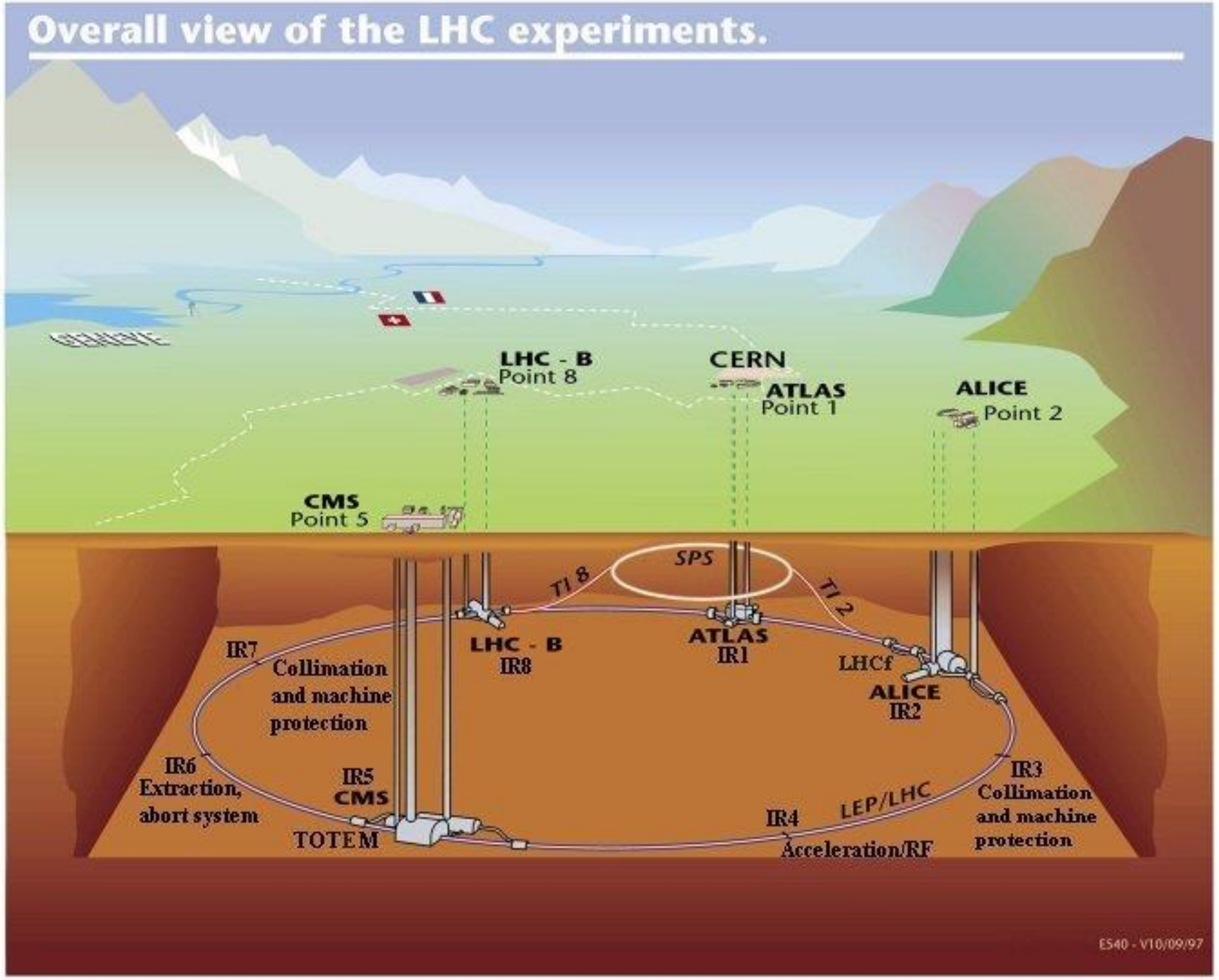
The LHC Machine and its journey towards 500 inverse femtobarns

Tobias Persson

Introduction

- Main purpose is to provide the 4 experiments with collisions (luminosity)
  - ATLAS and CMS do in general high luminosity and high energy collisions
  - This drives the parameters we use in operation

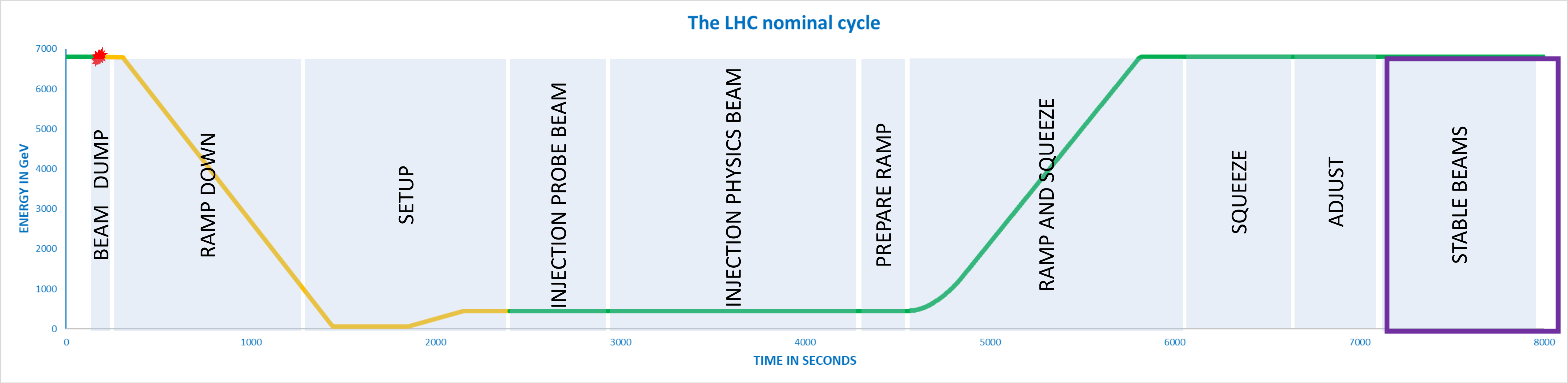


See previous seminar by [Andres Delannoy](#) for information on how to measure luminosity

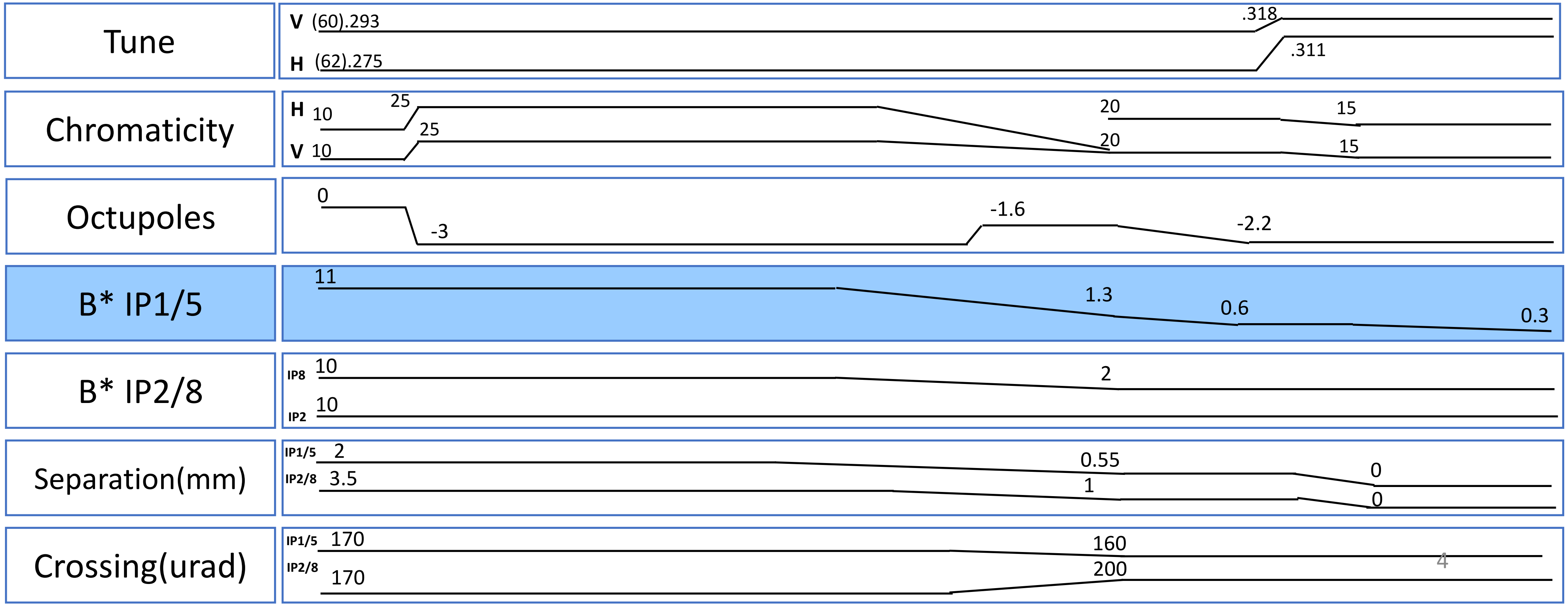
How to we accumulate luminosity?

- LHC is a cycling machine
  - It means that we go through the different stages where collision (or stable beams) is only one of them
- I will go through a normal LHC cycle and the different steps and why they are done and the accelerator physics behind
- The goal is to give insight to the different steps in the cycle and what is restricting the performance of the LHC in terms of energy and luminosity

Many thanks to E. Maclean and R. Steerenberg for many of the figures and plots.

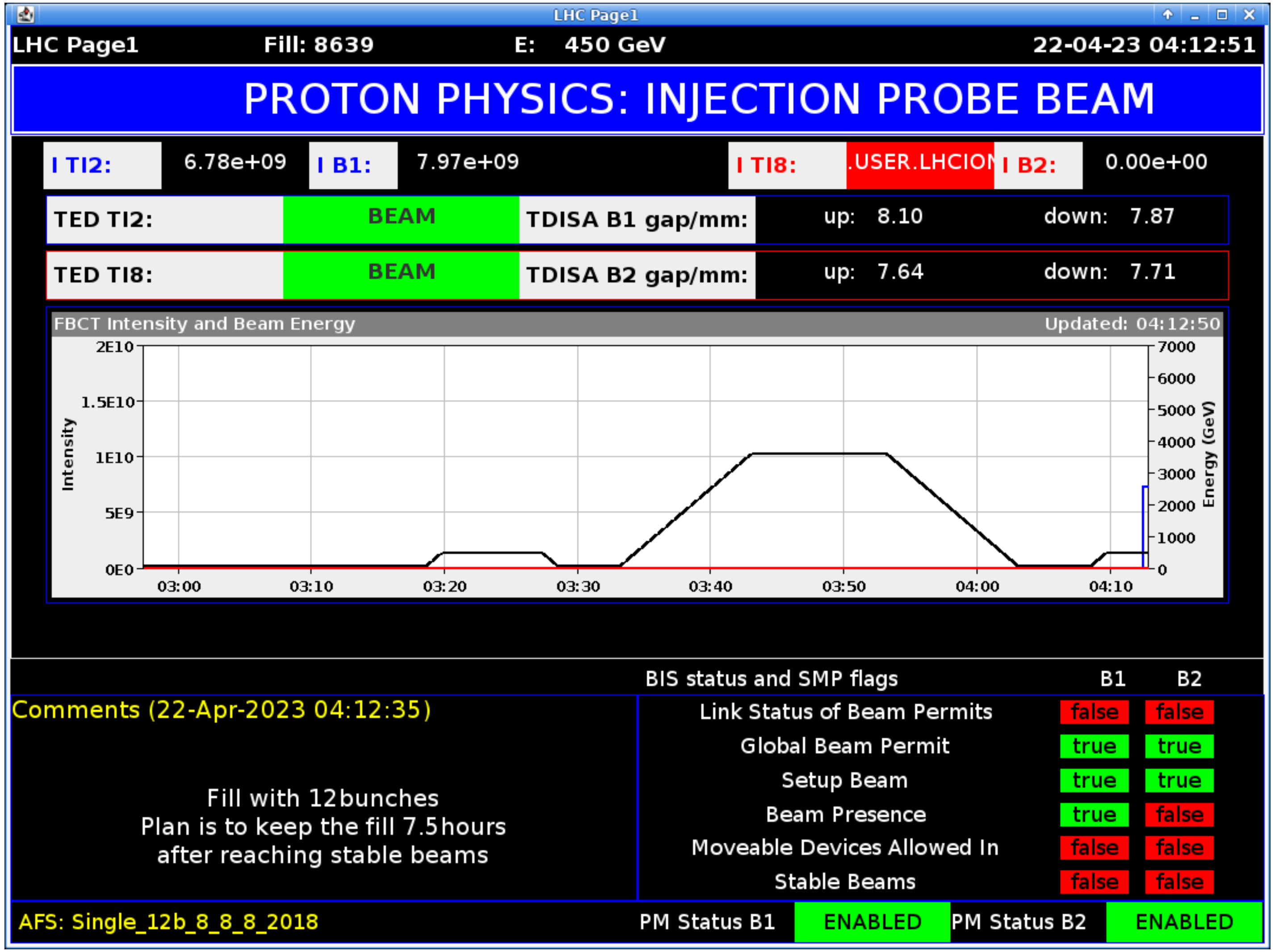


B* levelling from 120cm to 30 cm :



D.JACQUET - Chamonix 2023 - Session1 – LHC cycle, settings and efficiency

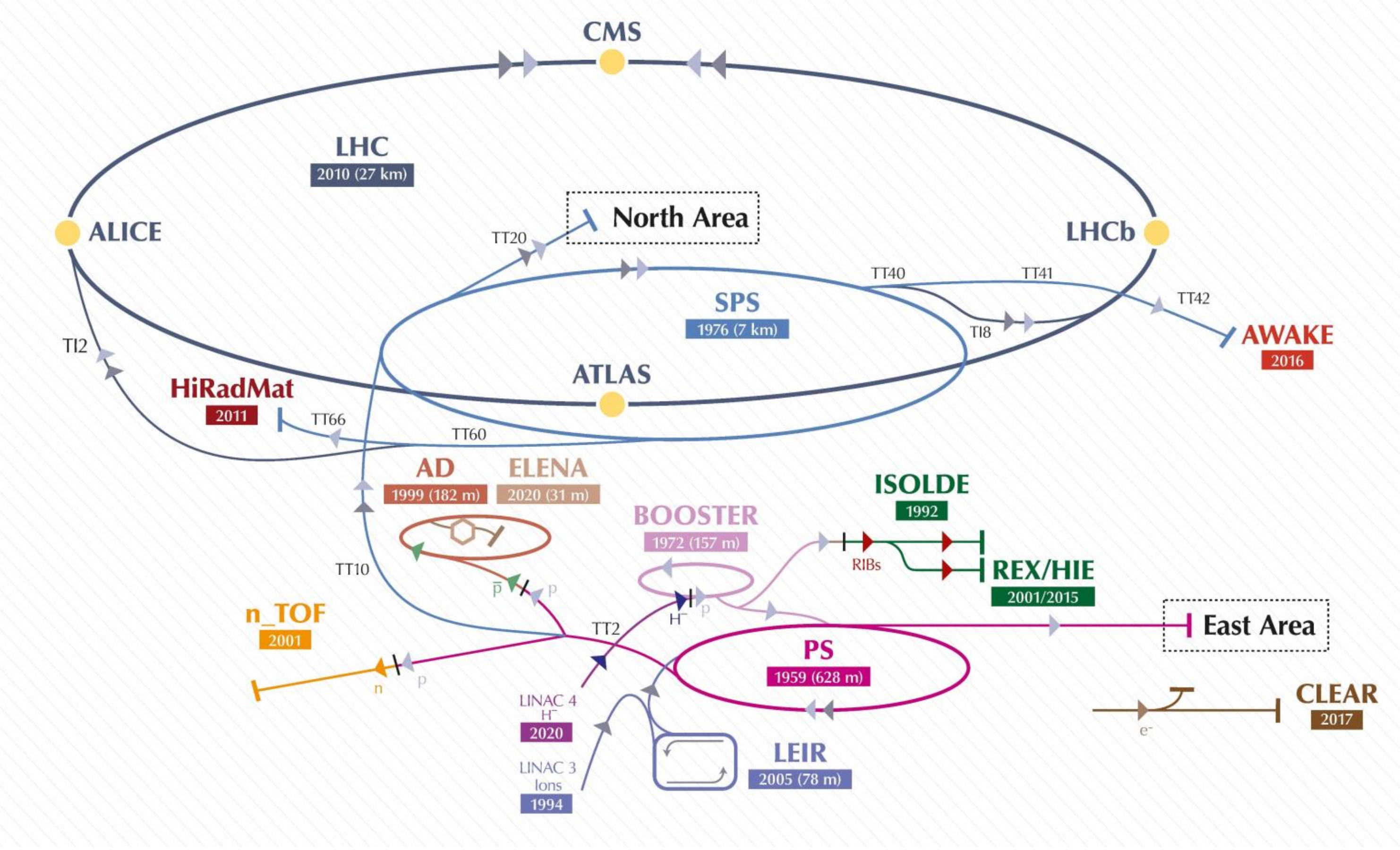
First step in the cycle



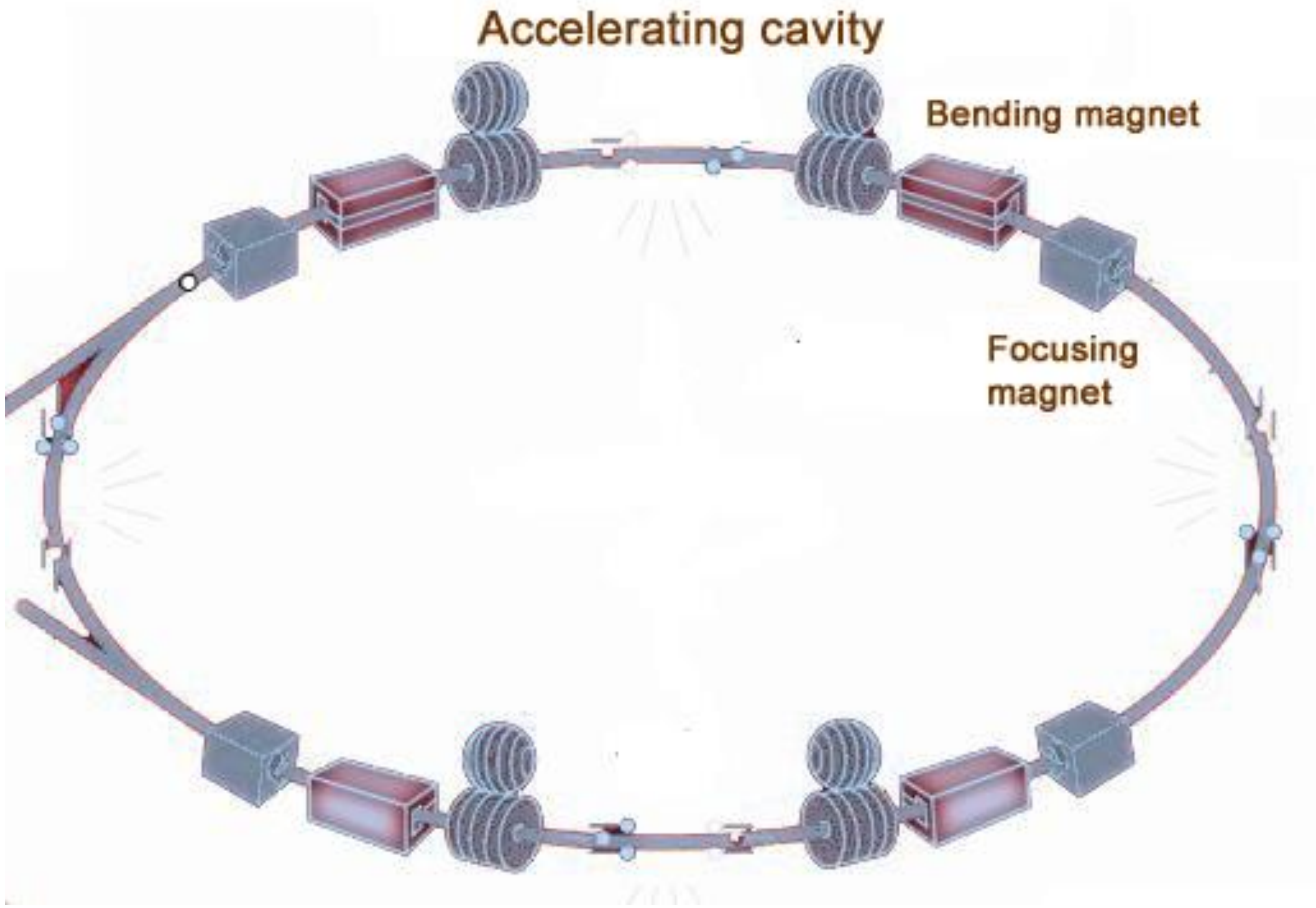
LHC Page 1

We have to start with the injectors!

- The LHC performance is dependent on the injector complex performance
- The **PSB** determines initial beam **brightness**
- The **PS** determines the **timing structure**
- 25ns, 50ns, BCMS, 8b4e, …
- The **SPS** boosts the energy and creates **bunch trains**



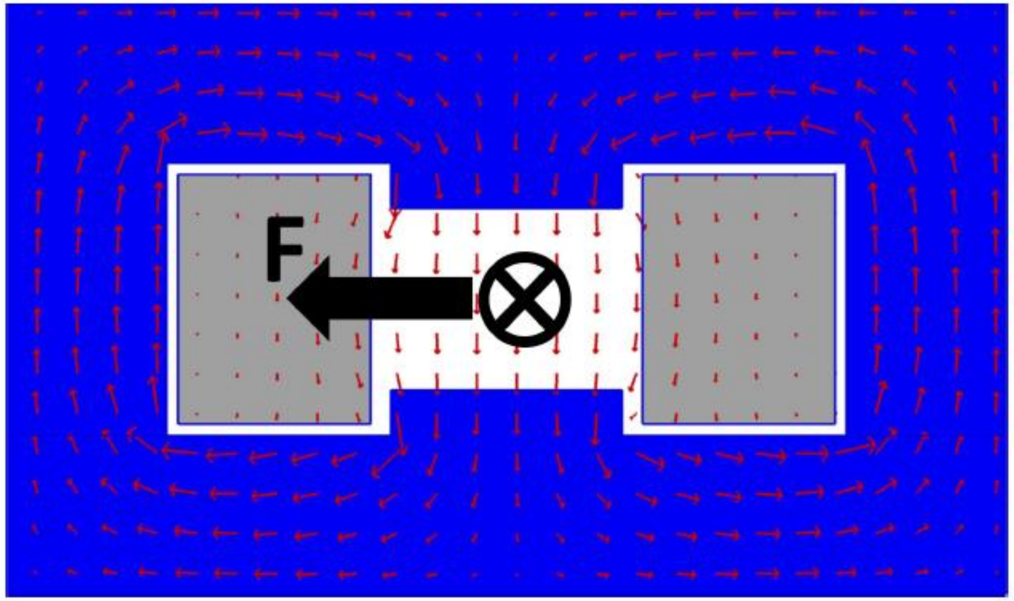
The basic components of an accelerator

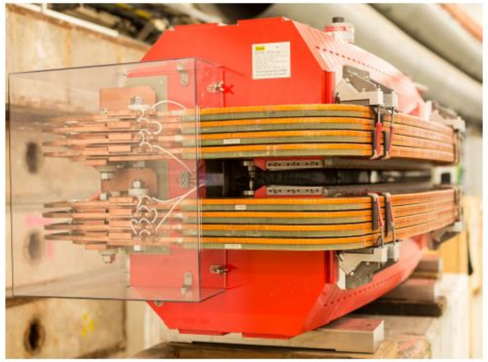


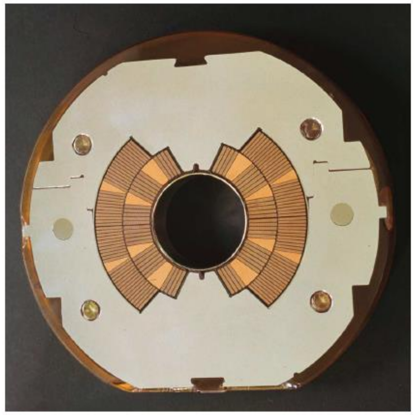
Bending

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

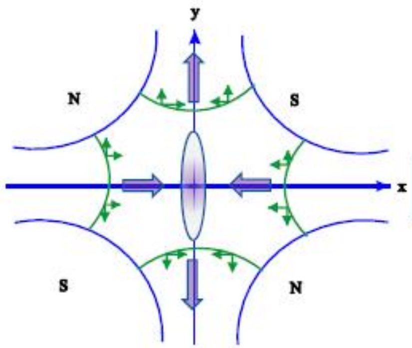
- Use Lorentz force to bend bunches around the synchrotron ring
- Use dipole magnets



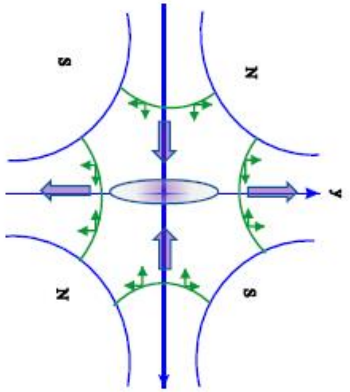




Focussing Particle Beams

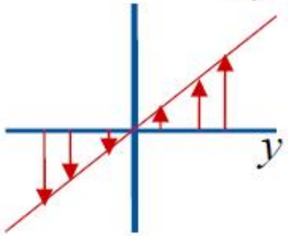


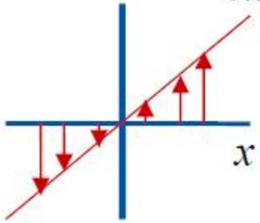
Focusing Quadrupole



De-focusing Quadrupole

$$B_x = \frac{\partial B_x}{\partial y} y \qquad B_y = \frac{\partial B_y}{\partial x} x$$

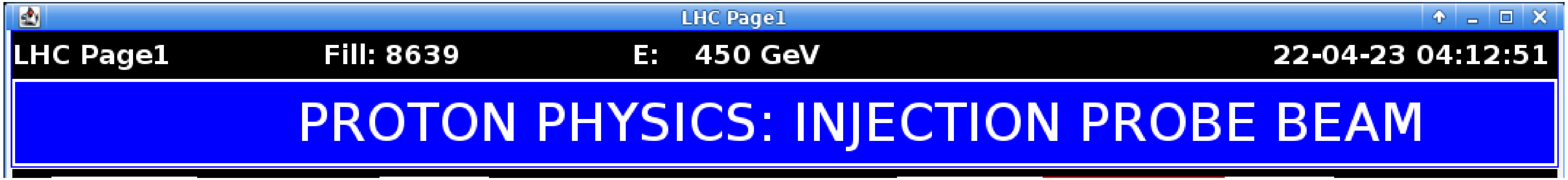




Field **gradient**

$$K = \frac{\partial B_y}{\partial x} [Tm^{-1}]$$

$$k = \frac{K}{B\rho} [m^{-2}]$$

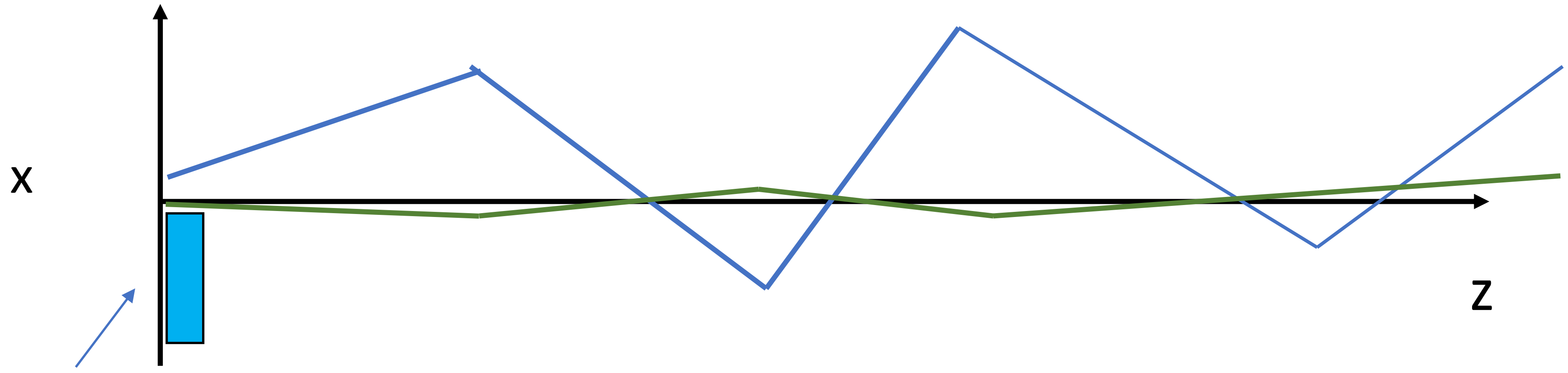


- A **probe beam** is ~10^{10} bunch of proton
- It serves two main purposes:
  - It used to validate that the machine is ready to receive higher intensity beams Without it we cannot inject high intensity beams
  - It is also used to setup up machine parameters such as
    - **Orbit**
    - **Tune**
    - **Transverse coupling**
    - Chromaticity
  - They are initially measured and setup at injection but controlled through out the cycle ! I will in the next slides explain these concepts, why they are important and how they are done

Transfer line steering

- So now the single probe bunch coming into the LHC
- Transfer line steering might be needed. A machine safety issue to avoid losing beam when injecting

Blue original orbit



Orbit corrector creating a deflection. An orbit corrector is a dipole that is used to steer the beam

The principle behind

$$\Delta\vec{u} = \mathbf{R}\cdot\Delta\vec{\theta}$$

Change in position ***The response matrix*** ***Deflection from orbit corrector***

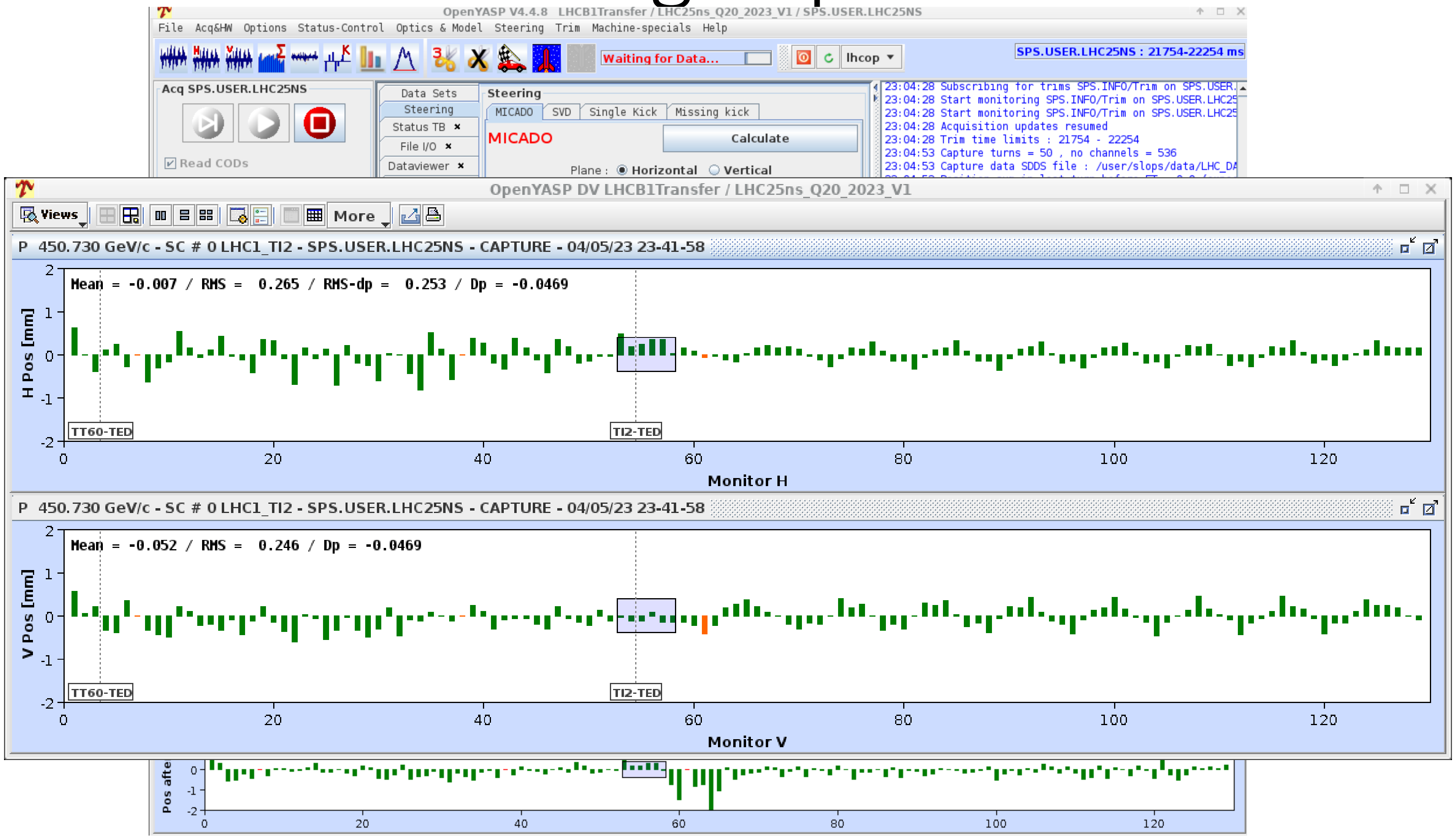
$$\begin{pmatrix} \Delta u_1 \\ \Delta u_2 \\ \Delta u_3 \\ \vdots \\ \Delta u_N \end{pmatrix} = \begin{pmatrix} R_{11} & R_{12} & R_{13} & \cdots & R_{1M} \\ R_{21} & R_{22} & R_{23} & \cdots & R_{2M} \\ R_{31} & R_{32} & R_{33} & \cdots & R_{3M} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ R_{N1} & R_{N2} & R_{N3} & \cdots & R_{NM} \end{pmatrix} \begin{pmatrix} \Delta\theta_1 \\ \Delta\theta_2 \\ \Delta\theta_3 \\ \vdots \\ \Delta\theta_M \end{pmatrix}$$

$$\| \vec{u}_m + \mathbf{R}\vec{\theta}_c \|^2 = \min.$$

- The response matrix depends on the layout and the strength of the magnets (optics)
  - In the LHC this is based on the MAD-X model
    - MAD-X is a software that is used for most optics design and operation at CERN
  - We can then find the strength of the correctors
    - Normally done using SVD

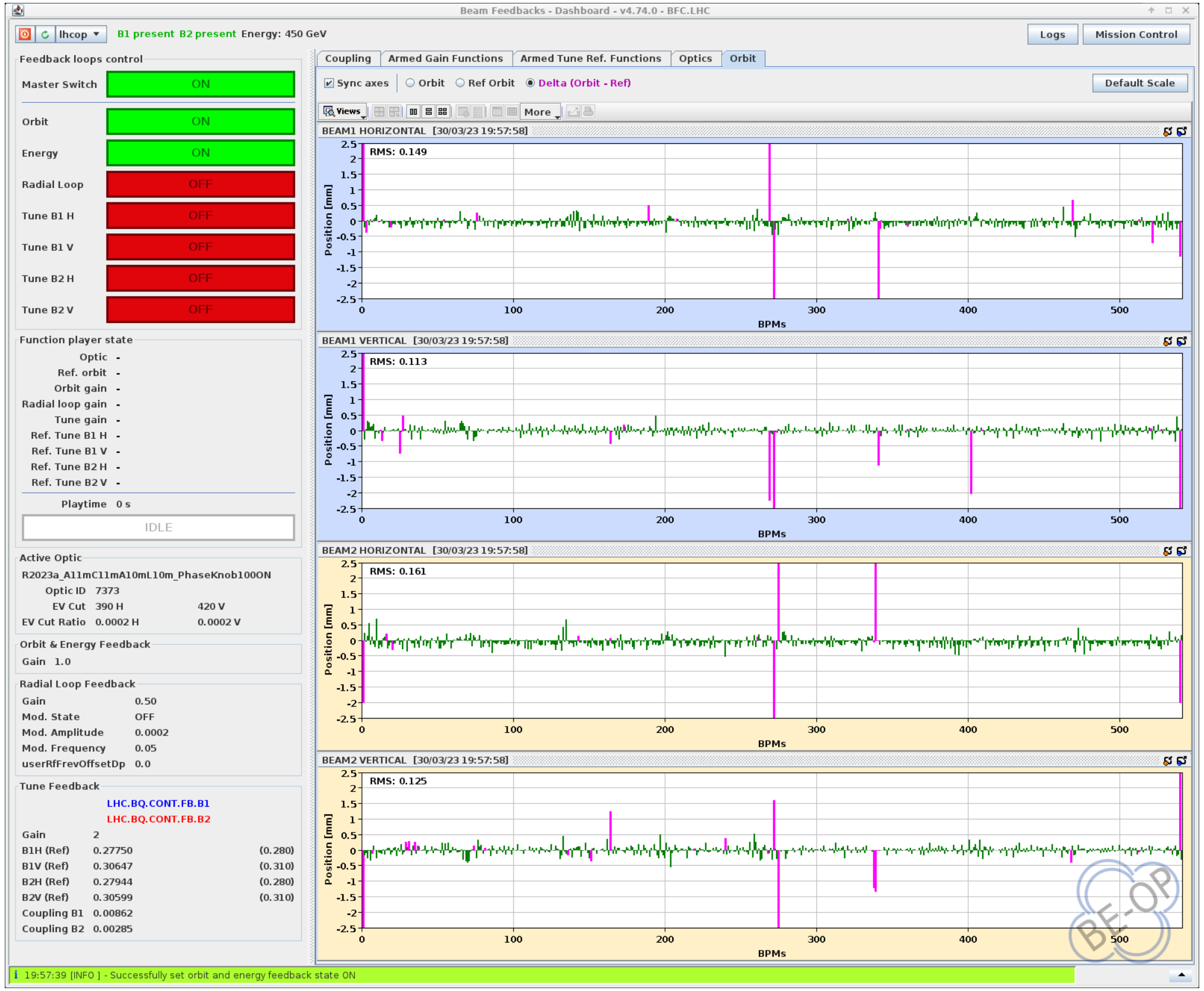
$$\vec{\theta}_c = \mathbf{V}\lambda^{-1}\mathbf{U}^T\vec{u}_m,$$

Steering in practice



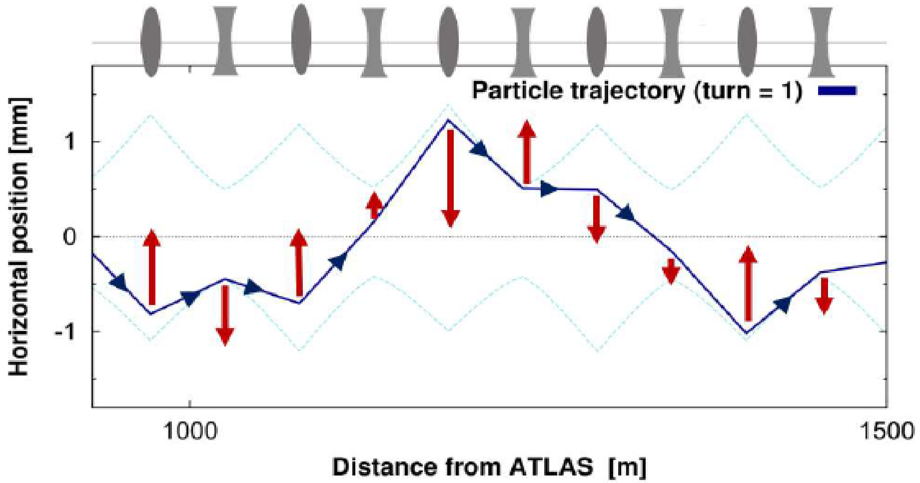
Correcting the closed orbit

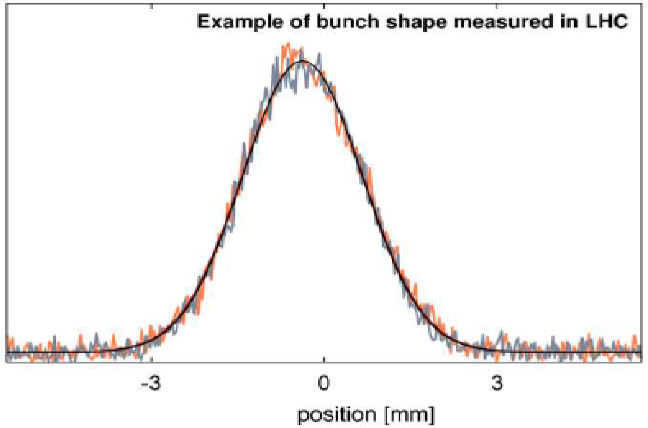
- Now we have circulating beams!
- Time to correct the closed orbit!
  - Now a change of a corrector impact the entire ring!
  - One can use the same principle
- In the LHC the correction is in practice handled by a feedback



Correcting the tune

- We have to understand the role of the quadrupoles





Particle motion about central closed-orbit described by **Hill's equation:**

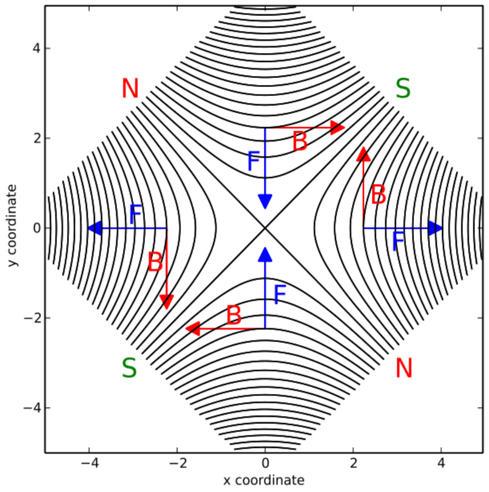
- linear restoring force from quadrupoles is a function of location around the ring
- restoring force is periodic to at least the accelerator circumference

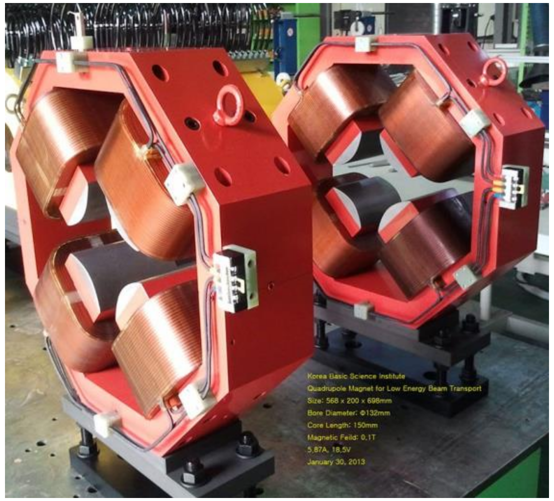
$$\frac{d^2x}{ds^2} - K(s)x = 0 \qquad\qquad x = \sqrt{2J_x\beta_x(s)}\cos\left(\phi_x(s) + \phi_0\right)$$

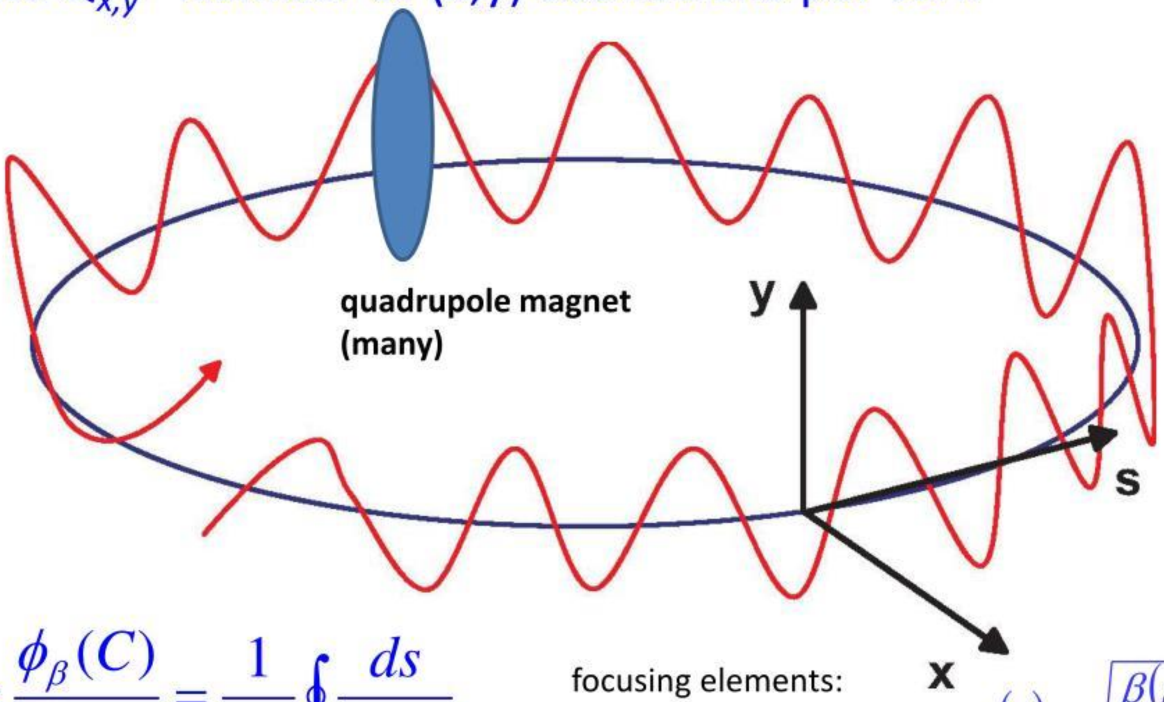
betatron oscillation & tune

schematic of betatron oscillation around storage ring

tune $Q_{x,y}$= number of (x,y) oscillations per turn







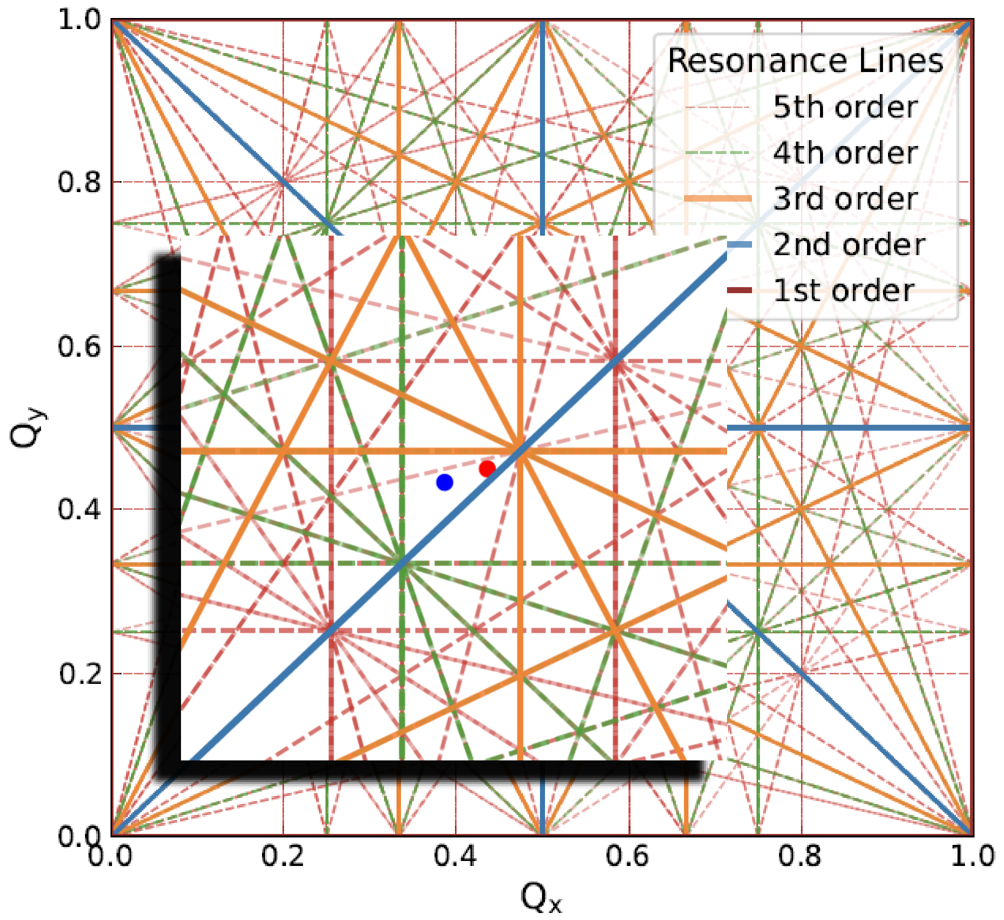
$$Q = \frac{\phi_\beta(C)}{2\pi} = \frac{1}{2\pi}\oint_C \frac{ds}{\beta(s)}$$

focusing elements:
quadrupole magnets

$$\sigma(s) = \sqrt{\frac{\beta(s)\varepsilon_N}{\gamma}}$$

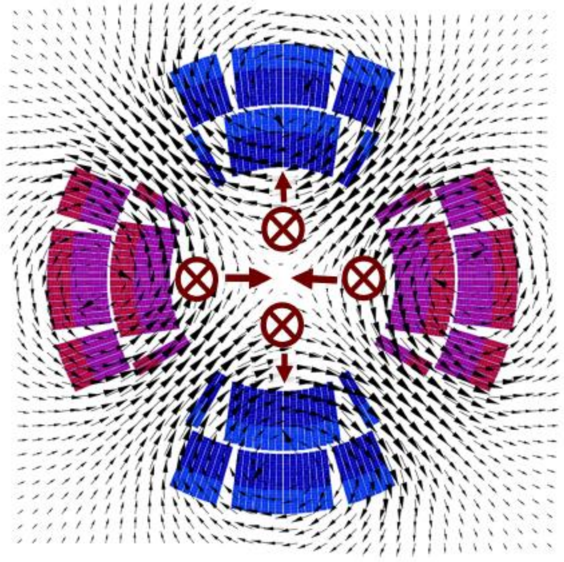
Why do we care about the tune?

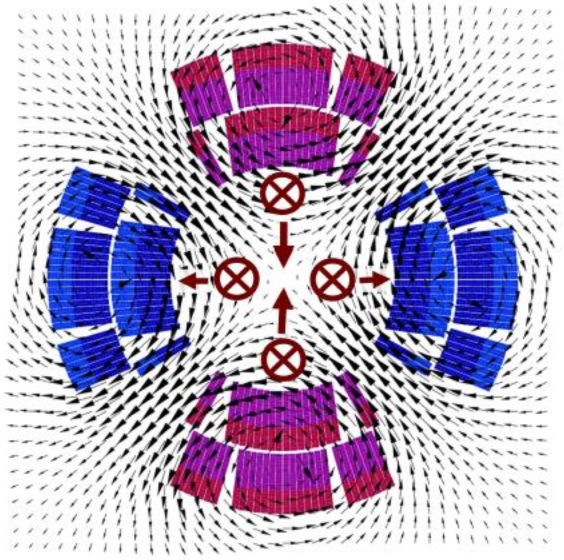
- The tune control is crucial to avoid resonances
  - Higher order resonance are generated by higher-order magnets, errors or other effect
- Avoiding resonance are crucial to life time.
  - Higher order resonance are in general less “violent” meaning that it has less impact for the beam



How do we control the tune?

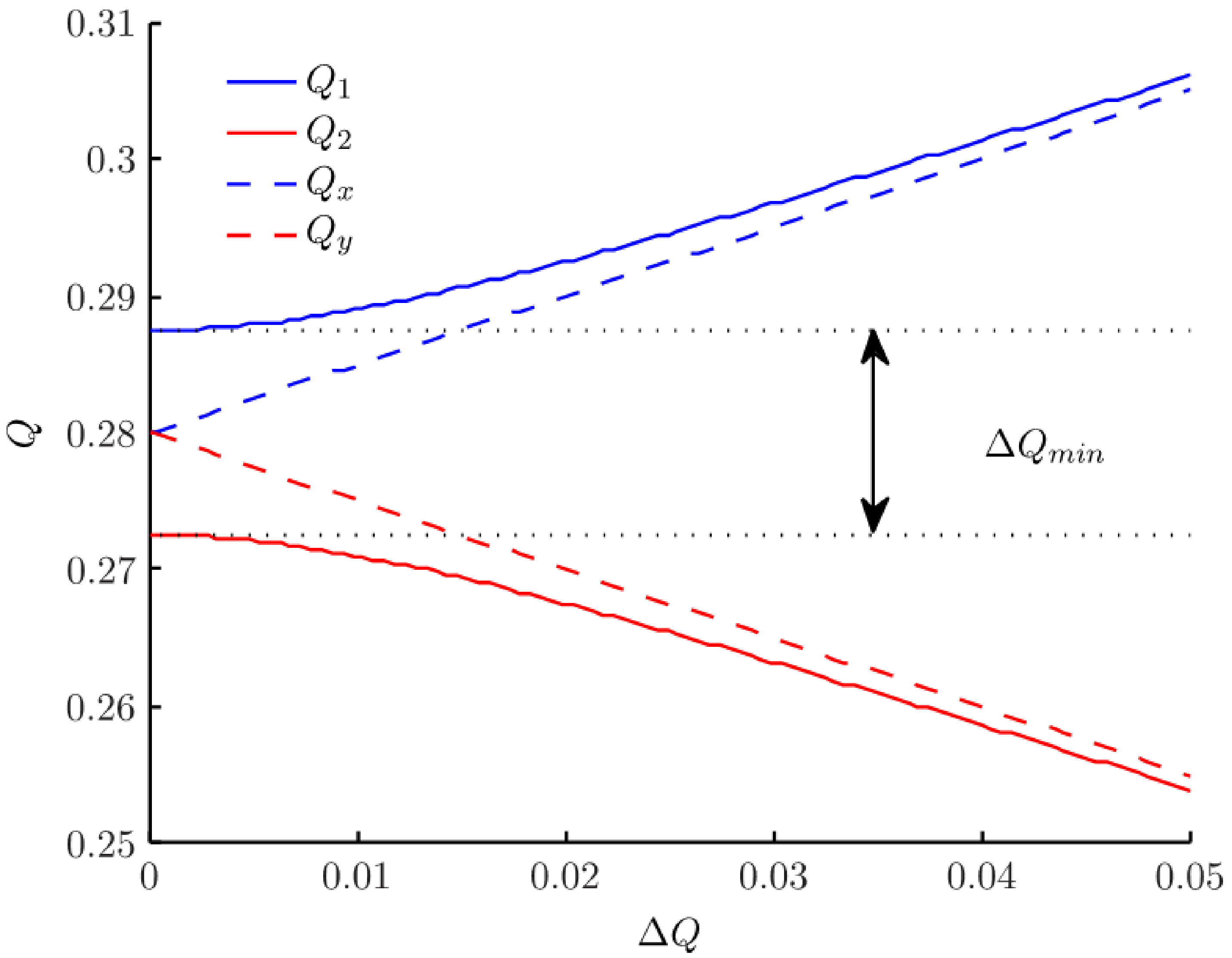
- Pre-design set linear combination of trim quadrupole magnets are changed
  - Allows us to correct the horizontal and vertical tune independently
  - In accelerator physics we call this a knob



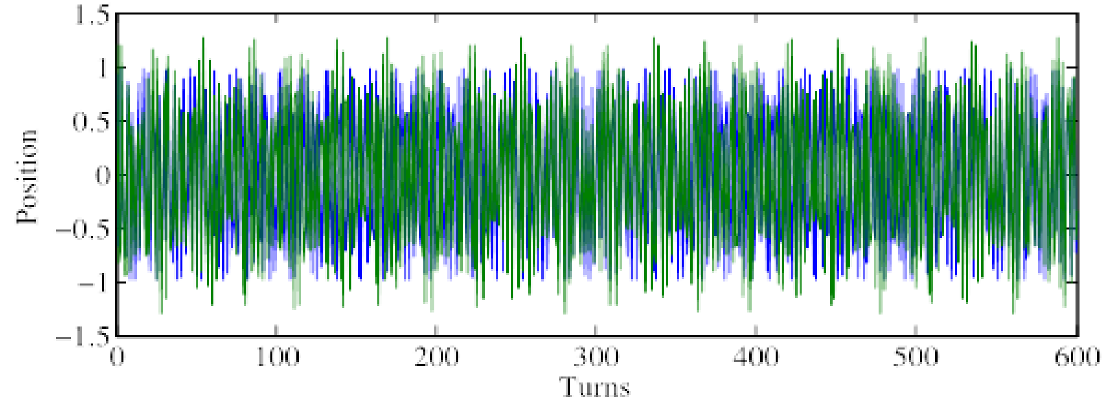


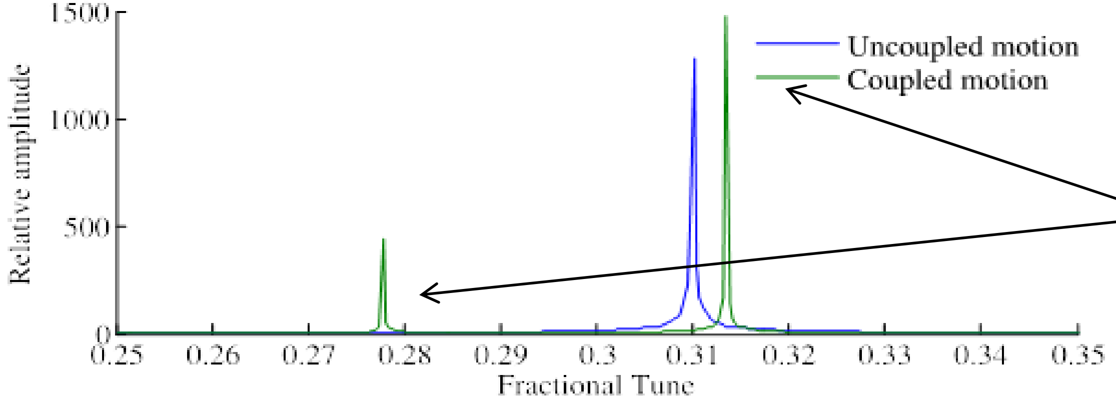
Correcting the transverse coupling

- The transverse coupling is another import parameter to control
    - Derives from skew quadrupolar fields (tilt of normal quadrupoles), solenoids and feed-down from higher order fields
    - Coupling disturbs the tune feedback, linked to instabilities and may reduce dynamic aperture



Measuring Coupling





We derive a coherent oscillations using the damper to get a measurable signal in the beam positioning system

From this we can calculate how to power the skew quadrupoles to correct the coupling

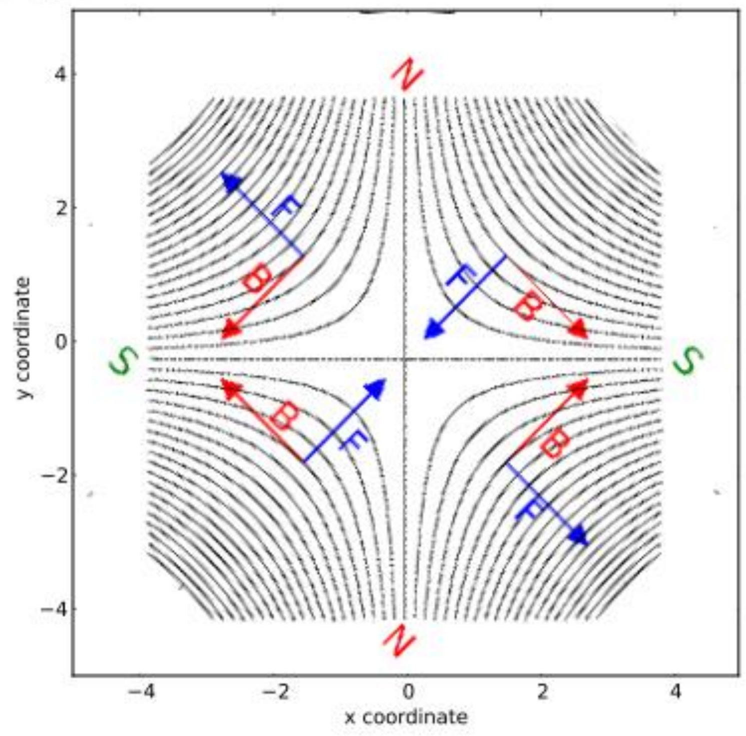
$$\frac{|Coupling_{peak}|}{|Tune_{peak}|} \propto |f_{1001}|$$

$$\Delta Q_{min} = |C^{-}| = |\frac{4\Delta}{2\pi R} \oint ds f_{1001} e^{-i(\phi_x - \phi_y) + is\Delta/R}|$$

Phys. Rev. ST Accel. Beams **17**, 051004

Correcting the transverse coupling

- We use skew quadrupoles in the LHC arcs
- Powering them correctly we can globaly decouple the motion
  - Horizontal and vertical tunes can now be set independently



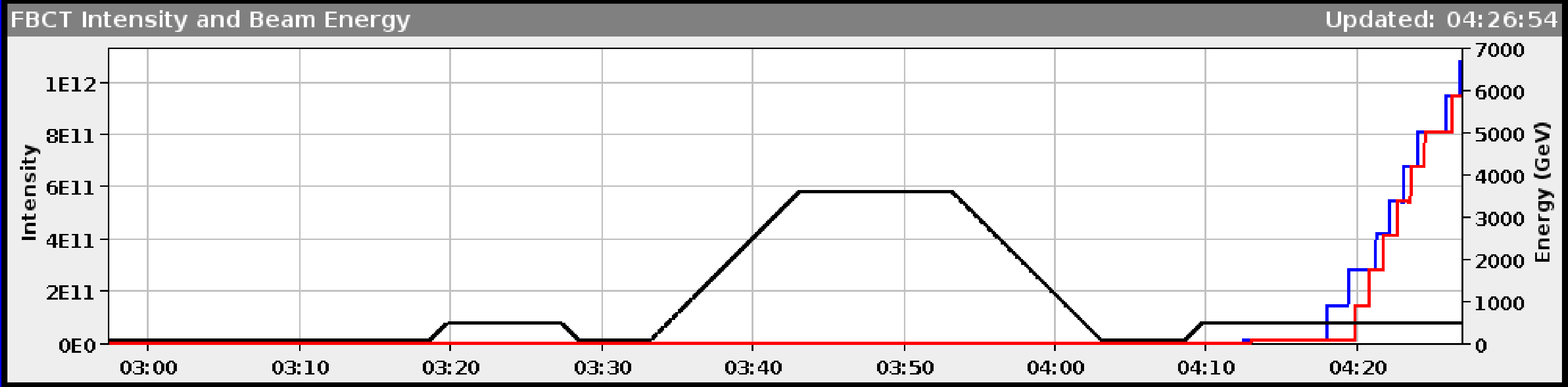
LHC Page1

LHC Page1 | Fill: 8639 | E: 450 GeV | 22-04-23 04:26:55

PROTON PHYSICS: INJECTION PHYSICS BEAM

I TI2:	1.38e+11	I B1:	1.08e+12	I TI8:	1.37e+11	I B2:	9.47e+11

TED TI2:	BEAM	TDISA B1 gap/mm:	up: 8.11	down: 7.87
TED TI8:	BEAM	TDISA B2 gap/mm:	up: 7.64	down: 7.71



Comments (22-Apr-2023 04:12:35)

Fill with 12bunches
Plan is to keep the fill 7.5hours
after reaching stable beams

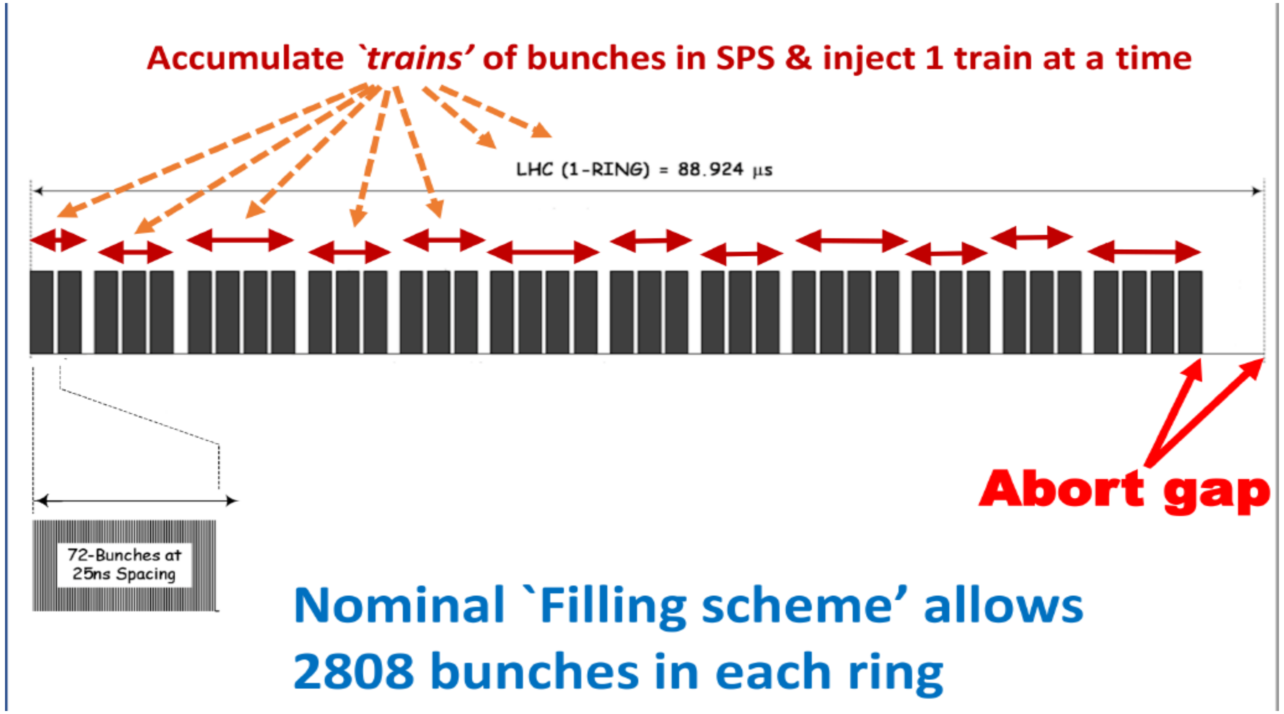
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: Single_12b_8_8_8_2018

PM Status B1: ENABLED | PM Status B2: ENABLED

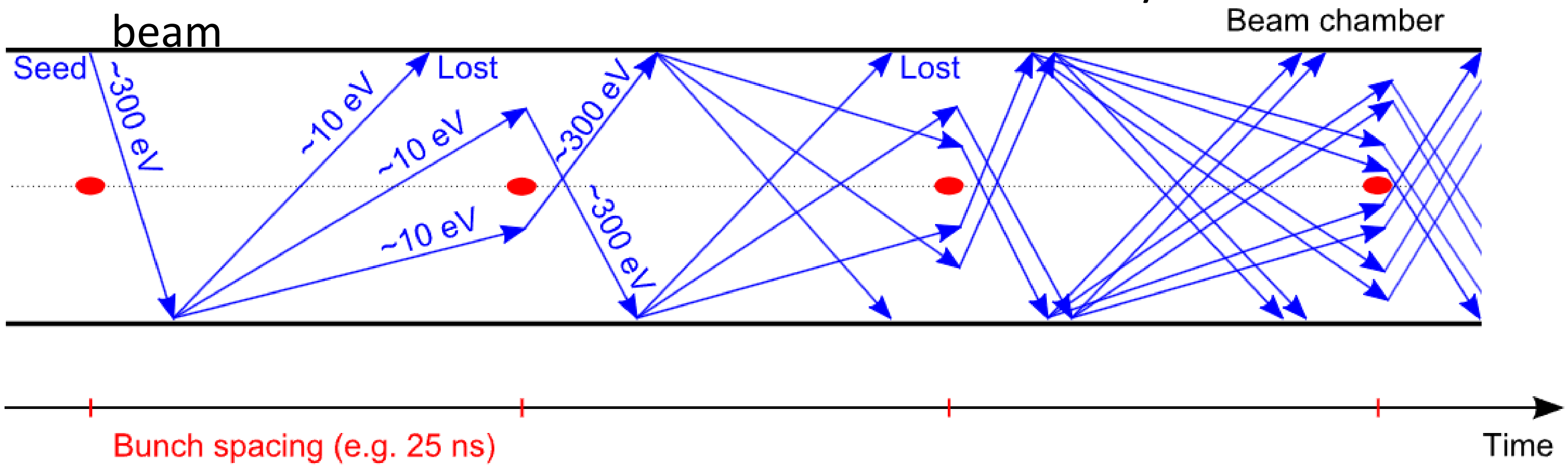
Filling schemes of the LHC

- The spacing between bunches in the LHC is 25ns. To get as much collision as possible we would like to fill as much as possible!
  - One could then get **3562** bunches in. Not possible!! The injection kicker and extraction kicker needs time to raise the strength
  - Particle in the abort gap would not be “sprayed”



Electron cloud

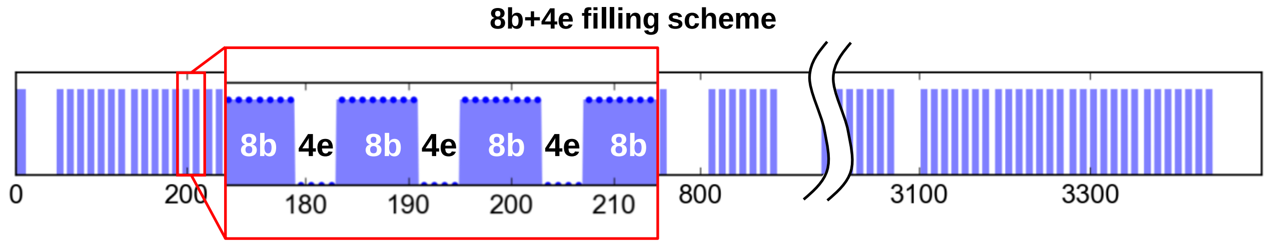
- Unfortunately, we cannot bring 2808 **very high intensity** bunches to collisions
  - The main limitation here is electron cloud
  - It can be created by several mechanisms:
    - Ionization of the residual gas
    - Photoemission from the chamber's wall due to the synchrotronradiation emitted by the beam

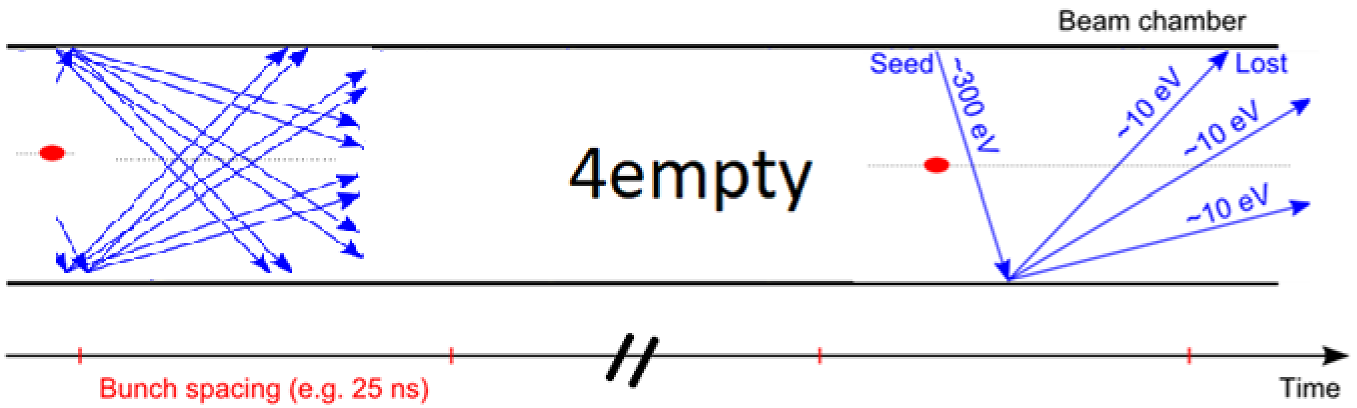


https://doi.org/10.23730/CYRSP-2017-003.411

8b4e to the rescue

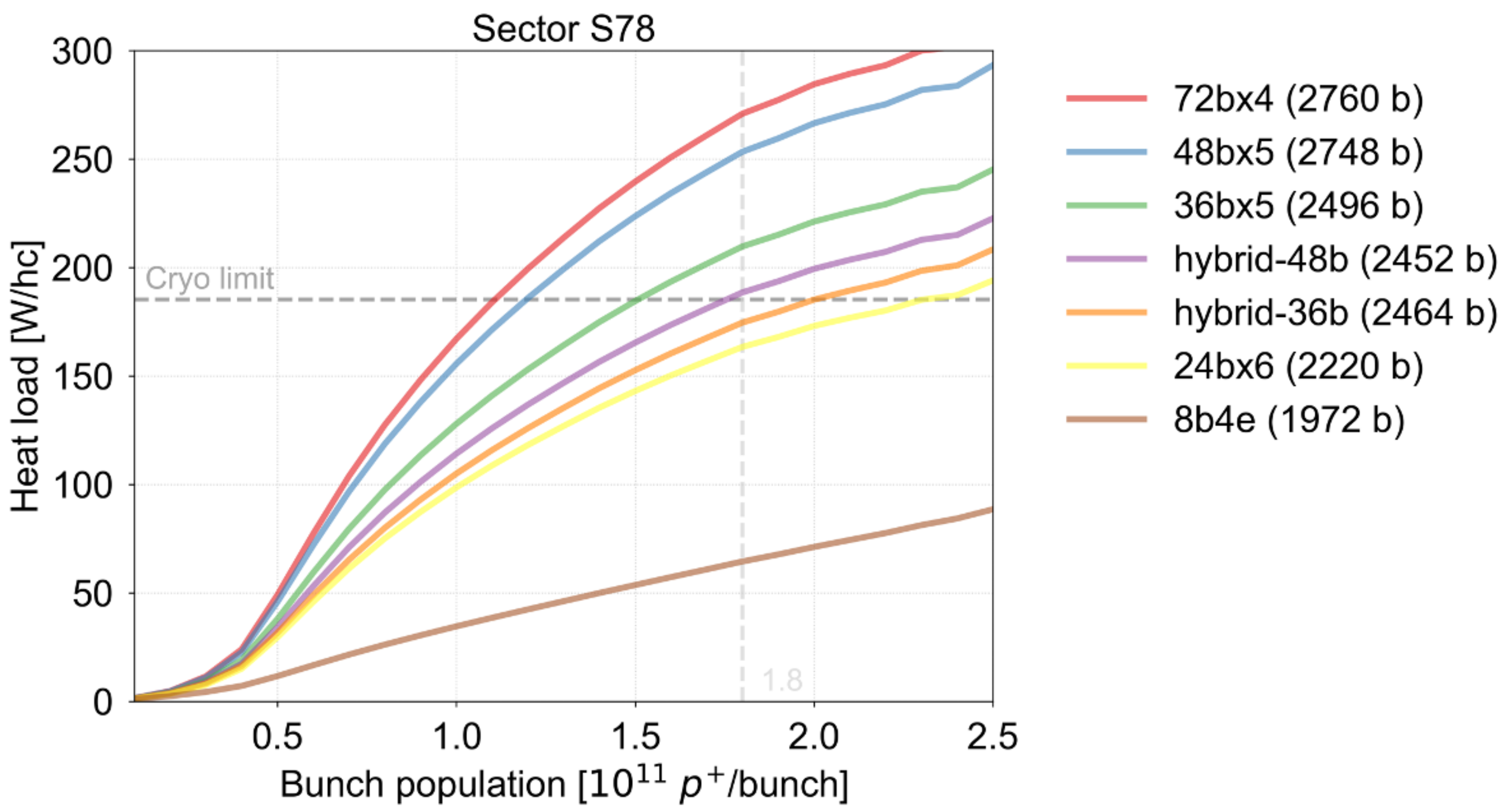
- We can create trains where some of the 25ns slots are empty. In that way the secondary electrons will not have high enough energy to create the avalanche will die off



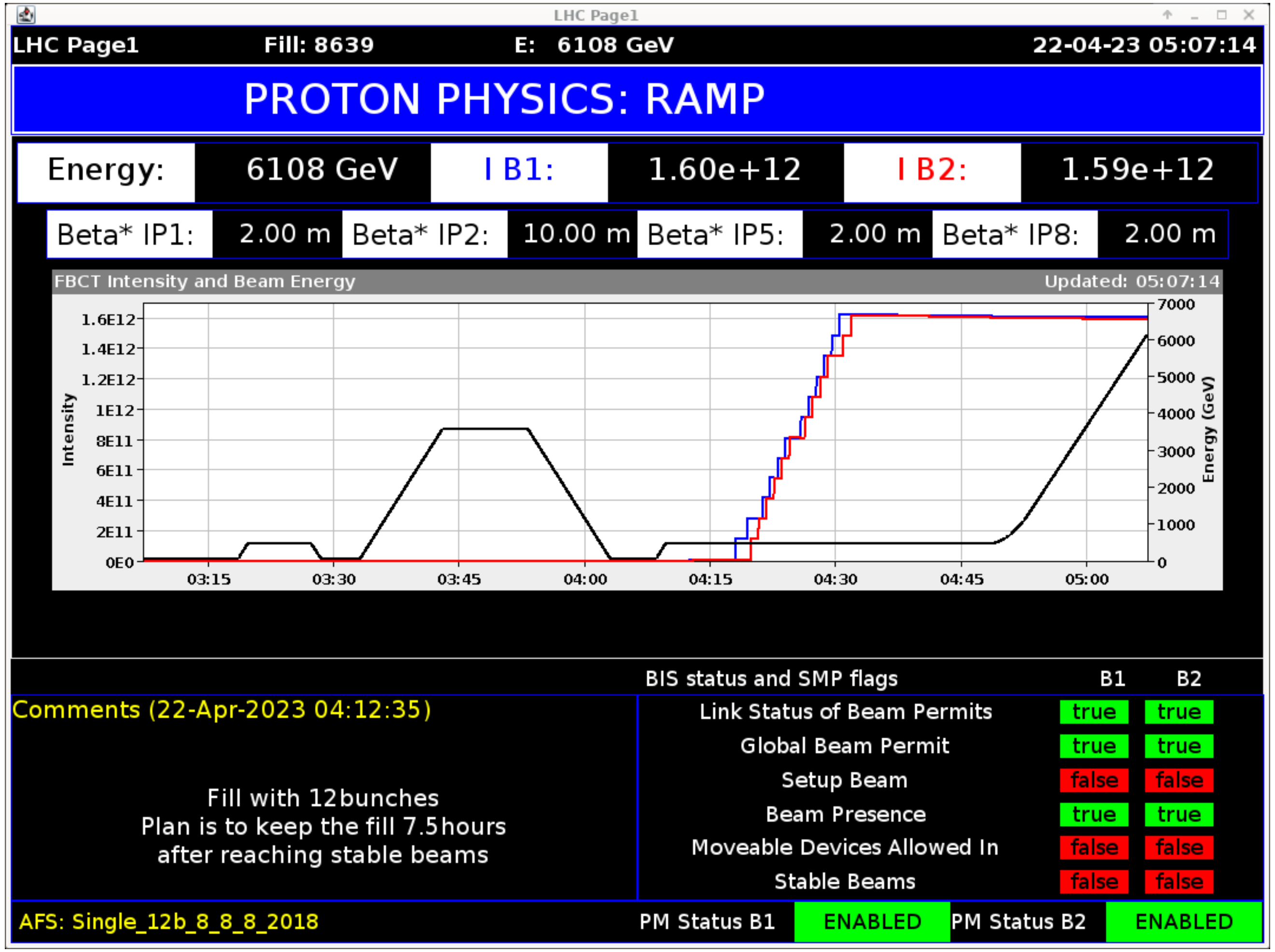


What is the impact of electron cloud?

- Many r… he beam s… e heat-load
  - The … ld parts.
  - The

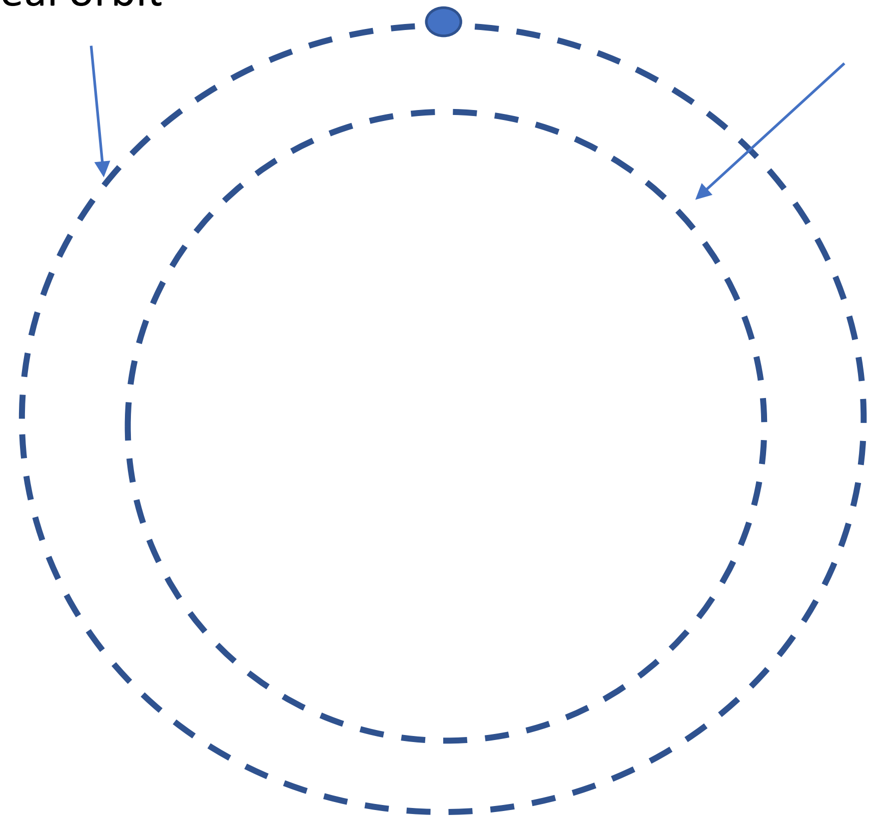


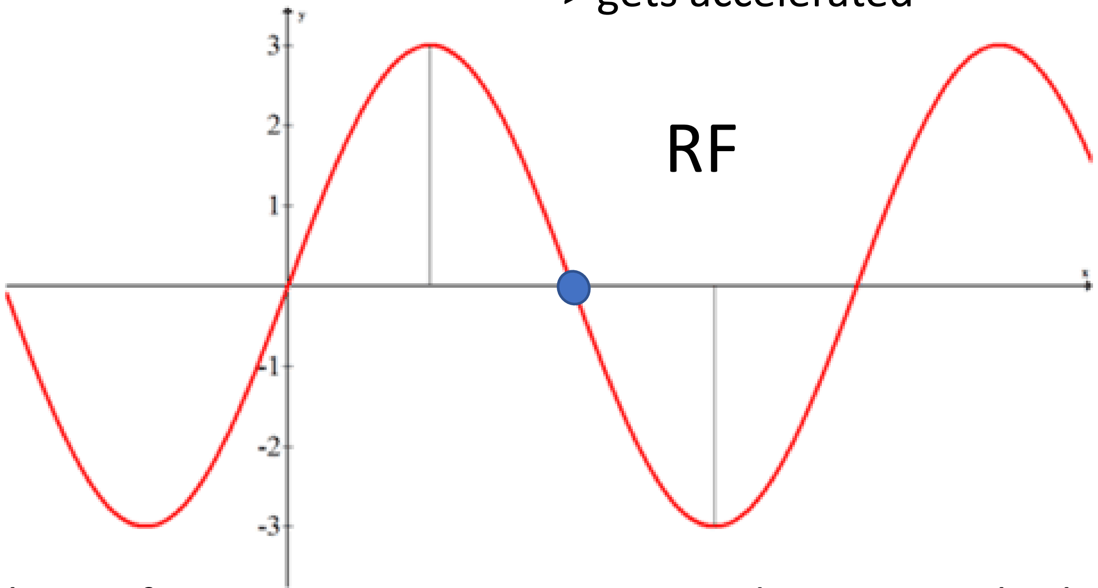
After we have filled we can ramp the energy of the beam!



The principle of the ramp

- Ramp is very complicated in practice because many parameters have to be timed and triggered to be executed at the same time but the principle is rather simple!





Caveat: This is of course a continues process and more complex but the principle is this

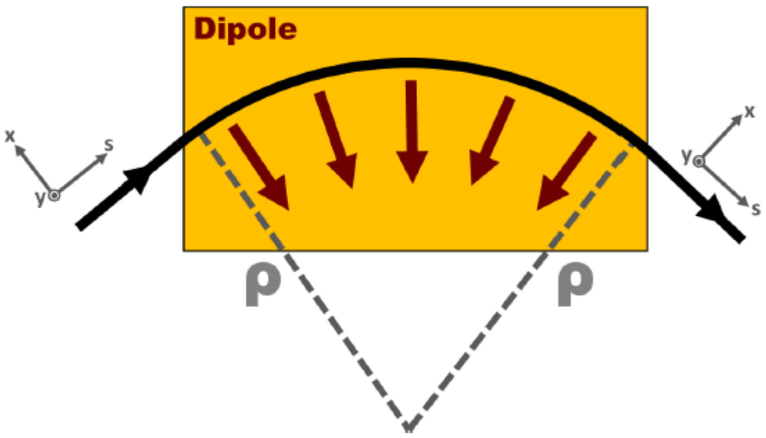
Why do we stop at 6.8 TeV per beam?

- Energy reach determined by two things in the LHC
  - The bending curvature
    - Note that the LHC also has straight section and other elements
  - The strength of the magnetic dipoles

$$F_{Lorentz} = F_{centrip}$$

$$qvB = \frac{\gamma m_{rest} v^2}{\rho} = \frac{pv}{\rho}$$

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



$$B\rho \ \ [\mathrm{Tm}] = \frac{p \ \ [\mathrm{kgms}^{-1}]}{q \ \ [\mathrm{C}]}$$

$$B\rho \ \ [\mathrm{Tm}] = \frac{10}{2.998} p \ [GeV/c]$$

So why don’t we just increase the magnetic fields then?

- There is a maximum of magnetic field the magnets can hold before they quench
  - In order to reach higher we “train” the magnets, i.e. to increase the current until they actually quench
- A quench results in a very fast increase in resistance, hence fast decay of the current, usually accompanied by dissipation of the stored magnetic energy in the coolant (-> rapid boil-off).

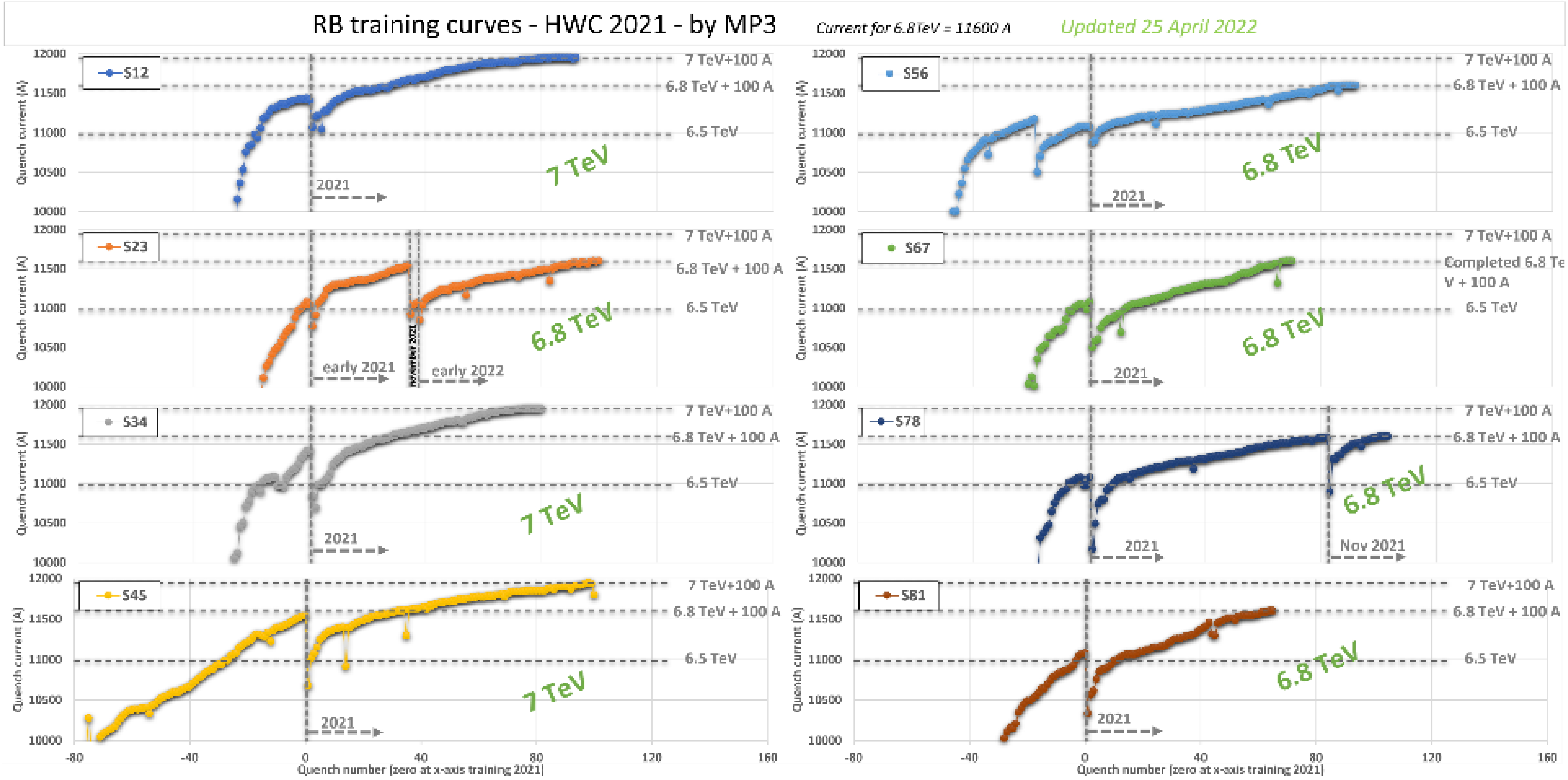
Quench

Each quench causes a tiny probability of coil damage (short-to-gnd, internal short, quench heater failure, etc), with possible collateral damage (especially in case of large stored energy in the magnet/circuit).

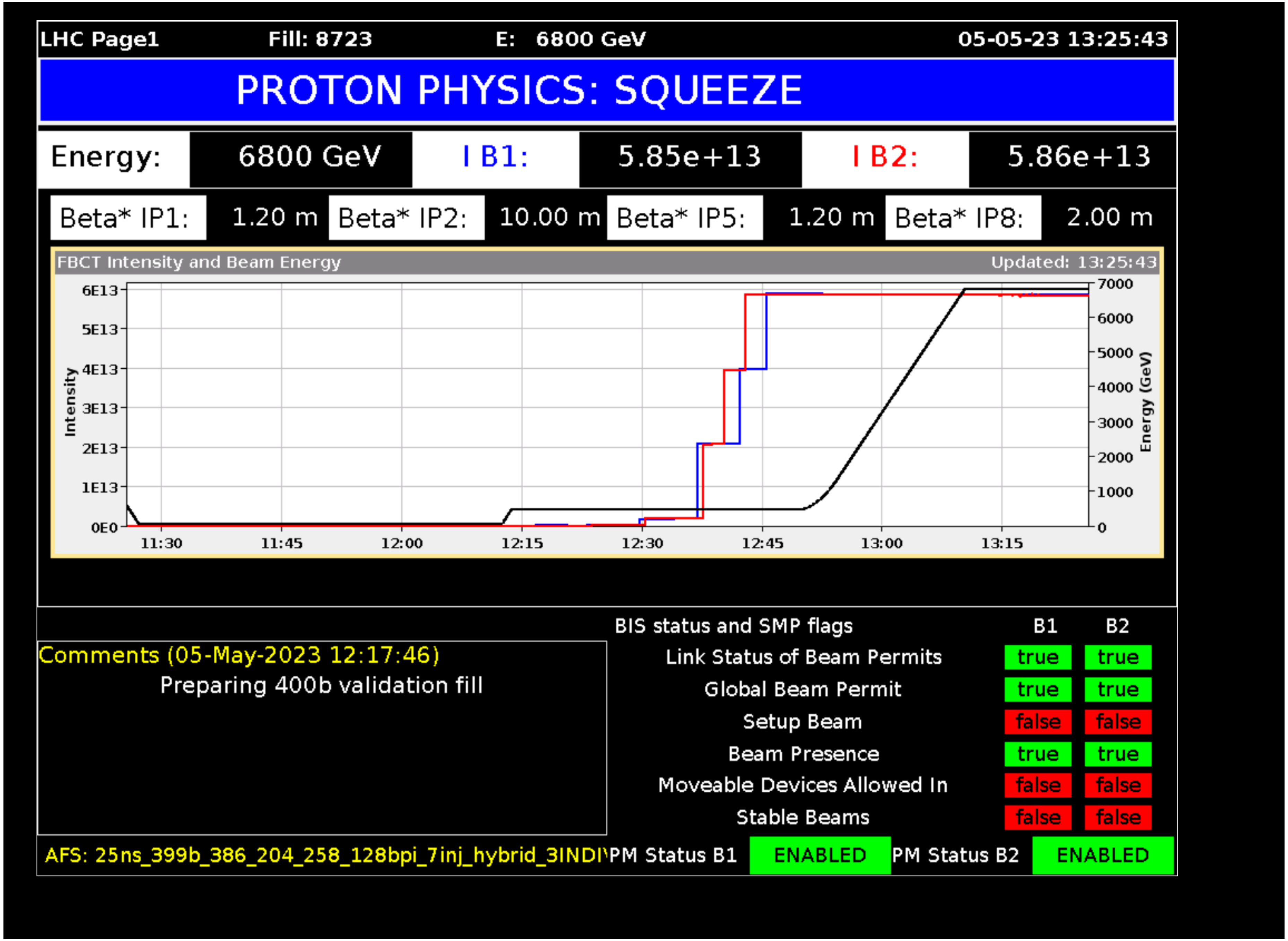
Stored energy in one main dipole circuit

1 GJ = 250 kg of TNT

RB training during HWC campaigns



Total: 980 magnet training quenches



LHC Page1
Fill: 8723
E: 6800 GeV
05-05-23 13:25:43
PROTON PHYSICS: SQUEEZE
Energy:
6800 GeV
I B1:
5.85e+13
I B2:
5.86e+13
Beta* IP1:
1.20 m
Beta* IP2:
10.00 m
Beta* IP5:
1.20 m
Beta* IP8:
2.00 m
FBCT Intensity and Beam Energy
Updated: 13:25:43
Intensity
Energy (GeV)
6E13
5E13
4E13
3E13
2E13
1E13
0E0
7000
6000
5000
4000
3000
2000
1000
0
11:30
11:45
12:00
12:15
12:30
12:45
13:00
13:15
Comments (05-May-2023 12:17:46)
Preparing 400b validation fill
BIS status and SMP flags
B1
B2
Link Status of Beam Permits
true
true
Global Beam Permit
true
true
Setup Beam
false
false
Beam Presence
true
true
Moveable Devices Allowed In
false
false
Stable Beams
false
false
AFS: 25ns_399b_386_204_258_128bpi_7inj_hybrid_3INDI
PM Status B1
ENABLED
PM Status B2
ENABLED

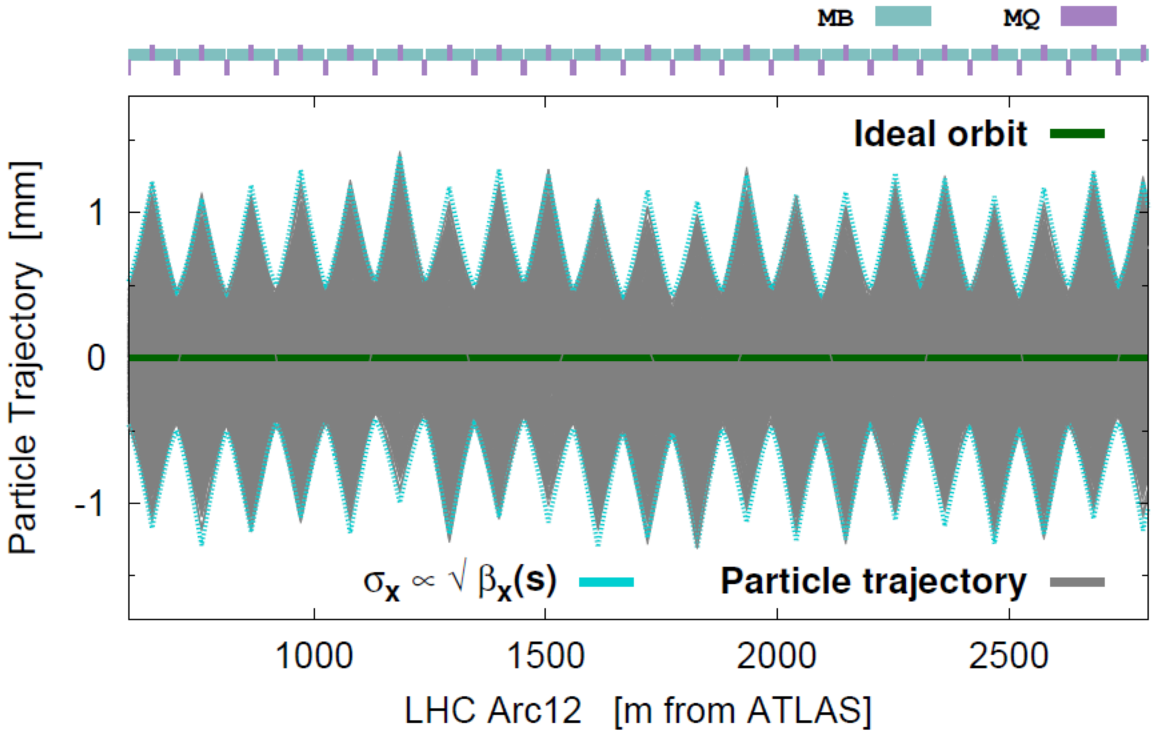
Why squeeze?

- What are we squeezing ?
  - The β^* of IP1 and IP5
- It used to be that the squeeze was done completely separately from the other parts of the cycle
  - Today we squeeze during ramp as well as in Stable beams!
- The reason to squeeze is to reduce the beam size at the experiments to obtain higher luminosity

$$\sigma_{x,y} = \sqrt{\beta_{x,y}(s)\ \epsilon_{x,y}}$$

What is the β-function?

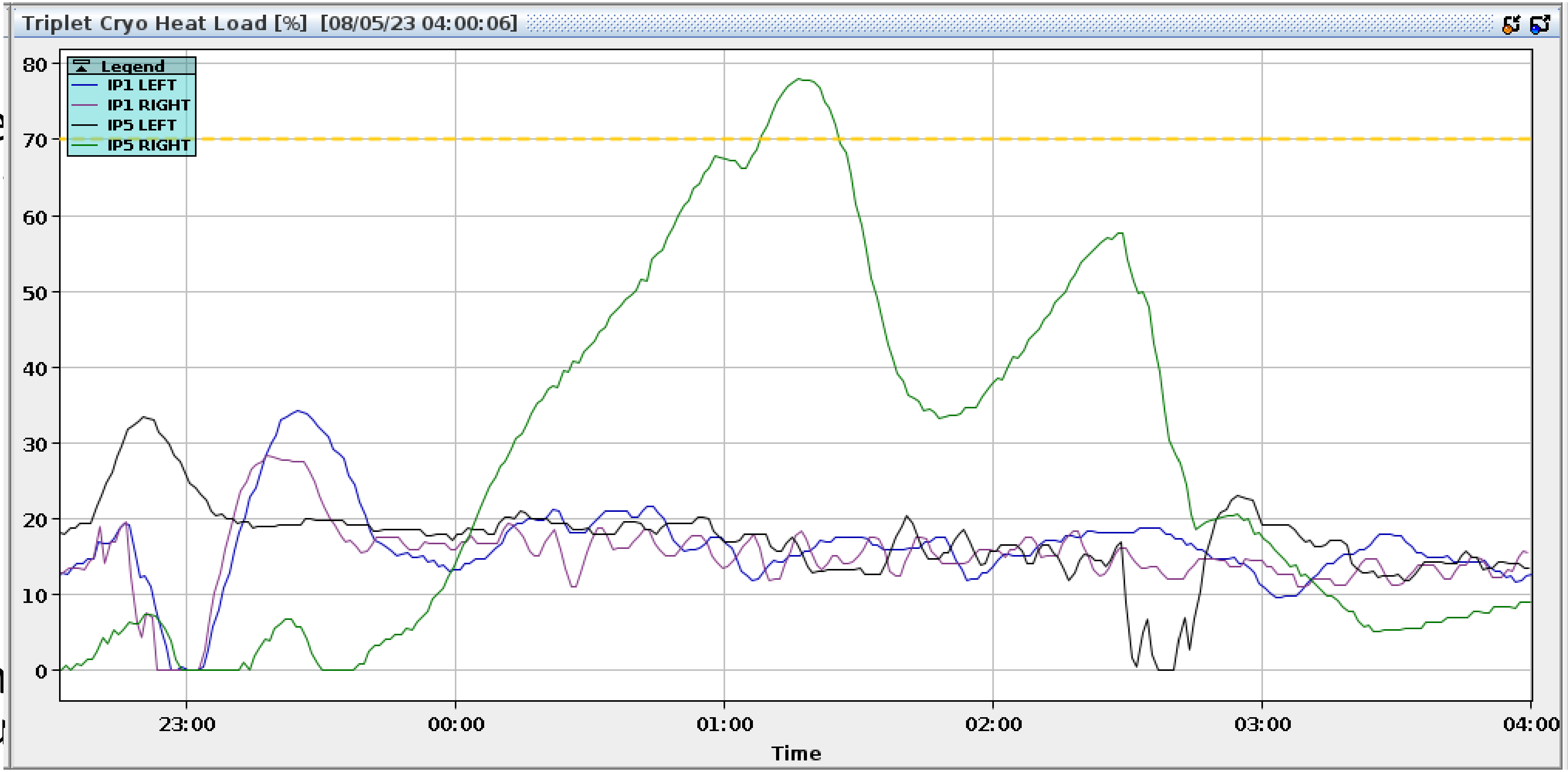
- The β-function is a property of the lattice, i.e. a function of the powering and distance of the magnets



$$\sigma_{x,y} = \sqrt{\beta_{x,y}(s)\ \epsilon_{x,y}}$$

What is limiting our squeeze? Why not just go

- The
  for



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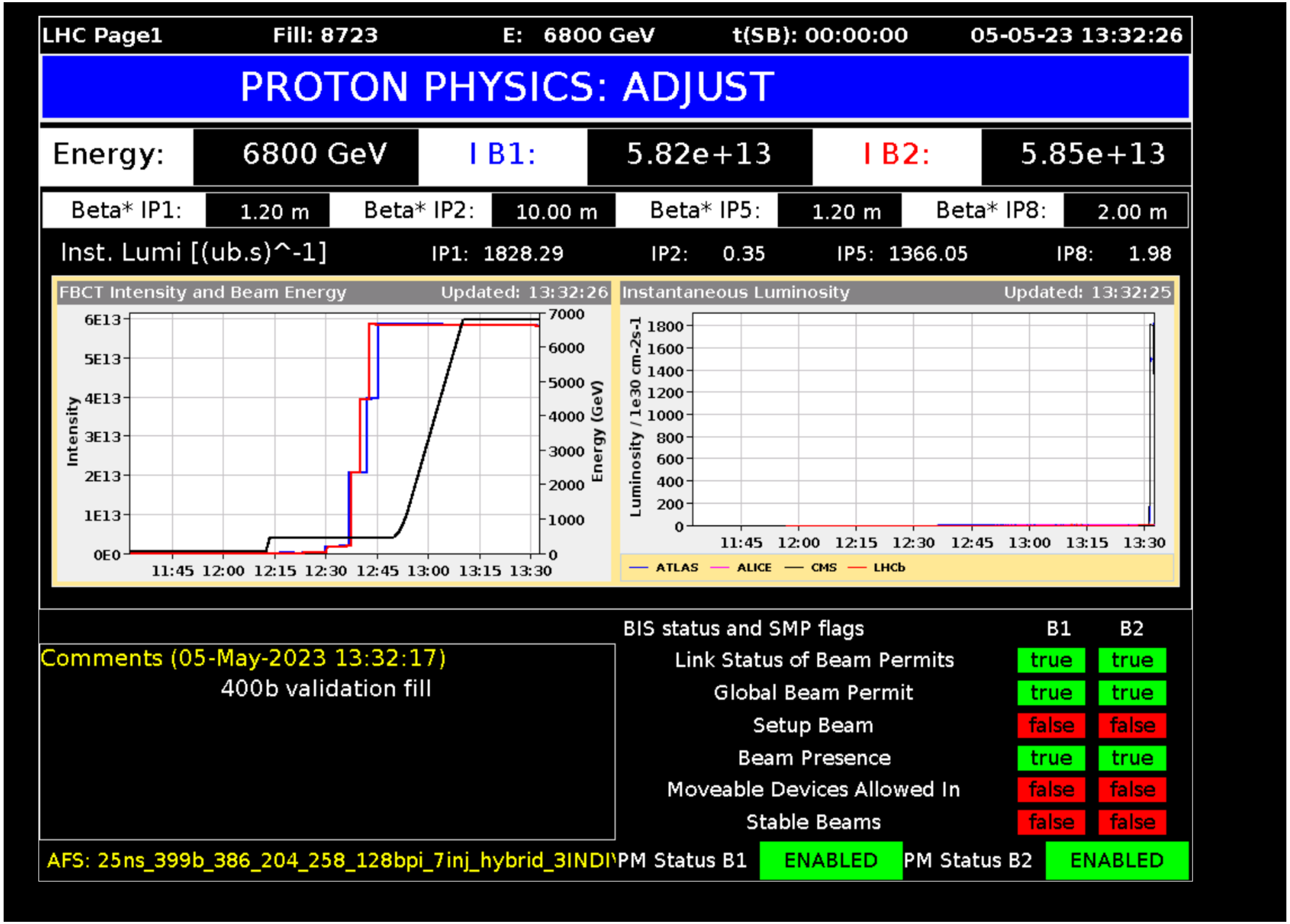
  nu

-> How much we can squeeze before we start colliding and how fast we can squeeze when in collisions


LHC Page1
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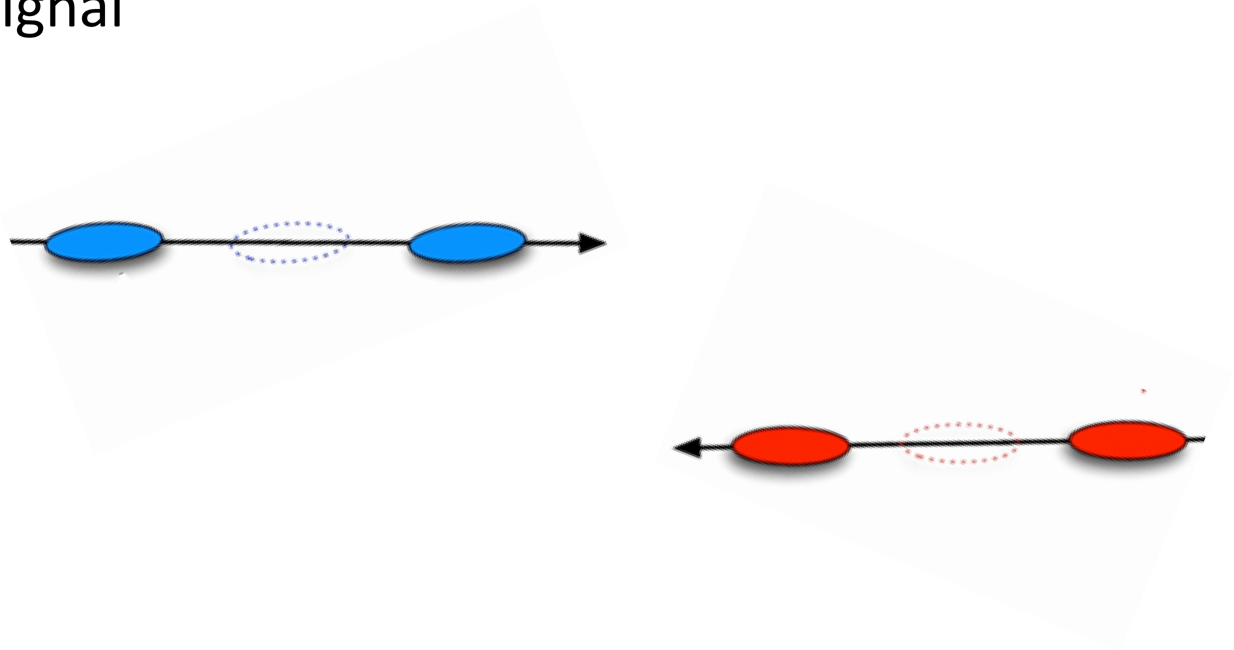
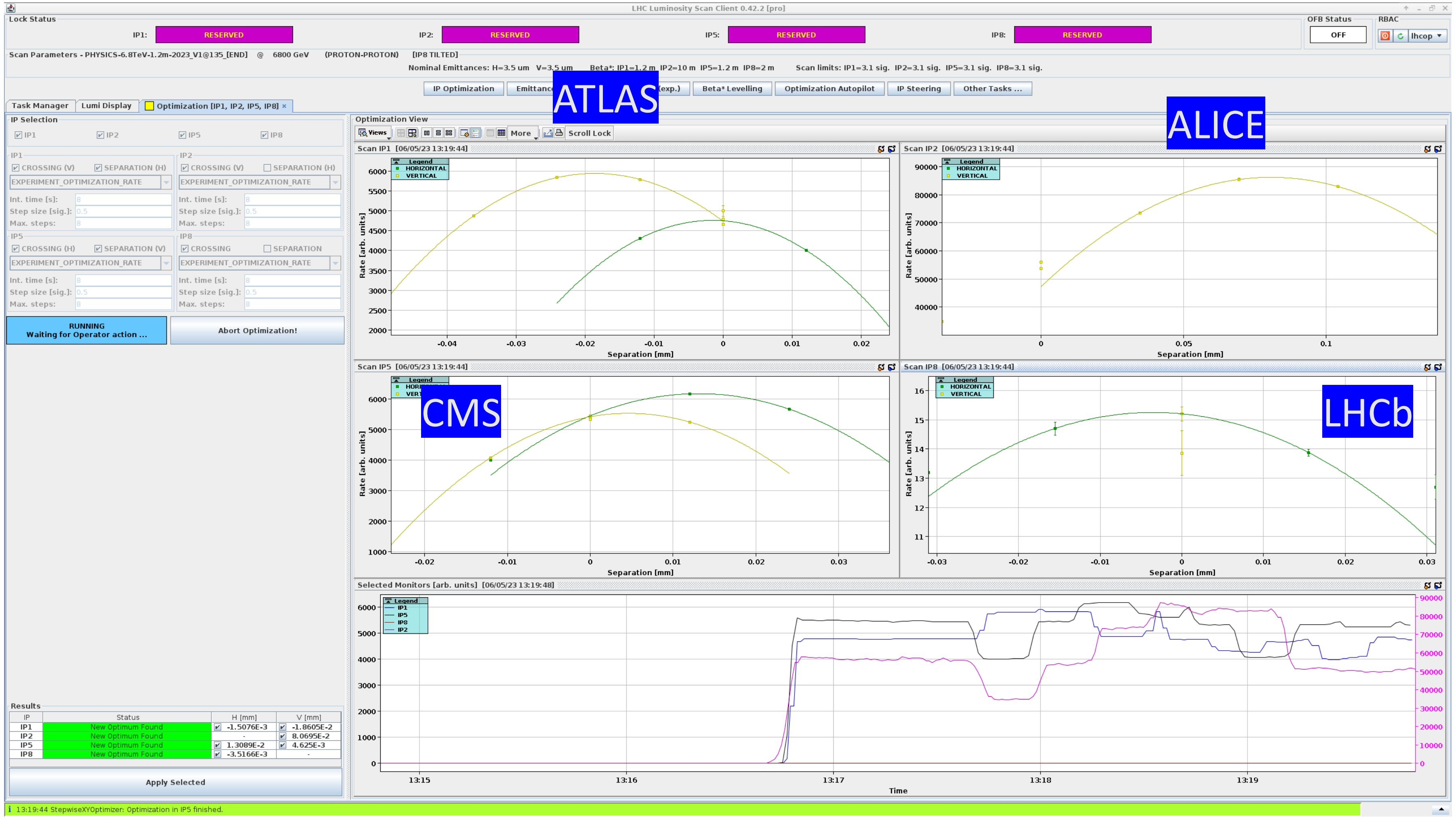
E: 6800 GeV
t(SB): 00:00:00
05-05-23 13:32:26
PROTON PHYSICS: ADJUST
Energy: 6800 GeV
I B1: 5.82e+13
I B2: 5.85e+13
Beta* IP1: 1.20 m
Beta* IP2: 10.00 m
Beta* IP5: 1.20 m
Beta* IP8: 2.00 m
Inst. Lumi [(ub.s)^-1]
IP1: 1828.29
IP2: 0.35
IP5: 1366.05
IP8: 1.98
FBCT Intensity and Beam Energy
Updated: 13:32:26
Intensity
Energy (GeV)
Instantaneous Luminosity
Updated: 13:32:25
Luminosity / 1e30 cm-2s-1
ATLAS
ALICE
CMS
LHCb
Comments (05-May-2023 13:32:17)
400b validation fill
BIS status and SMP flags
B1
B2
Link Status of Beam Permits true true
Global Beam Permit true true
Setup Beam false false
Beam Presence true true
Moveable Devices Allowed In false false
Stable Beams false false
AFS: 25ns_399b_386_204_258_128bpi_7inj_hybrid_3INDI
PM Status B1 ENABLED
PM Status B2 ENABLED

Adjust is when the collisions start

- There is a separation in one of the transverse plane in the experiments before this stage
  - This separation collapses during adjust
  - We then optimize each IP by moving the beam and finding the highest luminosity signal

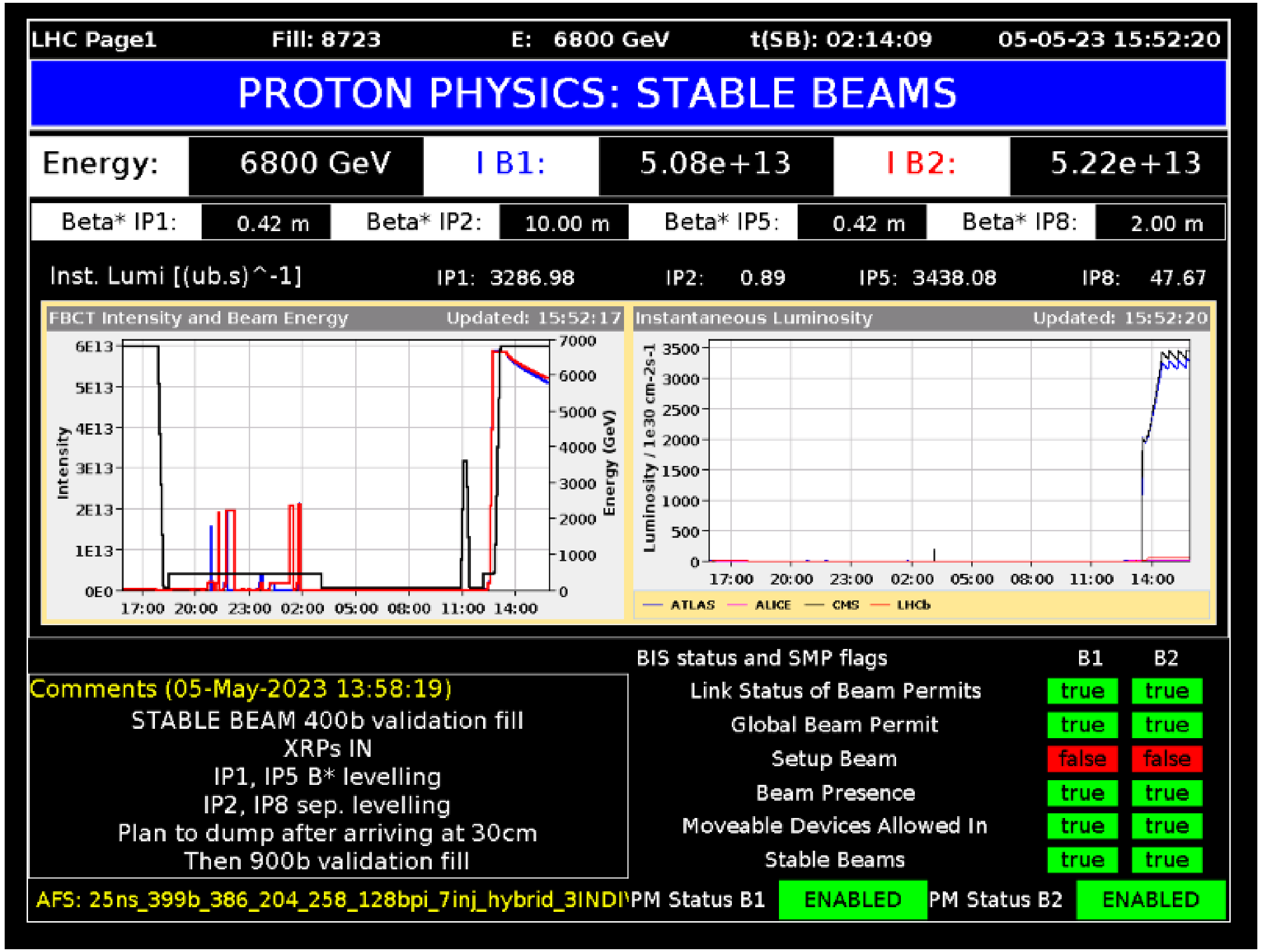


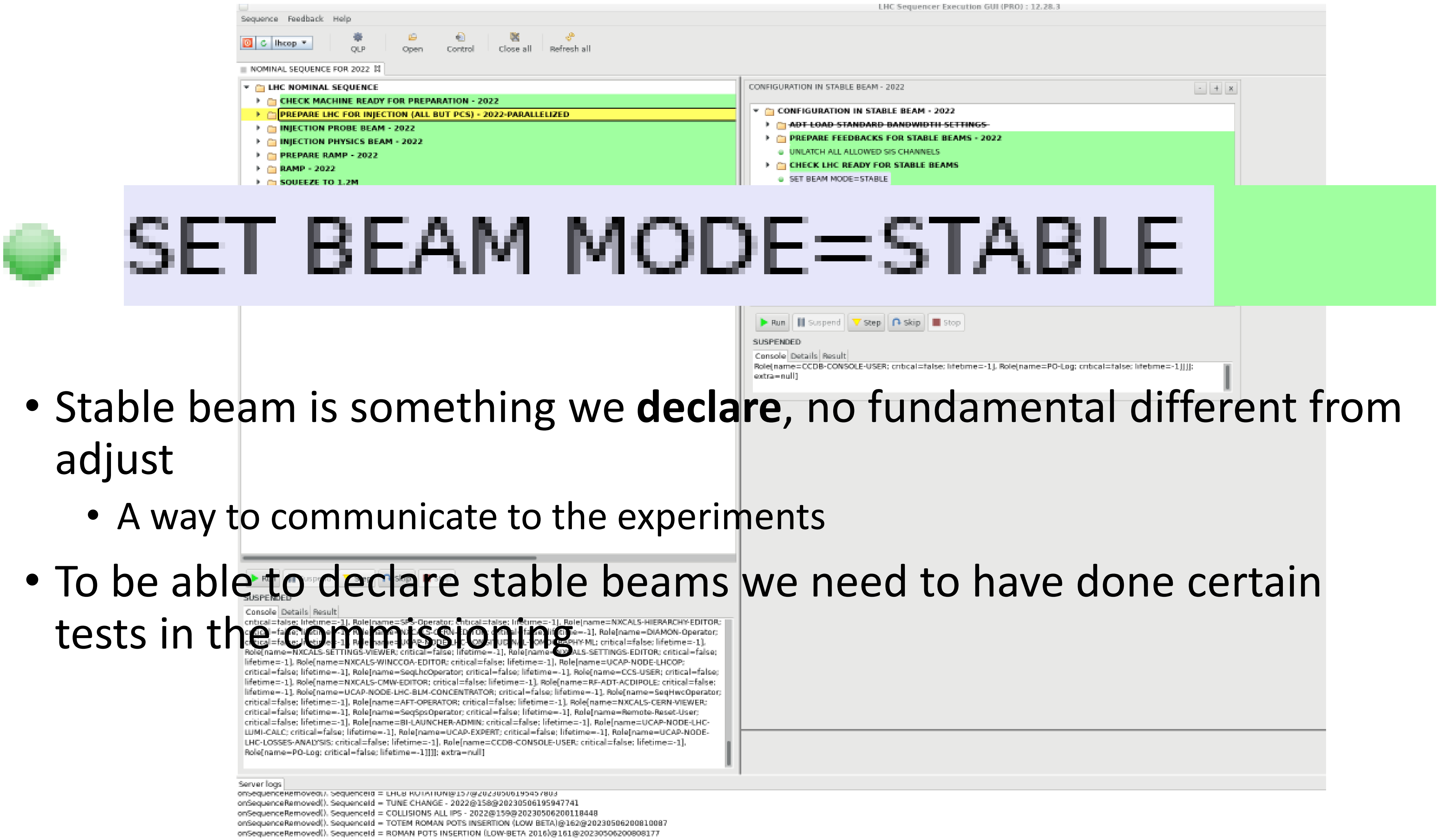
After we have to optimize, due to drifts between fills



IP	Status	H [mm]	V [mm]
IP1	New Optimum Found	-1.5076E-3	-1.8605E-2
IP2	New Optimum Found	-	8.0695E-2
IP5	New Optimum Found	1.3089E-2	4.625E-3
IP8	New Optimum Found	-3.5166E-3	-

We are now ready for stable beams!





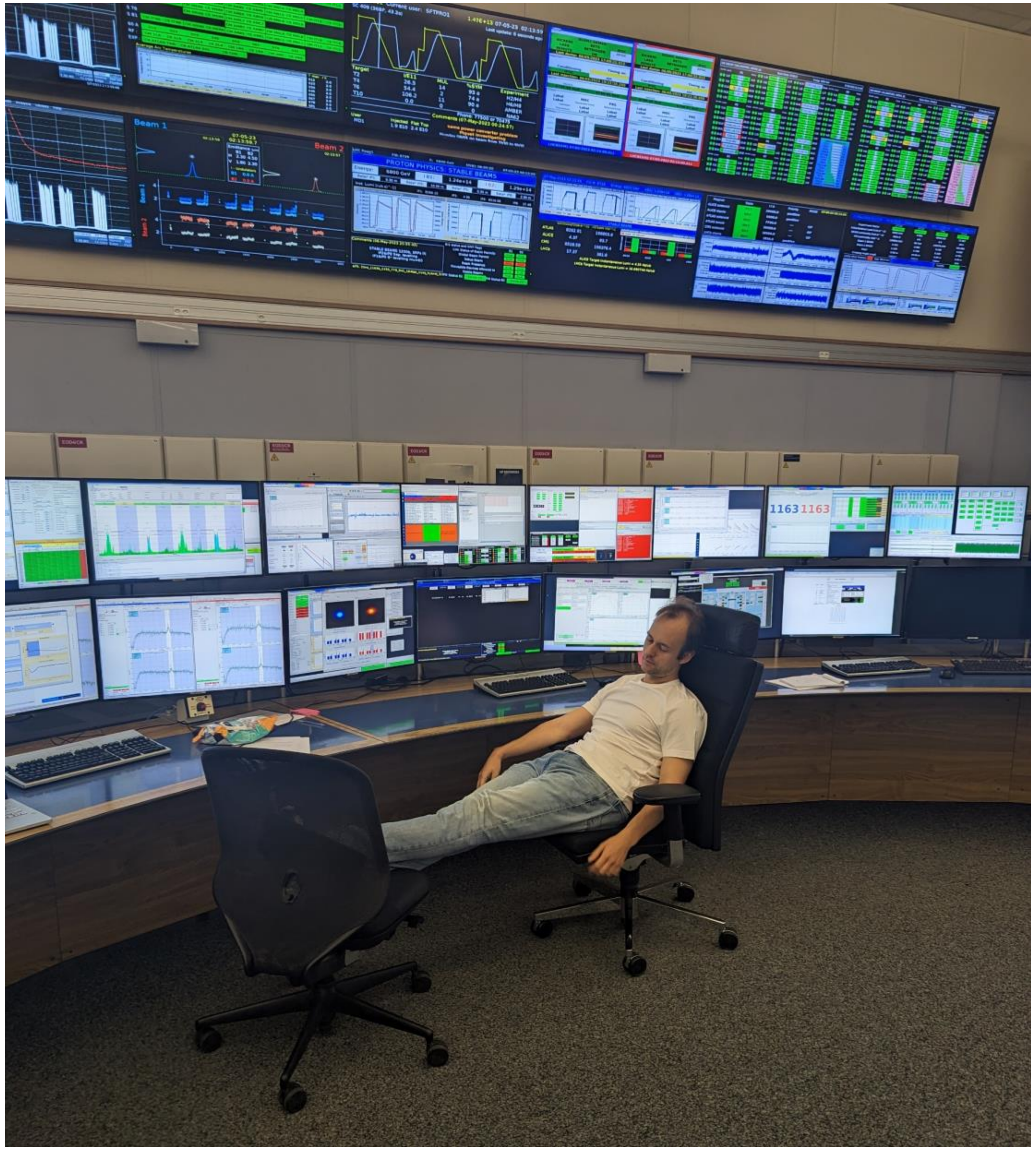
- Stable beam is something we **declare**, no fundamental different from adjust
  - A way to communicate to the experiments
- To be able to declare stable beams we need to have done certain tests in the commissioning

Makes people in the experiments this happy ! And very busy

Meanwhile in the CCC….

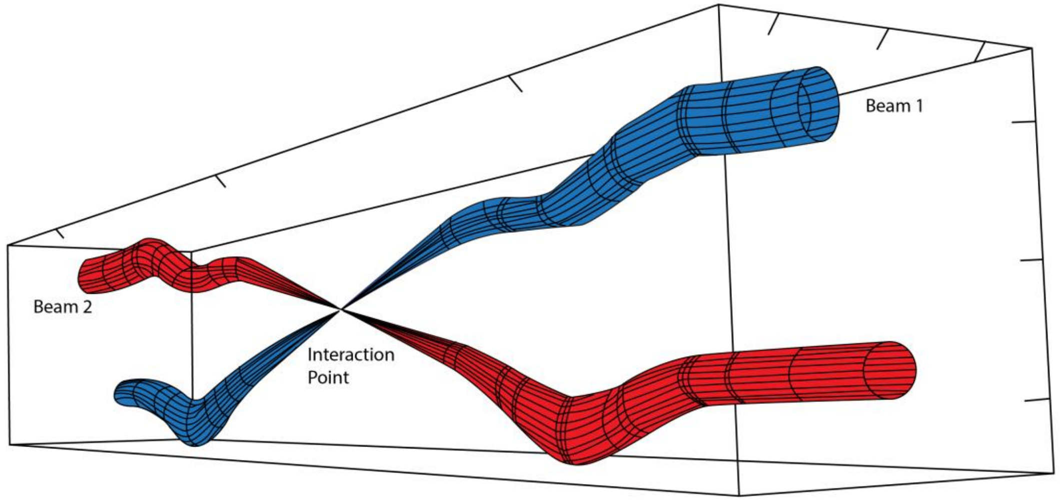
Well, maybe not really true but it is the most quiet period for us

- Most busy is general when we don’t have beam because then there is some issue we need to solve!



What is changing in Stable beams?

- **Crossing angle** and β*
  - Crossing angle going from 130u rad -> 160u rad when beta* goes from 1.2m down to 0.3m
- The rest we try to keep constant (except for requests of e.g. emittance scan)

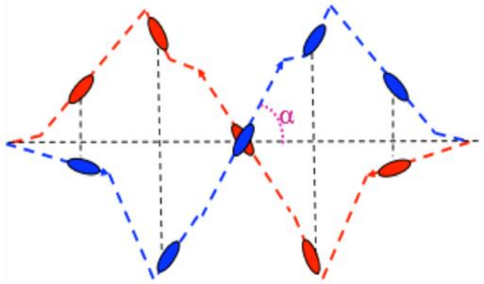


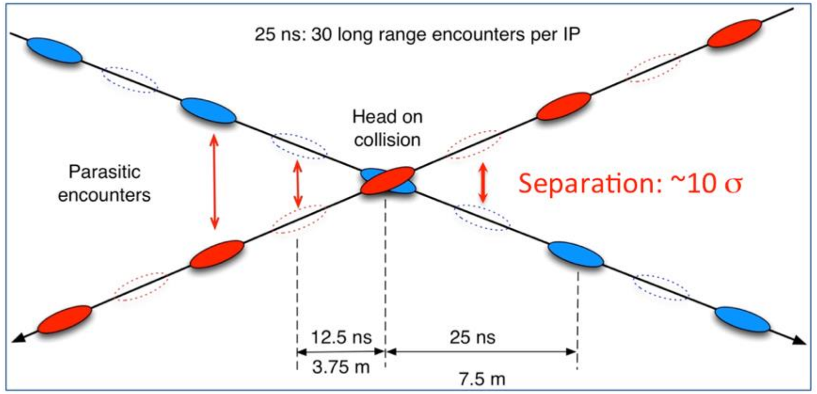
Crossing angle

- We need the crossing angle to reduce the parasitic encounters
- Has an impact on the luminosity
  - Larger crossing angle -> Less luminosity
- We just adjusted down the crossing angle for ATLAS by 10u rad and now the measured luminosity is much closer between ATLAS and CMS

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{2\pi \sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}\sqrt{\sigma_{2y}^2 + \sigma_{2y}^2}} .$$

https://cds.cern.ch/record/941318/files/p361.pdf



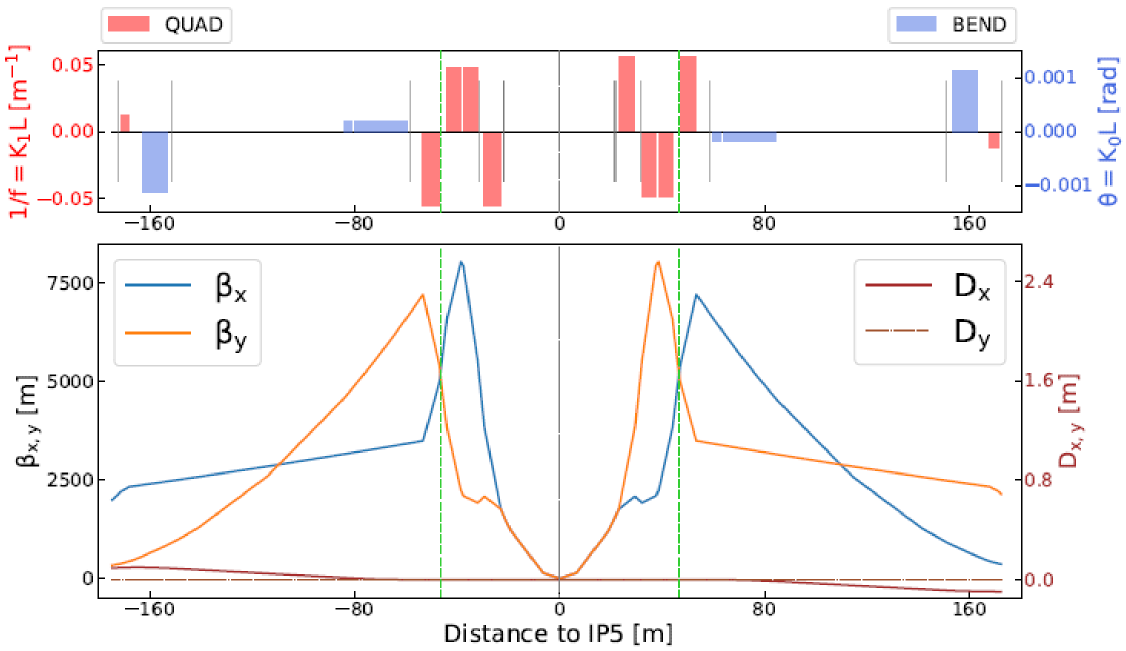


In case of a crossing angle one can calculate an approximative effective beam size following this formula

$$\sigma_{eff} = \sigma \cdot \sqrt{1 + \left(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2}\right)^2} .$$

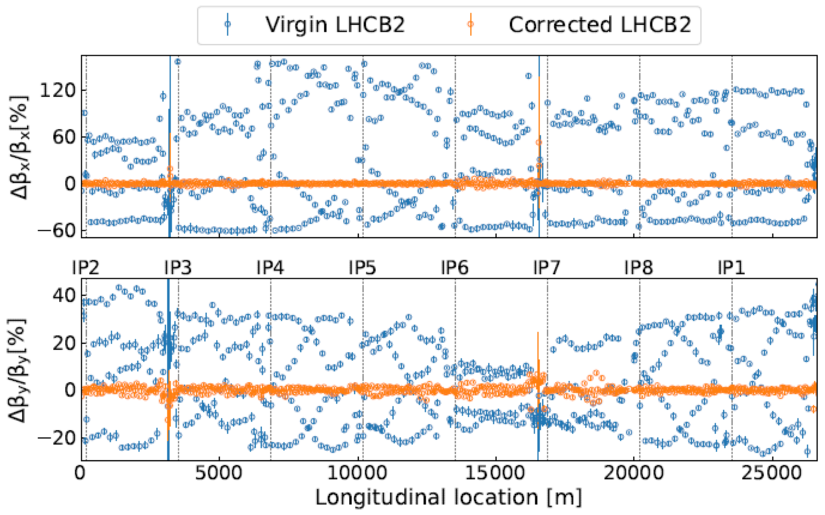
β*

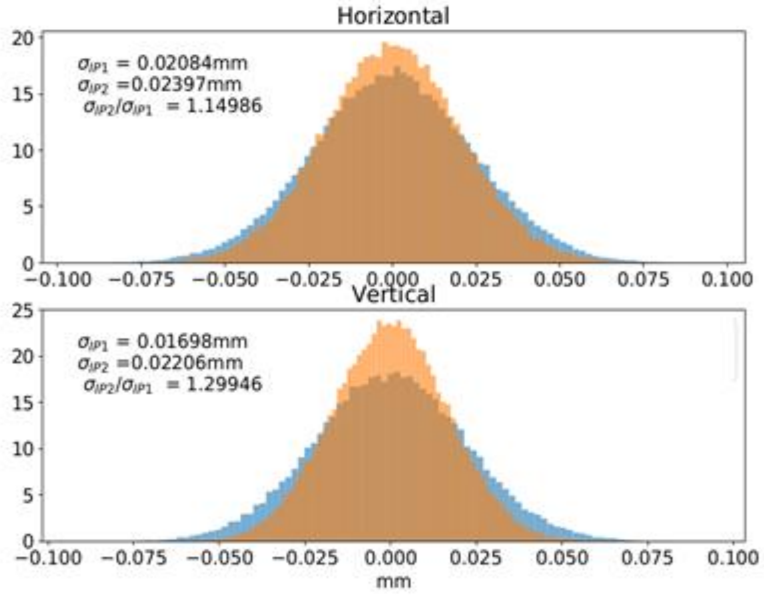
- Design optics around IP5
- It doesn't looks like this before we correct the machine!
  - Done during commissioning with low intensity beams



β* and β

- More than 100% β-beat when we turn on the machine
- Other sources such as local coupling (skew focusing) are also crucial to correct in order to get back to the design parameters

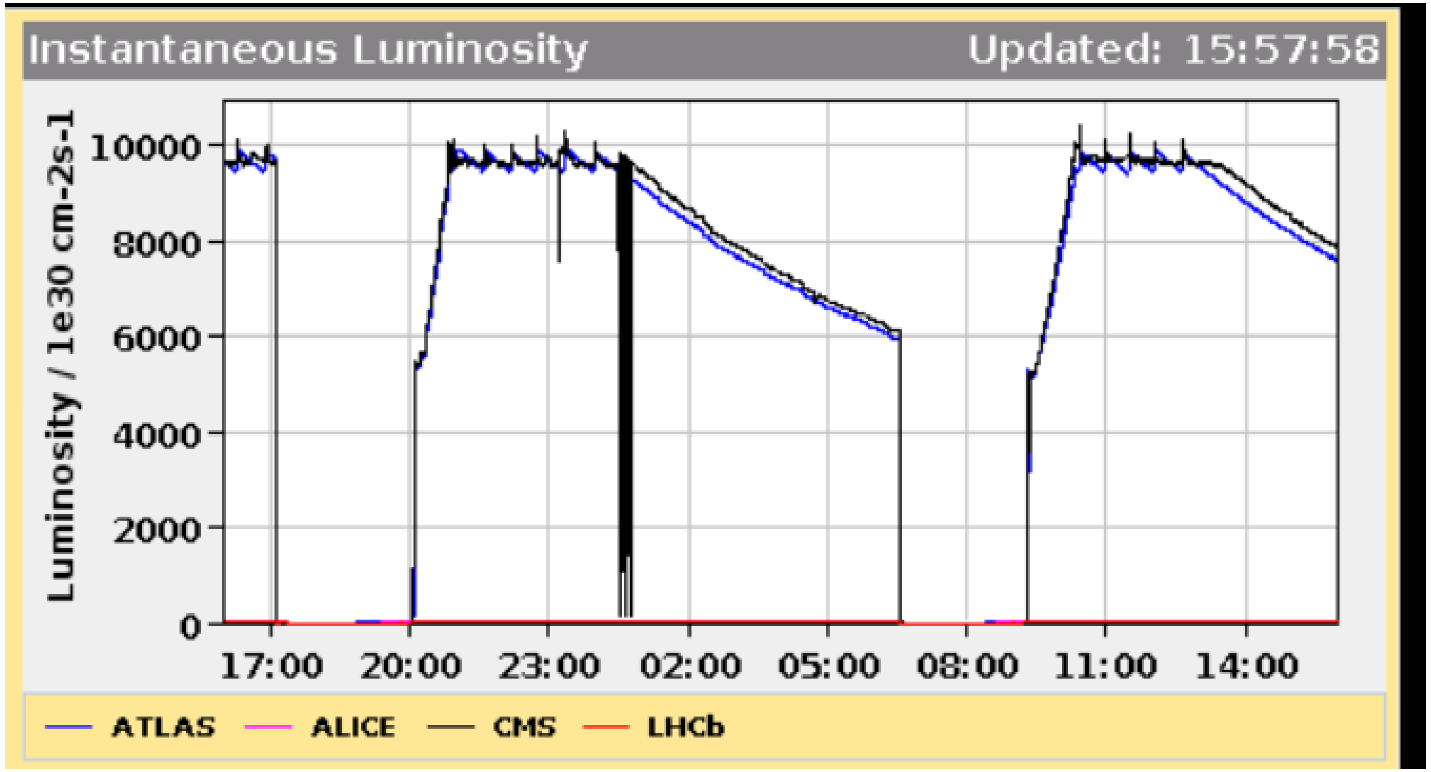




A lot of my research has been into how to measure and correct these parameters in LHC and future machines [1][2][3]!

Blue no coupling error
Orange with coupling error

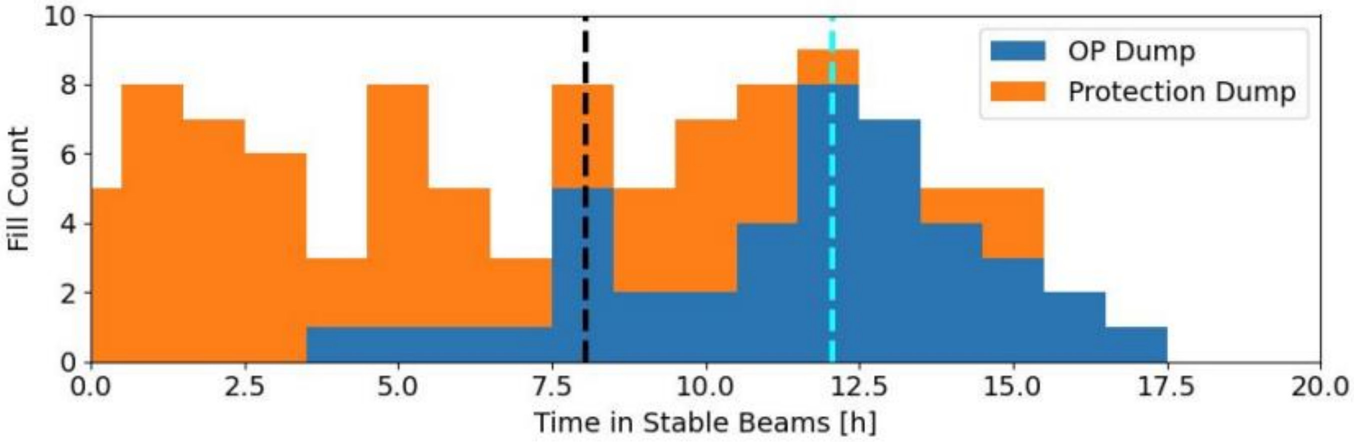
Example of stable beam with separation levelling as well



Screenshot from the 7th of May when I was on shift and CMS wanted to reduce the pileup slightly. Done by separating the beams slightly.

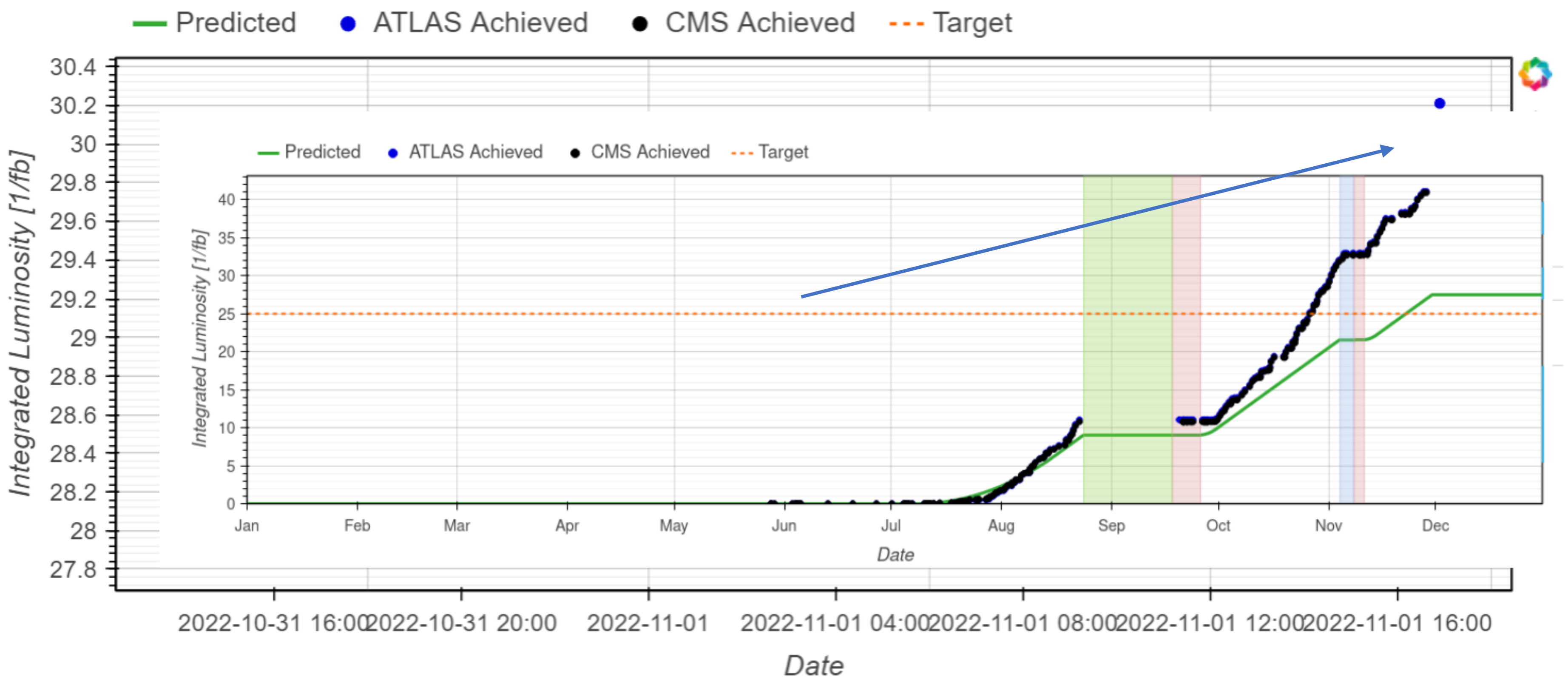
Time to dump?

- Not fully up to us!
  - Optimum fill length: ~12h in Stable Beams with ~5h median turnaround
    - < 3% integrated luminosity lost when stretched to 15h
- 42 OP dumps**, 60 protection dumps** of production fills in 2022
  - OP dumps include "forced" dumps for access (e.g. chimney heaters, …)
  - median fill length: ~8h in Stable Beams



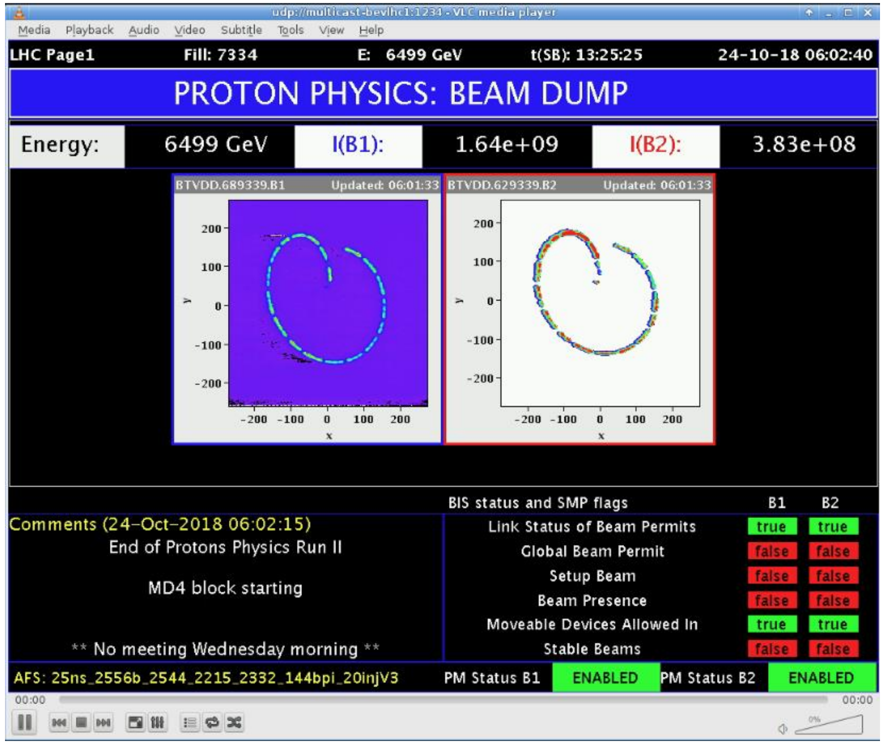
Michi Hostettler

One cycle is one step towards the 500 inverse femtobarn…



Just some final remarks

- I hope I have managed to give you an insight to what the different steps are for and what is the main limitations
- However, I have of course left out many things such as:
  - Nonlinear beam dynamics [4]
  - Instabilities
  - Chromaticity
  - Collimation
  - RF-system, dump system
- Don’t hesitate to contact me in case there is something you are curious about!



Thank you for listening!