CERN
European Organization for Nuclear Research
Organisation Européenne pour la Recherche Nucléaire

# Operational Experience with the LHC and SPS Tune Resonance Phenomena

**Tobias Baer**

**DESY Accelerator Physics Seminar**

*February, 9th 2010*

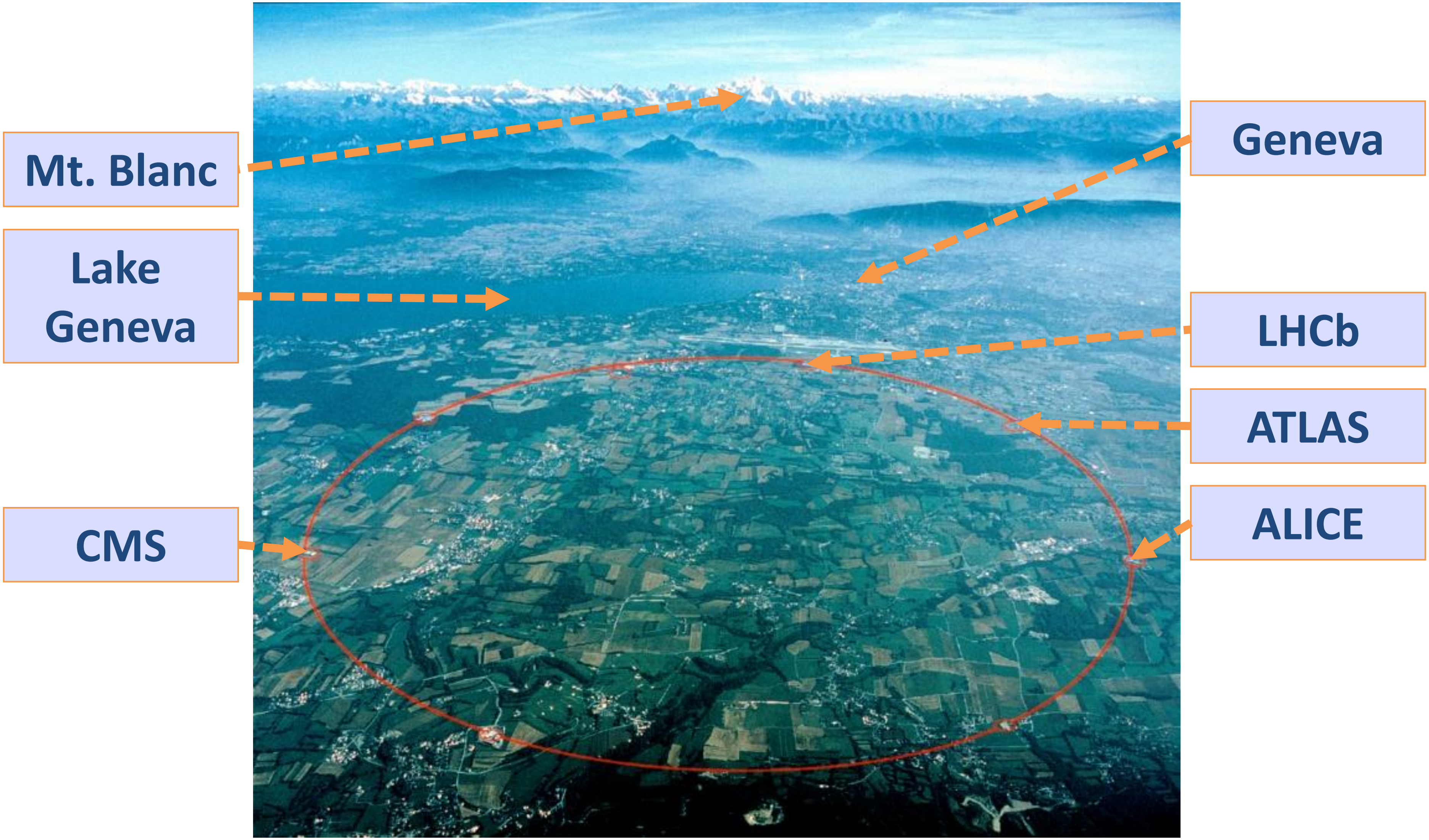
# Content

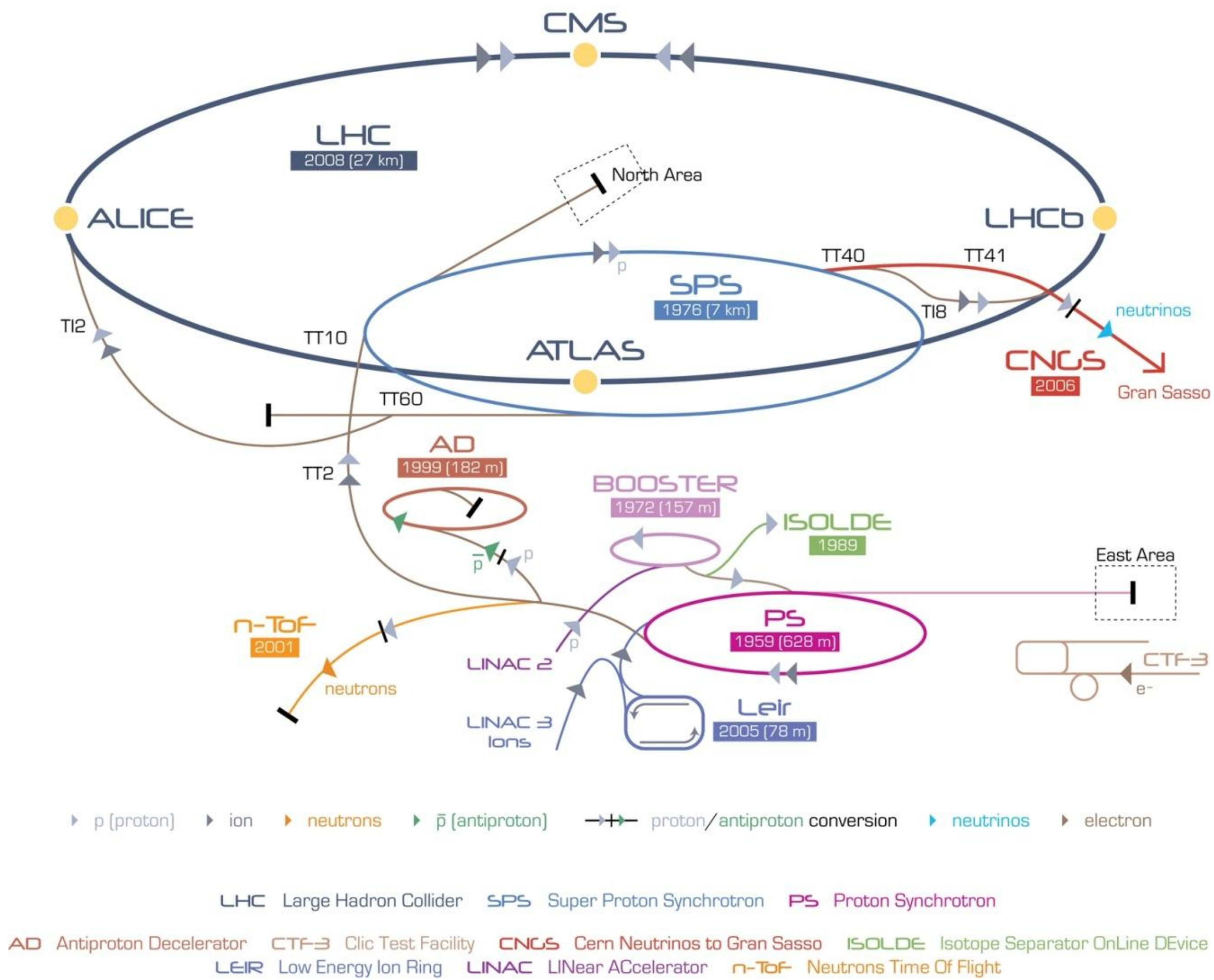
1. CERN Accelerator Complex

2. Operational Experience with the LHC

3. Tune Resonance Phenomena in the SPS and Machine Protection via Fast Position Interlocking

# CERN

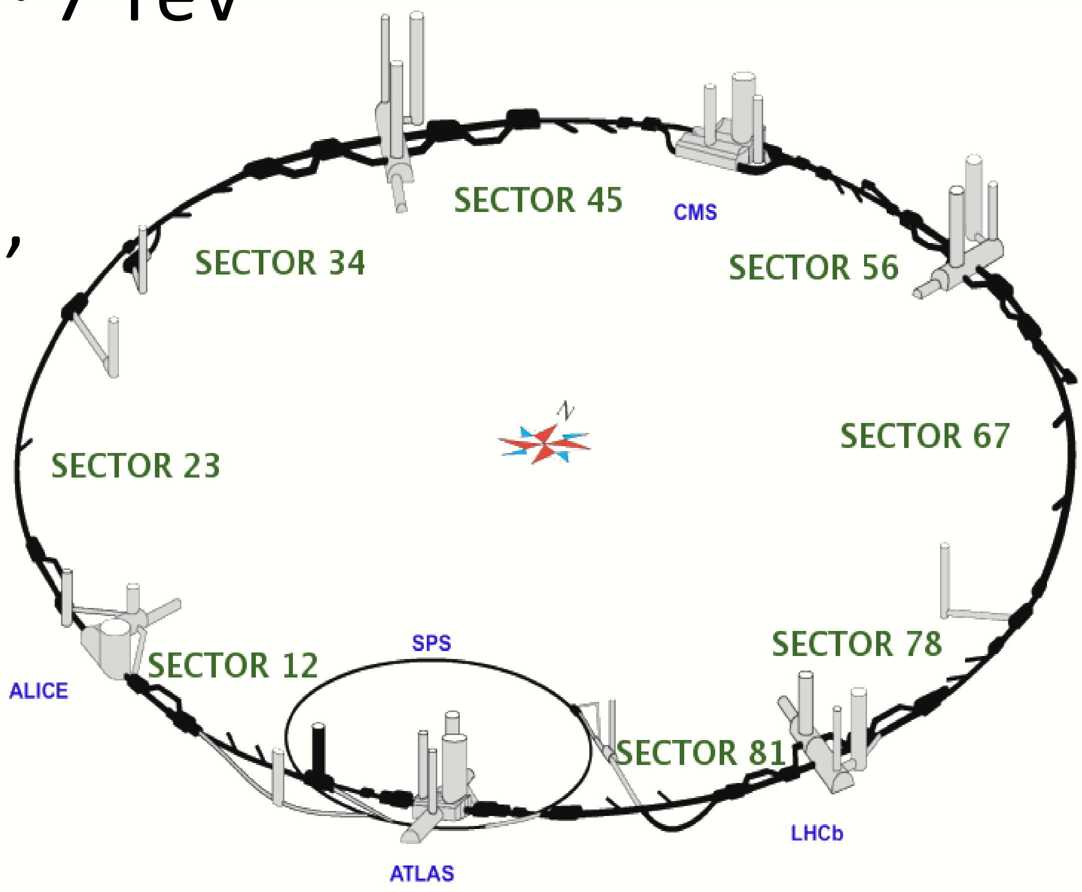




CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
p̄
p
n-ToF
2001
PS
1959 (628 m)
LINAC 2
CTF3
e–
neutrons
LINAC 3
Ions
LEIR
2005 (78 m)
p (proton)
ion
neutrons
p̄ (antiproton)
proton/antiproton conversion
neutrinos
electron
LHC Large Hadron Collider
SPS Super Proton Synchrotron
PS Proton Synchrotron
AD Antiproton Decelerator
CTF3 Clic Test Facility
CNGS Cern Neutrinos to Gran Sasso
ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring
LINAC LINear ACcelerator
n-ToF Neutrons Time Of Flight

# Large Hadron Collider

- Ring circumference: 26.7 km
- Collision Energy: 2 · 7 TeV
- 4+2 Experiments:
  ATLAS, CMS, ALICE,
  LHCb and
  TOTEM, LHCf



1. CERN Accelerator Complex

2. Operational Experience with the LHC

3. Tune Resonance Phenomena in the SPS and Machine Protection via Fast Position Interlocking

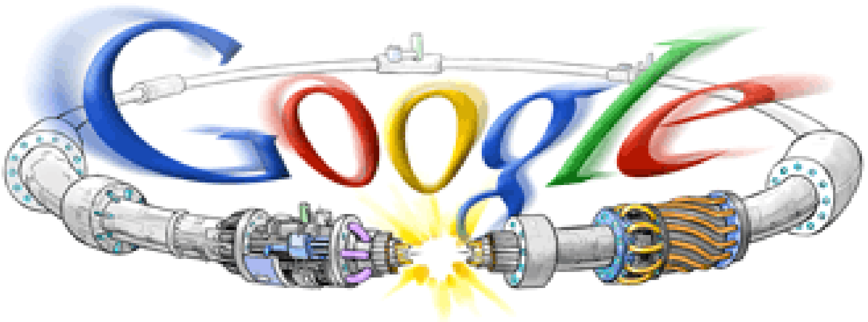
## 2. Operational Experience with the LHC

- LHC incident
- LHC run 2009
- Plans for 2010

# LHC startup 2008

LHC startup: September 10th 2008

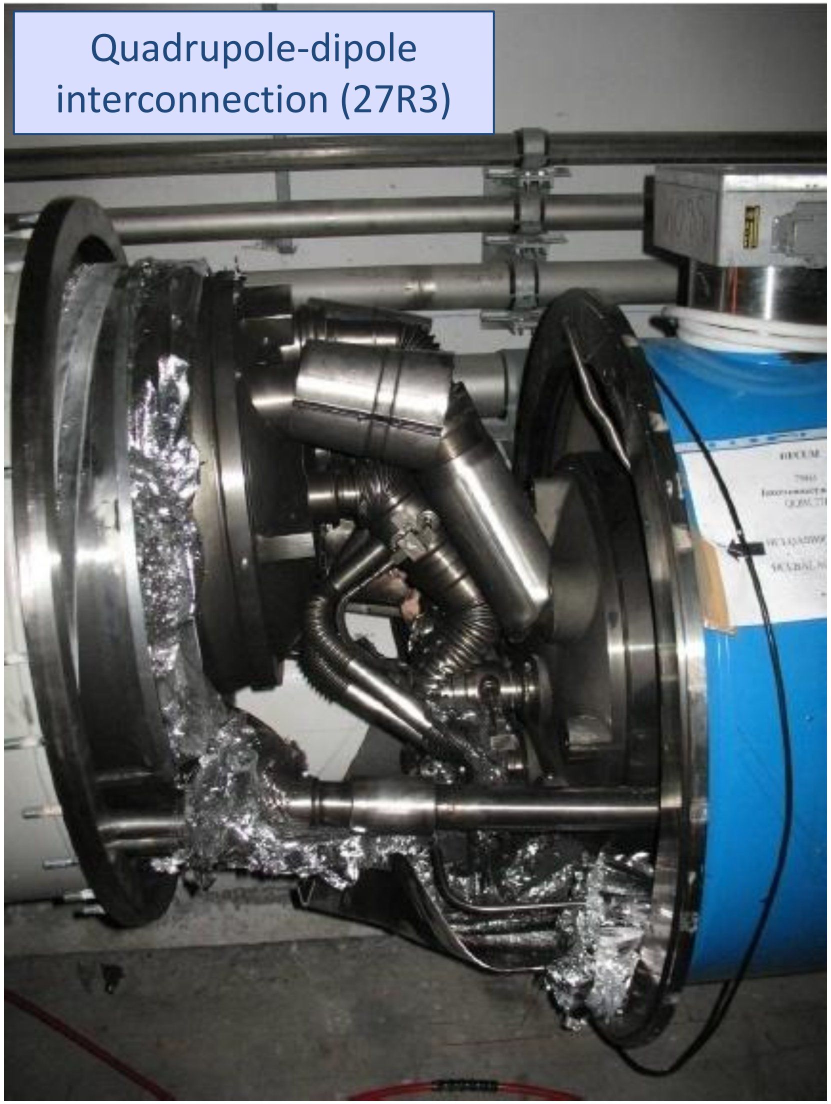
- Both beams around the ring (within few hours)

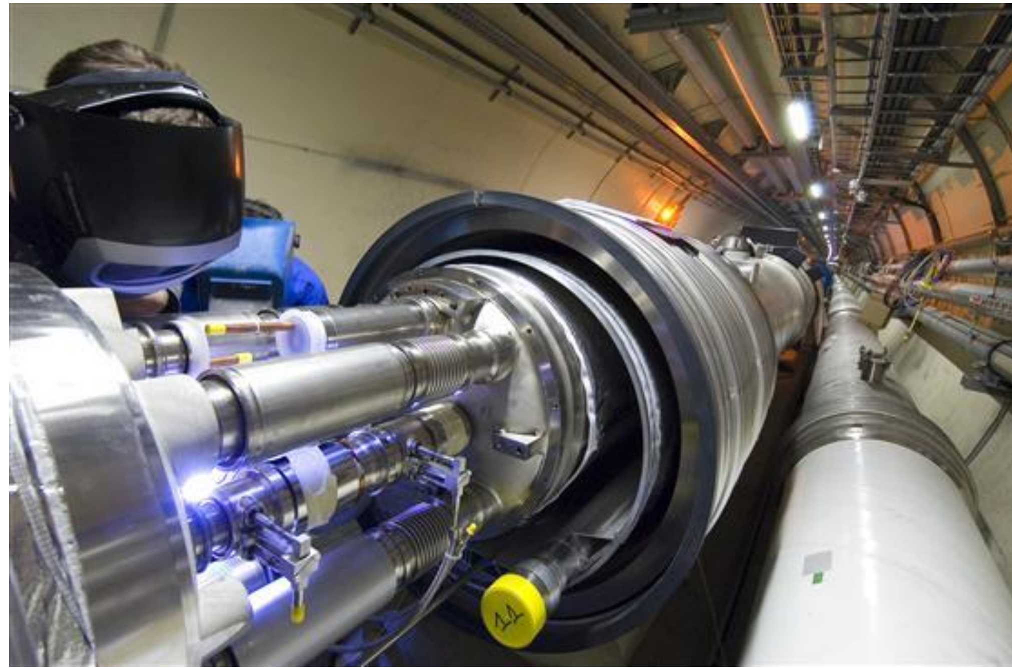



Following days:

- All base instrumentation operational (BPMs, BLMs, Tune, BCTs)
- Beam 2 captured by RF
- Beam lifetime > 1h

# September 19th Incident



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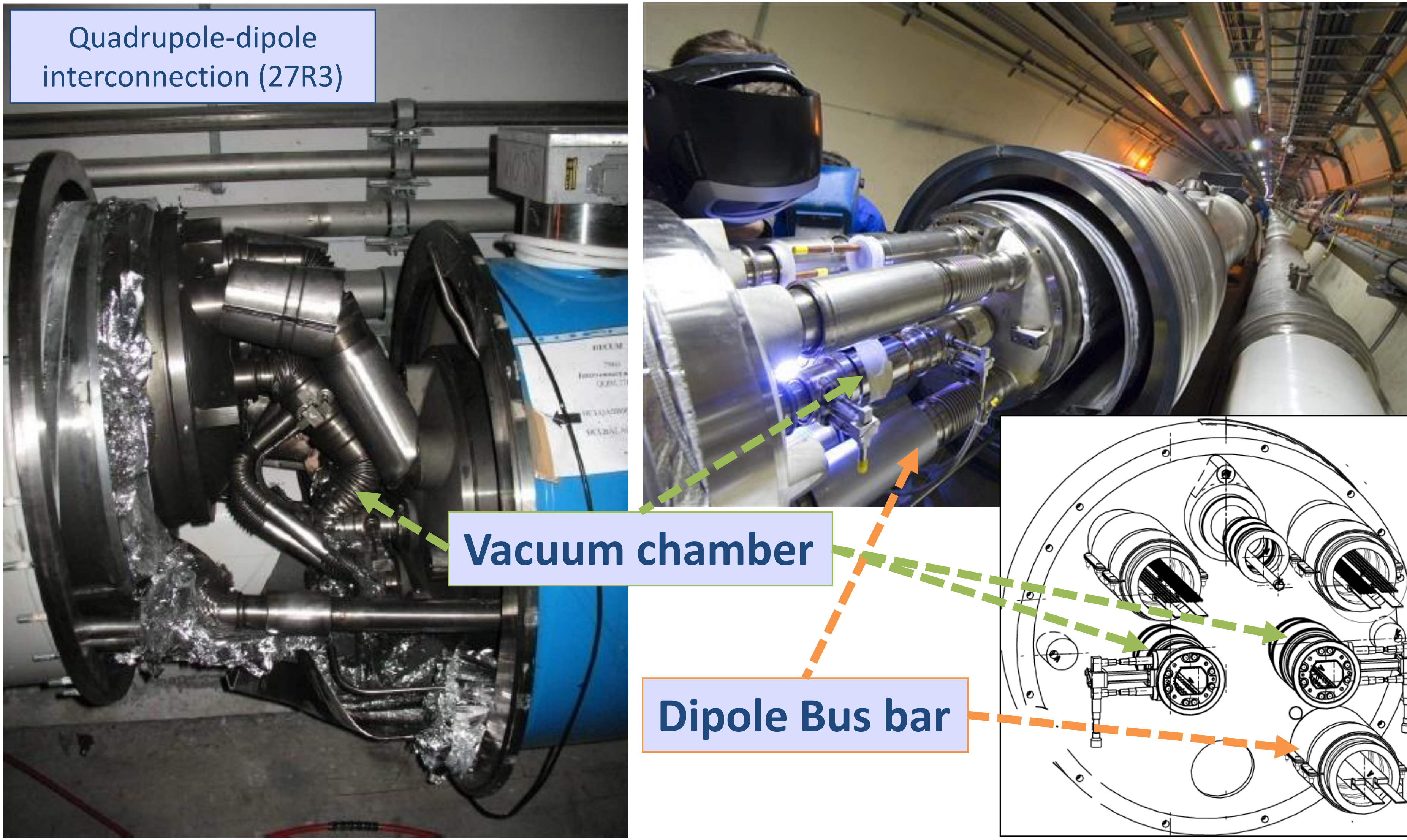
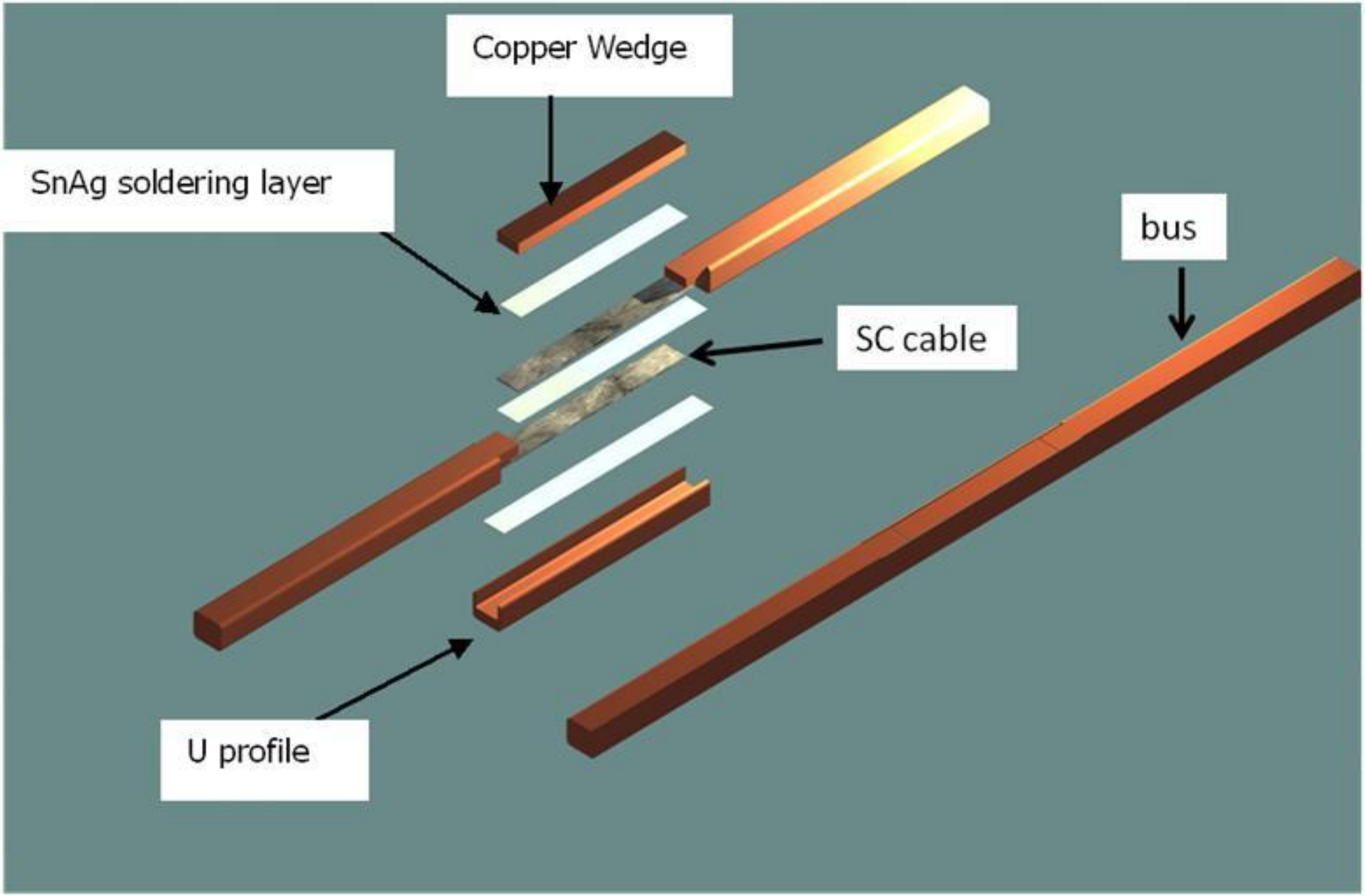
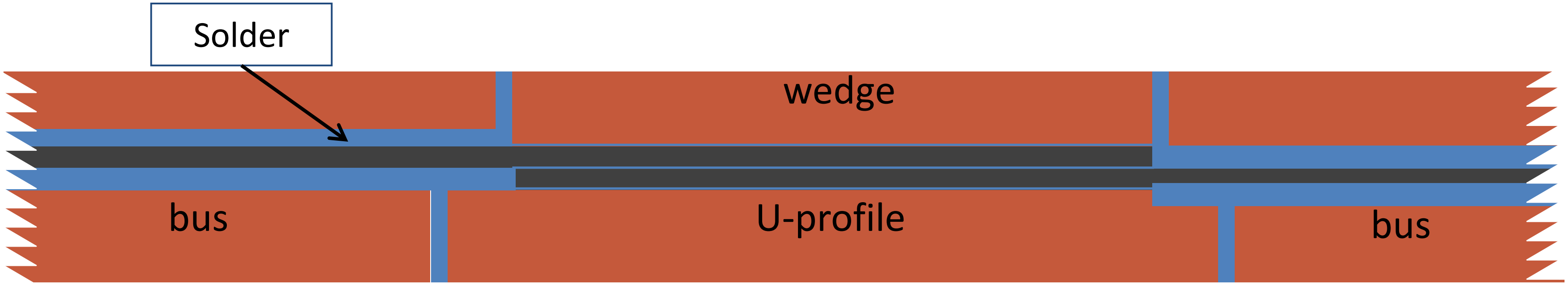


# Bus Bar

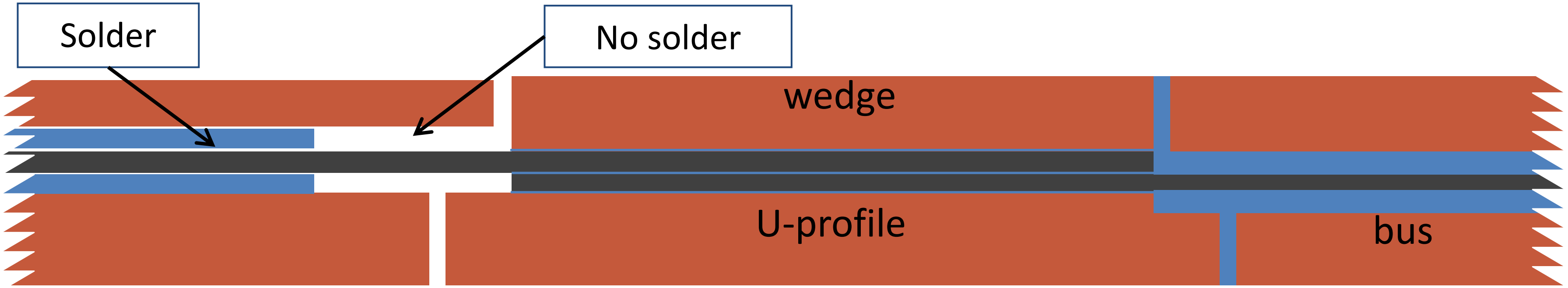


# Bus Bar

Good joint




Bad joint



# Event Sequence on Sept. 19th

- Last commissioning step of main dipole circuit in sector 34: **ramp to 9.3 kA (5.5 TeV)**
- At 8.7 kA electrical fault in **bus bar** between dipole and quadrupole
  - Local resistance: **~220 nΩ** (nominal 0.35 nΩ)
- **400MJ** out of 600MJ stored in the circuit were dissipated in cold-mass and electrical arcs
- **6 tons of helium** were released

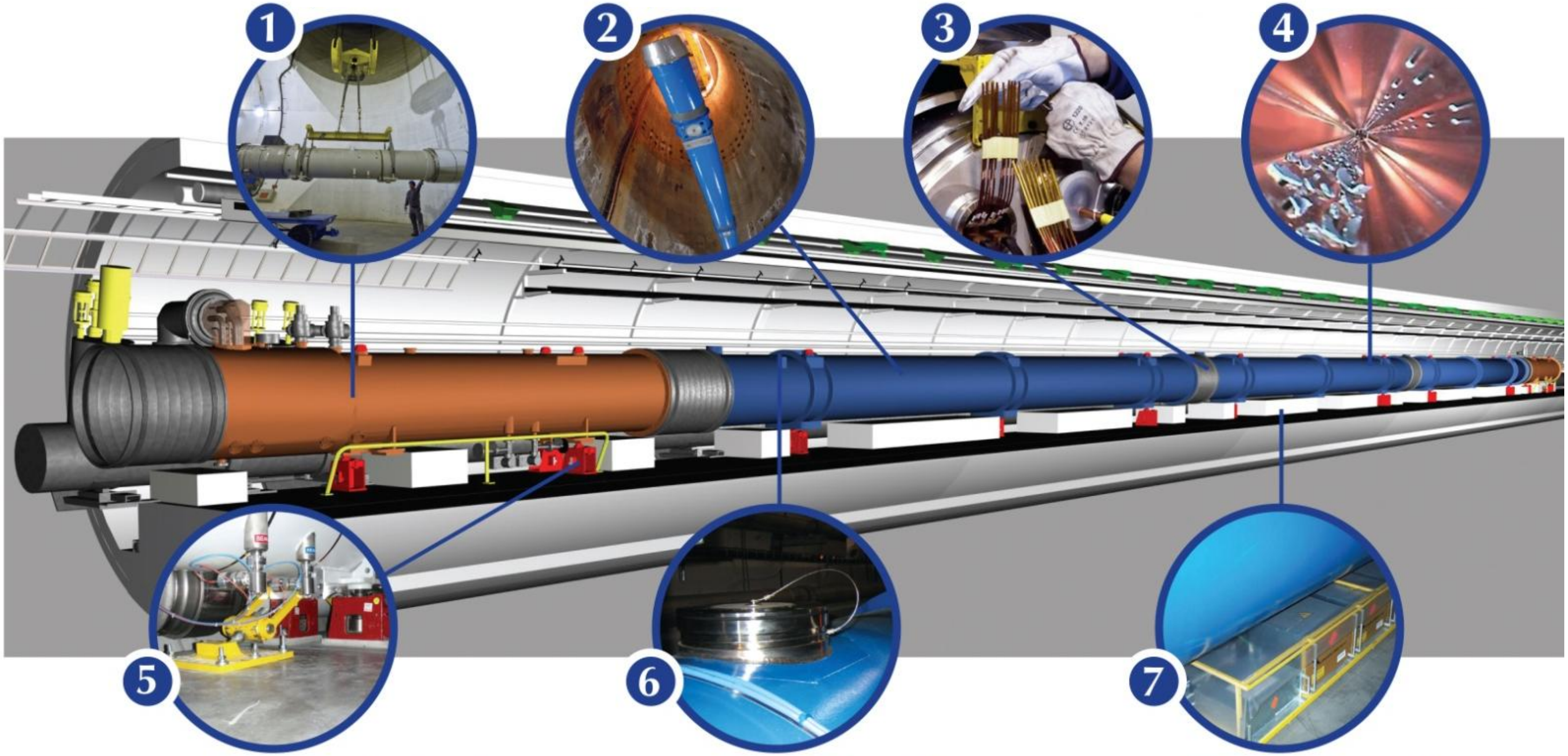
# LHC repairs in detail

14 quadrupole magnets replaced

39 dipole magnets replaced

204 electrical inter-connections repaired

Over 4km of vacuum beam tube cleaned



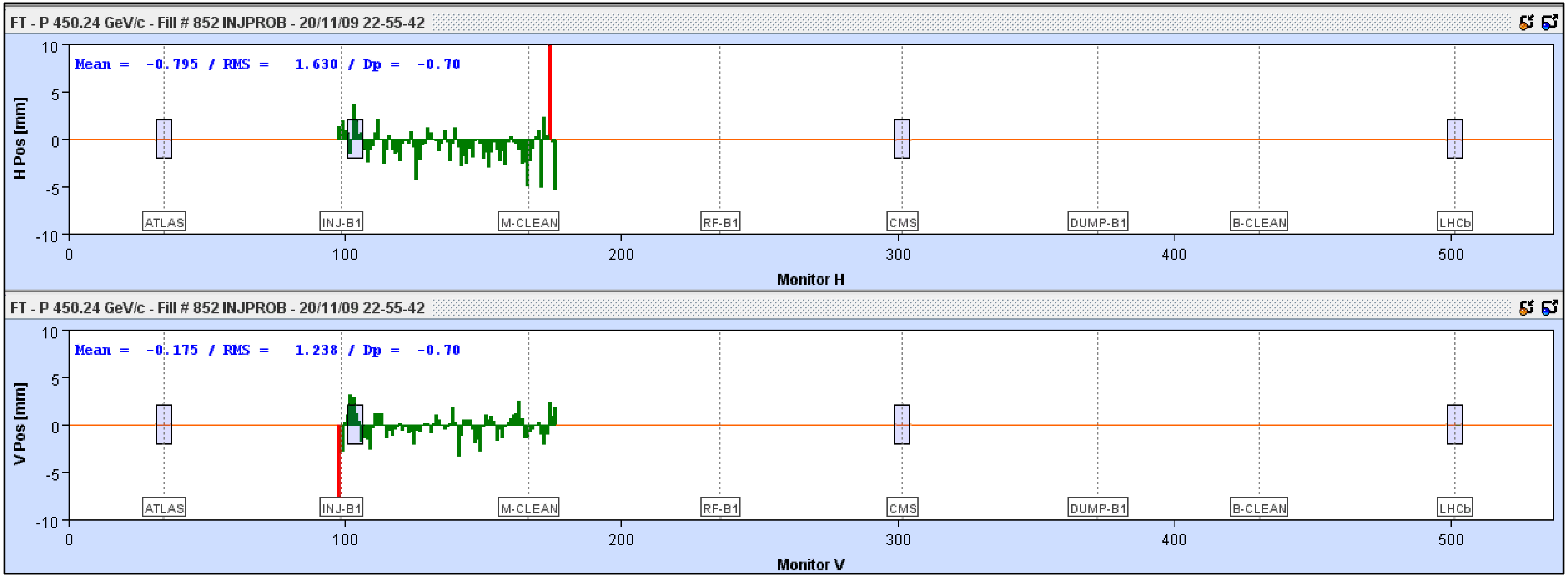

New longitudinal restraining system for 50 quadrupoles

Almost 900 new helium pressure release ports

6500 new detectors and 250km cables for new Quench Protection System

# LHC run 2009

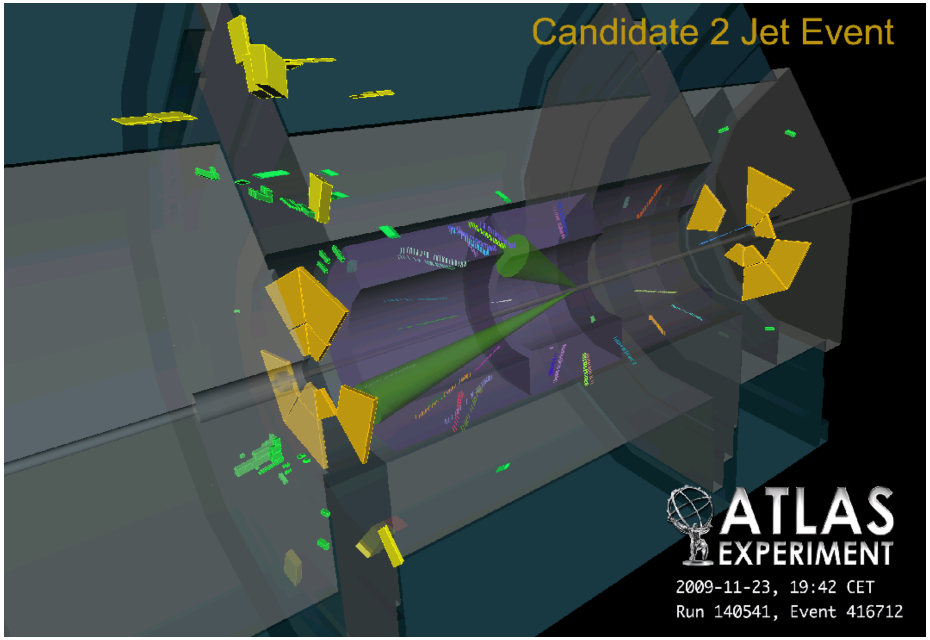
# Beam position



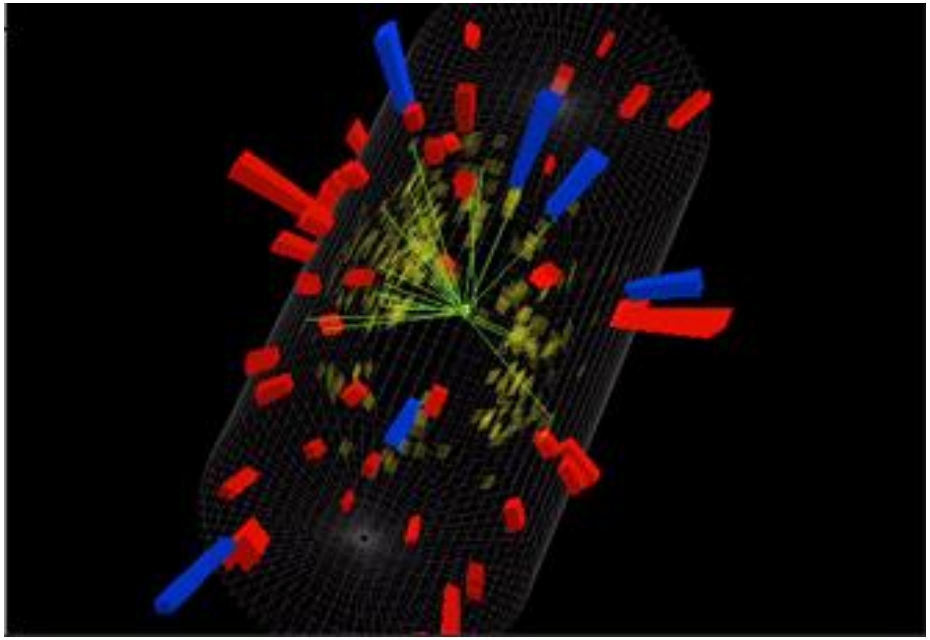

Also Day 1: Capture of both beams with RF

# Startup Nov. 20th 2009

## Day 4: First collisions at 2·450 GeV




ATLAS

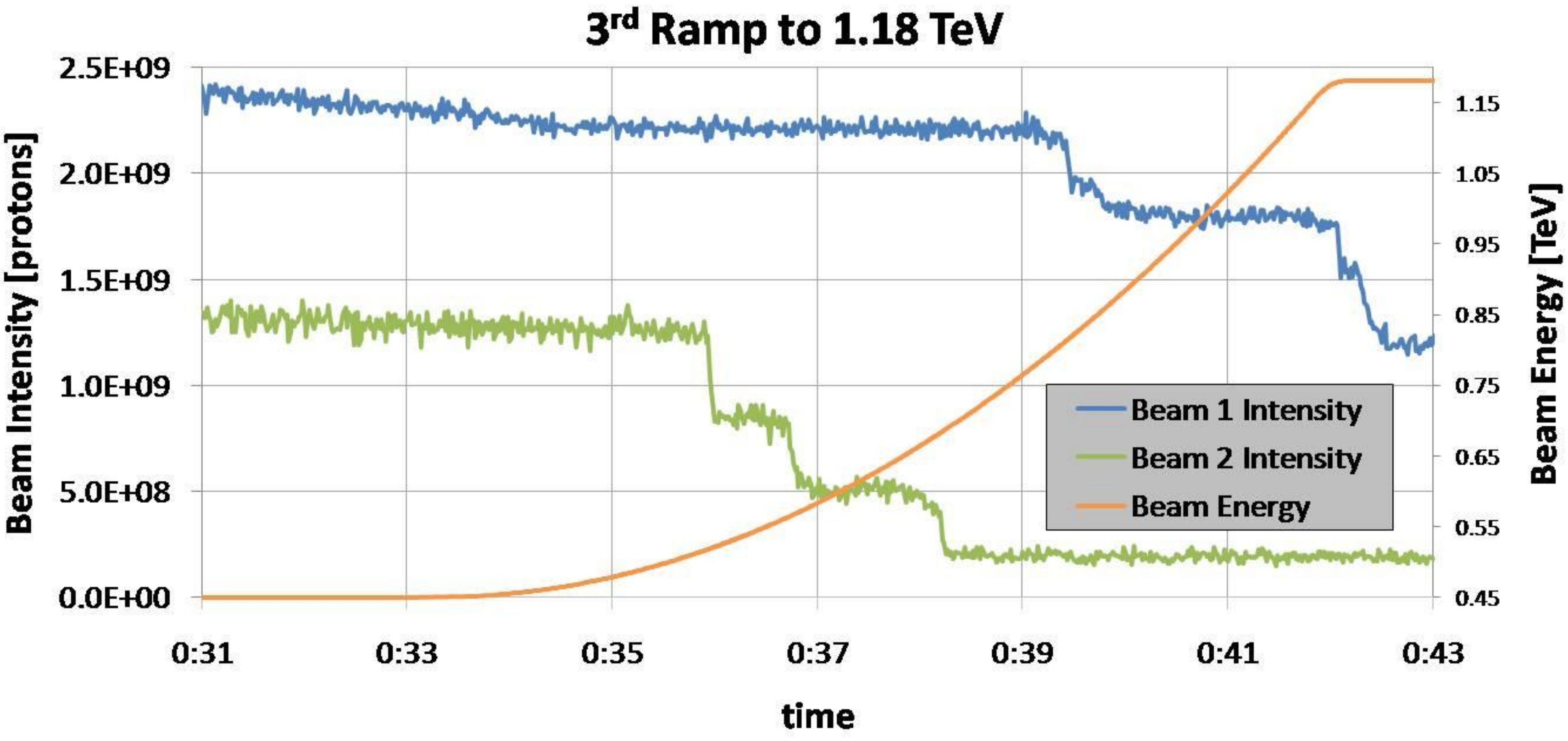


CMS

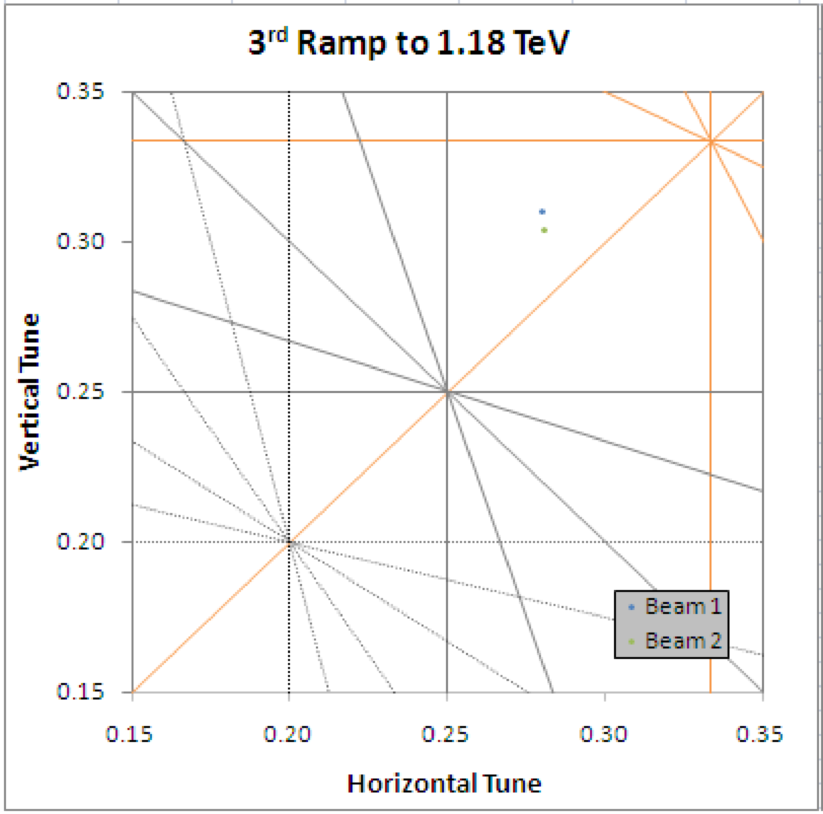
# Ramp

Day 4: 1st Ramp to 560 GeV

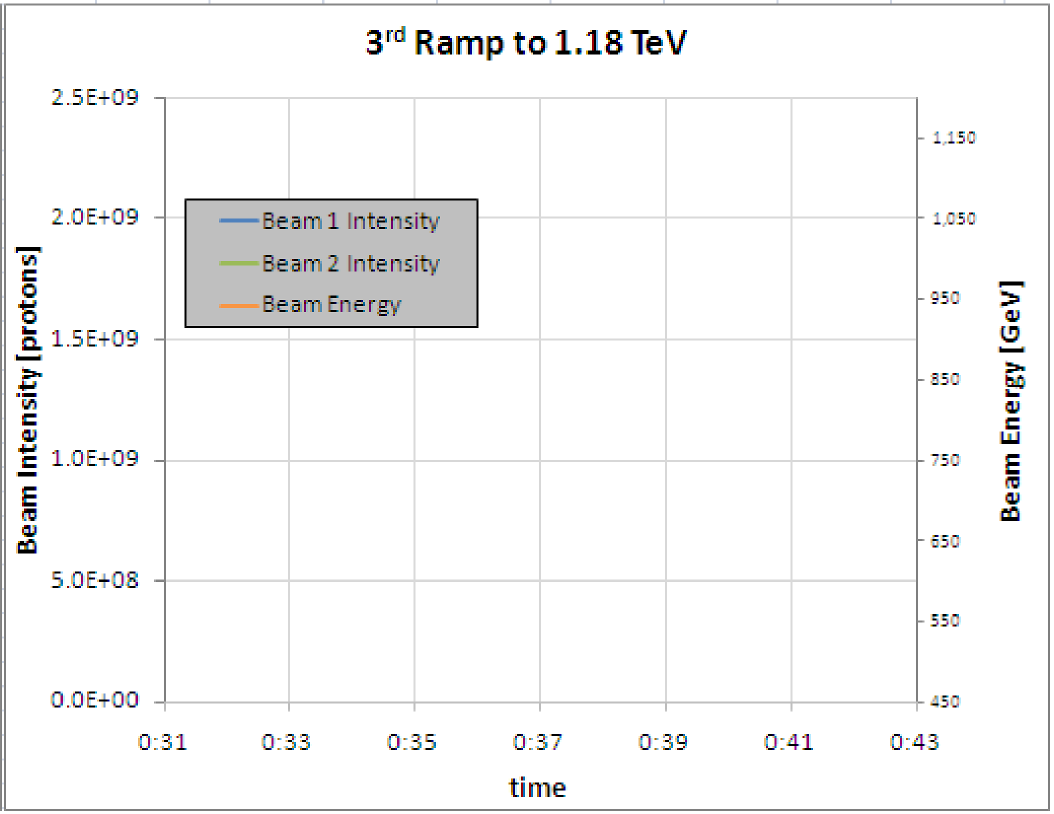
Day 11: 3rd Ramp to 1.18 TeV



# 3rd Ramp



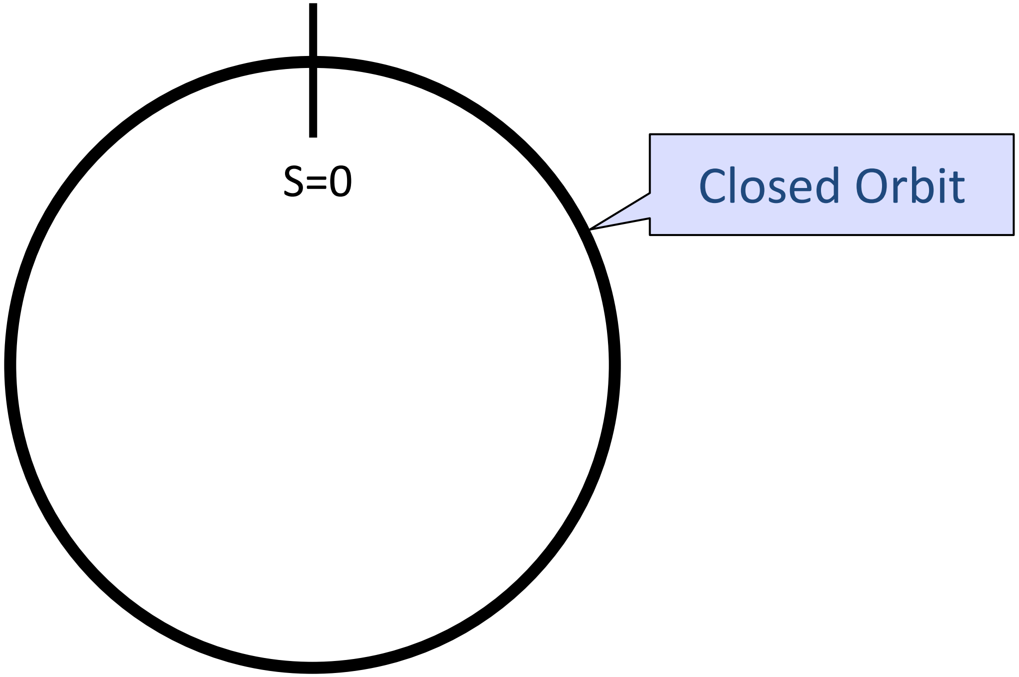
3rd Ramp to 1.18 TeV
0.35
0.30
0.25
0.20
0.15
Vertical Tune
0.15
0.20
0.25
0.30
0.35
Horizontal Tune
Beam 1
Beam 2

3rd Ramp to 1.18 TeV
2.5E+09
2.0E+09
1.5E+09
1.0E+09
5.0E+08
0.0E+00
Beam Intensity [protons]
1,150
1,050
950
850
750
650
550
450
Beam Energy [GeV]
0:31
0:33
0:35
0:37
0:39
0:41
0:43
time
Beam 1 Intensity
Beam 2 Intensity
Beam Energy

# Tune

**Tune** = Number of betatron oscillations per machine revolution



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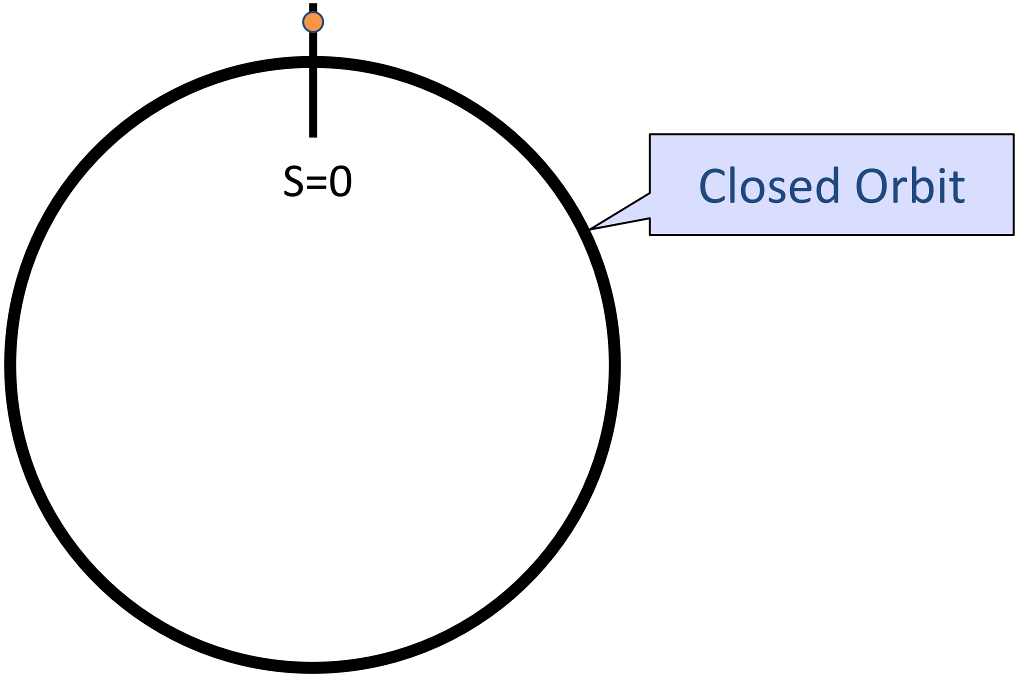

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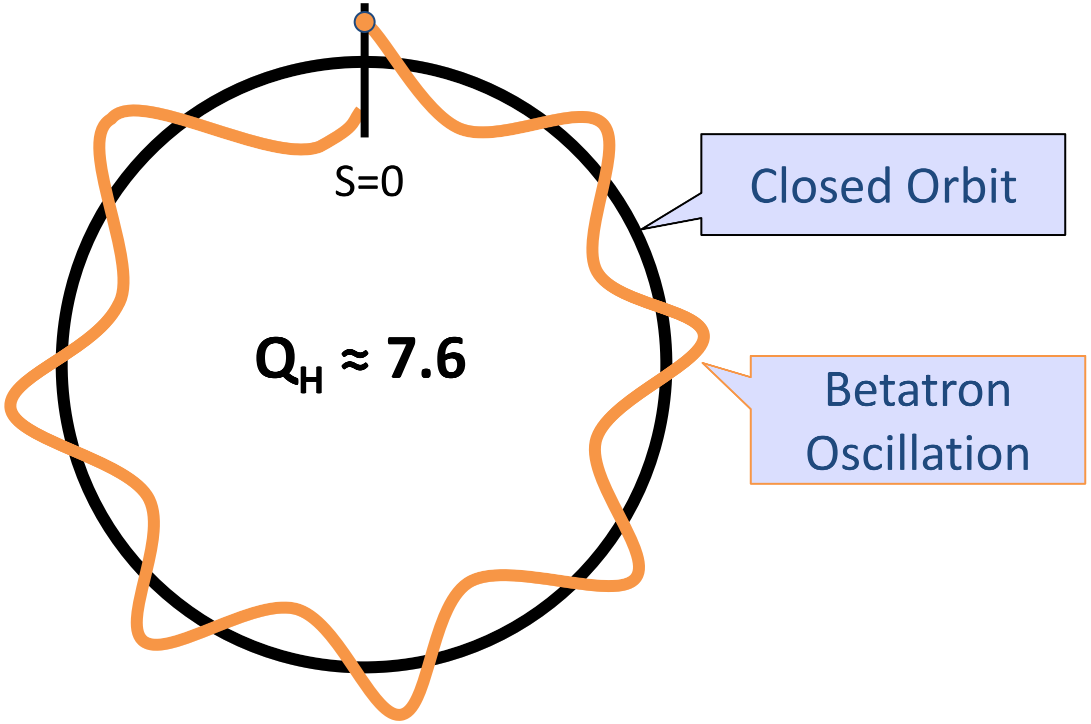

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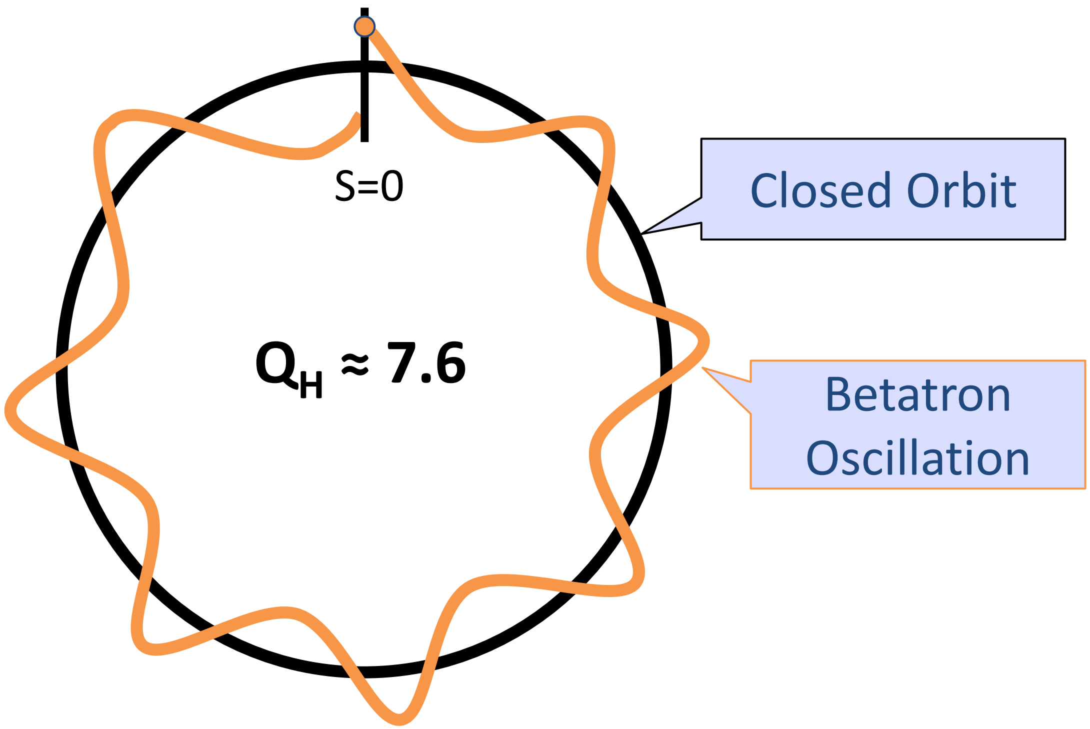



**Tune Resonance**: $m \cdot Q_H \pm n \cdot Q_V = k$ m, n, k = integer

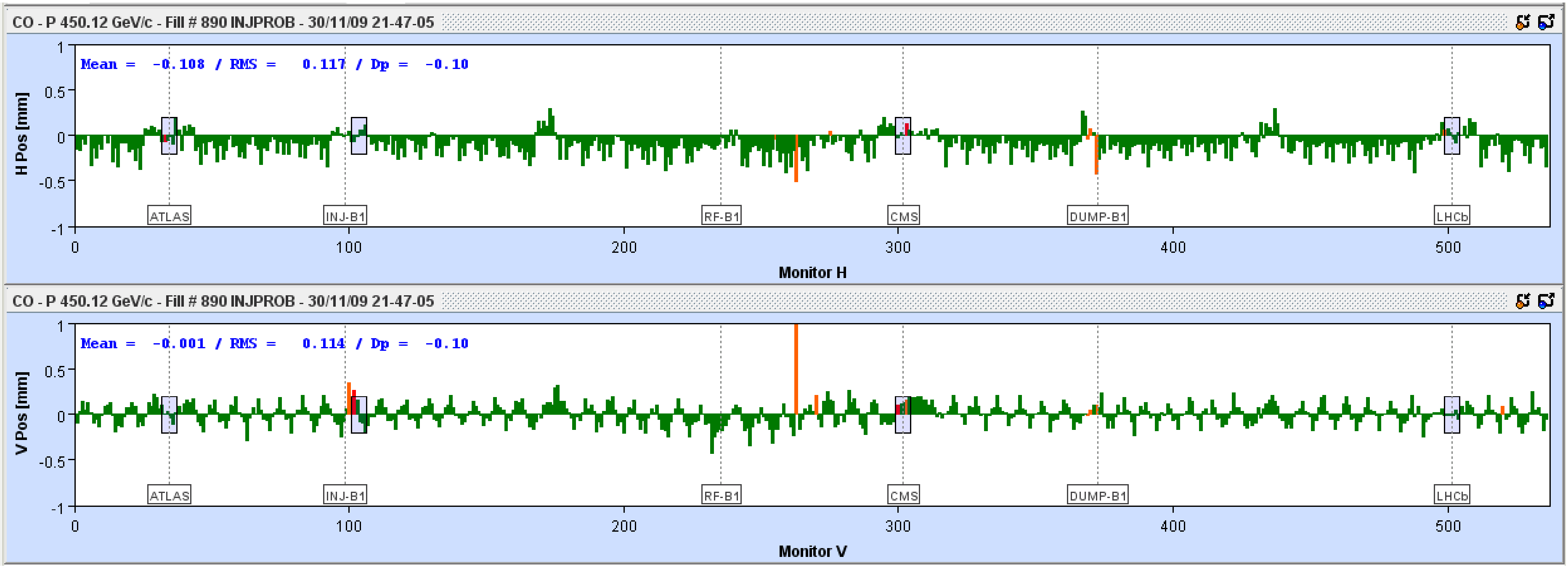
m+n = order of resonance

# Ramp to 1.18 TeV

# CMS Solenoid

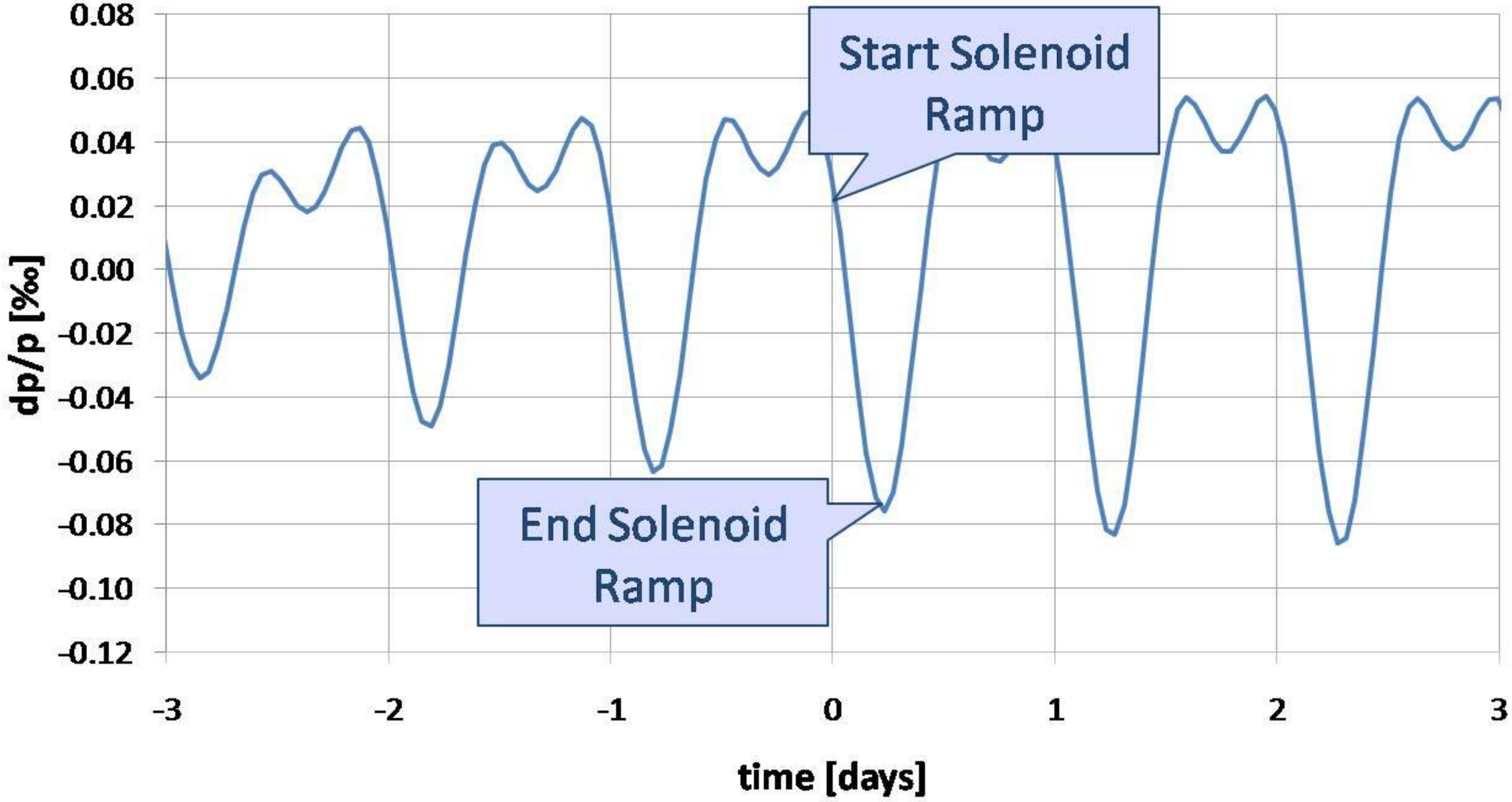
Day 10: Switching on CMS Solenoid.

Orbit difference with/without Solenoid on




Momentum change: dp/p = -0.1 ‰

# Tidal Effect on Energy




LHC measures influence of tidal forces 10 days after first beam

# Milestones in 2009 run

| Date | Day | Achieved |
|---|---|---|
| Nov 20 | 1 | Both beams circulating. Key beam instrumentation working. |
| Nov 23 | 4 | First collisions at 450 GeV. First ramp (reached 560 GeV). |
| Nov 30 | 11 | Ramp to 1.18 TeV. |
| Nov 30 | 11 | Experiment solenoids on. |
| Dec 04 | 15 | Aperture measurements finished. LHCb and ALICE dipoles on. |
| Dec 05 | 16 | Machine protection (Injection, Beam dump, Collimators) ready for safe operation with pilots. |
| Dec 08 | 19 | Ramp colliding bunches to 1.18 TeV |
| Dec 14 | 25 | Collisions with STABLE BEAMS, 16 on 16 bunches at 450 GeV, Intensity > $10^{10}$ protons per bunch |
| Dec 16 | 27 | Ramp 4 on 4 bunches to 1.18 TeV. Squeeze to $\beta^*=7$ m. |

# Plans for 2010

# Plans for 2010

| Date | Activity |
| --- | --- |
| Feb 16 | Injection Test |
| Feb 22 | Start recommissioning with Beam |
| End Feb | Ramp to 3.5 TeV. |
| Beg. Mar | Commission Squeeze |
| Mid Mar | Stable, Save Beams at 3.5 TeV |
| | Stepwise Increase Intensity, each step followed by extended running period (estimate: up to ≈$7 \cdot 10^{13}$ protons during 2010) |
| | Ramp to Higher Energies in 2013 (warm up of machine needed) |

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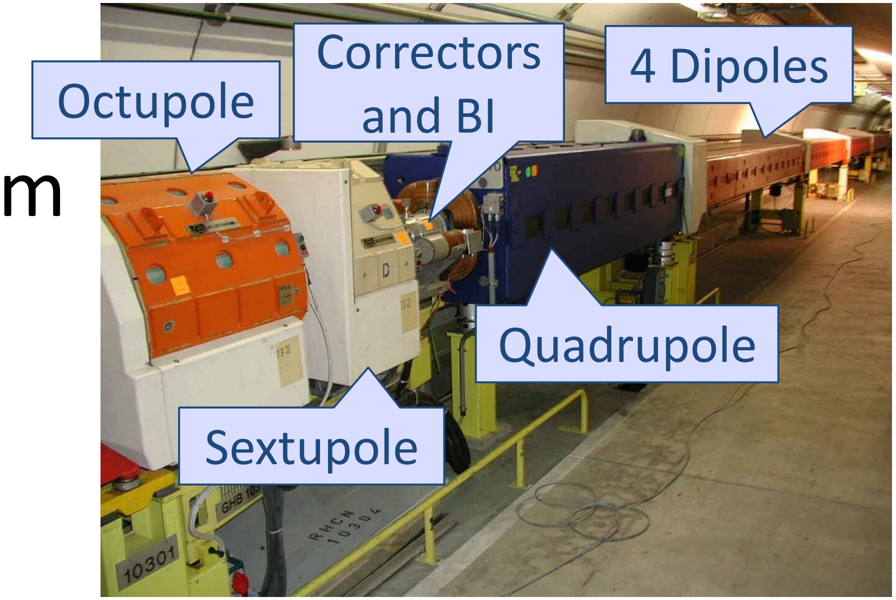
## 3. Tune Resonance Phenomena in the SPS and Machine Protection via Fast Position Interlocking

- Incident 27.06.2008
- Integer Tune resonances
  - Orbit Resonance
  - Dispersion Resonance
  - Supersymmetric Resonances
- Machine Protection

# Super Proton Synchroton

- Commissioned in 1976
- Ring circumference: 6.9 km
- Top Energy: 450 GeV
- Intensity:
  up to $5 \cdot 10^{13}$ protons
- Beam Energy:
  up to **2.5 MJ**
  - Tevatron: 2 MJ, LHC (nominal) 362MJ



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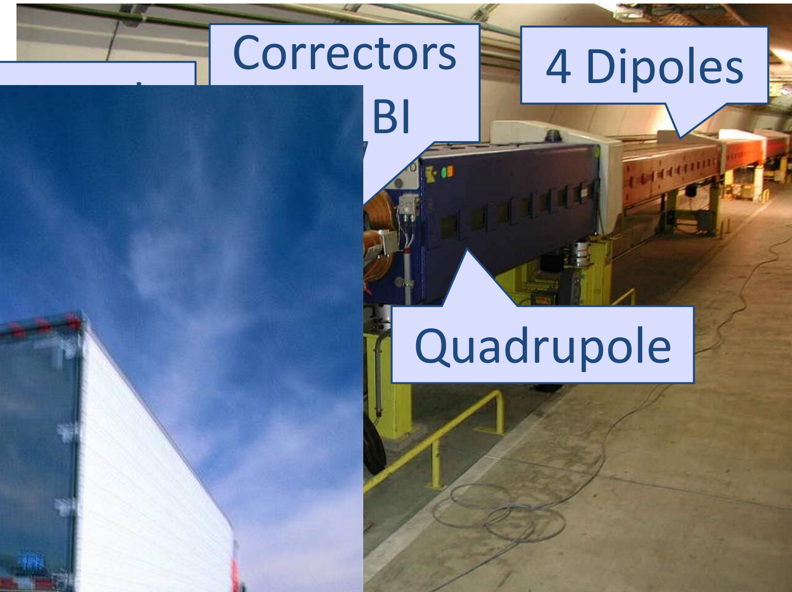
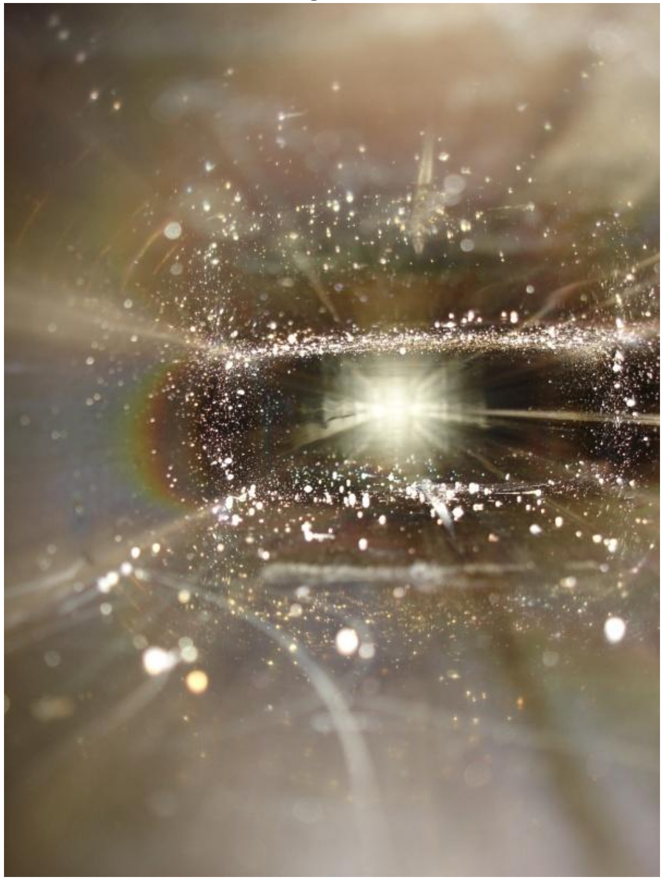



# SPS Incident 27.06.2008

# SPS Incident June 27th 2008

Beam impact of high intensity beam

(about $3 \cdot 10^{13}$ protons @ 400 GeV)



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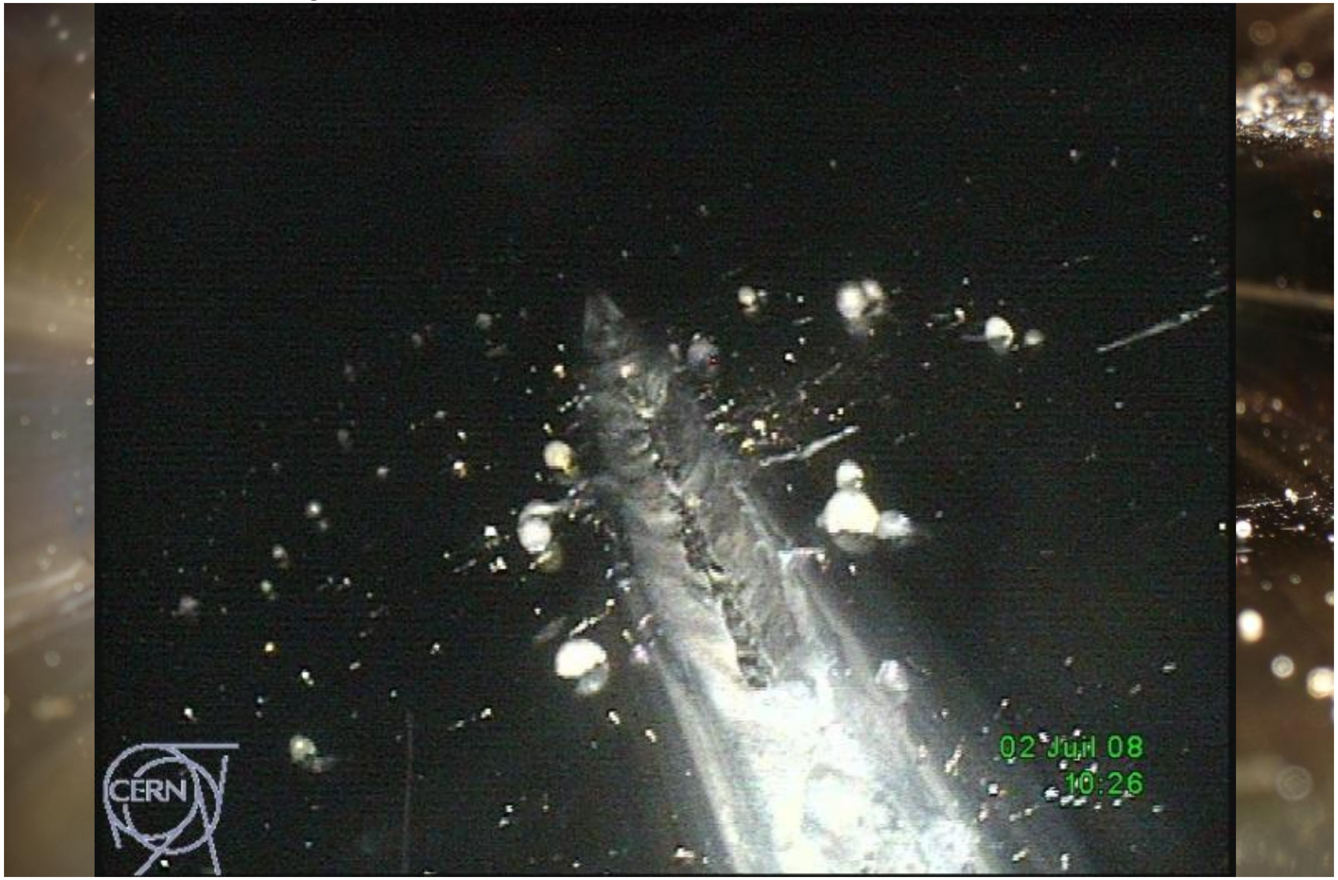
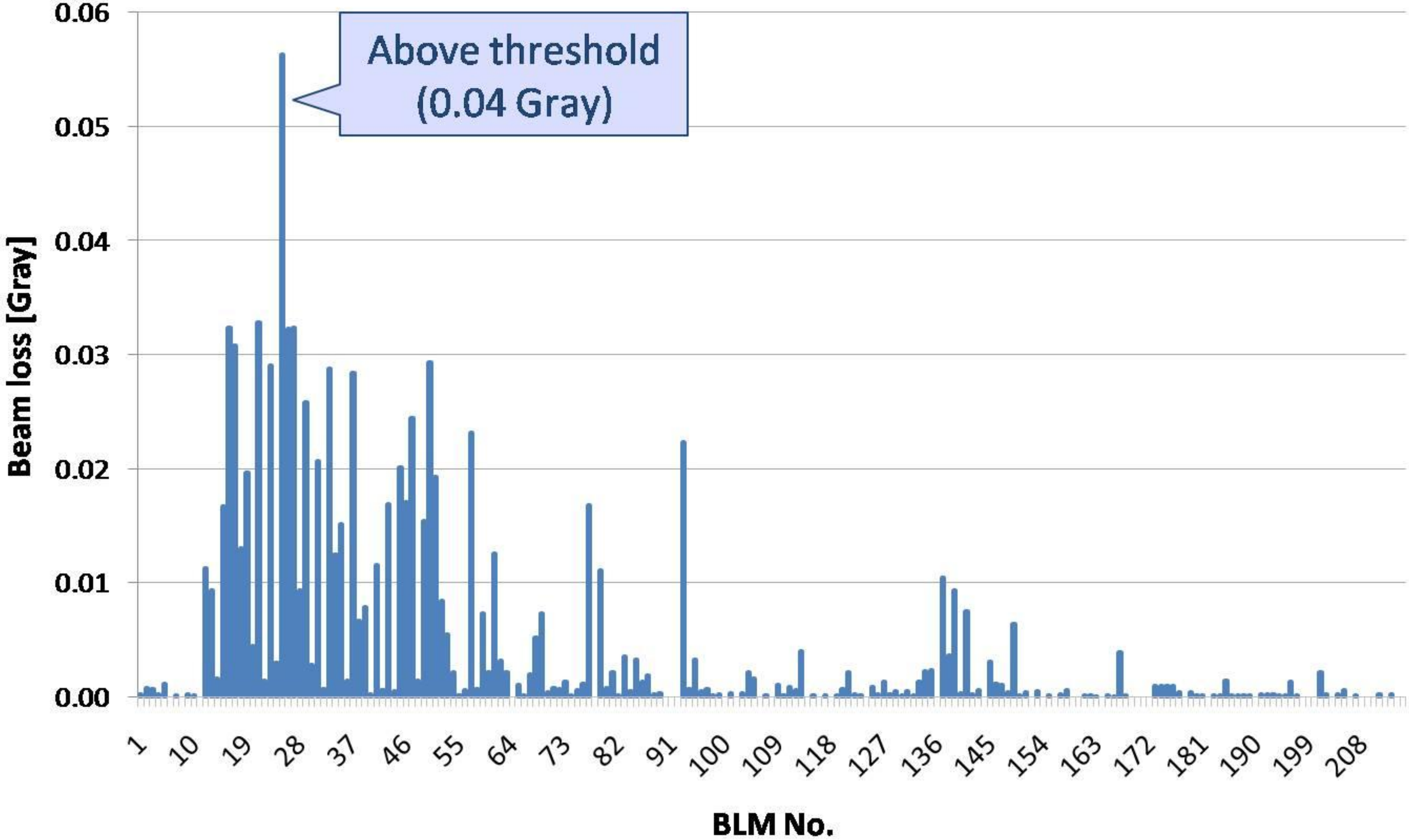


# Event Sequence on June 27th

- After injection of 2 high intensity batches a failure in the main timing system occurred
- The beam was **accelerated to 400GeV but not extracted**
- The magnets were **ramped down** again
- The tune shifted towards an **integer tune resonance** and the beam punctured the vacuum chamber in the vertical plane (dipole current corresponding to 399.05 GeV)

# SPS Incident June 27th 2008



# Integer Tune Resonance

# Integer Tune Resonance

- Influence of dipolar error on Closed Orbit:

(e.g. quadrupole misalignments)

$$x(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi \cdot Q)} \oint_s F(\bar{s})\sqrt{\beta(\bar{s})} \cdot \cos(\varphi(\bar{s}) - \varphi(s) - \pi Q)\, d\bar{s}$$

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Beta function

Betatron phase

Resonance condition

Error function

Tune

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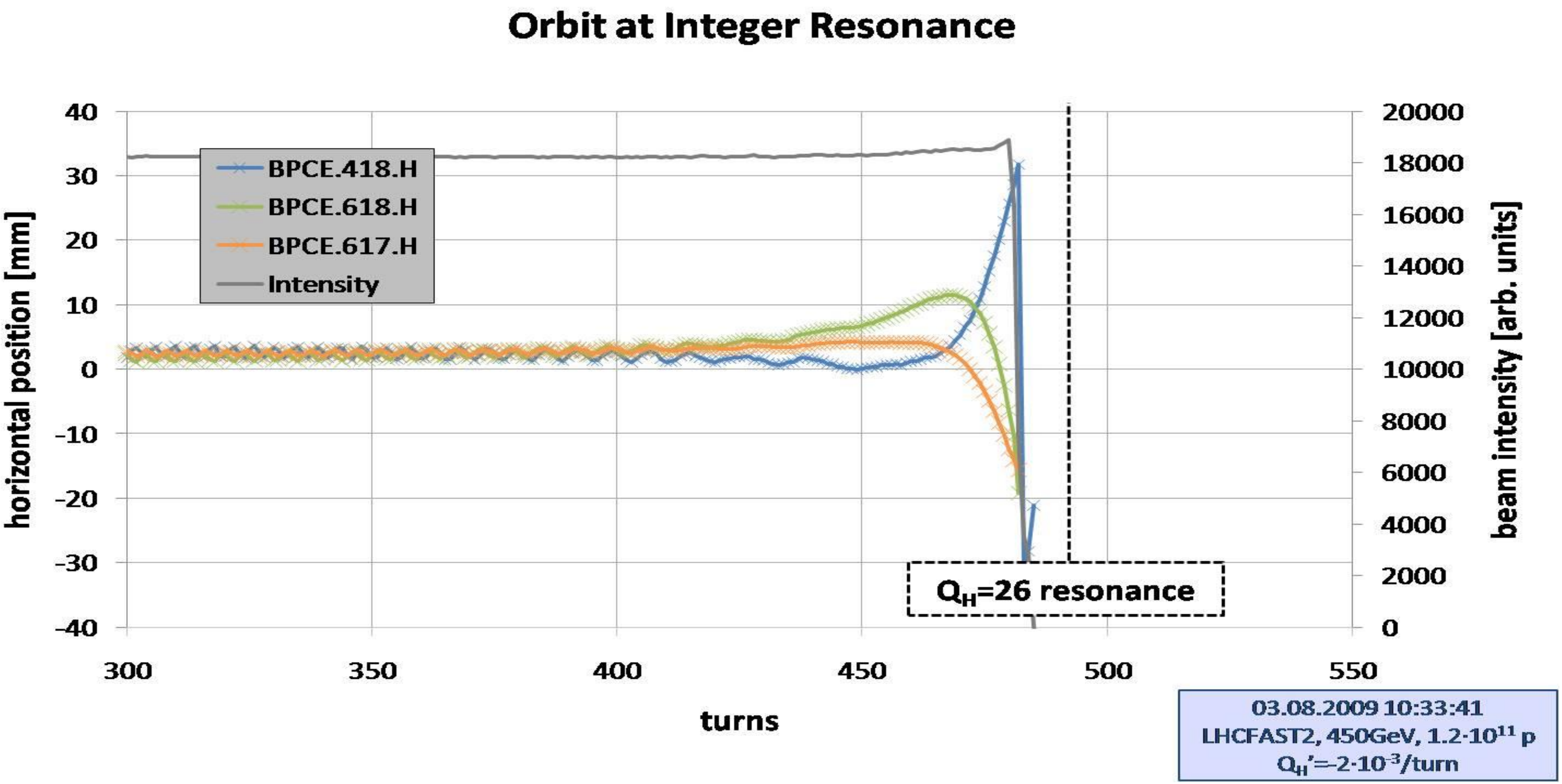
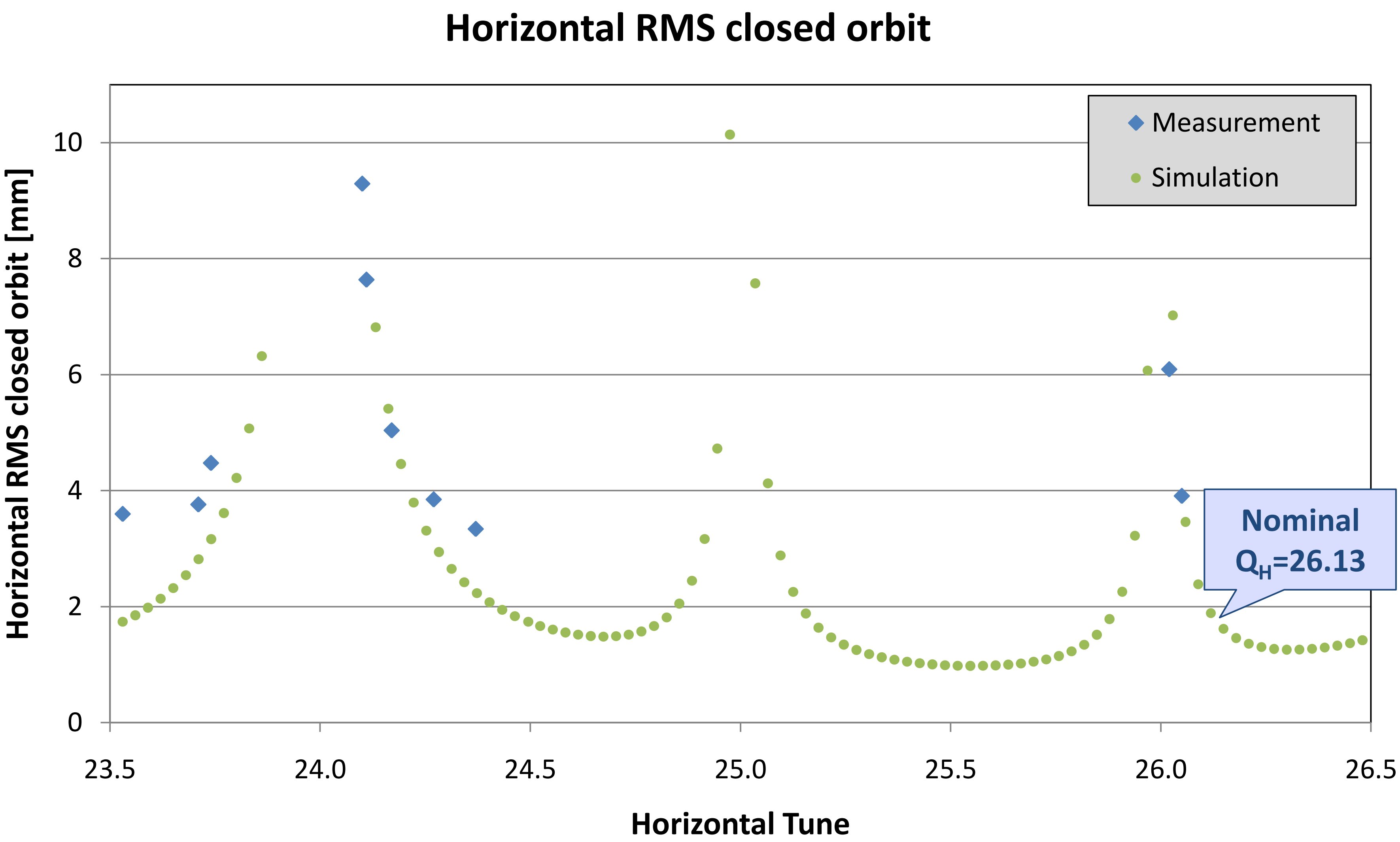
- $Q_H$, $Q_V$ = integer => diverging closed orbit

# Linear Decrease of Horizontal Tune

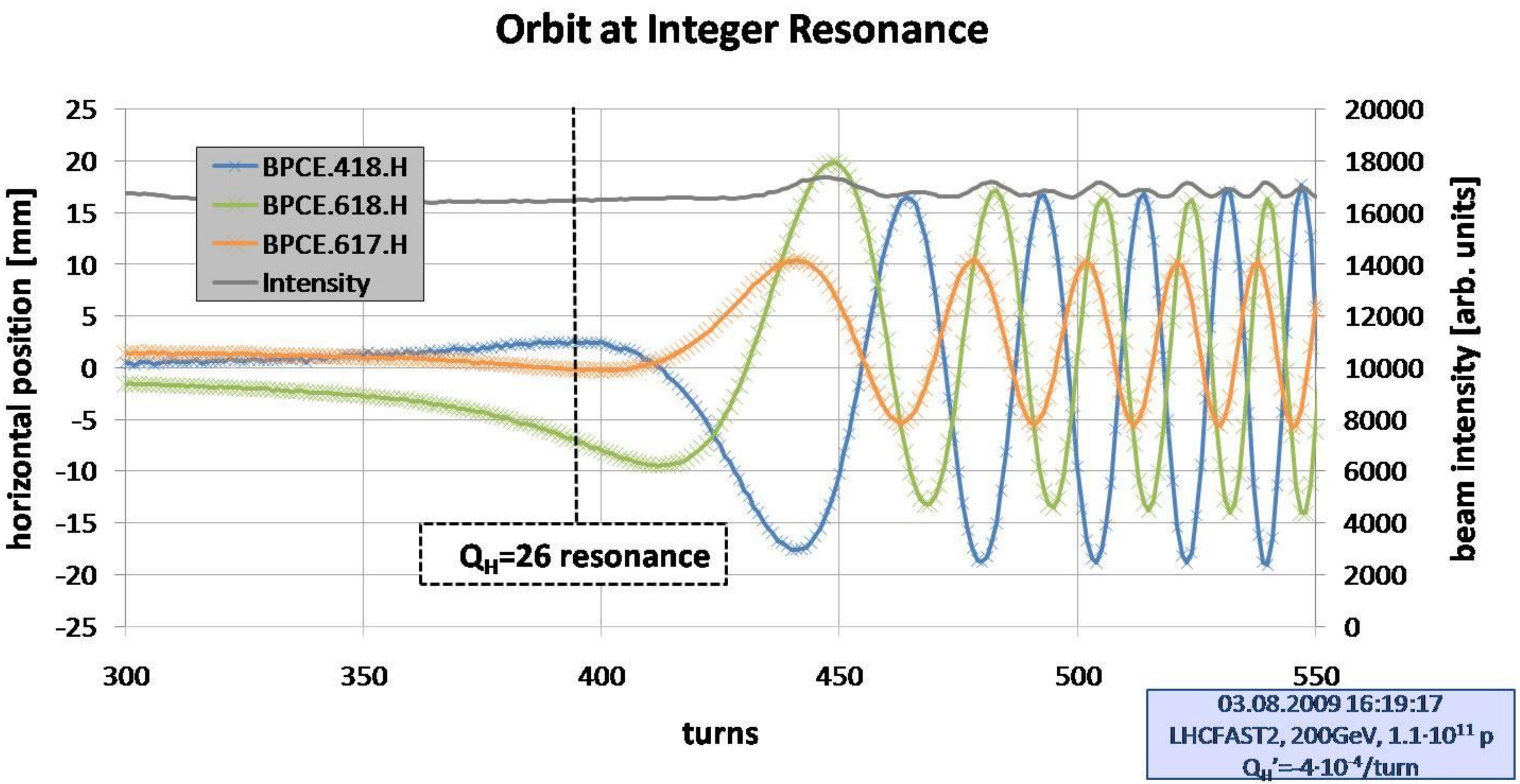


# Orbit Resonances



# Turn-by-Turn Position

## Linear Decrease of Horizontal Tune



# Dispersion Resonance

- Dispersion: $$\Delta x(s) = D(s) \cdot \frac{\Delta p}{p}$$

(generated by dipole magnets, transforms like orbit)

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Beta function

Betatron phase

Resonance condition

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# Dispersion Resonance

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$$D(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi \cdot Q)} \oint_s \frac{1}{\rho(\bar{s})} \sqrt{\beta(\bar{s})} \cdot \cos(\varphi(\bar{s}) - \varphi(s) - \pi Q) d\bar{s}$$

Beta function

Betatron phase

Resonance condition

Bending radius

Tune

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Resonance condition

Bending radius

Tune

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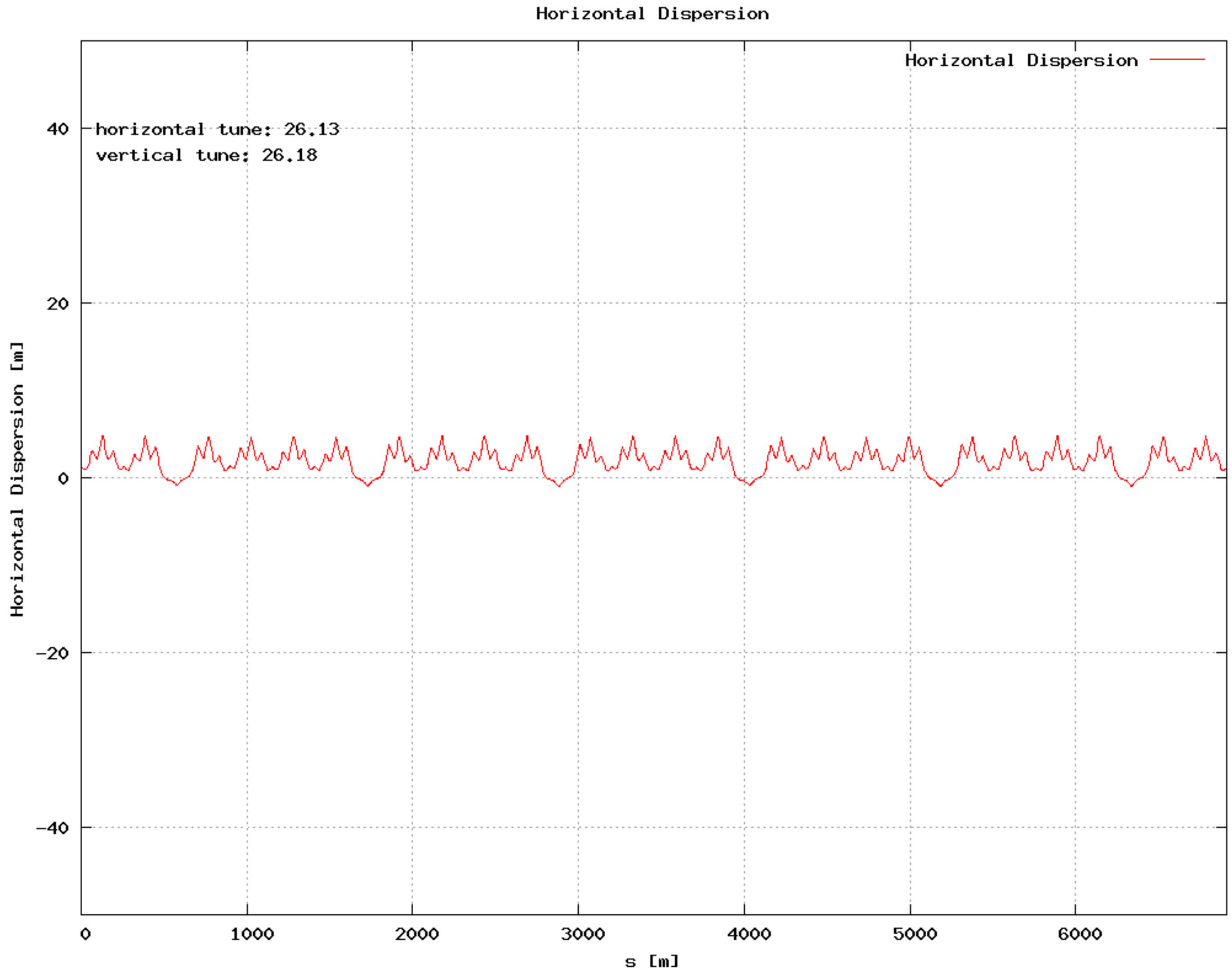
# Dispersion Resonance



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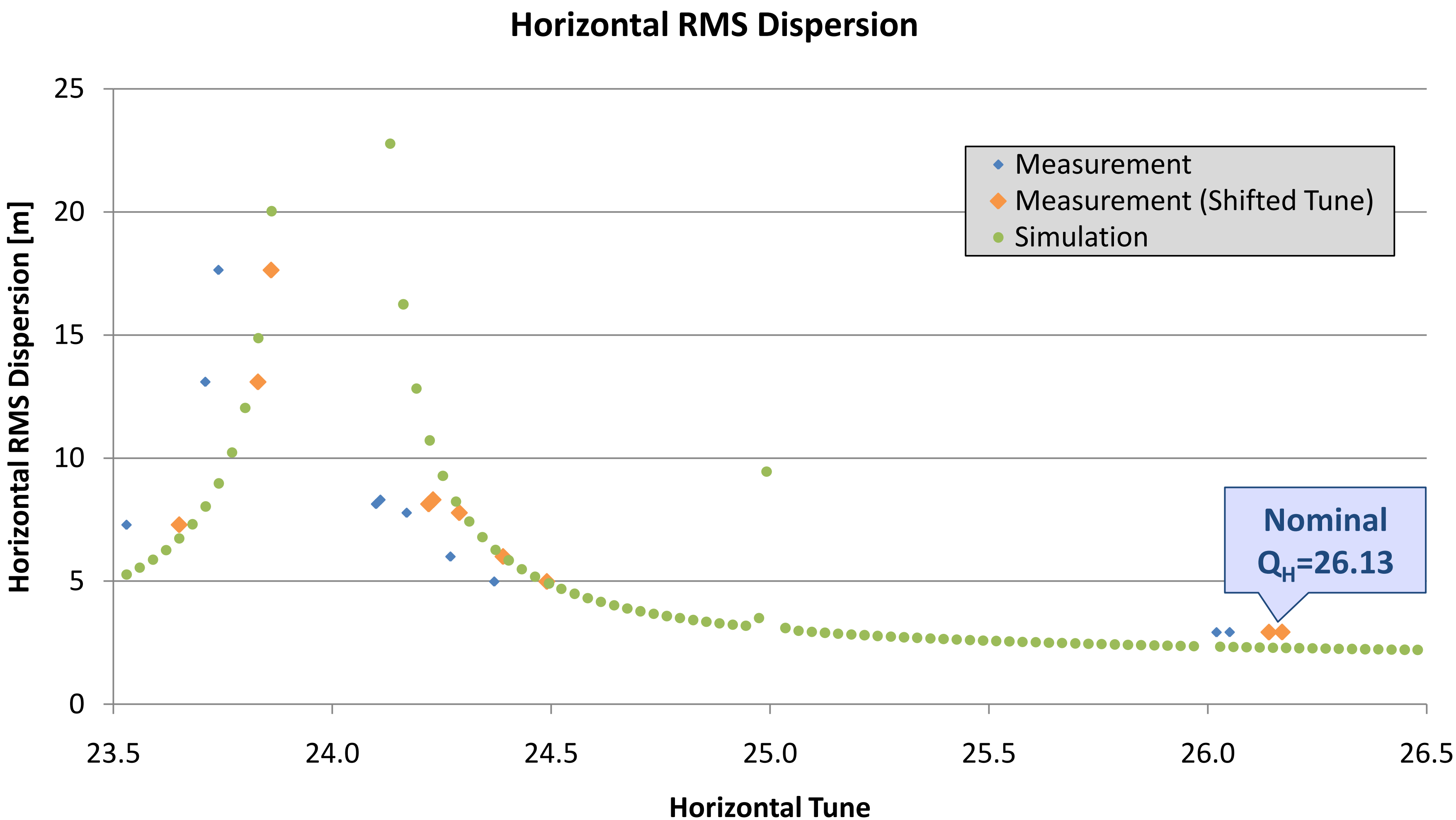
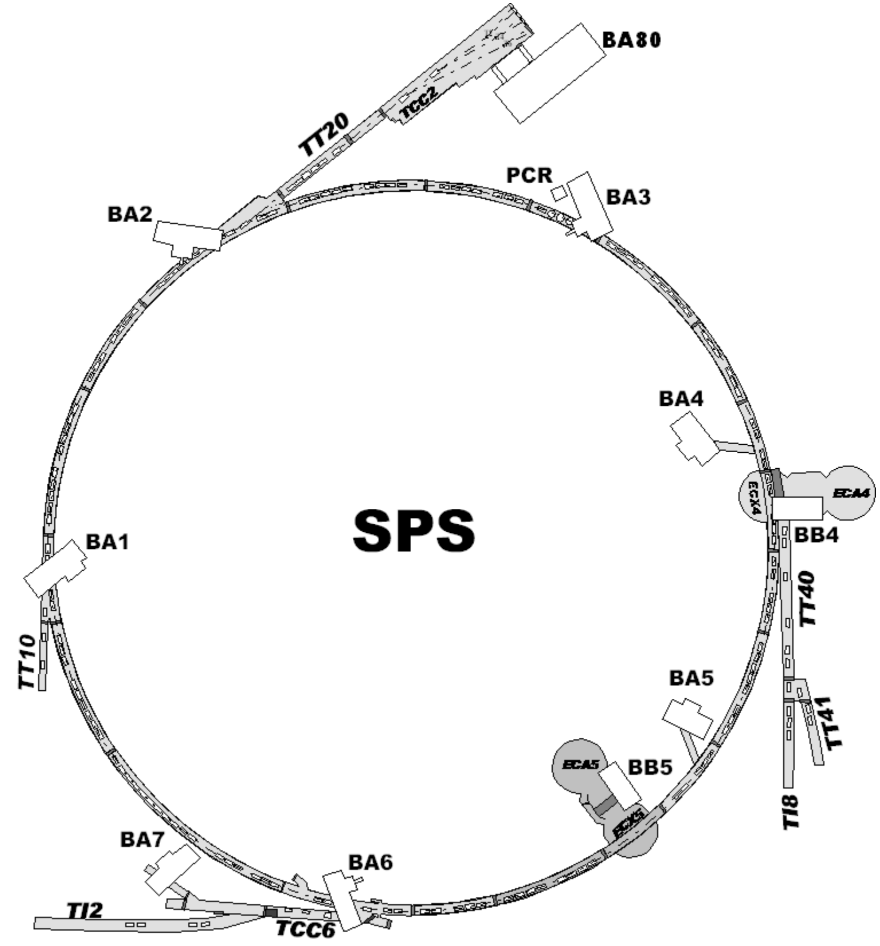


# Supersymmetric Resonances

SPS: Supersymmetry of 6



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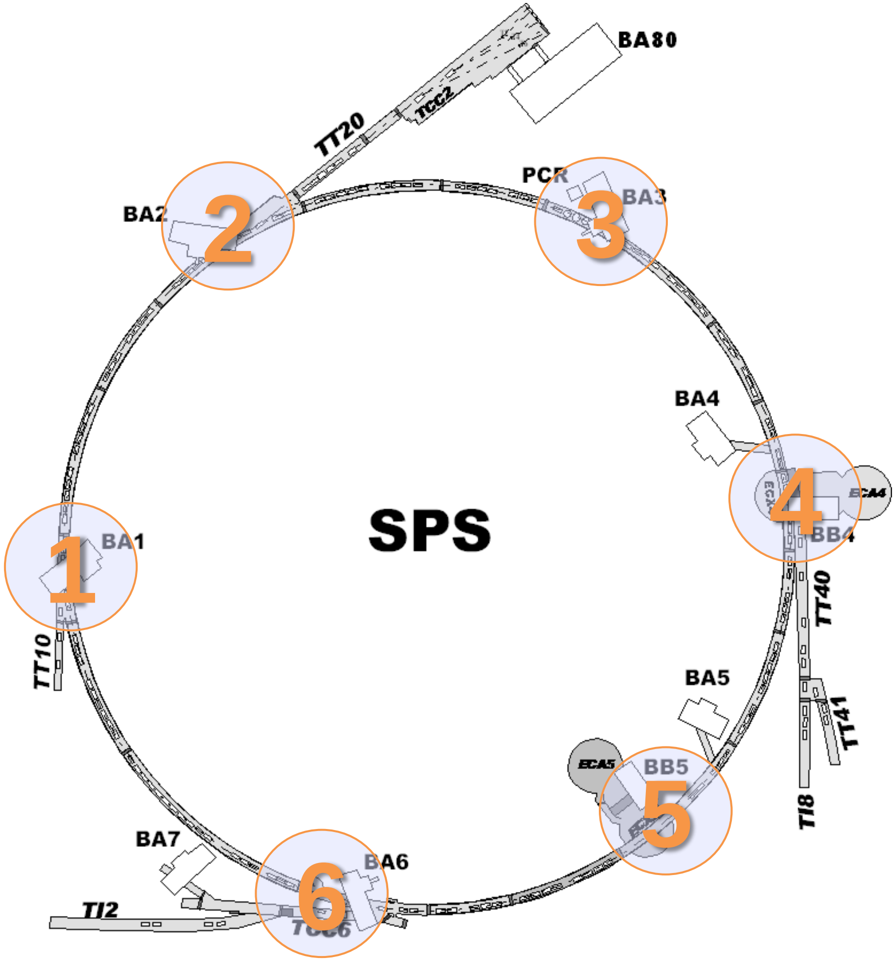

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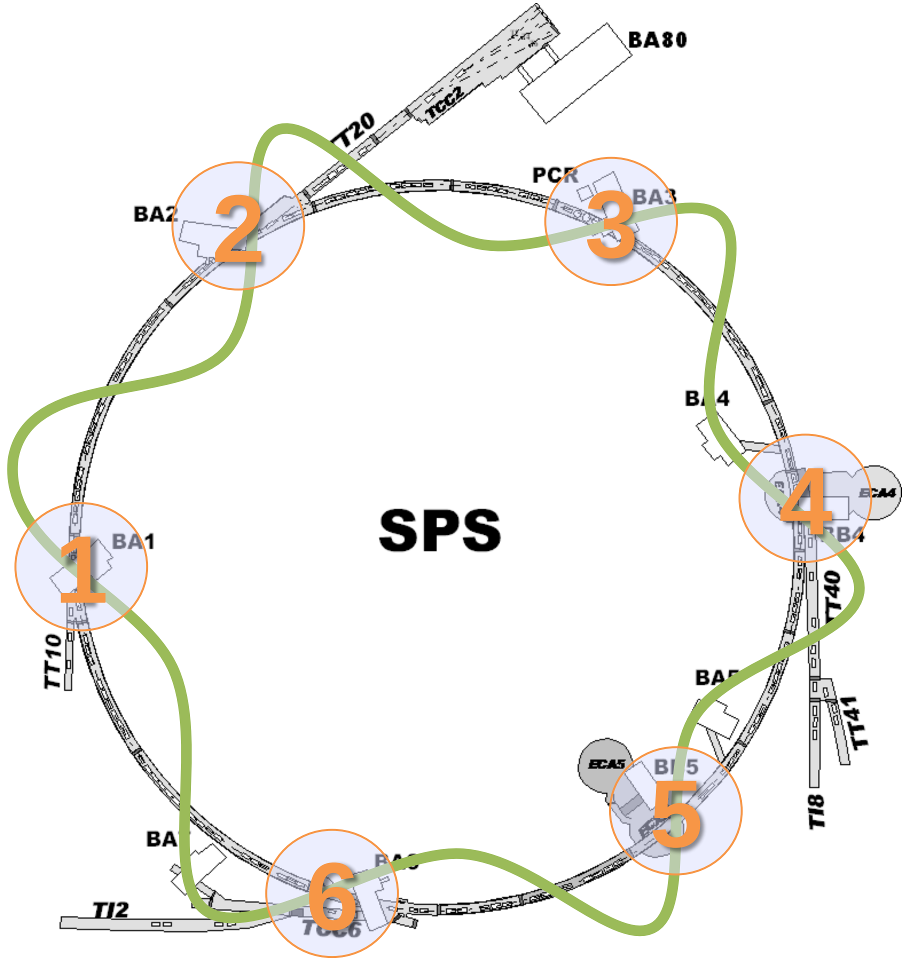
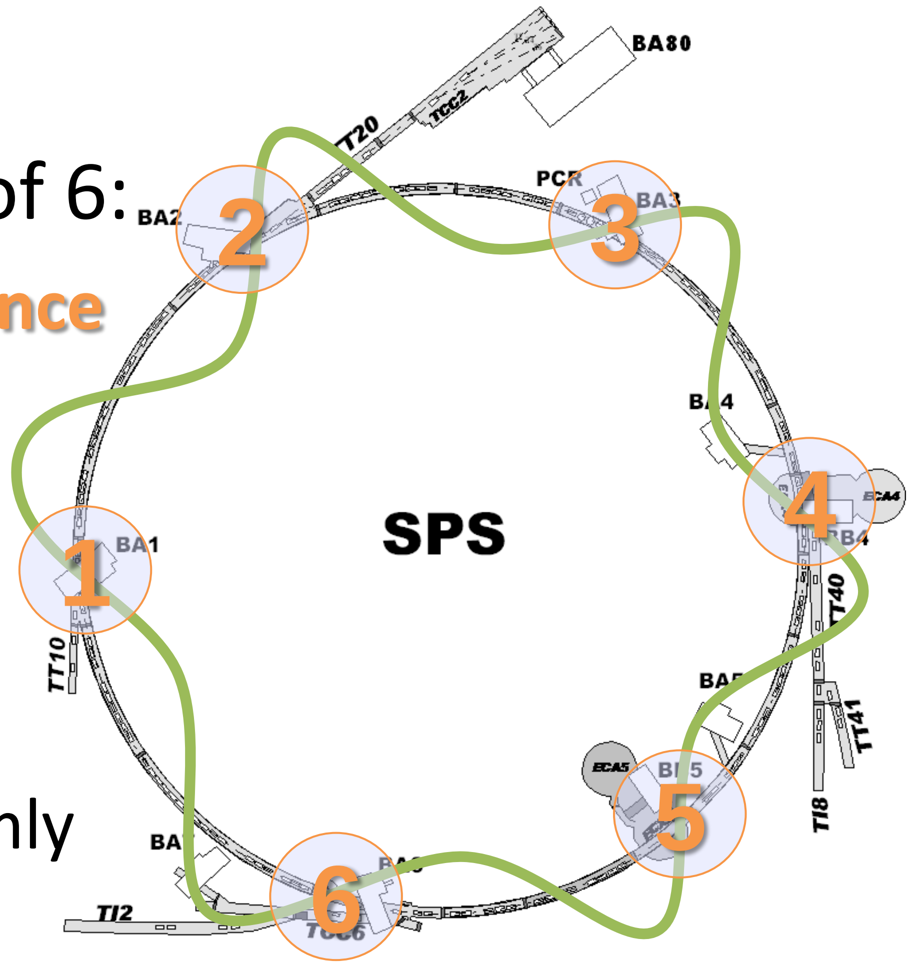


# Supersymmetric Resonances



SPS: Supersymmetry of 6

- When Tune is multiple of 6:




## Extreme Dispersion Resonance

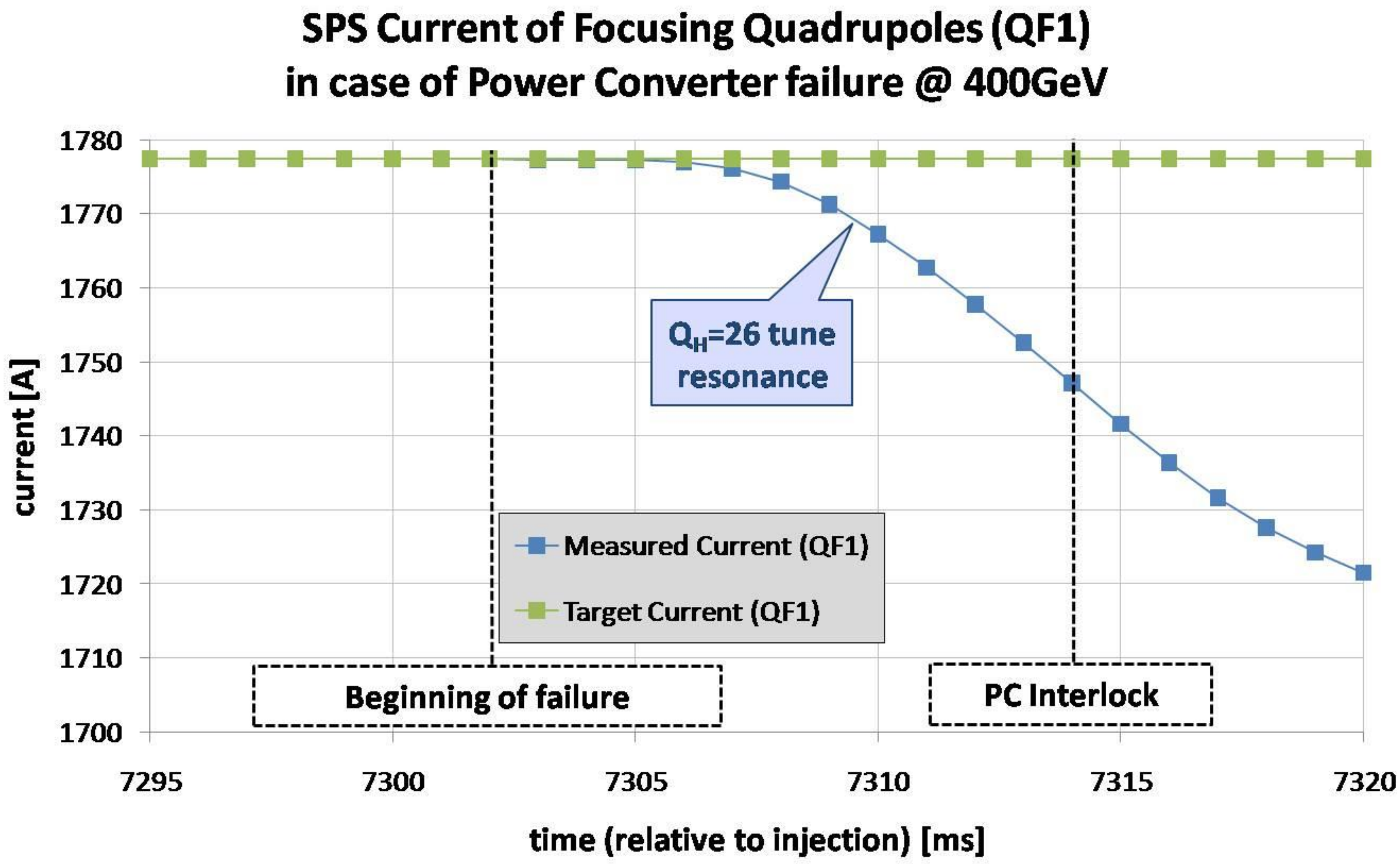
- Dipole fields are super-symmetric

## Integer Orbit Resonance

- Dipole errors are randomly distributed
(no strong supersymmetry)

# Machine Protection

# Power Converter Interlock

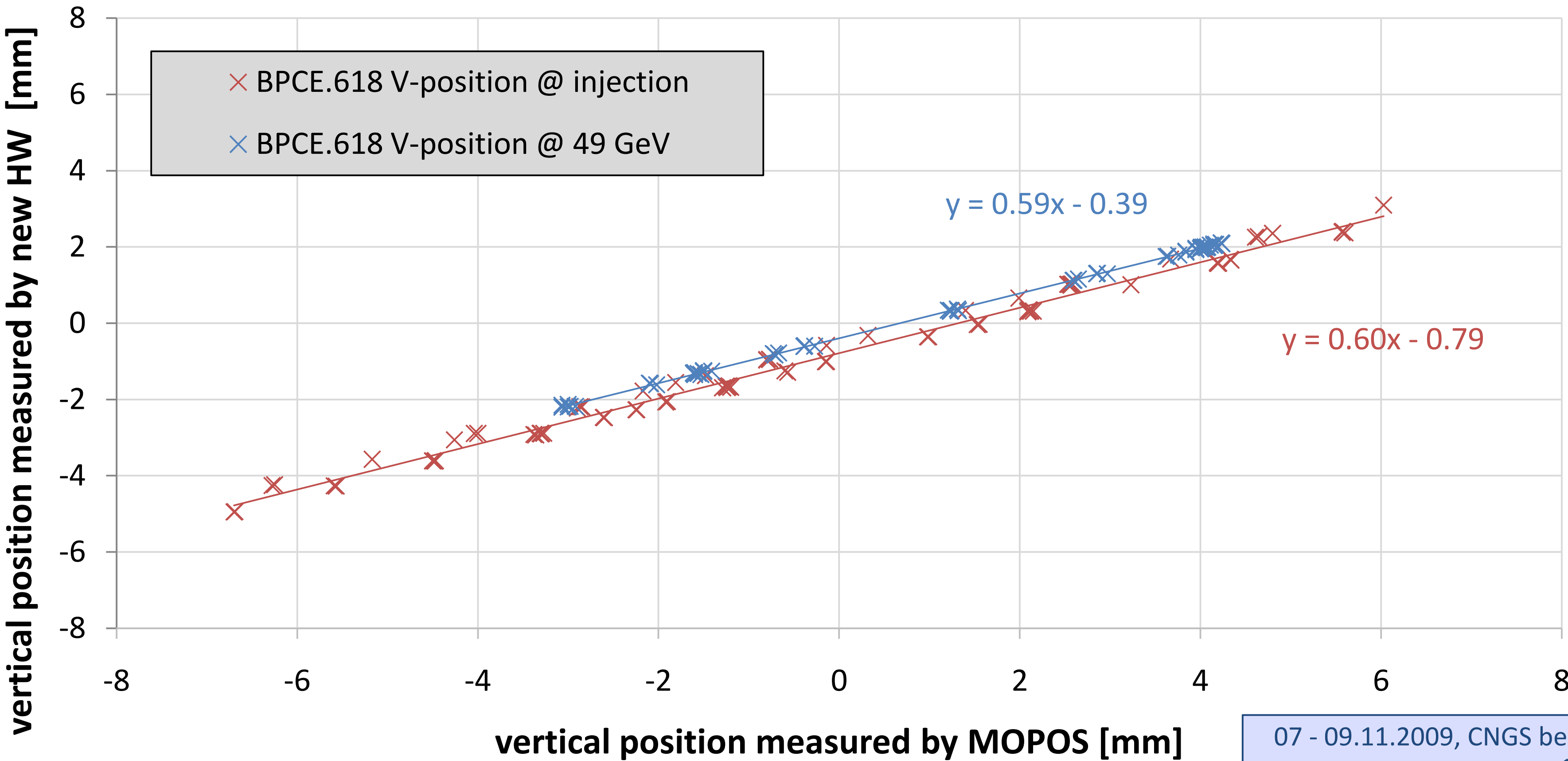


# Fast Position Interlock

- Original Design:
  - 6 stripline coupler BPMs
  - new Hardware using logarithmic amplifiers (large dynamic range)
  - Turn-by-Turn Acquisition and Interlock Processing via FPGA
  - Post Mortem Acquisition (1024 turns)

# Acquisition Commissioning

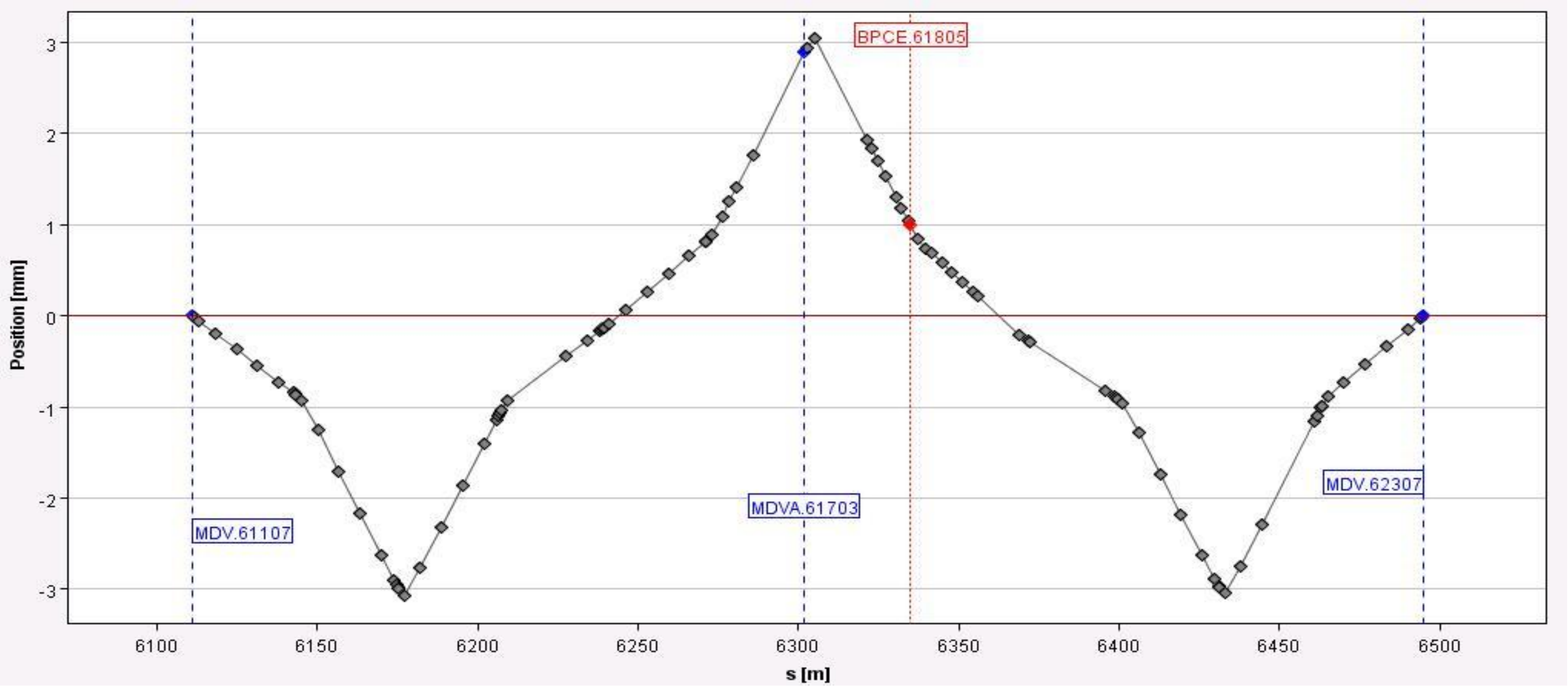
**New Hardware vs. Traditional Hardware (vertical orbit bump)**




07 - 09.11.2009, CNGS beam
@ injection: 14GeV, $2\cdot10^{13}$ p
@ 49GeV: $4\cdot10^{13}$ p

# Consistency Check:

## Vertical 3π orbit bump at BPCE 618



# Acquisition Commissioning

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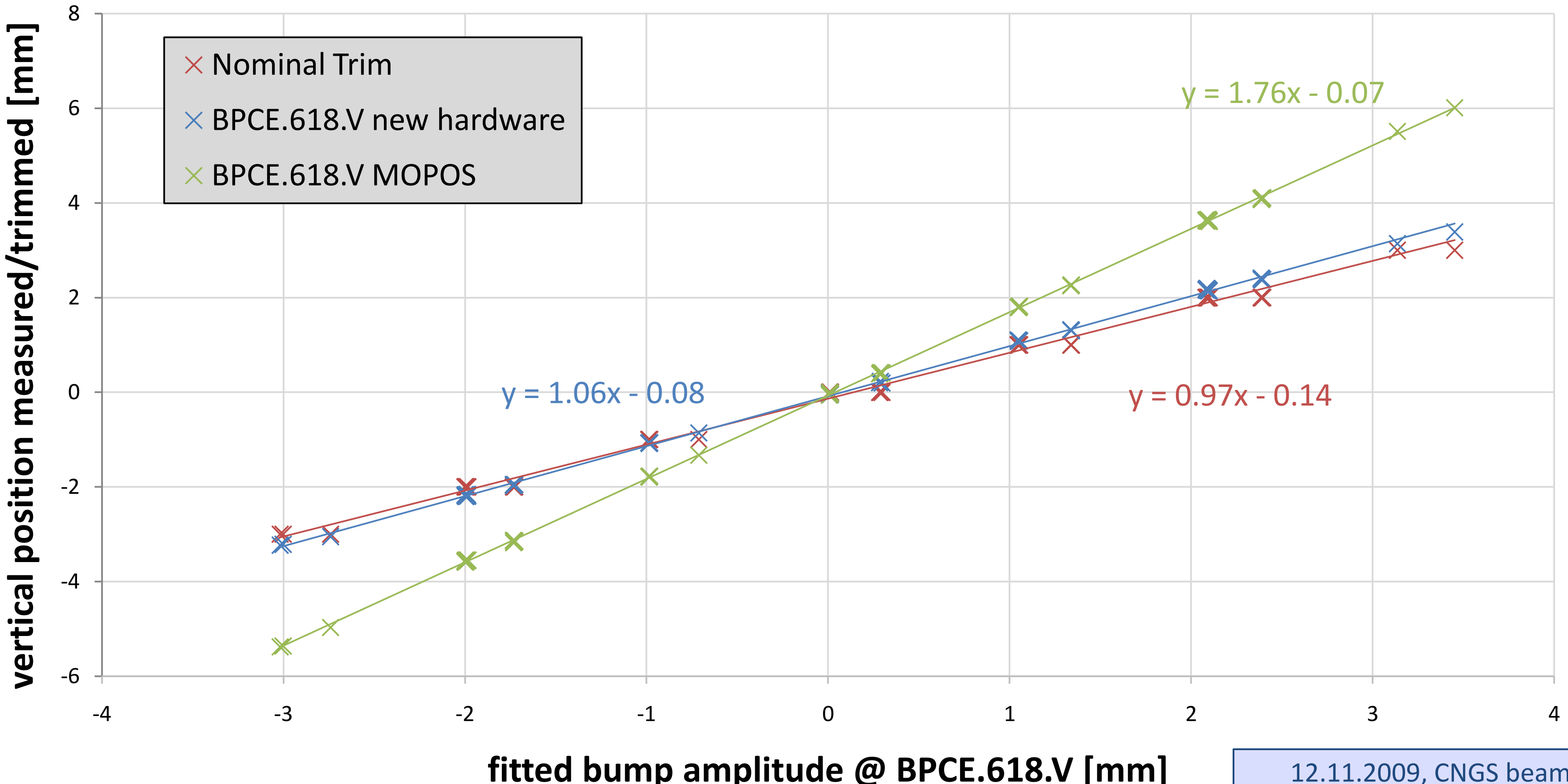


12.11.2009, CNGS beam
14GeV, $2{\cdot}10^{13}$ p

# Interlock Algorithm

- Compare current position with moving average of last 100 turns
- Interlock if difference larger 3mm
- Outlier detection

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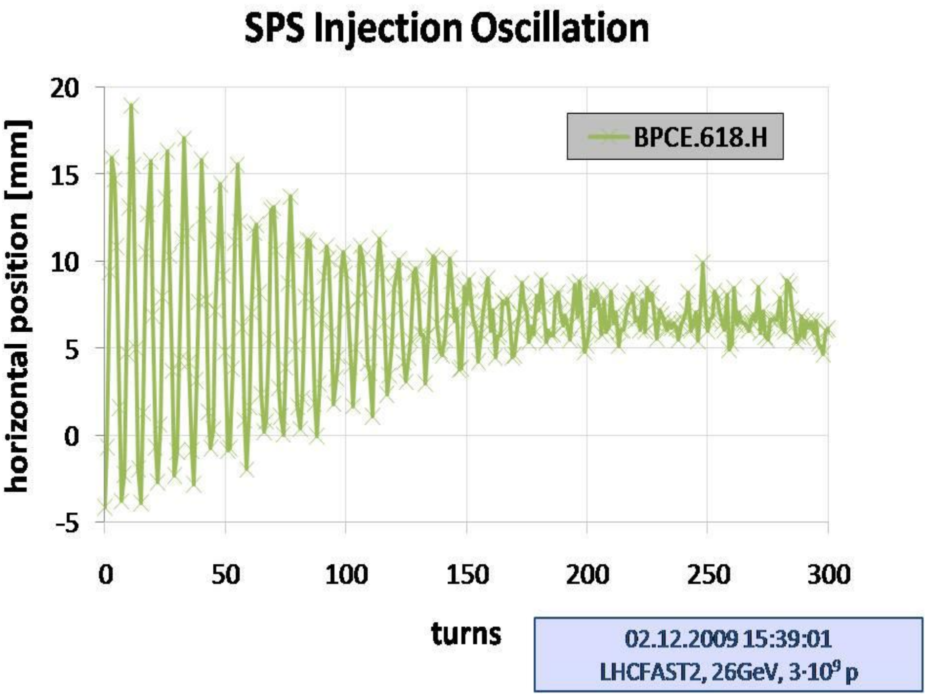
Problem:

**Injection Oscillations**



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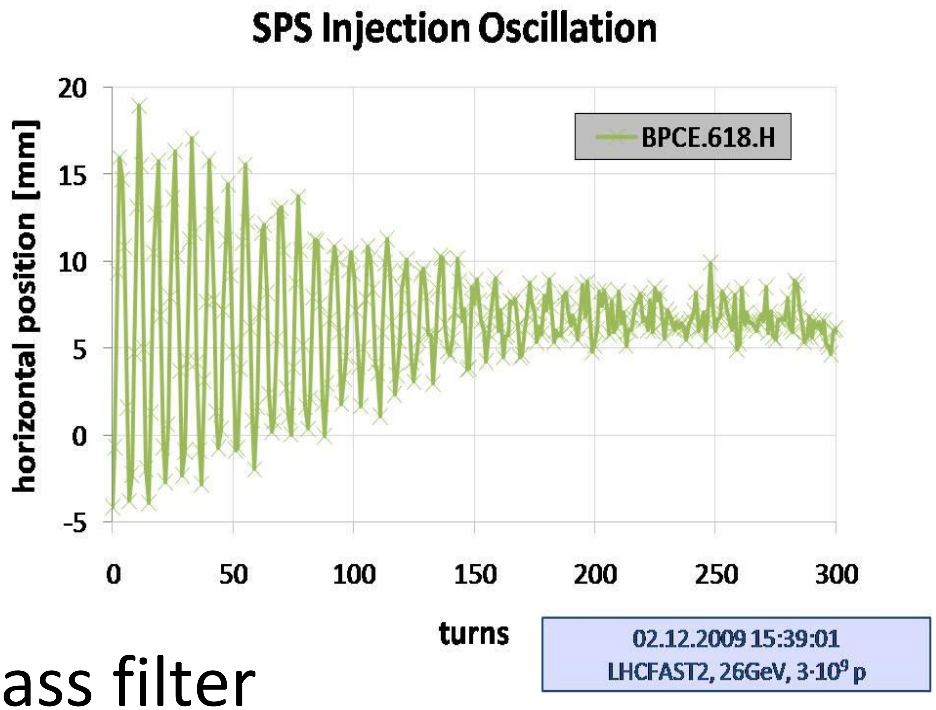
Problem:

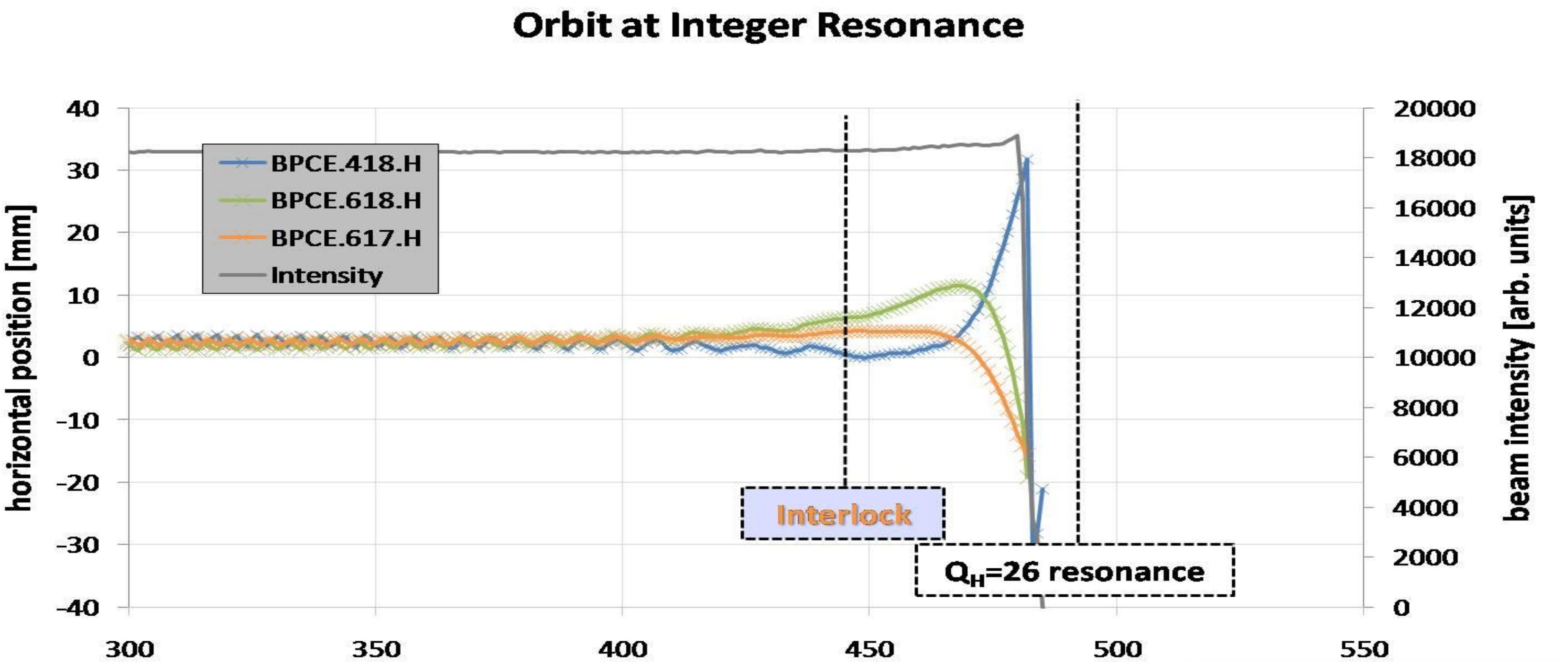
**Injection Oscillations**




- Probable solution:

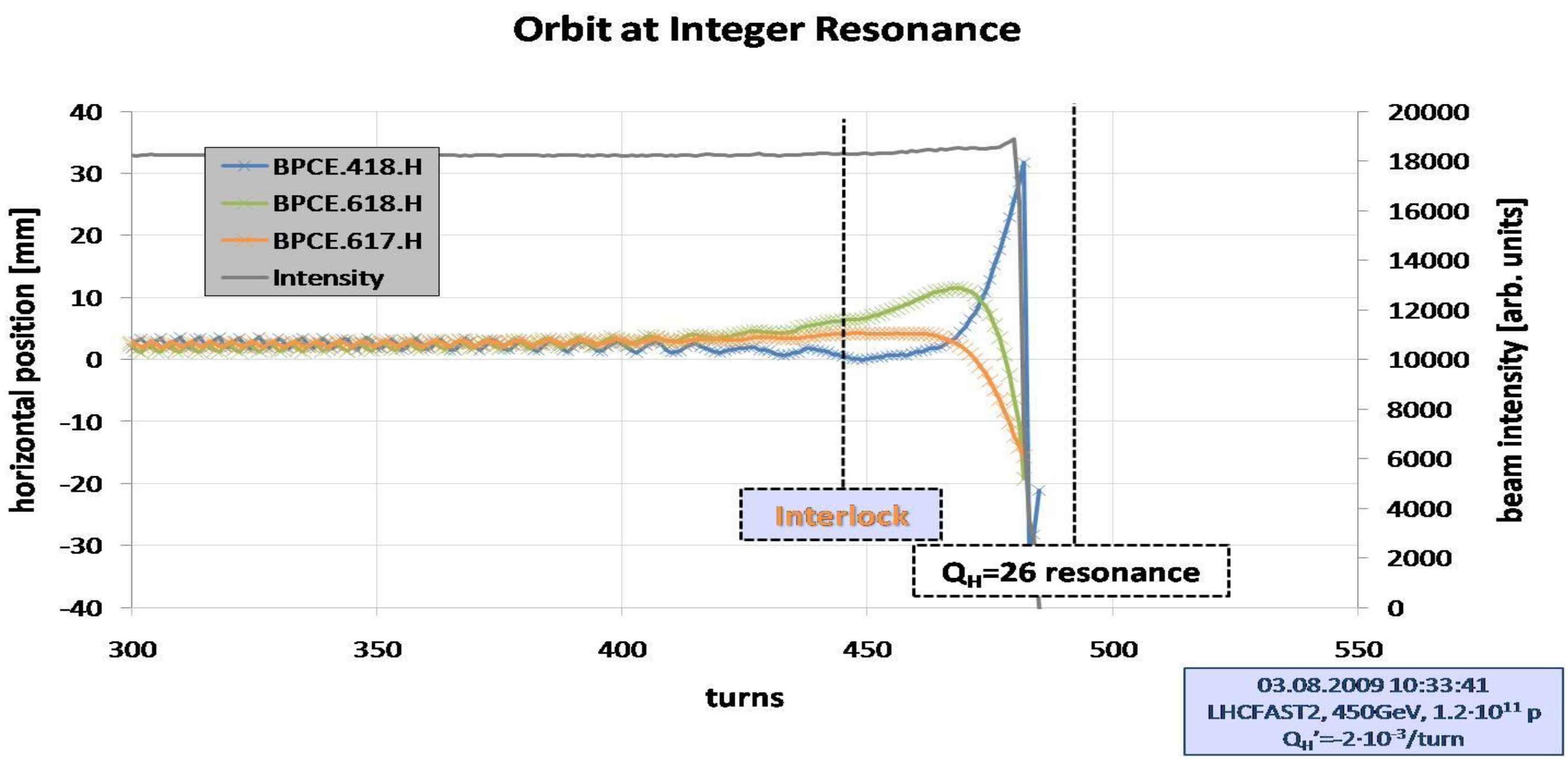
  (Time dependent) Low pass filter

# Fast Position Interlock




03.08.2009 10:33:41
LHCFAST2, 450GeV, $1.2\cdot10^{11}$ p
$Q_H' = -2\cdot10^{-3}$/turn

# Fast Position Interlock




Offline test: 428/428 tune resonances triggered,

0/554 normal orbits triggered

in-situ tests continue next week

# Summary

- (Integer) Tune Resonance are a challenging Machine Protection Issue
  - (cp. **complete beam loss in 3 turns**)
- Protection with **Turn-by-Turn Position Interlock**
- When you are fast enough you can **cross every resonance**
- Be aware of **Supersymmetric Tune Resonances**

# Thank you
# for your Attention

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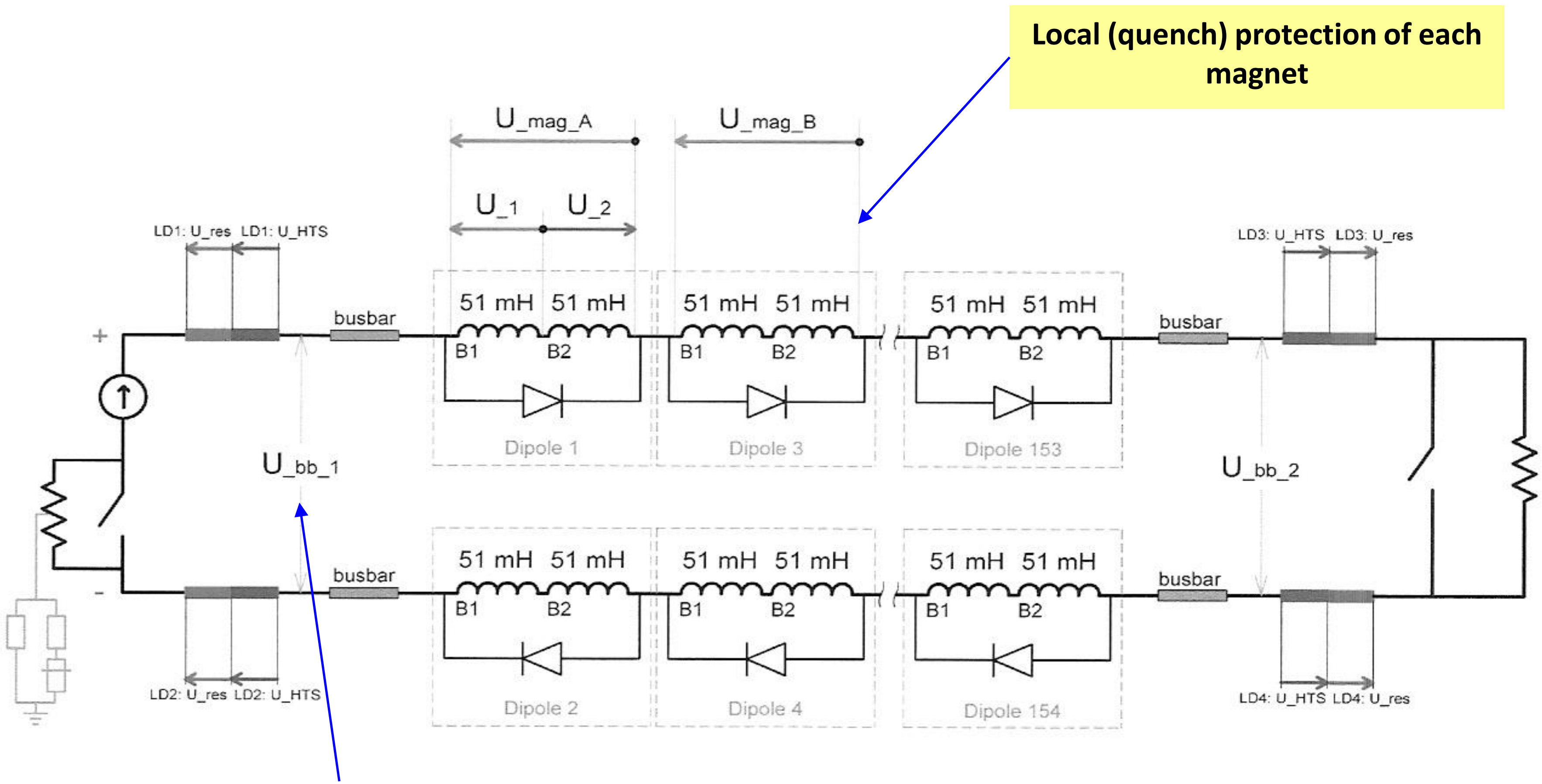
Backup slides

# LHC Main Dipole Circuit



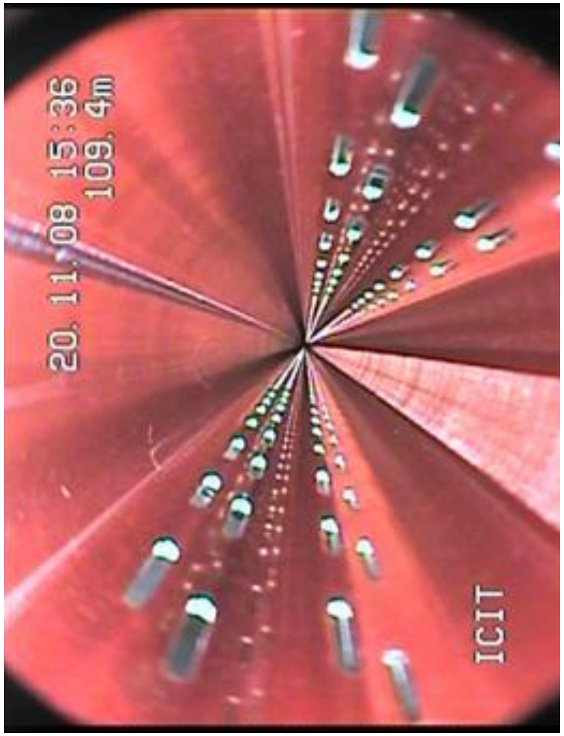
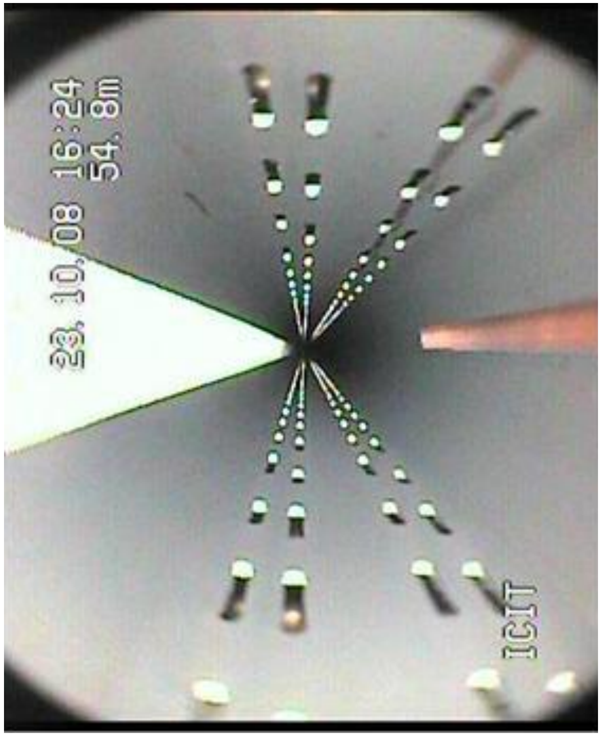



Global protection of the bus-bar and bus-bar joints (splices) between magnets.

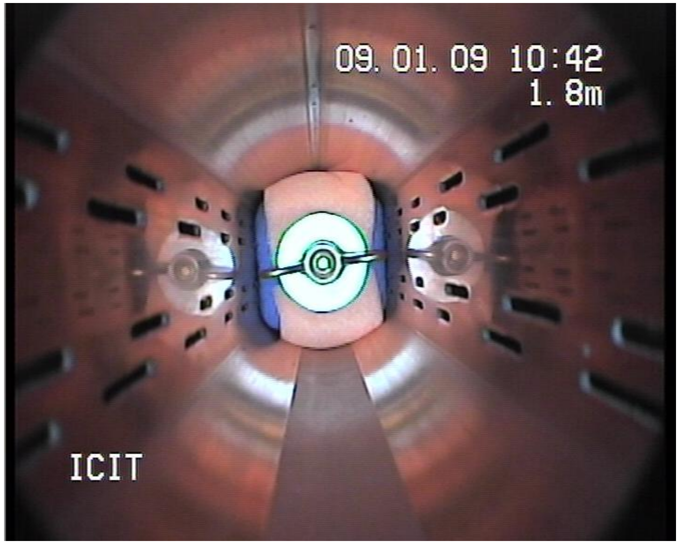
*Protection threshold 1 V (160 V inductive voltage during ramp).*

*Bus-bar must cope with 100 second discharge time of circuit.*

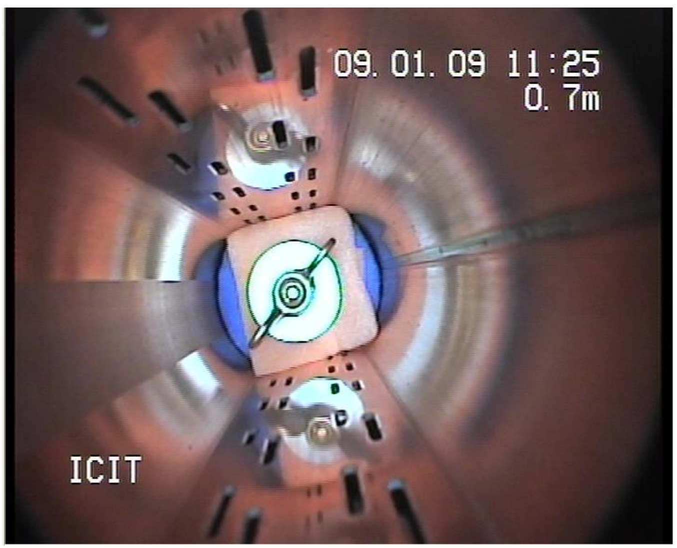
# Beam Screen Contamination

| Beam screen with clean Copper surface | contaminated by super-isolation | contaminated with soot |
|---|---|---|
|  |  |  |
| | ≈ 60% of the chambers | ≈ 20% of the chambers |

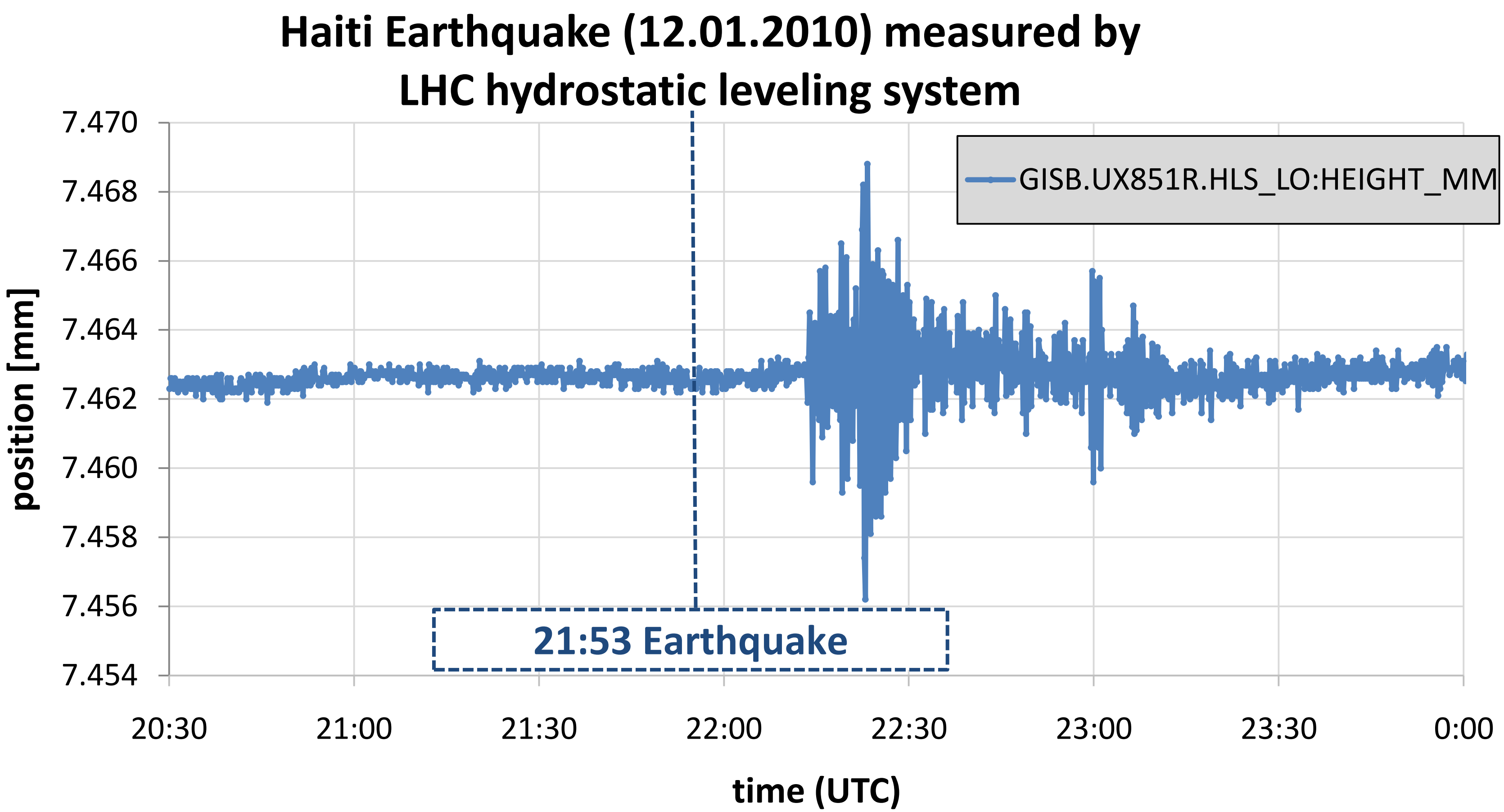
# Cleaning of Beam Screen




- Up to 50 passages in each direction with wet foam (alcohol)
- Up to 15 passages with dry foam

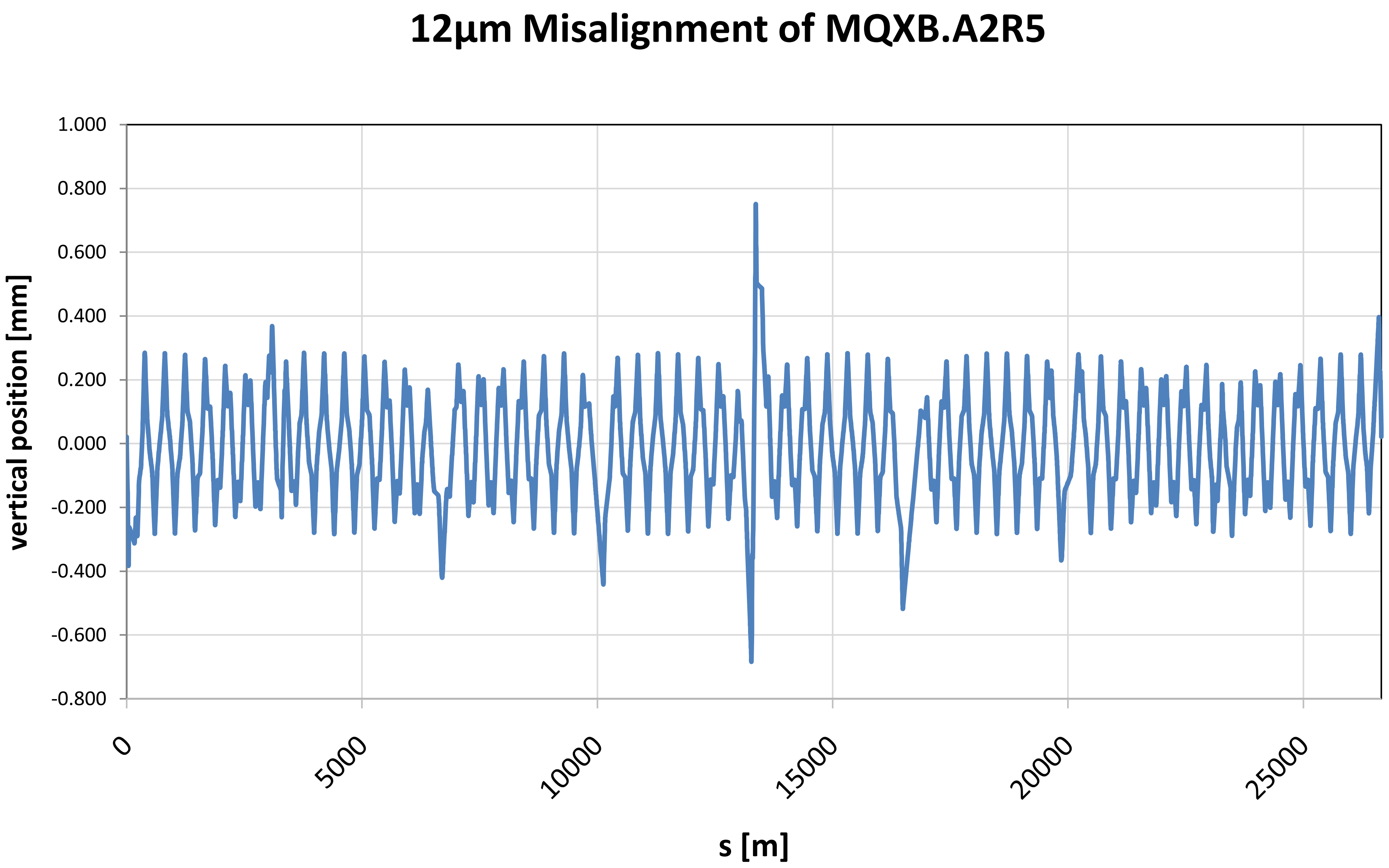



# Triplet Movement



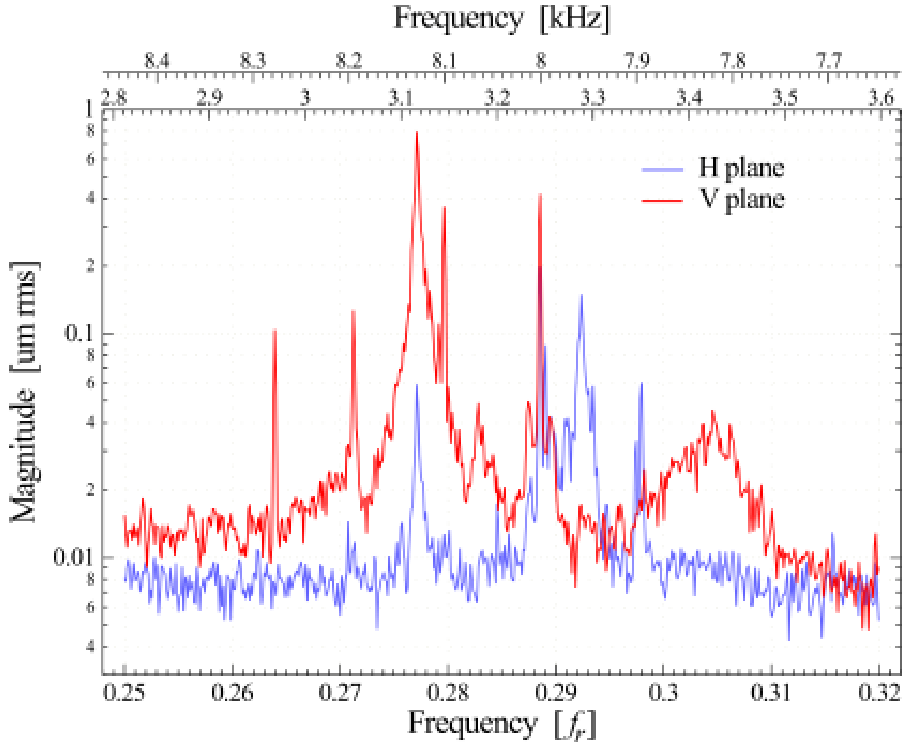

12µm triplet misalignment => beam oscillation amplitude 0.3mm (in arc)

# Triplet Movement



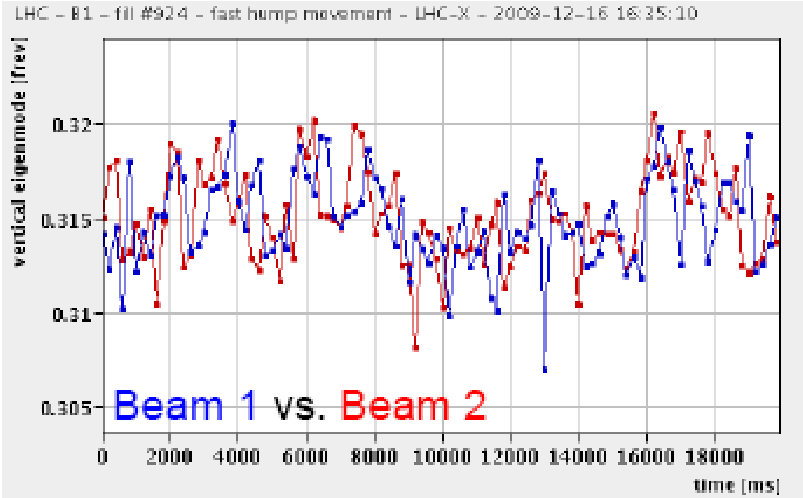
# Hump and UPS

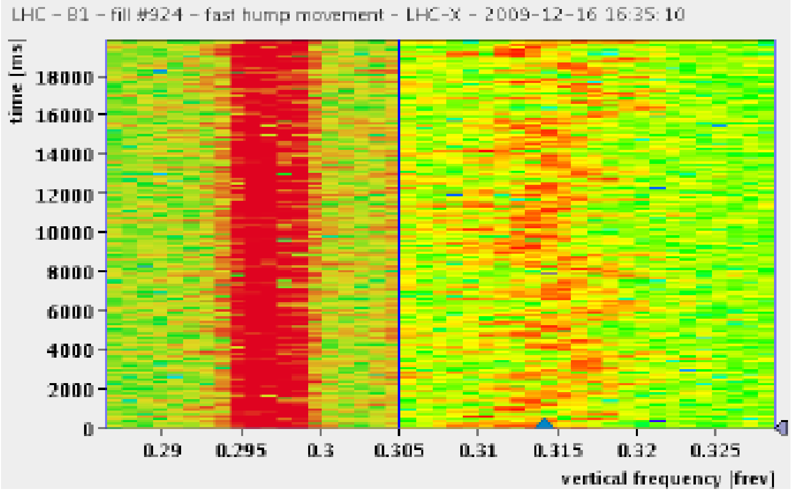
Hump: Fast frequency shifting oscillation with mean drifting slowly between 0.25 and 0.32



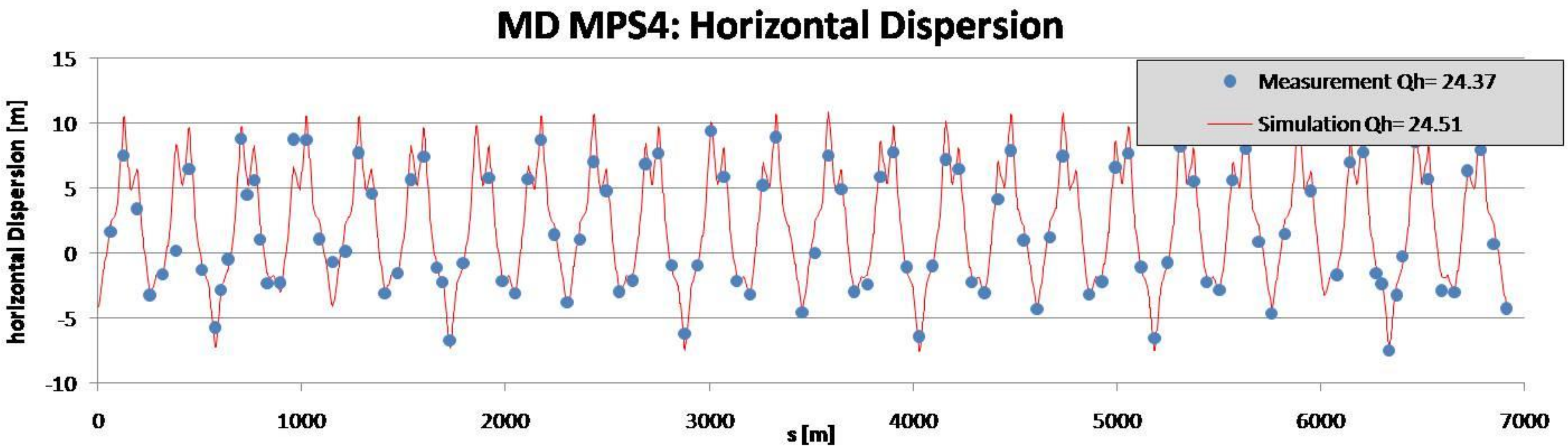

courtesy of Ralph Steinhagen

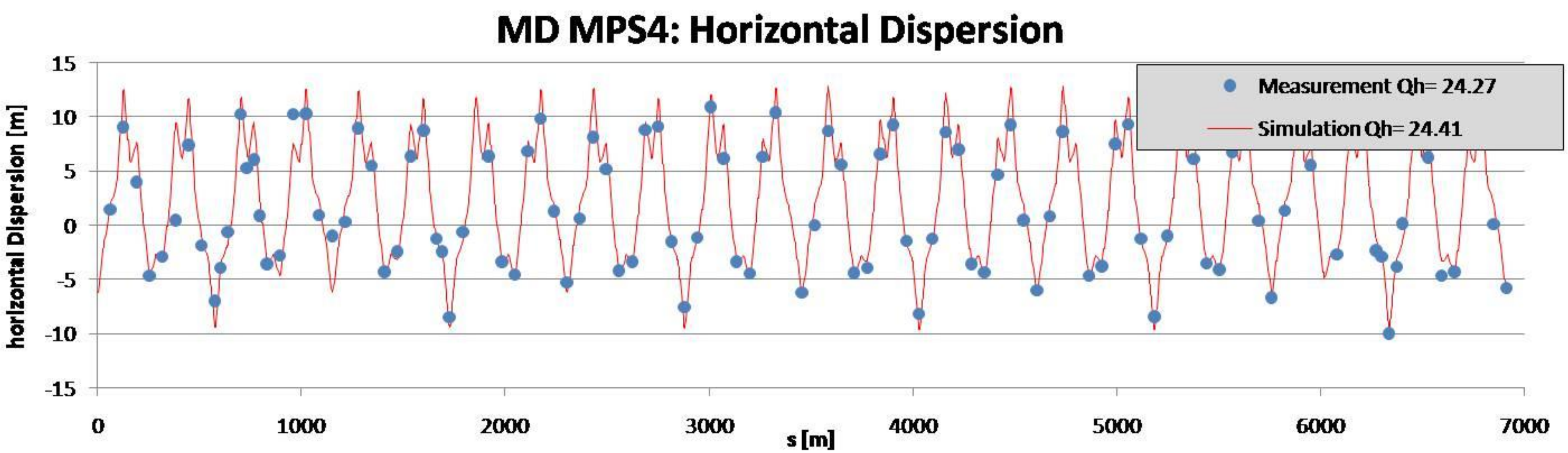
Time resolved Hump structure



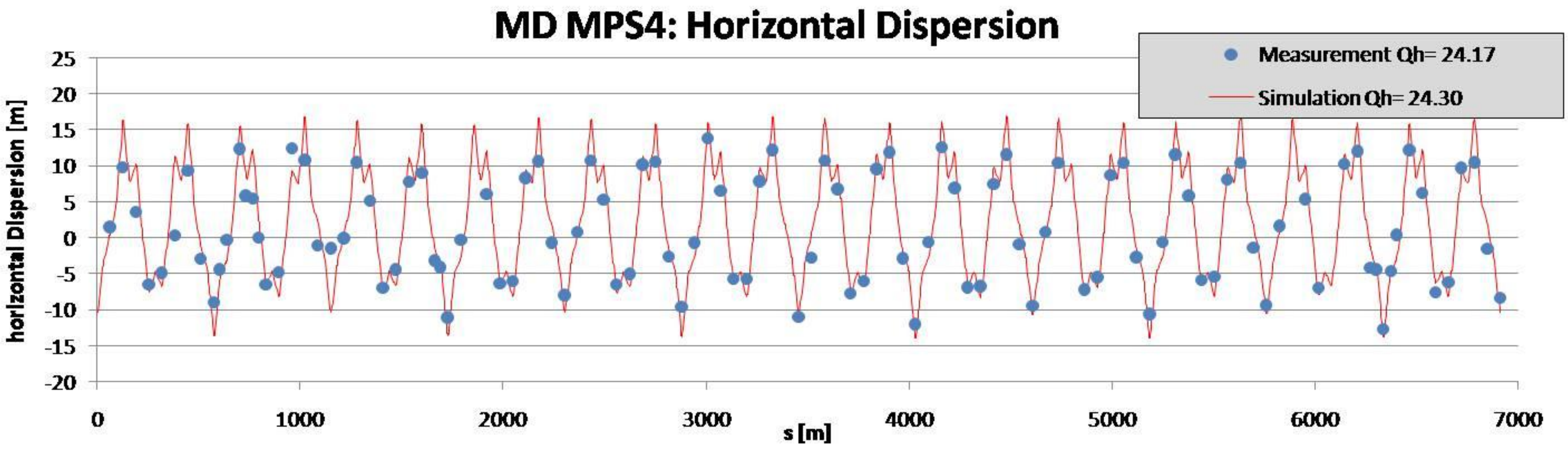



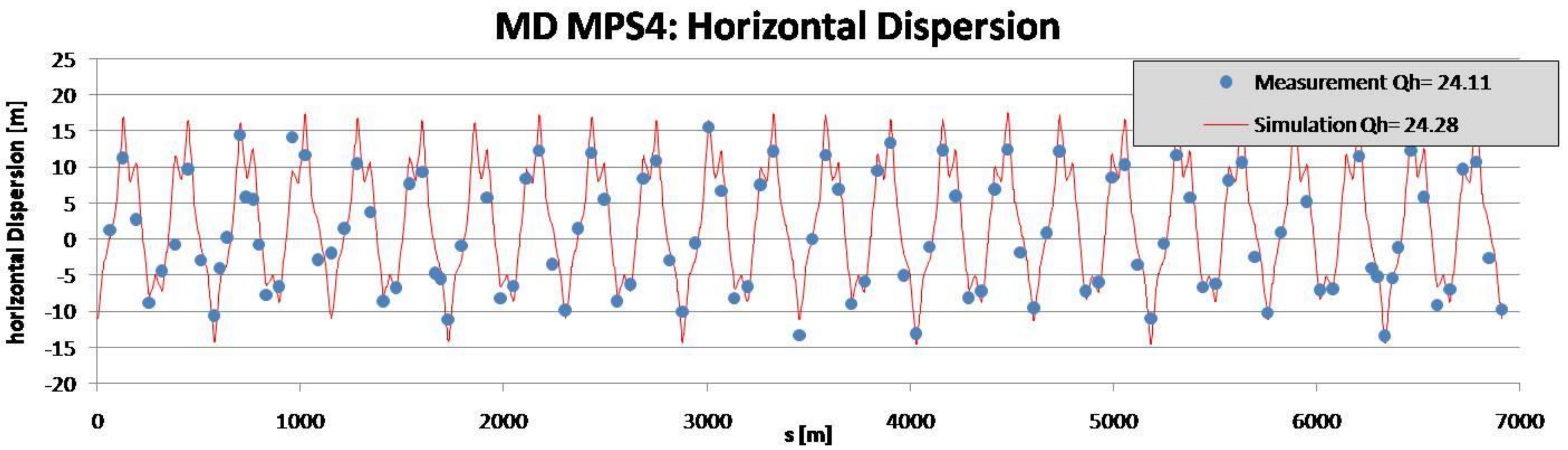
# Dispersion Resonance



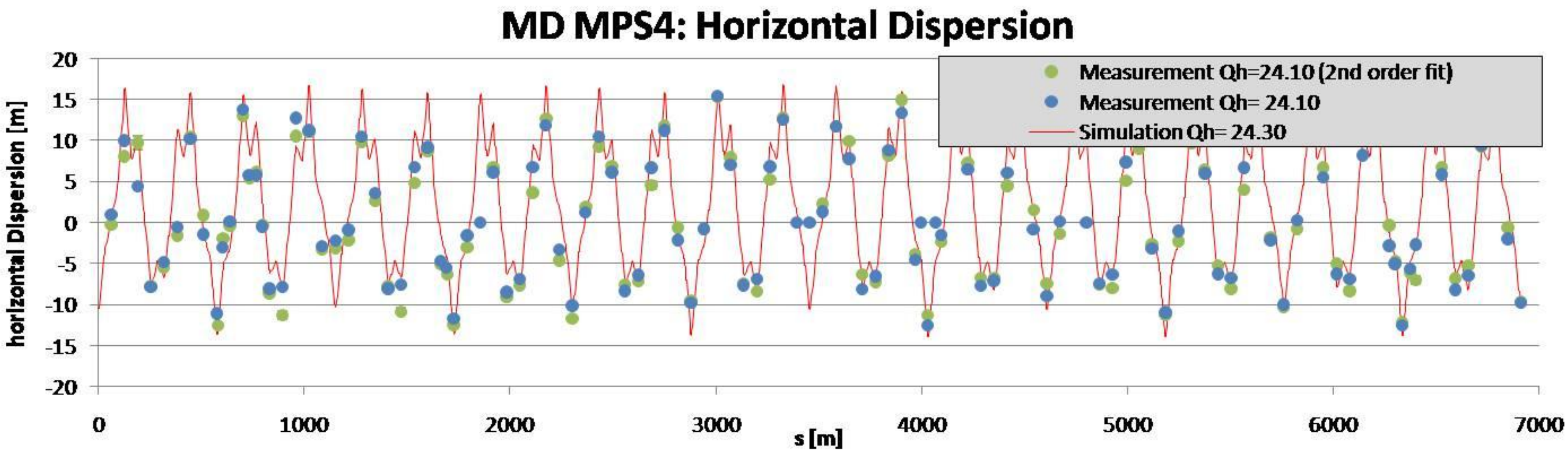



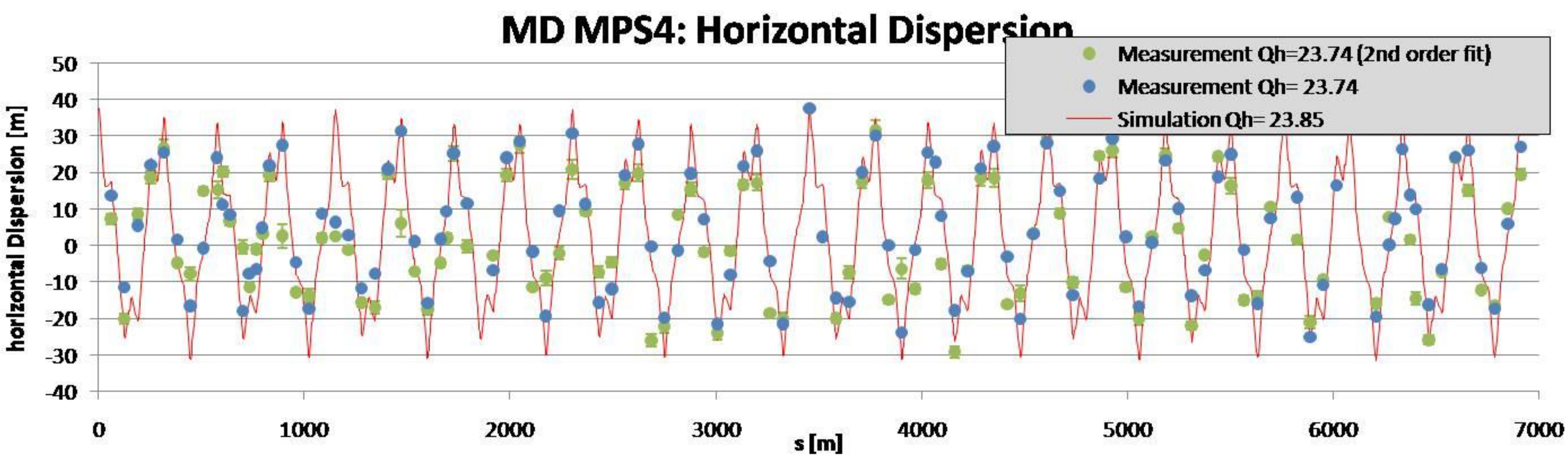
# Dispersion Resonance



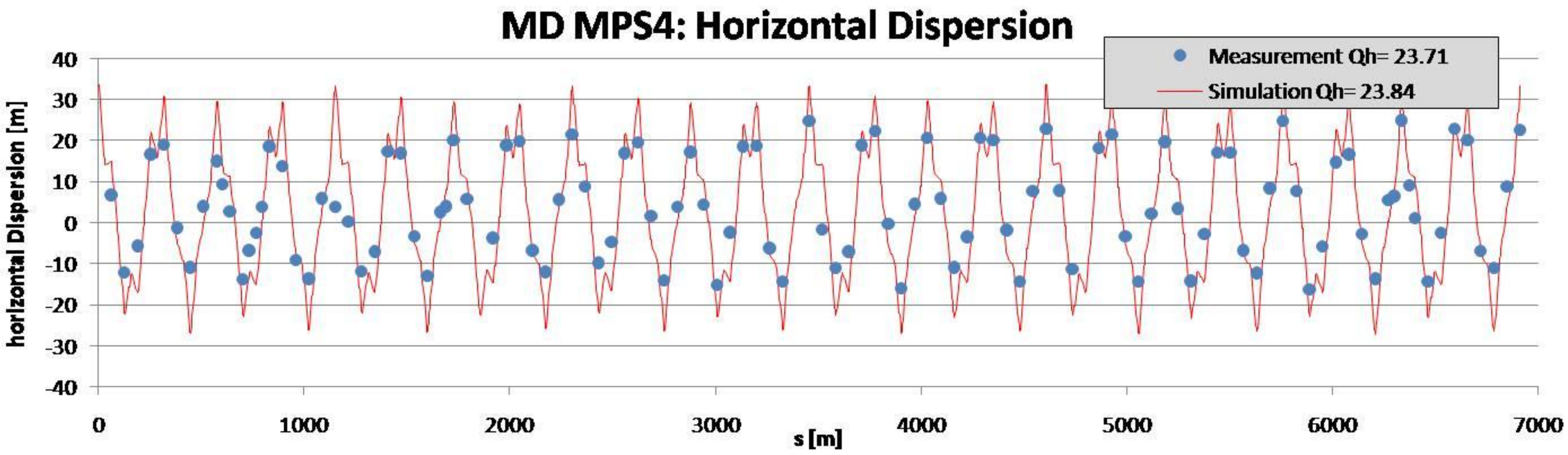



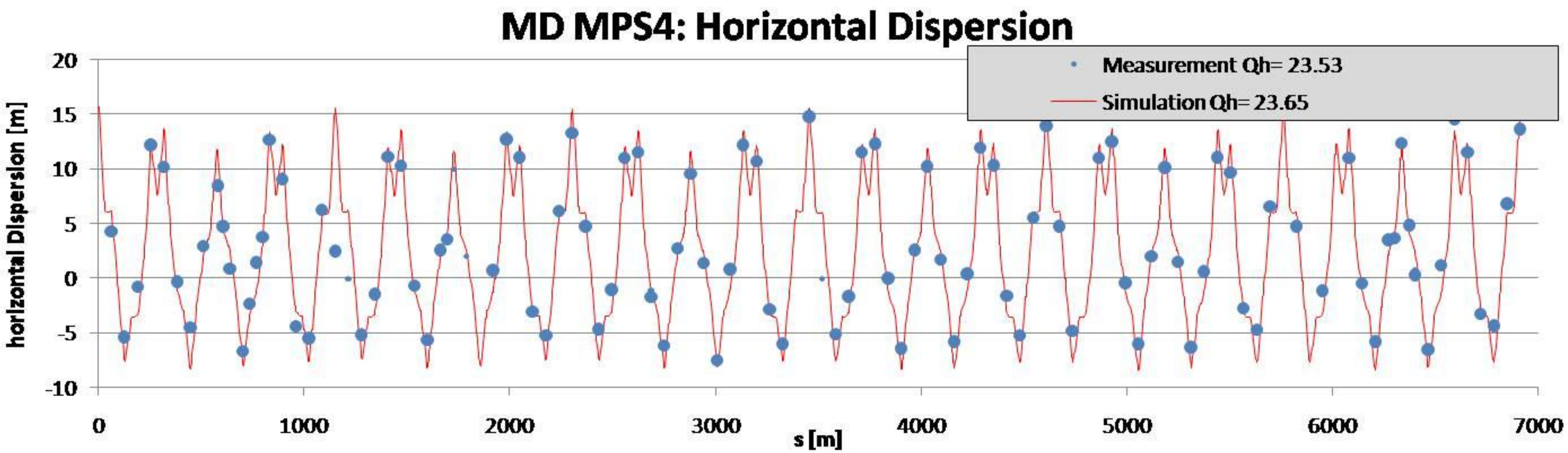
# Dispersion Resonance



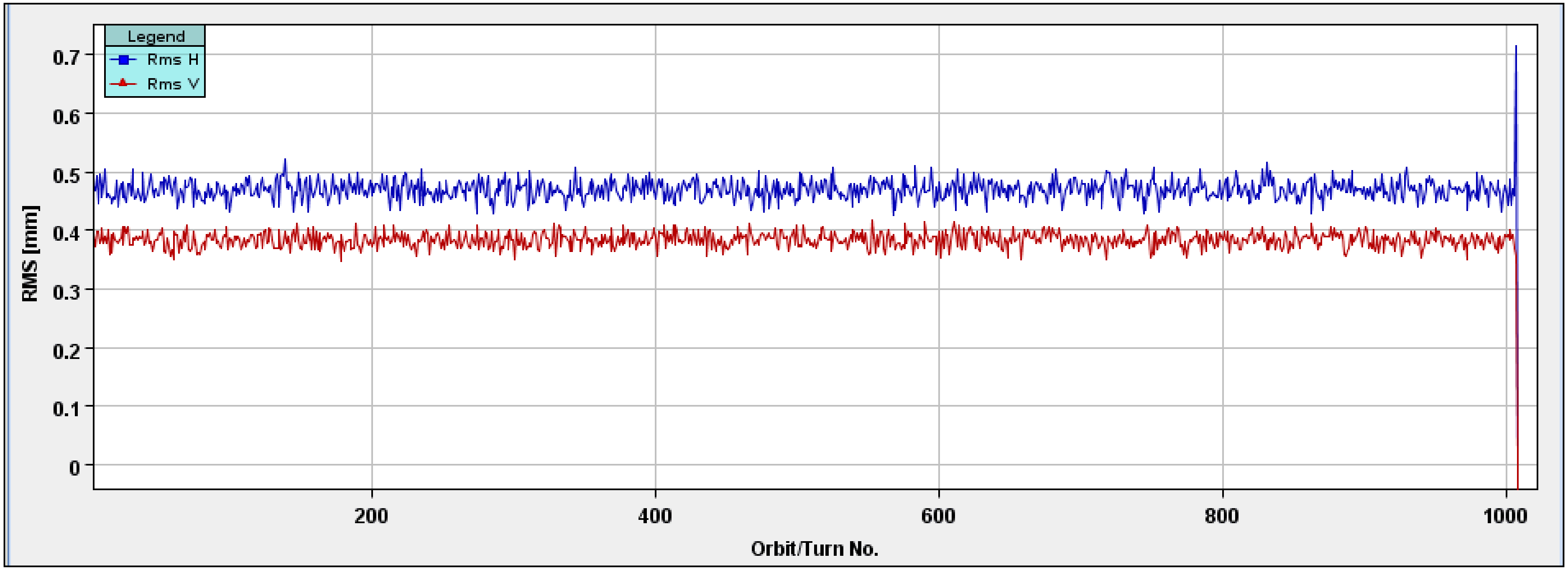



# Dispersion Resonance

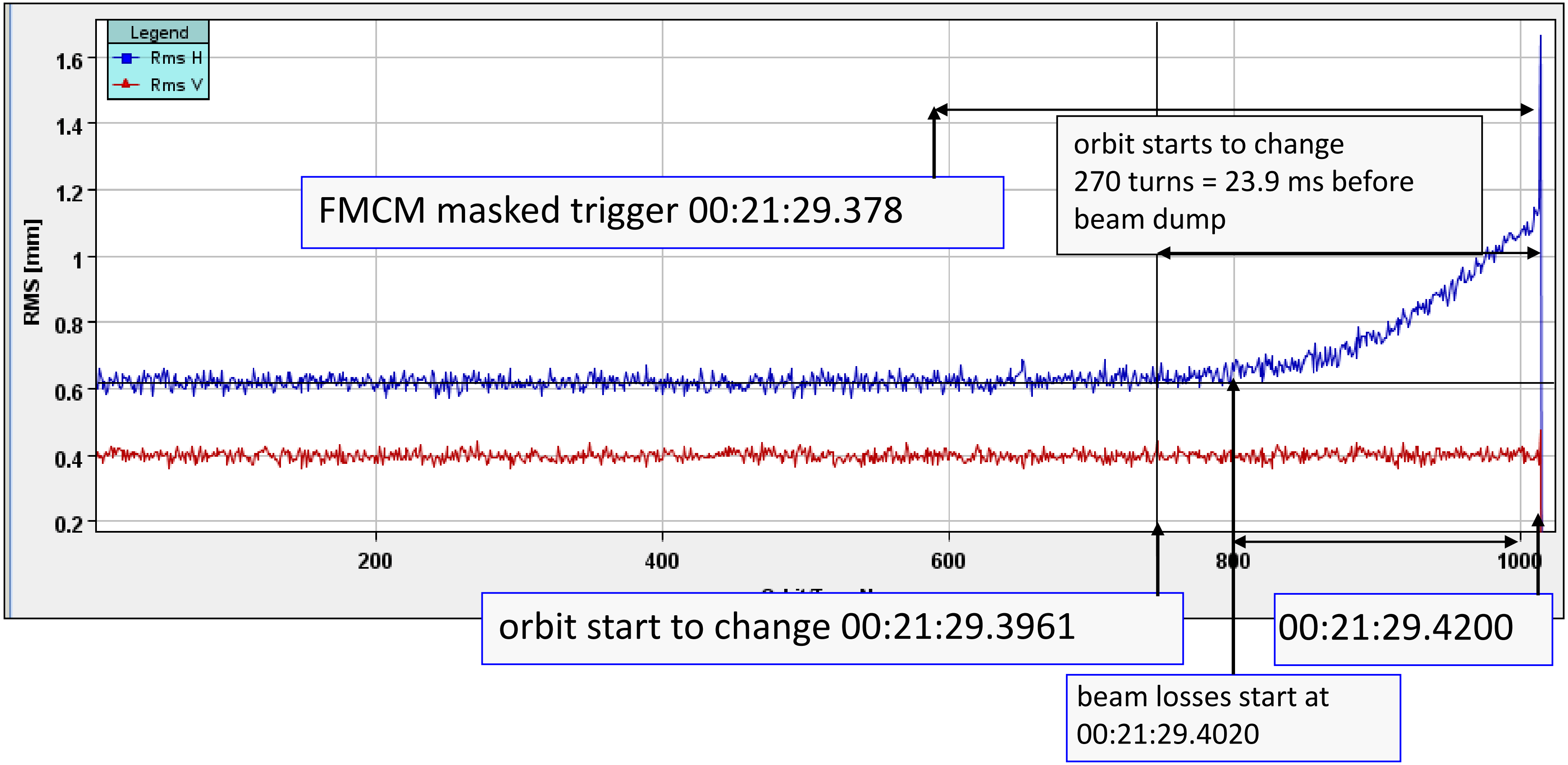


# Recombination Dipole RD1 OFF, FMCM active



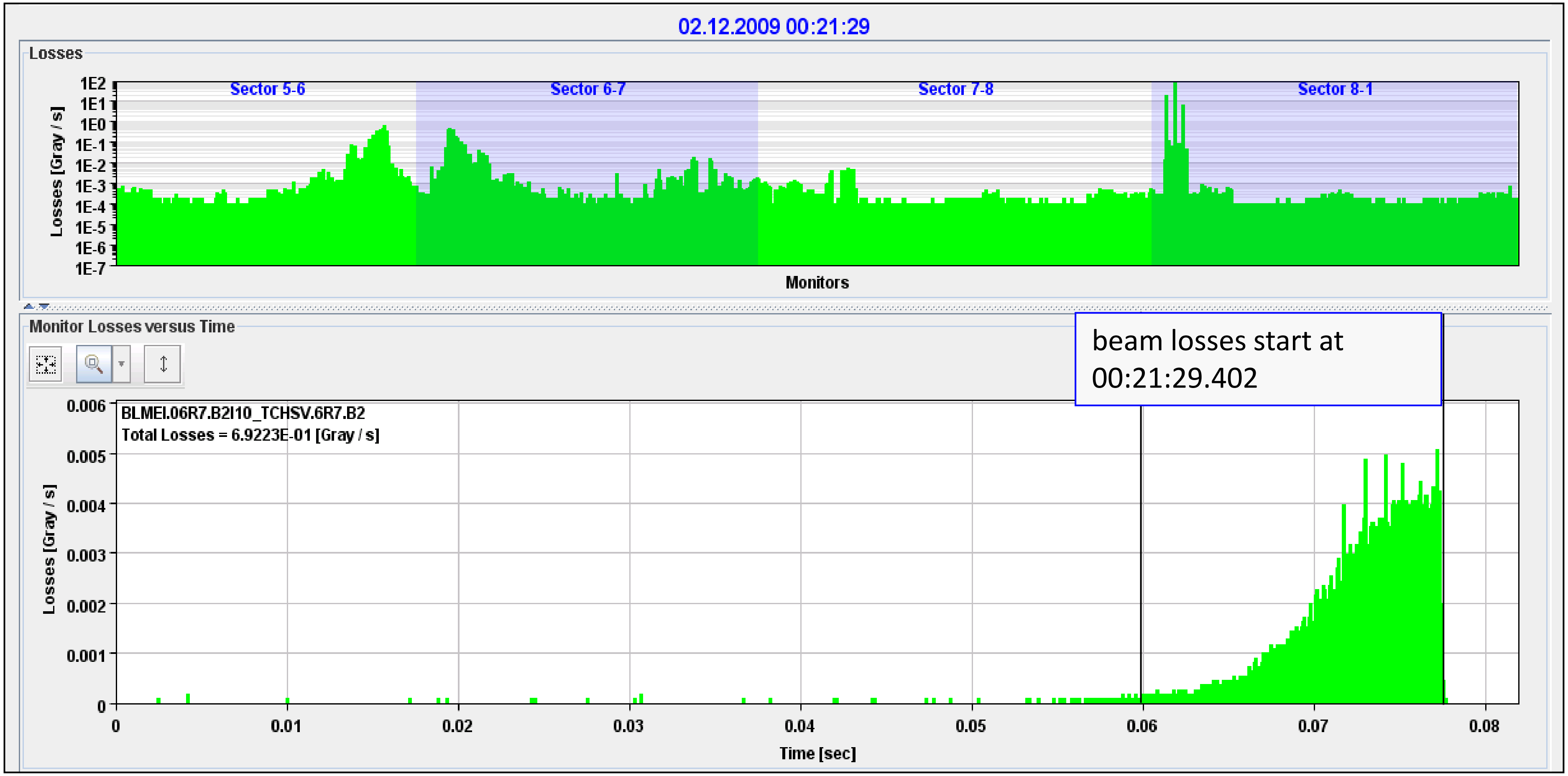
# Recombination Dipole RD1 OFF, FMCM masked (inactive)




courtesy of Rudiger Schmidt

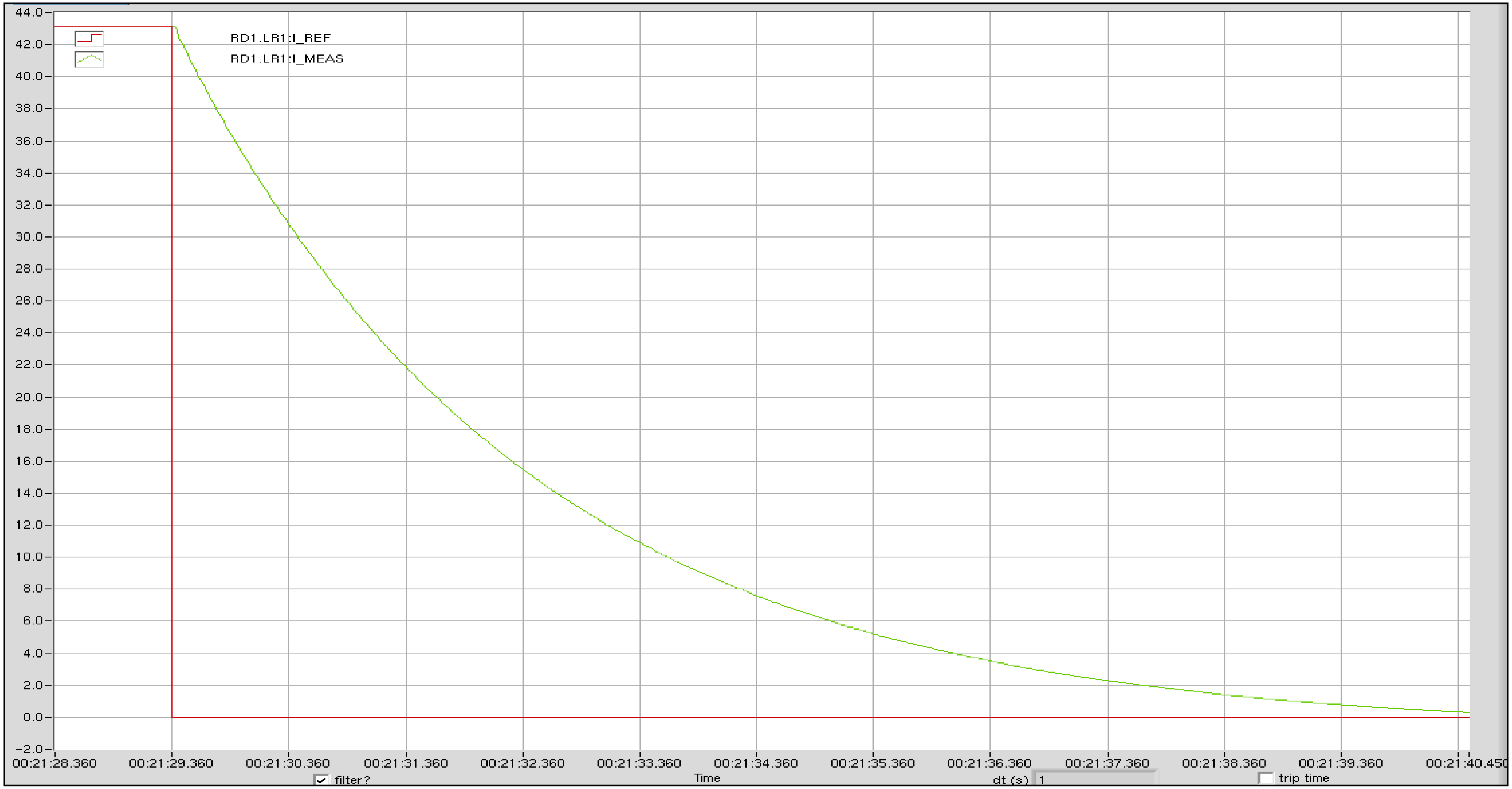
# Beam Losses

## Recombination Dipole RD1 OFF, FMCM masked (inactive)

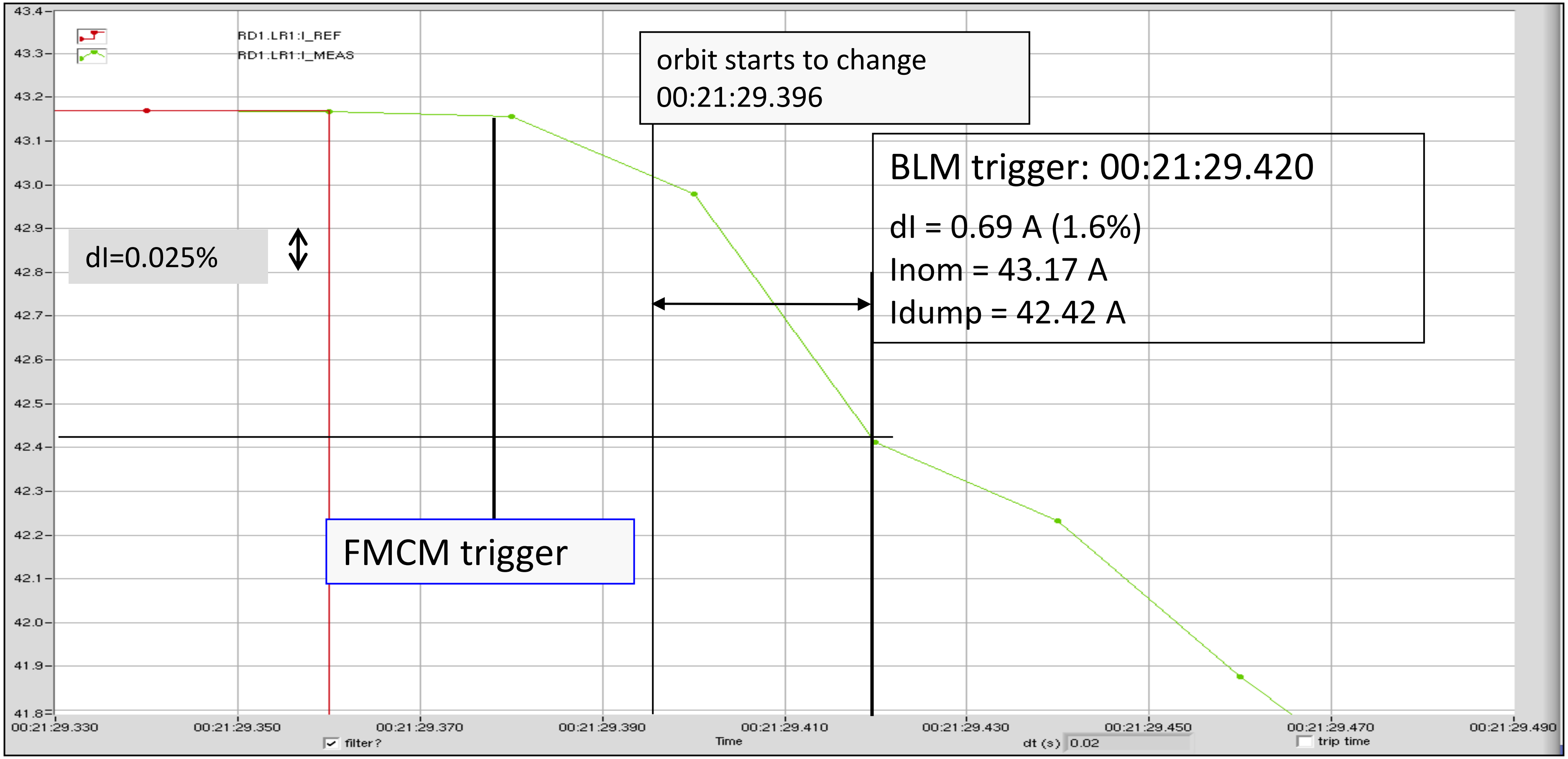



courtesy of Rudiger Schmidt

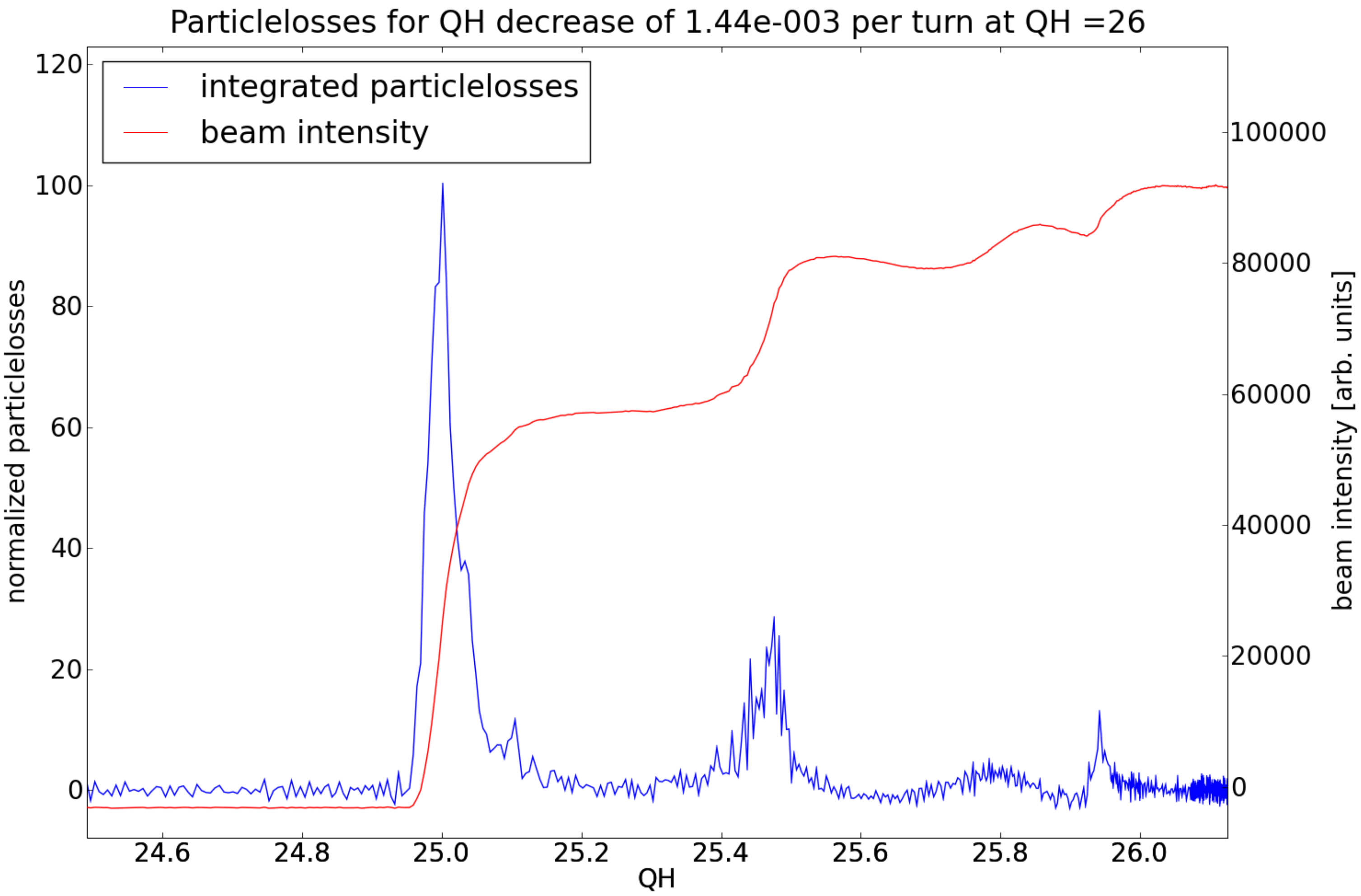
# Recombination Dipole RD1 OFF, FMCM masked (inactive)



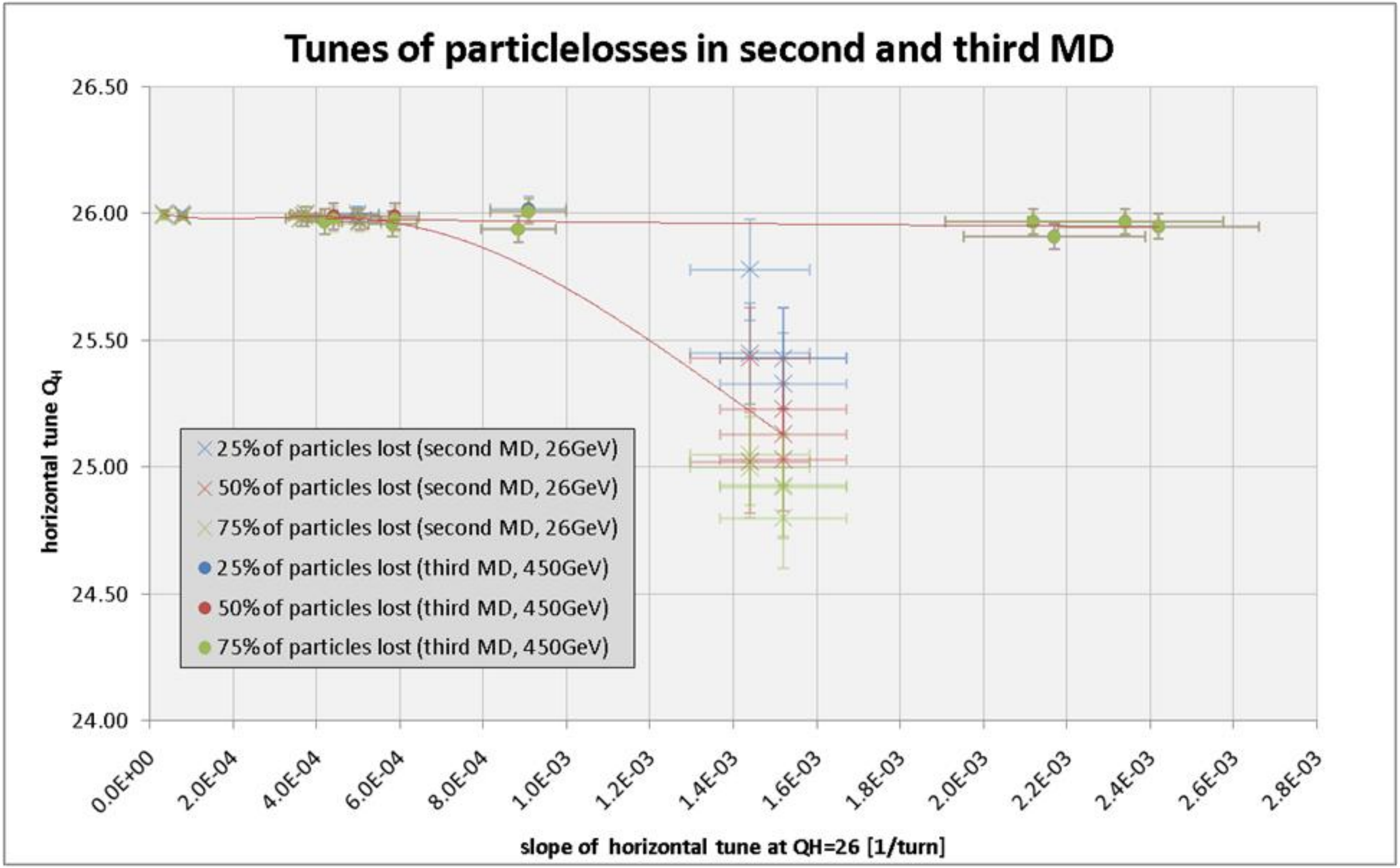
# Recombination Dipole RD1 OFF, FMCM masked (inactive)

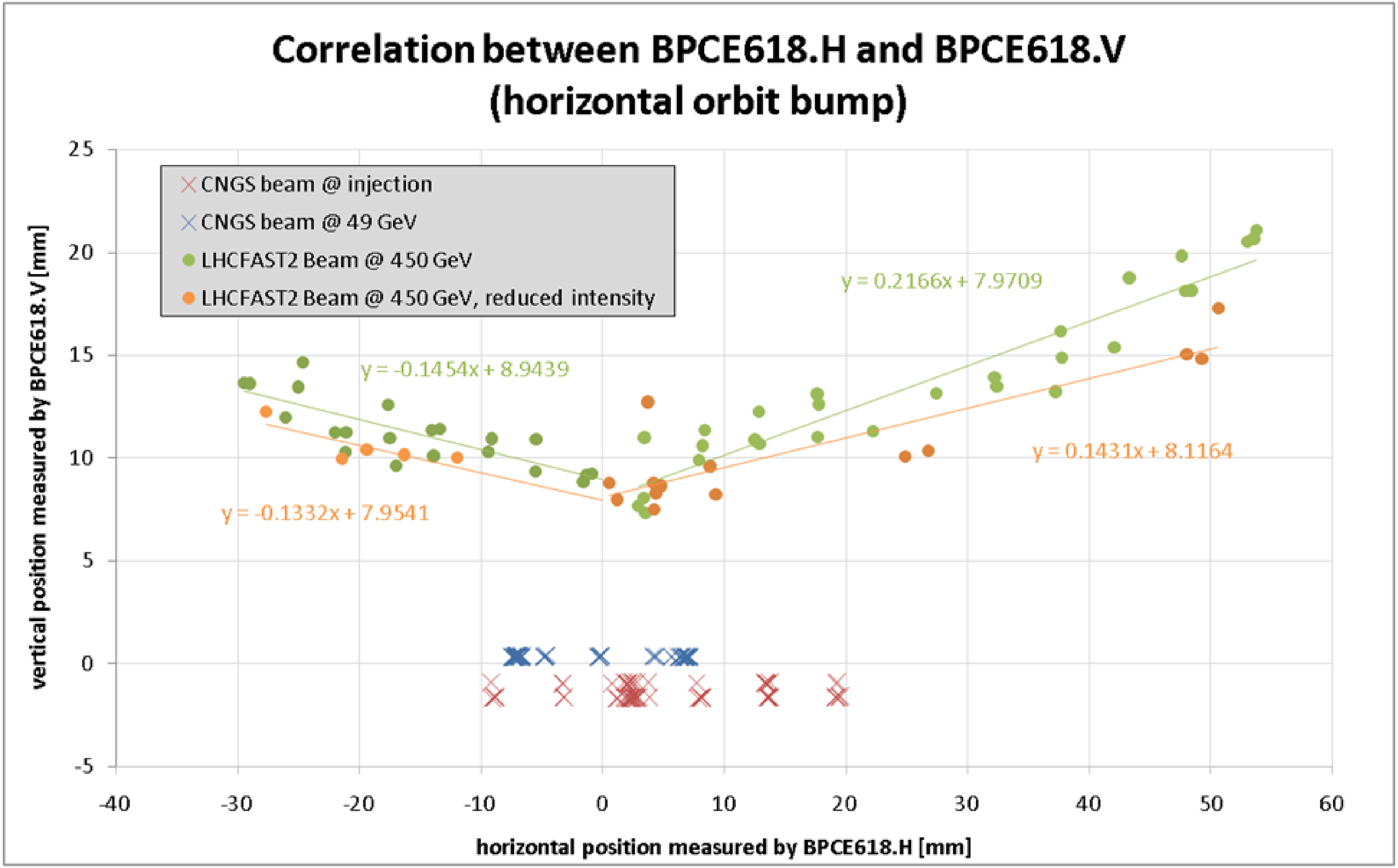



courtesy of Rudiger Schmidt



Particlelosses for QH decrease of 1.44e-003 per turn at QH =26
integrated particlelosses
beam intensity
normalized particlelosses
beam intensity [arb. units]
QH
120
100
80
60
40
20
0
100000
80000
60000
40000
20000
0
24.6
24.8
25.0
25.2
25.4
25.6
25.8
26.0


Tunes of particlelosses in second and third MD
26.50
26.00
25.50
25.00
24.50
24.00
horizontal tune $Q_H$
0.0E+00
2.0E-04
4.0E-04
6.0E-04
8.0E-04
1.0E-03
1.2E-03
1.4E-03
1.6E-03
1.8E-03
2.0E-03
2.2E-03
2.4E-03
2.6E-03
2.8E-03
slope of horizontal tune at QH=26 [1/turn]
25% of particles lost (second MD, 26GeV)
50% of particles lost (second MD, 26GeV)
75% of particles lost (second MD, 26GeV)
25% of particles lost (third MD, 450GeV)
50% of particles lost (third MD, 450GeV)
75% of particles lost (third MD, 450GeV)


Correlation between BPCE618.H and BPCE618.V
(horizontal orbit bump)
CNGS beam @ injection
CNGS beam @ 49 GeV
LHCFAST2 Beam @ 450 GeV
LHCFAST2 Beam @ 450 GeV, reduced intensity
y = 0.2166x + 7.9709
y = -0.1454x + 8.9439
y = 0.1431x + 8.1164
y = -0.1332x + 7.9541
vertical position measured by BPCE618.V [mm]
horizontal position measured by BPCE618.H [mm]