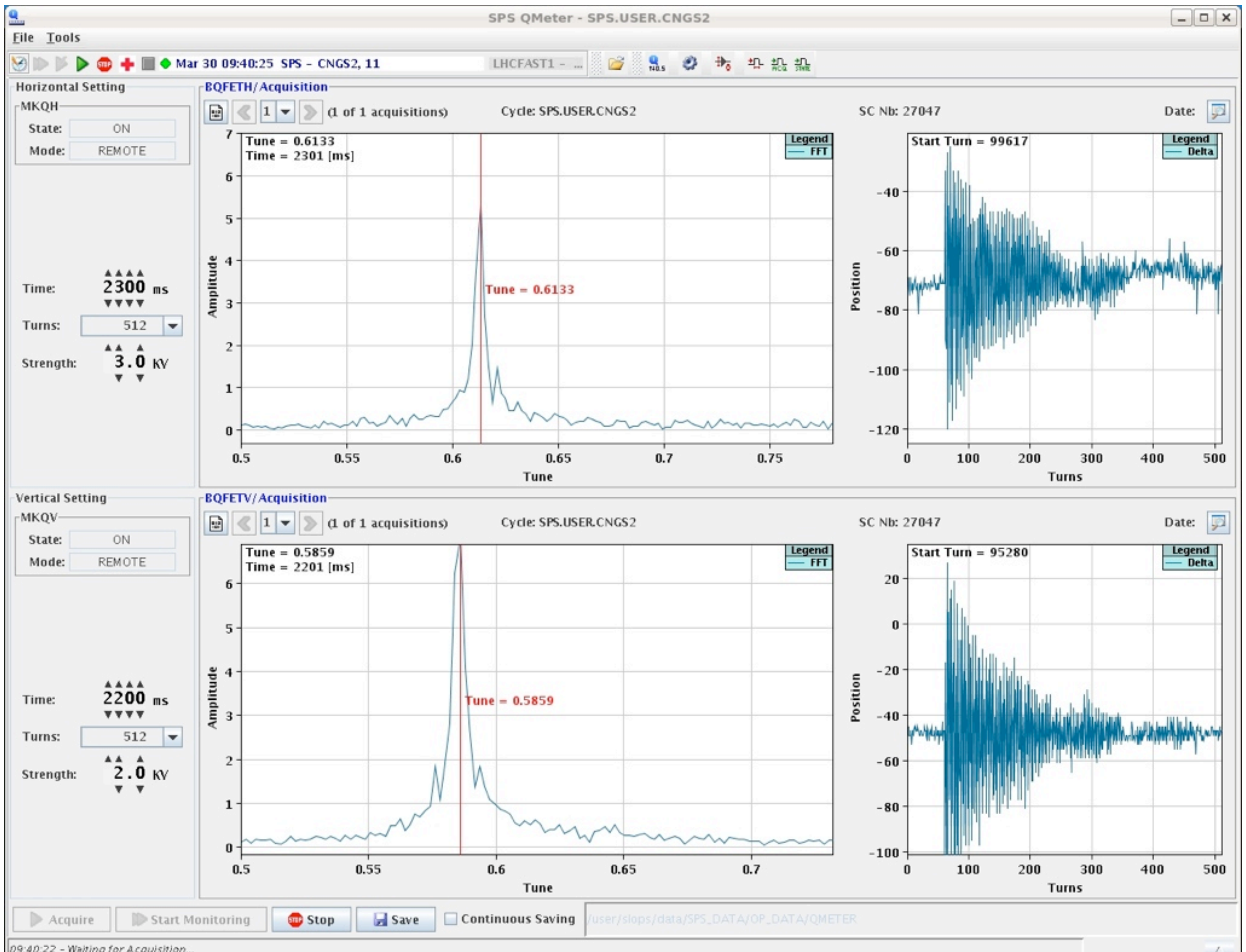


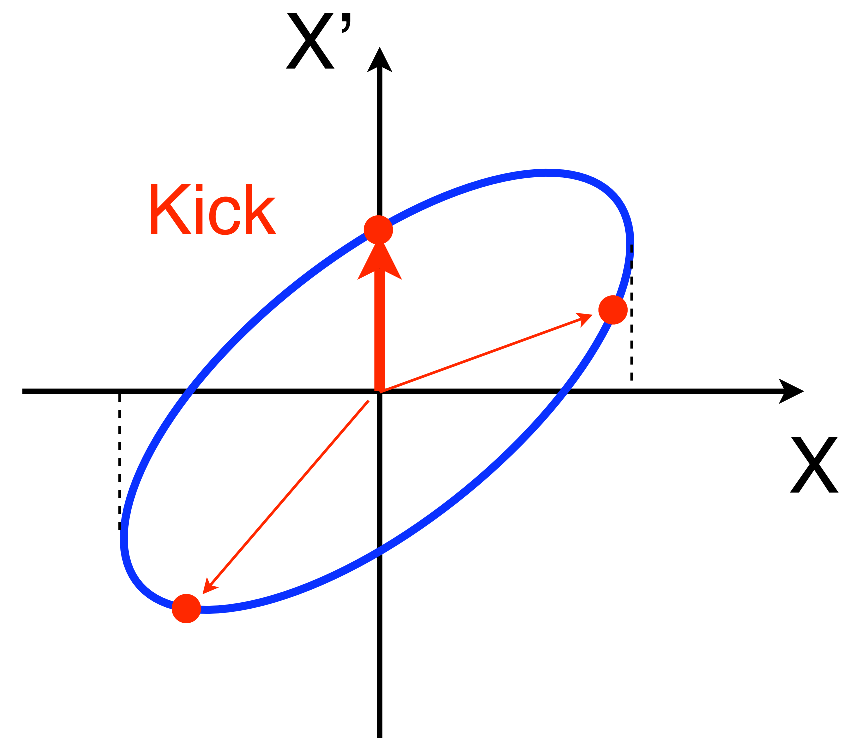
Multi-turn acquisitions



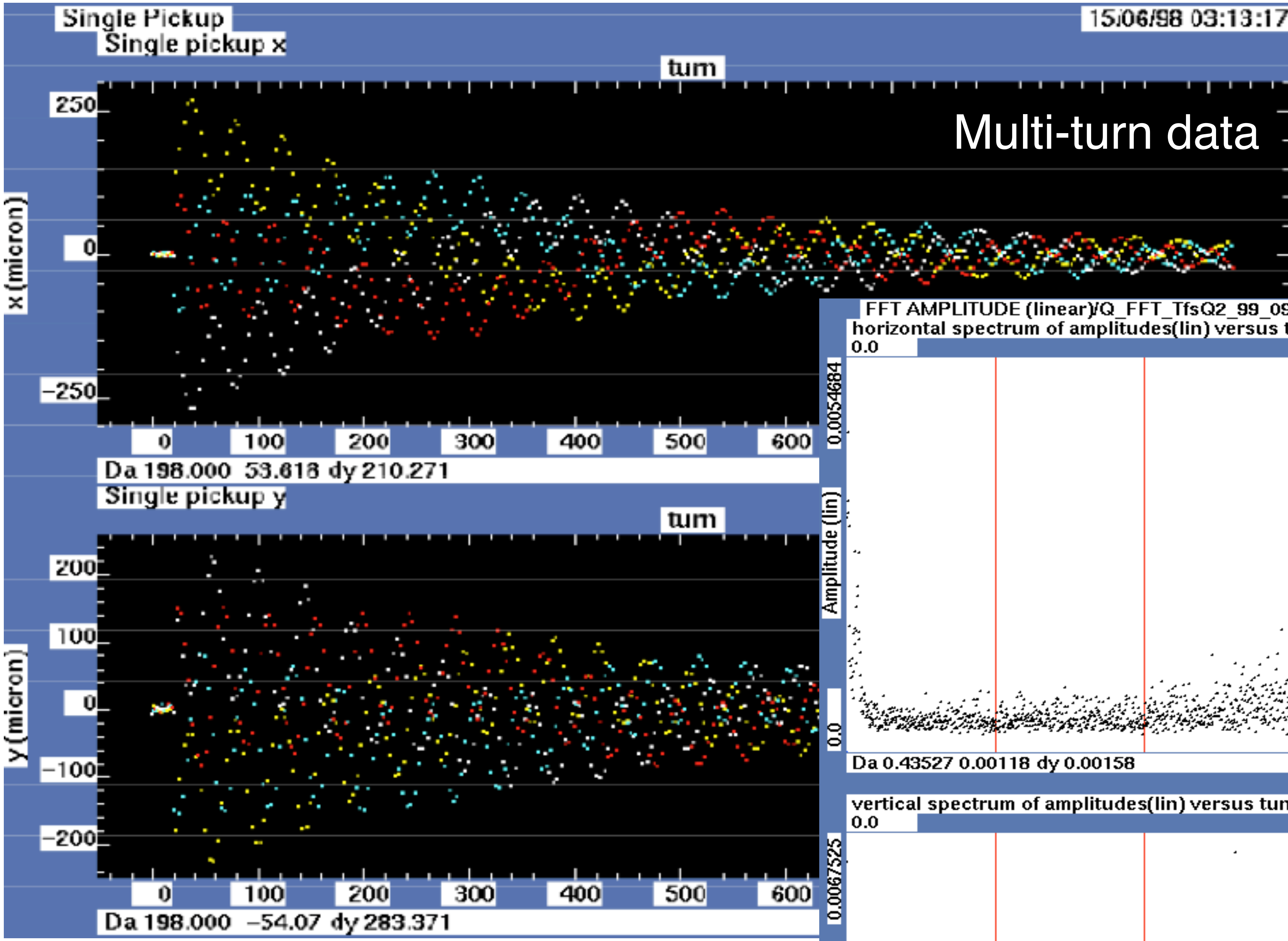
Tune measurements

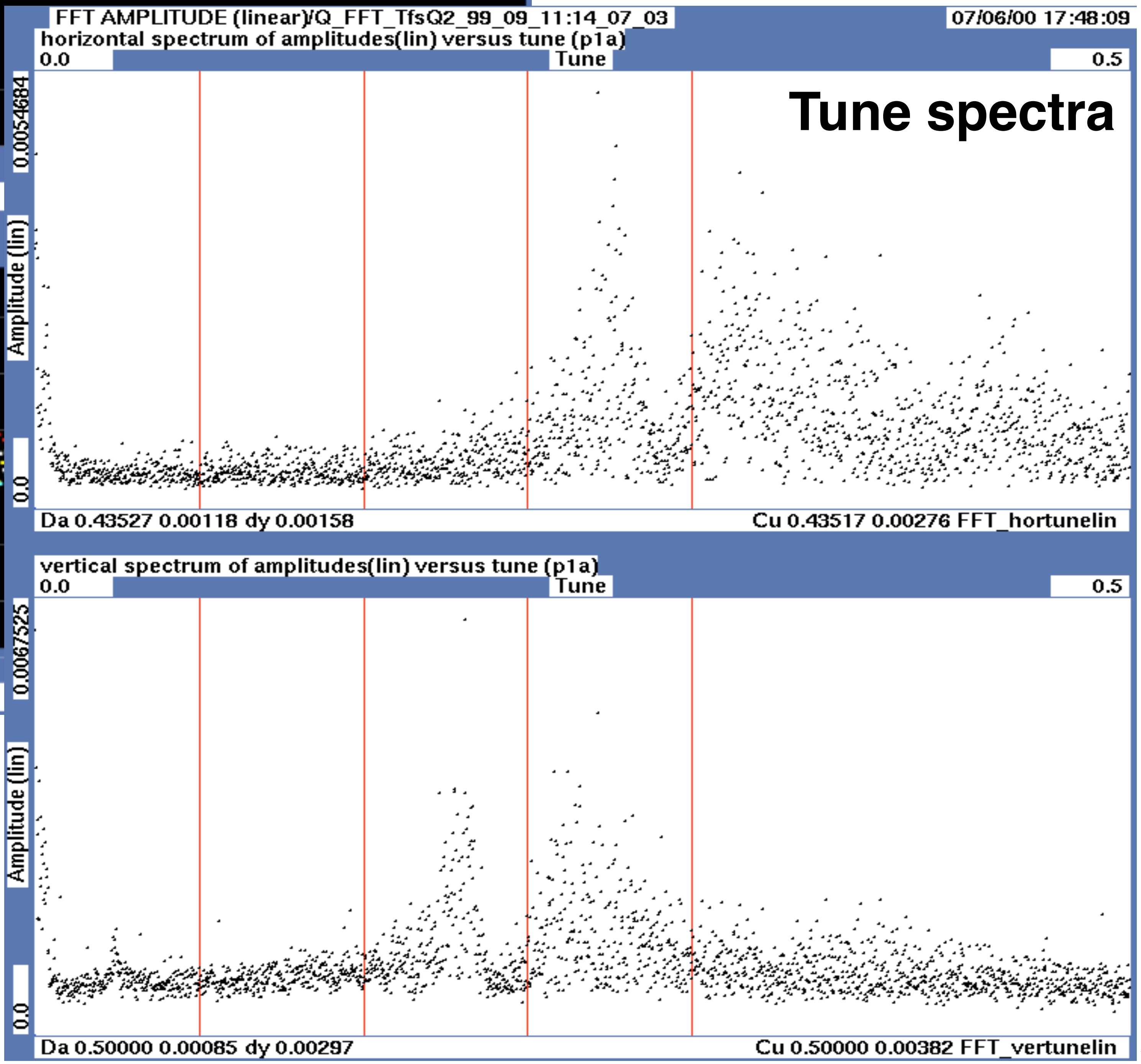
- Kick the beam with a fast kicker
- Measure beam position at every turn
- Make an FFT



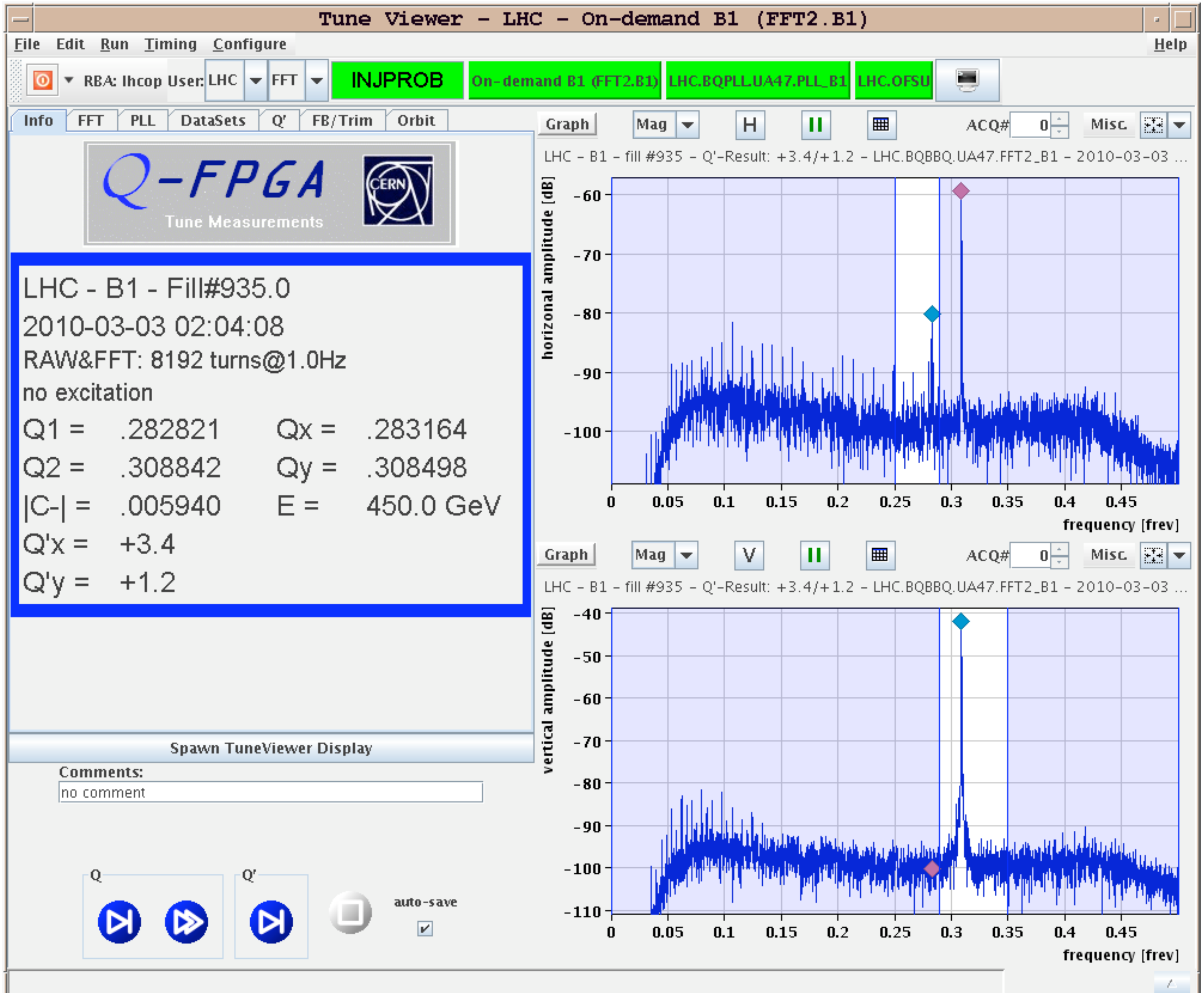


Tune measurements at the LEP





Tune measurements at the LHC

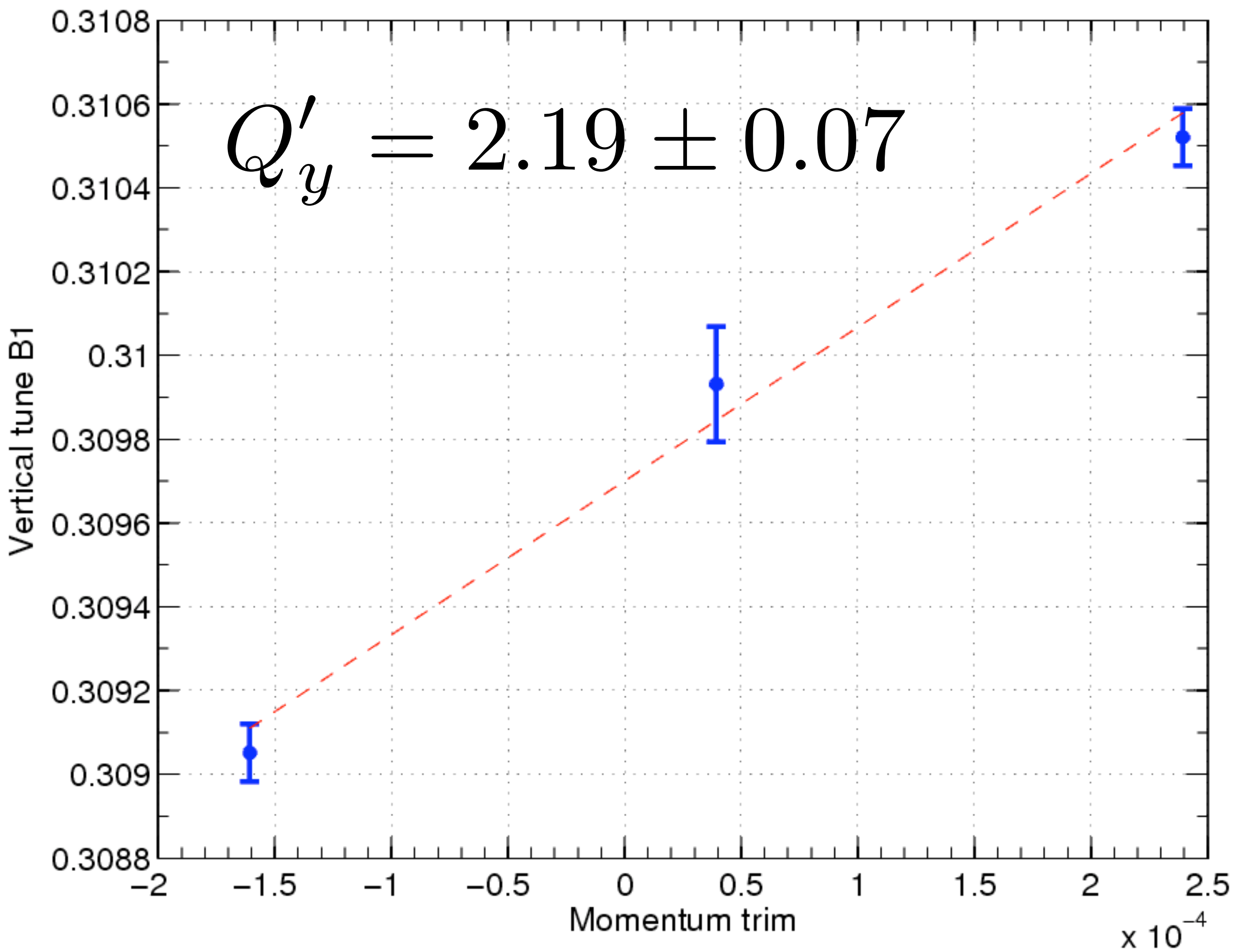


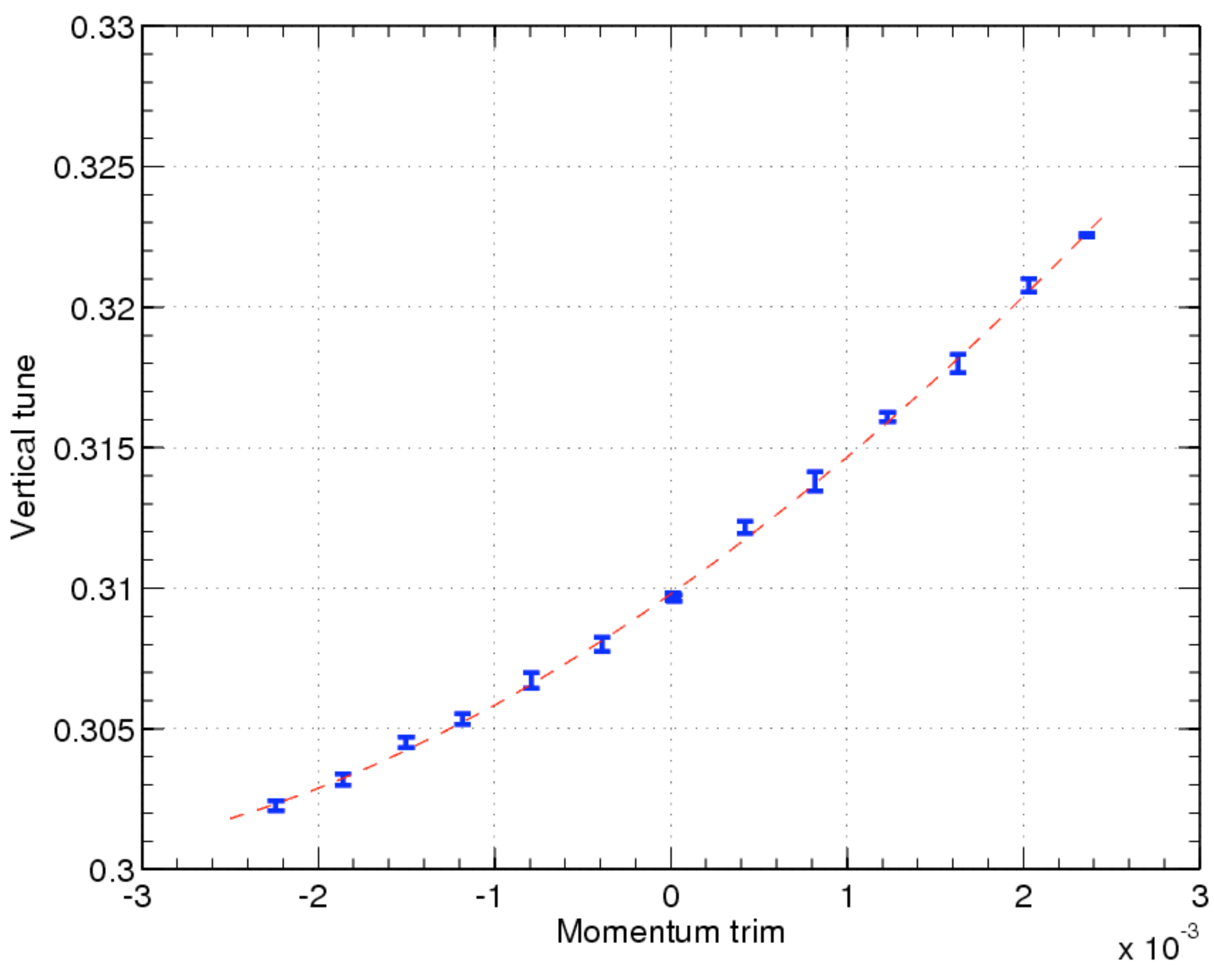
Chromaticity measurements

$$Q' = \frac{\Delta Q}{\Delta p / p}$$

→ We need to repeat tune measurements at different beam momenta

$$Q_y = Q_{y,0} + Q'_y \frac{\Delta p}{p}$$ → Linear fit

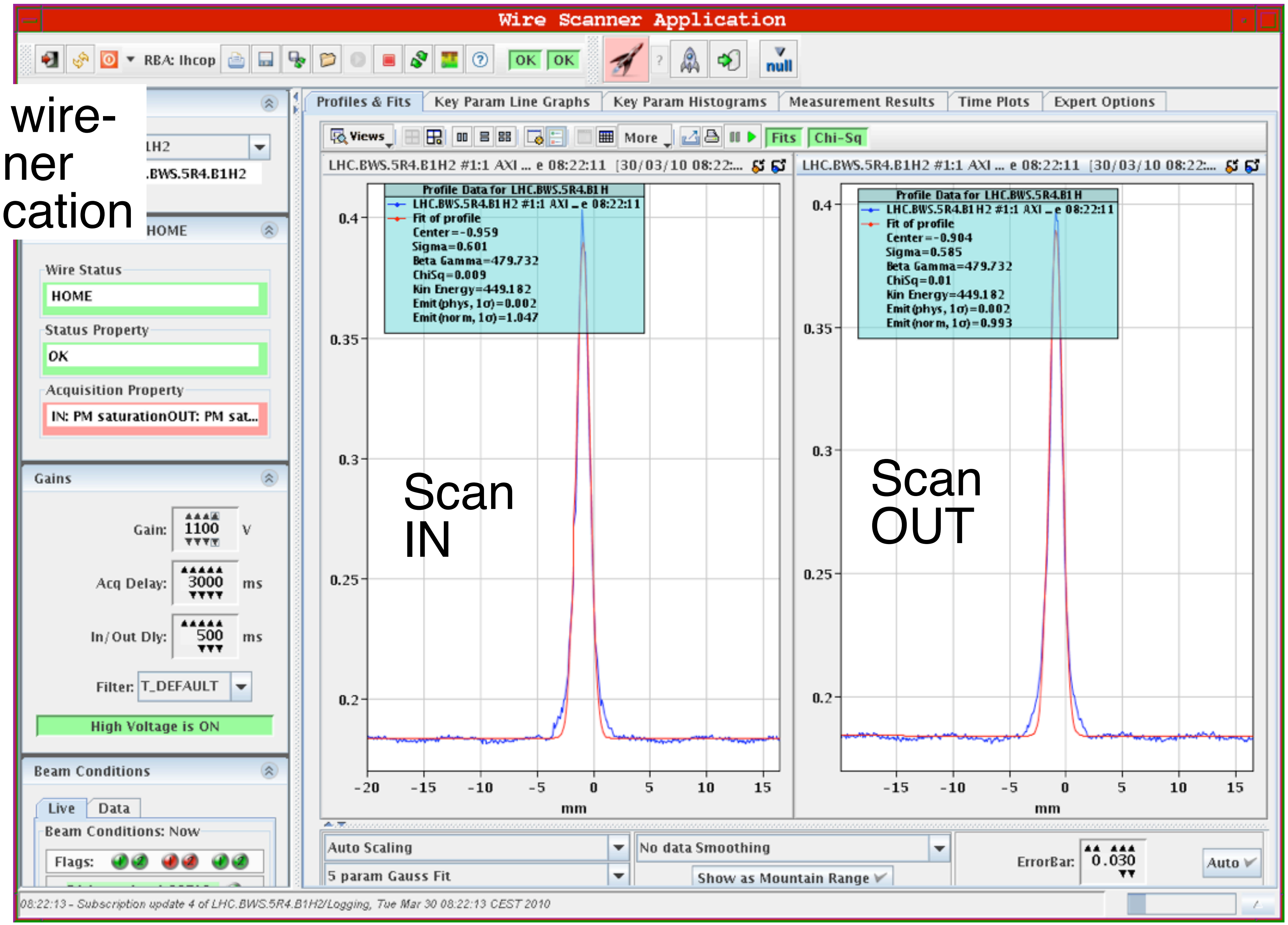




Beam size measurements

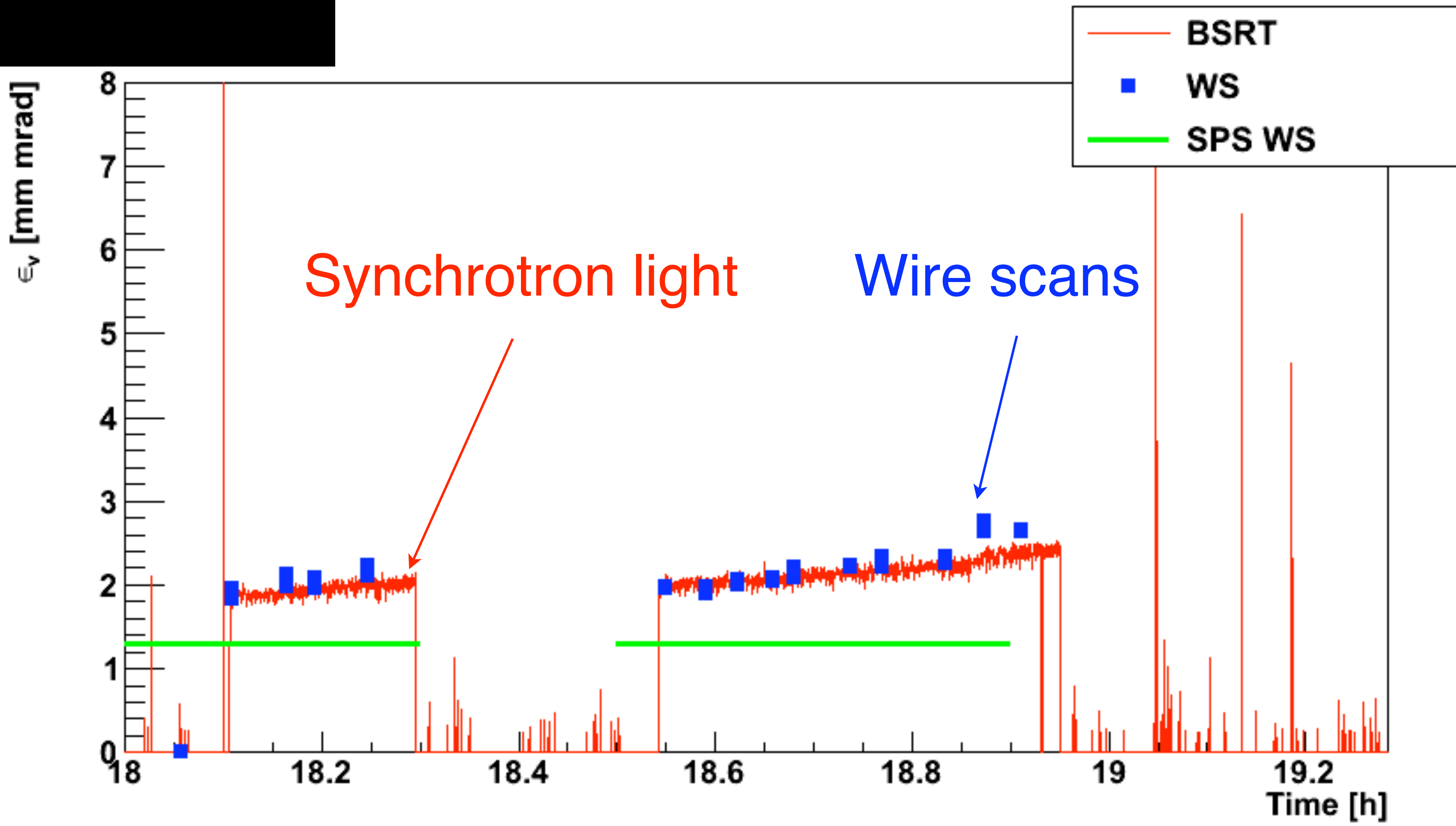
- Flying wire moved across the circulating beam
- Measure secondary particles
- Calibrate wire position to get size in mm

LHC wire-scanner application

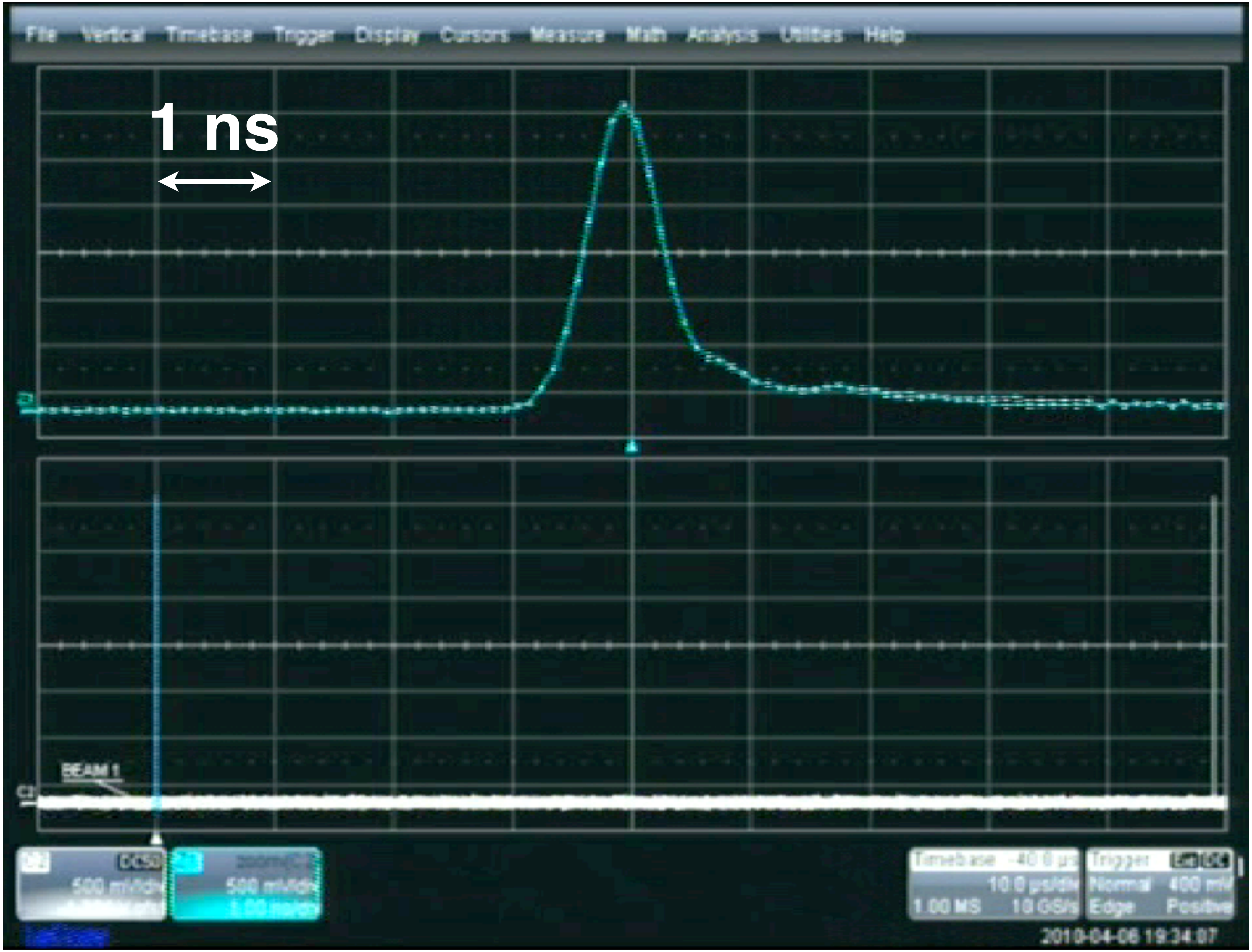


Synchrotron light monitor

Provides continuous beam size measurements, e.g. during ramp.



Longitudinal beam profile

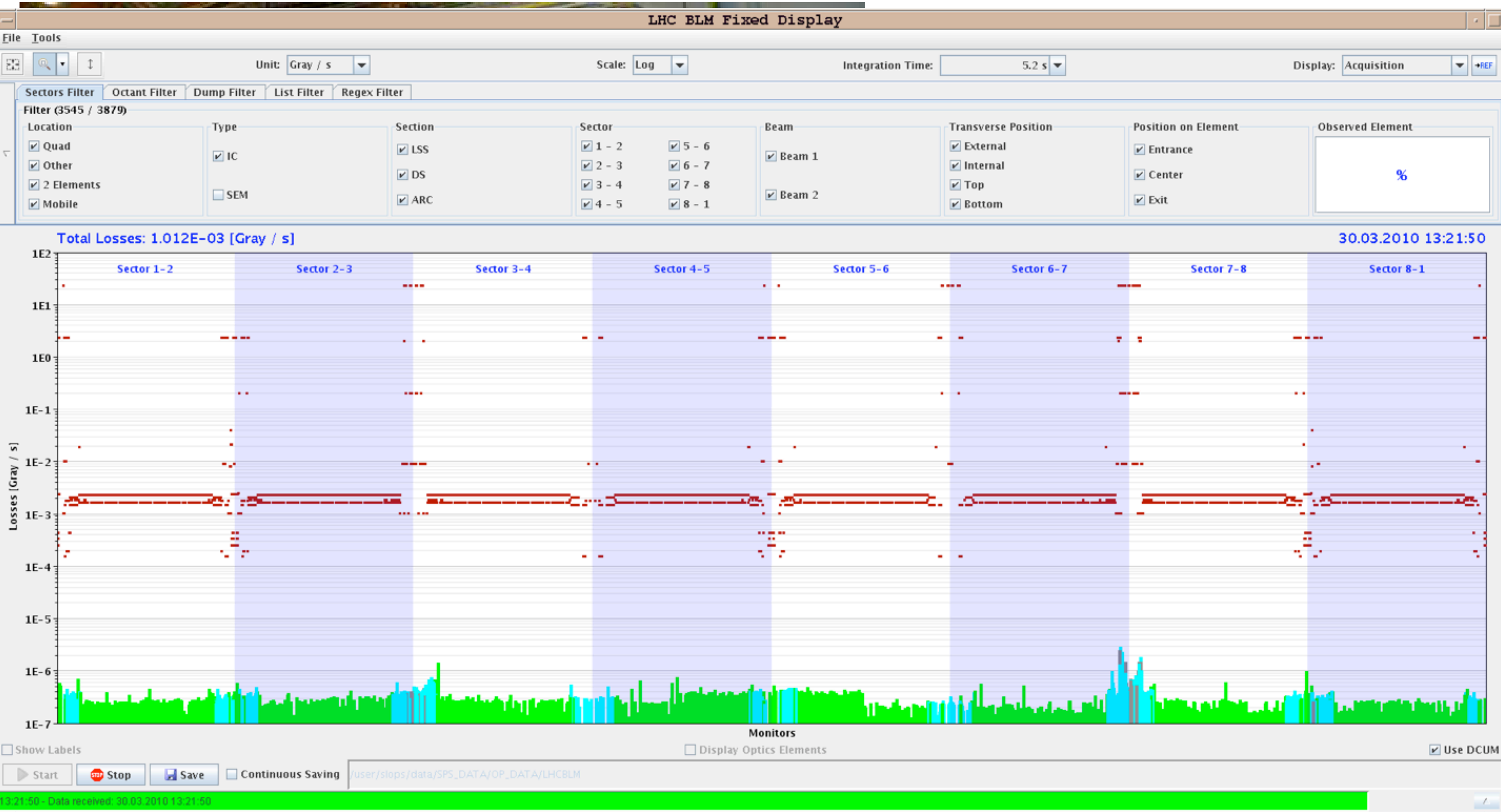


Beam loss monitoring

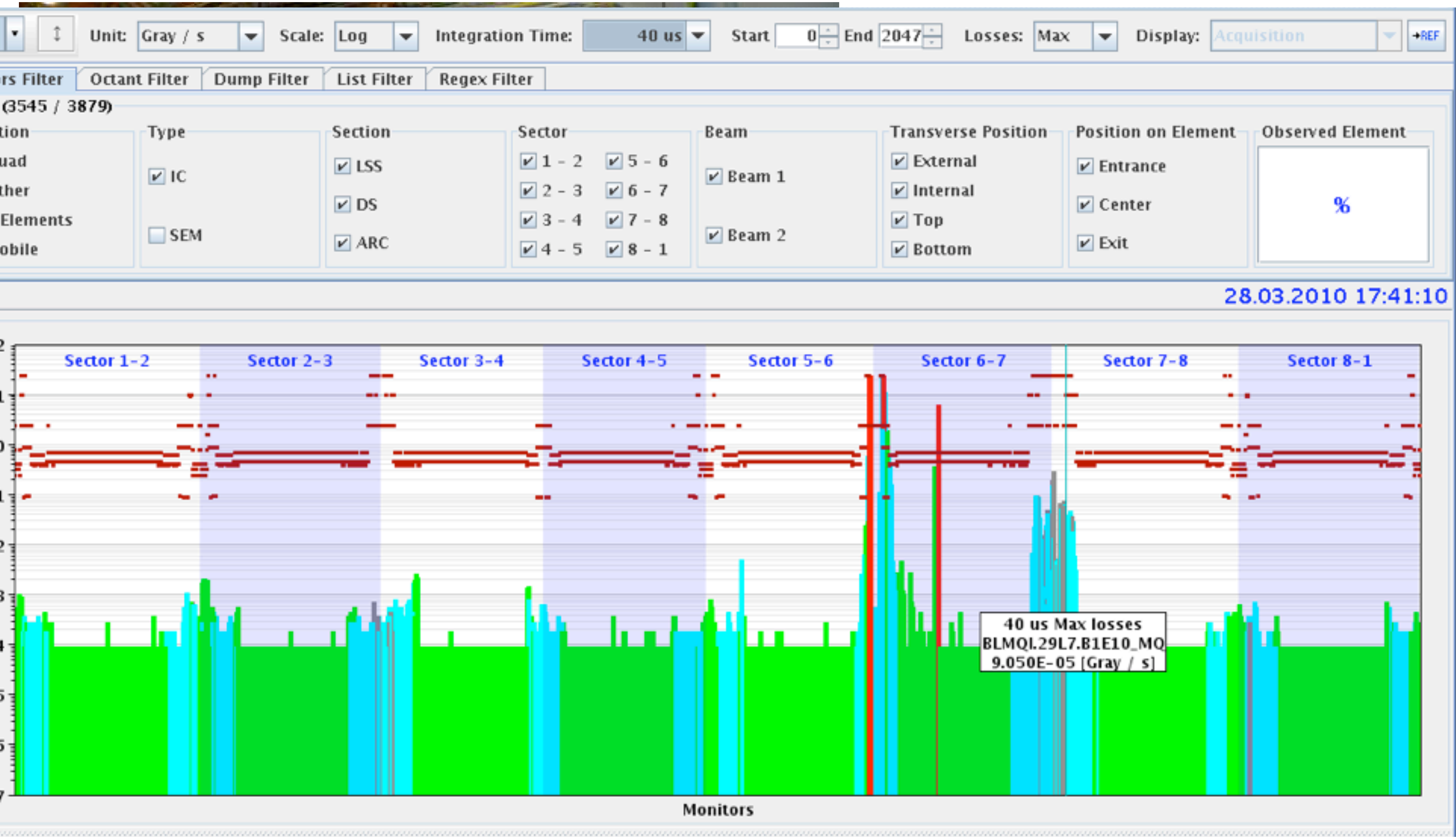
Ionization chambers detect secondary electromagnetic showers generated by particle loss.

4000 of these guys in the machine!!

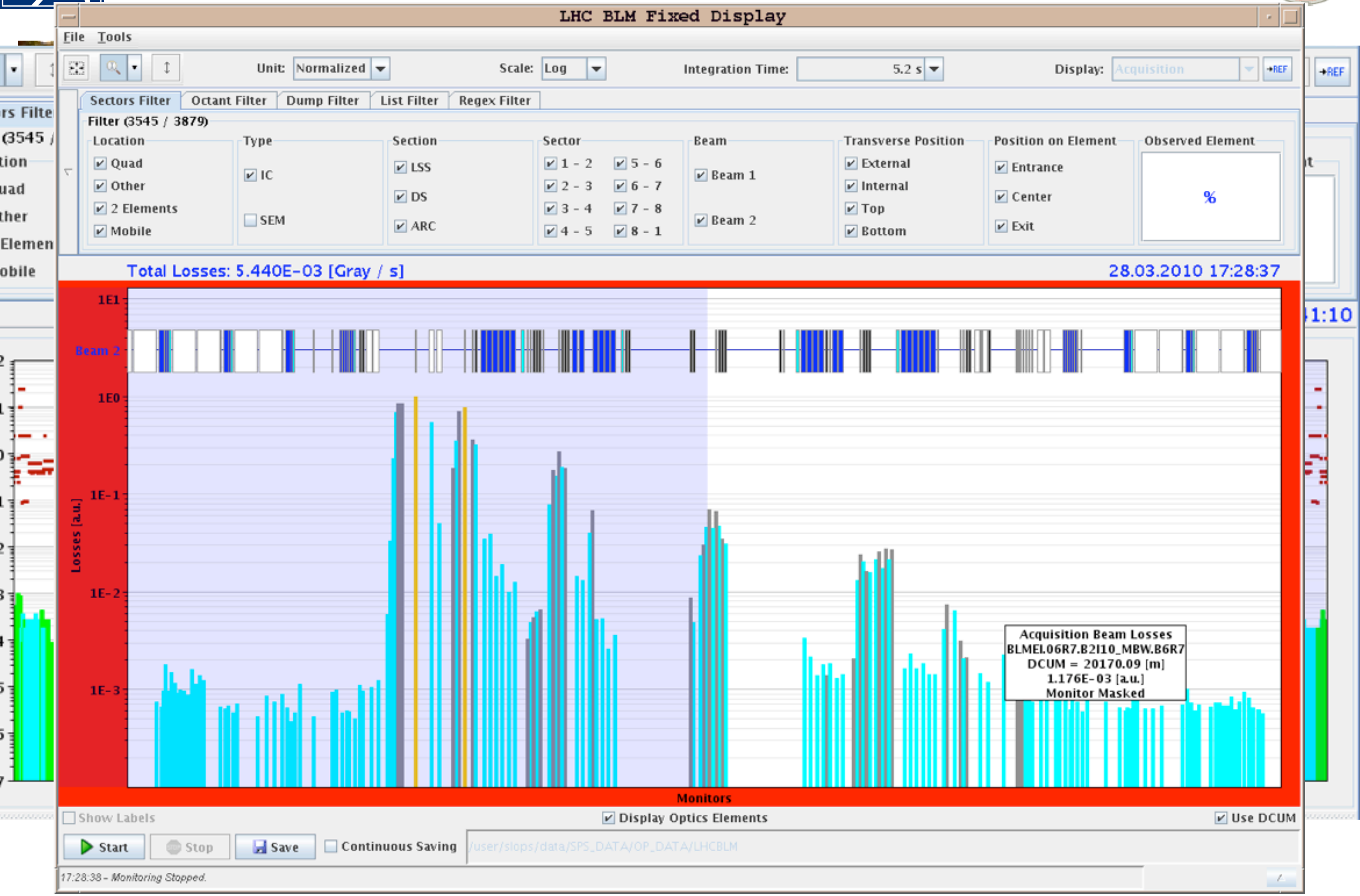
Beam loss monitoring



Beam loss monitoring



Beam loss monitoring



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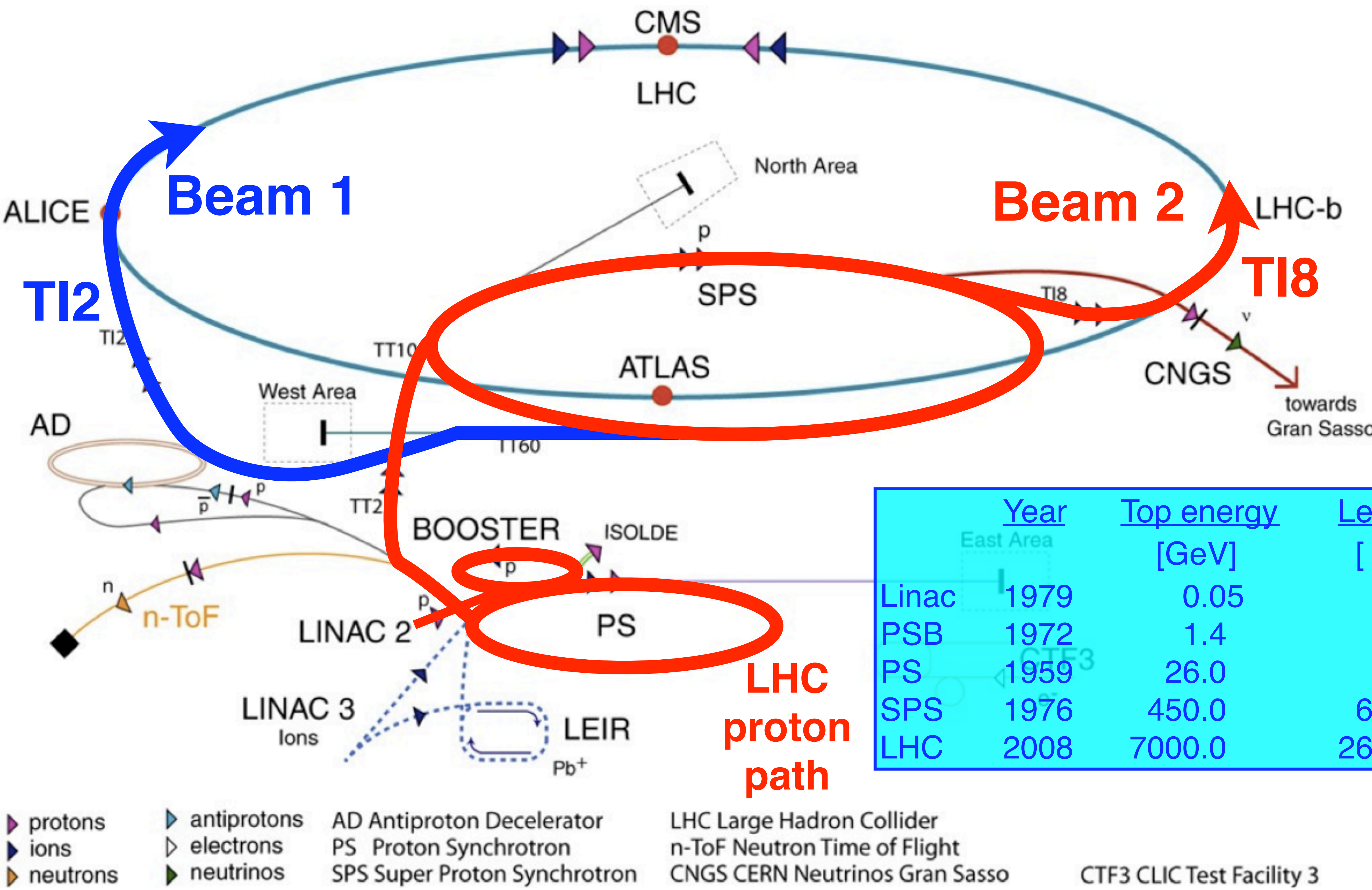
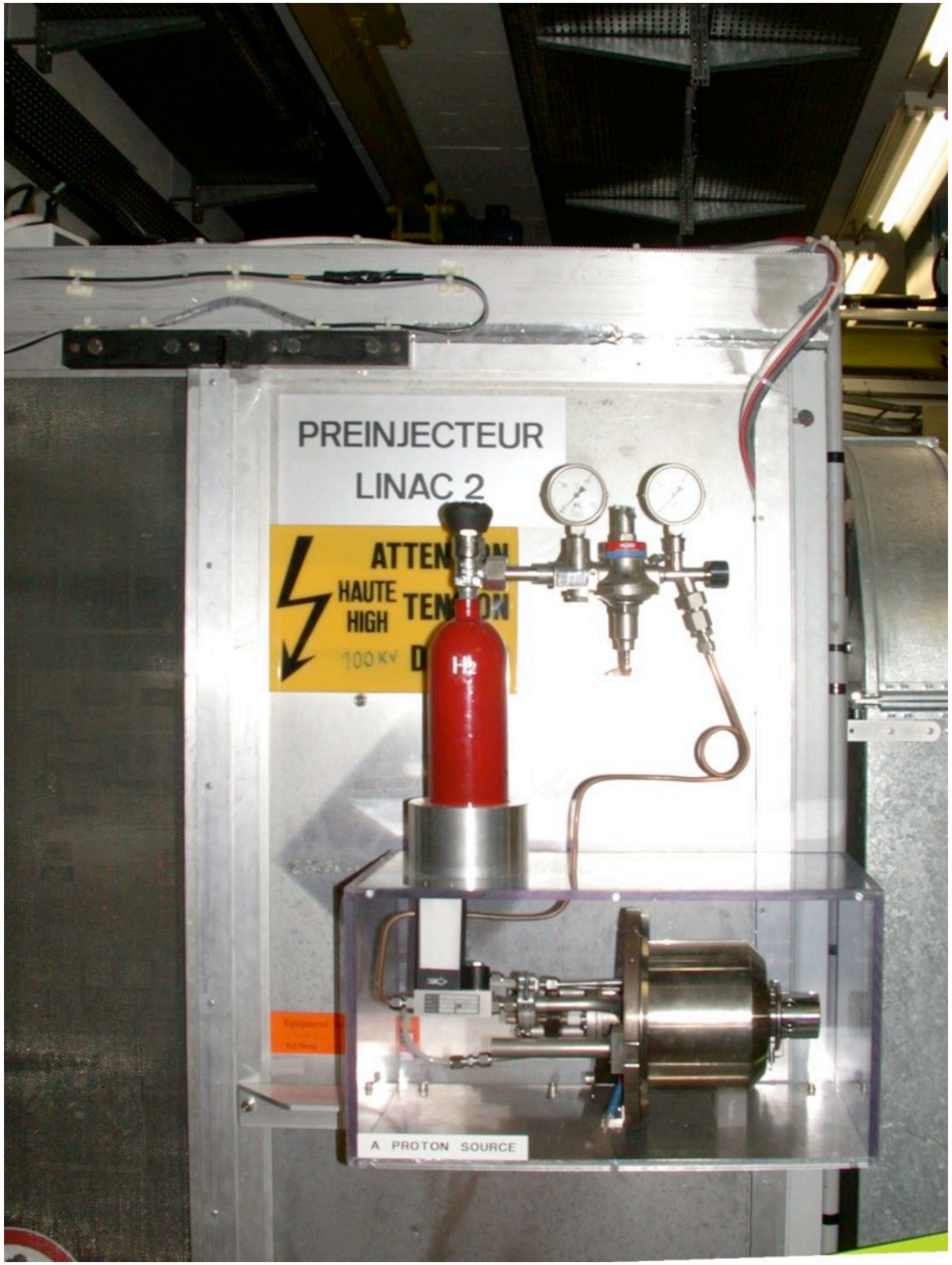
  - **Source and Linac2**
  - **PS Booster**
  - **Proton synchrotron**
  - **Super Proton Synchrotron**
- LHC parameters and layout
  - Arcs and straight sections
  - Machine protection system

The LHC accelerator complex



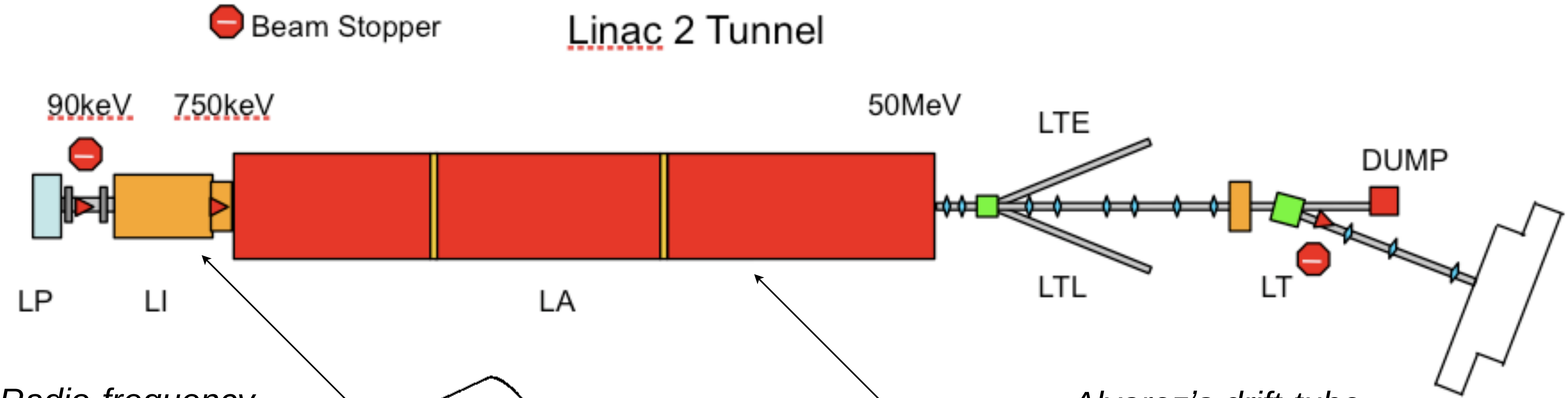
	Year	Top energy [GeV]	Length [m]
Linac	1979	0.05	30
PSB	1972	1.4	157
PS	1959	26.0	628
SPS	1976	450.0	6'911
LHC	2008	7000.0	26'657

Bottle of Hydrogen, to start with!

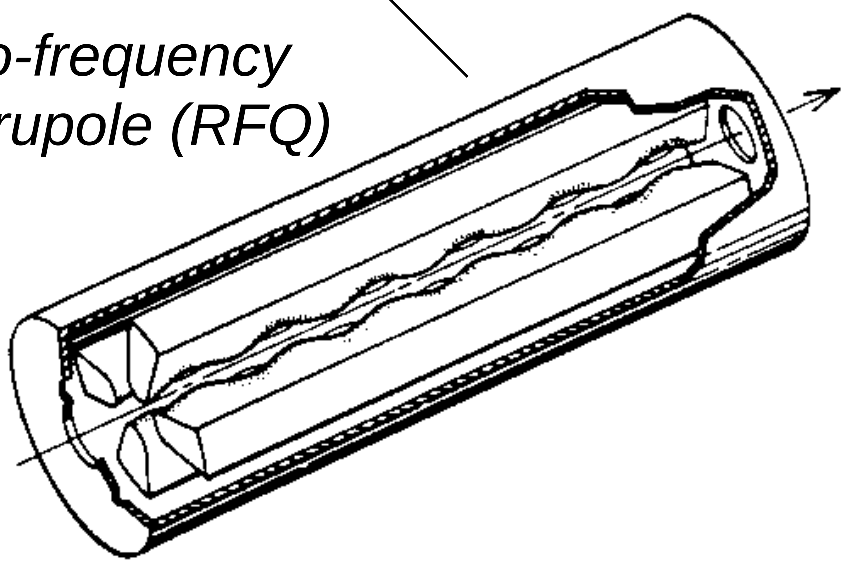


The real bottle is inside the cage

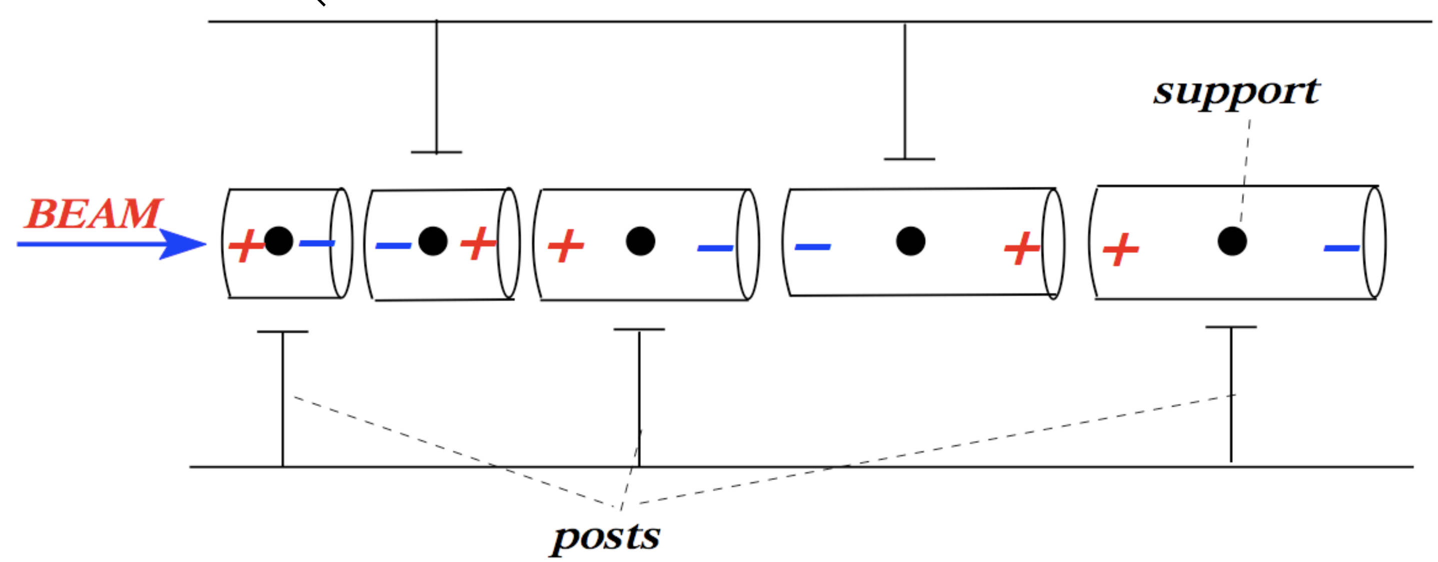
Linac2 - layout and parameters



Radio-frequency quadrupole (RFQ)

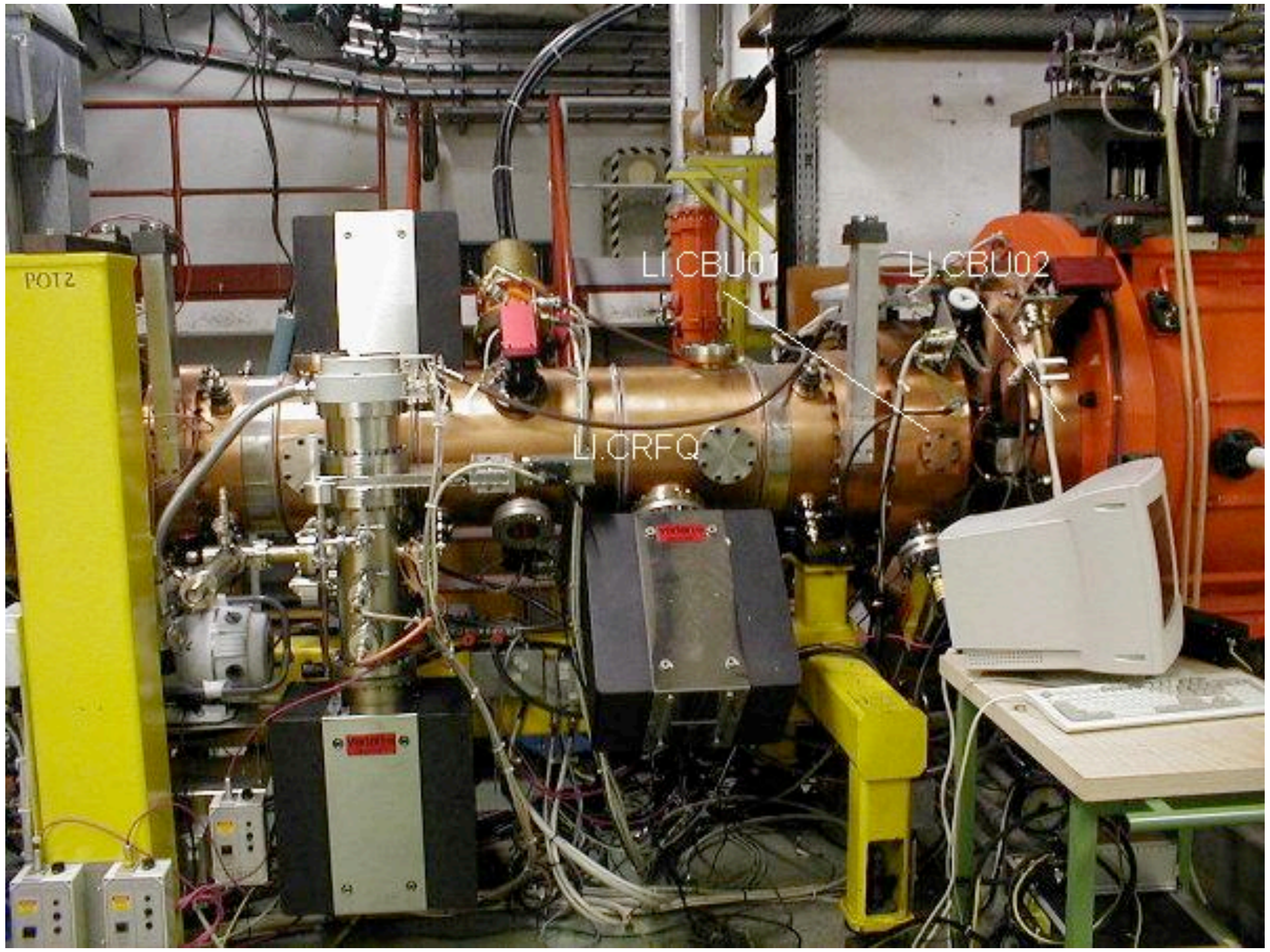


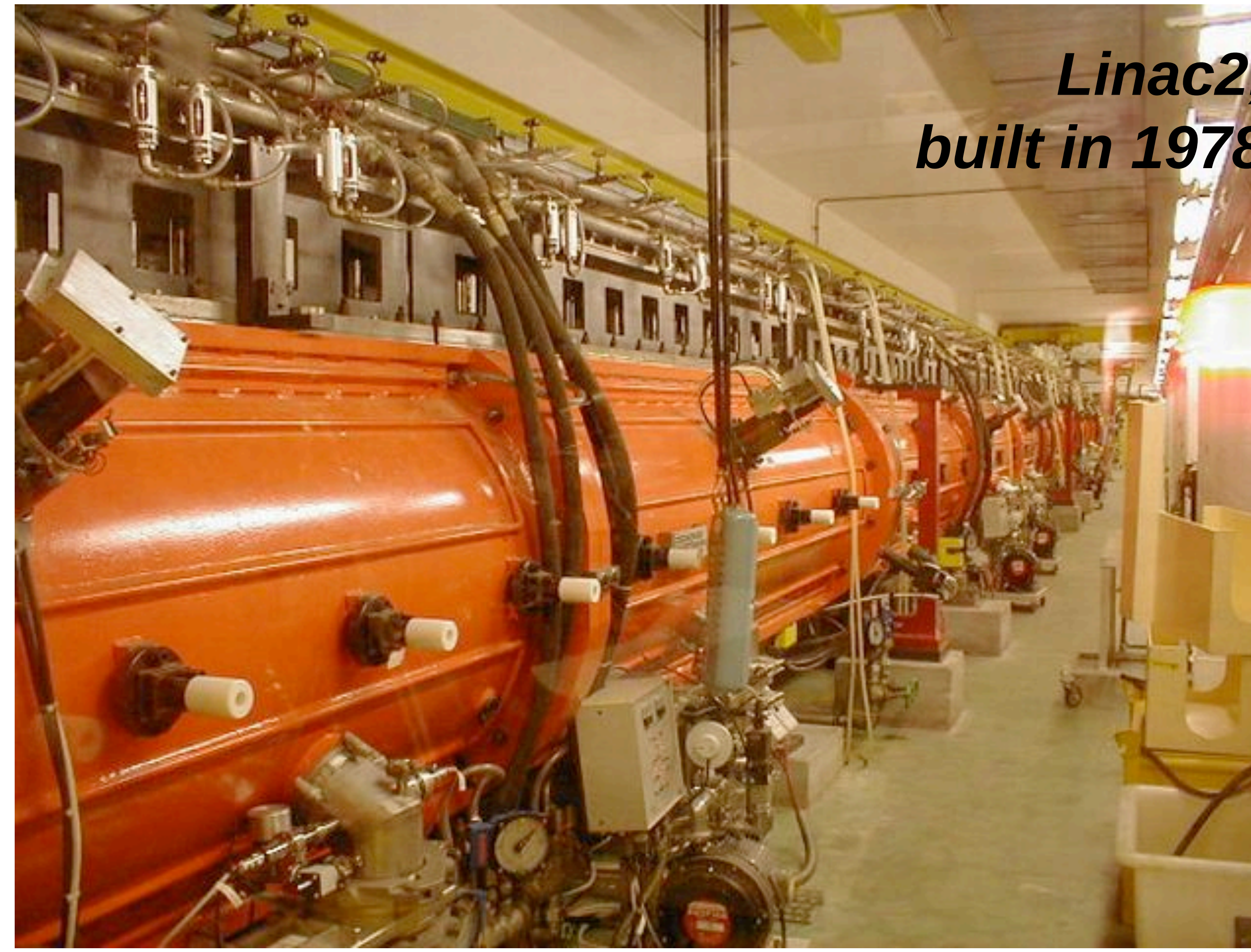
Alvarez's drift-tube



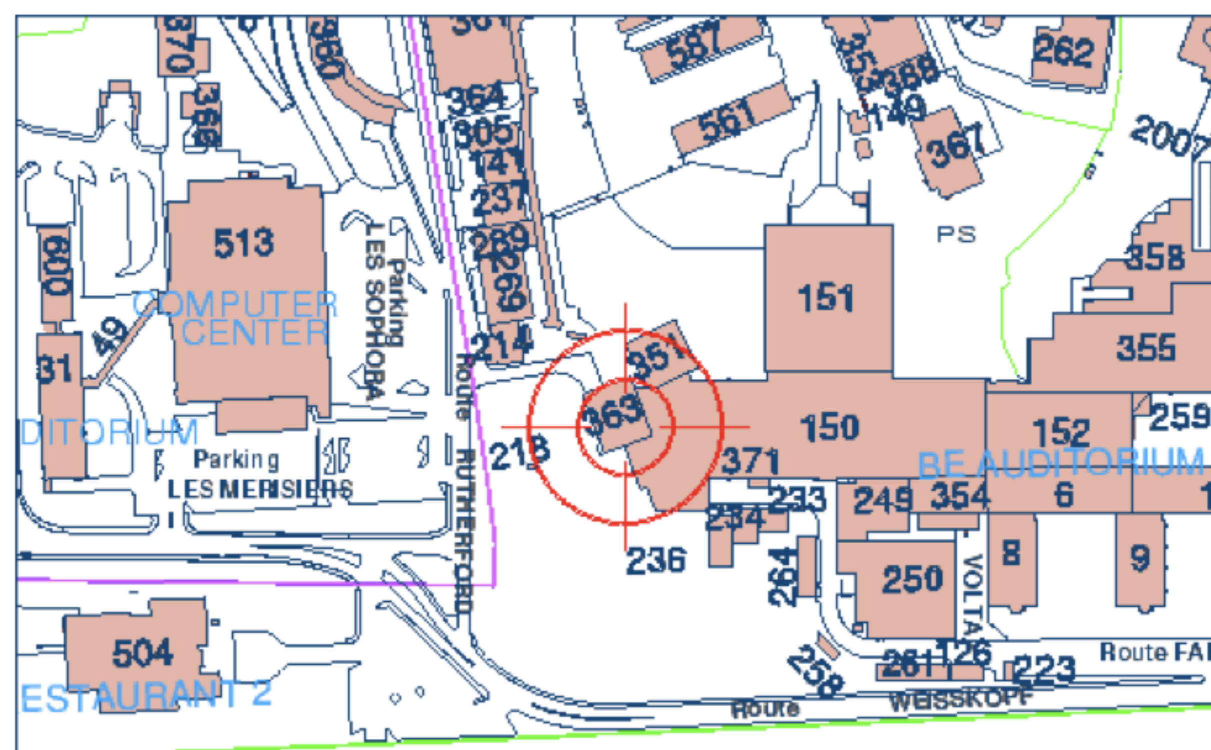
Delivered beam current:	**~150mA**
Beam energy:	90 keV (source) → 750 keV (RFQ) → **50 MeV**
Repetition rate:	**1 Hz**
Radio-frequency system:	202 MHz

Linac2: some pictures

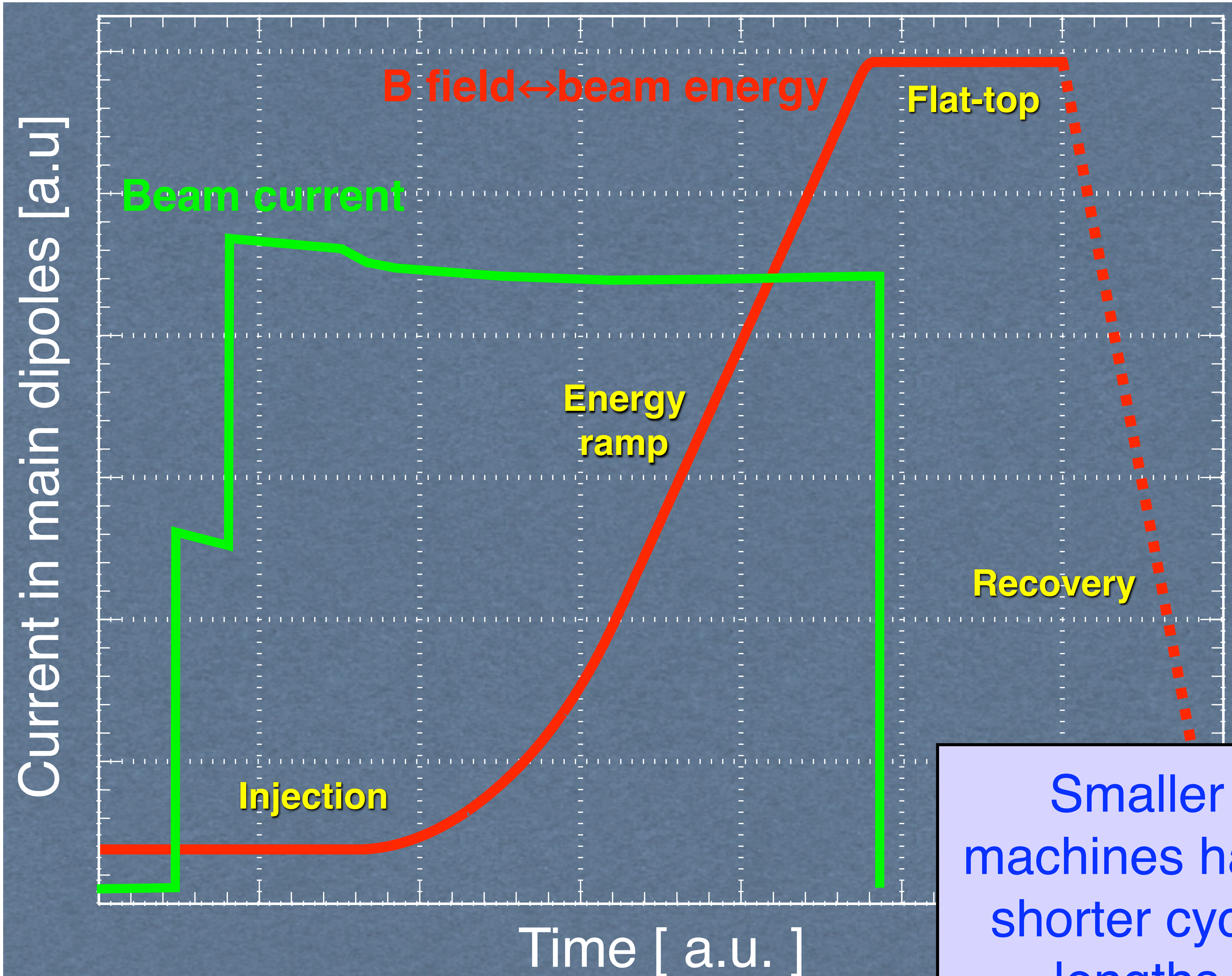




Downstream of Linac2, the proton beams will only encounter **circular accelerators** (and transfer lines)

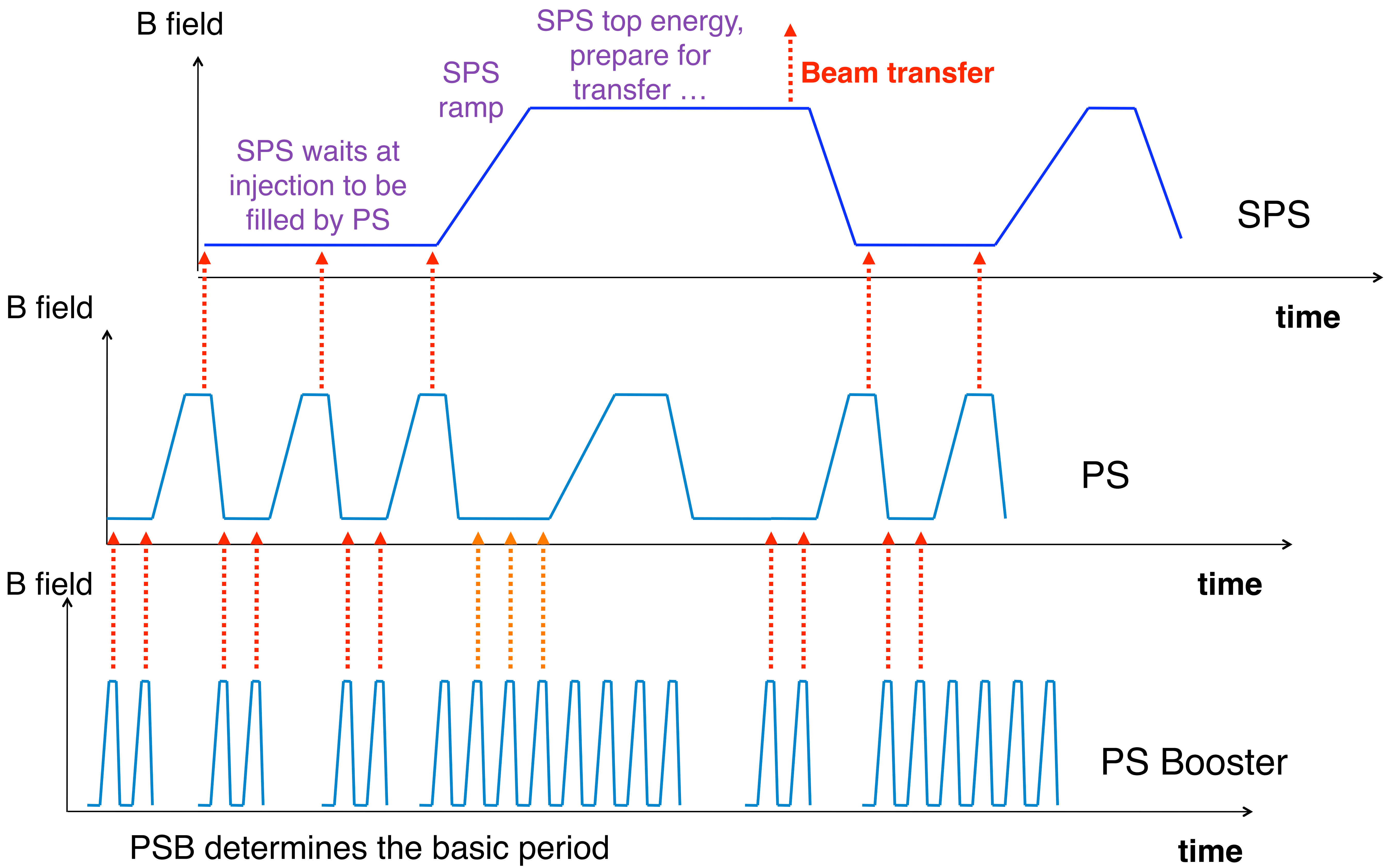


Magnetic cycle



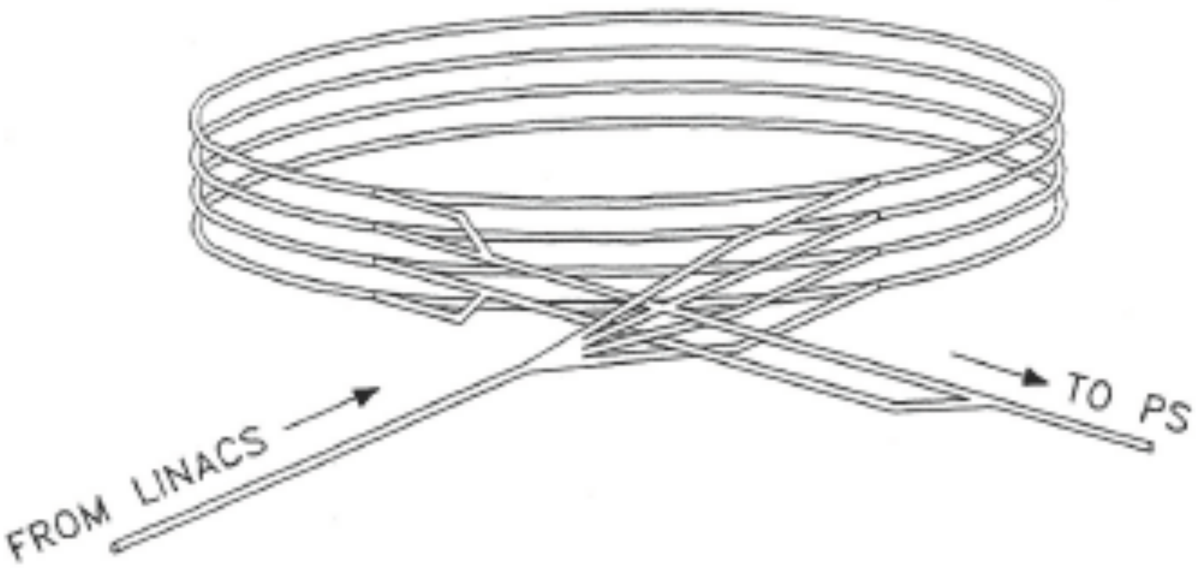
Smaller machines have shorter cycle lengths

Injector cycling



PSB determines the basic period

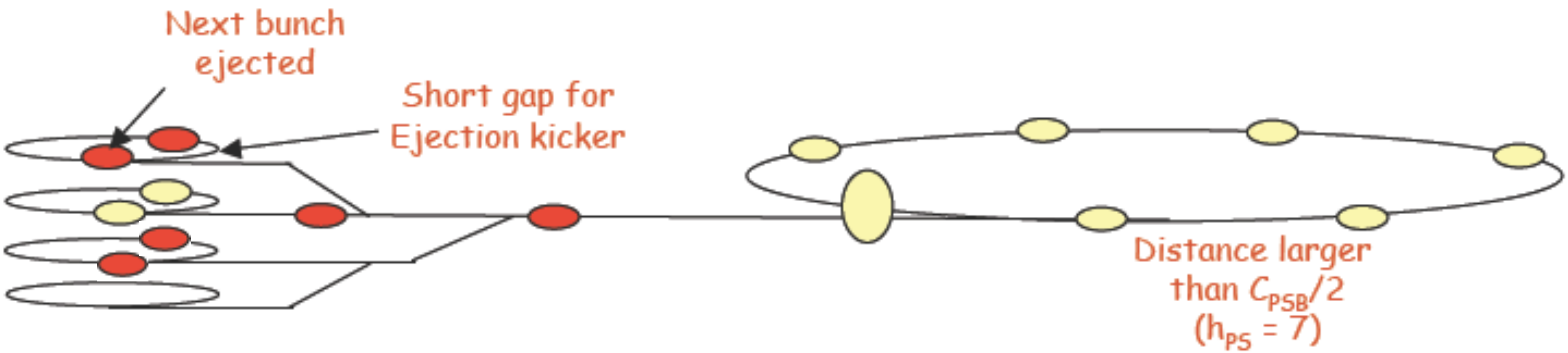
PS Booster



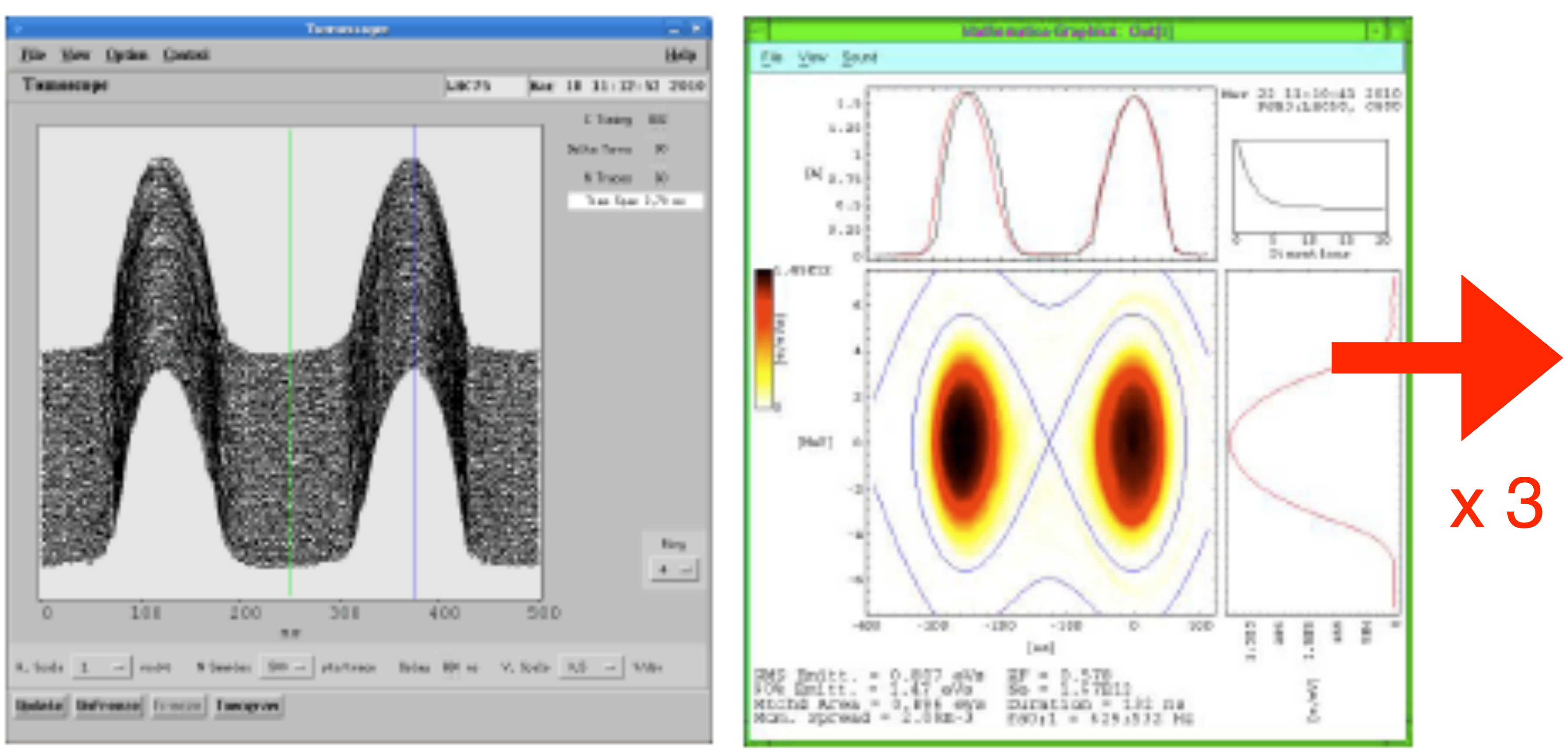
Sketch of the PS Booster with:
- Distribution of Linac beam into 4 rings
- Recombination prior to transfer

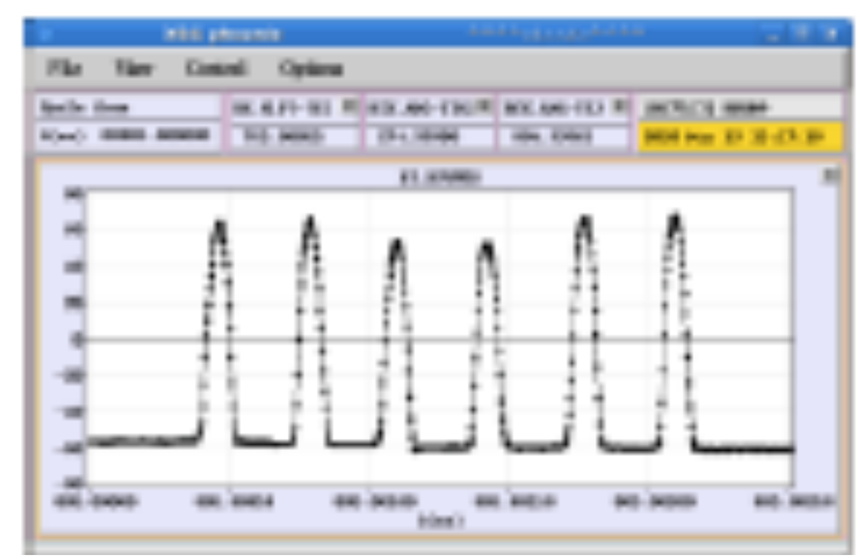
- Constructed in the 70ies to increase the intensity into the PS
- Made of four stacked rings
- Acceleration to $\mathbf{E_{kin}=1.4}$ **GeV**
- Intensities > $\mathbf{10^{13}}$ **protons** per ring obtained (i.e., four times design!!)
- Several types of beams with different characteristics
  - → *Physics beams for ISOLDE*
  - → *Beams for AD/PS/SPS physics*
  - → *LHC beams*

Filling the PS with LHC beams



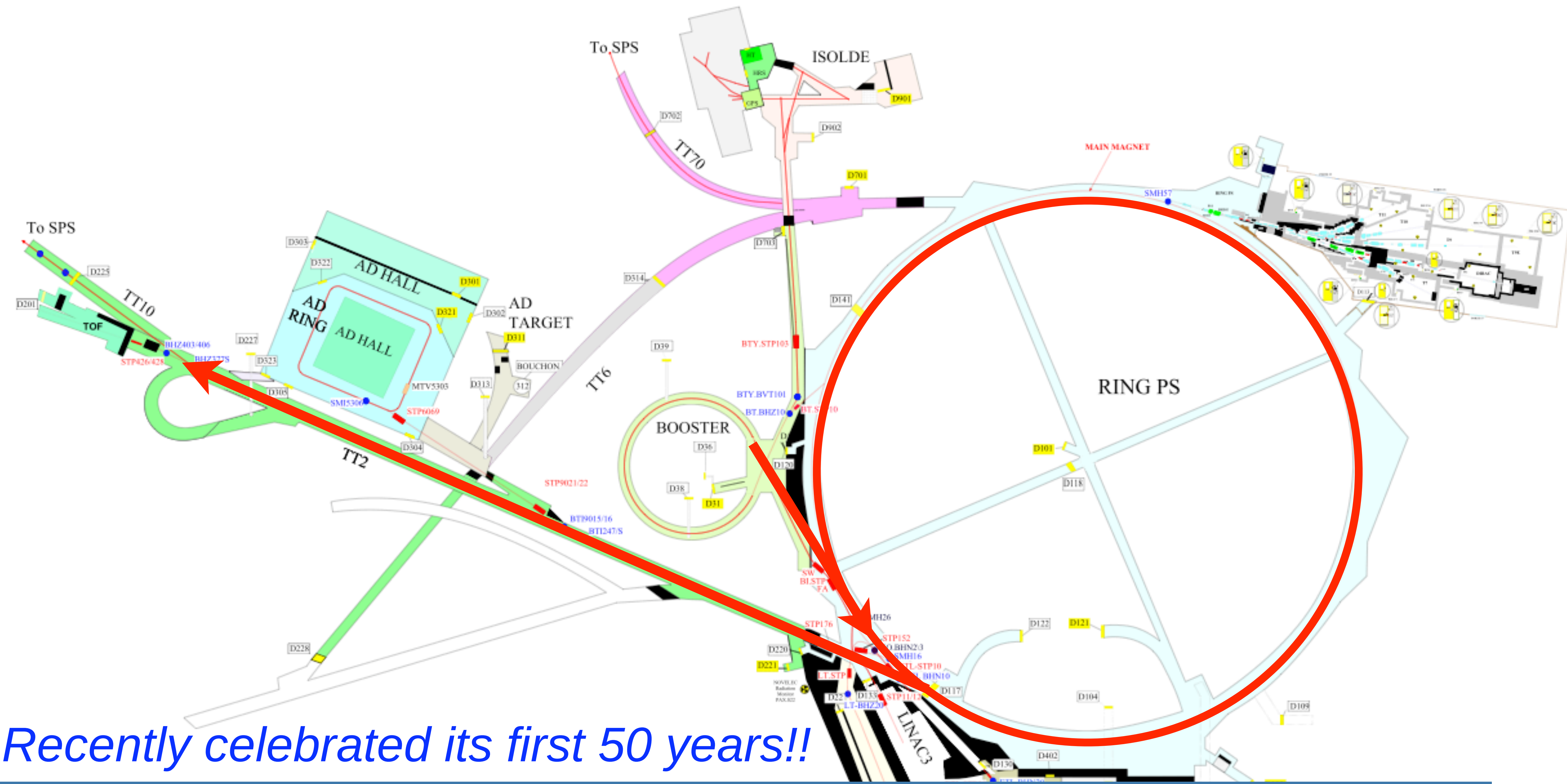
- In the single batch transfer, only rings 2,3 & 4 are filled on h=2 (i.e. 2 bunches per ring)
- The 6 bunches (1 or 2 extractions) can be transferred in one batch to the PS (on h=7)





Extract 6 bunches from 3 rings with 324ns spacing

Proton Synchrotron

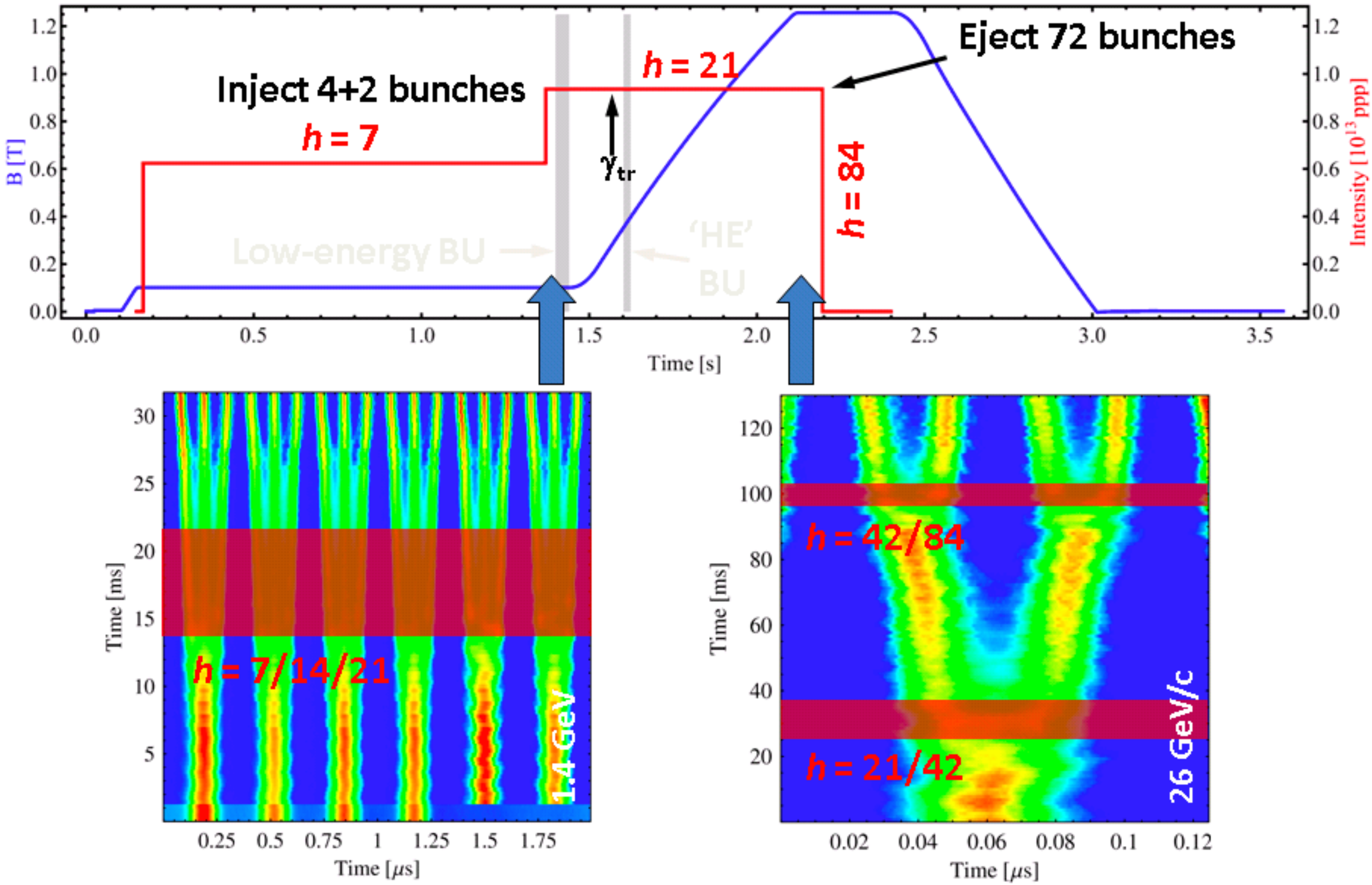


Recently celebrated its first 50 years!!

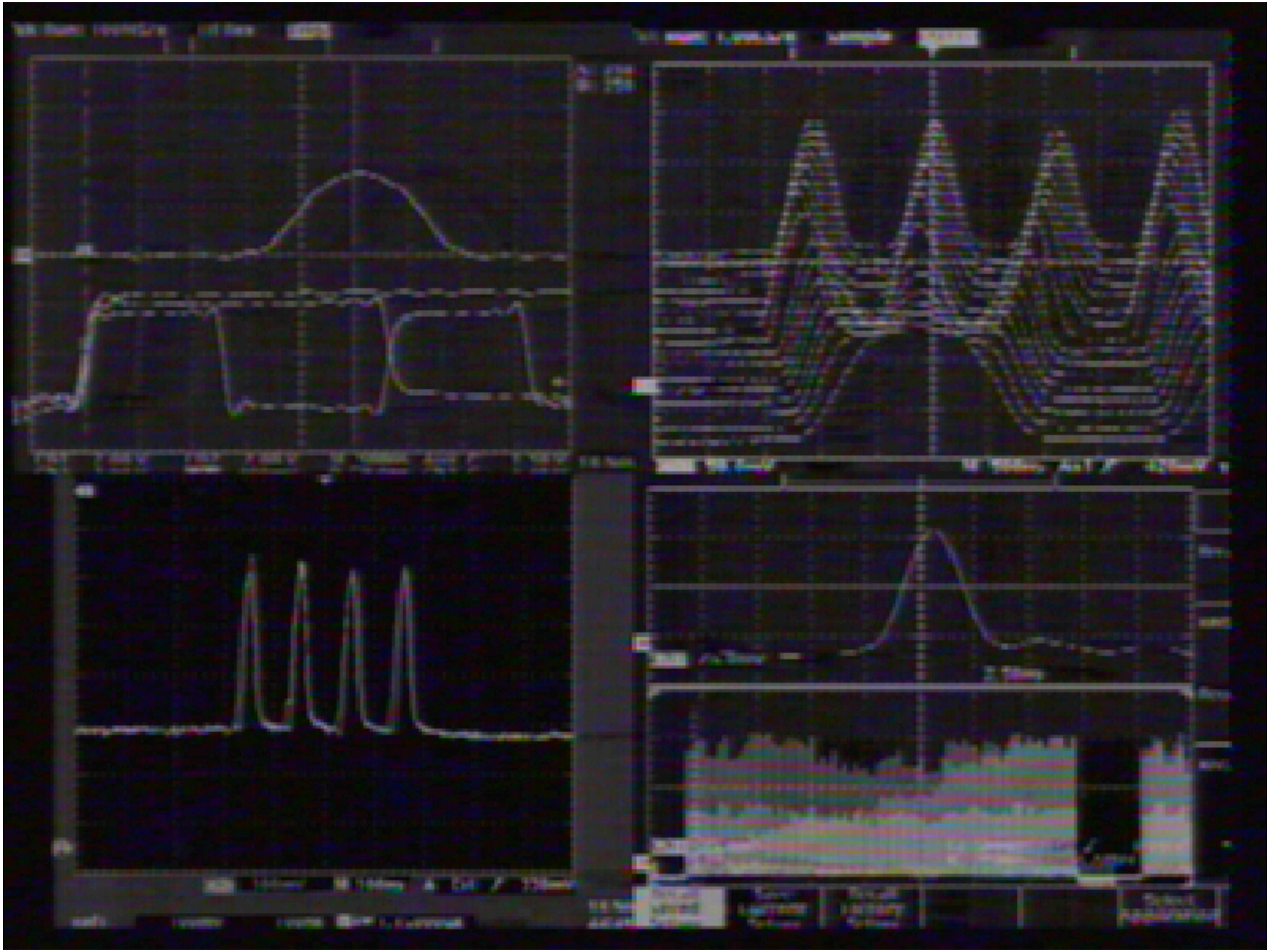
From the Proton Synchroton to the Large Hadron Collider - 50 Years of Nobel Memories in High-Energy Physics

from Thursday 03 December 2009 at **14:00** to Friday 04 December 2009 at **17:00** (Europe/Zurich)
at **CERN** (**500-1-001 - Main Auditorium**)

PS - bunch splitting

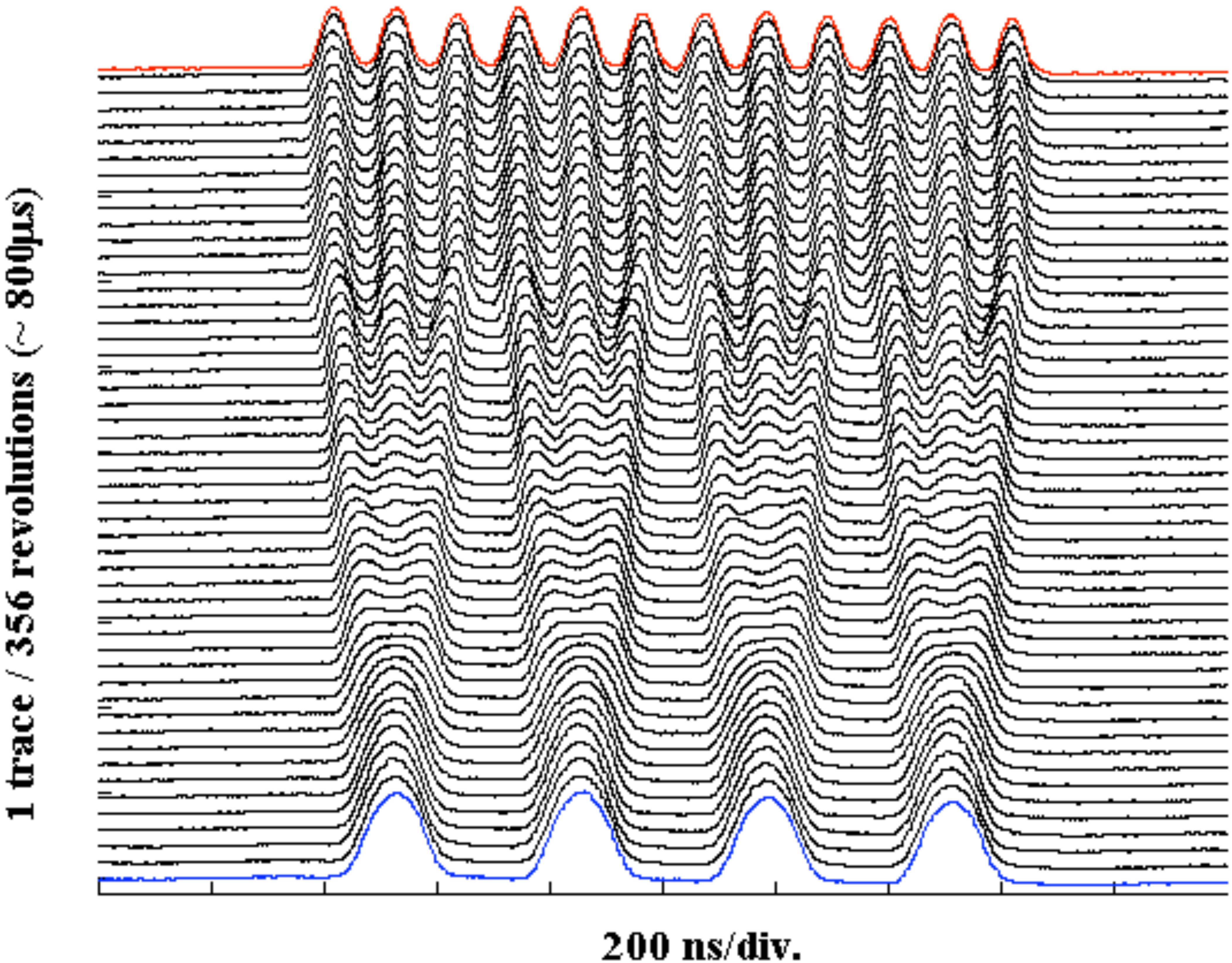


How it looks in reality



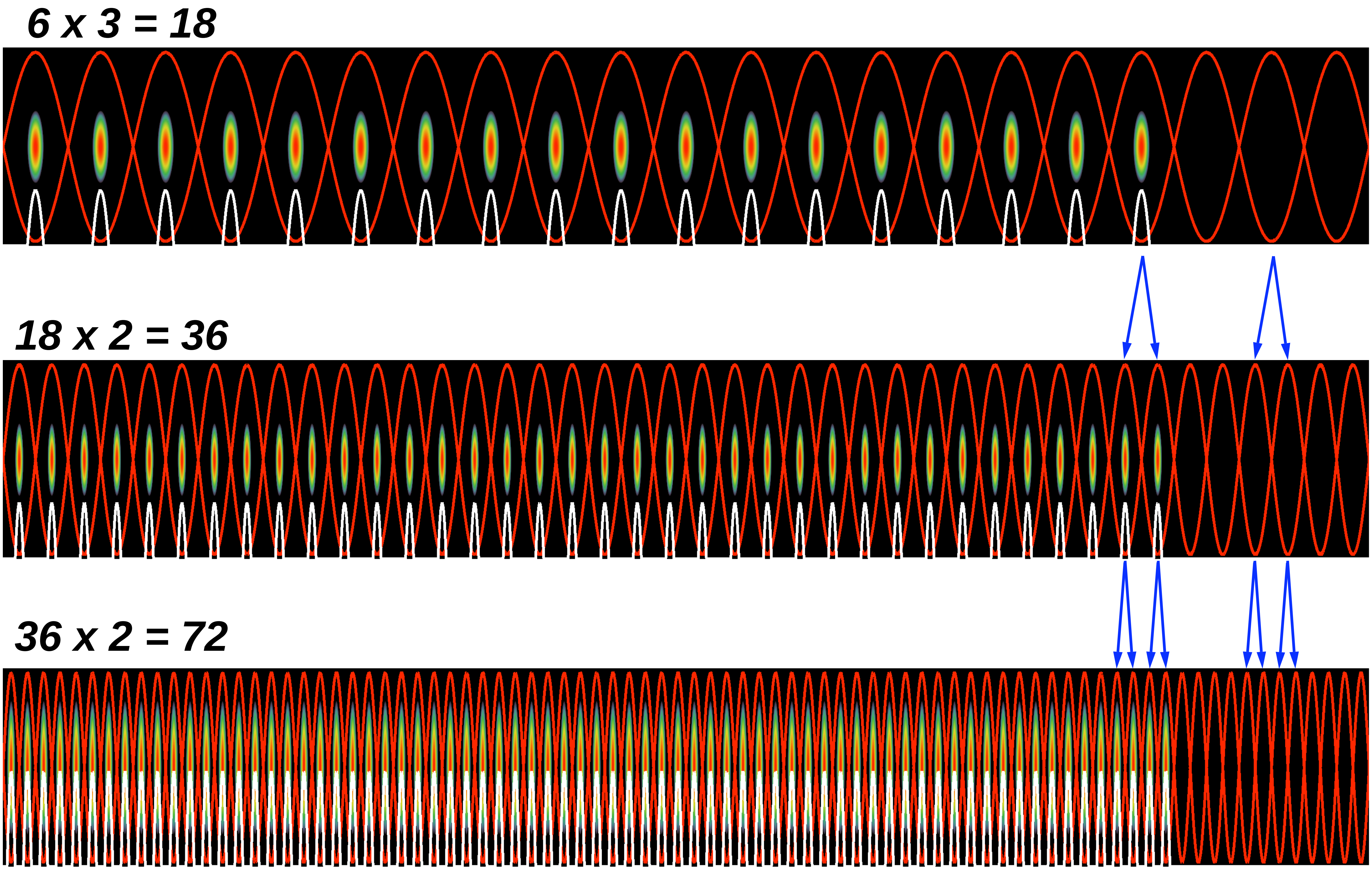
H. Damerau

How it looks in reality



H. Damerau

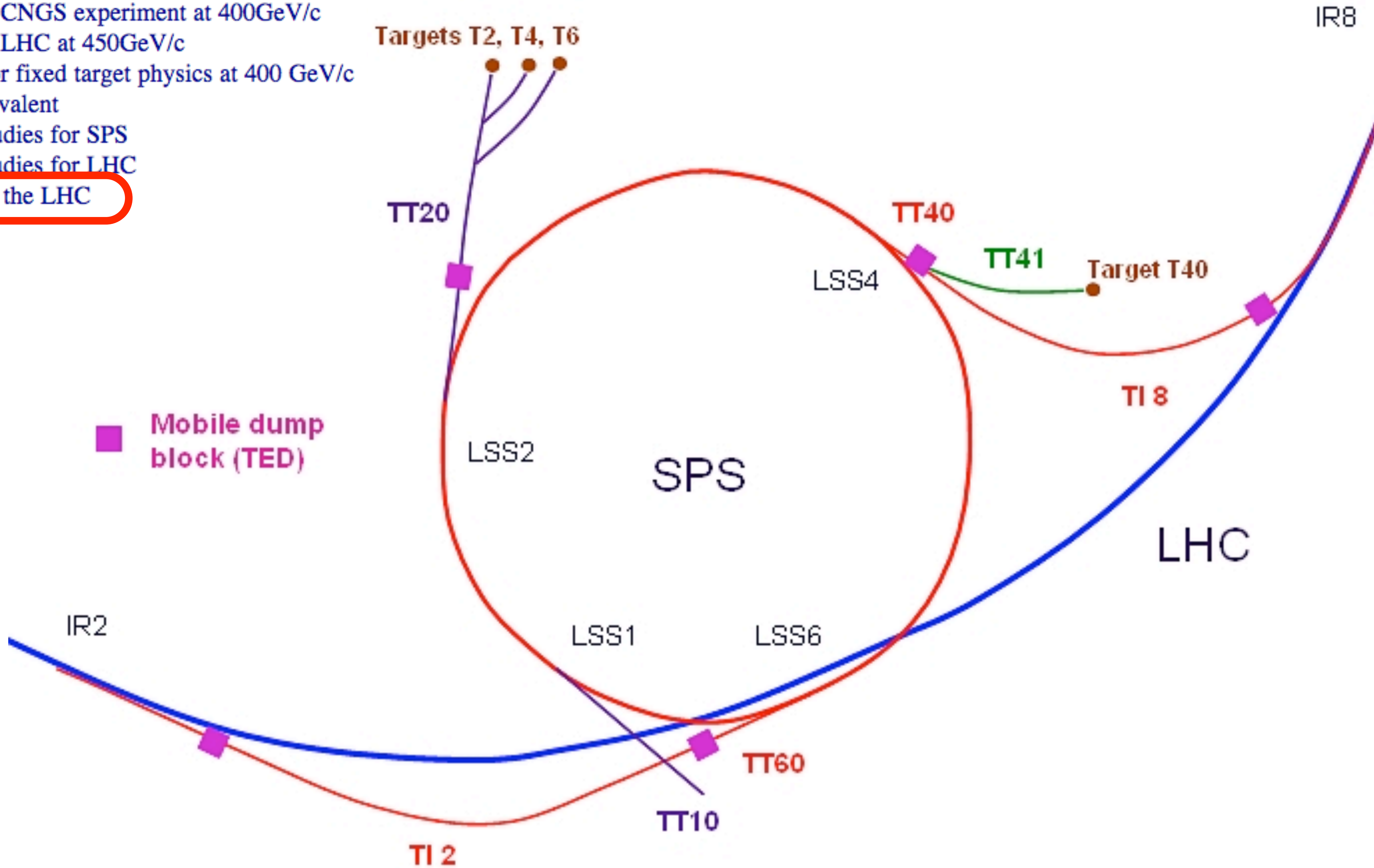
How it looks in reality



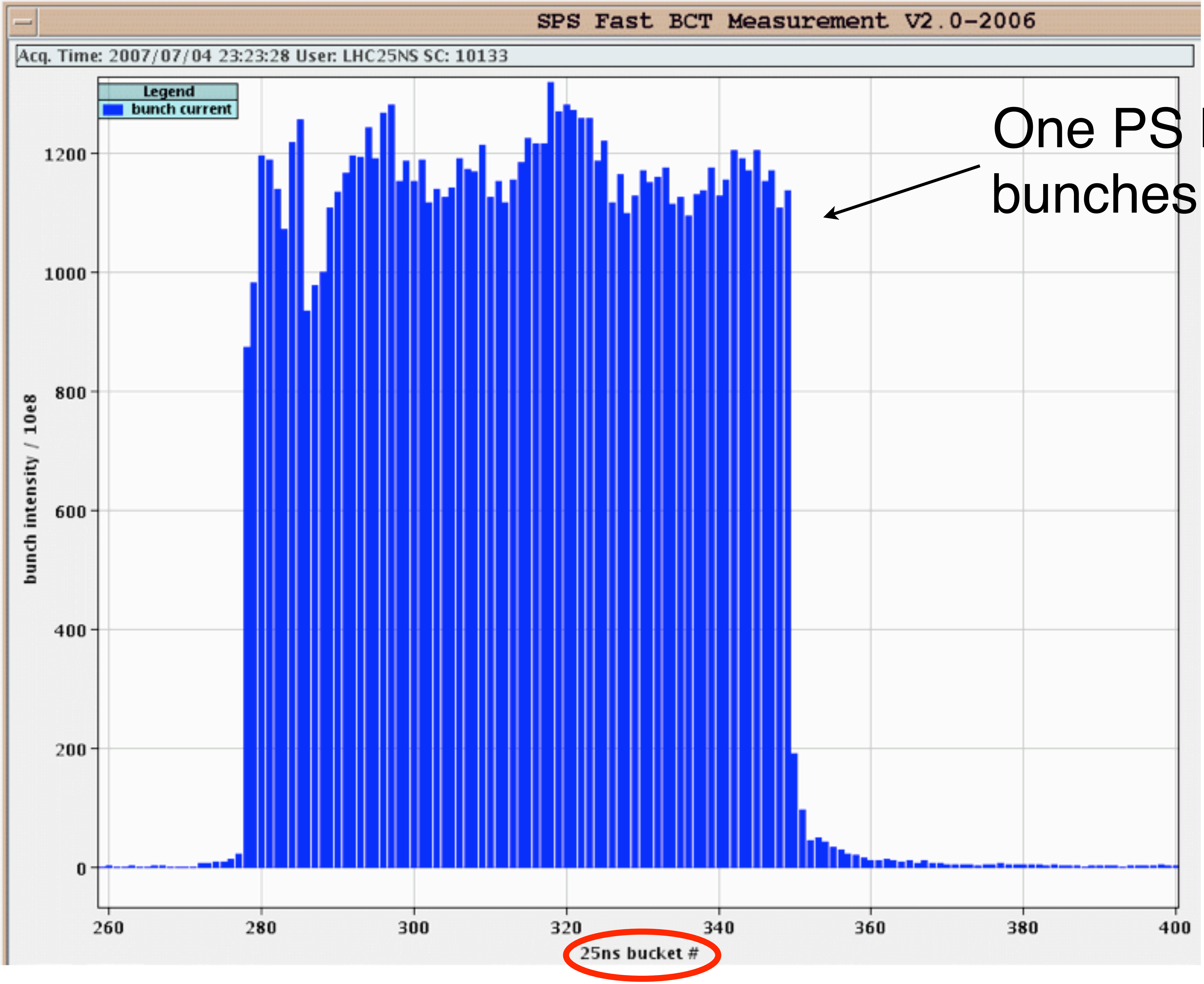
H. Damerau

Super-Proton Synchrotron

- Circumference : 6.9 km
- 2.5 km of secondary beam lines.
- protons for fixed target physics at 400 GeV/c
- protons for CNGS experiment at 400GeV/c
- protons for LHC at 450GeV/c
- lead ions for fixed target physics at 400 GeV/c proton equivalent
- machine studies for SPS
- machine studies for LHC
- Injector for the LHC

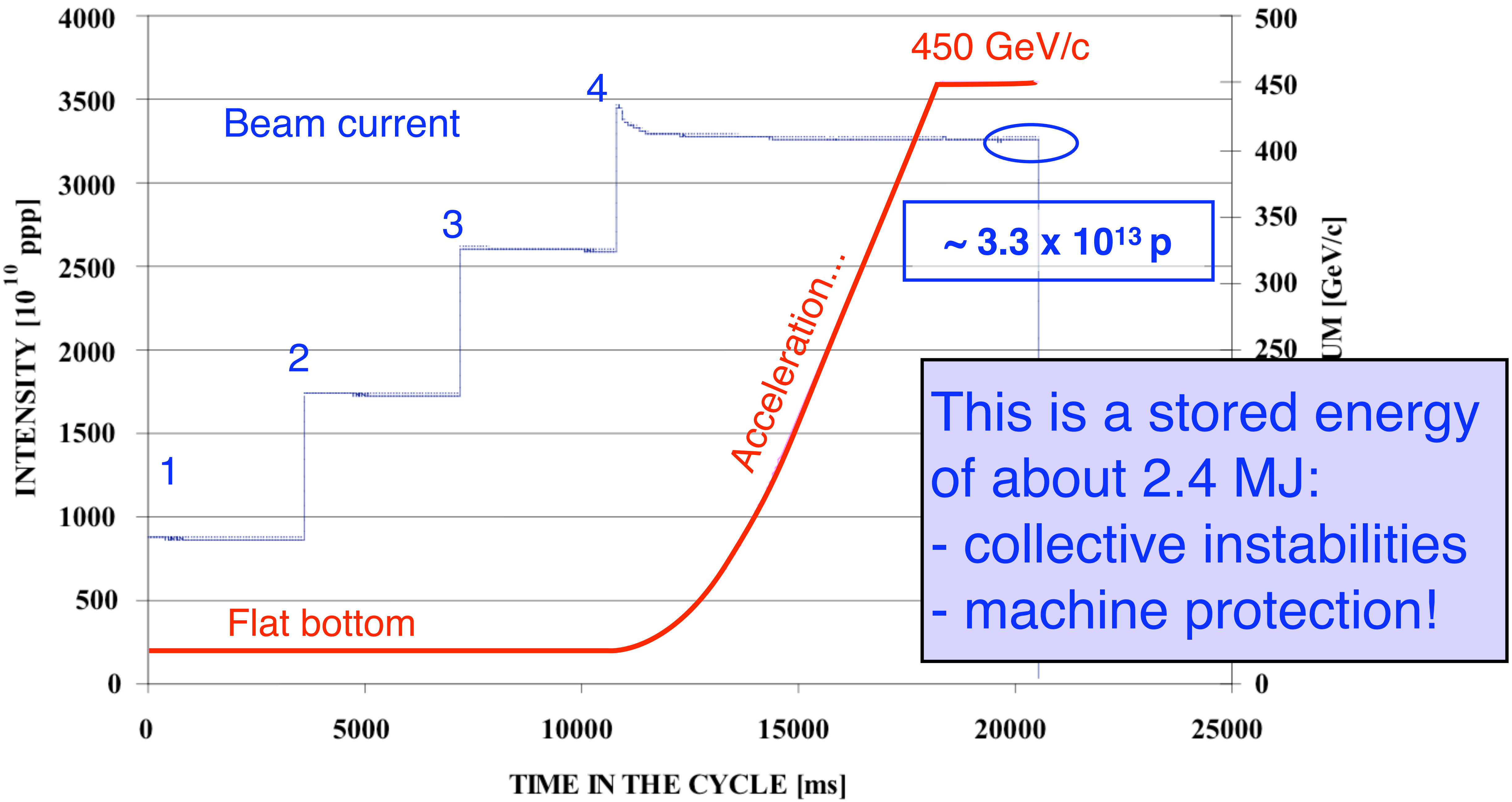


LHC beams in the SPS



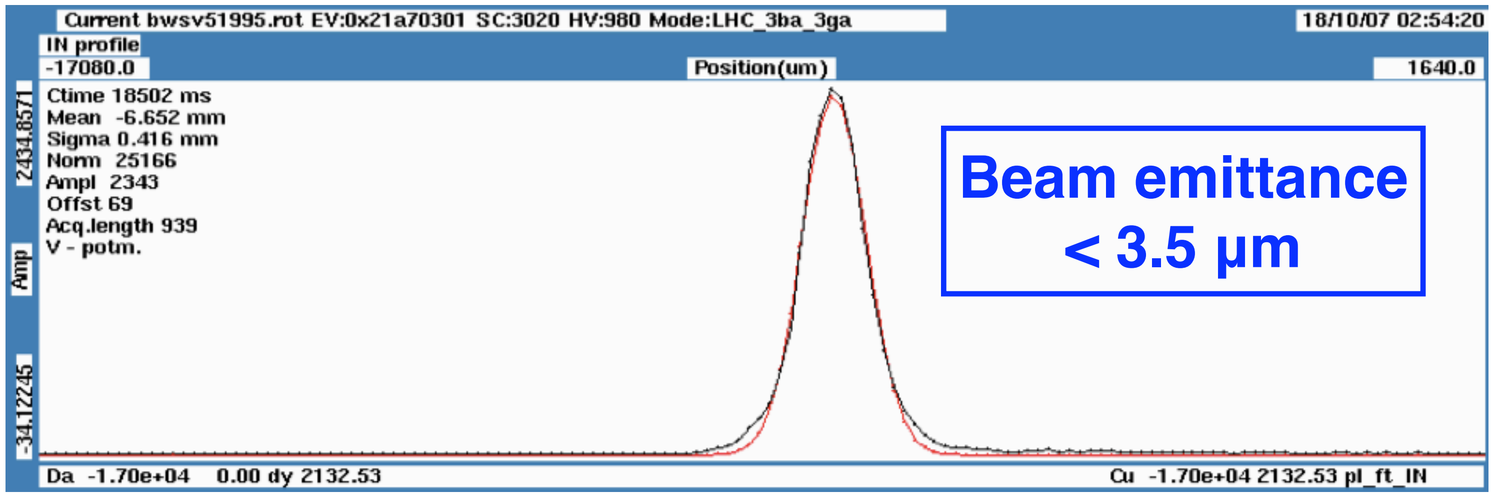
One PS batch of 72 bunches in the SPS

Nominal LHC beams at the SPS



This is a stored energy of about 2.4 MJ:
- collective instabilities
- machine protection!

Nominal LHC beams basically achieved in the SPS in 2004! Injectors have been since long ready for the nominal LHC...



If anything goes wrong...

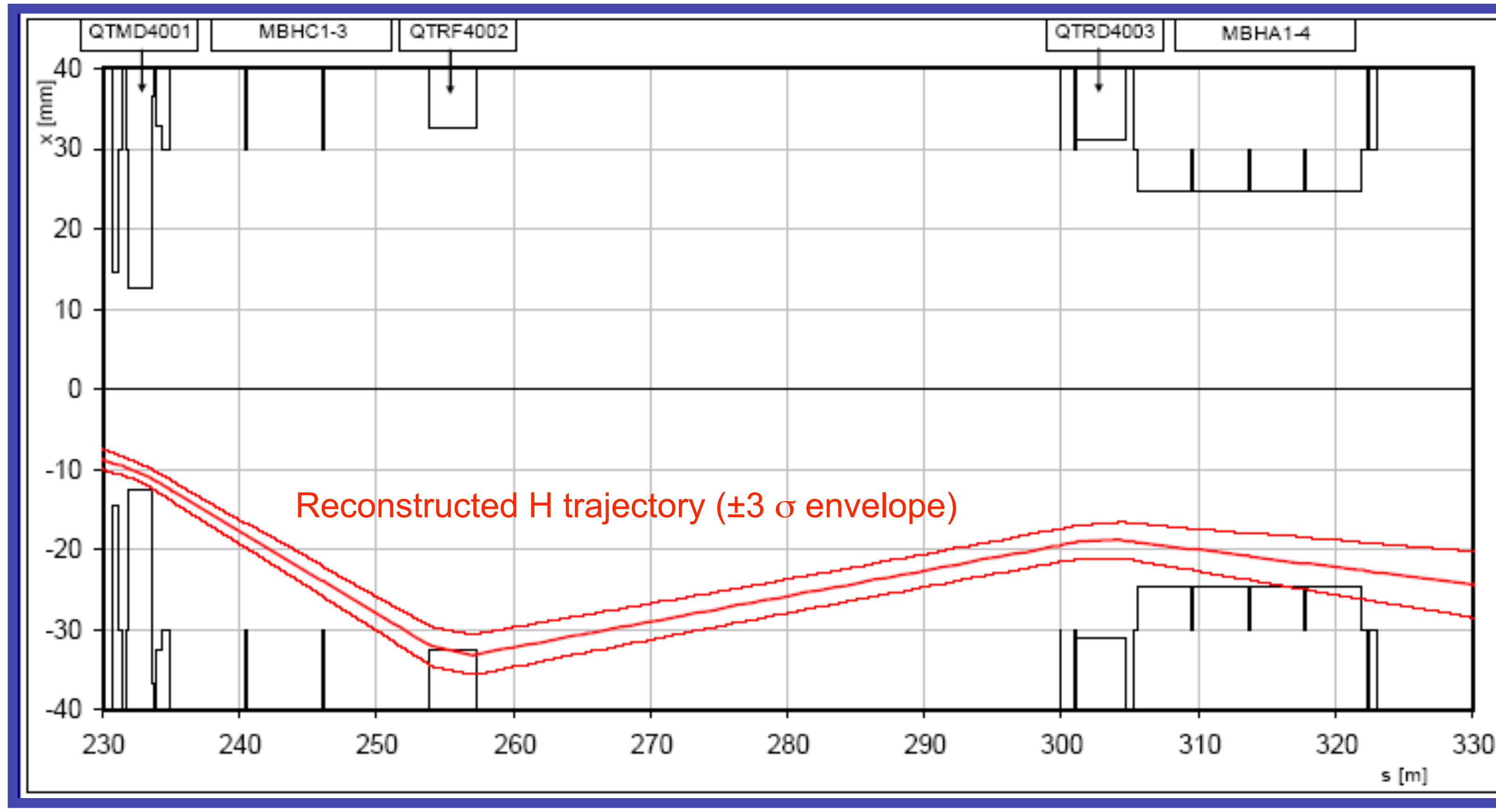
Failure in SPS during setting-up of LHC beam (25/10/04)

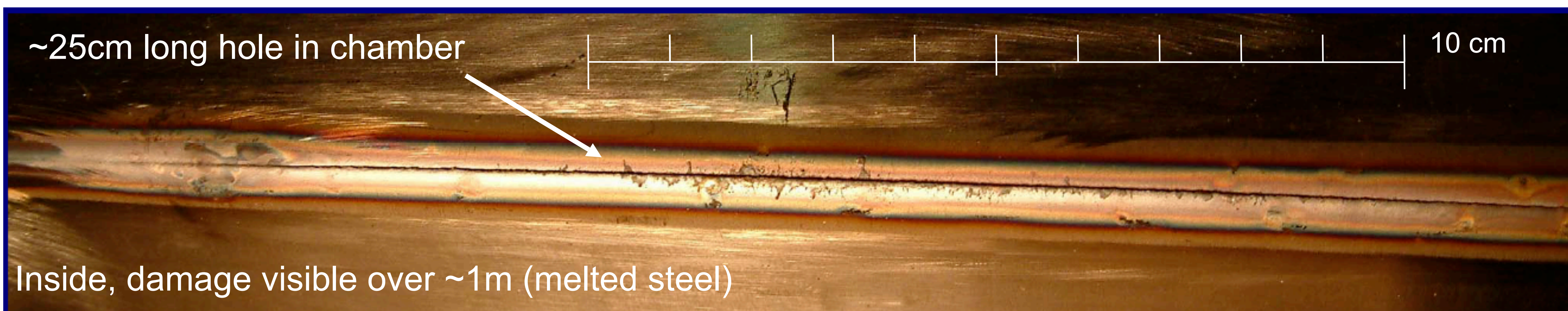
Extraction septum supply tripped due to EMC from the beam

In 11ms the field dropped 5%

3.4×10^{13} p+ @ 450GeV were wrongly extracted onto aperture

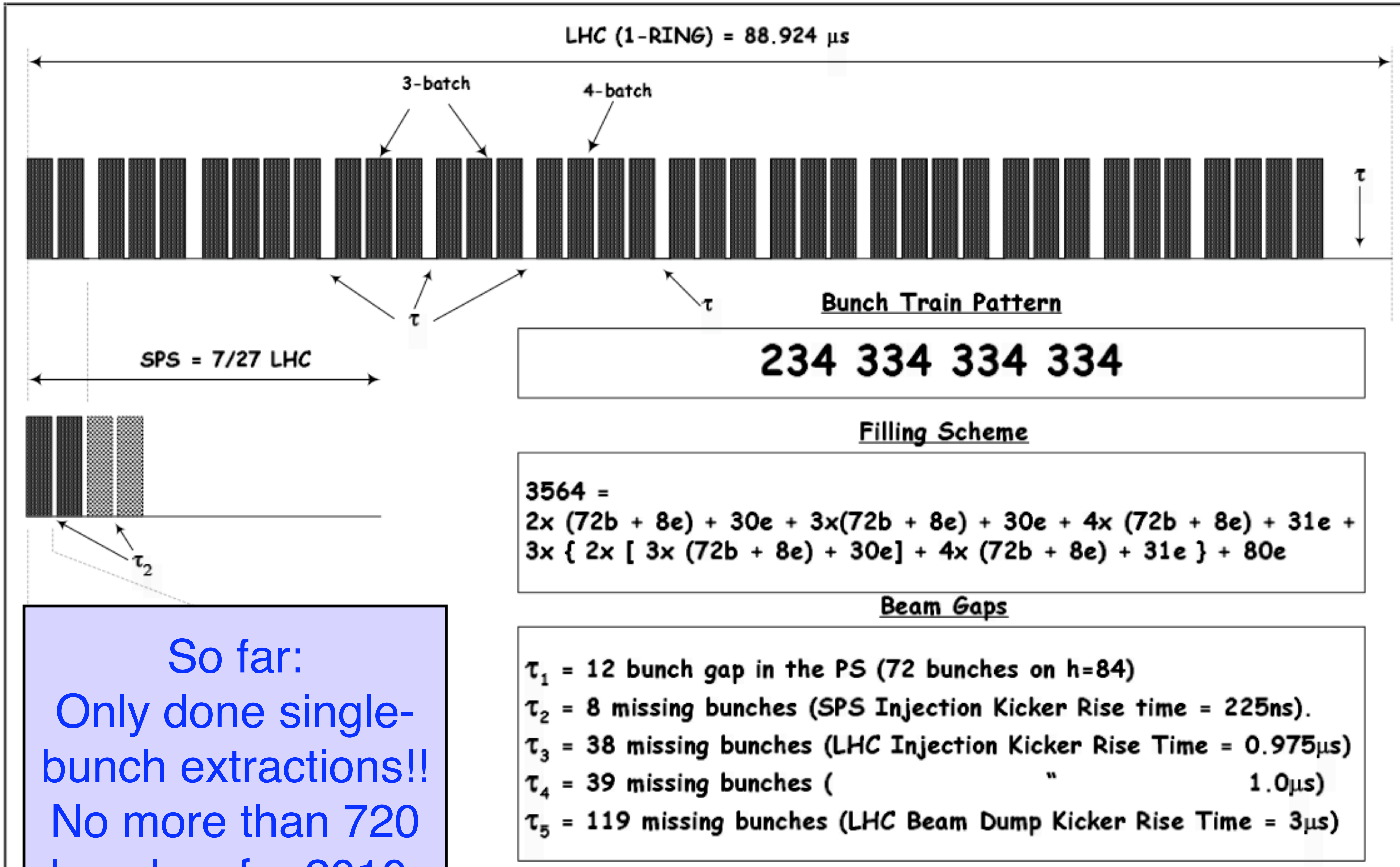
Chamber and magnet were damaged and had to be replaced





B. Goddard

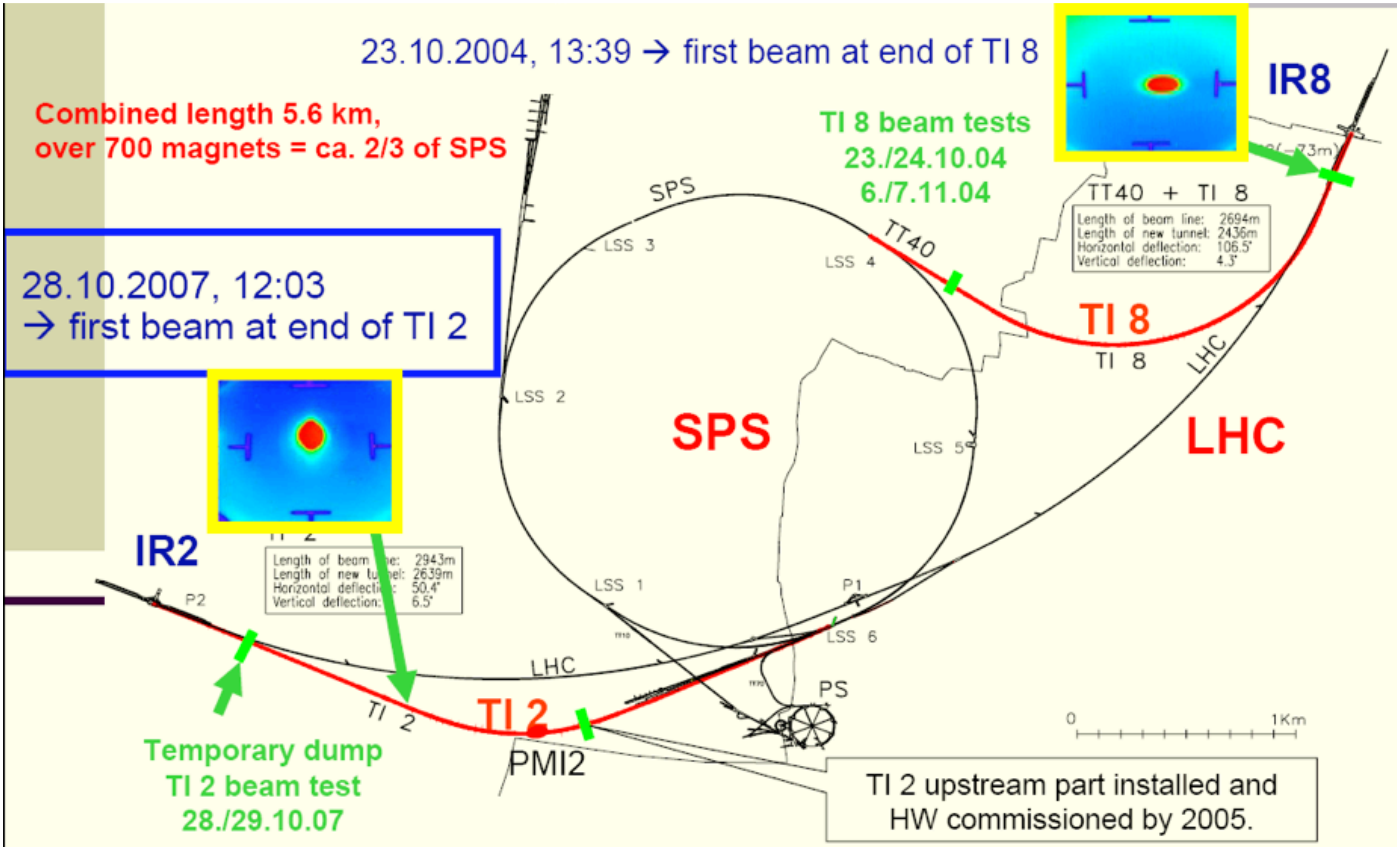
How do we get 2808 bunches ??



So far:
Only done single-bunch extractions!!
No more than 720 bunches for 2010.

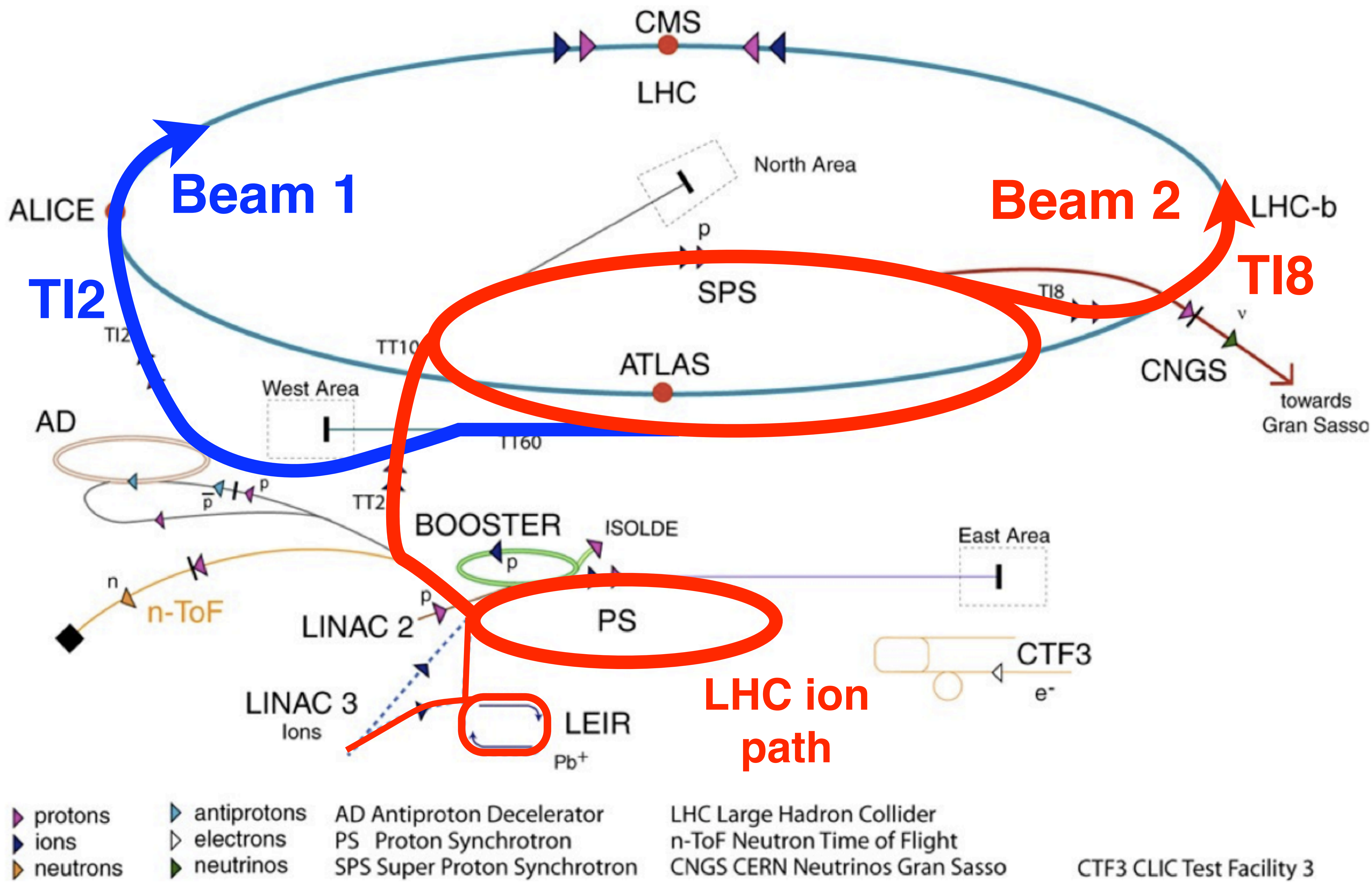
R. Bailey, P. Collier, LHC Proj. Note 323

SPS-to-LHC transfer lines

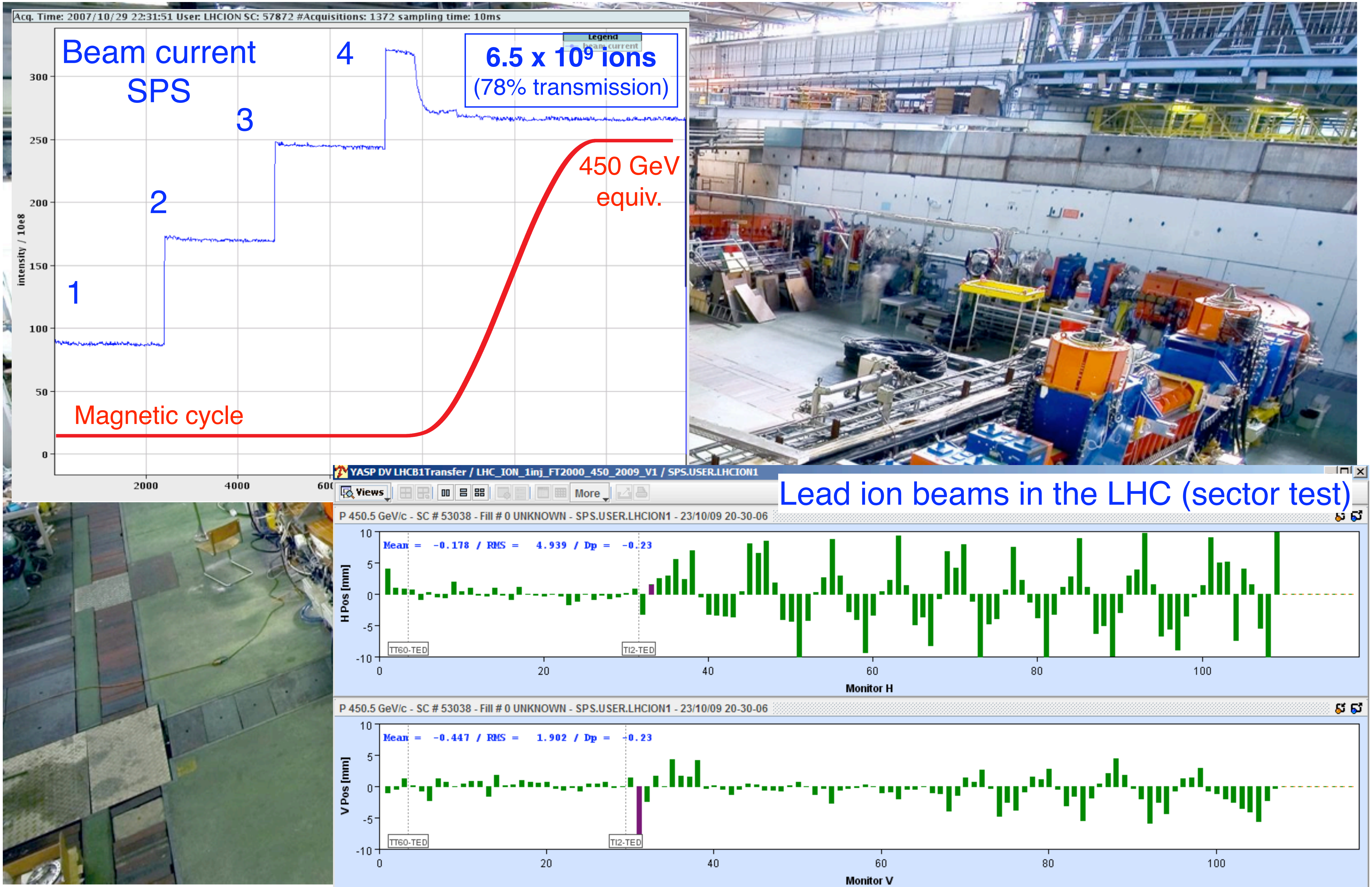


Courtesy of J. Uythoven

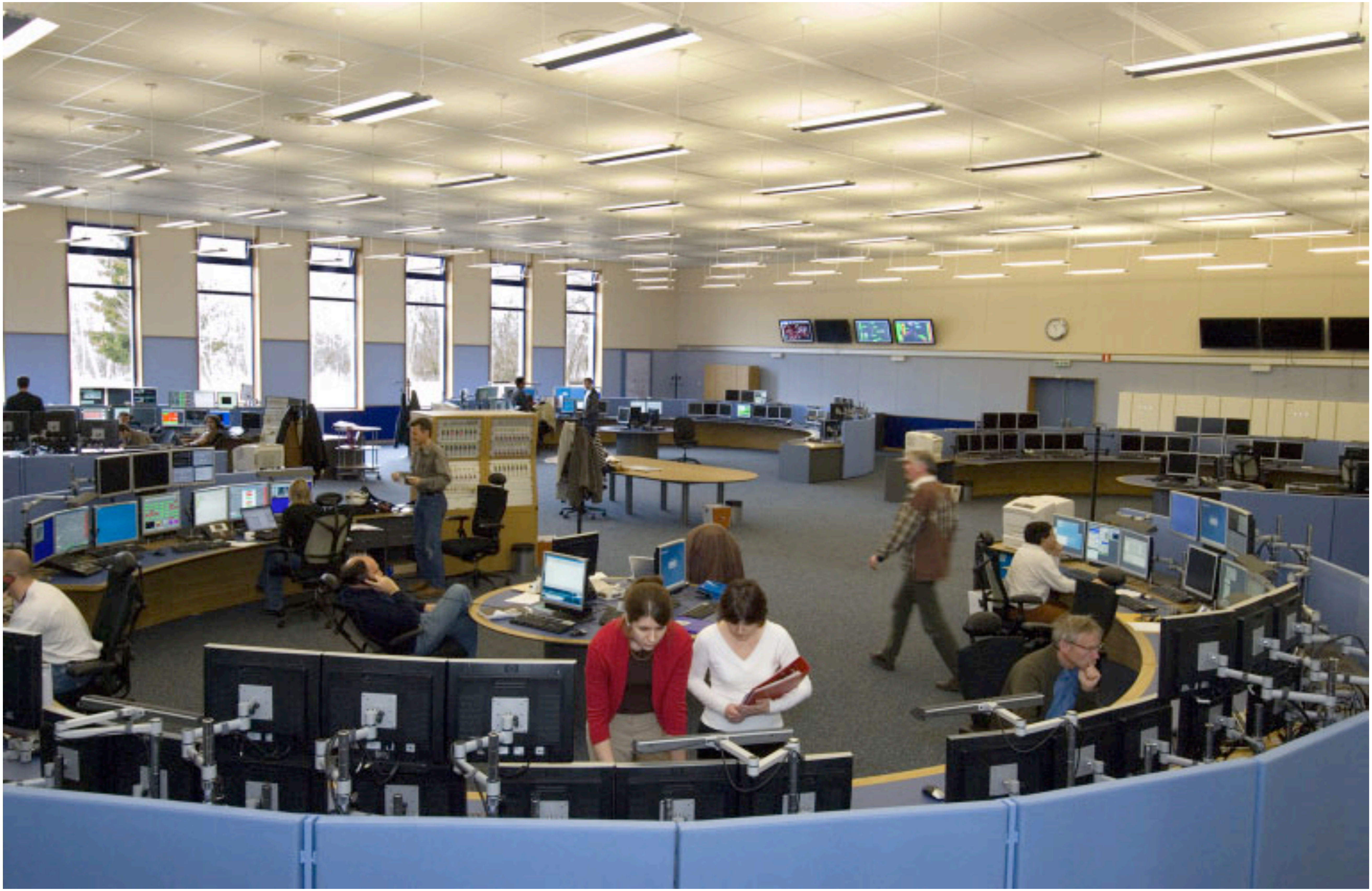
Ion beam path to the LHC



Low-energy ion ring (LEIR)



CERN Control Centre - Layout



CCC can be packed in these days...

3.5 TeV collisions on March 30th

... and even more in the past

Our secret to attract people

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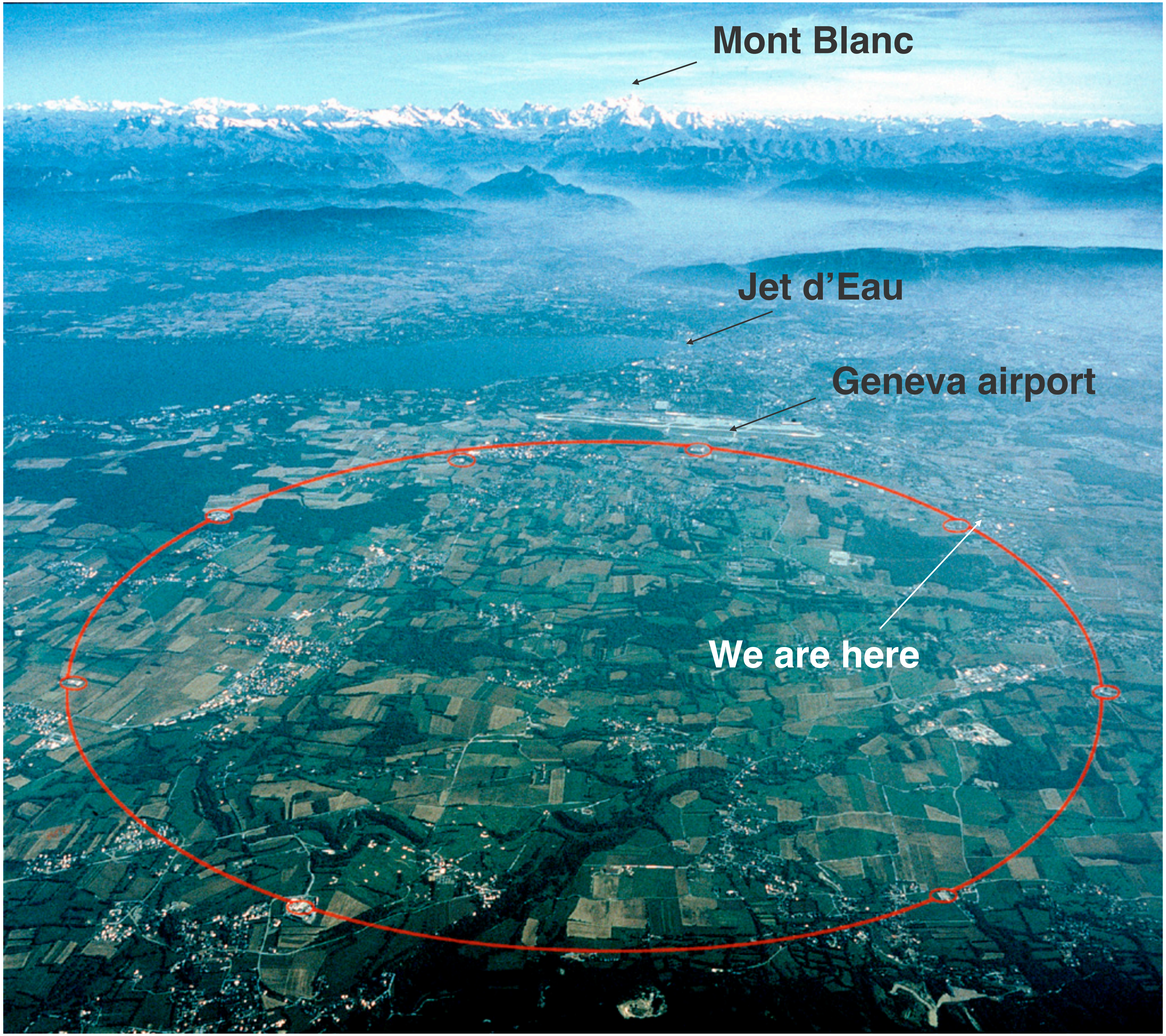
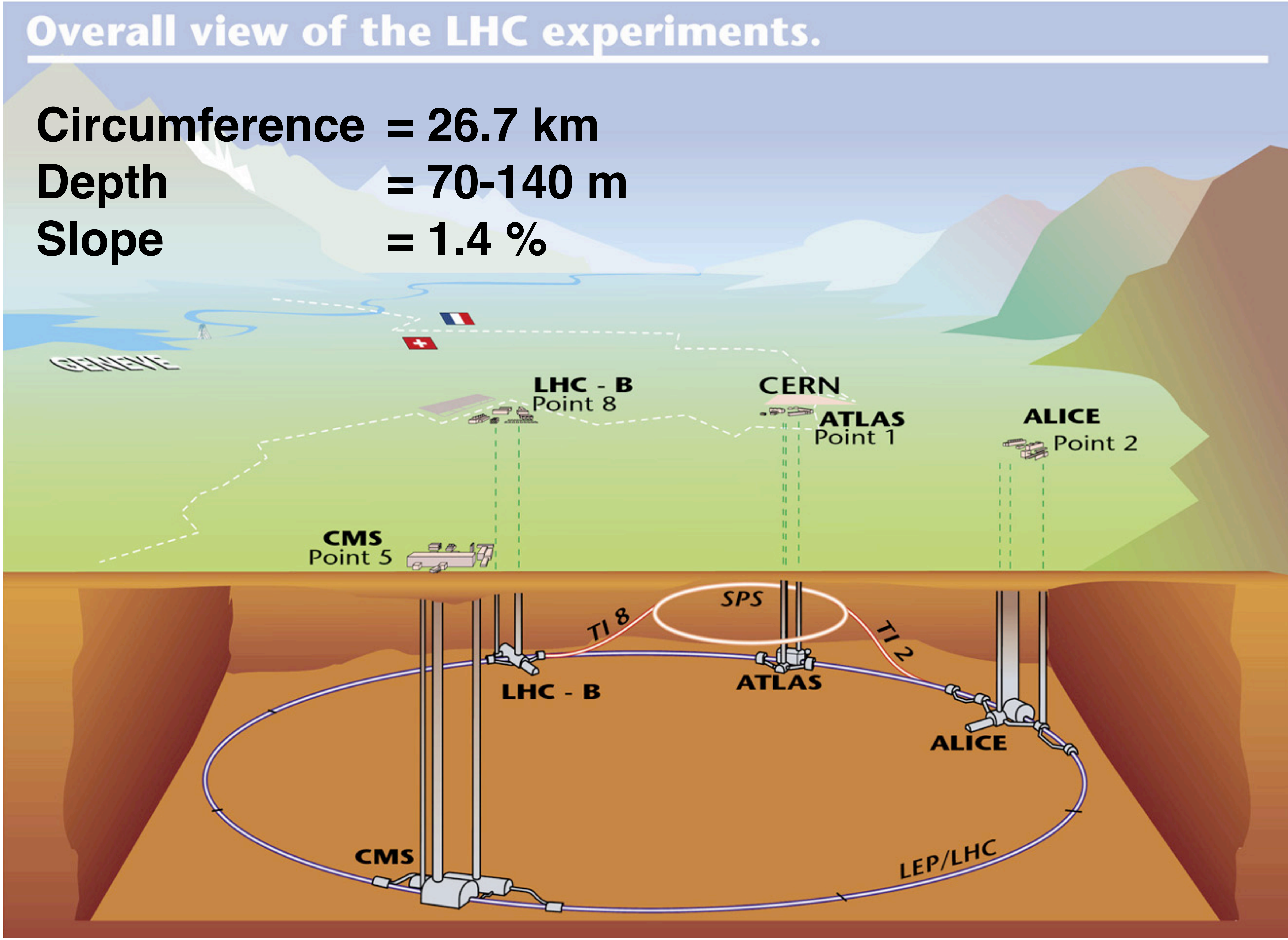
LHC: view from top



LHC layout - from bottom

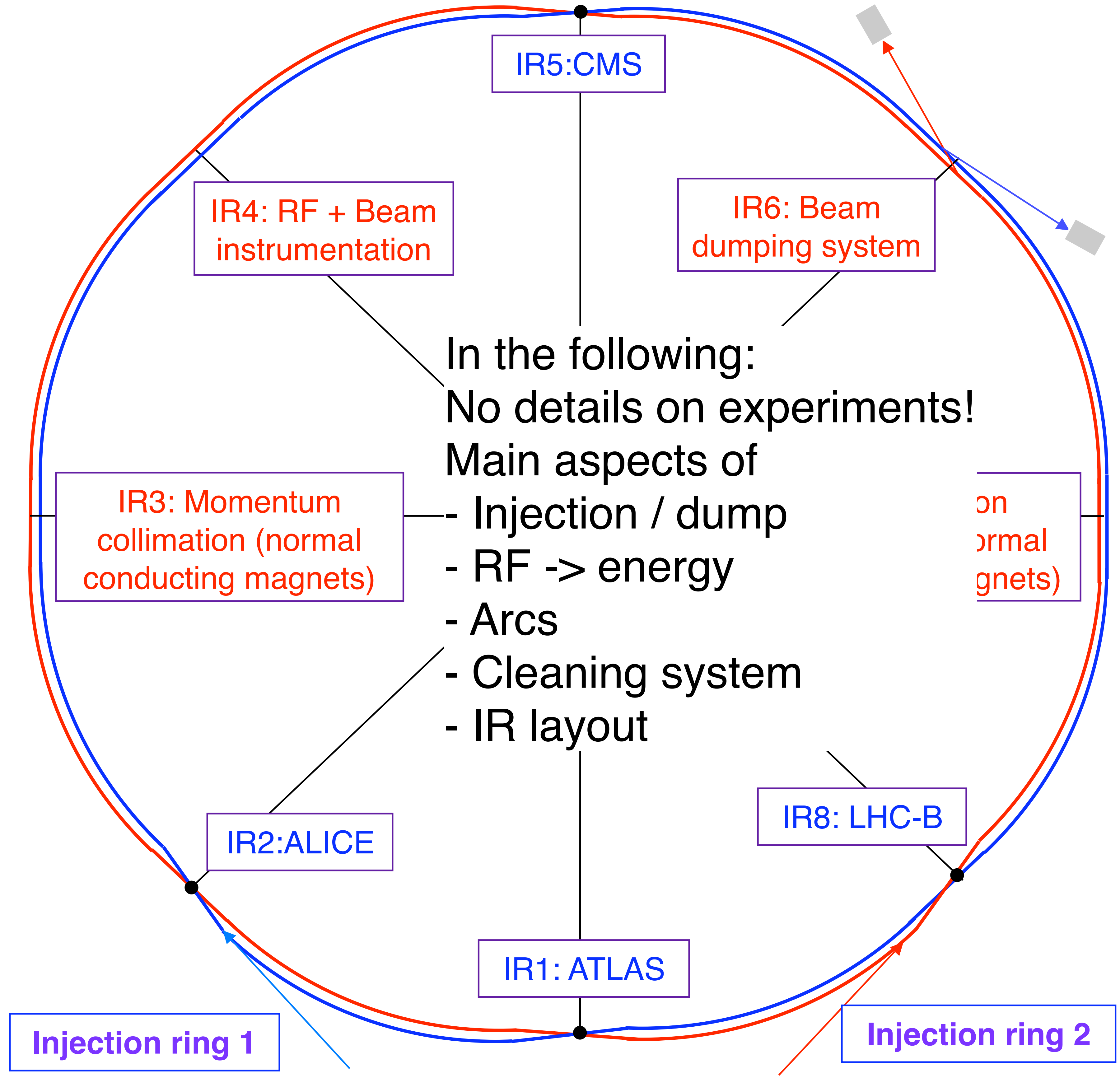
Circumference = 26.7 km
Depth = 70-140 m
Slope = 1.4 %



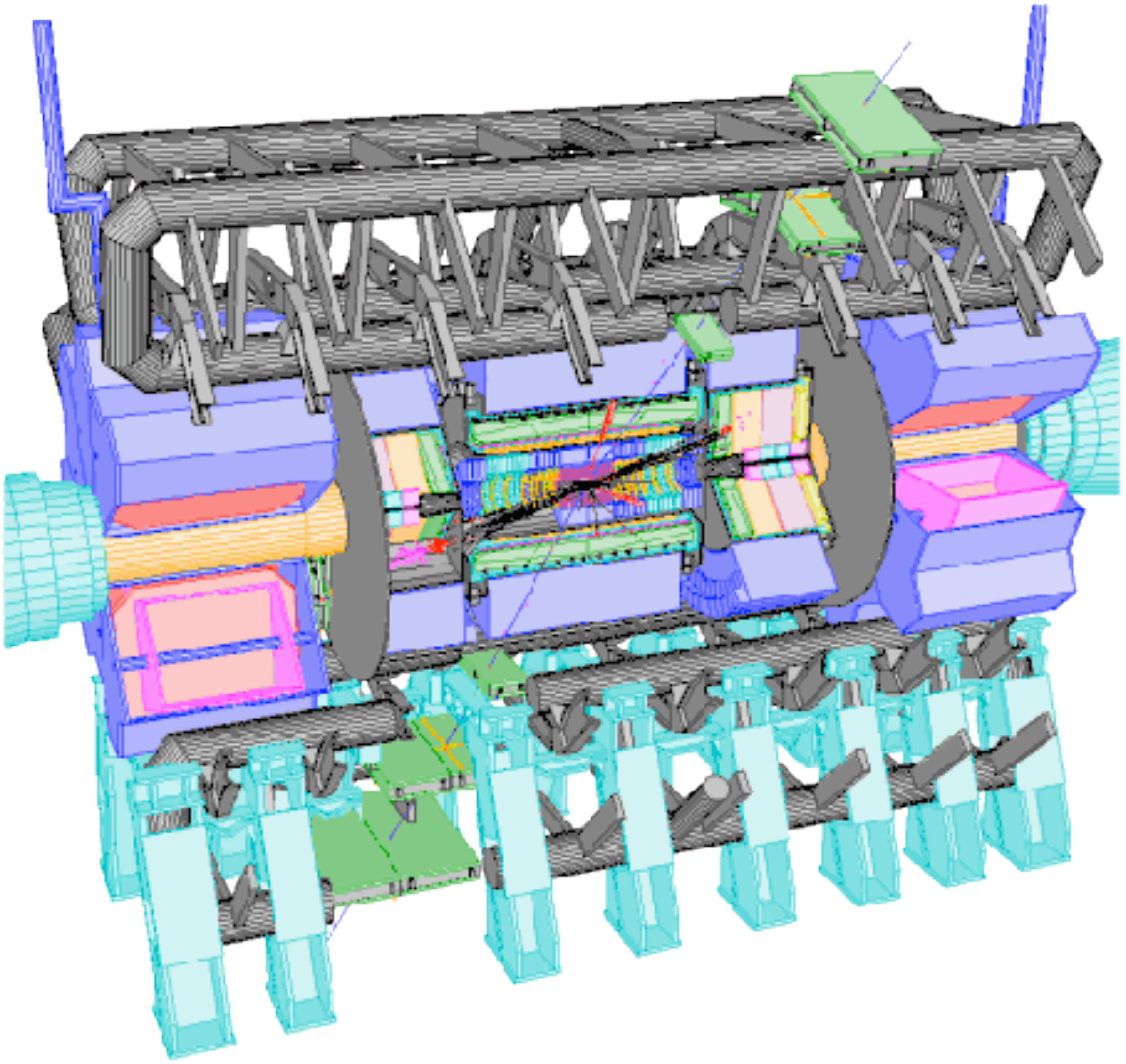
Layout and accelerator systems

LHC Layout

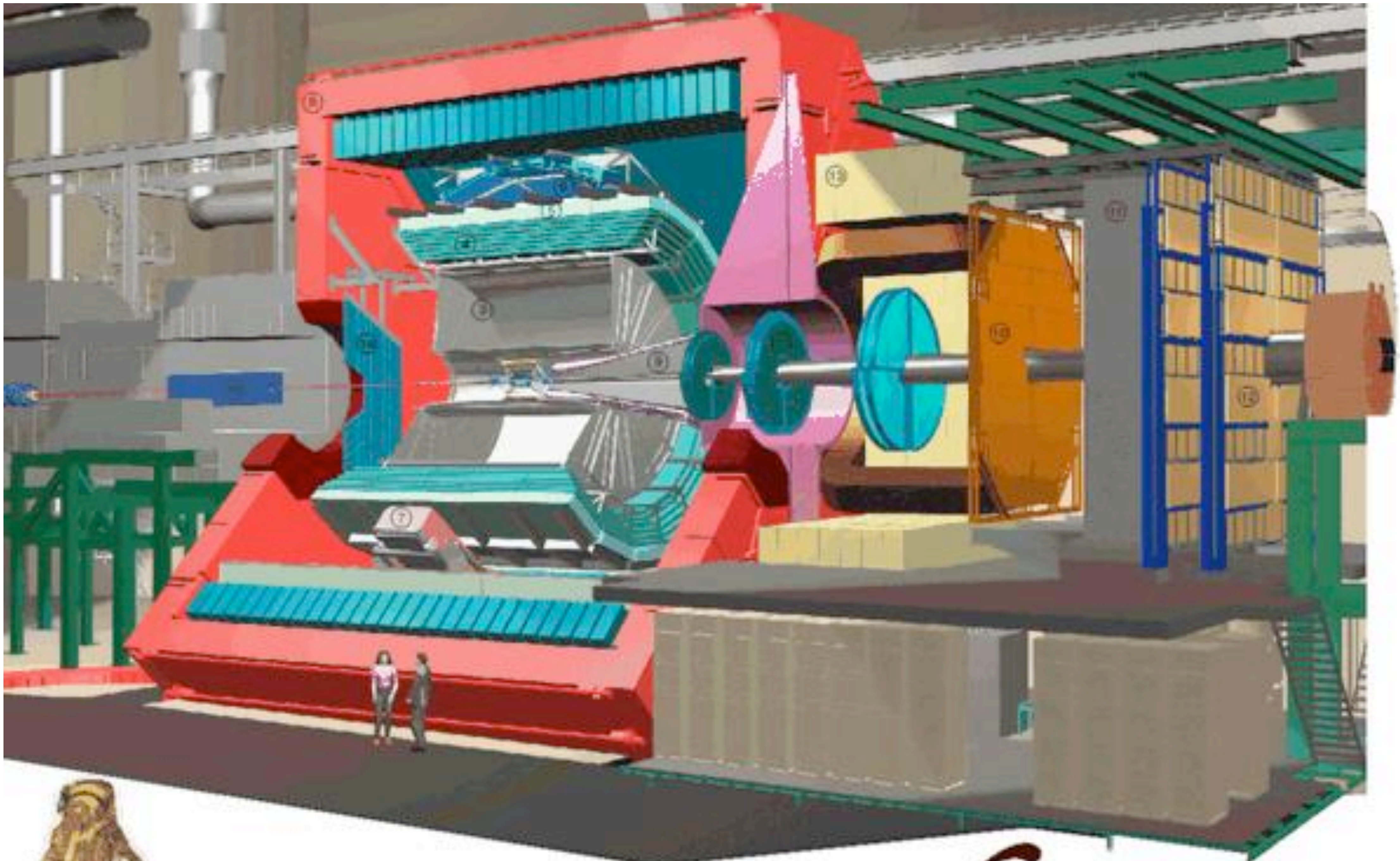
- 8 arcs (~3 km)
- 8 straight sections (~700 m).
- Two-in-one magnet design
- The beams cross in 4 points:
  - IP1: ATLAS, LHCf
  - IP2: ALICE
  - IP5: CMS, TOTEM
  - IP8: LHCb
- IP2/IP8: beam injection
- IP6: beam dump region
- IP4: RF (acceleration)
- IP3/IP7: beam cleaning



Interaction point 1: ATLAS



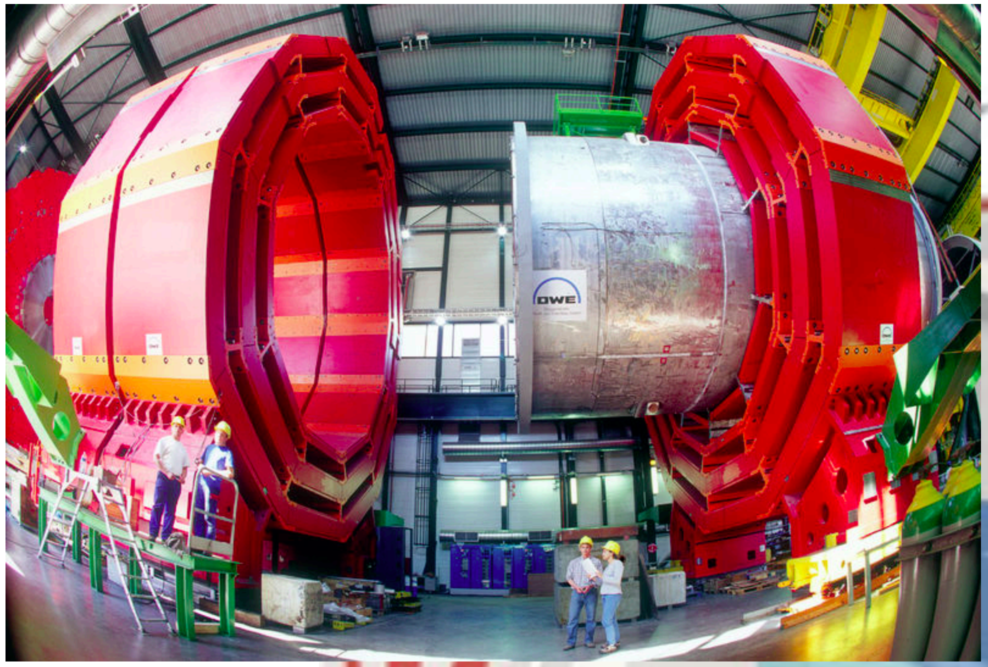
Interaction point 2: ALICE

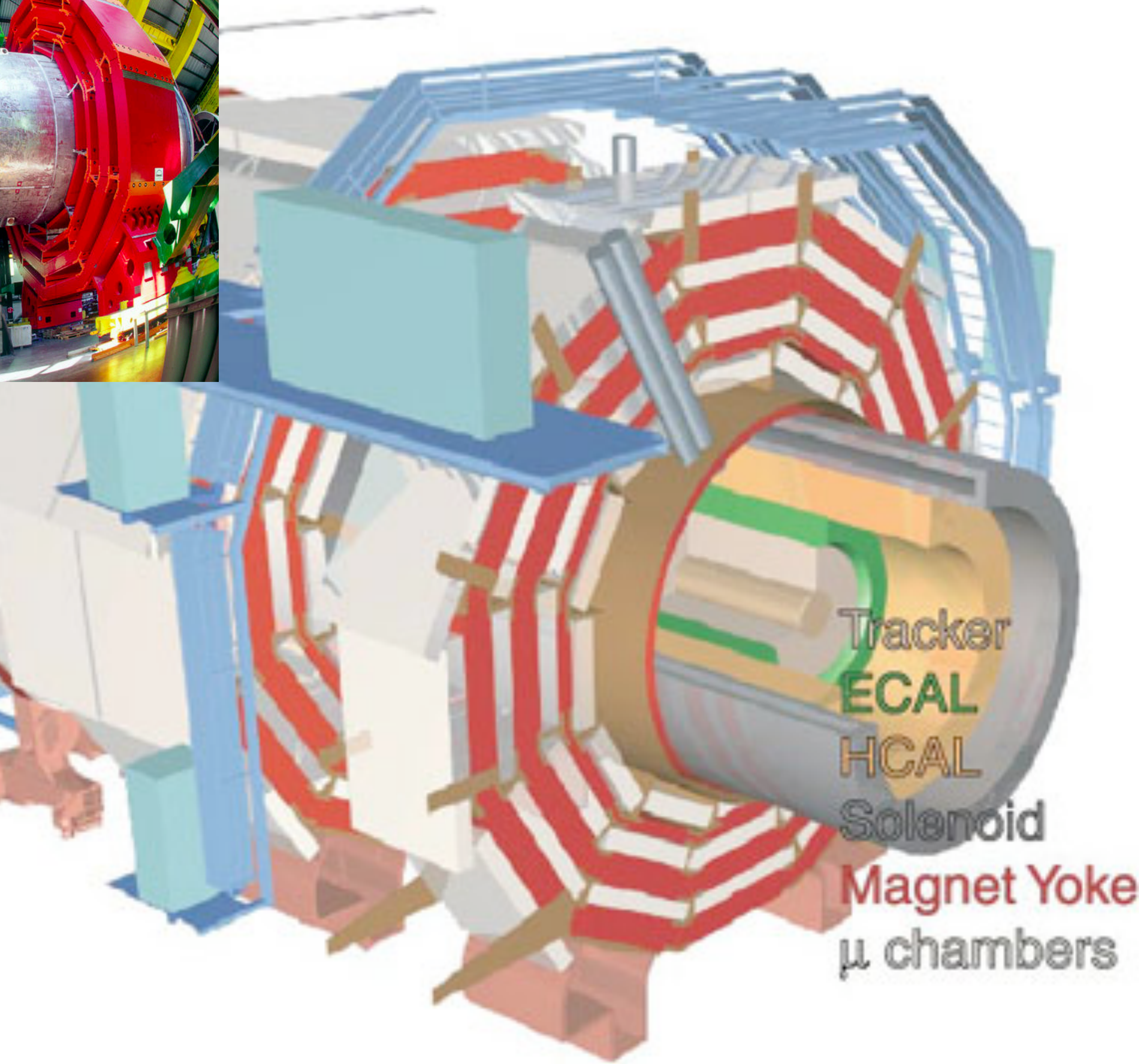


Heavy Ion Physics

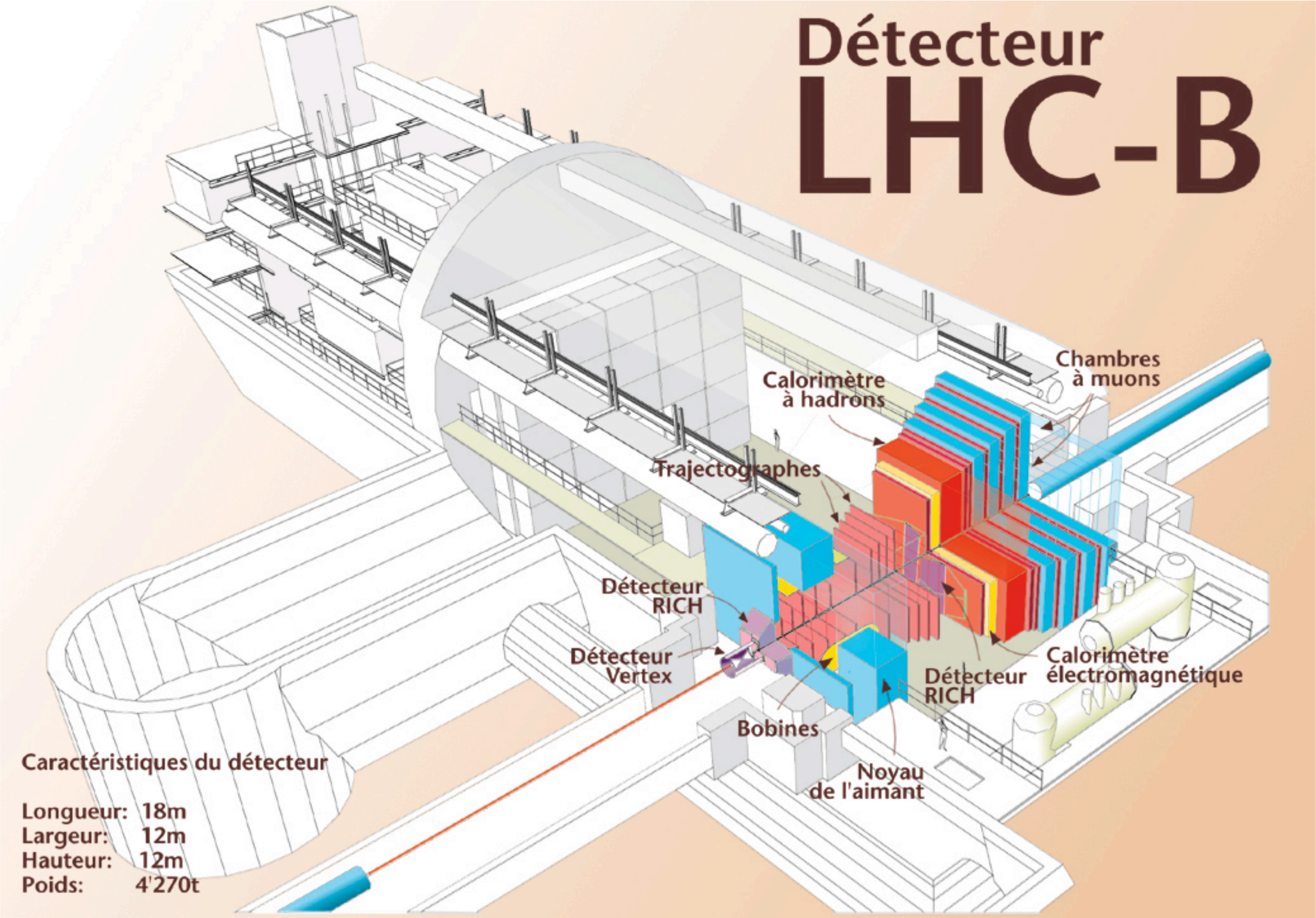
Alice

Interaction point 5: CMS

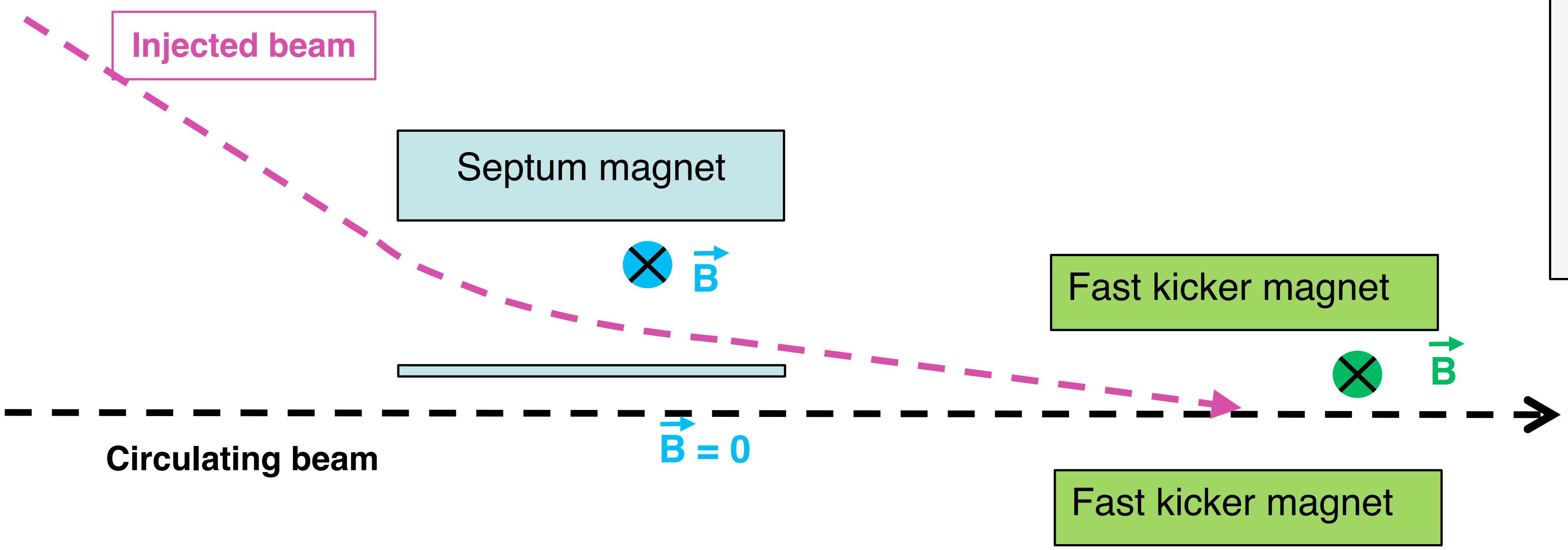


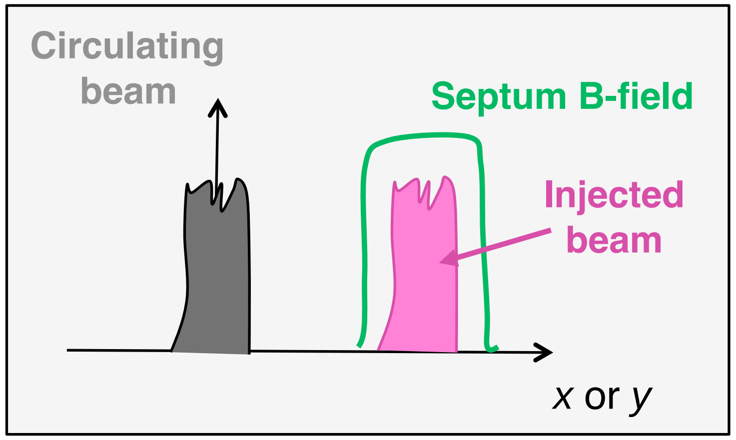


Interaction point 8: LHCb



How do we inject?



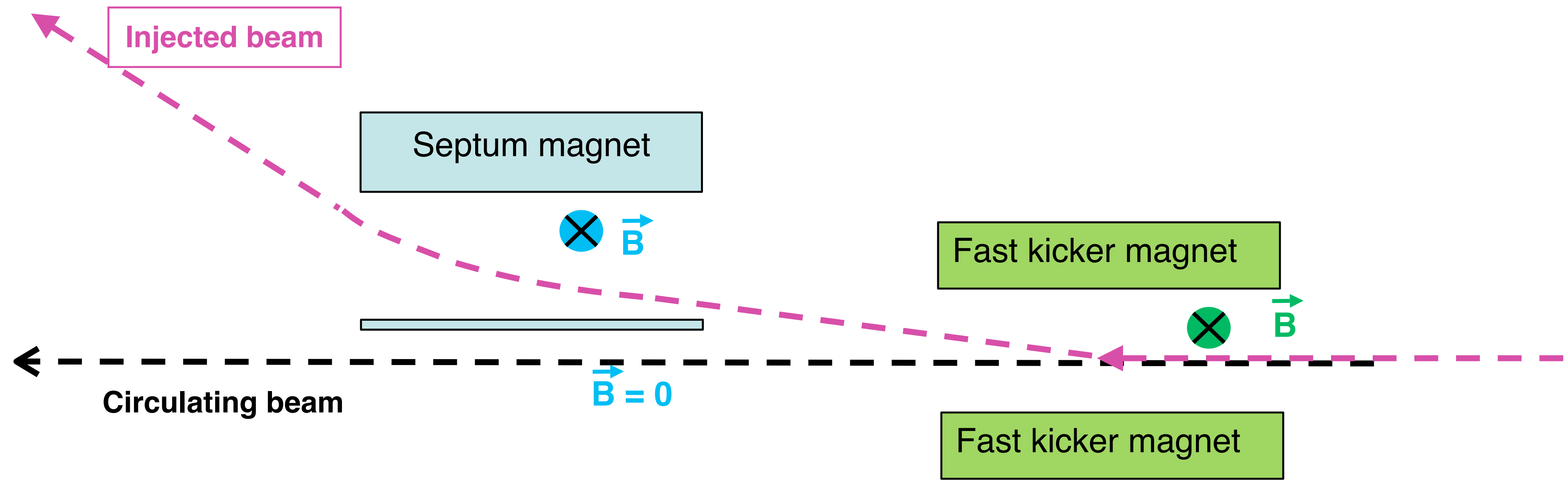


1. A septum dipole magnet (with thin coil) is used to bring the injected beam close to the circulating beam.

2. A fast pulsing dipole magnet ('kicker') is fired synchronously with the arrival of the injected beam: deflects the injected beam onto the circulating beam path.

3. 'Stack' the injected beams one behind the other.

How do we ~~inject~~? extract



2\. ~~1.~~ A septum dipole magnet (with thin coil) is used to bring the *extracted* beam ***far*** to the circulating beam.

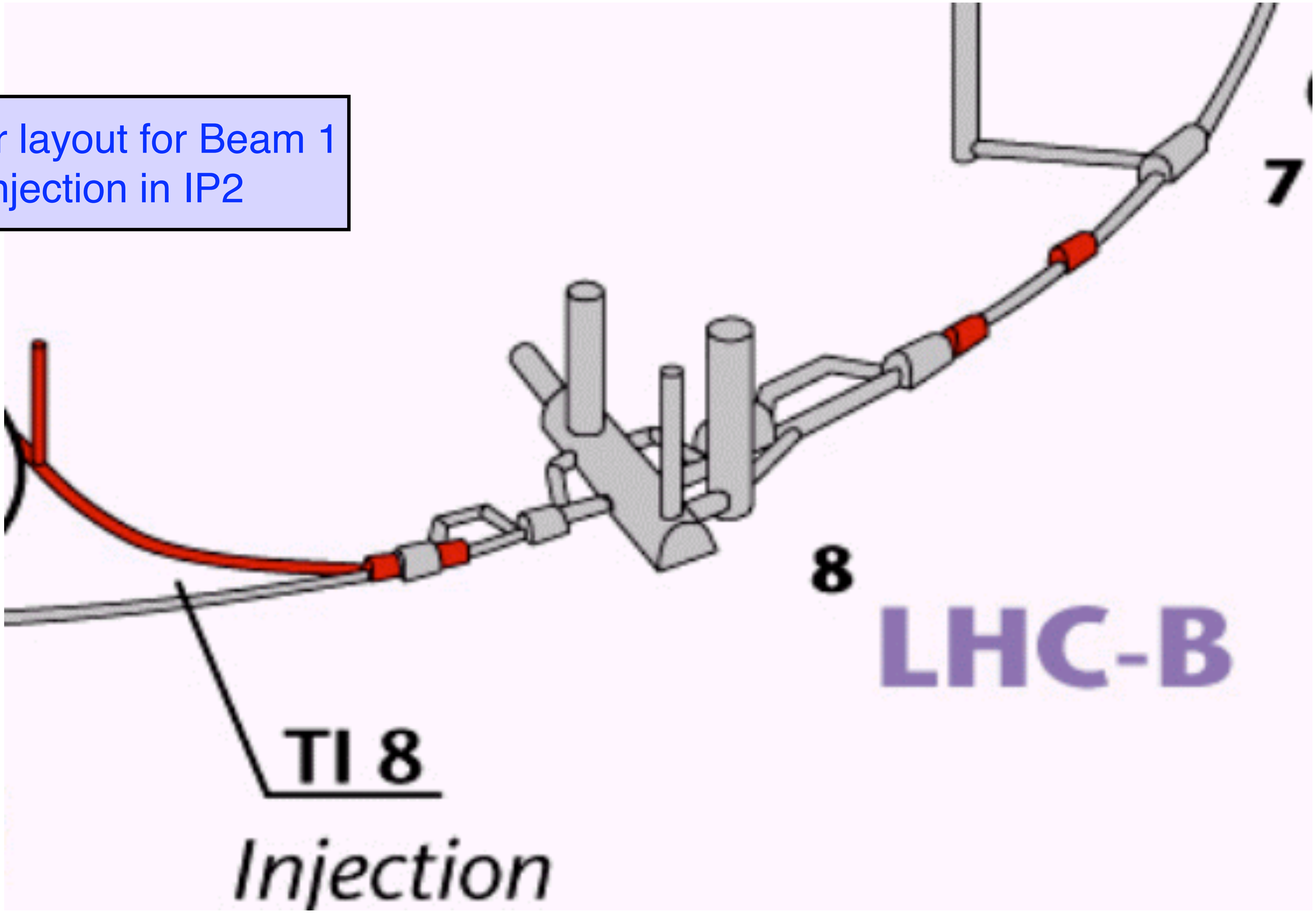
1\. ~~2.~~ A fast pulsing dipole magnet ('kicker') is fired synchronously with the arrival of the ***abort gap***: deflects the ***beam to be dumped onto the dump line***

3\. All the following bunches are extracted.

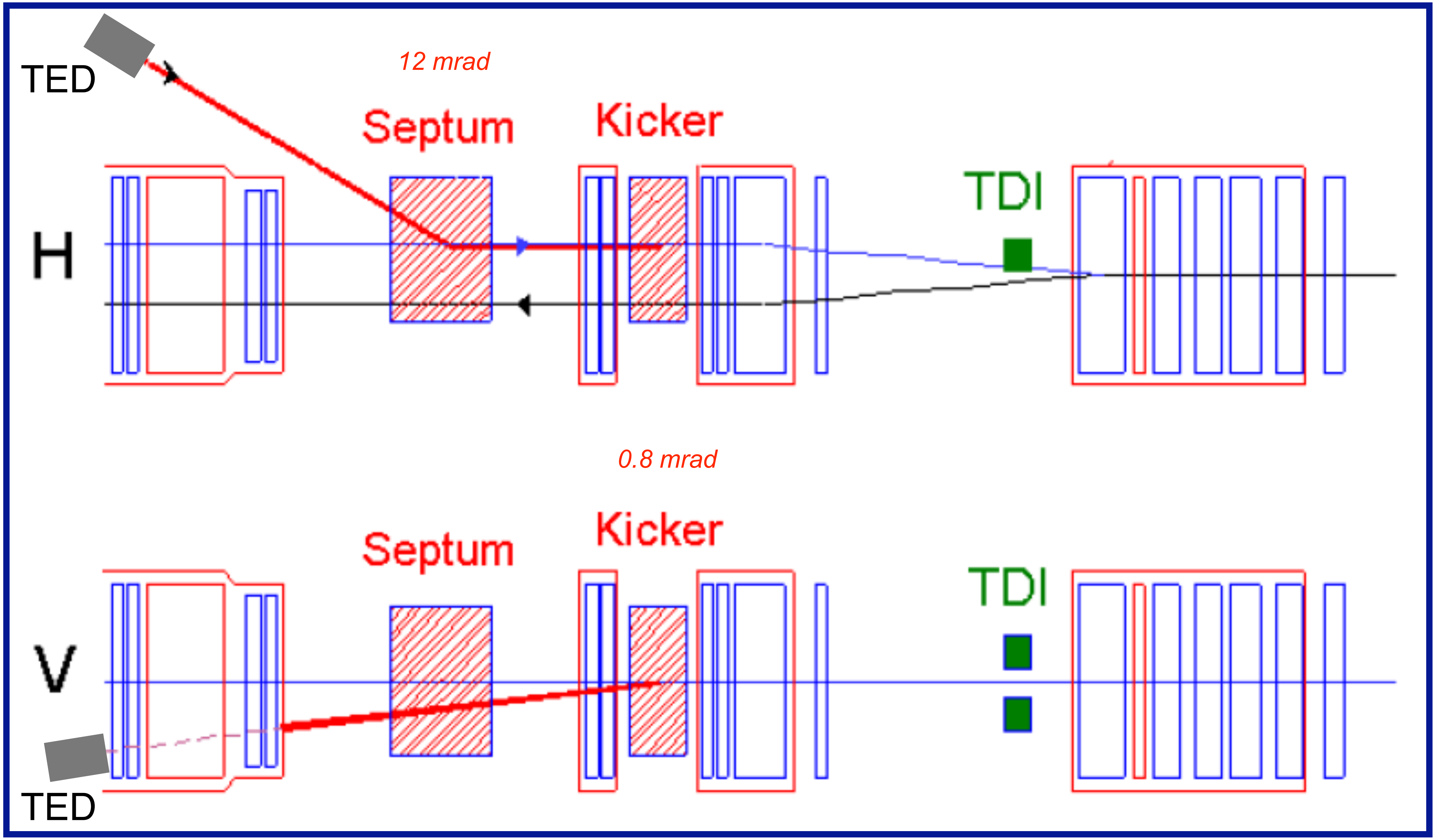
Injection into the LHC - layout

Similar layout for Beam 1 injection in IP2

SPS + TI8



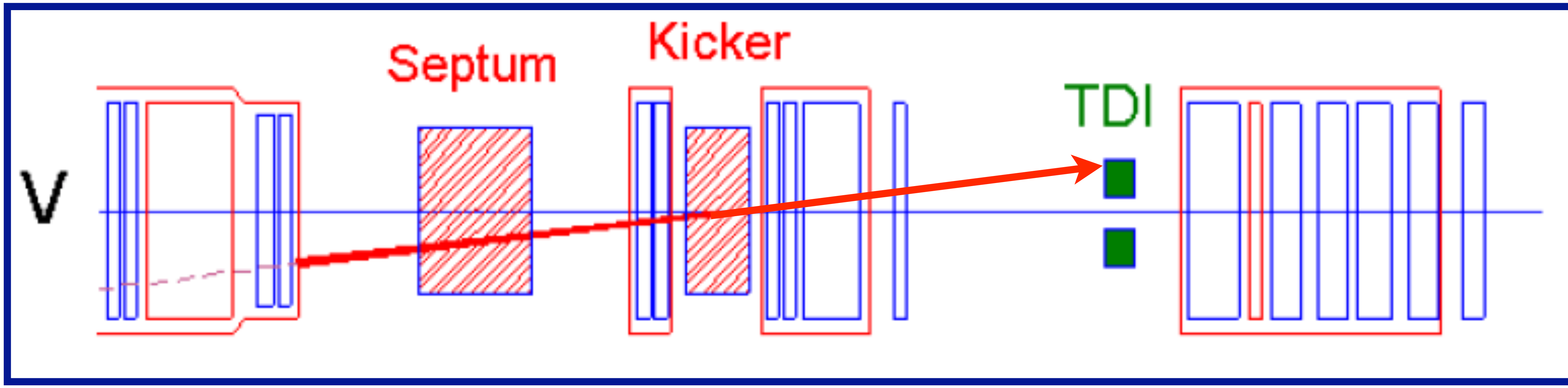
Injection elements

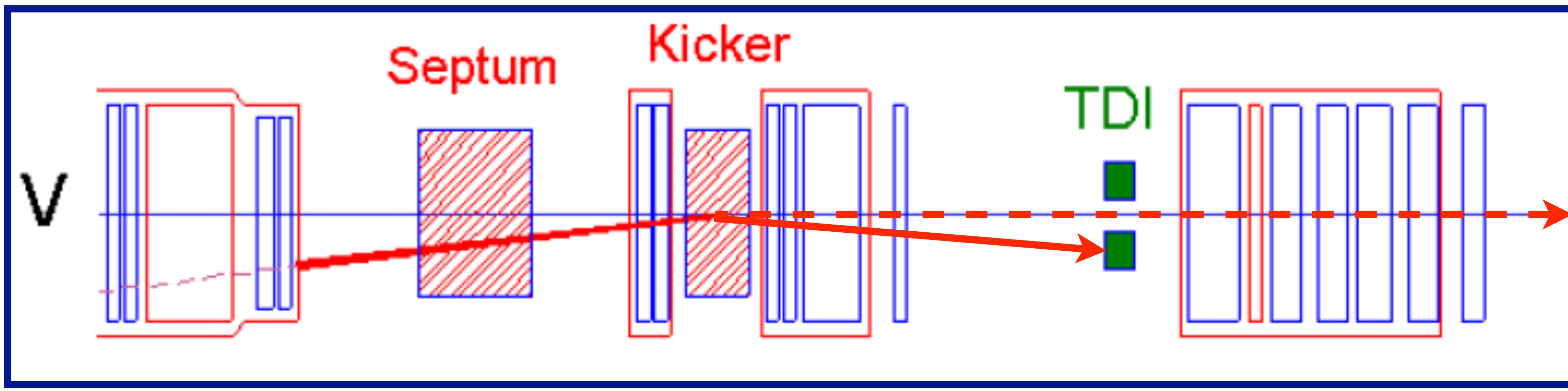


From the LHC Page1

TED TI2 position:	BEAM	TDI P2 gaps/mm	up: 9.05	down: 9.04
TED TI8 position:	BEAM	TDI P8 gaps/mm	up: 8.32	down: 8.36

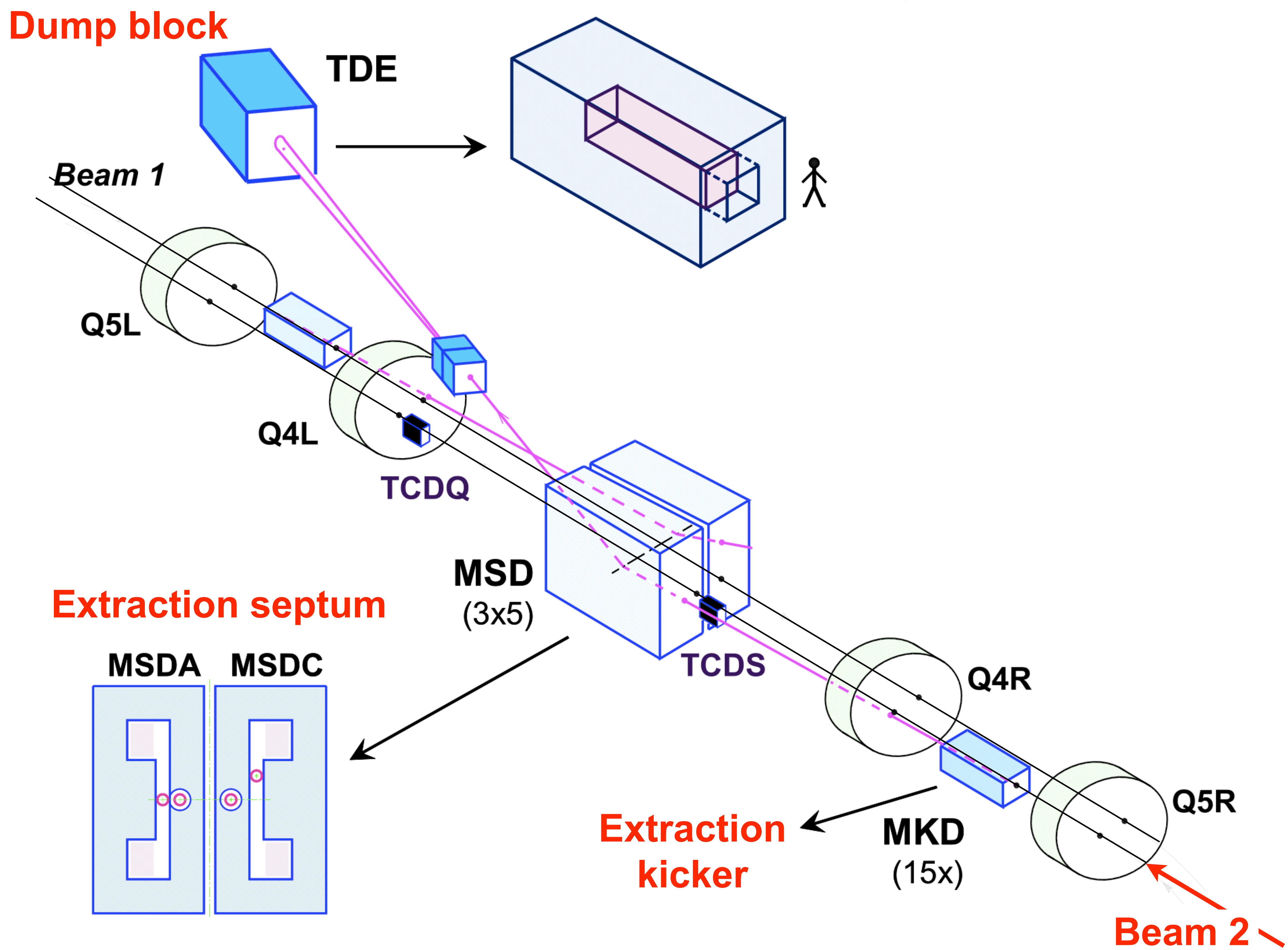
Role of the TDI collimator



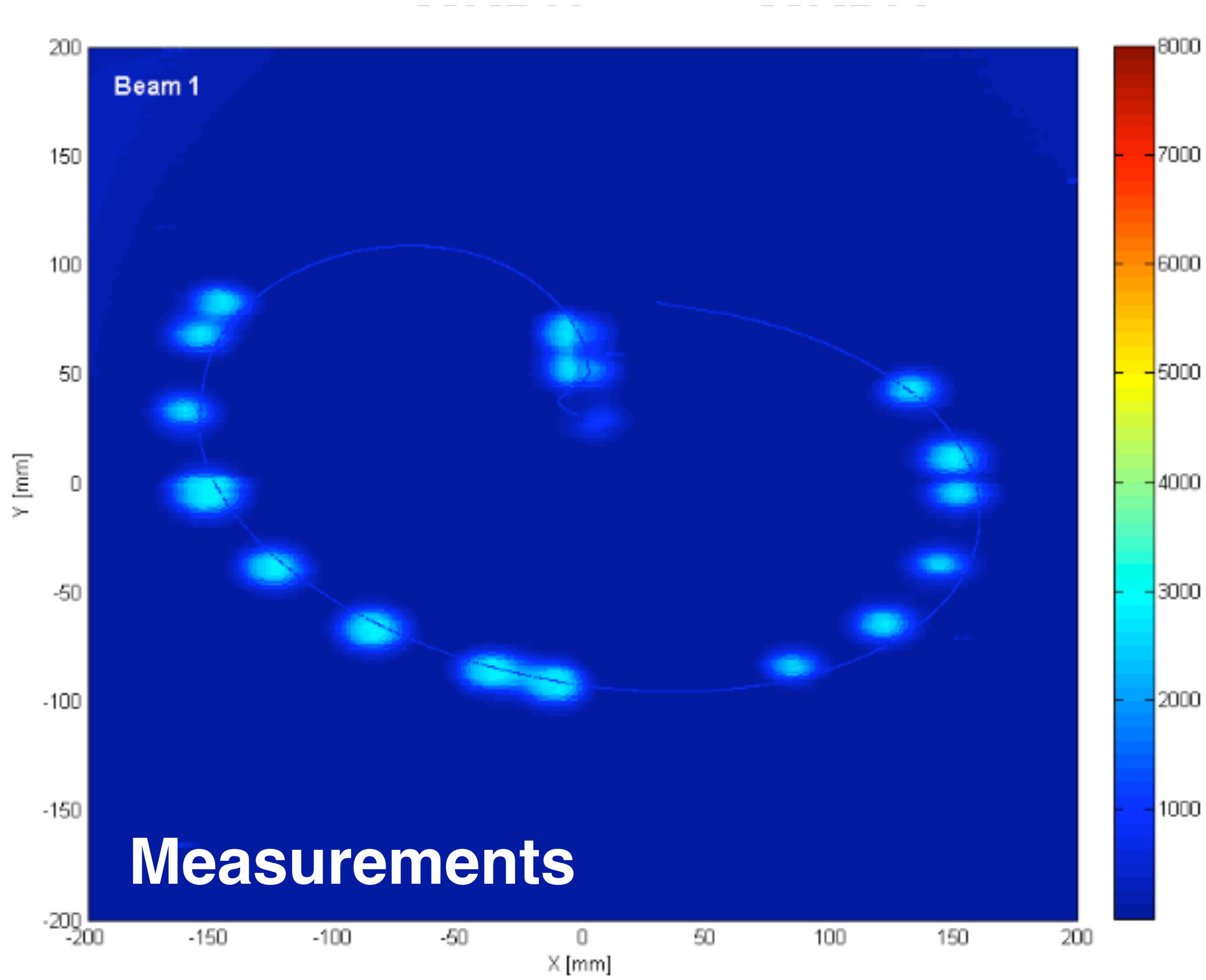


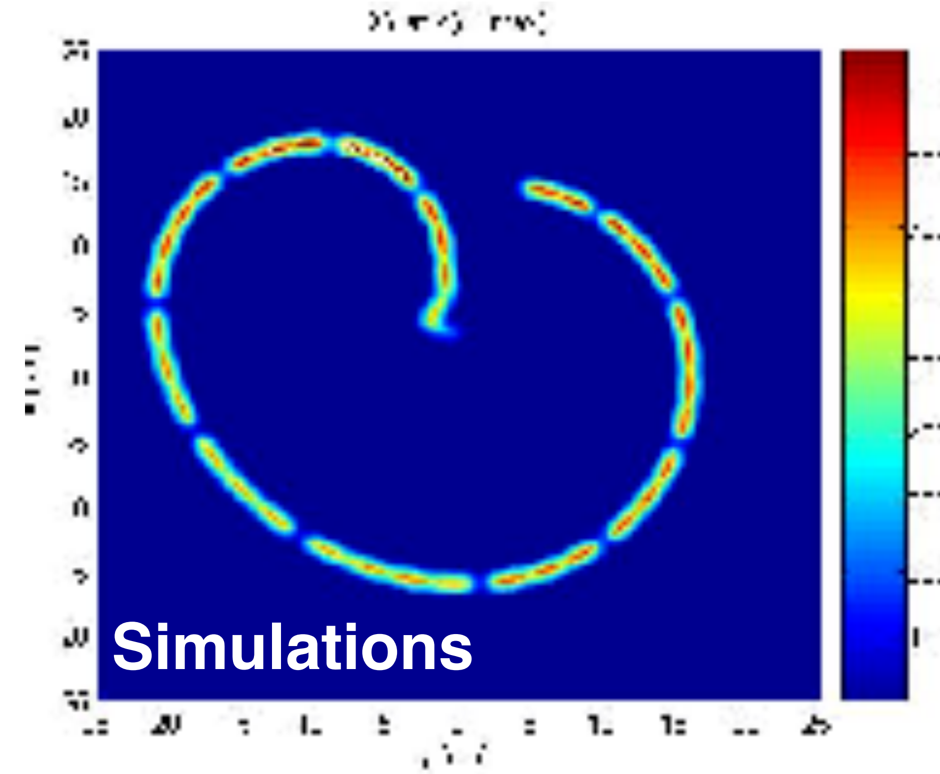
The TDI is one of the key injection protection collimators:
Protects the machine in case of (1) missing kicks on injected beam and (2) asynchronous kicker firing on the circulating beam.
It must be closed around the circulating beam trajectory when the kicker is ON.

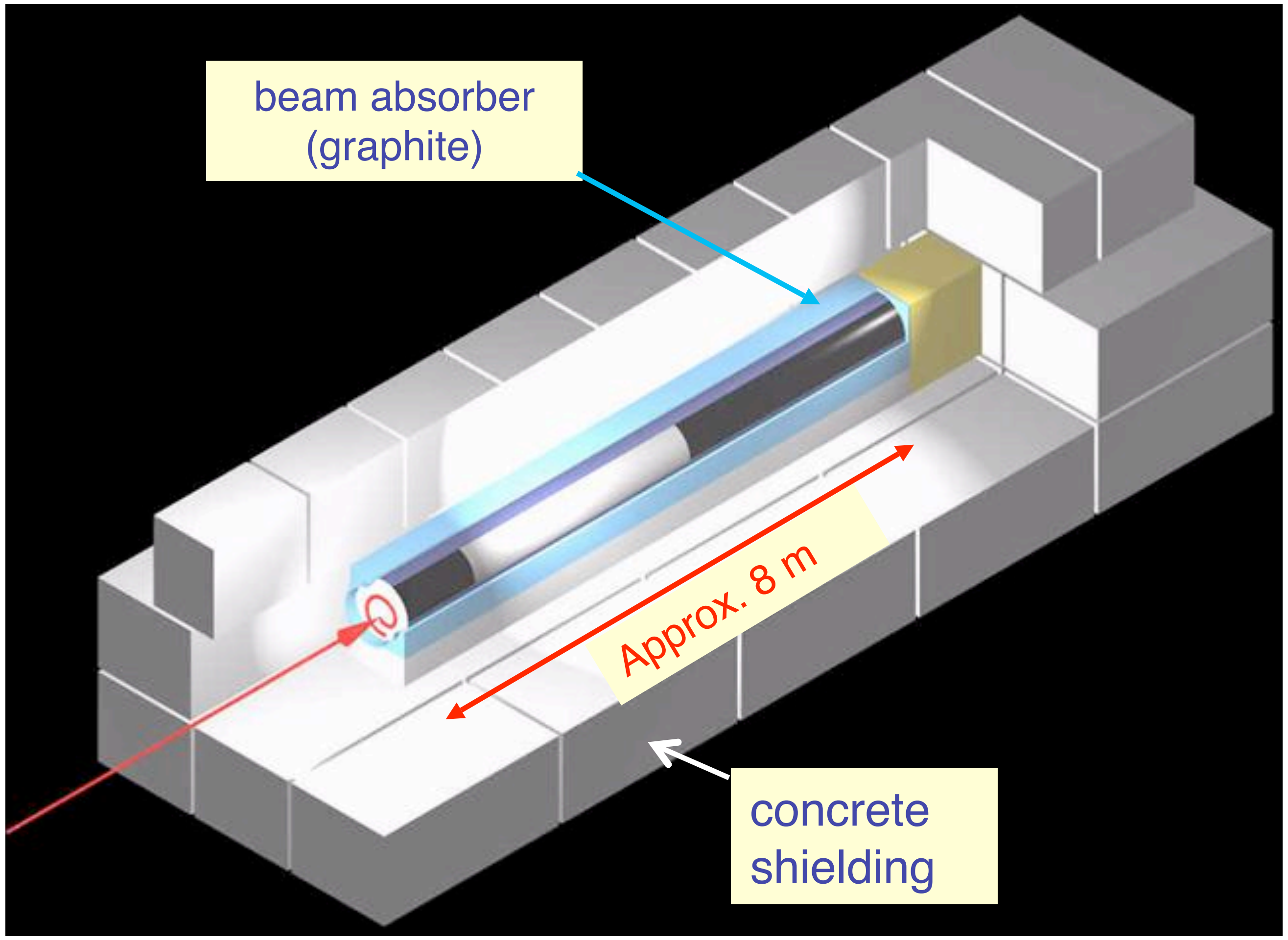
Beam dump (IP6)



Dilution of dumped beams







This is the **ONLY** element in the LHC that can withstand the impact of the full 7 TeV beam !

Nevertheless, the dumped beam must be painted to keep the peak energy densities at a tolerable level !

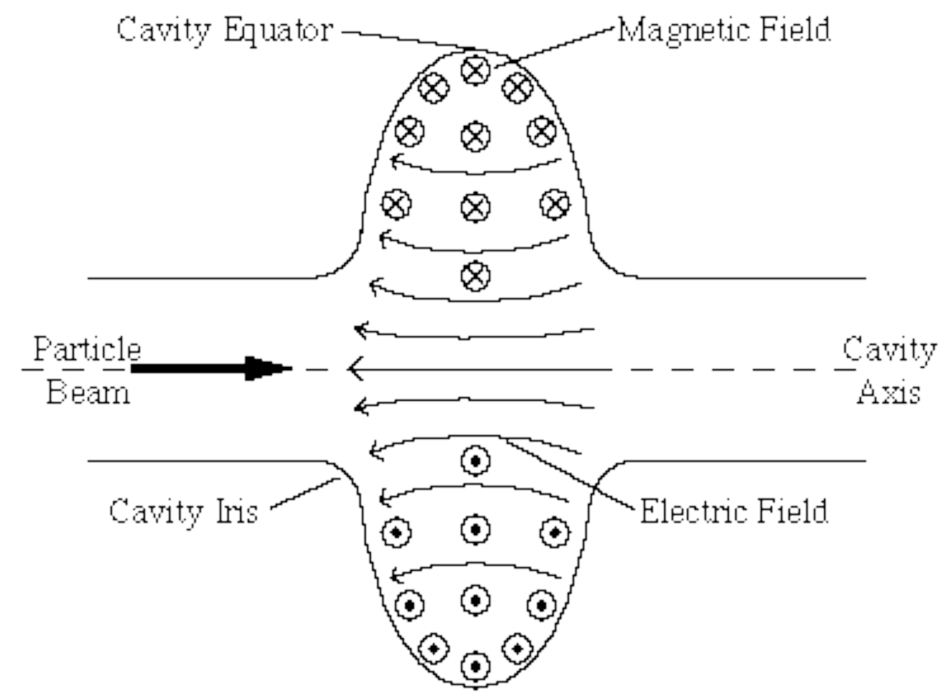
Radio frequency (IP4)

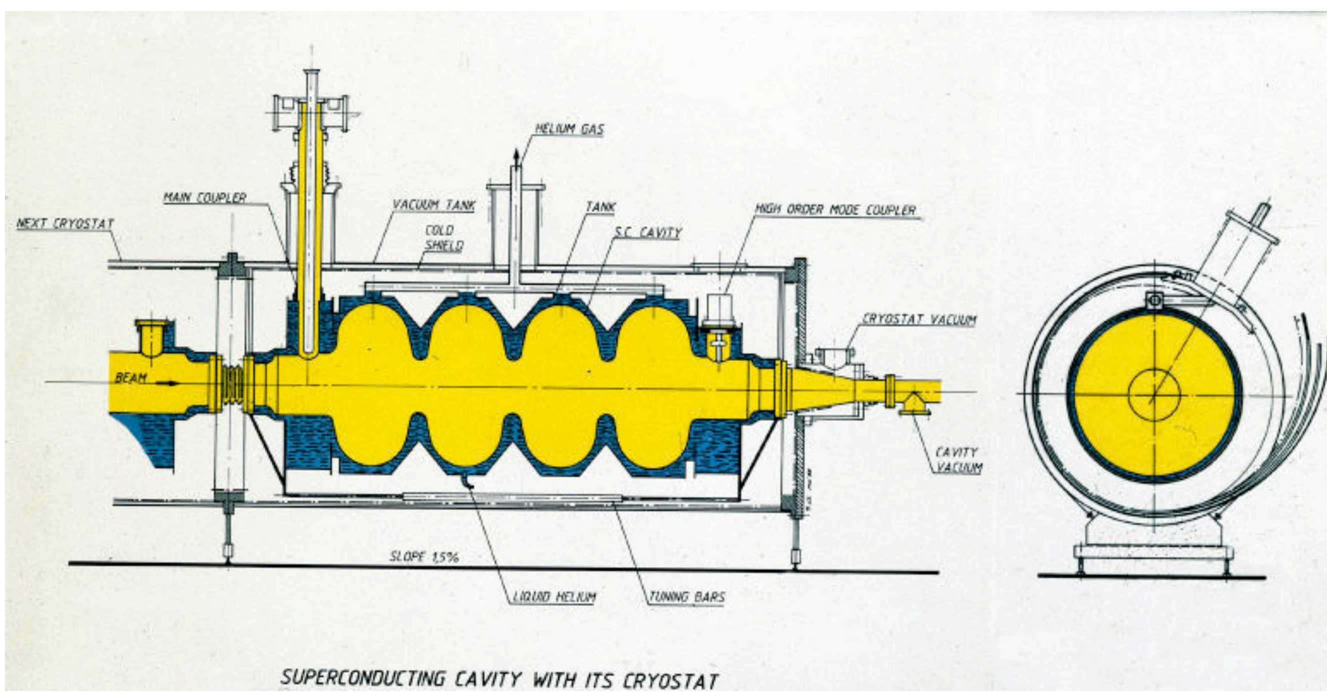
8 RF superconducting cavities per ring at 400.790 MHz: 2 modules per beam, 4 cavities per module

16 MV/beam at 7 TeV

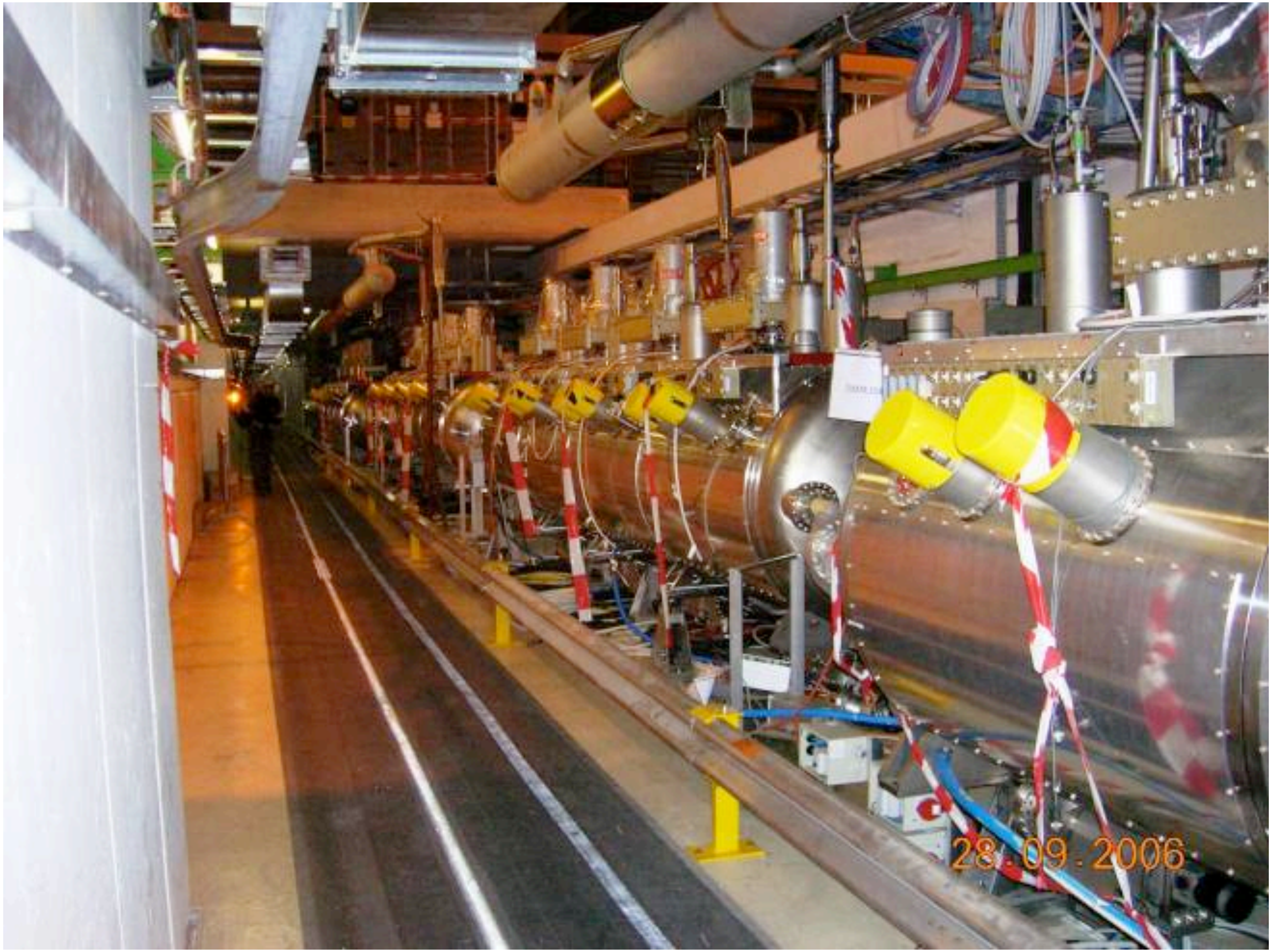
1 MV /cavity at injection

2 MV/cavity during physics

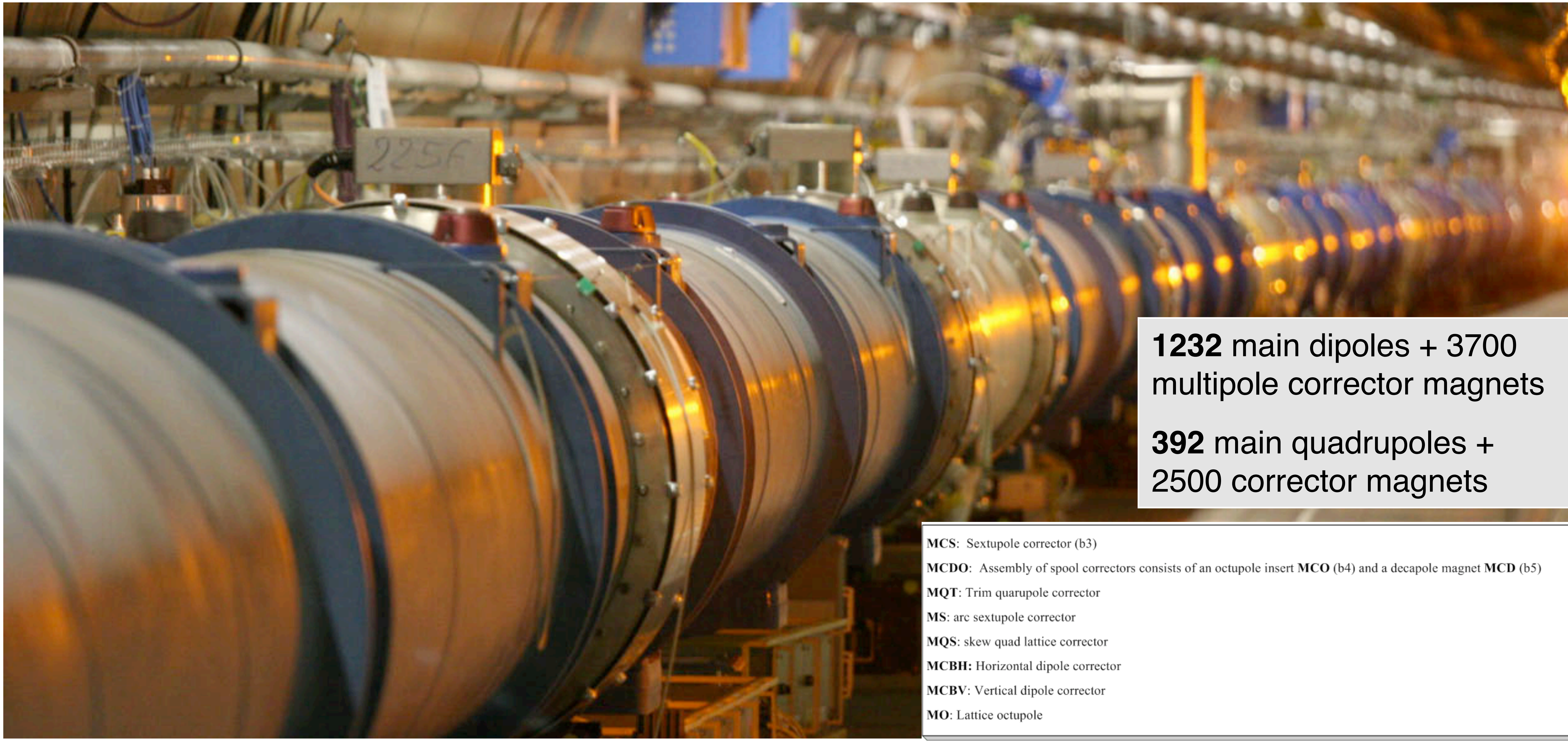




RF - tunnel view



The LHC arcs



1232 main dipoles + 3700 multipole corrector magnets

392 main quadrupoles + 2500 corrector magnets

MCS: Sextupole corrector (b3)

MCDO: Assembly of spool correctors consists of an octupole insert **MCO** (b4) and a decapole magnet **MCD** (b5)

MQT: Trim quarupole corrector

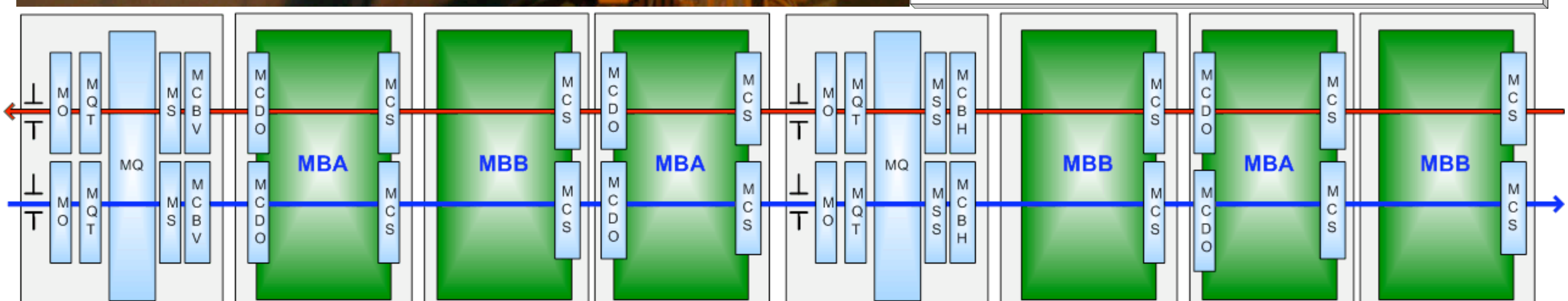
MS: arc sextupole corrector

MQS: skew quad lattice corrector

MCBH: Horizontal dipole corrector

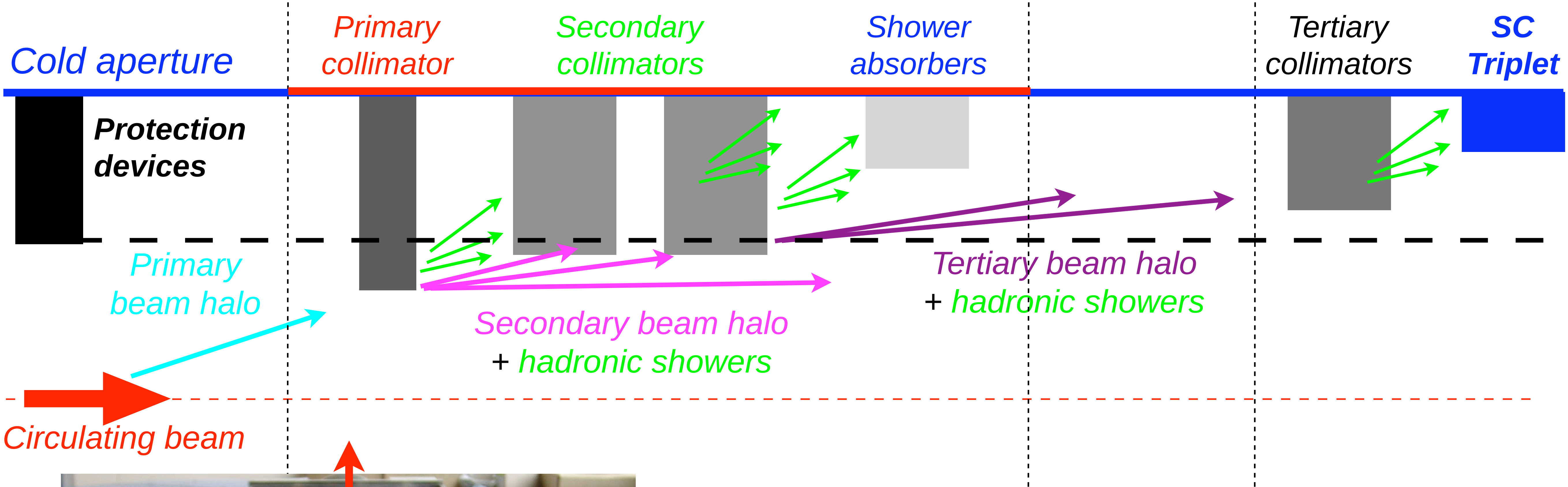
MCBV: Vertical dipole corrector

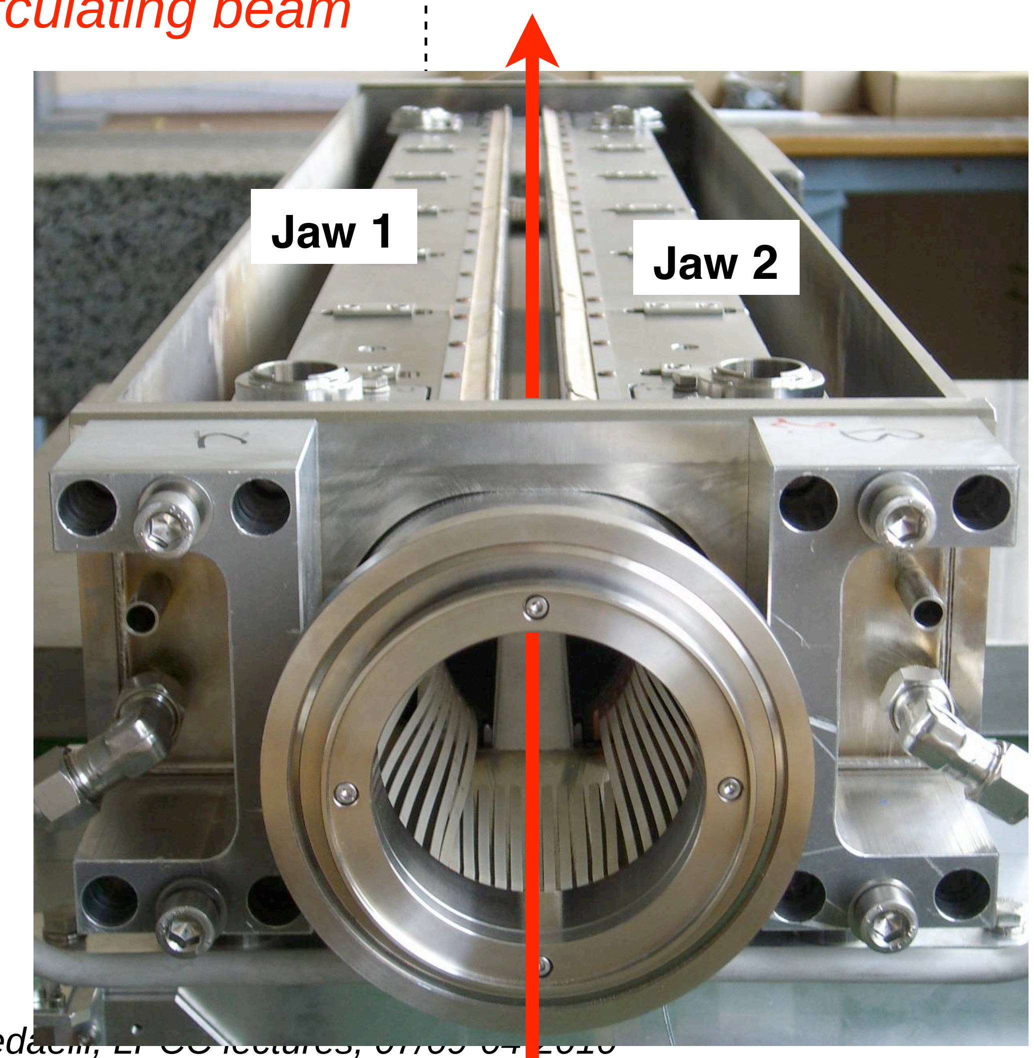
MO: Lattice octupole

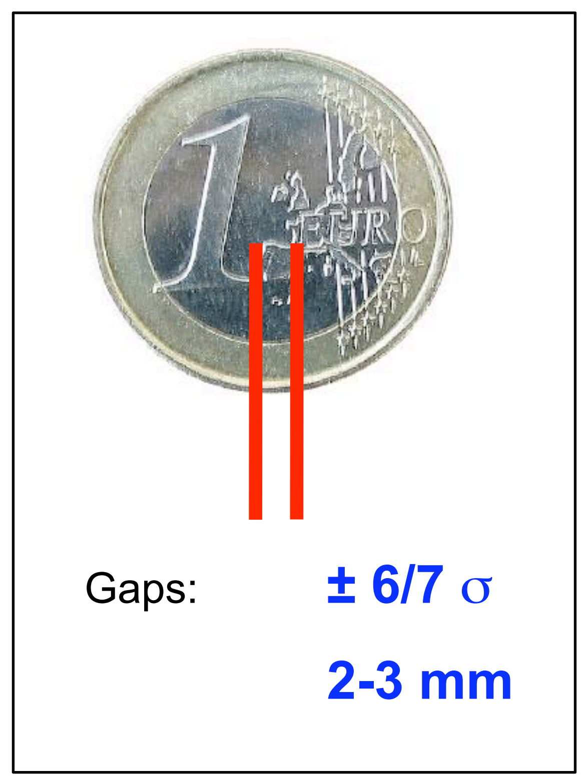


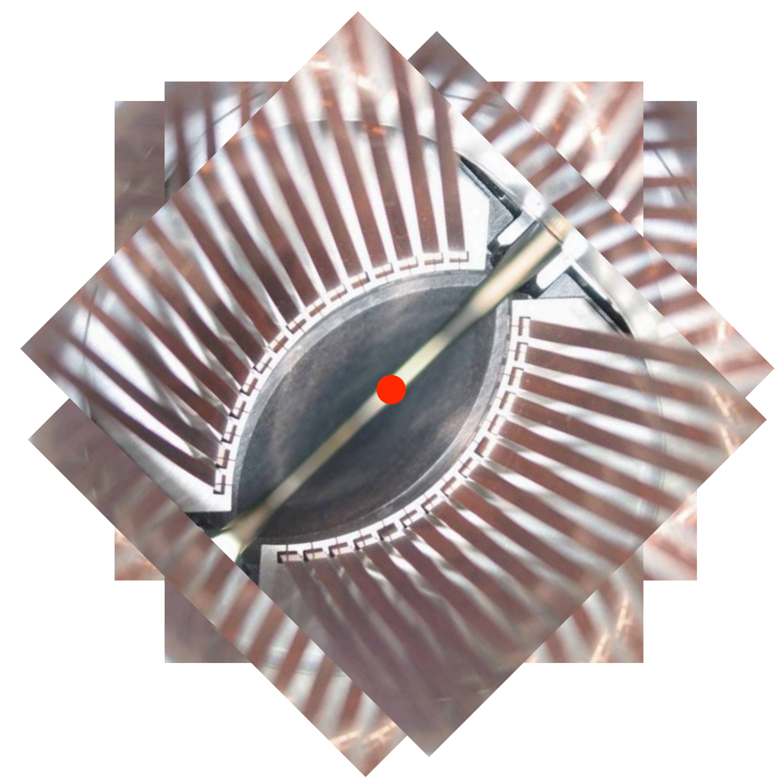
Collimation: multi-stage cleaning

(illustrative scheme)









Layout of the collimation system

Two warm cleaning insertions

- **IR3: Momentum cleaning**
  - **1 primary (H)**
  - **4 secondary (H,S)**
  - **4 shower abs. (H,V)**
- **IR7: Betatron cleaning**
  - **3 primary (H,V,S)**
  - **11 secondary (H,V,S)**
  - **5 shower abs. (H,V)**

Local cleaning at triplets

- **8 tertiary (2 per IP)**

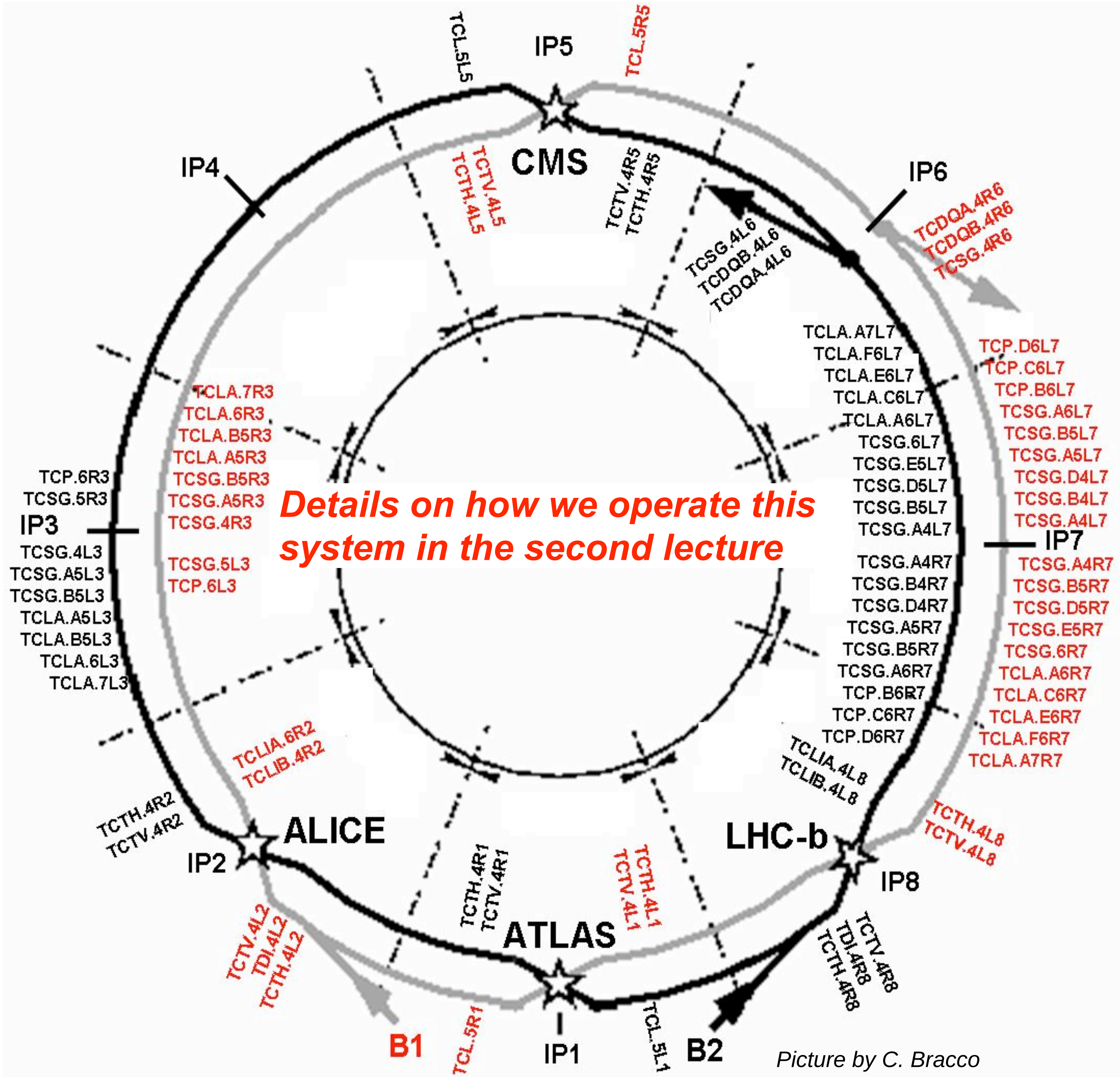
Passive absorbers for warm magnets

Physics debris absorbers

Transfer lines (13 collimators)
Injection and dump protection (10)

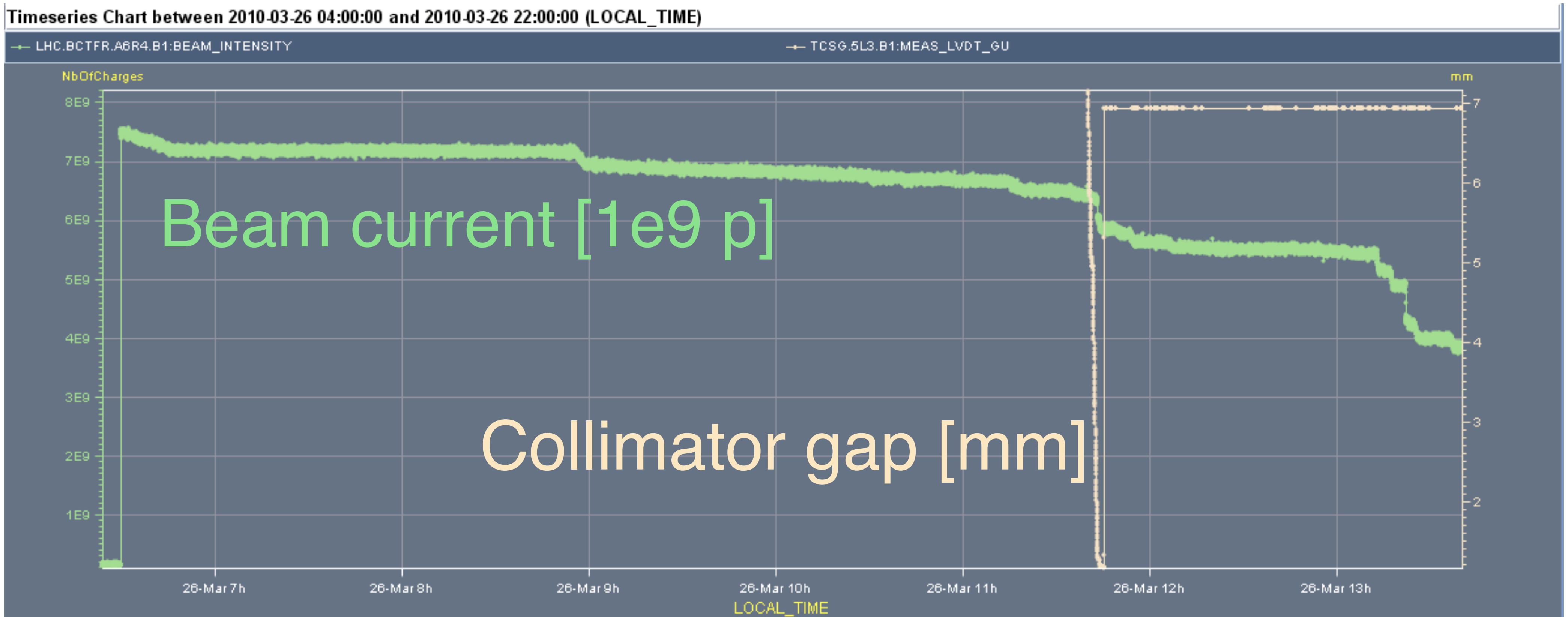
108 collimators and absorbers

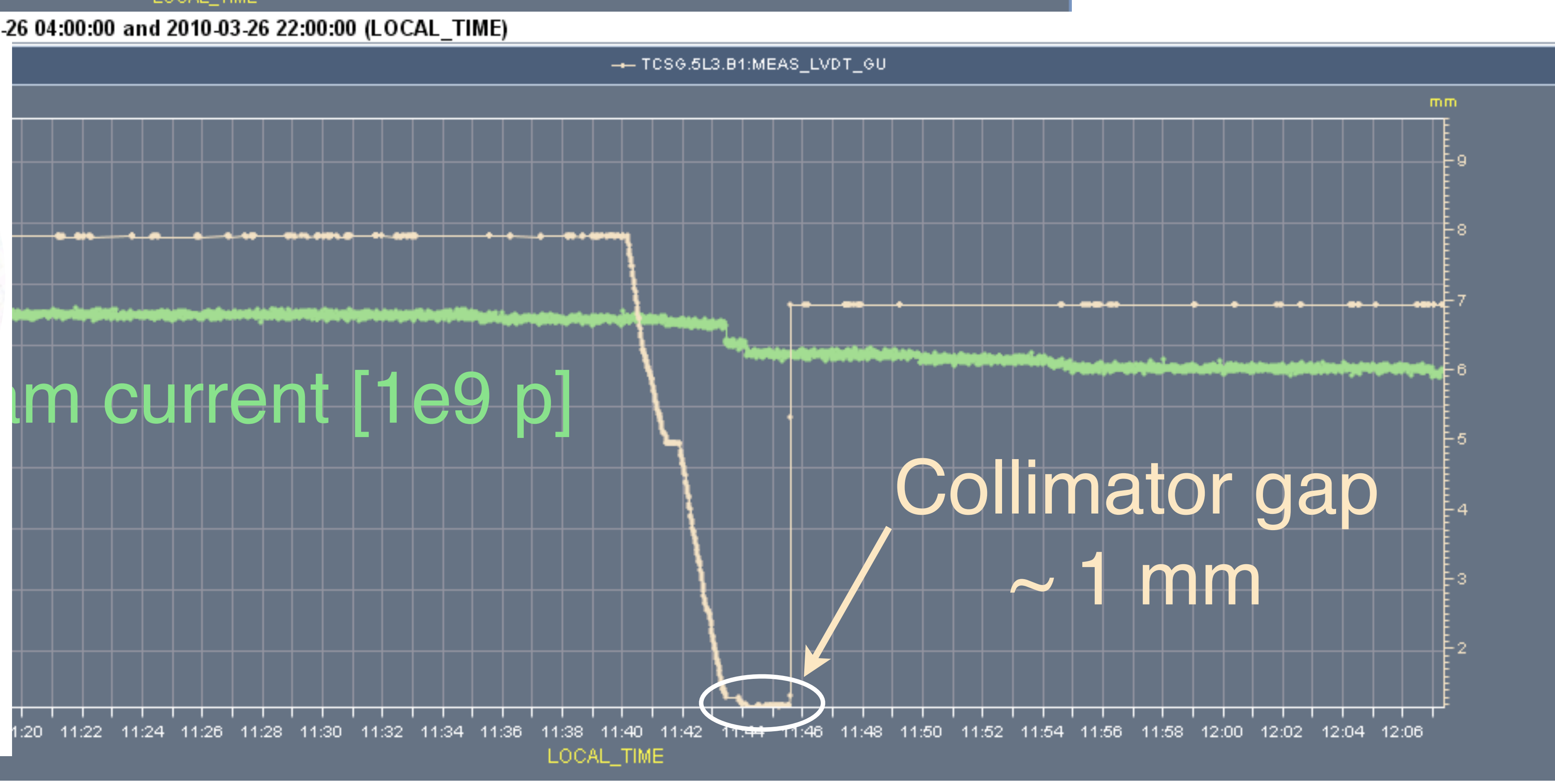
About 500 degrees of freedom. Most advance system for accelerators!



Picture by C. Bracco

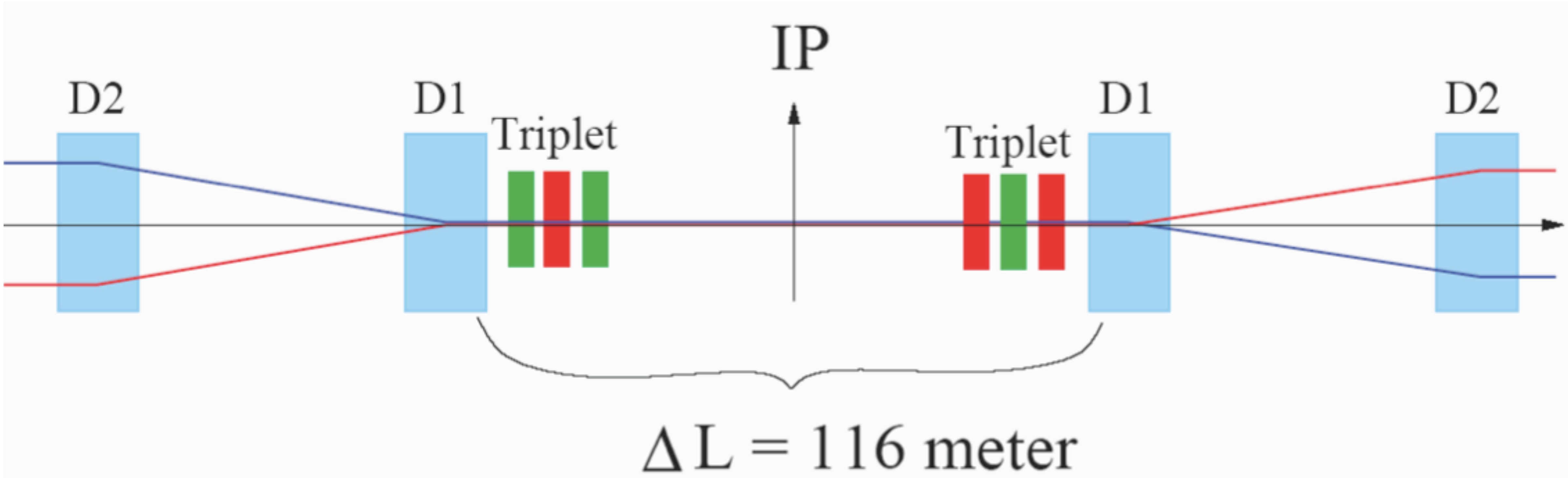
Min collimator gap with beam

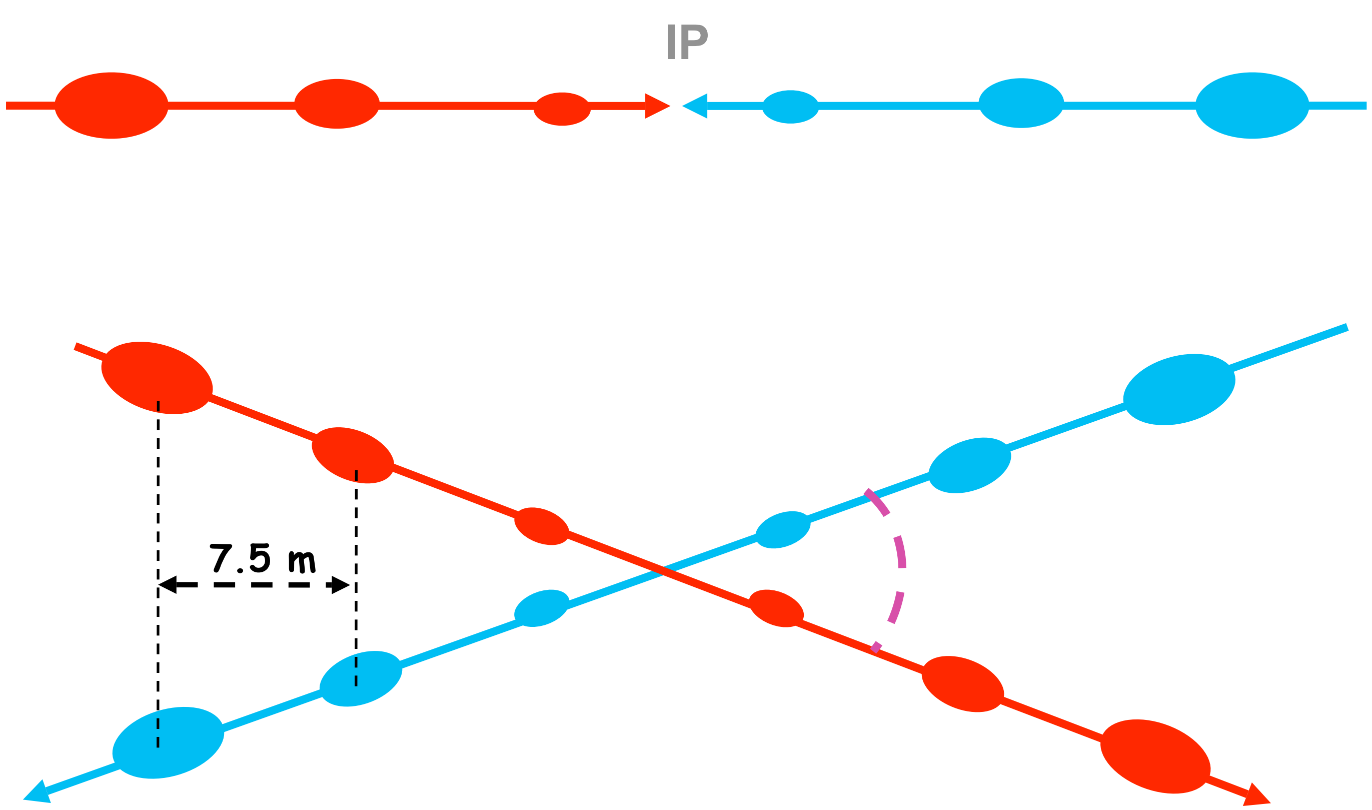




3.5 TeV beam circulating in a gap as wide as the Italy on the 1 euro coin!!

Interaction region layout



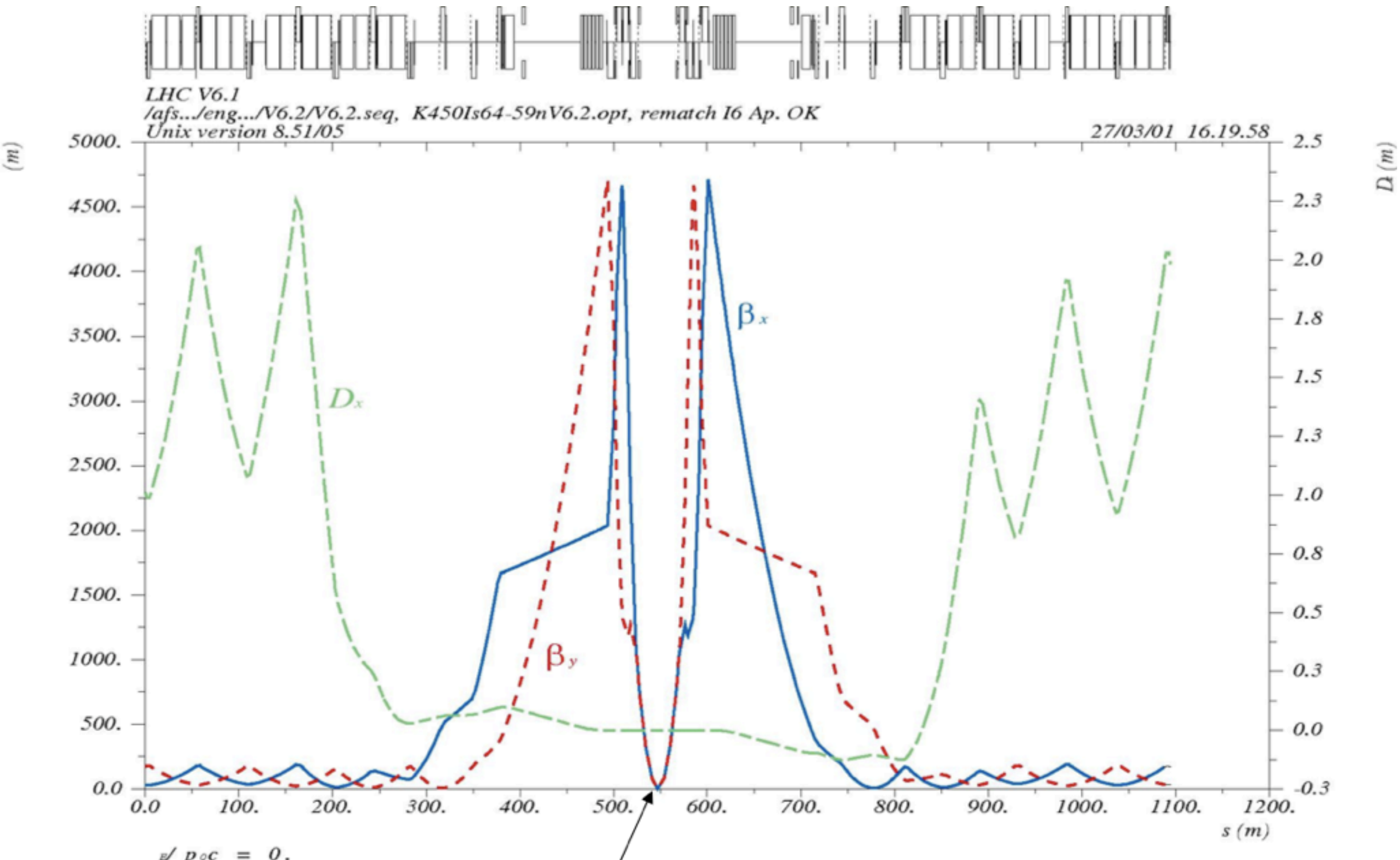


- With more than 154 bunches, we need a crossing angle to avoid parasitic collisions outside the IP.
- Beams are separated in the other plane during injection and ramp

$$\mathcal{L} = \frac{N^2 n_b f_{\text{rev}}}{4\pi\sigma_x\sigma_y} F$$

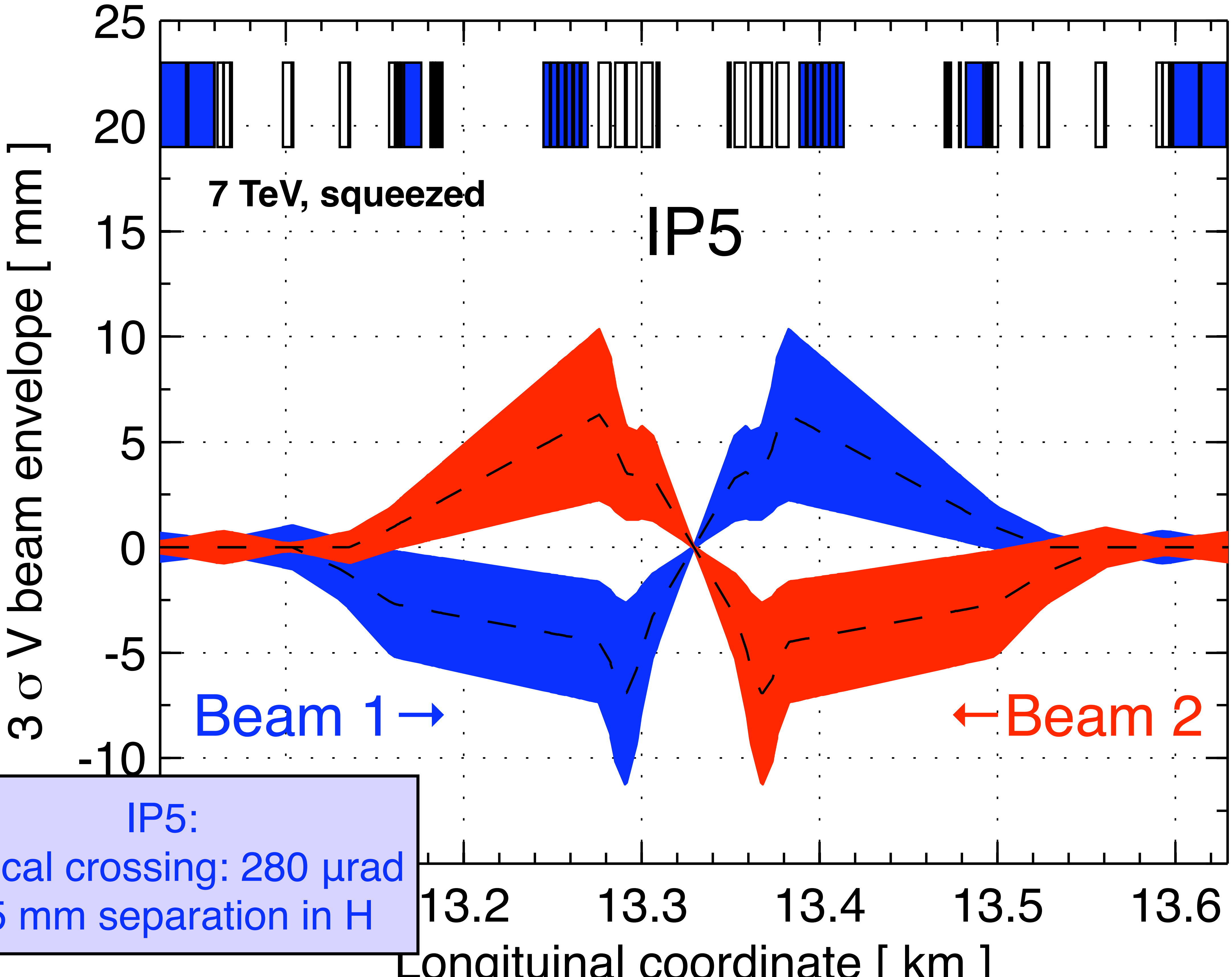
$$F = 1/\sqrt{1+\left(\frac{\theta_c\sigma_z}{2\sigma^*}\right)^2}$$

Beta functions for IP1 and IP5



β = 55 cm → σ = 16 μm; D = 0m

Beam envelope



IP5:
Vertical crossing: 280 μrad
0.5 mm separation in H

Machine protection

Why do we have to care??

Energy stored in the superconducting magnet **10.4 GJ**

Energy stored in the 7 TeV beams **362 MJ**

We've seen what 2 MJ can do to a magnet!

Why do we need so much?

Magnet energy is driven by the high field requirement.
Beam stored energy is driven by luminosity increase!

$$L = \frac{1}{4\pi \cdot m_0 c^2} \cdot \frac{f_{rev} \cdot N_p \cdot F}{\beta^* \cdot \varepsilon_n} \cdot E_{stored}$$

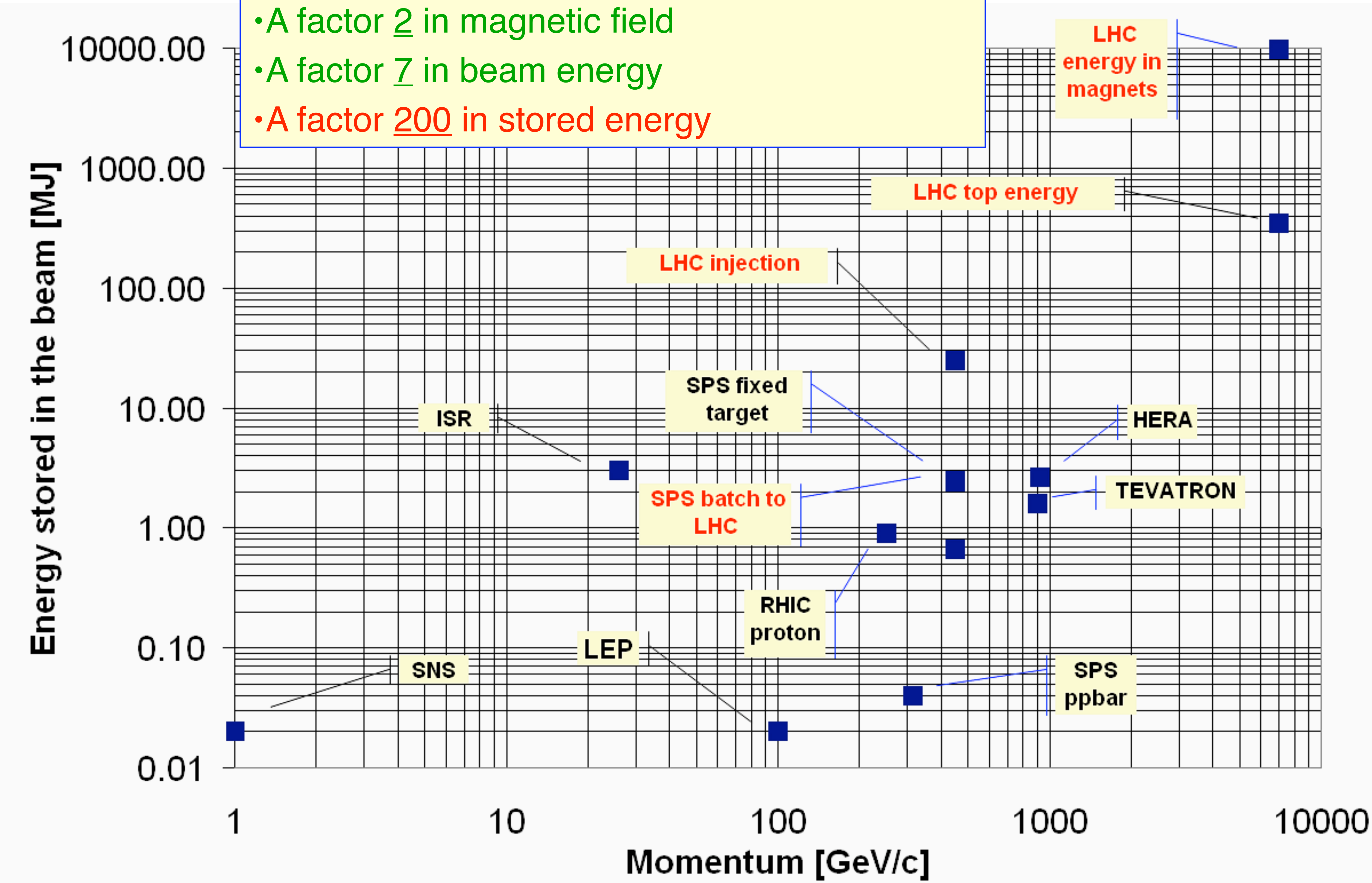
- **constant**: $\frac{1}{4\pi \cdot m_0 c^2}$
- **tunnel length**: f_{rev}
- **beam-beam limits**: $N_p \cdot F$
- **IR optics limits**: β^*
- **Injectors limits, Robustness limits**: ε_n
- **LHC luminosity is increased via stored energy!**: E_{stored}

β^* = IP beta function (β_x=β_y)
ε_n = norm. transv. emittance
N_p = protons per bunch
f_{rev} = revolution frequency
F = geometrical correction
m_0 = rest mass, e.g. of proton
c = velocity of light

The stored energy challenge

Increase with respect to existing accelerators :

- A factor 2 in magnetic field
- A factor 7 in beam energy
- A factor 200 in stored energy



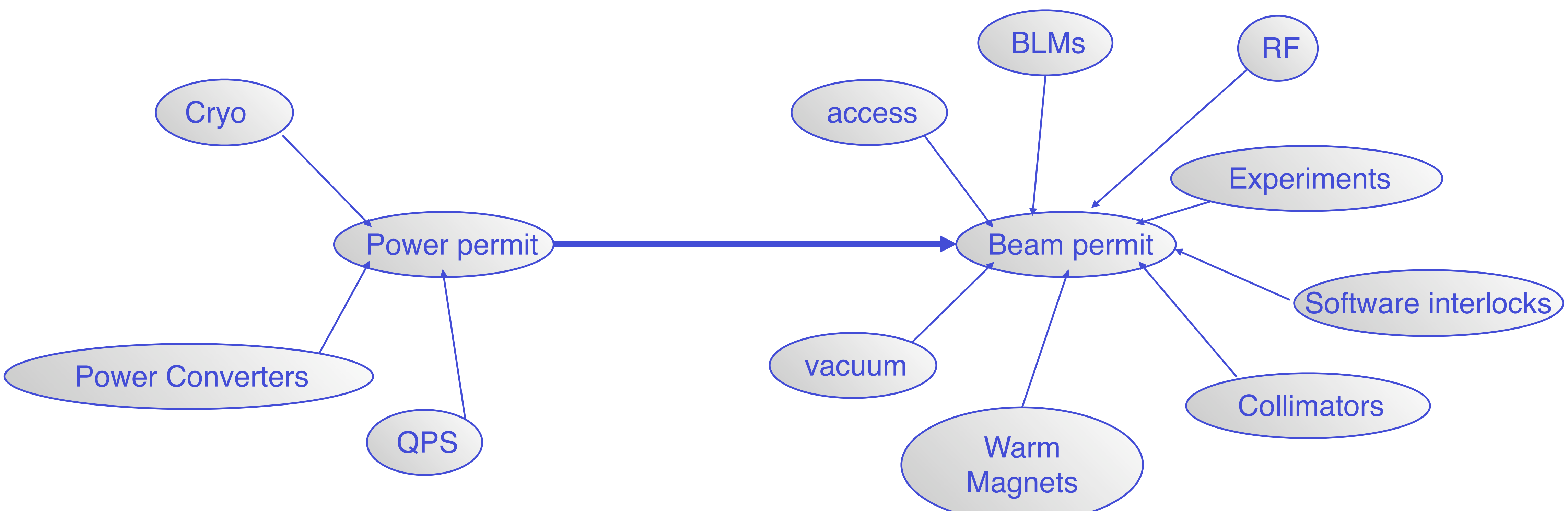
Machine protection philosophy

Stored magnetic energy → **Power Permit**

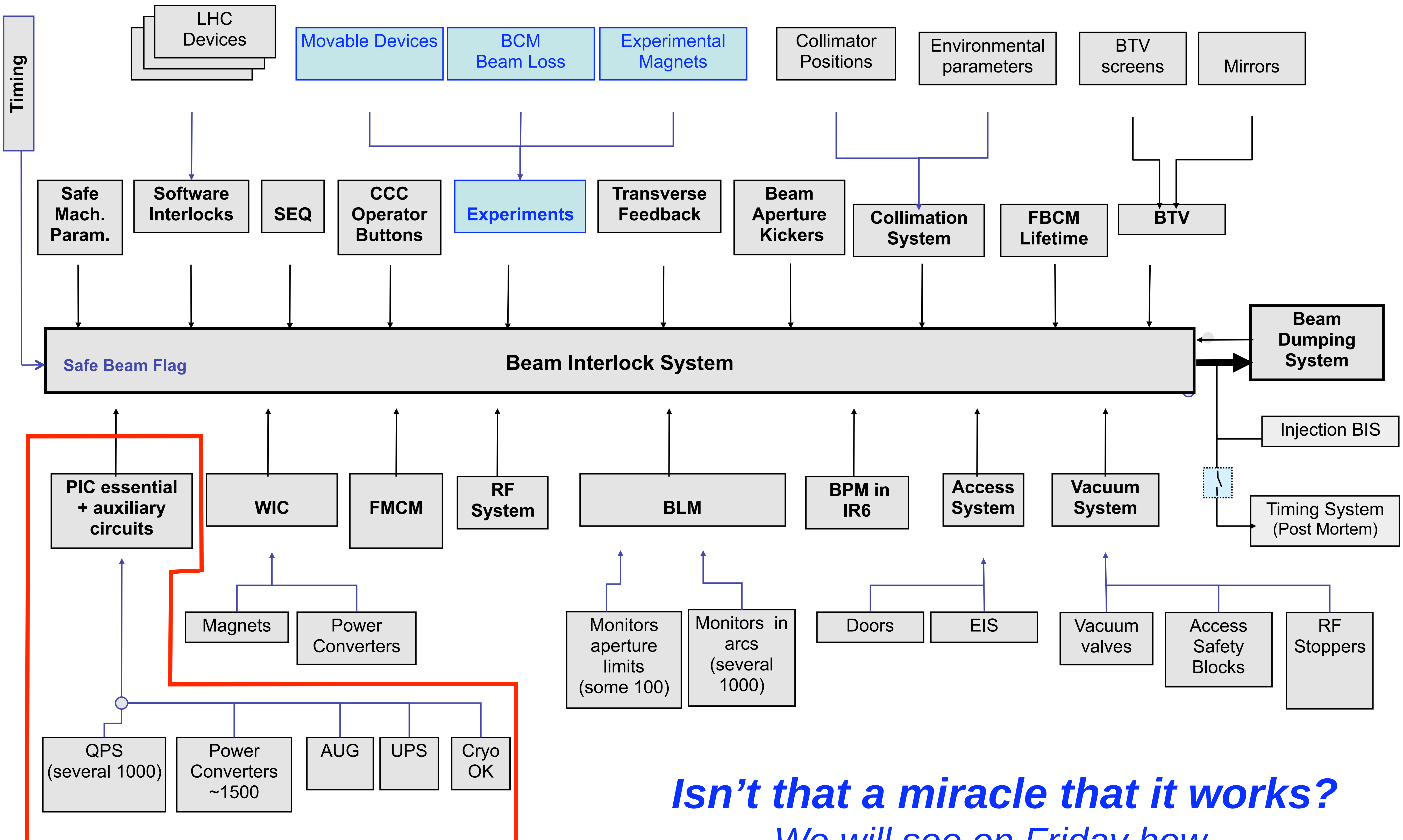
- → Authorises power on
- → Knocks power off in case of fault

Stored beam energy → **Beam Permit**

- → Authorises beam
- → Requests a beam dump in case of problems



In practice....



Isn't that a miracle that it works?

We will see on Friday how...

Conclusions

- ☑ We have reviewed the basic accelerator physics concepts
- ☑ We have seen how the LHC beam requirements are met by the injector chain
- ☑ We have introduced the main LHC accelerator systems

We are now ready to see how the LHC is operated!

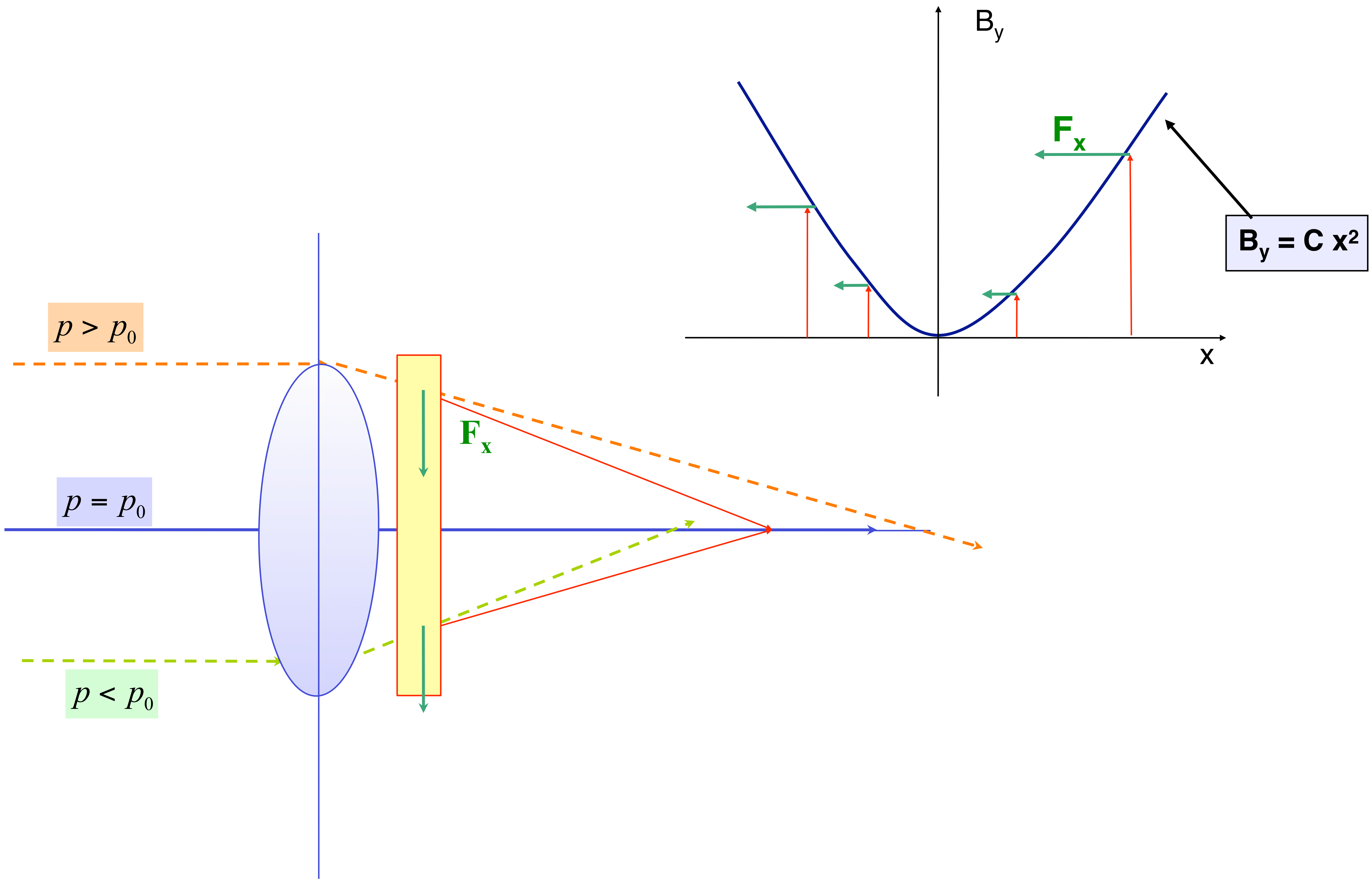
Agenda for the second part of the lecture:
- LHC commissioning and 2010-11 running scenarios
- Operational phases
- How do we operate the LHC

Acknowledgments

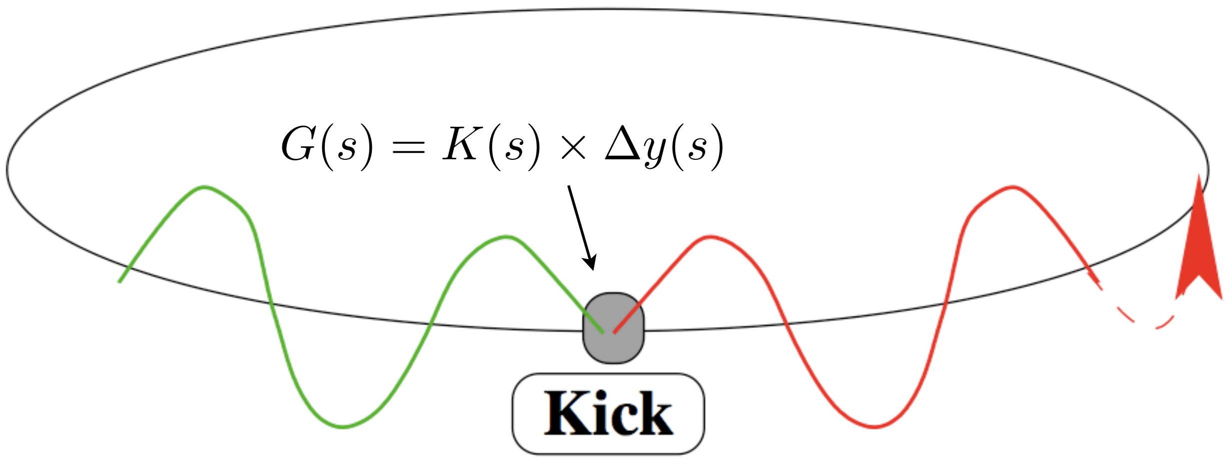
- Material on the injectors:
  - G. Rumolo
  - R. Steerenberg
  - G. Bellodi
  - K. Cornelis
  - D. Manglunki
  - E. Métral
- LHC layout and systems:
  - M. Lamont
  - R. Bailey
  - J. Wenninger
  - B. Goddard
  - R. Assmann
  - P. Baudrenghien
  - W. Herr

Reserve slides

Effect of sextupole magnets



Closed orbit



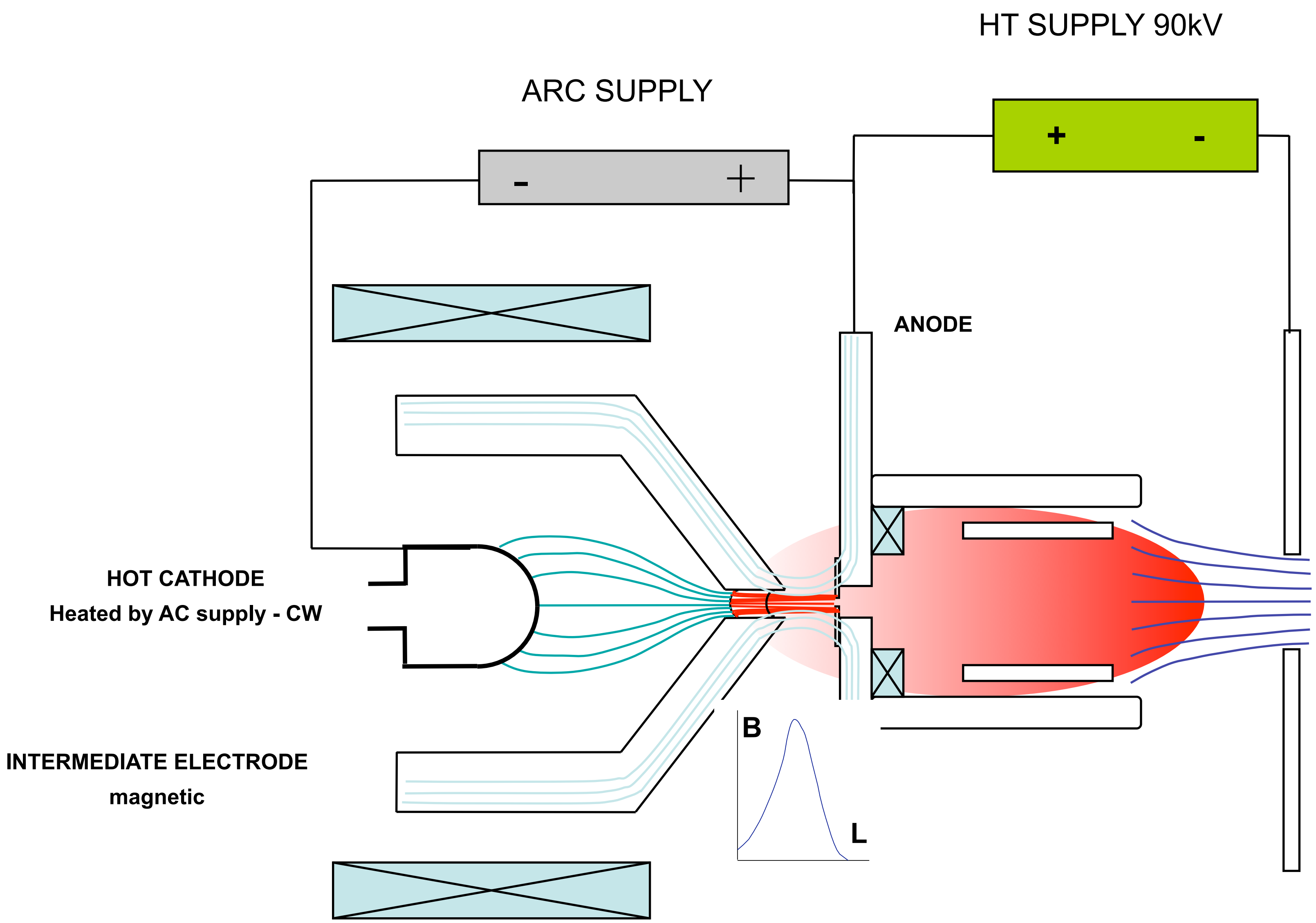
Closed orbit = closed, periodic solution of the equation of motion.

Ideal machine: orbit centred in the magnets.

Real world: imperfections of magnetic field cause perturbations of the

$$x(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi Q)} \times \int \sqrt{\beta(t)} G(t) \cos[|\phi(t) - \phi(s)| - \pi Q] dt$$

Linac2: source



This is a "duoplasmatron" proton source!

p^+: *Cathode Tube with* H

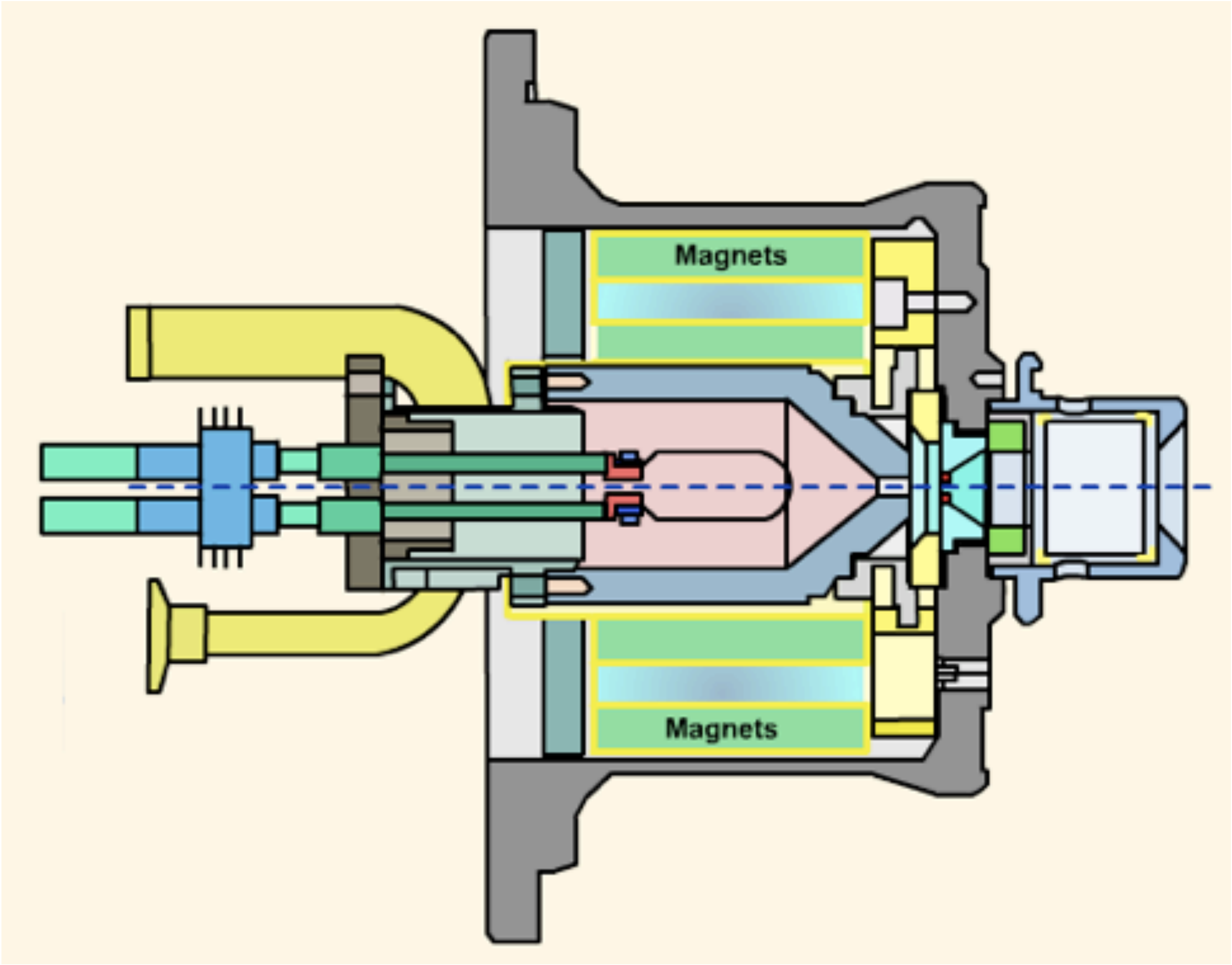
$$H_2 + e^- \rightarrow H_2^+ + 2e^-$$

$$H_2^+ + e^- \rightarrow H^+ + H + e^-$$

$$H + e^- \rightarrow H^+ + 2e^-$$

http://psdoc.web.cern.ch/PSDoc/acc/ad/VisiteGuidePS/Animations/Duoplasmatron/Duoplasmatron.html

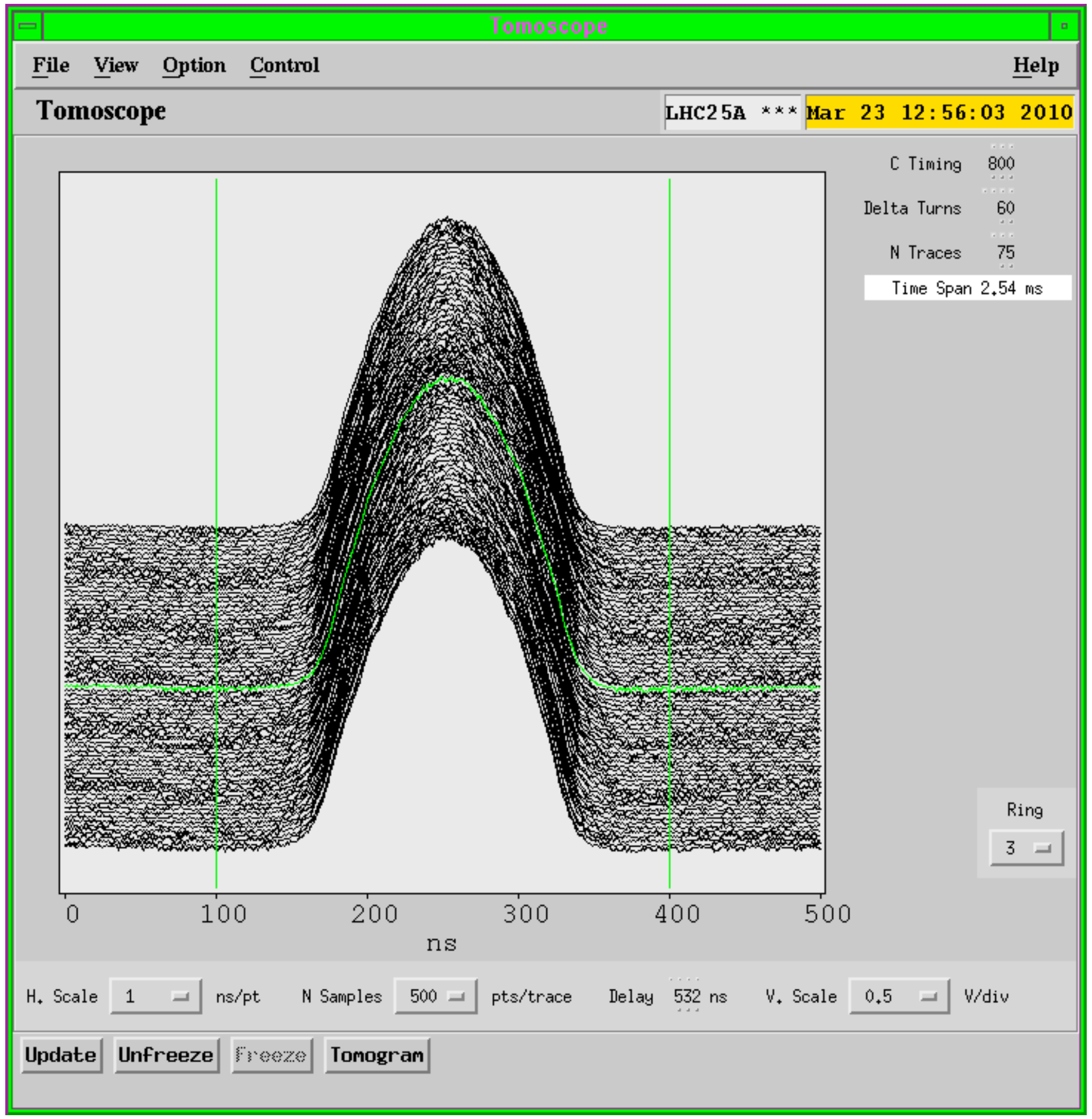
Linac2 source - details



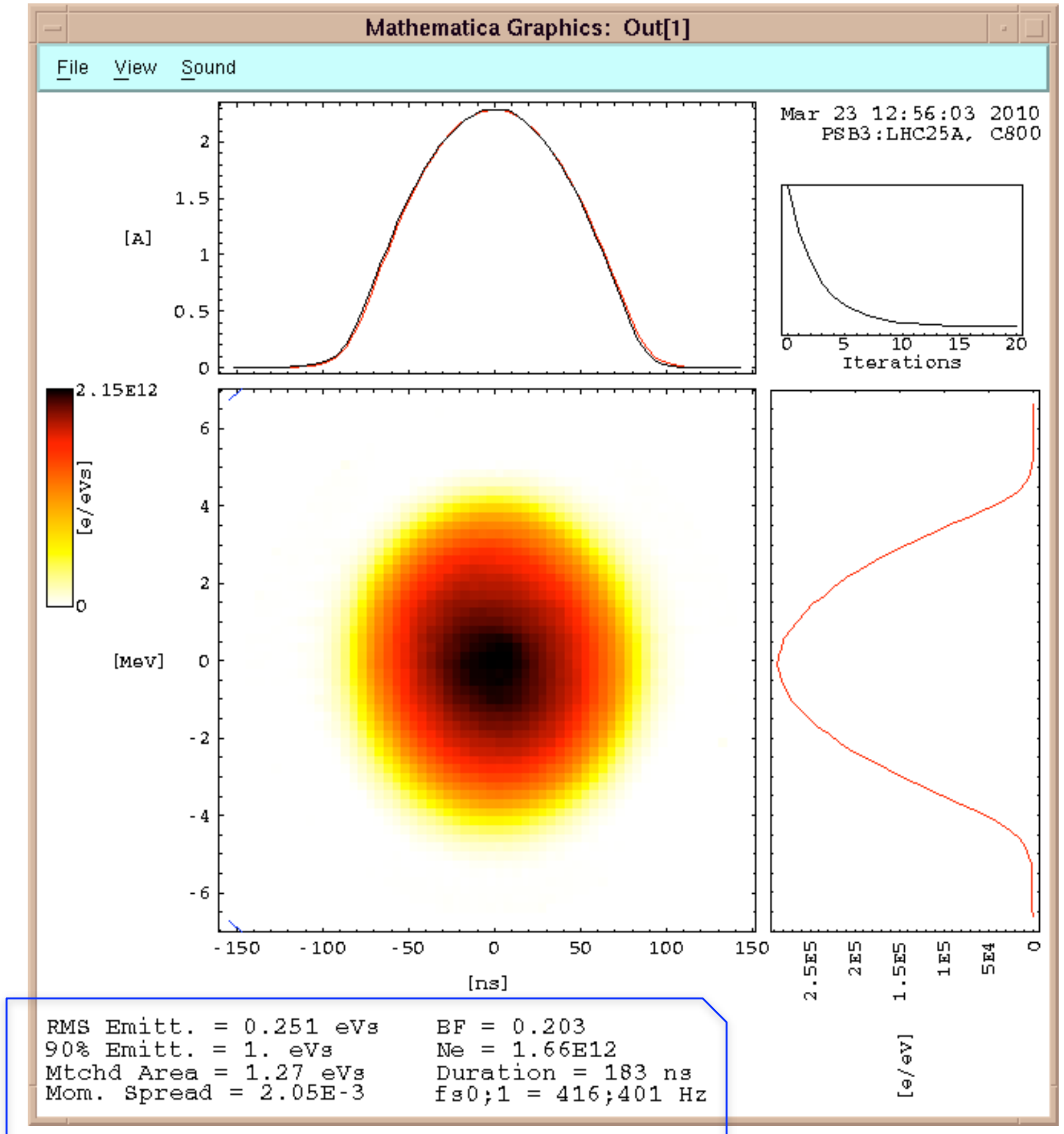
http://psdoc.web.cern.ch/PSDoc/acc/ad/VisiteGuidePS/Animations/Duoplasmatron/Duoplasmatron.html

LHC beams in the PSB

Longitudinal profile “mountain range”



Transverse profile



Intensity, longitudinal emittance and bunch length within specs!

For completeness...

Variety of LHC beams at the booster

LHC Beam Type	Intensity/ bunch [x10^{11}]	Number of bunches (PSB rings)	$\varepsilon_{rms, norm.}$ [μm]	$\varepsilon_{long.}$ [eVs]
25 ns physics	1.62-16.2	6 (4+2)	2.5	1.3
50 ns physics	8.1	6 (4+2)	2.5	1.3
75 ns physics	0.92-5.29	6 (4+2)	2.5	0.9
Indiv. physics	0.24-1.35	1 or 4	2.5	0.3
Pilot beam	0.05	1	2.5	≤0.3
Probe beam	0.05-0.23	1	<1.0	≤0.2

Values needed to have triple splitting at injection in the PS without additional longitudinal emittance blow up

Including margin for blow up (need to be 3.5 μm at the SPS extraction)

Intensity ranges covered from 10% of the nominal values up to the nominal (and even above nominal for MDs)

Assumed double batch transfer to the PS (h=1 in the PSB, 4 rings + 2 rings) -now replaced by a single batch transfer for LHC50 and LHC75 beams (h=2 in the PSB, 3 rings)

Fast extractions from the SPS

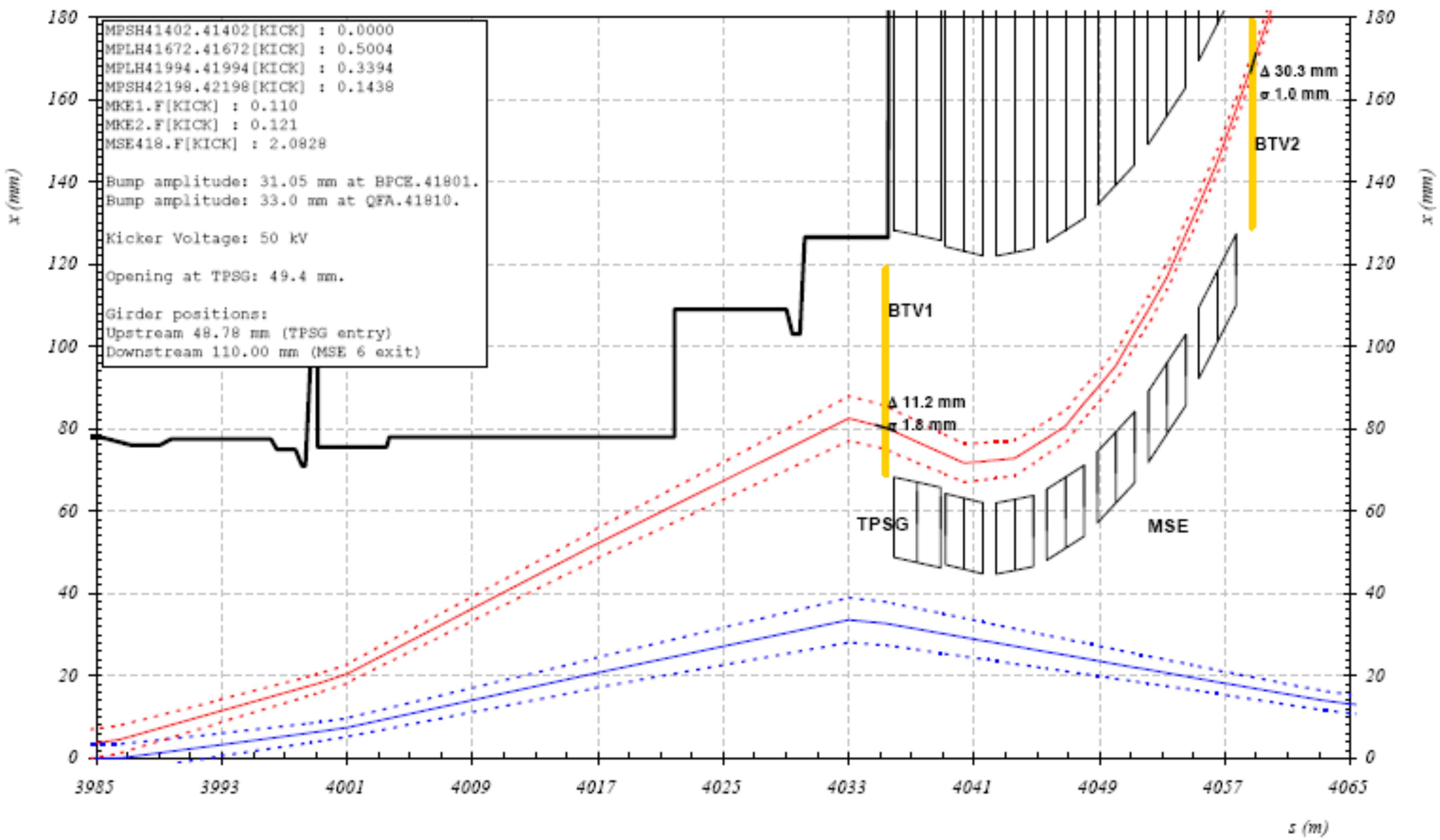
5 extraction kicker magnets (MKE) operated at 50 kV.

6 septum magnets (MSE), installed on a movable girder.

4 horizontal and 4 vertical bumper magnets:

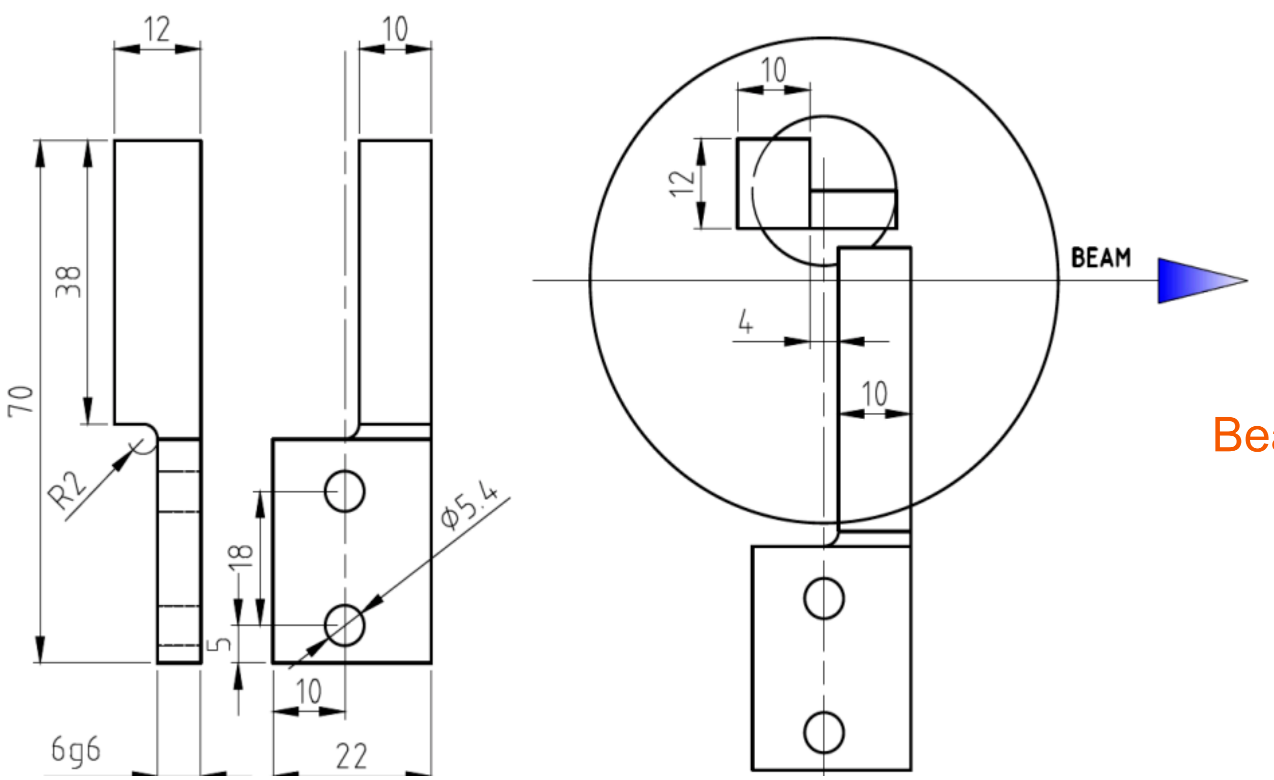
- Horizontal extraction bump of 31.1 mm @ monitor BPCE.418

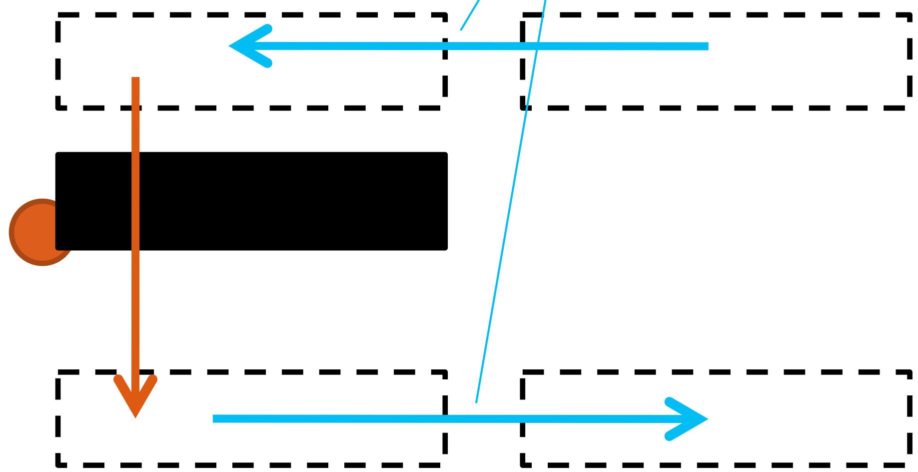
TPSG protection element for the MSE.

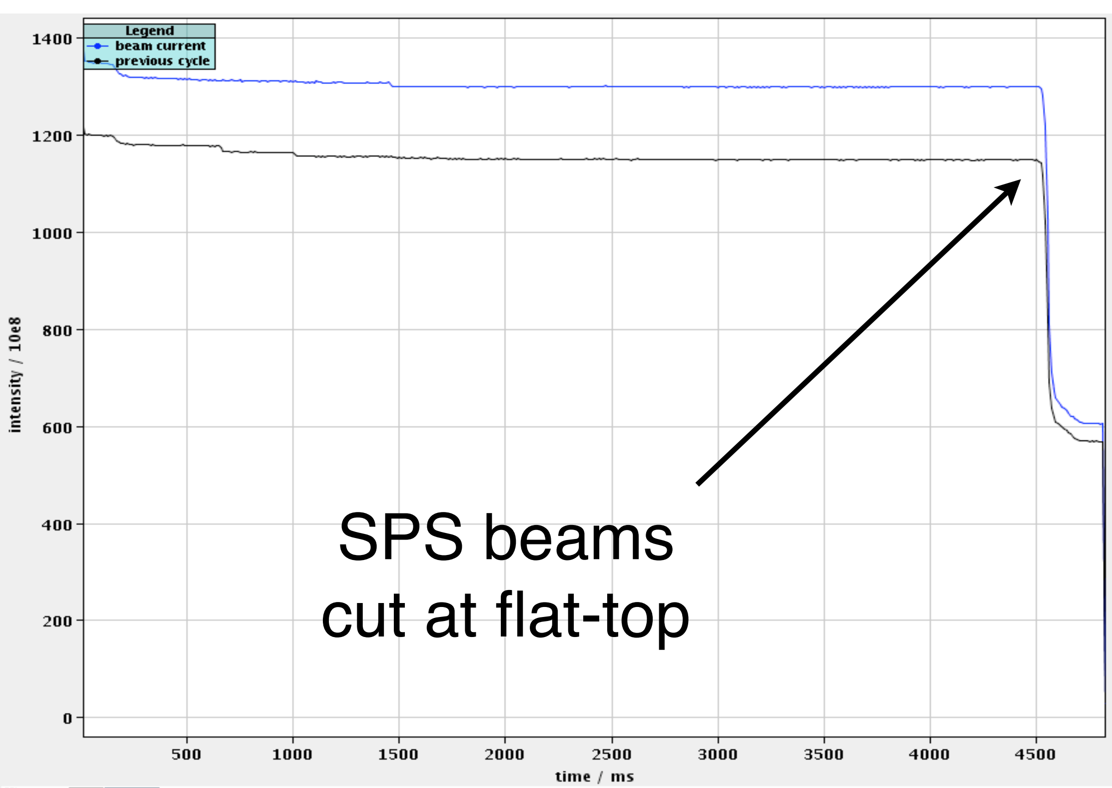


LHC beam scraping at the SPS

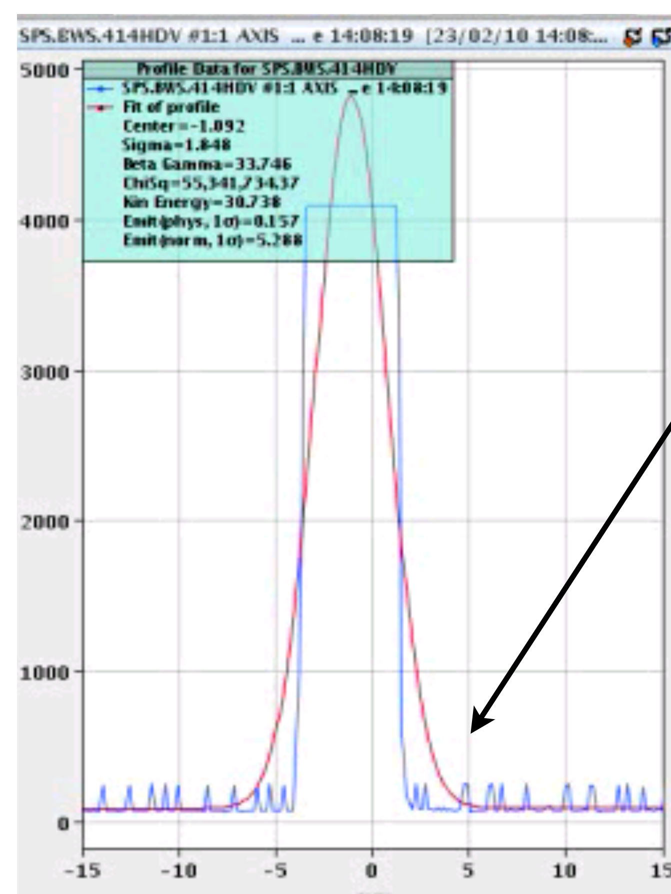
1 LHC injection batch in the SPS > 2 MJ
A few % of particles in the bunch tails could quench the LHC cold magnets!





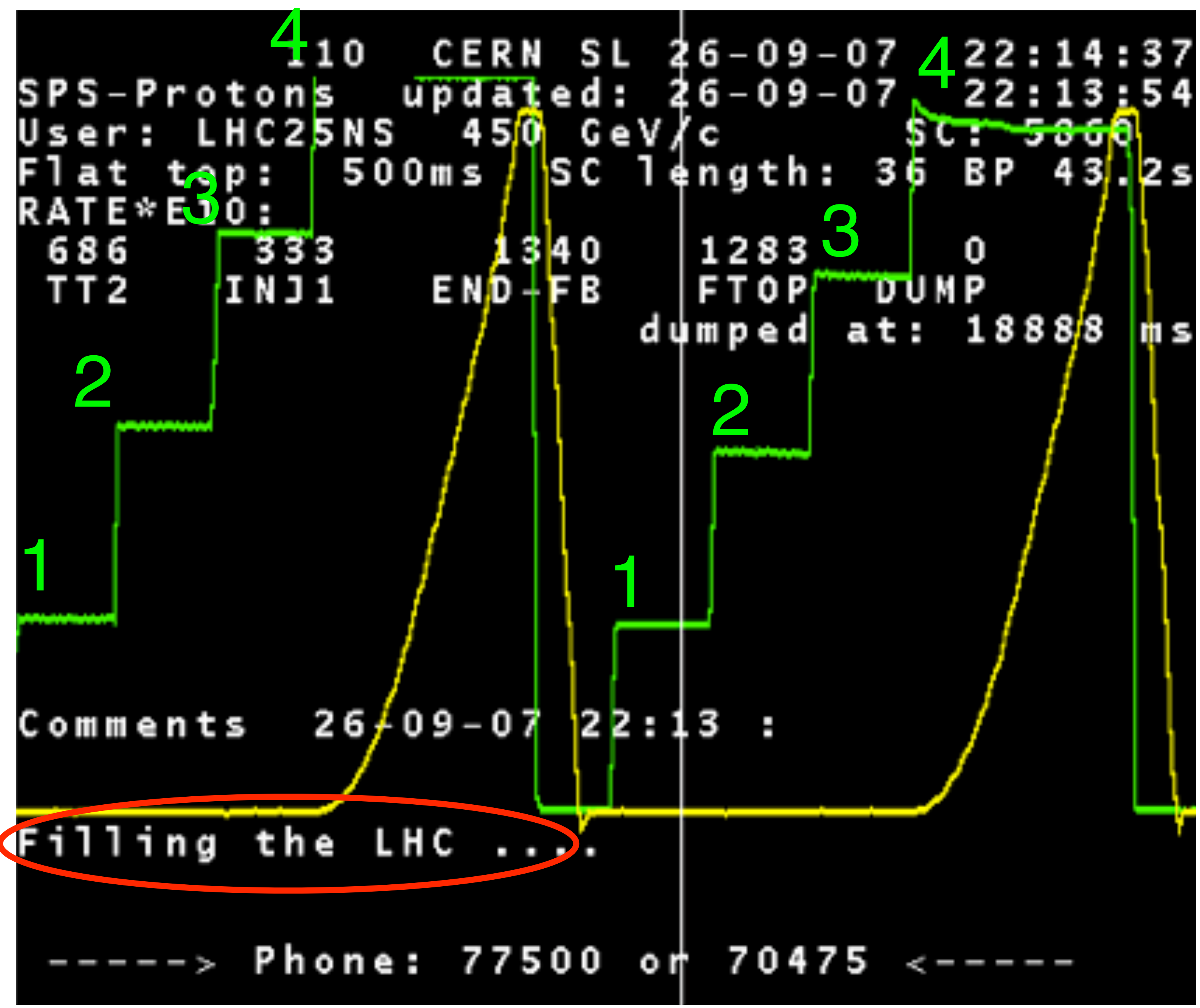


SPS beams
cut at flat-top



Sharp tail cut
(more than
needed)

First B1/B2 interleaved extractions

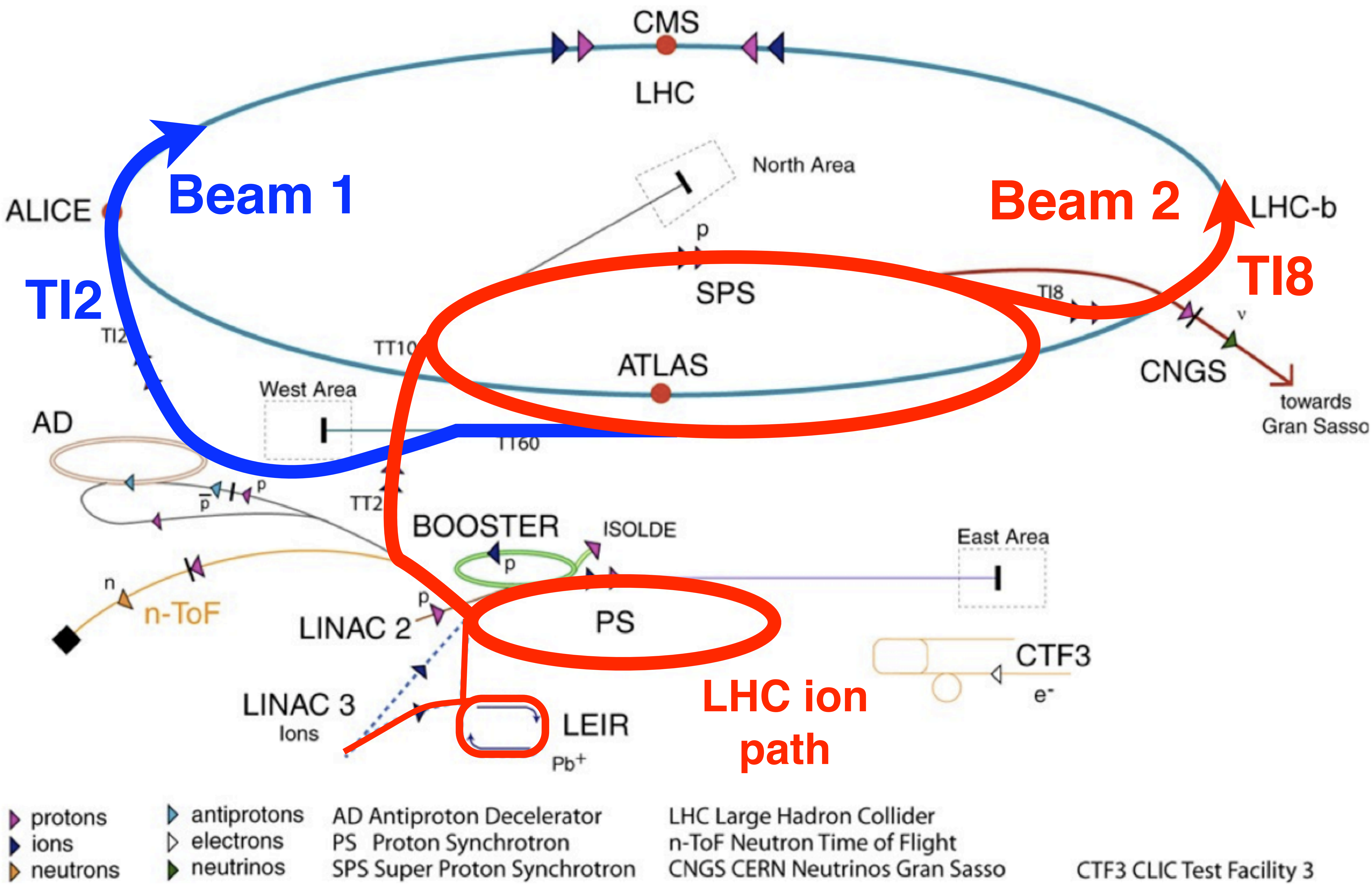


***SPS 2007 run**. Courtesy of J. Wenninger*
Beam intensity lower than nominal (no dedicated studies for beam optimization)

Cycle for interleaved extractions of Beam1 and Beam2 successfully set-up in 2007!
“Page 1” could announce that we were ready for “Filling the LHC....”

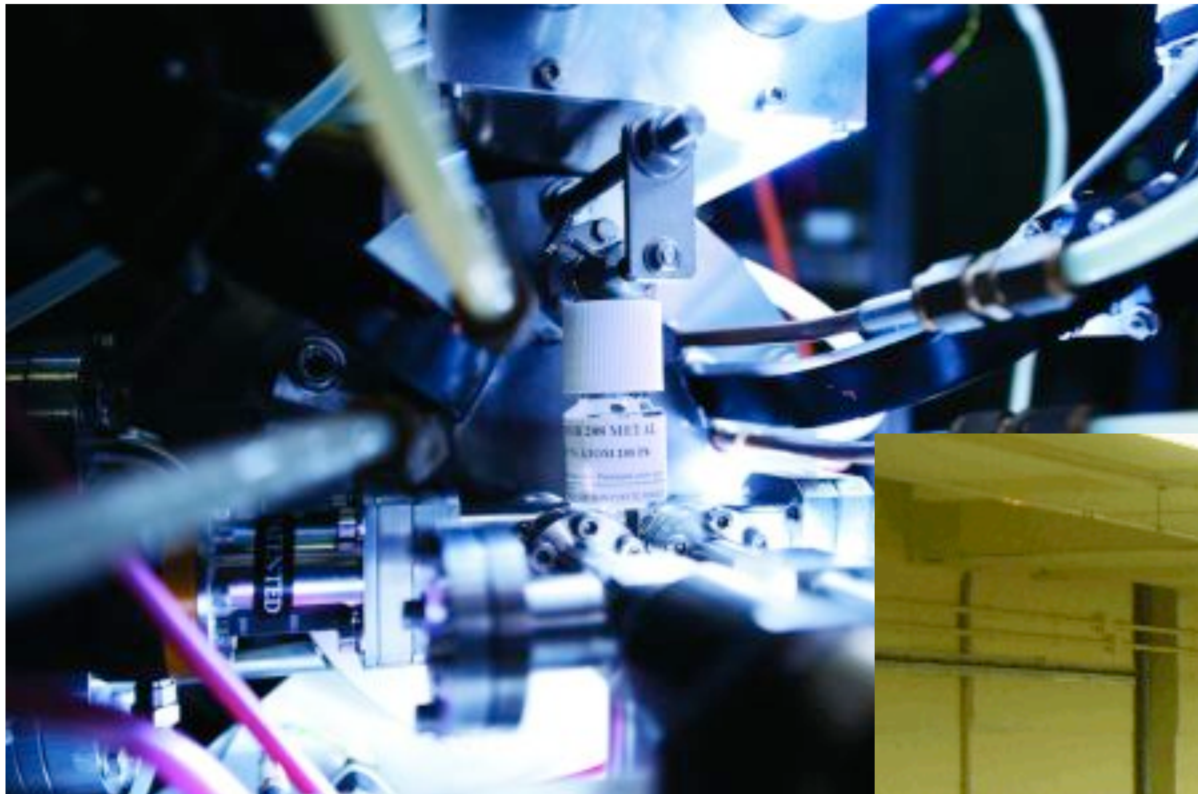
Shorter cycles also available for lower beam intensities: faster and more flexible operation for commissioning scenarios

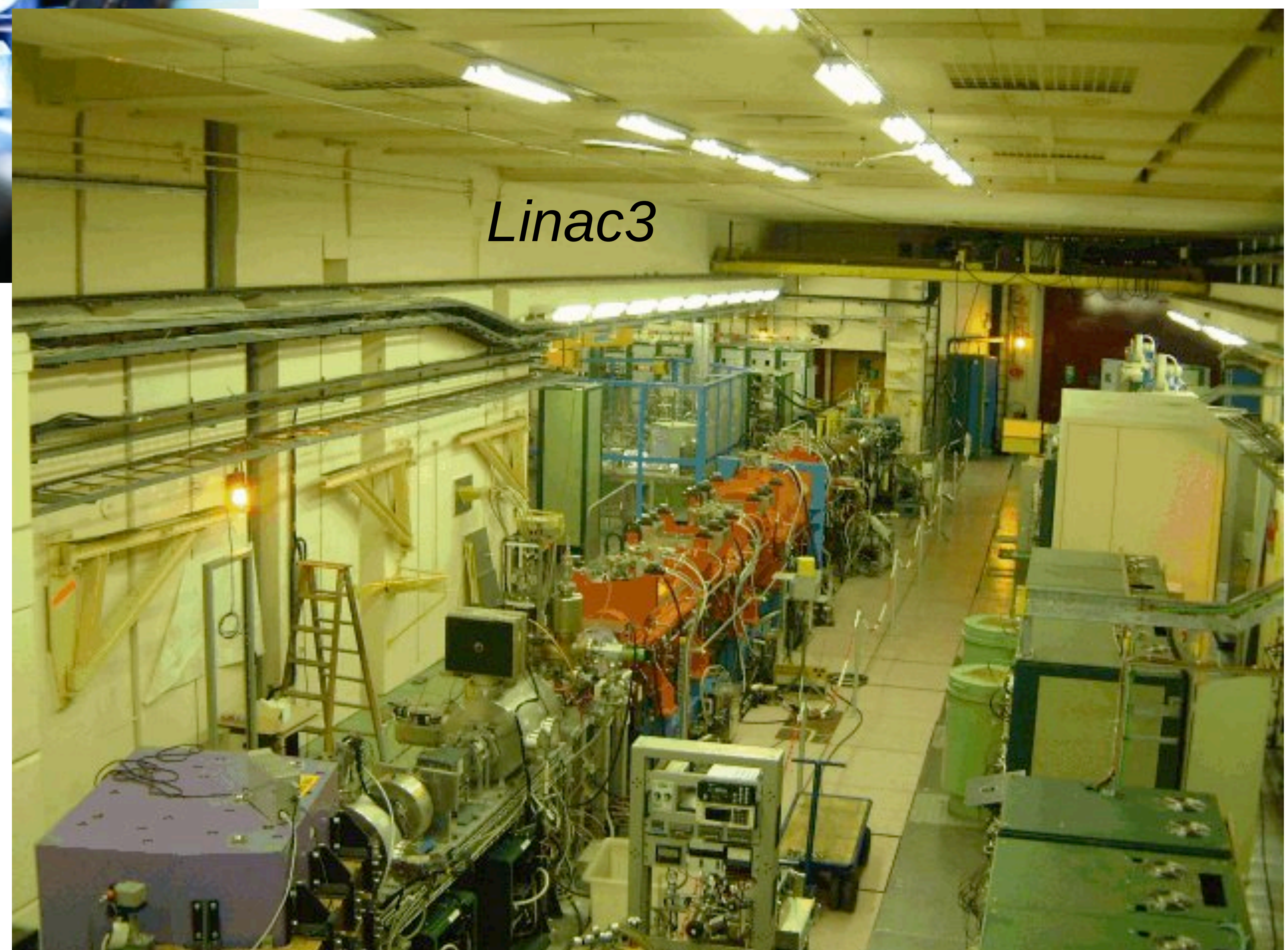
Ion beam path to the LHC



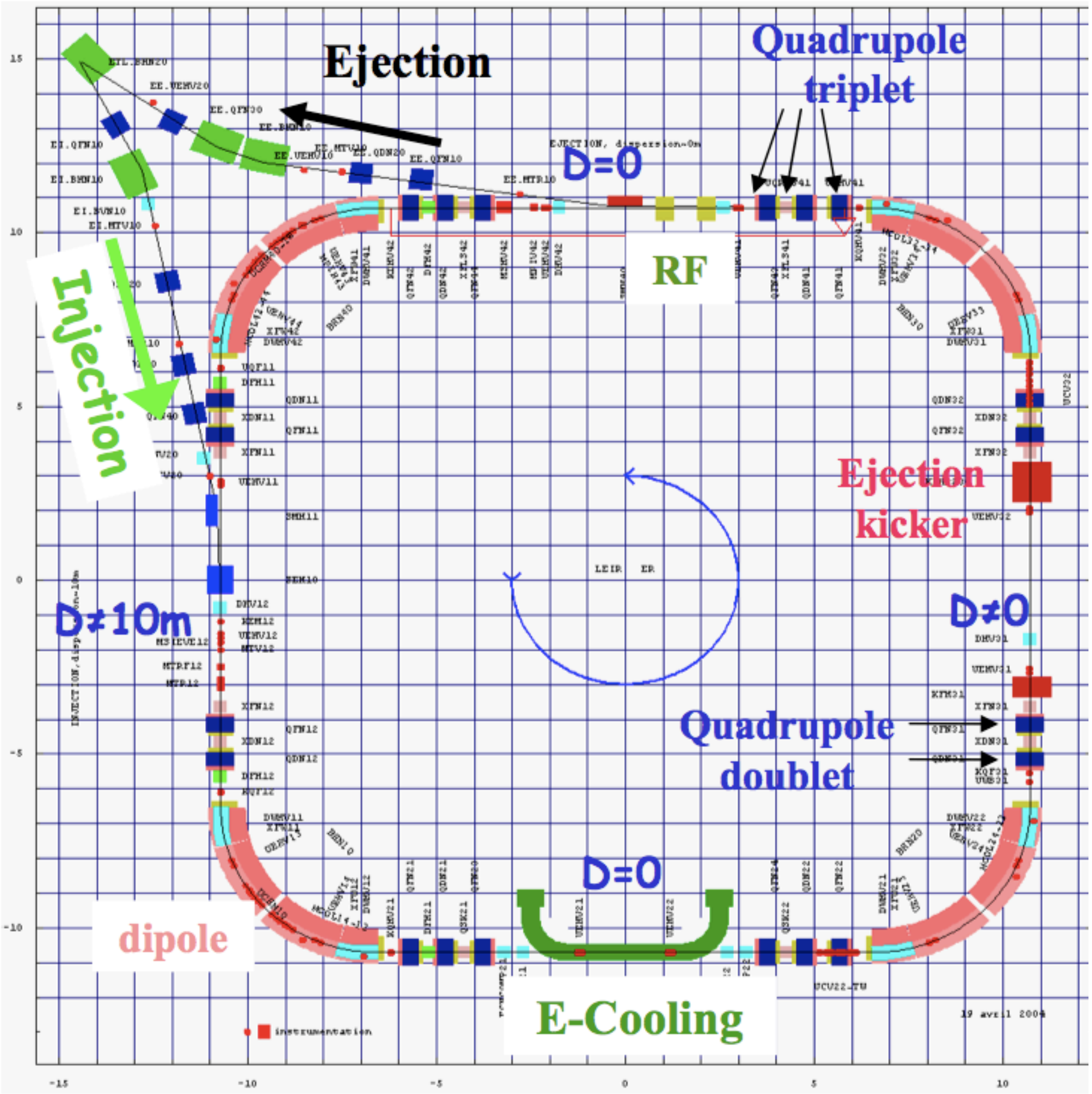
Ion beams for the LHC

It also all start with a small bottle...

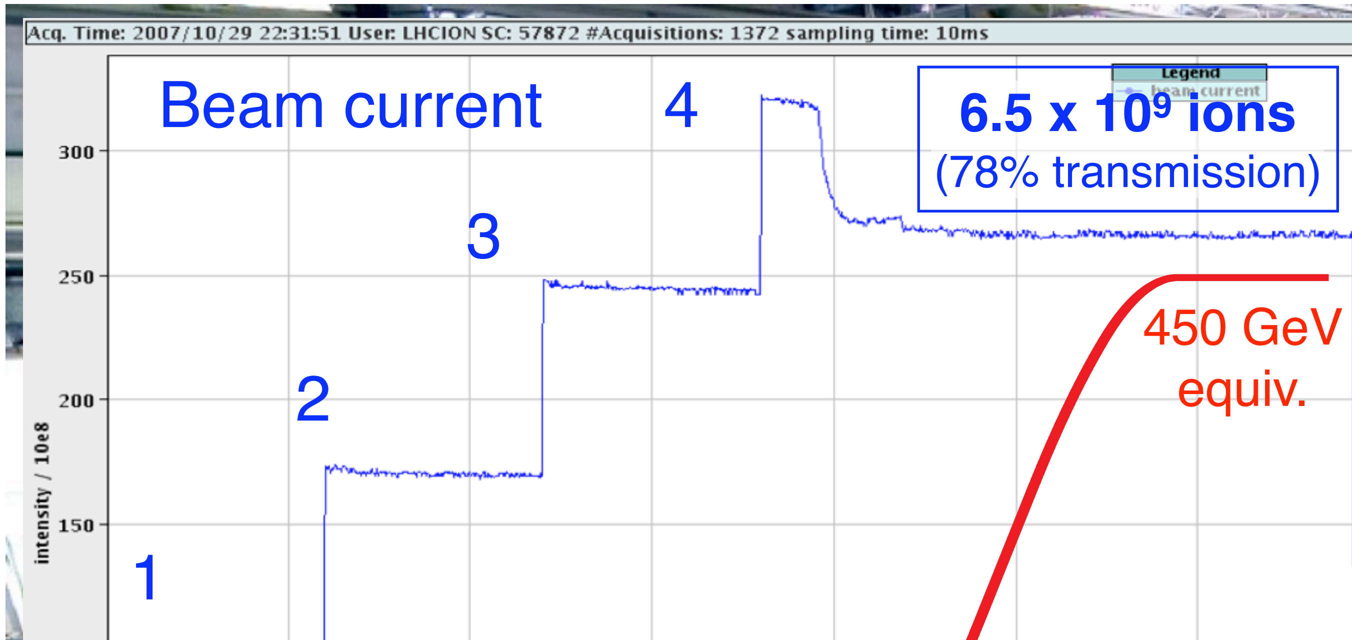


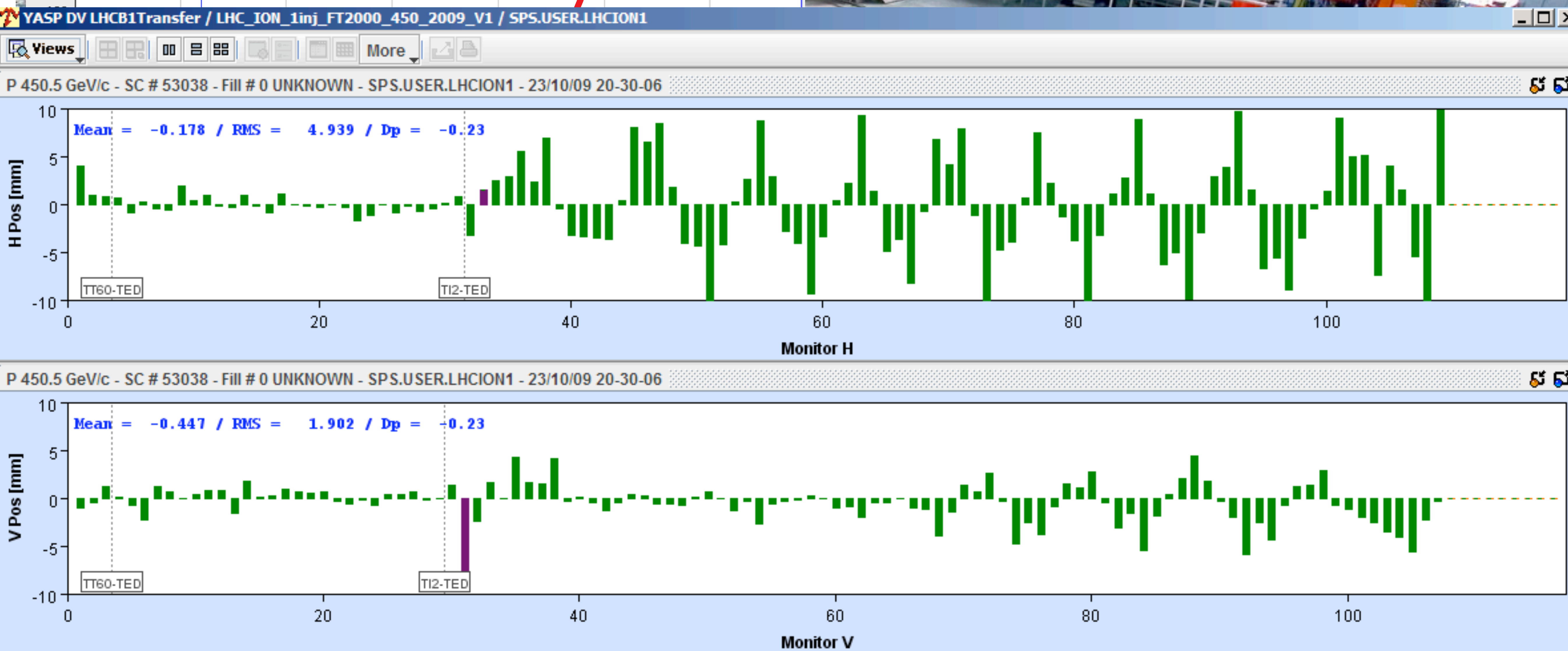


Schematic LEIR layout

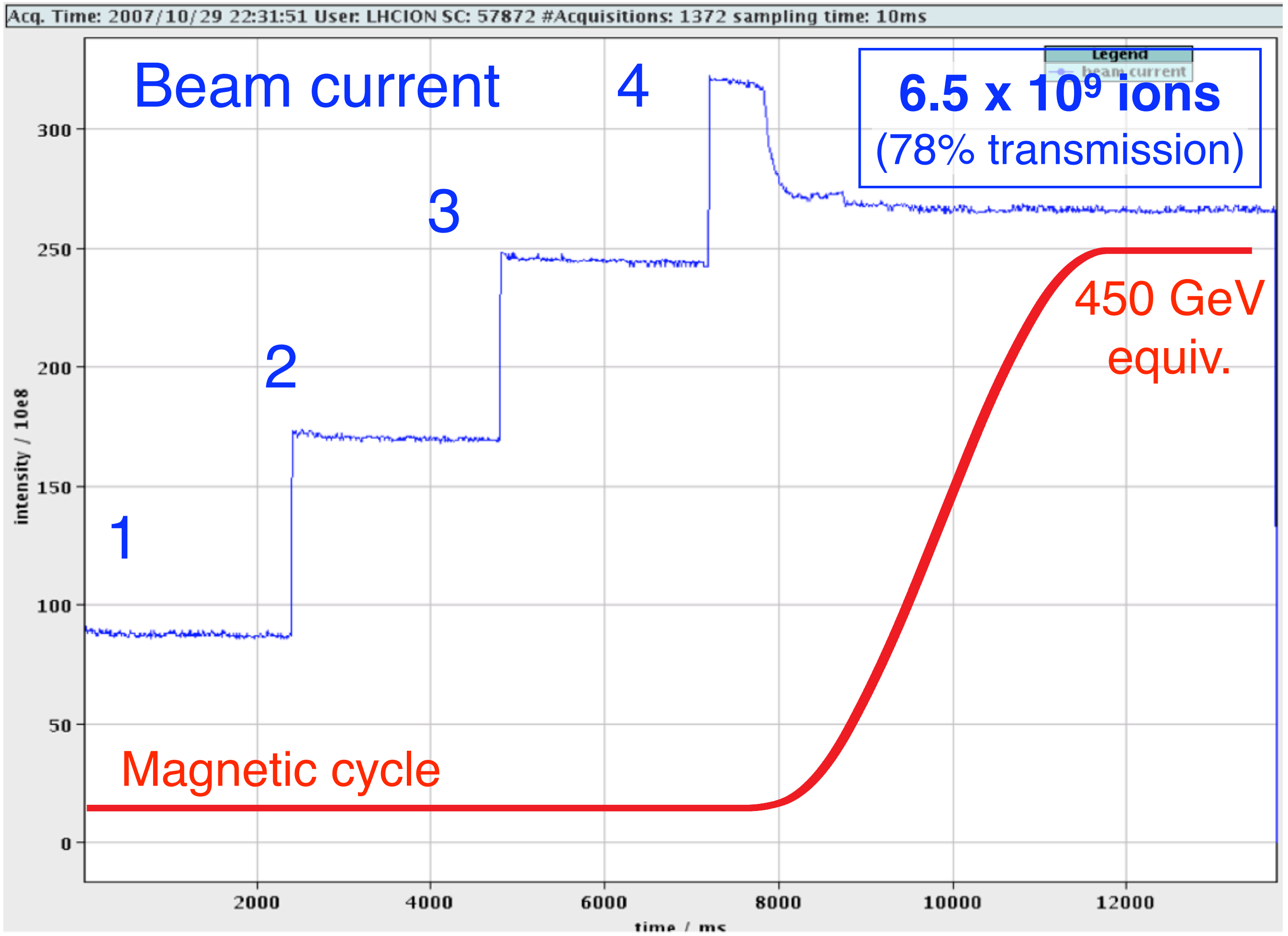


Low-energy ion ring (LEIR)



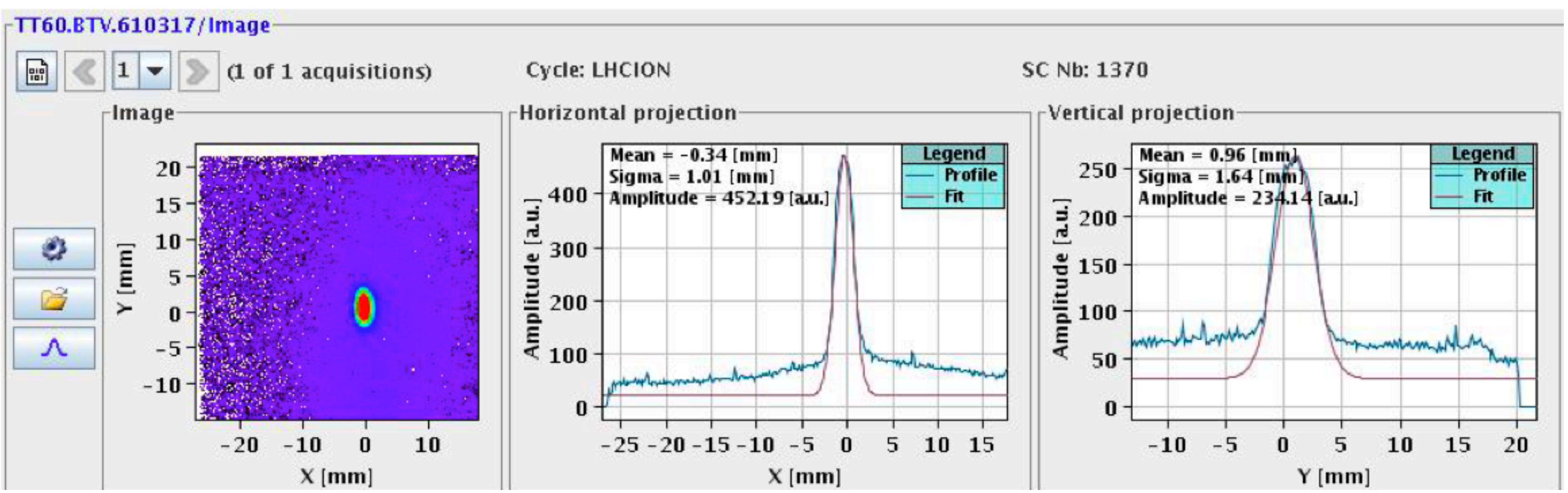


The "early" LHC ion beam in the SPS (2007)



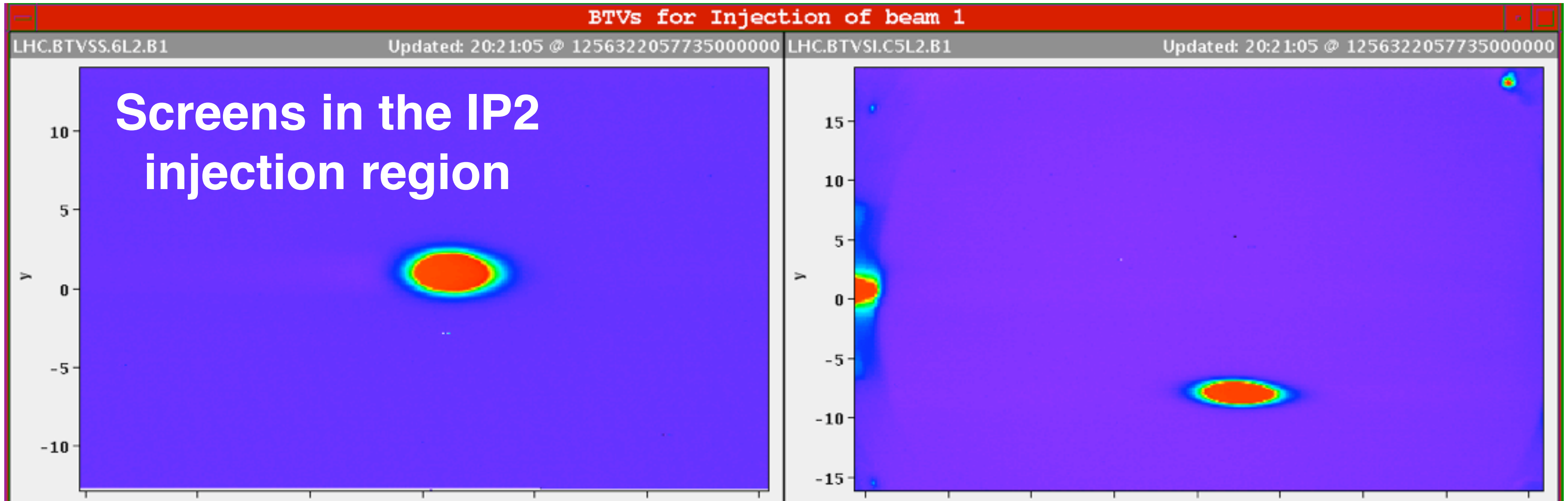
	expected	obtained				
		Bunch				
		1	2	3	4	
transmission	75%					78%
N_Q	7.4×10^9					6.5×10^9
ϵ/A (eVs)	0.28	0.068	0.076	0.083	0.12	
τ (ns)	1.8	0.90	0.94	1.0	1.2	
$\Delta p/p$ (10^{-4})	6.3	2.7	2.9	3.1	3.6	

Courtesy of T. Bohl

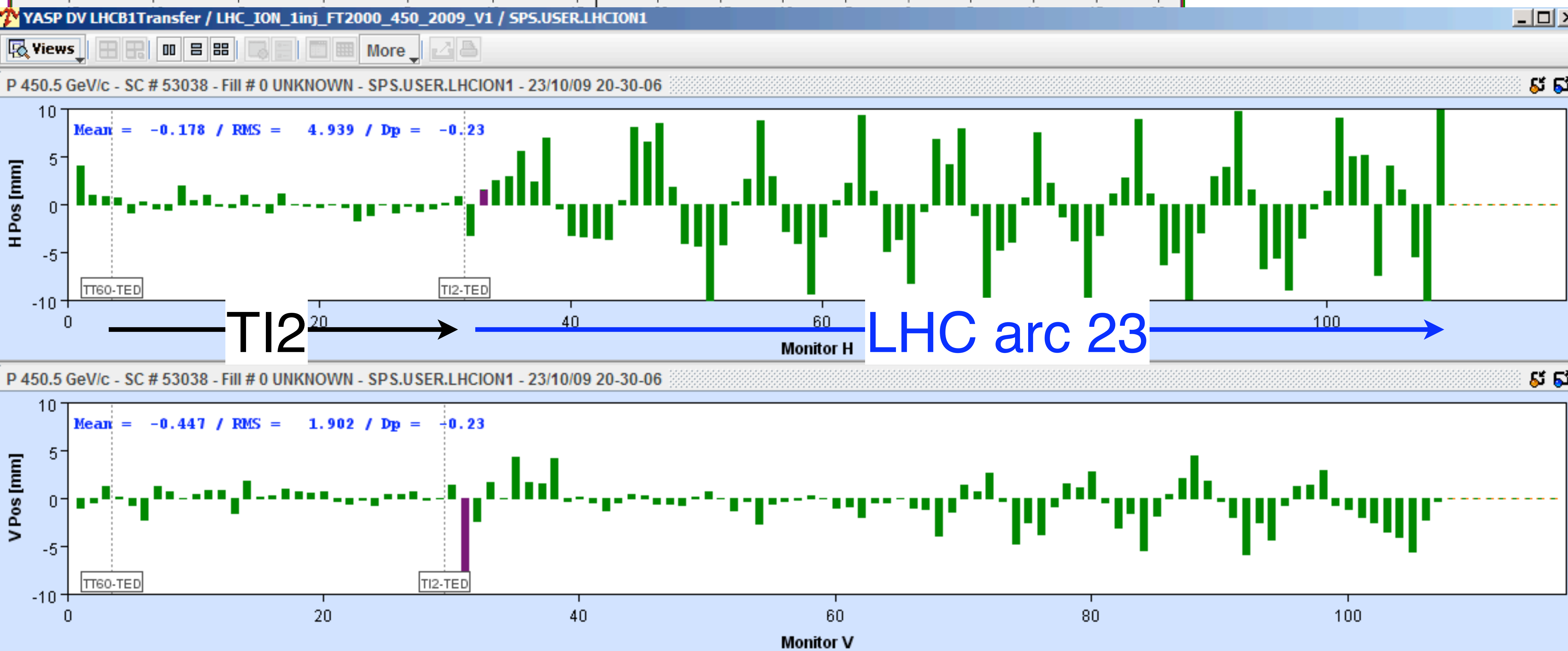


Extracted Lead ion beam in TT60!

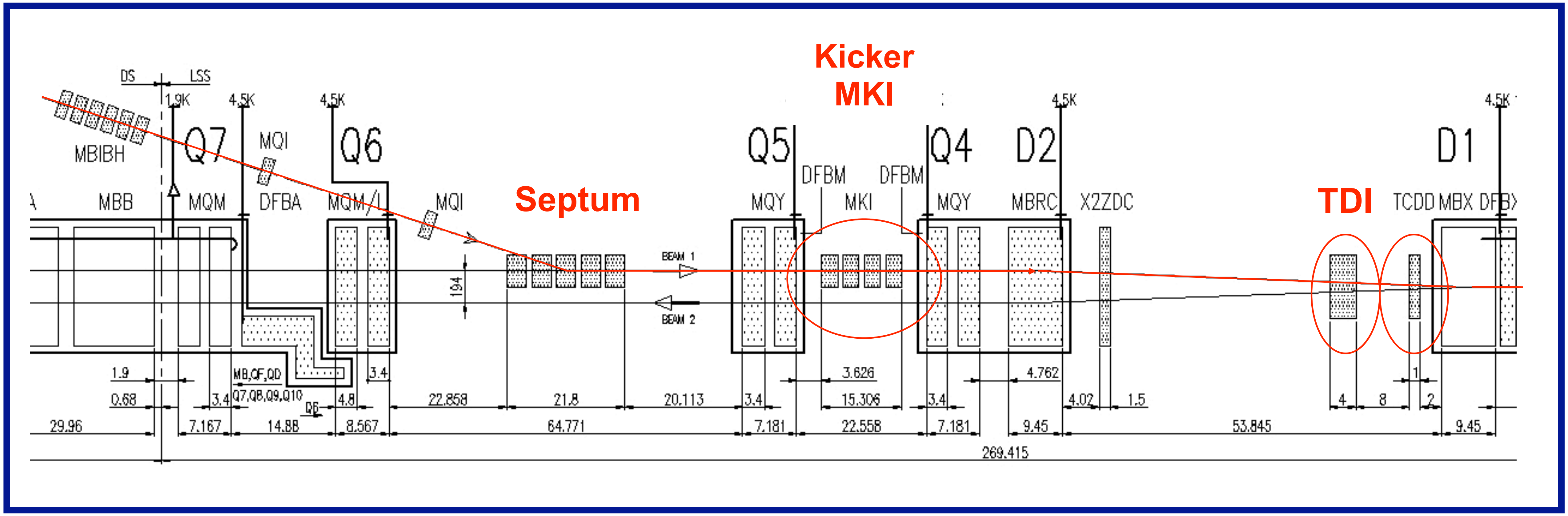
First ion beams in the LHC (2009)

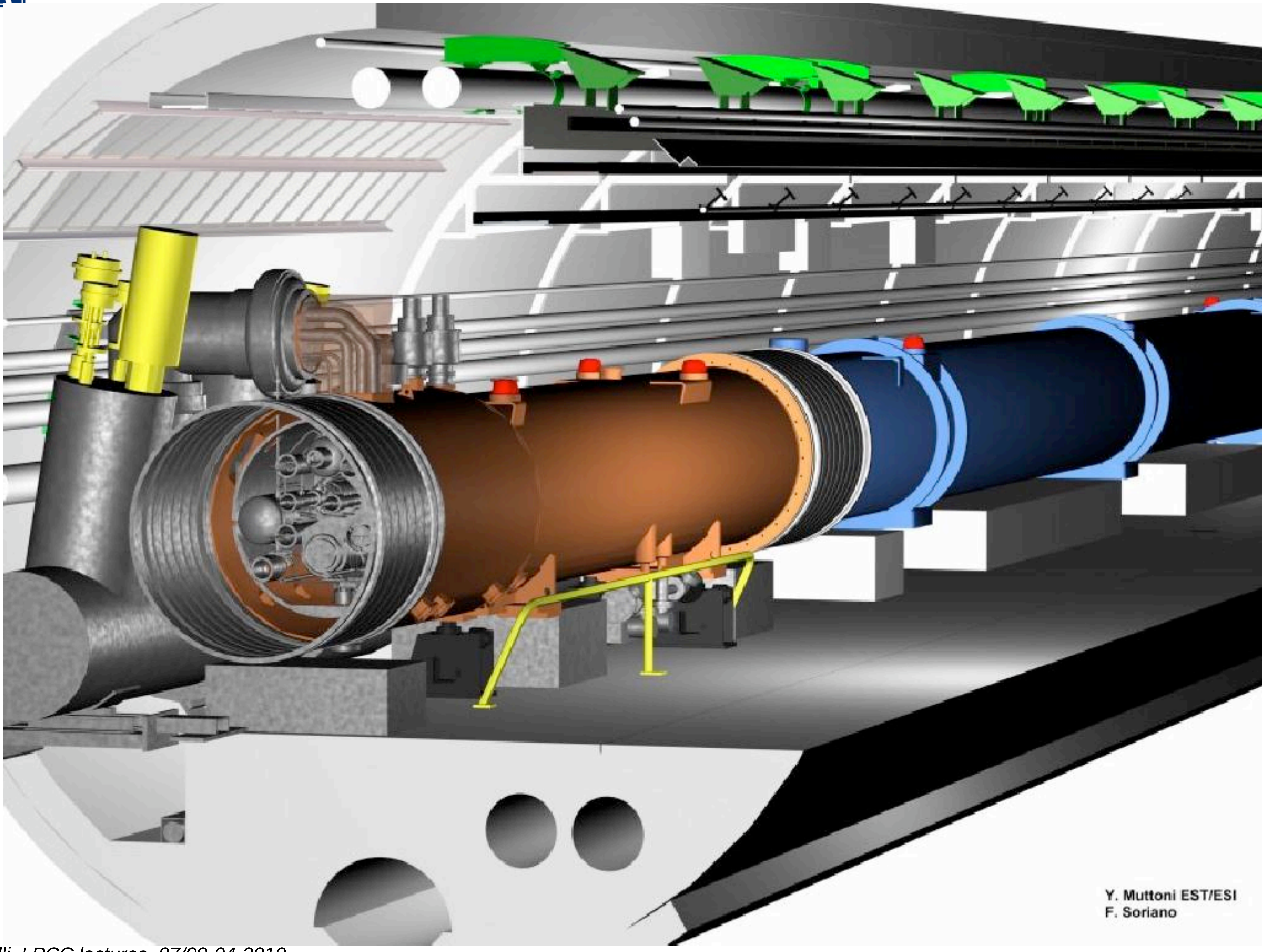


Ion beams stopped at the collimators in the LHC-P3



LHC injection: Technical layout




Y. Muttoni EST/ESI
F. Soriano

Corrector magnet count

Name	Quantity	Purpose
MSCB	376	Combined chromaticity/ closed orbit correctors
MCS	2464	Dipole spool sextupole for persistent currents at injection
MCDO	1232	Dipole spool octupole/decapole for persistent currents
MO	336	Landau octupole for instability control
MQT	256	Trim quad for lattice correction
MCB	266	Orbit correction dipoles
MQM	100	Dispersion suppressor quadrupoles
MQY	20	Enlarged aperture quadrupoles

Inside one cell