Diagnostics Examples from High Energy Colliders

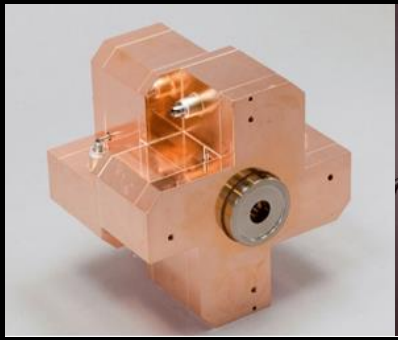
BI CAS 2018

Tuusula, Finland

2nd – 15th June, 2018

Rhodri Jones

Head of the CERN Beam Instrumentation Group



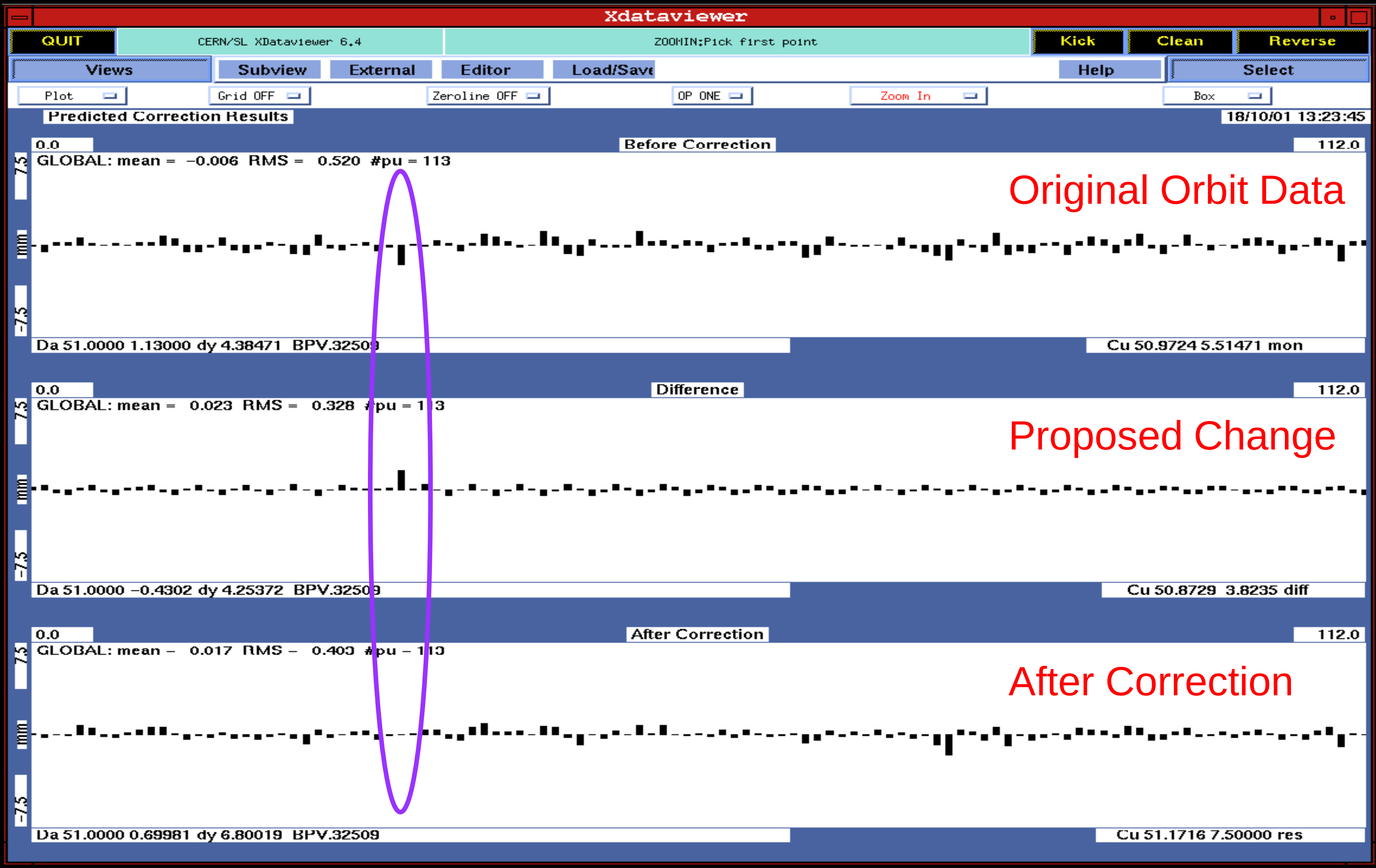
Diagnostics using Beam Position Systems

Orbit or Trajectory Acquisition

- Main use of BPM systems
  - Measure & correct orbit or trajectory

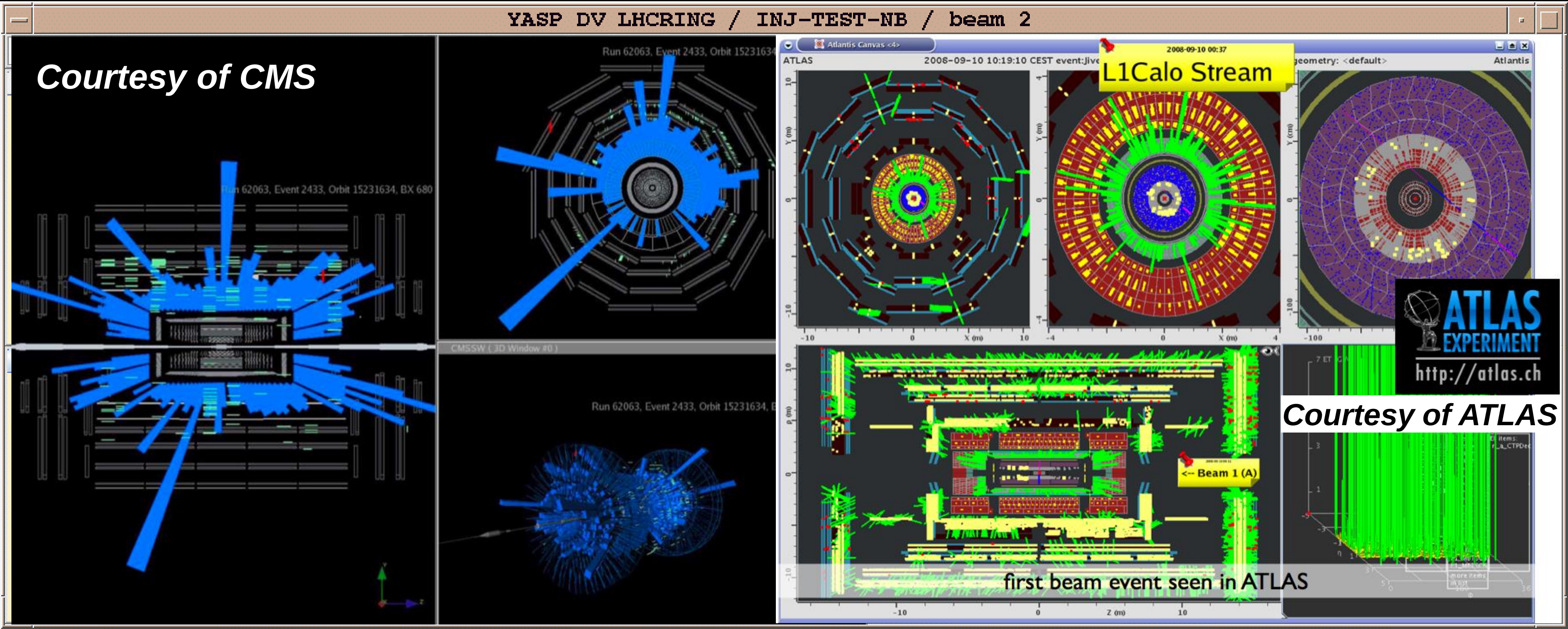
Orbit excursion too large ⇒ need to correct

Orbit or Trajectory Correction

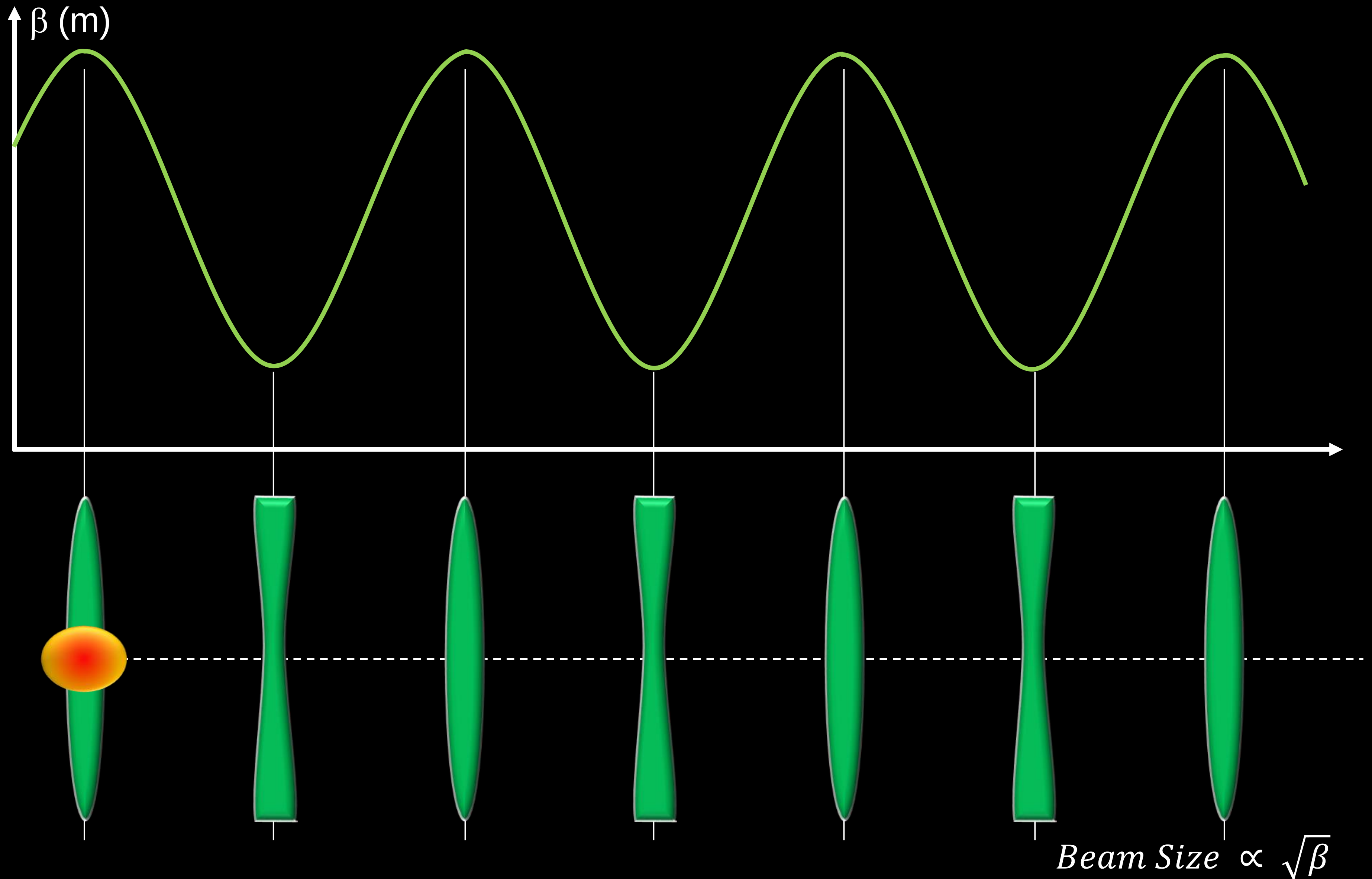


Initial Commissioning

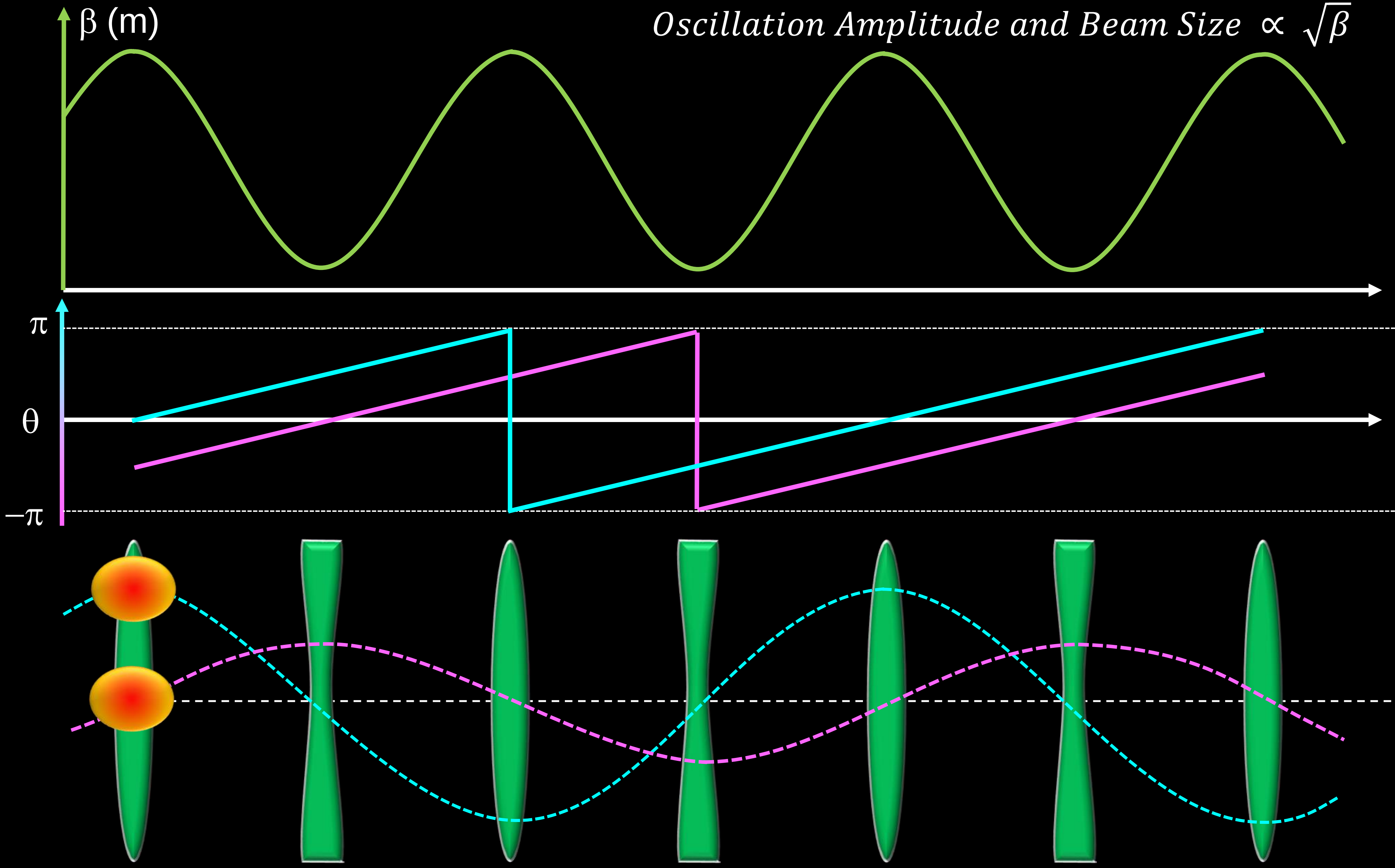
- Threading the first pilot bunch round the LHC
  - One beam at a time, one hour per beam
  - Collimators used to intercept the beam
  - Correct trajectory, open collimator and move on



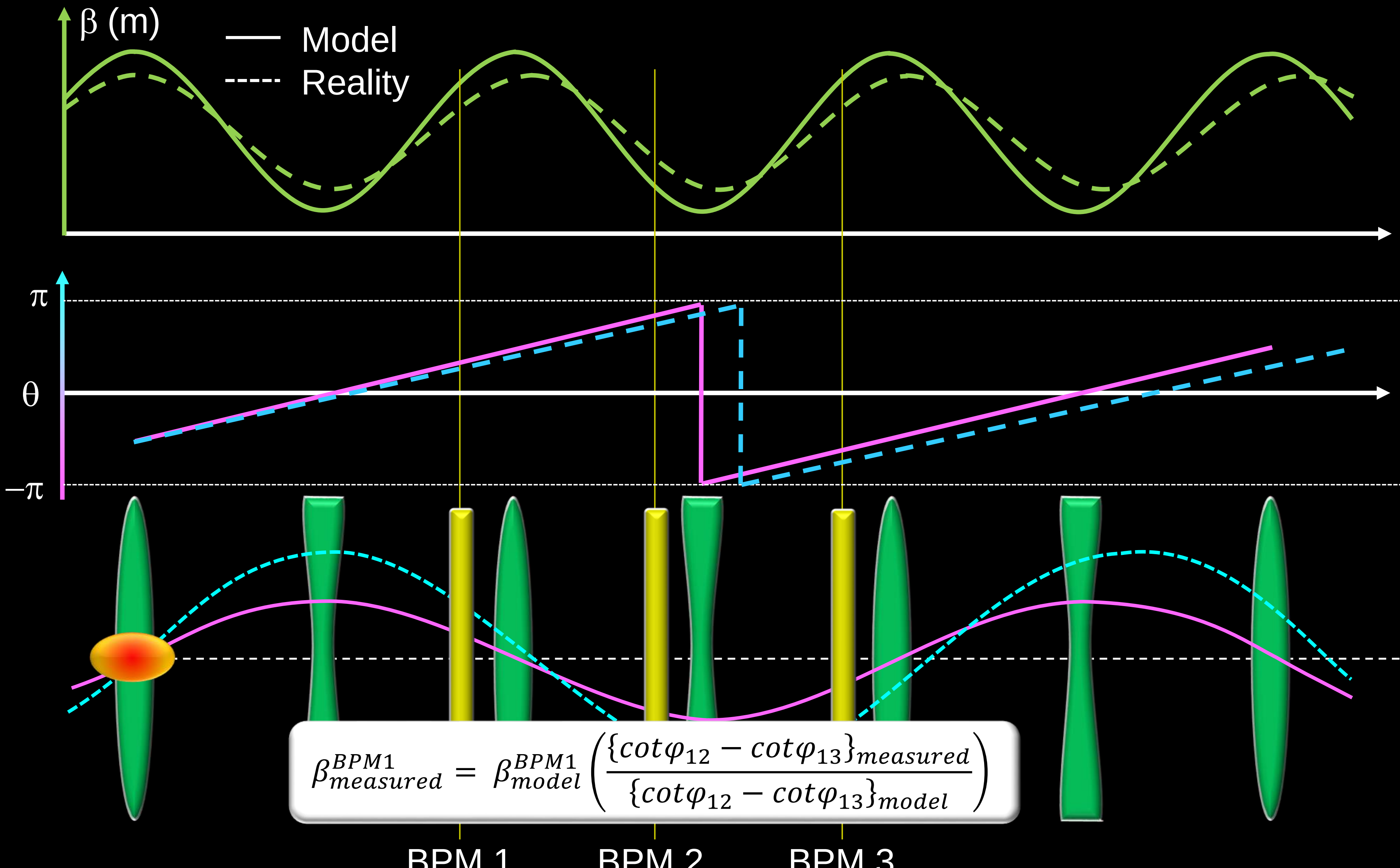
Measuring the Machine β-Function



Measuring the Machine β-Function



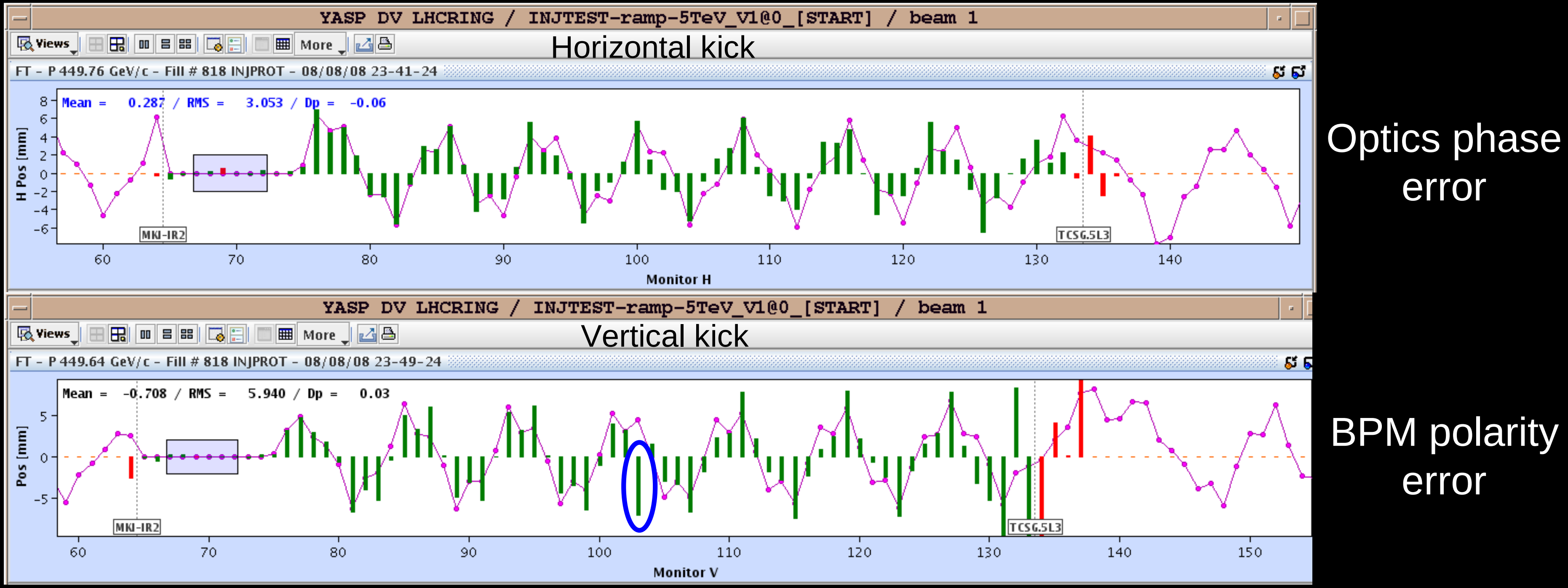
Measuring the Machine β-Function



$$\beta^{BPM1}_{measured} = \beta^{BPM1}_{model}\left(\frac{\{cot\varphi_{12} - cot\varphi_{13}\}_{measured}}{\{cot\varphi_{12} - cot\varphi_{13}\}_{model}}\right)$$

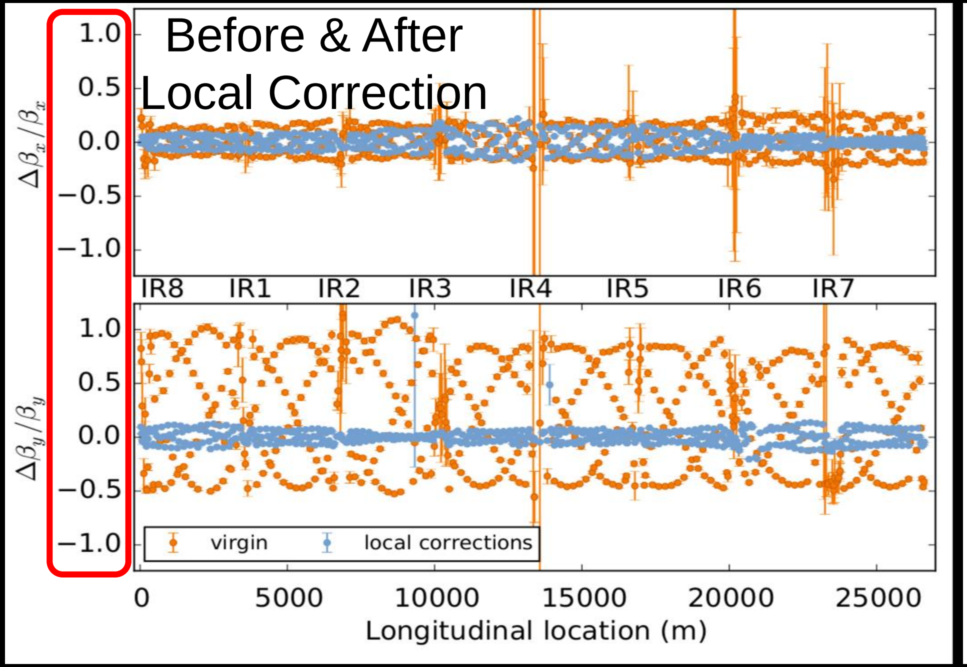
Analysis of BPM Data

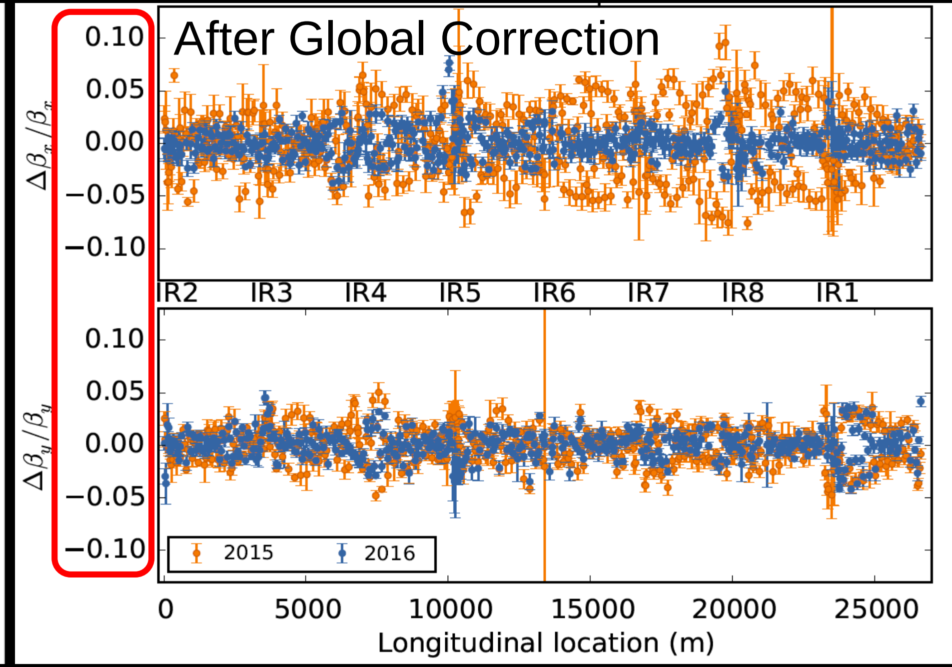
- On line analysis of BPM Data
  - Polarity errors easily identified with 45° BPM sampling
  - Quick indication of phase advance errors
  - Used to verify optics functions
    - e.g. matching from transfer lines into ring



Machine Optics Measurements

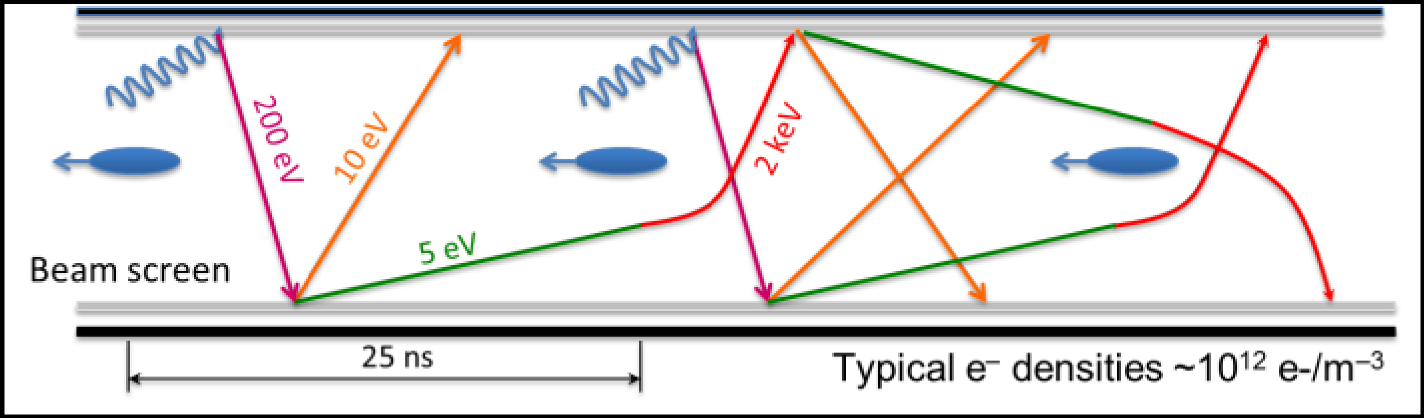
- Light Sources
  - Dominated by closed orbit techniques (Orbit Response Matrix - e.g. LOCO)
    - Activate one orbit corrector & observe change in orbit
    - SOLEIL & DIAMOND achieved 0.3 - 0.4% β-beating
  - Recently improved BPM electronics
    - Now allows turn-by-turn techniques to start competing with orbit response
- LHC
  - Only turn-by-turn technique feasible with correction < 2% achievable

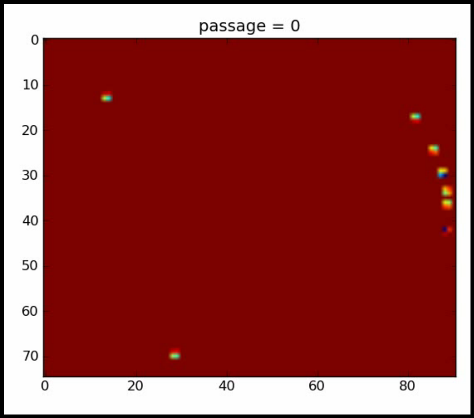




Diagnostics using Instruments Capable of Bunch-by-Bunch Measurements

Monitoring Electron Cloud Activity





G. Iadarola, G. Rumolo, G. Arduini (CERN)

- Secondary Emission Yield [SEY]
  - SEY > Threshold ⇒ avalanche effect (multipacting)
- Possible consequences:
  - Instabilities, emittance growth, vacuum degradation, background
  - Energy deposition in cryogenic surfaces
- Electron bombardment can reduce SEY of a material
  - A function of the delivered electron dose
  - This technique of "scrubbing" can suppress electron cloud build-up

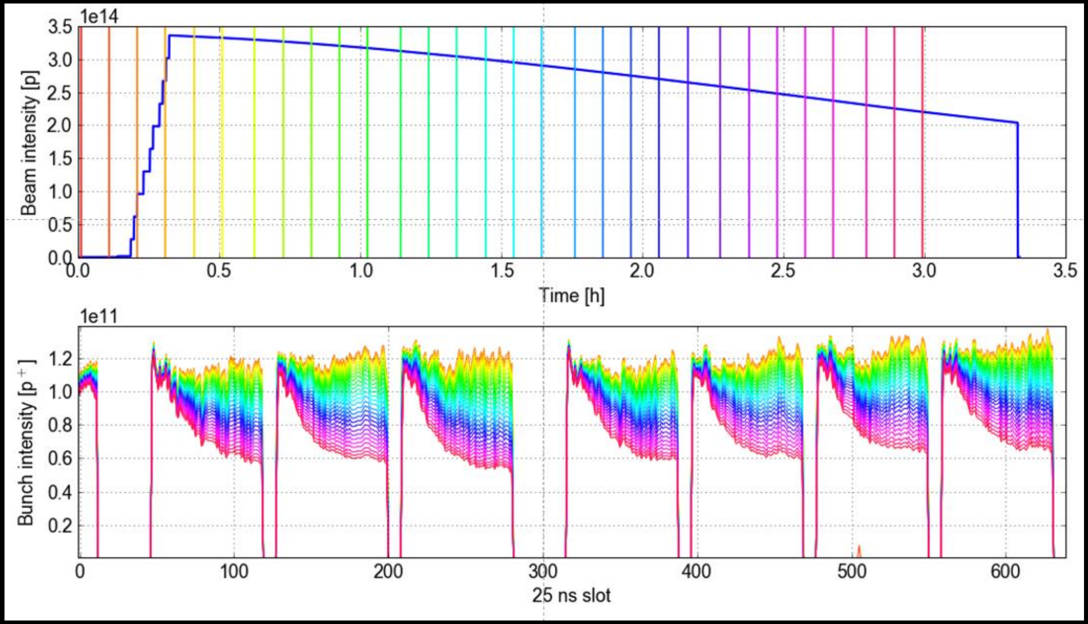
Bunch by Bunch Diagnostics

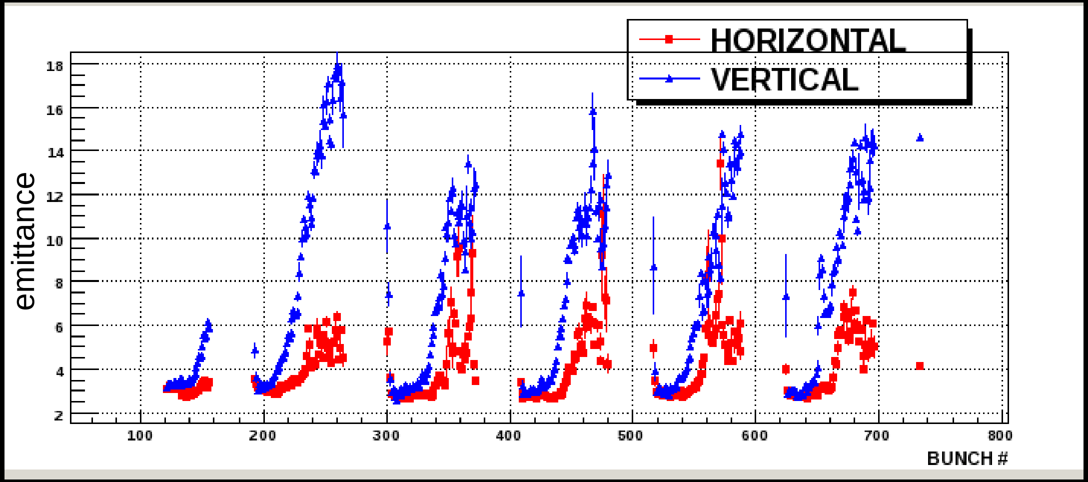
Electron Cloud in LHC

- Electron cloud creates instability in tail of bunch trains
- Increases the size of the bunches towards the end of each bunch train
- Leads to losses for these bunches
- Adjustments made to counter this effect
  - Chromaticity
  - Transverse feedback
  - Beam scrubbing

Diagnostics

- LHC fast BCT
  - Allows bunch by bunch intensity measurement
- LHC Synchrotron Light Monitor
  - Gated intensified Camera
  - Allows bunch by bunch profile measurement





Bunch by Bunch Diagnostics

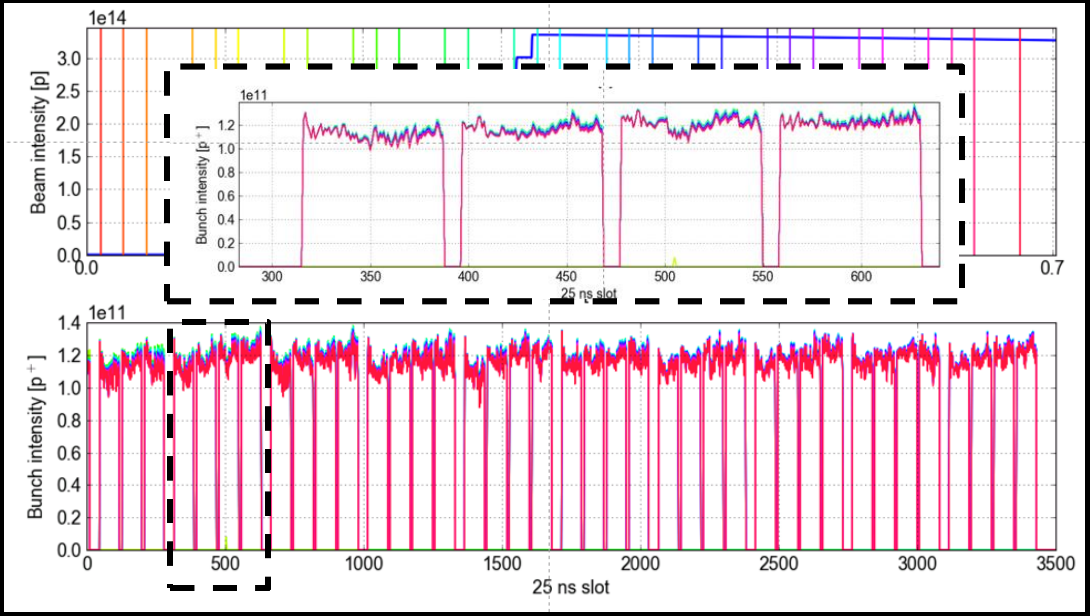
Electron Cloud in LHC

– Electron cloud creates instability in tail of bunch trains
– Increases the size of the bunches towards the end of each bunch train
– Leads to losses for these bunches
– Adjustments made to counter this effect
  - Chromaticity
  - Transverse feedback
  - Beam scrubbing

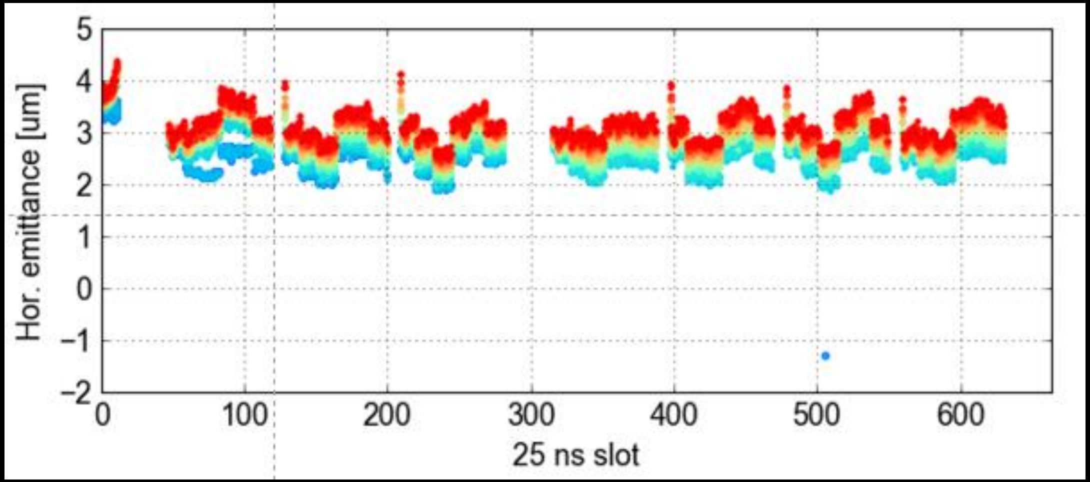
- ## Diagnostics

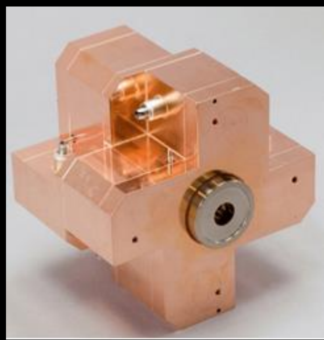
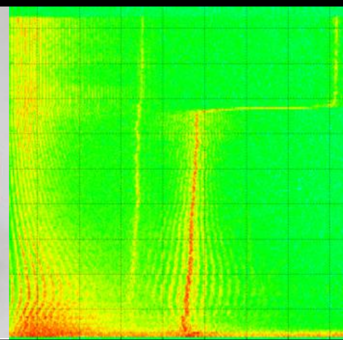
– LHC fast BCT
  - Allows bunch by bunch intensity measurement

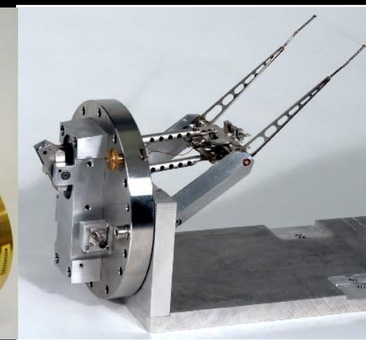
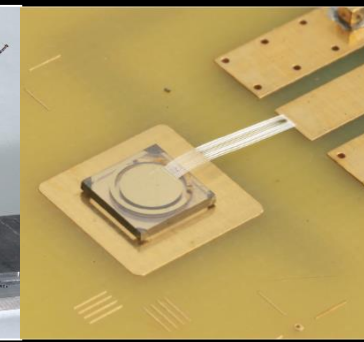
– LHC Synchrotron Light Monitor
  - Gated intensified Camera
  - Allows bunch by bunch profile measurement



AFTER SCRUBBING



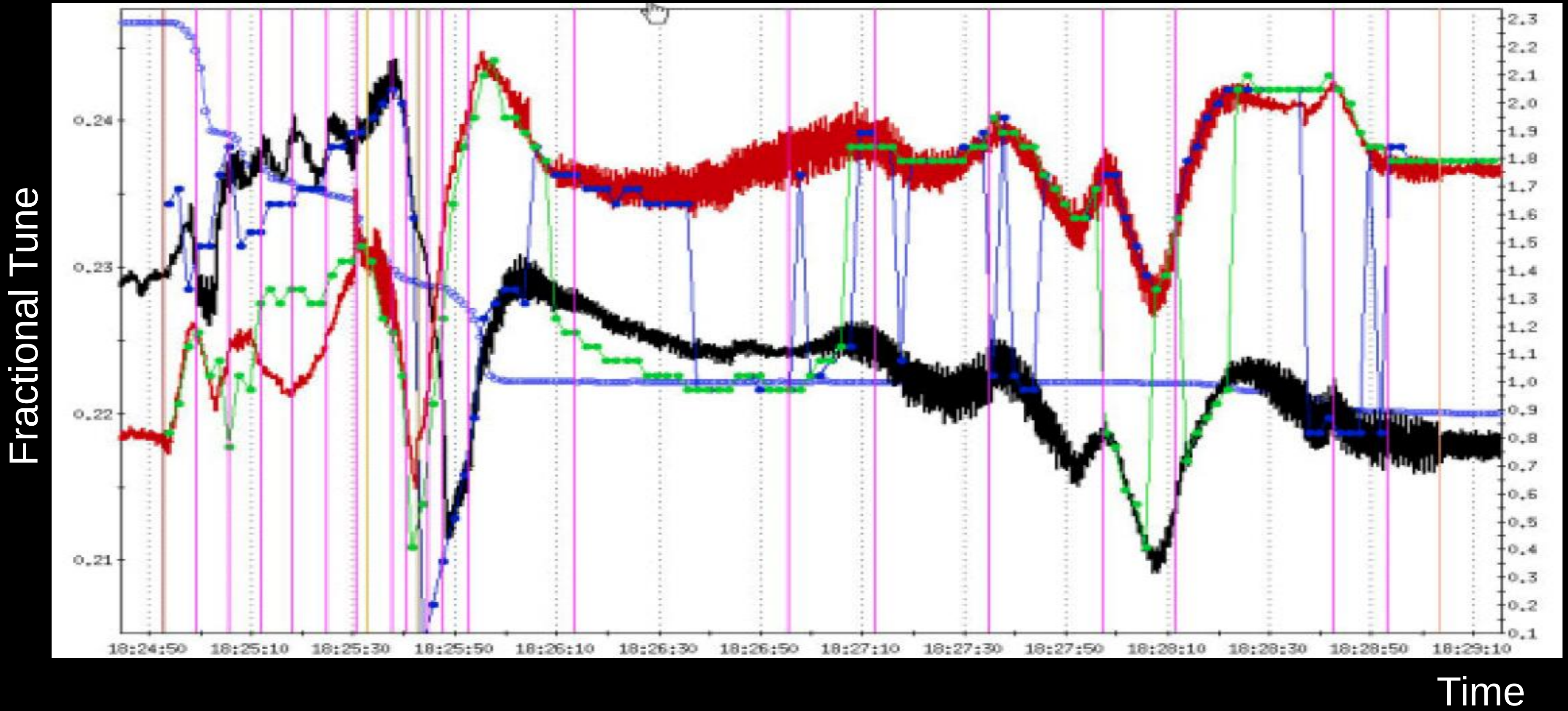



Understanding Tune Feedback Systems

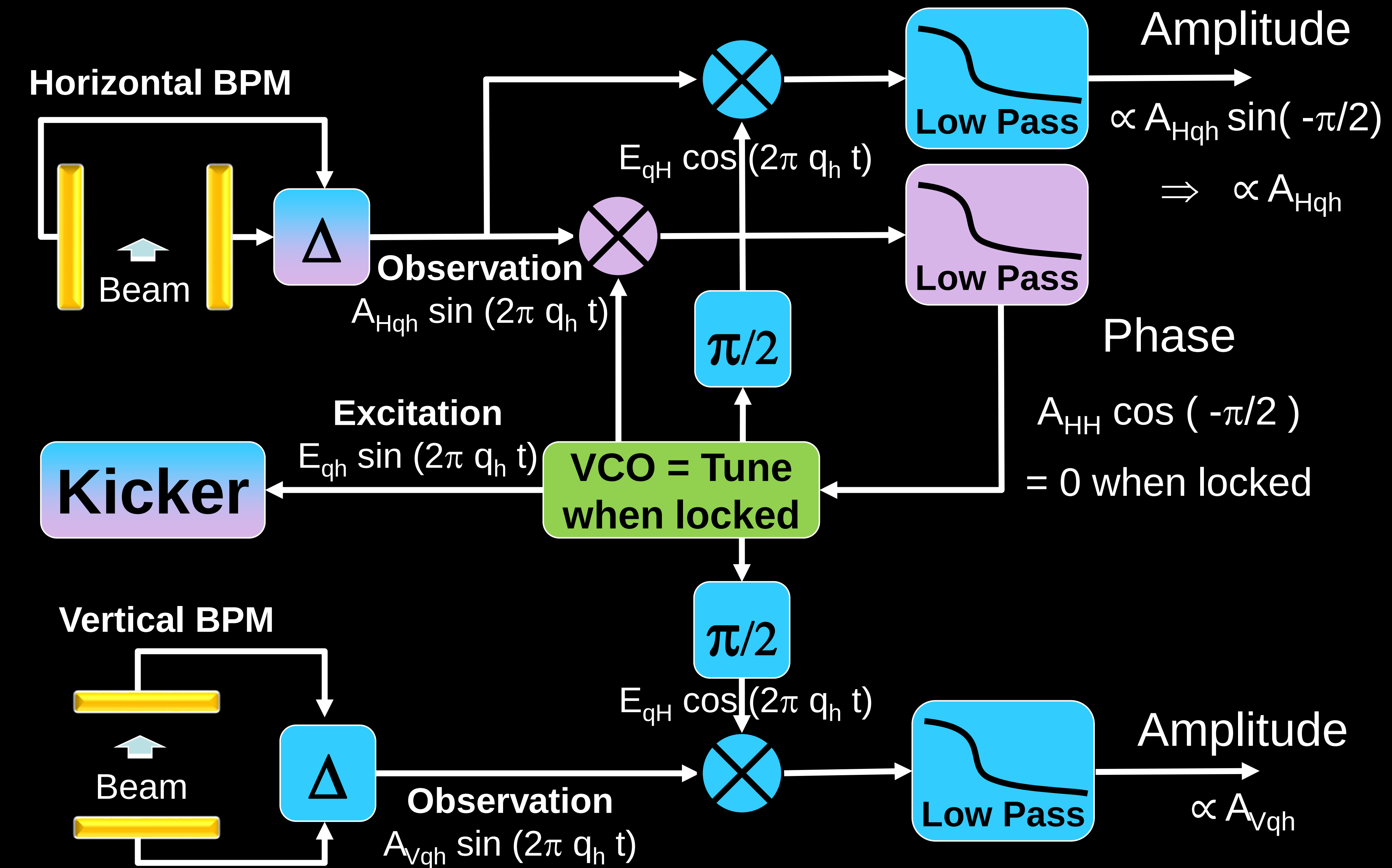
A RHIC Example

Implementing Tune Feedback at RHIC

- PLL system tracked tune nicely
  - Used as input to close feedback loop
  - Loop would continually "break" at specific times in the ramp
    - Could not understand why with such a nice tune signal
  - Coupling suspected but could not be continually measured

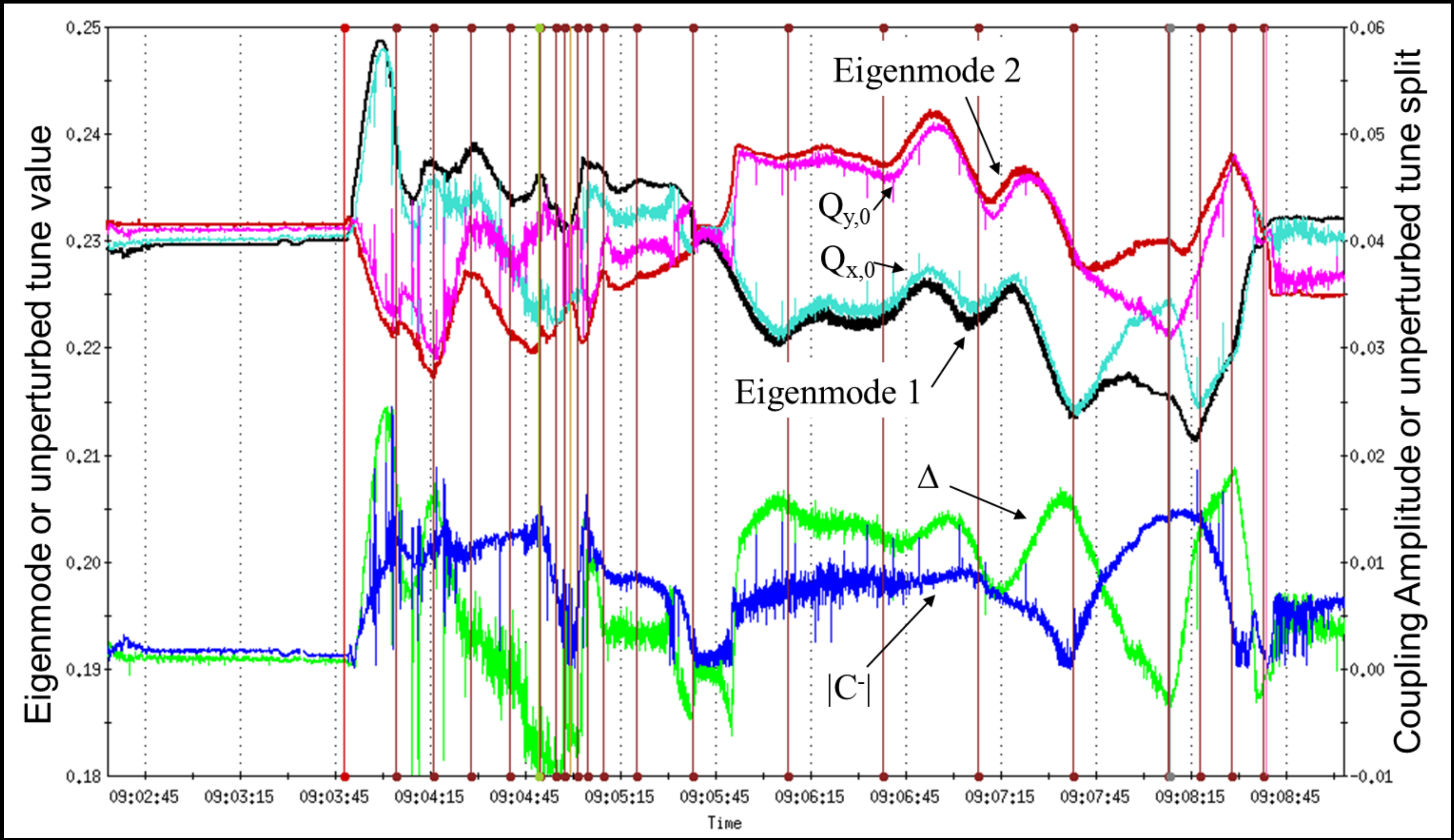


PLL for Coupling - Schematic



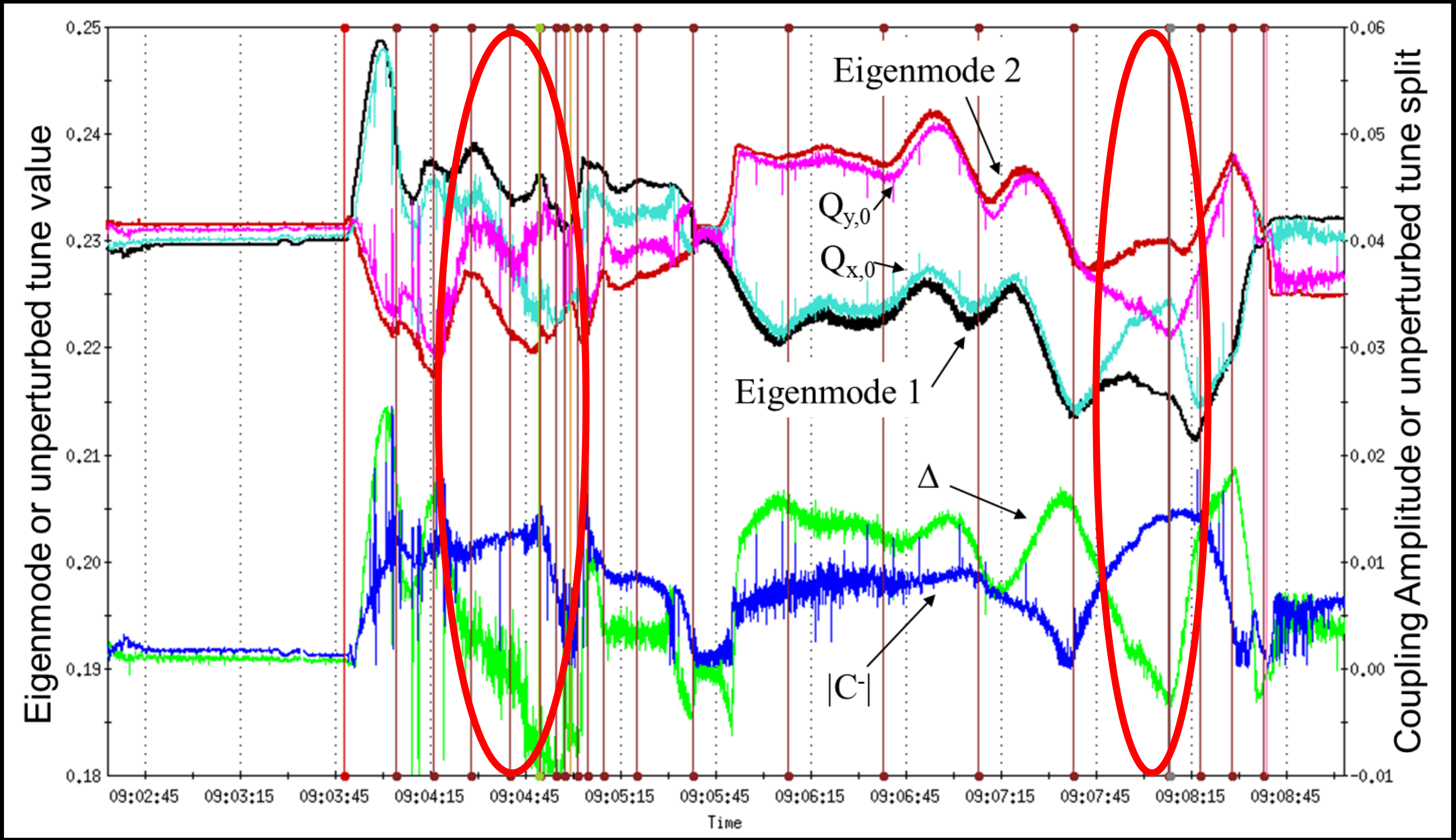
Coupling & Tune Feedback

- Measurement from RHIC during acceleration cycle
  - Tune & coupling measurement using 4 phase locked loops
    - Q_H loop (excite H, observe H) : Q_V loop (excite V, observe V)
    - $Q_{H,V}$ loop (excite H, observe V) : $Q_{V,H}$ loop (excite V, observe H)



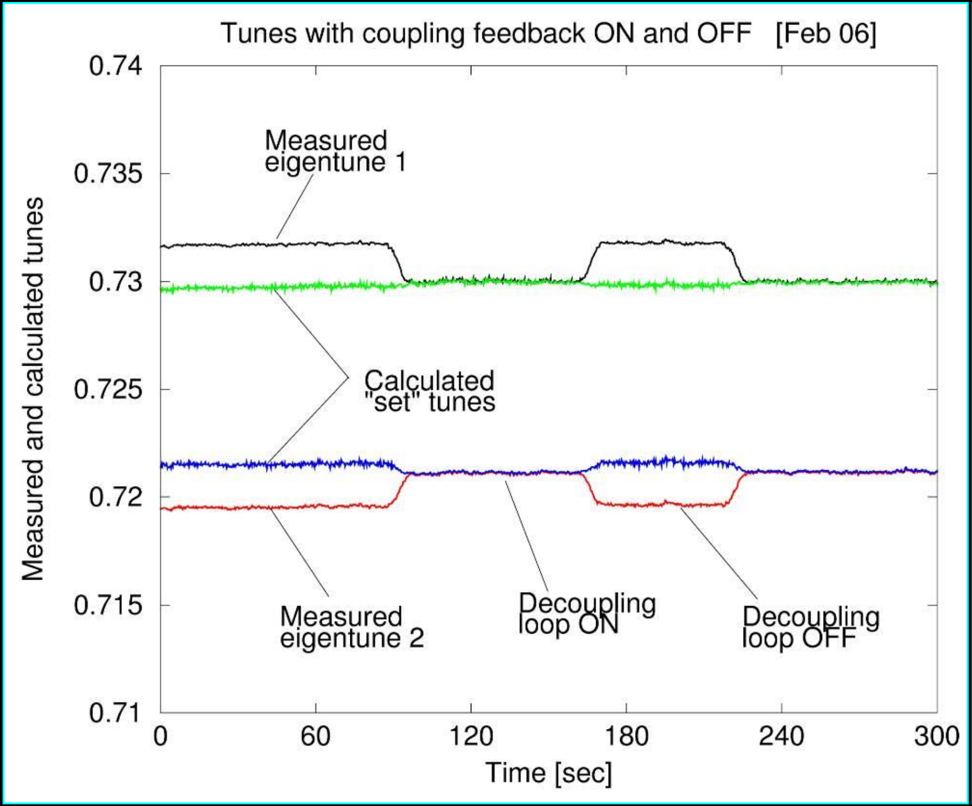
Coupling & Tune Feedback

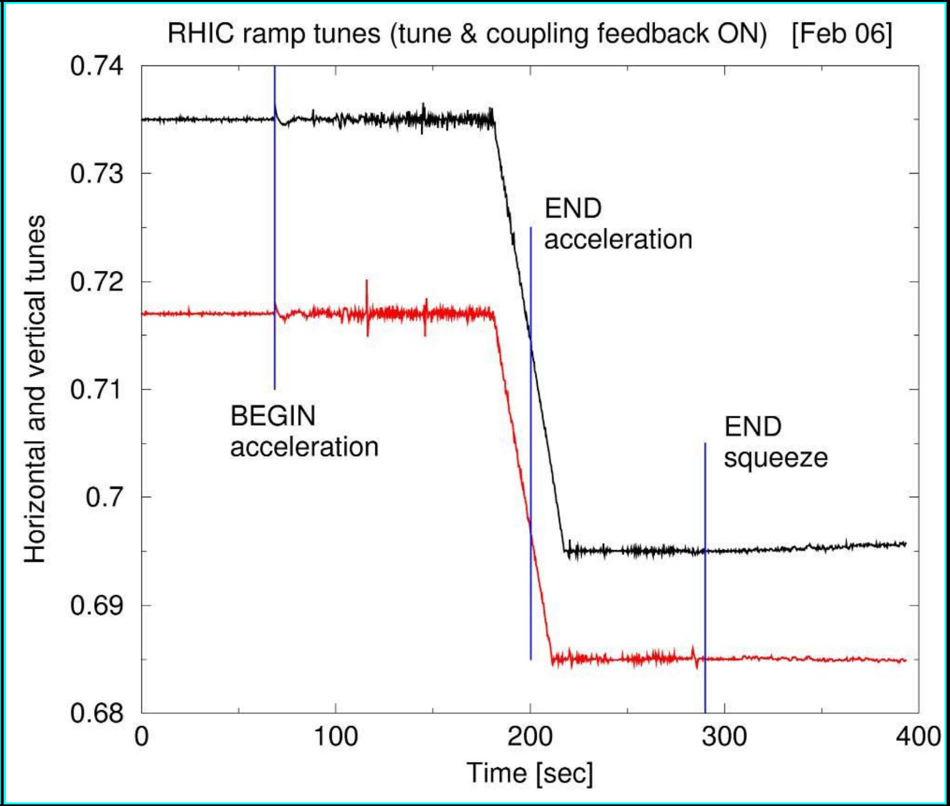
- Measurement from RHIC during acceleration cycle
  - At several points measured tune is defined by coupling
  - Tune feedback breaks down at these points
    - Need to correct coupling first



Coupling & Tune Feedback

- Coupling Feedback at RHIC
  - Measure coupling & feed-back on skew quadrupole families
    - Maintains a decoupled machine
  - Coupling & Tune feedback ON
    - Easily tracks & correct tune throughout acceleration cycle



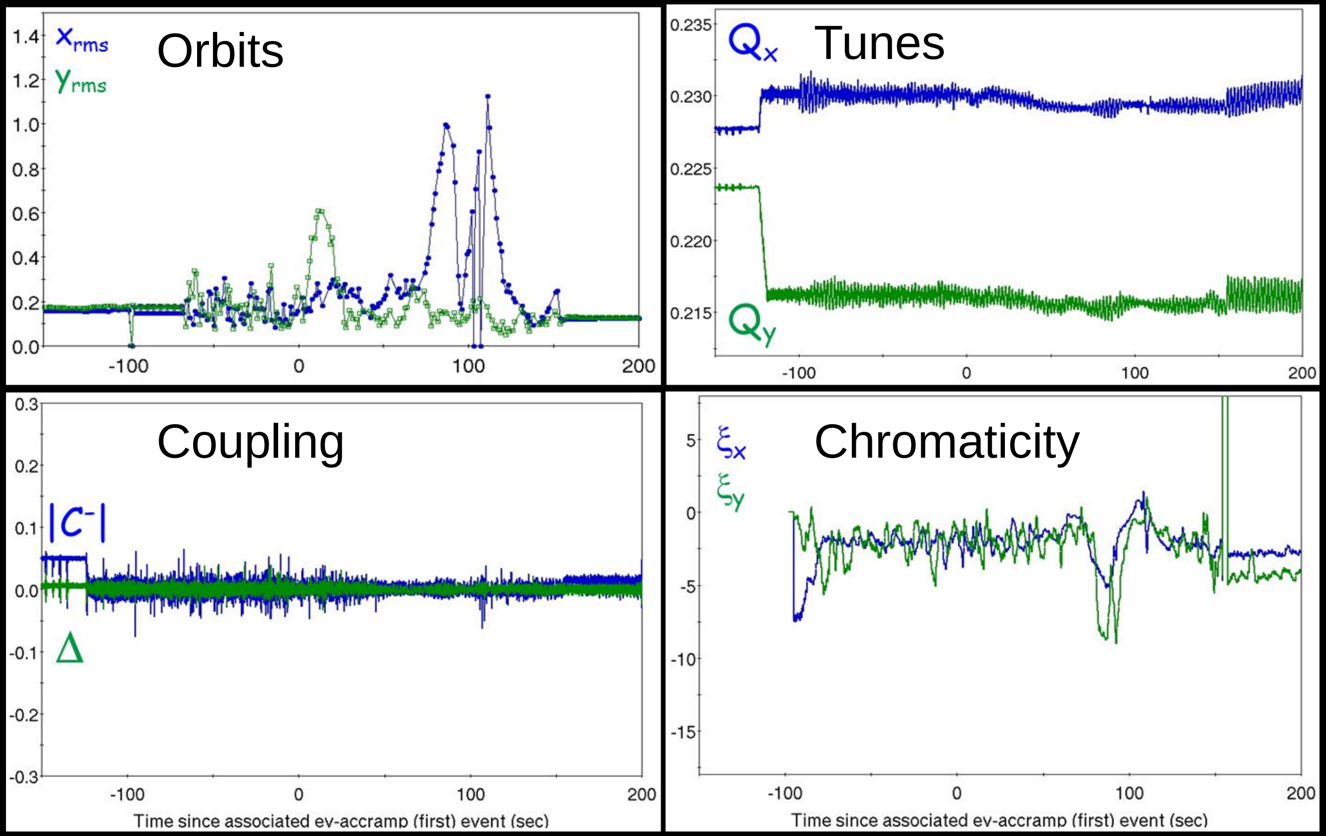


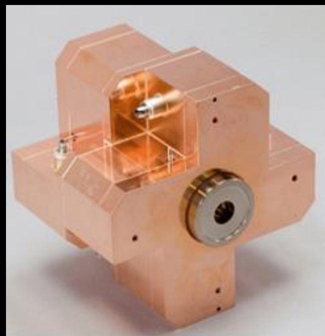
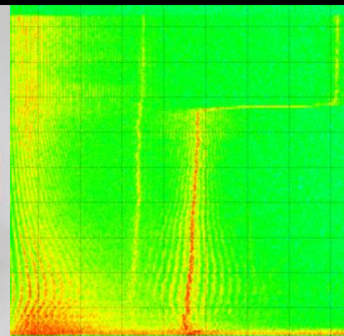
Full Beam Feedback at RHIC

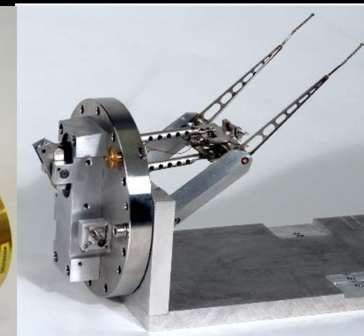
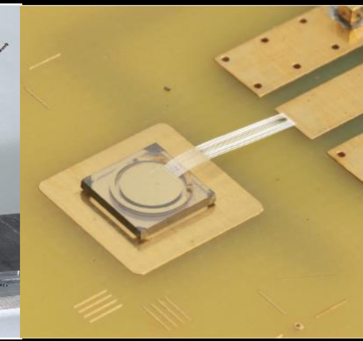
- Measurement Examples
  - Tune & coupling measured using BBQ & Phase Locked Loop
  - RF continuously modulated to obtain chromaticity
- First machine to simultaneously close 4 beam feedback loops

Feedback on:

- Orbit
- Tune
- Coupling
- Chromaticity



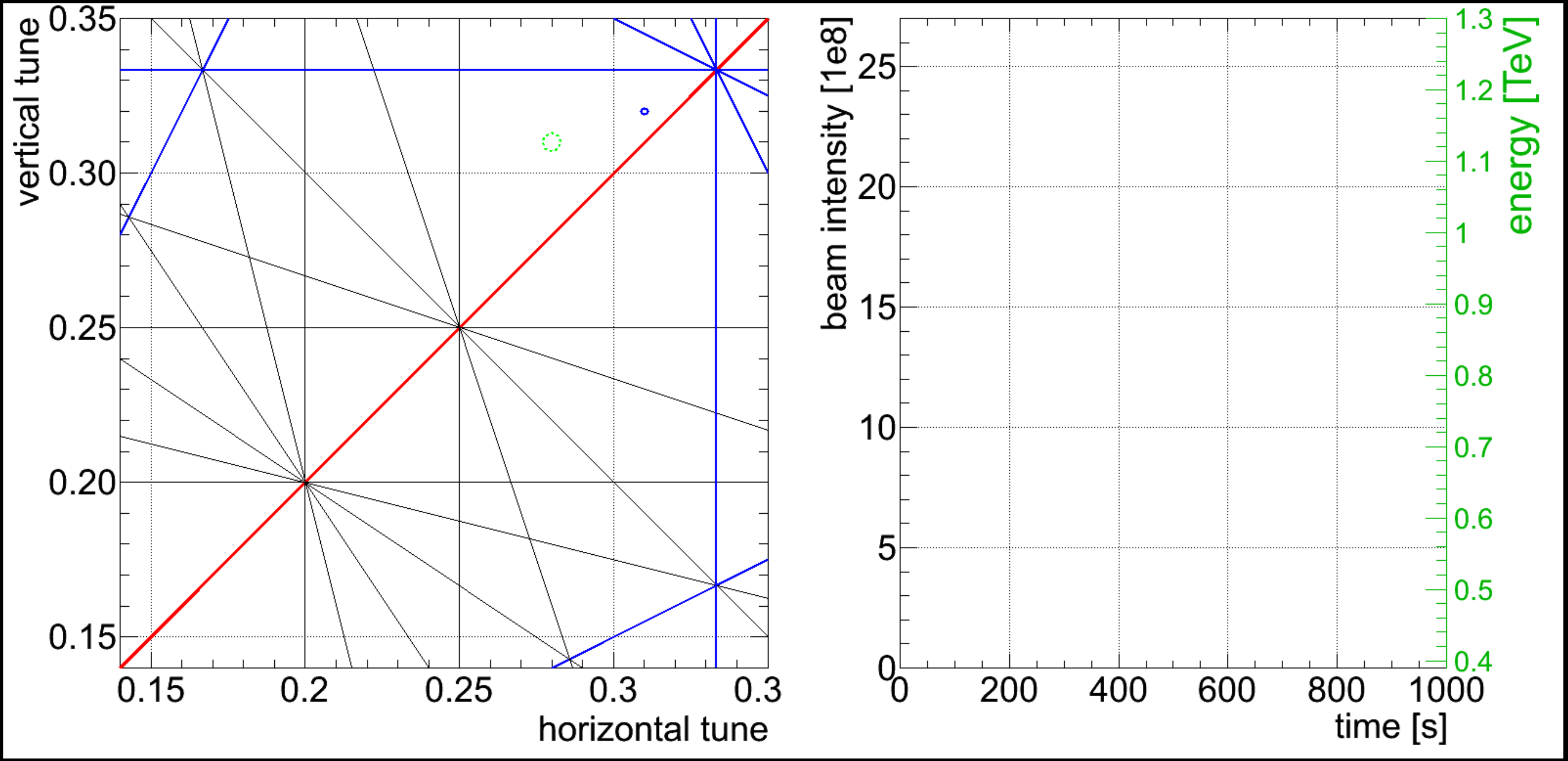



Understanding Tune Feedback Systems

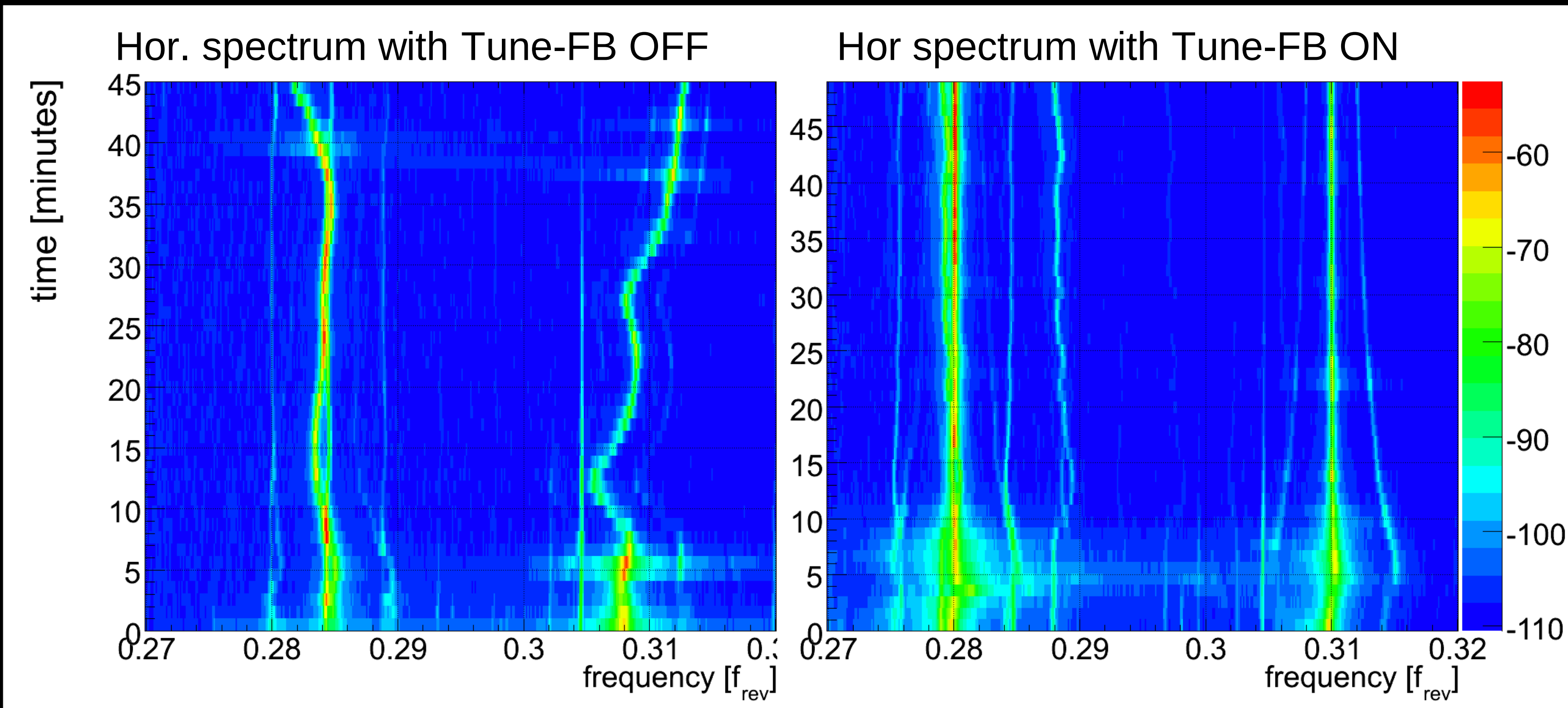
An LHC Example

Tune Measurement in the LHC

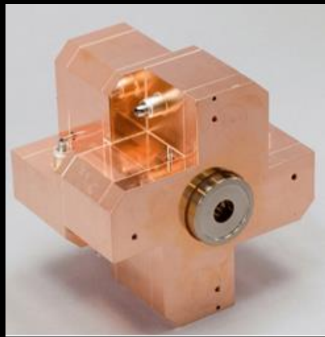
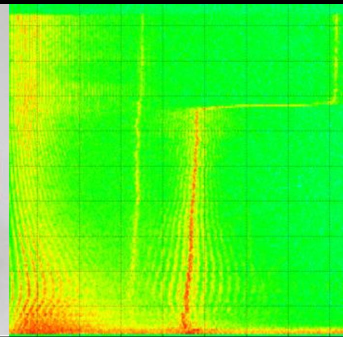


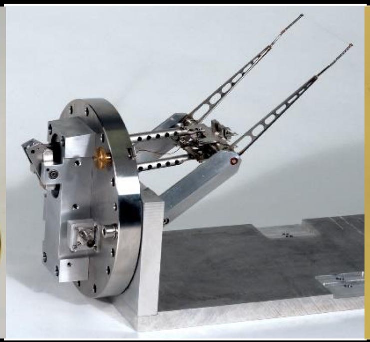
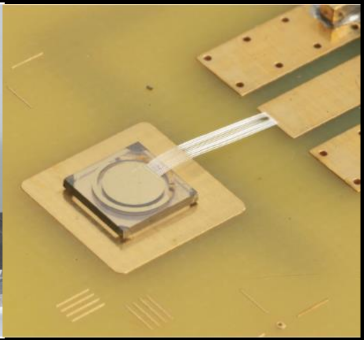
- Tune diagnostics throughout the ramp
  - Early ramps had poor tune control
  - Beam loss observed every time tune crossed a resonance line

Tune Feedback in the LHC



- Routinely used to compensate fill-to-fill variations
  - Uses peak fit on FFT from BBQ system with 0.1-0.3 Hz bandwidth
  - Feedback on trim quadrupoles

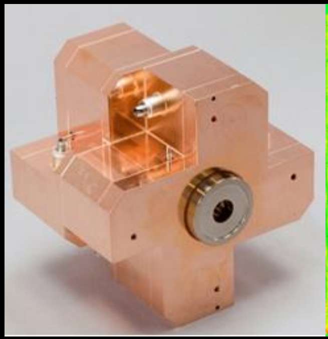
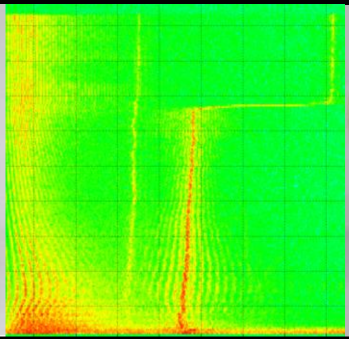



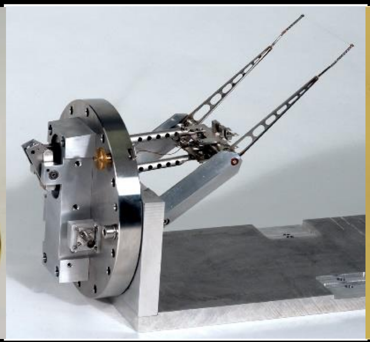
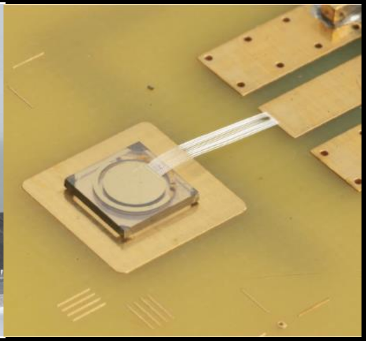
Understanding Tune Feedback Systems

A HERA Example

Feedback at HERA

- Real-Time operator Feedback on Tune, Chromaticity & Coupling
  - Using 6 joysticks : BLL – Brain Locked Loop!
    - Quadrupoles (H&V tunes)
    - Sextupoles (H&V chromaticity)
    - Skew quadrupoles (coupling)

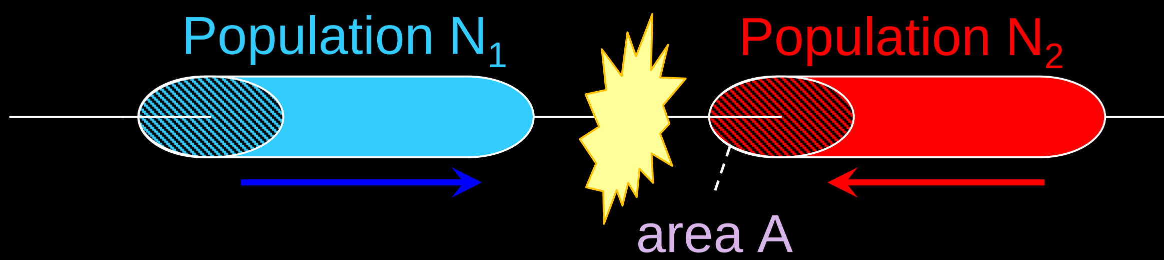
Luminosity Measurement

Collider Luminosity

- A key parameter for a collider is the event rate dN/dt
- For a physics process with cross-section σ it is proportional to Luminosity L

$$dN / dt = L\sigma$$

unit of L :
1/(surface × time)



$$\text{Collision rate} \propto \sigma \times \underbrace{\frac{N1 \times N2}{A} \times \text{encounters / second}}_{L}$$

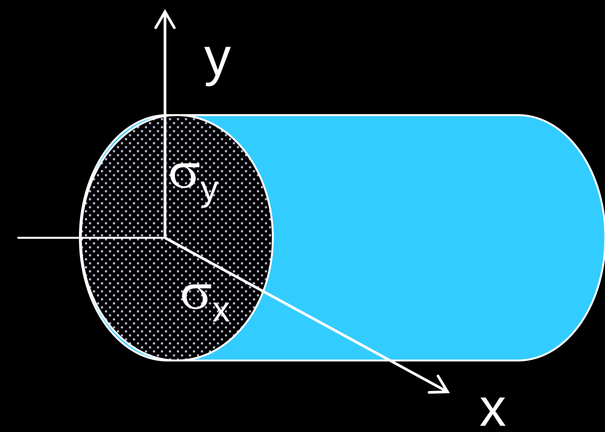
J. Wenninger (CERN)

Collider Luminosity

- Luminosity for equal particle populations & Gaussian profiles:
  - * refers to the interaction point (IP)

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

round beams



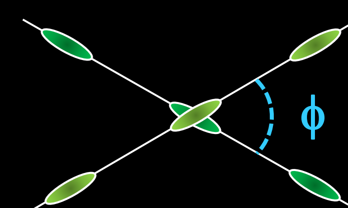
k, N, ε : beam properties

$\beta*$: property of the beam optics

F : beam dynamics

- *σ^*_x, σ^*_y : transverse rms beam sizes - $(\sigma^*)^2 = \beta^*\varepsilon$*
- *σ_s : longitudinal rms bunch length*
- *β^* : betatron (beam envelope) function ⇔ optics*
- *ε : beam emittance (phase space volume)*
- ***k** : number of particle packets / bunches per beam.*
- ***N** : number of particles per bunch.*
- ***f** : revolution frequency*
- ***F** : geometric correction factor (crossing angles...) :*
- *ϕ : crossing angle at the IP*

$$\frac{1}{F} = \sqrt{1 + \left(\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2}\right)^2}$$



J. Wenninger (CERN)

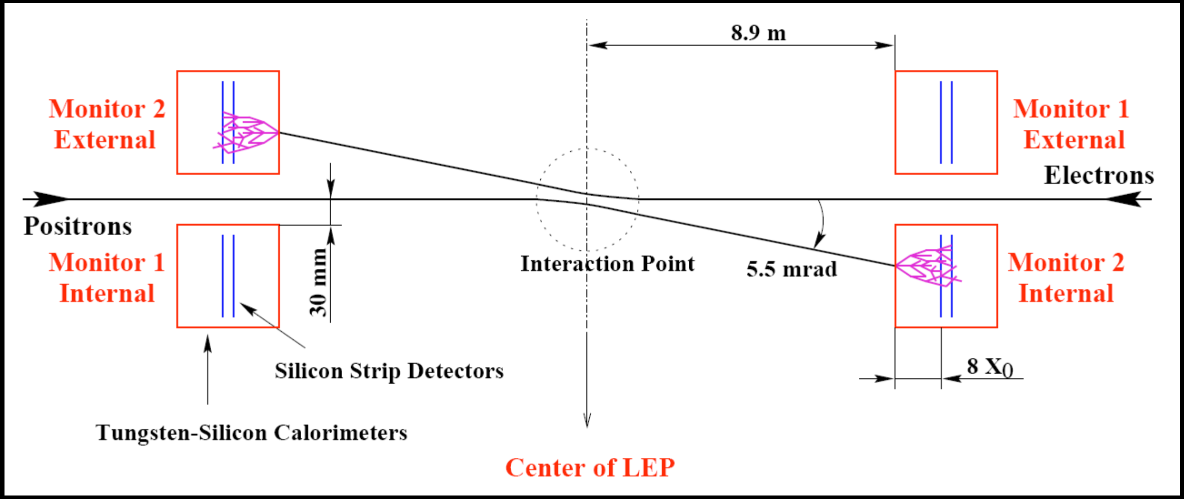
Collider Peak Luminosities

Machine	Beam type	Beam energy (GeV)	Luminosity ($cm^{-2}\ s^{-1}$)
LEP I	e^+e^-	45	2×10^{30}
LEP II	e^+e^-	90-104	$\sim 10^{32}$
SLC	e^+e^-	45	2.5×10^{30}
PEP-II	e^+e^-	9 and 3.1	1.2×10^{34}
KEKB	e^+e^-	8 and 3.5	2.1×10^{34}
superKEKB	e^+e^-	7 and 4	8×10^{35}
SppS	p p-bar	270	6×10^{30}
TEVATRON	p p-bar	980	2×10^{32}
RHIC	AuAu	100 (/nucleon)	$\sim 10^{27}$
LHC	pp	6’500	2×10^{34}
LHC	PbPb	2’760 (/nucleon)	$\sim 10^{27}$
FCC-ee	e^+e^-	45-175	2×10^{34} - 2×10^{36}
FCC-hh	pp	50’000	$\sim 10^{35}$
ILC	e^+e^-	45-250	10^{34} - 10^{35}

J. Wenninger (CERN)

Luminosity Measurement

- At e+e- colliders luminosity measured using small angle Bhabha scattering process $e^+ e^- \rightarrow e^+ e^-$
  - At very small angles (up to 100 mrad) this is process has a well known cross section dominated by the electromagnetic force
  - Provides high rates at the smallest angles
  - Accuracies of 0.1% achievable (detector alignment to 10's of μm required !)



Layout of Bhabha luminosity monitors at LEP

- At hadron colliders luminosity measured by event counting high rate processes
  - Very high rates BUT cross-sections often poorly known & complex experimental corrections required e.g. for high pile-up (many collisions per bunch crossing)
  - Accuracy of ~1% achievable when coupled to Van de Meer scan techniques.

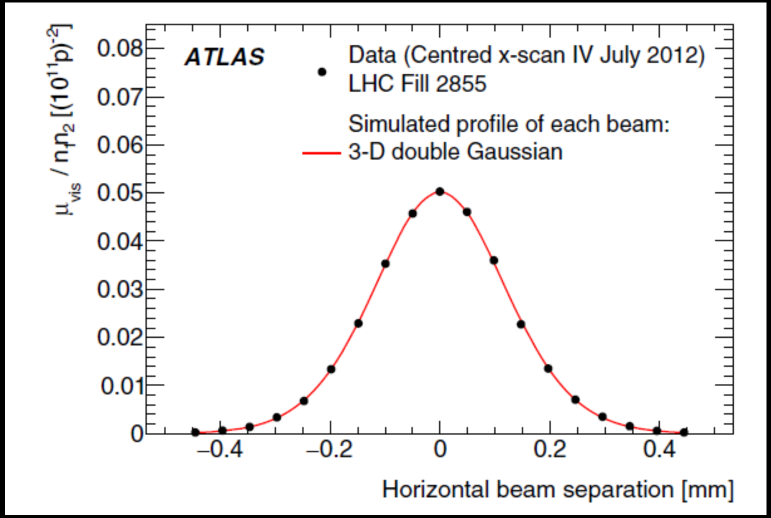
J. Wenninger (CERN)

Luminosity Optimisation

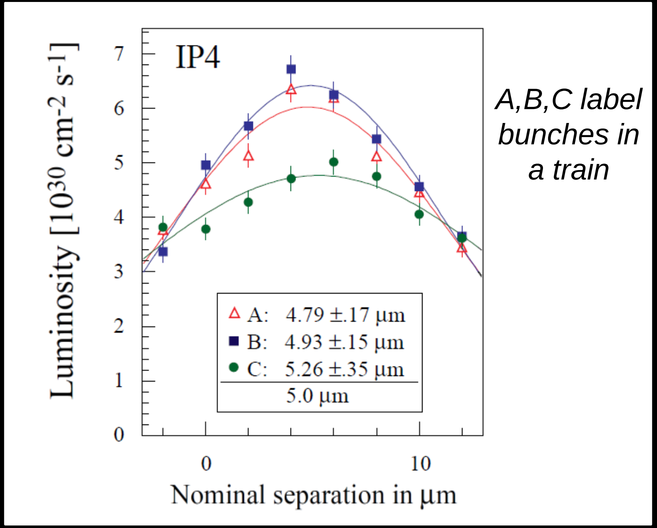
- To optimise beam overlap beams scanned across each other & event rate recorded
  - Fit (typically Gaussian) provides optimum head-on position & convoluted beam size at IP
  - Scan must be performed for both planes
- For equal sized beams luminosity dependence on beam separations Δx(y) given by:

$$L = \frac{kN_1N_2 f}{4\pi\sigma_x\sigma_y} \exp\left\{-\frac{\Delta x^2}{4\sigma_x^2} - \frac{\Delta y^2}{4\sigma_y^2}\right\} = L_0 \exp\left\{-\frac{\Delta x^2}{4\sigma_x^2} - \frac{\Delta y^2}{4\sigma_y^2}\right\}$$

Luminosity optimisation at LHC



Luminosity optimisation at LEP



A,B,C label bunches in a train

J. Wenninger (CERN)

Van de Meer Scans

- Van de Meer scan a variant of luminosity scan that provides an absolute measurement of the luminosity
  - Introduced by S. van de Meer at the CERN Intersecting Storage Rings (ISR)
- Concept based on observation that event rate (~ L) is given by:

$$N(\Delta x,\Delta y)=N_0\exp\left\{-\frac{\Delta x^2}{4\sigma_x^2}-\frac{\Delta y^2}{4\sigma_y^2}\right\}$$

$$\int N(\Delta x,\Delta y=0)d(\Delta x)=N_0\sqrt{4\pi}\sigma_x$$

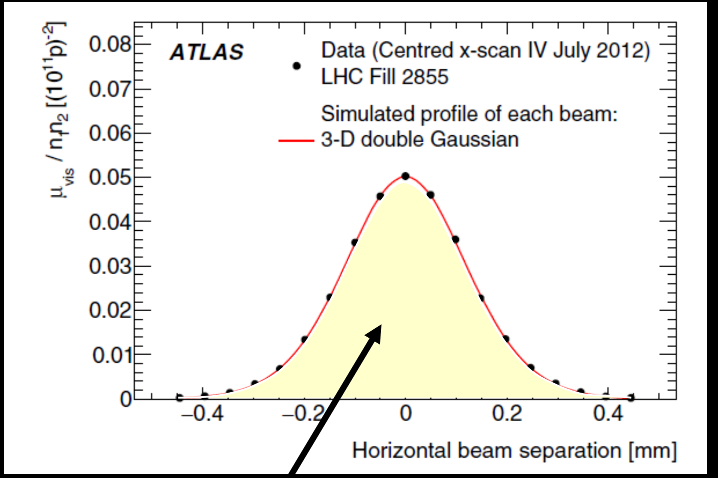
$$\int N(\Delta x=0,\Delta y)d(\Delta y)=N_0\sqrt{4\pi}\sigma_y$$

$$\frac{N_0}{\int N(\Delta x,\Delta y=0)d(\Delta x)}=\sqrt{4\pi}\sigma_x$$

$$\frac{N_0}{\int N(\Delta x=0,\Delta y)d(\Delta y)}=\sqrt{4\pi}\sigma_y$$

J. Wenninger (CERN)

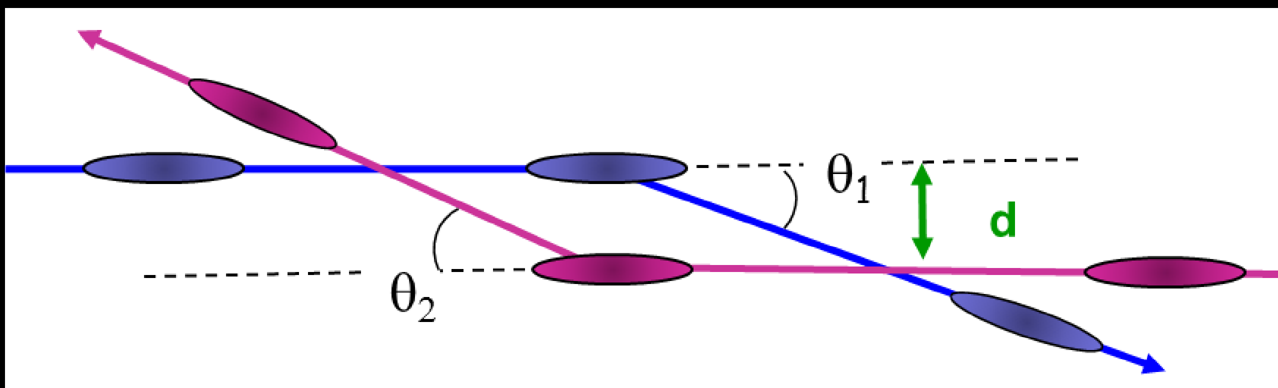
- Beam sizes can be extracted without need of an absolute 'rate' scale
  - Only the x,y scales must be known accurately
- If bunch populations are measured accurately absolute luminosity measurement possible from such scans
  - At LHC the errors on L are ~ 1-2%



Ratio of peak to area measures the beam size !

Beam-beam deflection

- Alternative for beam optimization at IP is beam-beam deflection scan
  - In particular for linear colliders
  - Rely on shape of beam-beam deflection to determine optimum beam overlap
  - Beam positon monitors on each side of IP used to reconstruct deflection angles θ1, θ2



Focusing lens for e^+e^-

Defocusing lens for pp

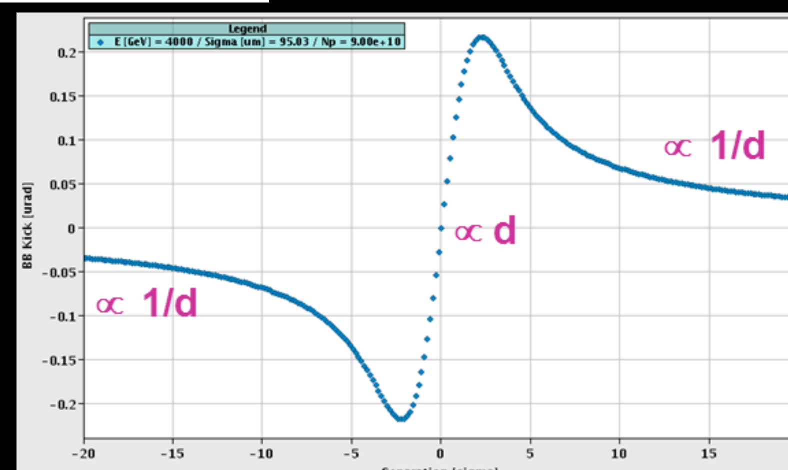
- For round beams the deflection is given by:

$$\theta_1(d)+\theta_2(d)=\theta_{BB}(d)=\pm\frac{4Nr_{p(e)}}{d\,\gamma}\left(e^{-d^2/4\sigma^2}-1\right)$$

$r_{p(e)}$: classical radius of the proton (electron)

Sign (±) : depends on relative beam charge

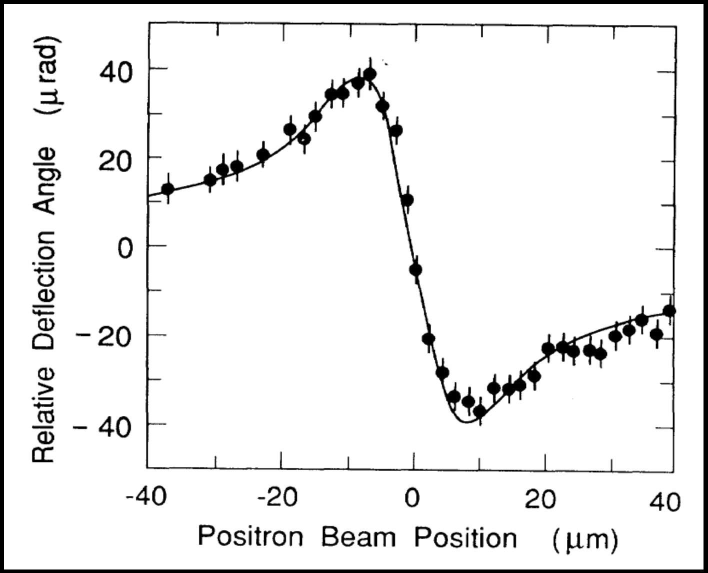
(- for pp, + for e^+e^-)



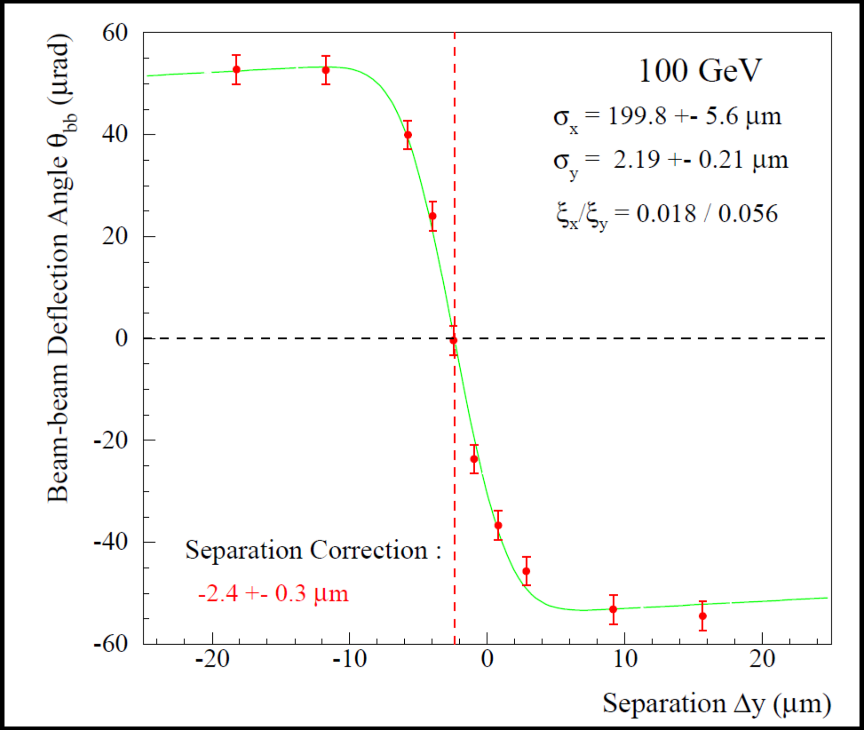
J. Wenninger (CERN)

Beam-beam Deflection Scans

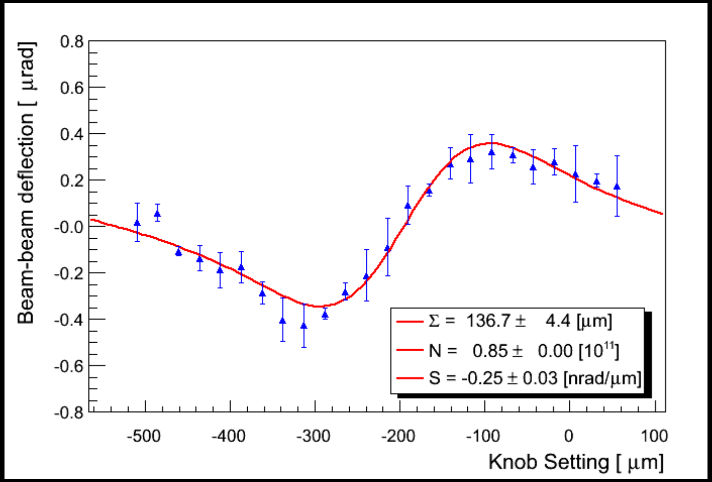
e+ BB deflection scan at SLC



Vertical BB deflection scan at LEP



BB deflection observation at LHC



*Note difference in **deflection scale** of ~100 between SLC/LEP and LHC due to much **larger beam-beam tune shift** ξ and **smaller** β******

The slope of the BB deflection is:

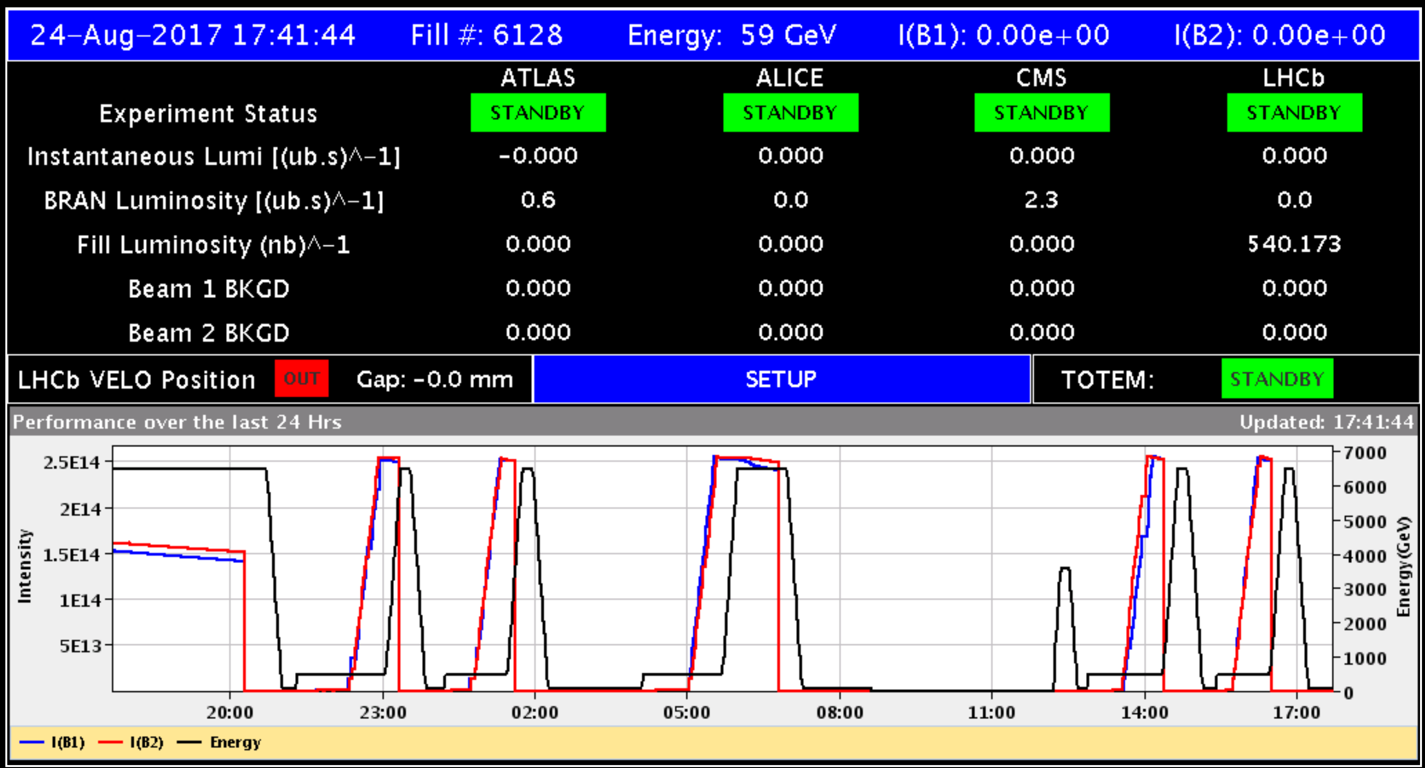
$$\frac{d\theta_{bb}}{du}(\theta_{bb}=0) = -\frac{4\pi\xi}{\beta^*}$$

Diagnosing Machine Issues using Beam Instrumentation

An LHC Example

Recent Example from LHC

- Beam continually lost due to losses
  - What is going on?



Dump #1 5.9TeV

RF issue

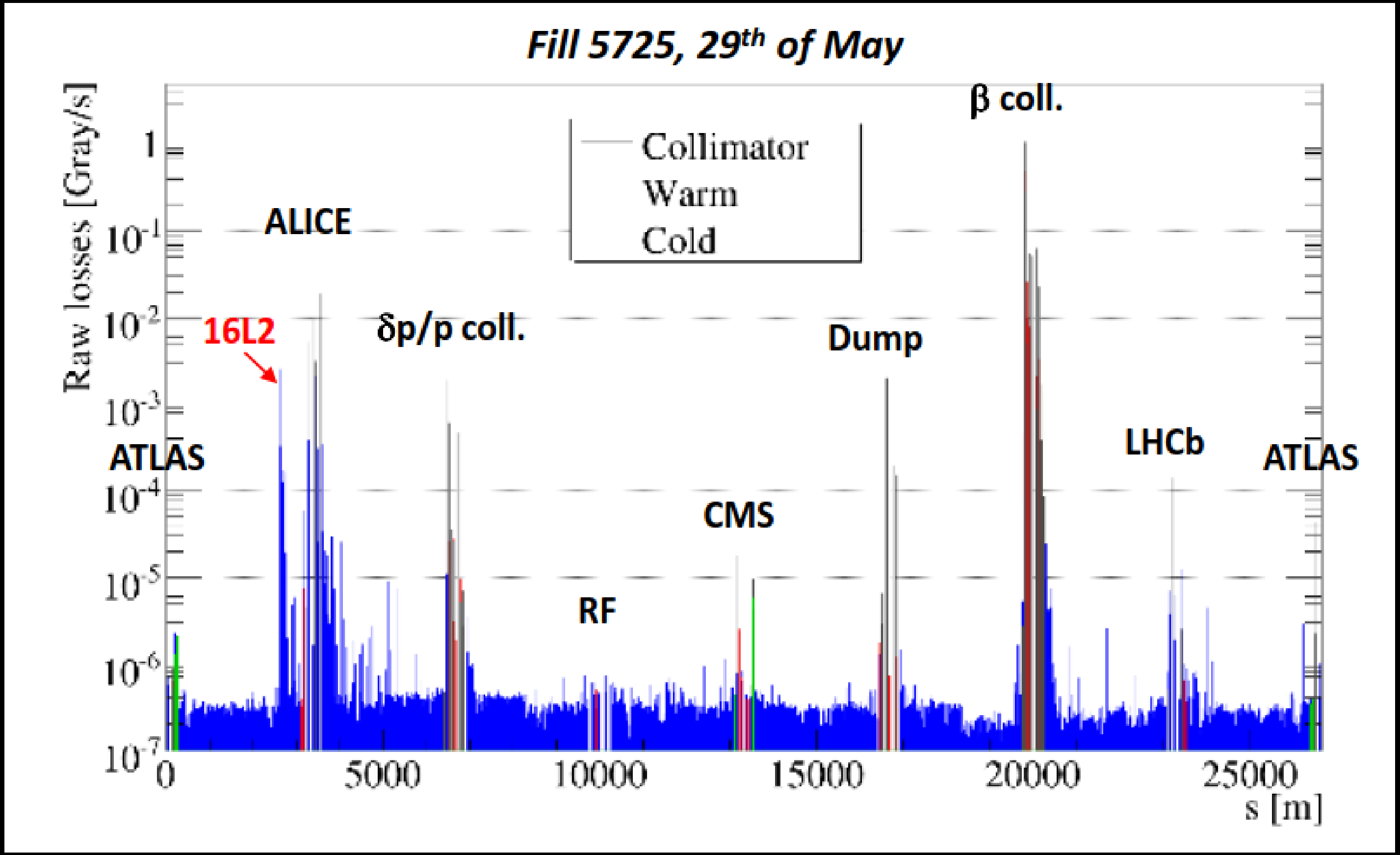
Dump #2 7TeV

Dump #3 0.9TeV

Dump #4 0.8TeV

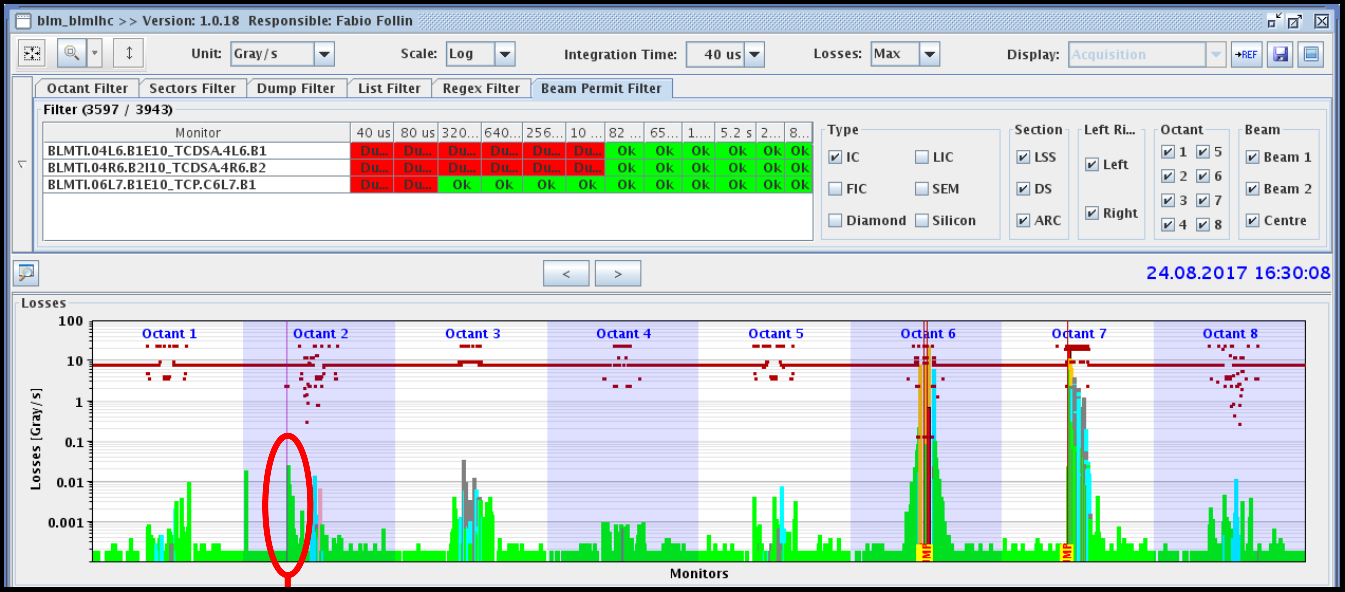
16L2 – First Event

- First beam dump event – as seen by the BLMs
  - Local aperture measurements did not reveal evident aperture restriction
  - Clear signature of losses from both beams
    - Both beams interacting with nuclei



BLM Diagnostics

- Time evolution of Losses

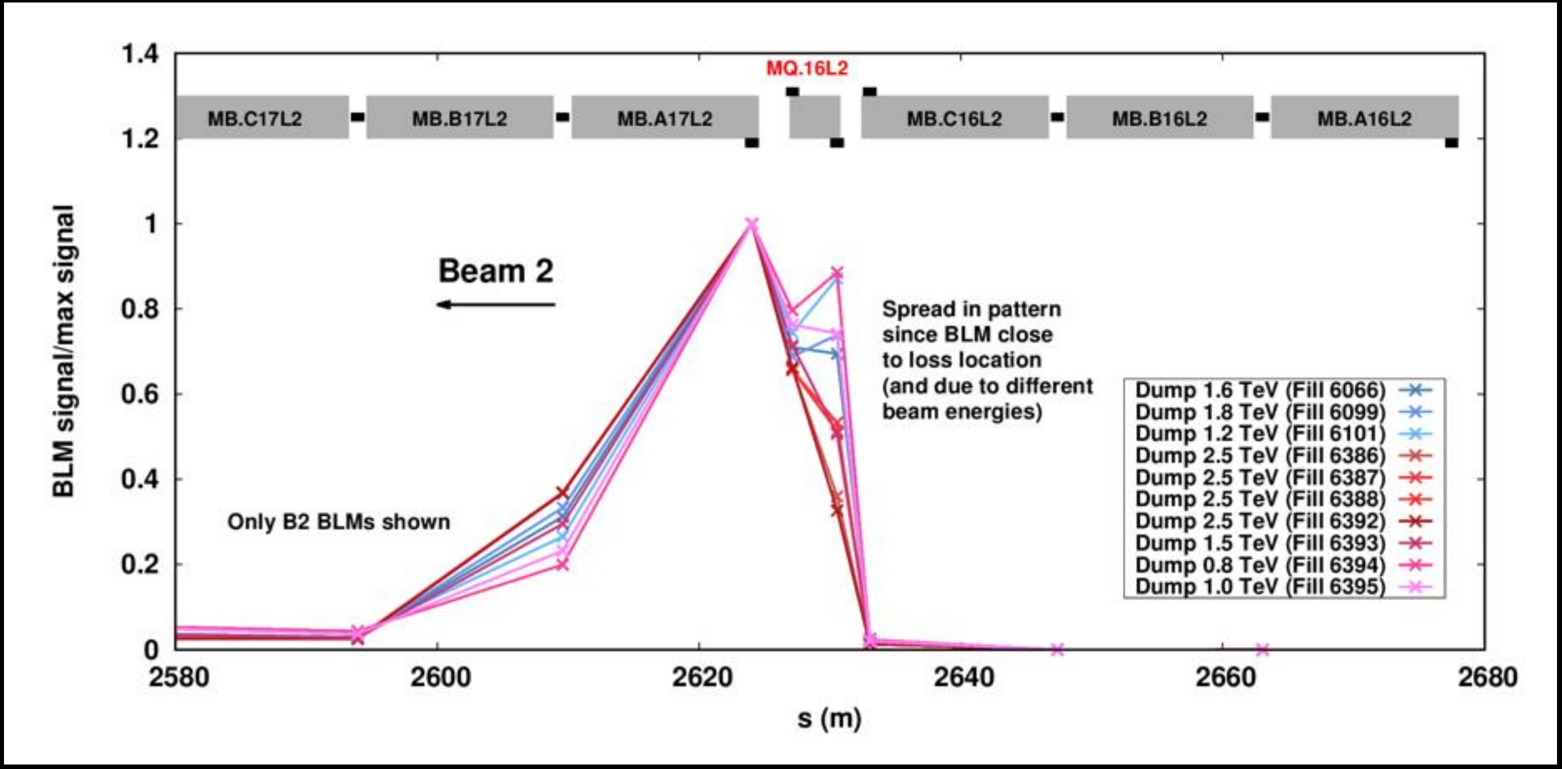


Looking for constant losses

- Installation of additional BLMs!
  - Factor 15 improvement in sensitivity

BLM Diagnostics

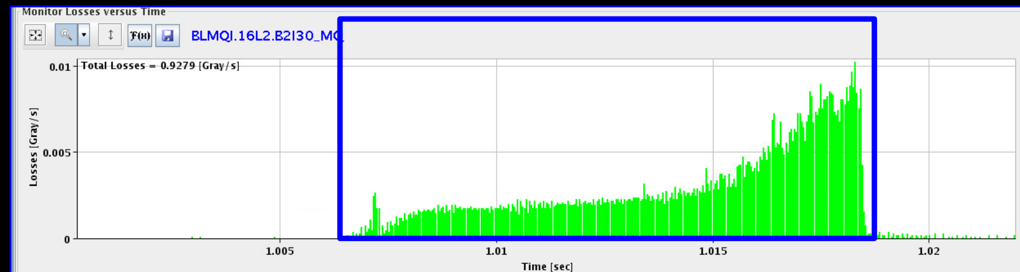
- Localisation
  - BLM Spatial patterns clearly show losses originate from one specific interconnection
    - MQ16L2 (Cell 16 left of LHC Point 2)
    - Localisation possible to within 1m comparing with simulation
  - Losses can be on either beam



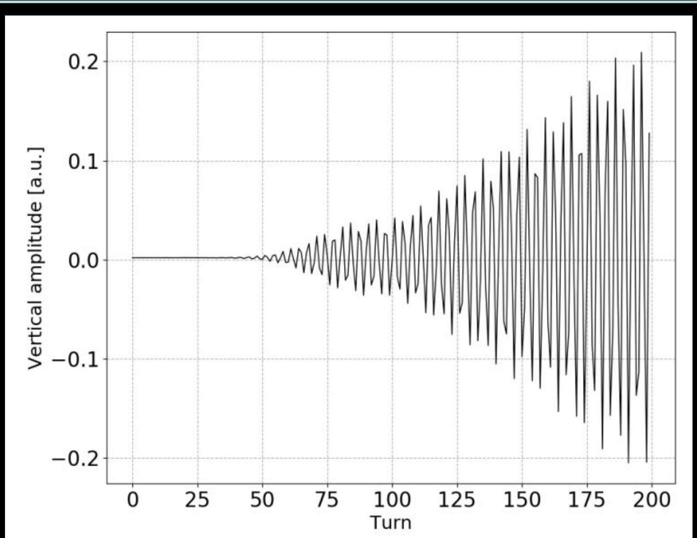
Additional Observations

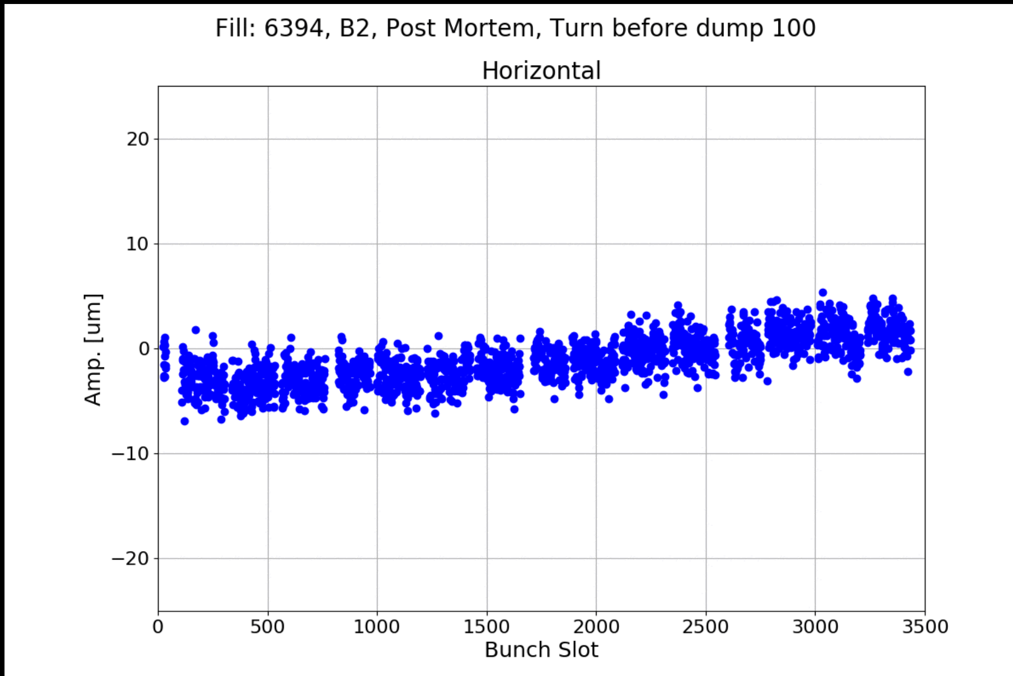
- Beam not always dumped by BLMs in 16L2
  - Often dumped by BLMs near primary collimators
    - Indicating development of transverse instability

Losses at BLM
12 ms from event to dump



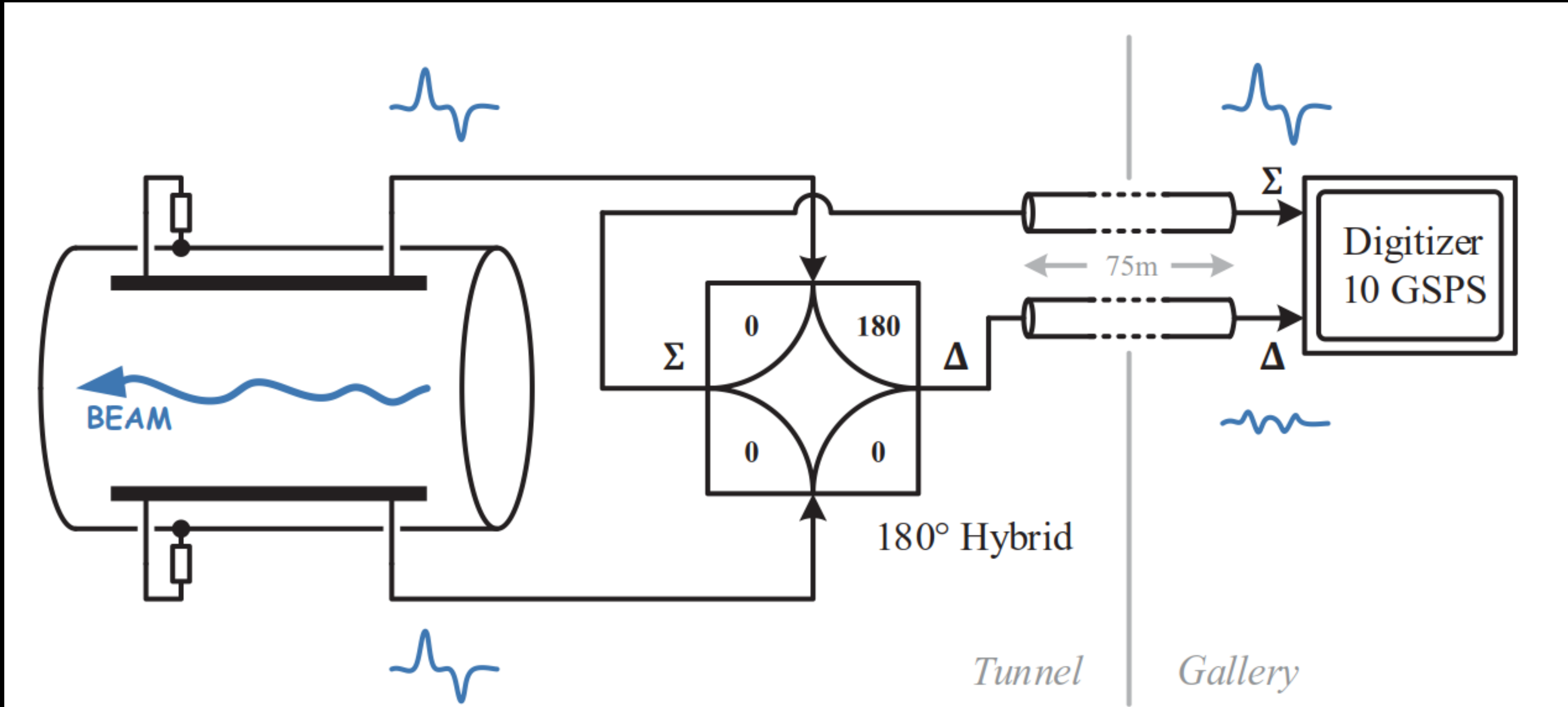
Bunch by bunch position from transverse damper BPMs





Other Diagnostics

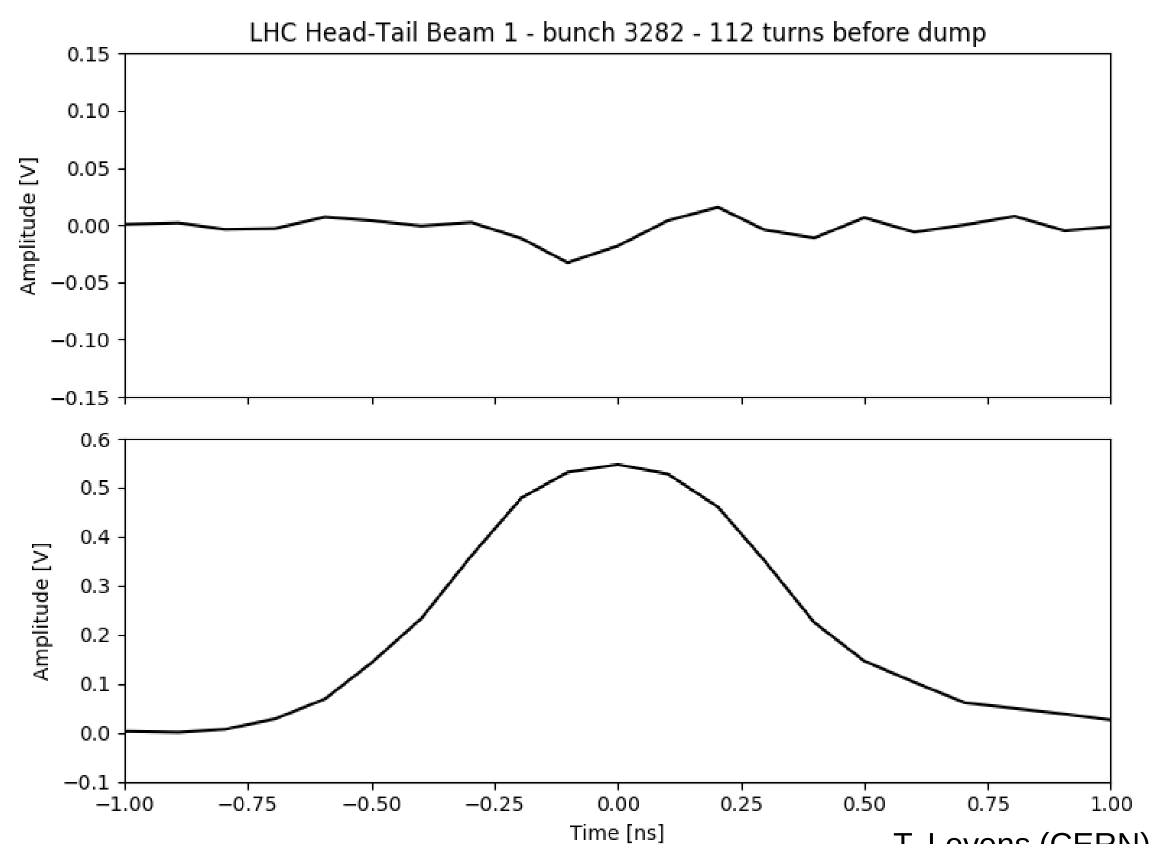
- Head-Tail Instability Monitor
  - Capable of detecting intra-bunch motion
  - Based on long stripline coupler beam position monitor



T. Levens (CERN)

Head-Tail Instability Monitor

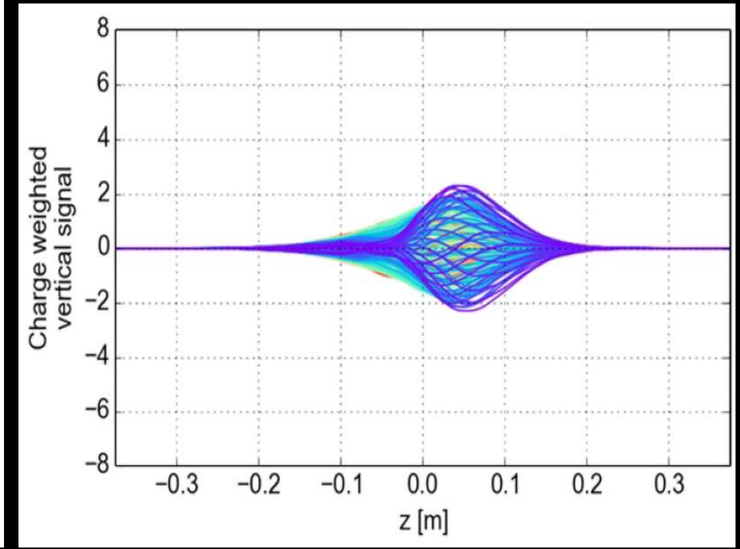
- Clearly shows instability in tail of bunch
  - Allowed simulations to try and re-create similar instability
  - Achieved when considering a large density of electrons over a short distance
    - Compatible with an ionised gas cloud



T. Levens (CERN)

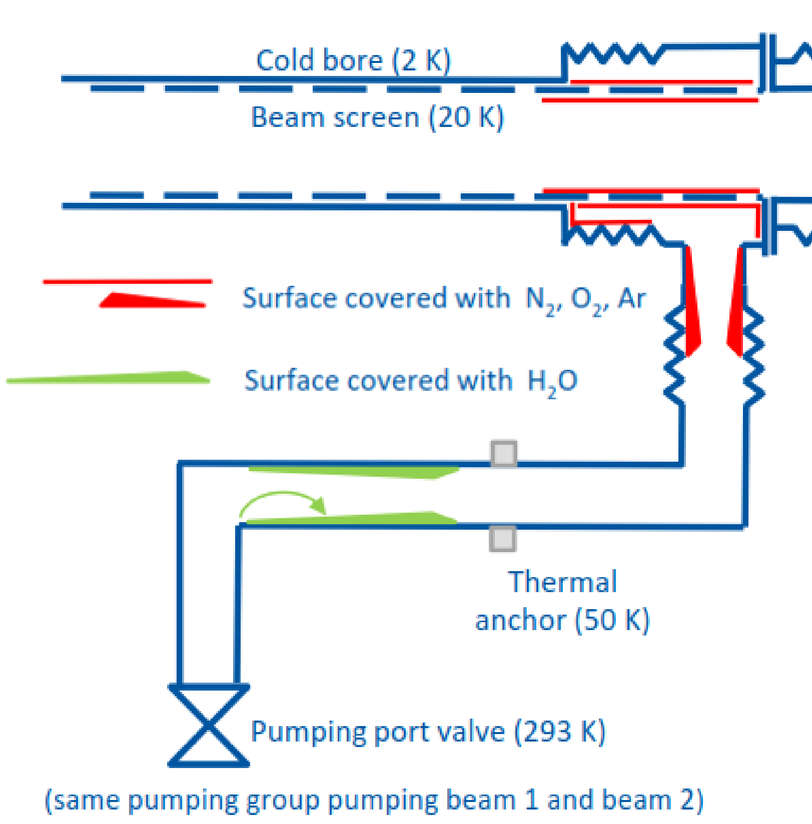
Measurement from head-tail monitor

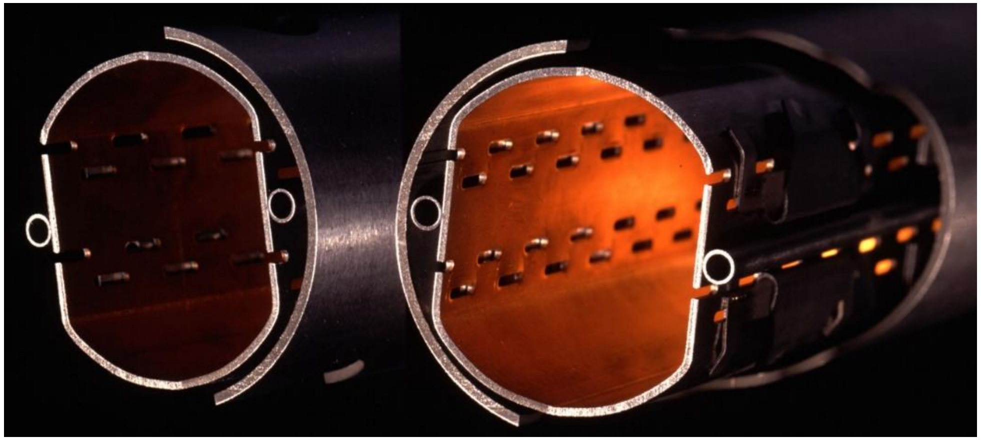
Simulation



16L2 - Hypothesis

- Something went wrong during vacuum pumpdown
  - Air trapped on beam screen & cold bore of both beams
    - Solid nitrogen & oxygen formed
  - Falls into the beam & immediately vaporised
    - Creates local pressure rise with beam interaction producing ionized gas cloud
    - Leads to losses & beam instability



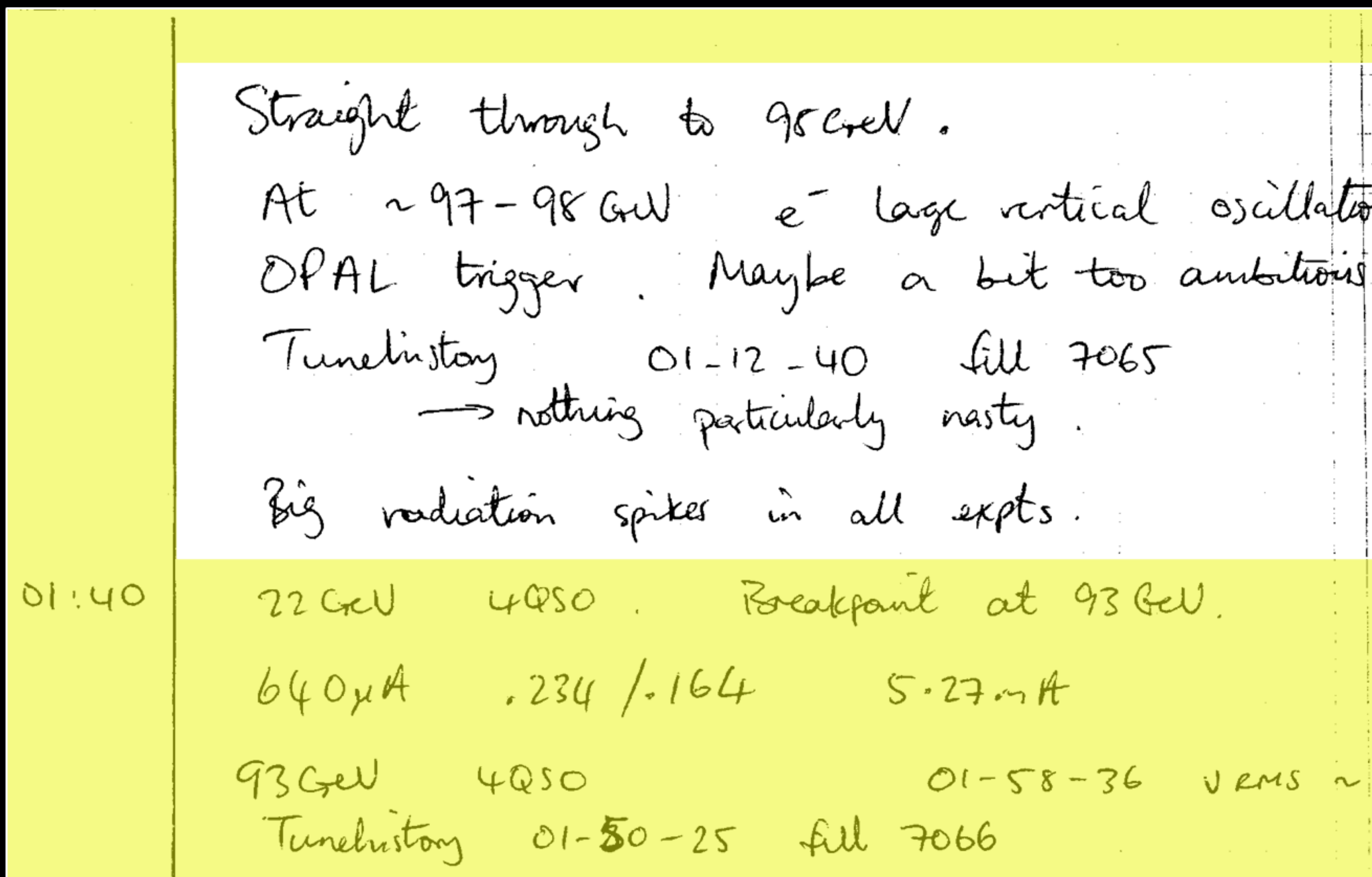


Diagnosing Machine Issues using Beam Instrumentation

Some LEP Examples

LEP Beams Lost During β-Squeeze

- Extract from LEP logbook (when pen & paper still used!)
  - OK when stepping through the β-squeeze slowly
  - Beams lost when attempting to go straight through



Straight through to 95 GeV.

At ~97-98 GeV e^- large vertical oscillation

OPAL trigger. Maybe a bit too ambitious

Tunelistory 01-12-40 fill 7065

→ nothing particularly nasty.

Big radiation spikes in all expts.

01:40 22 GeV 4QSO. Breakpoint at 93 GeV.

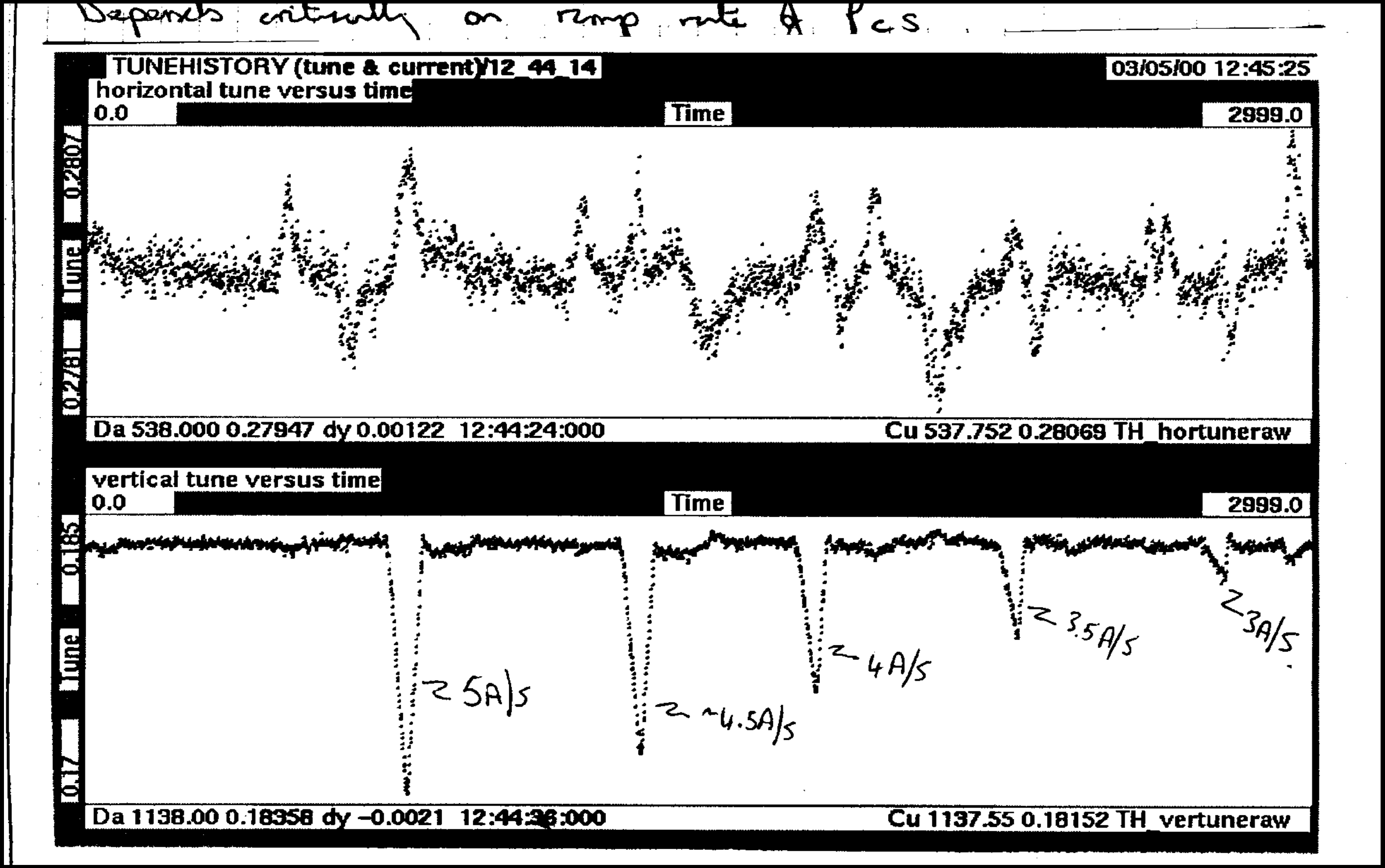
640μA .234/.164 5.27mA

93 GeV 4QSO 01-58-36 V RMS ~

Tunelistory 01-50-25 fill 7066

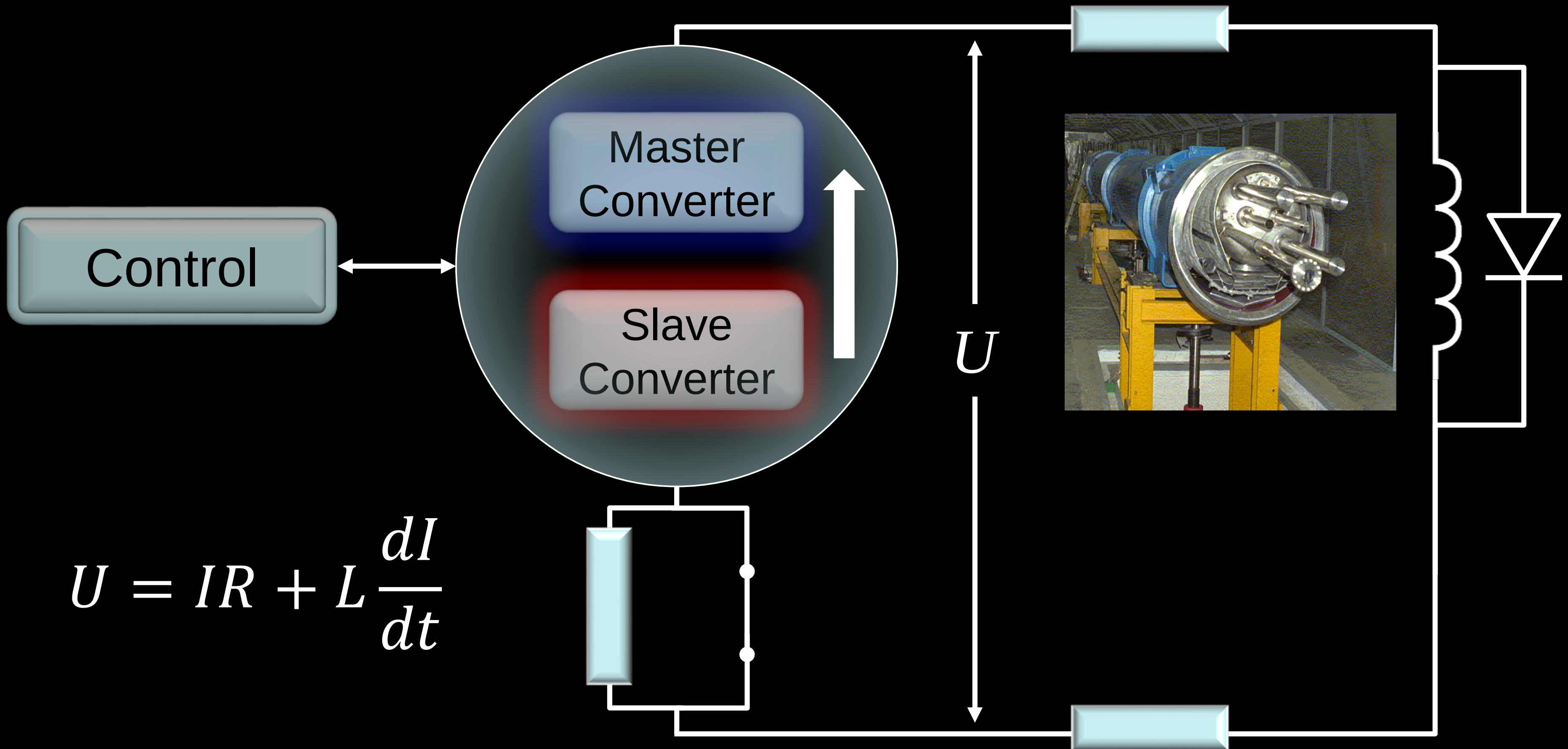
The Diagnostics

- Tune Variation
  - Tracked for different power converter ramp rates



The Explanation

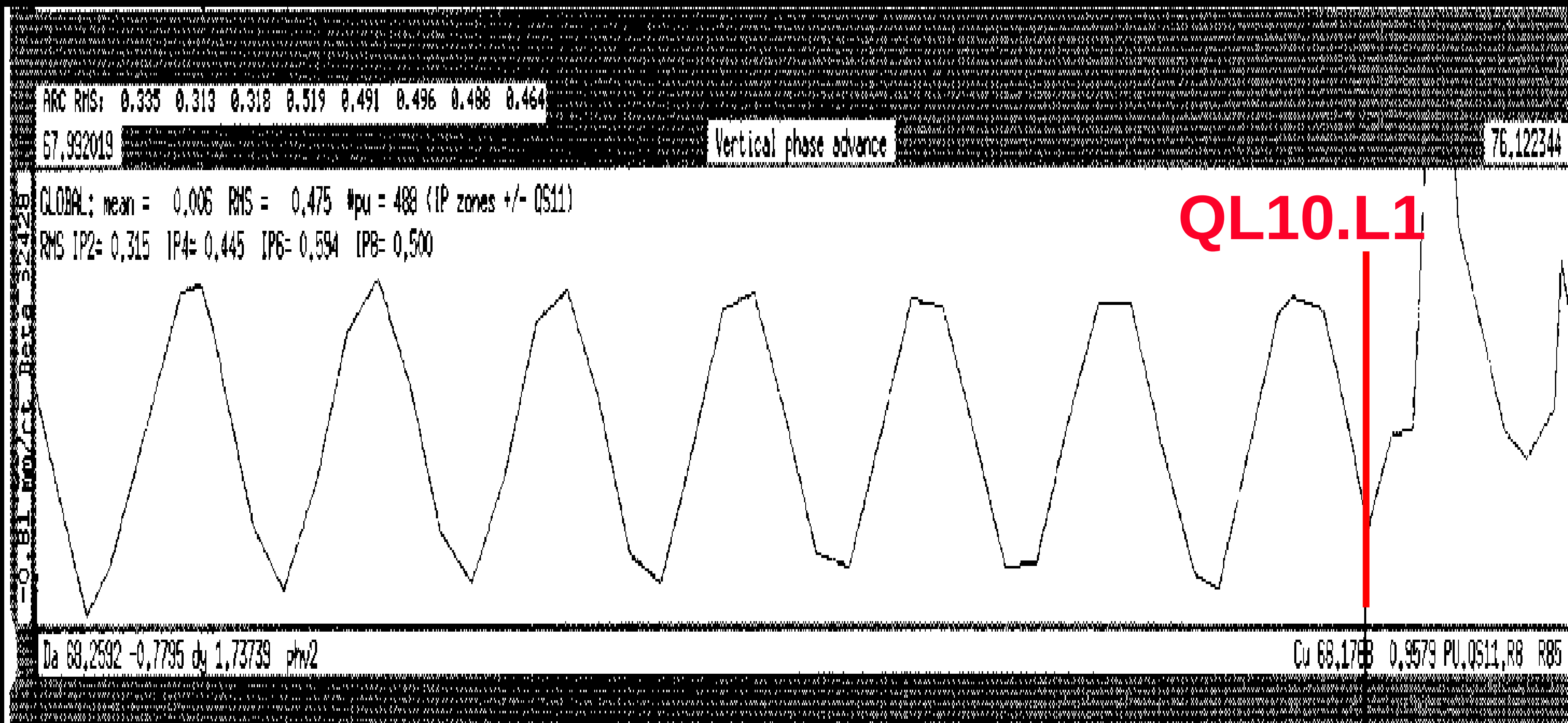
- Master-Slave Configuration for Power Converter
  - Each converter can deliver full DC current
  - Slave converter not working
    - Slave only needed to give increased voltage for fast current changes



$$U = IR + L\frac{dI}{dt}$$

LEP – No Circulating Beam

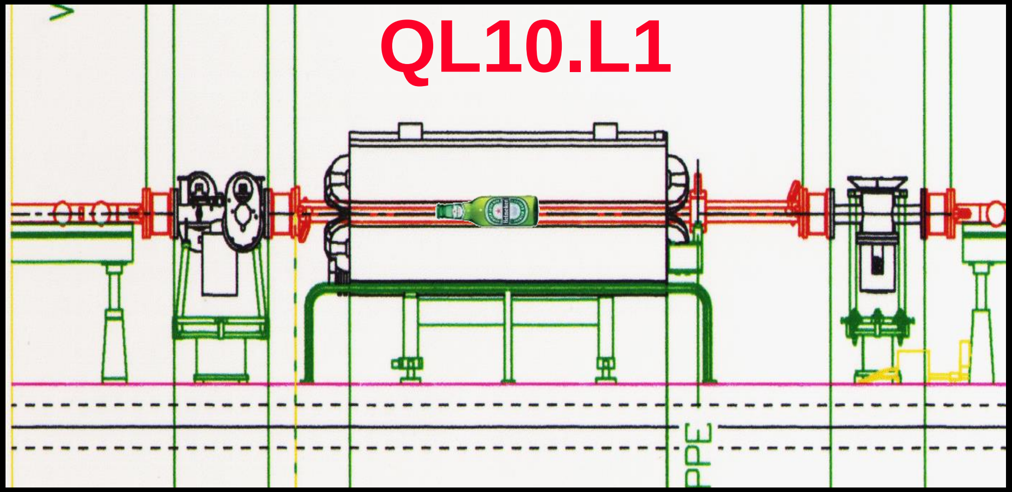
- No Circulating Beam after Technical Stop
  - Phase advance from BPMs show that optics no longer correct after specific quadrupole

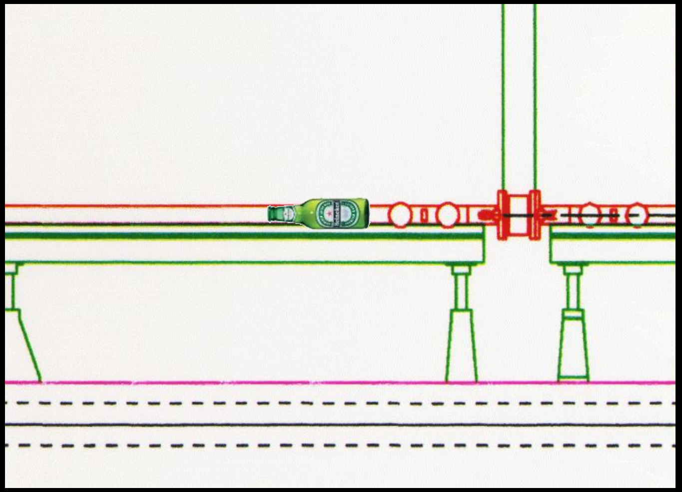


Positrons →

The Explanation

- After many trials - open vacuum chamber in QL10.L1
  - & 10m to the right ….





- Unsociable sabotage
  - Both bottles were empty!!

Summary

- Beam Instrumentation for Diagnostics
  - Basic functionality of a basic subset of instruments often sufficient for everyday operation
    - Orbit, tune, total intensity, global losses, …
  - Enhanced functionality & specialized systems essential when things don't go as planned
    - Especially true for "one of a kind" High Energy Colliders
  - For most machines the cost of instrumentation is a fraction (~1%) of the total cost
    - Should not be sacrificed when budgets become tight!
    - There is no such thing as over instrumenting a new machine!