Performance of and First Experiences with the LHC Beam Diagnostics

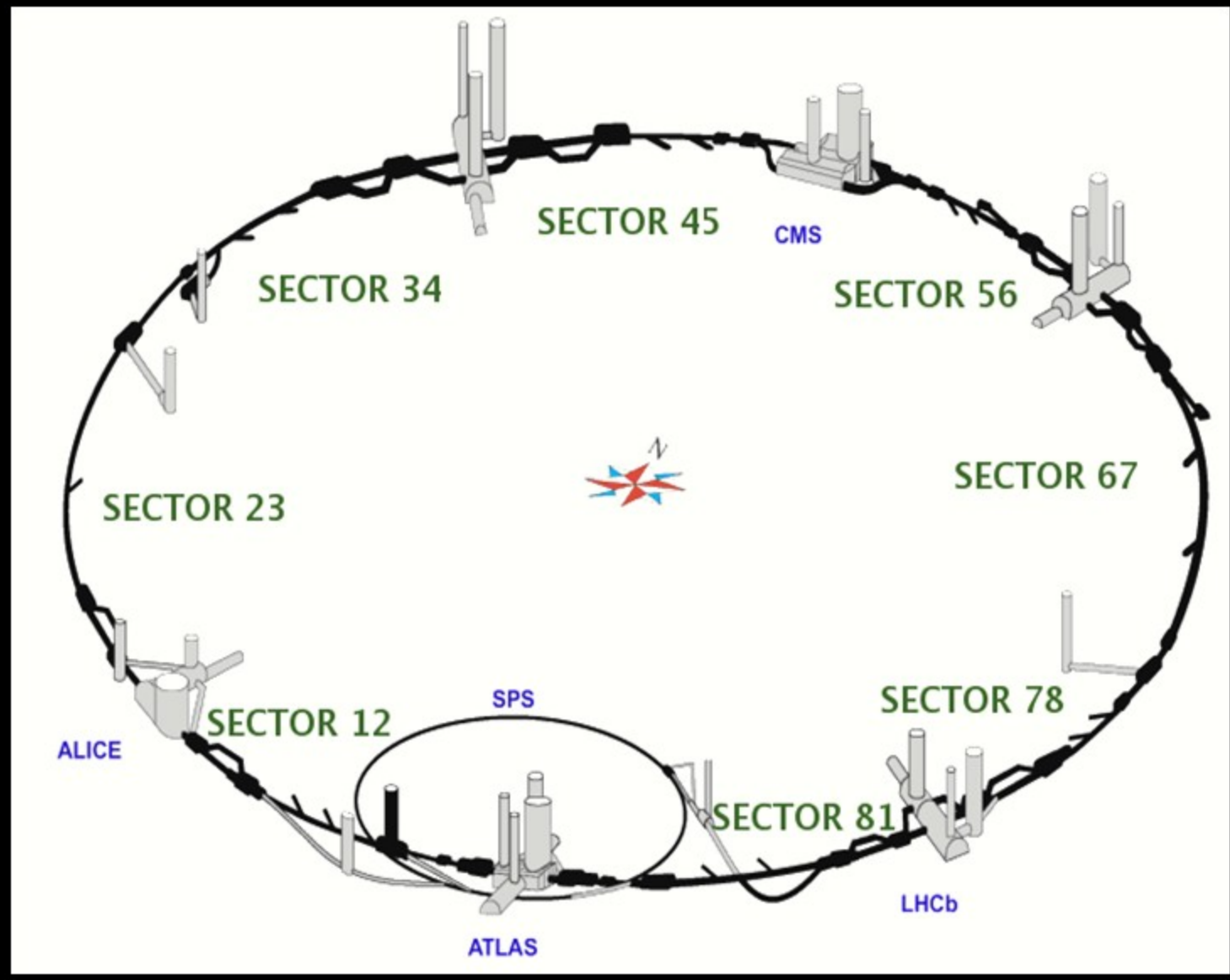
DIPAC 2009

25th - 27th May
Mercure Hotel Europe, Basel, Switzerland

Rhodri Jones (CERN)
on behalf of the CERN Beam Instrumentation Group & all our collaborators

Injection tests – First Beam into LHC

- Injection tests of up to 4 adjacent sectors
- Almost all hardware systems involved in tests
- Essential for:
  - Beam instrumentation
    - BPM / BLM
    - Screens
  - Control system
  - Optics
    - magnetic model and aperture



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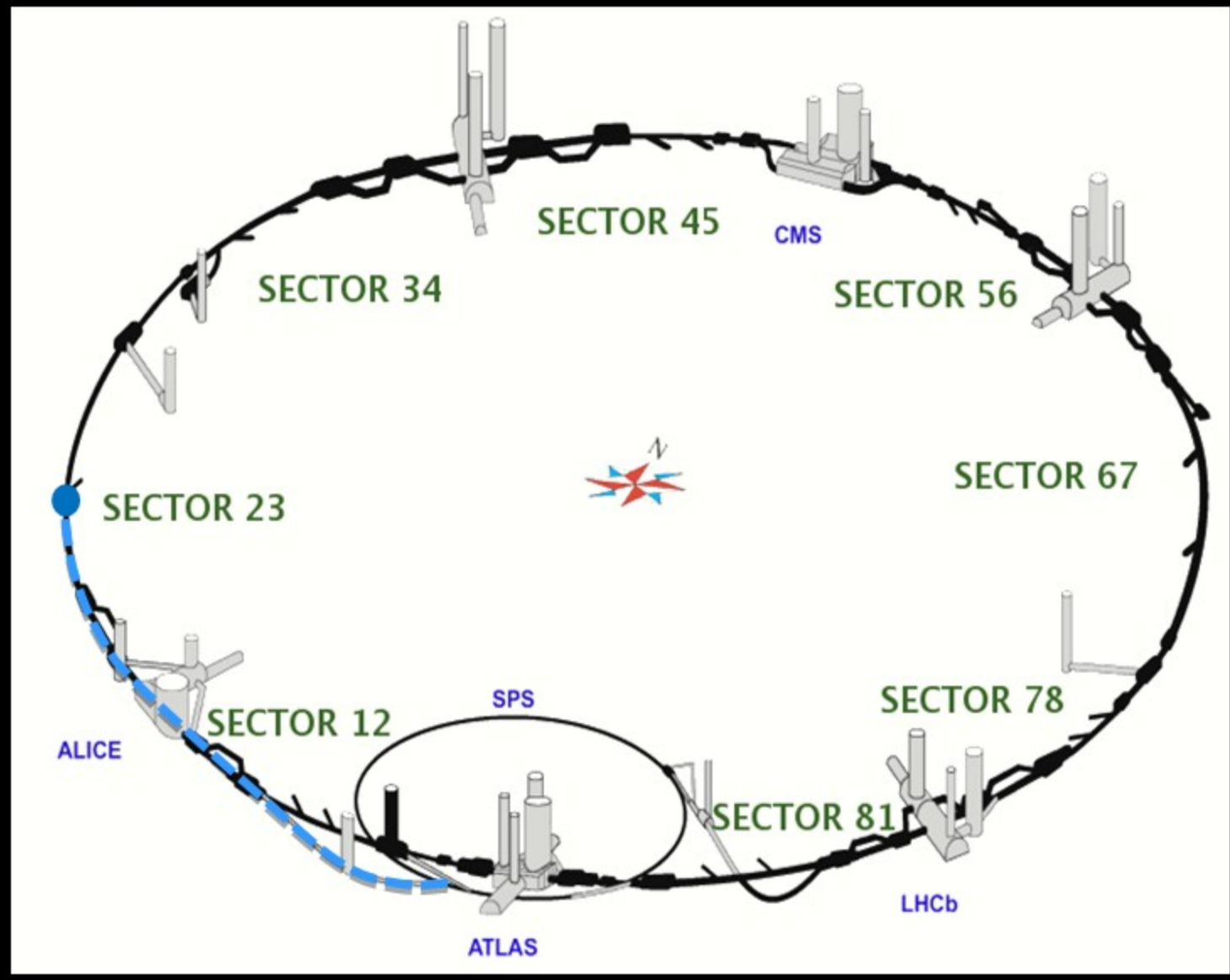
8th – 10th of August



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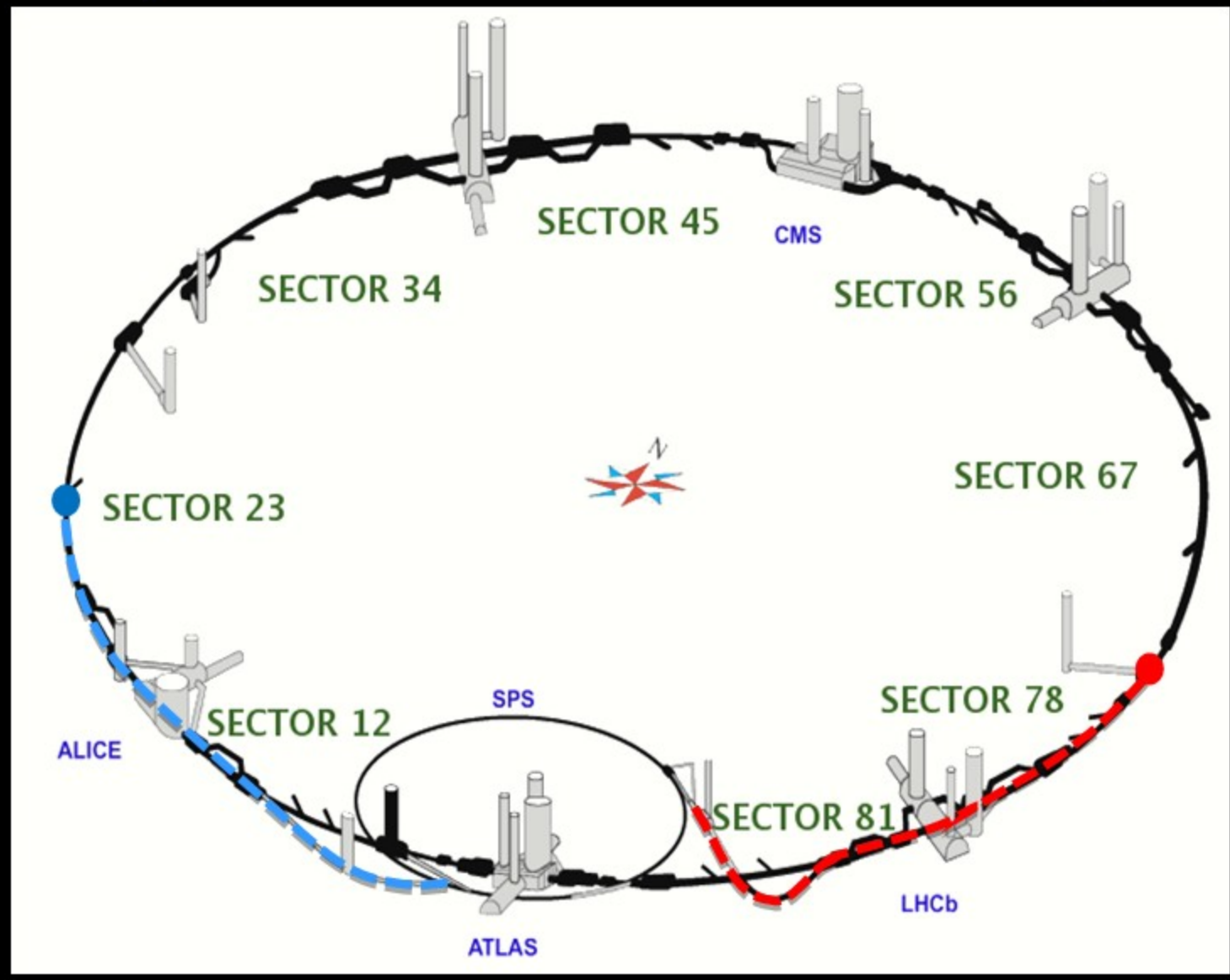
22nd – 24th of August



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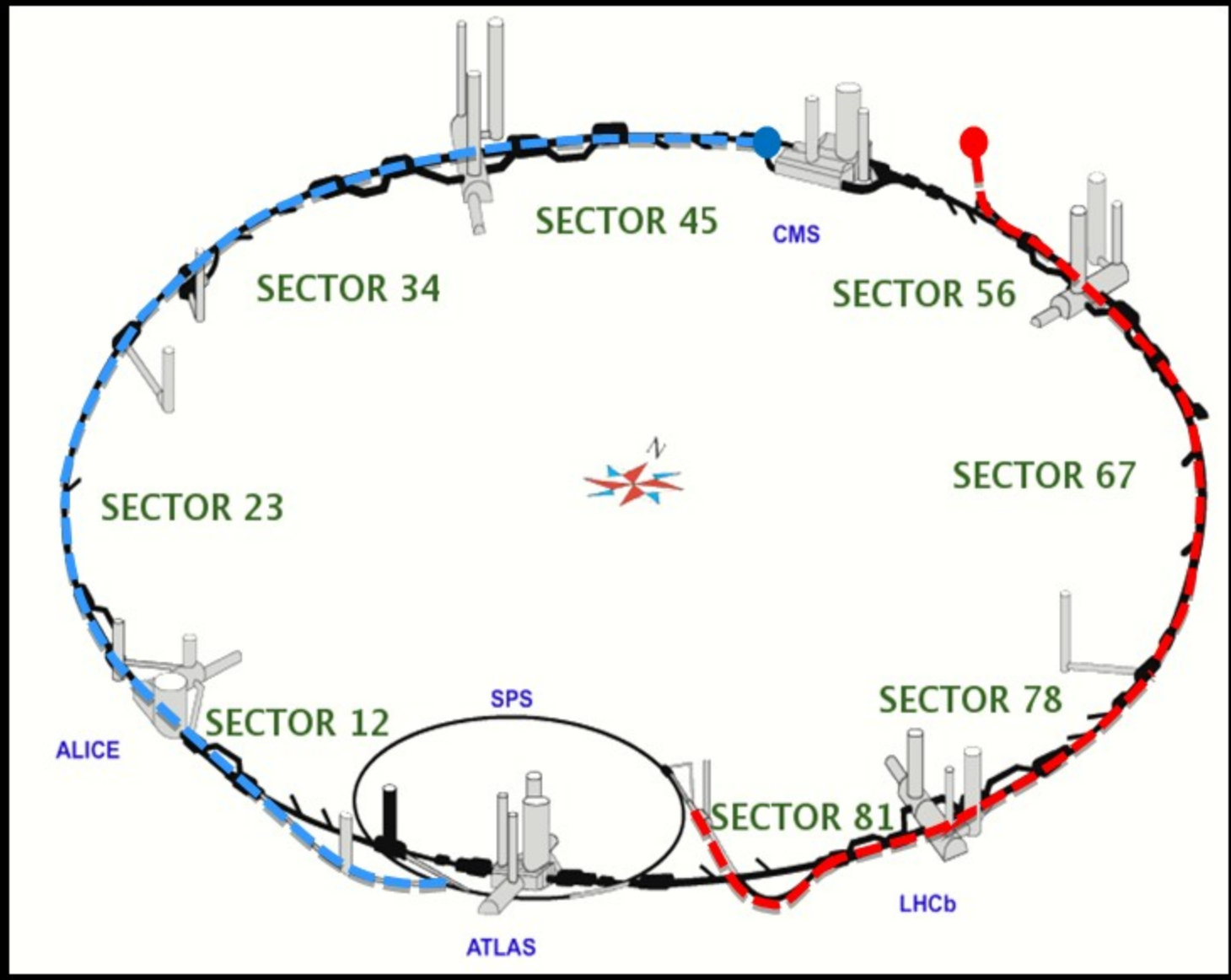
5th – 7th of September



September 10th - Control (Show) Room

Beam Threading

- Threading the beam round the LHC ring
  - One beam at a time, one hour per beam.
  - Collimators were used to intercept the beam (1 bunch, 2×10^9 protons)
  - Beam through 1 sector (1/8 ring)
    - correct trajectory, open collimator and move on.

Beam 2 threading

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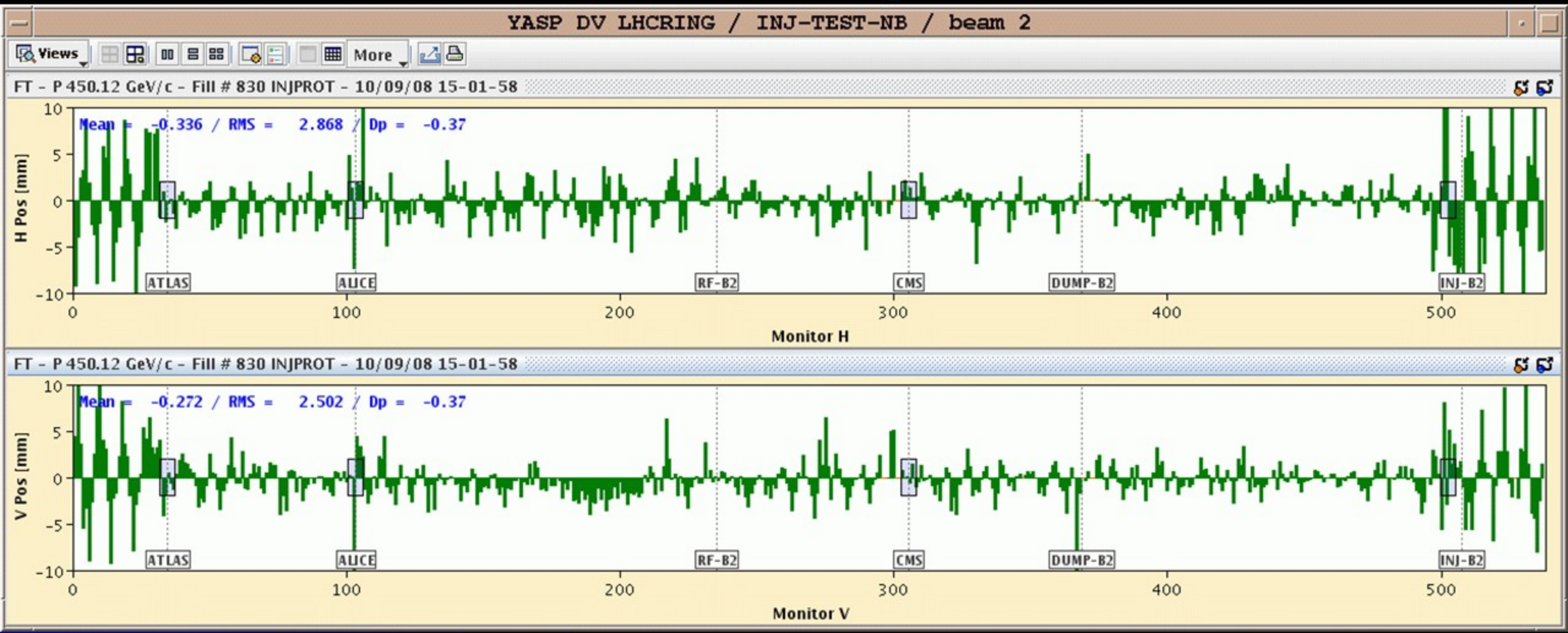
BPM availability ~ 99%

Beam 2 threading



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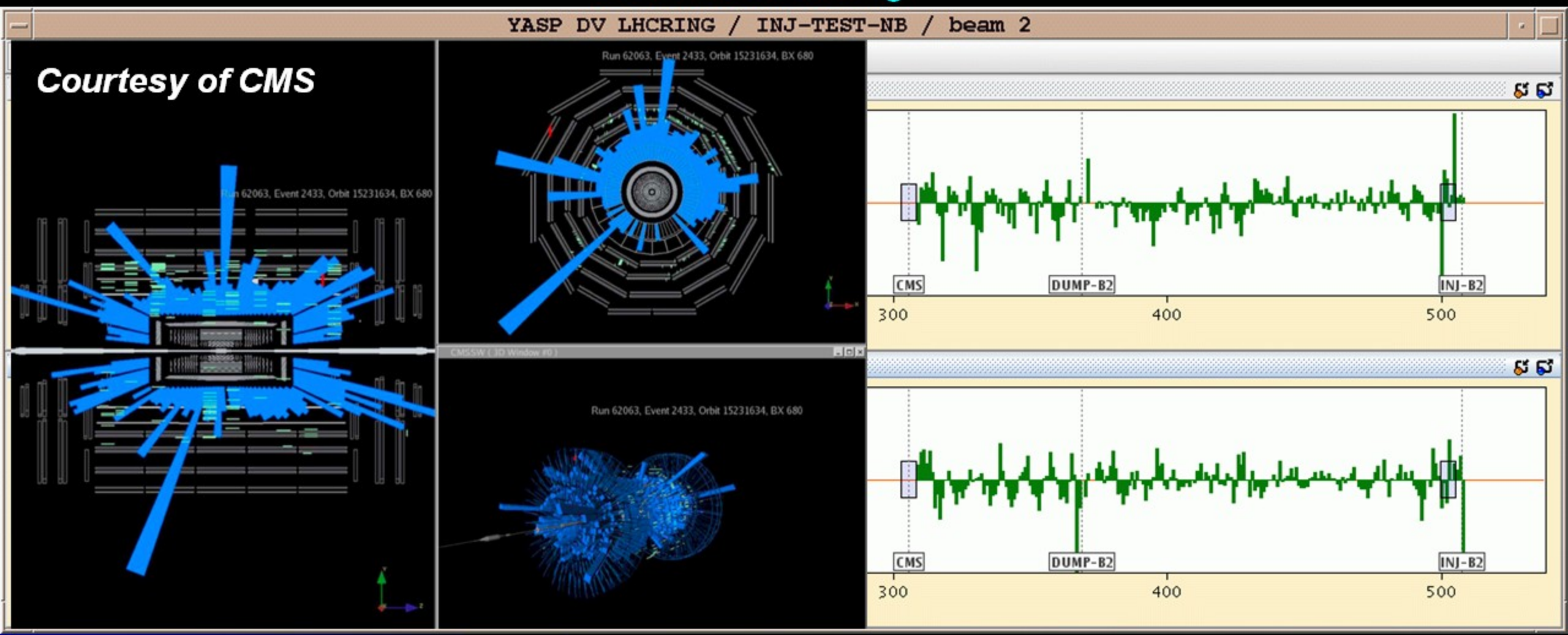

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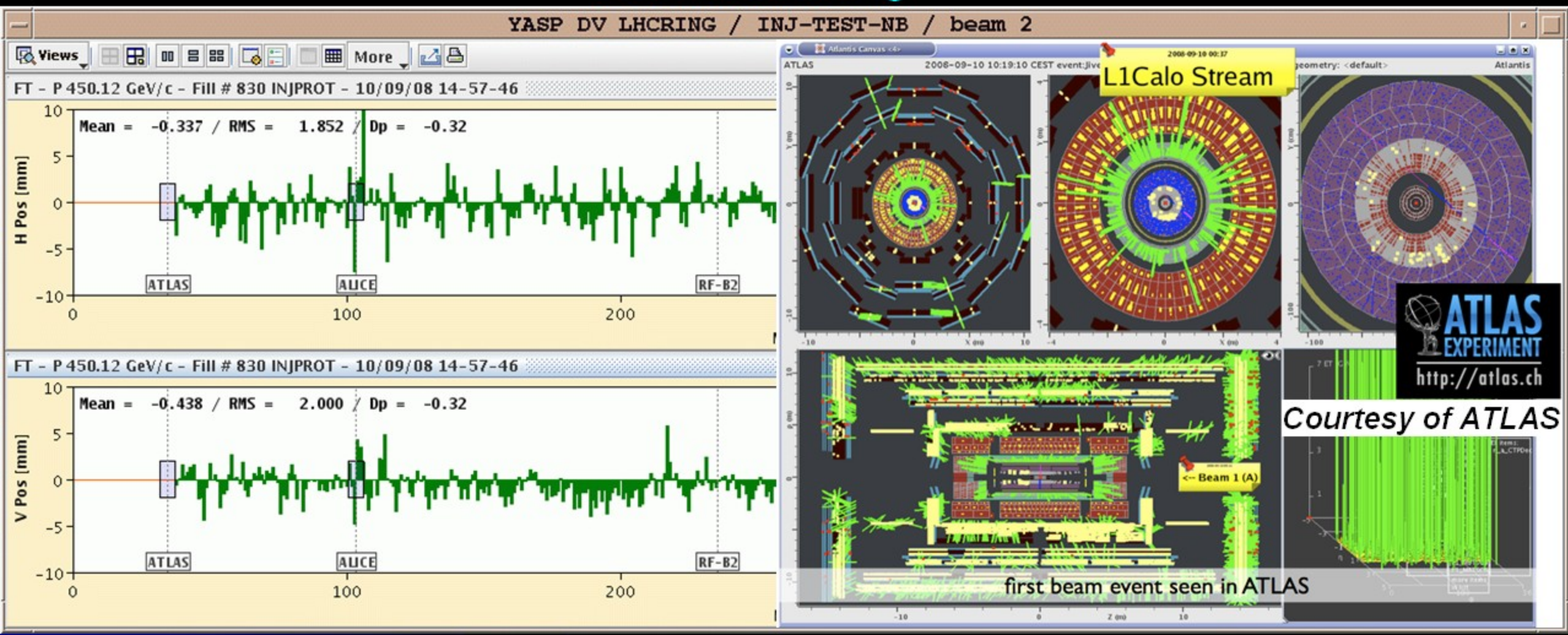
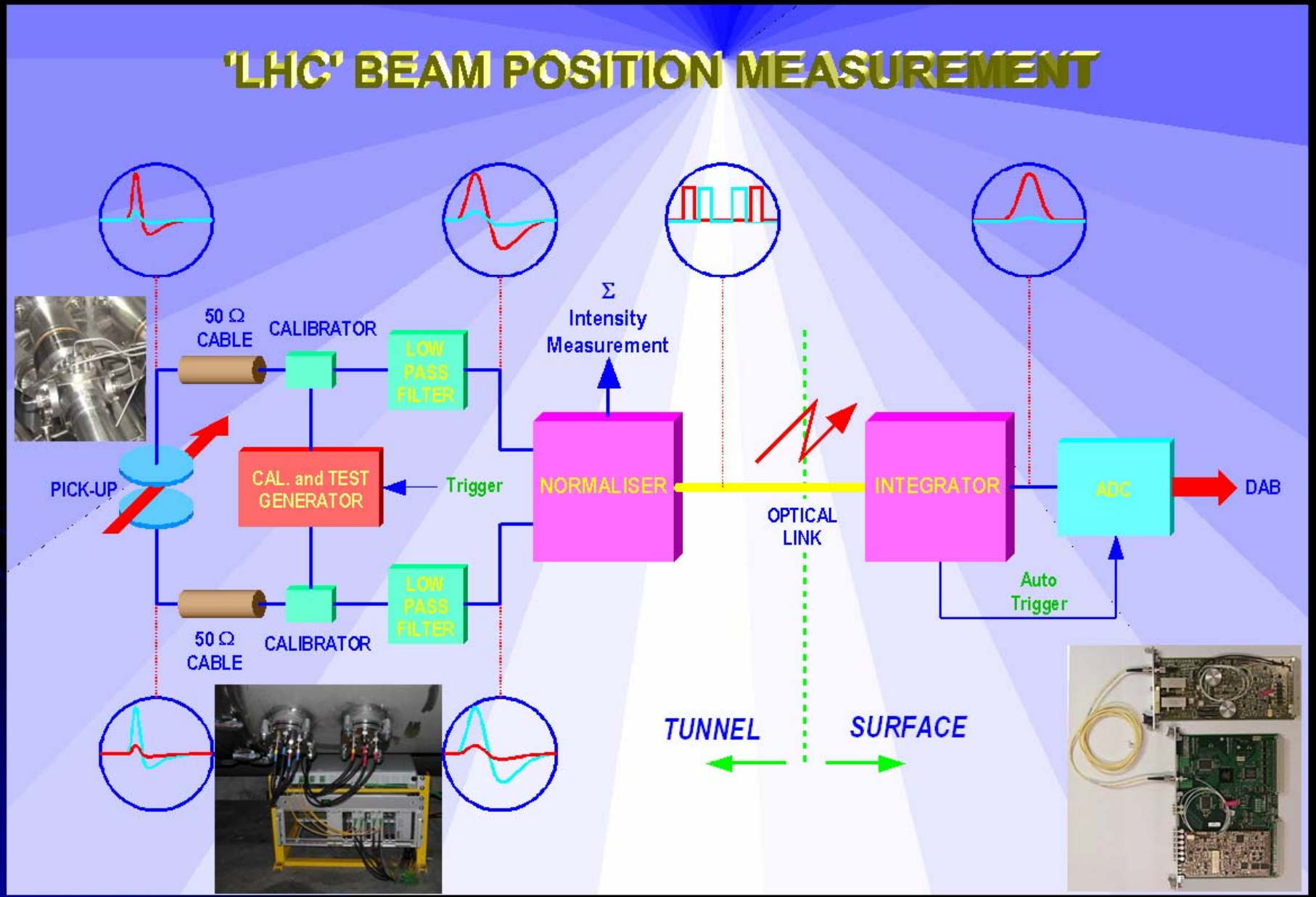
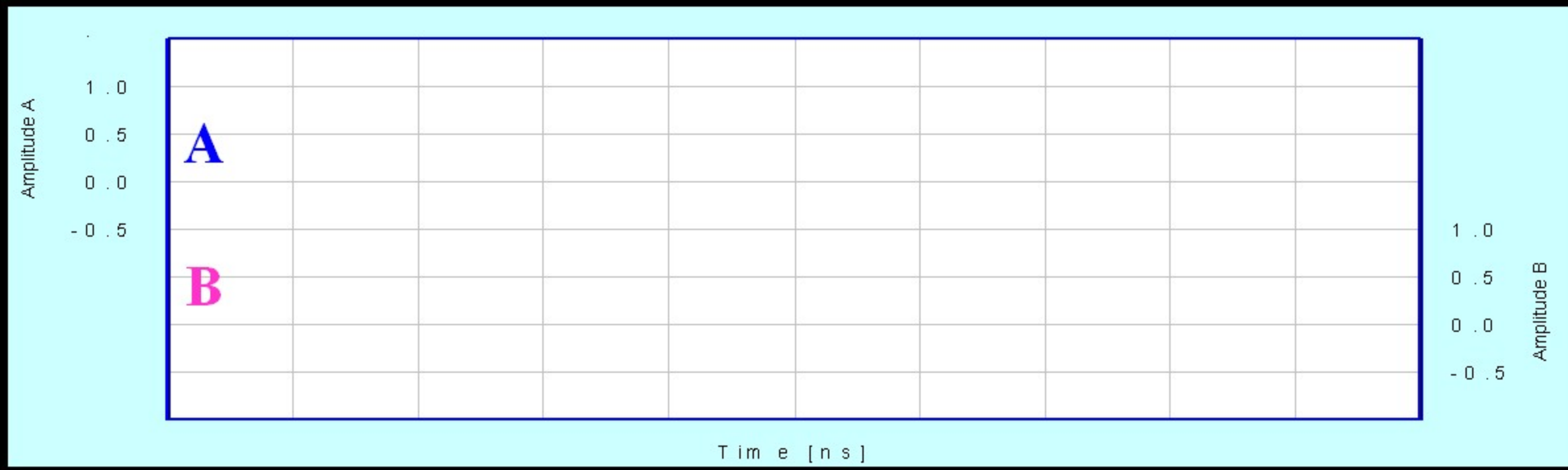
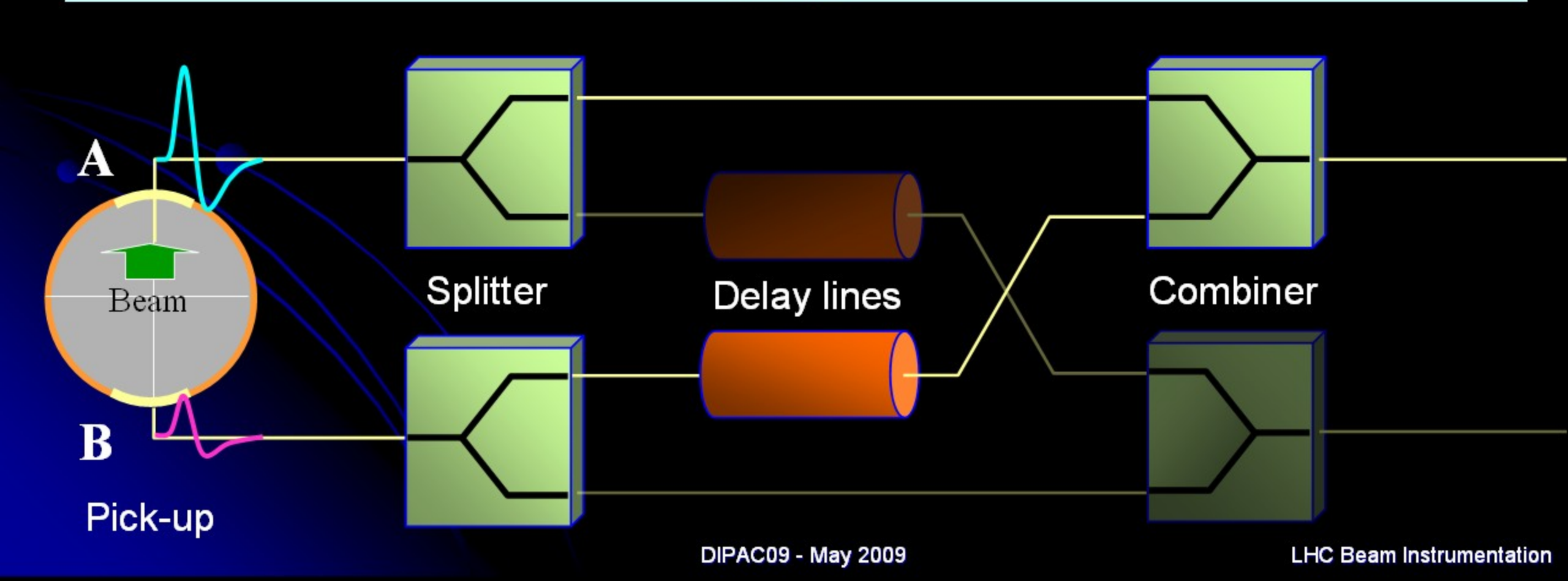


LHC Beam Position System Layout



The Wide Band Time Normaliser





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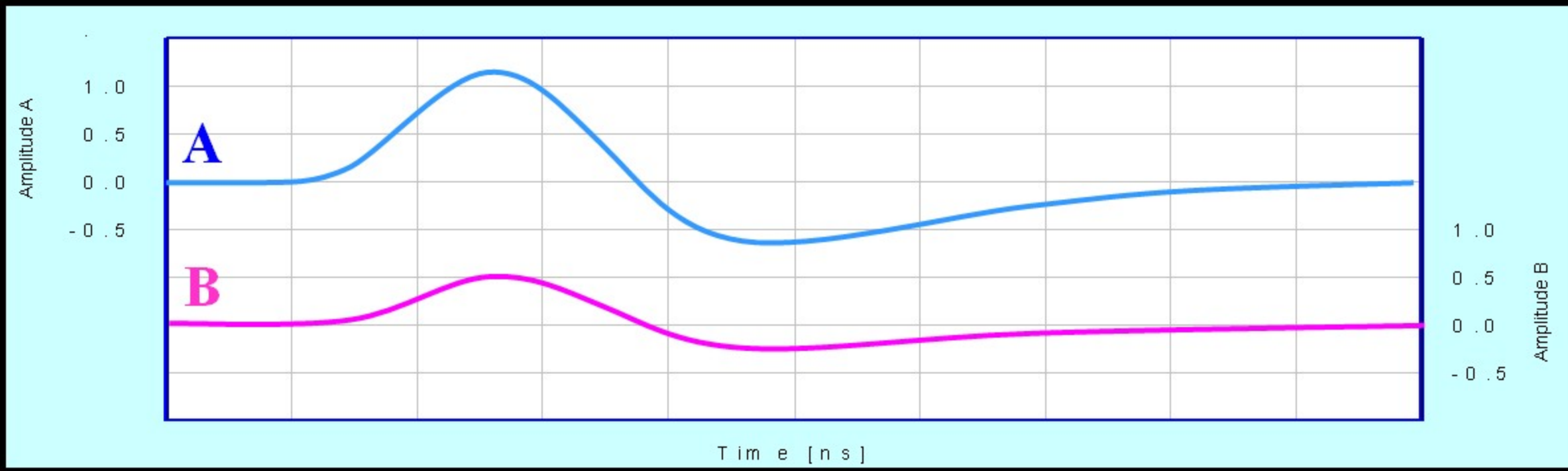

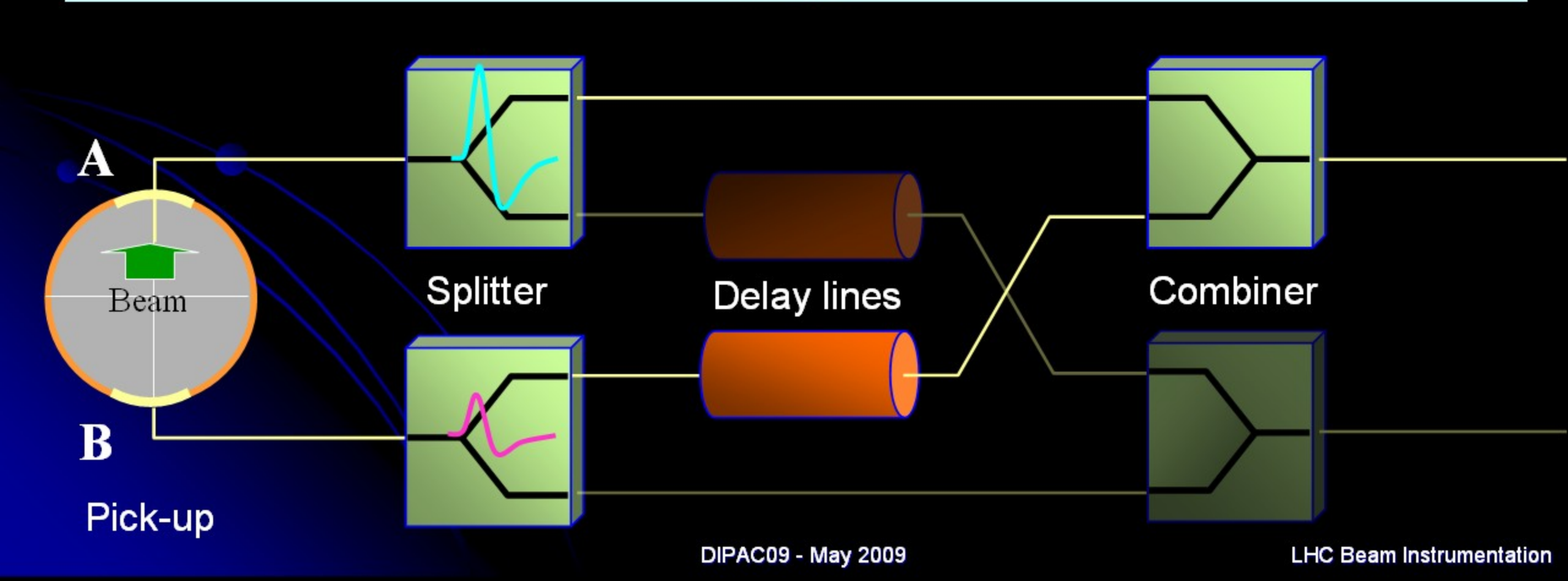

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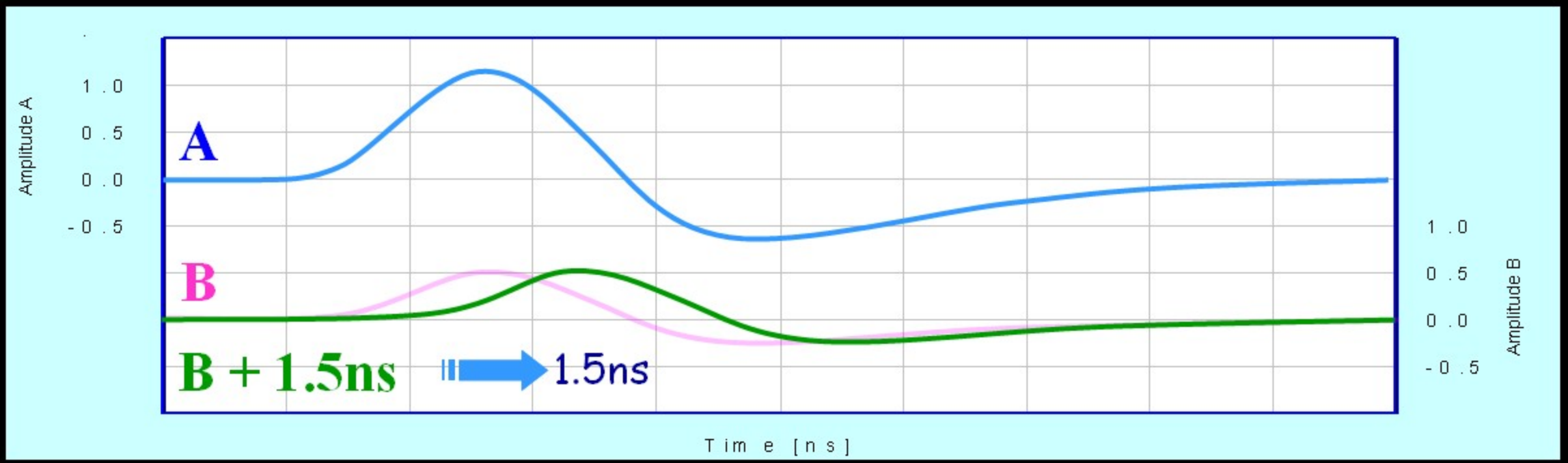

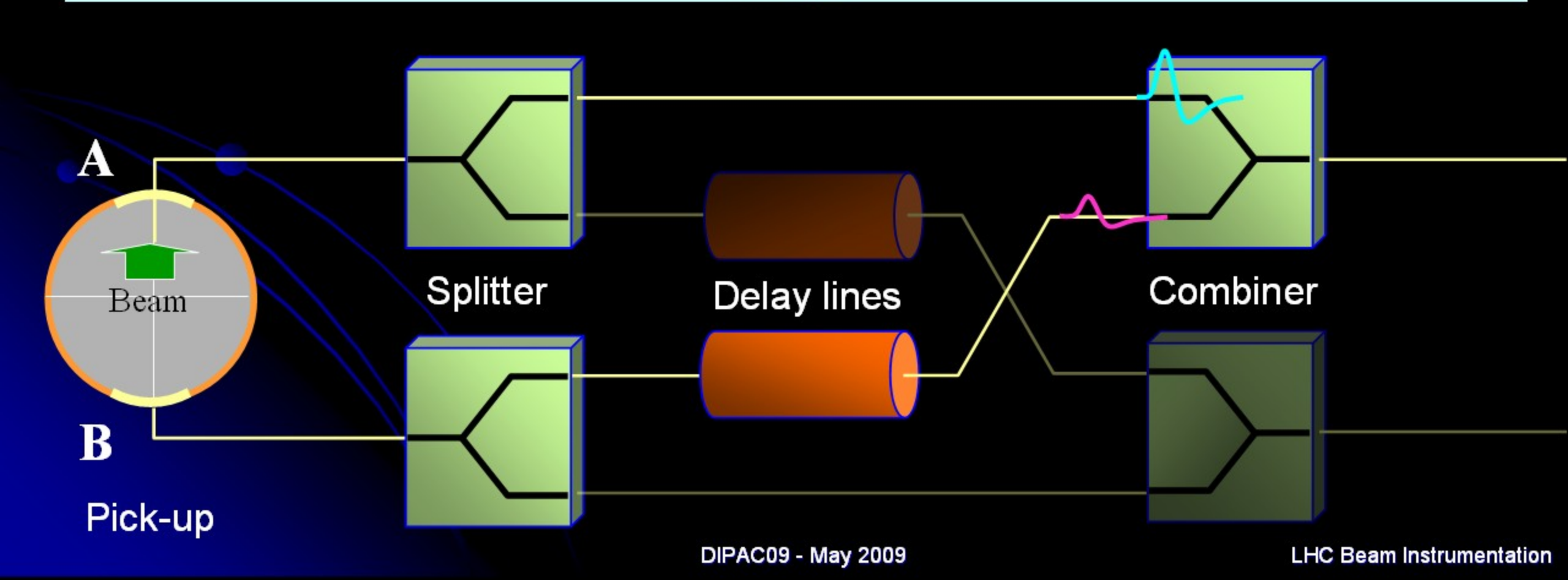

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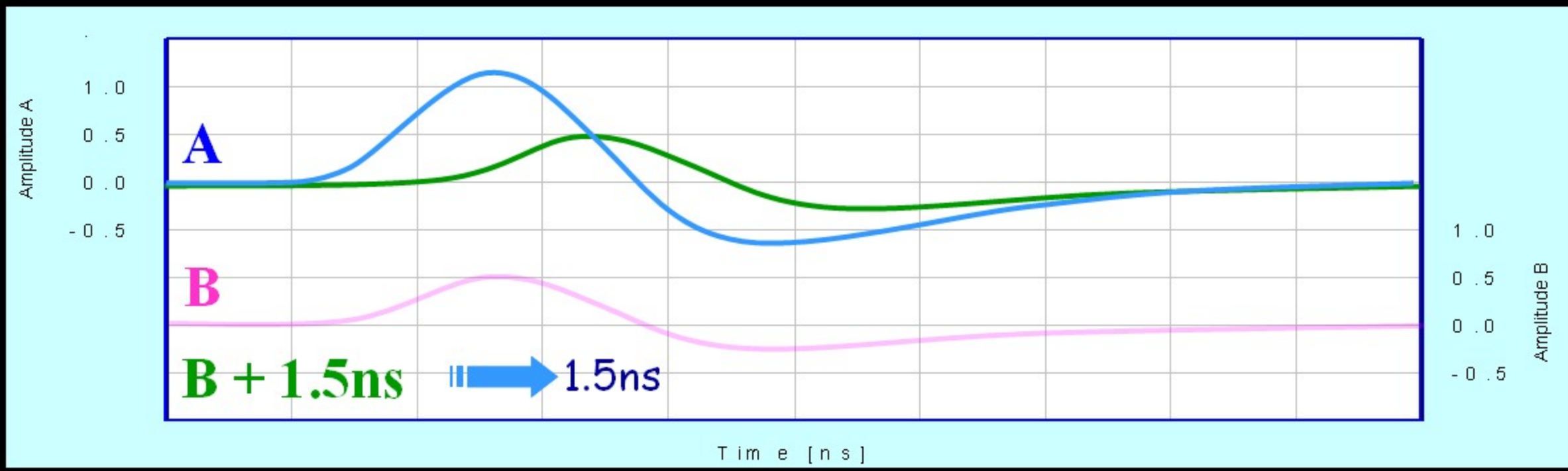

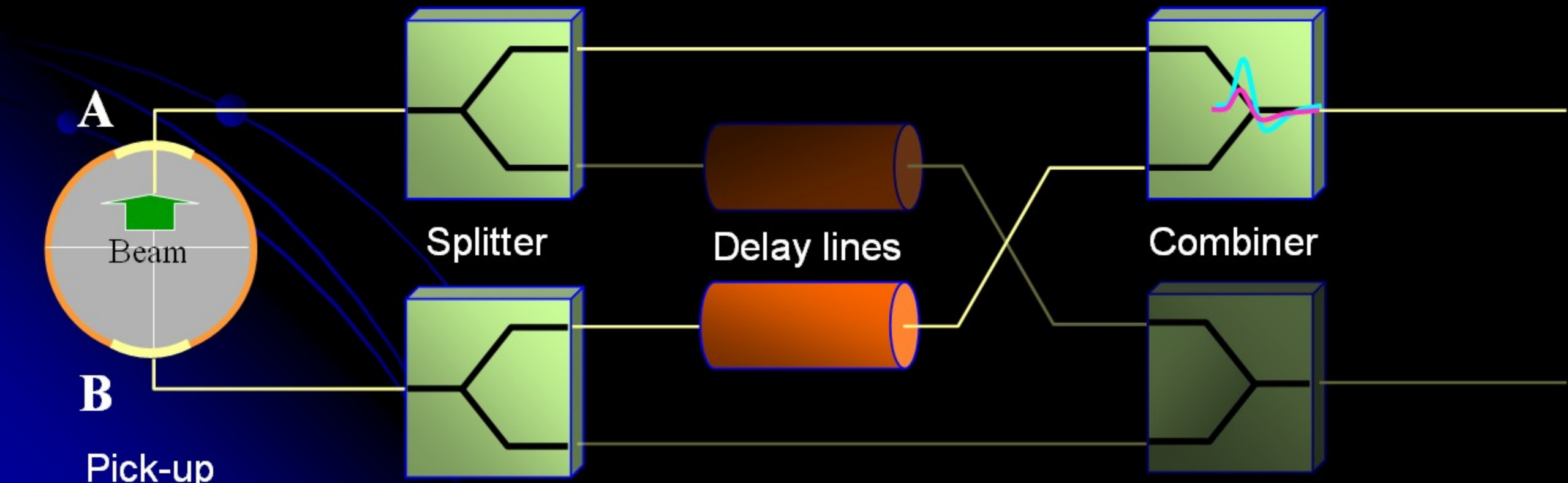

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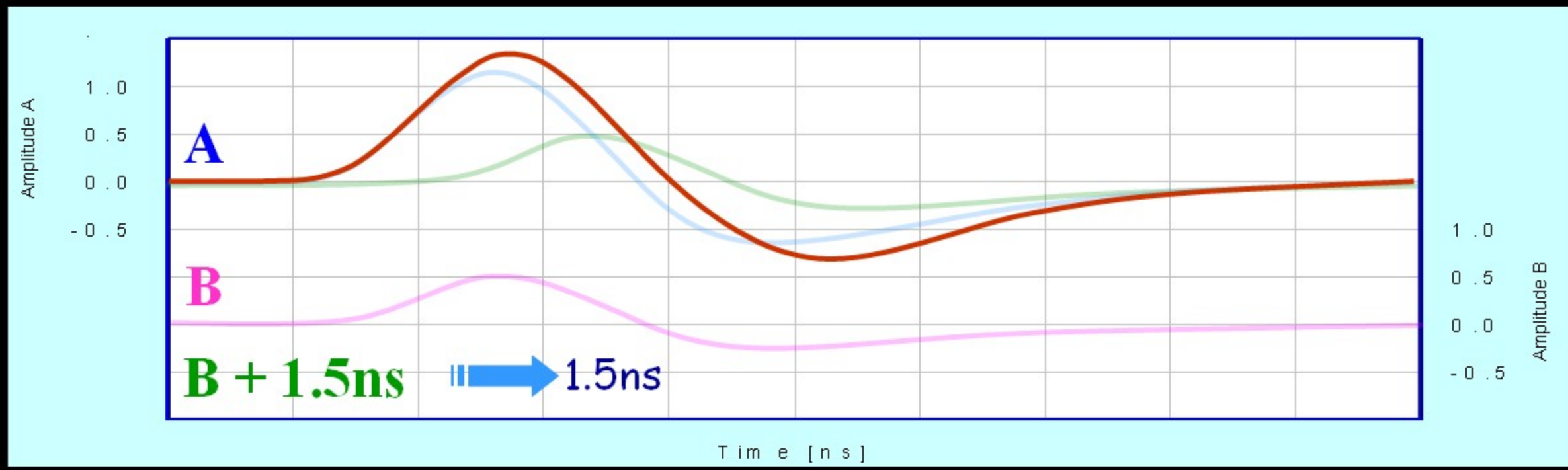

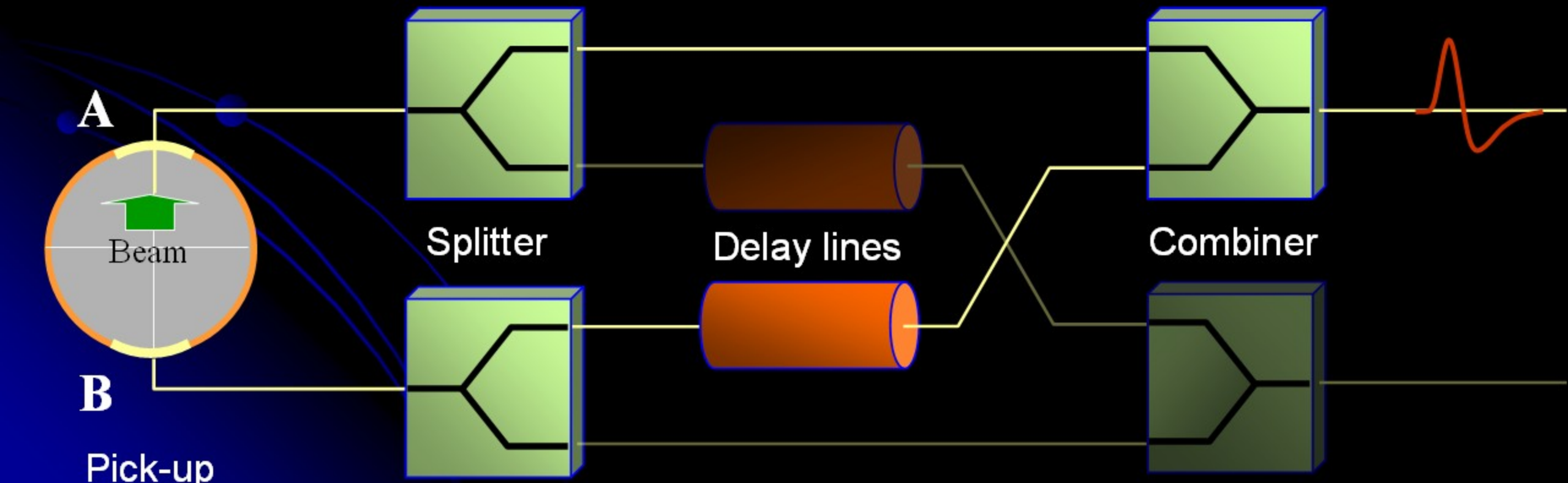

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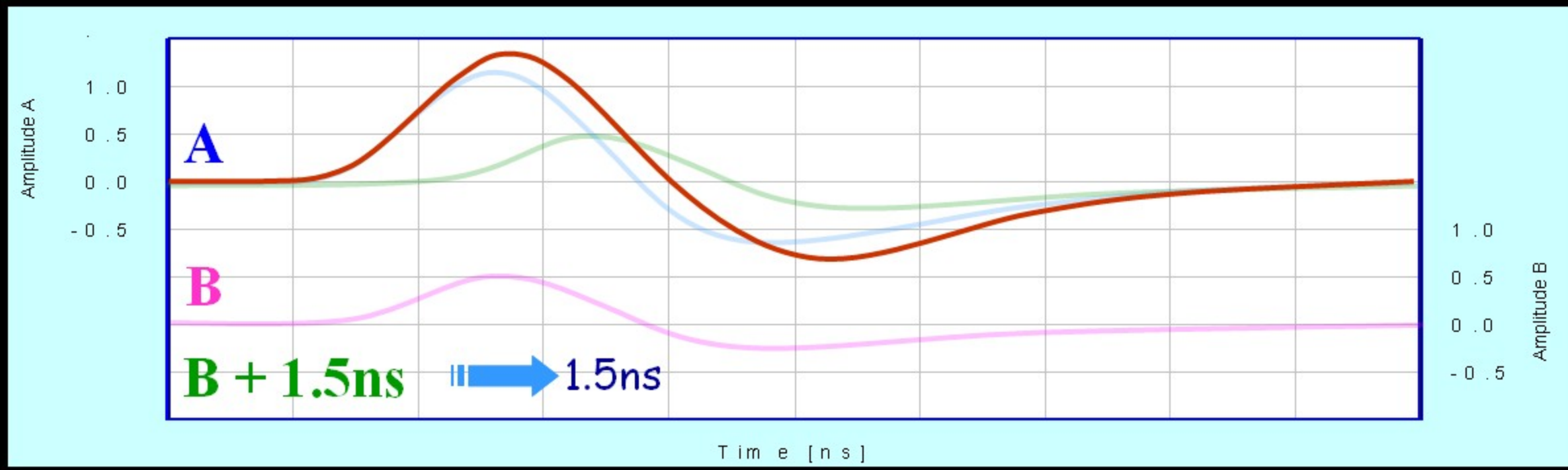

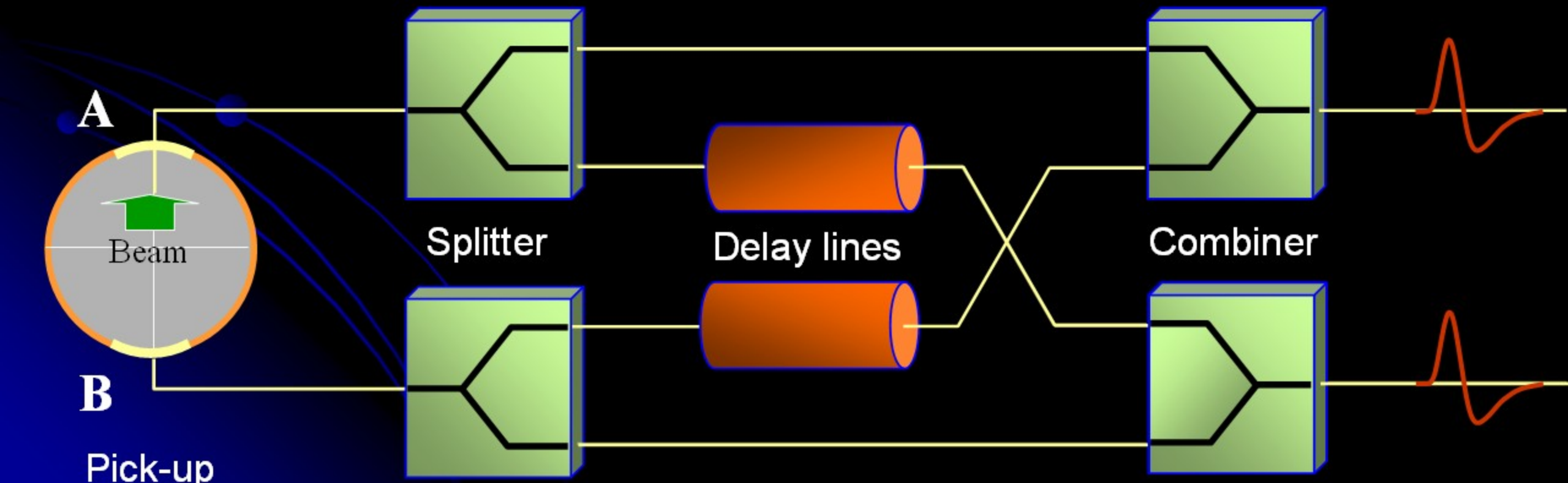

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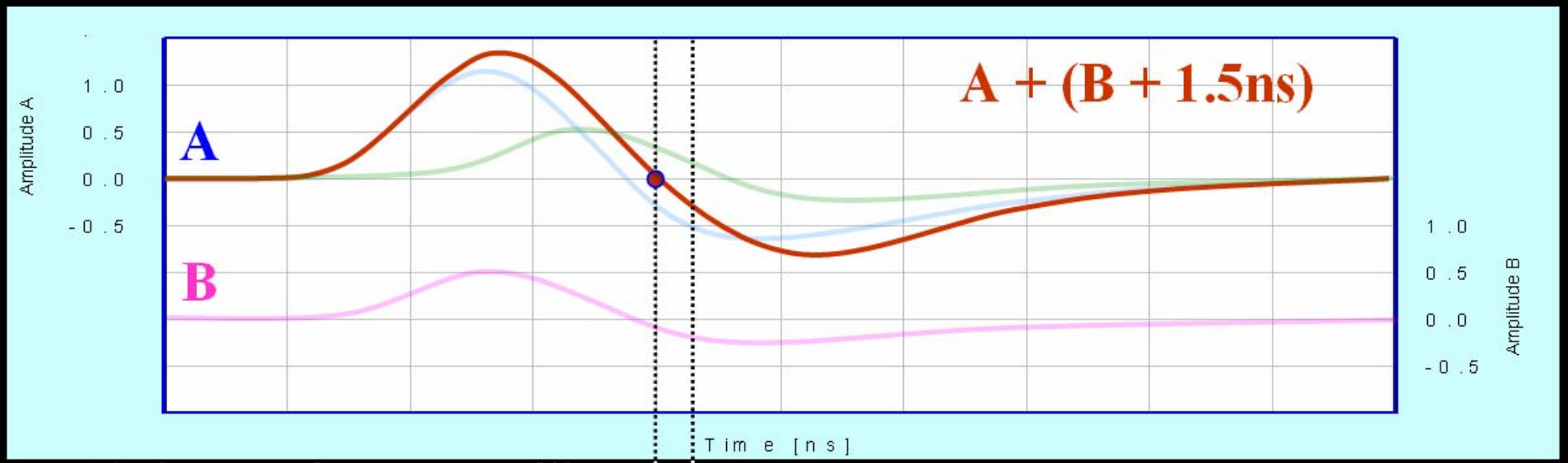
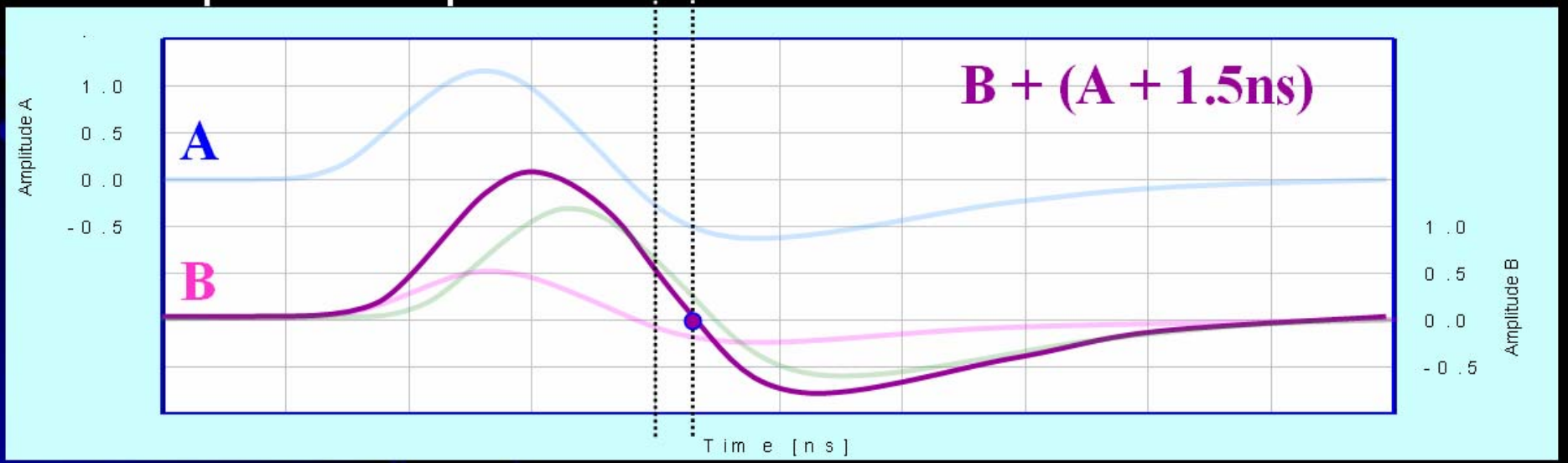
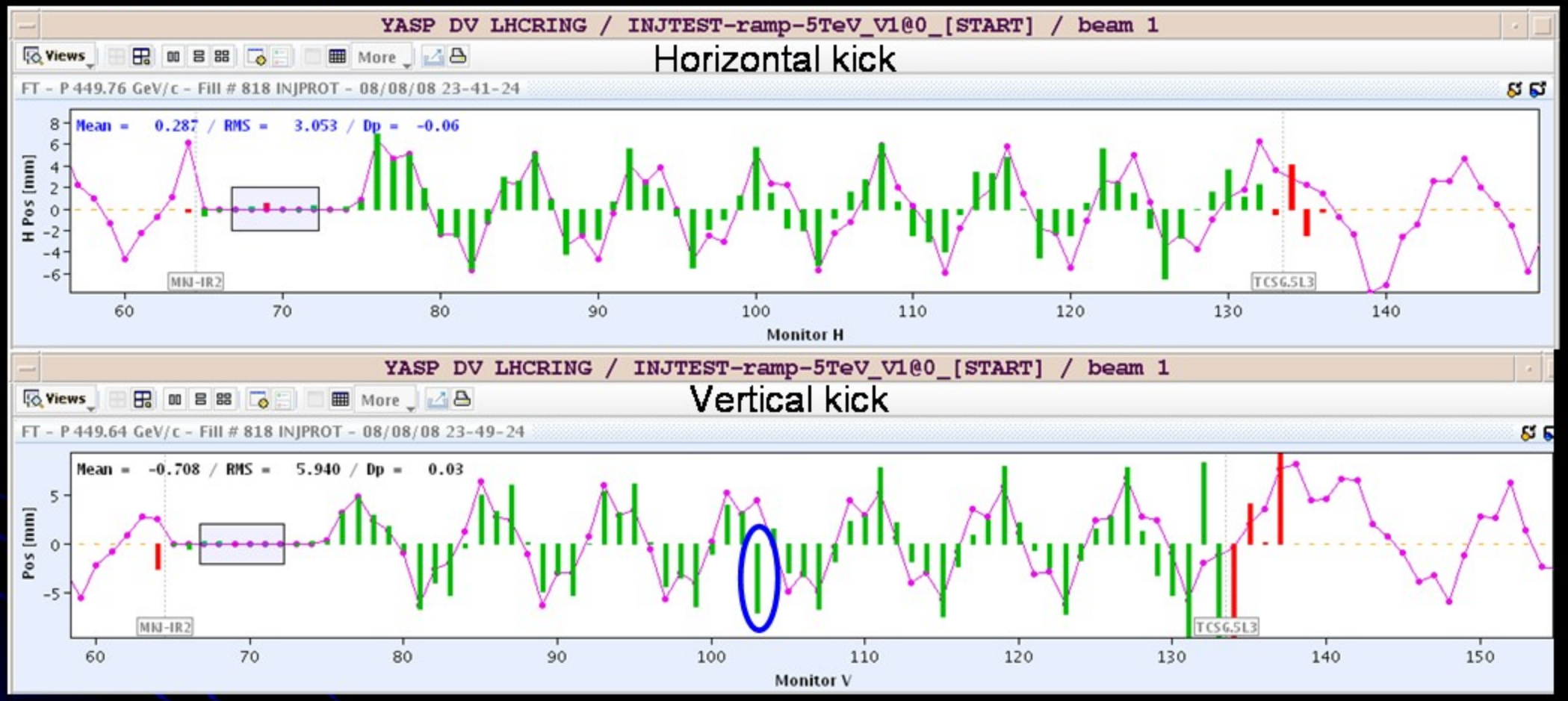


Δt depends on position



LHC BPM System Performance I

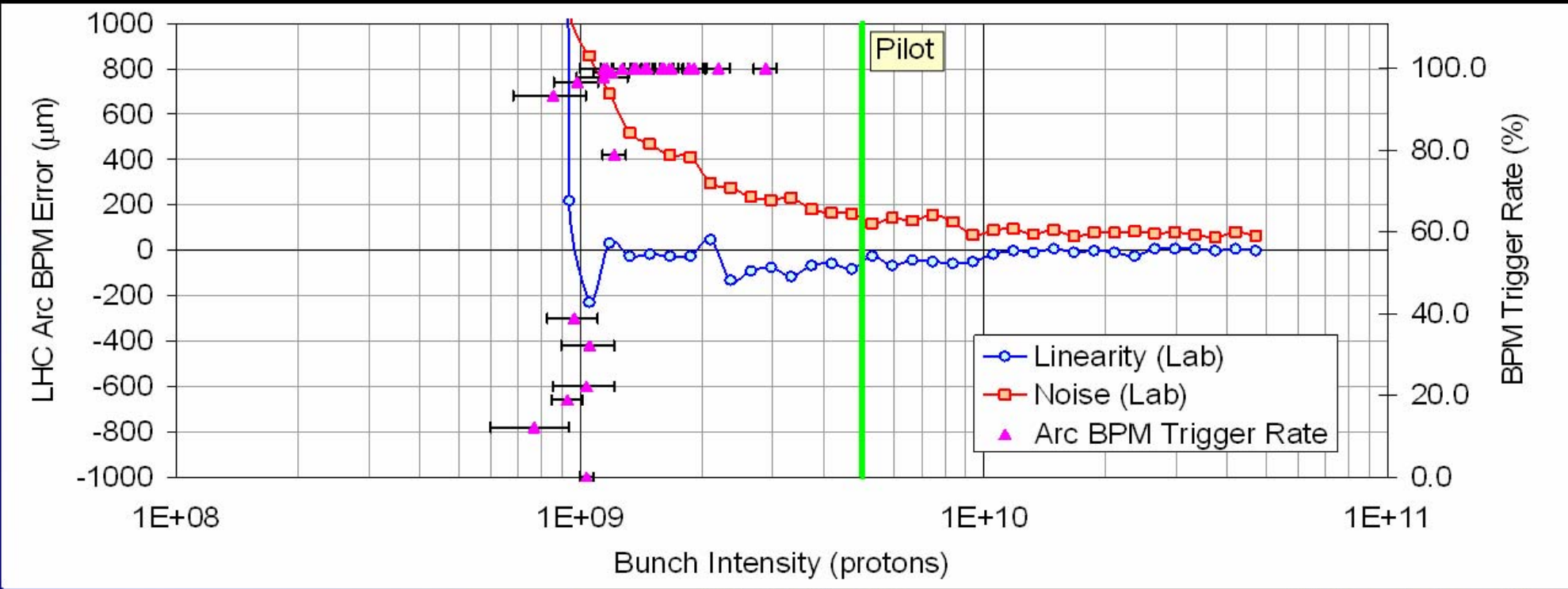
- On line analysis of BPM Data
  - Powerful on-line tools developed by the CERN Operations crew
  - Polarity errors easily identified with 45° BPM sampling
  - Quick indication of phase advance errors



- Some statistics to date
  - 4 polarity errors
  - 2 H to V inversions & 7 BPM mapping errors (LSS8L)
  - 1 B1 to B2 inversion
  - Some 10 remaining suspect BPMs (noisy or incoherent data)
  - Total of ~24 out of 2156 channels (~1%)

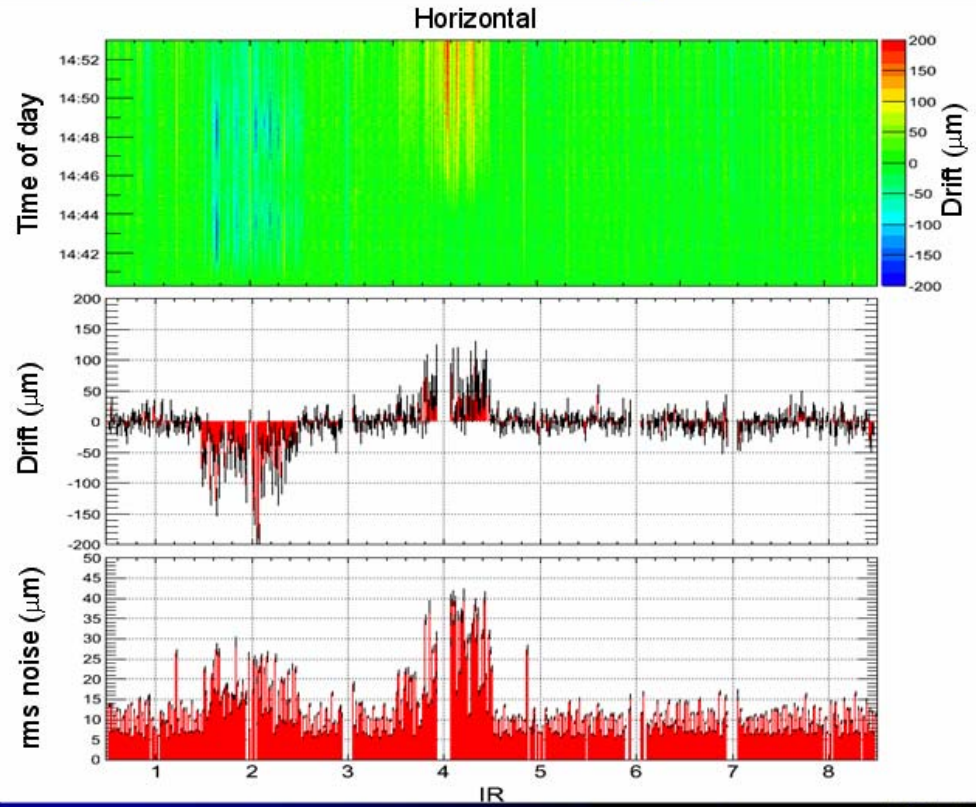
LHC BPM System Performance II

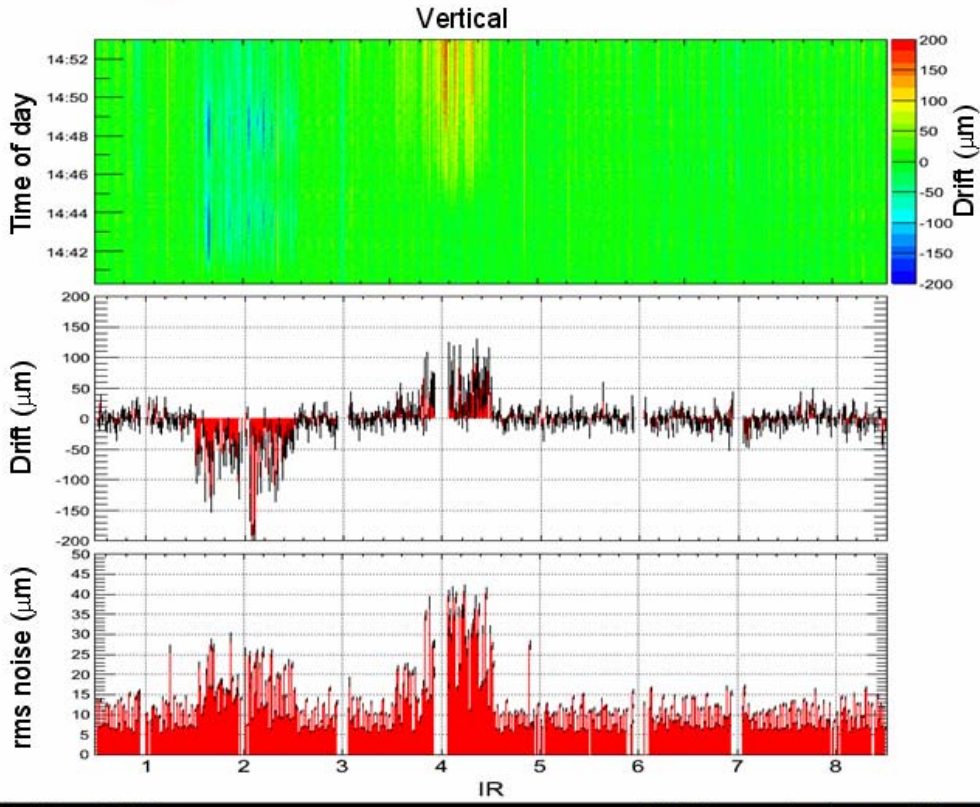
- Check of BPM Threshold Levels
  - Threshold determined to be 1.5×10^9 protons
    - Compared to pre-declared limit of 2.0×10^9
  - Initial values did not correspond to lab measurements
    - Threshold was 6dB lower in the laboratory
    - Accurate re-measurement of electronics & cables for final bandwidth & signal loss
    - Final model now agrees with beam measurements
      - Understanding important for intensity card



LHC BPM System Performance III

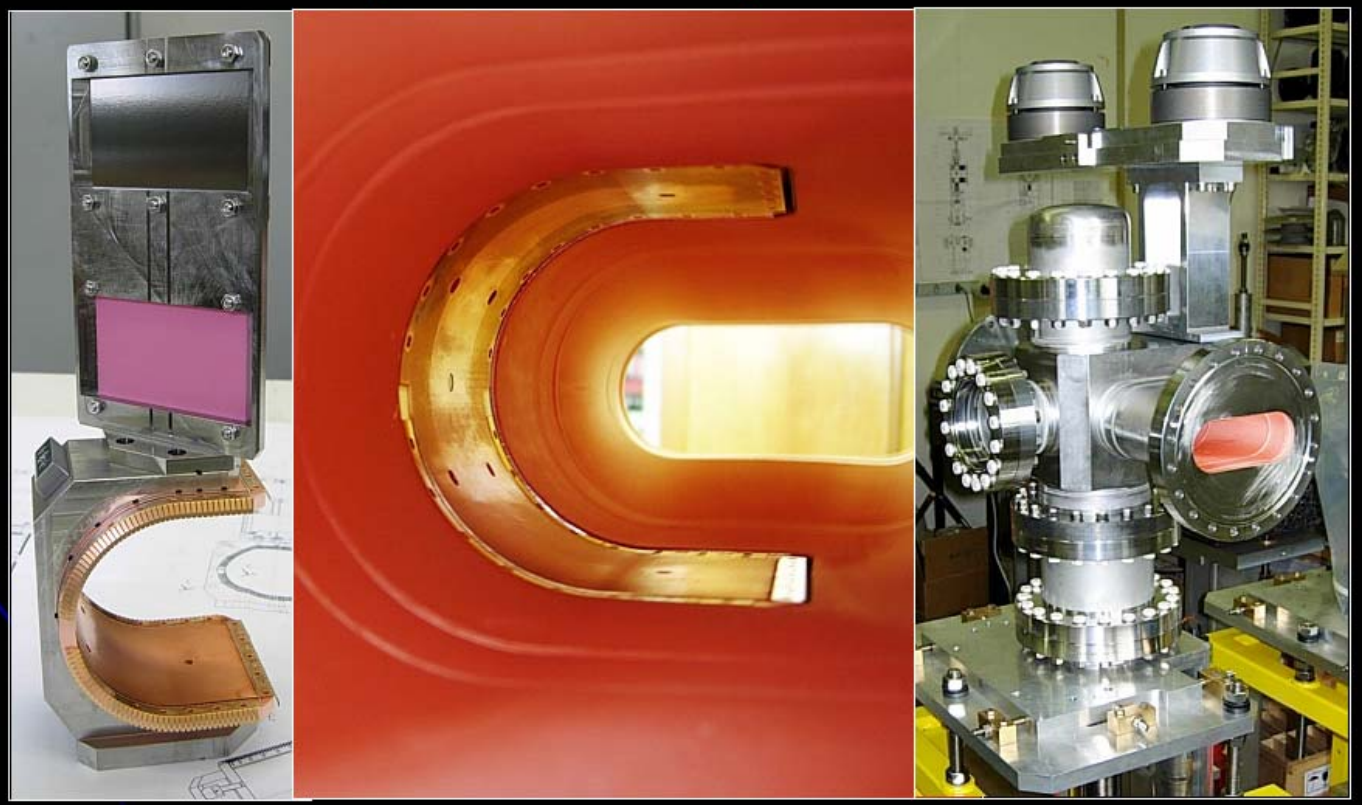
- Orbit & BPM Stability
  - Short term stability (15 minutes) better than 10μm
  - Alternating high/low peaks follow the beta function indicating that:
    - large fraction of noise results from beam (orbit corrector power supplies ⇒ 5-10μm orbit rms)
    - resolution & stability of BPM system in orbit mode with single pilot bunch is ~5μm
  - BUT - Surface electronics sensitive to temperature variations (~50μm per degree)
    - Point 4 – electronics in BI control room so much more sensitive to variations
    - Point 2 – electronics in standard outbuilding where source of fluctuation is unclear
  - Several solutions being looked into to solve this problem





LHC Beam TV (BTV) System

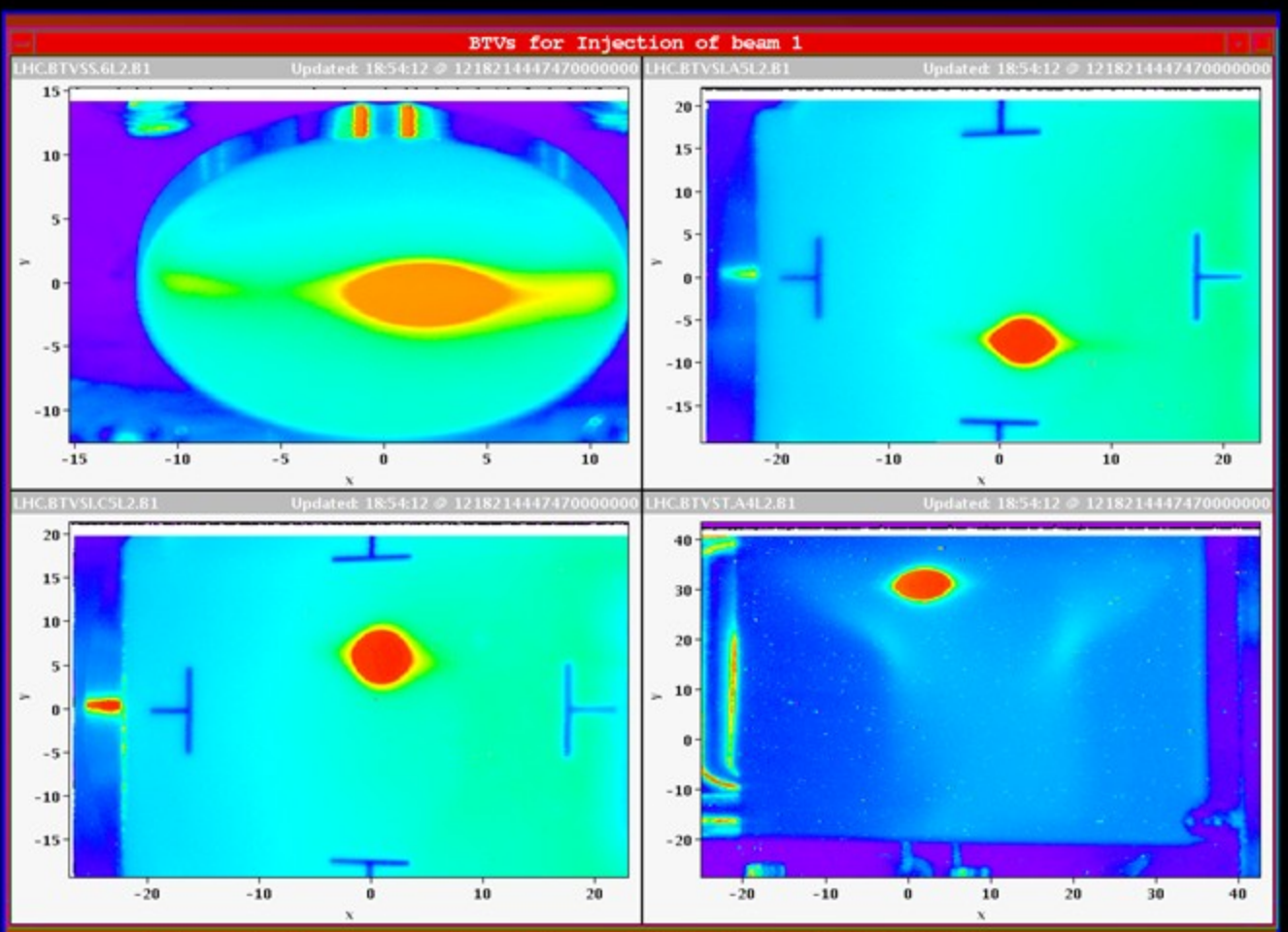
- Beam Profile Measurements in the LHC
  - For injection, dump & matching
    - 1mm Alumina (scintillator screen)
    - 12μm Titanium Foil (OTR screen)



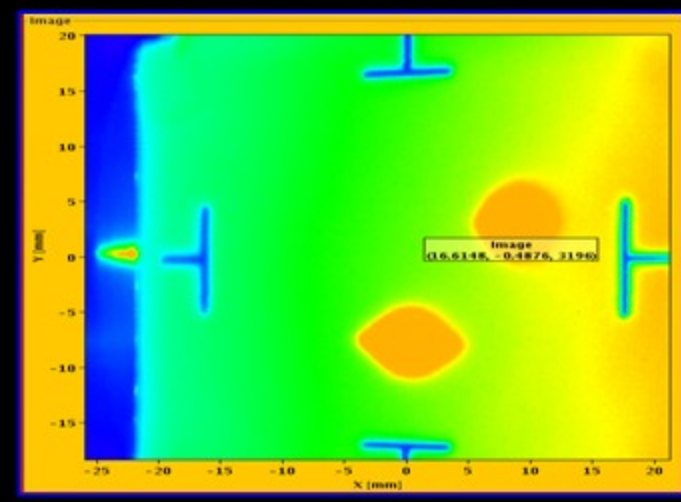
Dump line BTV tanks awaiting final installation

LHC BTV System

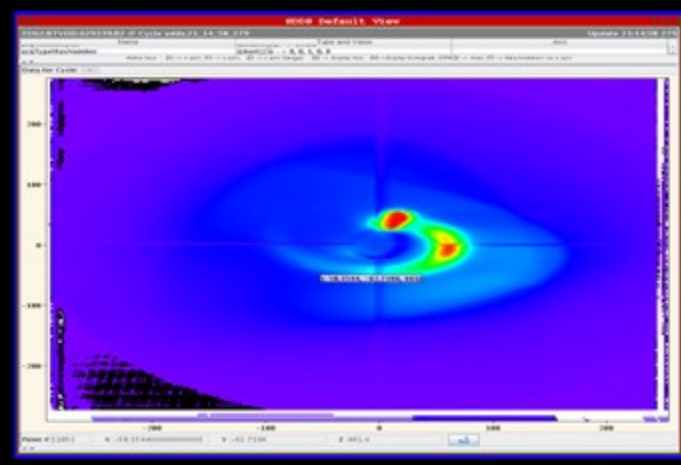
- All screens fully commissioned
  - 18 BTV in the LHC transfer lines
  - 13 BTV in the LHC ring
  - 6 BTV in the LHC dump lines
- Both video link and digitised data acquired on first shot



First Beam in the LHC 8/8/2008



First full turn as seen by the BTV 10/9/2008



Uncaptured beam sweeps through he dump line

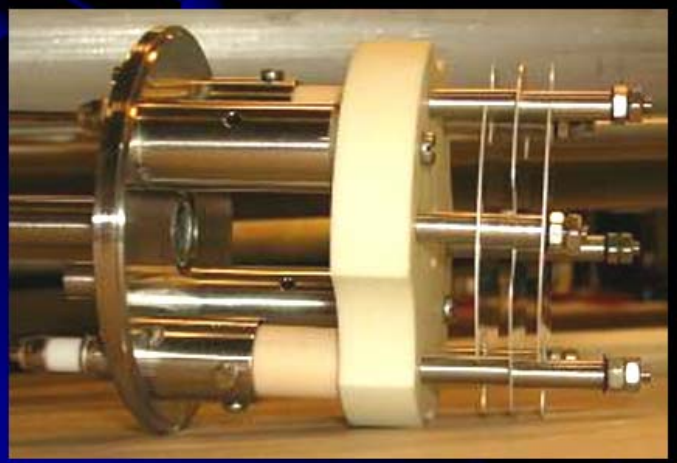
- Still to do
  - Gradual replacement of the 13 LHC ring CCD cameras with rad hard cameras
  - Turn by turn acquisition for matching measurements using fast cameras

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

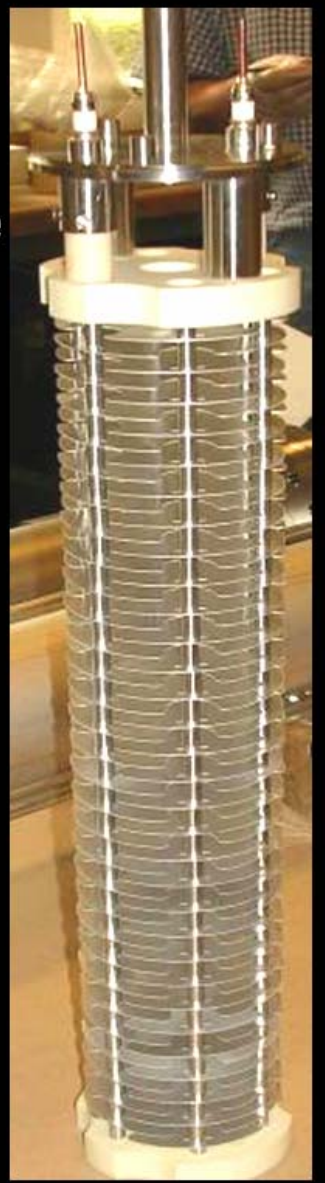


Ionization chamber:

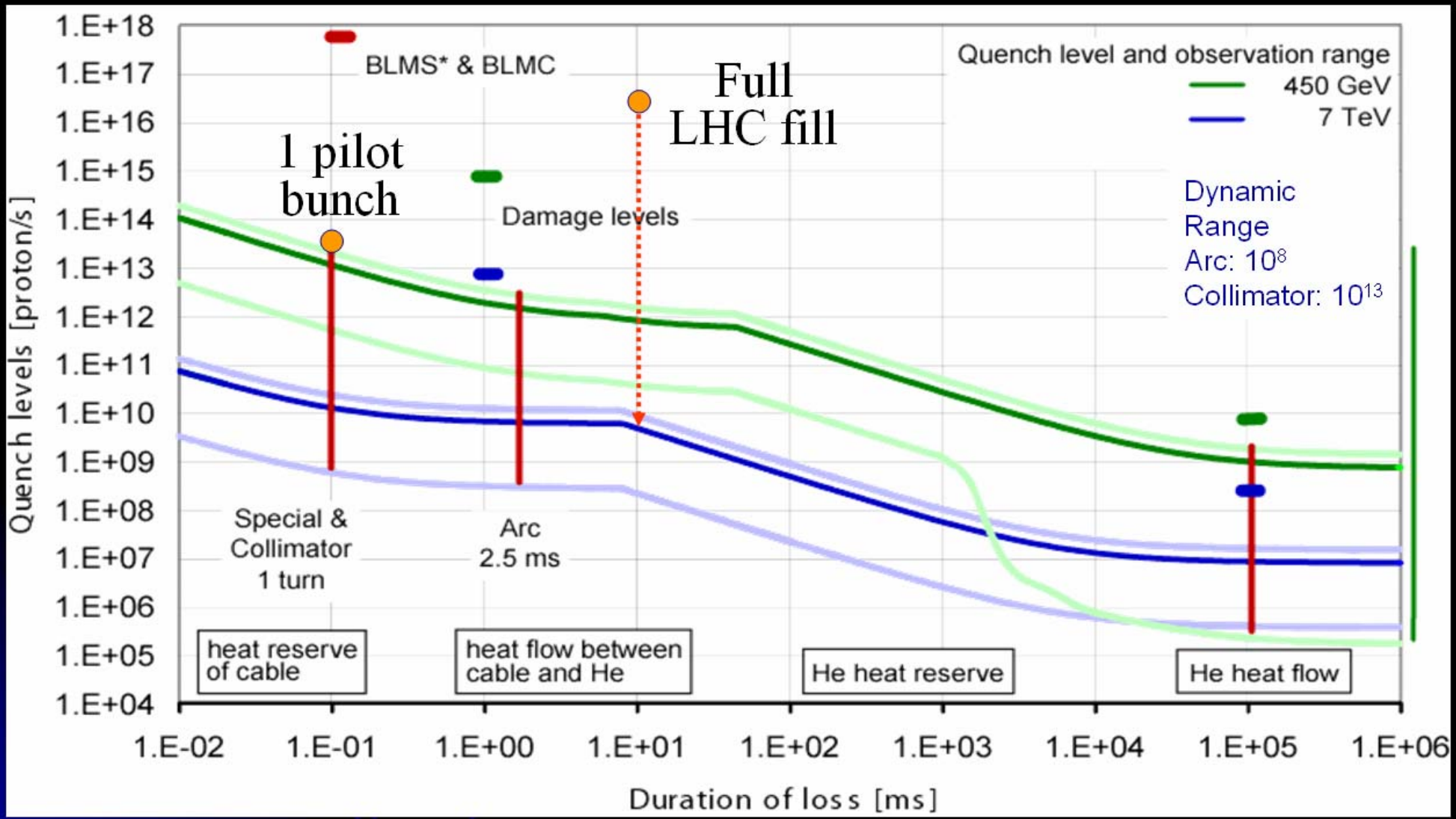
- N_2 gas filling at 100 mbar over-pressure
- Length 50 cm
- Sensitive volume 1.5 l
- Ion collection time 85 μs

Both monitors:

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



BLM Detection Range



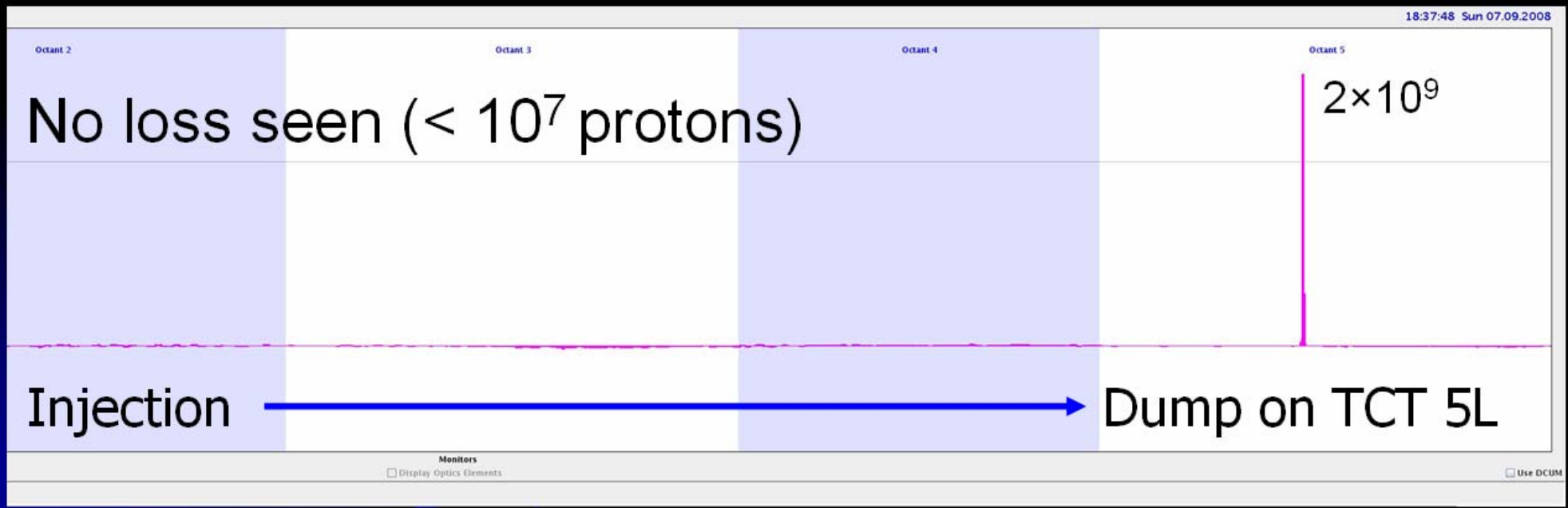
- Pilot bunch of 5×10^9 close to damage level at 7TeV
- Loss of 3×10^{-7} of nominal beam over 10ms can create a quench at 7TeV

Installed BLM Monitors

4000 BLMs installed throughout the LHC

LHC BLM System I

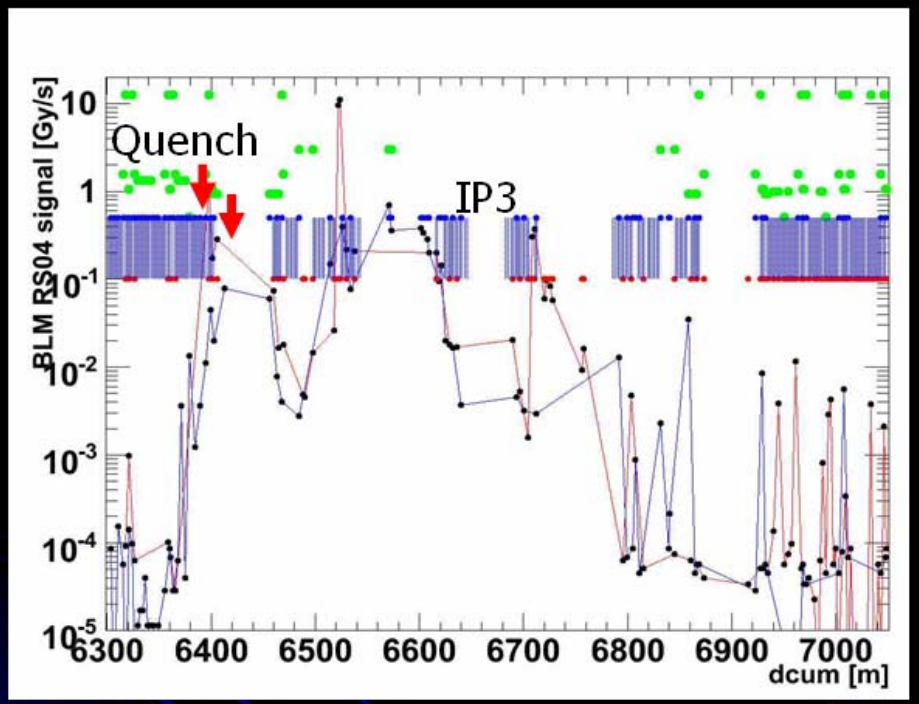
- Worked well from first injection tests
  - Noise level 2 orders of magnitude less than bunch of 2×10^{9}
    - Sufficient to allow quenchless injection of 5×10^{11}
  - Data concentration and logging a big issue
    - on-demand capture & continuous monitoring tested



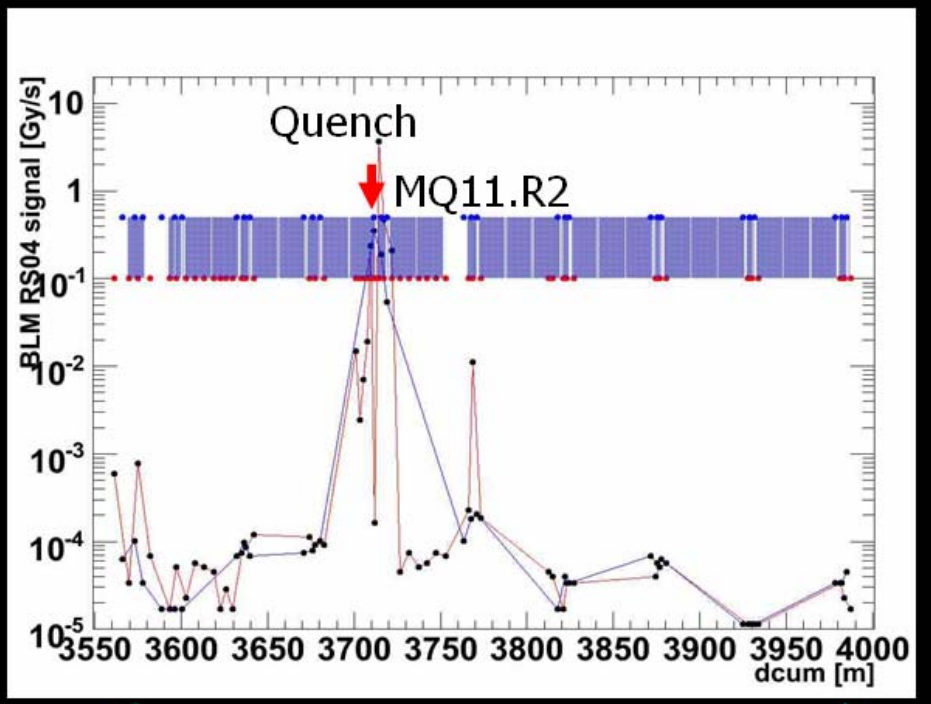
Clean injection (IP2 to IP5)

LHC BLM System II

- 2 beam induced triggers of quench protection system during injection tests
  - Loss of between 2 - 4 × 10^9 protons with very different loss patterns



700m



450m

LHC BLM System II

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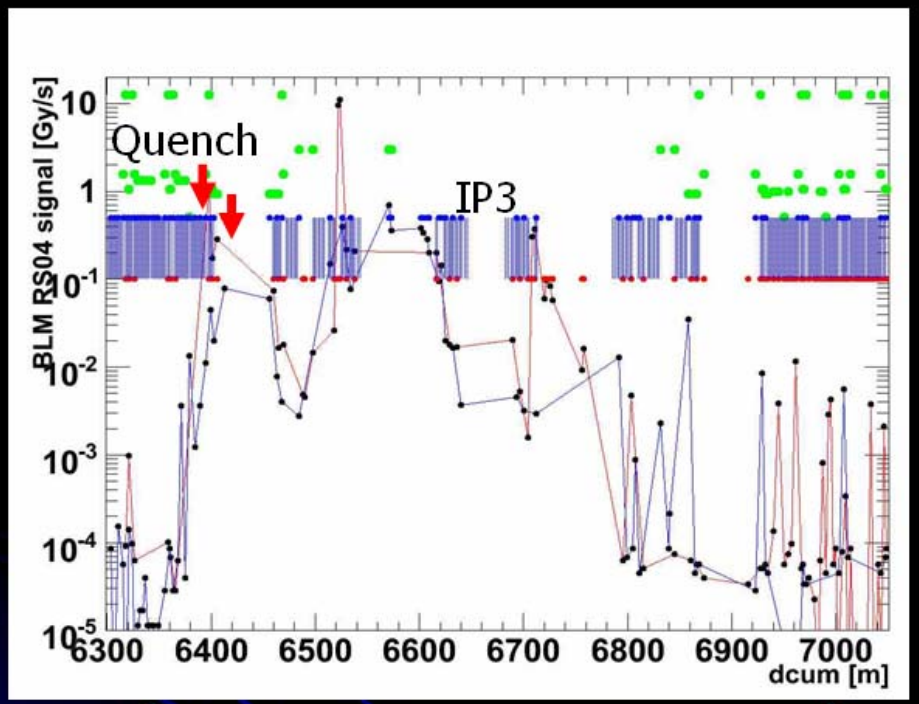
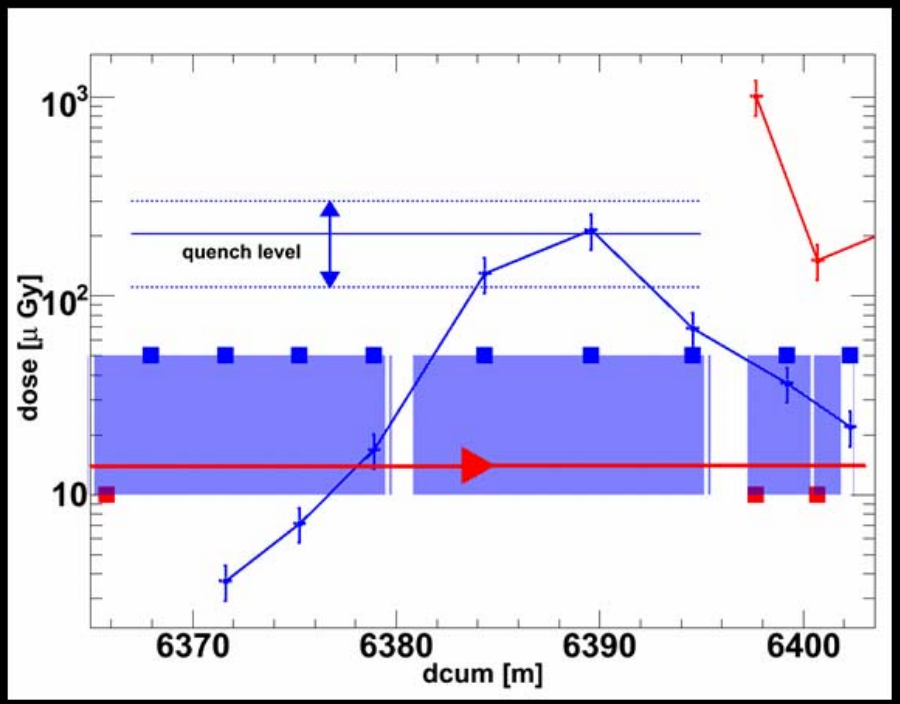
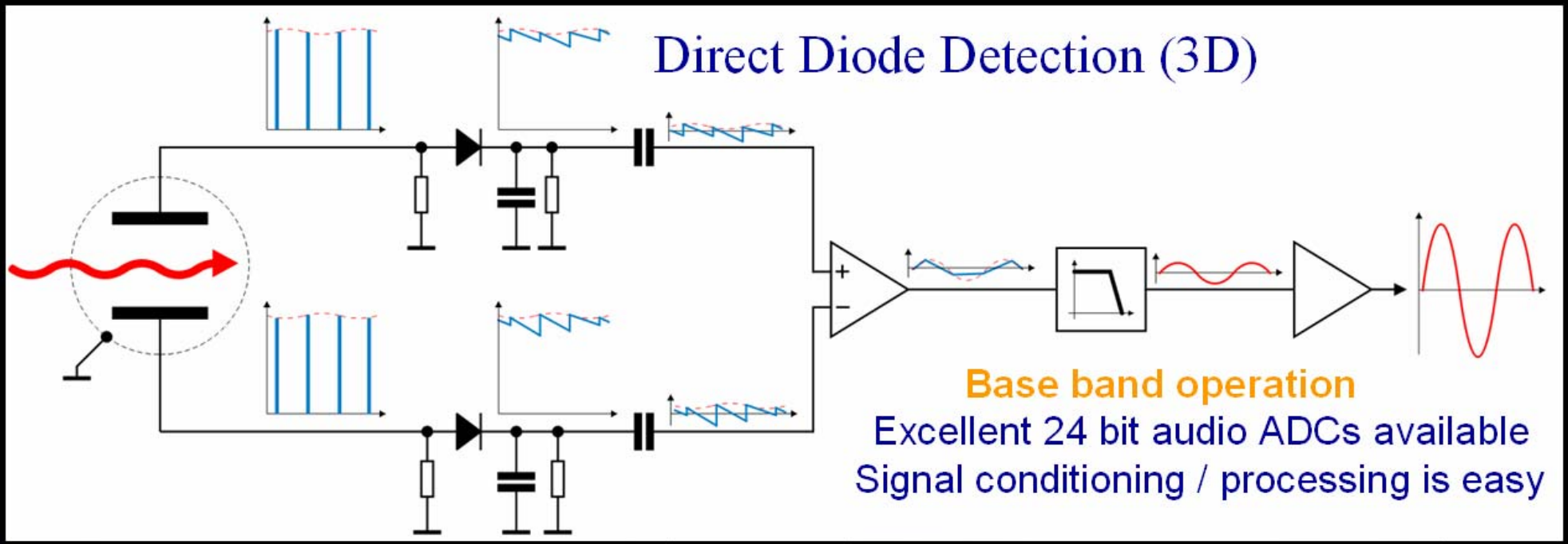


700m



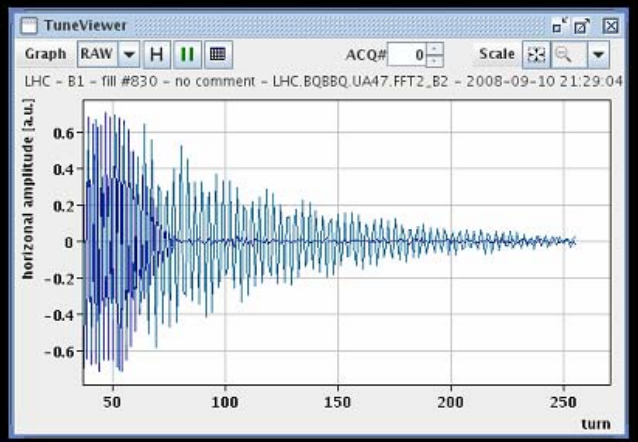
- Quench reconstruction
  - Quench in middle of dipole ideal for analysis
    - Beam current, impact location & loss distribution width used to constrain simulations
    - Result factor 2 lower compared to value obtained by calculating enthalpy of the coil
      - ~15 mJ/cm^3 estimated compared to 30 mJ/cm^3 expected

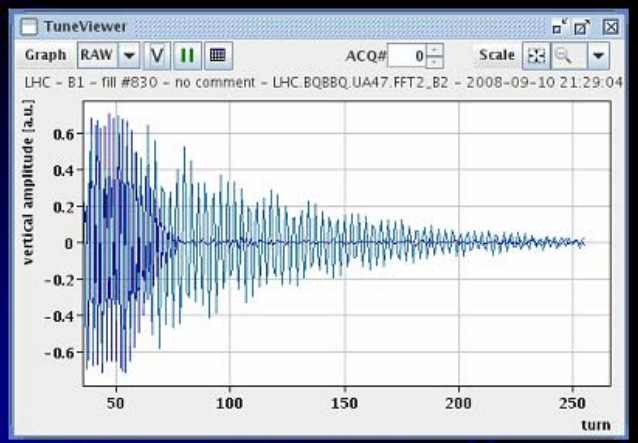
The Base Band Q Measurement (BBQ) System

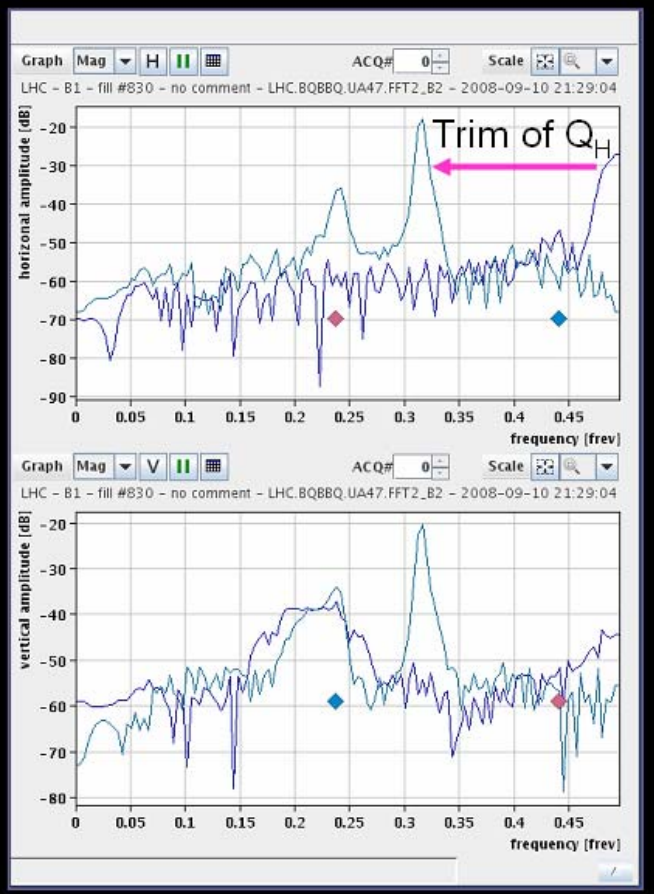


LHC Q, Q' & C Systems I

- BBQ Tune Measurement Systems Commissioned for Beam 2
  - Observed nice signals for injection oscillations
    - Allowed tune to be adjusted early-on to improve initial lifetime
  - Visible in residual non-excited circulating beam spectra with S/N ratio > 10dB







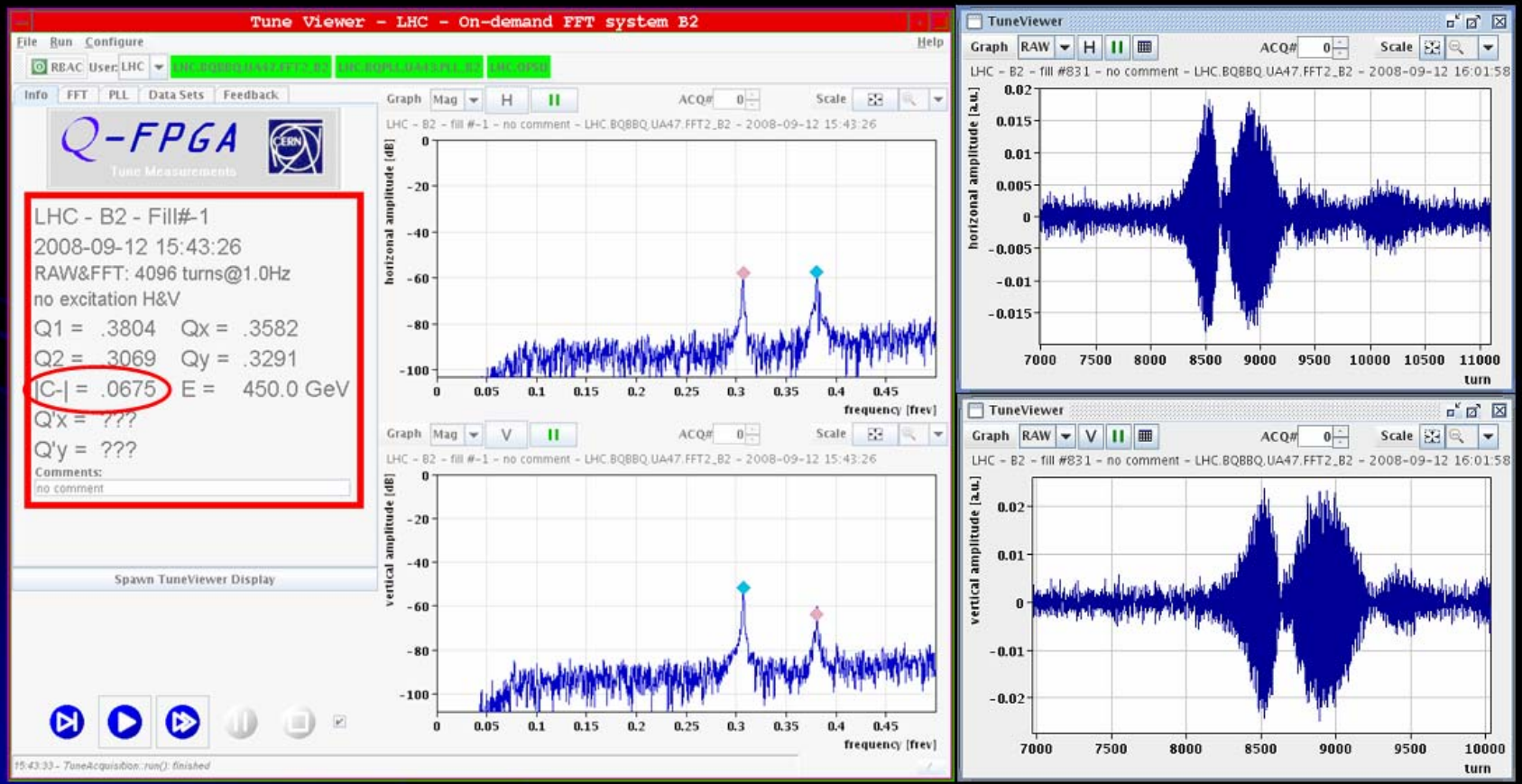
- Initially
  - No RF capture
  - $Q_H \approx 0.50$
  - $Q_V \approx 0.24$
- Trim of ΔQ_H by -0.2
  - $Q_H \approx 0.50 \rightarrow 0.32$
  - Moving from the half-integer resonance increases circulation time to 300+ turns (still no RF capture)

Before correction

After correction

LHC Q, Q' & |C Systems II

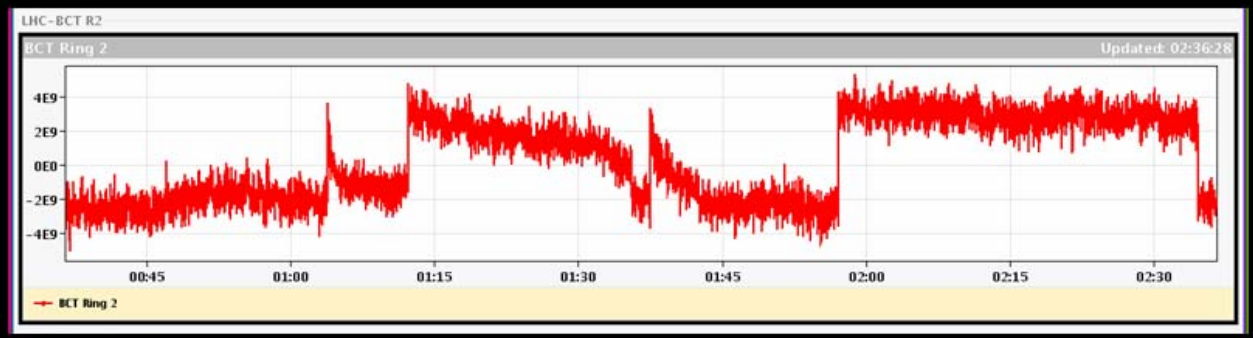
- BBQ Tune On-Demand system commissioned
  - Chirp excitation using transverse damper
    - Polarities verified to be correct (excitation & acquisition)
  - Allowed first measurement of coupling
    - Measured coupling |C-| ≈ 0.07



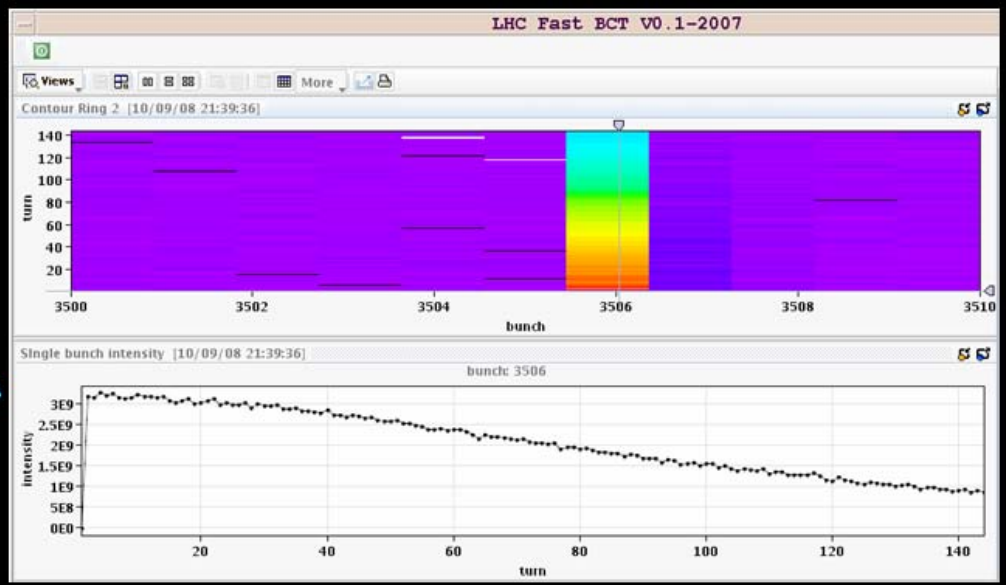
LHC BCT Systems

- BCTDC (DCCT)
  - Main Beam 2 acquisition system commissioned
    - Noise signal rms of 7×10^{8} for 1 second integration (1.3μA)
    - Offset of ~2×10^{8} (4.5μA) will be automatically corrected for in the future
    - SAFE BEAM flag & DIP transmission to experiments tested but not yet activated
  - Beam 1 system still to be commissioned with beam

Beam 2
DCCT sees first
circulating beam



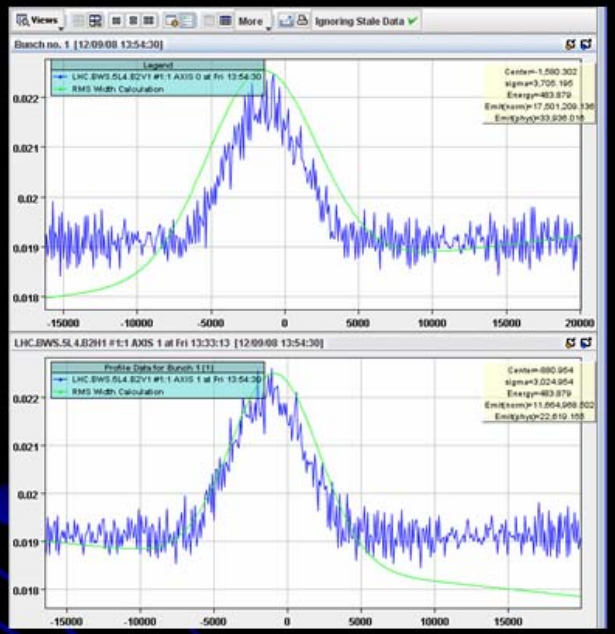
- BCTFR (Fast BCT)
  - Beam 1 & Beam 2 high sensitivity channels have seen beam
    - Calibration looks OK
  - Still to do
    - Full timing in of system for bunch to bunch measurements
    - Full commissioning of dump line systems
    - Commissioning of the beam presence flags
    - Adaptive lifetime algorithm
    - dI/dt link to machine protection

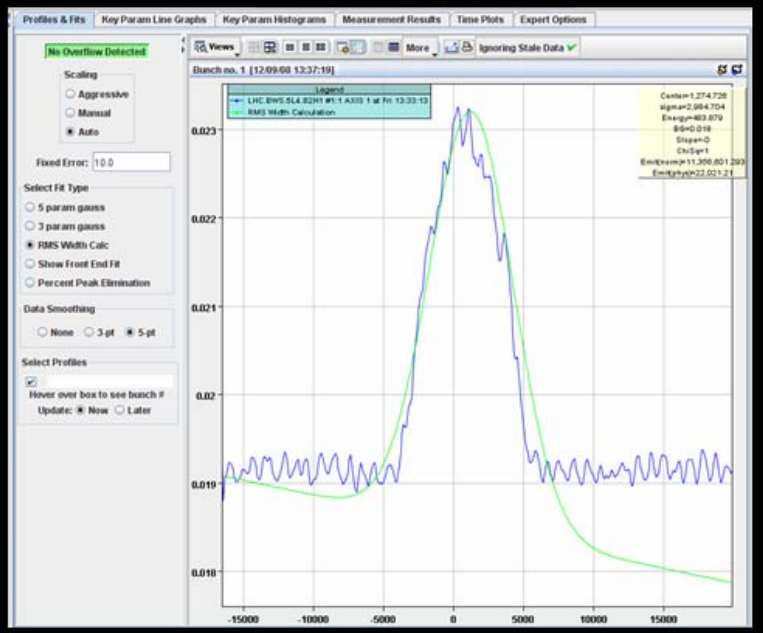


LHC Wire Scanner System

- Beam 2 System Commissioned
  - Linear wire scanner : 30μm carbon wire scanned at up to 2m/s
  - Low intensity single bunch gives expected noisy signals
    - Calibration verified & looks to be OK

Vertical In / Out Scan on Beam 2

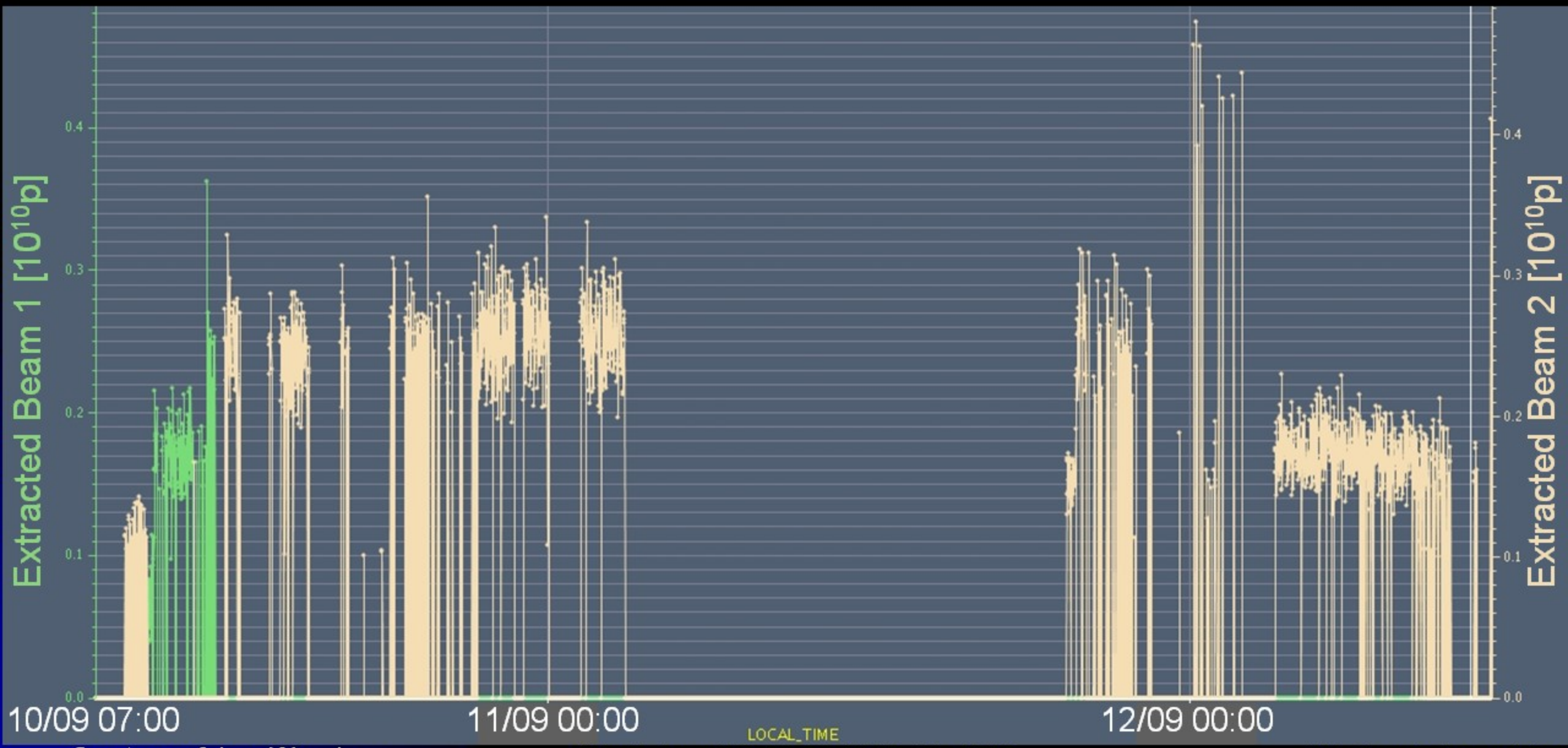




Horizontal Scan on Beam 2

- Still to do
  - Commissioning of Beam 1 system
  - Accurate timing in of acquisition systems
  - Bunch by bunch acquisition
  - Commissioning of wire protection system software

60 hours of Beam Commissioning



Courtesy of Jorg Wenninger

60 hours of Beam Commissioning

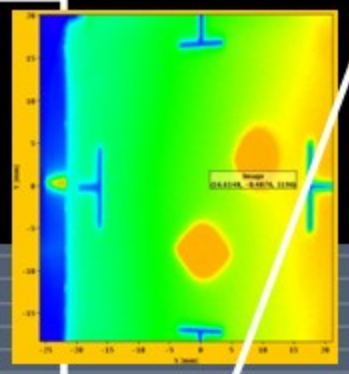
First turn!
10:26

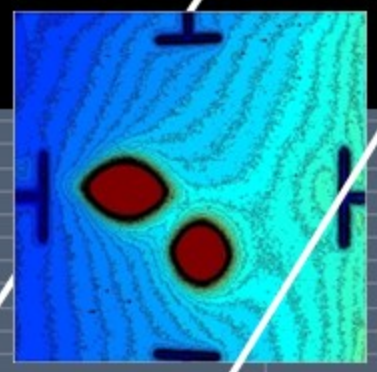
Beam 2 injection
13:34

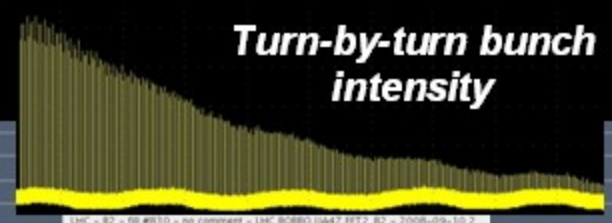
First turn!
14:59

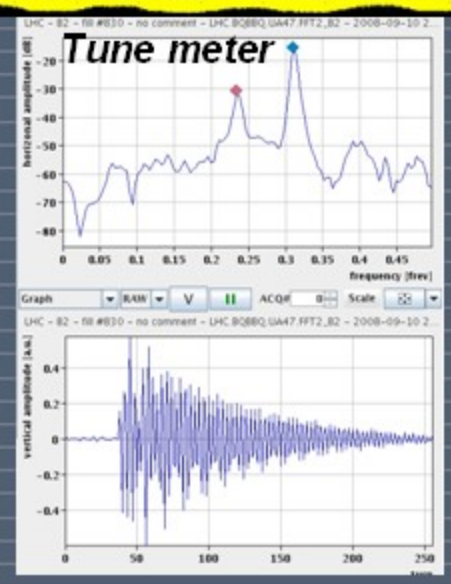
Circulating beam:
300+ turns
First tune

Beam1
injection
09:35









Extracted Beam 1 [10^{10}p]

Extracted Beam 2 [10^{10}p]

10/09 07:00

11/09 00:00

12/09 00:00

LOCAL_TIME

60 hours of Beam Commissioning

First turn!
10:26

Beam 2 injection
13:34

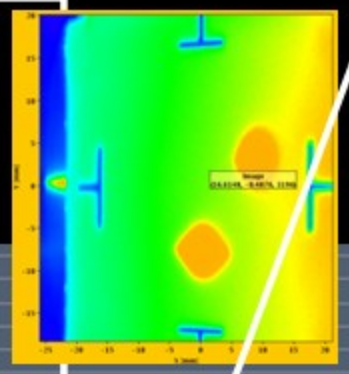
First turn!
14:59

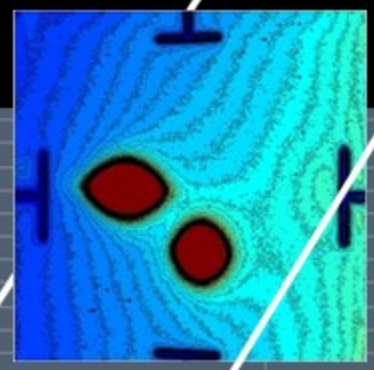
Circulating beam:
300+ turns
First tune

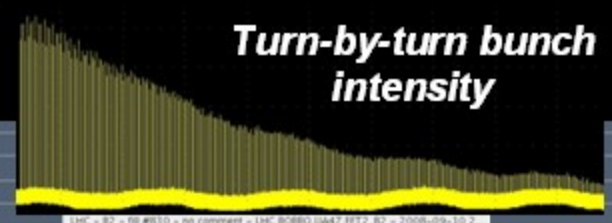
Beam captured!
Circulating>15min

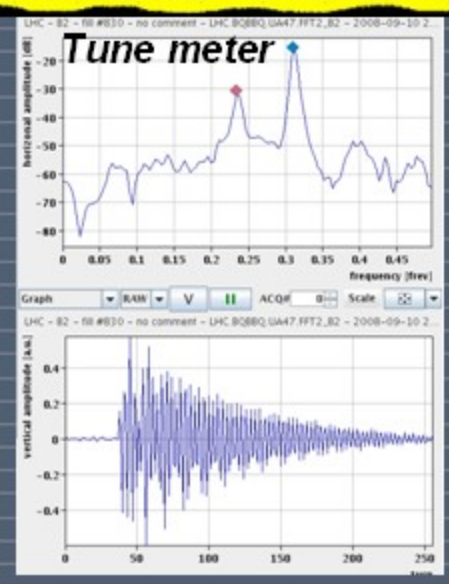
Beam1
injection
09:35

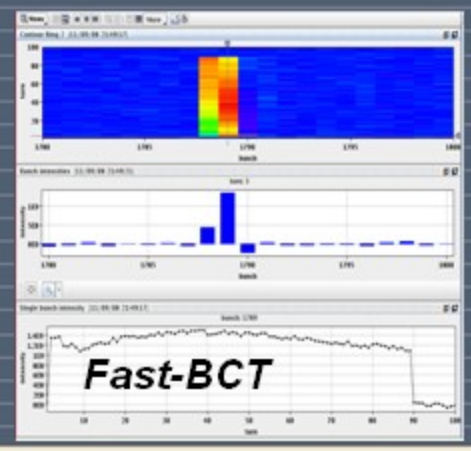
Detailed
measurements

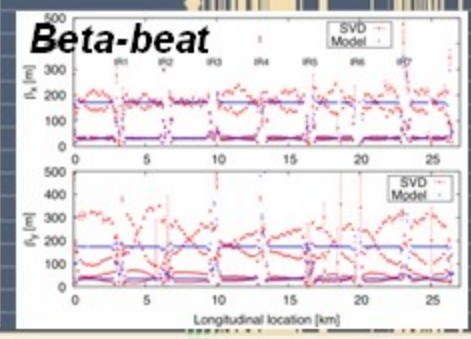












Extracted Beam 1 [10^{10}p]

Extracted Beam 2 [10^{10}p]

10/09 07:00 11/09 00:00 12/09 00:00

LOCAL_TIME

Summary

- A Good Start for all Beam Instrumentation Systems
  - Thanks to years of planning, testing & HW commissioning within the BI Group, with the help of many other Groups & external collaborators
- Next Steps - Still a lot to do!
  - Main Shutdown Work
    - BPM & BLM consolidation with considerable dismounting & remounting
    - Improvements to the synchrotron light monitor optical layout
    - Installation of US-LARP luminosity monitors (fast ionisation chambers)
  - Commissioning in 2009
    - Full commissioning of the already tested systems
      - Systematic measurements & fine timing
        - Fast Timing System already used for many systems and has worked very well
    - Commissioning of
      - Synchrotron light monitors (requires undulator)
      - Abort gap monitors (requires undulator)
      - Rest Gas Ionisation Monitors – needed for ions (requires gas injection)
      - PLL Tune measurement & Chromaticity with RF modulation
      - Orbit, tune, coupling and chromaticity feedback systems
      - Schottky & finally the luminosity monitors!

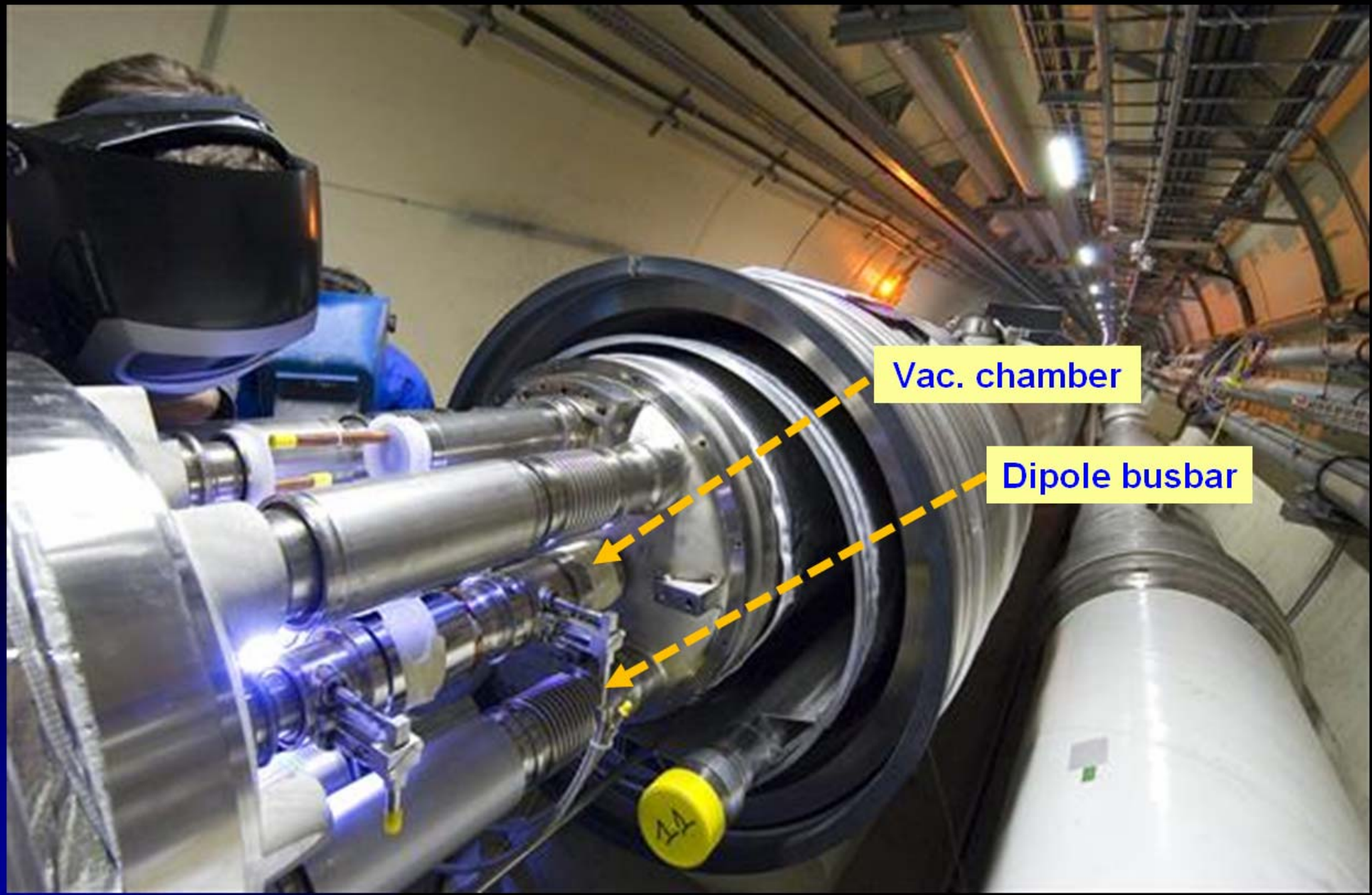
September 19th Incident

Slides courtesy of Jorg Wenninger (CERN)

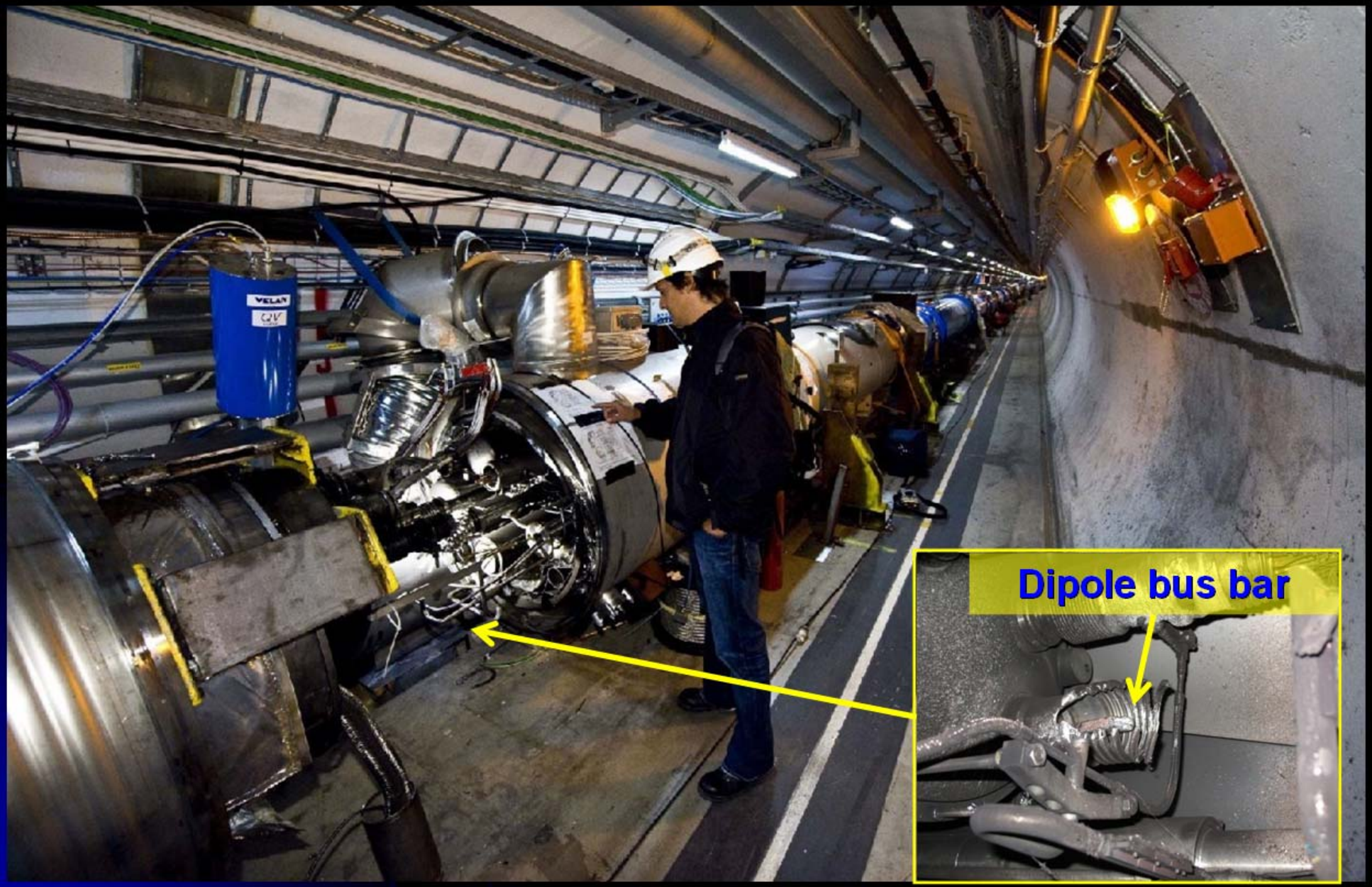
Event sequence on September 19th

- Last commissioning step of the main dipole circuit in sector 34
  - Ramp to 9.3kA (5.5 TeV)
- At 8.7kA an electrical fault developed in dipole bus bar located in interconnection between quadrupole Q24.R3 & neighbouring dipole
  - Later correlated to local resistance of ~220 nΩ – nominal value 0.35 nΩ
- An electrical arc developed which punctured the helium enclosure
- Secondary arcs developed along the magnet chain
- Around 400 MJ from a total of 600 MJ stored in the circuit were dissipated in the cold-mass and in electrical arcs
- Large amounts of Helium were released into the insulating vacuum
  - In total 6 tons of Helium was released

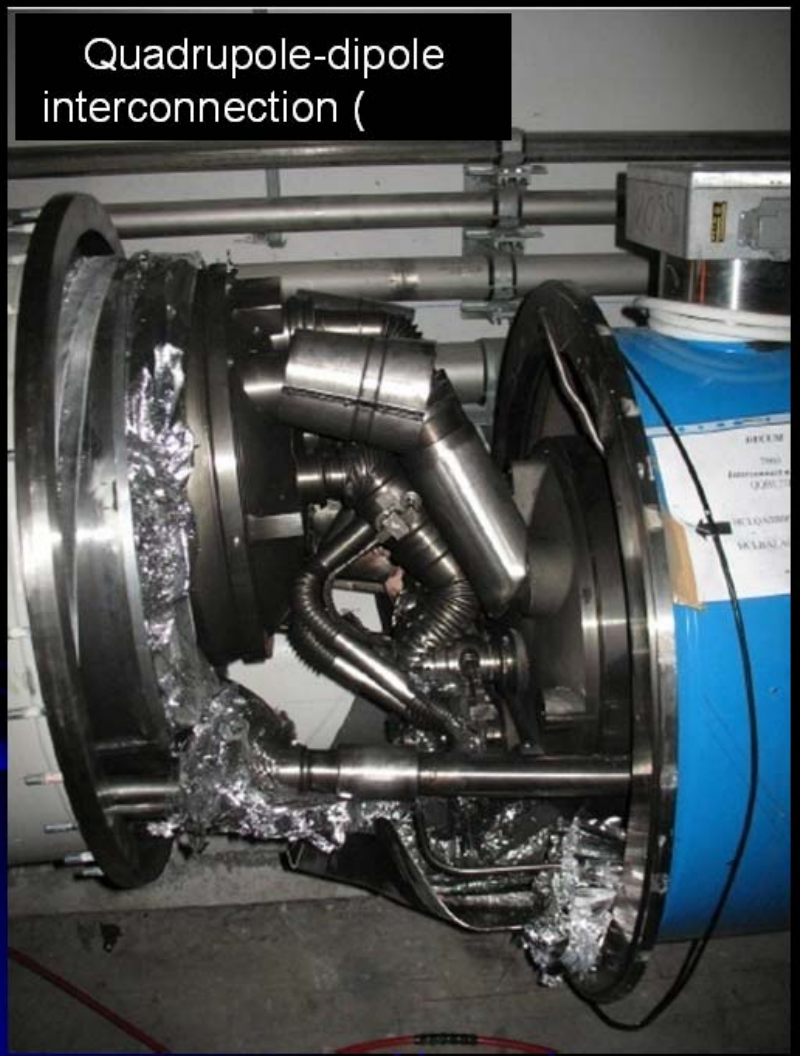
Interconnection



Incident Location



Collateral Damage

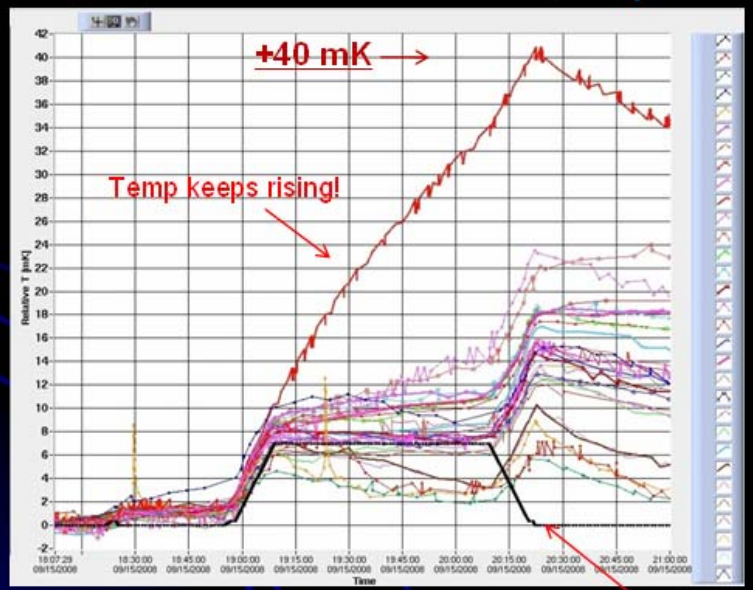


- Main damage area ~ 700 metres
  - 39 out of 154 dipoles
  - 14 out of 47 quadrupoles
- 16 repaired on surface
- 37 replaced

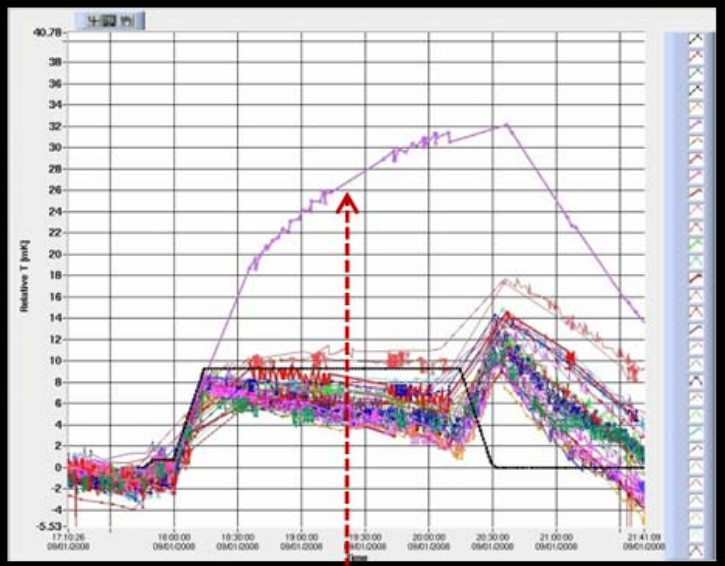
Calorimetric Data

- Logged cryogenic data revealed temperature anomaly of ~40 mK
  - Found in cell of incident during a previous (lower current) powering cycle
- Data from other powering tests indicated presence of anomaly in sector 12
  - Calorimetric analysis suggested a ~100 nΩ resistance
- 2 magnets removed from tunnel & confirmed to have poor internal splices

ΔT (mk) 7 kA test on Sector 3-4, Sept 15th



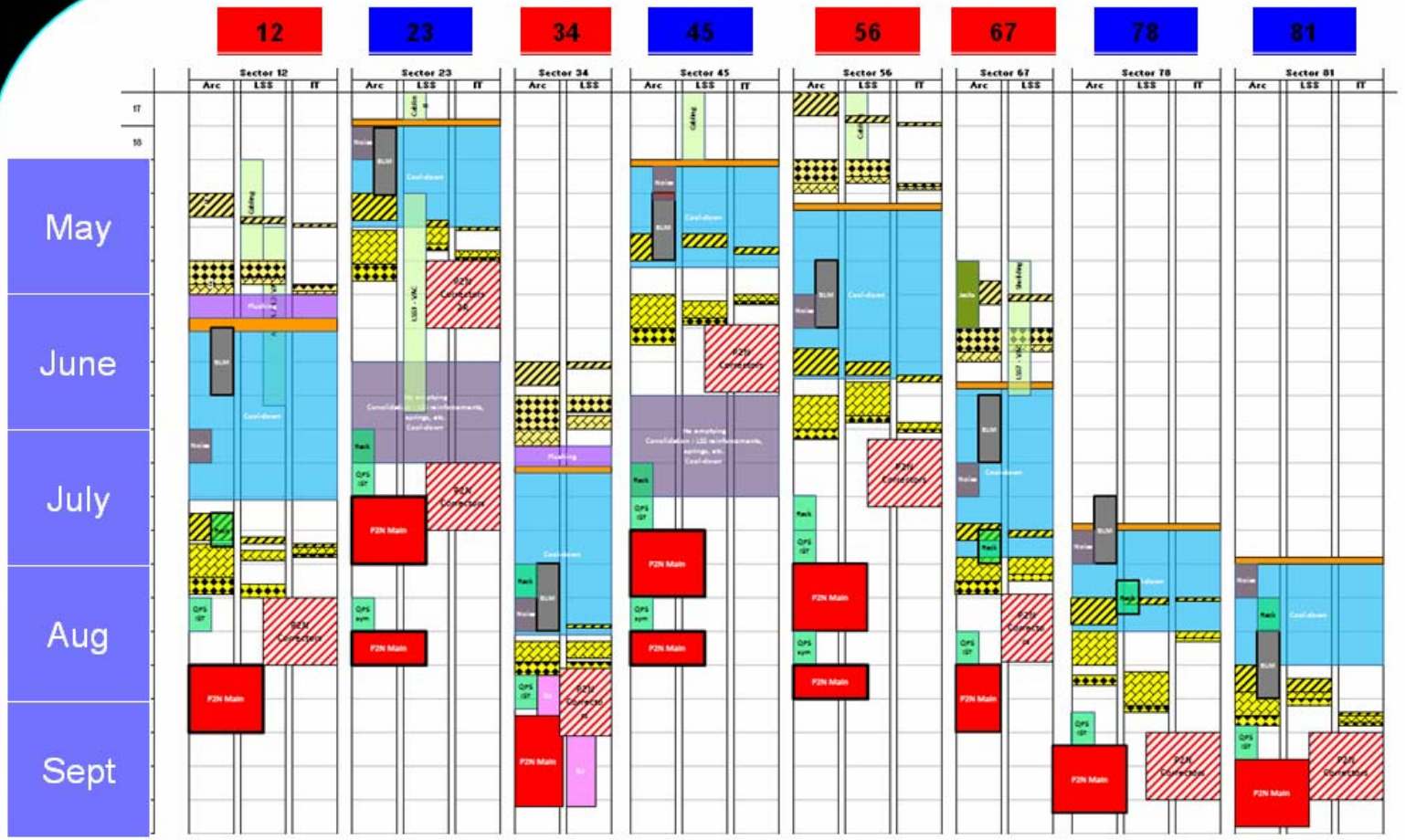
9.3 kA test on Sector 1-2, Sept 1st



Repair & Consolidation

- Vacuum chamber cleaning in situ
  - Majority of magnets remain in place
  - Cleaning of soot with special cleaning head
  - Removal of MLI debris by venting and pumping
- Major upgrade of the quench protection system
  - Protection of all main quadrupole and dipole joints
  - Protection against symmetric quenches of beam apertures
  - High statistics measurement accuracy to < 1 nΩ.
  - Provides high precision online resistance monitoring of all joints!
- Reinforcement of quadrupole supports
- Improvement of pressure relief system
  - Will eventually be able to cope with 2× 3-4 incident

Planning for 2009



…followed by a long LHC run until November 2010, with short break around Christmas/new year 2009/2010.

*Target beam energy for physics : **5 TeV**.*