*Graduate Studies in Accelerator Physics — PhD Student lectures*
*June 5th-7th, 2017*
*Università La Sapienza, Rome, Italy*

# The LHC machine protection and beam collimation

## Part 1

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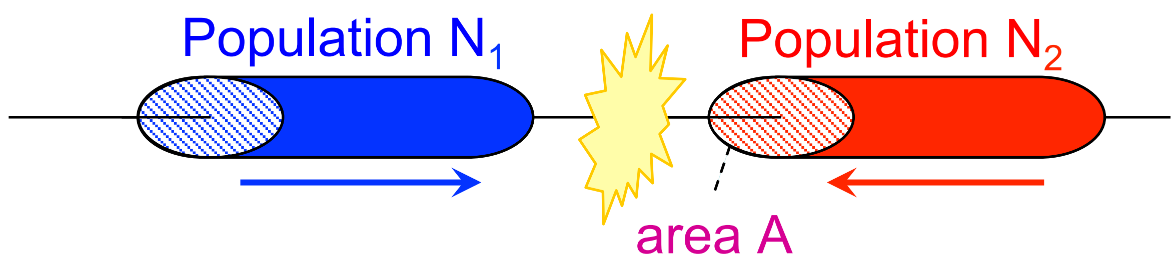
# What do experiments want?

The Large Hadron Collider (LHC): is the state-of-the-art circular collider in operation since 2010 at the European Organisation for Nuclear Research (CERN) that provides high-energy collisions for particle's physics studies.




## High energy

$B$ = bending field
$\rho$ = 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 ($\sigma$)*

*"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 parameters

| Nominal LHC parameters | | |
|---|---|---|
| | Design | 2016 |
| Beam injection energy (TeV) | 0.45 | 0.45 |
| Beam energy (TeV) | 7 | 6.5 |
| Number of particles per bunch | $1.15 \times 10^{11}$ | $1.2 \times 10^{11}$ |
| Number of bunches per beam | 2808 | 2220 |
| Max stored beam energy (MJ) | 362 | 270 |
| Beam current (A) | 0.58 | 0.42 |
| Norm transverse emittance (μm | 3.75 | 2.1 |
| Colliding beam size (μm) | 16 | 11 |
| Bunch length at 7 TeV (cm) | 7.55 | 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?
- **How do we handle these unprecedented stored beam energies?**
- **What are the implication on machine protection?**
- **Why do we need a halo collimation system?**
- **How do we design it and operate it?**

# Outline

- **Introduction to the LHC**
  - Recap. of basic accelerator physics
  - CERN accelerator complex
  - LHC parameters and detailed layouts
- **Machine protection and collimation**
  - Machine protection and collimation system
  - Design of beam halo collimation
  - The LHC beam collimation system
  - Collimation in practice: LHC operation
- **Advanced beam collimation**
  - Simulations and measurements
  - HL-LHC upgrade
  - Advanced concepts: crystals, hollow lenses
  - Challenges for the future: FCC-*hh*

# Outline - 1st lecture

- **Introduction**
- **Recap. of accelerator physics**
  - Basic equations
  - Relevant beam measurements
- **CERN accelerator complex**
  - Lower energy injectors
  - Super Proton Synchrotron
- **LHC parameters and layout**
  - Arcs and straight sections
- **Machine protection and collimation**
  - Concepts and LHC implementation
  - Case study: 2008 event

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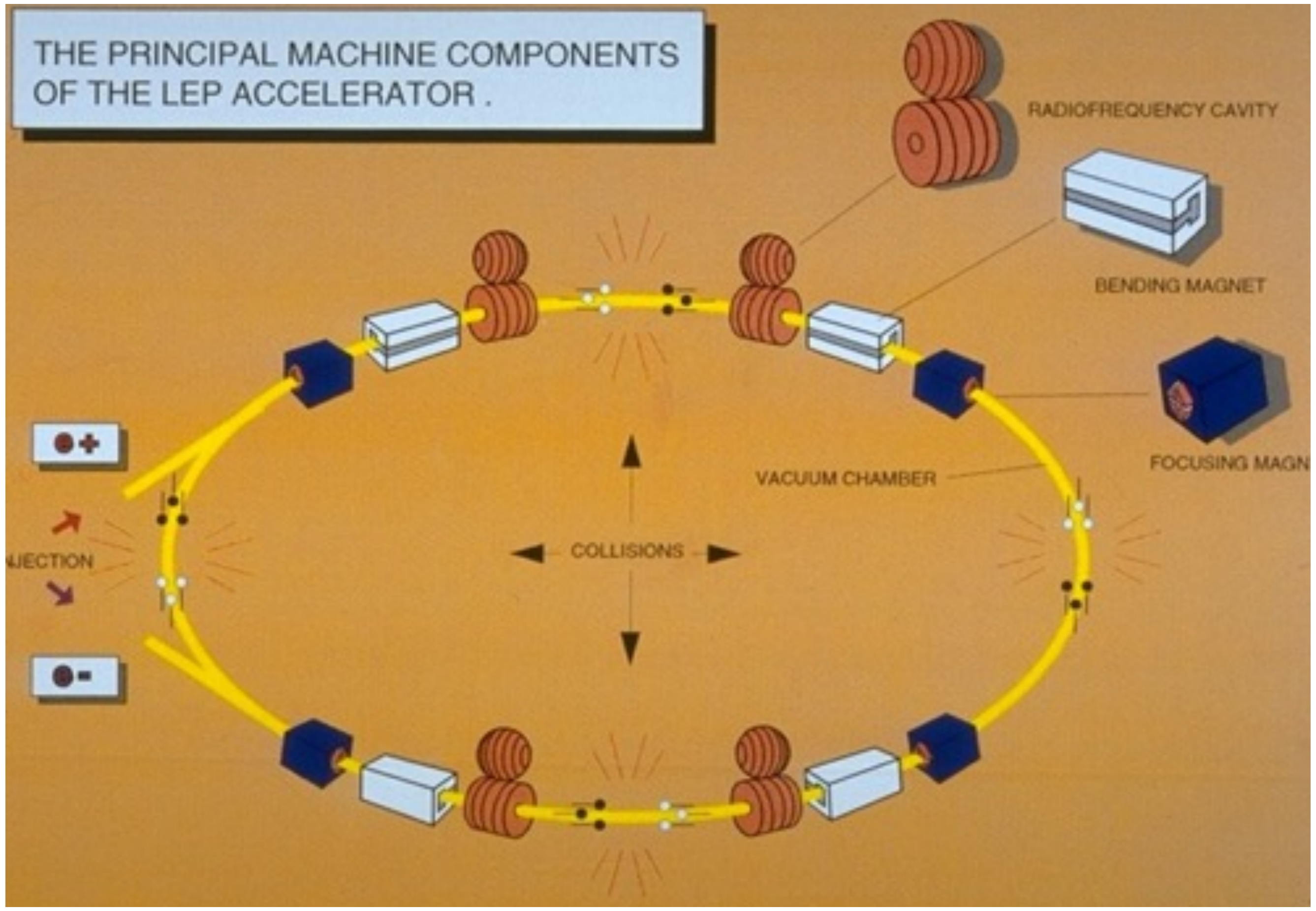
# Circular colliders — basic components




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

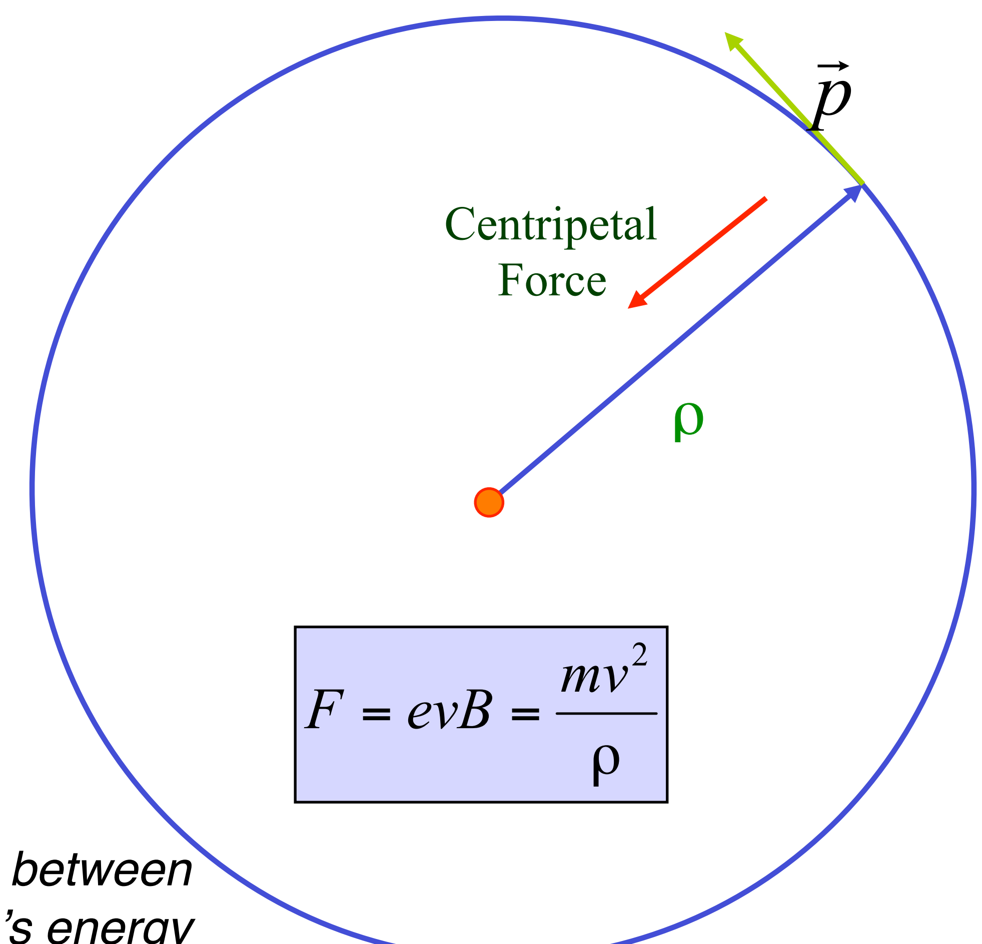
$$\vec{F} = e(\vec{v} \times \vec{B} + \vec{E})$$

Magnetic rigidity

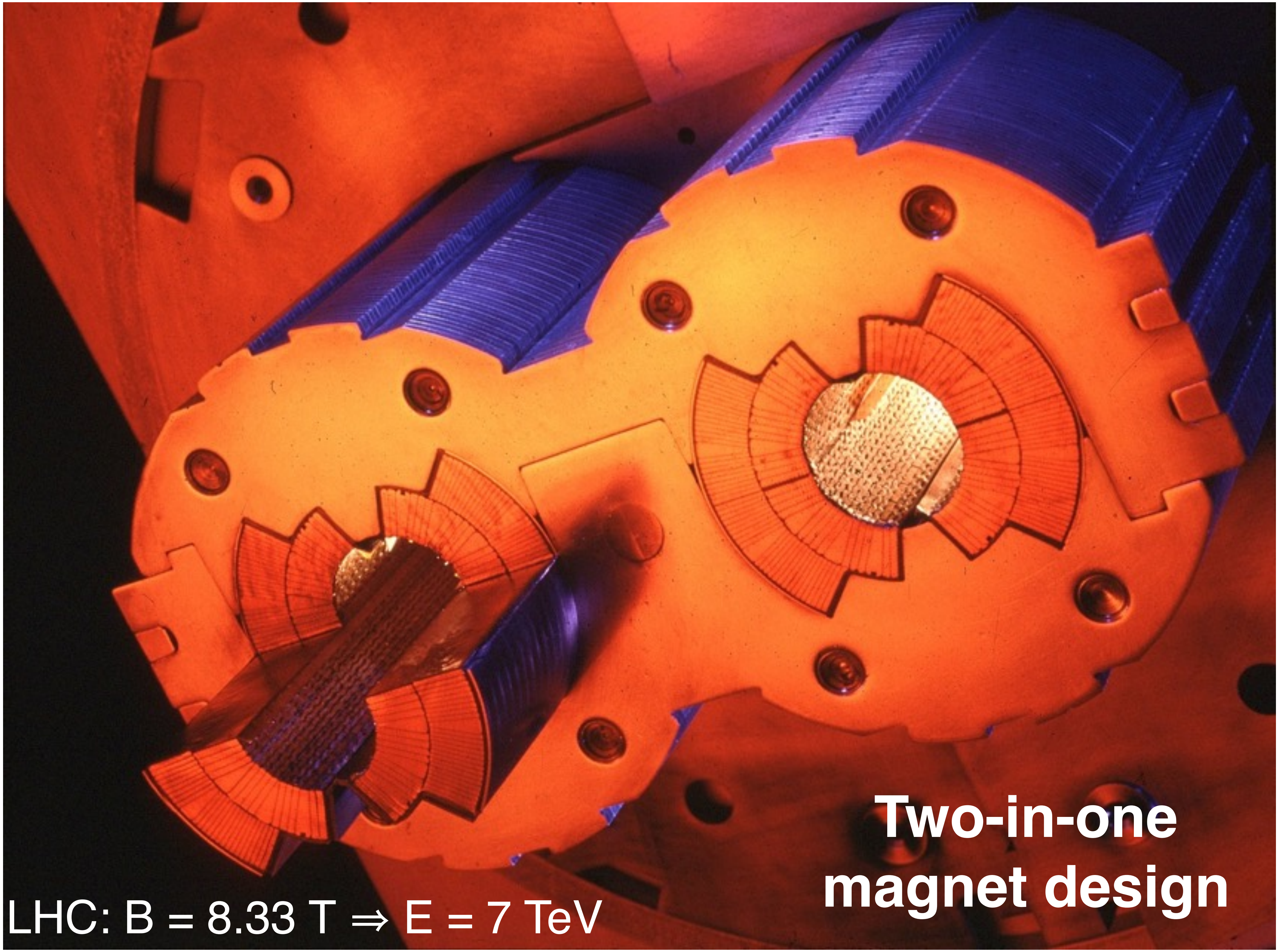
$$B\rho = \frac{mv}{e} = \frac{p}{e}$$

*LHC: ρ = 2.8 km*
*(given by existing LEP tunnel)*

*Fixes the relation between magnetic field and particle's energy*



# Bending



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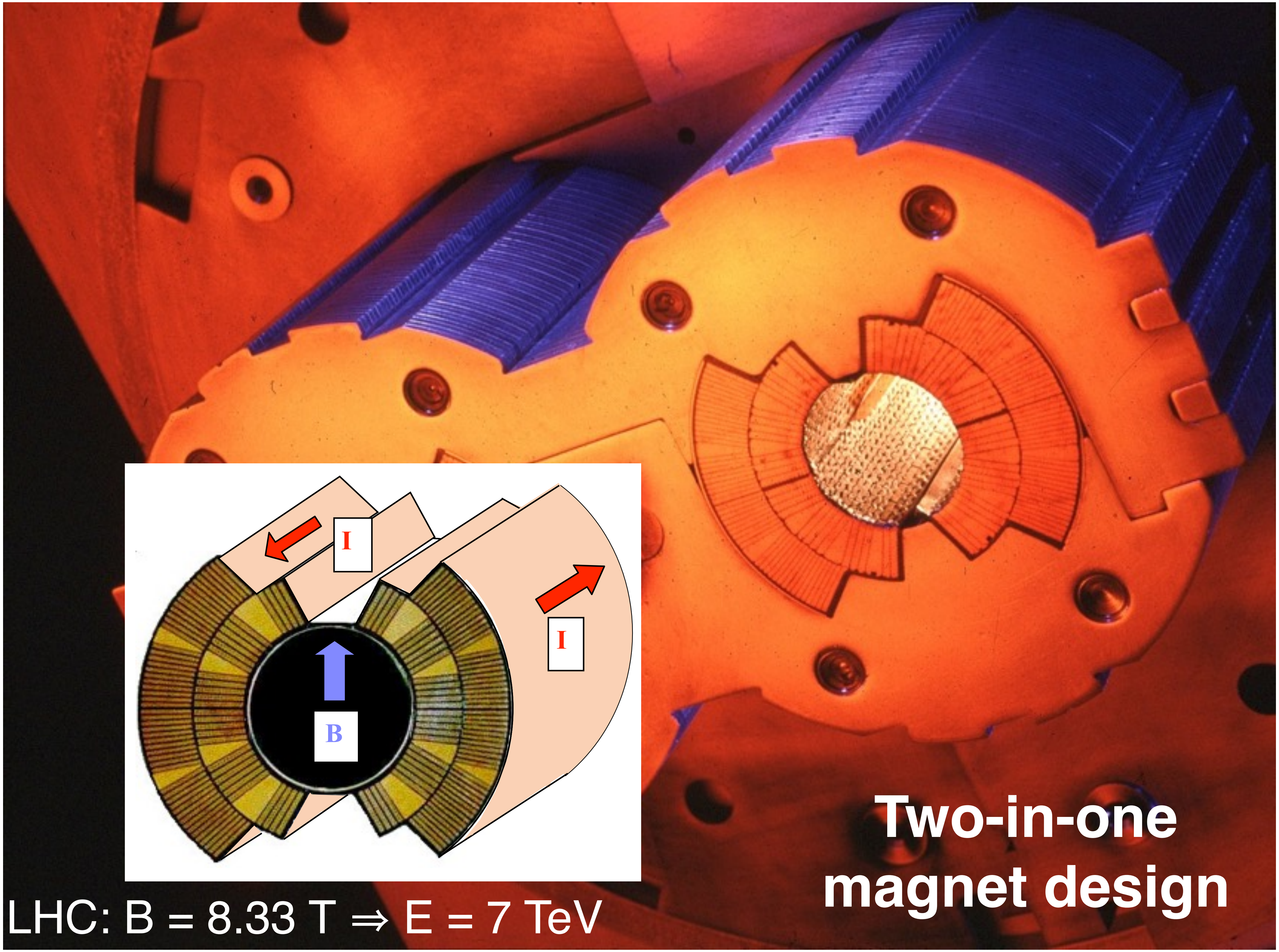
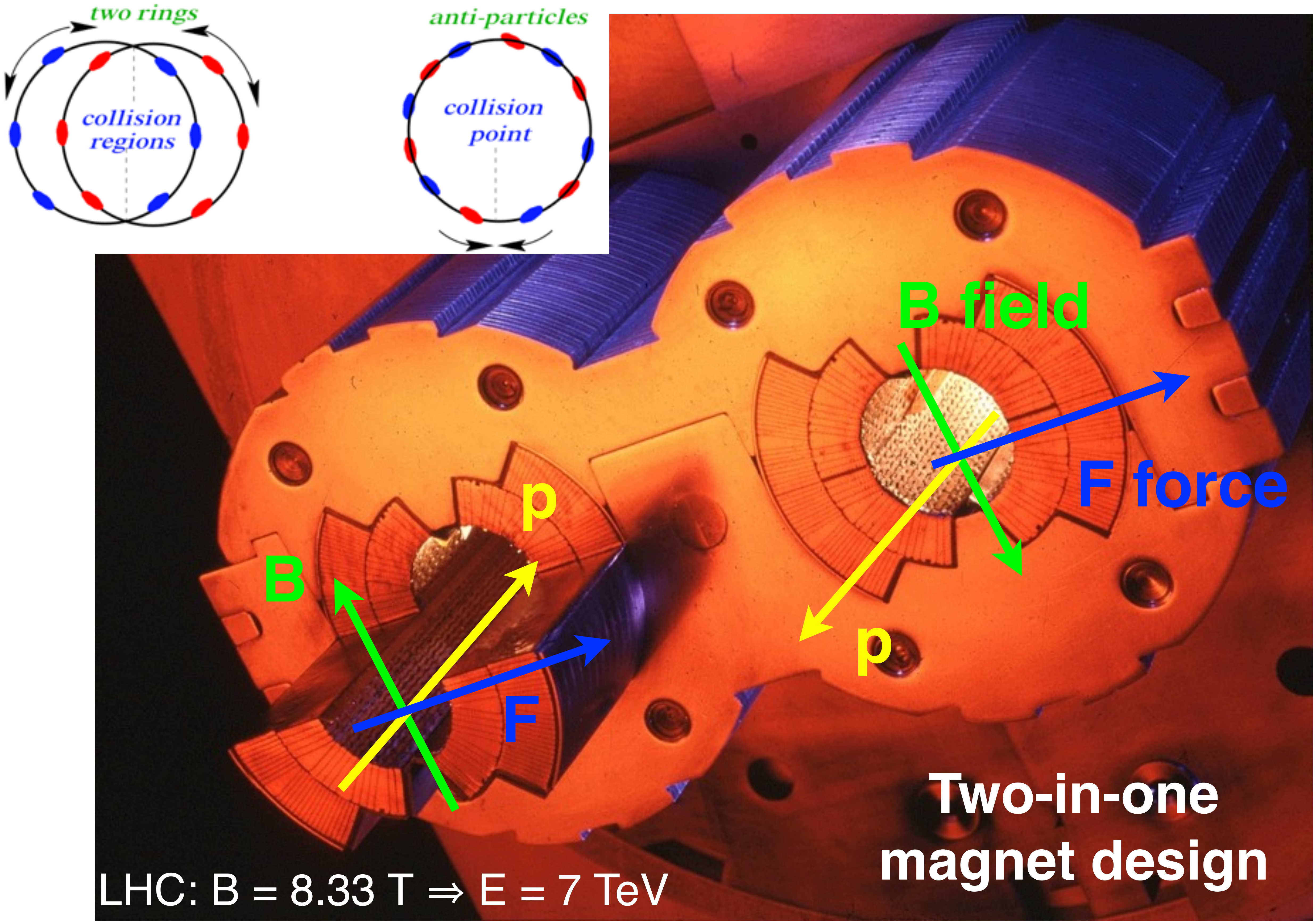
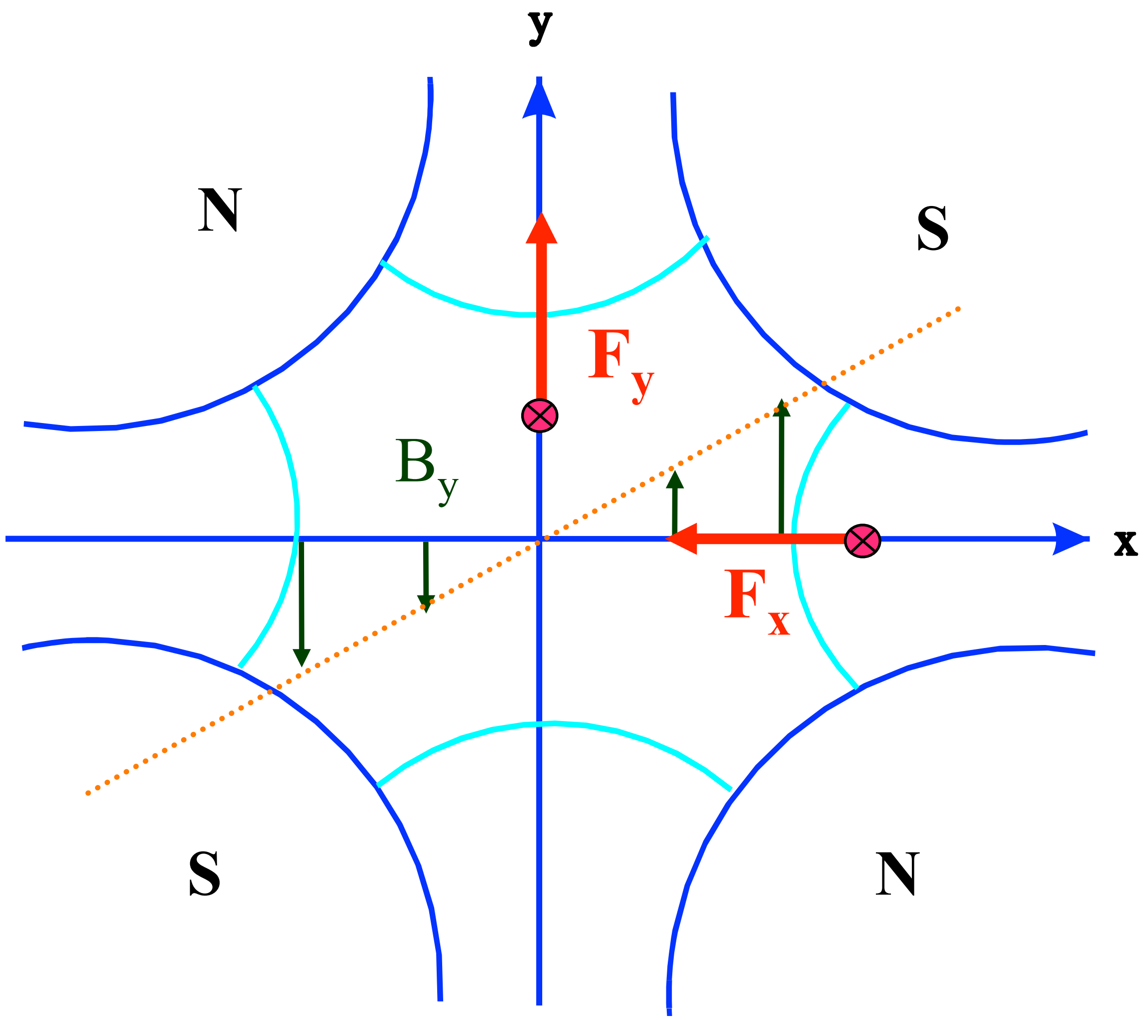
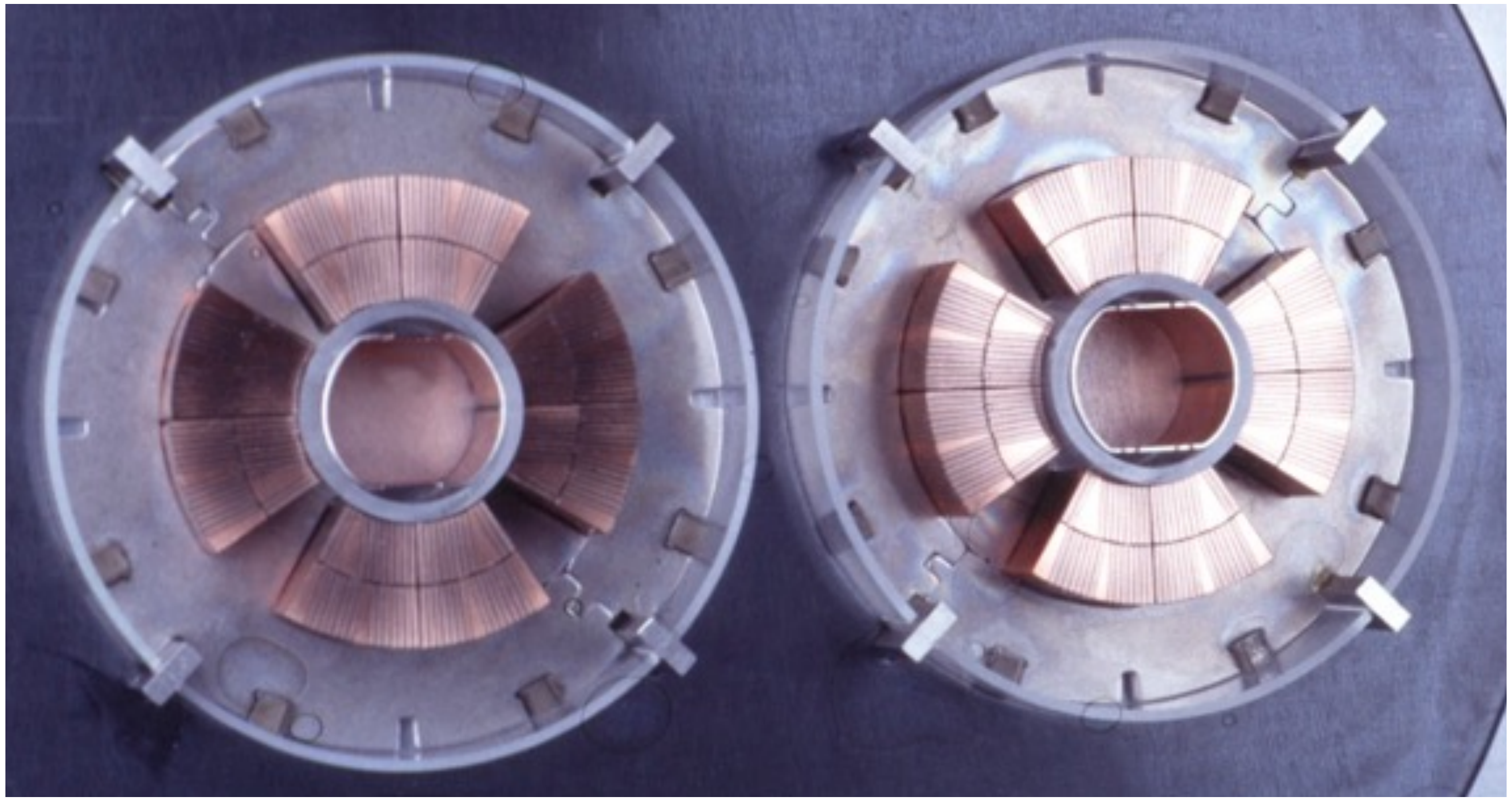


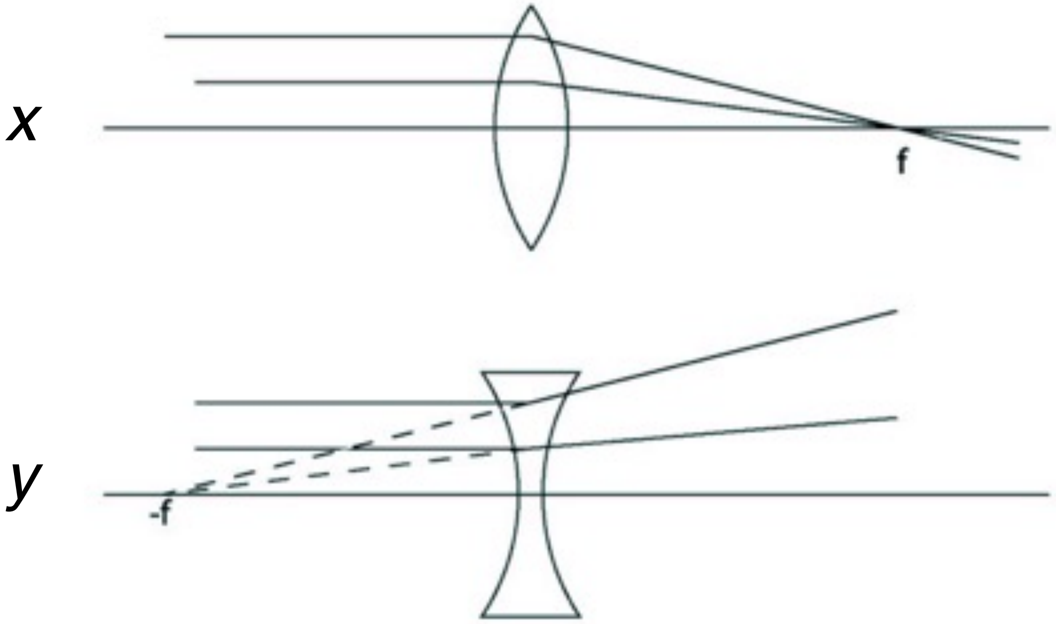
# Bending


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

# Focusing



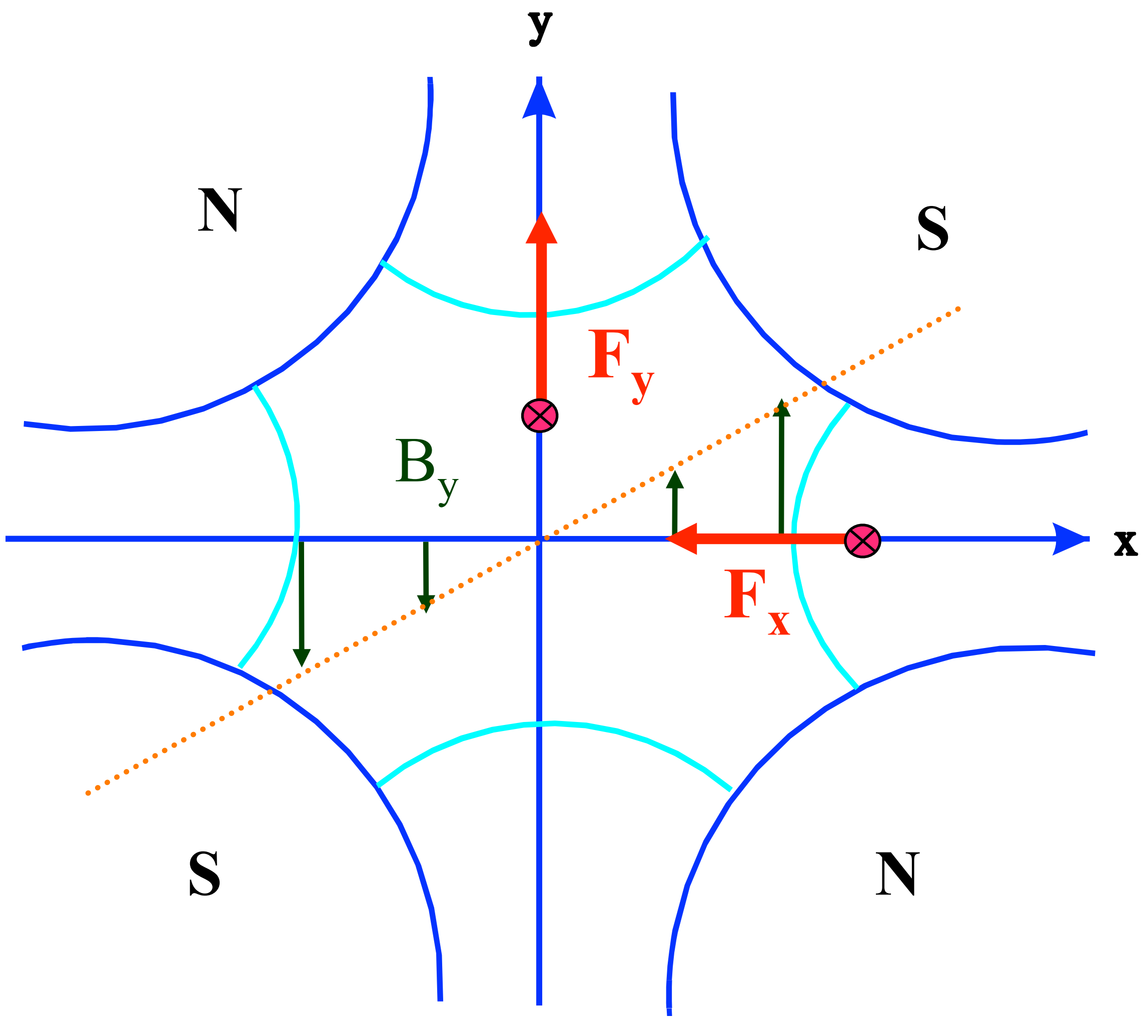


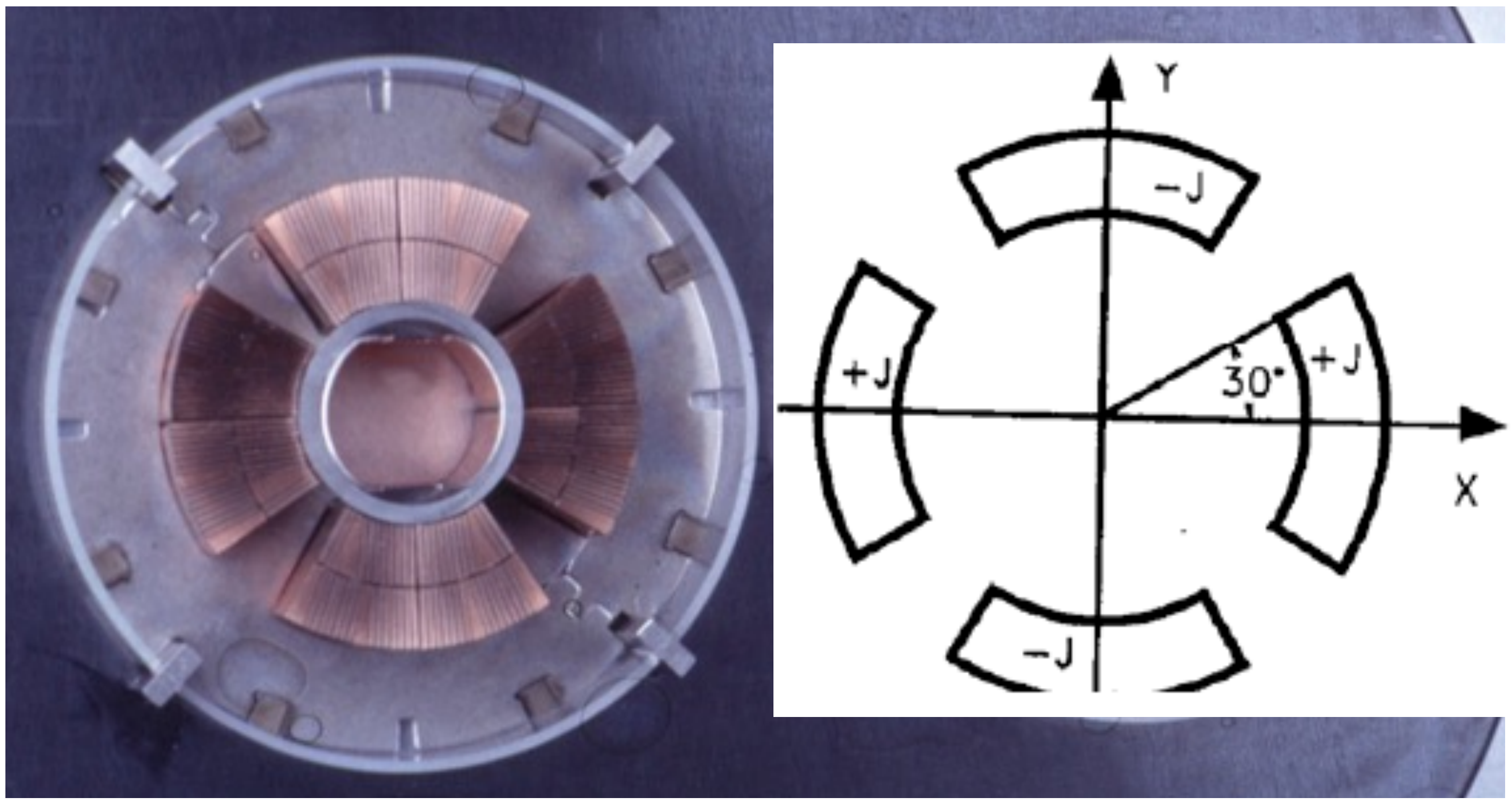

Transverse focusing is achieved with **quadrupole magnets**, which act on the beam like an optical lens.

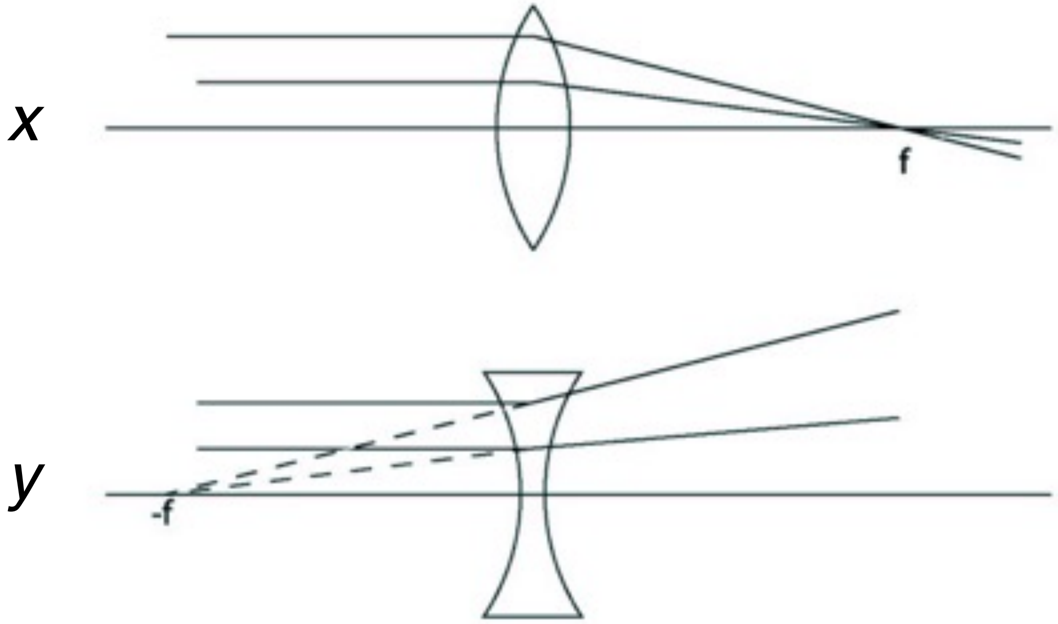
Linear increase of the magnetic field along the axes (no effect on axis) — quadrupole **gradient**.

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

# Focusing

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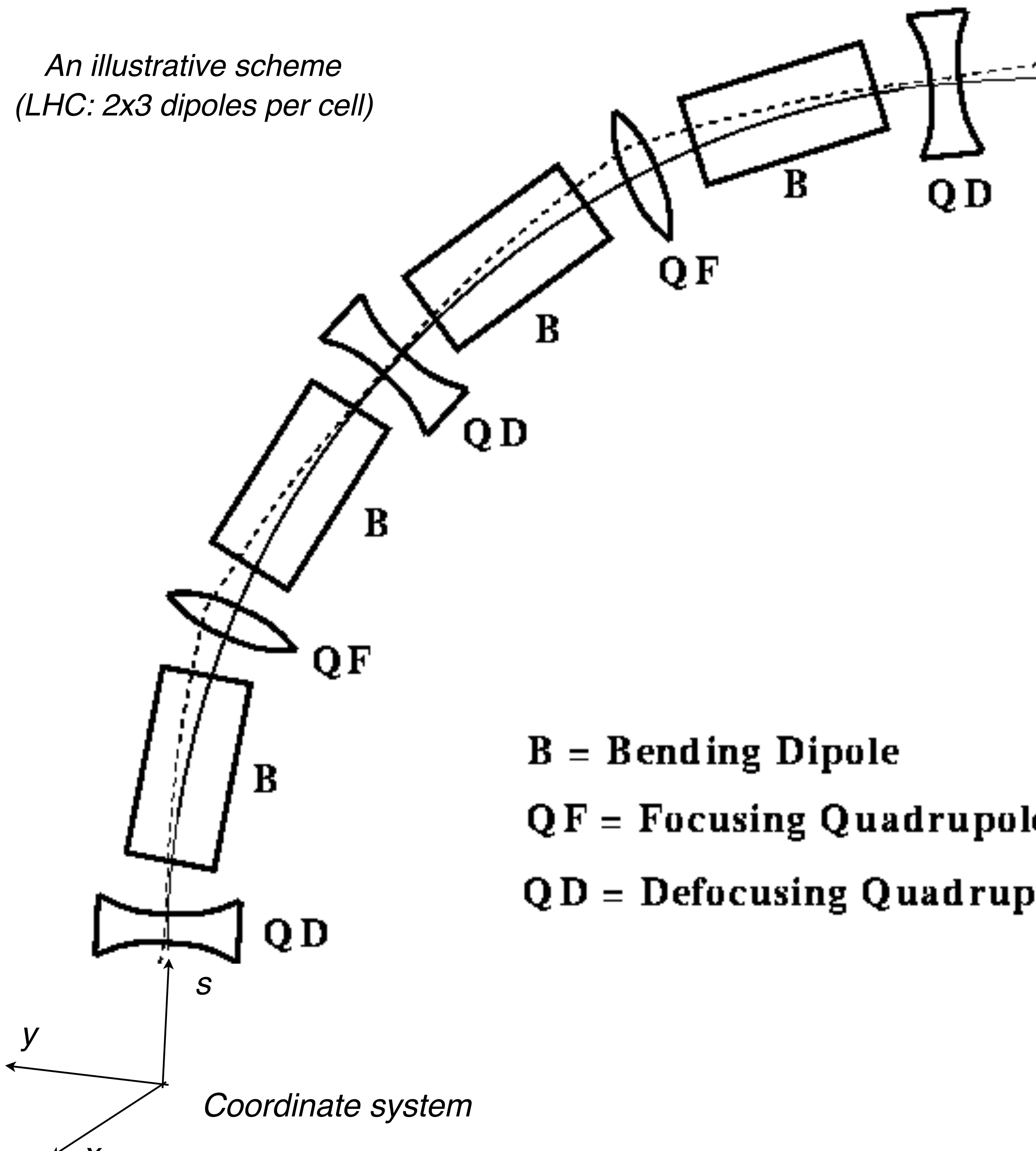
# Alternating gradient lattice

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




B = Bending Dipole

QF = Focusing Quadrupole

QD = Defocusing Quadrupole

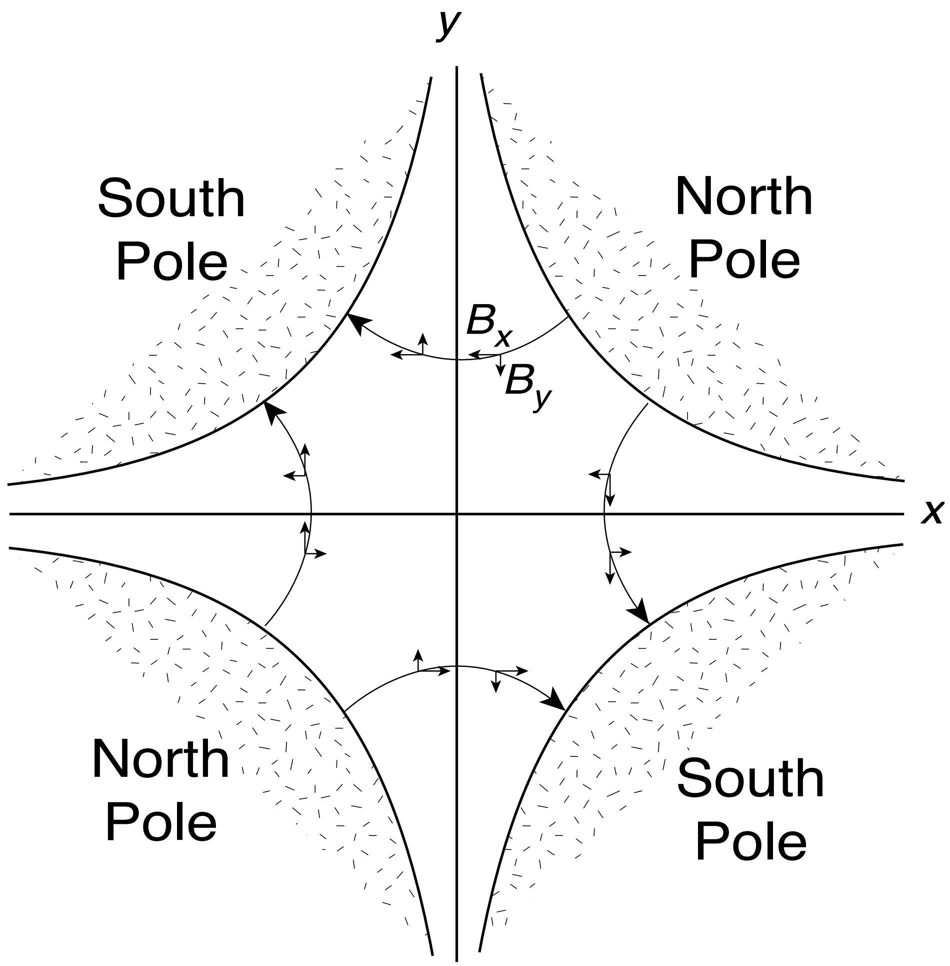
*Coordinate system*

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.

Alternate-gradient quadrupole magnets focus 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$^{-2}$] : $$K = \frac{g}{p_0/e} = \frac{1}{f}$$

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

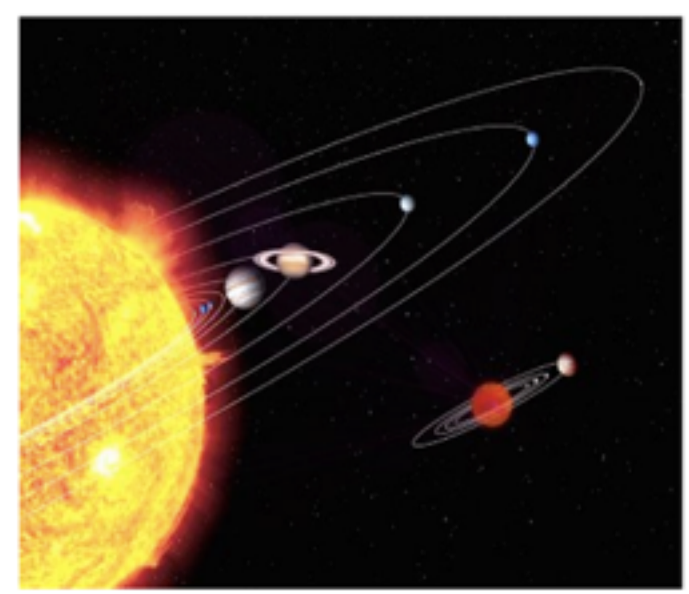
**Hill's equation**

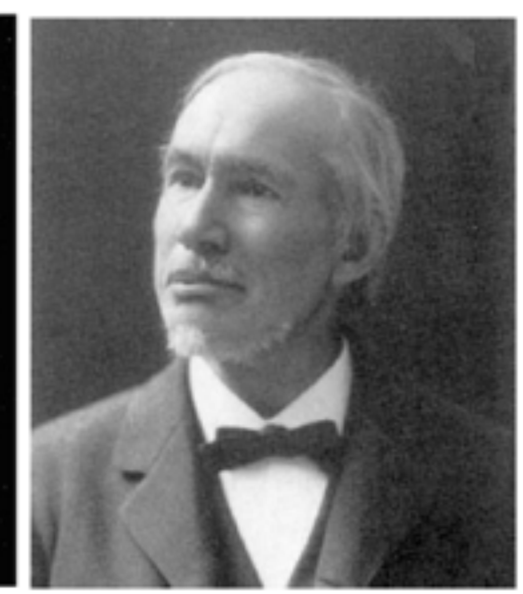
K(s) describes the distribution of focusing strength along the lattice.

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

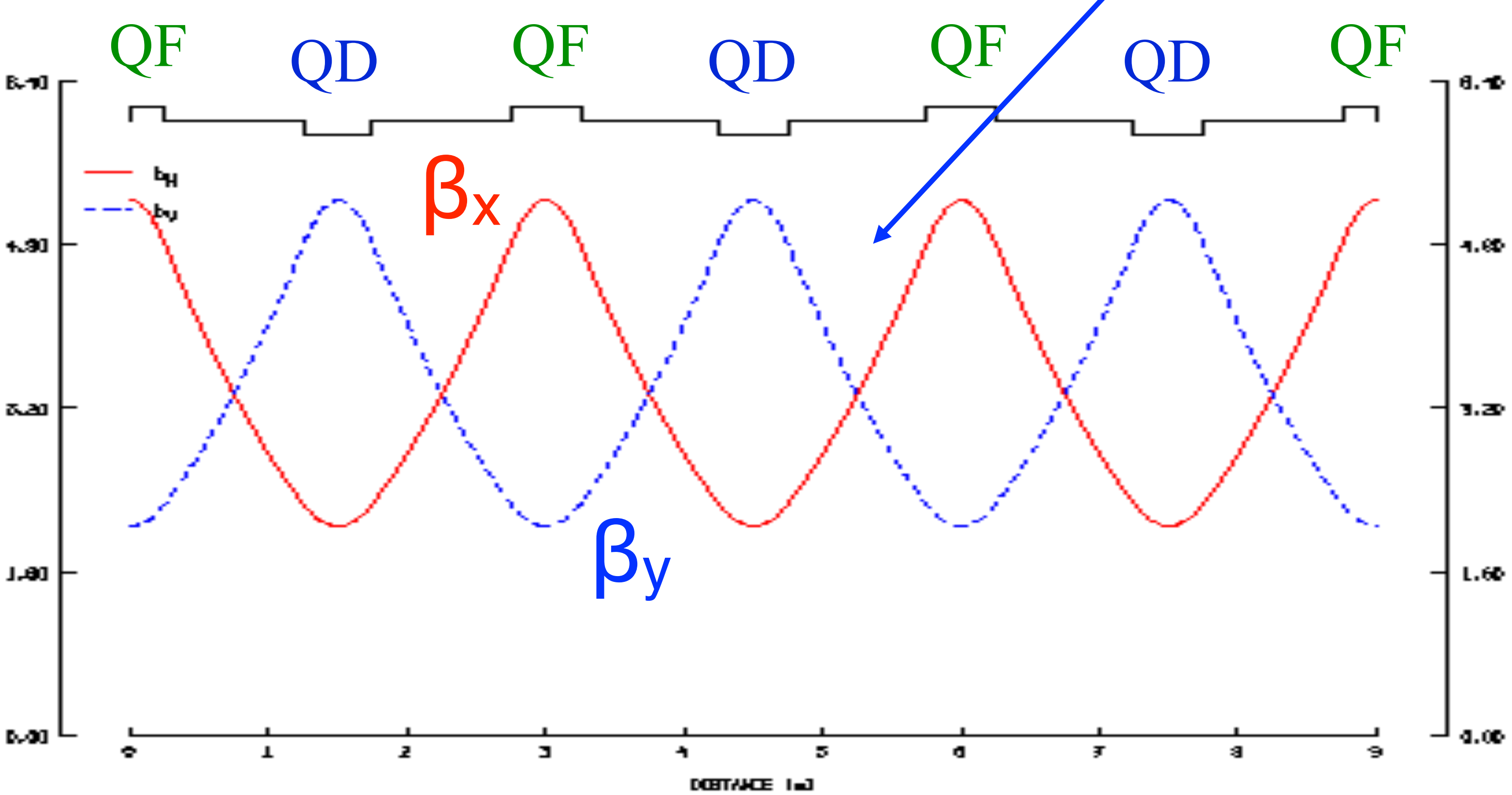
The solution of Hill's equation:

(*s* is the longitudinal coordinate)

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

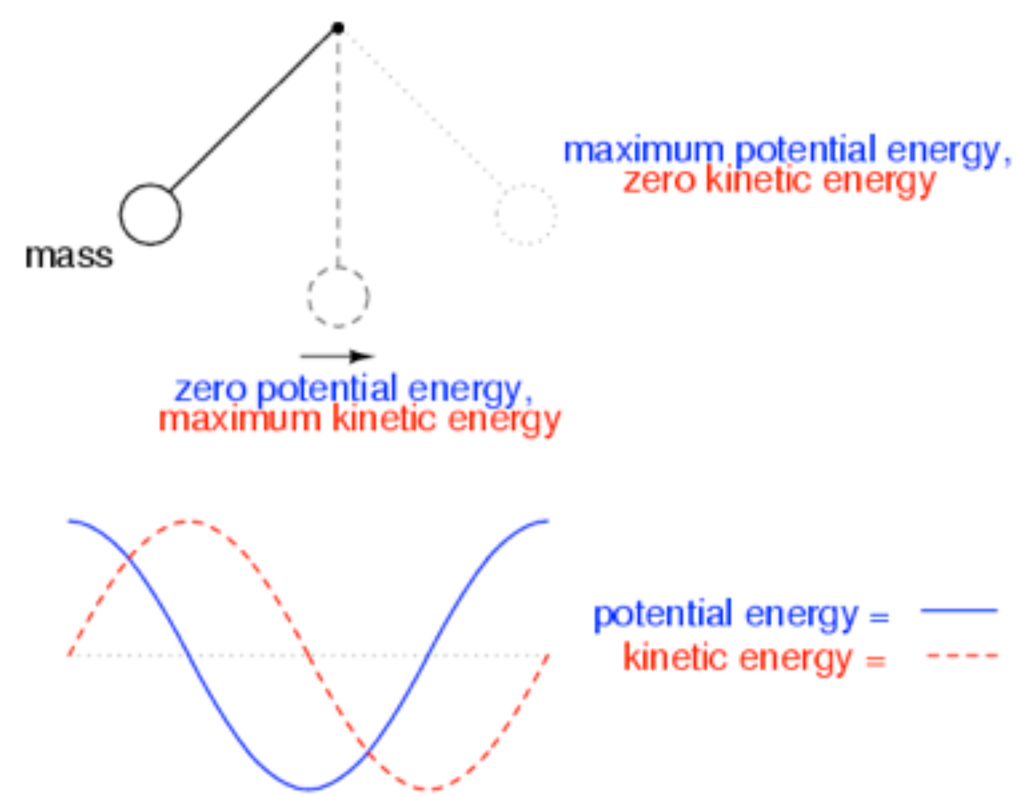
*s*-dependent amplitude

Oscillatory term




Betatron functions in a simple FODO cell

It is analogous to the general solution of a simple harmonic motion:



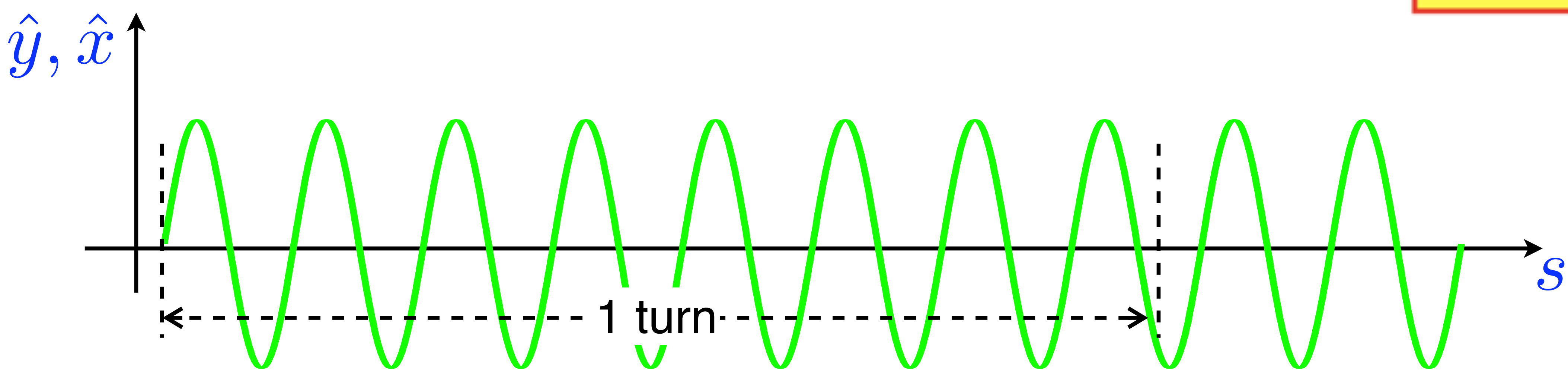
# Betatron tune

Betatron phase advance over 1 turn:

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

**Betatron tune:**

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

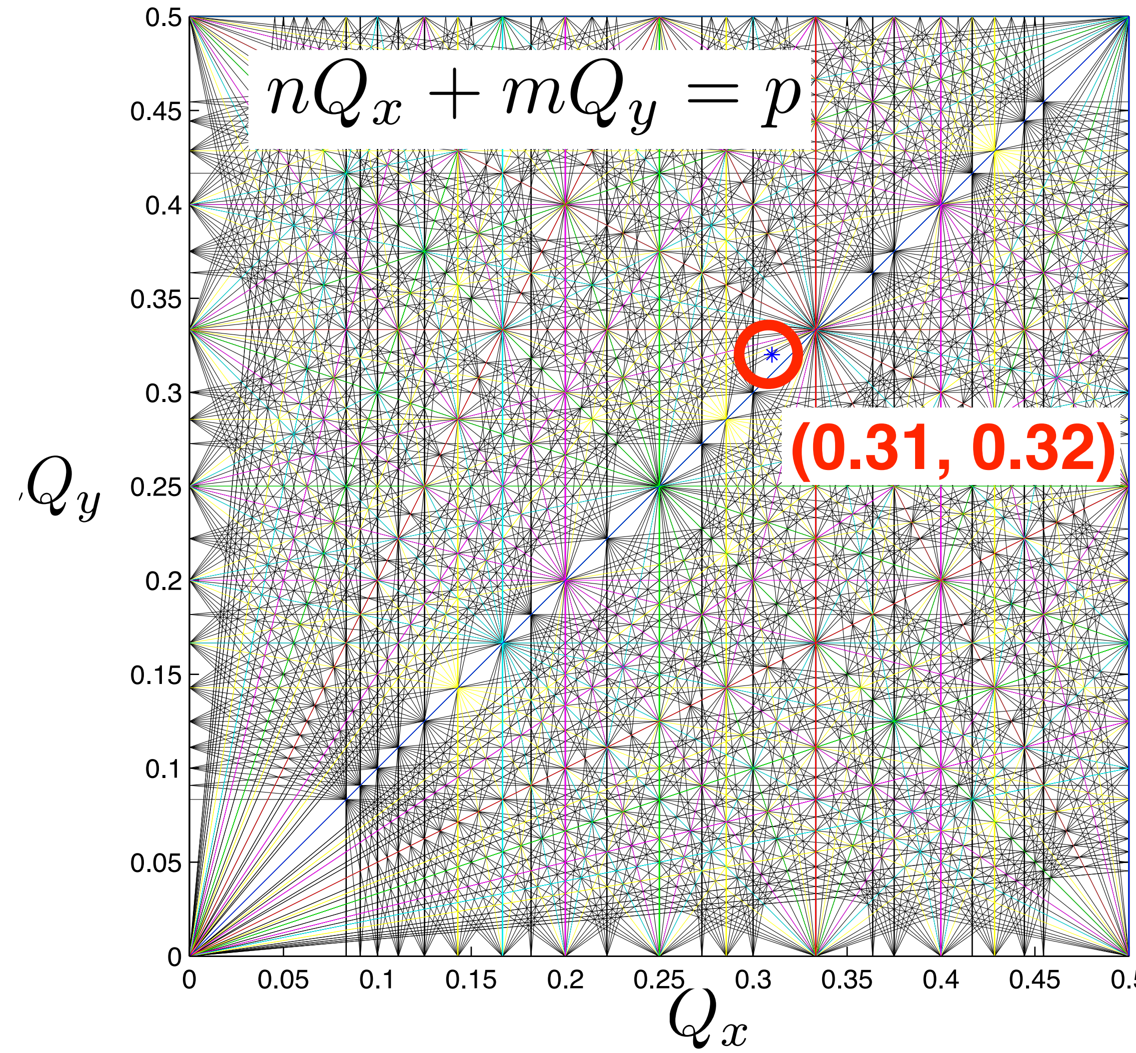



The tune is the **number of betatron oscillations per turn**.

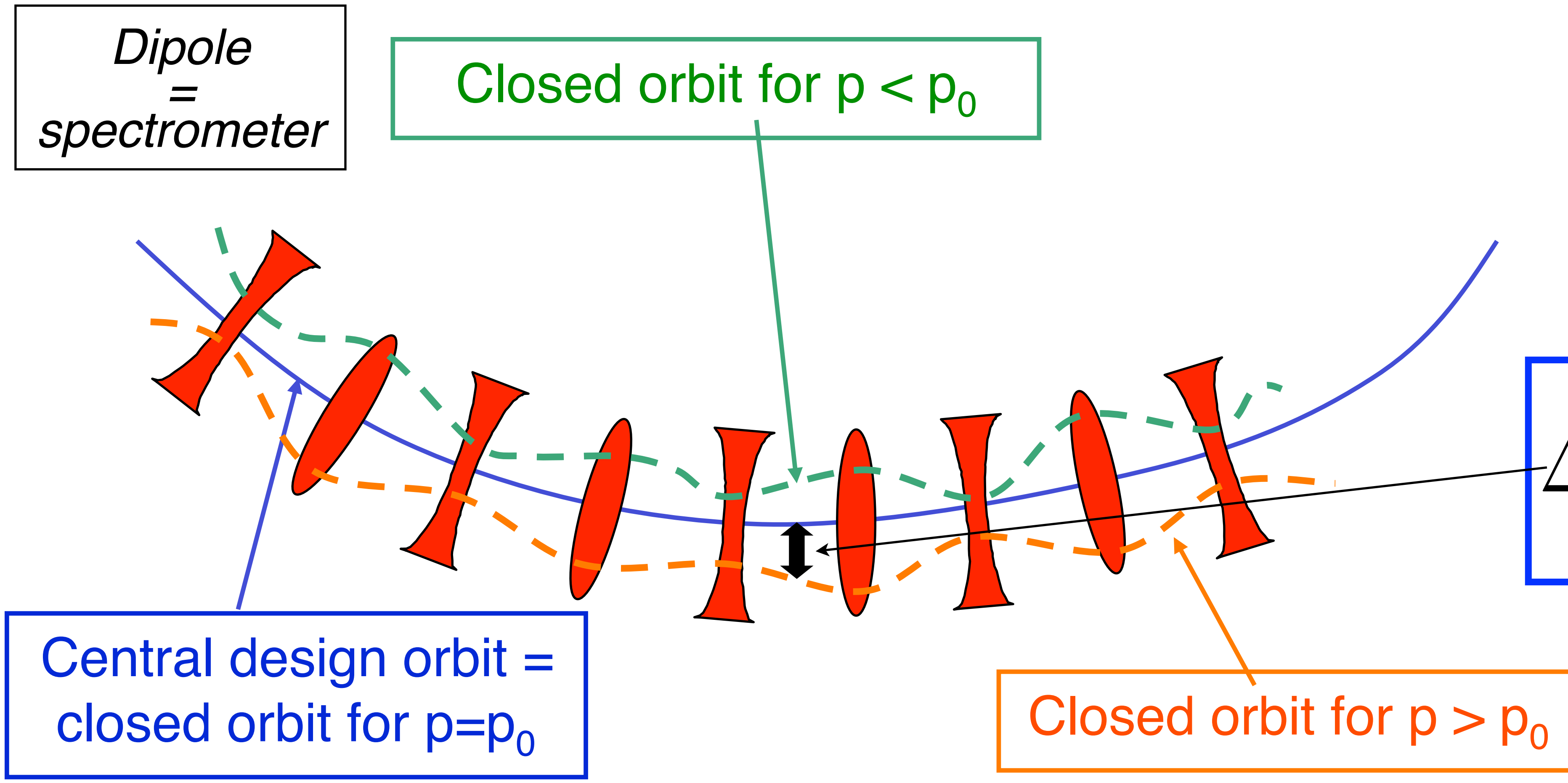
We *normally* only care about the **fractional part** of the tune! 64.31 is 0.31!

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

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

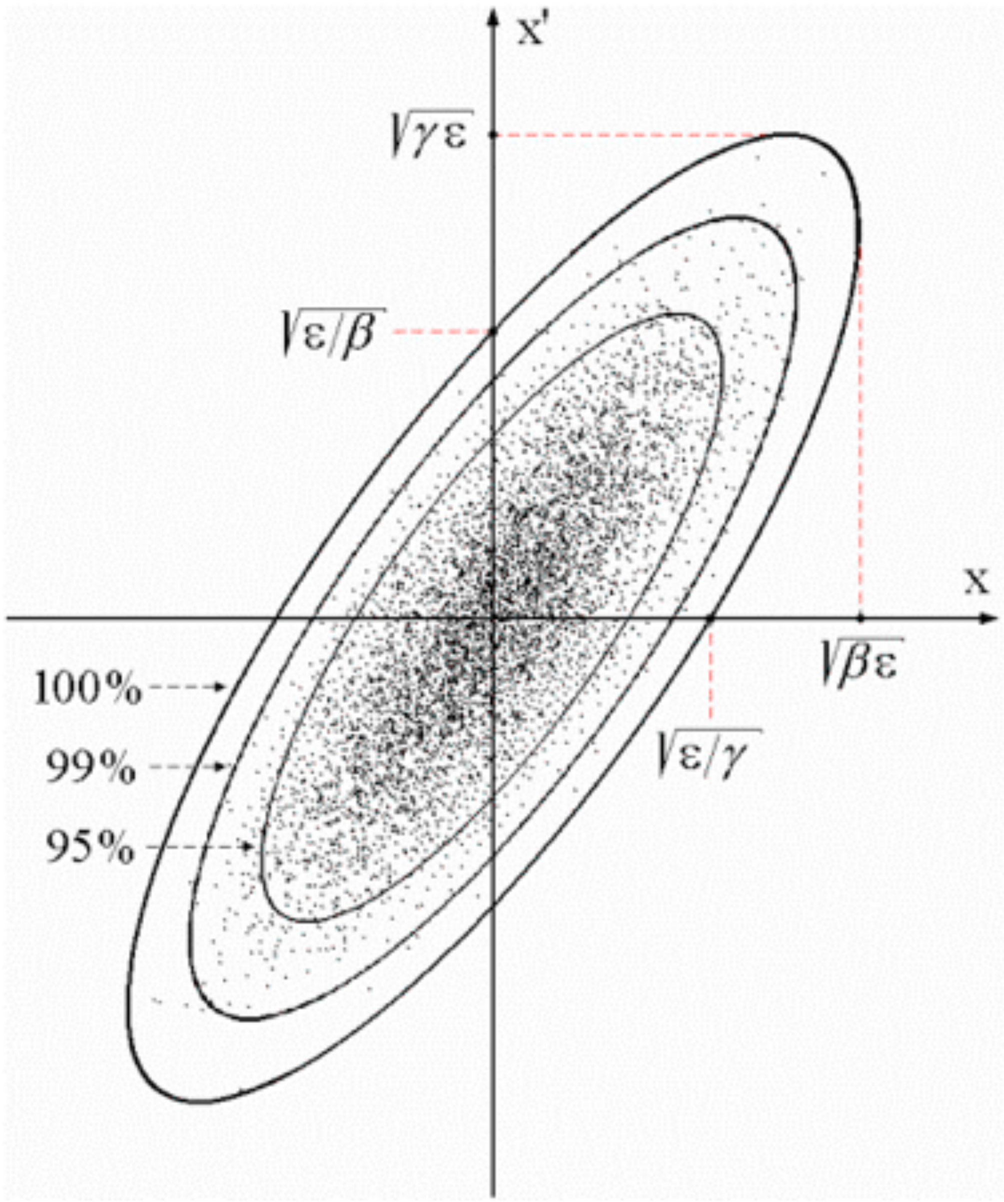
$$x'' + K(s)x = \frac{1}{\rho}\frac{\Delta p}{p_0}$$

*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

$A_i$, $\phi_i$, $\Delta p/p_i$ → 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

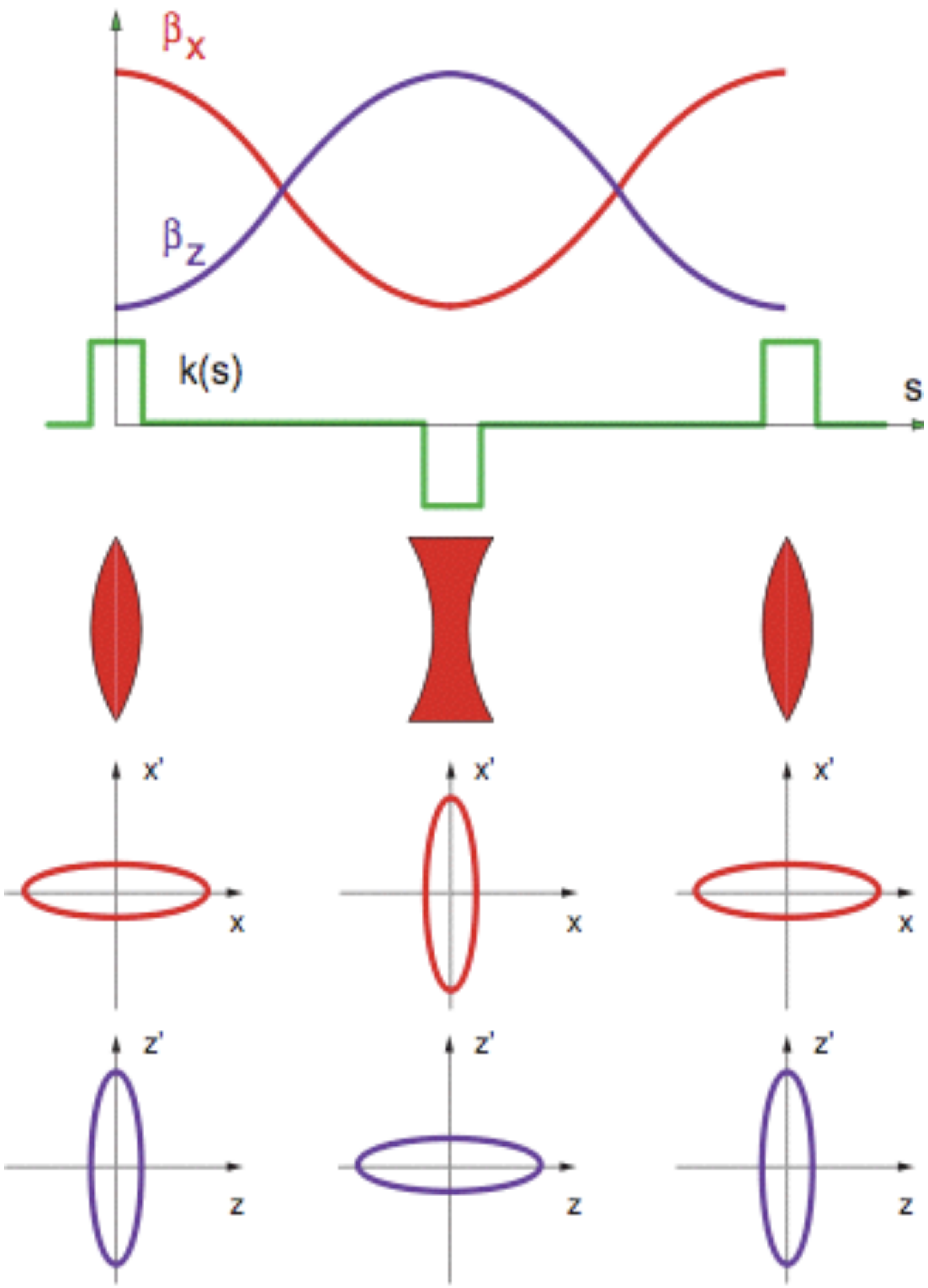
Beam size $$\sigma_x(s) = \sqrt{\epsilon\beta_x(s) + [D_x(s)\delta]^2}$$

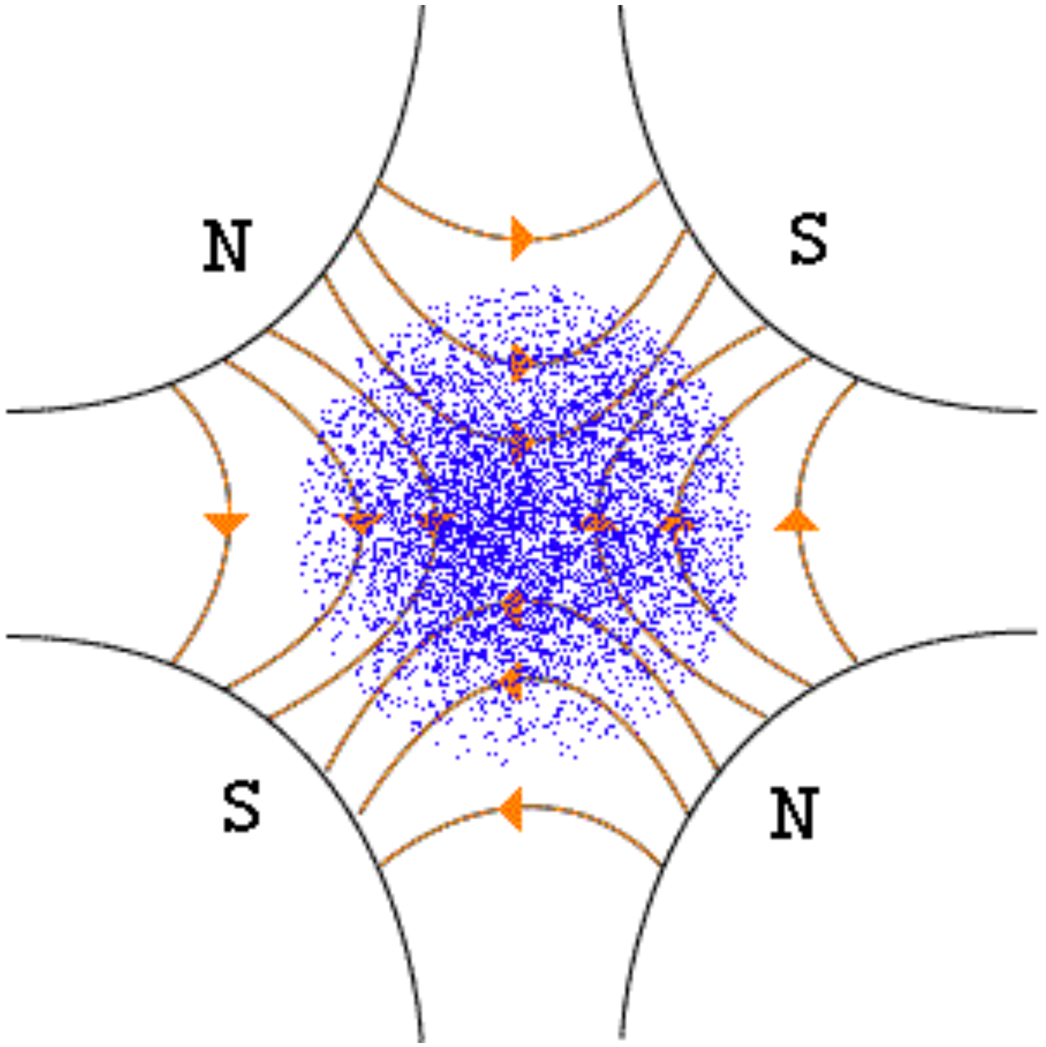
Bunch energy spread $$\delta = \left(\frac{\Delta p}{p}\right)_{\rm rms}$$

*Betatronic contribution*

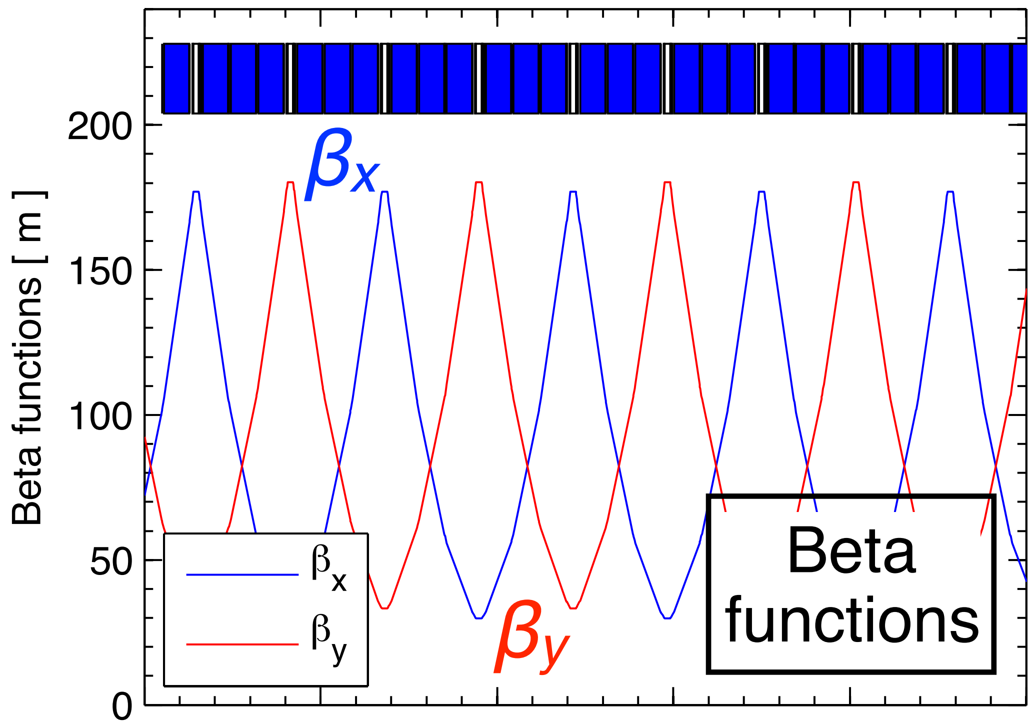
*Dispersive contribution*

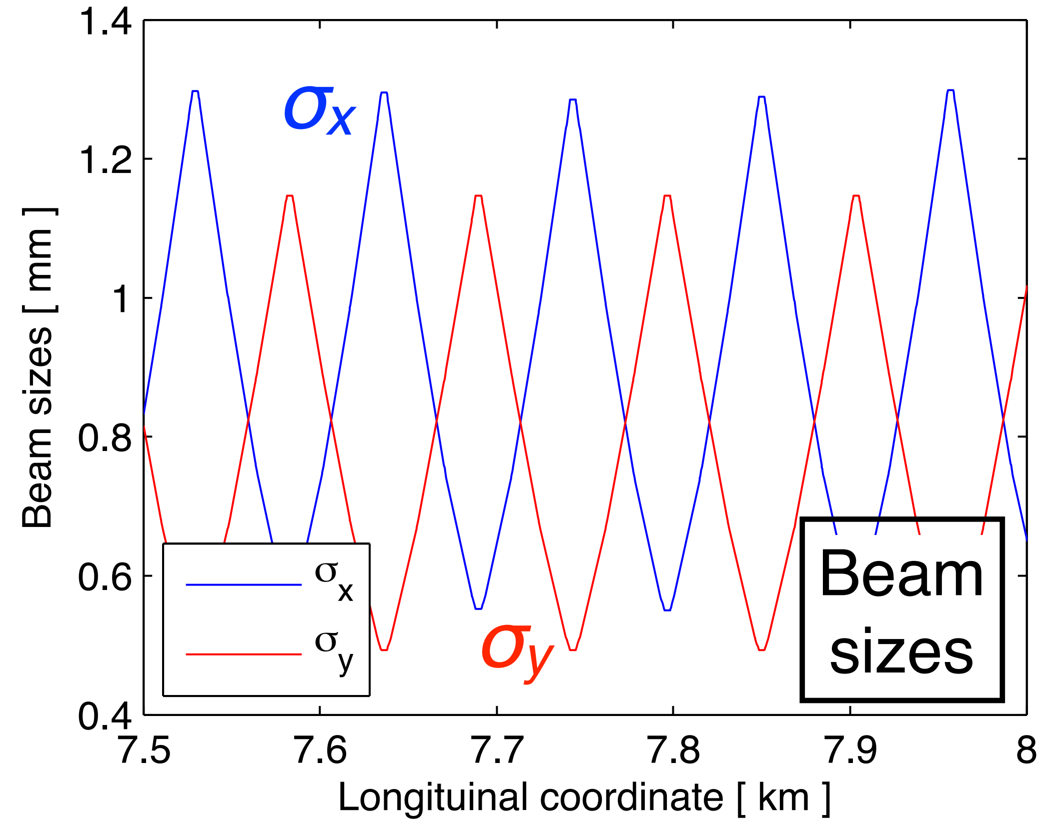
# Emittance and beam size (ii)

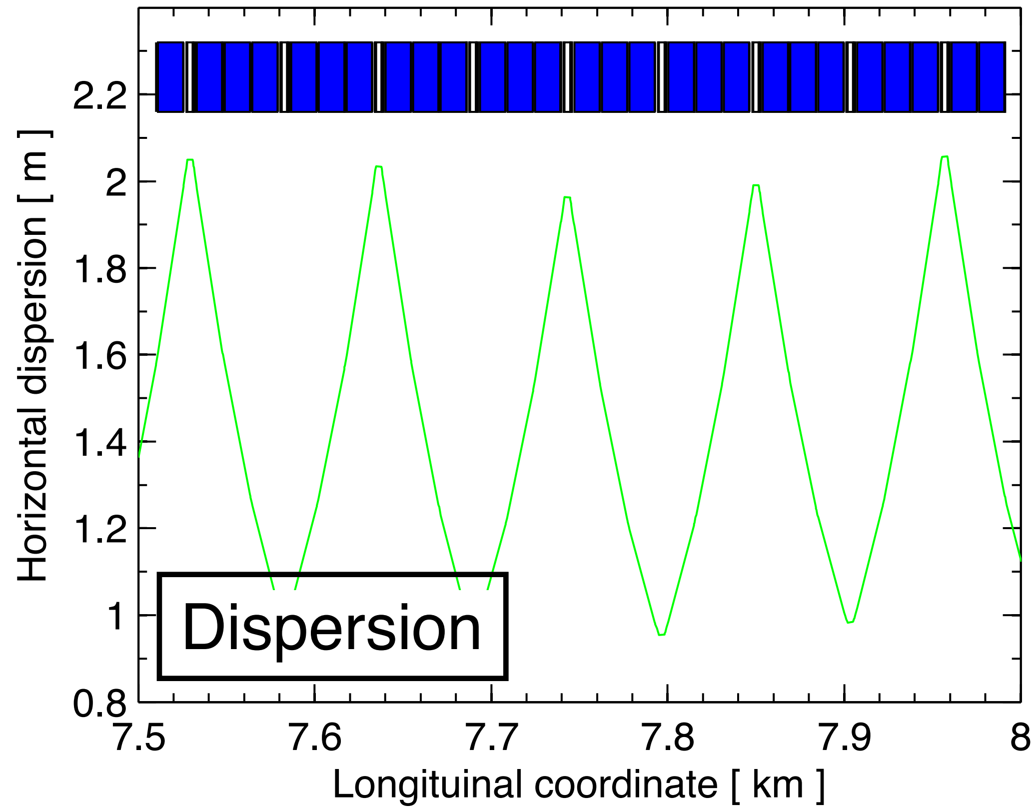


# Example for the LHC arc (450 GeV)



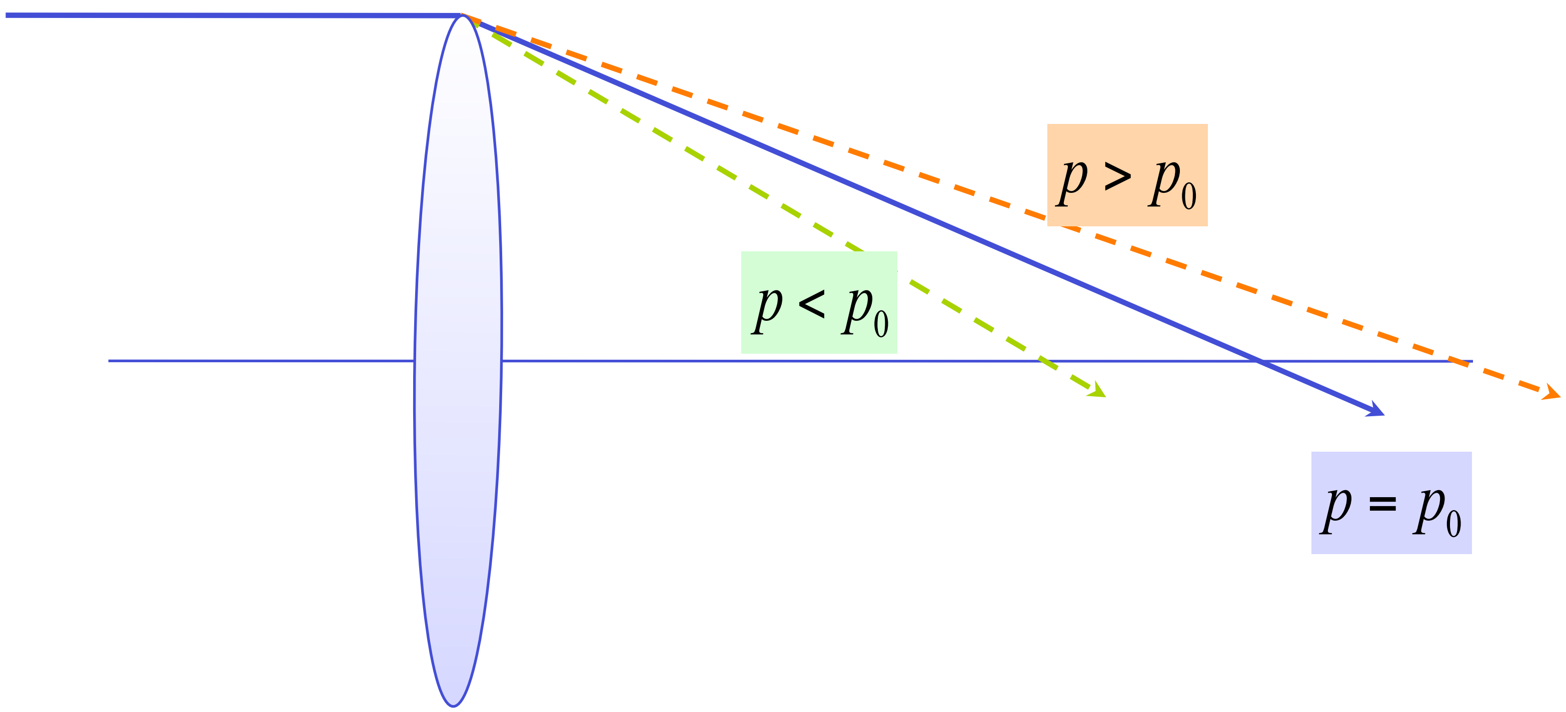

$$\beta_{x,y} = 30 \div 180\text{m}$$

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

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

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

# Chromaticity




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

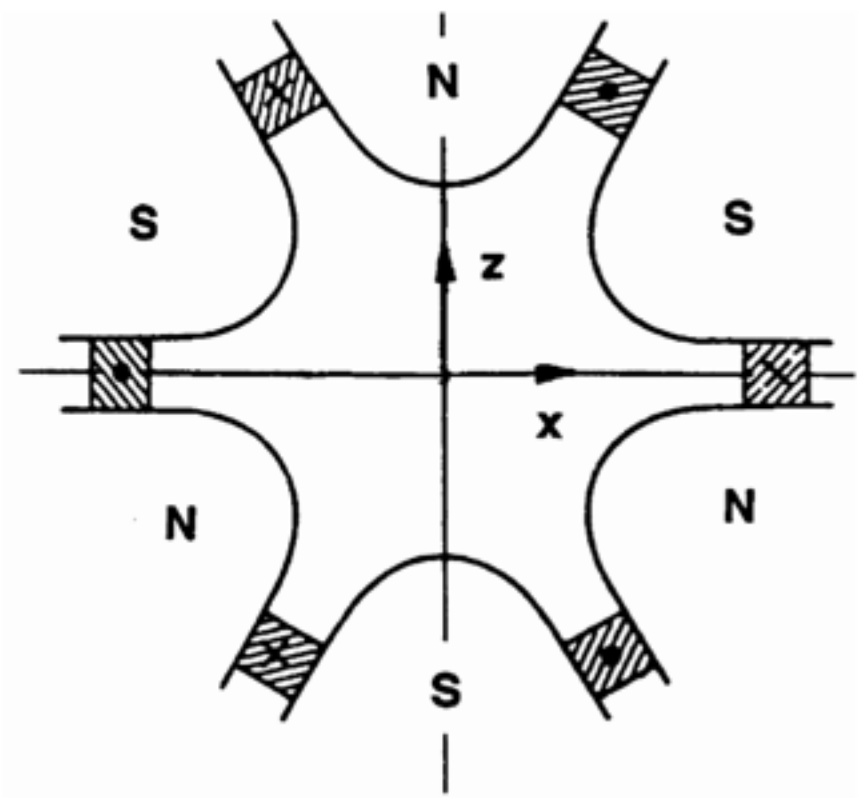
Particles with different energies have different betatron tunes.

Bad 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.



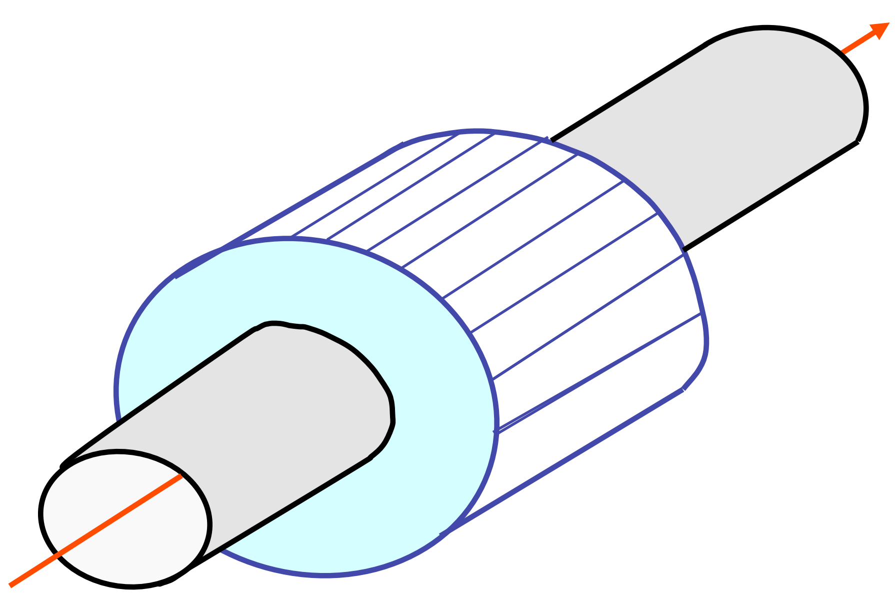
# Beam acceleration

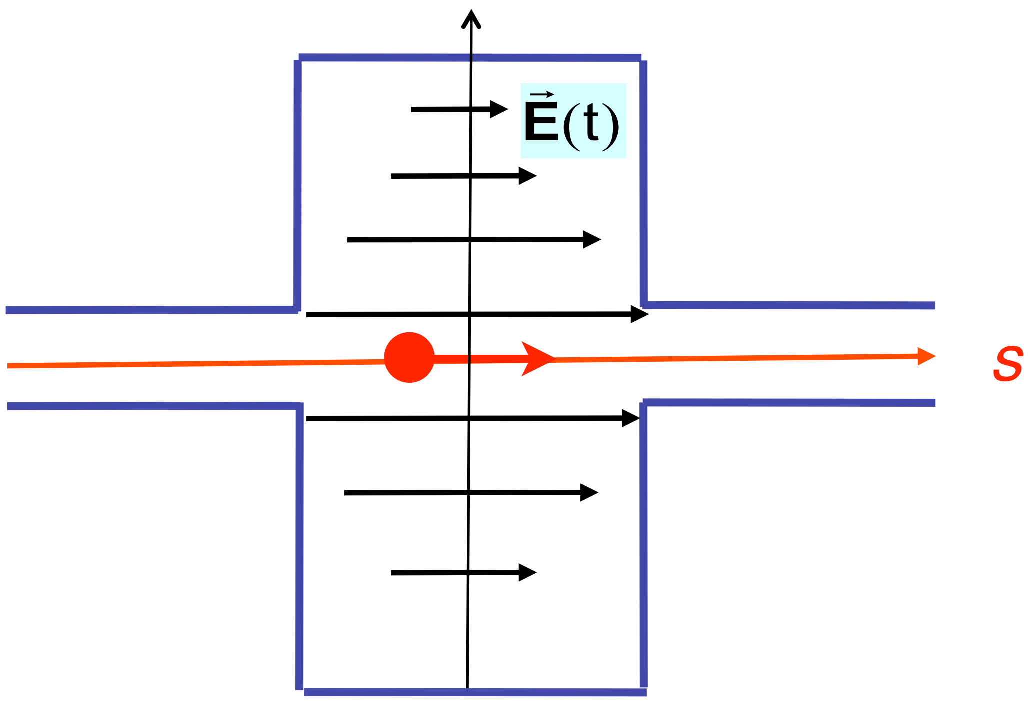
**Acceleration** is performed with electric fields fed into **Radio-Frequency (RF) cavities**.
RF cavities are basically resonators tuned to a selected frequency.

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

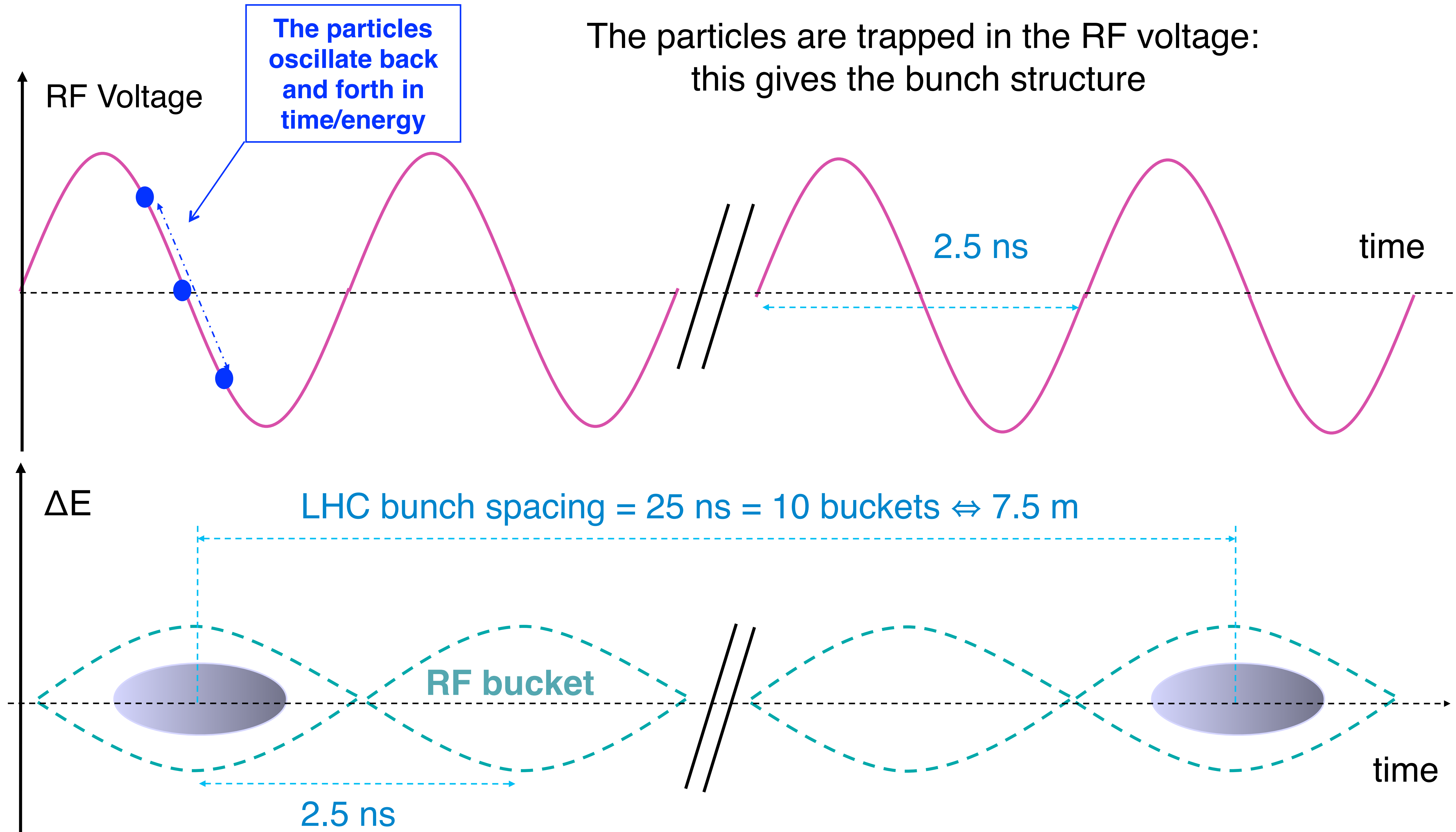
At the LHC, the acceleration from **450 GeV** to **7 TeV** lasts ~ 20 minutes (nominal!), with an average energy gain of ~ 0.5 MeV on each turn.





# Buckets and bunches

The particles are trapped in the RF voltage:
this gives the bunch structure




| | 450 GeV | 7 TeV |
|---|---|---|
| RMS bunch length | 11.2 cm | 7.6 cm |
| RMS energy spread | 0.031% | 0.011% |

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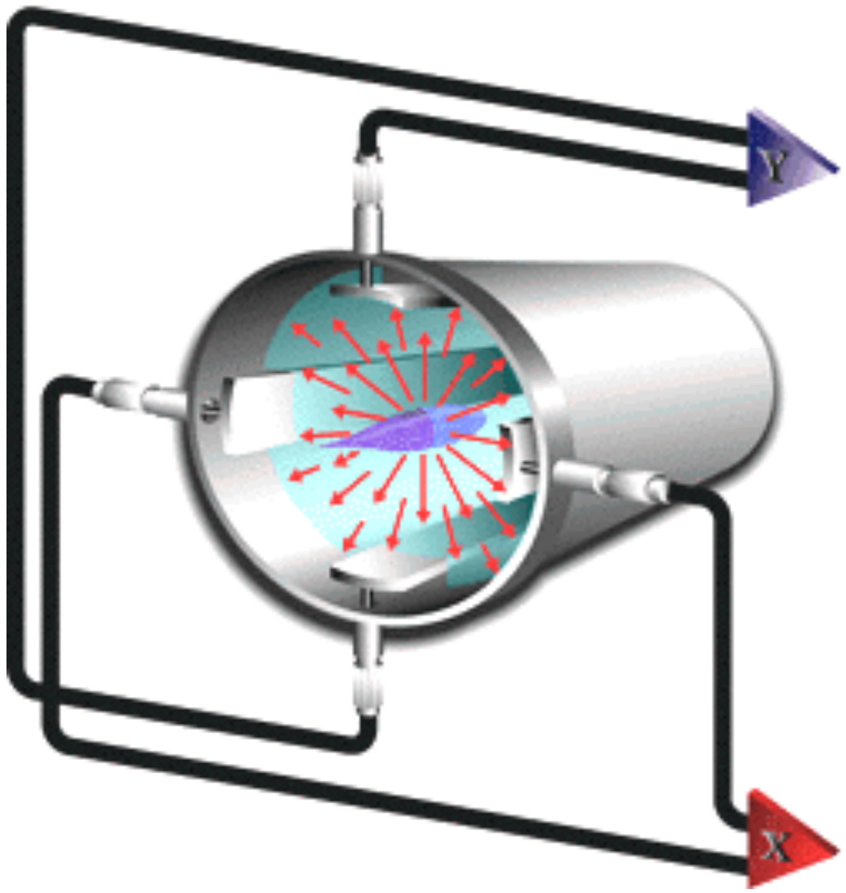
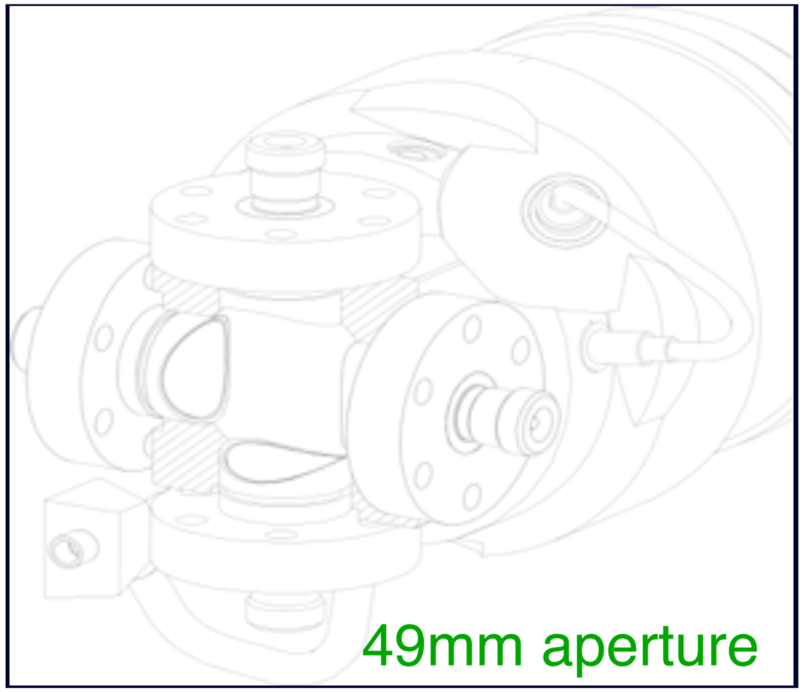
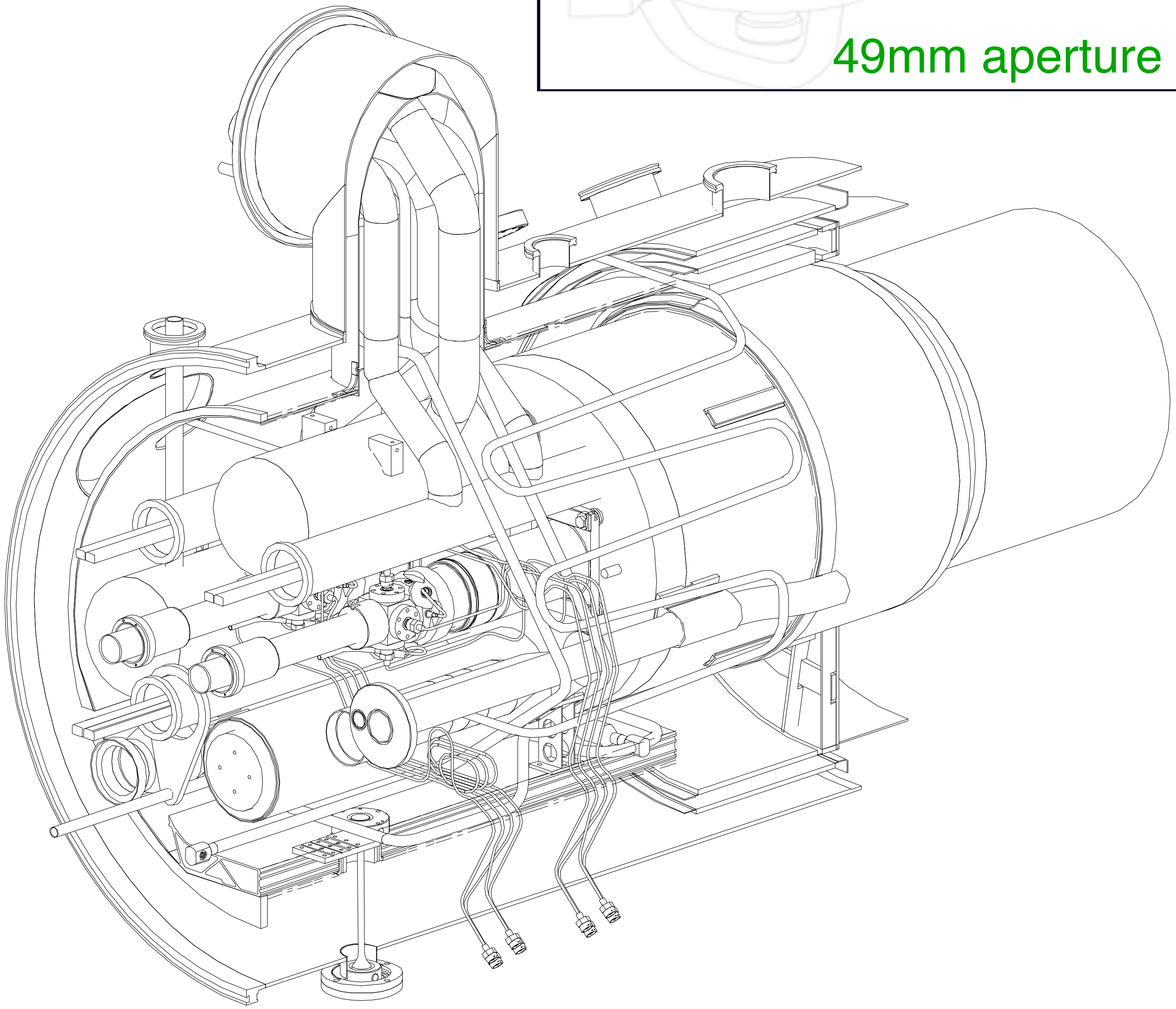
# LHC beam position monitors (BPMs)




*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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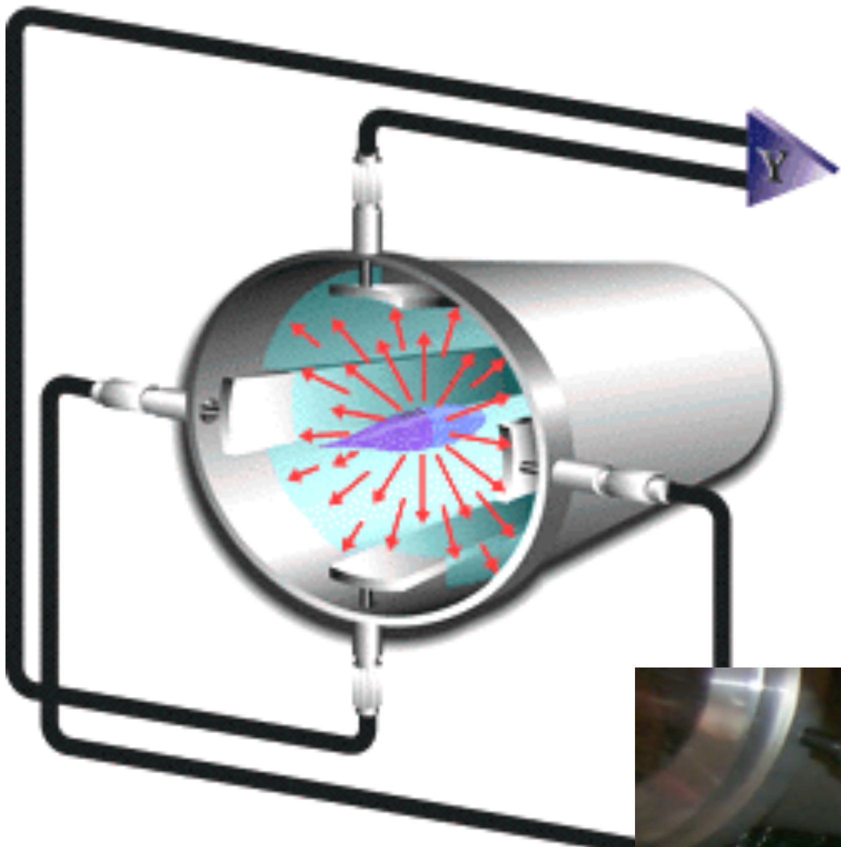


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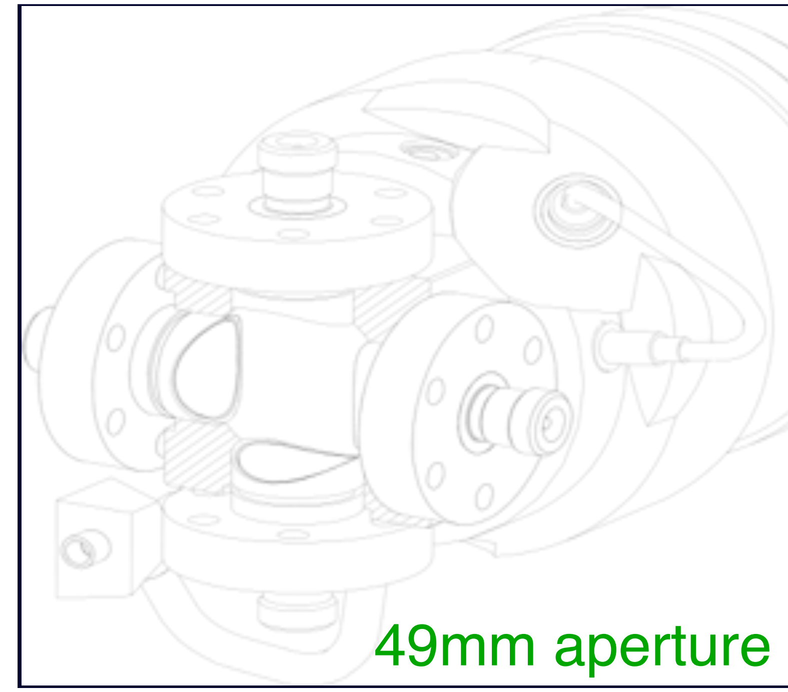
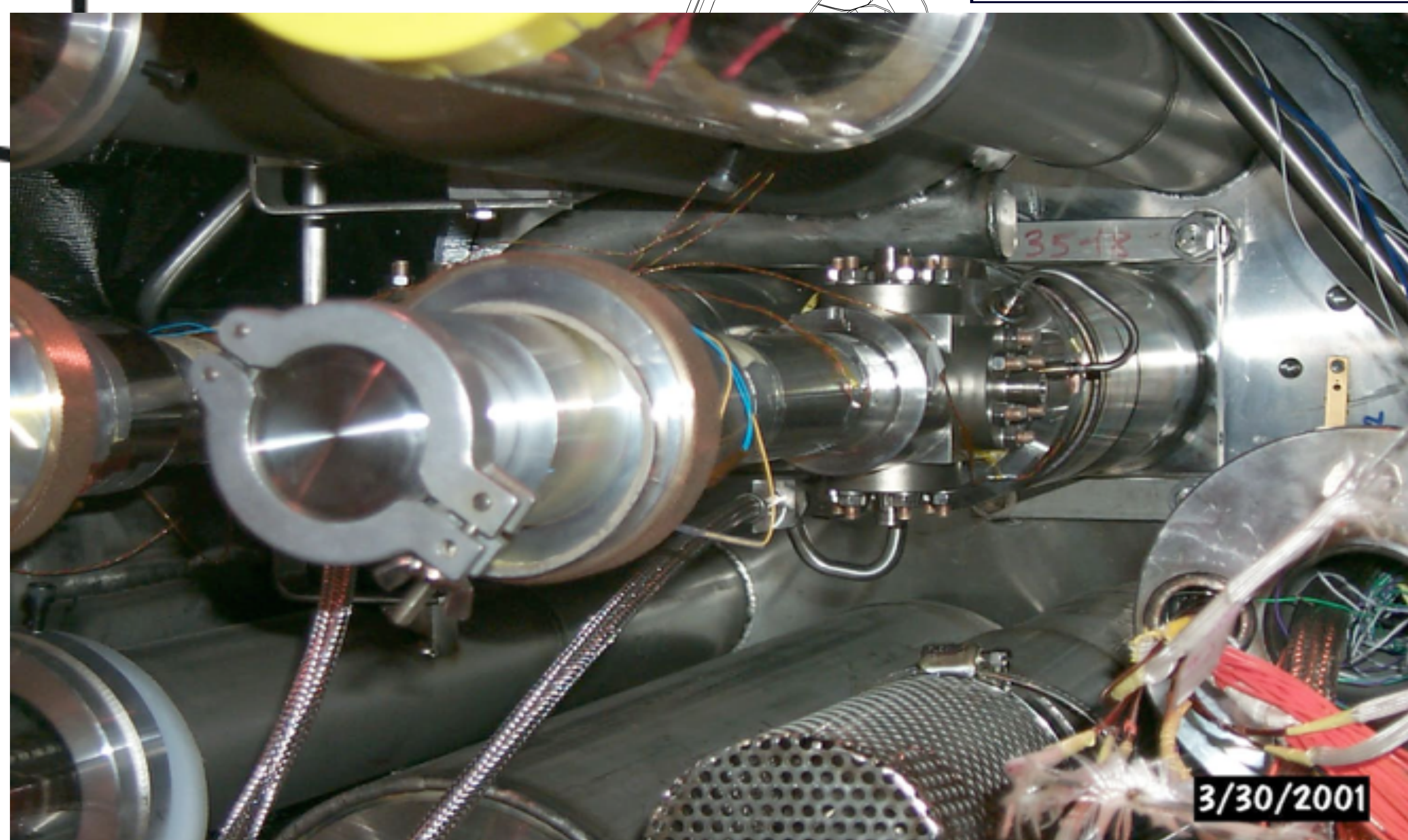
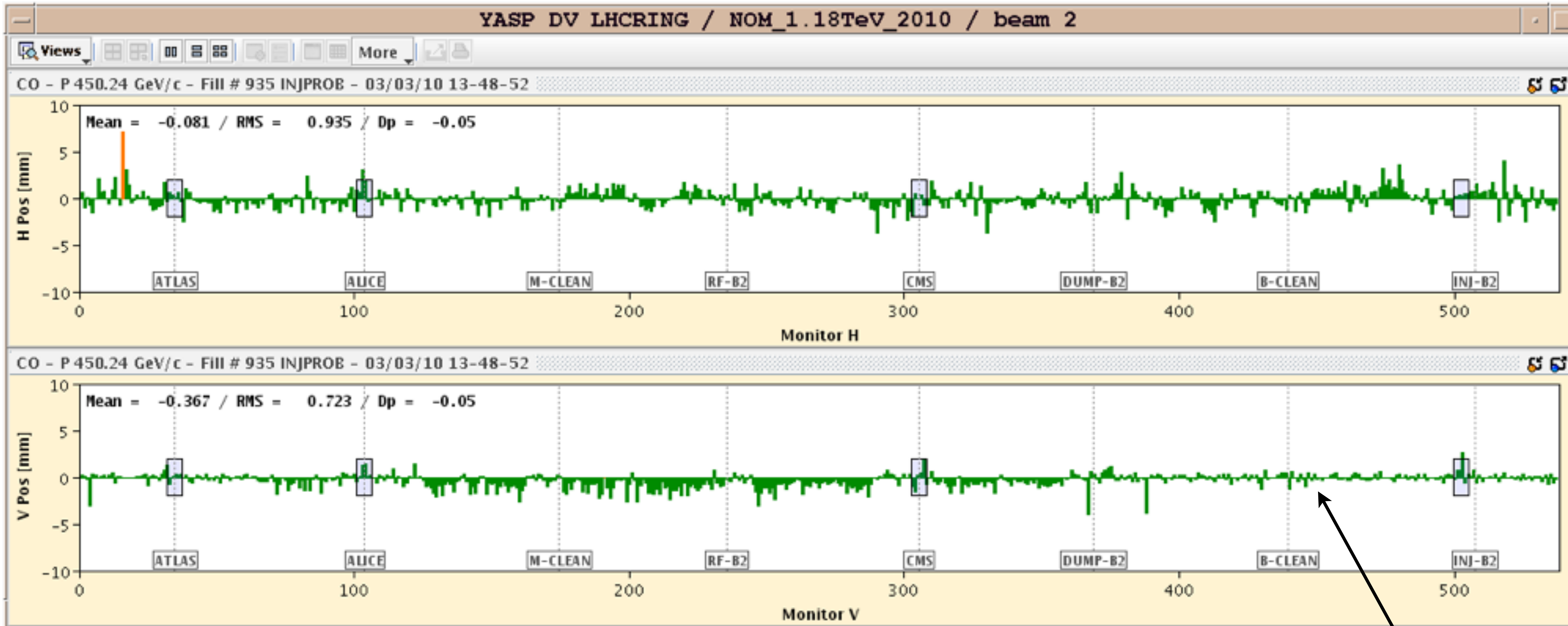


# Closed-orbit measurements





*An orbit measurement at LEP*

*> 500 measurements per beam per plane!*

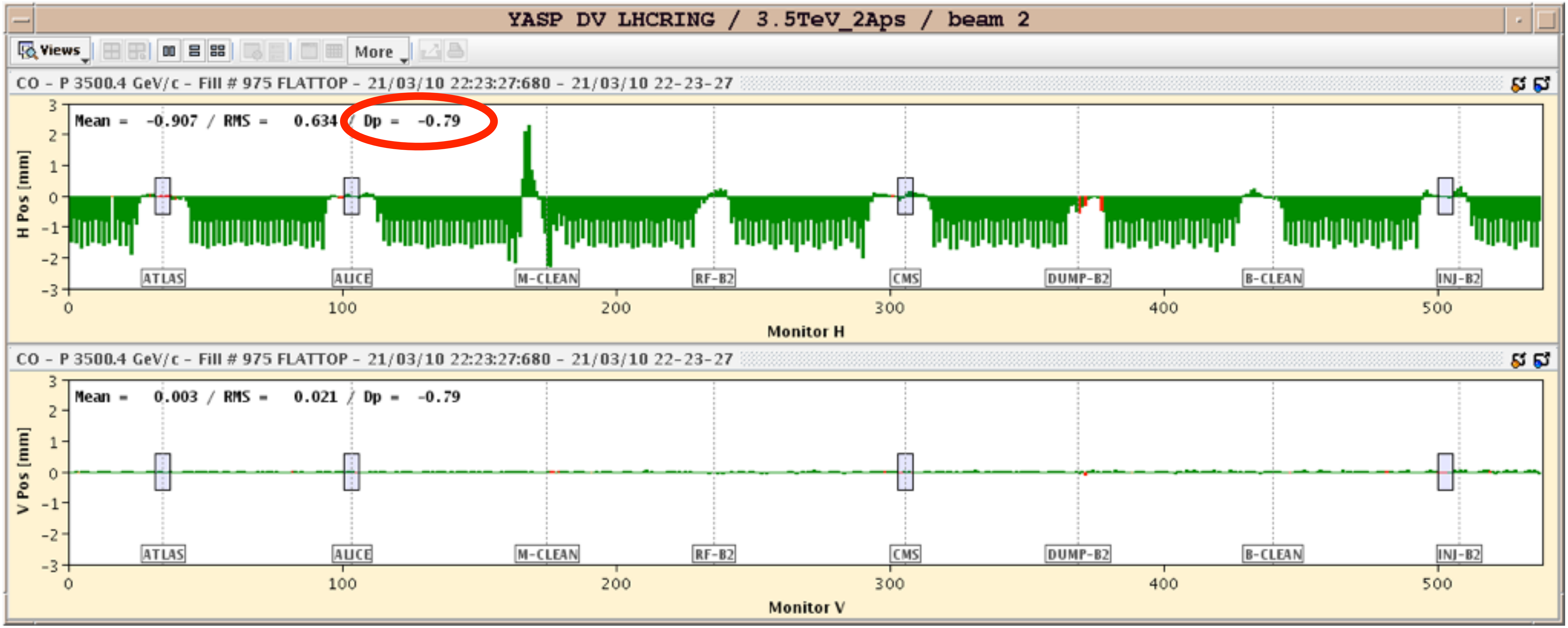
*More than 1 per quad!*

*1 Hz data + turn-by-turn are possible*

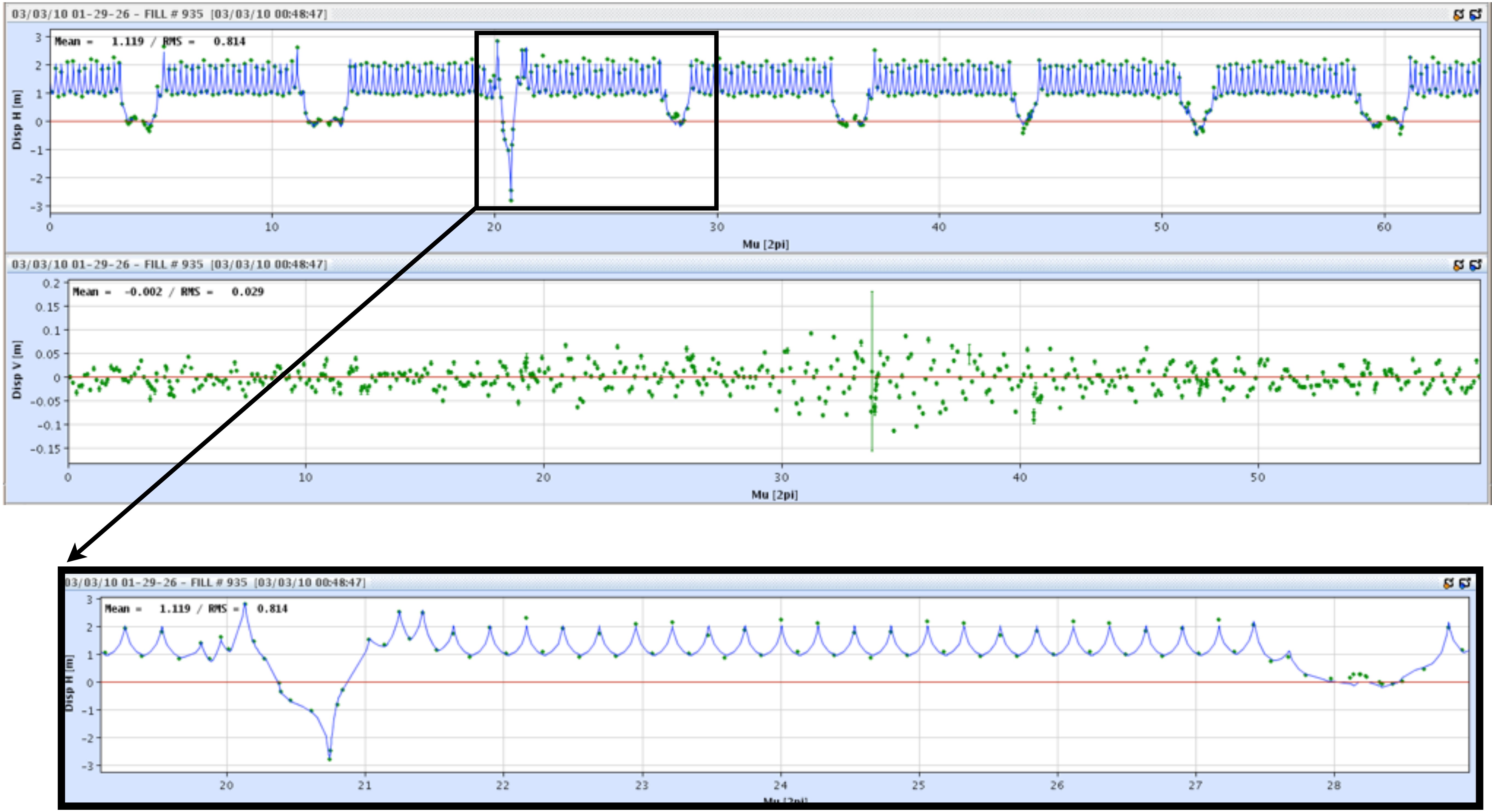
# Dispersion measurements (i)

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

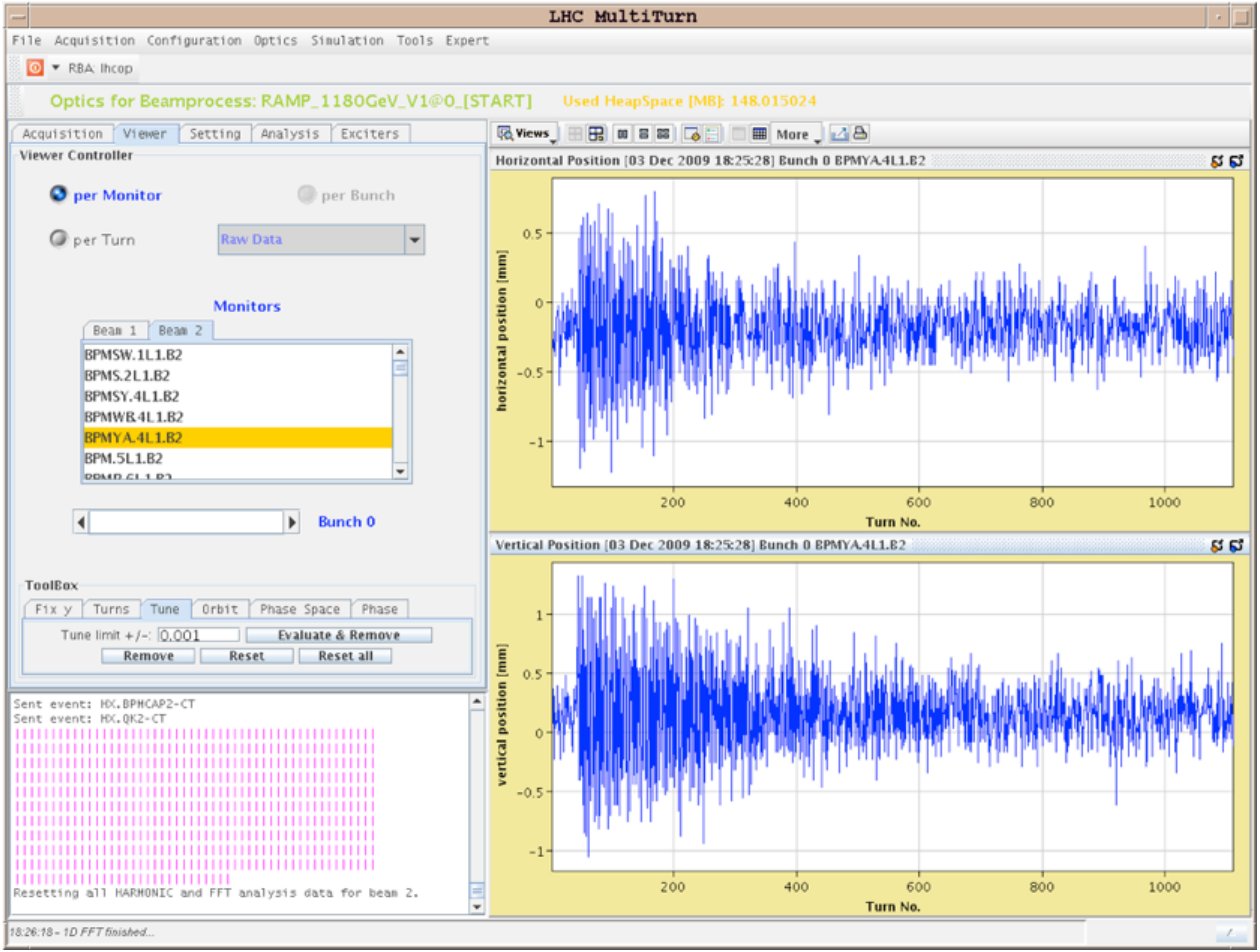
Measure the orbit offset for different beam energies.



# Dispersion measurements (ii)

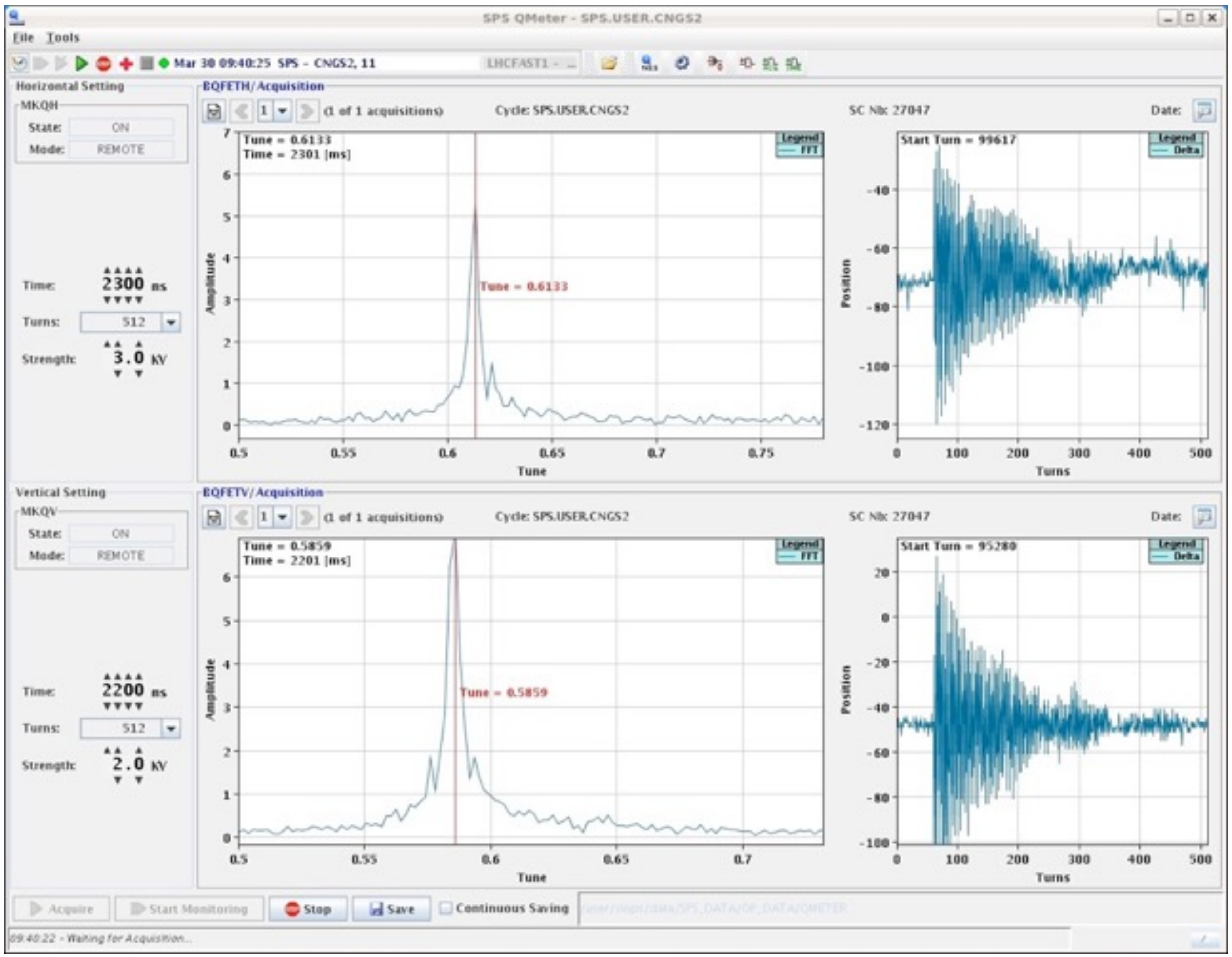


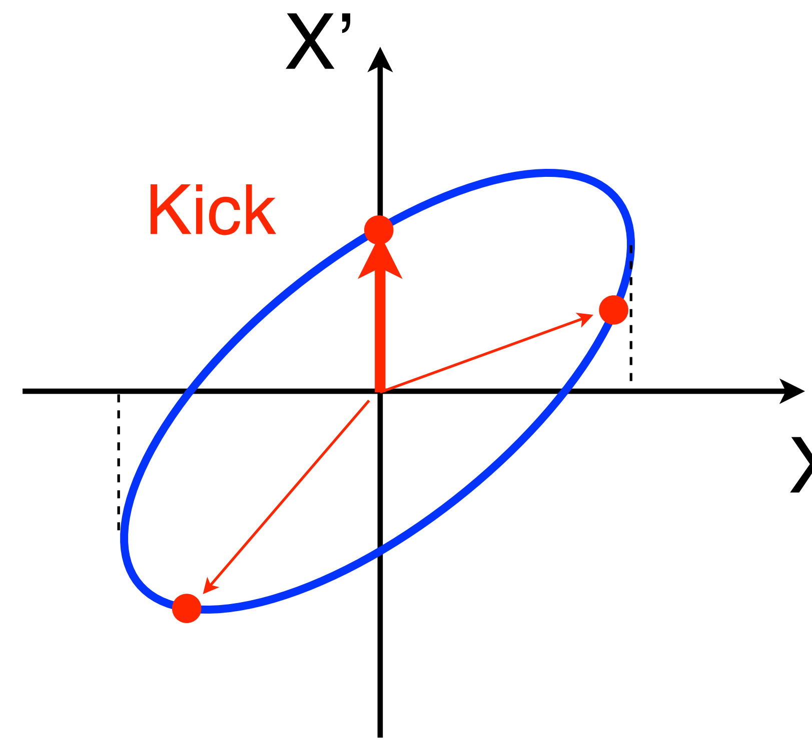
# Multi-turn acquisitions



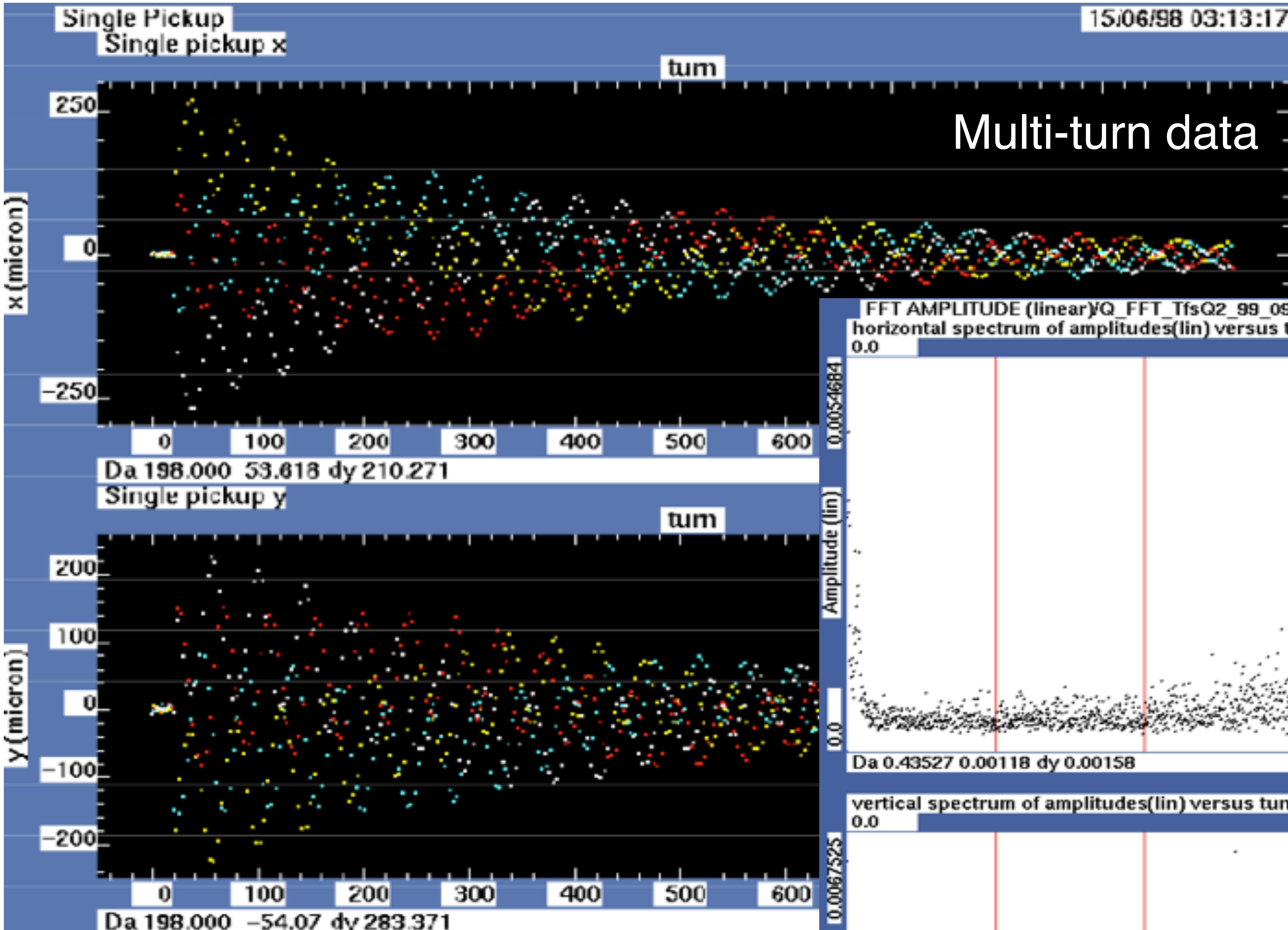
# Tune measurements

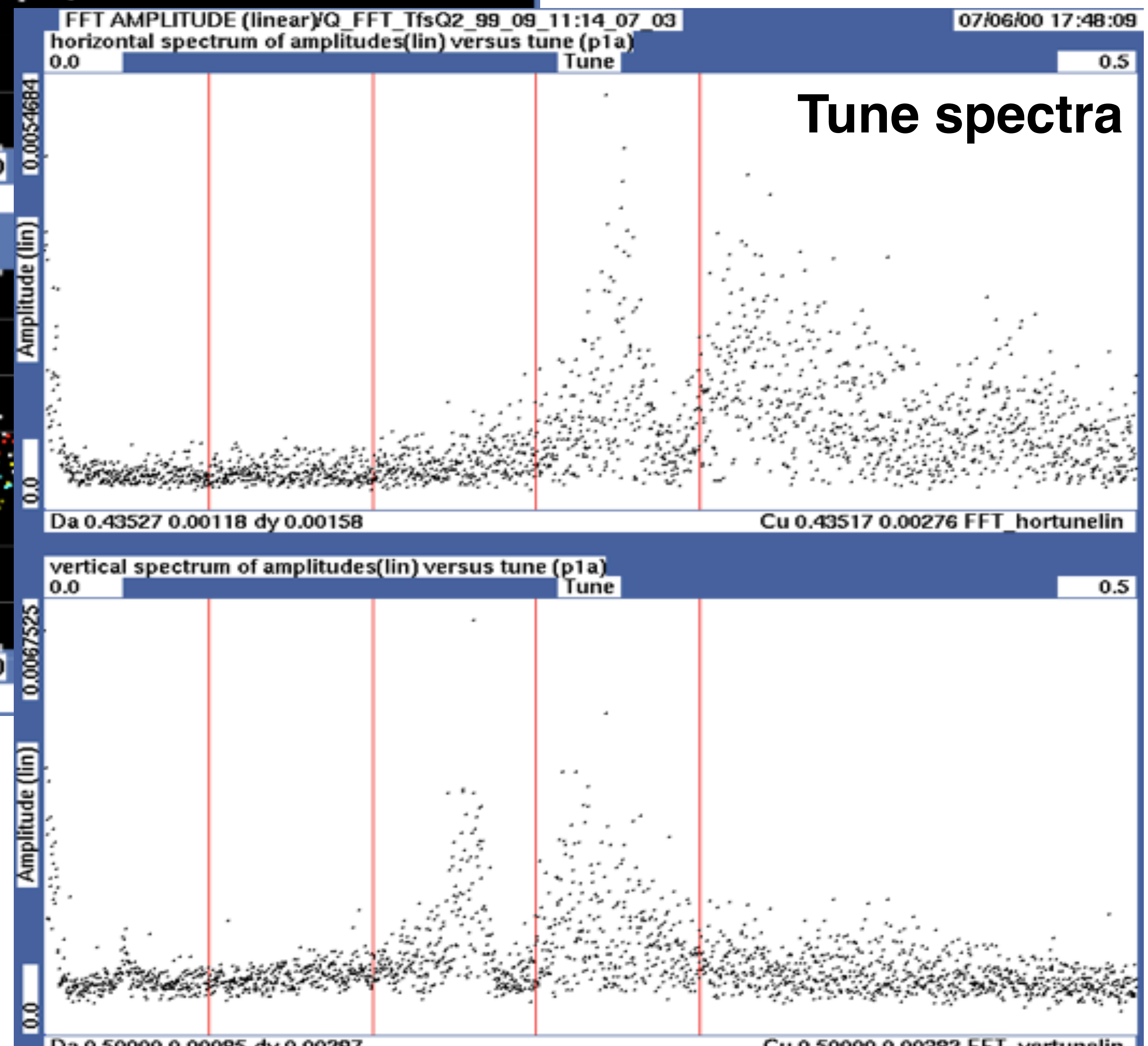
- Kick the beam with a fast kicker
- Measure beam position at every turn
- Make an FFT



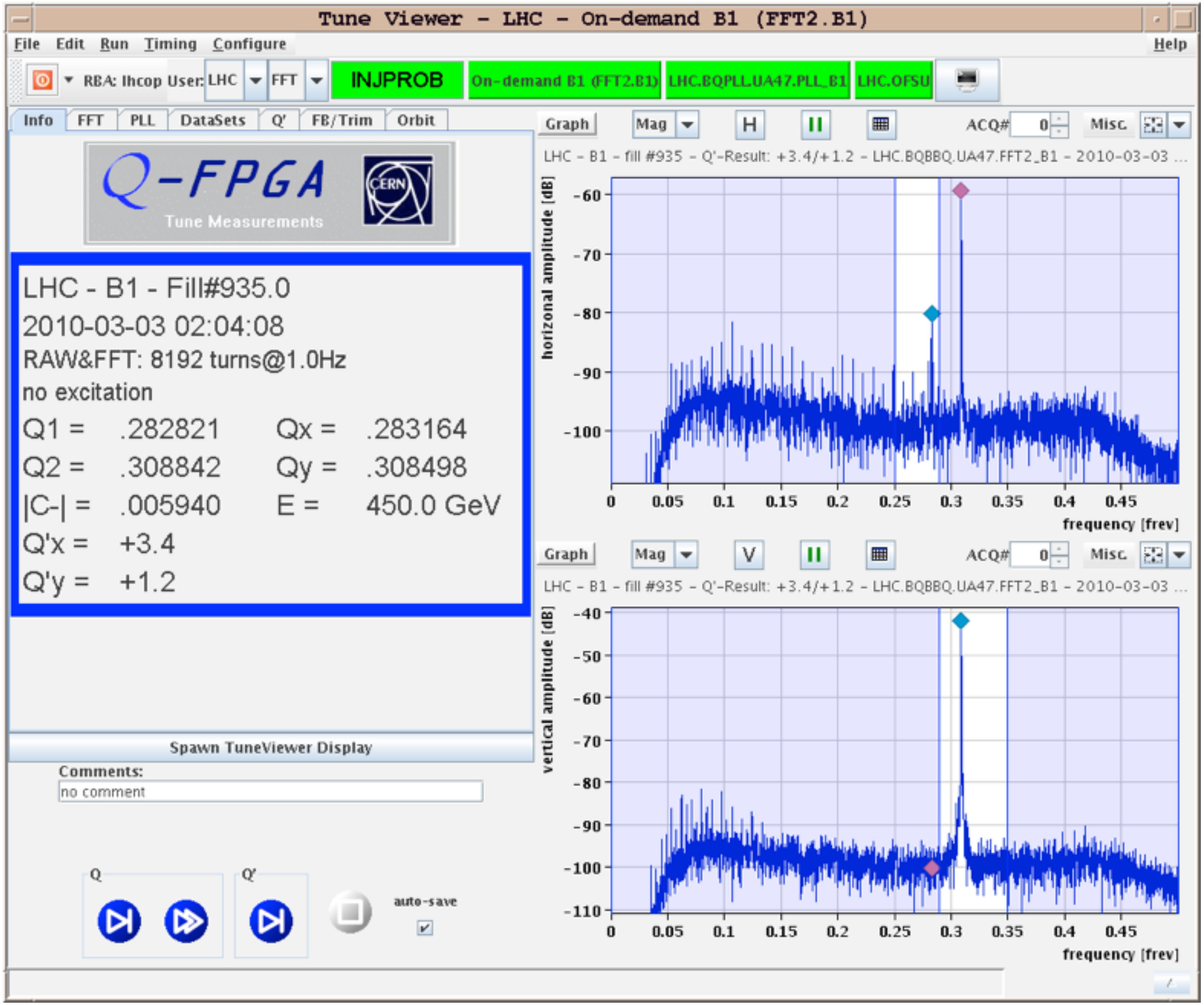



# Tune measurements at the LEP



# Tune measurements at the LHC

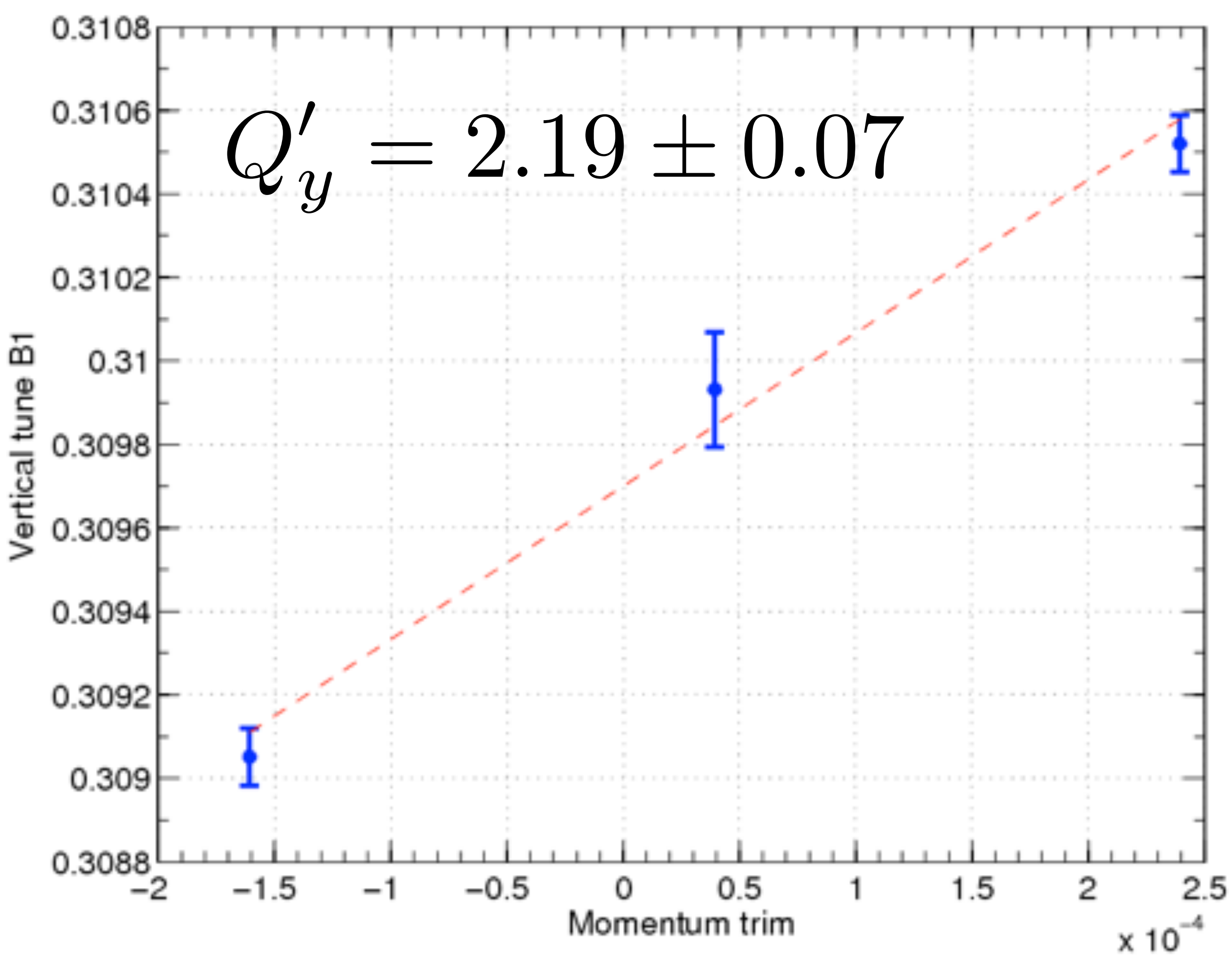


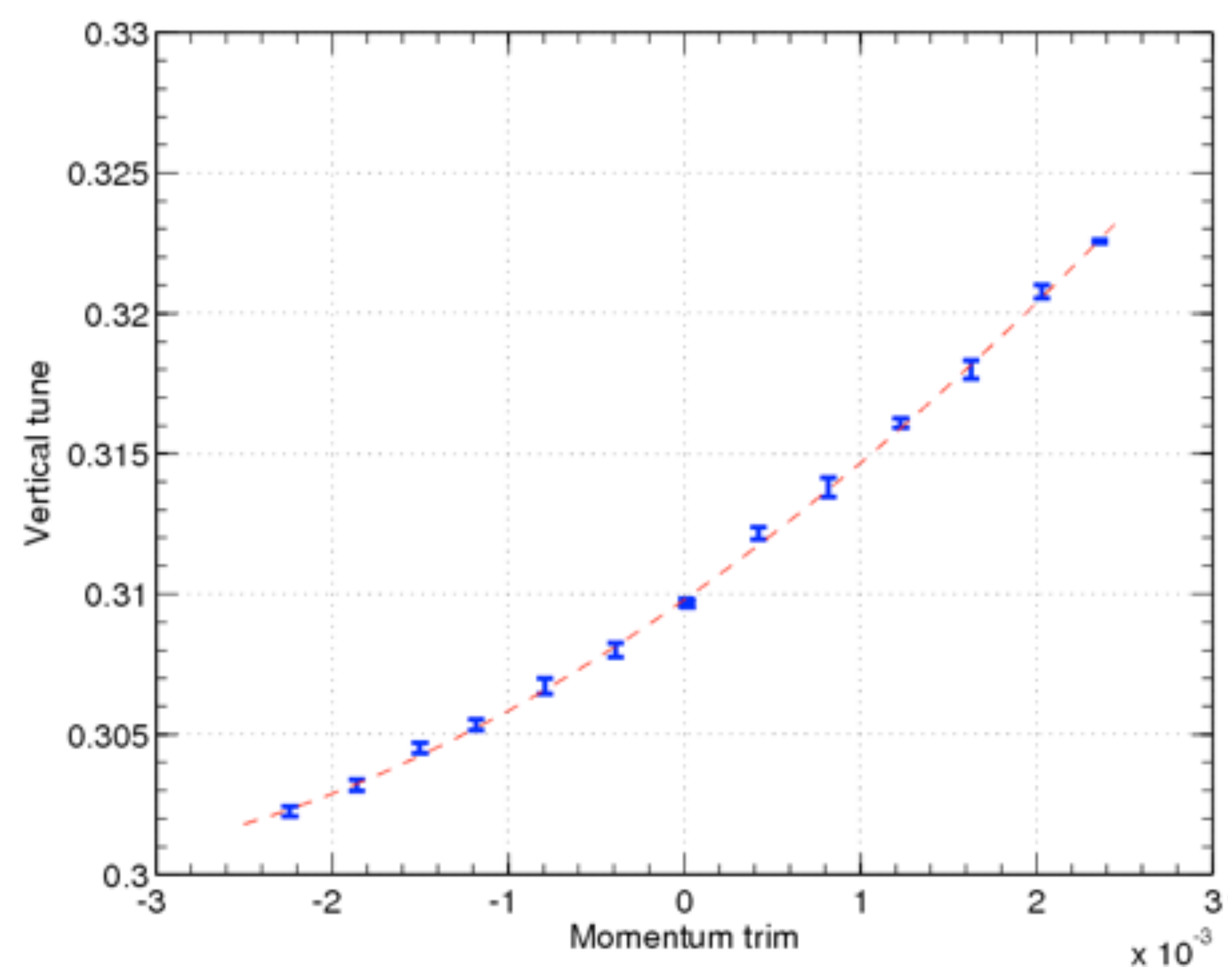
# Chromaticity measurements

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

→ We need to repeat tune measurements at different beam momenta

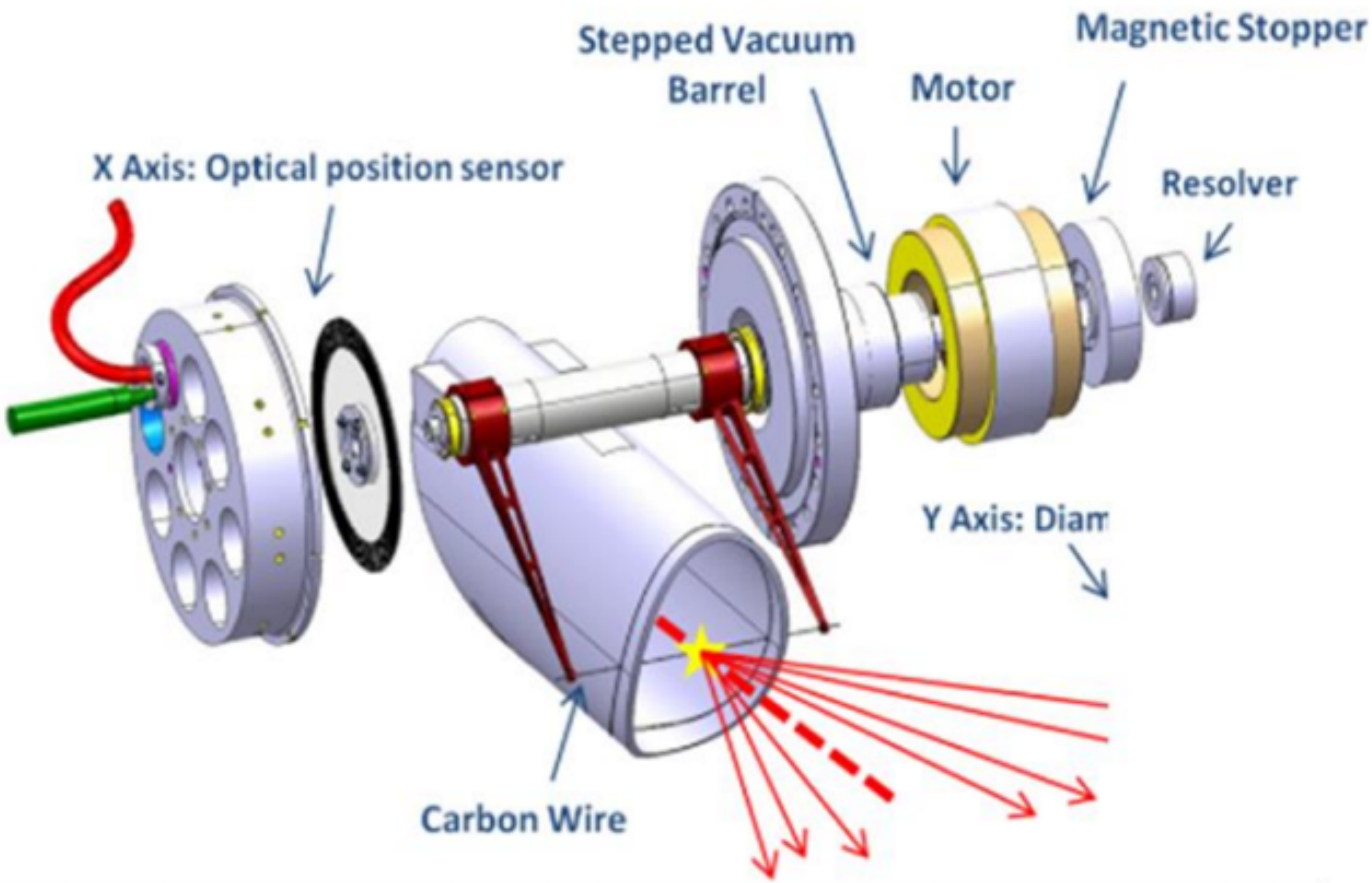
$$Q_y = Q_{y,0} + Q'_y \frac{\Delta p}{p}$$ → Linear fit



# Beam size measurements

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



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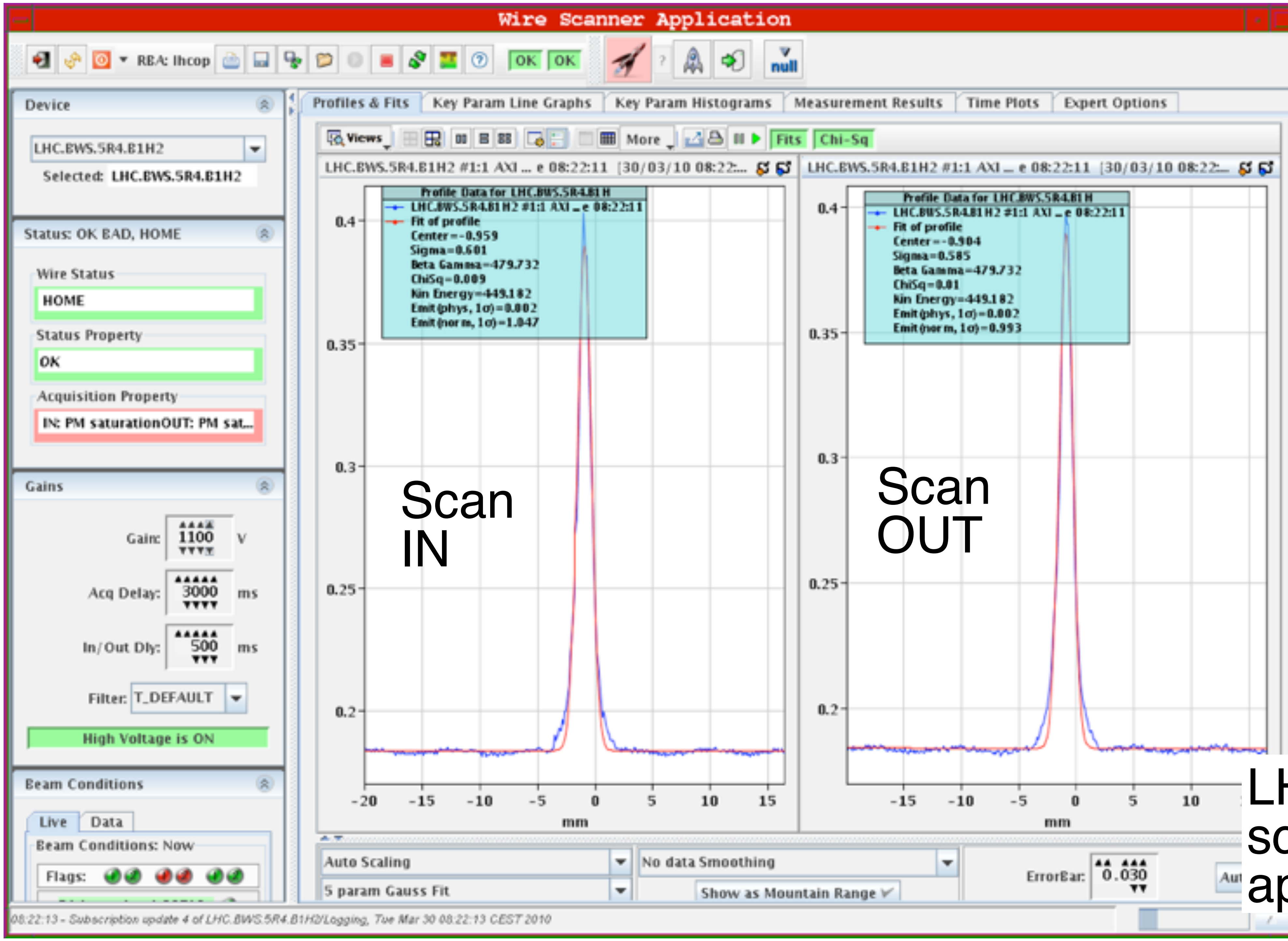
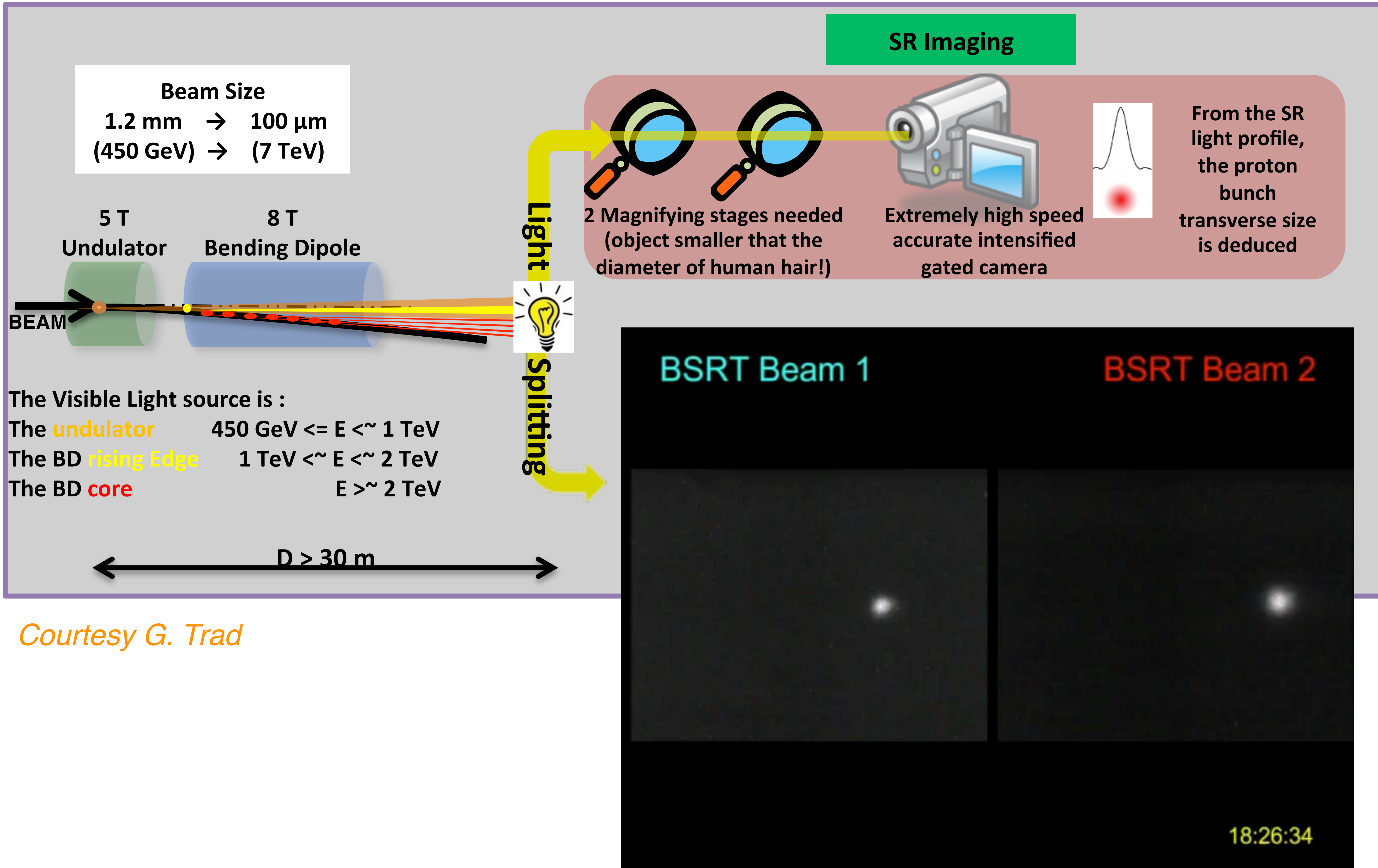


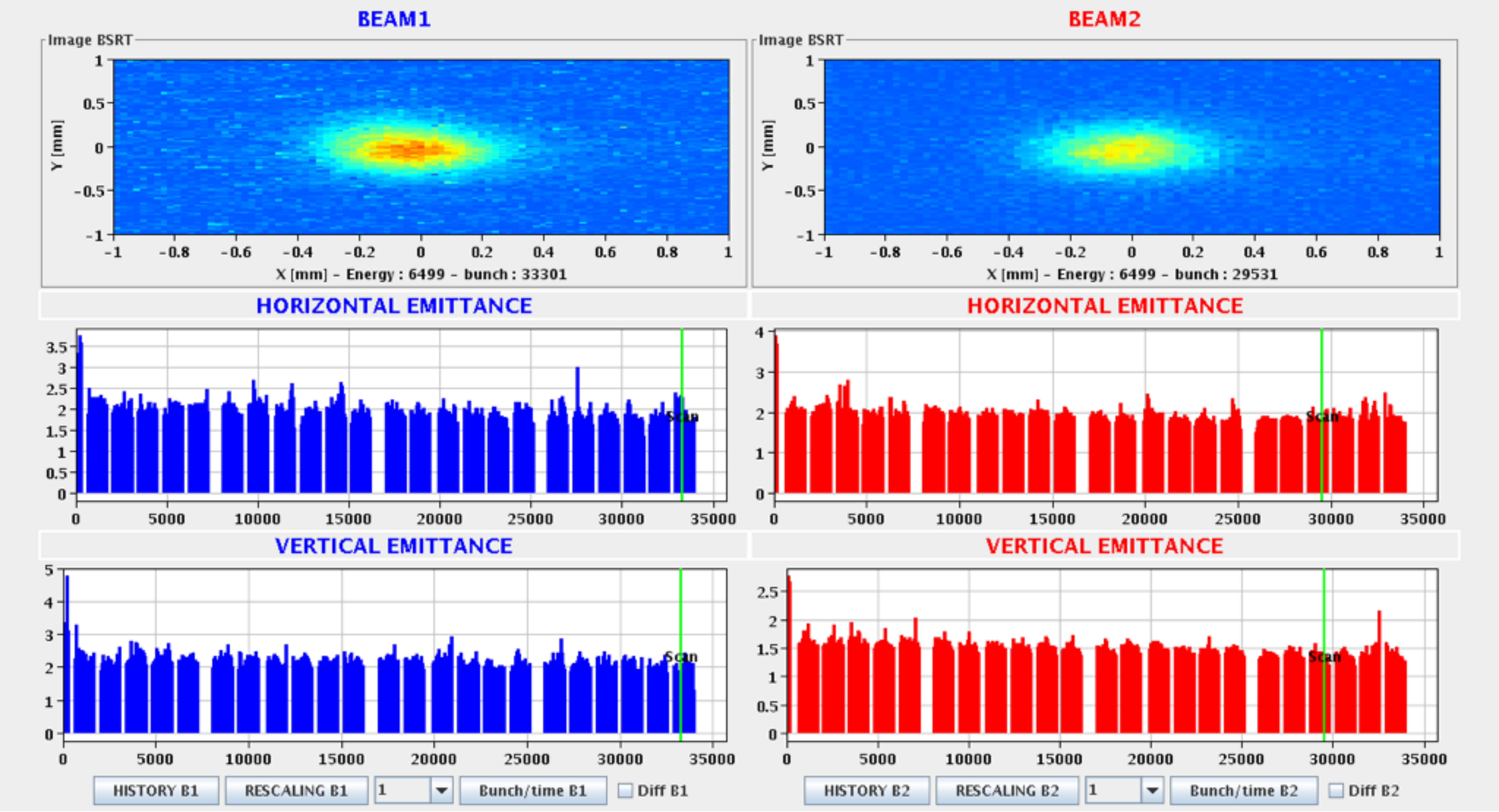

LHC wire-scanner application

# Synchrotron light monitor




*Courtesy G. Trad*

# Bunch-by-bunch beam size



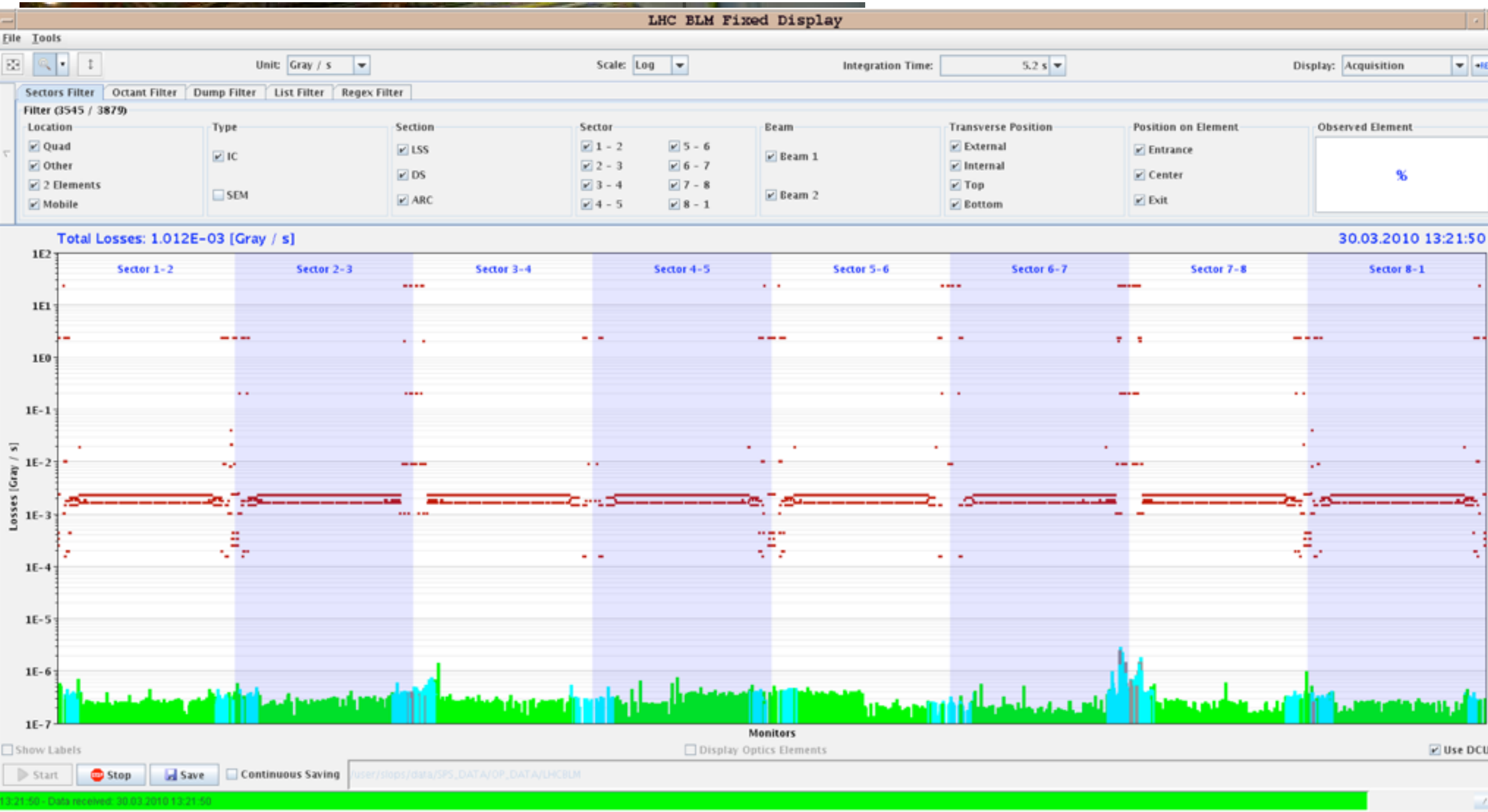

By gating the acquisitions on different bunches, one can measure all the ~3000 bunches with the BSRT (not possible with wires: would quench the magnets and break the wire!)

# Beam loss monitoring

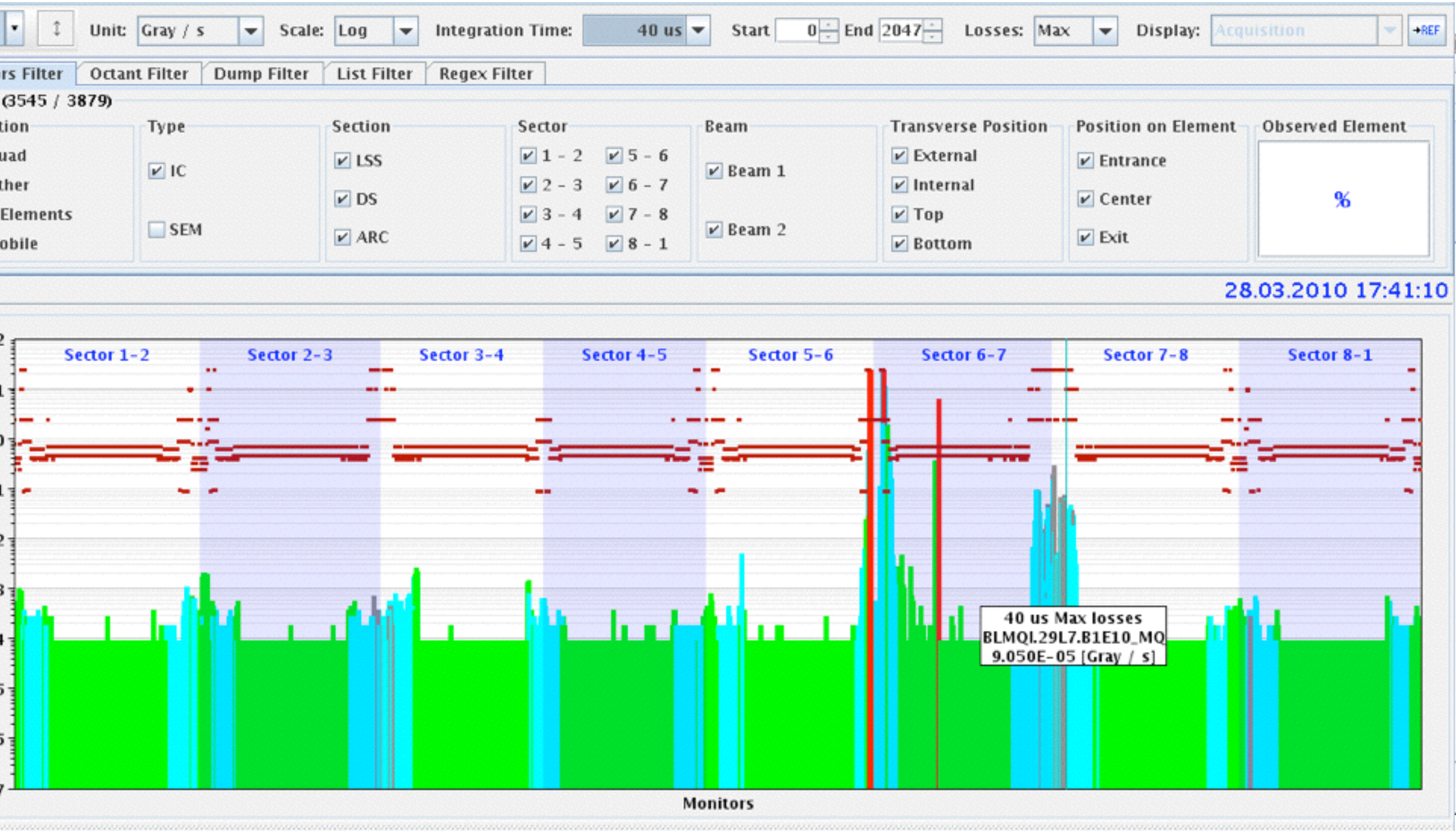
Ionization chambers detect secondary electromagnetic showers generated by particle loss.

4000 of these guys in the machine!!

# Beam loss monitoring



# Beam loss monitoring



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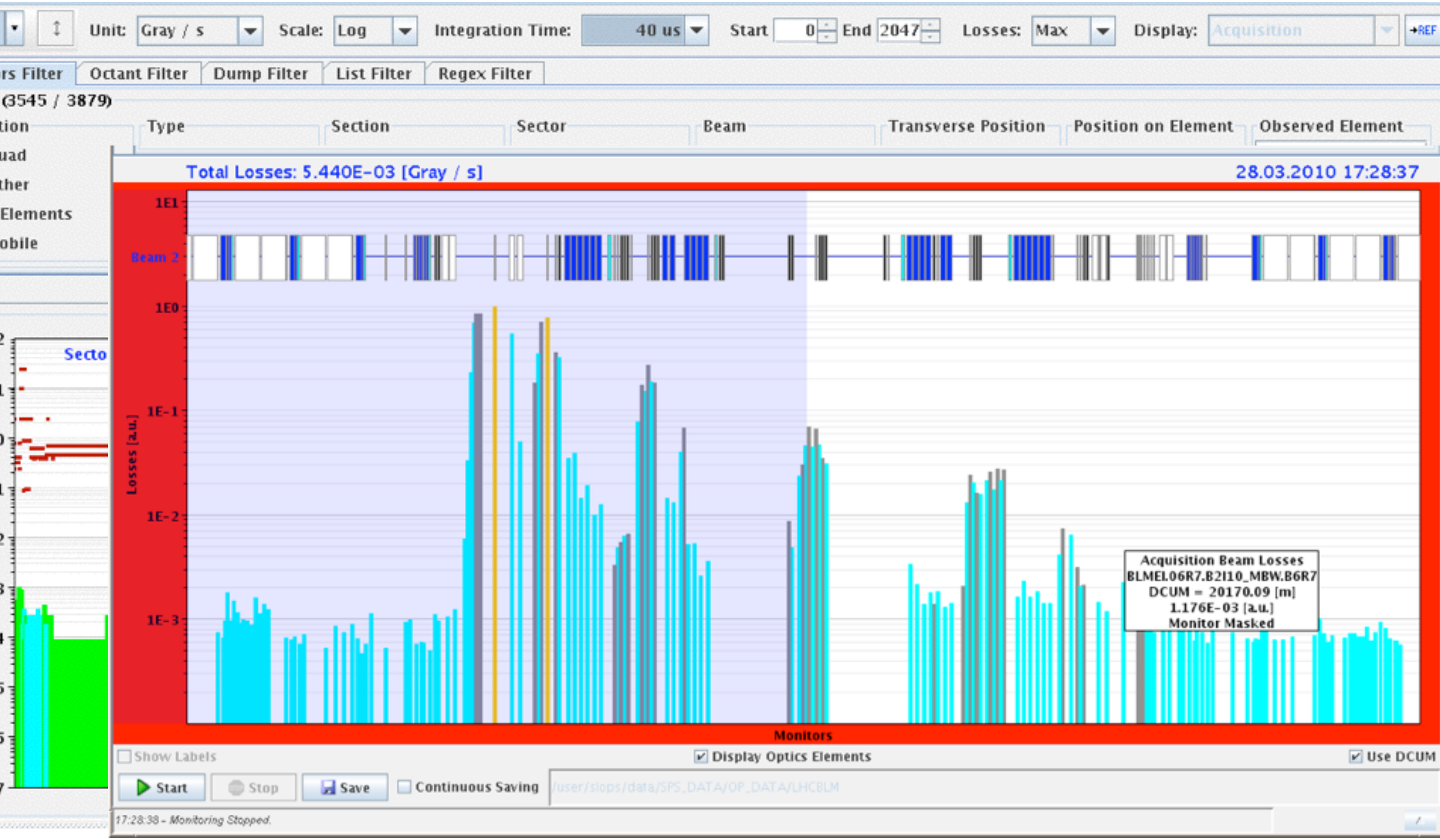


The back-bone of machine protection at the LHC: nearly 4000 channels can request a beam dump if abnormal losses are detected anywhere around the ring!

# Outline

- Introduction
- Recap. of accelerator physics
  - Basic equations
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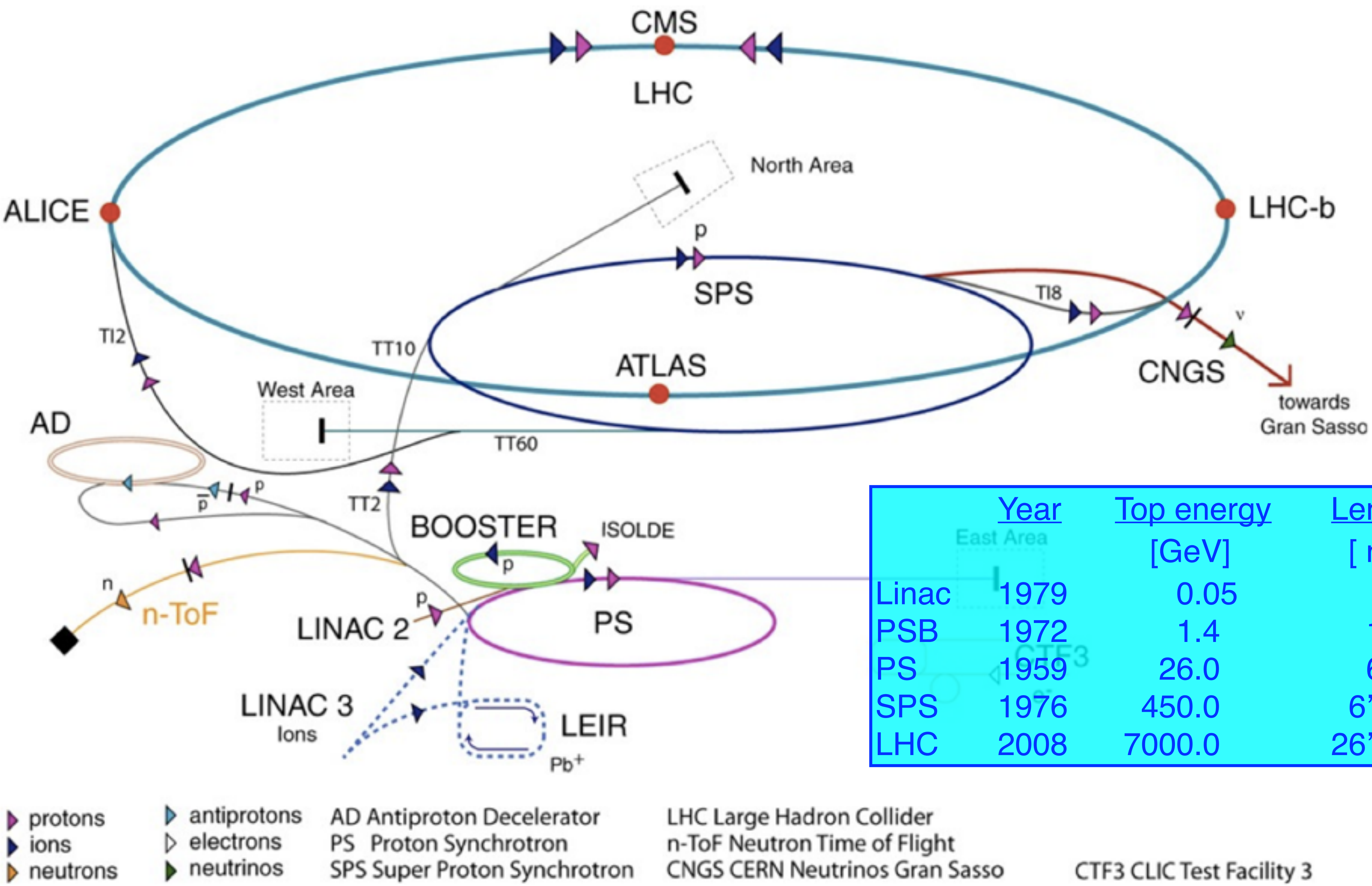
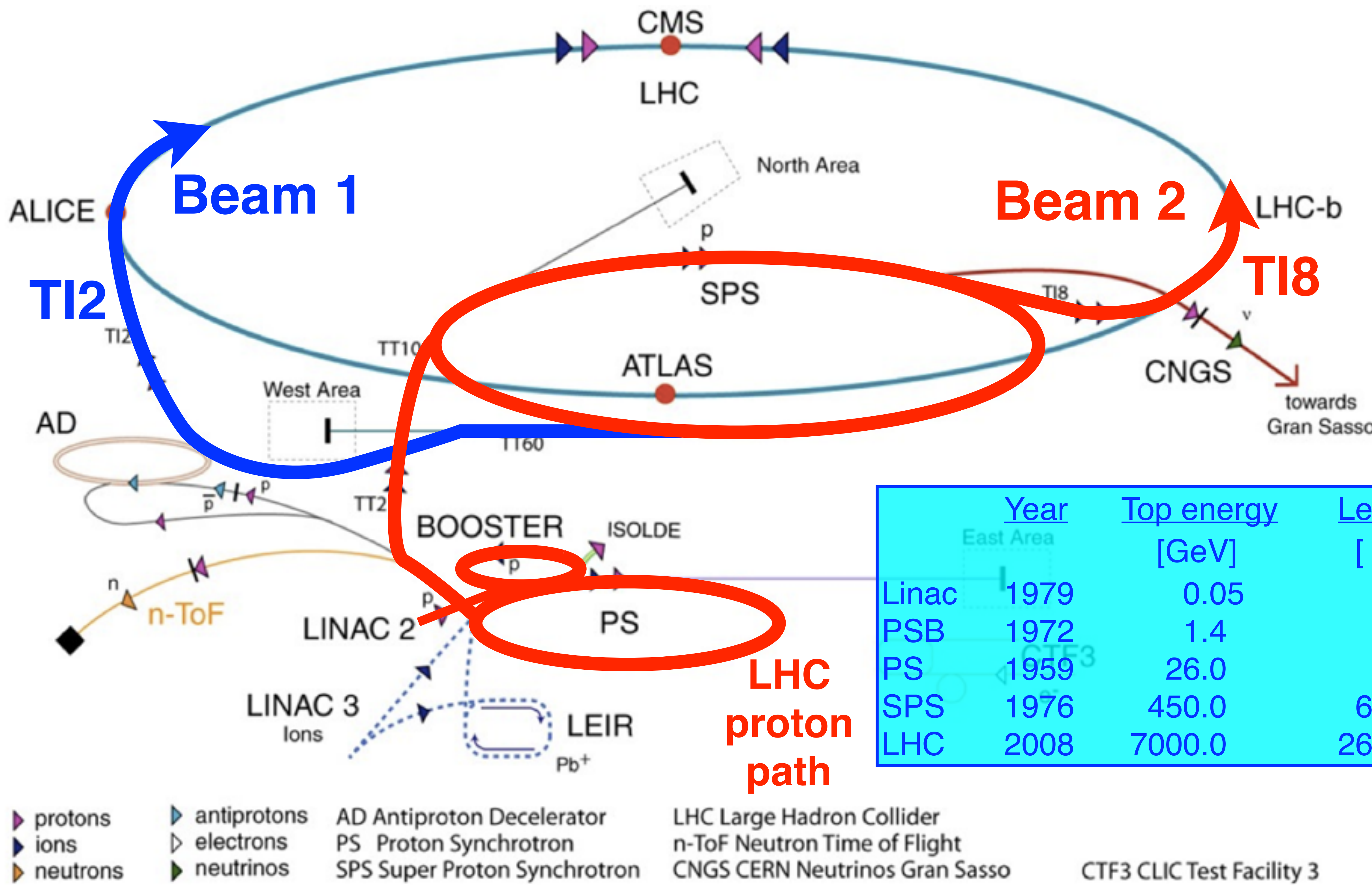
- **CERN accelerator complex**
  - **Lower energy injectors**
  - **Super Proton Synchrotron**
- LHC parameters and layout
  - Arcs and straight sections
- Machine protection and collimation
  - Concepts and LHC implementation
  - Case study: 2008 event

# 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 |

# The LHC accelerator complex

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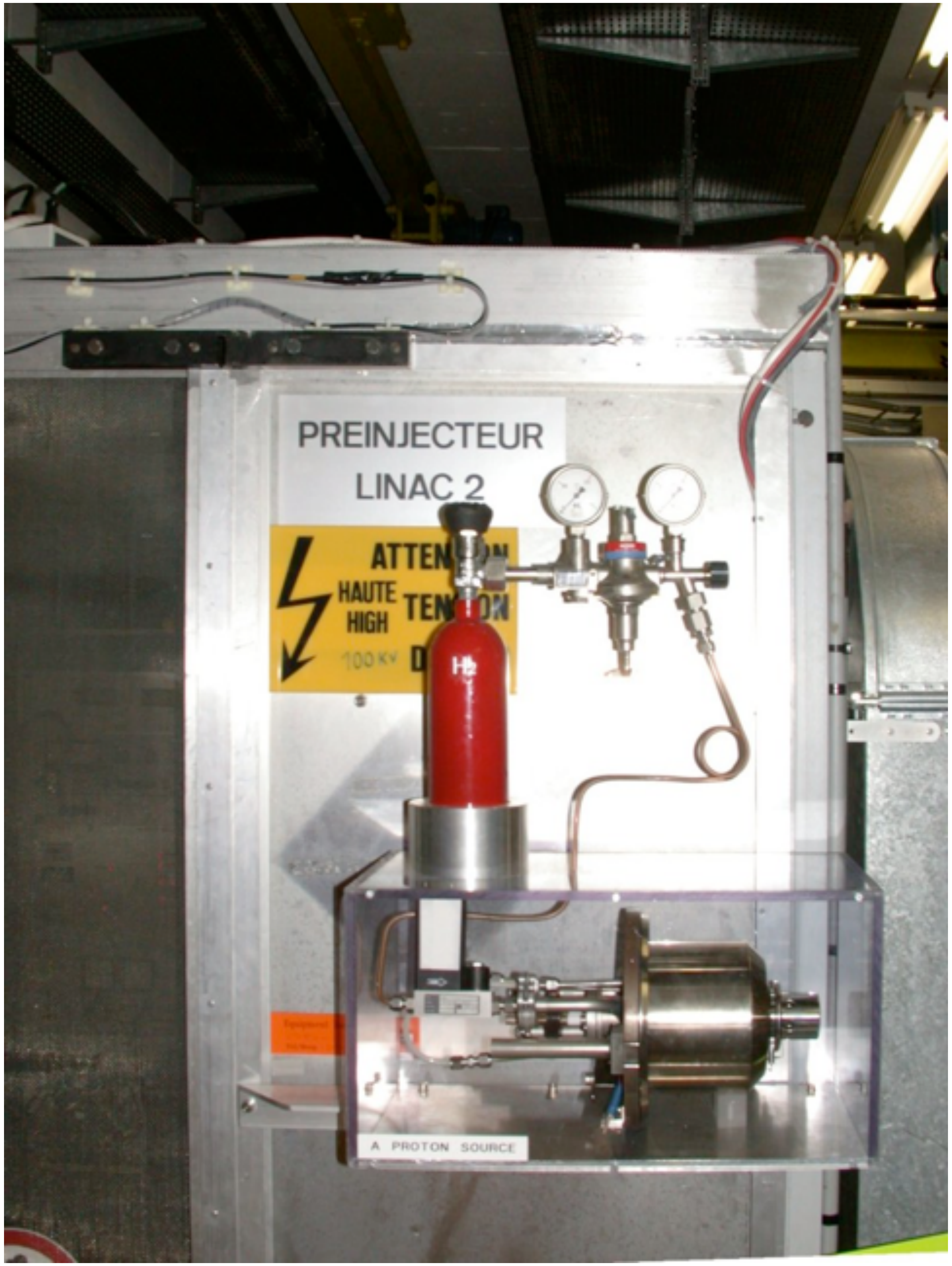
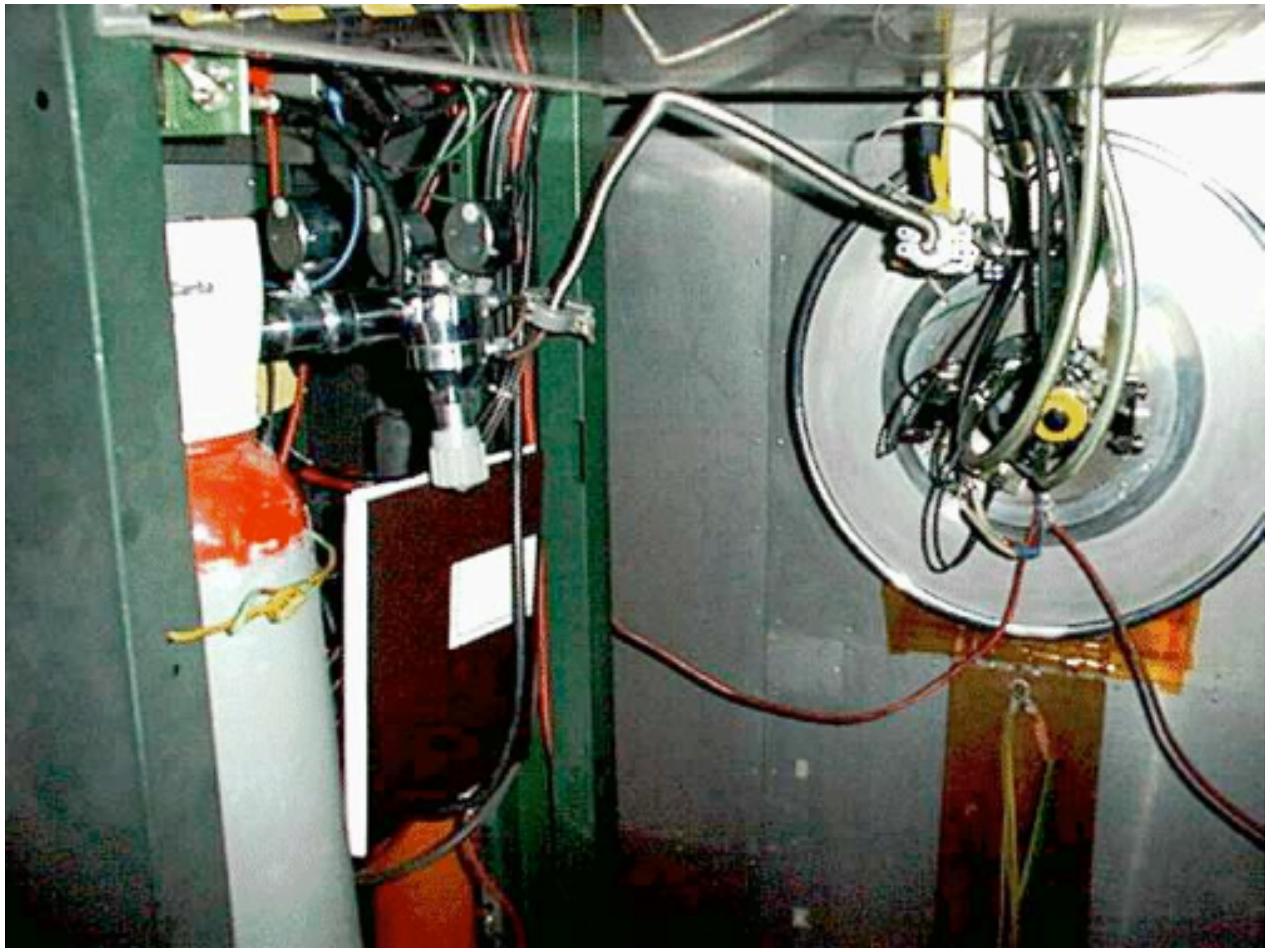
| LHC | 2008 | 7000.0 | 26'657 |

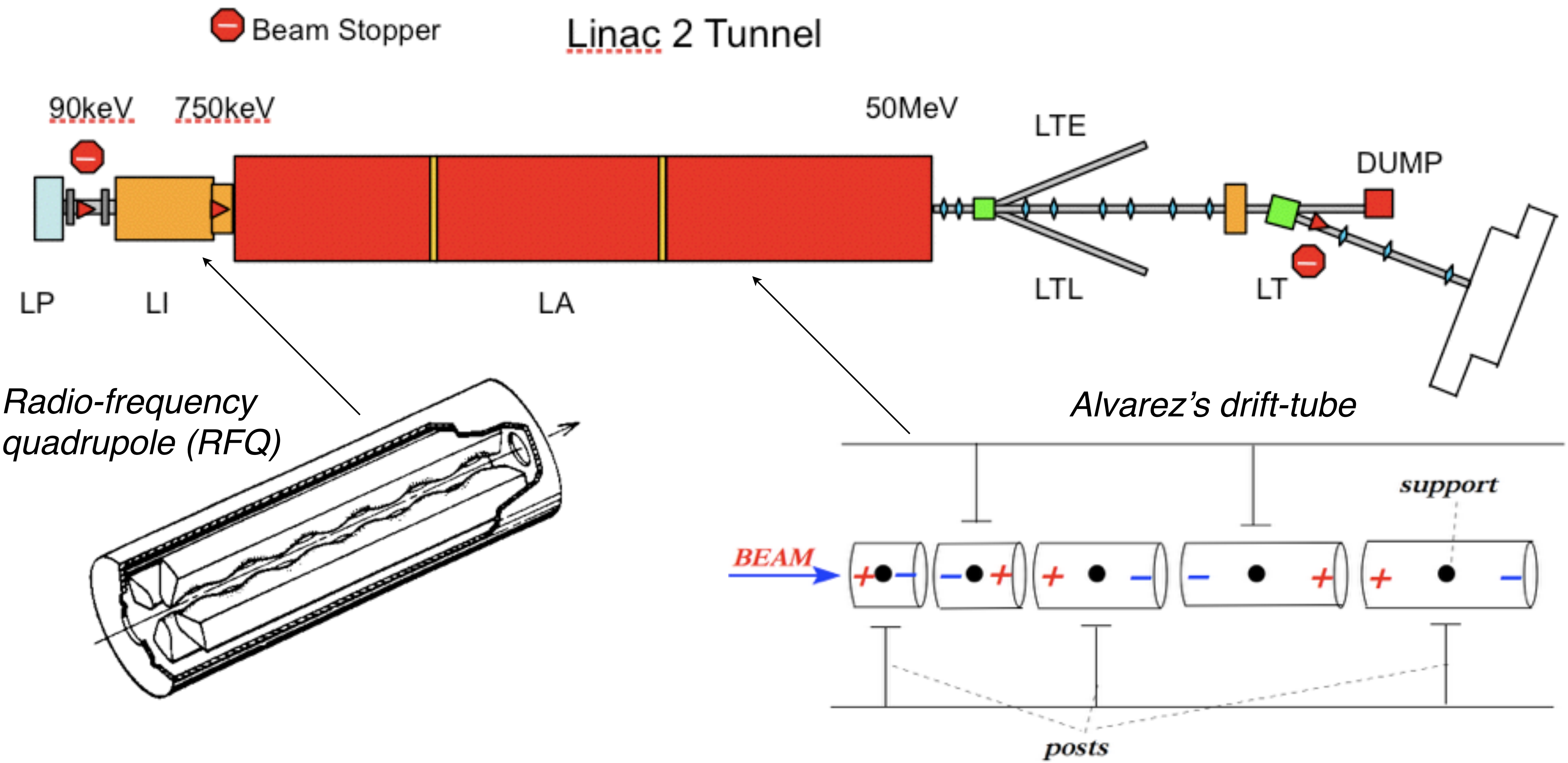
# Bottle of Hydrogen, to start with!




*The real bottle is inside the cage*

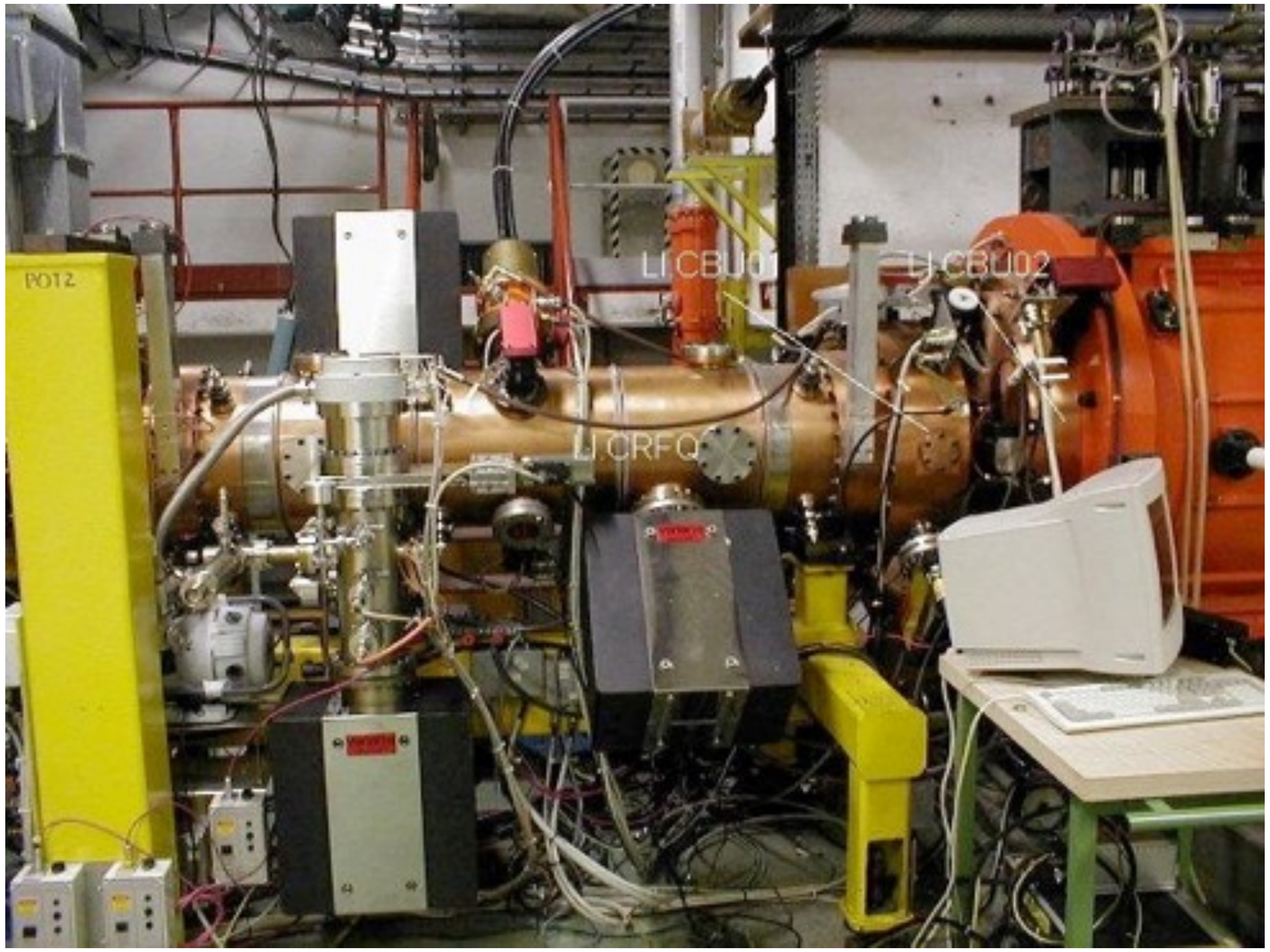


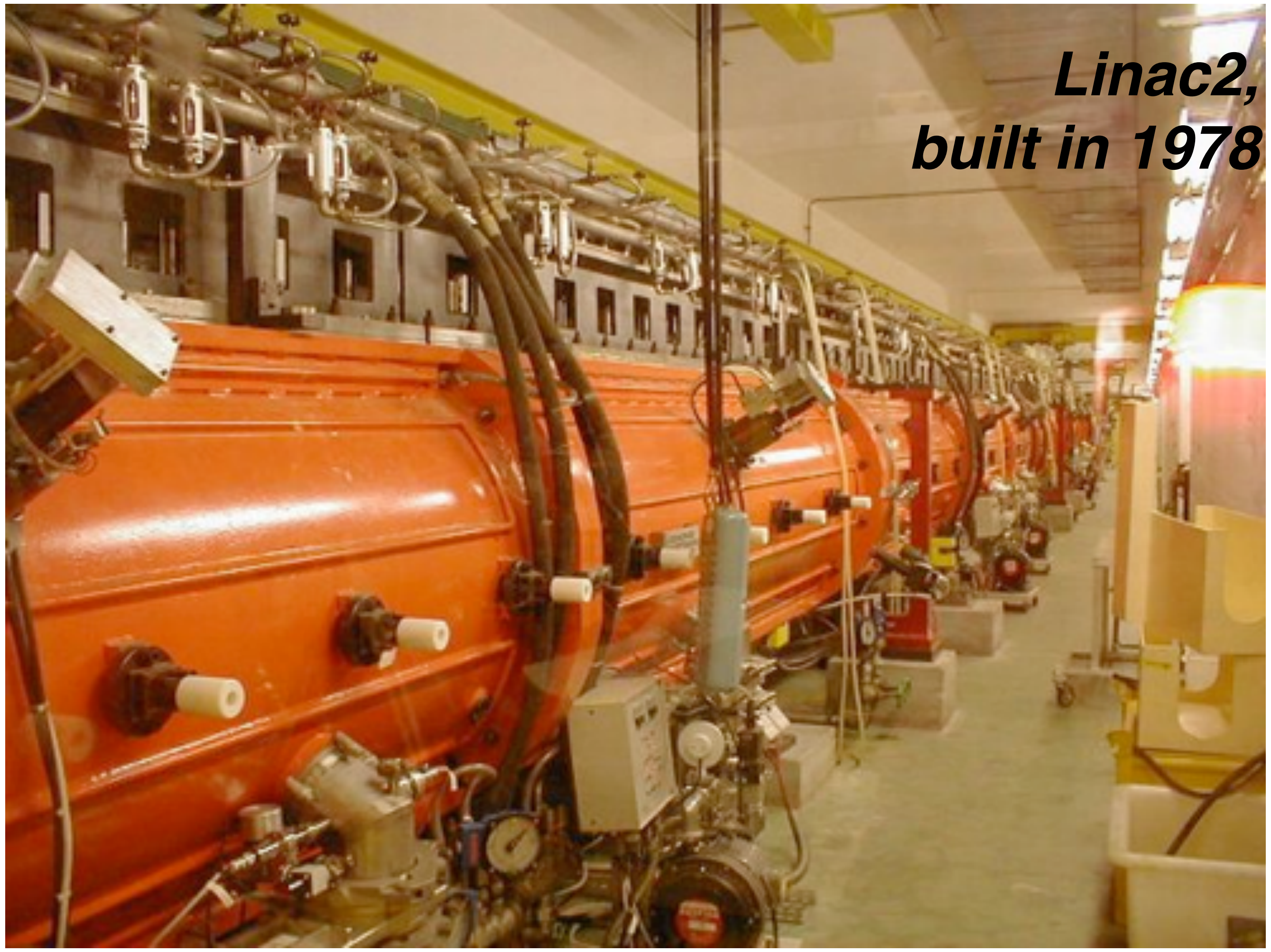
# Linac2 - layout and parameters



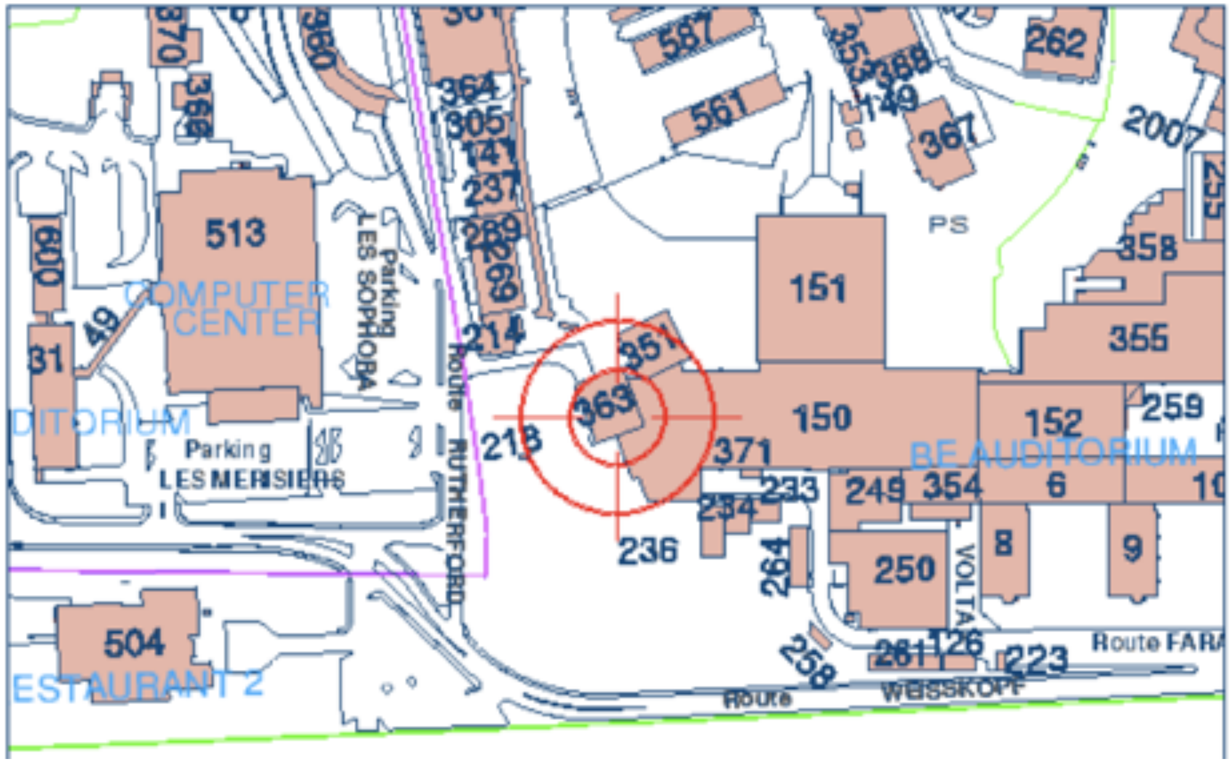

| | |
|---|---|
| Delivered beam current: | **~150mA** |
| Beam energy: | 90 keV (source) → 750 keV (RFQ) → **50 MeV** |
| Repetition rate: | **1 Hz** |
| Radio-frequency system: | 202 MHz |

# Linac2: some pictures

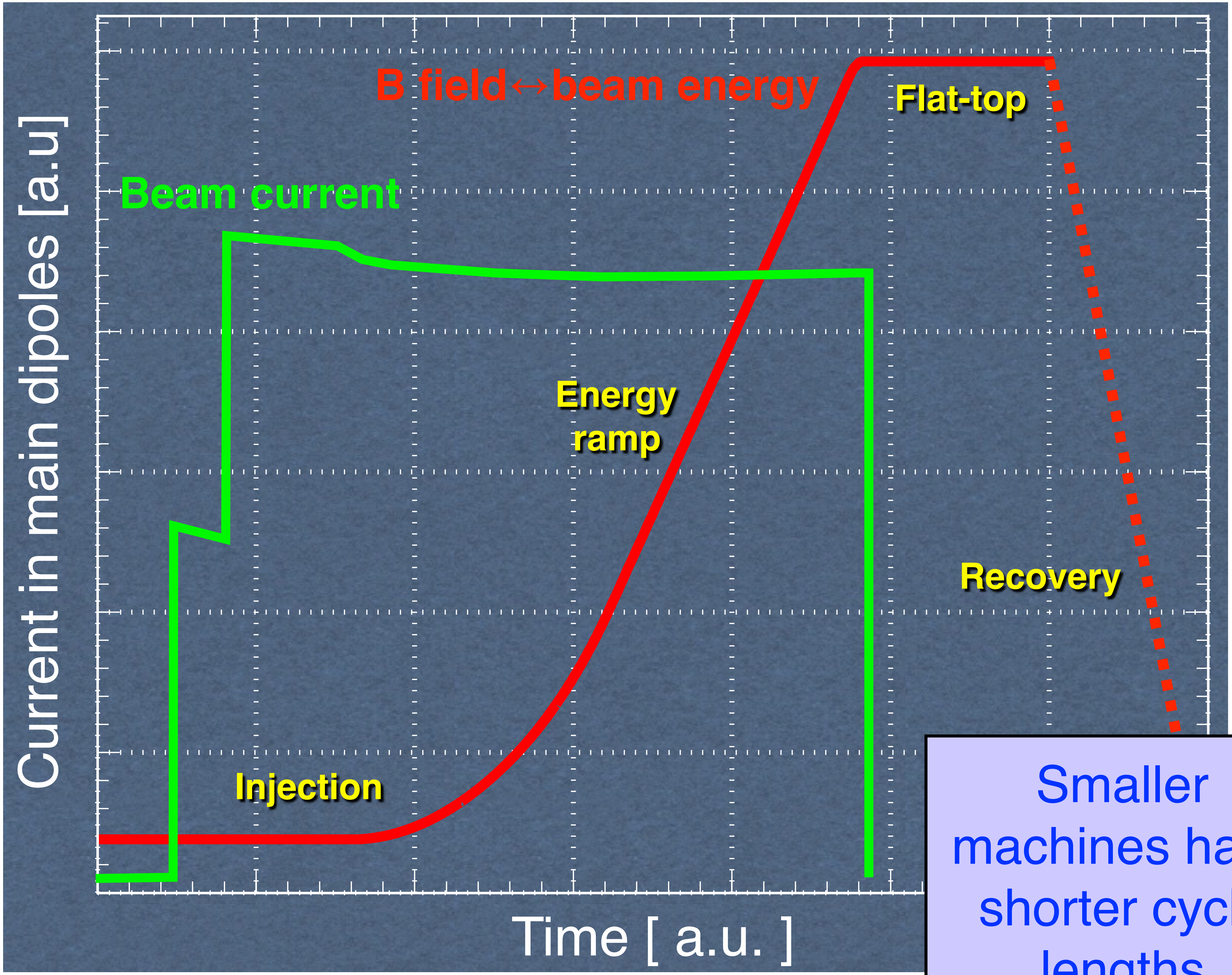



Downstream of Linac2, the proton beams will only encounter **circular accelerators** (and transfer lines)

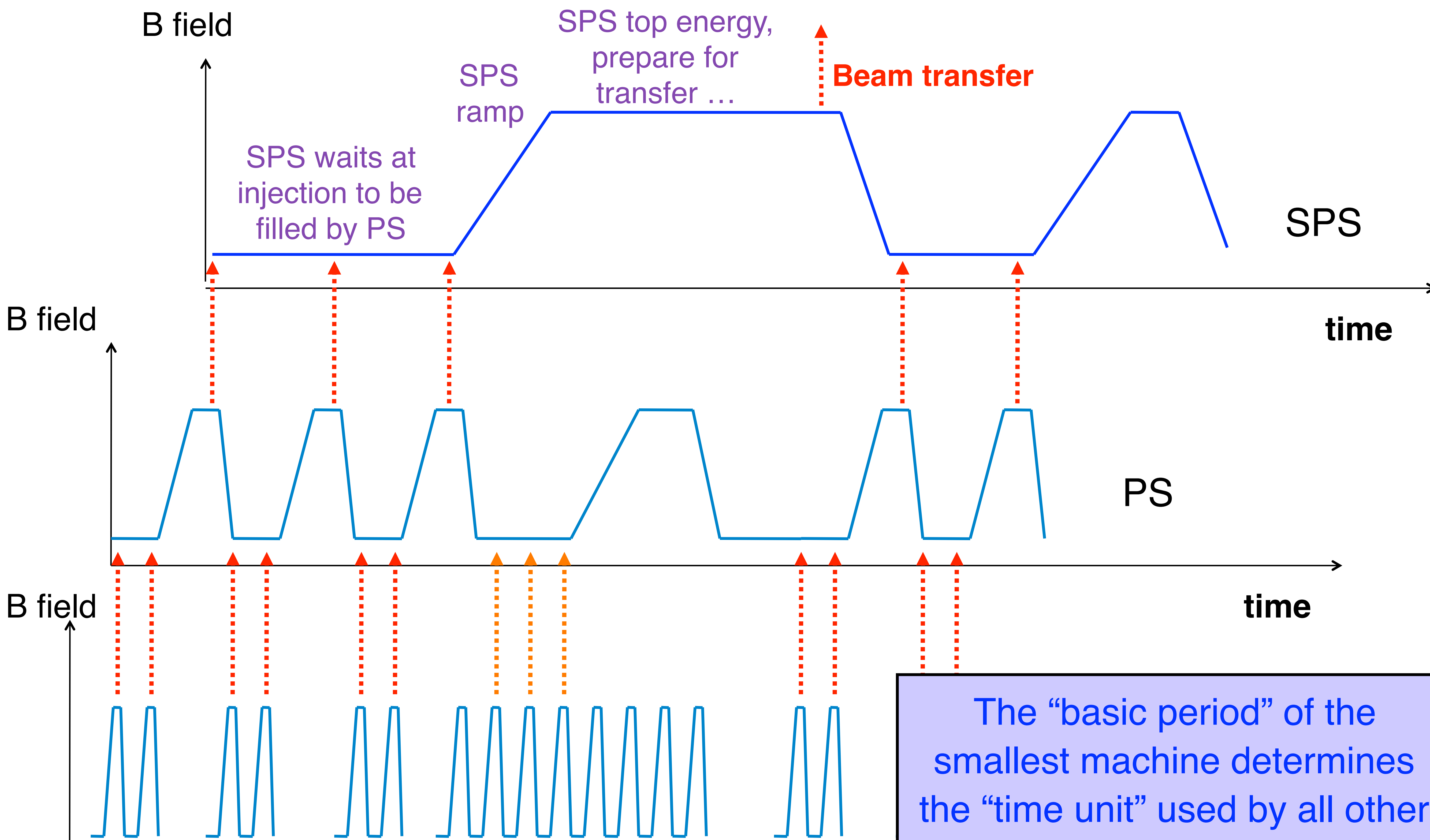


# Magnetic cycle in a synchrotron




Smaller machines have shorter cycle lengths

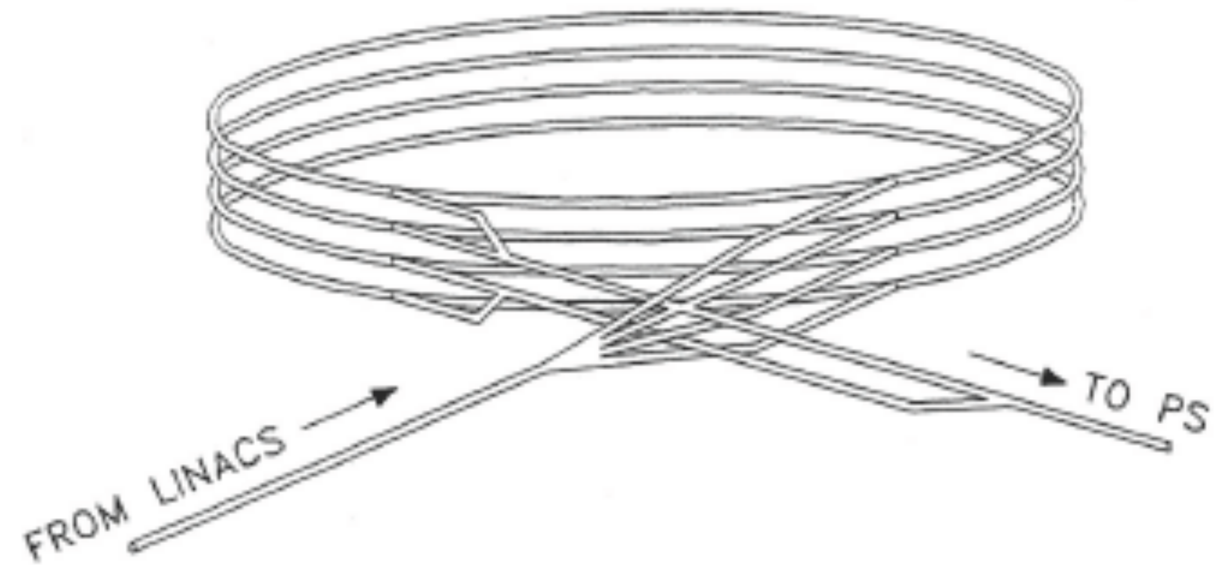
# Injector cycling




The "basic period" of the smallest machine determines the "time unit" used by all other accelerators in the chain.

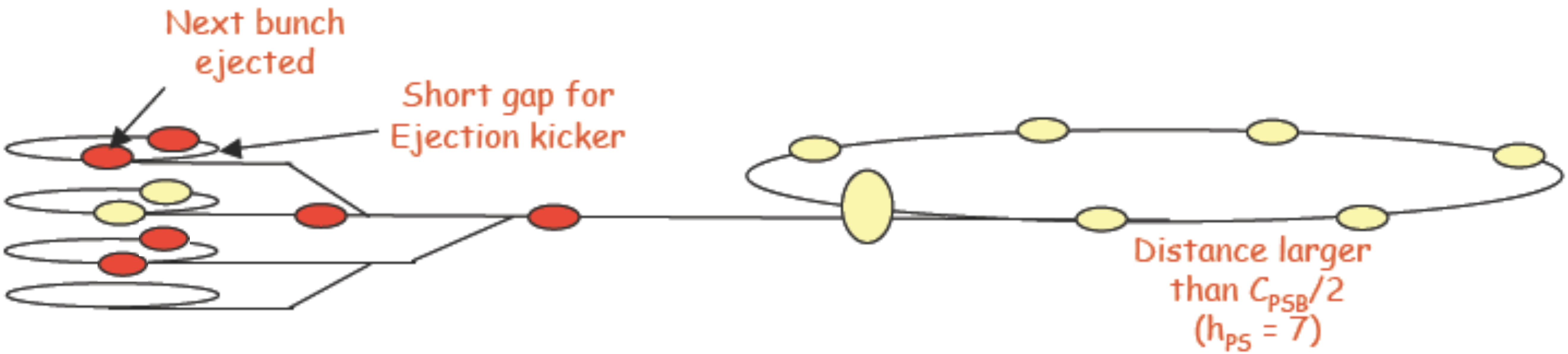
PSB determines the basic period

# PS Booster

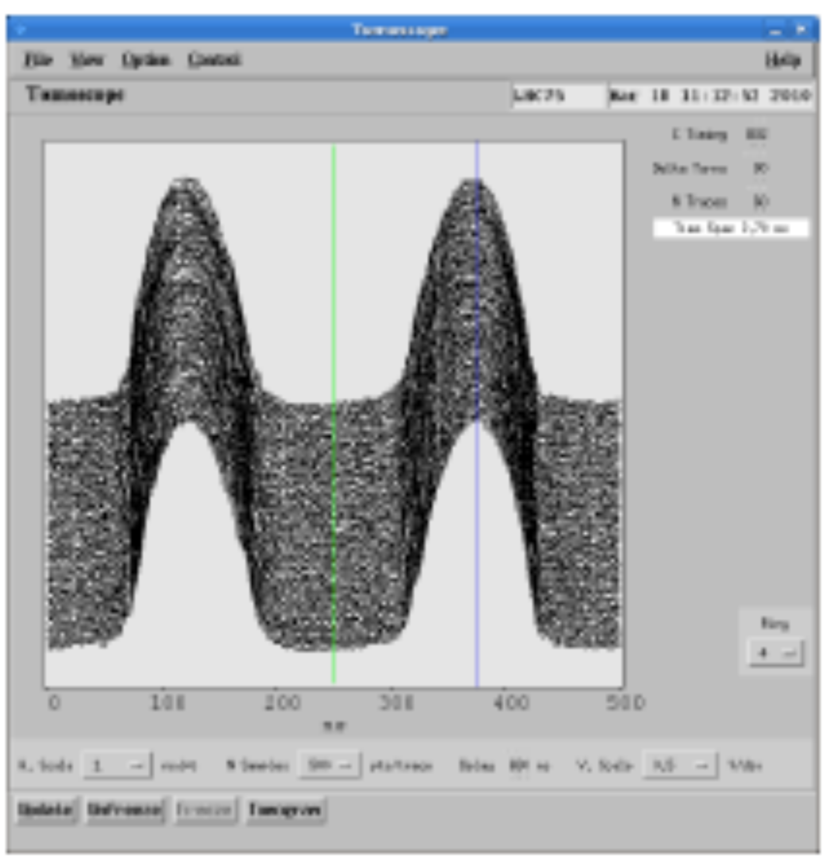


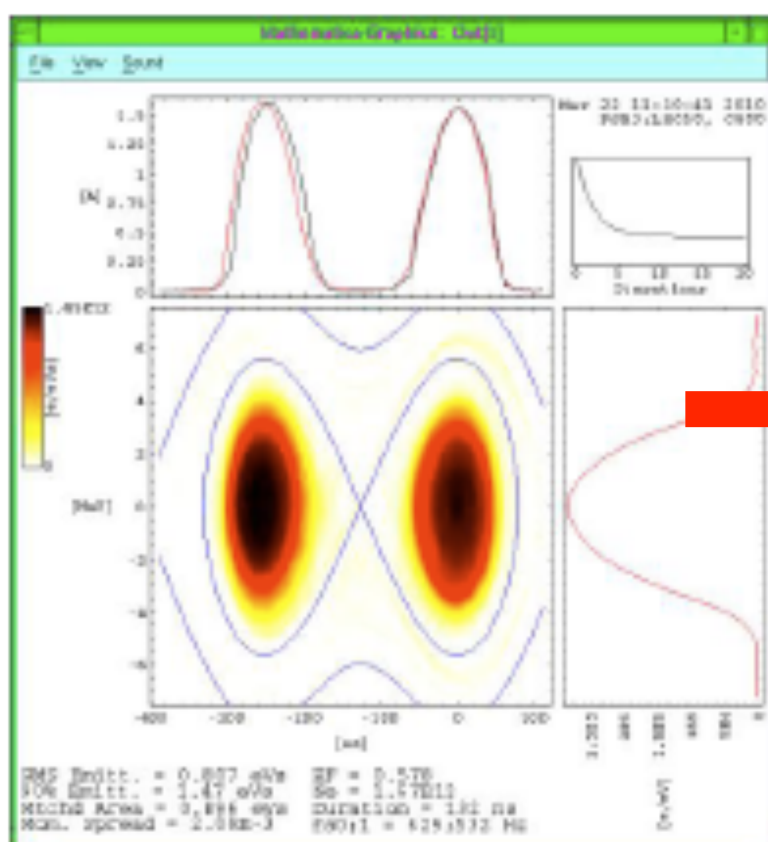

- Constructed in the 70ies to increase the intensity into the PS
- Made of four stacked rings
- Acceleration to $\mathbf{E_{kin}}$**=1.4 GeV**
- Intensities > $\mathbf{10^{13}}$ **protons** per ring obtained (i.e., four times design!!)
- Several types of beams with different characteristics
  - → *Physics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

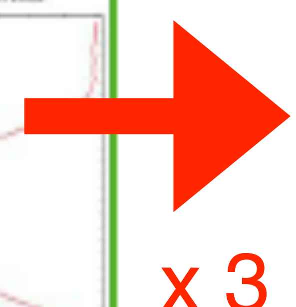
# Filling the PS with LHC beams

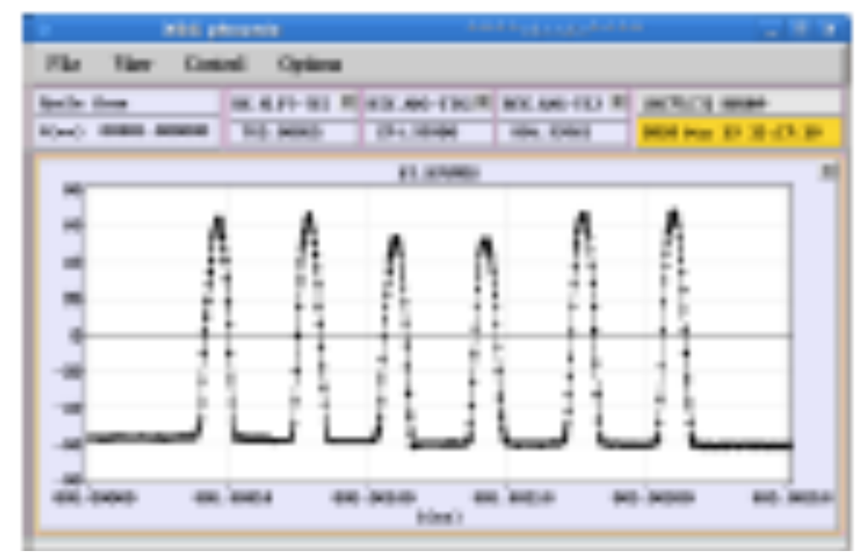



- In the single batch transfer, only rings 2,3 & 4 are filled on h=2 (i.e. 2 bunches per ring)
- The 6 bunches (1 or 2 extractions) can be transferred in one batch to the PS (on h=7)



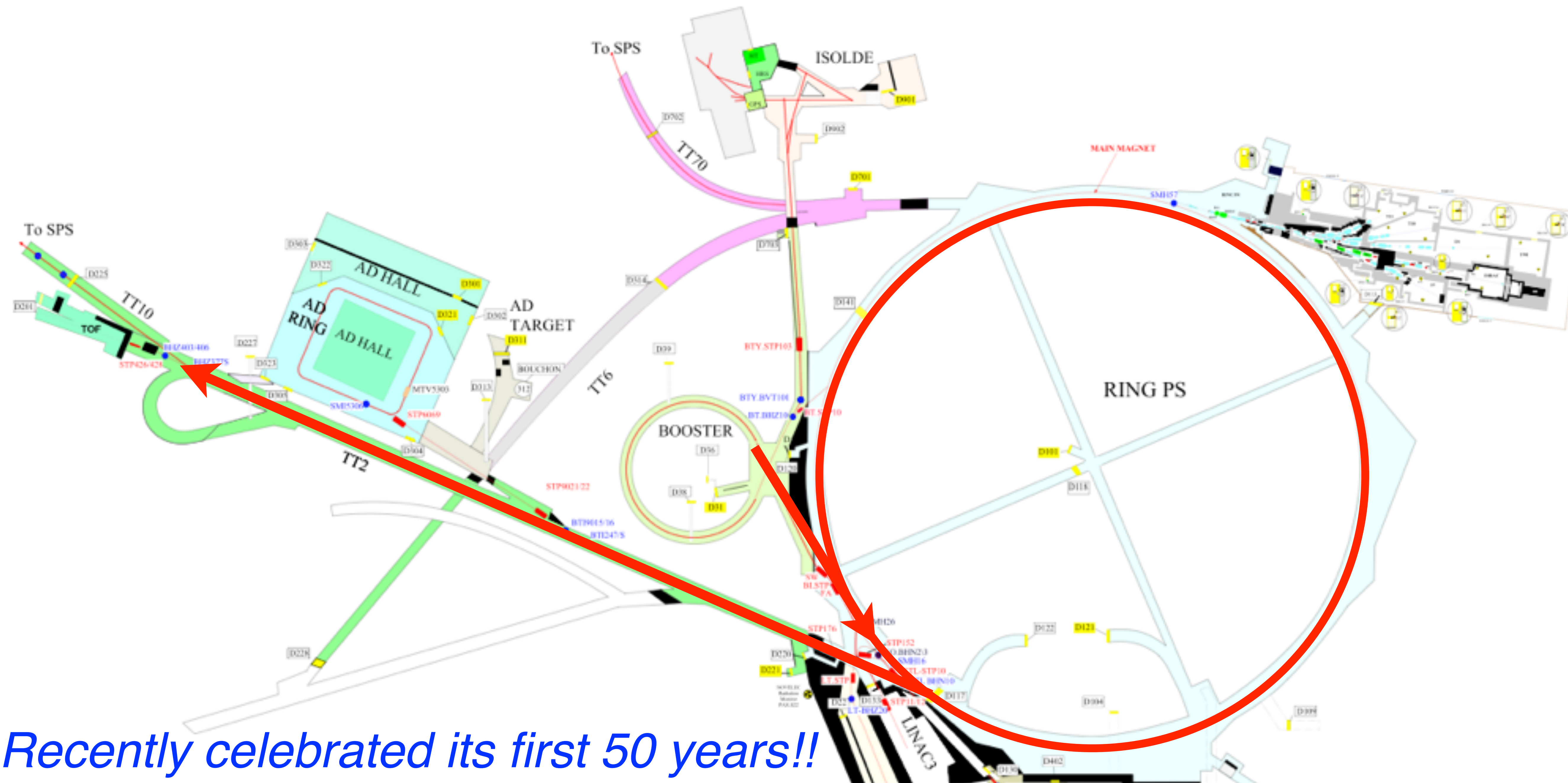




Extract 6 bunches from 3 rings with 324ns spacing

# Proton Synchrotron

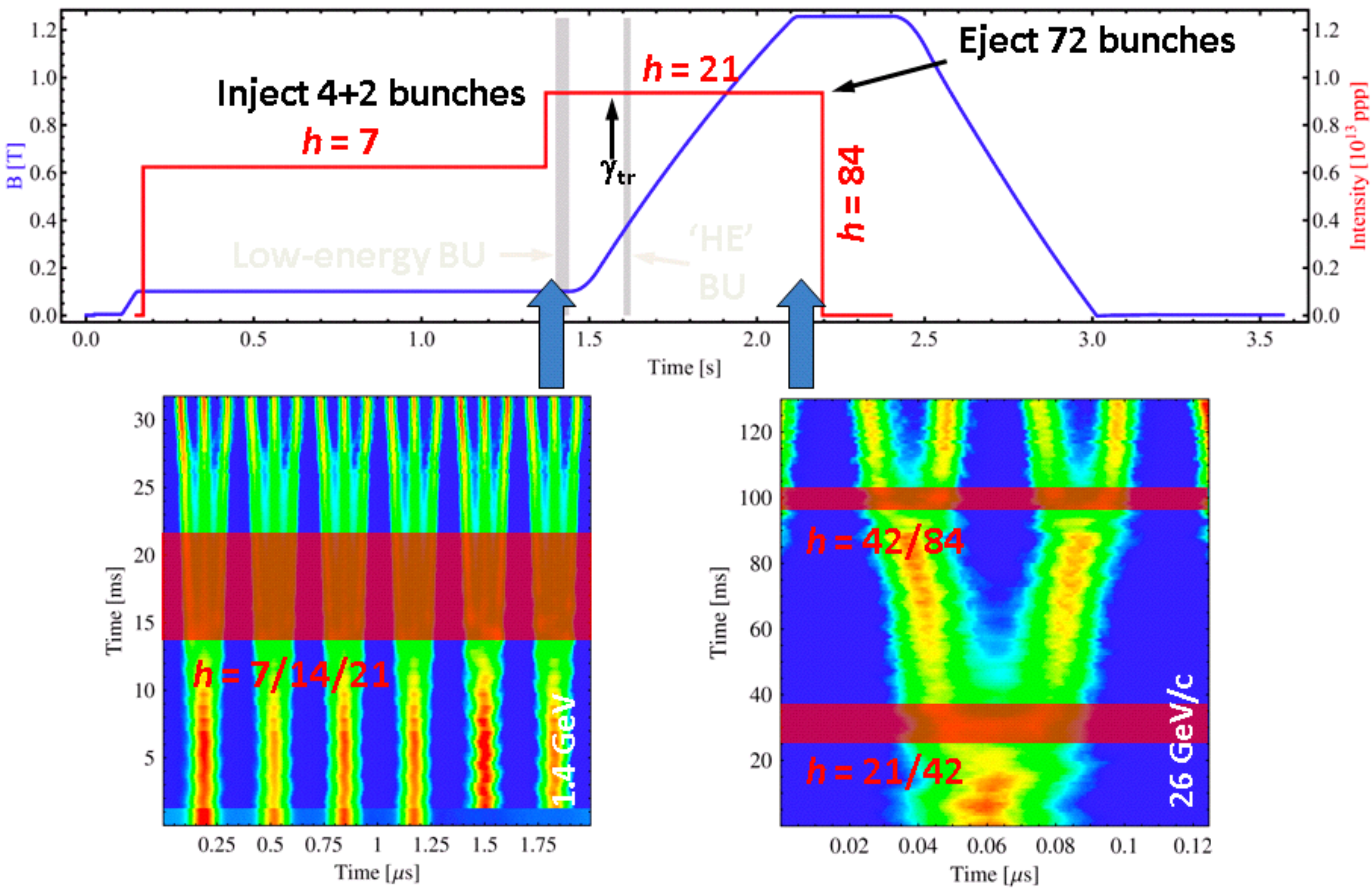



*Recently celebrated its first 50 years!!*

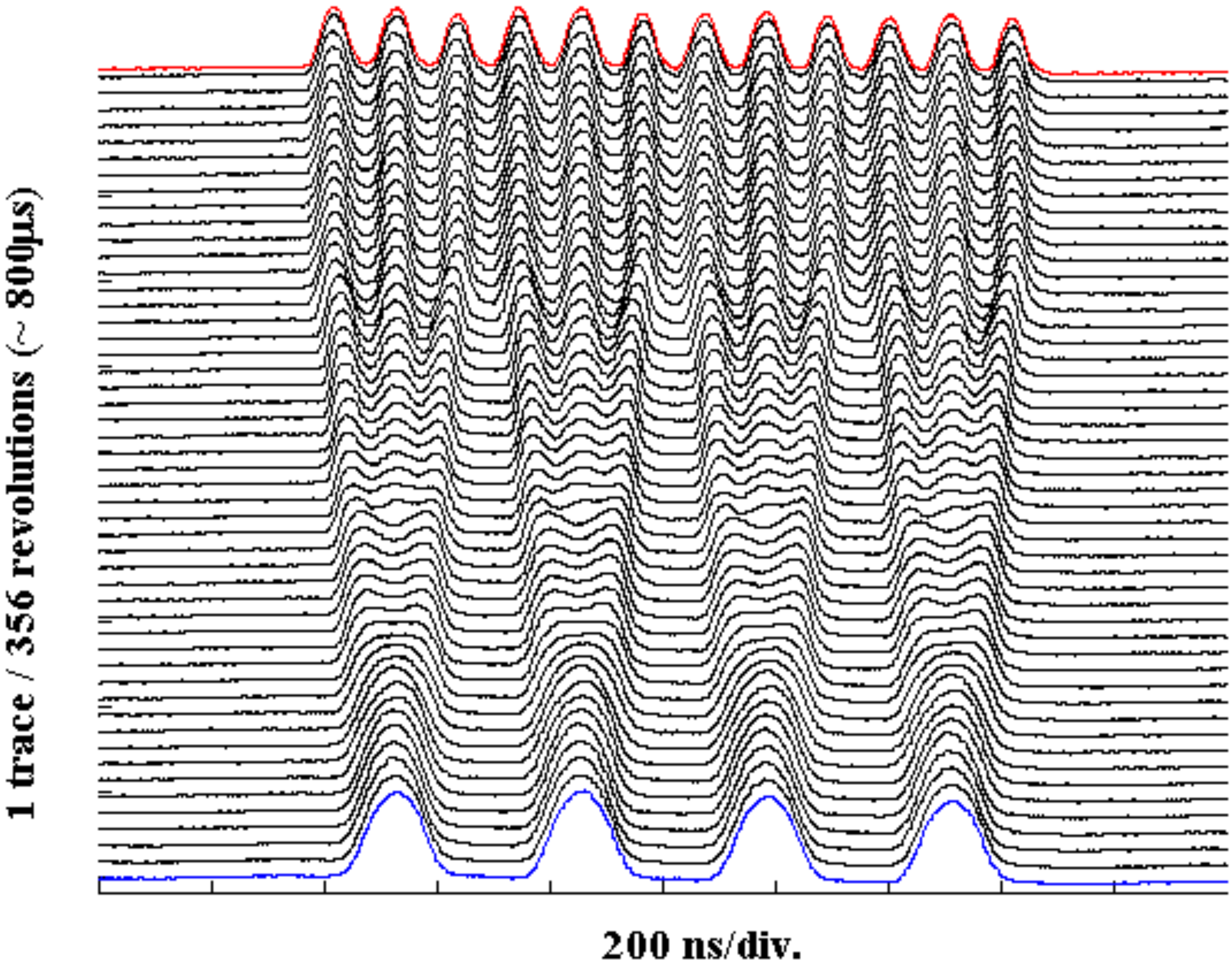
**From the Proton Synchroton to the Large Hadron Collider - 50 Years of Nobel Memories in High-Energy Physics**

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

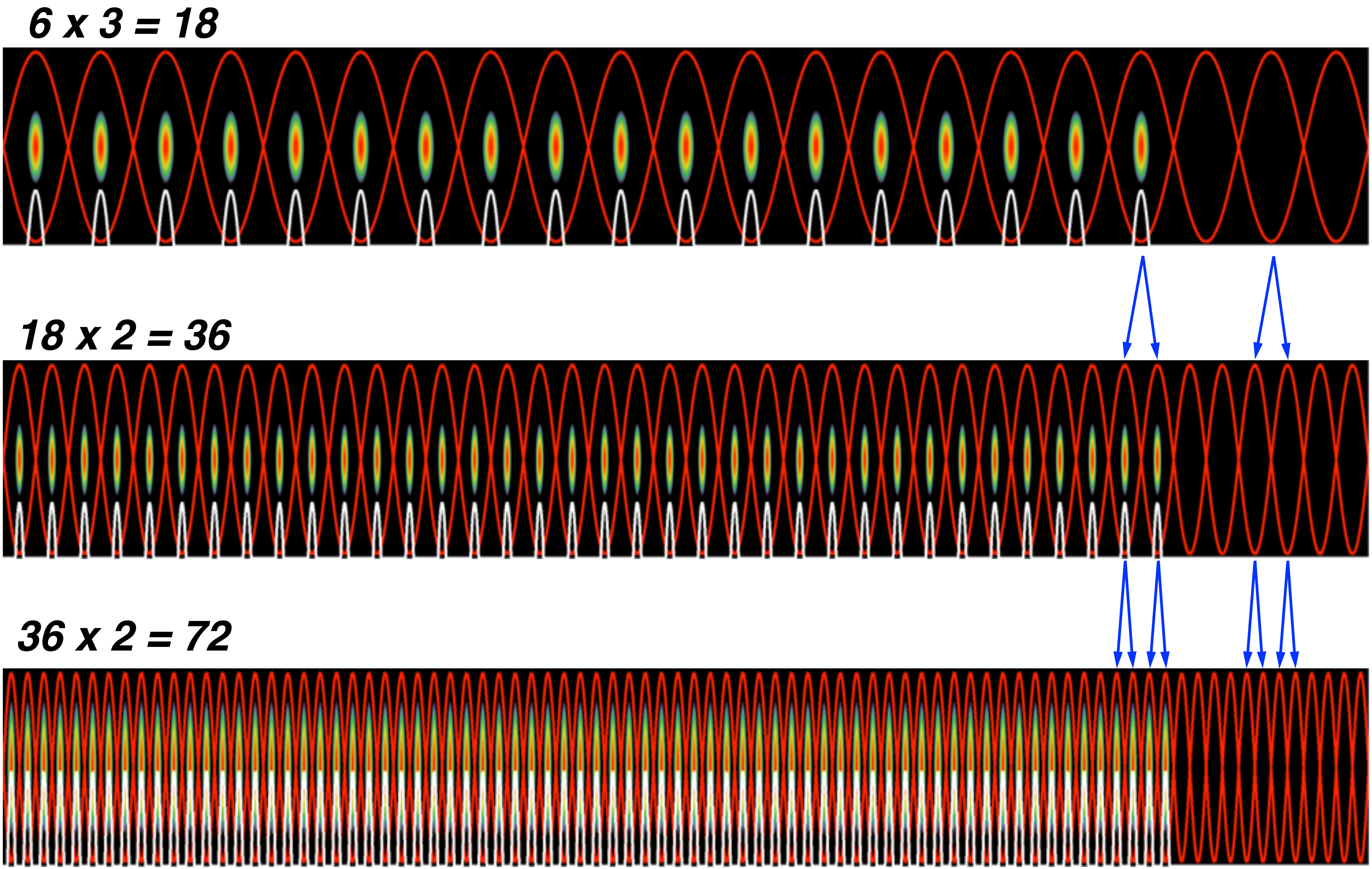


# How it looks in reality




H. Damerau

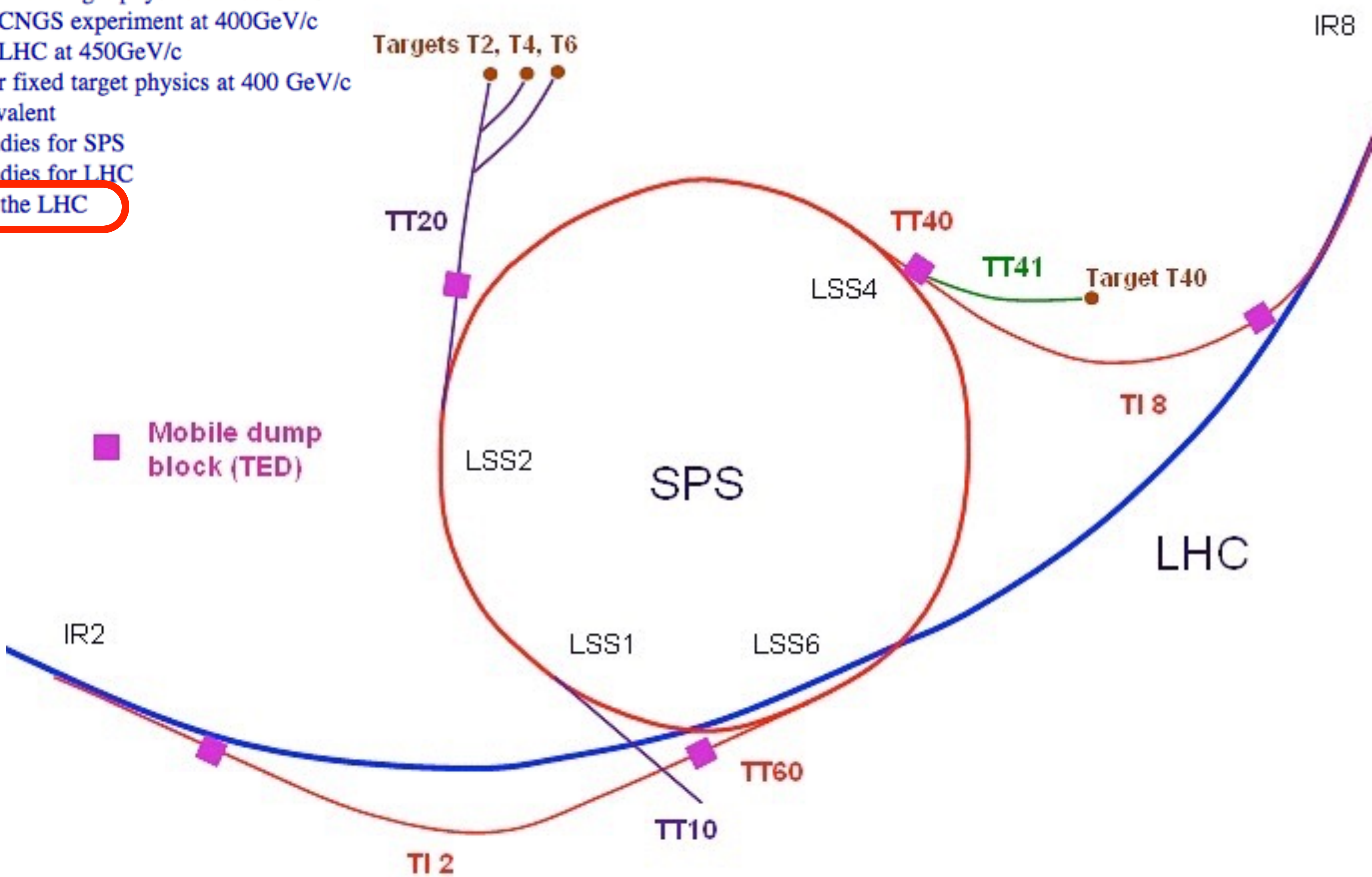
# How it looks in reality



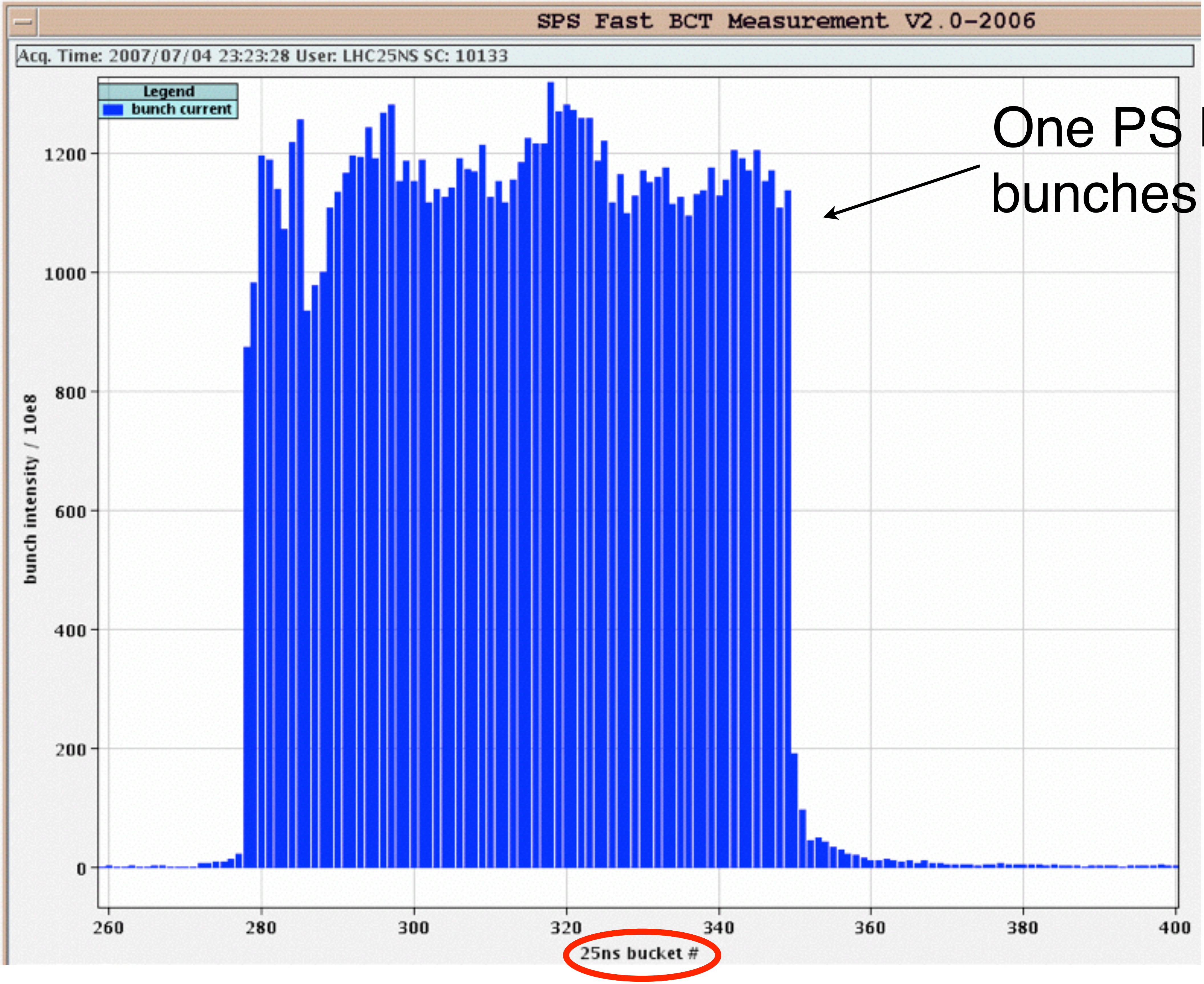

H. Damerau

# 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

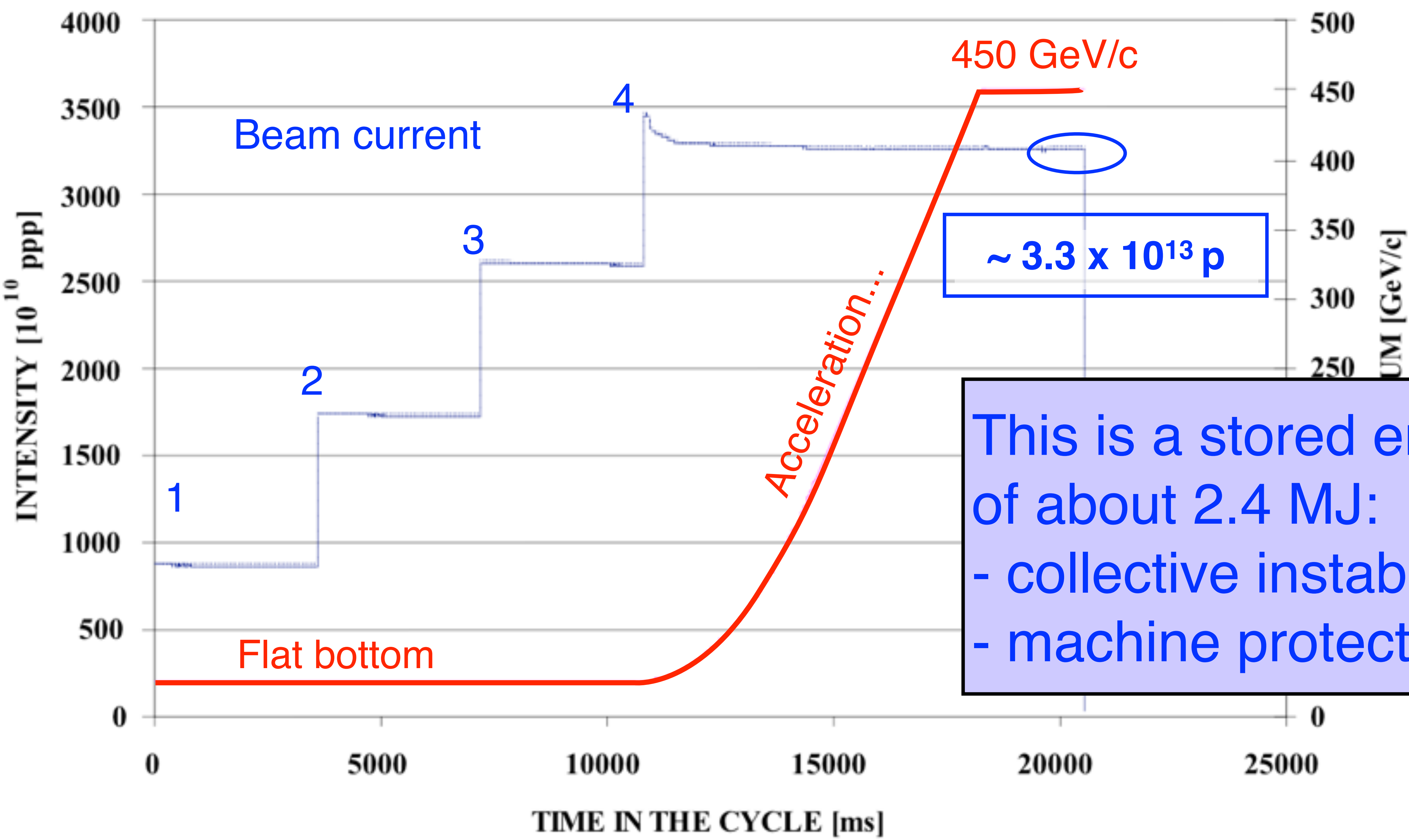


# LHC beams in the SPS



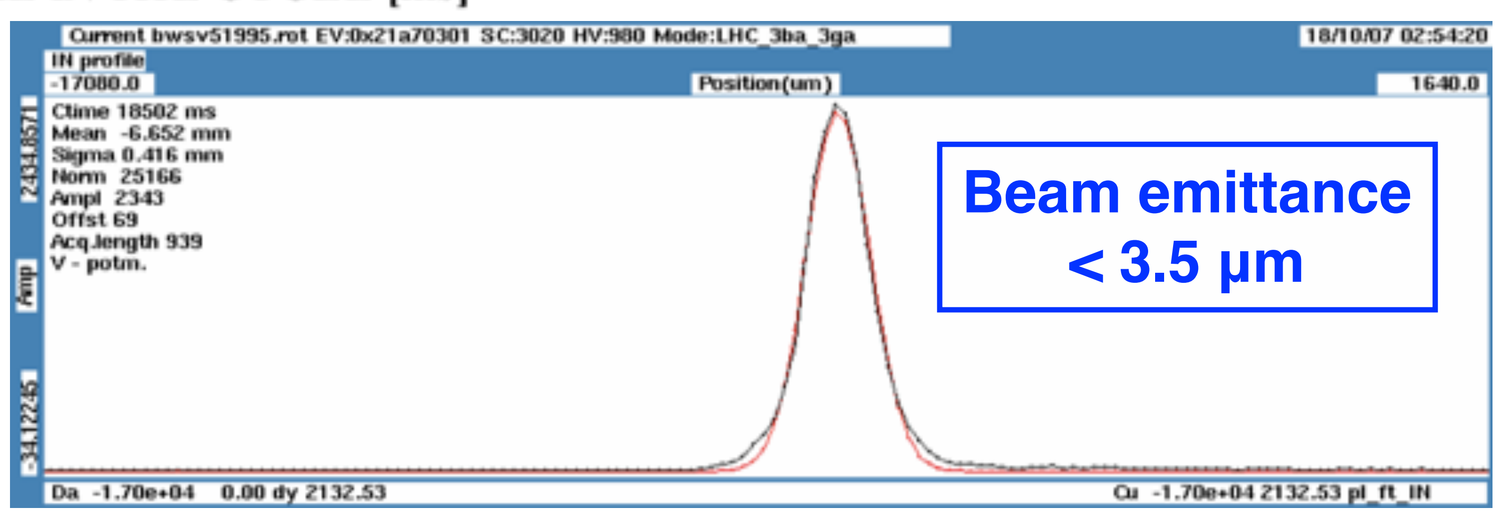

One PS batch of 72 bunches in the SPS

# 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...***




**Beam emittance < 3.5 µm**

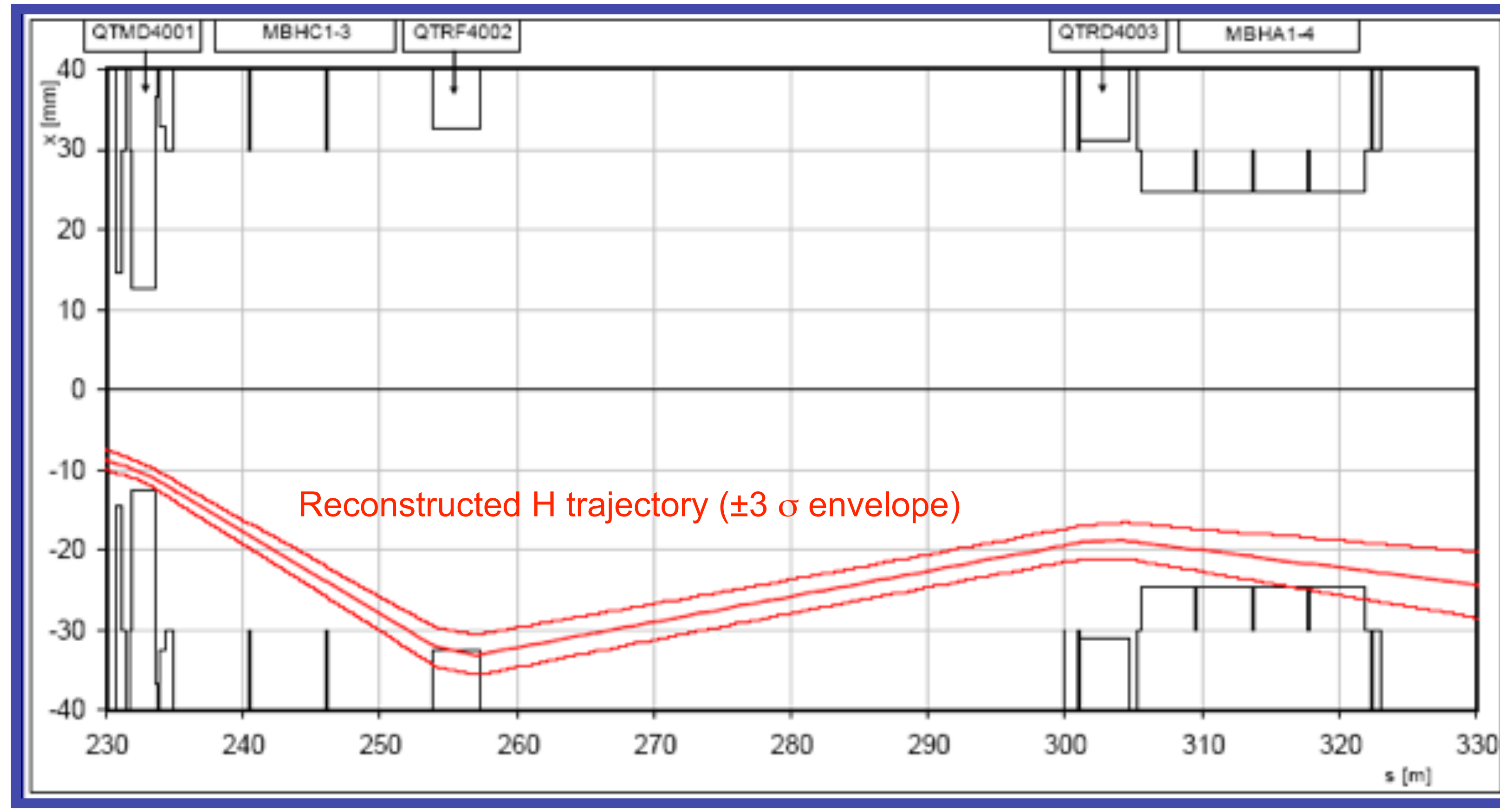
# If anything goes wrong...

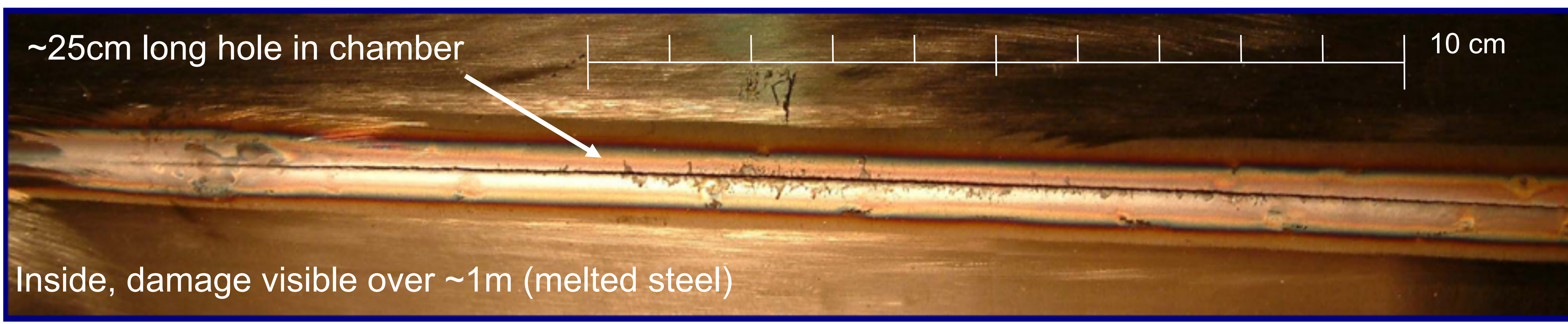
Failure in SPS during setting-up of LHC beam (25/10/04).

Extraction septum supply tripped due to EMC from the beam.

In 11ms the field dropped 5% and the beam of $3.4\times10^{13}$ protons at 450GeV (2.45MJ) were wrongly extracted onto aperture.

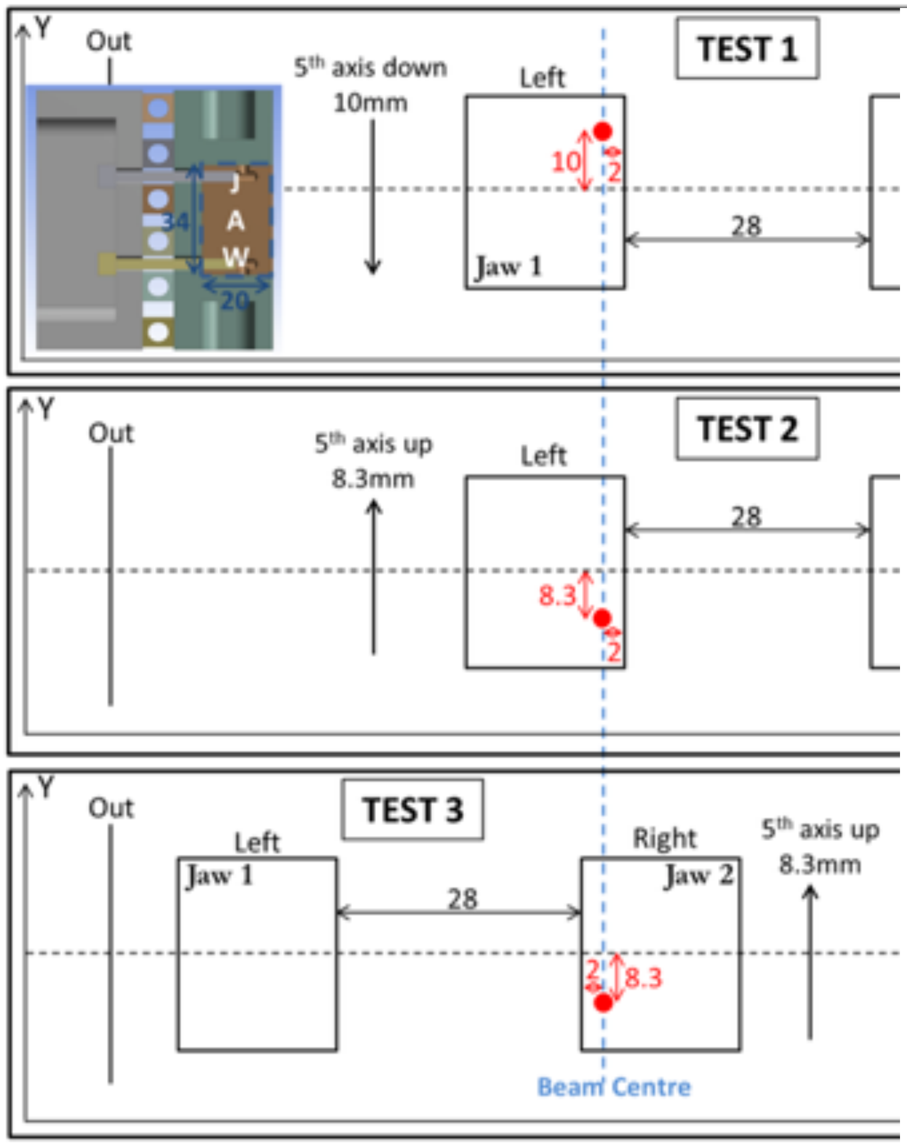
Chamber and magnet were damaged and had to be replaced.

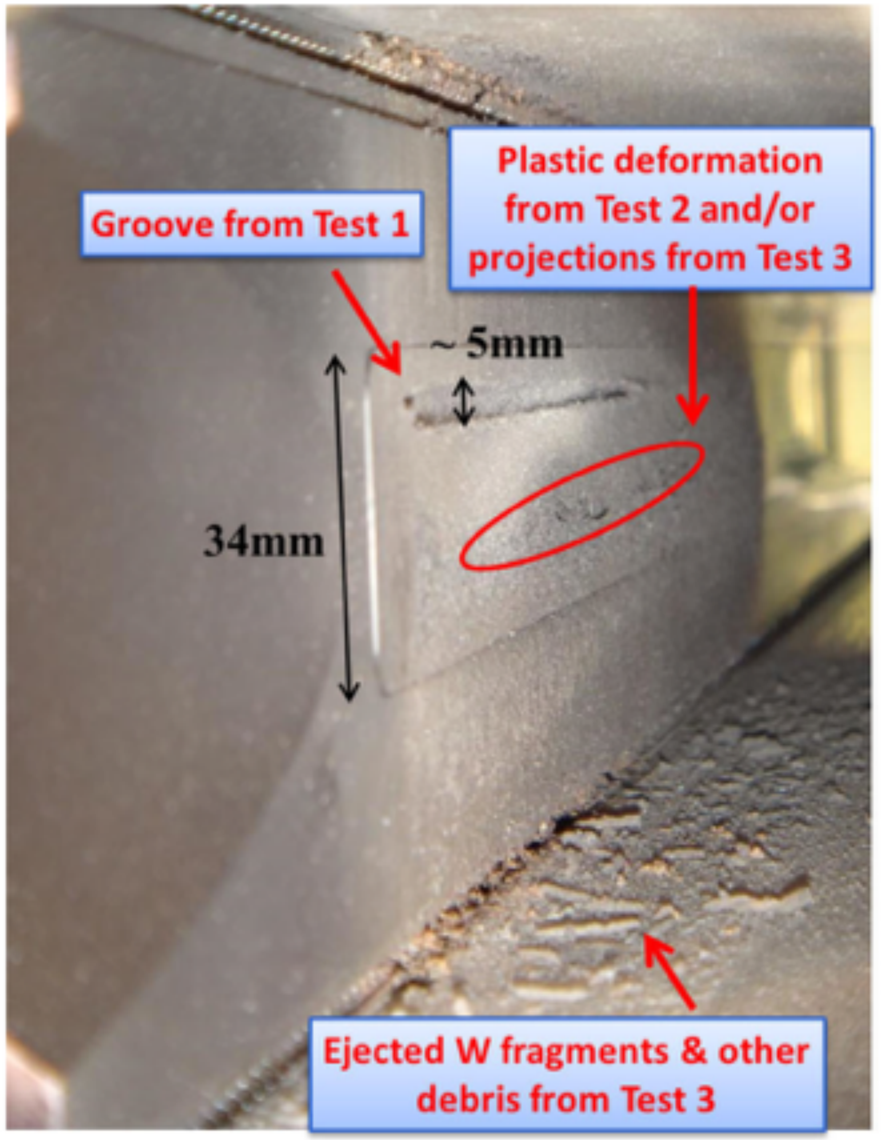


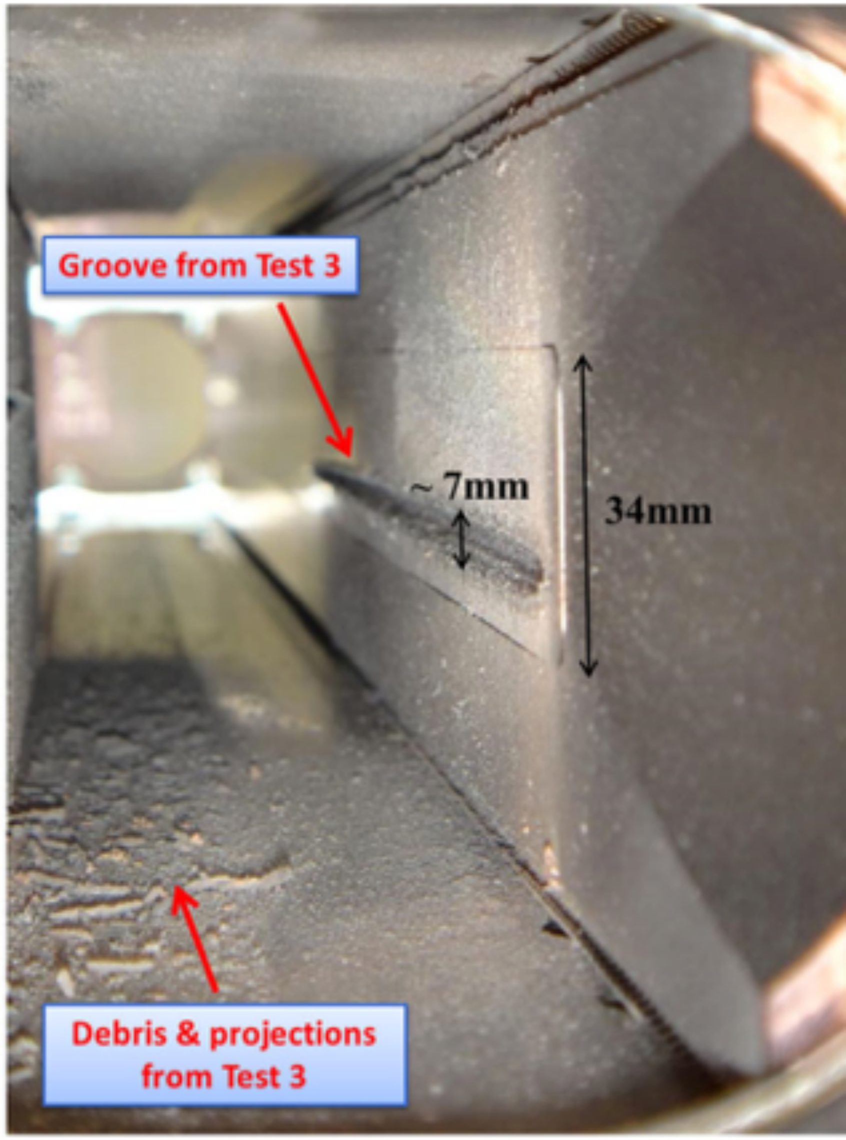




*… a first look at concerns from machine protection…*

# Example — damage from 1 bunch




*M. Cauchi et al., Phys. Rev. ST Accel. Beams 17, 021004*

*Controlled experiment at the CERN HiRadMat facility where 440GeV beam were used with energy equivalent to one 7 TeV LHC bunch.*

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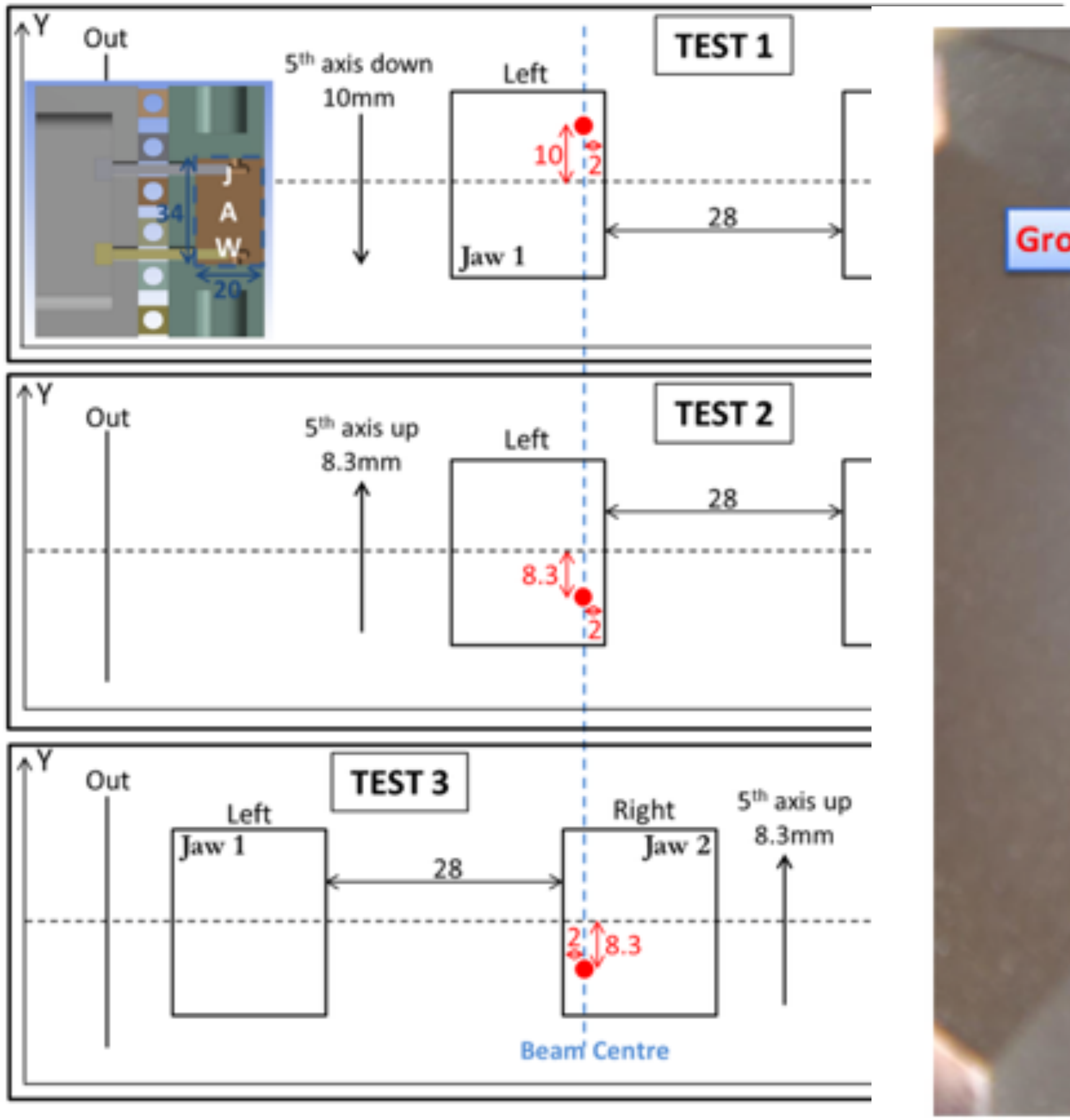


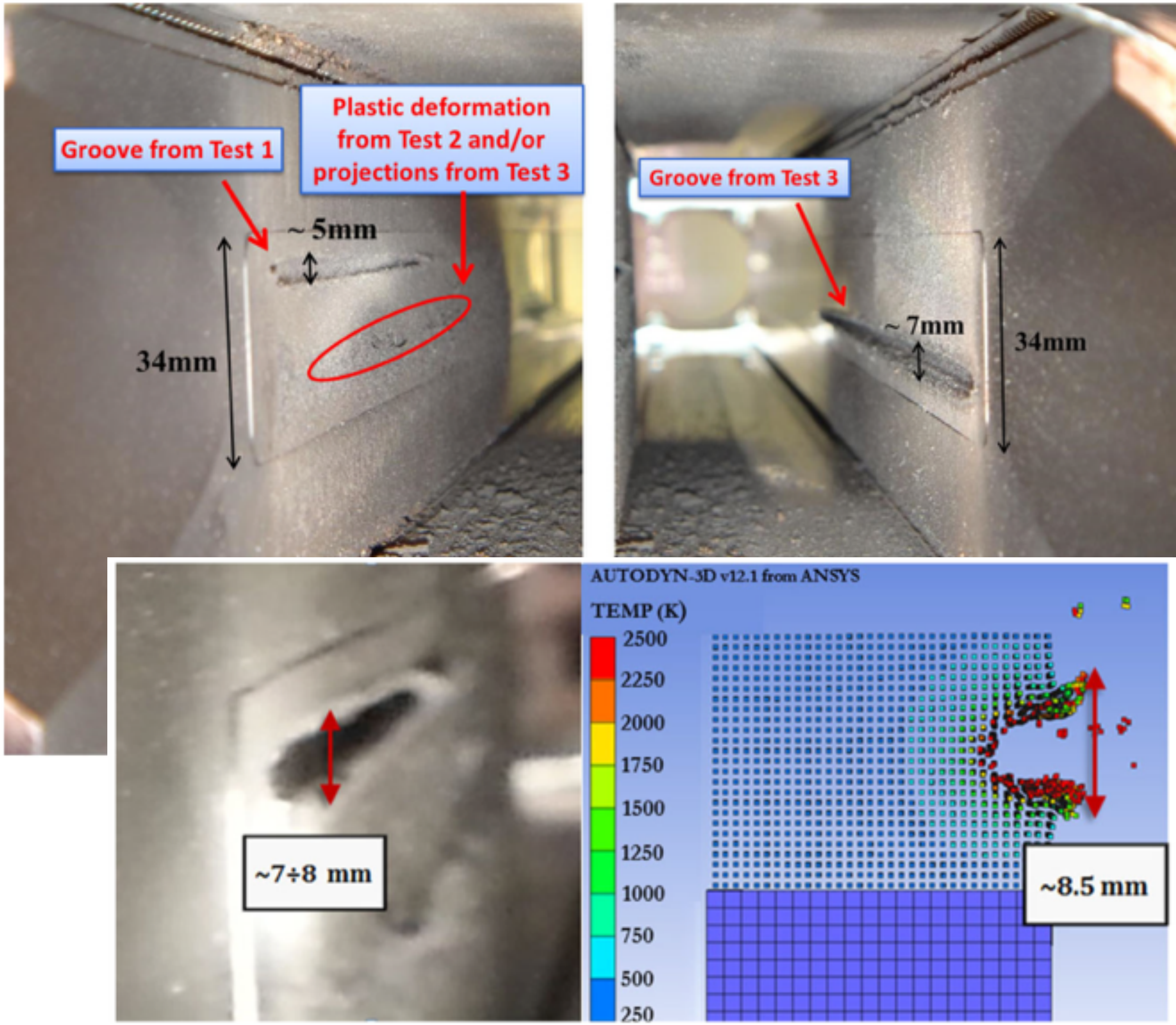


*M. Cauchi et al., Phys. Rev. ST Accel. Beams 17, 021004*

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# All manned from the control centre

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- Introduction
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  - Basic equations
  - Relevant beam measurements
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  - **Arcs and straight sections**
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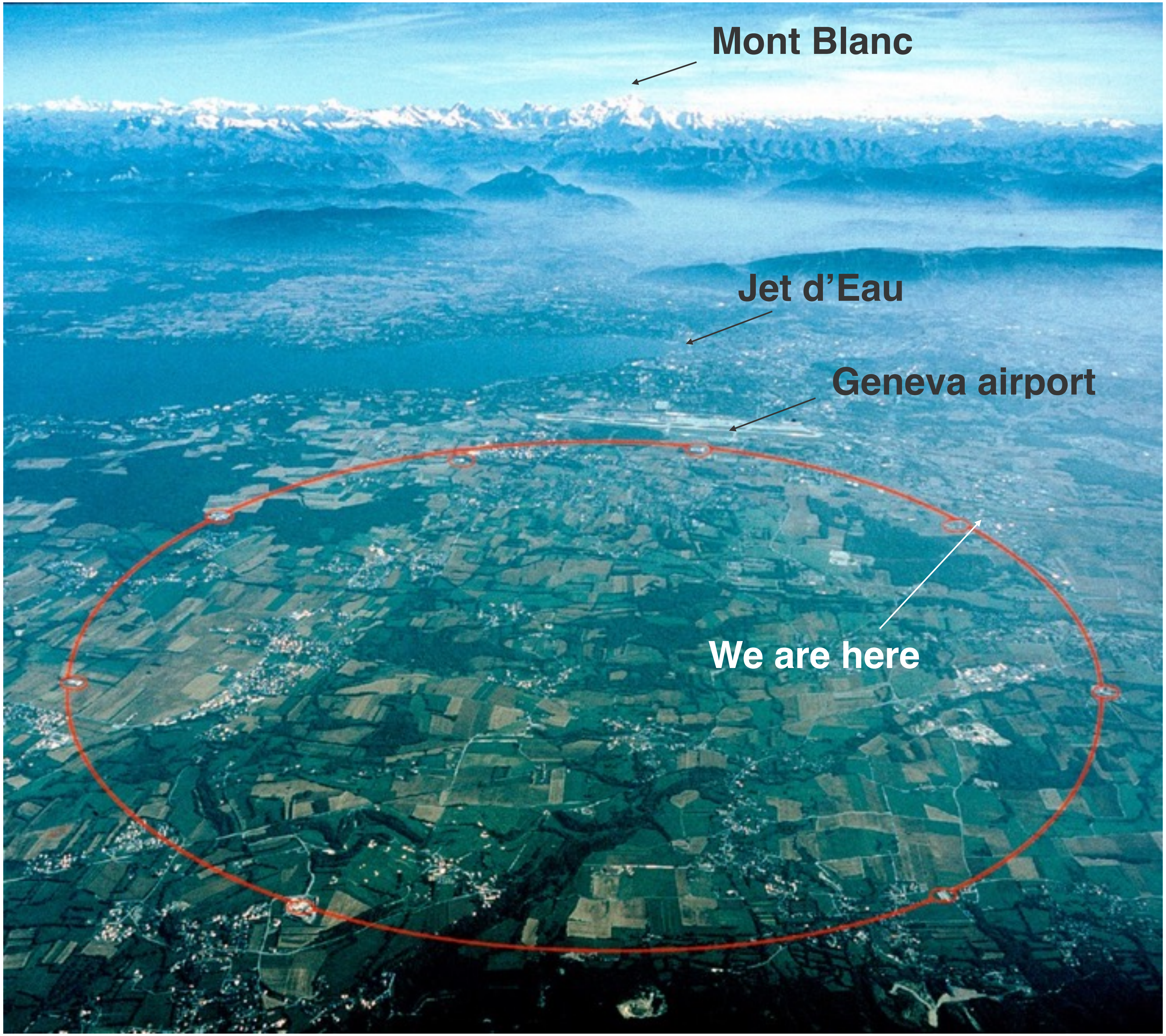
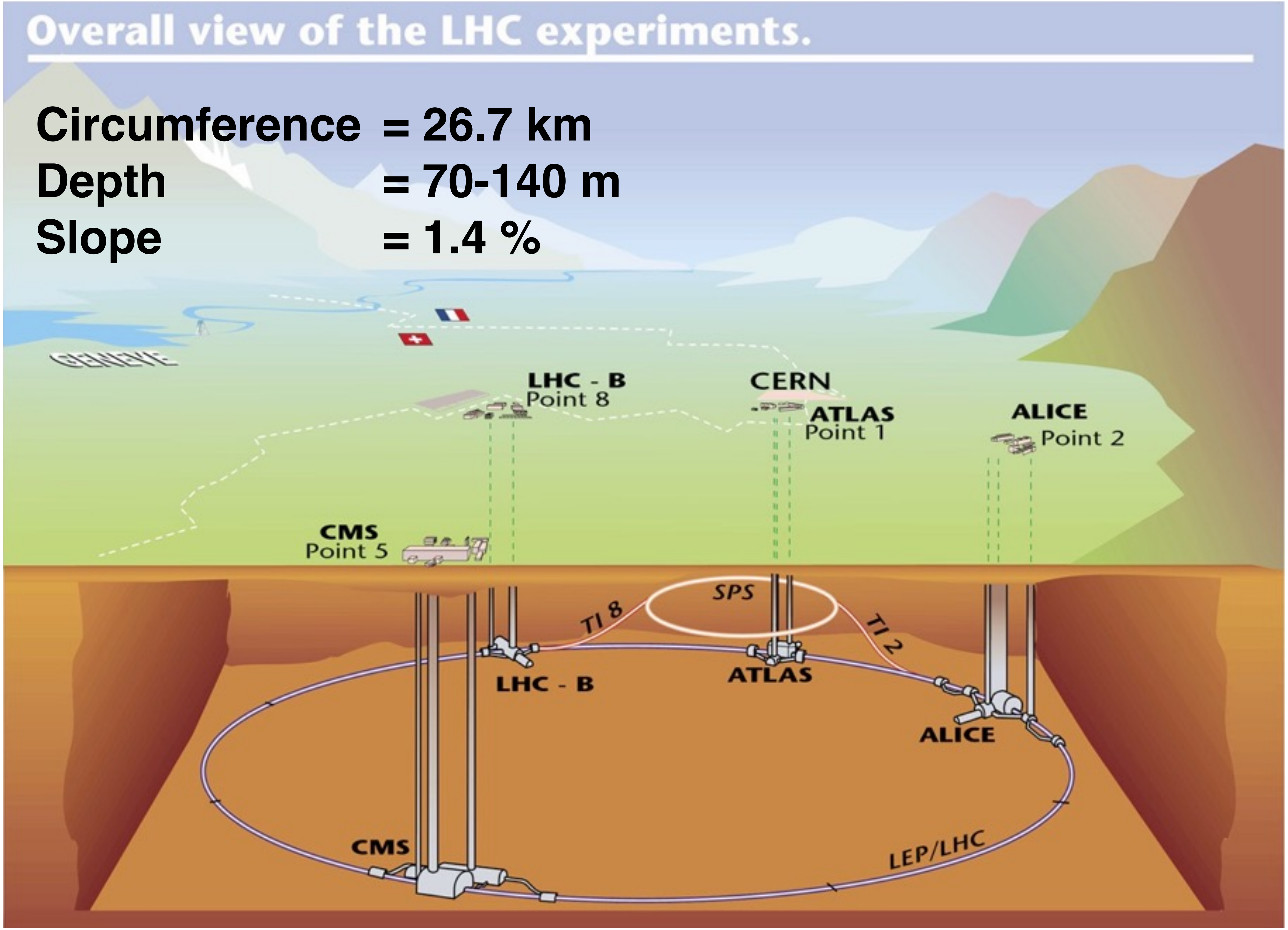
# LHC: aerial view



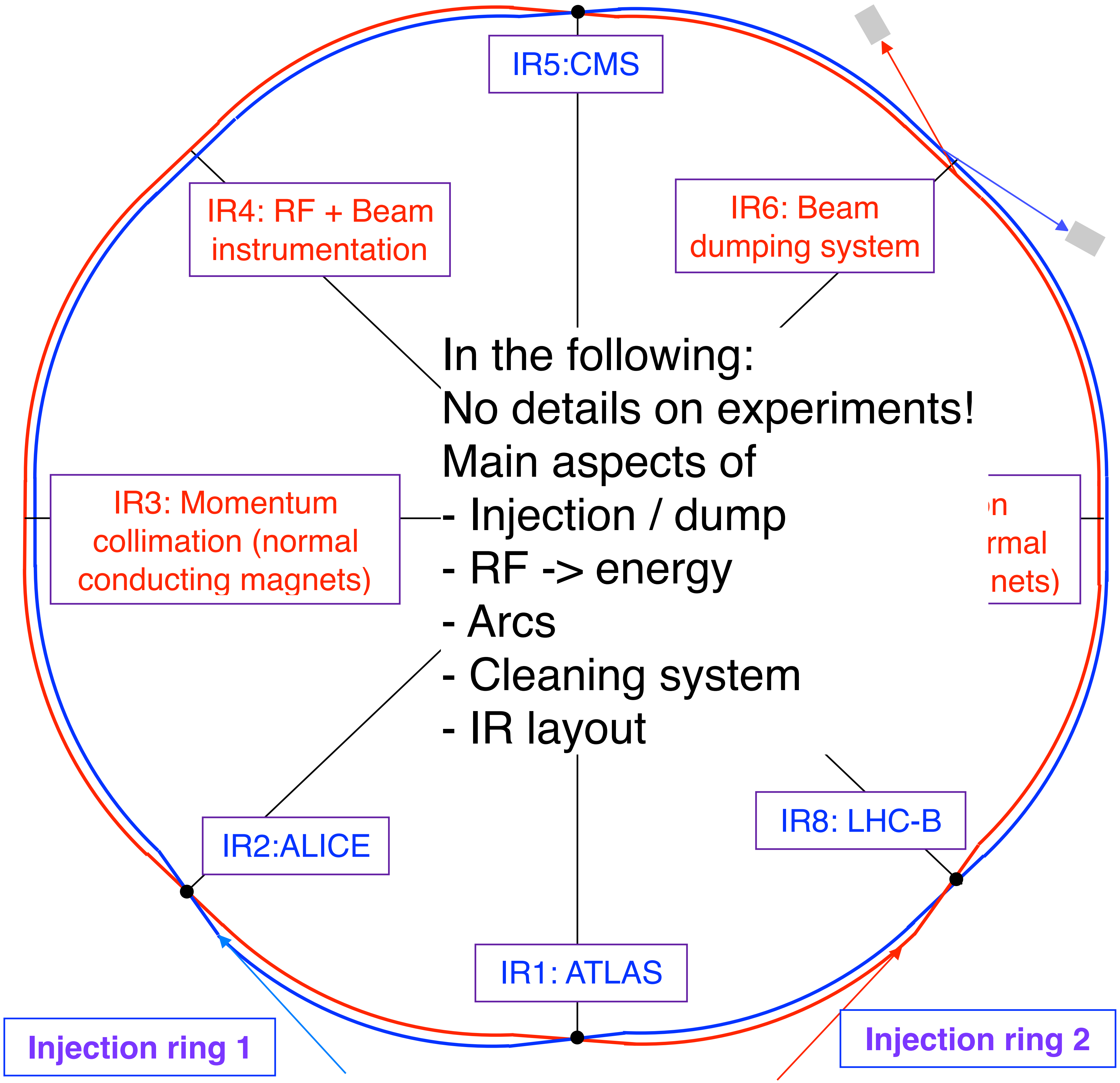
# LHC layout - from bottom



# Layout and accelerator systems

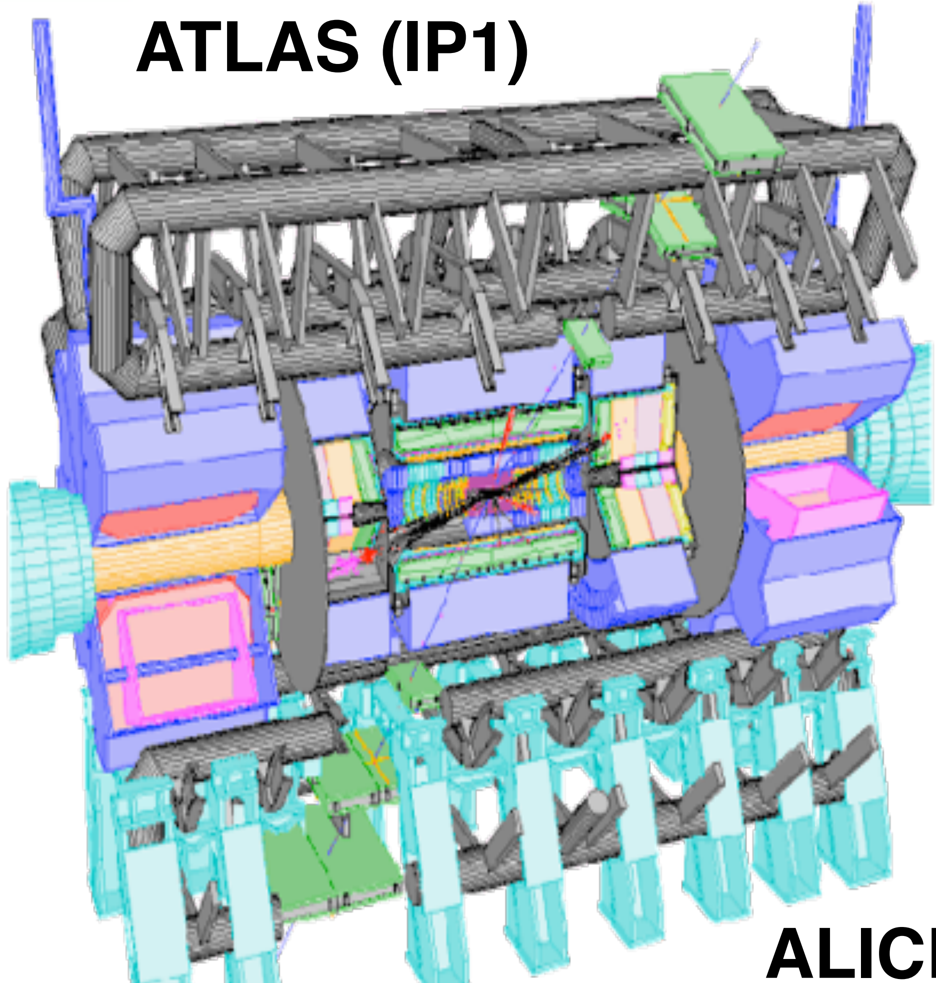
**LHC Layout**

- ➡ 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

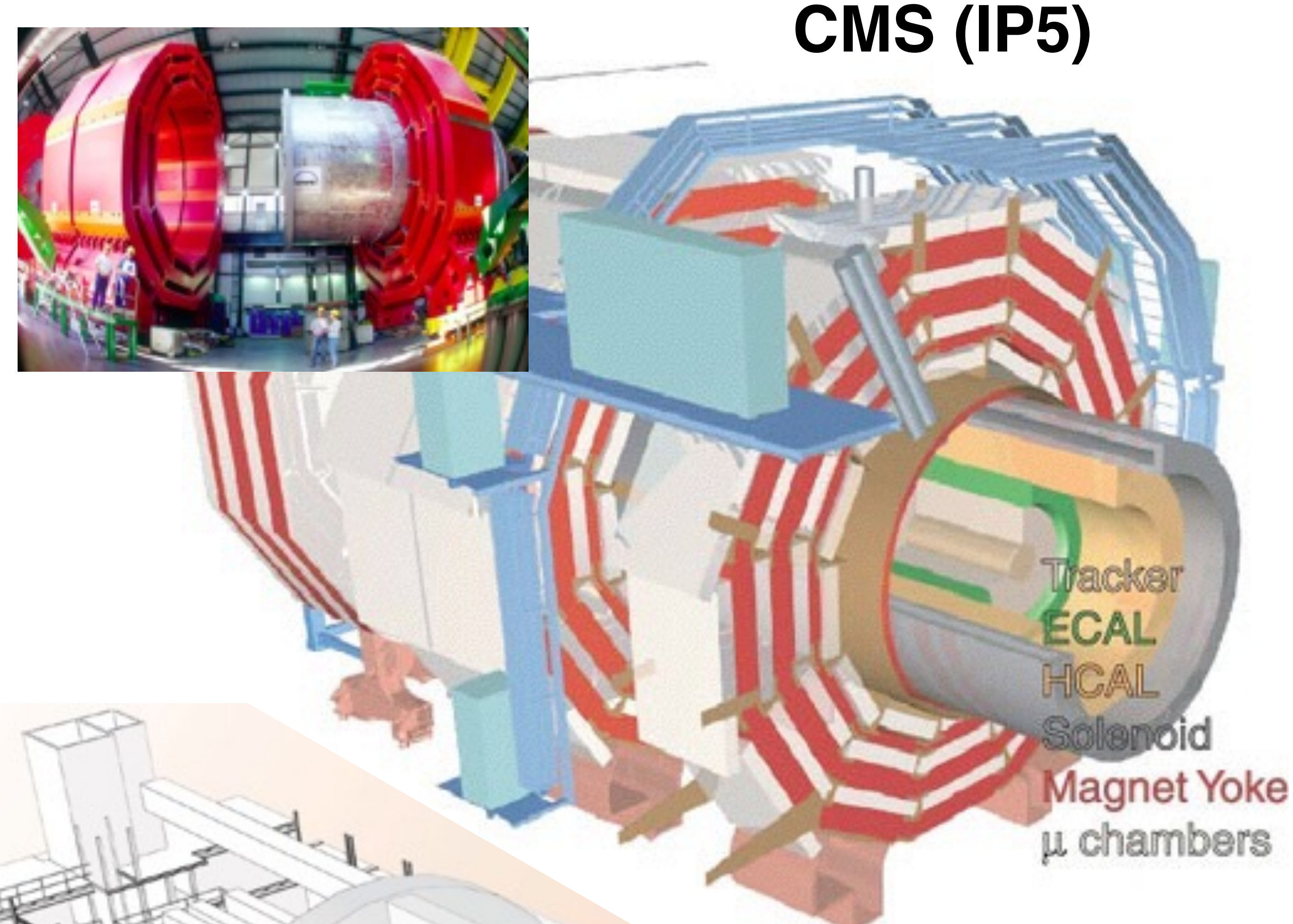


# Main LHC experiments

## ATLAS (IP1)

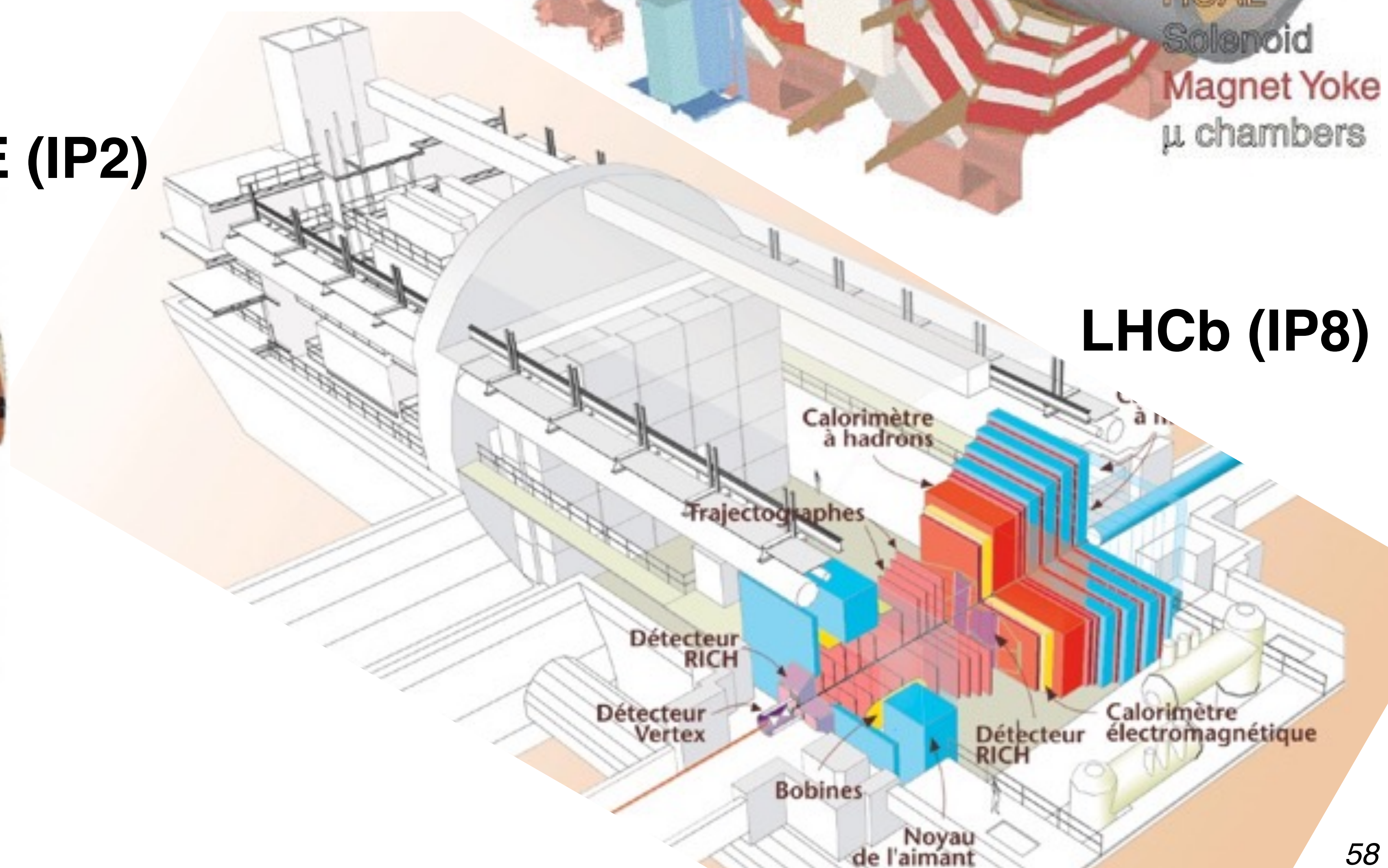


## CMS (IP5)

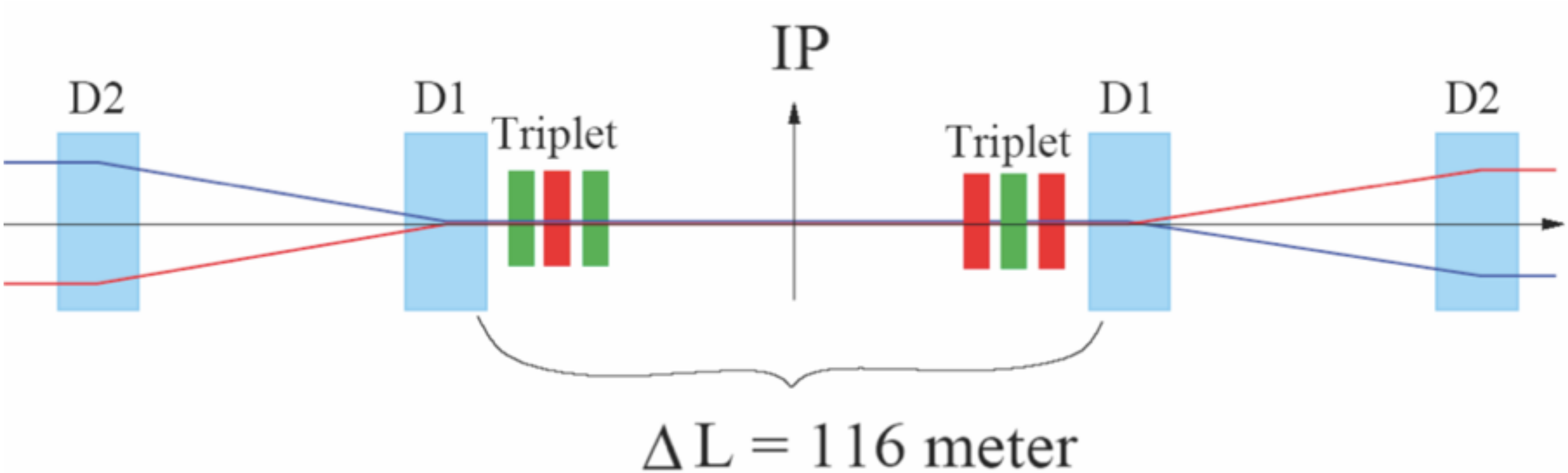


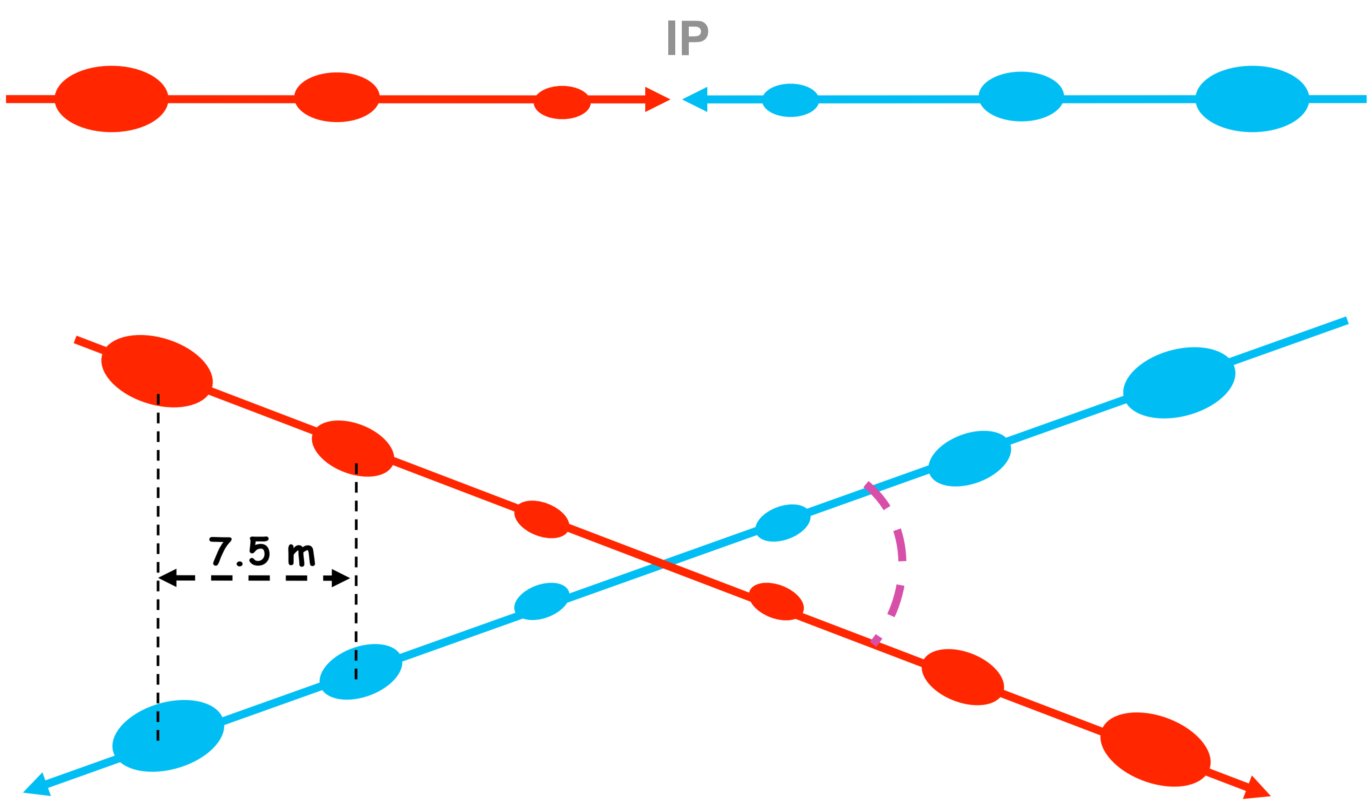

## ALICE (IP2)


## LHCb (IP8)



# Interaction region layout



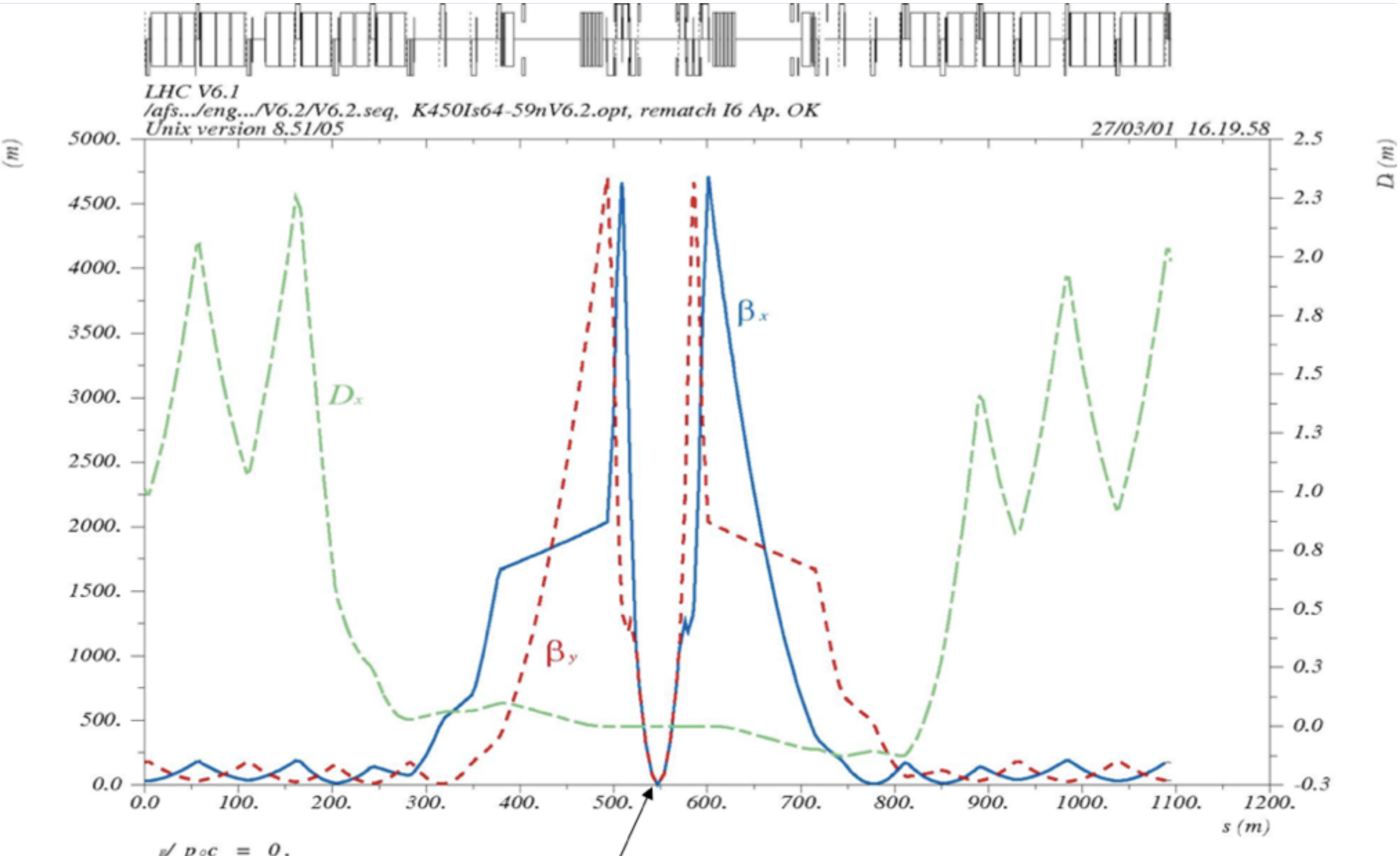




- With more than 154 bunches, we need a crossing angle to avoid parasitic collisions outside the IP.
- Beams are separated in the other plane during injection and ramp

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

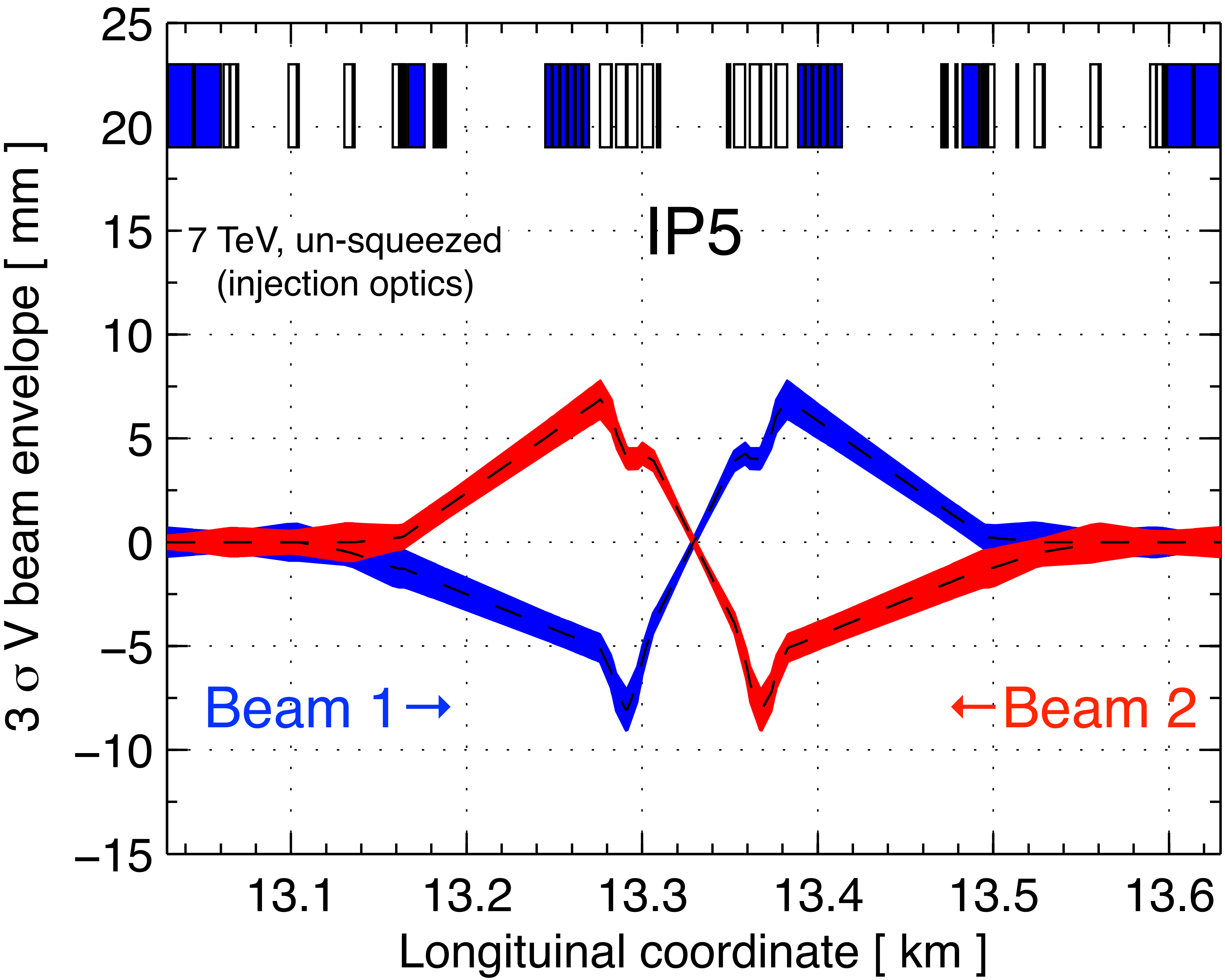
$$F = 1/\sqrt{1+\left(\frac{\theta_c\sigma_z}{2\sigma^*}\right)^2}$$

# Beta functions for IP1 and IP5

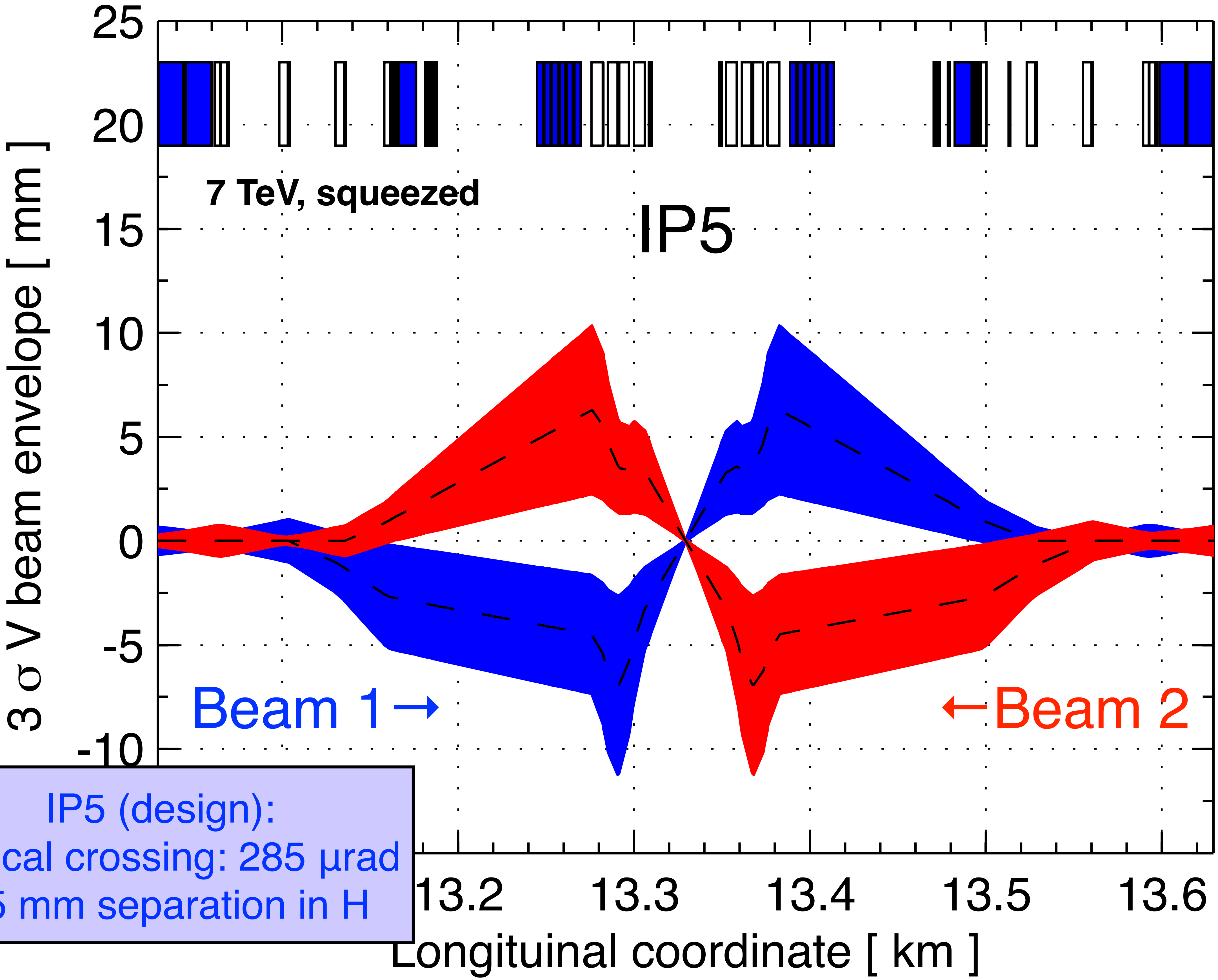



**β = 55 cm → σ = 16 μm; D = 0m**

# Beam envelope



# Beam envelope




IP5 (design):
Vertical crossing: 285 μrad
0.5 mm separation in H

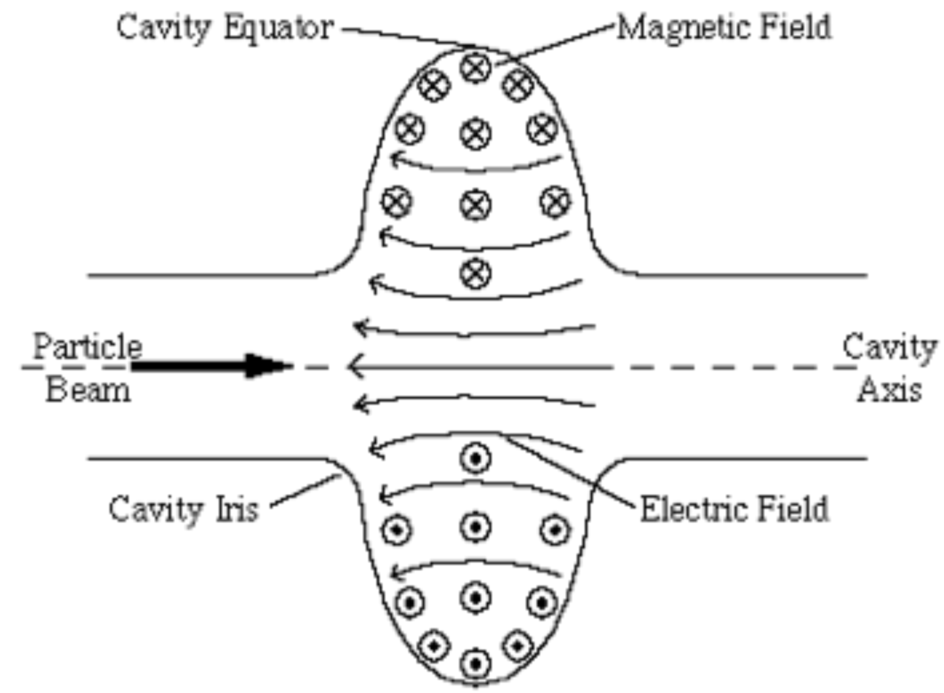
# Radio frequency (IP4)

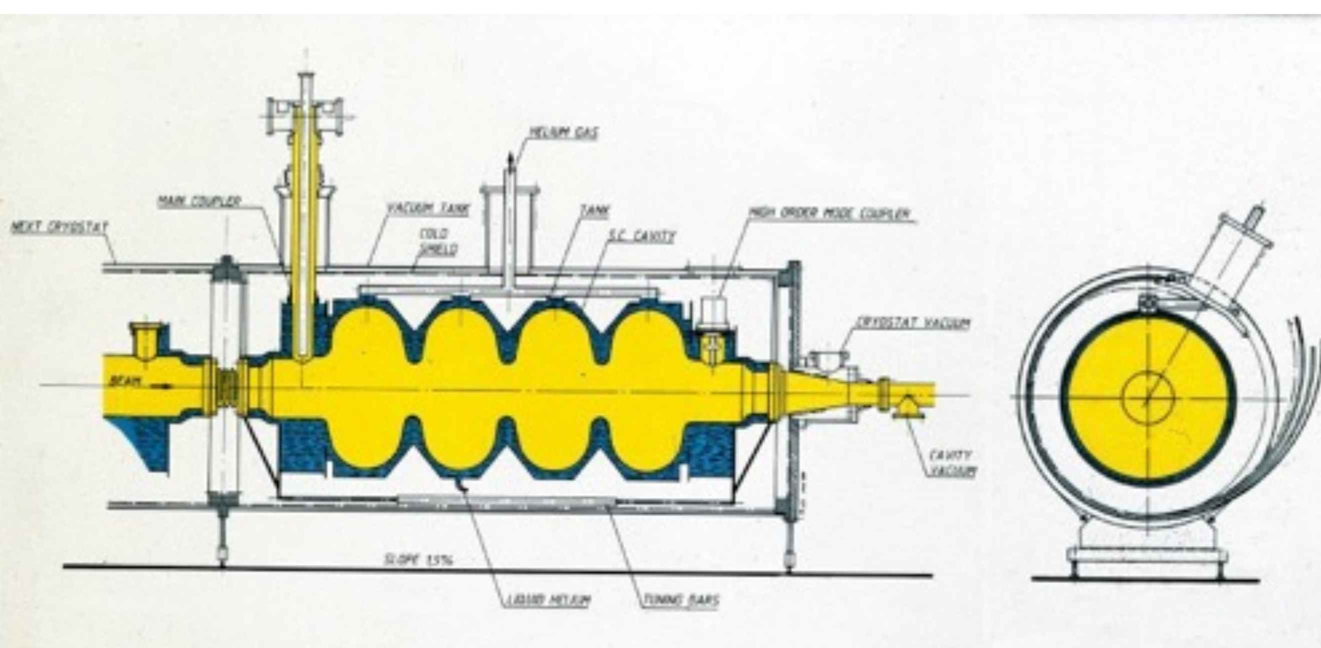
8 RF superconducting cavities per ring at 400.790 MHz: 2 modules per beam, 4 cavities per module

16 MV/beam at 7 TeV

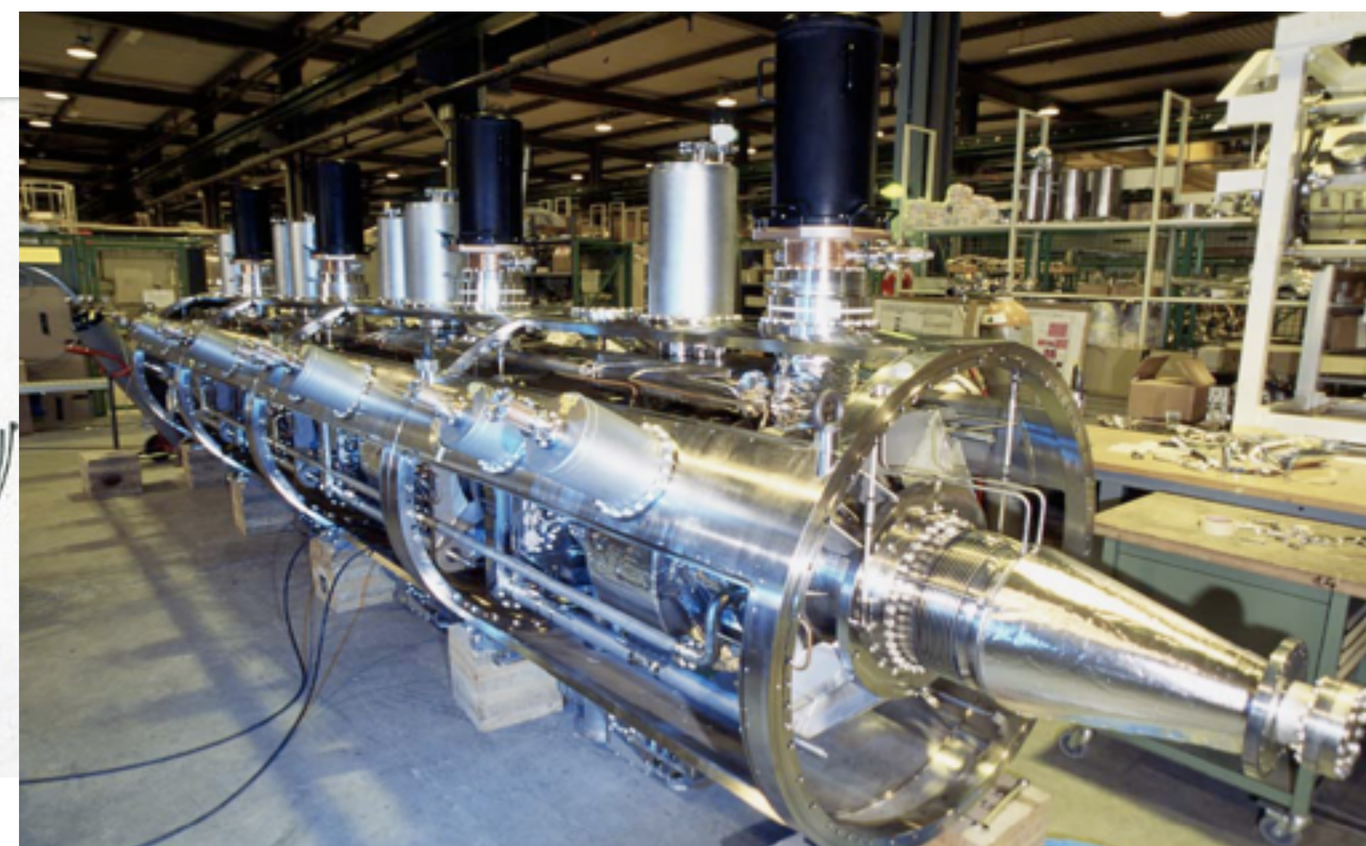
1 MV /cavity at injection

2 MV/cavity during physics

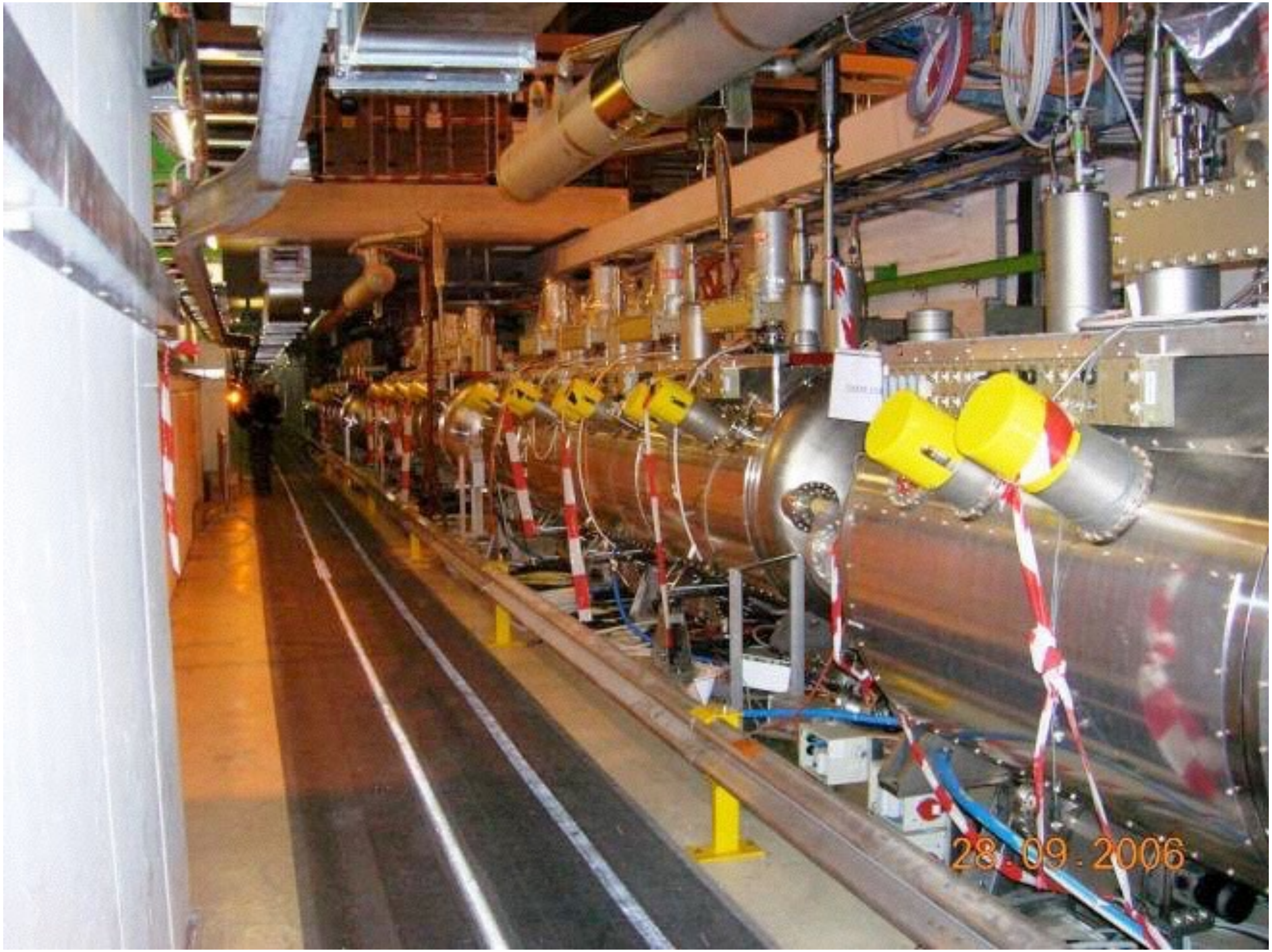


SUPERCONDUCTING CAVITY WITH ITS CRYOSTAT



# RF - tunnel view



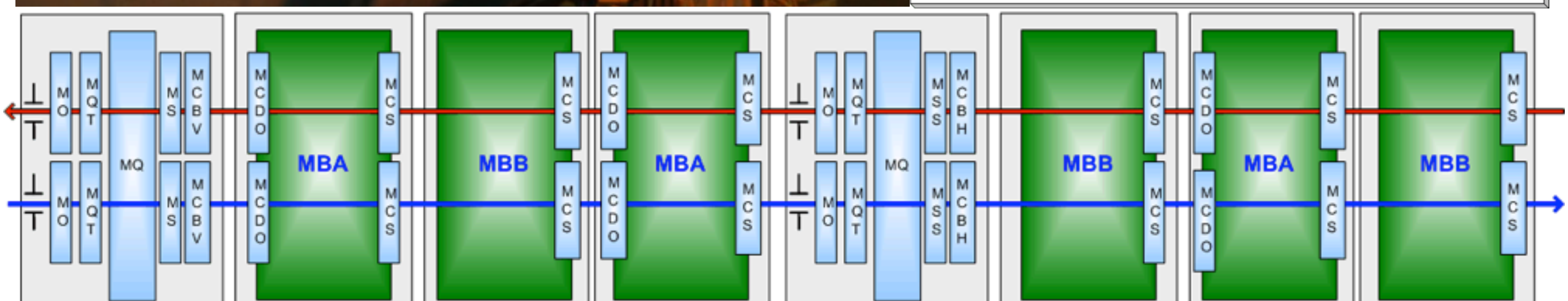
# The LHC arcs

MUCH more complex than the simple view showed before!

**1232** main dipoles + 3700 multipole corrector magnets

**392** main quadrupoles + 2500 corrector magnets

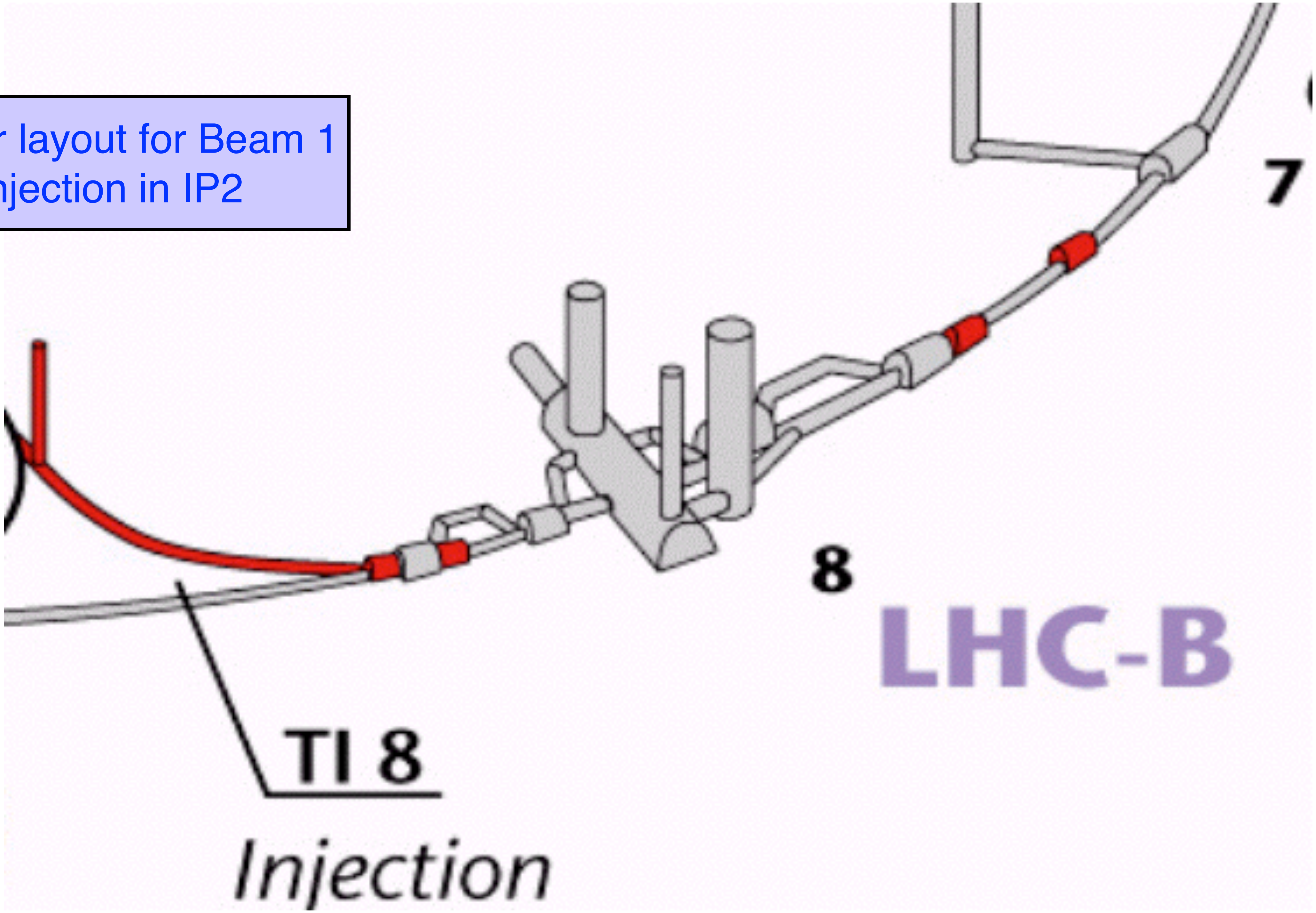
**MCS**: Sextupole corrector (b3)
**MCDO**: Assembly of spool correctors consists of an octupole insert **MCO** (b4) and a decapole magnet **MCD** (b5)
**MQT**: Trim quarupole corrector
**MS**: arc sextupole corrector
**MQS**: skew quad lattice corrector
**MCBH**: Horizontal dipole corrector
**MCBV**: Vertical dipole corrector
**MO**: Lattice octupole



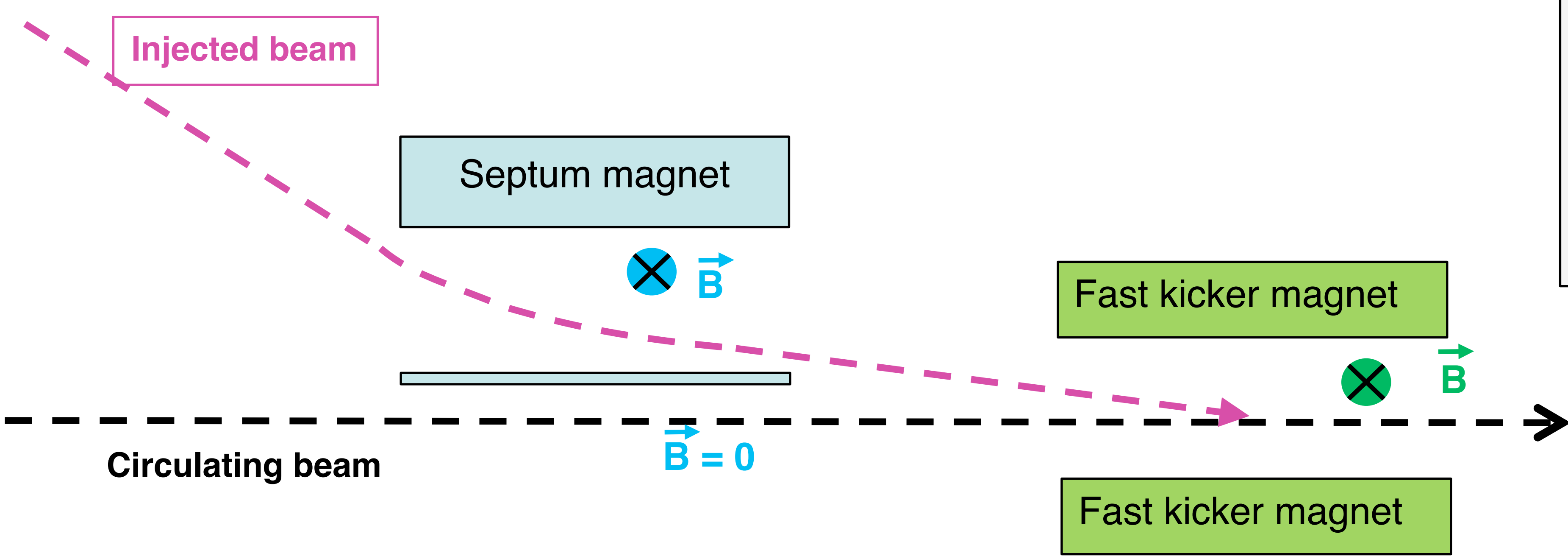
# Injection into the LHC - layout

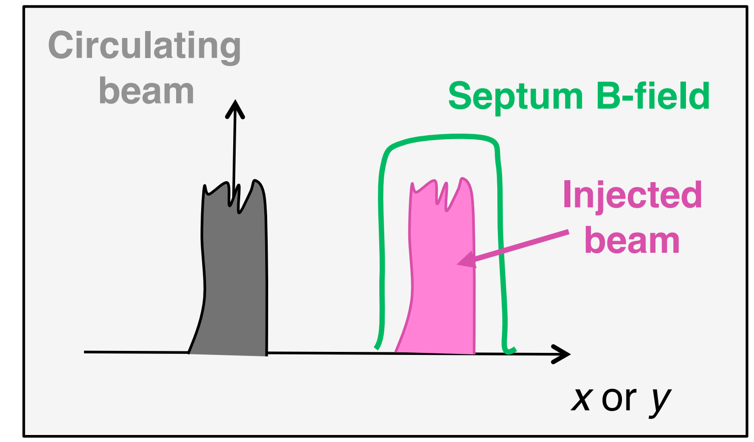
Similar layout for Beam 1 injection in IP2

SPS + TI8



# How do we inject?



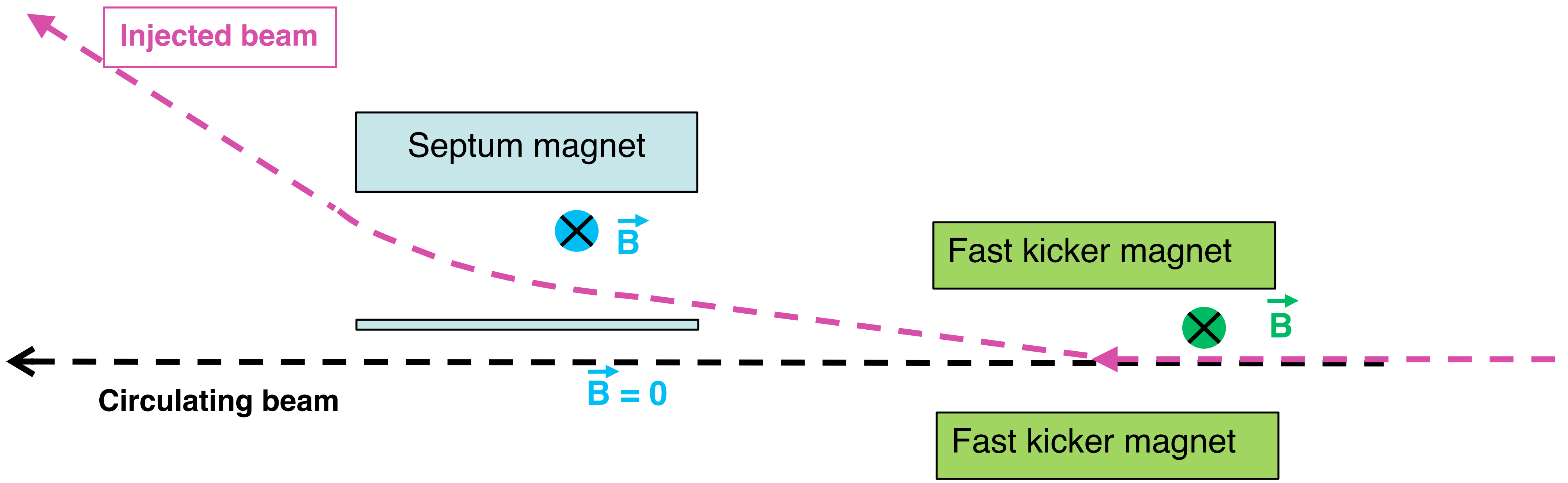




1. A septum dipole magnet (with thin coil) is used to bring the injected beam close to the circulating beam.

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

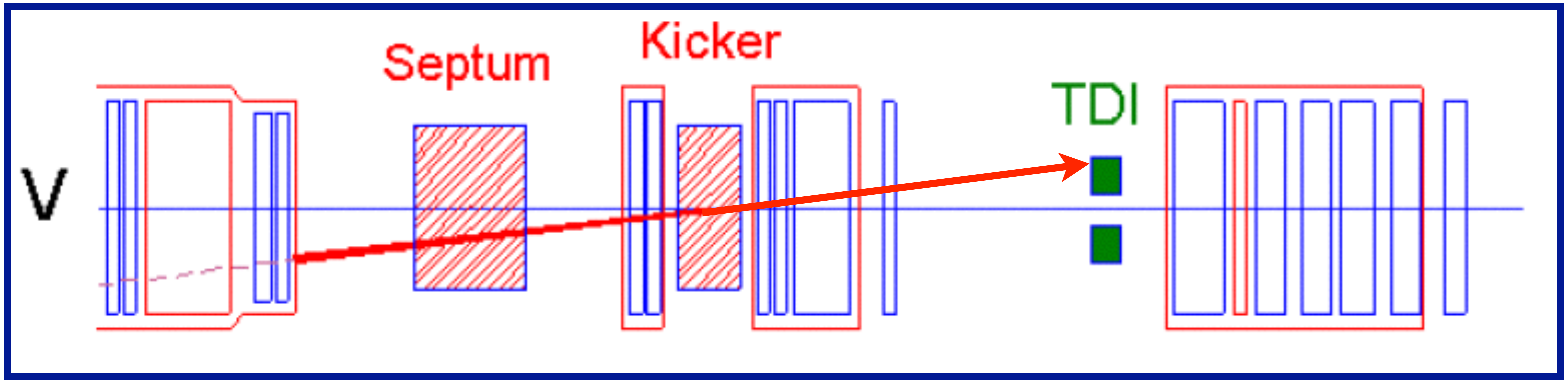


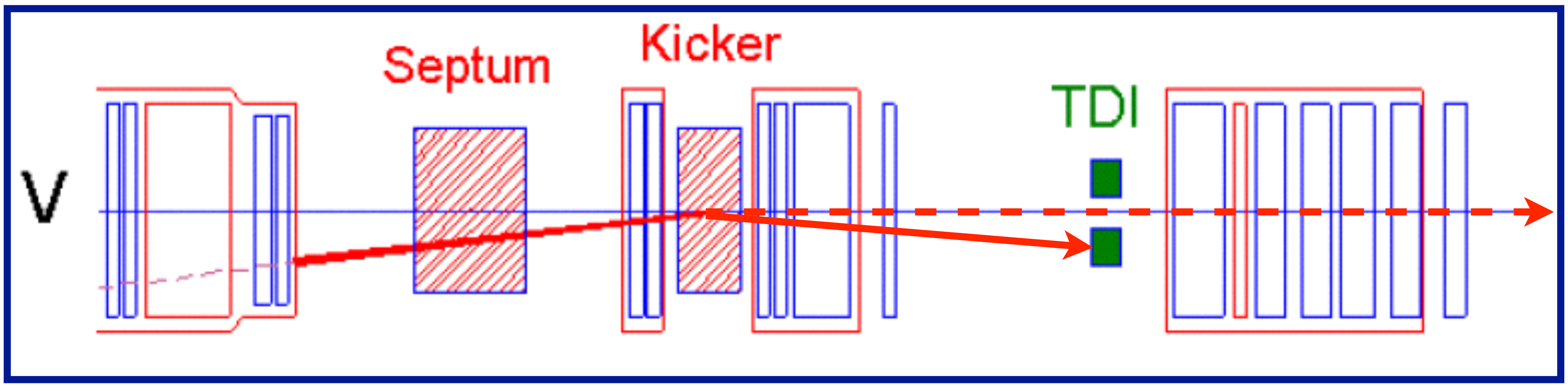

2. ~~1.~~ A septum dipole magnet (with thin coil) is used to bring the *extracted* beam ***far*** to the circulating beam.

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

3. All the following bunches are extracted.

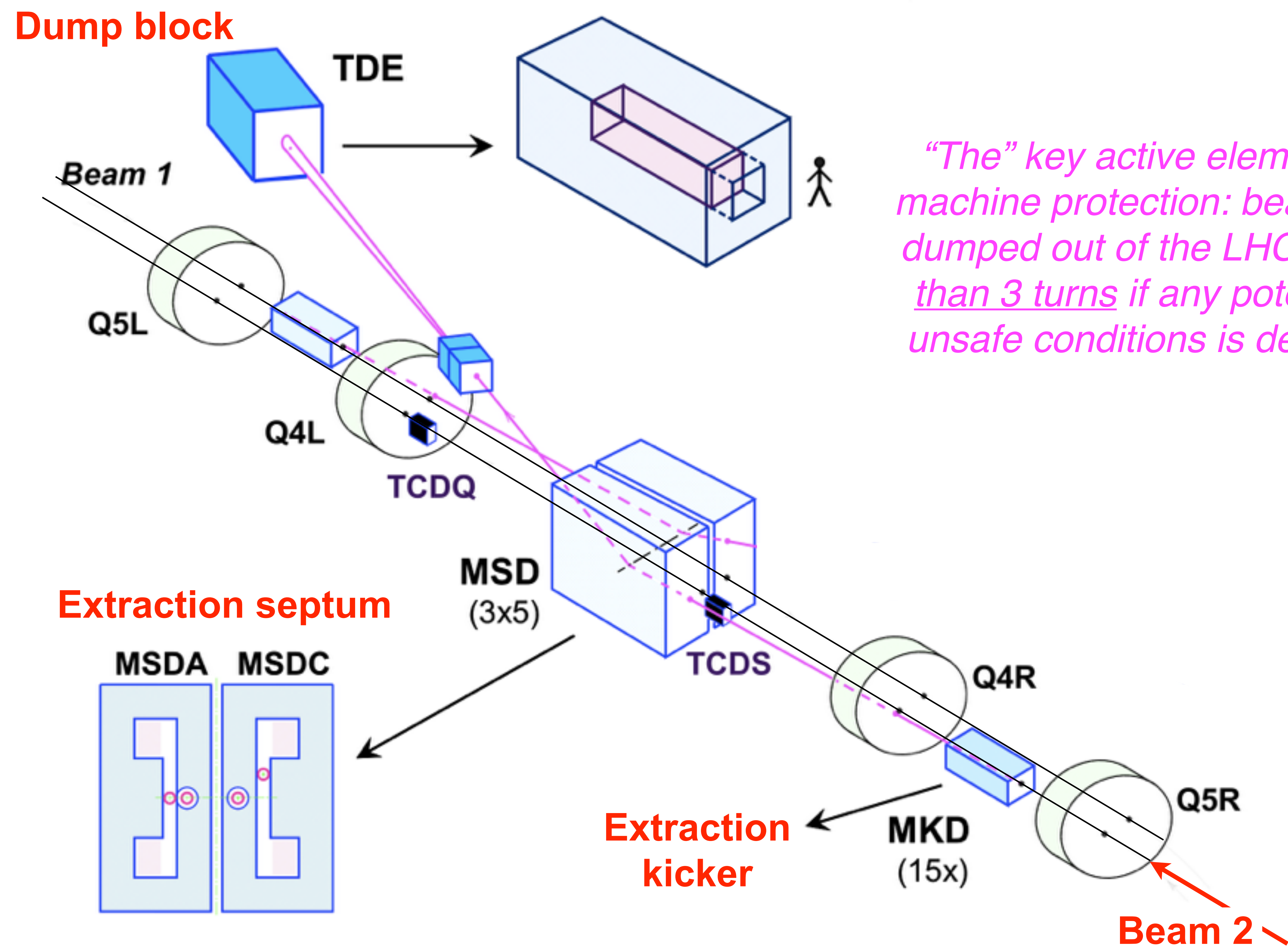
# Role of the TDI collimator



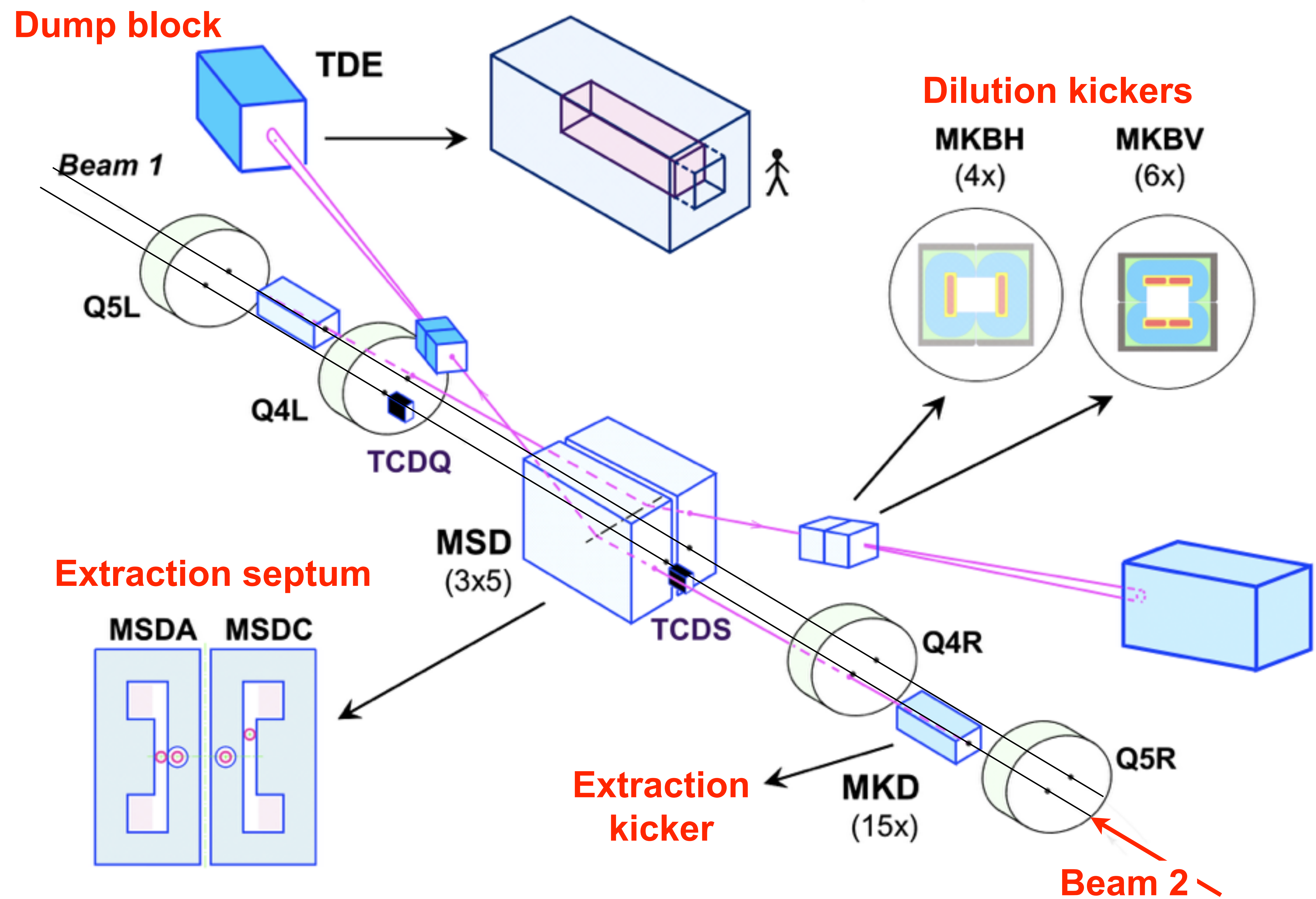

The TDI is one of the key injection protection collimators:
Protects the machine in case of (1) missing kicks on injected beam and (2) asynchronous kicker firing on the circulating beam.
It must be closed around the circulating beam trajectory when the kicker is ON.

# Beam dump (IP6)

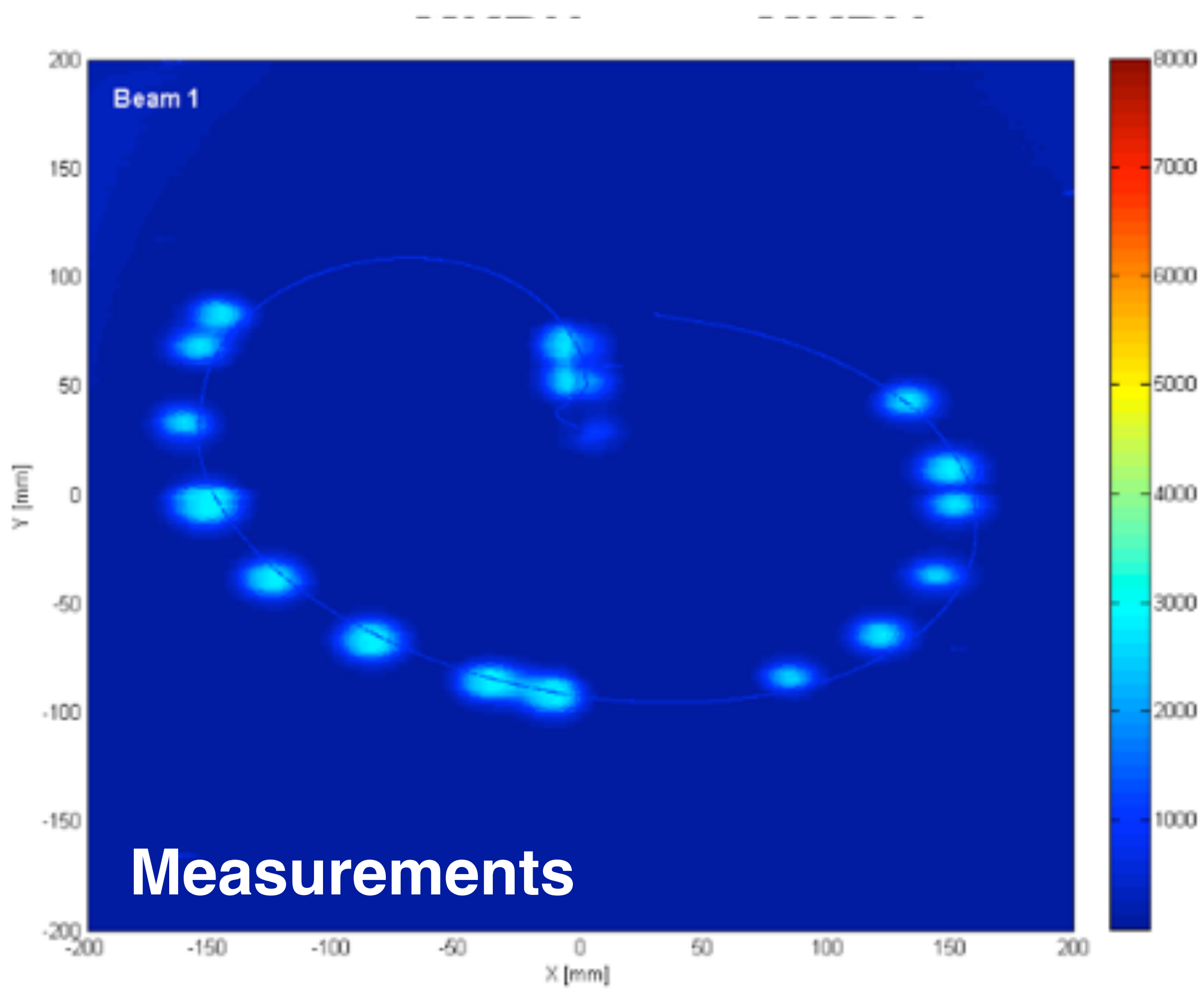


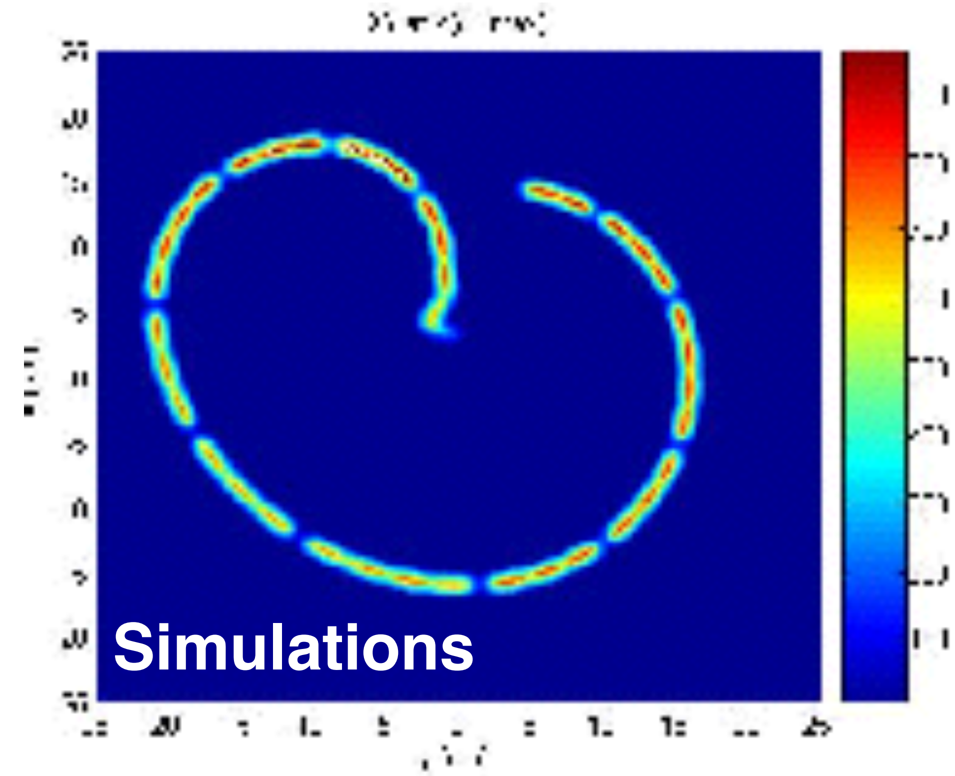

*"The" key active element for machine protection: beams are dumped out of the LHC in <u>less than 3 turns</u> if any potentially unsafe conditions is detected.*

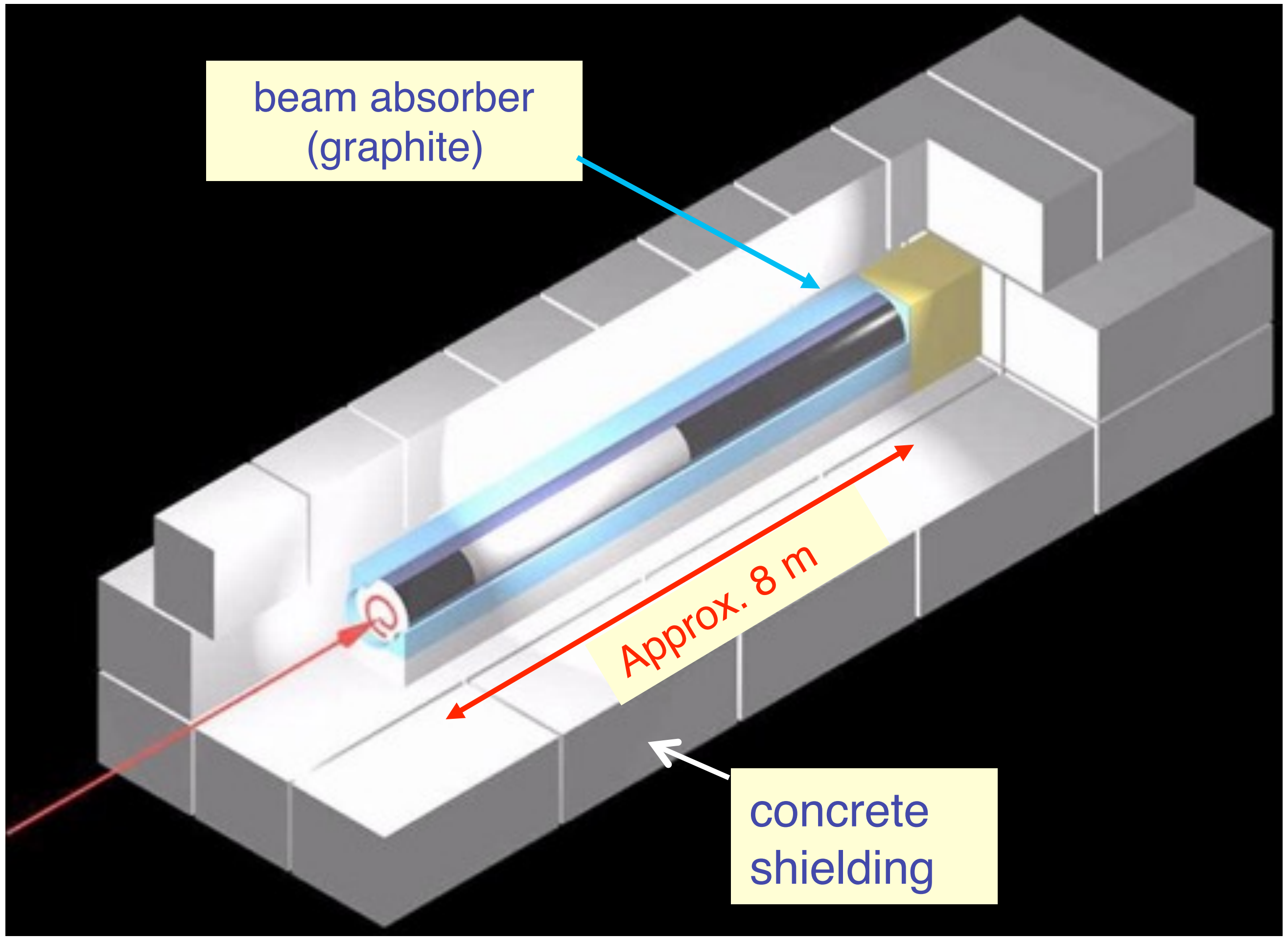
# Beam dump (IP6)



# 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 !

# 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)**

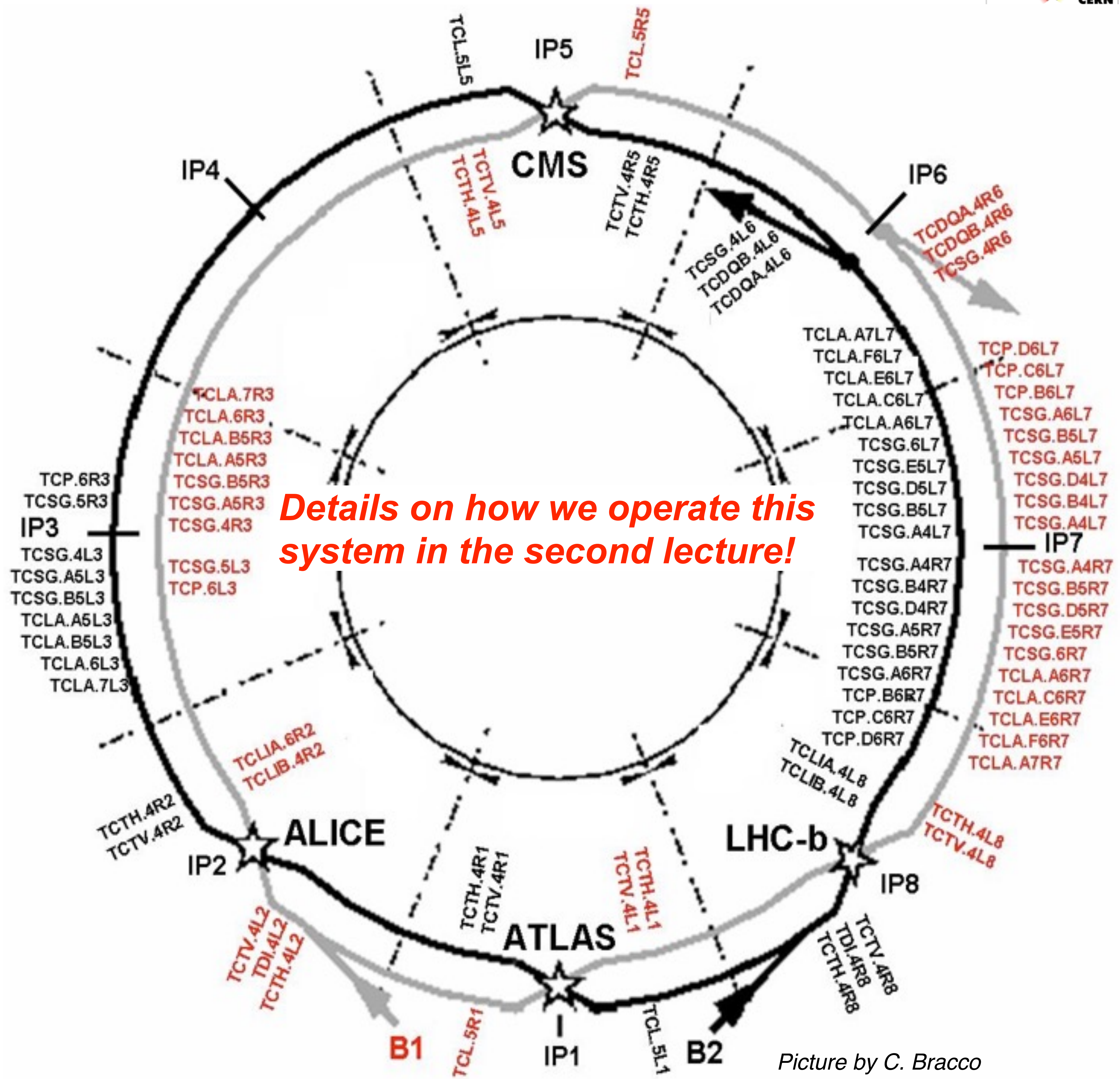
Passive absorbers for warm magnets

Physics debris absorbers

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

**108 collimators and absorbers**

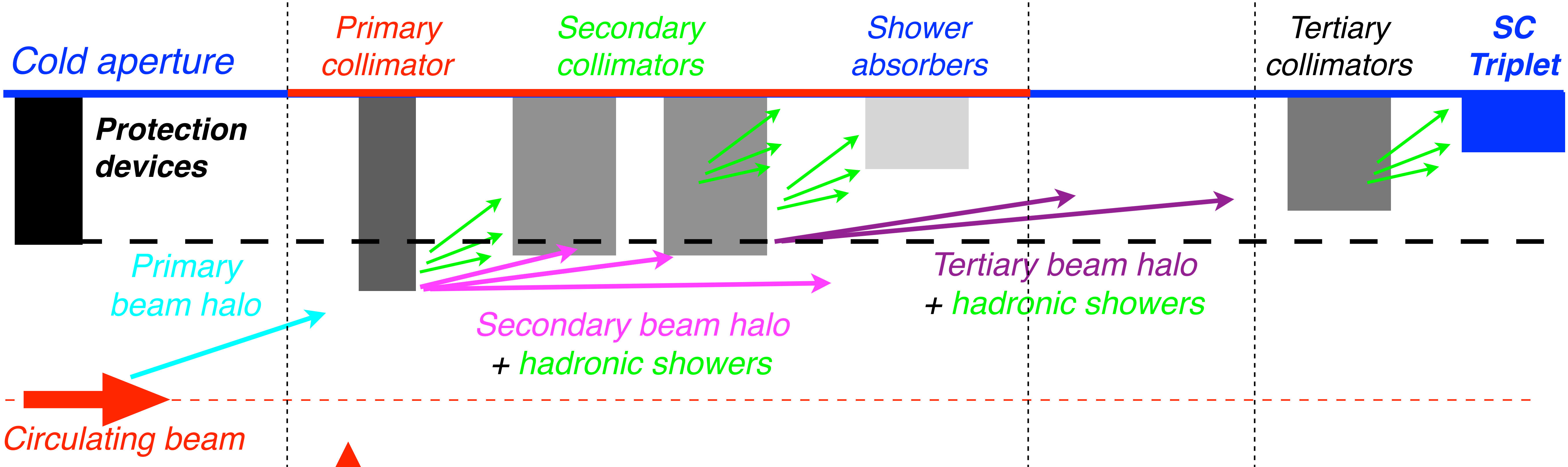
**About 500 degrees of freedom. Most advance system for accelerators!**

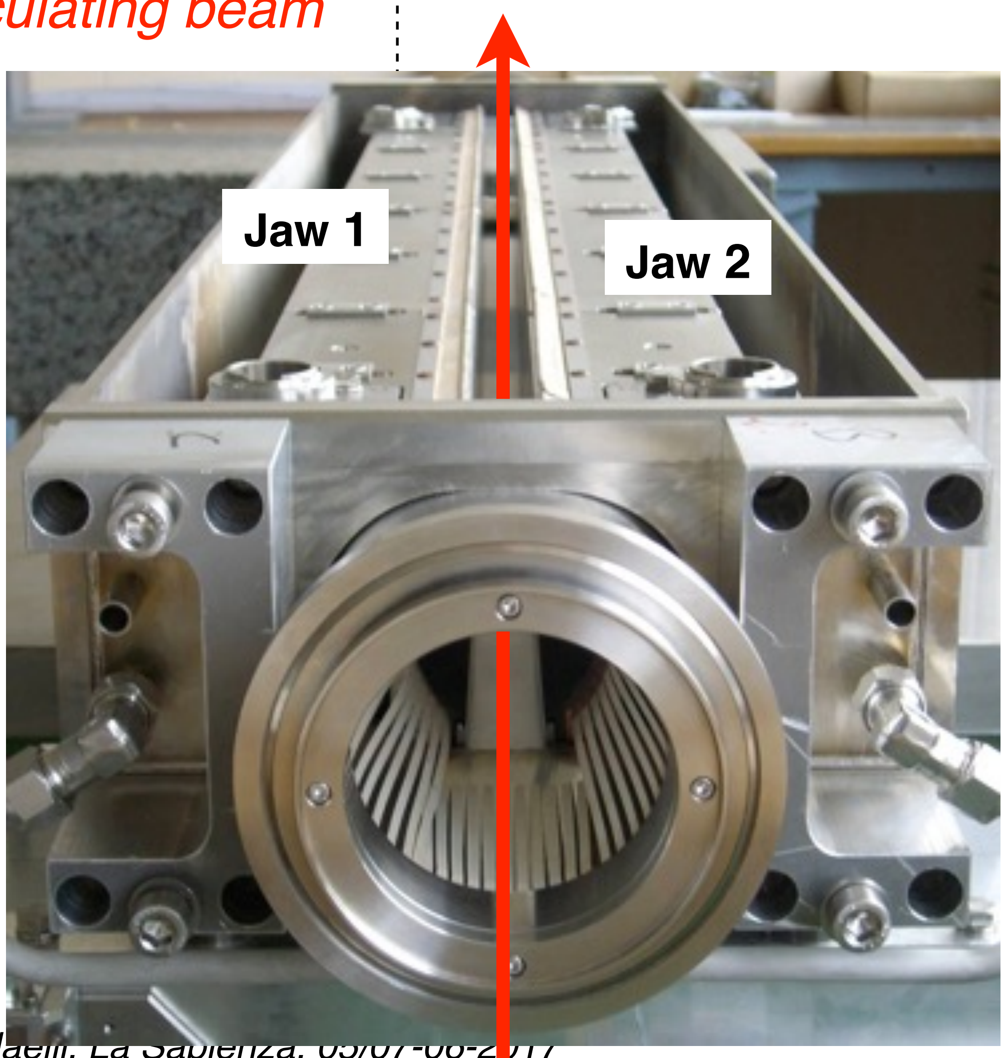


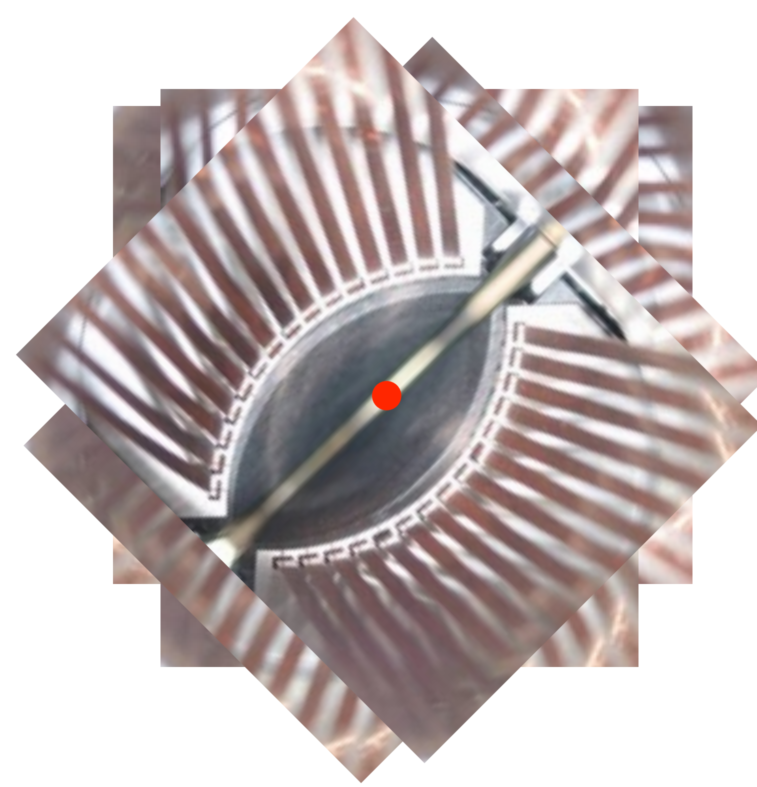

*Picture by C. Bracco*

# Collimation: multi-stage cleaning

(illustrative scheme)



*Designed to avoid “quenches” of superconducting magnets, but also a **crucial** element of the LHC “passive” machine protection.*

# Outline

- Introduction
- Recap. of accelerator physics
  - Basic equations
  - Relevant beam measurements
- CERN accelerator complex
  - Lower energy injectors
  - Super Proton Synchrotron
- LHC parameters and layout
  - Arcs and straight sections
- **Machine protection and collimation**
  - **Concepts and LHC implementation**
  - **Case study: 2008 event**

# Conclusions

- ☑ We have reviewed the basic accelerator physics concepts
- ☑ We have seen how the LHC beam requirements are met by the CERN accelerator complex
- ☑ We have introduced the main LHC accelerator systems
- ☑ We have introduced the key parameters for the LHC magnet system and for the LHC beam and seen how they determine the machine protection constraints. Driven by the quest for pushing luminosity of high-energy beams!

***We are now ready to see the details of machine protection implementations and of the LHC collimation system!***

# Acknowledgments


- LHC layout and systems: thanks to various LHC teams (many people).
- Various materials on machine protection taken from J. Wenninger
- Material on the injectors: G. Rumolo, R. Steerenberg, G. Bellodi, K. Cornelis, D. Manglunki (ions material in backup), E. Métral