LHC Beam Instrumentation

Particle Accelerator Conference 07

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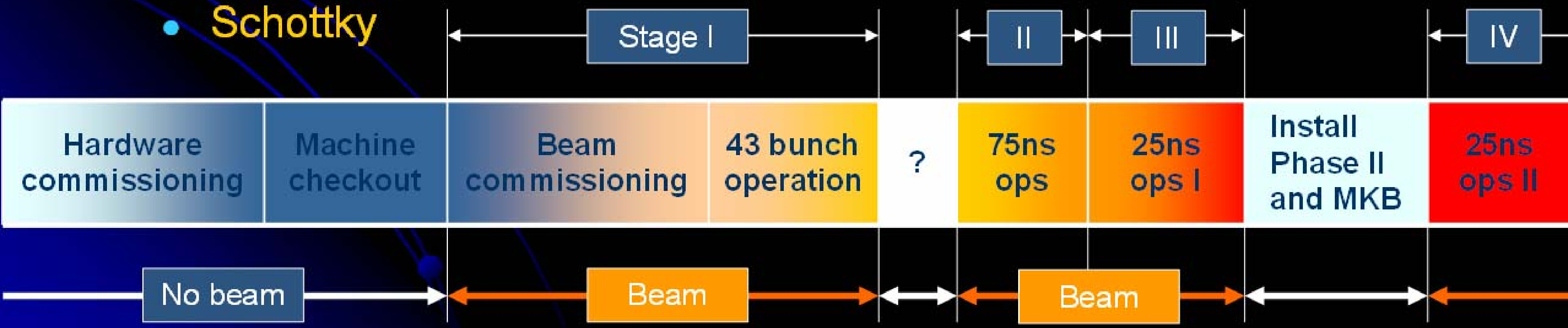
Overview

- What's Required & When
- Distributed Systems
  - Beam position measurement
  - Beam loss measurement
- Other Systems
  - Tune, chromaticity & coupling measurement
  - Collision rate measurement
  - Beam size measurement

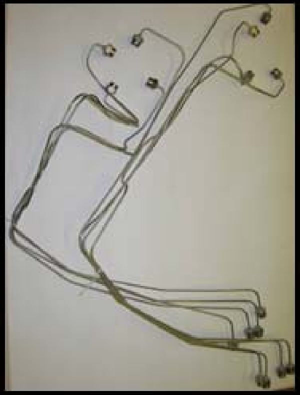
Instrumentation - what's required & when

- First turn
  - Screens, BPMs, fast BCT, BLMs
- Circulating beams at 450 GeV
  - DC BCT & lifetime
  - Tune Coupling & Chromaticity
  - Emittance: wire scanners
- Snapback and Ramp
  - Continuous Orbit, Tune, Coupling & Chromaticity (+ feedback)
  - Continuous emittance monitoring: synchrotron light, IPM
- First Collisions
  - Luminosity
  - Schottky

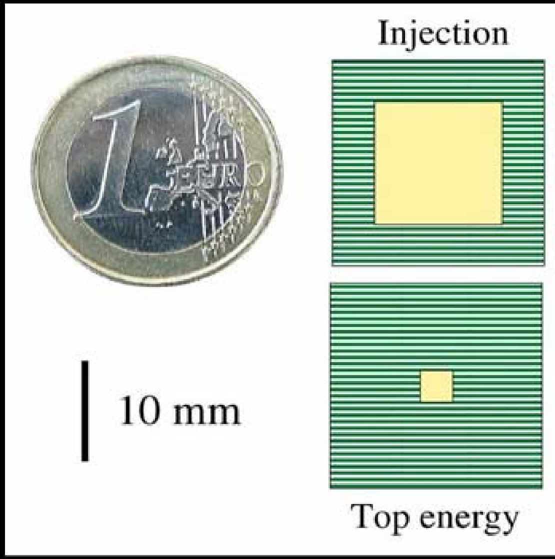


Beam Position System Challenges

- Pick-up requirements
  - Mechanics that can operate at ~4K
  - Maximise aperture & signal strength
  - Minimise transverse impedance



- Dynamic Range
  - From 1 bunch of 1×10^9 charges to 2808 bunches of 1.7×10^{11} charges
- Linearity
  - Better than 1% of half radius, ~130μm for arc BPMs
    - Over whole intensity range
    - Over large fraction of the aperture
- Resolution
  - In the micron range for accurate global orbit control
    - Driven by collimation requirements
    - Over 120 collimator jaws in the LHC



BPM Acquisition Electronics

Amplitude to Time Normaliser

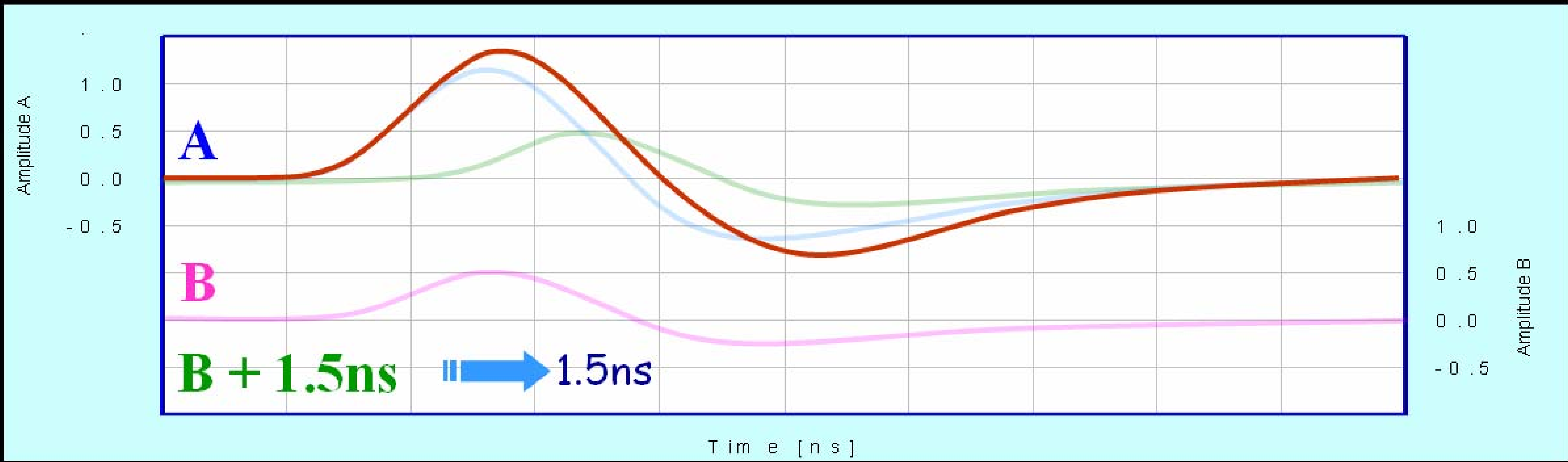
Advantages

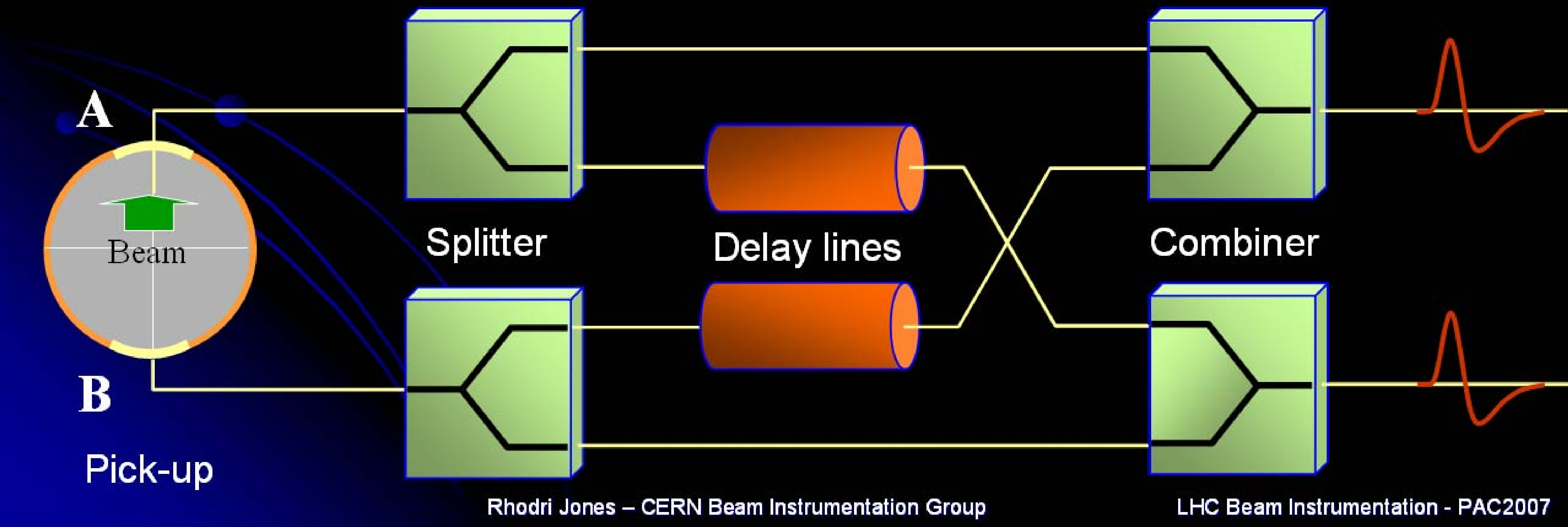
- Fast normalisation (< 25ns)
  - bunch to bunch measurement
- Signal dynamic independent of the number of bunches
  - Input dynamic range ~45 dB
  - No need for gain selection
- Reduced number of channels
  - normalisation at the front-end
- ~10 dB compression of the position dynamic due to the recombination of signals
- Independent of external timing

Limitations

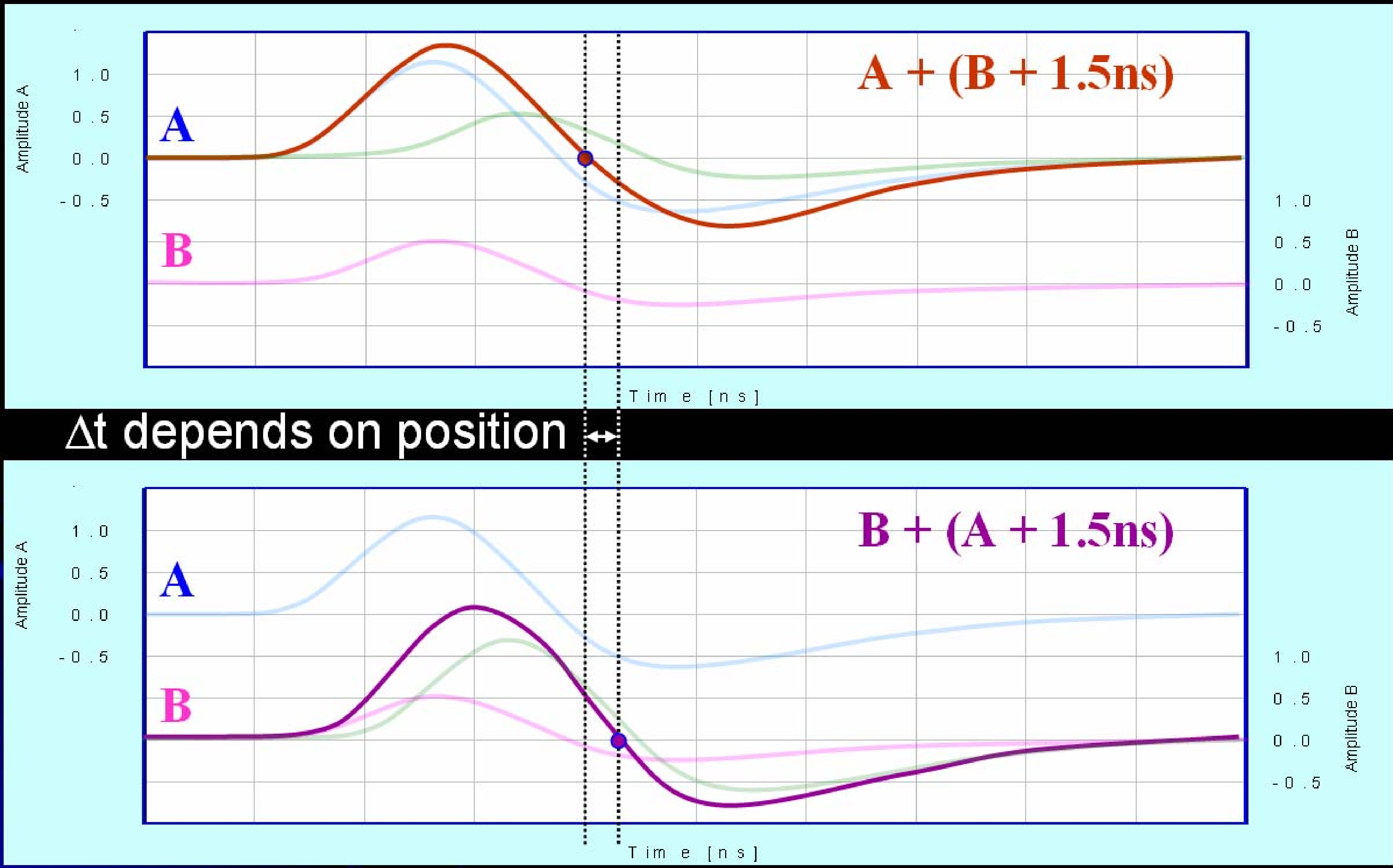
- Currently reserved for beams with empty RF buckets between bunches
  - LHC 400MHz RF but 25ns spacing
  - 1 bunch every 10 buckets filled
- Tight time adjustment required
- No Intensity information
- Propagation delay stability and switching time uncertainty are the limiting performance factors

The Wide Band Time Normaliser

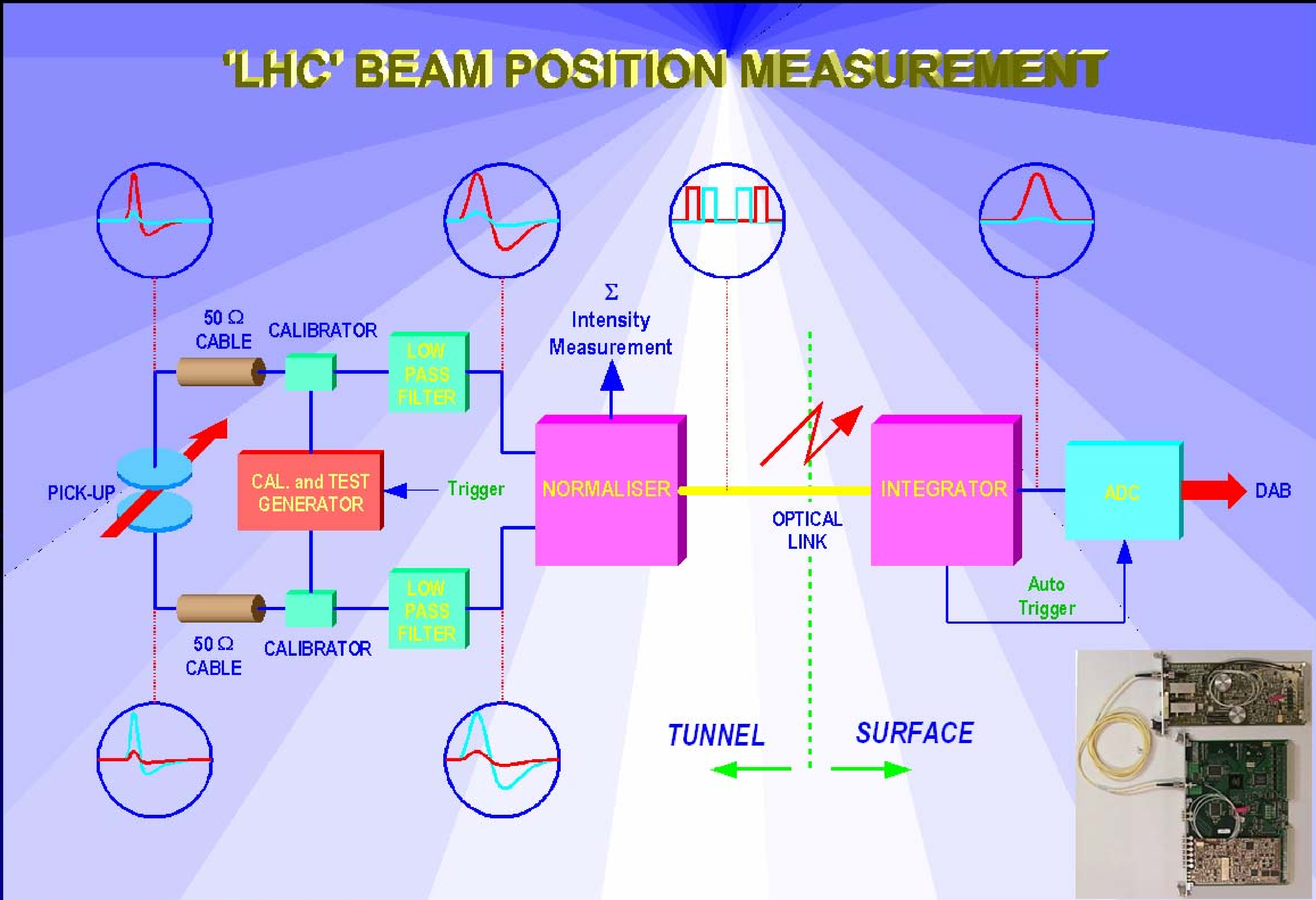




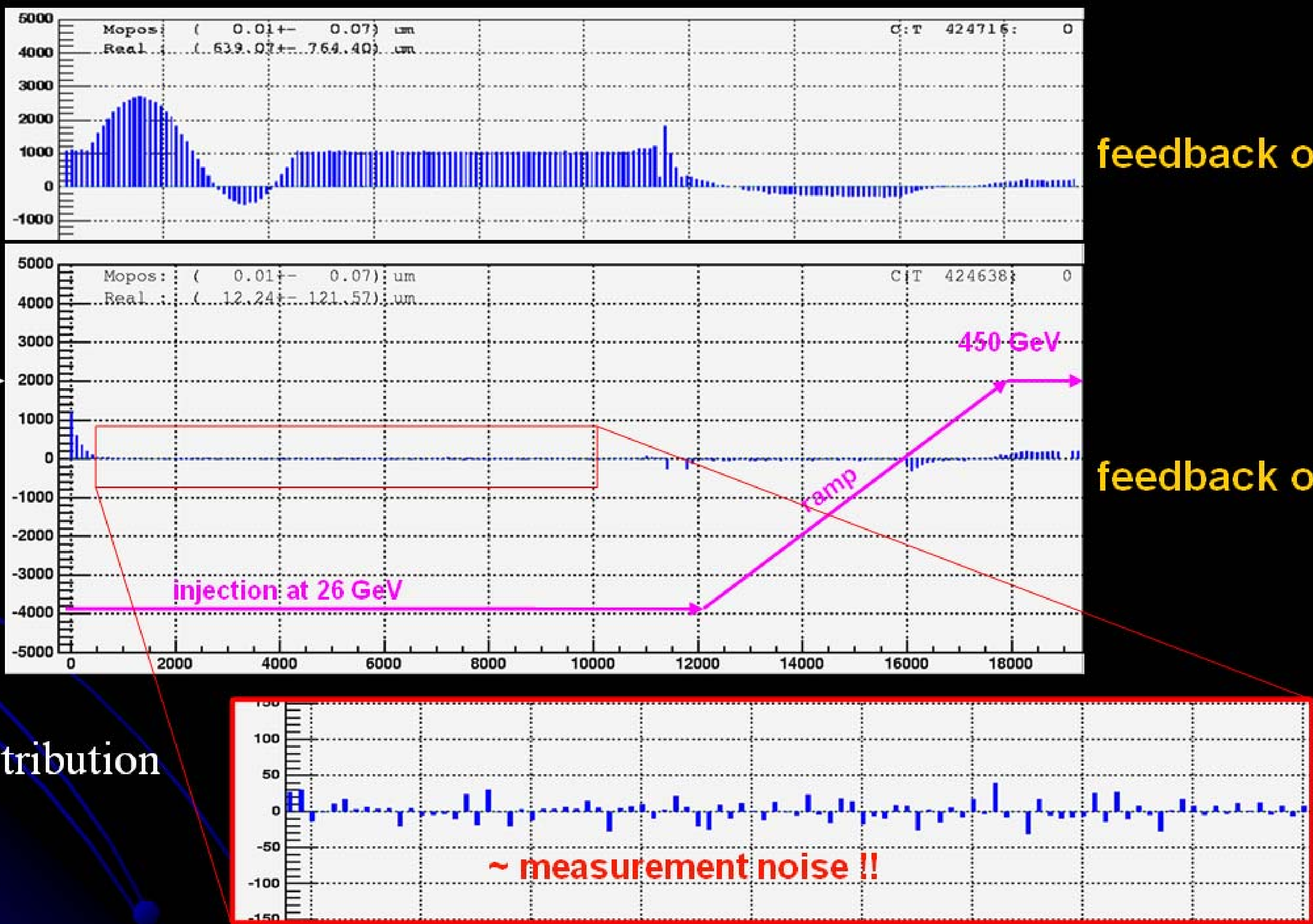
The Wide Band Time Normaliser



LHC Beam Position System Layout



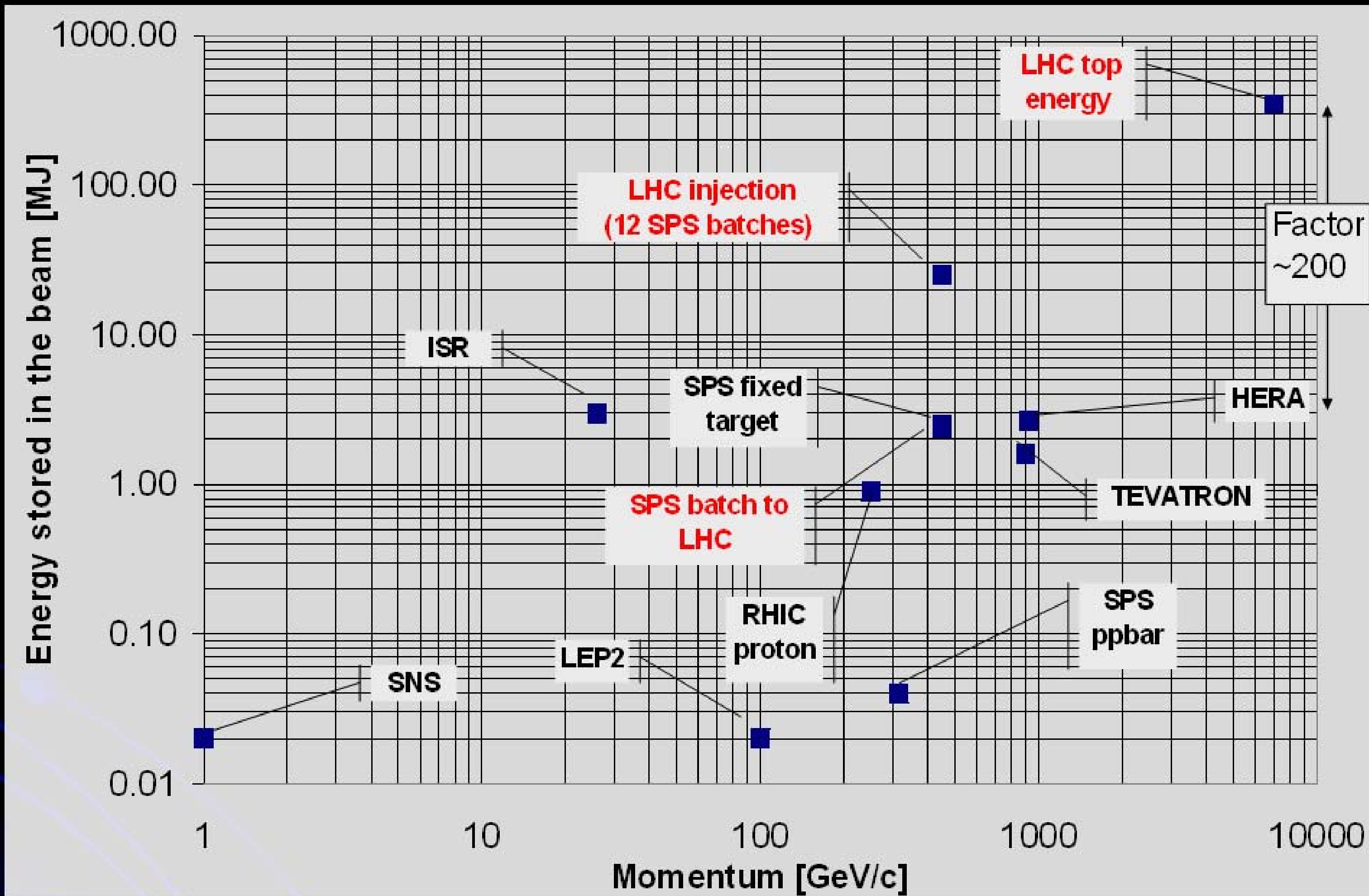
Orbit feedback results from the CERN-SPS



Position distribution
@ 100 Hz
$\sigma = 8.5\ \mu m$

The LHC Beam Loss System

Coping with a Huge Stored Beam Energy



Quench Levels	Units	*Tevatron*	*RHIC*	*HERA*	*LHC*
***Instant loss* (0.01-10 ms)**	[J/cm³]	$4.5\ 10^{-03}$	$1.8\ 10^{-02}$	$2.1\ 10^{-03}$ - $6.6\ 10^{-03}$	$8.7\ 10^{-04}$
***Steady loss* (> 100 s)**	[W/cm³]	$7.5\ 10^{-02}$	$7.5\ 10^{-02}$		$5.3\ 10^{-03}$

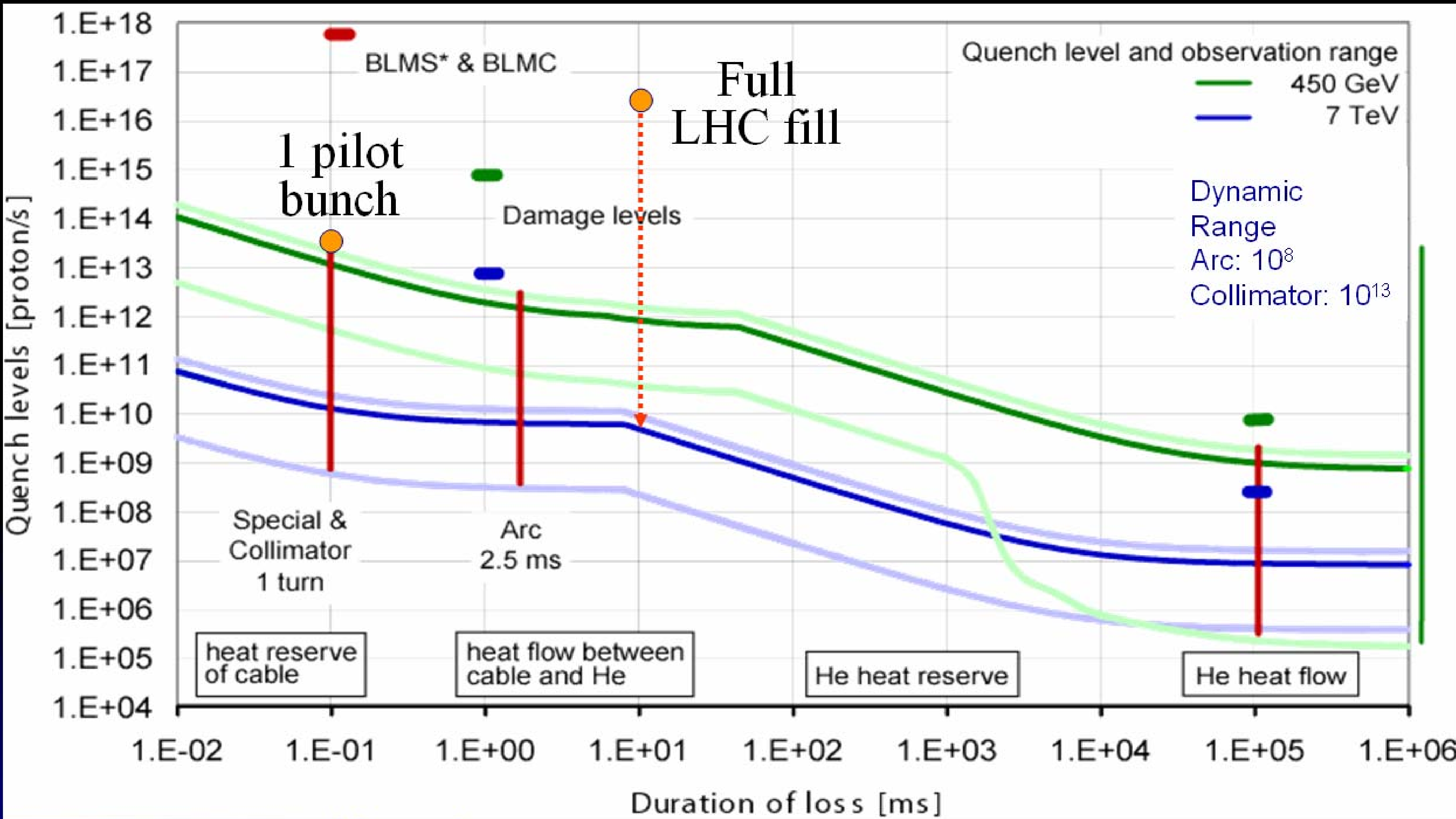
The LHC Beam Loss System

Role of the BLM system:

1. Protect the LHC from damage
2. Dump the beam to avoid magnet quenches
3. Diagnostic tool to improve the performance of the LHC

Name	Type	*Number*	*Area of use*	*Maskable*	*Time resolution*
BLMAI	Ionisation Chamber	~3000	Arcs	yes	1 turn
BLMCI BLMCS	Ionisation Chamber SEM	~150 ~150	Collimation regions	no	1 turn
BLMSI BLMSS	Ionisation Chamber SEM	~400 ~150	Critical aperture limits or positions	no	1 turn
BLMB	ACEM	~10	Primary collimators	yes	bunch-by-bunch

BLM Detection Range



- Pilot bunch of 5×10^9 close to damage level at 7TeV
- Loss of 3×10^{-7} of nominal beam over 10ms can create a quench at 7TeV

Beam Loss Detectors

- Design criteria: Signal speed and reliability
- Dynamic range (> 10^9) limited by leakage current through insulator ceramics (lower) and saturation due to space charge (upper)

Secondary Emission Monitor (SEM):

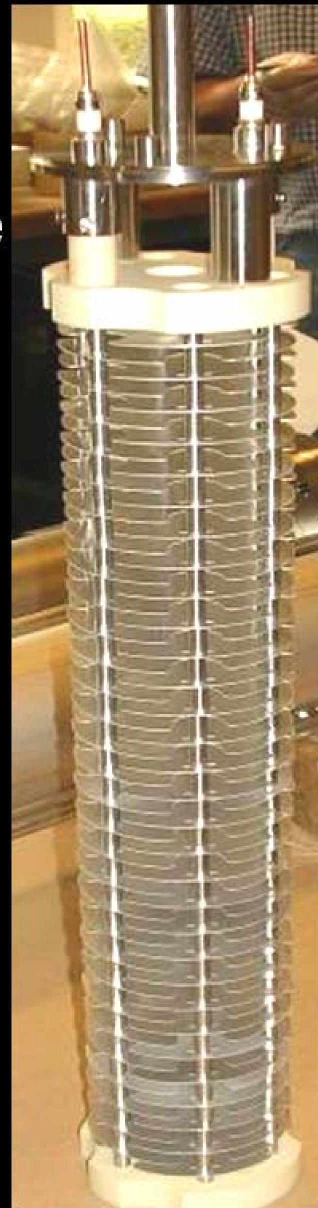
- Length 10 cm
- P < 10-7 bar
- ~ 30000 times smaller gain

Ionization chamber:

- N_2 gas filling at 100 mbar over-pressure
- Length 50 cm
- Sensitive volume 1.5 l
- Ion collection time 85 μs

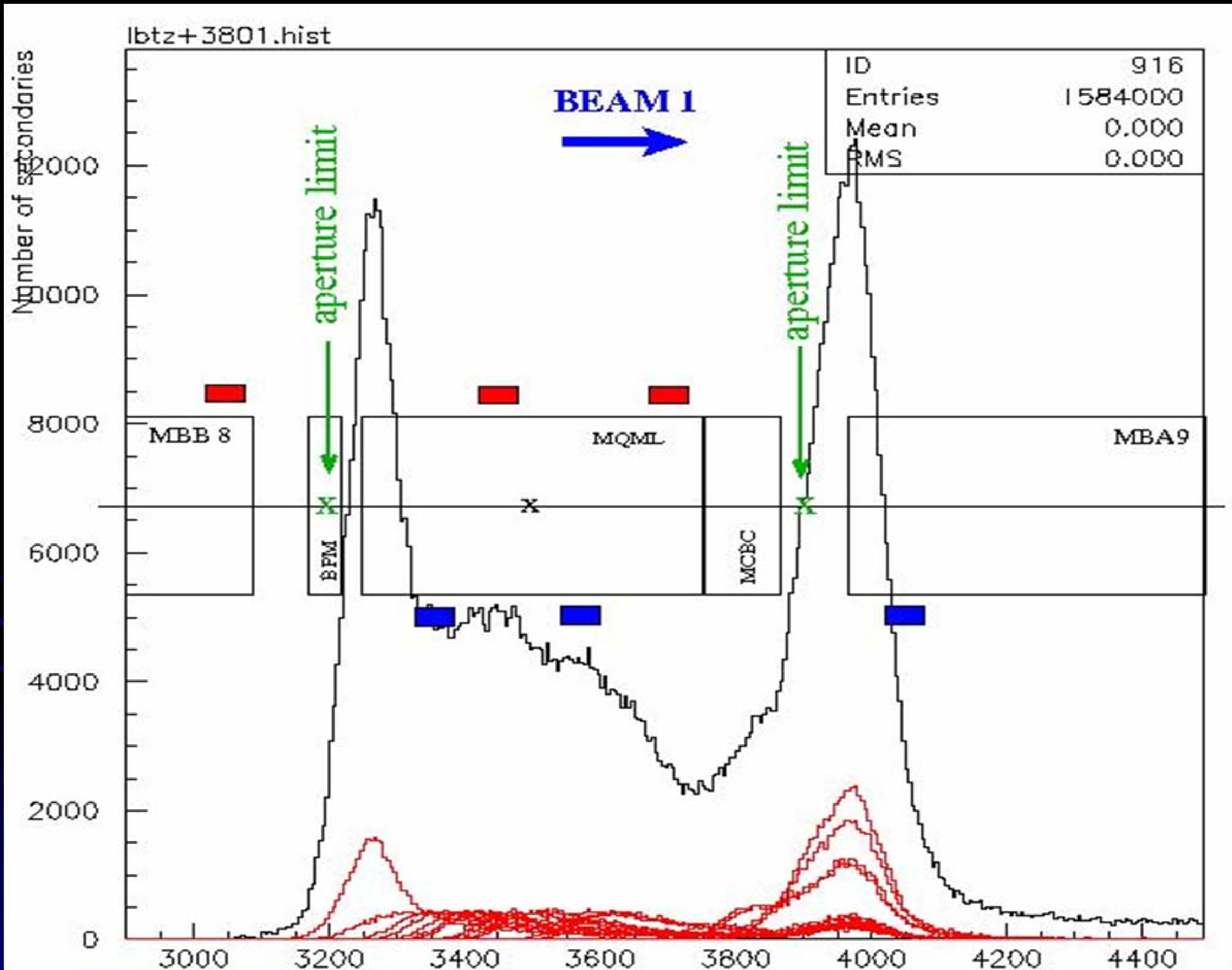
Both monitors:

- Parallel electrodes (Al or Ti) separated by 0.5 cm
- Low pass filter at the HV input
- Voltage 1.5 kV



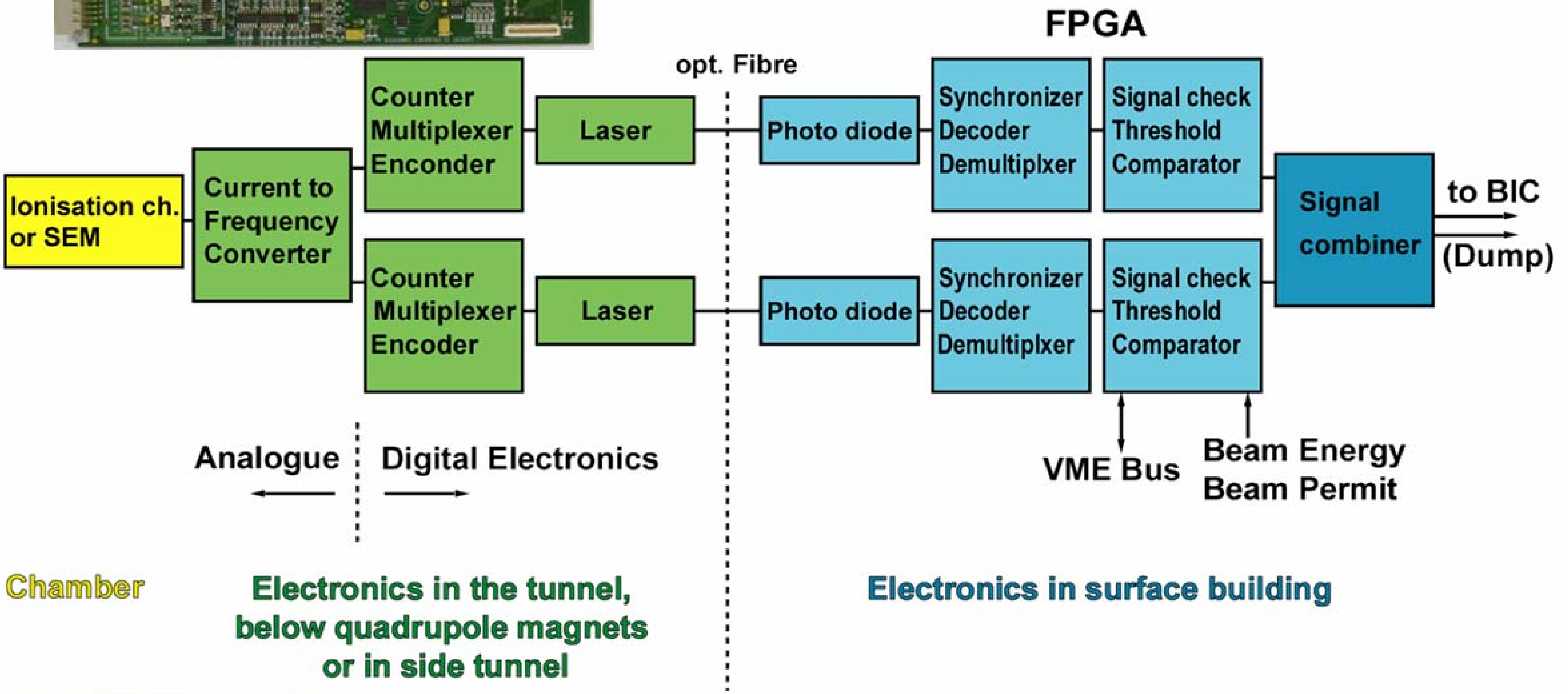
Installed BLM Monitors

BLM Threshold Level Estimation



BLM Acquisition Electronics

Implemented on VME64x Board



- Threshold Comparator:
  - Losses integrated and compared to threshold table
  - 12 time intervals and 32 energy ranges).

Tune, Chromaticity & Coupling

- Clear three step approach:

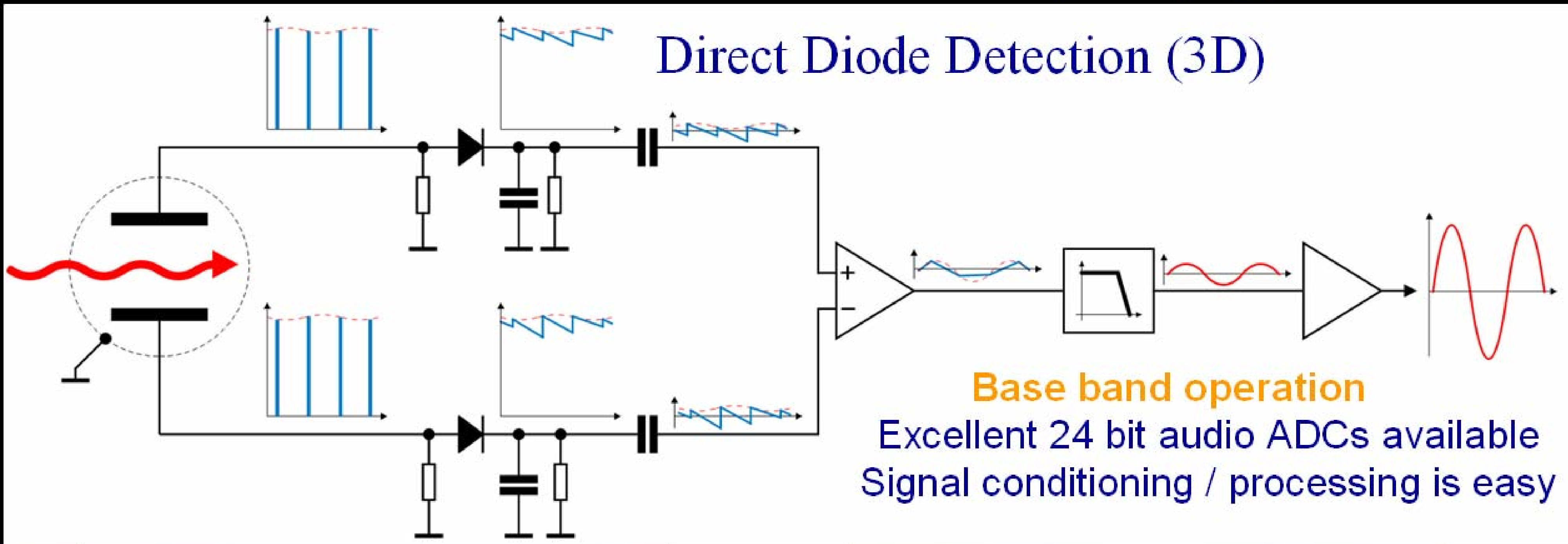
  1) Day 1 with kicked beams and classical motion analysis
     - Q kicker for both planes & both beams (limited to 2Hz rep rate)
     - Base Band Tune (BBQ) system for tune & coupling
     - Head-tail system for chromaticity
     - Chirp excitation using transverse damper allows faster repetition rate

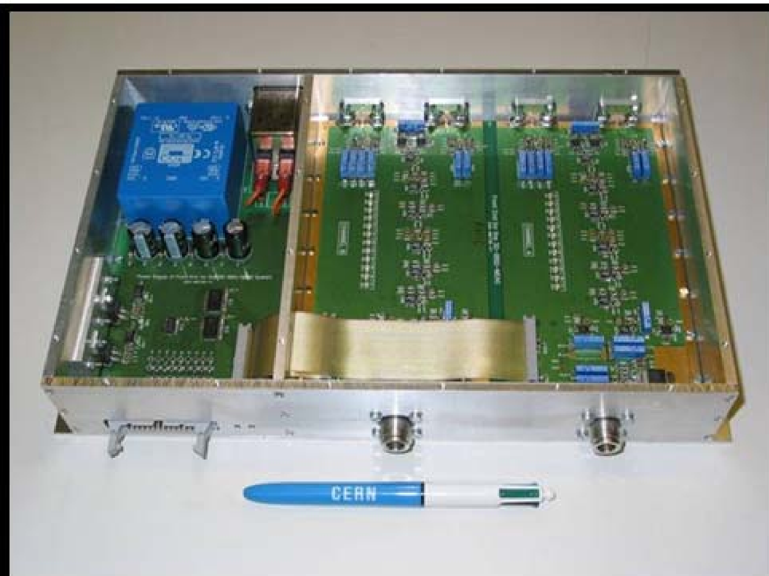
  2) Day N with PLL tune tracking (US-LARP)
     - Continuous tune and coupling measurements
     - $\delta p/p$ modulation via RF allows continuous chromaticity measurement

  3) Day N++ with PLL measurement & Feedback (US-LARP)
     - Fully automatic tune, chromaticity & coupling control

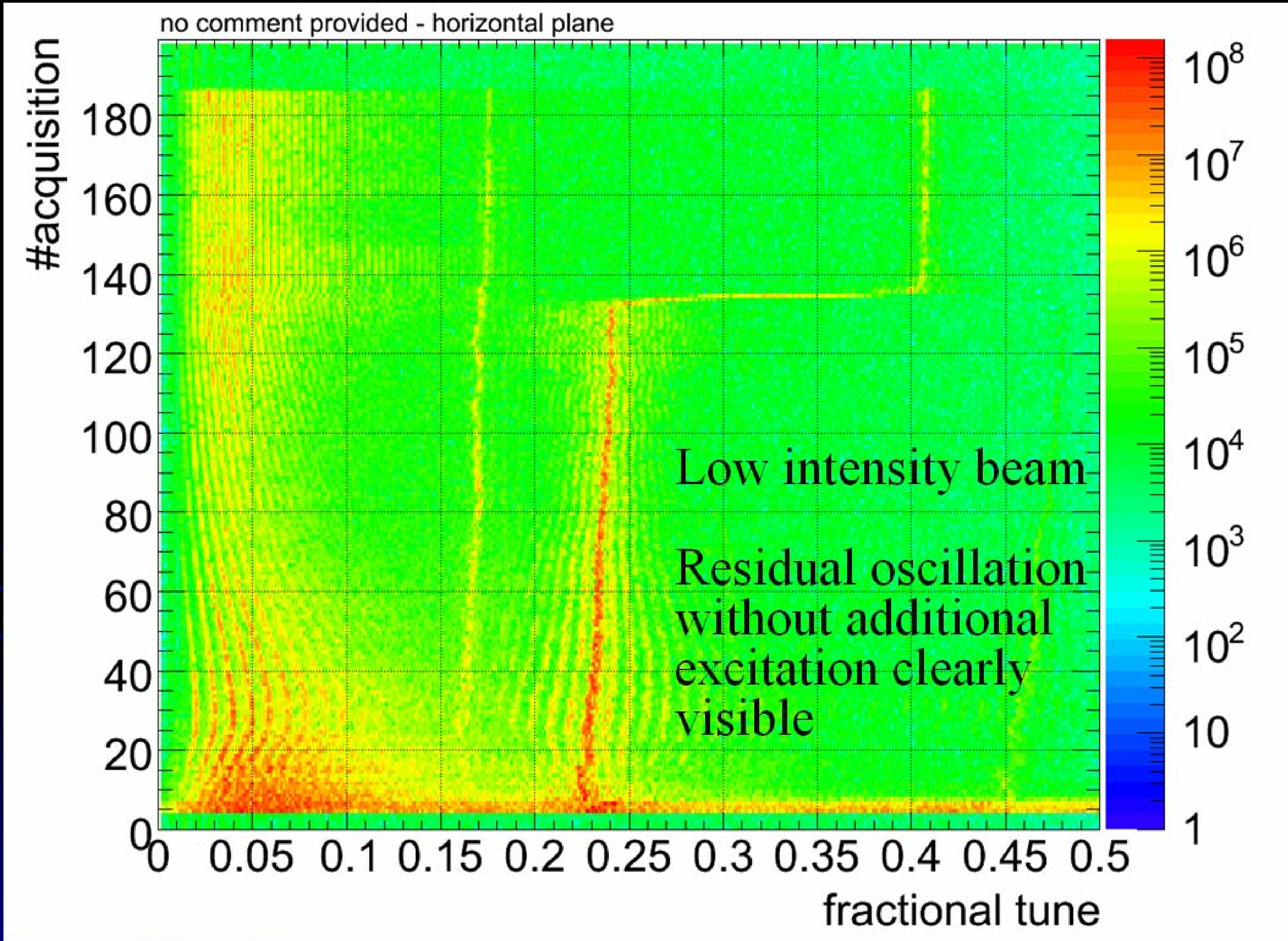
- For operational beams the additional problems will be:
  - lowering the excitation level to an insignificant level
  - coping with coupling
  - achieving compatibility with resistive transverse damping

Measuring with Little or No Excitation –
The Base Band Q Measurement (BBQ) System



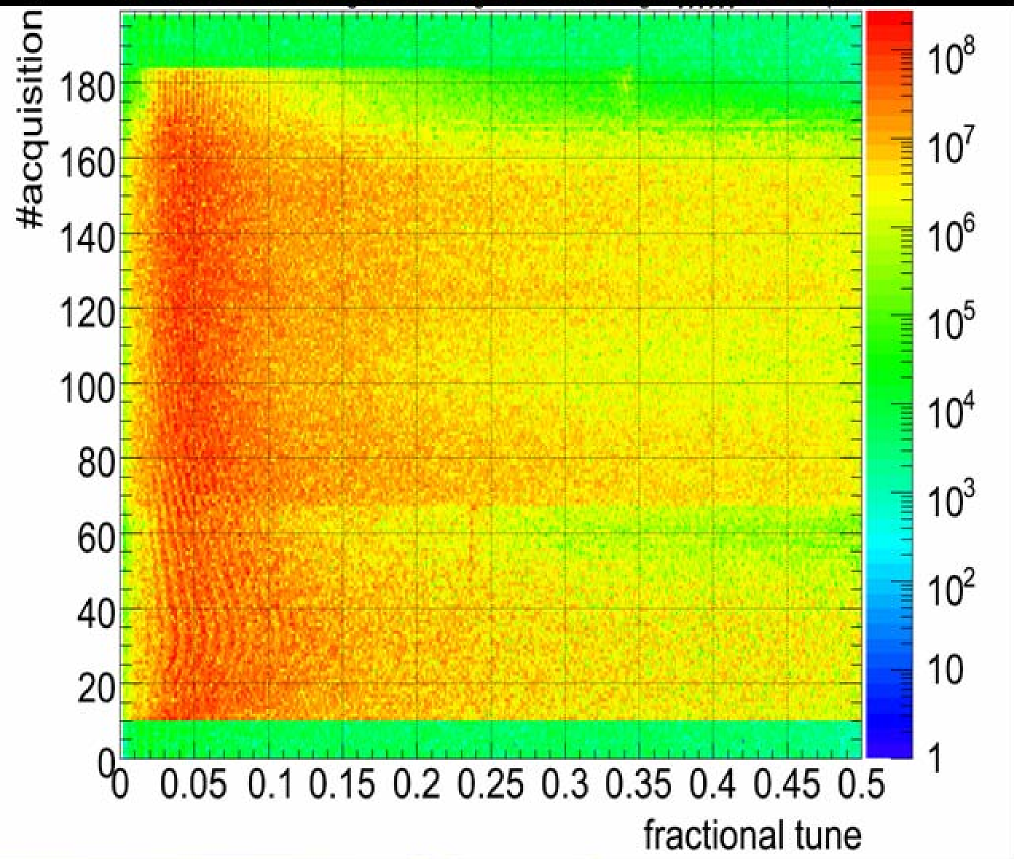


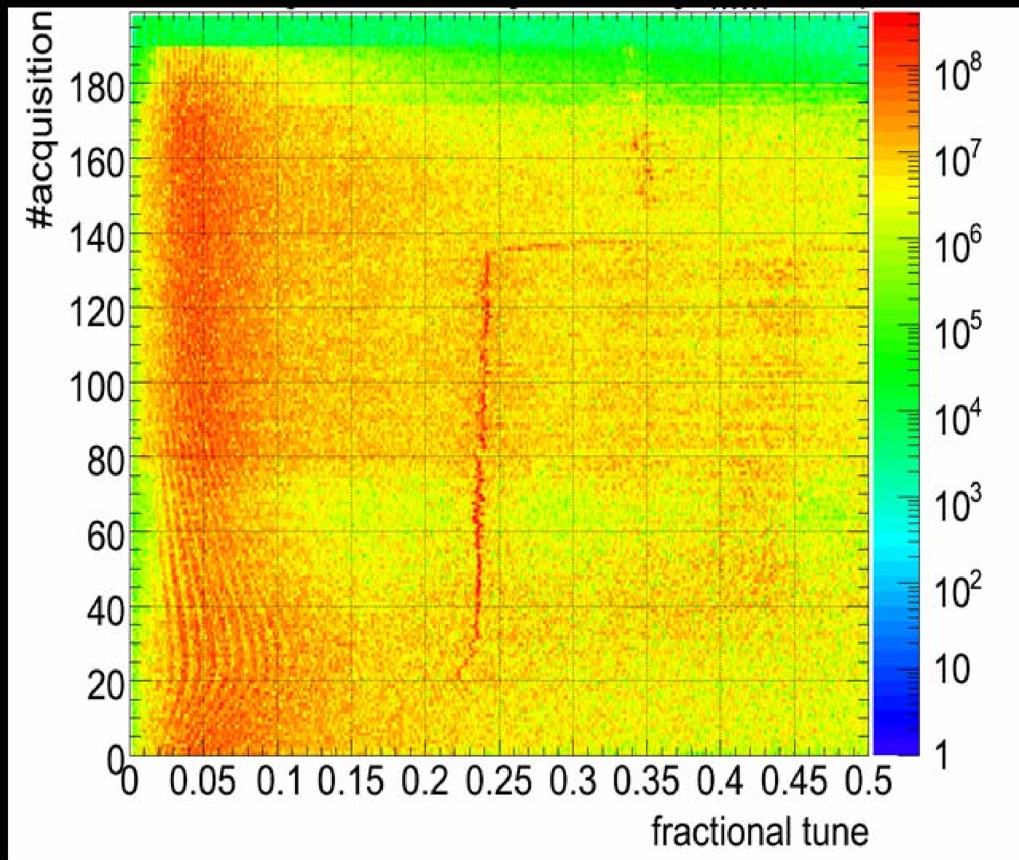
Setting-up the 25ns LHC Beam in the SPS



PLL tracking in the SPS

Resonantly Extracted 25ns LHC Beam in the SPS
Real-time Tune Display



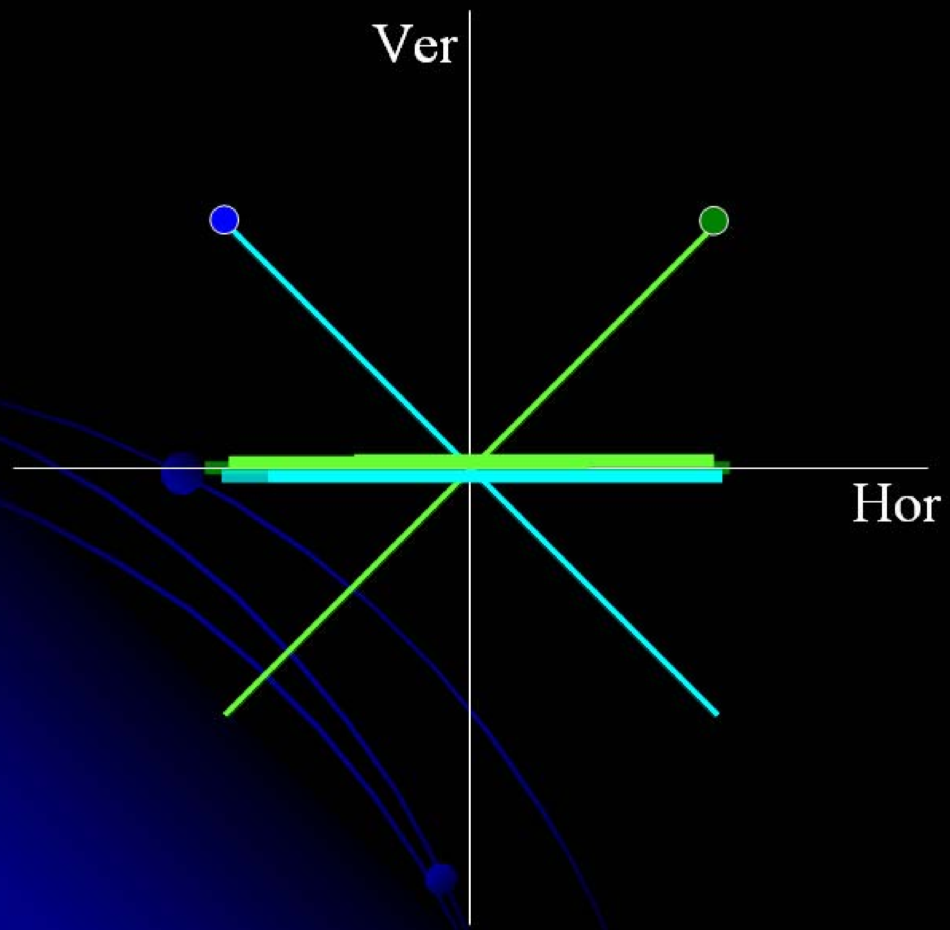


- Nominal Beam - PLL OFF
  - tune hardly visible
- Nominal Beam – PLL ON
  - tracking achieved throughout cycle

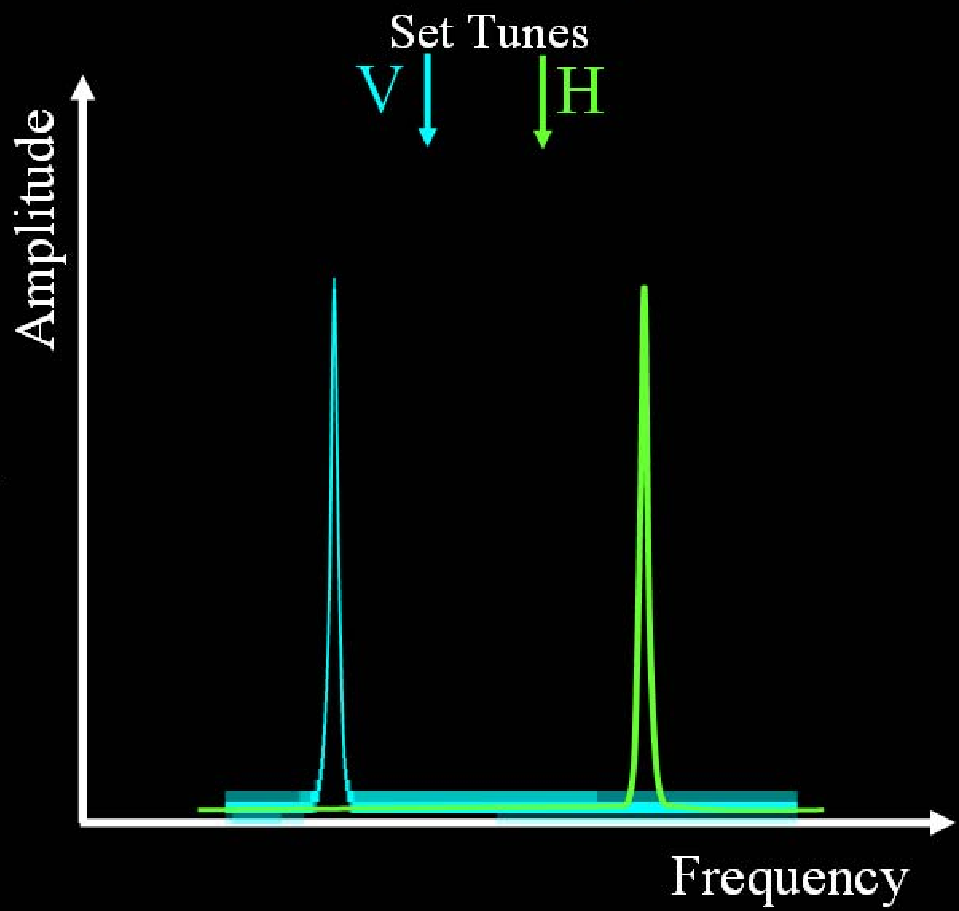
Coupling via PLL Tune Tracking

Start with decoupled machine ➡ Only horizontal tune shows up in horizontal FFT

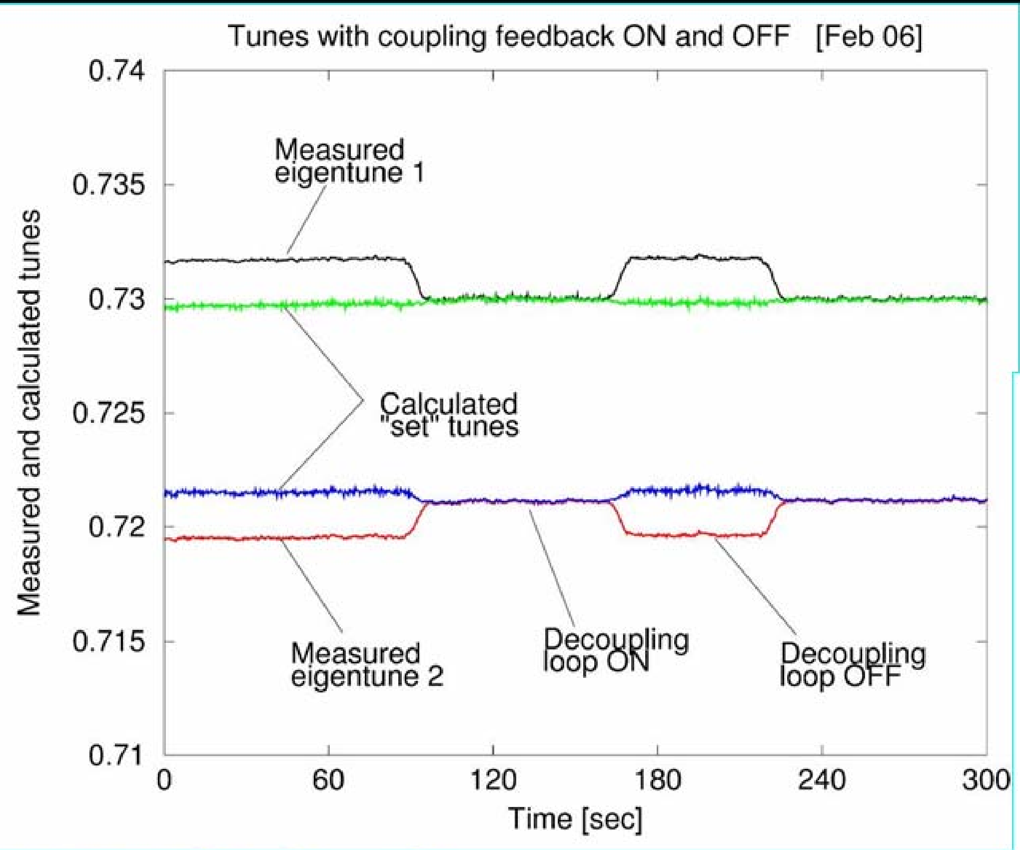
Gradually increase coupling ➡ Vertical mode shows up & frequencies shift

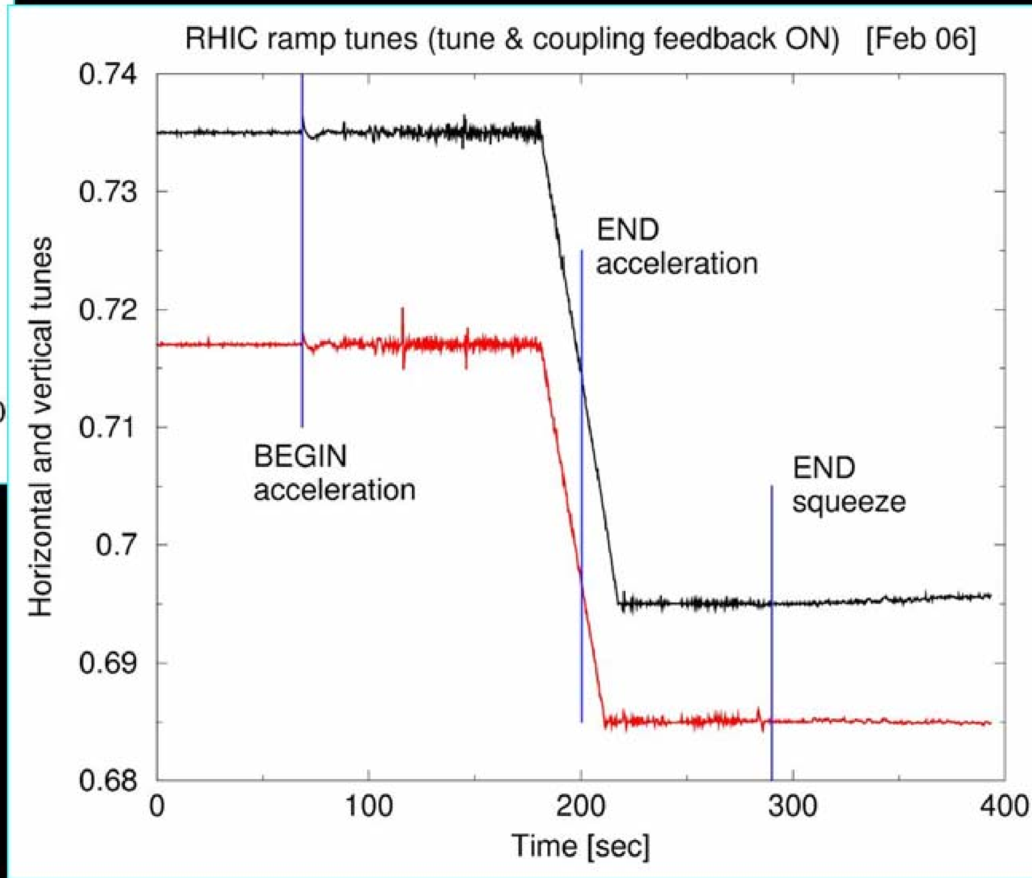


FFT of Horizontal Acquisition Plane



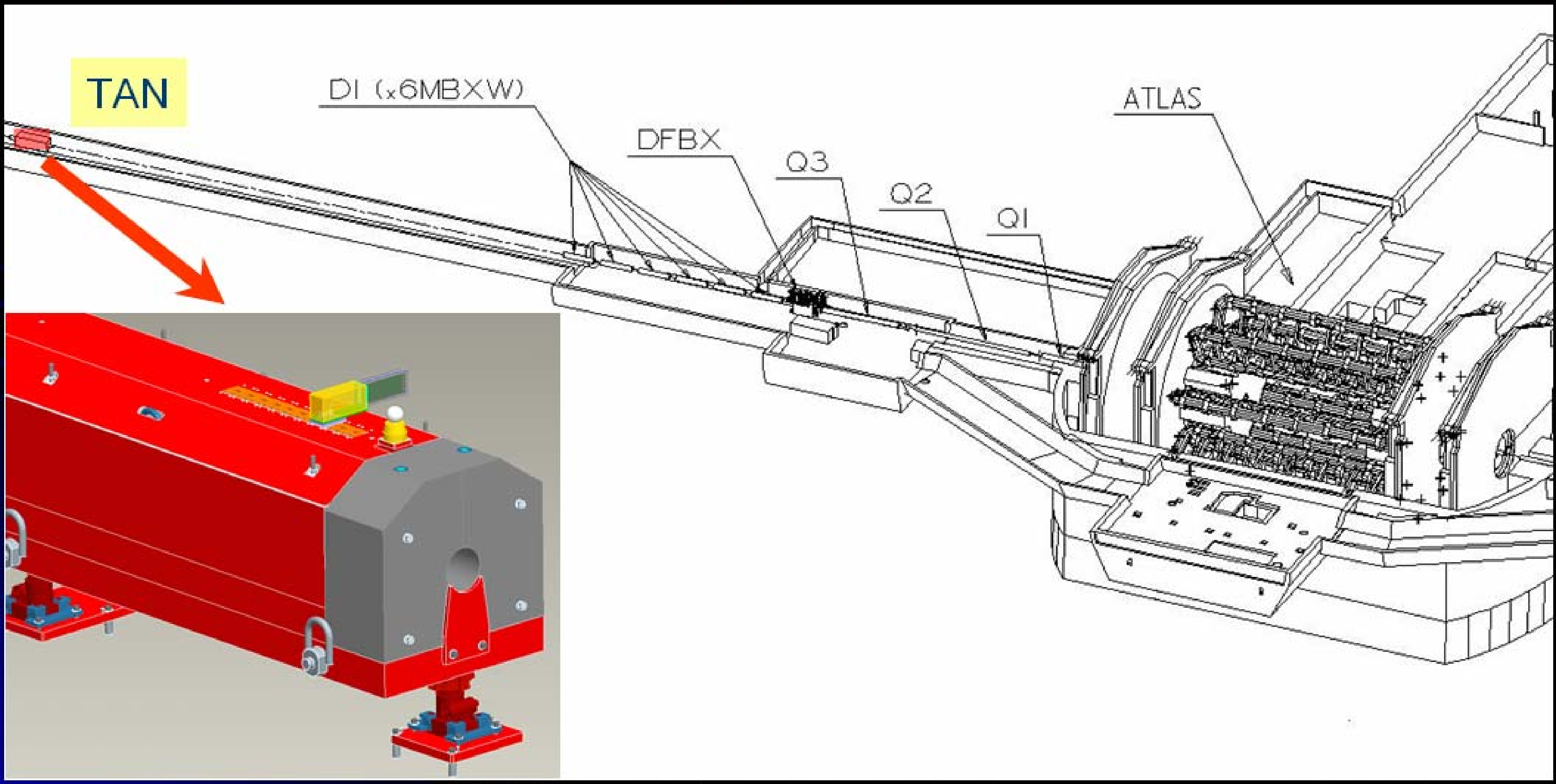
Tune & Coupling Feedback at RHIC (2006)



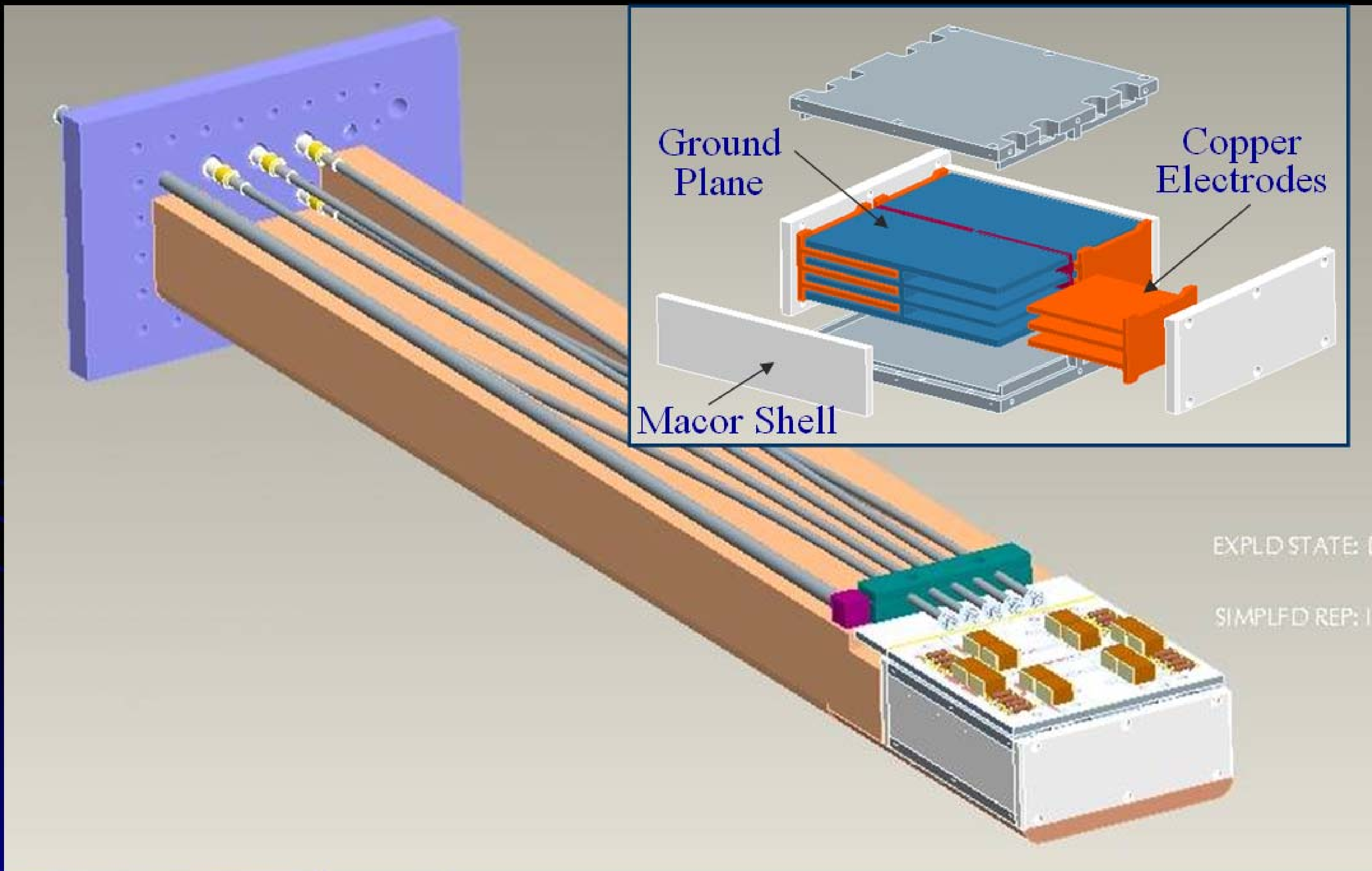


Collision Rate Monitoring

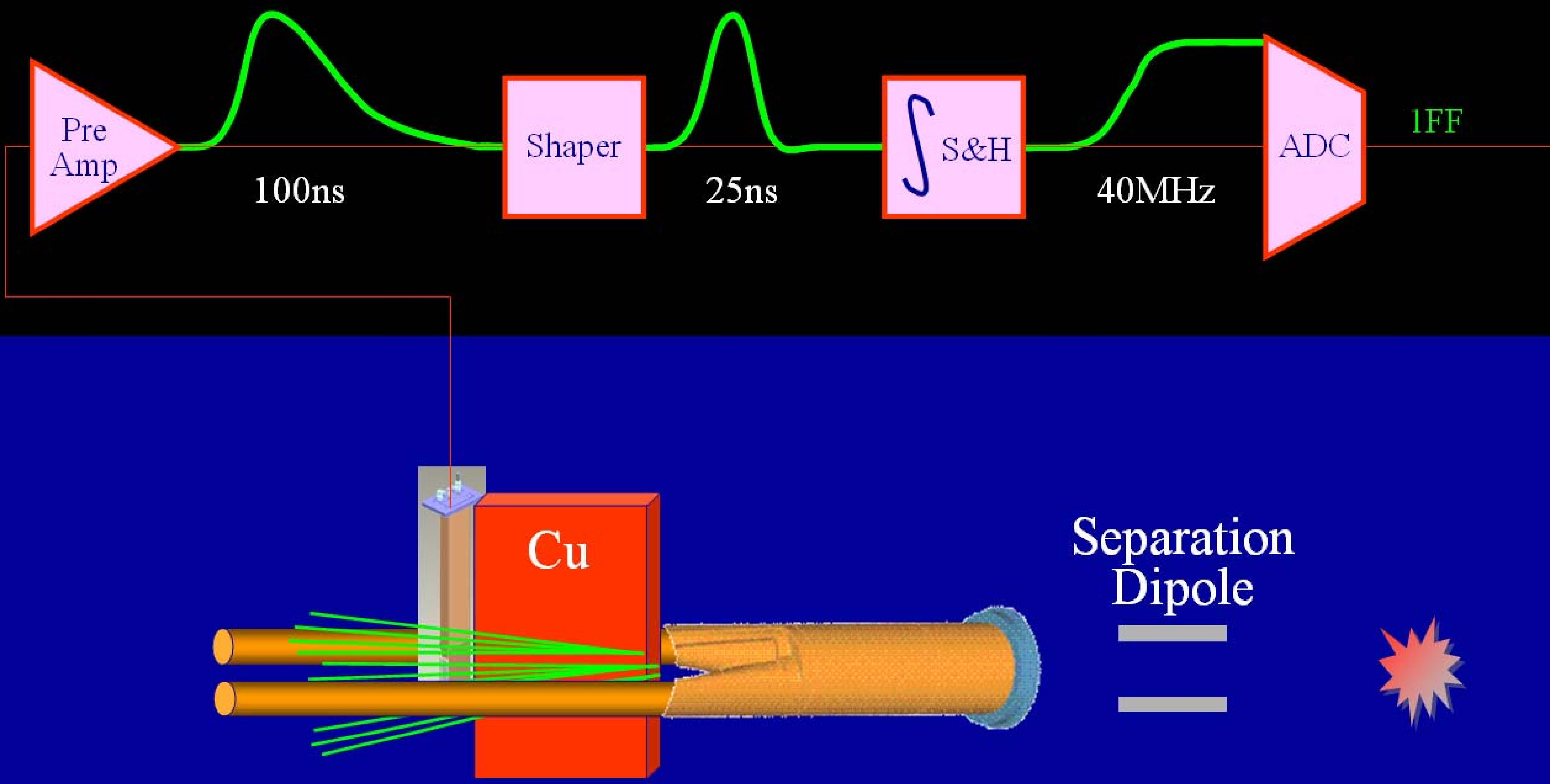
- Requires a region where signal is proportional to collision rate
  - Can be found in the neutral absorber (TAN) at ~150m from the IP
  - Ionisation chambers supplied by LBNL (Berkeley) as part of US-LARP
- The Challenges
  - Has to withstand a very harsh radiation environment
  - Has to provide 40MHz bunch by bunch data with 1% relative accuracy



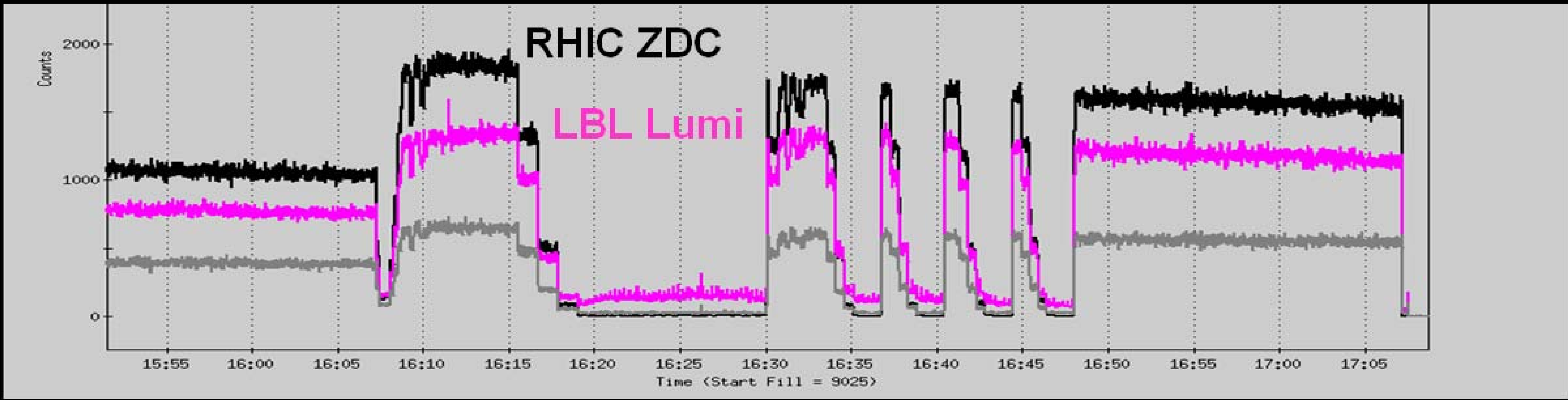
TAN Collision Rate Monitor

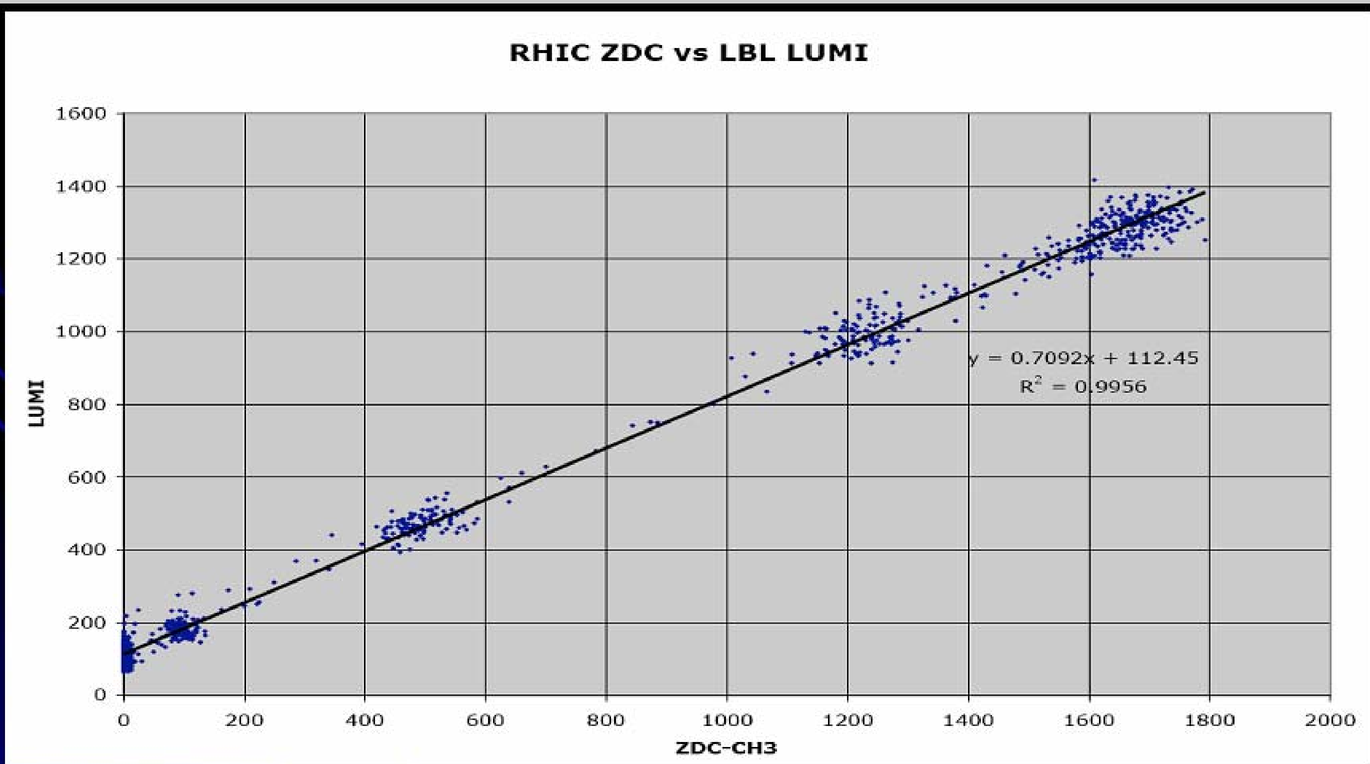


TAN Collision Rate Monitor



TAN Collision Rate Monitor
Recent Results from Tests at RHIC

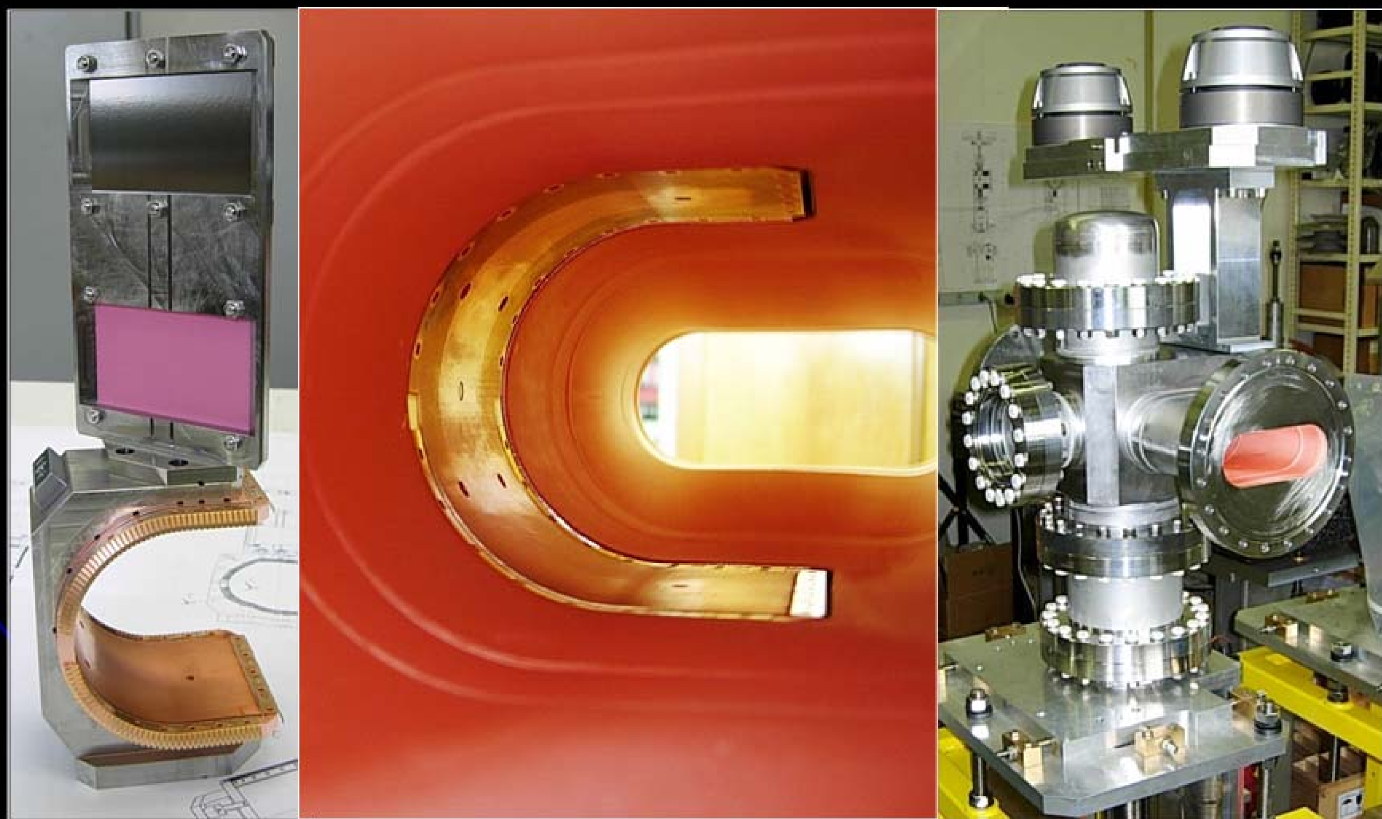




Measuring Beam Size

- Beam Profile Measurements in the LHC
  - For injection, dump & matching
    - Phosphor and OTR screens

Dump line BTV tanks awaiting final installation



Measuring Beam Size

- Beam Profile Measurements in the LHC
  - Workhorses
    - Wire scanners for cross calibration (30μm carbon wire at $2ms^{-1}$)

Wire scanner tanks and mechanisms in place

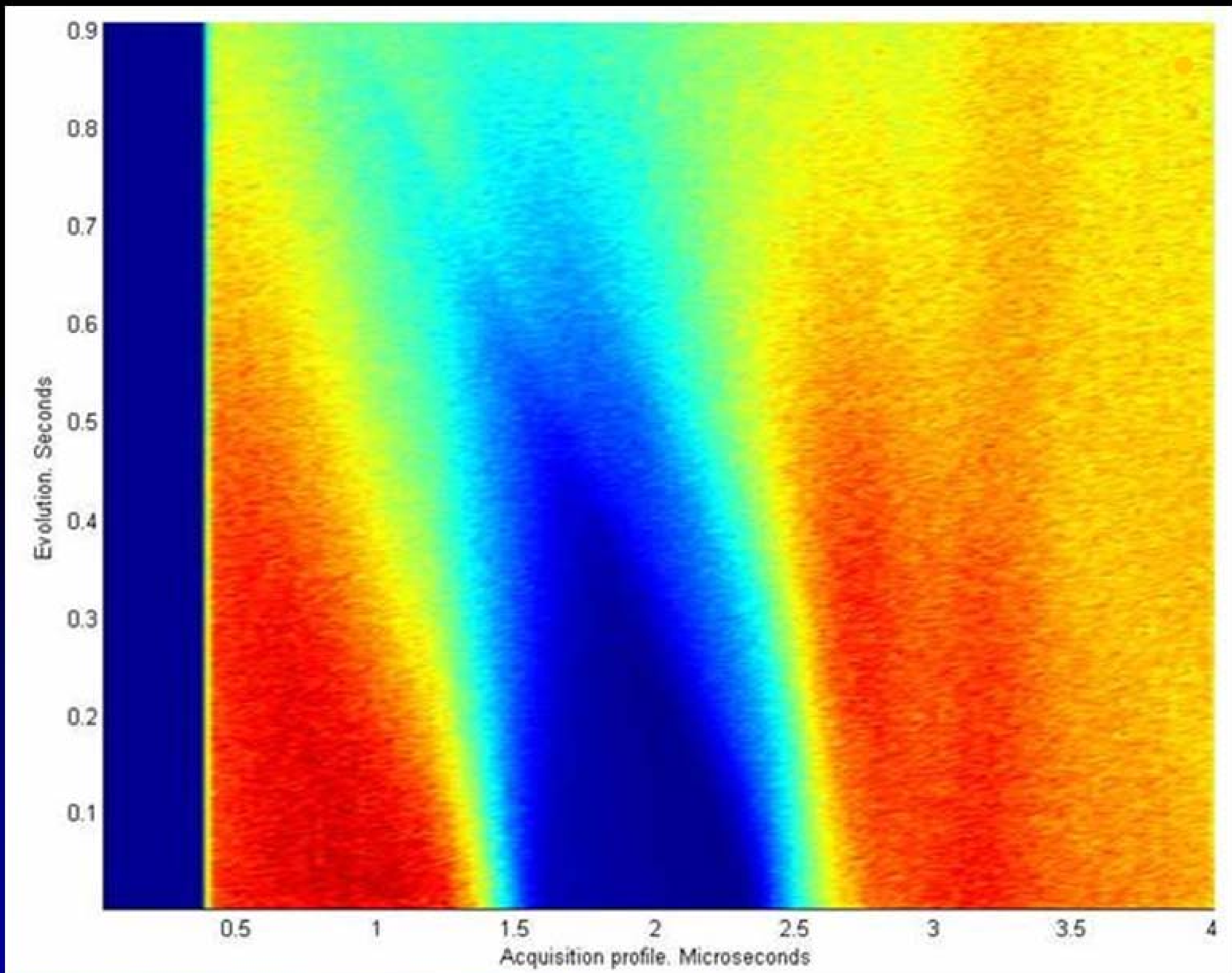
Measuring Beam Size

- Beam Profile Measurements in the LHC
  - Workhorses
    - Wire scanners for cross calibration (30μm carbon wire at 2ms^{-1})
    - Synchrotron light monitor
  - For ions
    - Rest Gas Ionisation Monitor
      - Also used as back-up for SR monitor

Rest gas ionisation chambers and compensation magnets in place

Abort Gap Monitor

- Avoid quenches during a programmed beam dump or at start of ramp
- System based on gated photomultiplier
- Tested in SPS on 450GeV fixed target beam with synchrotron light source
  - Observation of injection kicker gap while beam is debunched



LHC Quench level at 7TeV is 7×10^7 protons per 100ns

- 0.2ppm of nominal beam
- Detection required at 1/10th of quench level
  - 18,000 photons/100ns/turn

Available light

- Light is shared with the synchrotron light monitor
- Fast, gated photomultiplier has efficiency of ~7%

Requires detection of 128 photons/100ns/turn

Summary

- Installation of the vacuum components for LHC beam instrumentation is nearing completion
  - Acquisition systems for BPM & BLM systems are being hardware commissioned
  - Production of acquisition systems for other monitors will shortly be complete
- Significant progress has been made to address the remaining challenges
  - Much of this has been made possible through collaboration and testing on existing machines such as HERA, RHIC and Tevatron.
- LHC will turn on with a comprehensive set of beam instrumentation

Acknowledgements

Many thanks to all the members of the Beam Instrumentation Group at CERN & our European and US collaborators for their input for this presentation.