Beam diagnostics for circular colliders

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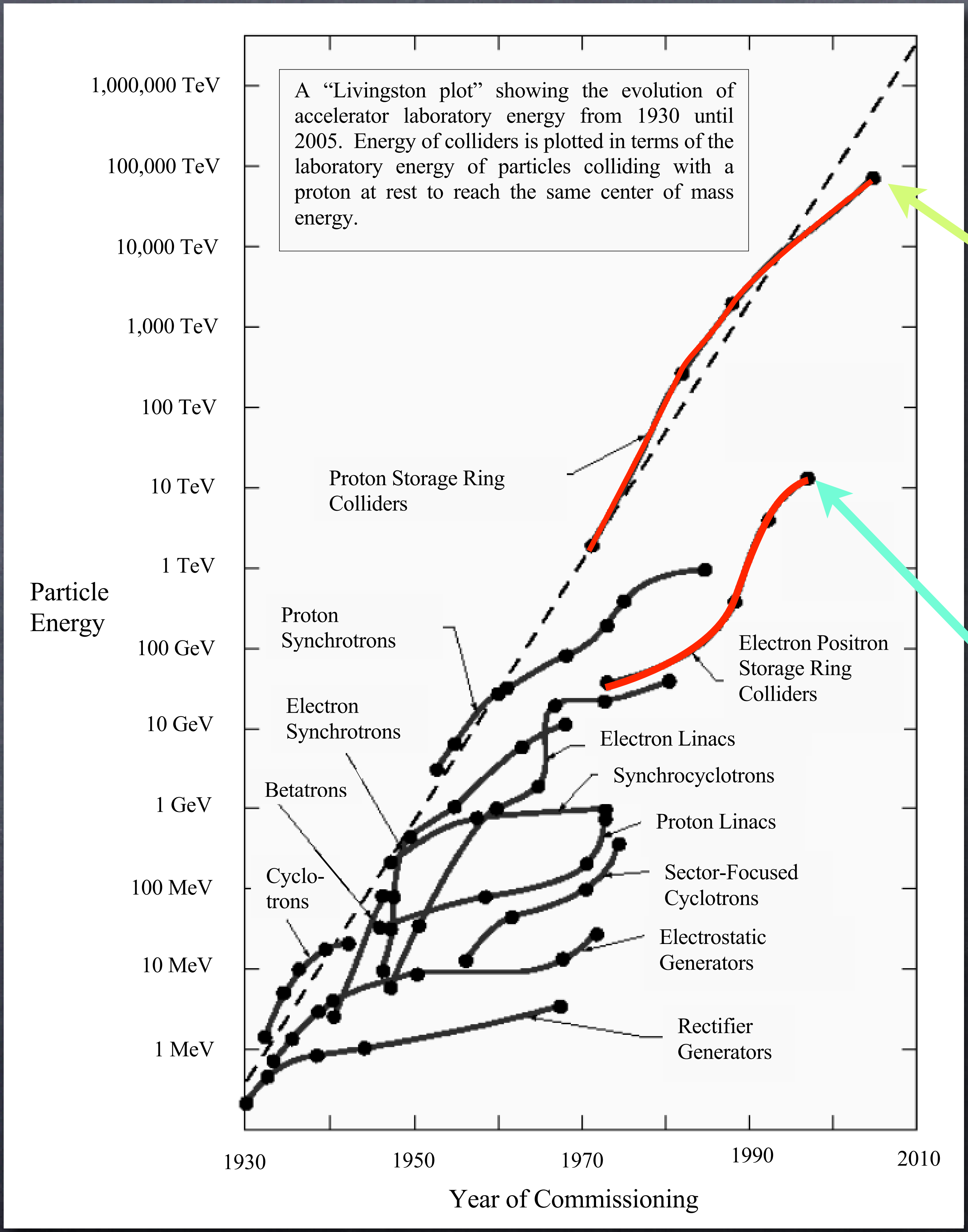
DITANET School 2011 - Stockholm

Why colliders ?

- Initially accelerated beams where sent on fixed targets, but due to conservation laws…
- As the beam energy increases the fraction of energy "available" for the interaction decreases dramatically
- Colliding particles of opposite momentum is much more favorable since 100% of the energy is "available" for creating debris



7+7 TeV (LHC) equivalent to ~100'000 TeV fixed target experiment

100+100 GeV (LEP) equivalent to ~10 TeV fixed target experiment

Brief history

- First co… …i (Italy)
  - e^-+e^+…
- First ha… …RN
  - p^++p^+… …/c
- SLC, 45… …SLAC
- LEP II,…
- Tevatron…
- RHIC, 2… …haven
- LHC, 7 T…
- Many lo…

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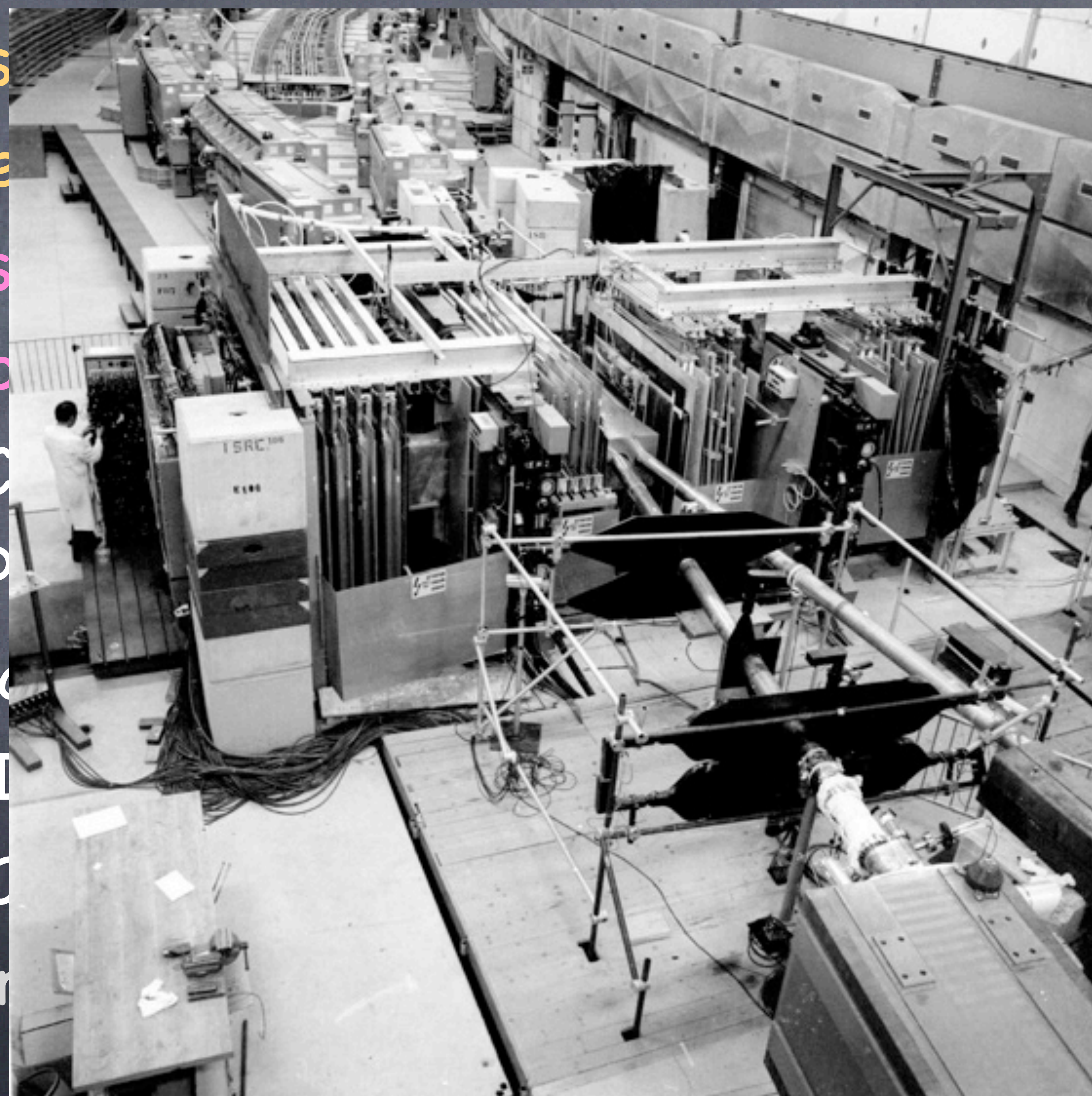
Brief history

- Firs  aly)
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Brief history

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Brief history

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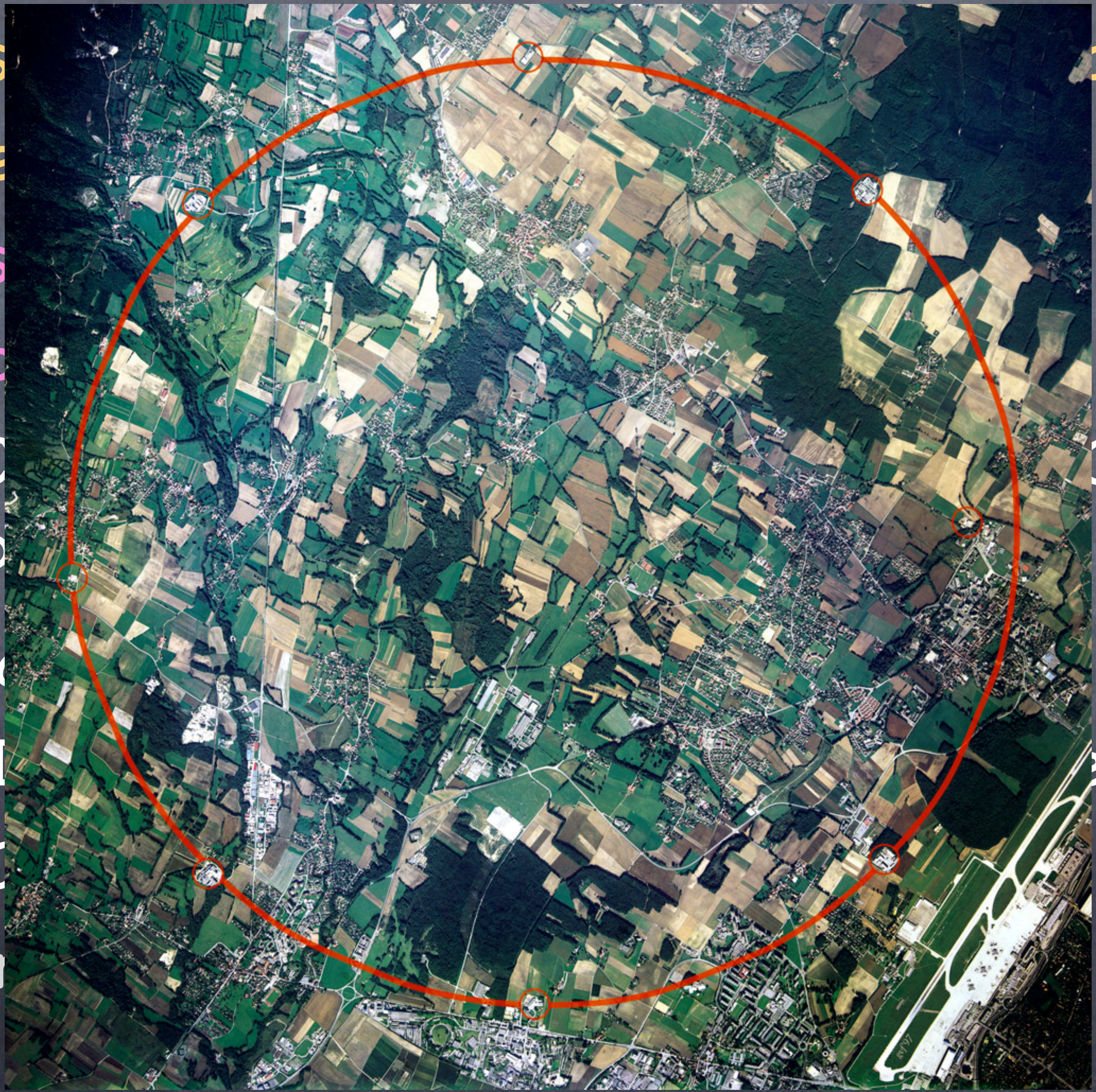
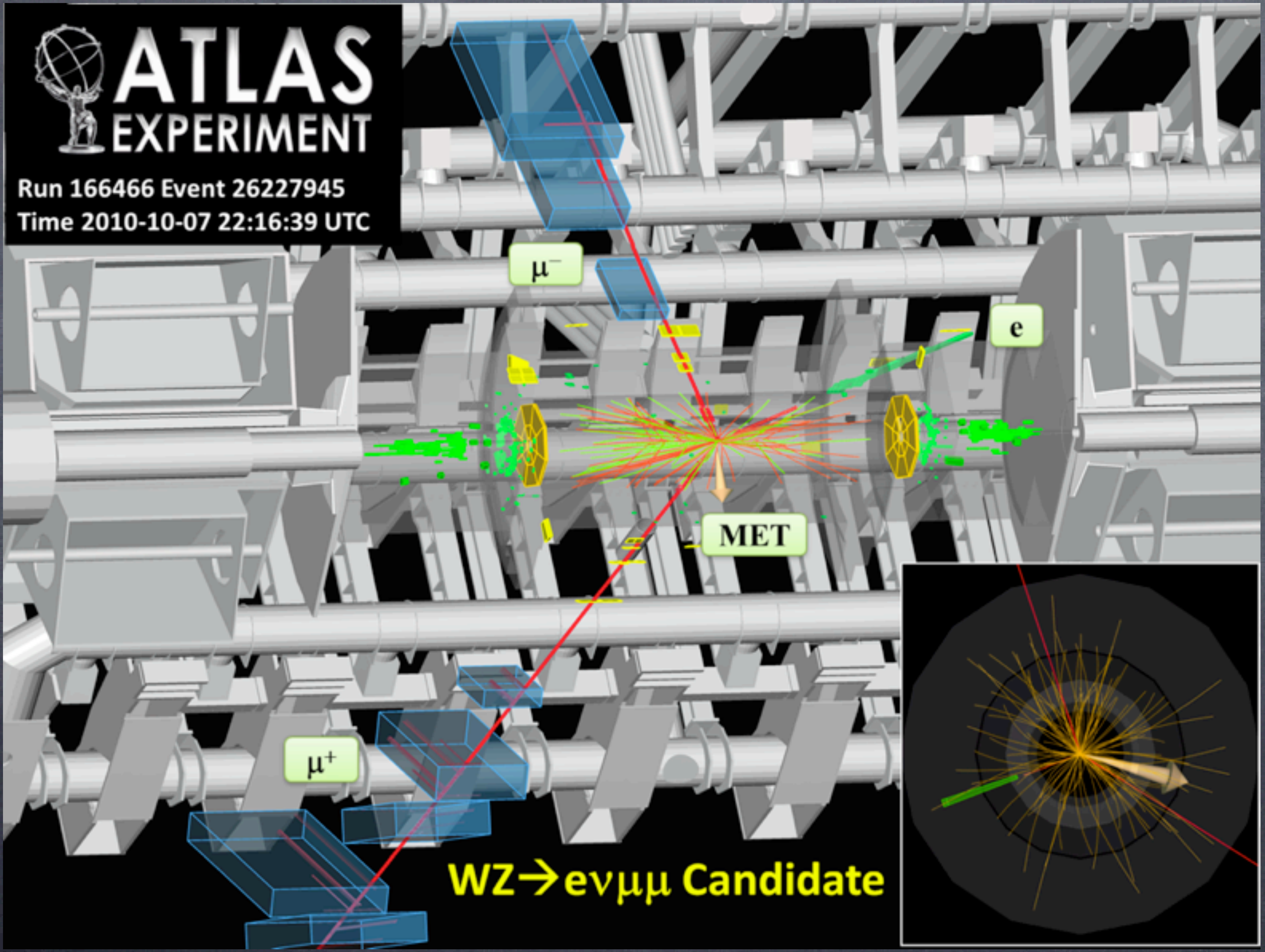


Brief history

- First collider, 1961, AdA in Frascati (Italy)
    - e^-+e^+, common ring, E=200MeV
- First hadron collider, 1971, ISR CERN
    - p^++p^+, double ring, p= 26.5 GeV/c
- SLC, 45 GeV e^-+e^+ linear collider, SLAC
- LEP II, 100 GeV e^-+e^+, CERN
- Tevatron, 1 TeV, p^++p^-, FermiLab
- RHIC, 250 GeV p^++p^+ or HI, Brookhaven
- LHC, 7 TeV p^++p^+ or HI, CERN
- Many lower energy factories

The deliverables



Physics with colliders

- Key parameters for the physics that can be done on a collider are
  - Type of particles
  - Energy of the interacting “partons”
  - Rate of interesting events

Energy

- The higher the energy of the partons the higher the rest mass of the debris produced
- High energy machines are needed for the discovery of new particles (and physics)
- In hadron collisions only part of the total energy of a particle will be available (collisions are between quarks or gluon)
- Lepton collisions use the whole energy of the particles, very nice for precise measurement

Lepton colliders

- So far only e^-+e^+ colliders have been built
- Electron and positron are light particles and the maximum energy of a circular collider is limited by the emission of synchrotron radiation (SR power$\propto E^4$)
- At LEP-II the energy lost per turn was almost 3% of the total (~100 GeV)
- Muon colliders would allow far higher energies ($M\mu^\pm/Me^\pm \approx 200$)

Hadron colliders

- Energy limited by the magnetic field
- In LHC the B field at 7 TeV is of the order of 8 Tesla (SC magnets) (27 km circumference)
- Difficult to develop SC magnets with field much higher that this ...
- Need very large rings (VLHC, SSC, Eloisatron)

Rate - Luminosity

- The rate of collisions is given by the luminosity
- The luminosity is defined as

$$L = \frac{\dot{N}_i}{\sigma_i}$$

and can also be derived from the beam parameters

$$L = \frac{N_{b1} N_{b2} f_{rev} k_b}{2\pi\sqrt{(\sigma_{x1}^2+\sigma_{x2}^2)(\sigma_{y1}^2+\sigma_{y2}^2)}} \cdot \exp\left[-\frac{(\bar{x}_1-\bar{x}_2)^2}{2(\sigma_{x1}^2+\sigma_{x2}^2)} - \frac{(\bar{y}_1-\bar{y}_2)^2}{2(\sigma_{y1}^2+\sigma_{y2}^2)}\right]$$

$L_{LHC} = 10^{34}$ $L_{TEVATRON} = 10^{32}$ $L_{LEP} = 10^{32}$ [Hz/cm^2]

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Beams current

L RON=10^{32} L_{LEP}= 10^{32} [Hz/cm^2]

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L_{LHC}= **Beams size** ON=10^{32} L_{LEP}= 10^{32} [Hz/cm^2]

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$L_{LHC} = 10^{34}$ $L_{TEVATRON} = 10^{32}$ L_{L}]

Beams overlap

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$L_{LHC}= 10^{34}$ $L_{TEVATRON}=10^{32}$ $L_{LEP}= 10^{32}$ [Hz/cm^2]

Beam current

- Beam current should be as high as possible
- Luminosity proportional to the product of the two colliding bunches
  - If bunches are equal $L \propto I_{bunch}^2$
- Luminosity proportional to the number of bunches
  - For a given maximum current better to keep the number of bunches as low as possible (LEP-II had only 4-on-4 bunches)

Beam size

- Beam size should be as small as possible
- Beam size given by transverse emittance and beta-function at the IP
- Reduce and/or preserve emittance
- Create small-beta insertion at the IP

Small size, high current and high energy

⇓

potential for destruction

Beam overlap

- The two beams must be precisely overlapped
- Any offset between the beams will reduce the luminosity
- Beams are usually very small at the IP (LEP-II few microns, LHC ~30μm)
- No direct position measurement at the IP possible (inside experiment!)

Collider diagnostics

- Like any other accelerator a collider requires the monitoring of various parameters
- The use of diagnostics can be divided in three families
  - Initial phase of commissioning
  - Injection and acceleration of the beams
  - Optimization of the luminosity
  - Protection of the machine

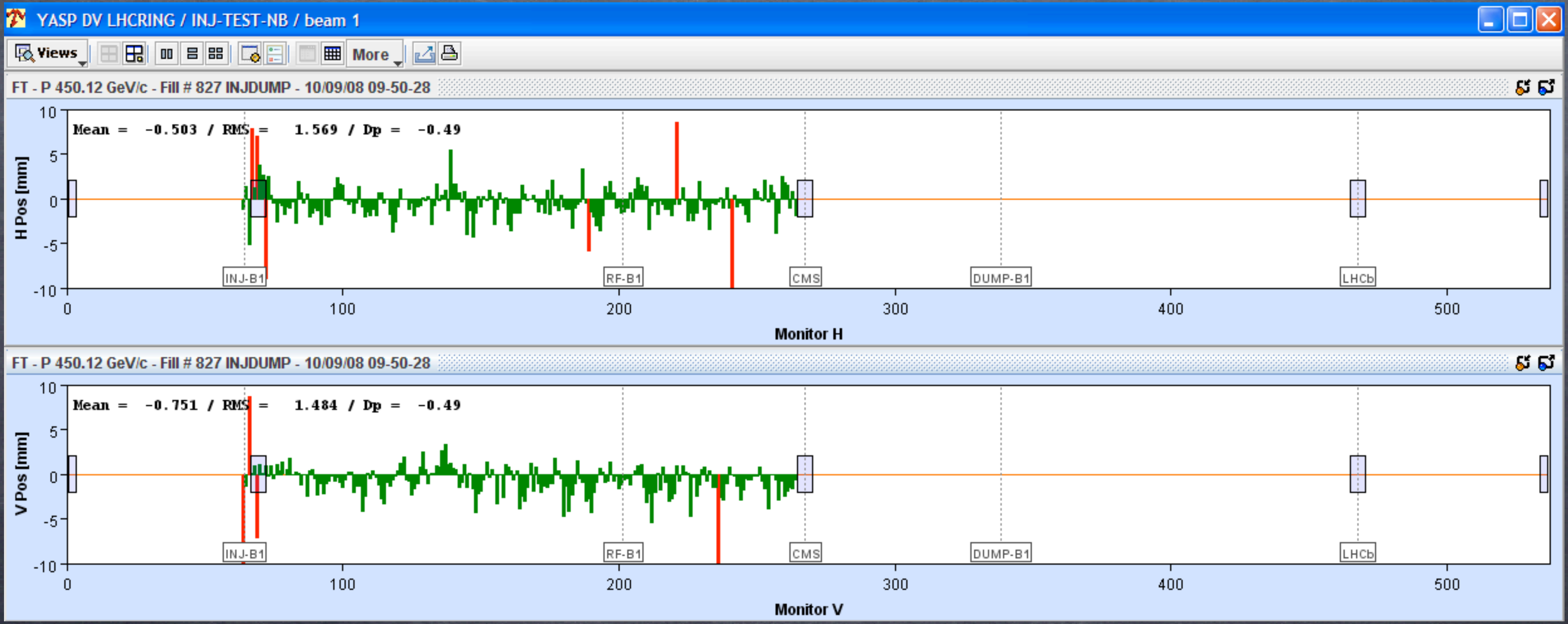
Commissioning

- Need to provide "eyes" for the operators
  - Beam imaging screens
  - Beam position monitors
  - Beam current monitors
  - Beam loss monitors
  - Tune meter

Threading

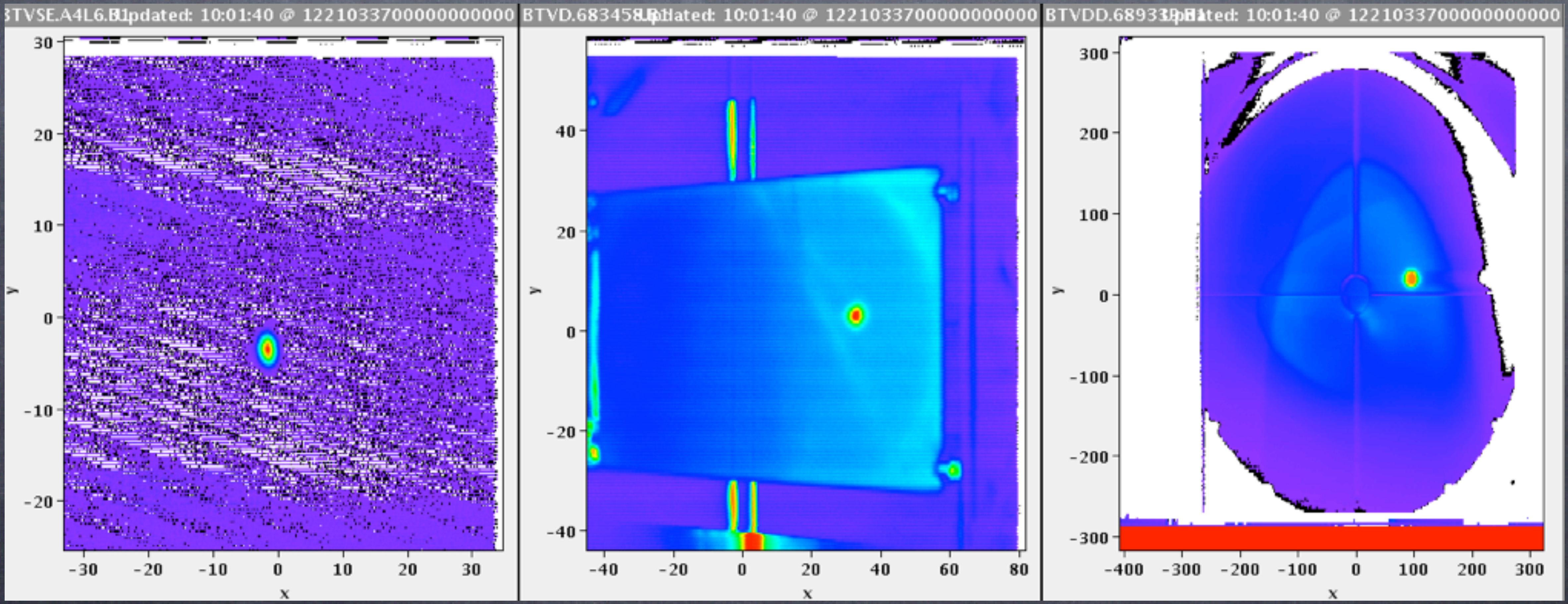
- The very first phase consists of getting the beam around the ring, this operation is called threading
- For this operators use BPMs in single passage acquisition (trajectory) and imaging screens (scintillators or OTR)
- It is important to have self-triggering systems since the timing is not precise yet!

LHC beam 1 threading



LHC beam 1 threading

LHC beam 1 threading



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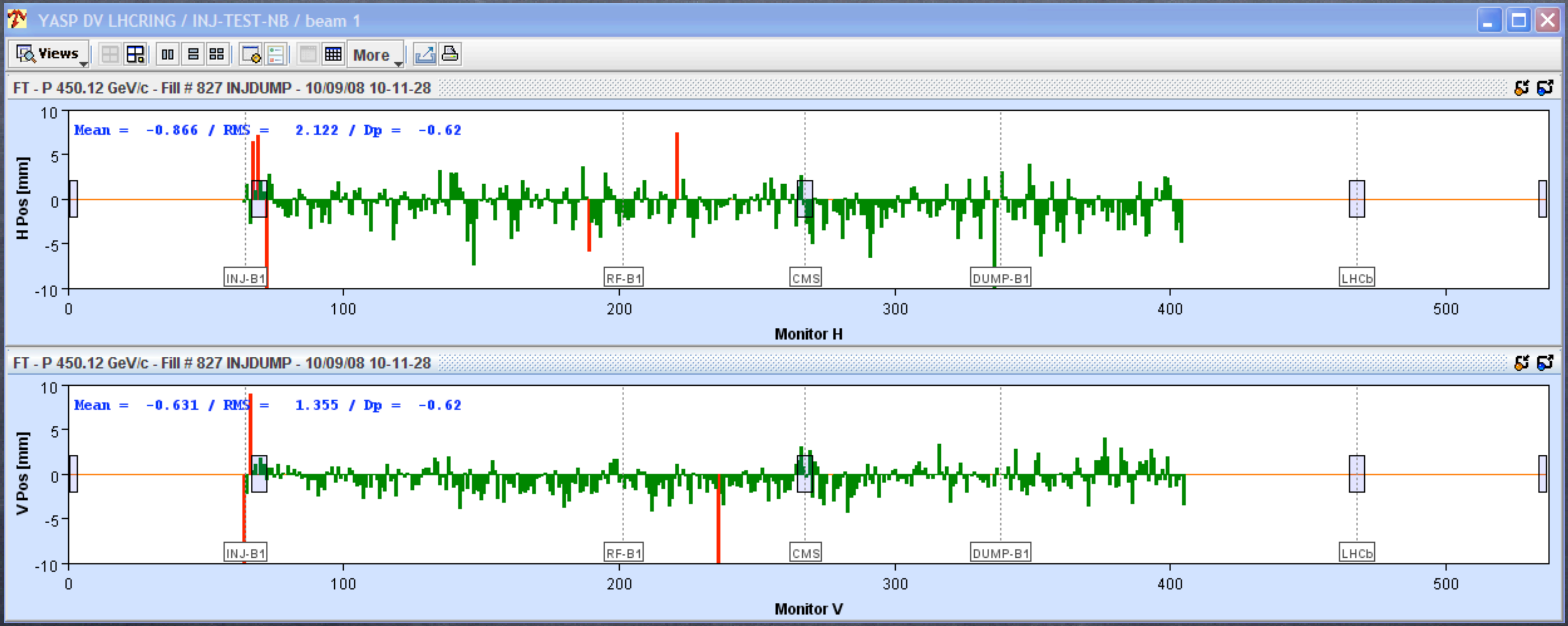

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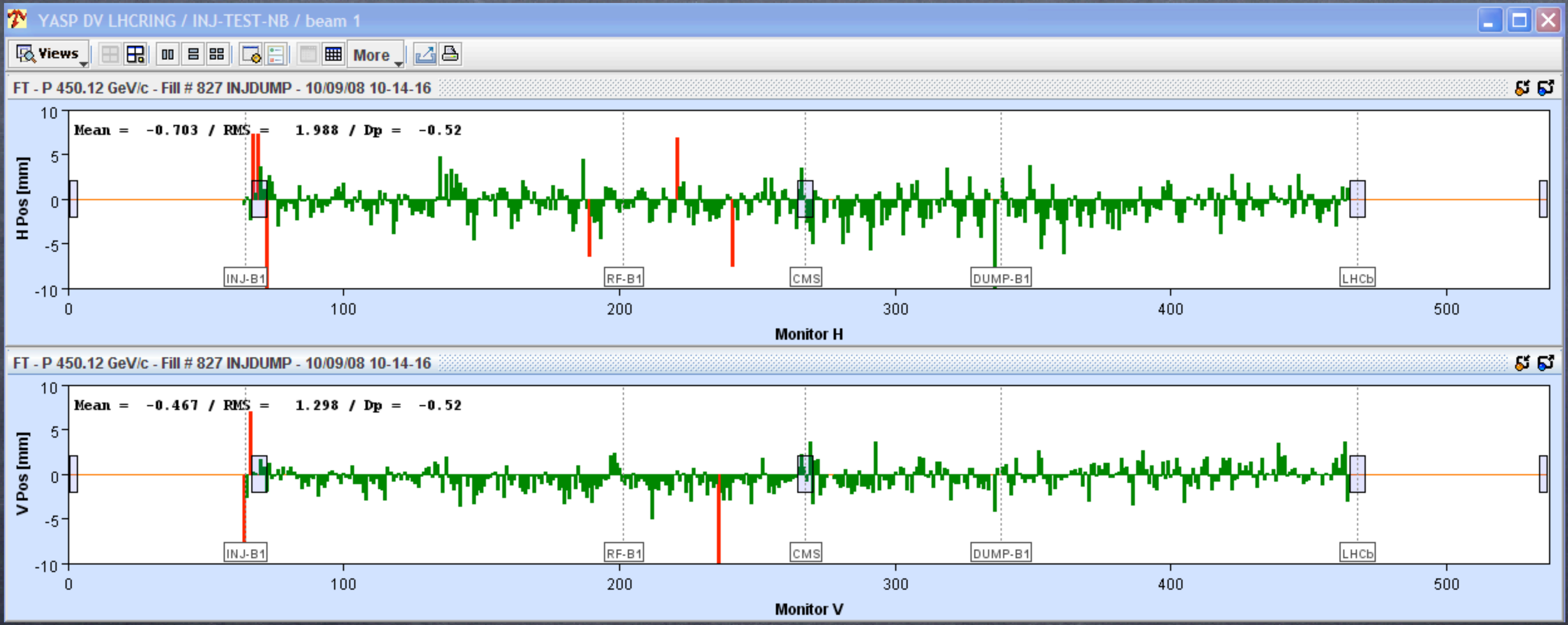
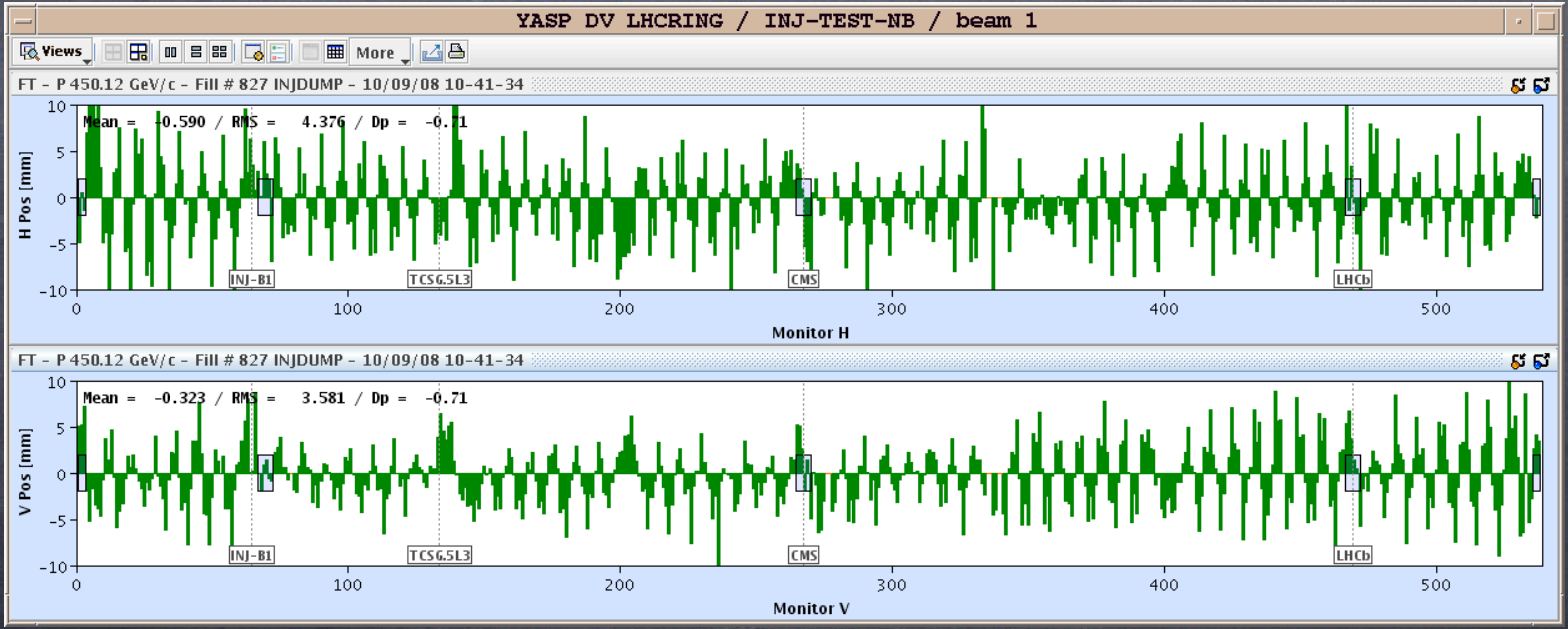


LHC beam 1 threading



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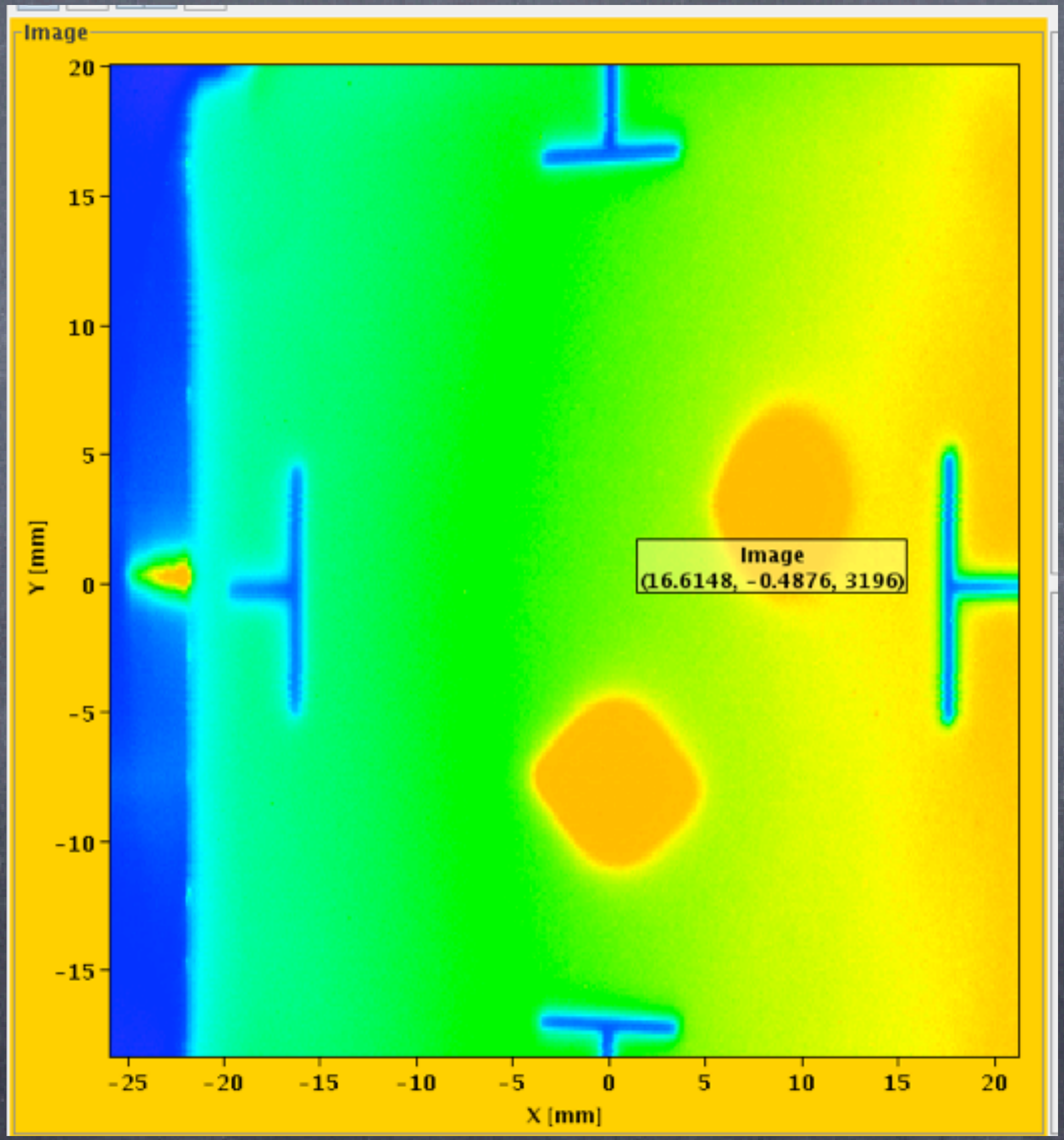

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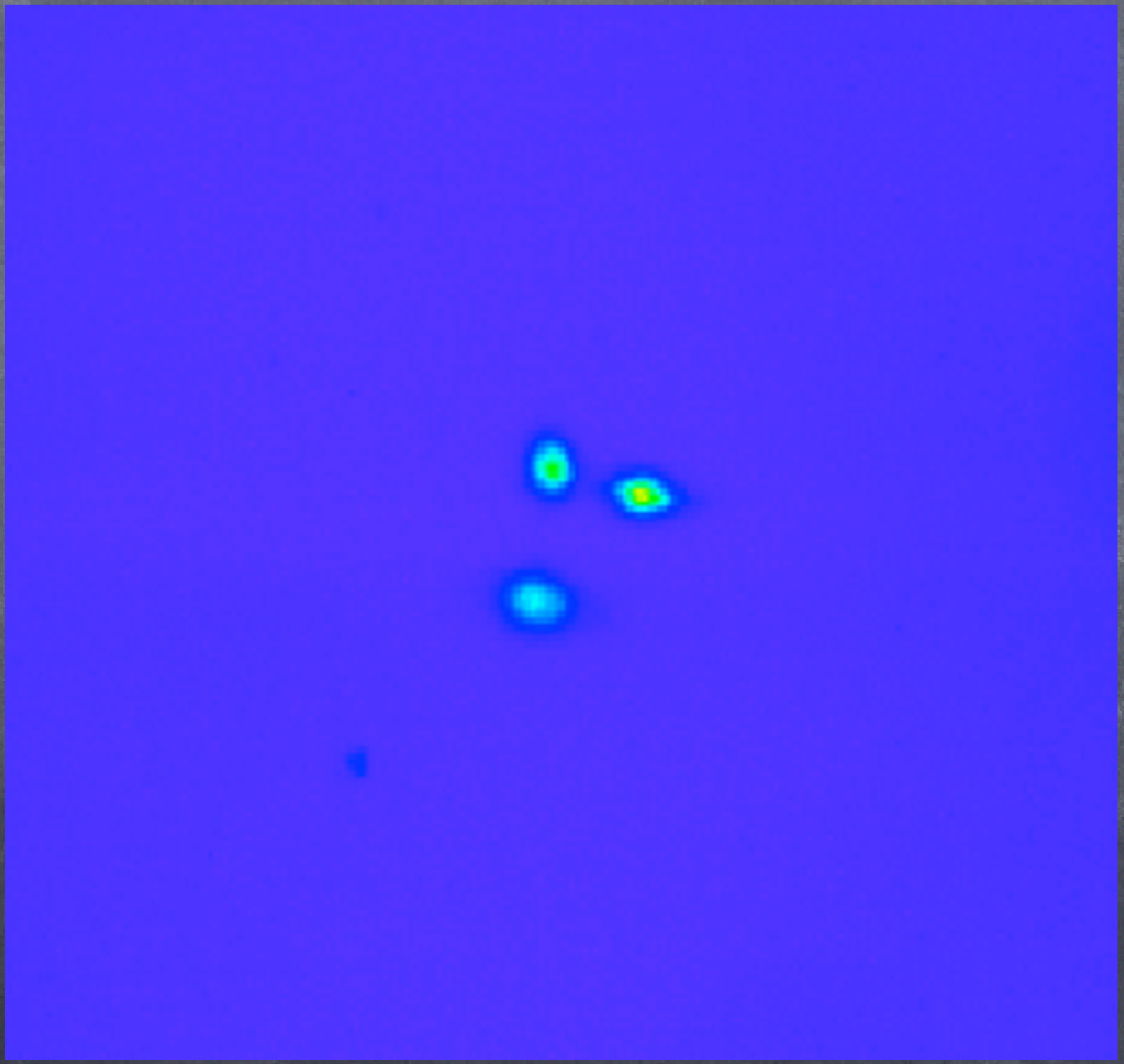


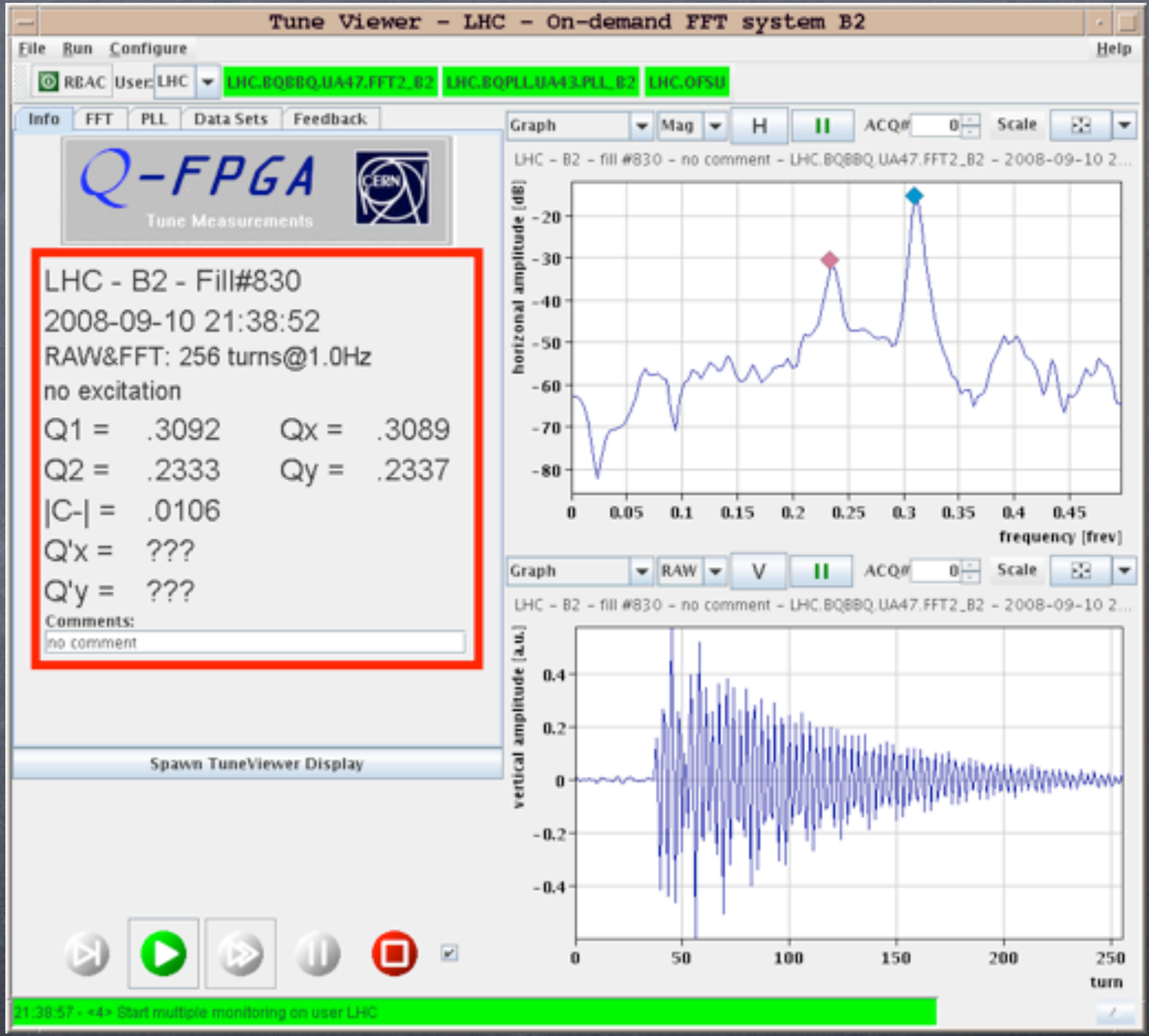
Few turns

- After the beam has made the first turn operators try to get several turns
- This stage is still mainly based on "feeling", but a multi-turn trajectory BPM system comes very handy
- As soon as the beam makes a few hundred turns it is possible to use the tune-meter

Tune

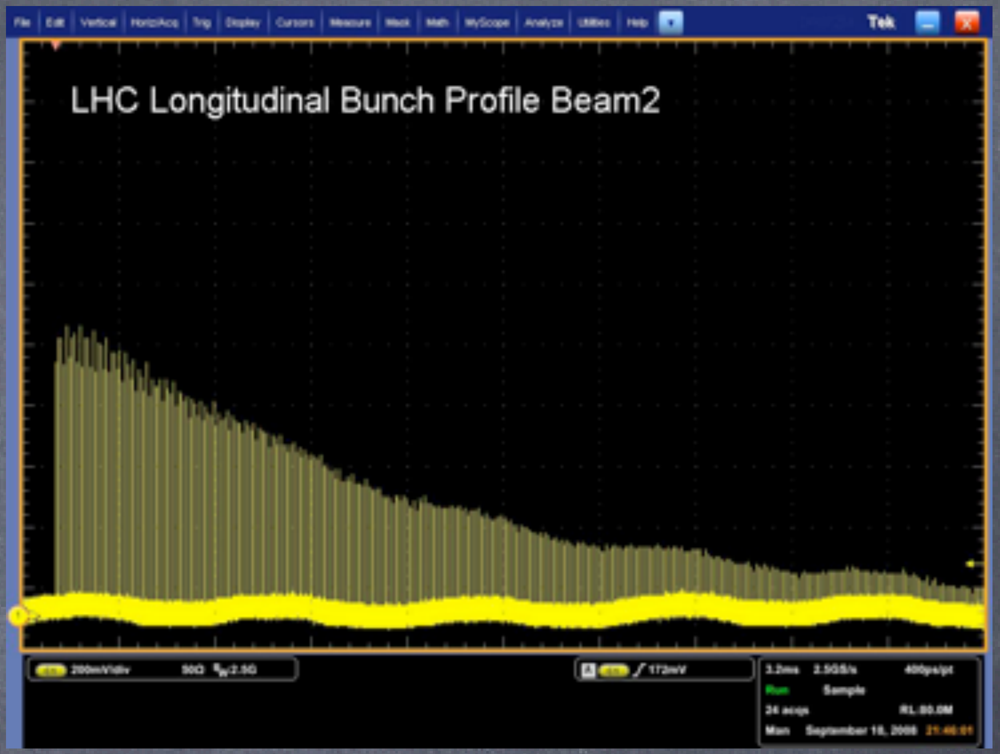
The tune-meter computes the frequency spectrum of the turn-by-turn reading of a dedicated BPM (FFT)

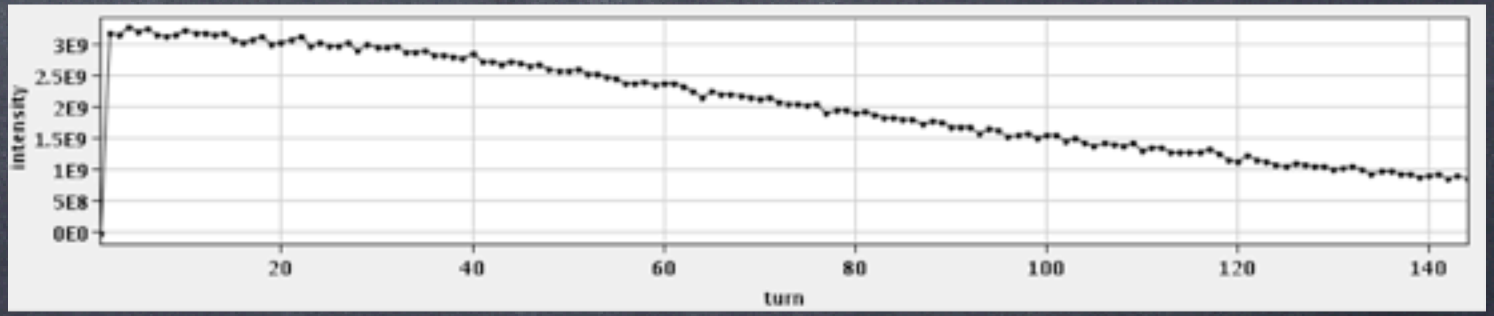
This gives the fractional part of the tune (0-0.5)



Current measurement

- Another important measurement once the beam begins to circulate is the decay of the beam current
- This is done with fast current transformers and wall current monitors





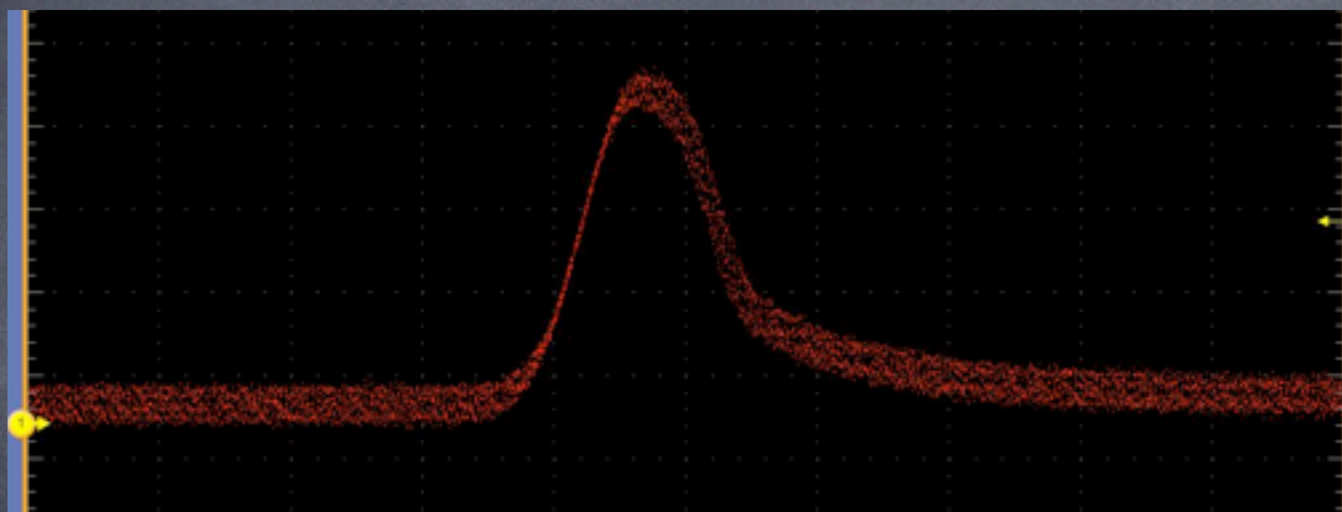
Beam loss monitors

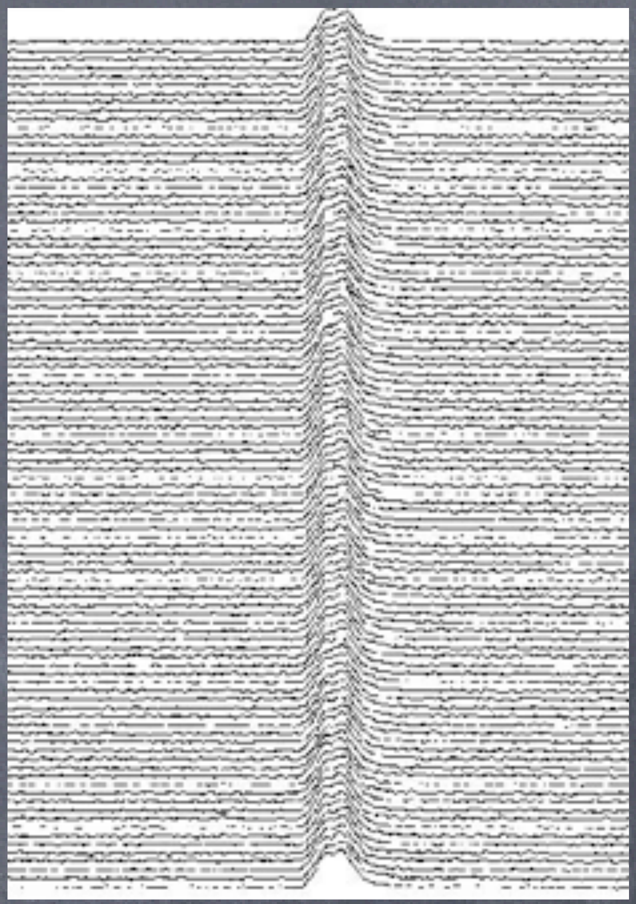
- In case of an aperture restriction (due to a physical restriction of the beam pipe or due to a wrong cabling of focusing elements) particles get lost
- A fine grain beam loss system can be very useful in identifying the location of the restriction
- The beam loss system is also used to measure the aperture around the machine by creating ad-hoc bumps until limit reached

Circulating beam

- After a few more adjustments of tune and orbit the beam starts to circulate (lifetime of minutes at least)
- Now most of the instrumentation can be used

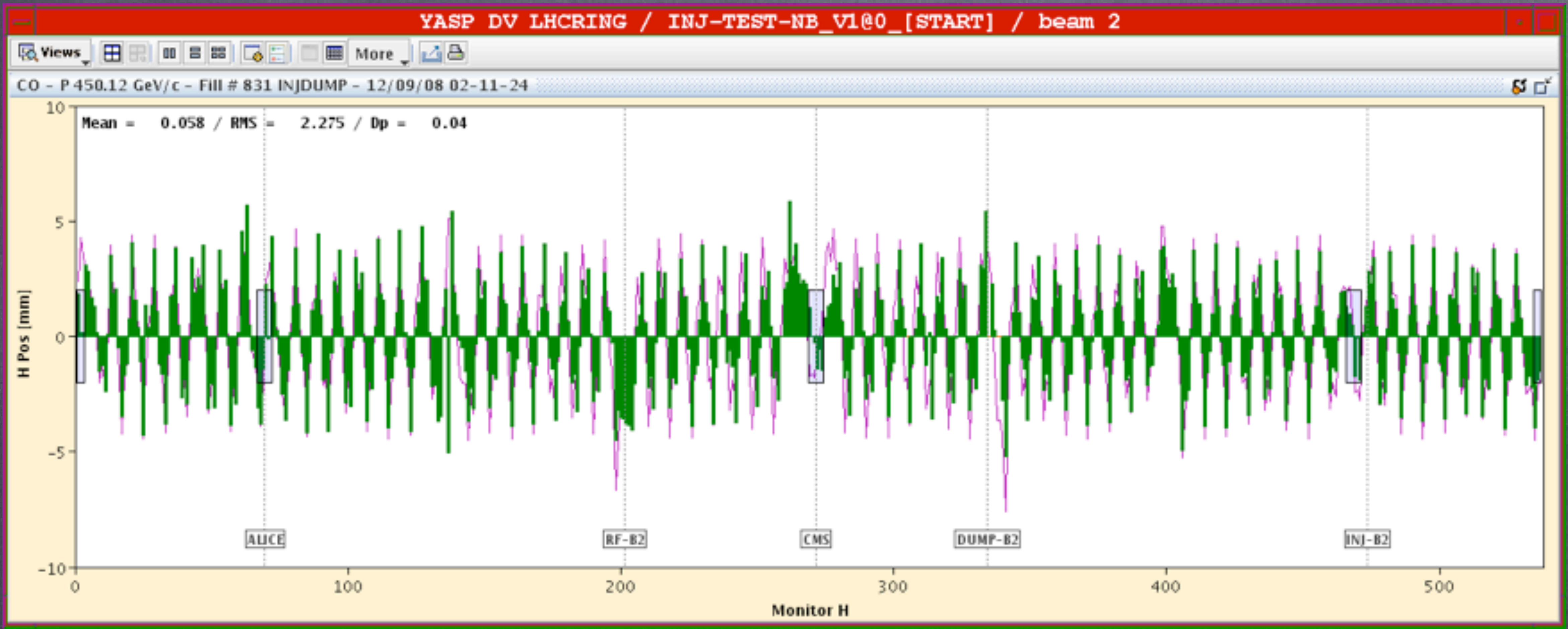
RF capture





- Need to synchronize the RF with the incoming beam
- The wall current monitor is used in turn-by-turn mode

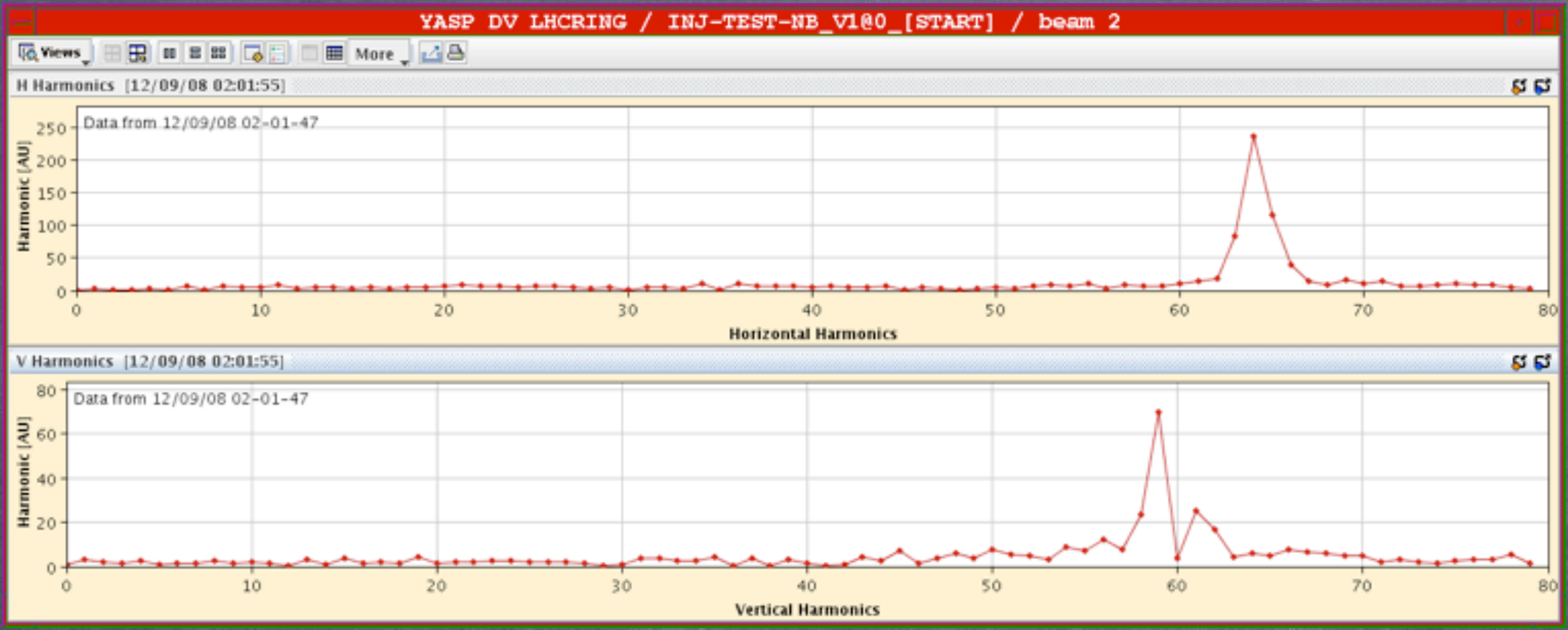
BPM - Orbit mode



Each BPM averaged over a certain time (e.g. 1s)

Important to have many BPMs! ($\Delta\varphi \leq 90°$)

Integer part of tune



From analysis of the orbit the integer part of the tune is calculated

Response matrix

- The effect of each corrector is measured by applying a kick and measuring the orbit distortion it produces
- The orbit system (BPM) is needed
- Long process (many correctors), better if automatic
- BPM orbit mode must be very sensitive (very faint beam used for safety reasons)

Beam modes

- A collider requires many beam modes, in particular
  - Injection, usually many injection cycles that can take many minutes
  - Acceleration, parameters change rapidly and by large amounts
  - Squeeze, beta functions are reduced dramatically at the IP distorting the orbit and the optics
  - Stable beams, coasting for many hours of physics

Impact of beam modes

- Instruments must be able to cope with a large range of beam currents and filling patterns
- Parameters can change very rapidly requiring automatic procedures to change the settings in the diagnostics
- Real time data and continuous acquisition are needed for the feedback systems and for optimizing the dynamic phases (ramp, squeeze etc.)

Beam optimization

- After the beam is circulating it is time to start with “precision” measurements
  - Optics (beta-beat)
  - Orbit
  - Tune and chromaticity
  - Lifetime

Beta beat

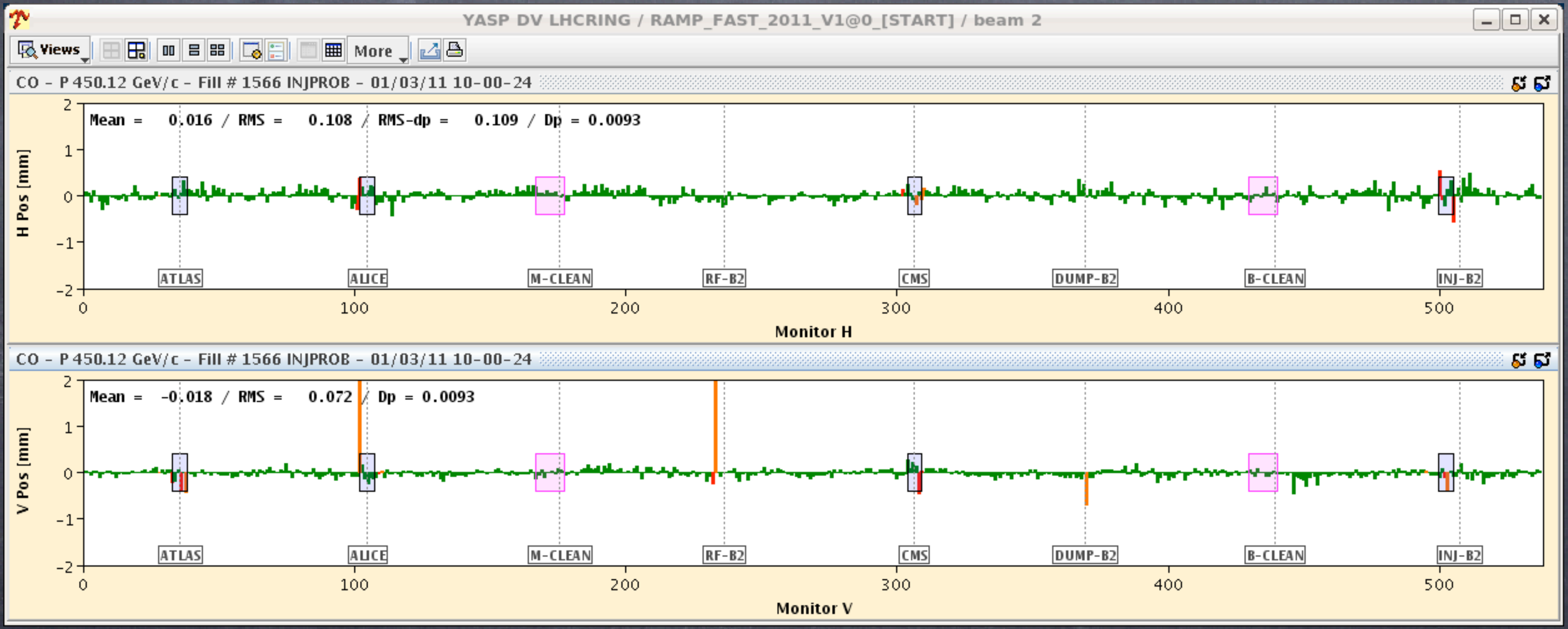
- Need to measure the "real" optics of the machine w.r.t. the model (K errors)
- Kick the beam (better with an AC dipole)
- Measure the phase advance of oscillations using turn-by-turn BPM mode
- Fit the real beta function using the measured phase advance values

$$\Delta\phi \propto \int_{x_0}^{x_1} \frac{1}{\beta}$$

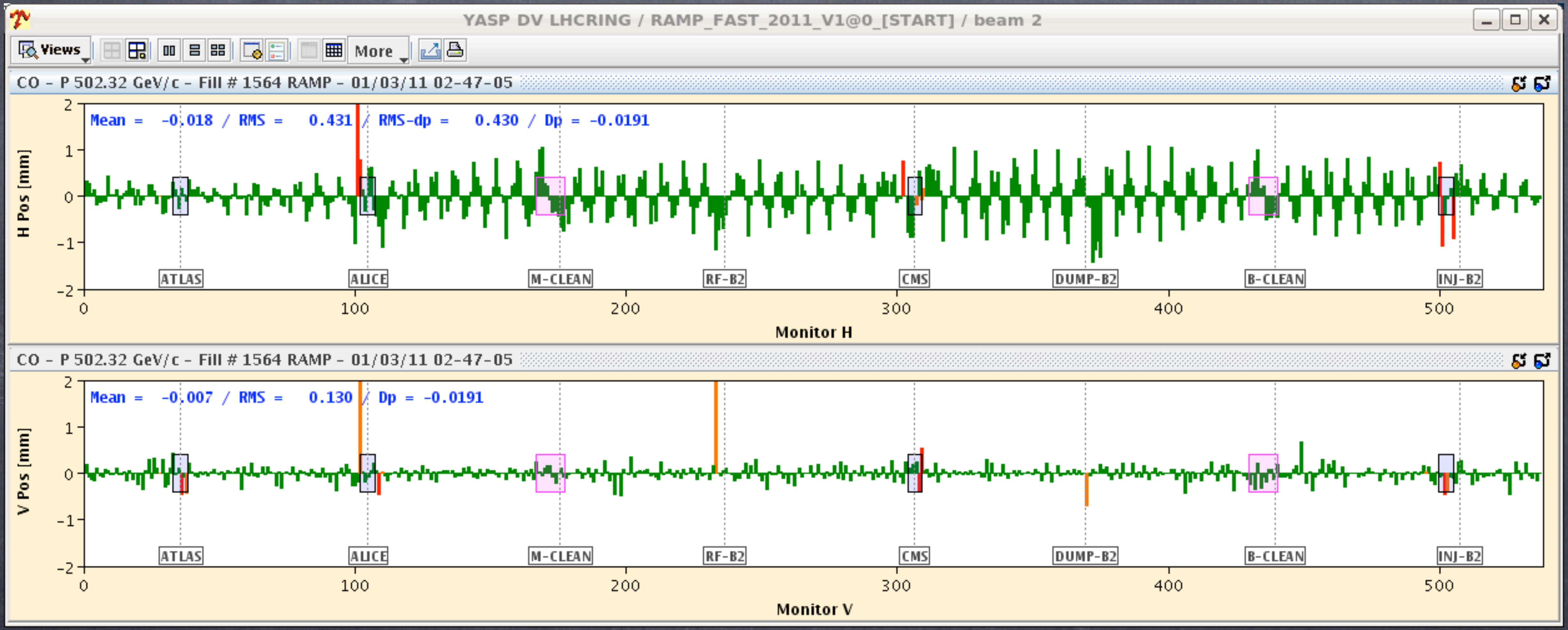
Orbit

- Errors in the magnetic field and in the alignment of the components leads to distortion of the closed orbit
- This effect reduces the aperture of the machine (maximum beam envelope) and amplifies non linear effects as the higher order field components increase off-axis
- Non linear effects lead to emittance growth and reduce the dynamic aperture

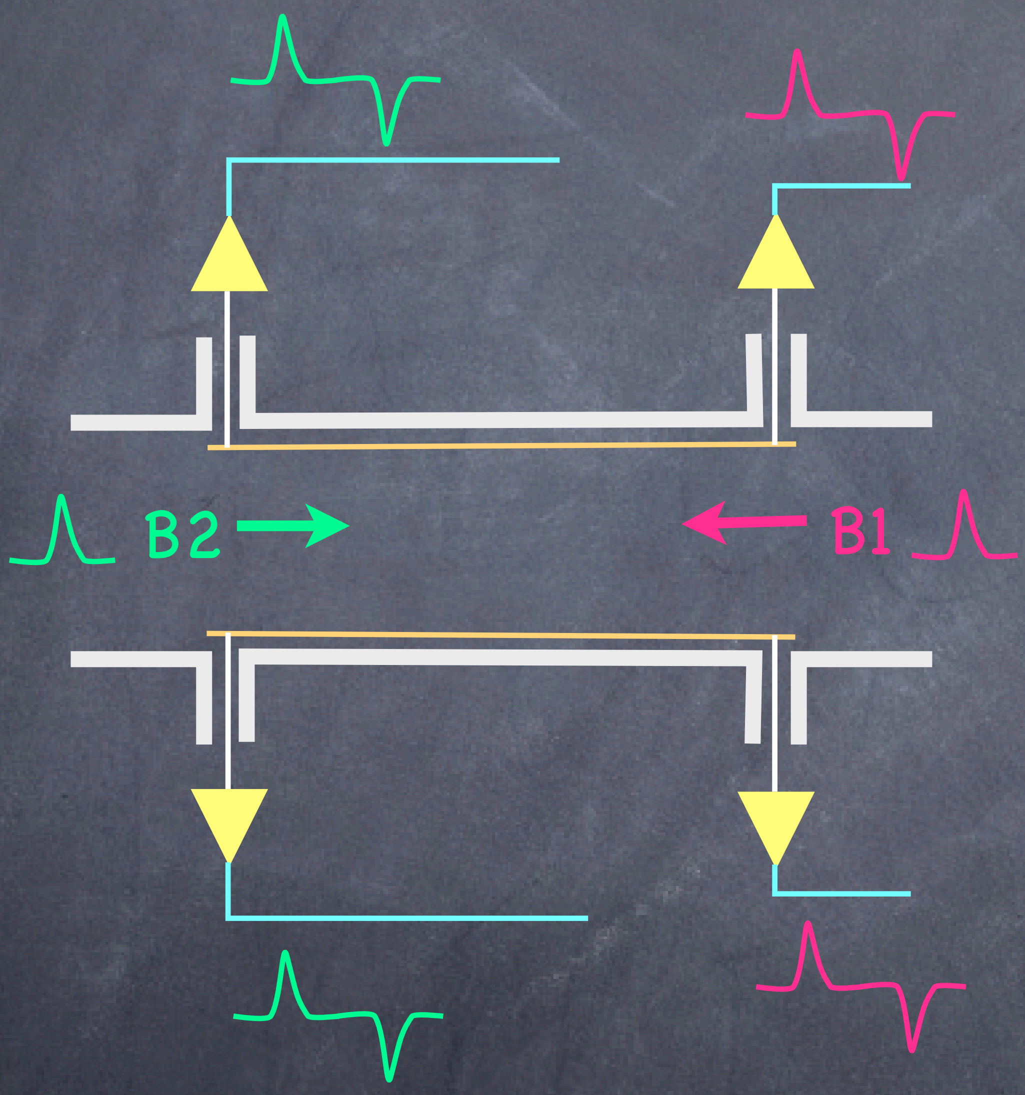
Orbit example



Orbit example

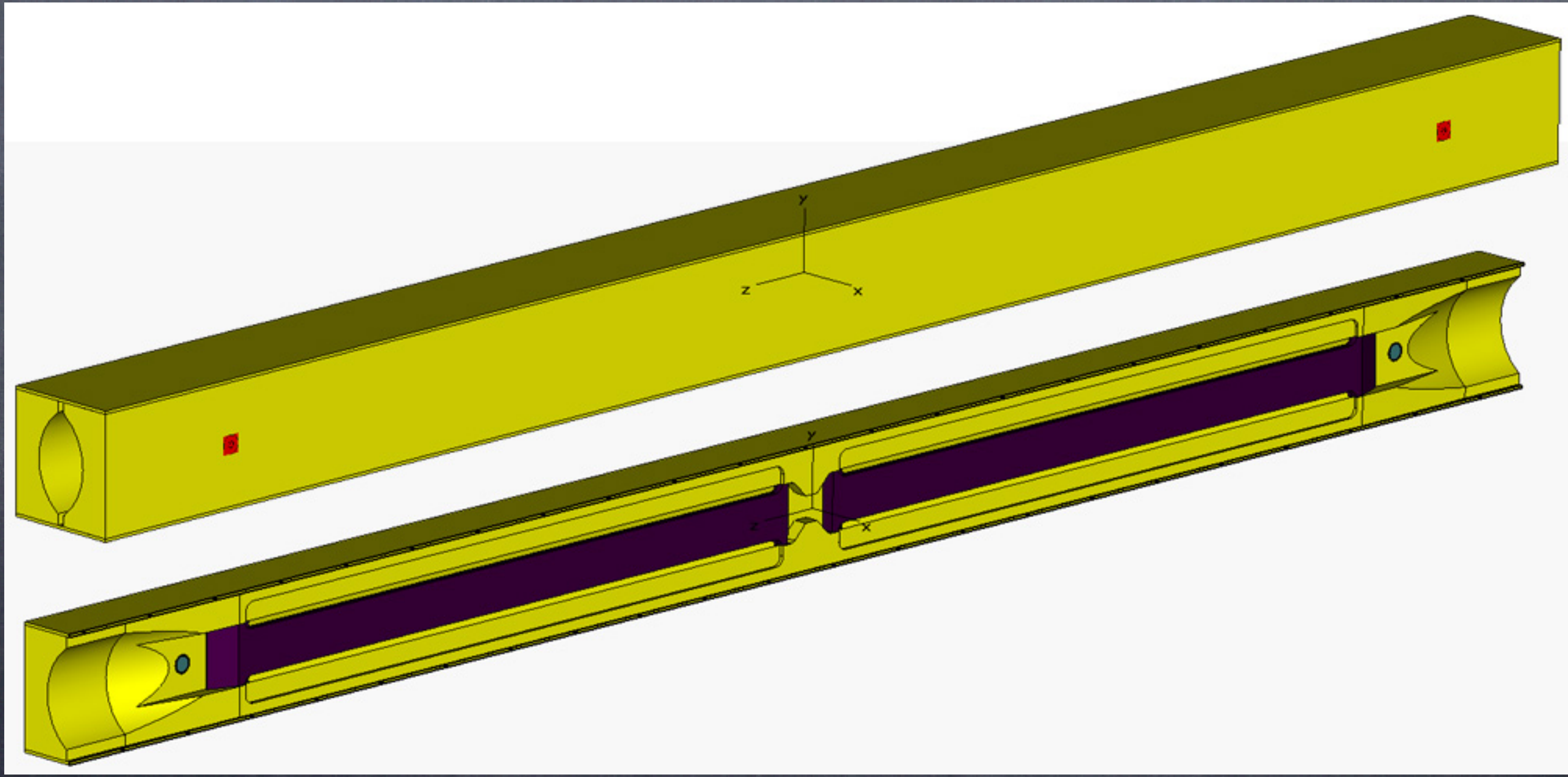


Directive strip lines



- Bunch spacing too small to distinguish the two beams around the interaction region (few ns)
- Use directive strip lines

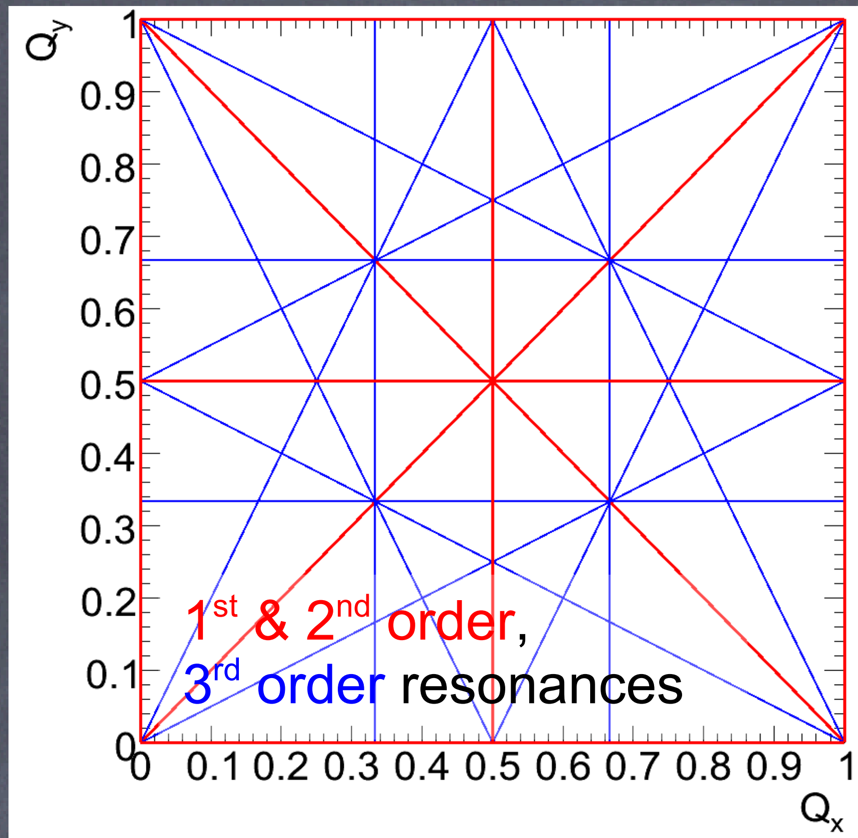
BPM embedded in collimators (LHC)



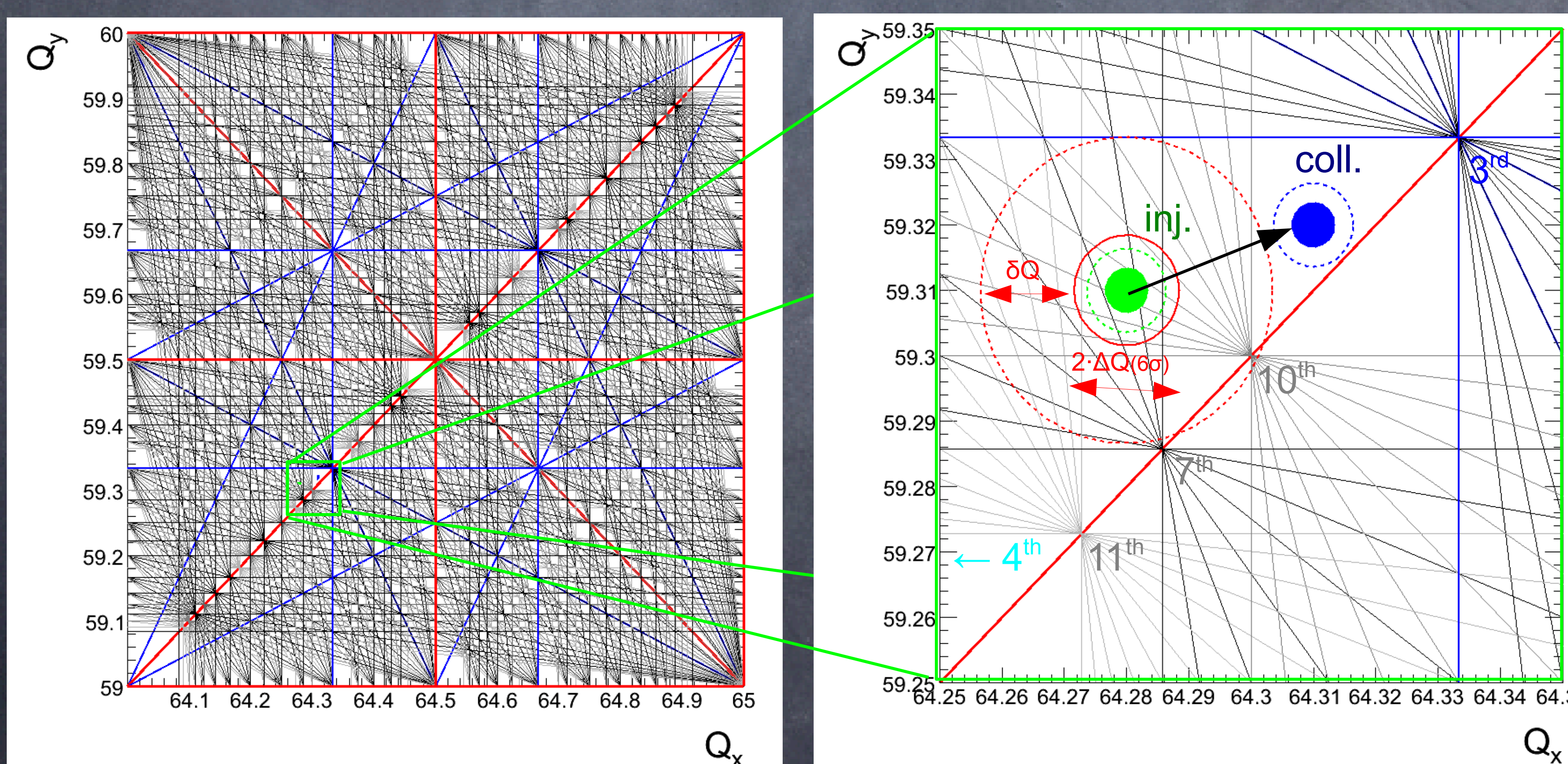
BPM embedded in collimators (LHC)

Tune and chromaticity

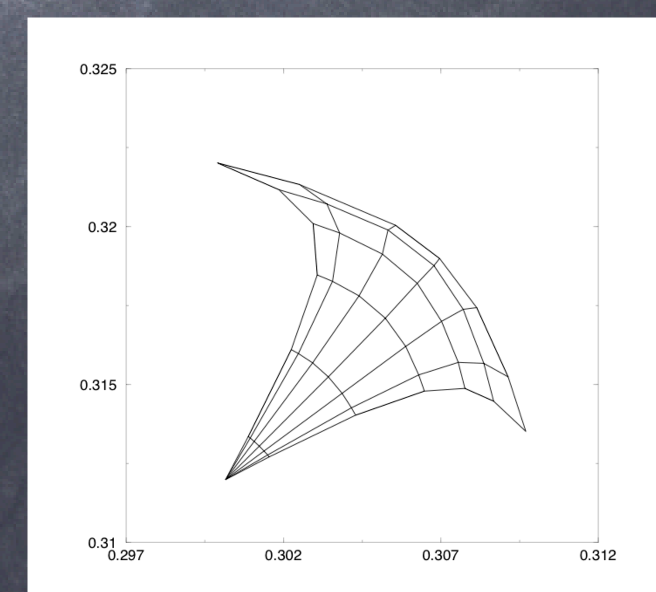
- Tune, chromaticity and coupling are key parameters for the lifetime of the beam
- Tune must be precisely set in order to avoid resonances → coupling must minimized
- Chromaticity must be minimized to reduce the tune footprint (slightly pos. for stability)
- A continuous tune monitoring helps a lot!
- For hadron machines this is not easy



- In hadron storage rings need to avoid up to 12th order !
- Very little space left
- Need tight control of tune $\Delta Q \leq 10^{-3}$

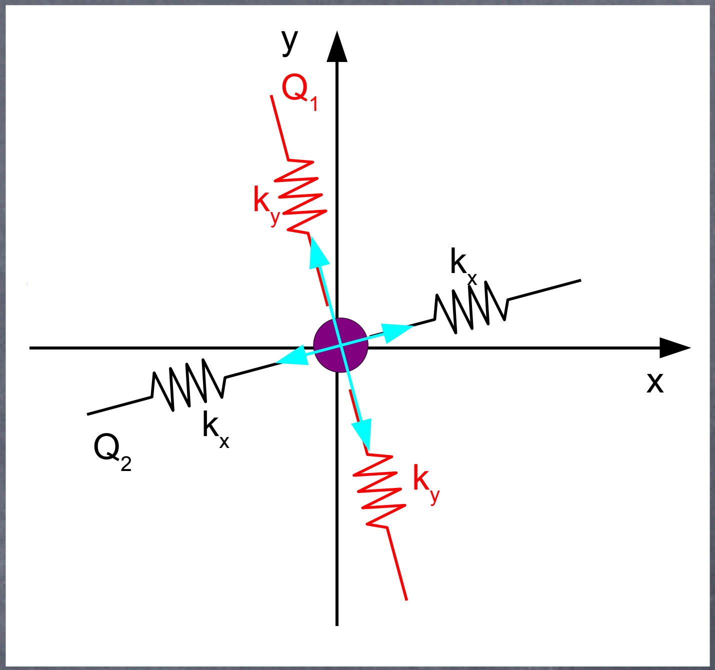


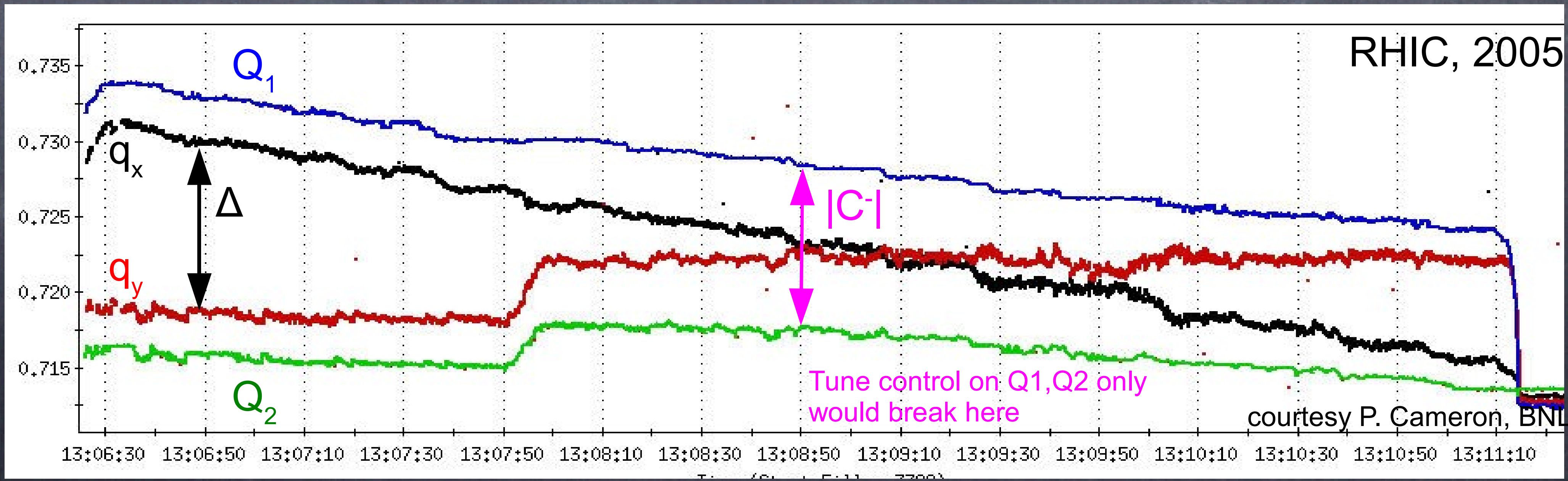
"beam-beam"



Coupling

- Solenoids or skew quads can couple the oscillations in the two transverse planes
- What the tune monitor measures are Q_1 and Q_2 !

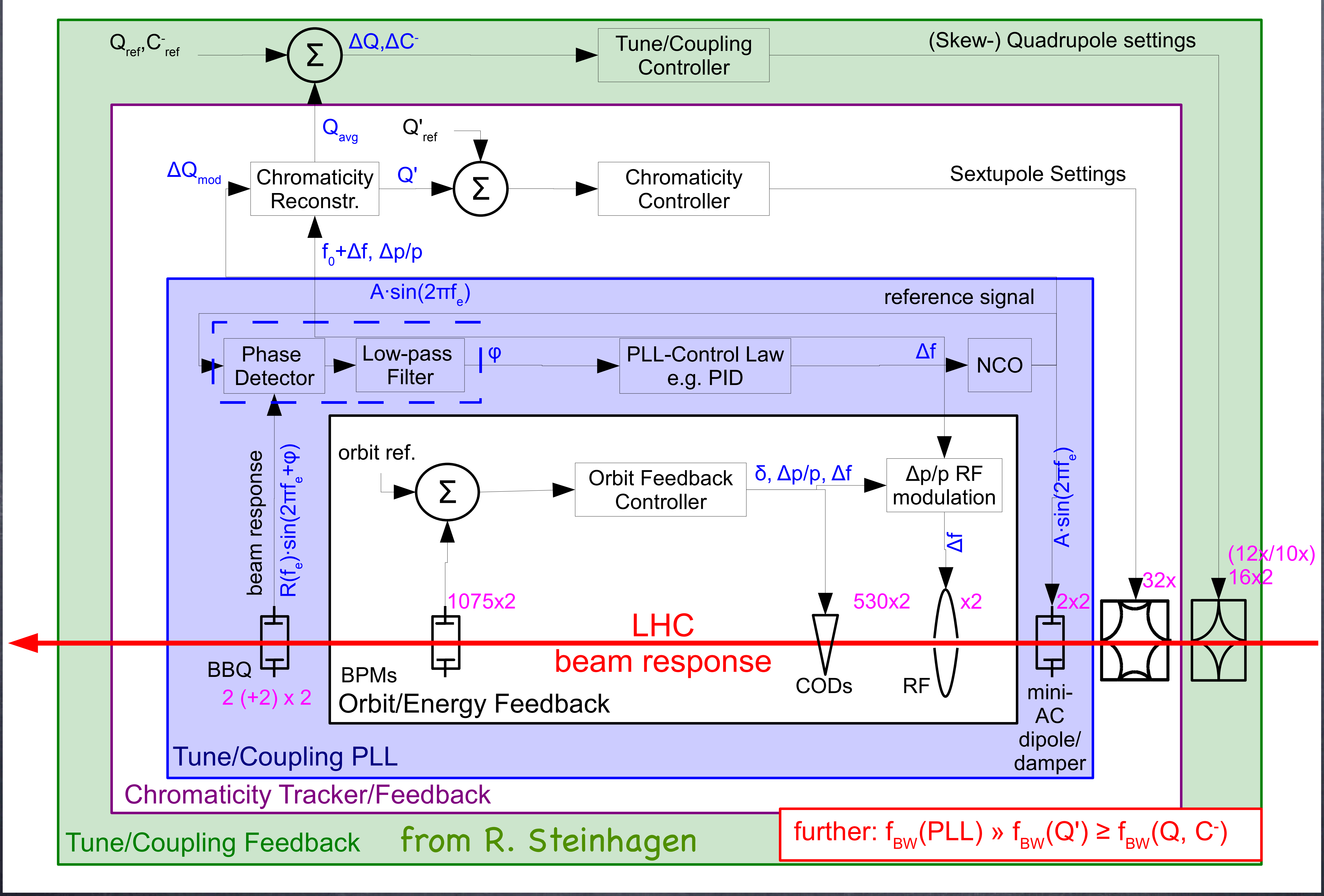




Feedbacks

- Orbit and tune need to be precisely controlled all the time
- Difficult for operators to correct the parameters in real time, especially during ramp, squeeze and other dynamic situations
- Need an automated system that controls these parameters

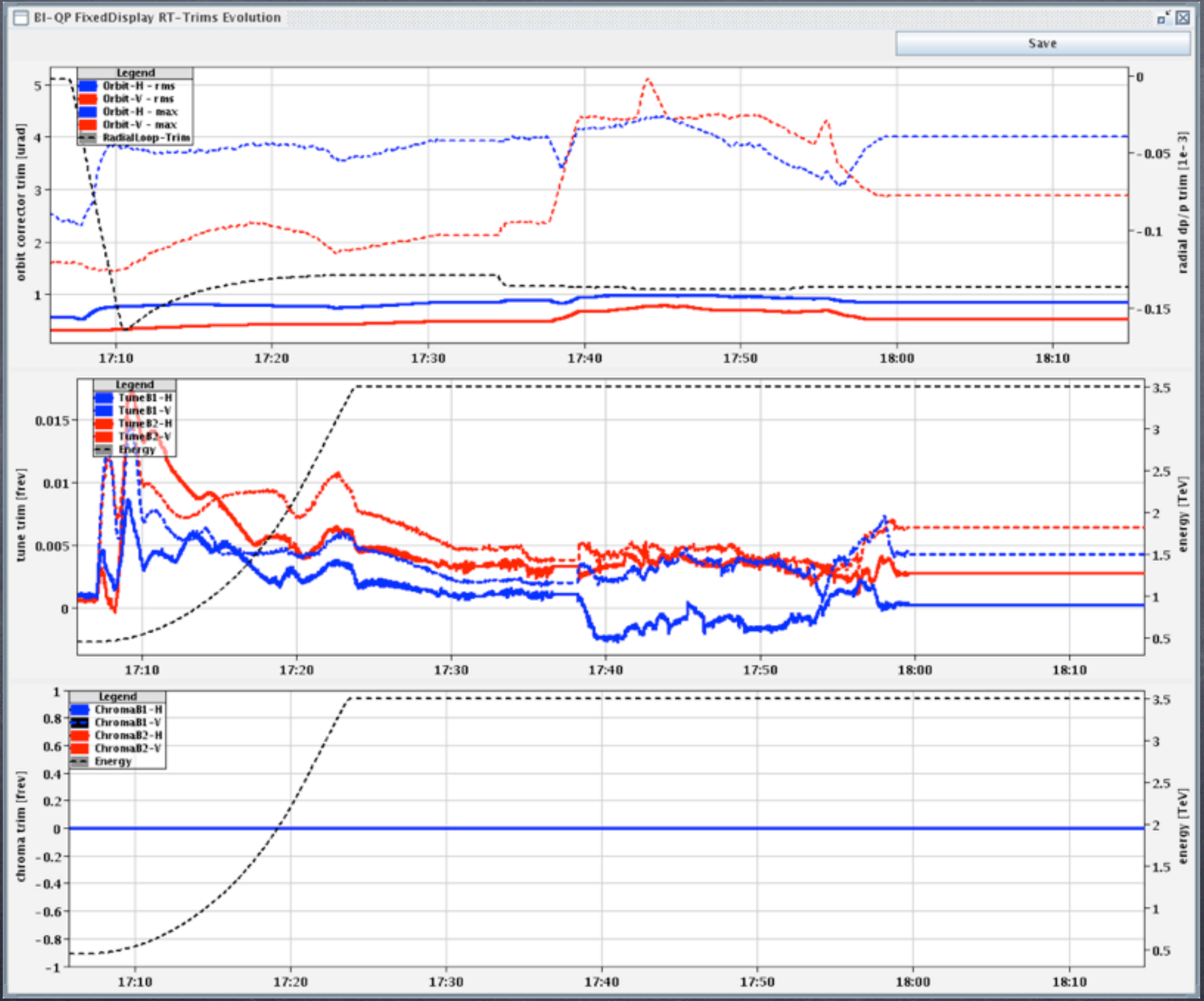
Feedback loops



from R. Steinhagen

further: $f_{BW}(PLL) \gg f_{BW}(Q') \geq f_{BW}(Q, C^-)$

Feedback trims



Emittance and life-time

- The rate of collisions depend on the emittance and beam current
- These parameters evolve during a physics fill (in LHC ~10 hours long)
  - Emittance growth
  - Current decay (beam lifetime)
- Both affect the "luminosity life-time"

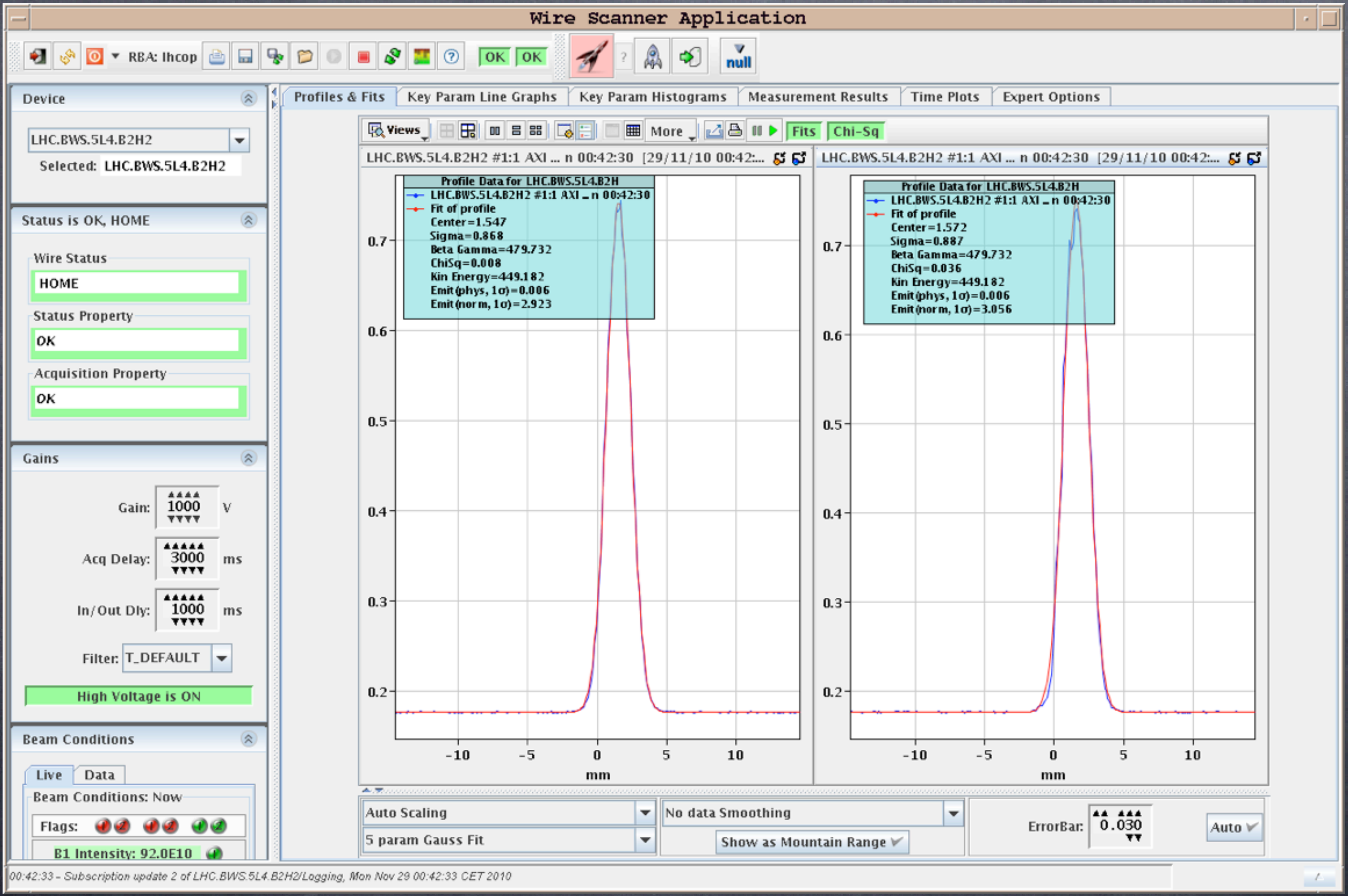
Emittance

- The beam emittance is inferred from profile measurements and/or from the Schottky spectrum
  - Wire scanners
  - Synchrotron light imaging
  - Ionization profile monitors
  - Diffraction radiation (never done)

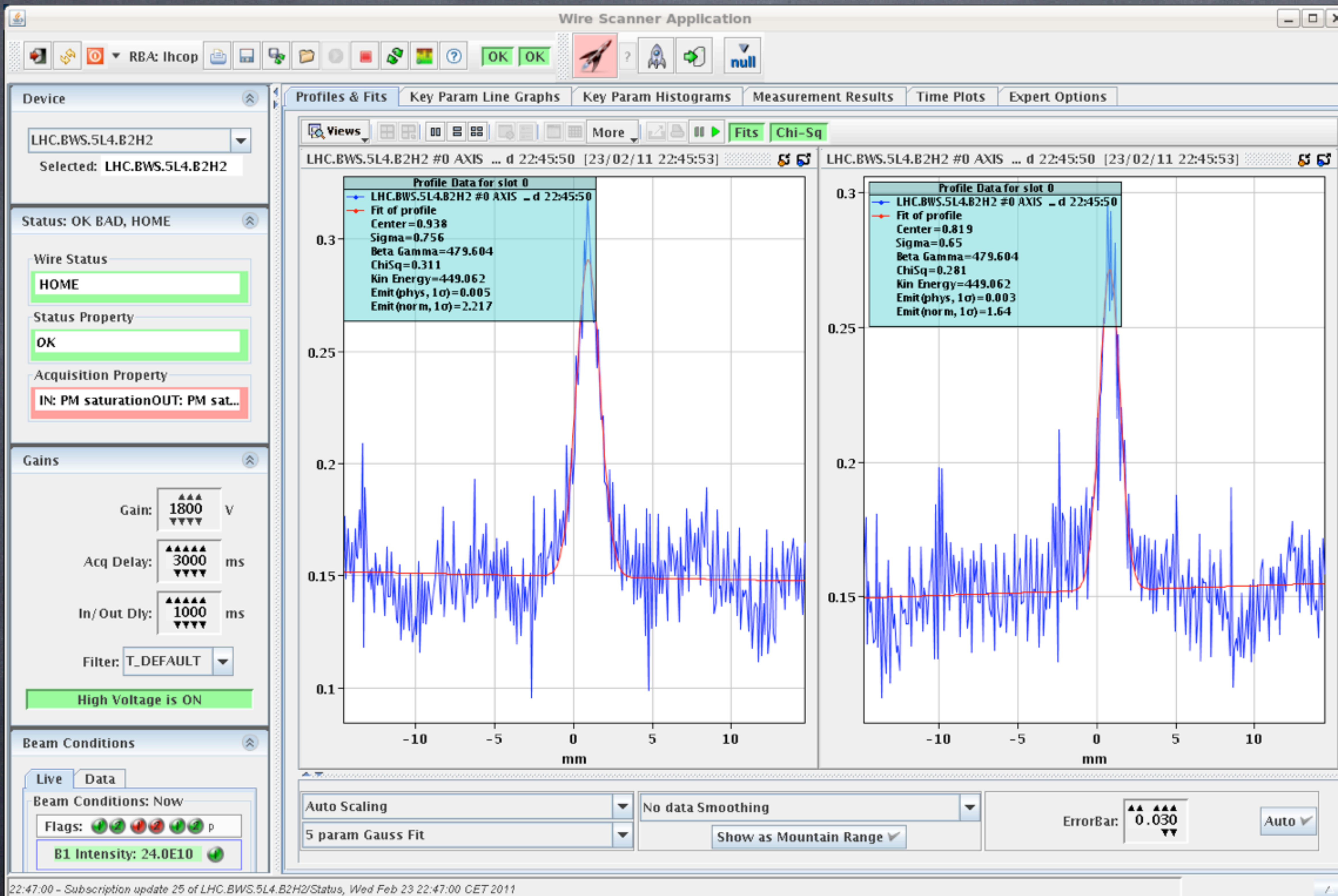
Wire scanner

- Usually the reference instrument because it has better controllable systematic errors
- Only provides a measurement on demand
- Perturbs the beam
- May not be usable in all conditions
- Not suited to follow the emittance evolution

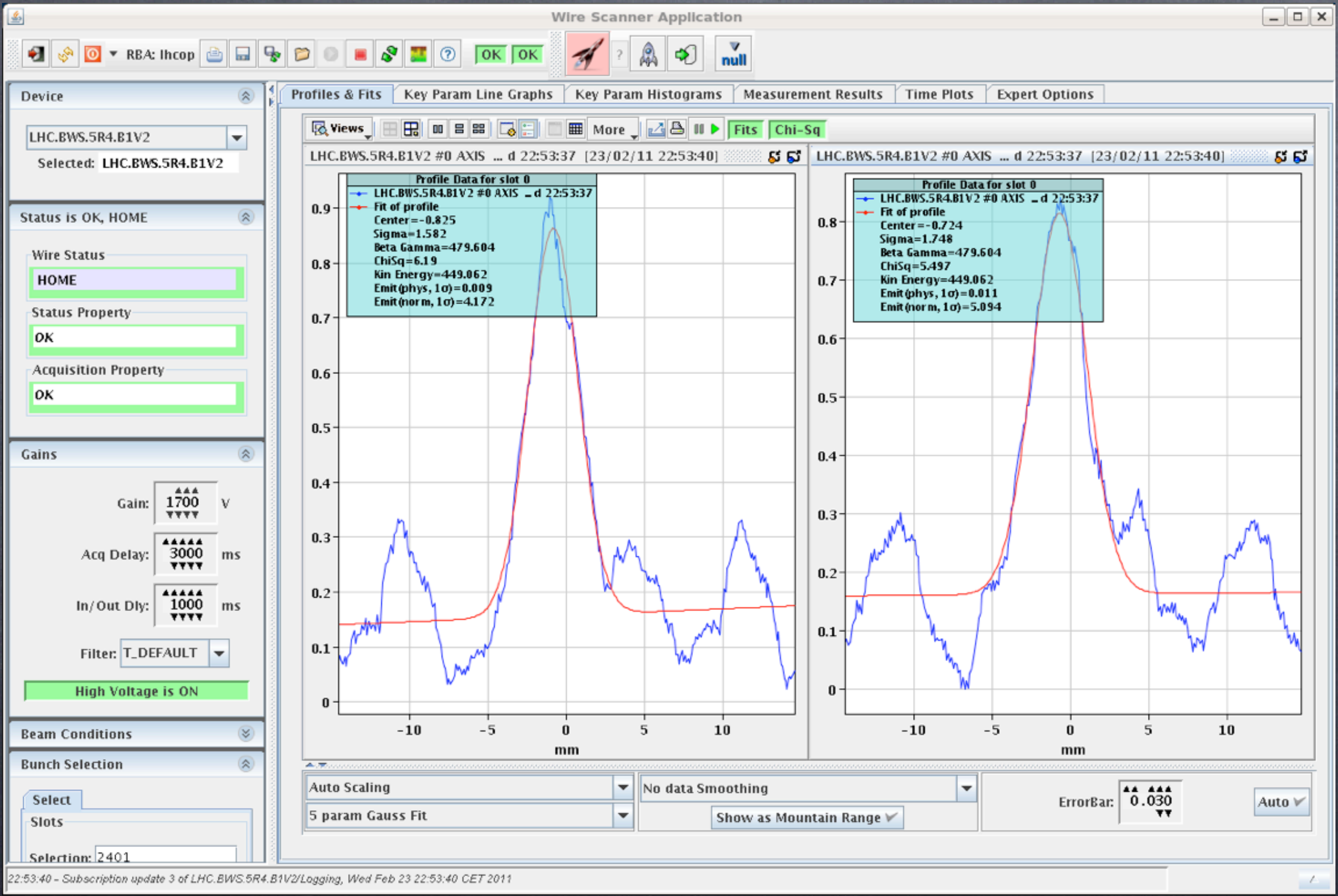
Wire scanner



Wire scanner

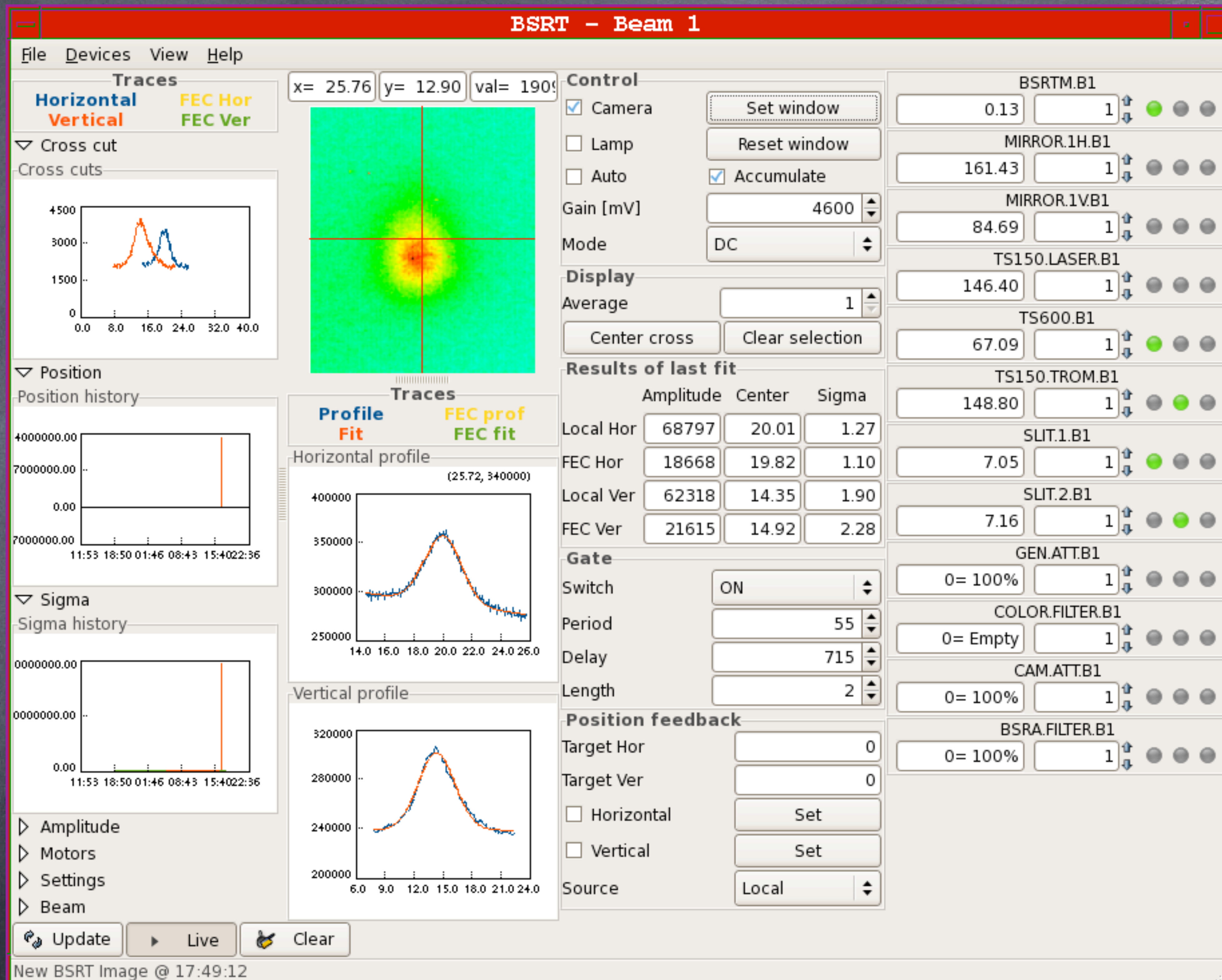


Wire scanner



Synchrotron light

- Provides continuous monitoring
- Can do bunch-by-bunch and t-by-t
- Only works with beams of large γ
- Suffers from diffraction limitations
- Complex optical system in the machine tunnel (remote adjustments)
- Absolute calibration not easy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FEC Ver 21615 14.92 2.28
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TS600.B1 67.09
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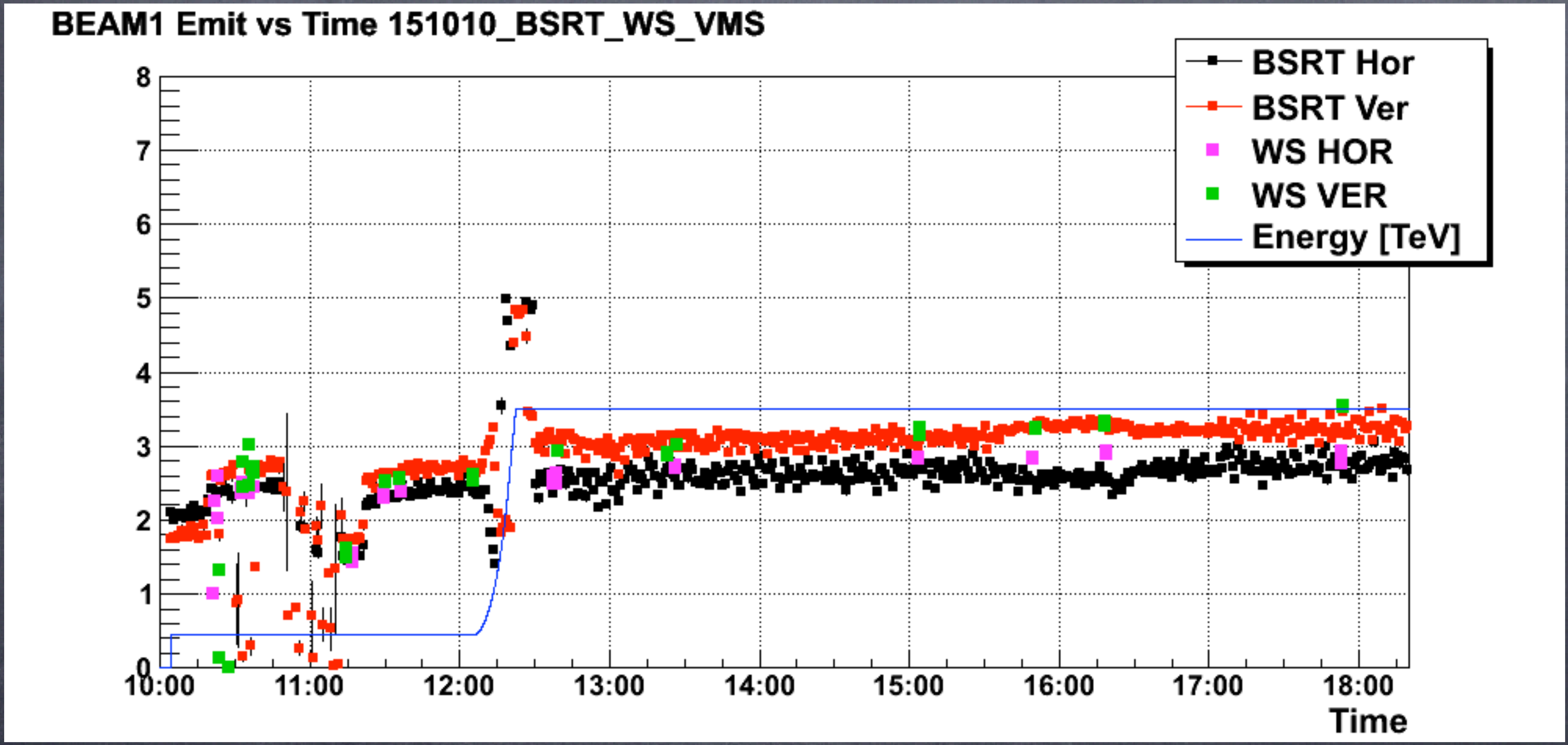
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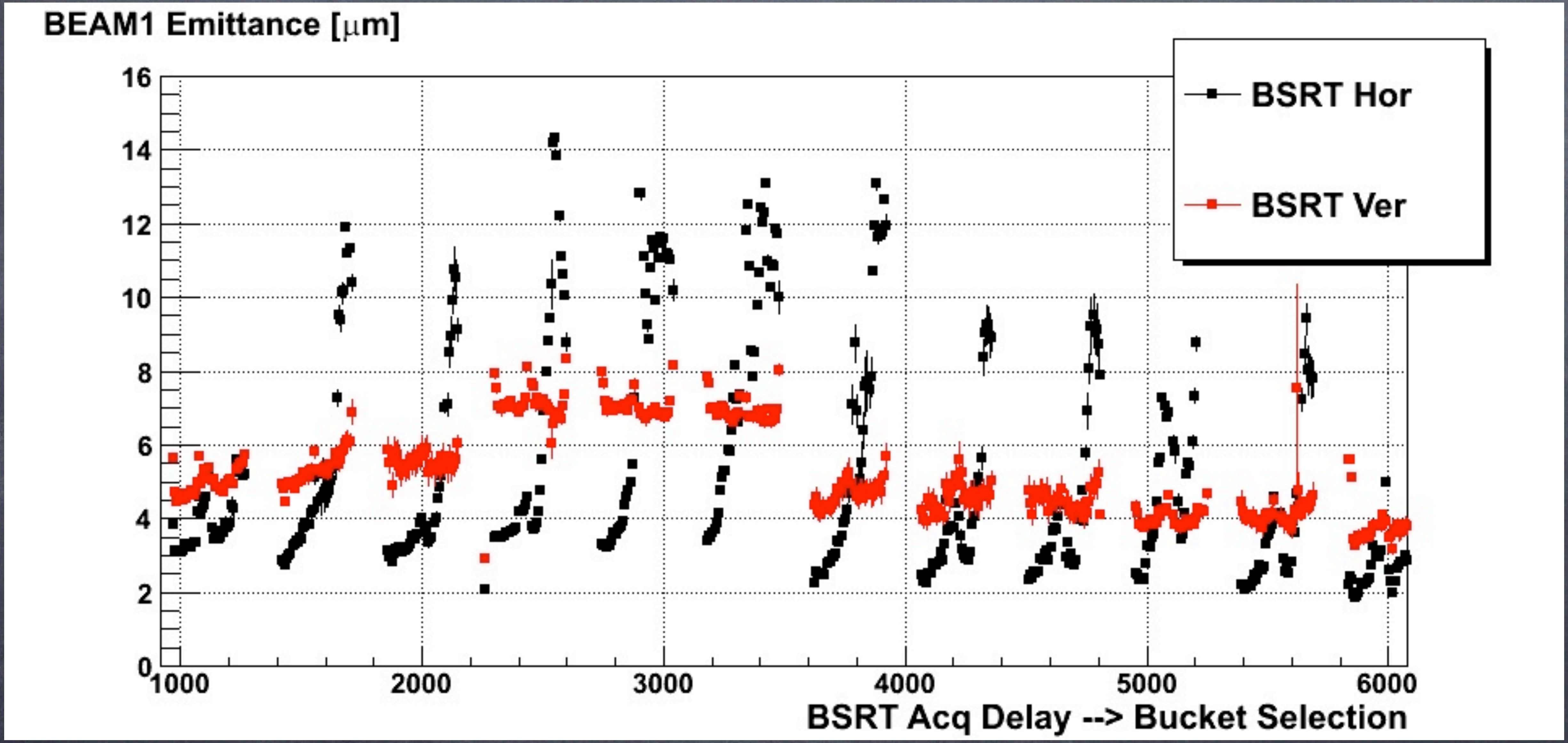
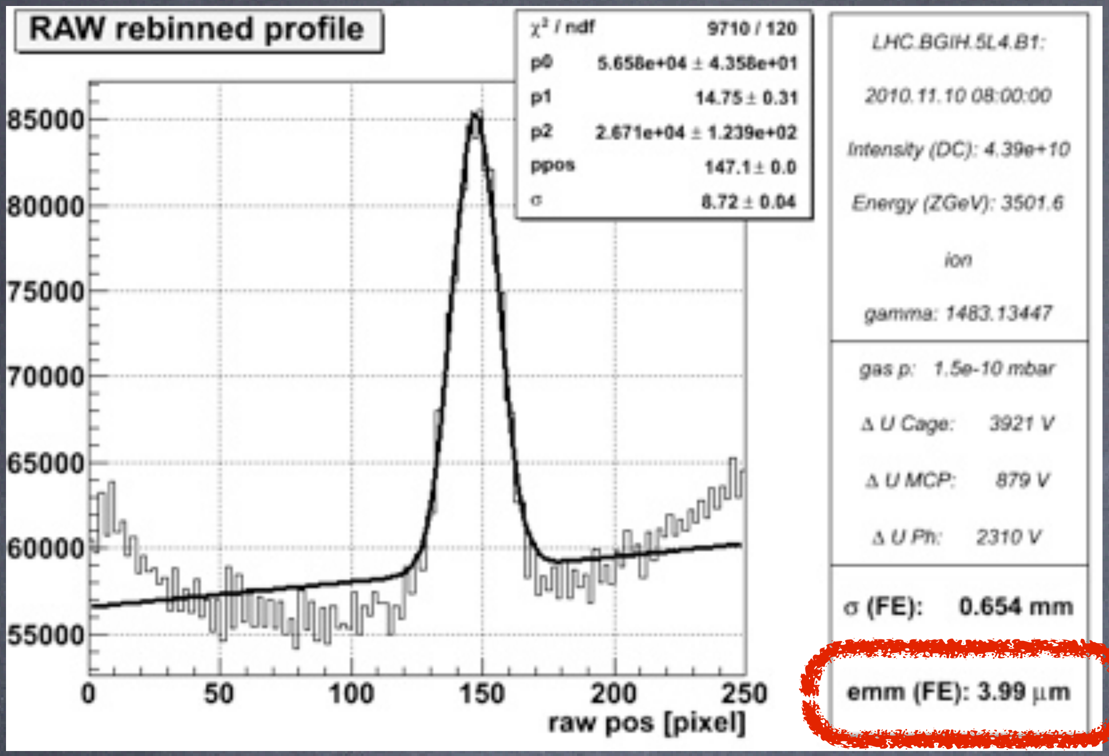
BSRT Ver
WS HOR
WS VER
Energy [TeV]
0
1
2
3
4
5
6
7
8
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
Time


BEAM1 Emittance [μm]
BSRT Hor
BSRT Ver
16
14
12
10
8
6
4
2
0
1000
2000
3000
4000
5000
6000
BSRT Acq Delay --> Bucket Selection

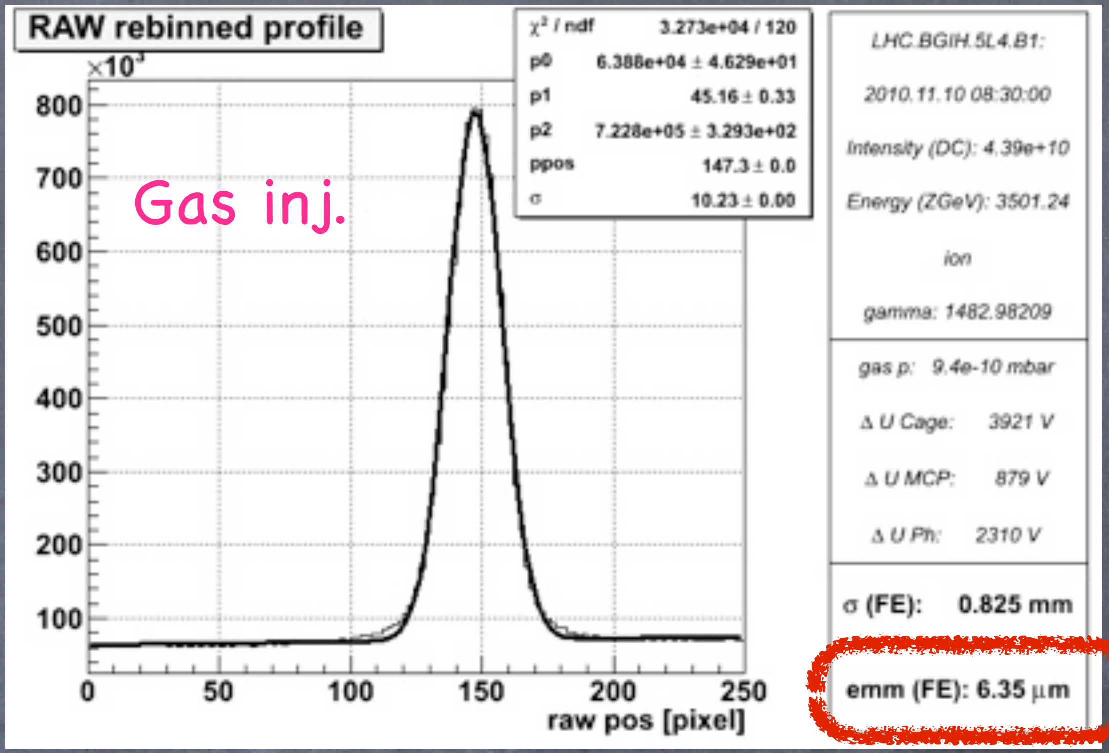
Ionization profile monitor

- Need either an intense beam or a local pressure bump
- Provides continuous measurement of beam profiles (1 plane per instrument)
- Suffers from space charge effects
- Calibration has to be studied in detail

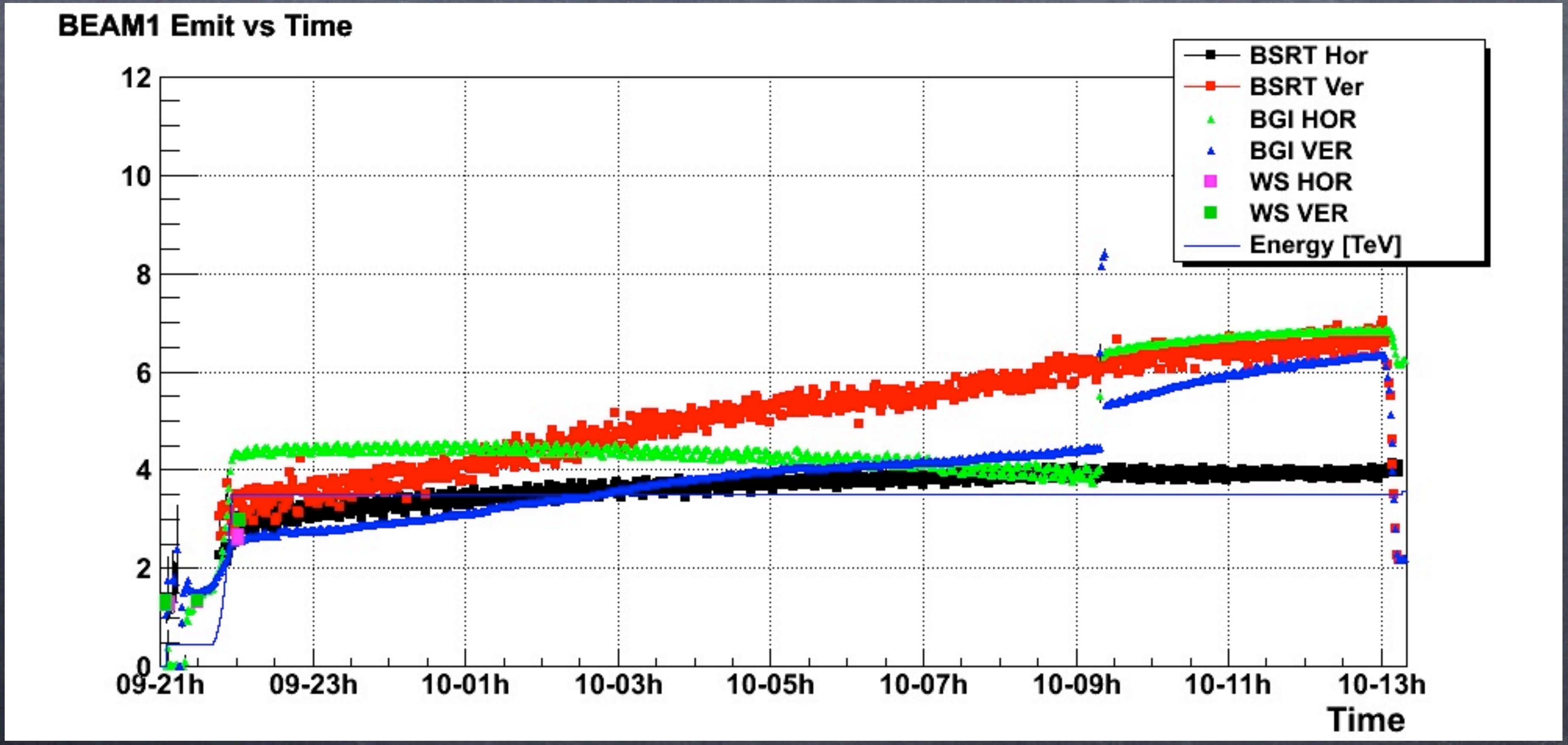
IPM



RAW rebinned profile
χ² / ndf 9710 / 120
p0 5.658e+04 ± 4.358e+01
p1 14.75 ± 0.31
p2 2.671e+04 ± 1.239e+02
ppos 147.1 ± 0.0
σ 8.72 ± 0.04
LHC.BGIH.5L4.B1:
2010.11.10 08:00:00
Intensity (DC): 4.39e+10
Energy (ZGeV): 3501.6
ion
gamma: 1483.13447
gas p: 1.5e-10 mbar
Δ U Cage: 3921 V
Δ U MCP: 879 V
Δ U Ph: 2310 V
σ (FE): 0.654 mm
emm (FE): 3.99 μm
raw pos [pixel]



RAW rebinned profile
×10³
Gas inj.
χ² / ndf 3.273e+04 / 120
p0 6.388e+04 ± 4.629e+01
p1 45.16 ± 0.33
p2 7.228e+05 ± 3.293e+02
ppos 147.3 ± 0.0
σ 10.23 ± 0.00
LHC.BGIH.5L4.B1:
2010.11.10 08:30:00
Intensity (DC): 4.39e+10
Energy (ZGeV): 3501.24
ion
gamma: 1482.98209
gas p: 9.4e-10 mbar
Δ U Cage: 3921 V
Δ U MCP: 879 V
Δ U Ph: 2310 V
σ (FE): 0.825 mm
emm (FE): 6.35 μm
raw pos [pixel]



BEAM1 Emit vs Time
BSRT Hor
BSRT Ver
BGI HOR
BGI VER
WS HOR
WS VER
Energy [TeV]
09-21h
09-23h
10-01h
10-03h
10-05h
10-07h
10-09h
10-11h
10-13h
Time

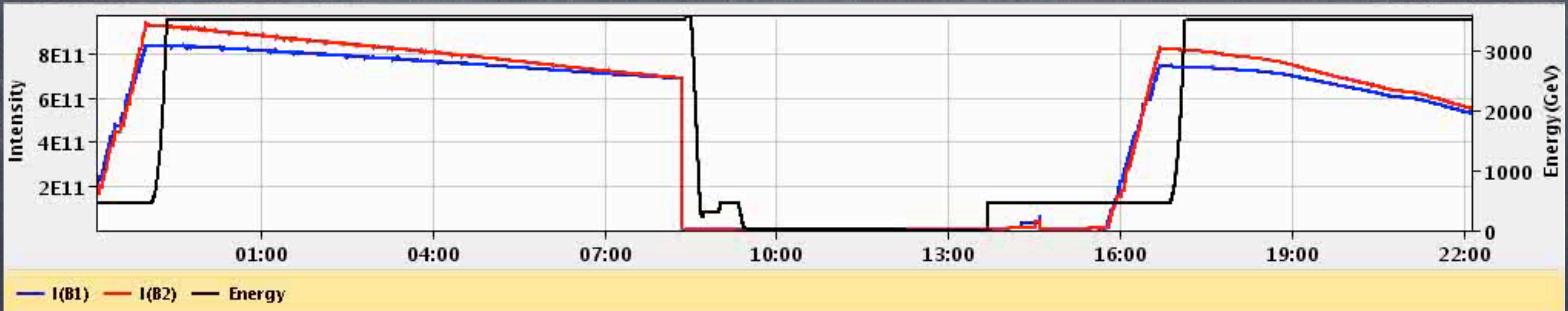
Beam current monitors

- Primary devices are transformers
  - Fast current transformer for b-by-b measurement (and t-by-t)
  - DC current transformer for total intensity
- The FCT does not see de-bunched beam!
- Other possible monitors are wall current monitor (AC) and synchrotron light based long. monitor (DC+AC)

Transformers

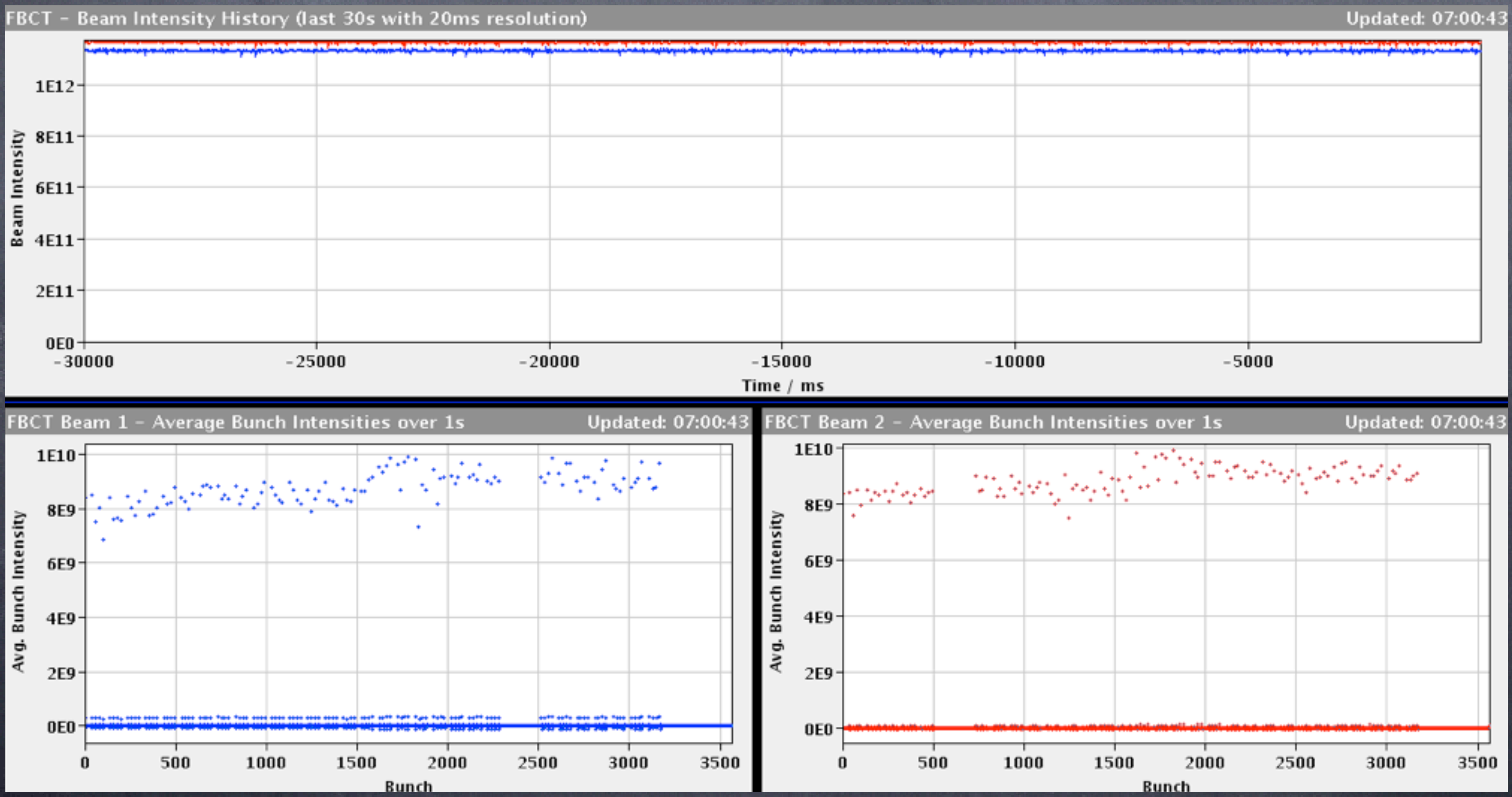
- Transformers are used to monitor the total current in the machine and the bunch-by-bunch charge
- The evolution over time of the beam current is very important
  - Beam lifetime

BCTs



8E11
6E11
4E11
2E11
Intensity
3000
2000
1000
0
Energy (GeV)
01:00
04:00
07:00
10:00
13:00
16:00
19:00
22:00
I(B1)
I(B2)
Energy

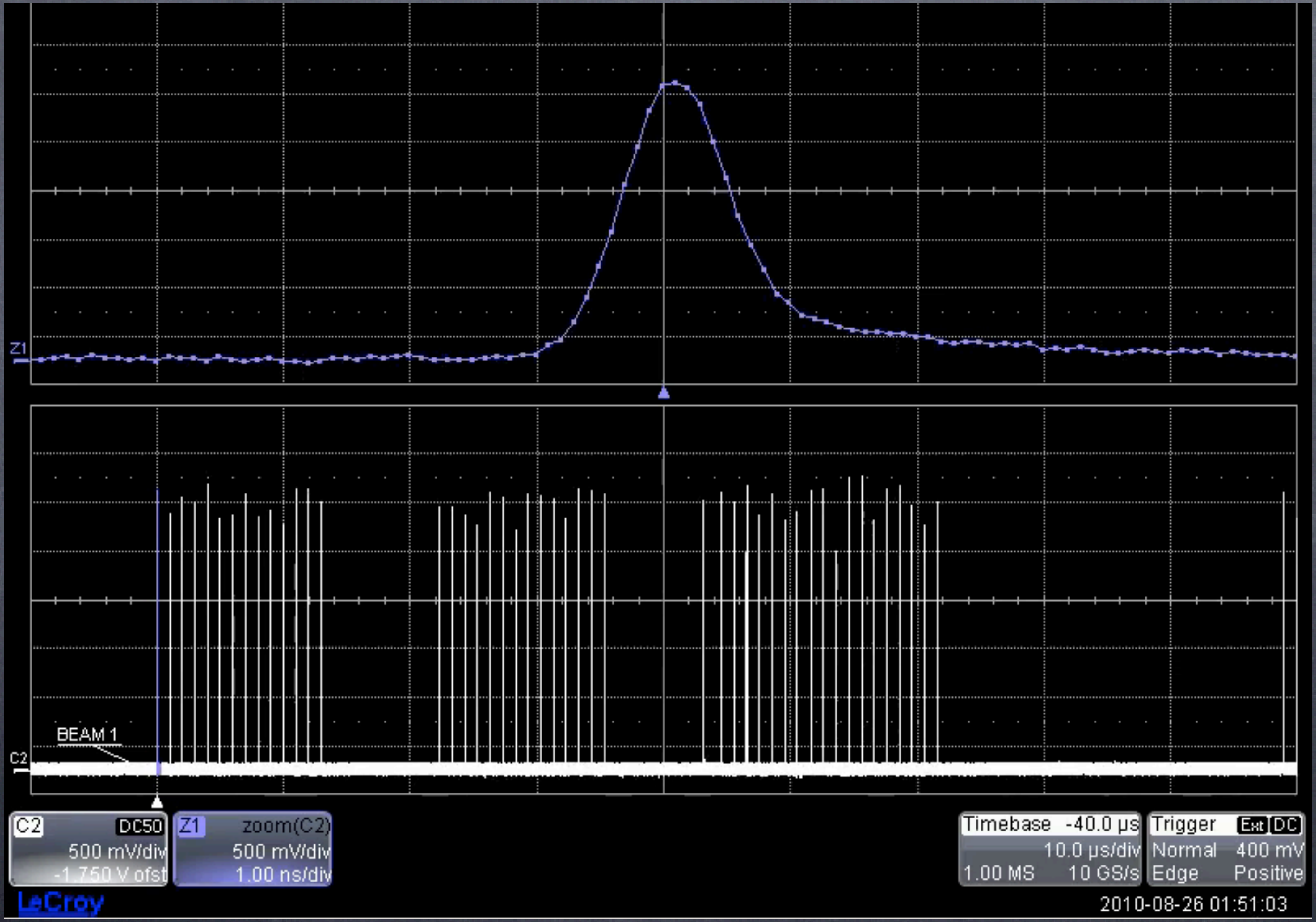
BCTs


FBCT - Beam Intensity History (last 30s with 20ms resolution)
Updated: 07:00:43
Beam Intensity
1E12
8E11
6E11
4E11
2E11
0E0
-30000
-25000
-20000
-15000
-10000
-5000
Time / ms
FBCT Beam 1 - Average Bunch Intensities over 1s
Updated: 07:00:43
Avg. Bunch Intensity
1E10
8E9
6E9
4E9
2E9
0E0
0
500
1000
1500
2000
2500
3000
3500
Bunch
FBCT Beam 2 - Average Bunch Intensities over 1s
Updated: 07:00:43
Avg. Bunch Intensity
1E10
8E9
6E9
4E9
2E9
0E0
0
500
1000
1500
2000
2500
3000
3500
Bunch

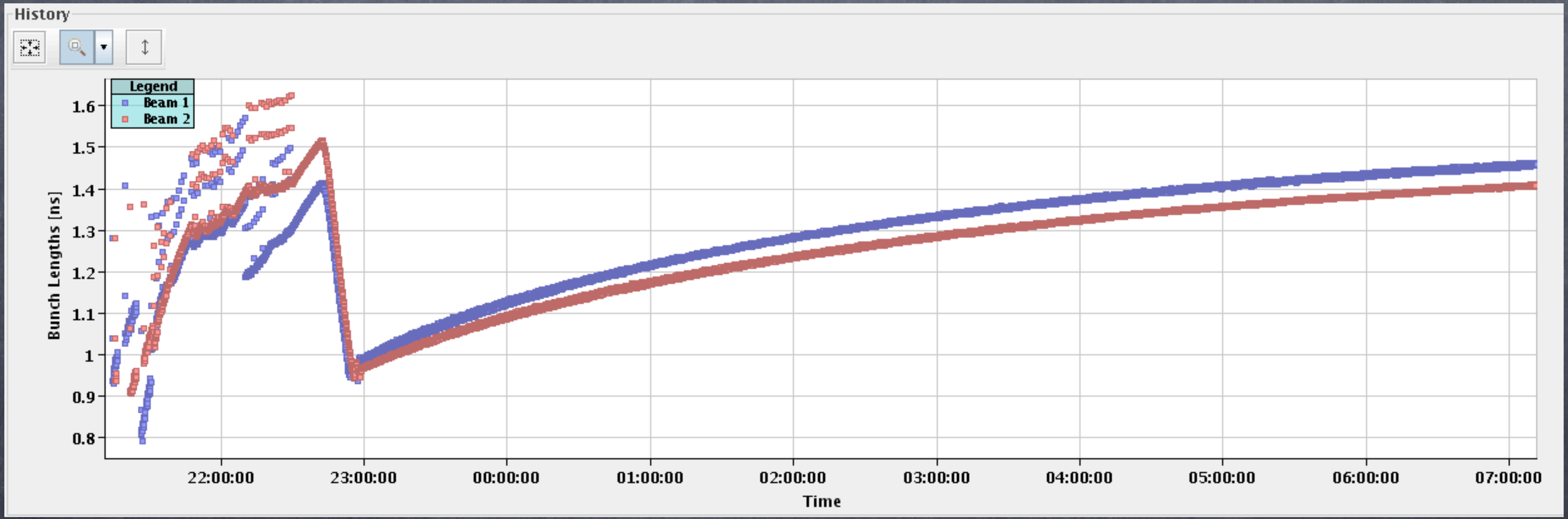
Bunch length

- The bunch length is an important parameter for the longitudinal stability of the beam
- It is monitored usually with
  - Wall current monitor
  - Strip line pick-ups
  - Synchrotron radiation (streak camera)

Wall current monitor



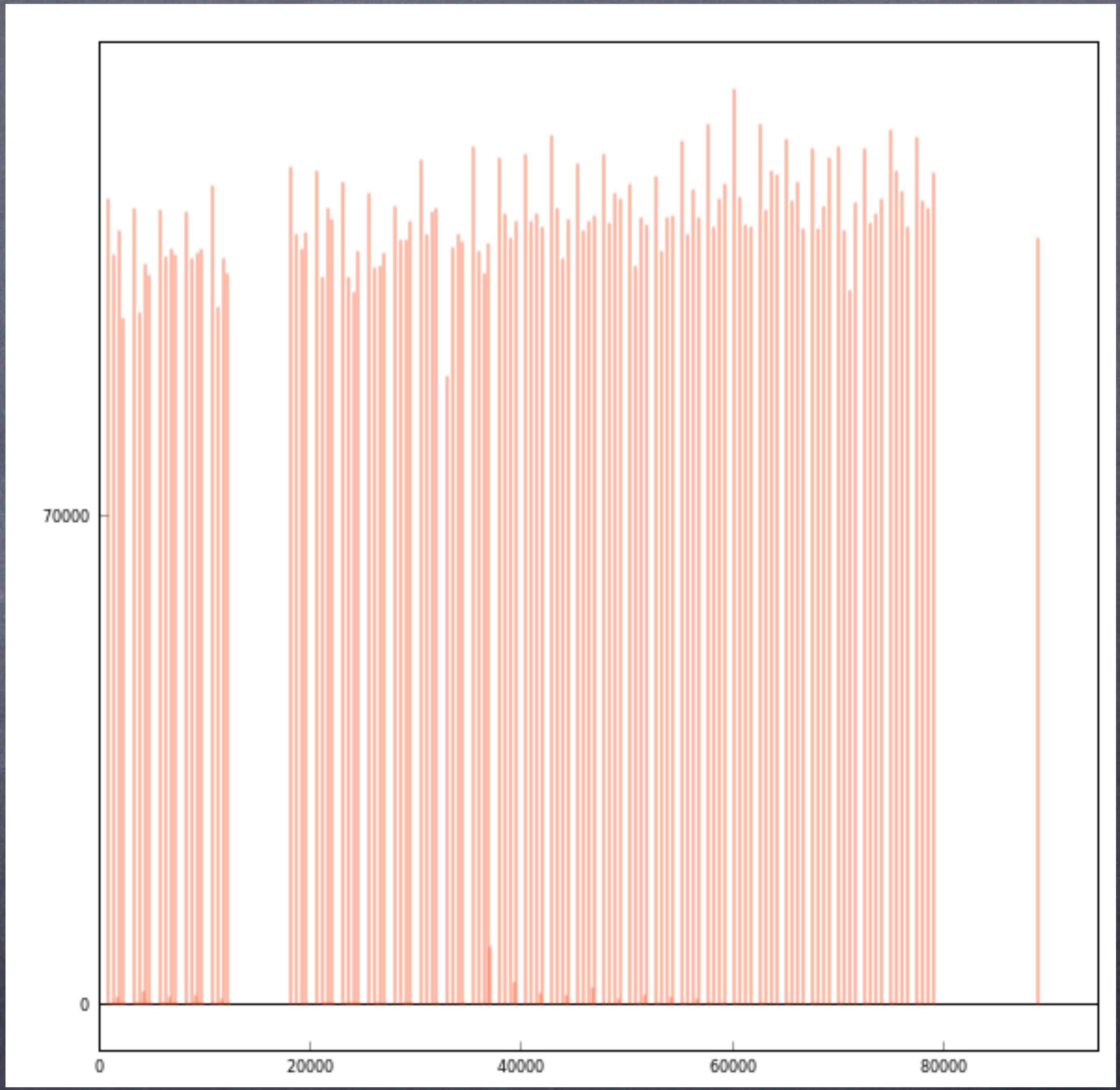
Wall current monitor



SL (LDM)

Single SL photons counting with precise time of arrival detection

(~50 ps time resolution, >10^4 dynamic range)



SL (LDM)

Single SL photons counting with precise time of arrival detection

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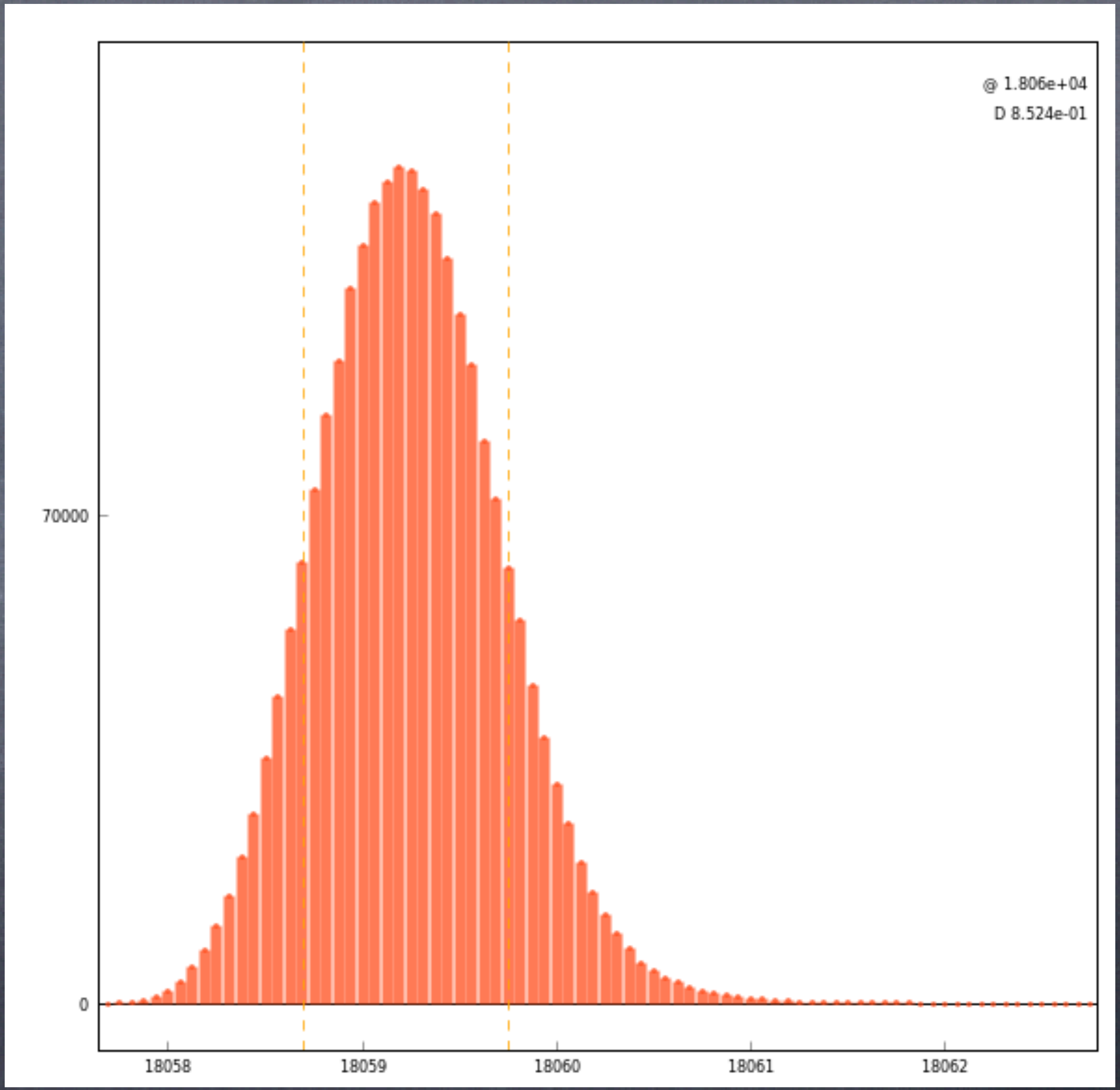

SL (LDM)

Single SL photons counting with precise time of arrival detection

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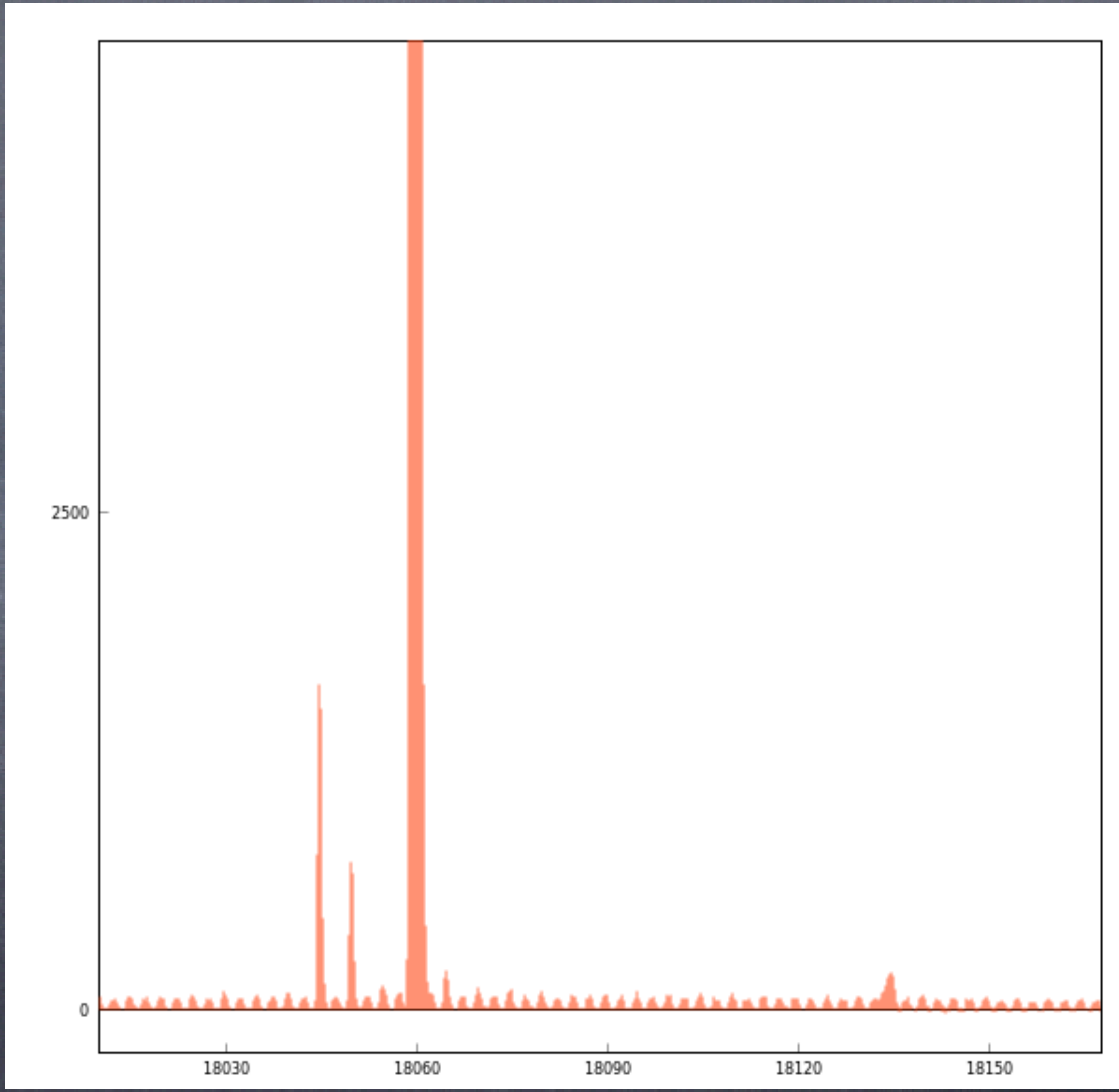
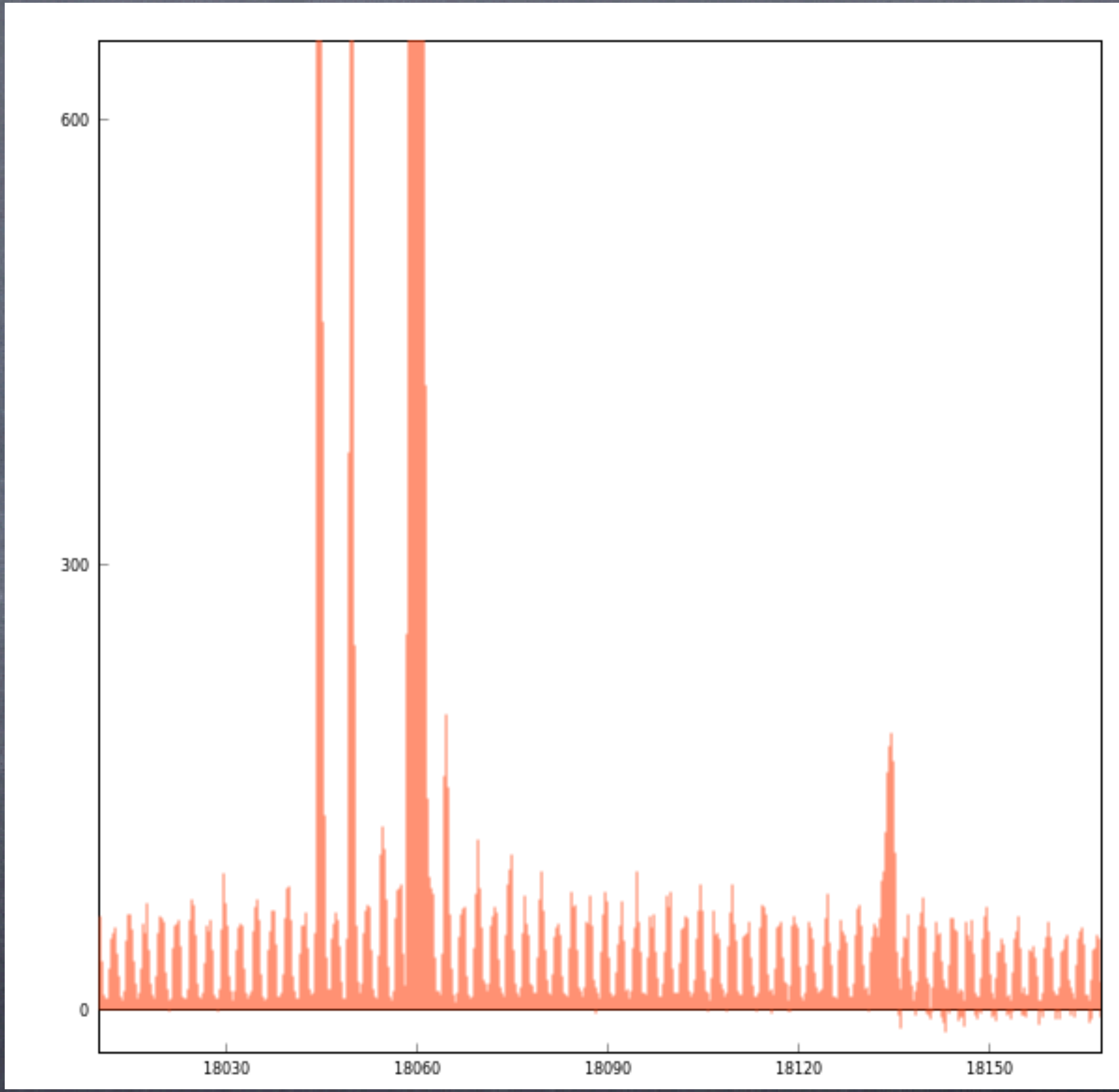


SL (LDM)

Single SL photons counting with precise time of arrival detection

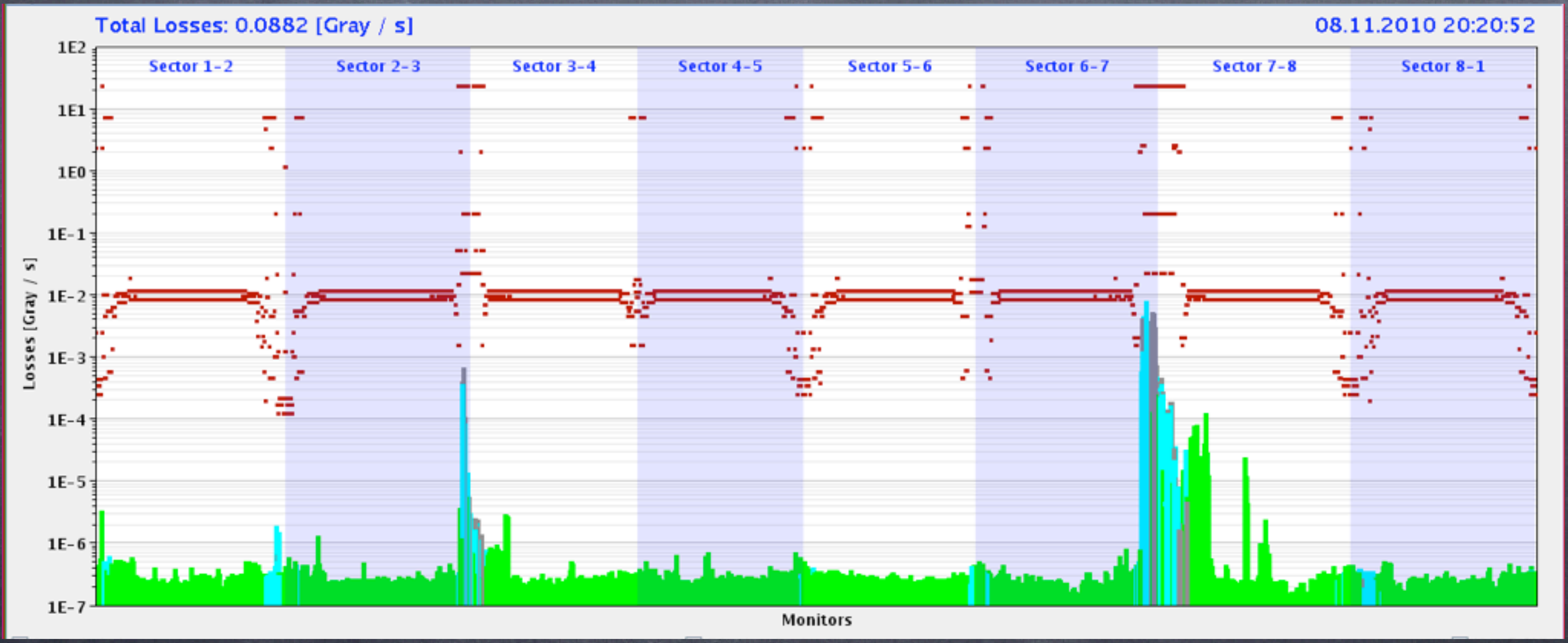
(~50 ps time resolution, >10^4 dynamic range)



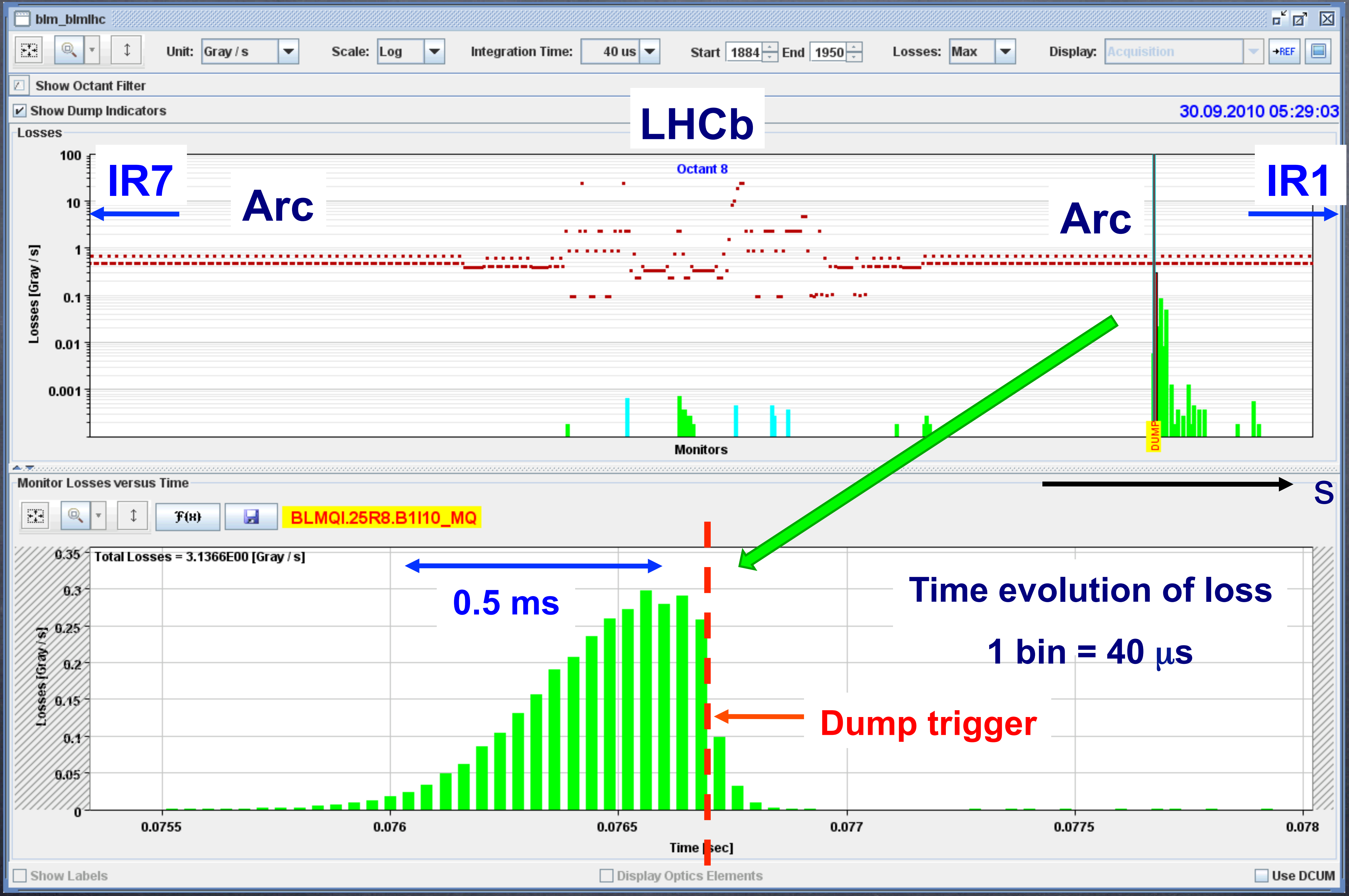
Beam loss monitors

- Used mainly to
  - Protect the elements of the machine from damage (if using SC magnets also to prevent quenches)
  - Reduce background to experiments
  - Avoid irradiating machine elements (interventions)
  - Collimation setup

BLMs


Total Losses: 0.0882 [Gray / s]
08.11.2010 20:20:52
Sector 1-2
Sector 2-3
Sector 3-4
Sector 4-5
Sector 5-6
Sector 6-7
Sector 7-8
Sector 8-1
1E2
1E1
1E0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
Losses [Gray / s]
Monitors

BLMs


blm_blmlhc
Unit: Gray / s
Scale: Log
Integration Time: 40 us
Start 1884 End 1950
Losses: Max
Display: Acquisition
Show Octant Filter
Show Dump Indicators
LHCb
30.09.2010 05:29:03
Losses
IR7
Arc
Octant 8
Arc
IR1
Losses [Gray / s]
Monitors
DUMP
Monitor Losses versus Time
S
BLMQI.25R8.B1I10_MQ
Total Losses = 3.1366E00 [Gray / s]
0.5 ms
Time evolution of loss
1 bin = 40 μs
Dump trigger
Time [sec]
Show Labels
Display Optics Elements
Use DCUM

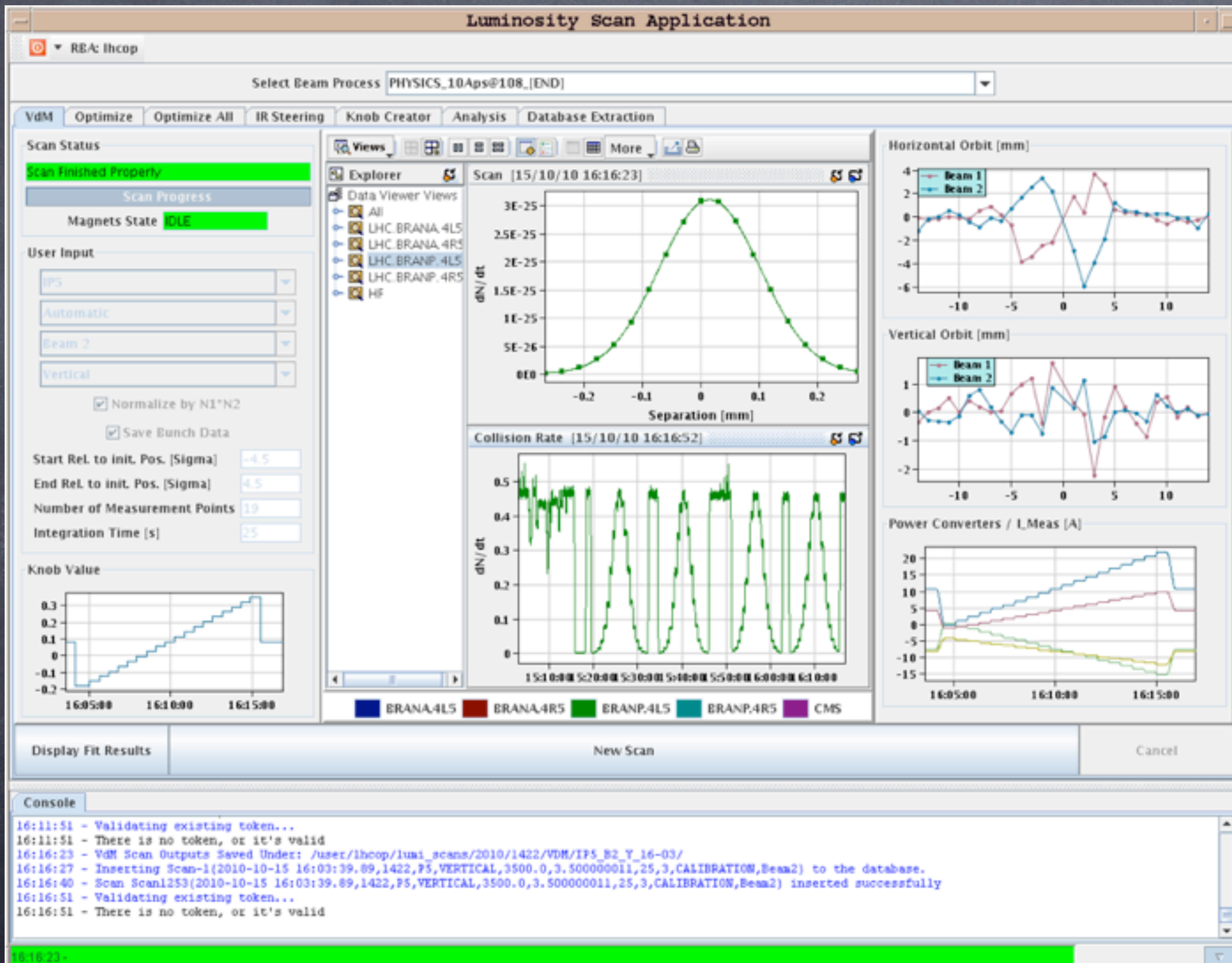
Luminosity monitors

- The luminosity is one of the most important parameters (our deliverable)
  - Prepare and keep the "best possible" beams
  - Keep them colliding
- No monitor available to measure directly the beams overlap at the IP → measure the luminosity as function of beam position

Luminosity monitors

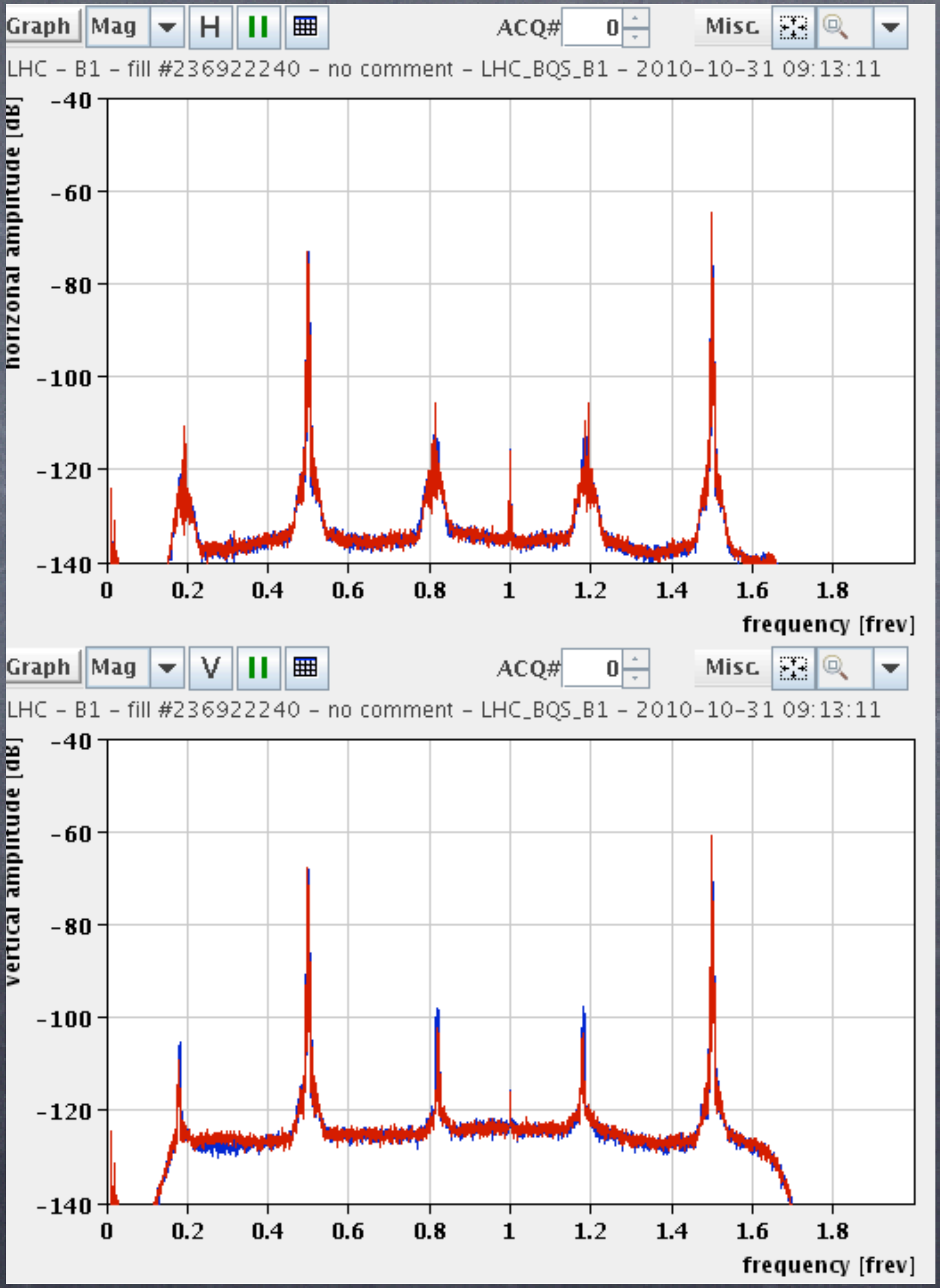
- The experiments are the best possible luminosity monitor!
- Some time they do not deliver online information and a back-up solution is needed
  - Machine luminosity monitors (just small particle detectors that count the rate of debris from the collisions)
  - Can be a simple scintillator pad

Van der Meer scans

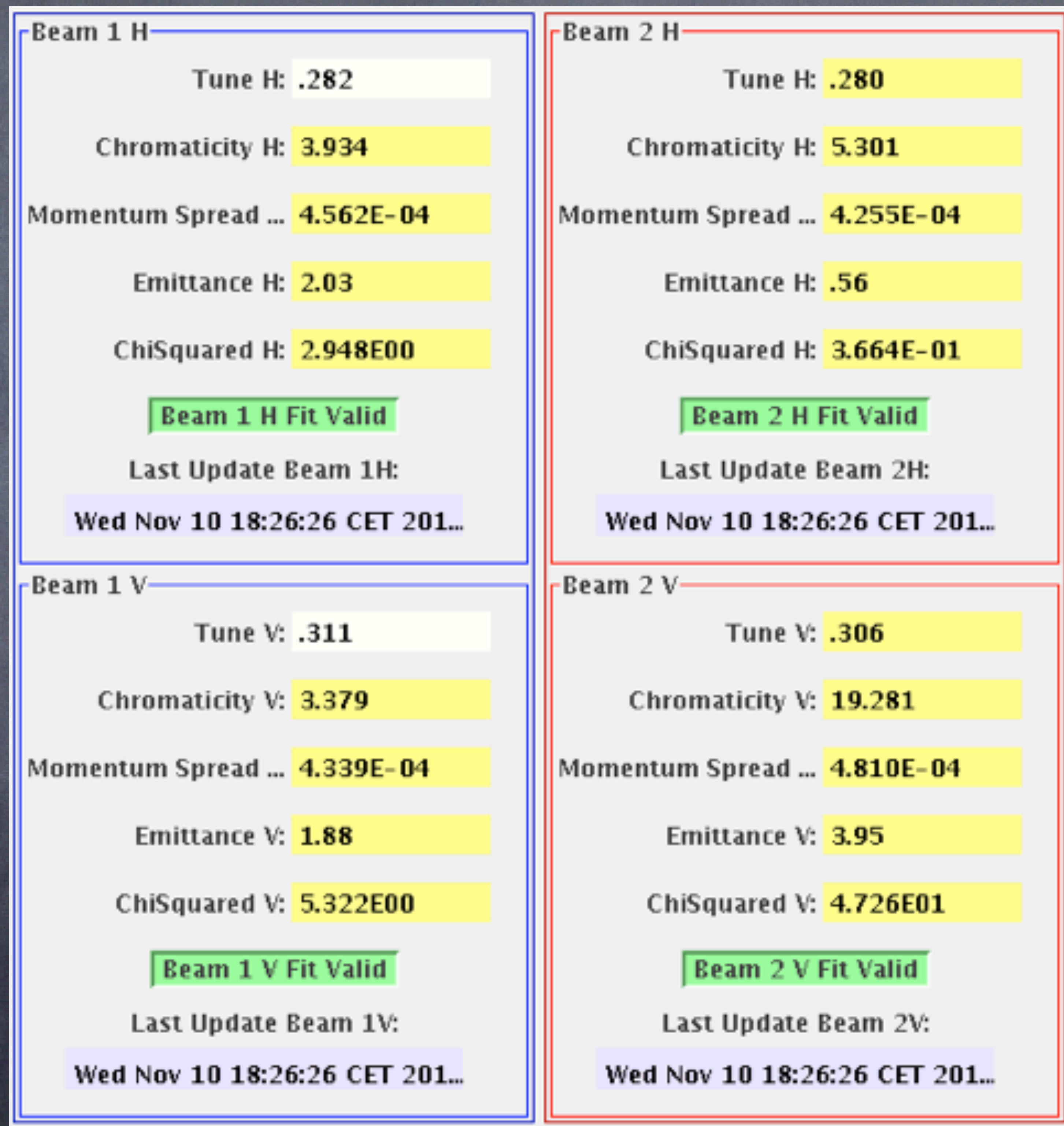


Scan one beam across the other one at the IP and monitor the variations in luminosity

Schottky (transverse)



Schottky (transverse)



Beam energy

- For lepton colliders it is very important to know exactly the energy of the colliding particles
- For hadron machines this is less important since the initial status of the partons is anyway unknown
- In LEP the error on the beam energy was 1 MeV at 45 GeV and 10 MeV at 100 GeV

Energy measurement

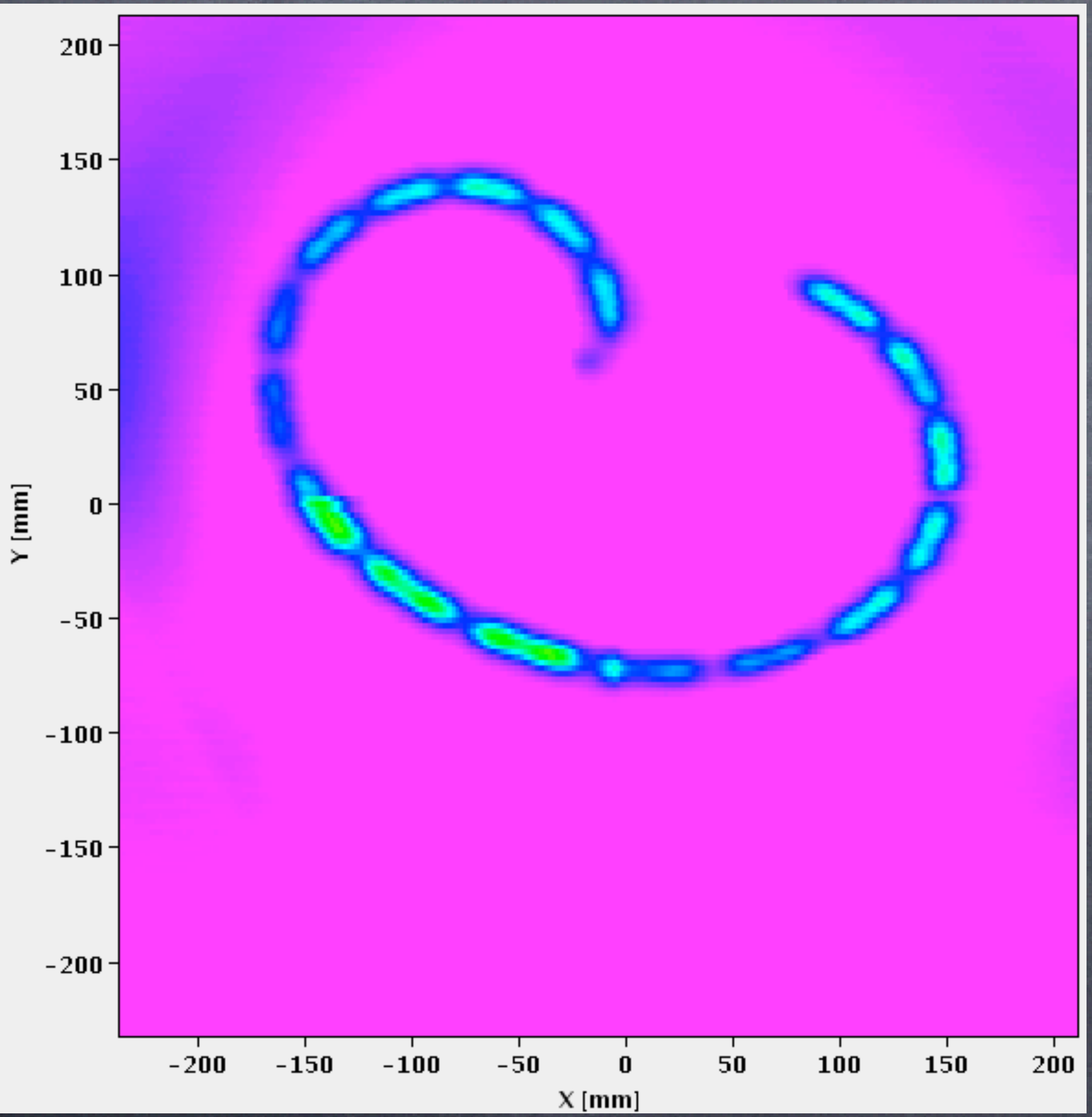
$$P \propto \oint B dl$$

- Direct magnetic measurement of dipole field around the ring (Hall probes, NMR probes, coils etc.)
- Indirect Bdl measurement with resonant depolarization
- Spectrometer magnet

Beam dump

- Collider have huge amount of energy stored in the beams
- At some point you have to get rid of them
- Usually some sort of dilution is needed
- Need a reliable monitoring of the successful beam dump (also for national authorities!)

Beam dump monitor at the LHC



It is over !!!

It is over !!!

… Unless you have questions ?

It is over !!!

... Unless you have questions ?

EVERYTHING in this presentation is the intellectual property of someone else
THANKS to EVERYBODY who "provided" the material