Hadron Accelerators

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2011 CERN-Fermilab HCP Summer School

Accelerator Beam Physics Group

Beams Department - CERN

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- LHC
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Reference Terms I

- Bunch
  - Packet of particles, confined in transverse x longitudinal volume.
- Intensity N
  - Number of protons per bunch.
- Lorentz factor (γ)
  - Measure of beam energy: $E = \gamma mc^2$
- Ramp:
  - Increase of beam energy after end of beam injection
- Stable beams:
  - Mode of data production for physics: Beams after end of squeeze, put into collision, every IP optimized for luminosity.

Reference Terms II

- Emittance ($\gamma\varepsilon$ or ε)
  - Transverse normalized emittance ($\gamma\varepsilon$): Invariant phase space area, ideally conserved with energy. Unit: m-rad or m.
  - Transverse emittance (ε): Phase space area, is reduced with energy ("adiabatic energy damping"). Unit: m-rad or m.
  - Both terms are a beam property: everywhere in the ring the same!
- Beta function (β):
  - Function to describe beam envelope. Describes focusing from quadrupoles. Unit: m
- Transverse beam sizes (σ_x, σ_y): unit m

$$\sigma_x = \sqrt{\varepsilon_x \cdot \beta_x}$$

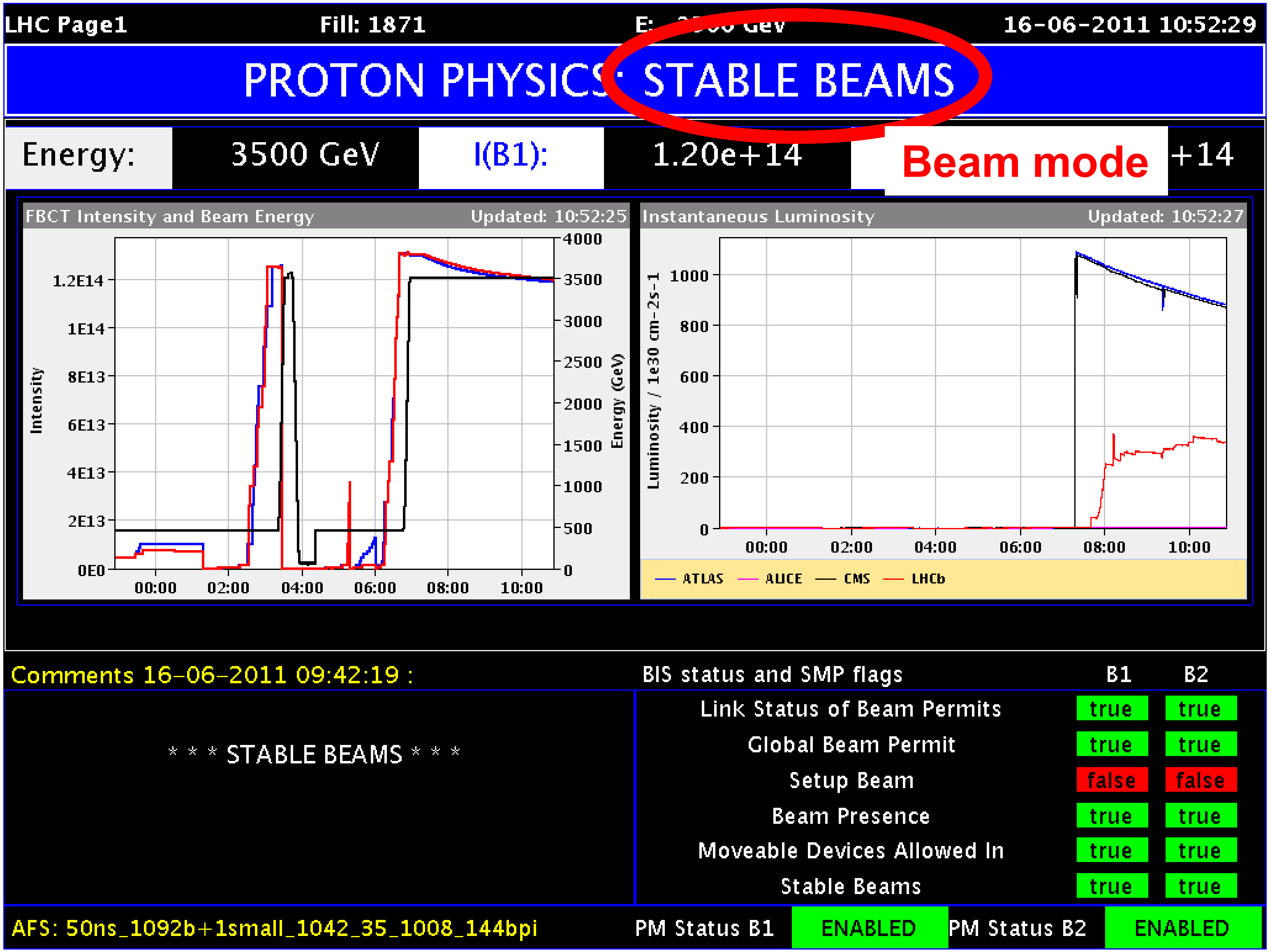
Reference Terms III

- IP beta function (β^*):
  - Beta function at the interaction point → used to reduce beam size in the IP and to increase lumiosity.
- IP transverse beam size (σ^*):

$$\sigma_x^* = \sqrt{\varepsilon_x \cdot \beta_x^*}$$

- Squeeze: Reduction of β^* before going into physics production.
- Example: $\gamma\varepsilon$ = 3.75 μm
  ε = 0.5 nm (@7 TeV)
  β^* = 0.55 m
  $\sigma^* = (\beta^* \varepsilon)^{1/2}$ = 17 μm
-

Understanding LHC Page 1



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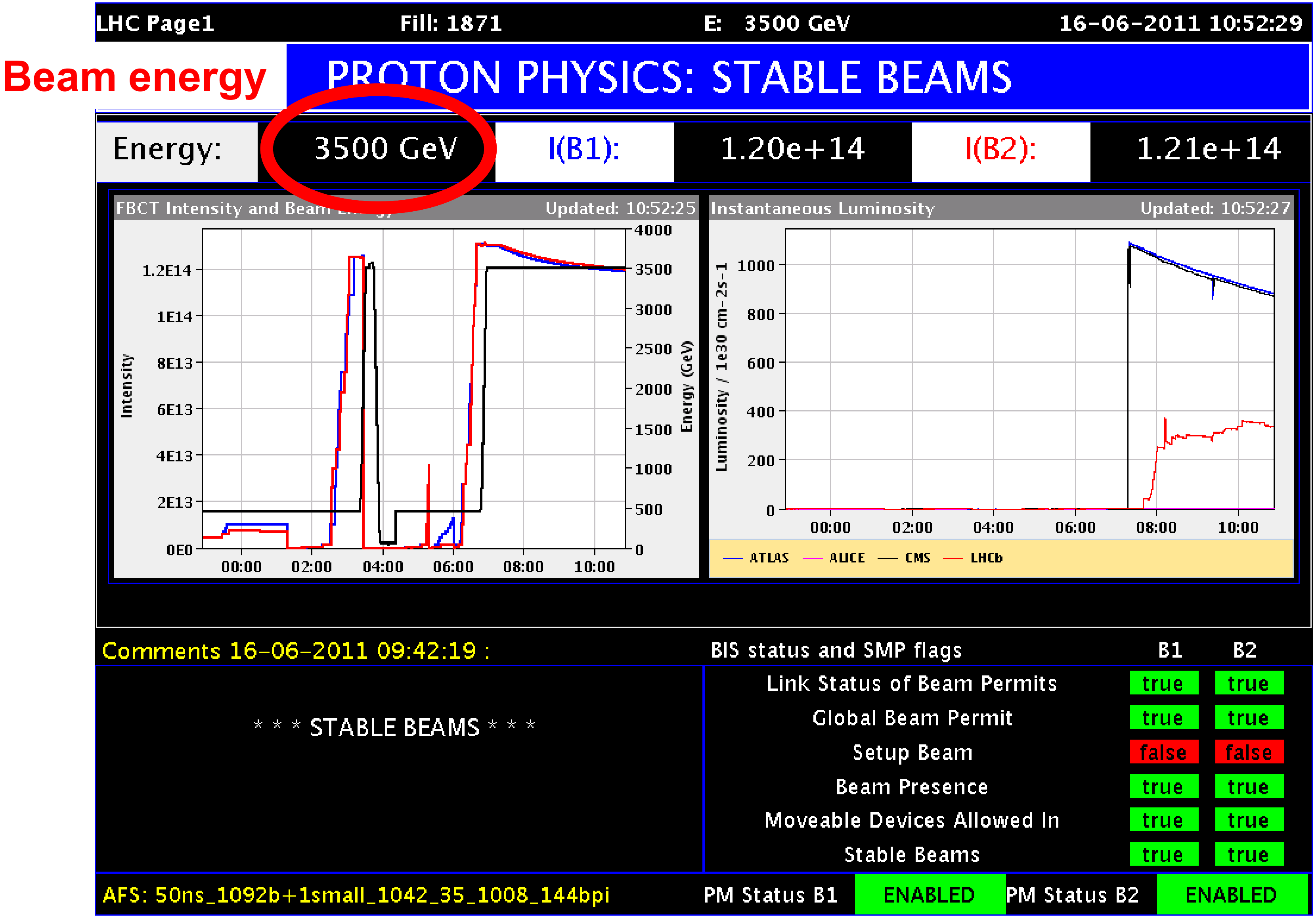

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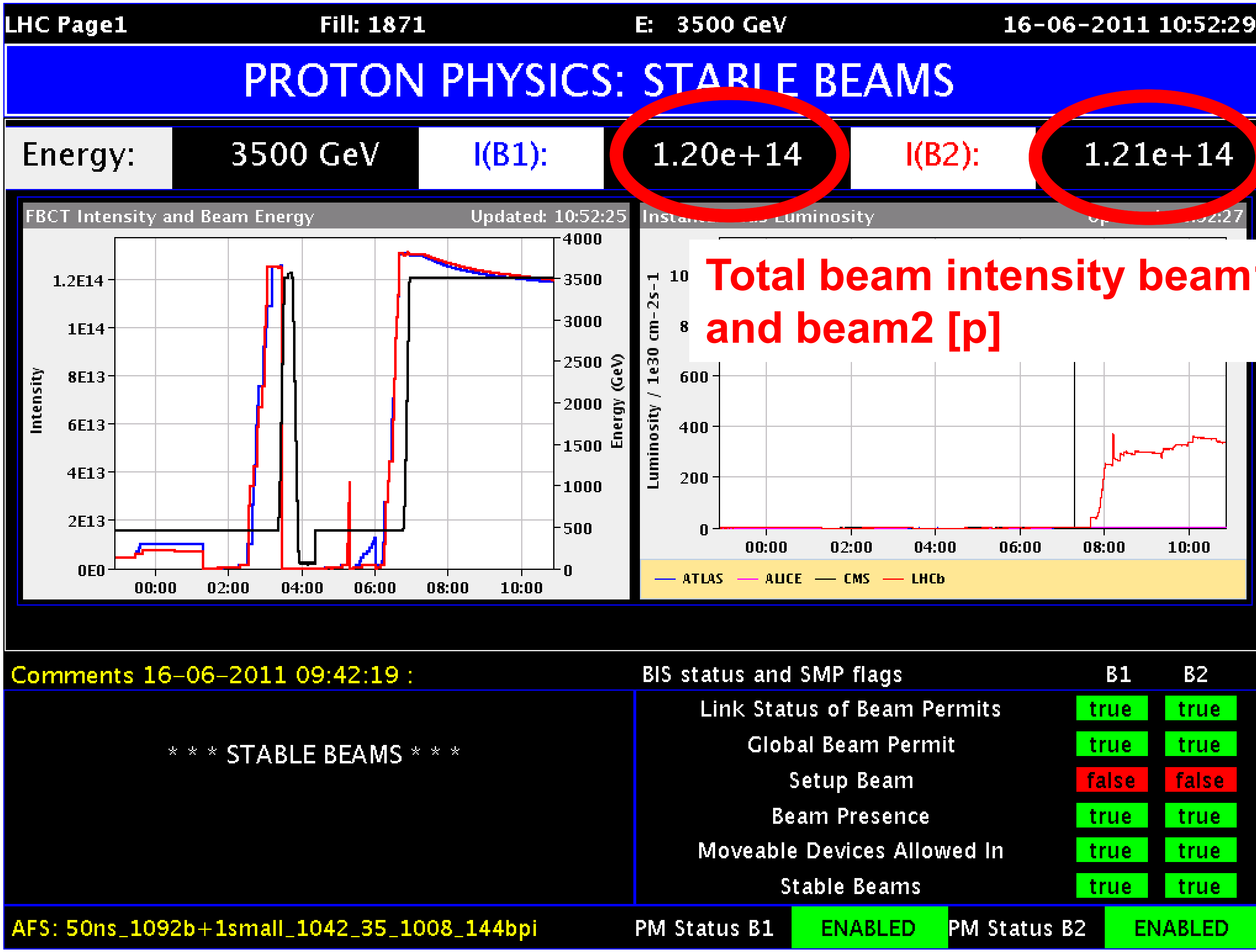

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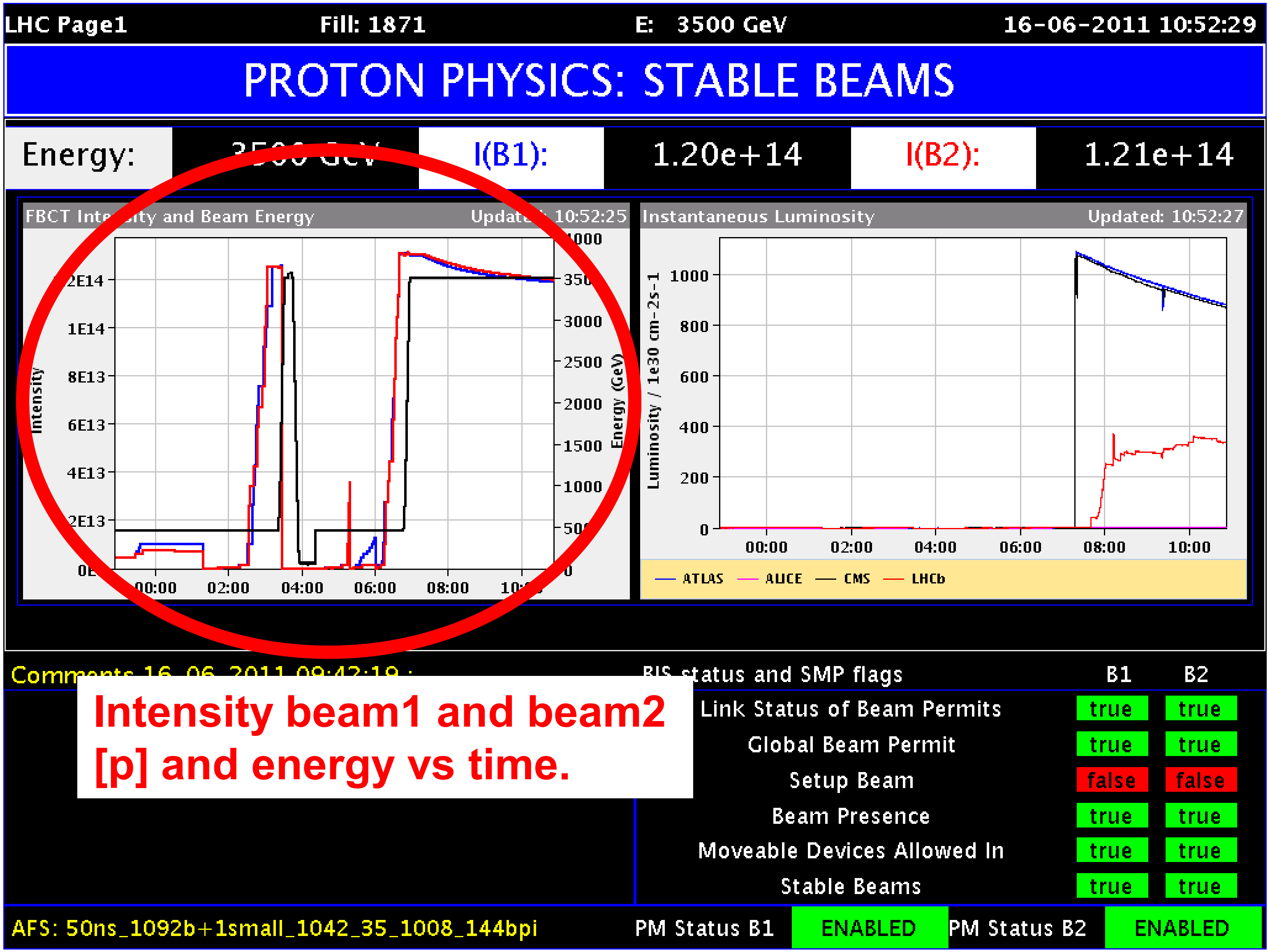

Intensity beam1 and beam2 [p] and energy vs time.

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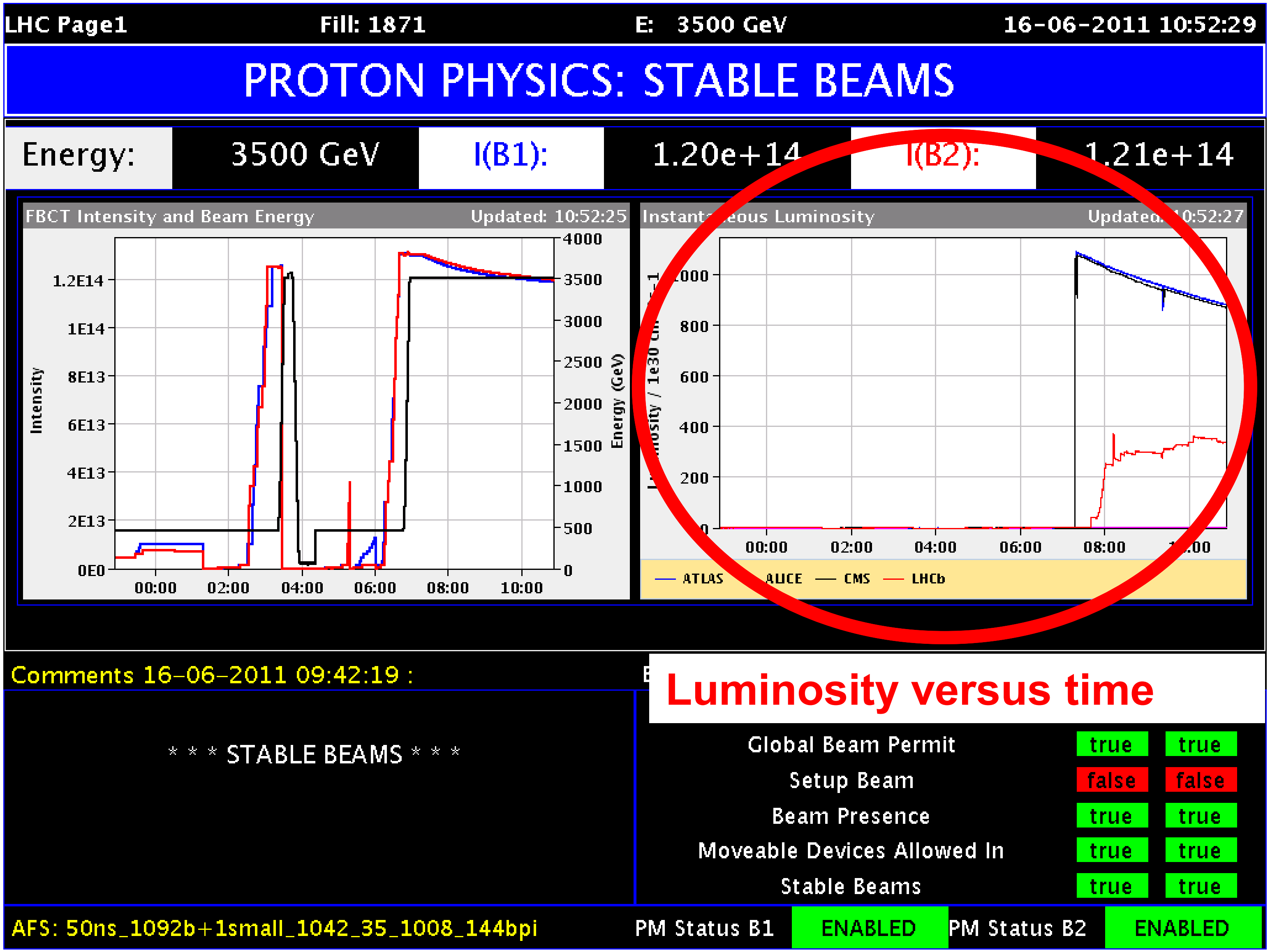

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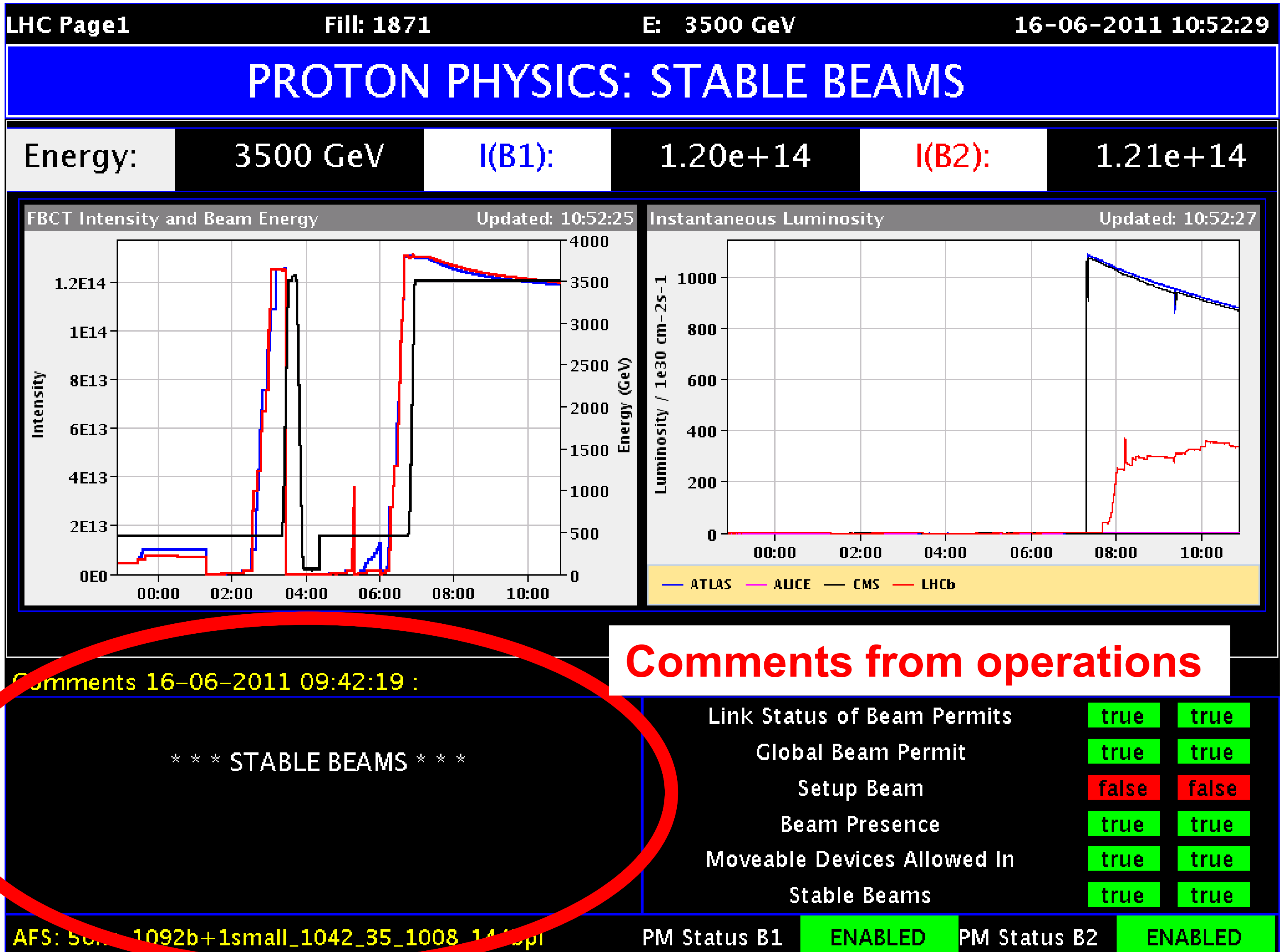

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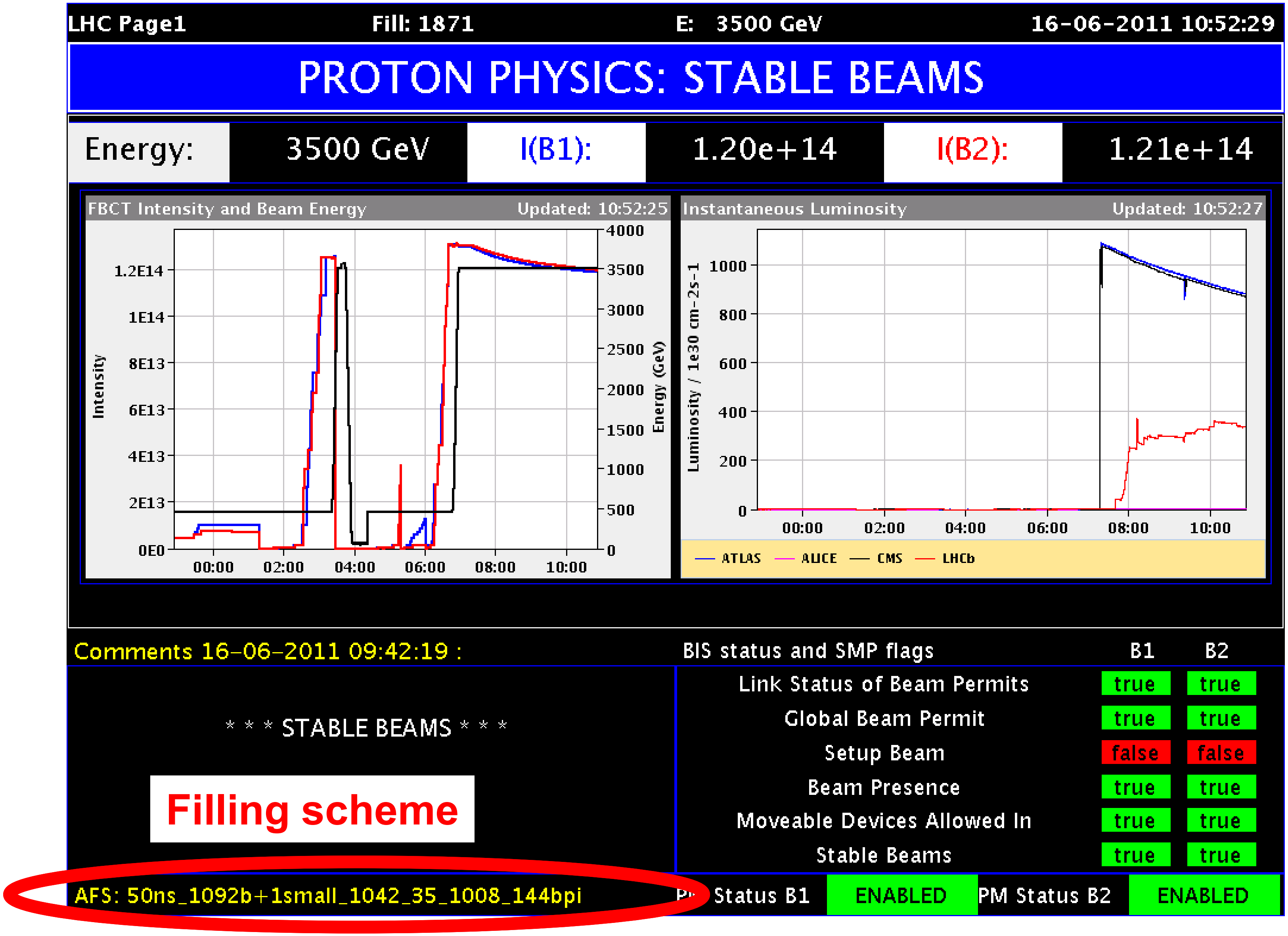

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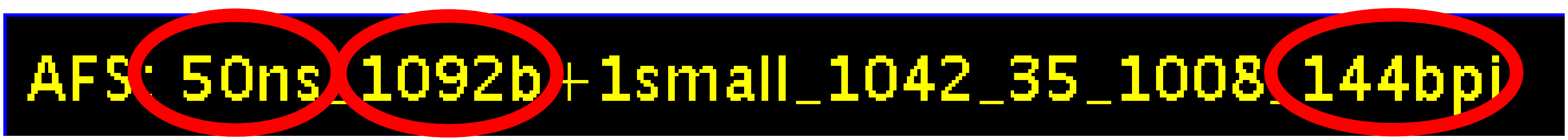
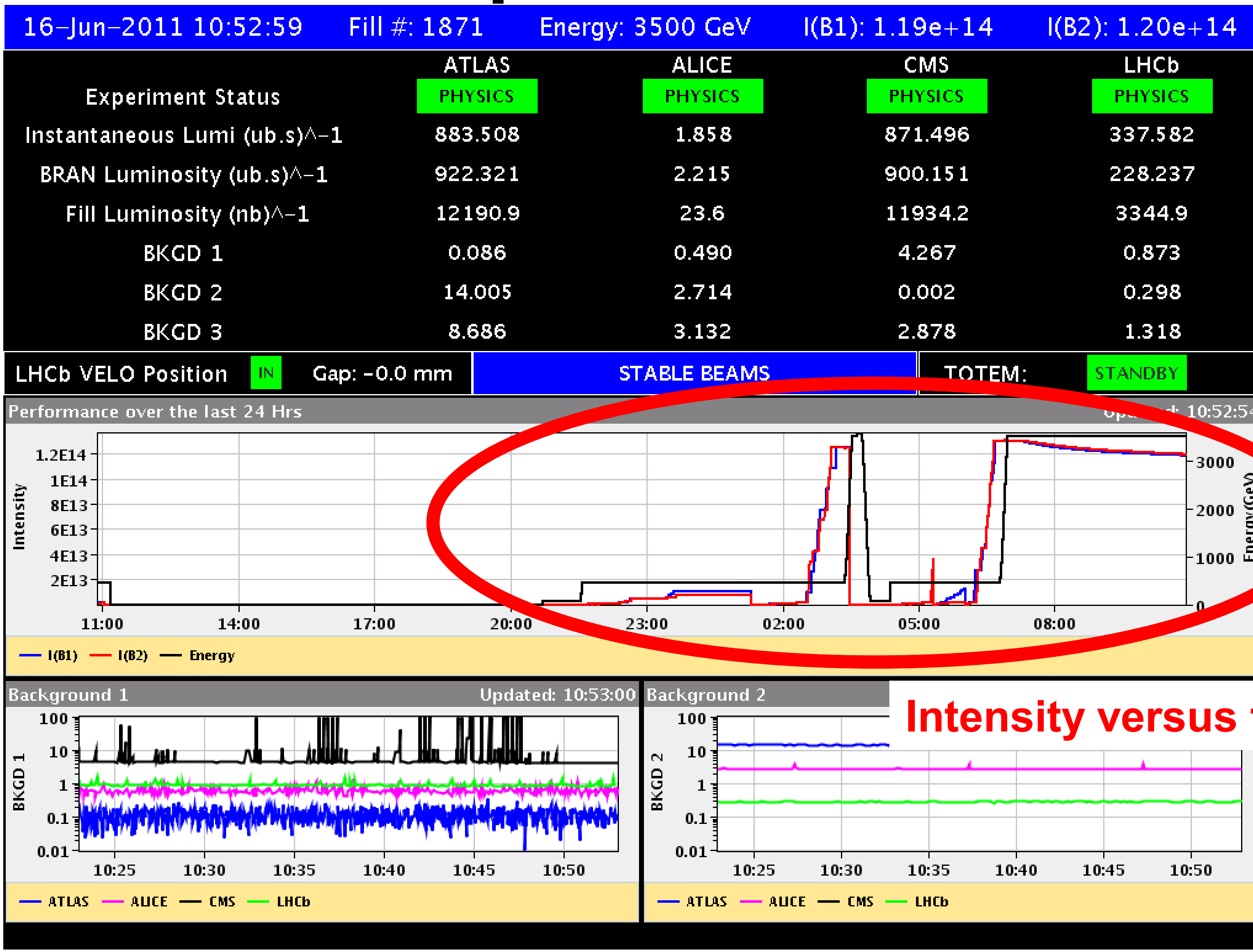
Bunches per injection

Bunch spacing



Number of bunches

Understanding LHC Page 1 Operations



Understanding LHC Dashboard

Stored energy

Understanding LHC Dashboard

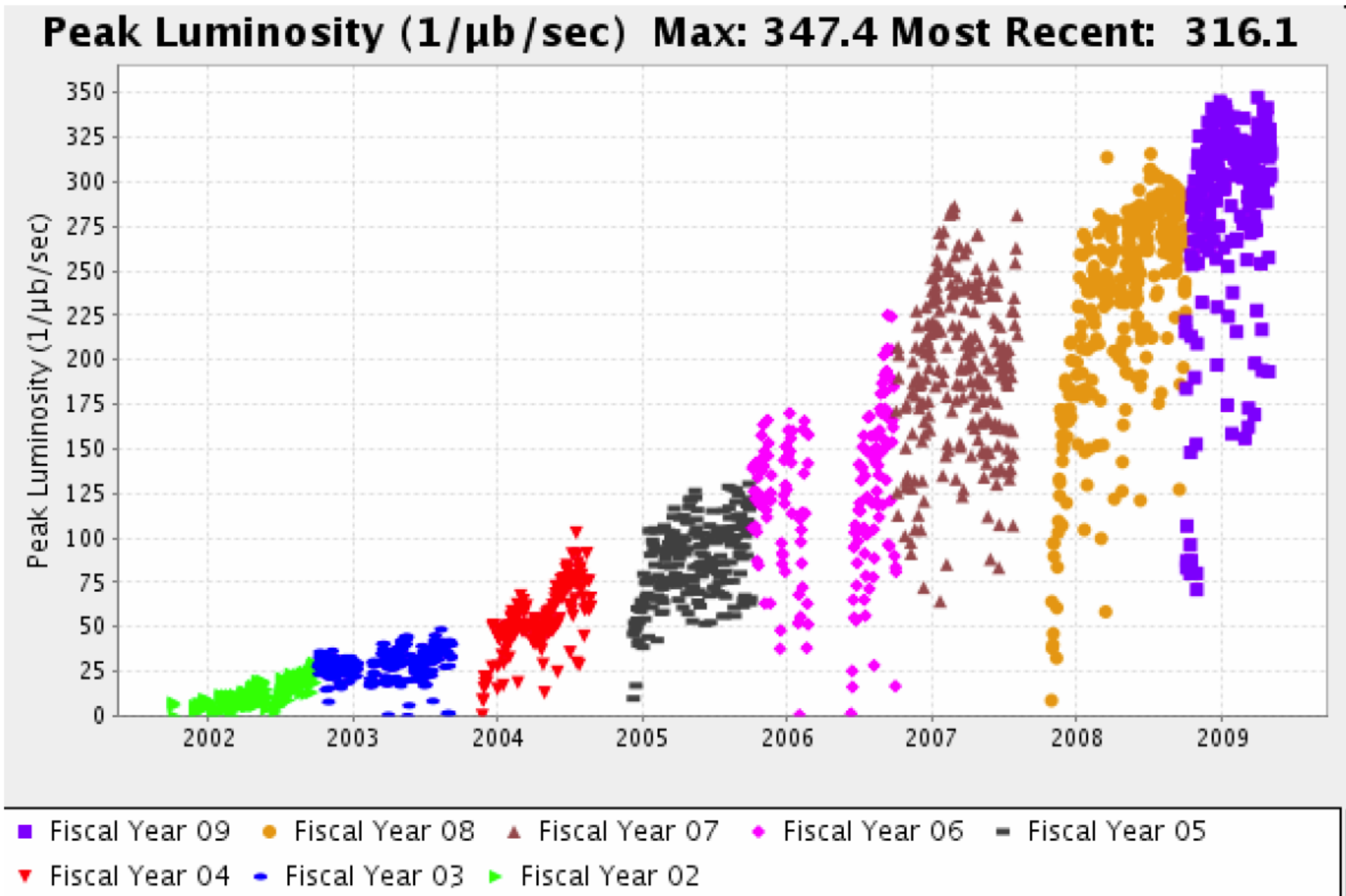
Luminosity [E30 s-1 cm-2] [nb-1]

	ATLAS	ALICE	CMS	LHCb
	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous	882.4	1.9	870.2	336.2
Integrated fill	12245.0	23.6	12020.5	3378.4
Integrated/h	3227.0	6.8	3154.9	1217.7
beta * [m]	1.6	10.0	1.5	3.0

Beta star

Tevatron Luminosity

Peak Luminosity of the Tevatron



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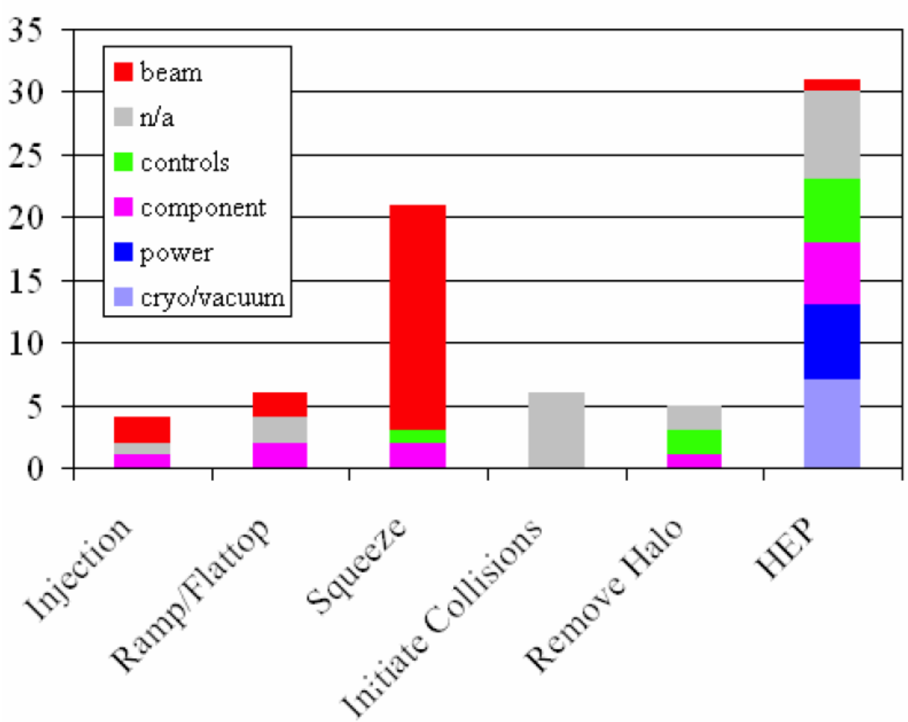
Tevatron quenches: ~3 per month

Categorization of Quenches

- Total quenches since Oct. 2007 - 73
- Distribution
  - Injection: 4
  - Ramp/Flattop: 6
  - Squeeze: 21
  - Initiate Collisions: 6
  - Remove Halo: 5
  - HEP: 31
- Most quenches in squeeze (18) were caused by a combination of beam-beam and orbit issues.
- Only 1 beam related quench in HEP



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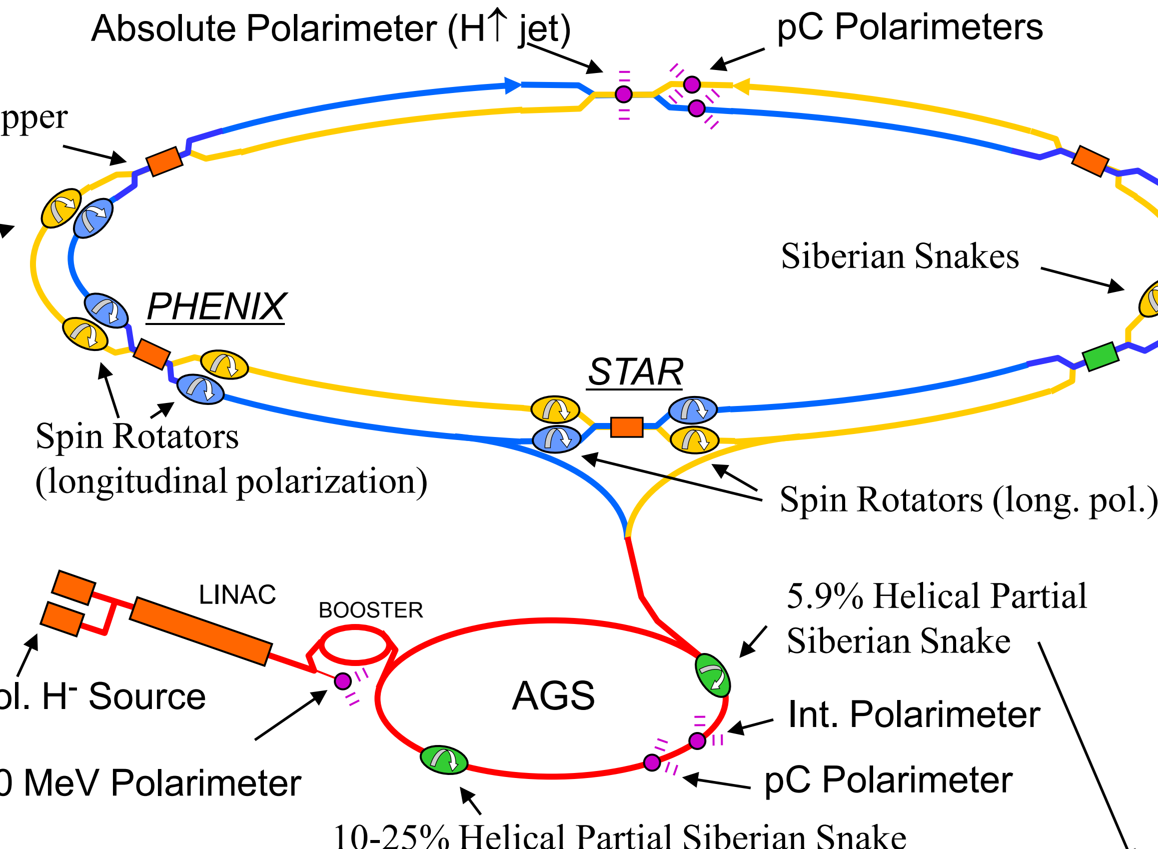
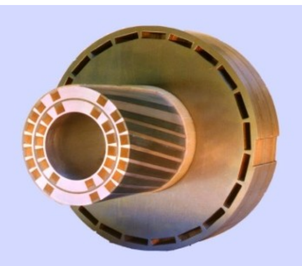
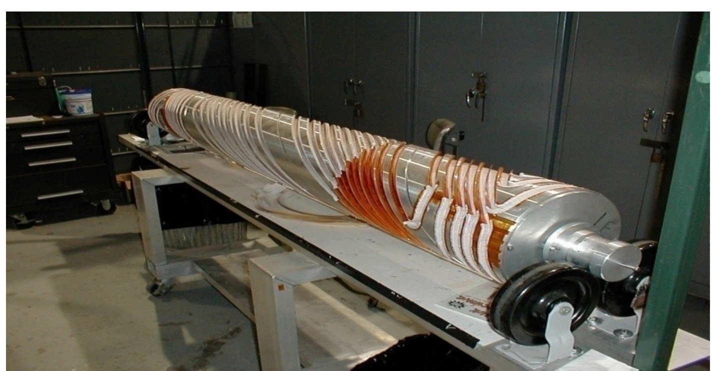
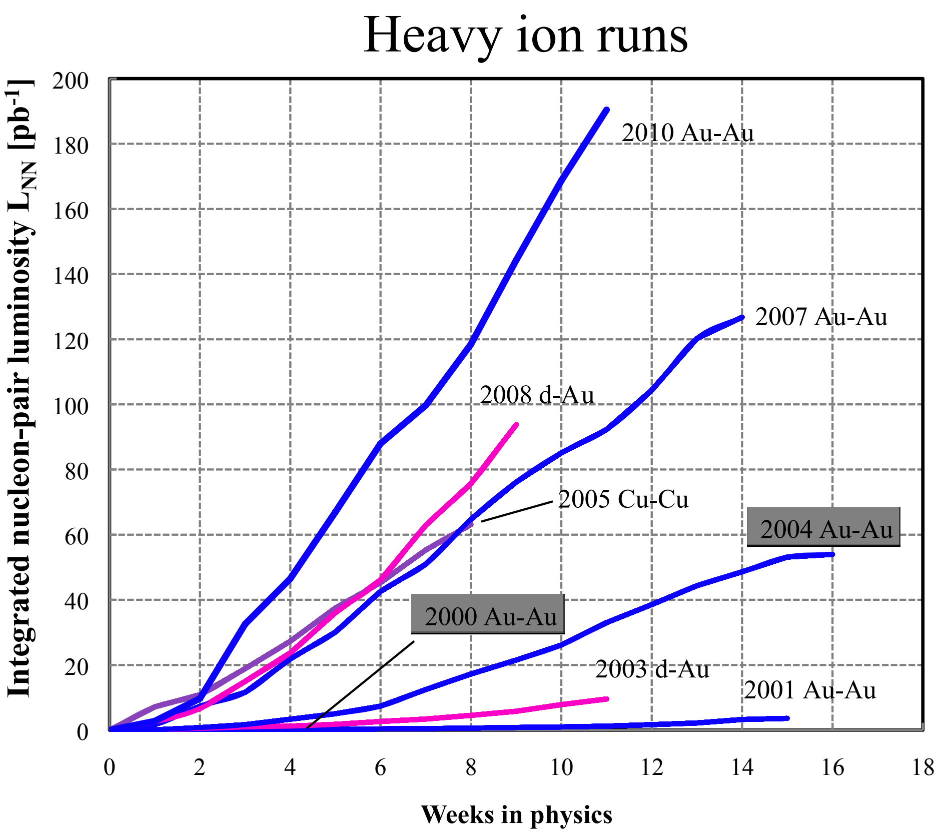
RHIC – First Polarized Hadron Collider

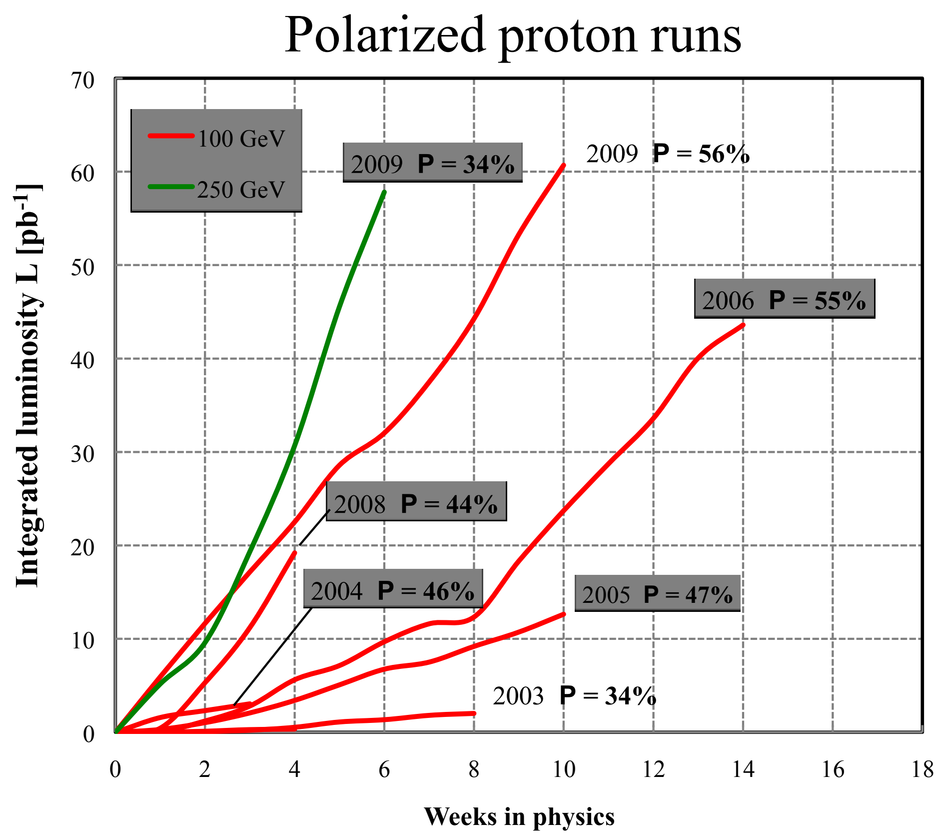






RHIC: Int. Luminosity and Polarization





Nucleon-pair luminosity: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.

Luminosity and Polarization Goals

Parameter	unit	Achieved	With full stoch. cooling	
Au-Au operation		**2010**	**≥ 2012**	
Energy	GeV/nucleon	100	100	
No of bunches	…	111	111	
Bunch intensity	10^9	1.1	1.0	
Average Luminosity	**10^{26} cm^{-2} s^{-1}**	**20**	**40**	
p↑- p↑ operation		**2009**	**≥ 2011/12**	**≥ 2014**
Energy	GeV	100 / 250	100 / 250	250
No of bunches	…	109	109	109
Bunch intensity	10^{11}	1.3 / 1.1	1.3 / 1.5	2.0
Average Luminosity	**10^{30} cm^{-2} s^{-1}**	**24 / 55**	**30 / 150**	**300**
Polarization	**%**	**56 / 34**	**70**	**70**

RHIC Facility Upgrade Plans

- EBIS (≥ 2011) (low maintenance linac-based pre-injector; all species including U and polarized ^{3}He)

- RHIC luminosity upgrade (≥ 2012):
  [Au-Au: 40 × 10^{26} cm^{-2} s^{-1}; 500 GeV p-p: 1.5 × 10^{32} cm^{-2} s^{-1}]
  - 0.5 m β^* for Au – Au and p↑ – p↑ operation
  - Stochastic cooling of Au beams and 56 MHz storage rf system in RHIC

- Further luminosity upgrade for p↑ – p↑ operation (≥ 2014):
  [500 GeV p-p: ~ 3 × 10^{32} cm^{-2} s^{-1}]
  - 0.3 m β^* for 500 GeV p↑ – p↑ operation (× 1.6)
  - Electron lens in RHIC for head-on beam-beam compensation (× 2)

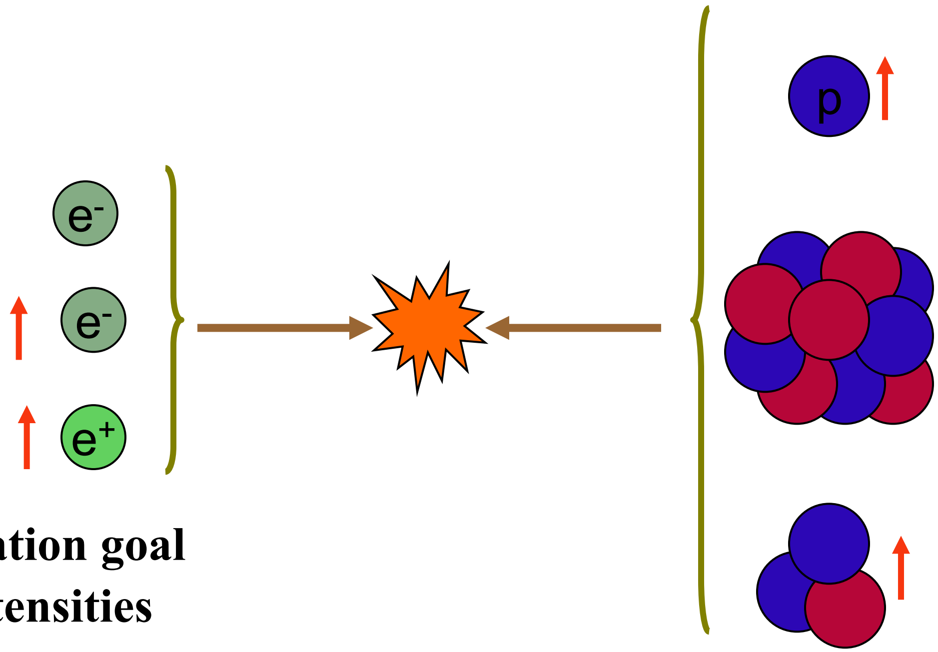
- eRHIC: high luminosity (10^{33} – 10^{34} cm^{-2} s^{-1}) eA and pol. ep collider using 5 GeV and later 10 - 30 GeV electron driver, based on an Energy Recovering Linac (ERL), and strong cooling of hadron beams (~ 2020)
  Exploring gluons at extreme density!

eRHIC

Electron accelerator

RHIC

Unpolarized and
polarized leptons
5 – 30 GeV



Polarized protons
25 – 250 (325) GeV

Heavy ions (Au, U)
20 – 100 (130) GeV/n

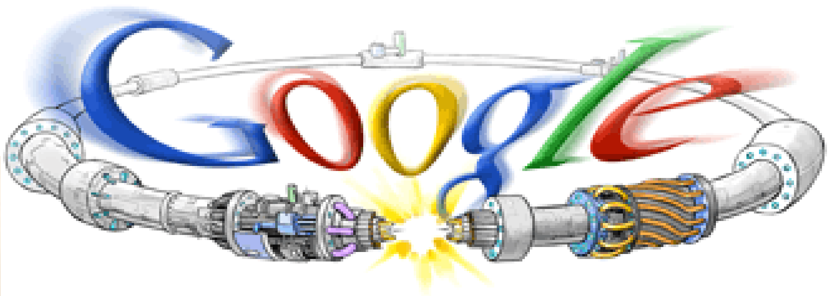
Polarized light ions
d,He^3: 125,167 GeV/n

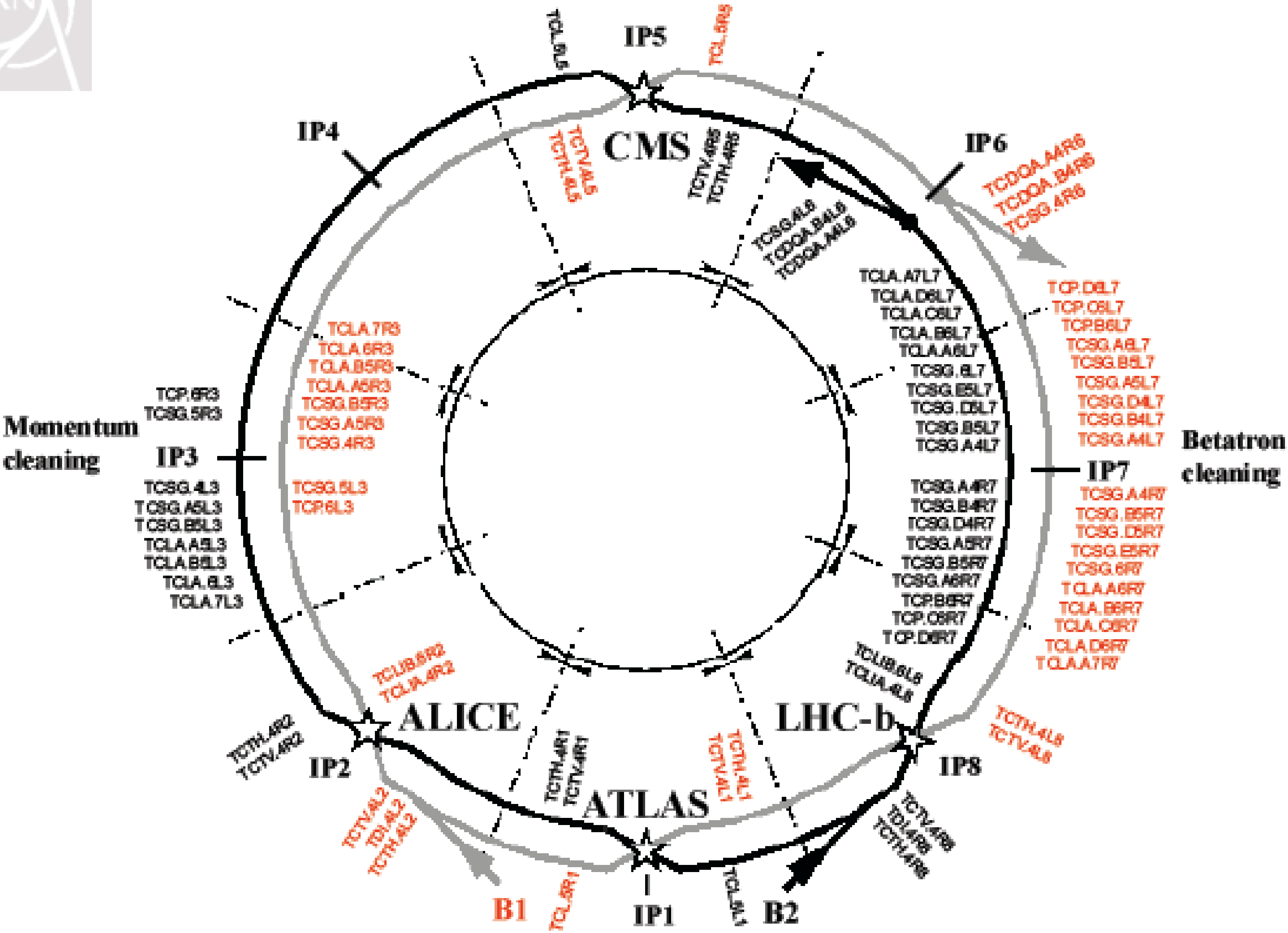
70% beam polarization goal
Positrons at low intensities

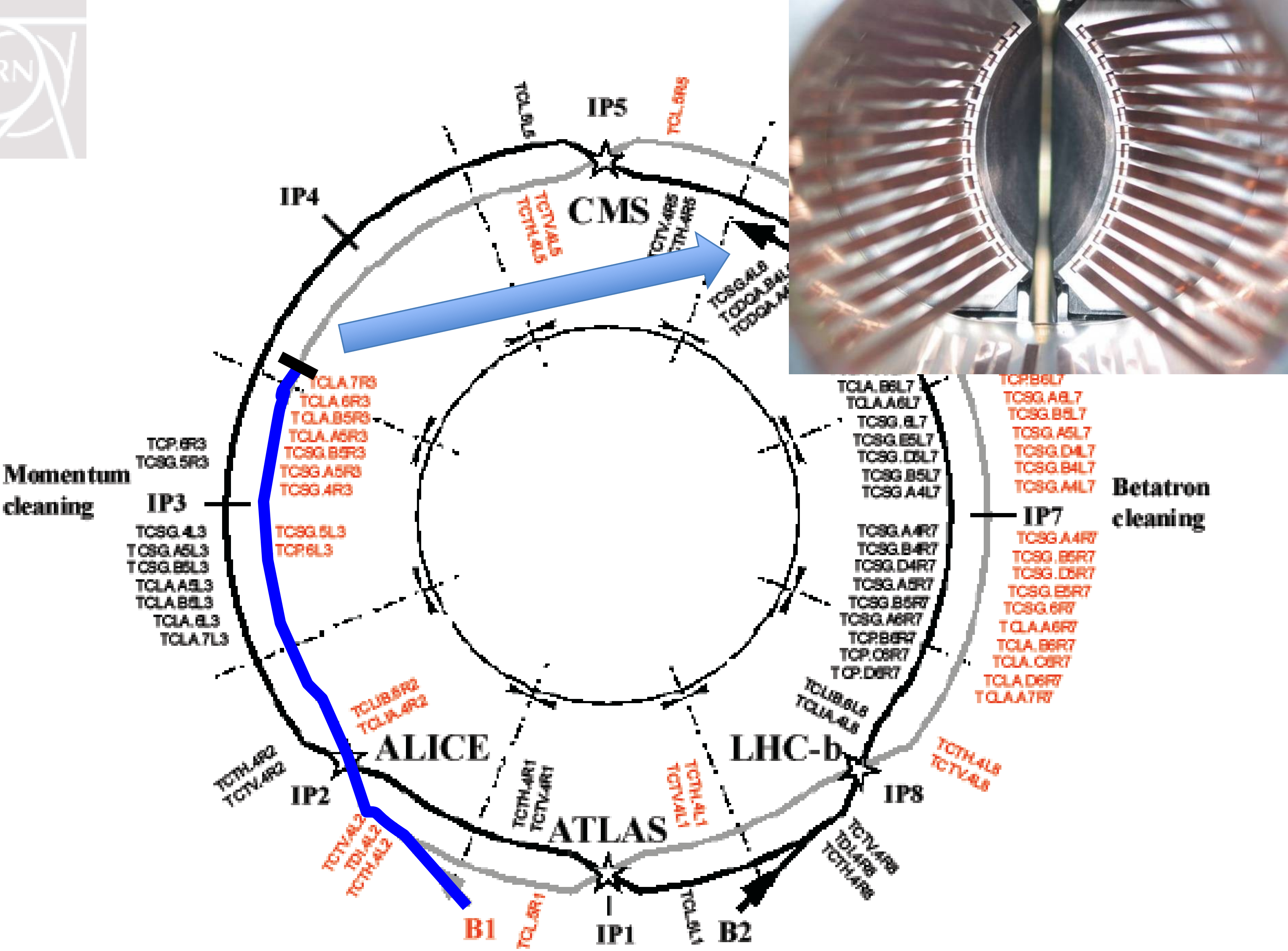
Center mass energy range: 15 – 200 GeV

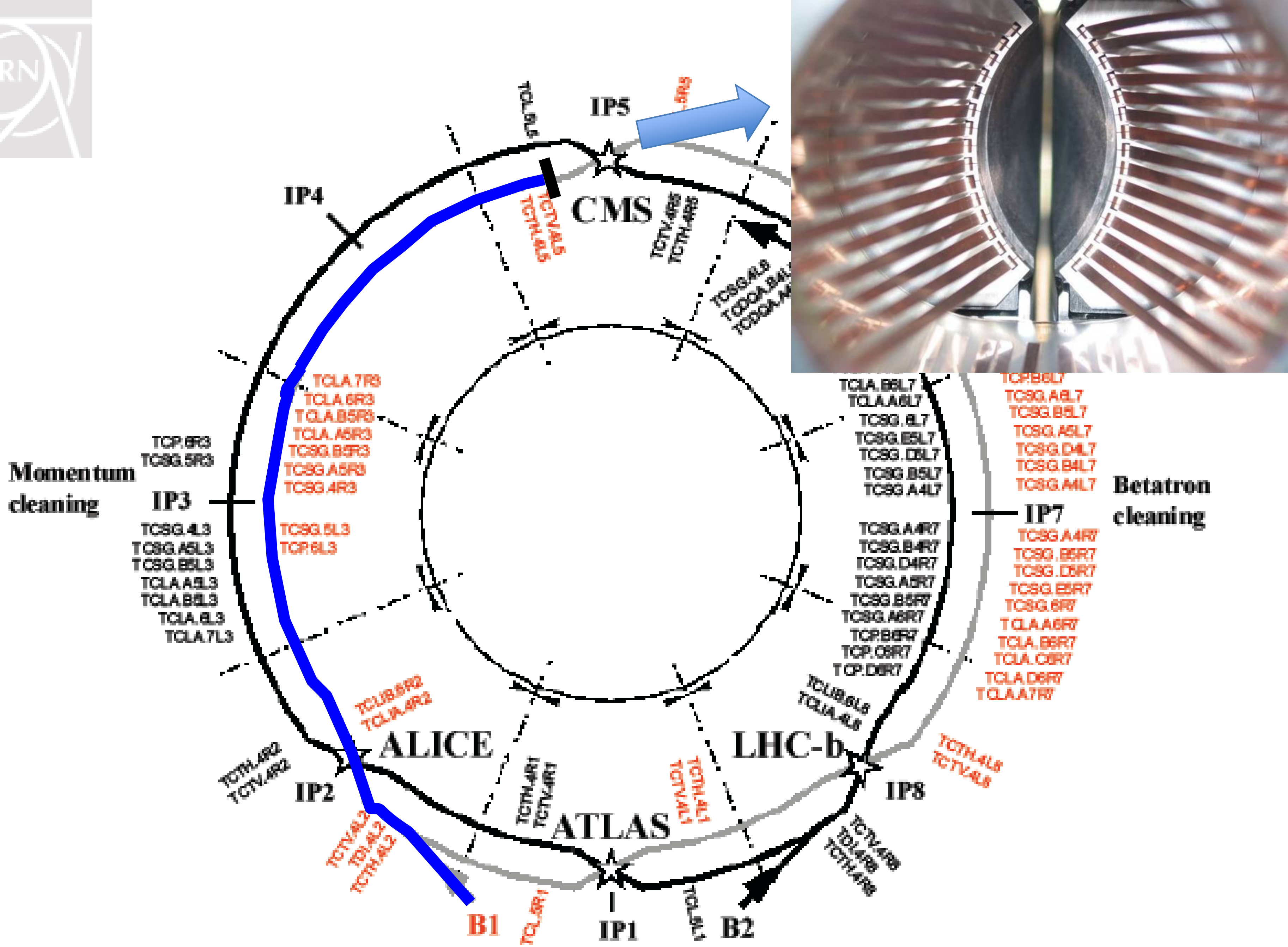
LHC Commissioning / Operation

First Beam Day: 10 Sep 2008

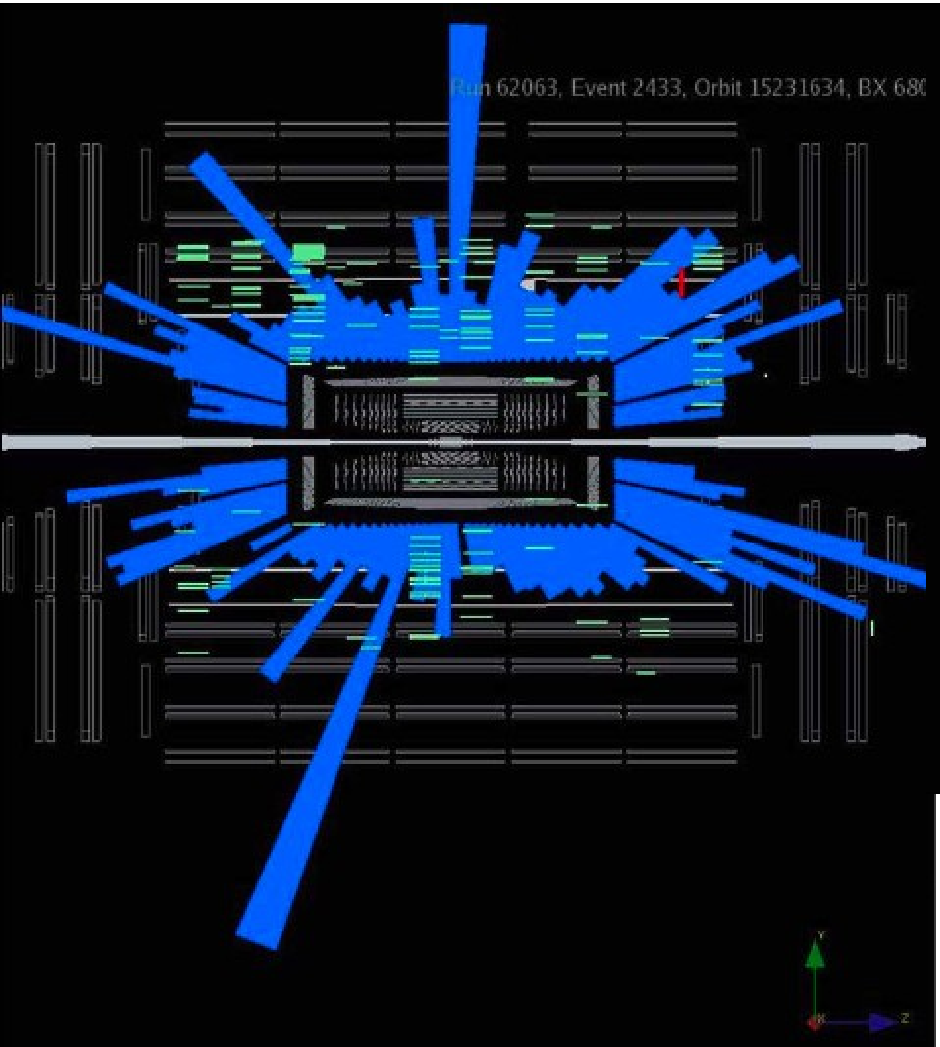



IP1
IP2
IP3
IP4
IP5
IP6
IP7
IP8
CMS
ALICE
ATLAS
LHC-b
Momentum cleaning
Betatron cleaning
B1
B2

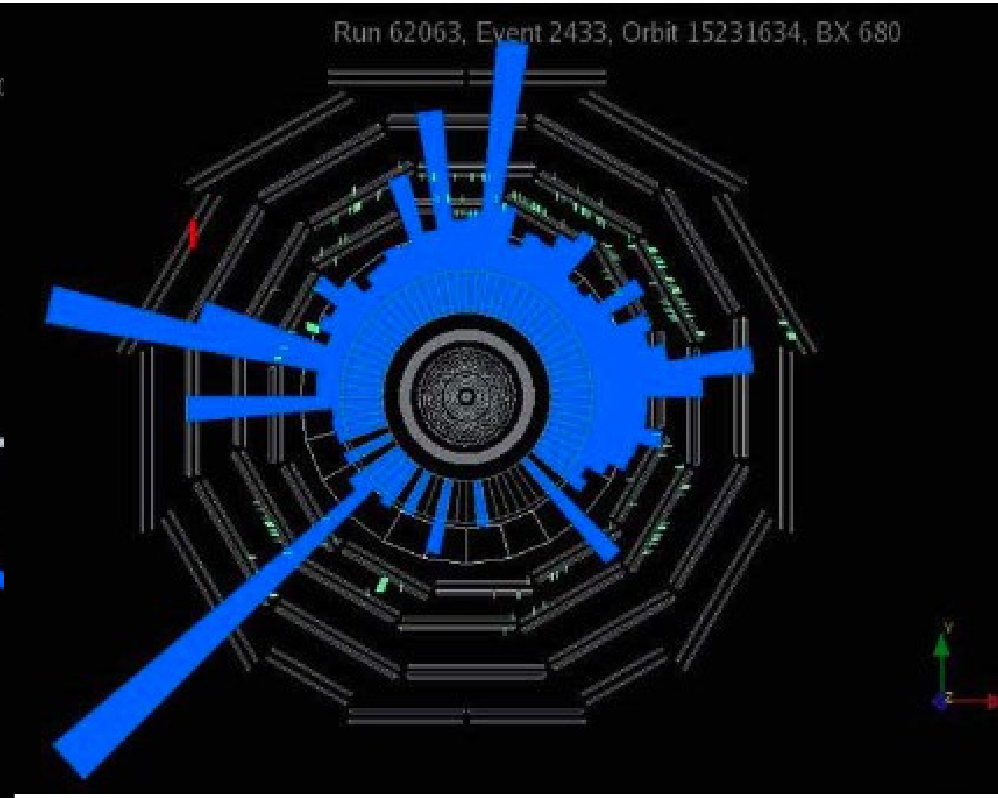

IP5
IP4
CMS
Momentum cleaning
IP3
TCLA.7R3
TCLA.6R3
TCLA.B5R3
TCLA.A5R3
TCSG.B5R3
TCSG.A5R3
TCSG.4R3
TCP.6R3
TCSG.5R3
TCSG.4L3
TCSG.A5L3
TCSG.B5L3
TCLA.A5L3
TCLA.B5L3
TCLA.6L3
TCLA.7L3
TCSG.5L3
TCP.6L3
TCLA.B6L7
TCLA.A6L7
TCSG.6L7
TCSG.E5L7
TCSG.D5L7
TCSG.B5L7
TCSG.A4L7
TCSG.A4R7
TCSG.B4R7
TCSG.D4R7
TCSG.A5R7
TCSG.B5R7
TCSG.A6R7
TCP.B6R7
TCP.C6R7
TCP.D6R7
TCSG.A6L7
TCSG.A5L7
TCSG.D4L7
TCSG.B4L7
TCSG.D5R7
TCSG.E5R7
TCSG.6R7
TCLA.A6R7
TCLA.B6R7
TCLA.C6R7
TCLA.D6R7
TCLA.A7R7
IP7
Betatron cleaning
ALICE
IP2
ATLAS
IP1
LHC-b
IP8
B1
B2


IP5
CMS
IP4
IP3
Momentum cleaning
IP7
Betatron cleaning
ALICE
IP2
ATLAS
IP1
LHC-b
IP8
B1
B2

Tertiary Collimator "Splash" Events



CMS view of beam hitting collimator

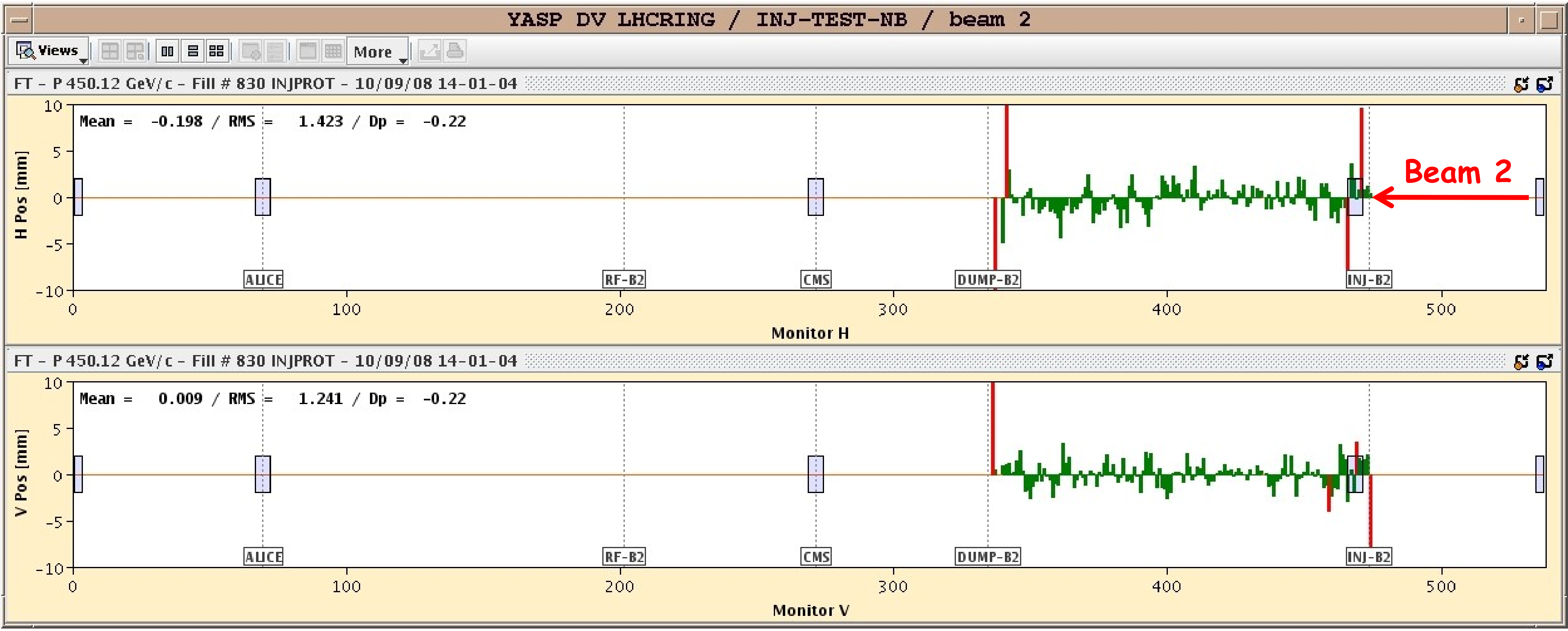


Events now, background later…

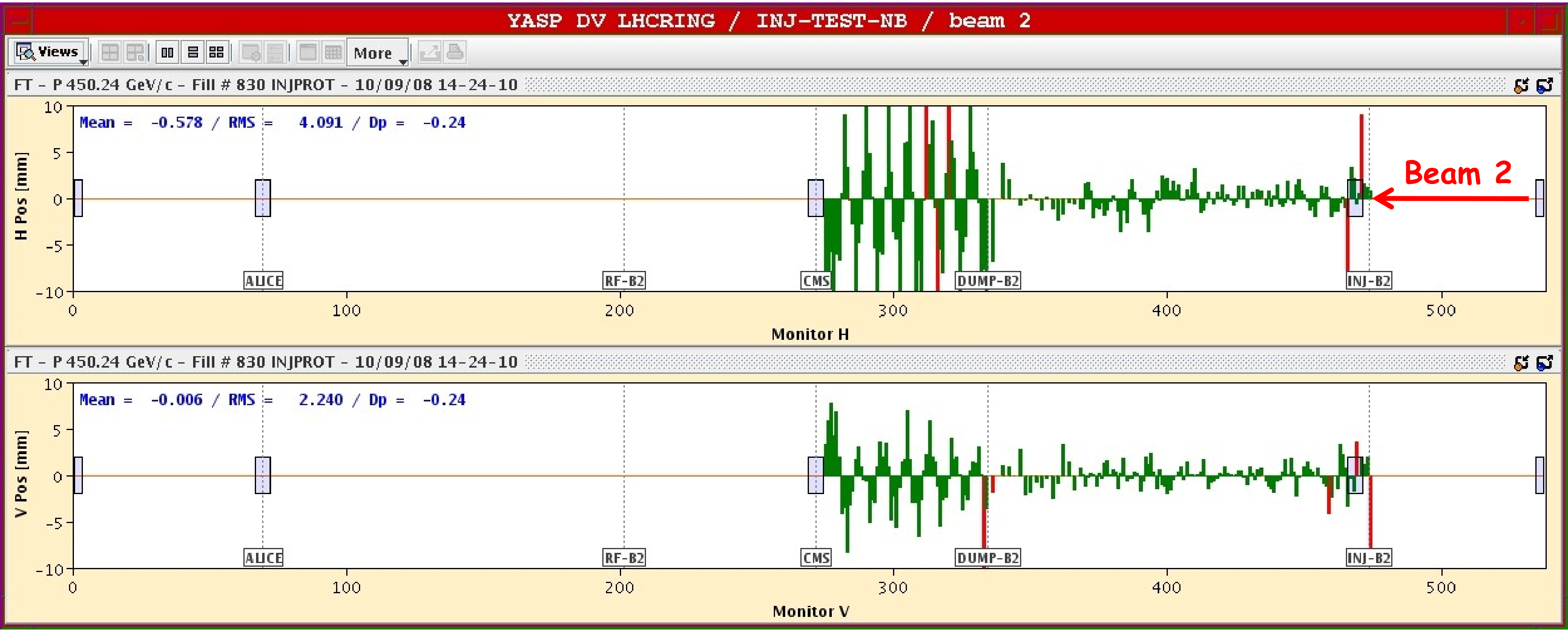
Similar events for ATLAS…

Experiments liked the data…

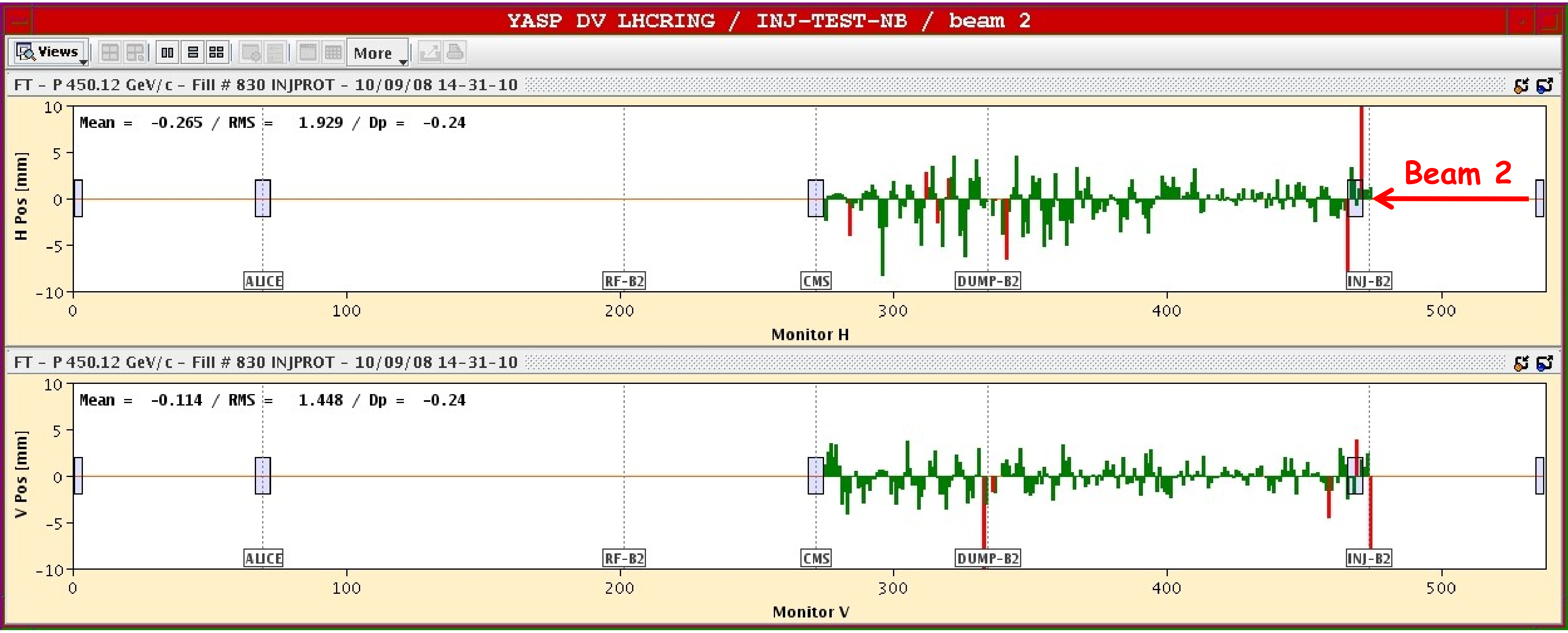
Measure and correct – first turn trajectory steering



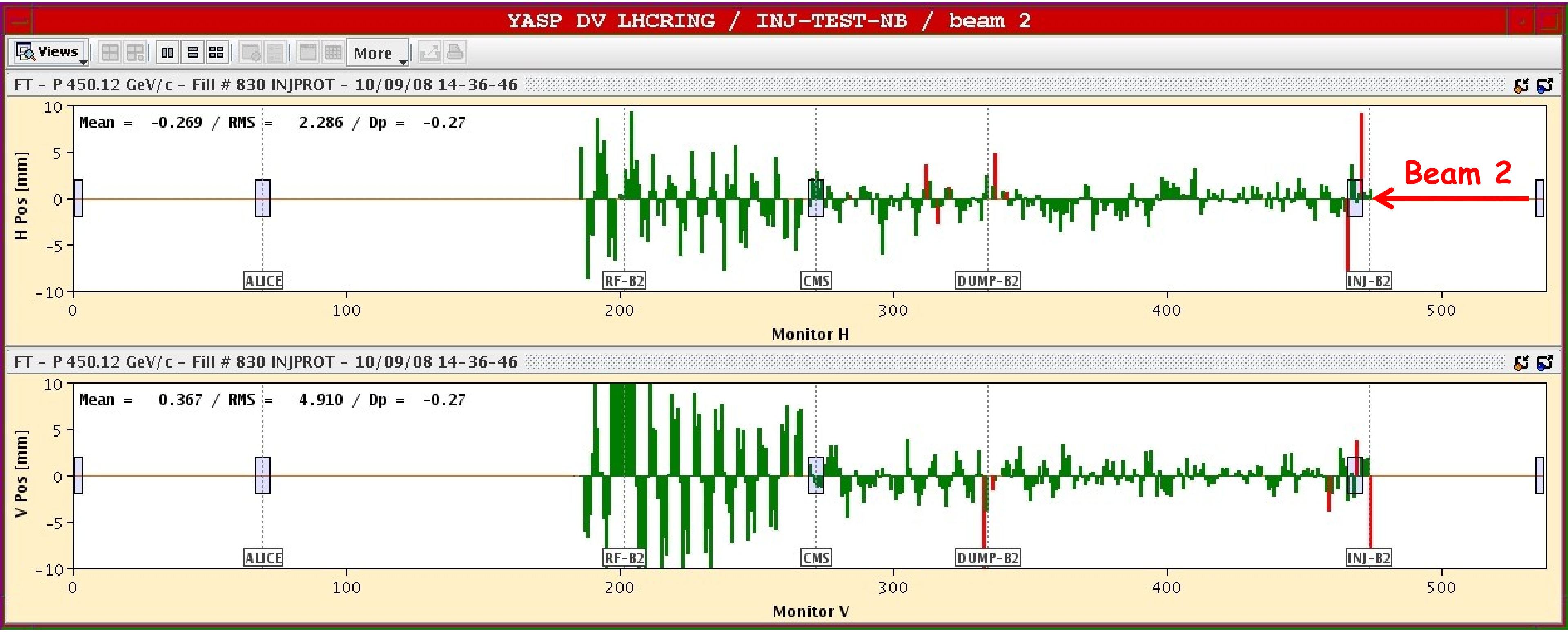
Measure and correct – first turn trajectory steering



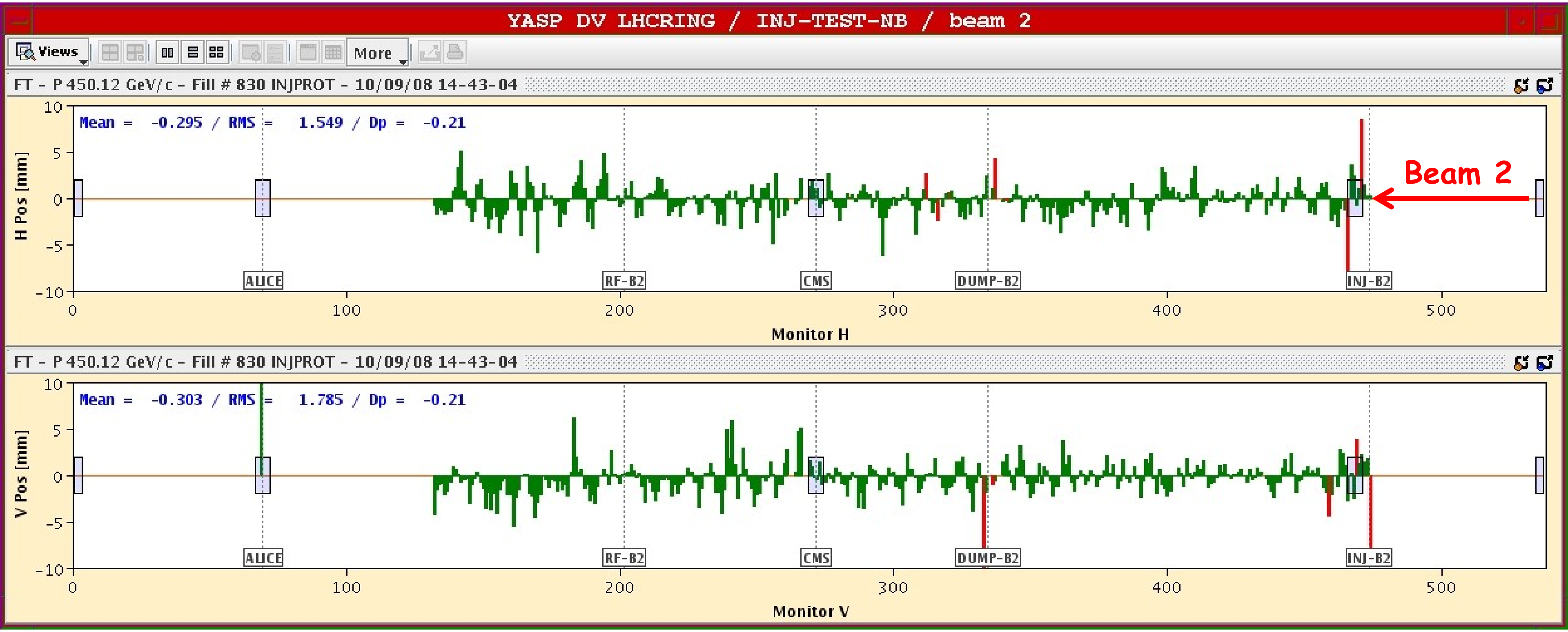
Measure and correct – first turn trajectory steering



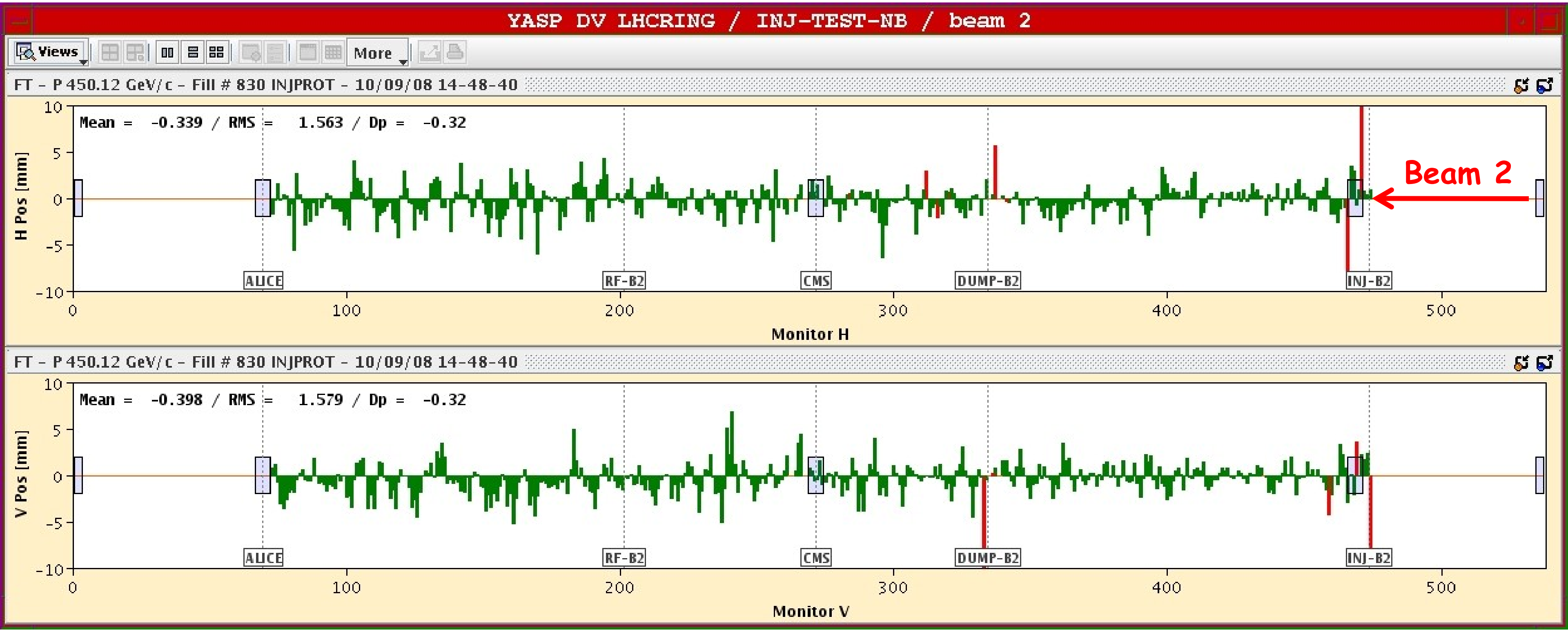
Measure and correct – first turn trajectory steering



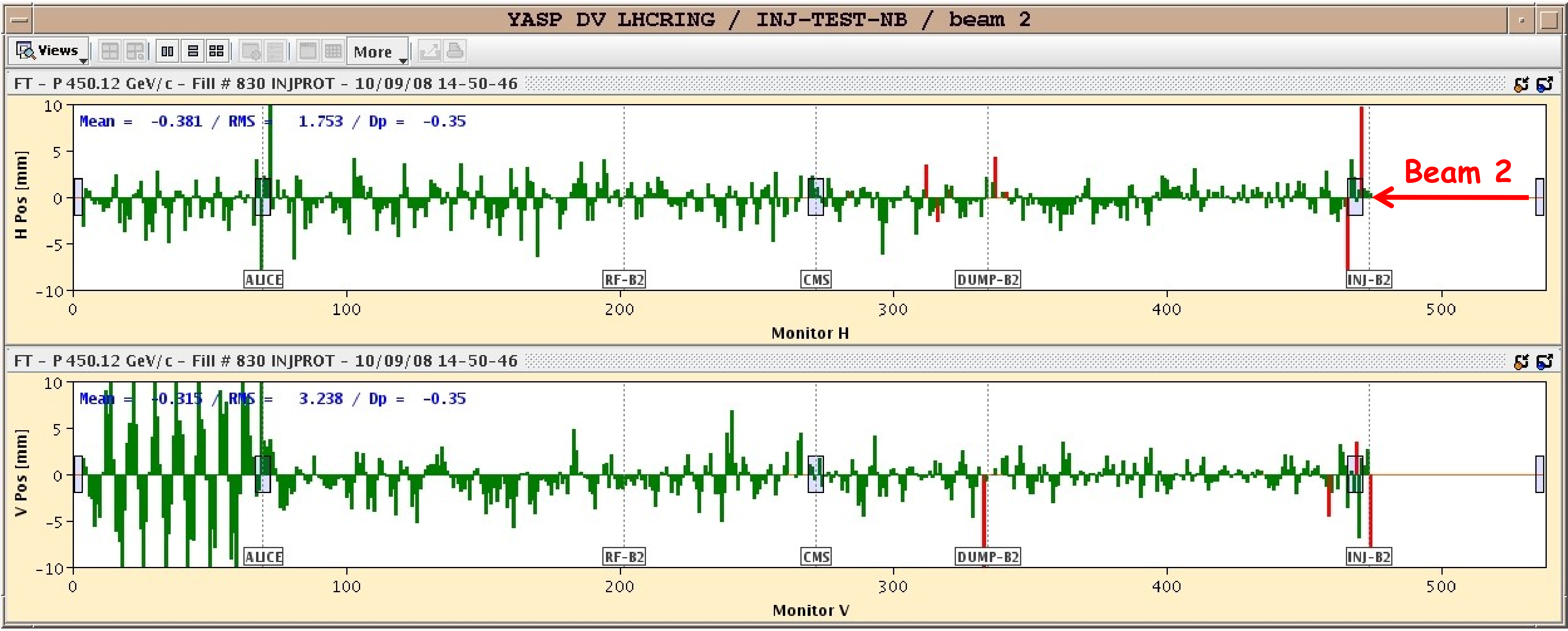
Measure and correct – first turn trajectory steering



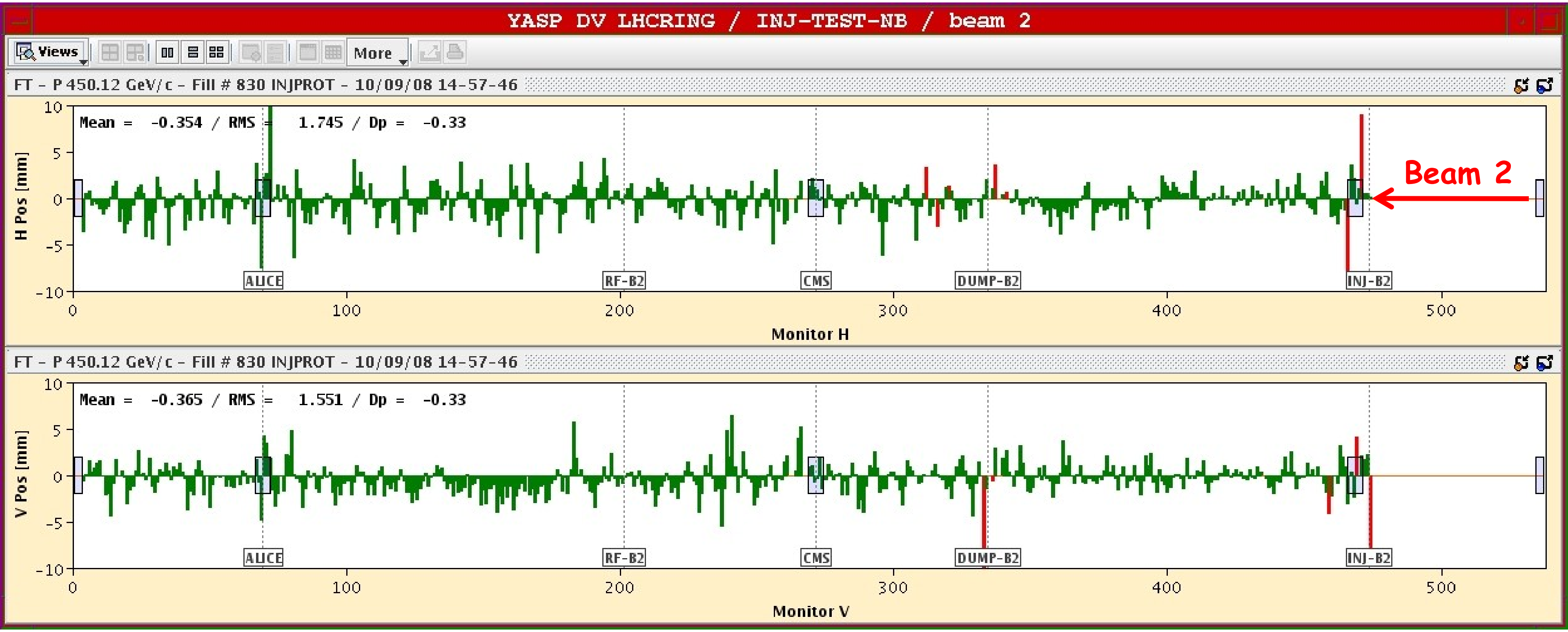
Measure and correct – first turn trajectory steering



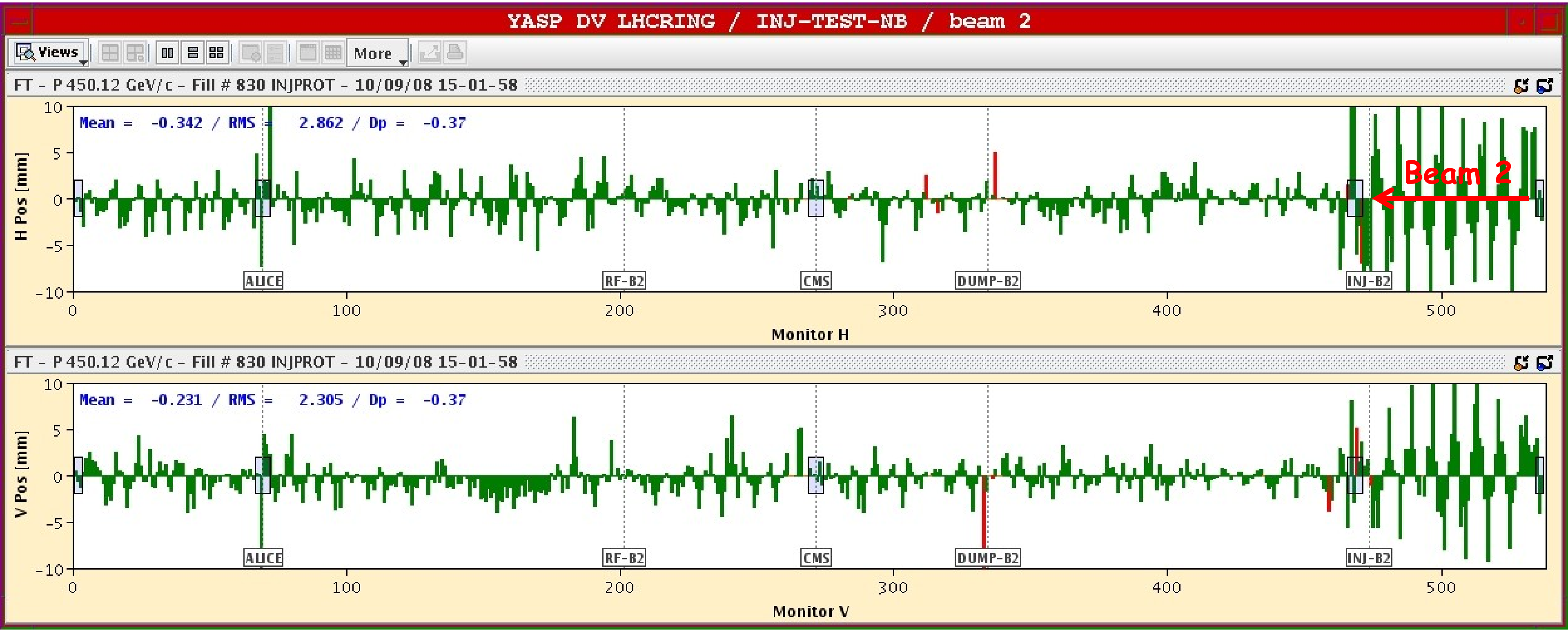
Measure and correct – first turn trajectory steering



Measure and correct – first turn trajectory steering



Measure and correct – first turn trajectory steering



The success of stored beam is not to underestimate: Shows that the basic machine design is very well. Worries for proton stability in large rings (➔ SSC aperture increase) were too conservative…

Delivering Luminosity

- Started luminosity operation 2010 at 3.5 TeV.
- Lower beam energy due to inter-connects (see incident, explained yesterday…).
- Experiments get data and can publish results…

Luminosity

$$\mathcal{L} = \frac{1}{4\pi\, m_0 c^2} \cdot \frac{f_{rev} \cdot F}{\gamma \cdot \beta^*} \cdot \frac{\mathbf{N_p}}{\epsilon} \cdot \mathbf{E_{stored}}$$

$$5.3 \times 10^8\ \mathrm{J}^{-1}$$

Triplet aperture and collimation setup accuracy

Beam-beam, brightness & robustness limits

Loss limits: collimation, (UFO's), …

m_0 = Proton rest mass

c = Light velocity

f_{rev} = Revolution frequency

F = Geometric correction factor

β^* = IP beta function

E_{stored} = $\gamma\, N_p\, N_{bunch}\, m_0 c^2$ = Stored energy

N_{bunch} = Number of bunches per beam

N_p = Number of protons per bunch

γ = Relativistic Lorentz factor

ϵ = Transverse (round) emittance (geom)

R. Assmann

$$\mathcal{L} = \frac{1}{4\pi\, m_{(}} \quad \frac{f_{rev} \cdot F}{\gamma \cdot \beta^*} \quad \frac{\mathbf{N_p}}{\epsilon} \cdot \mathbf{E_{stored}}$$

- Good news:
  - Available aperture about 50% larger than guaranteed by design (smaller orbit errors, better alignment, …). Gain here for luminosity!
  - Optics very well controlled (5-10% beta beat, … for $\beta^* = 1.5$m). Gain here!
- As expected:
  - Very challenging to achieve collimation & protection tolerances (only infrequent setups possible, drifts over months, …) → β^* limited.

$$\mathcal{L} = \frac{1}{4\pi\, m_0 c^2} \cdot \frac{f_{rev} \cdot E_{stored}}{\gamma \cdot \beta^*} \cdot \frac{\mathbf{N_p}}{\epsilon}$$

- Good news:
  - Collided successfully three times nominal brightness (head-on). Long-range beam-beam soon to be checked. Gain factor 3 here, if LR beam-beam OK as well!

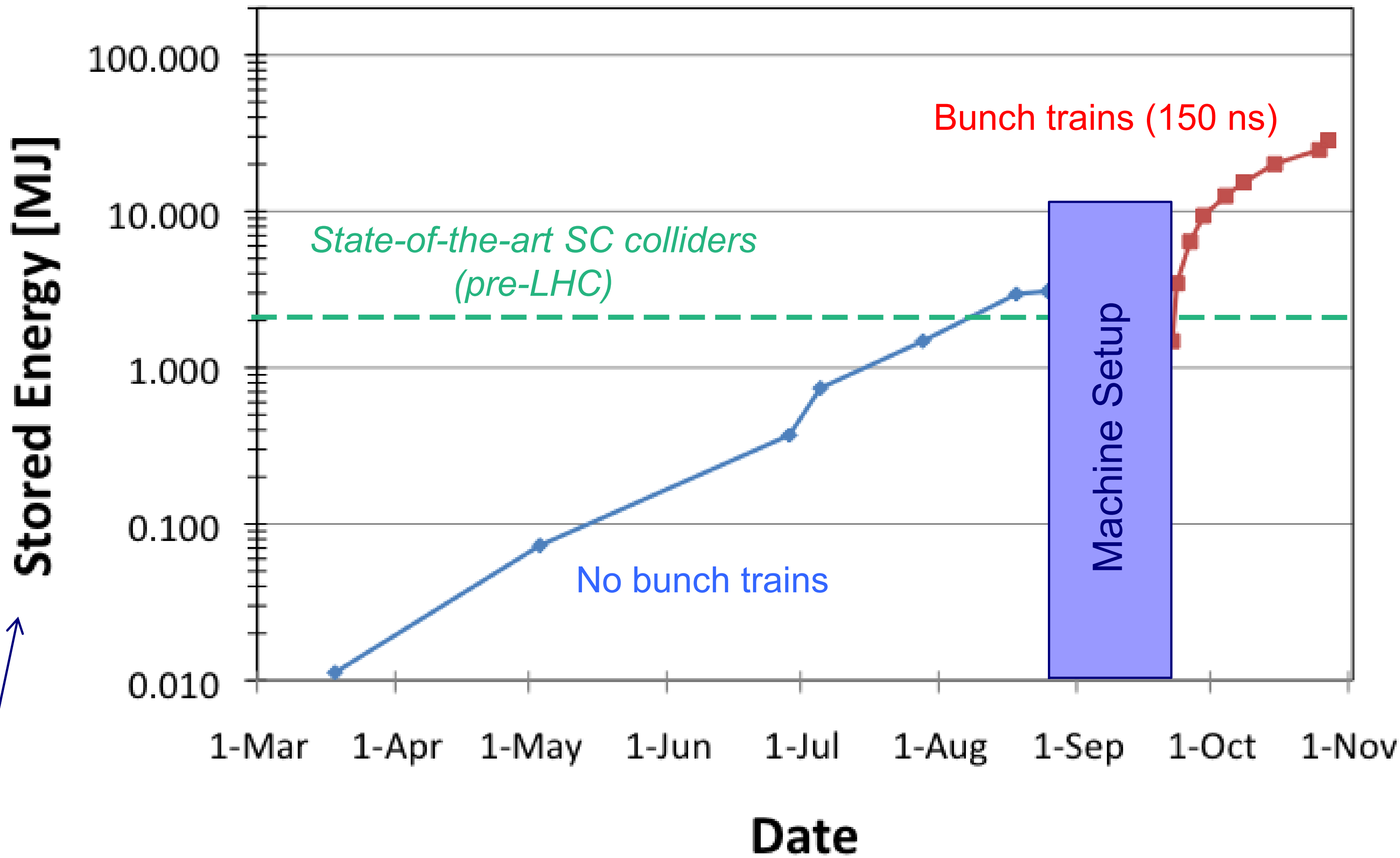
$$E_{\text{stored}} = N_p \cdot N_b \frac{E_b}{(\text{GeV})} 1.6022 \cdot 10^{-10}\ \text{J}$$

$$\mathcal{L} = \frac{1}{4\pi\, m_0 c^2} \cdot \frac{f_{rev} \cdot F}{\gamma \cdot \beta^*} \mathbf{E_{stored}}$$

- Good news:
  - Reached the design 500 kW peak beam loss (protons) at primary collimators without quench of a super-conducting magnet!
  - Reached 80 MJ without a single quench from stored beam losses.
  - Transverse damper stabilizes beam at 3.5 TeV → high impedance OK.
  - Reached 99.995% collimation efficiency with 50% smaller gaps than design.
  - Minimum beam lifetime at 3.5 TeV is ~4 times better than specified.

2010

Evolution Proton Run 2010 (Stored Energy)

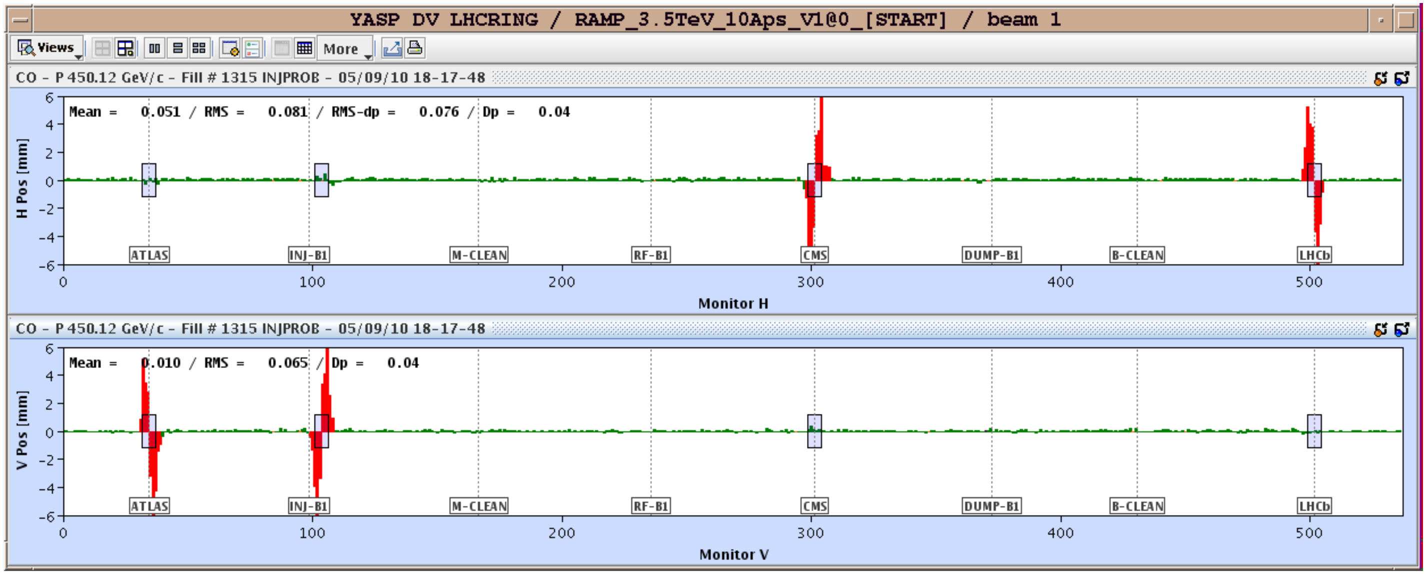


$$E = N_p \cdot N_b \frac{E_b}{(\mathrm{GeV})} 1.6022 \cdot 10^{-10}\ \mathrm{J}$$

3.5 TeV Operation

- 2010
  - Mar - Aug — Flat machine, up to 43b nominal bunch charge, β^* = 2 – **3.5m**
  - Sep — Crossing angle setup
  - Oct – Nov — 150 ns bunch spacing (up to 436 b)

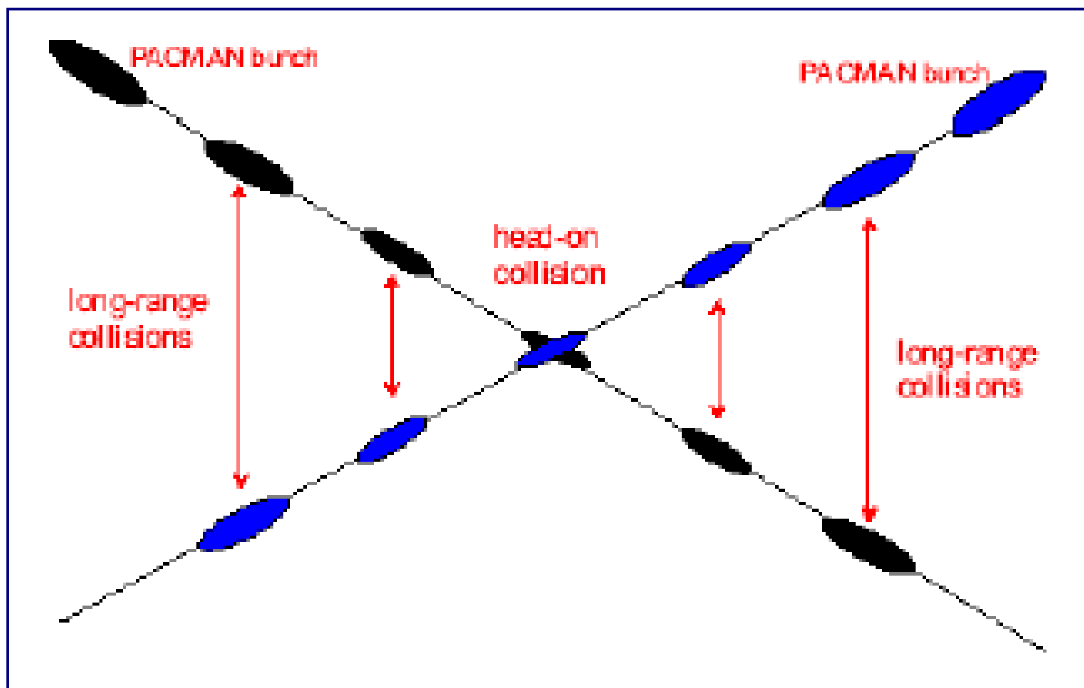
Crossing Angles: Avoid Parasitic Collisions



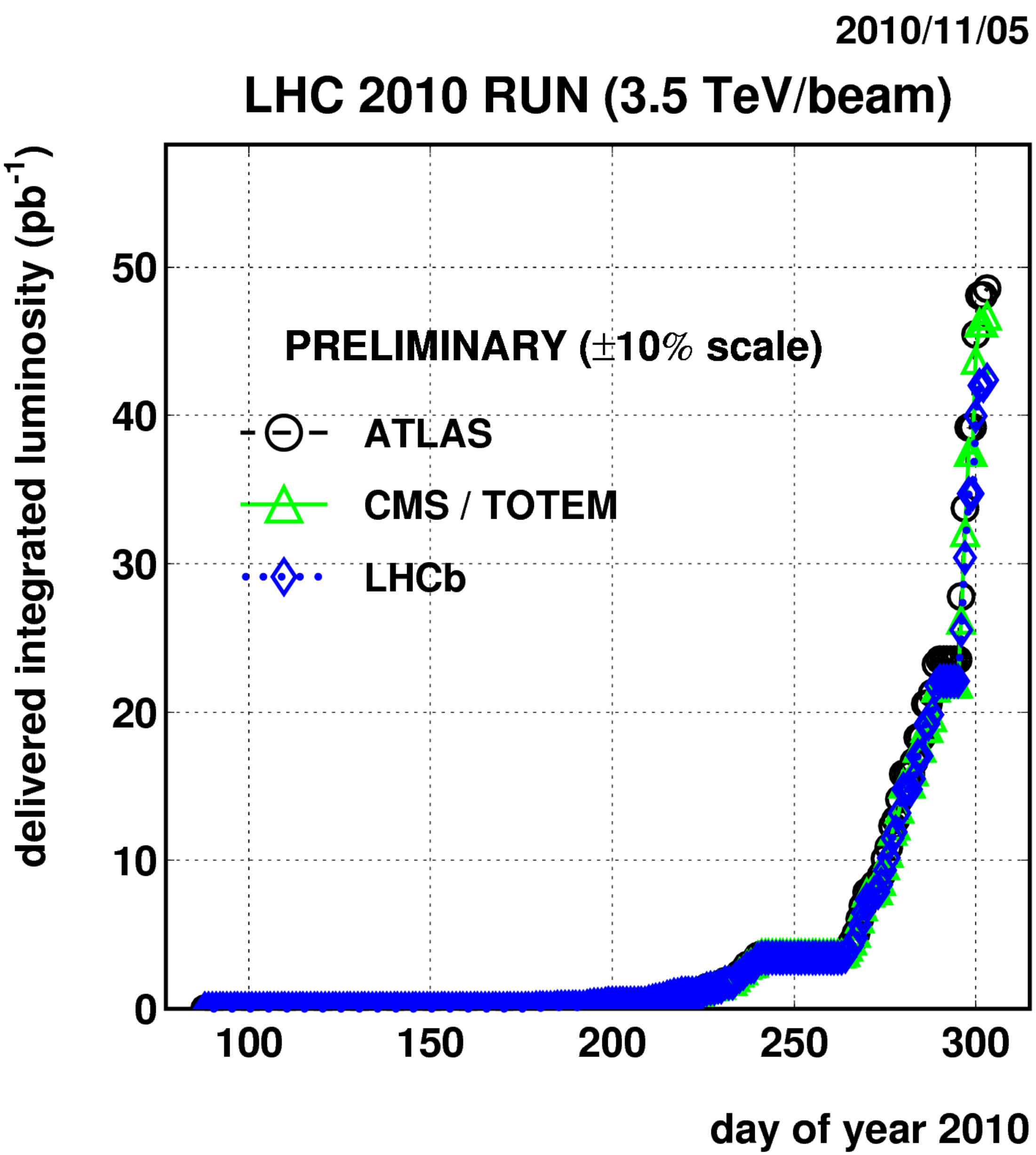
Closed Orbit

September 2010

Flat → Crossing



Delivered Integrated p-p Luminosity 2010



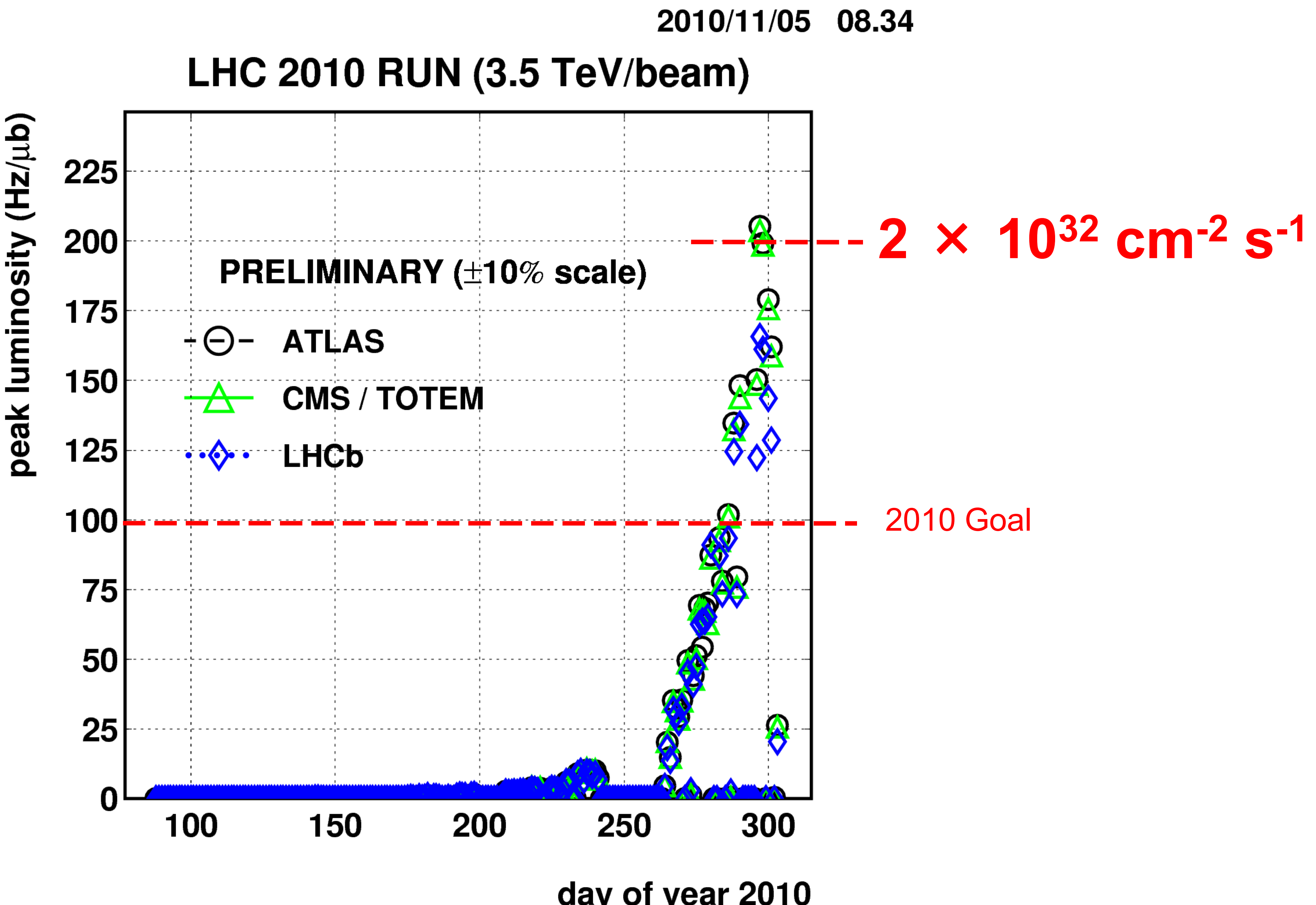
~ 50 pb^{-1}

(half in last week)

Two ingredients:

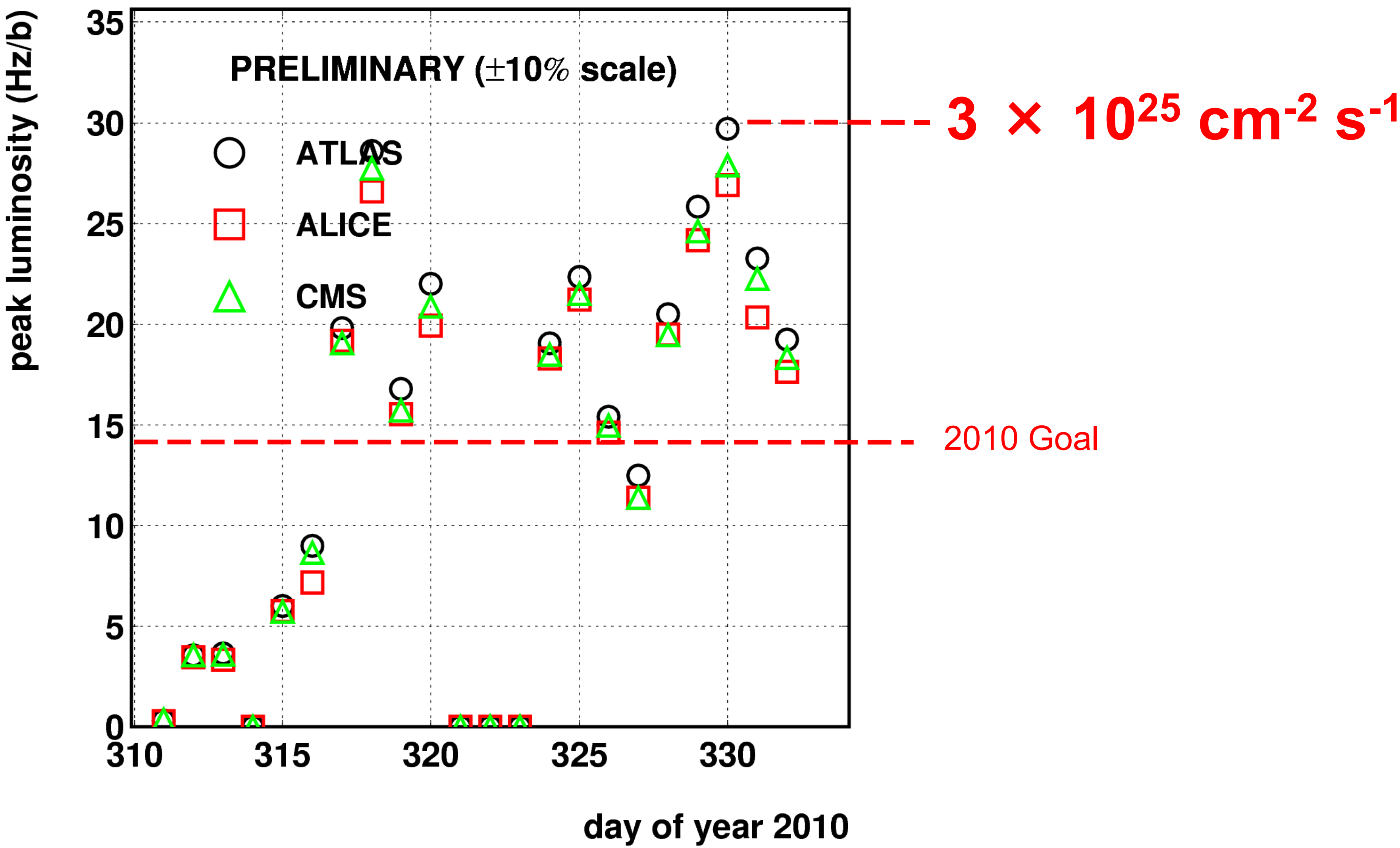
1) Efficiency of LHC operation & availability
2) Peak luminosity

2010 Performance: Peak p-p Luminosity

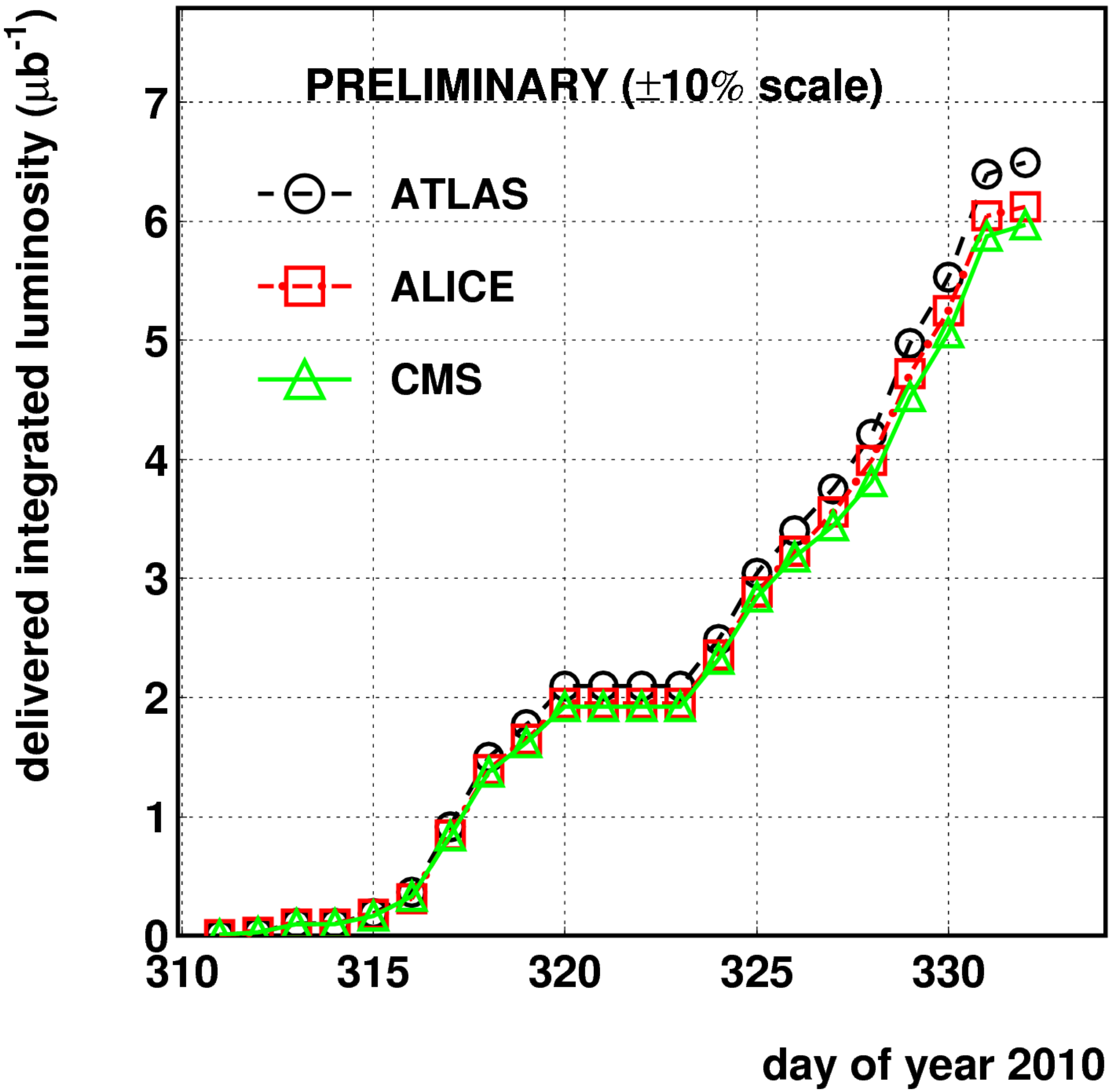


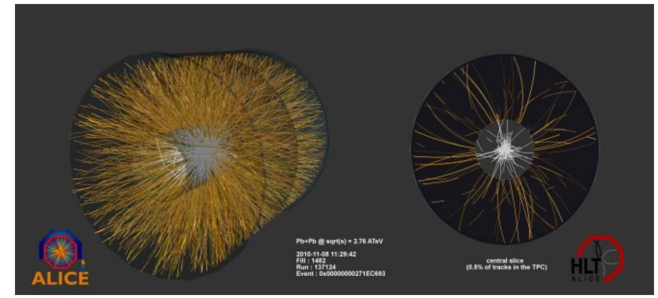
Peak Luminosity for Ions

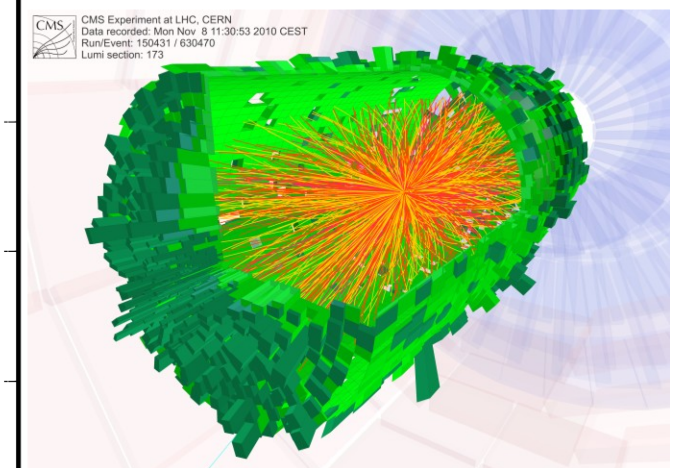
	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	STANDBY	STANDBY	STANDBY
Instantaneous Lumi (ub.s)^-1	3.22e-05	2.79e-05	2.81e-05	0.00e+00



Integrated Lumi for Ions







Reached ~10 μb^{-1}

2011

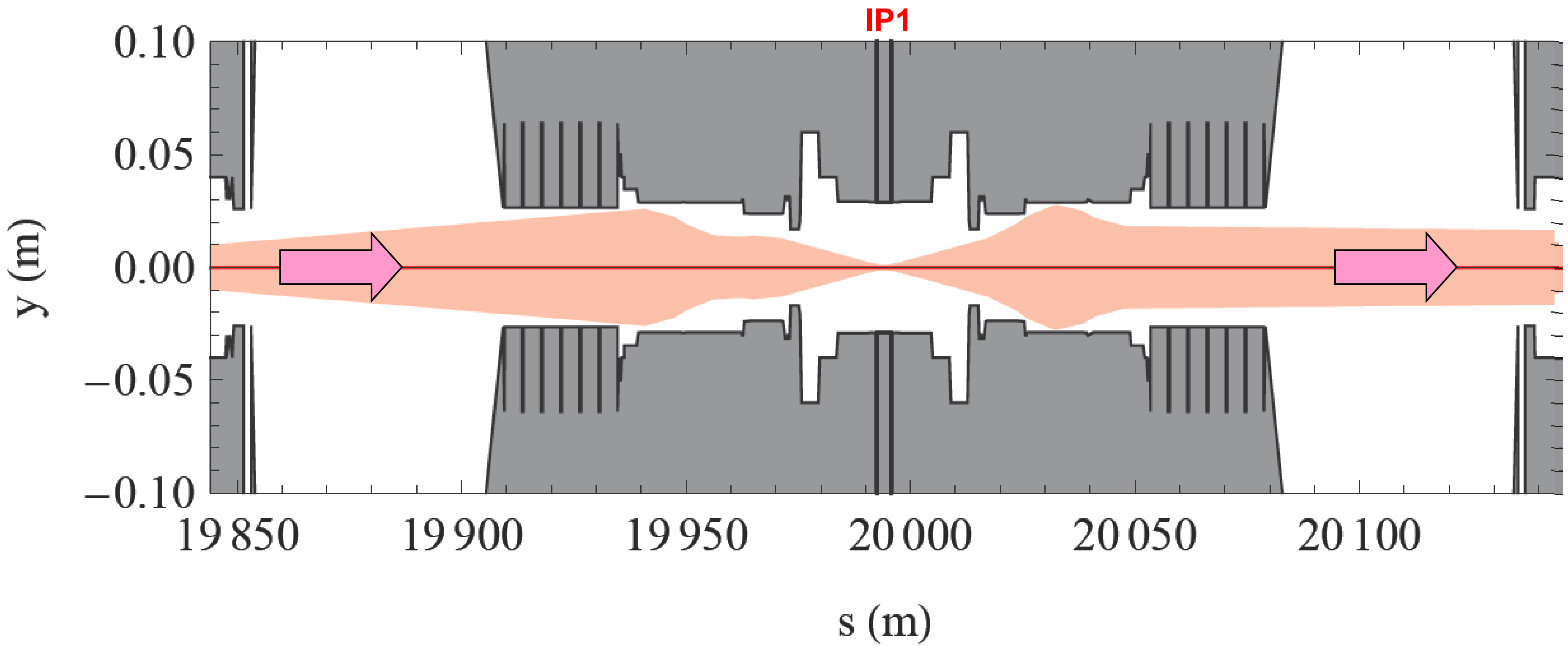
3.5 TeV Operation

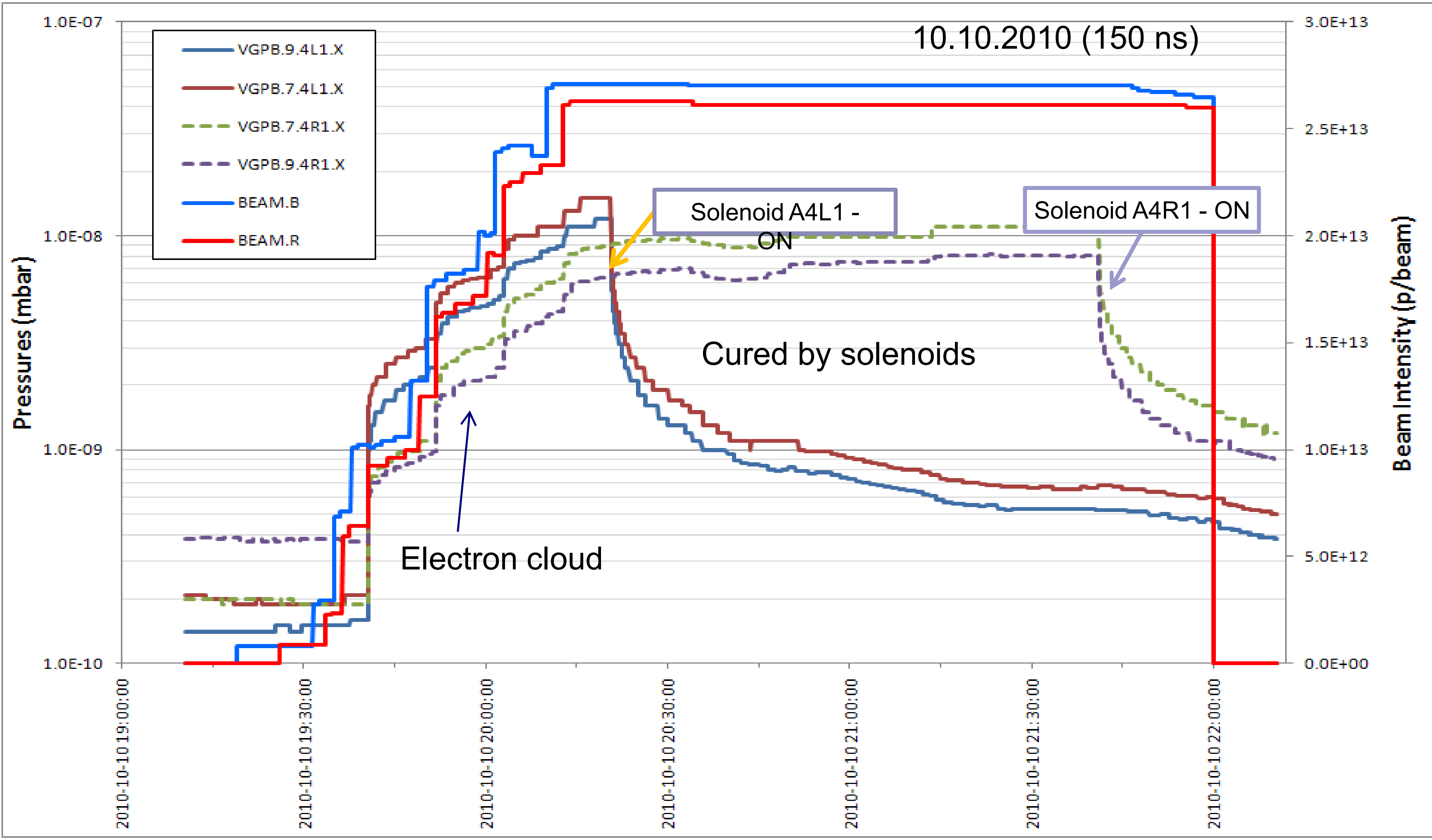
- 2010
  - Mar - Aug: Flat machine, up to 43b nominal bunch charge, β* = 2 – **3.5m**
  - Sep: Crossing angle setup
  - Oct – Nov: 150 ns bunch spacing (up to 436 b)

- 2011
  - Mar: 75 ns bunch spacing, **β* = 1.5 m**
  - Apr: 12 days “scrubbing” for e-cloud
  - Apr – Jun: 50 ns bunch spacing (up to 1092 b)

Squeeze to 1.5 m

- Main limitations when going to smaller β*
  - Magnetic limits: max gradient in quadrupoles and chromaticity
  - Beam-beam limit …
  - Aperture limit: decreasing margins in triplet when decreasing β. Present LHC limit! New regime compared to other machines

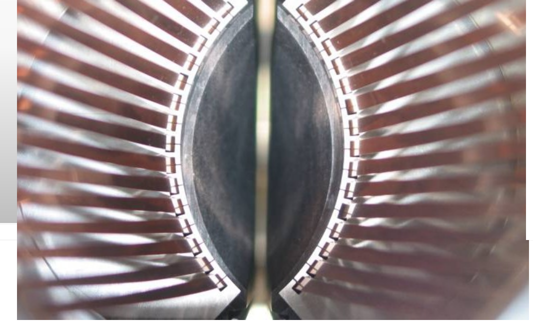


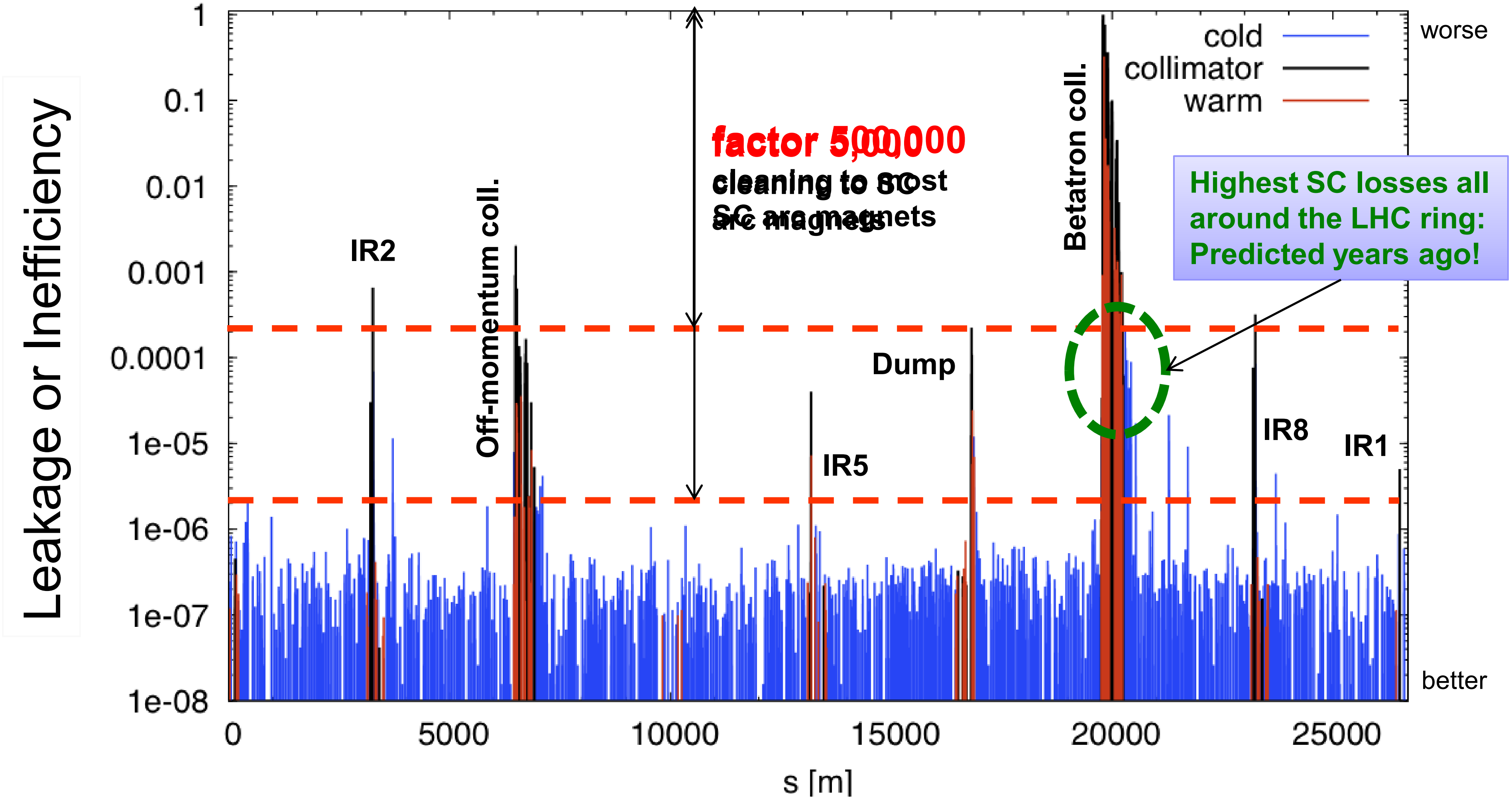


→ Scrubbing conditions the vacuum!

Measured Cleaning at 3.5 TeV – Provoked Loss

(beam1, vertical beam loss, intermediate settings)





R. Assmann

Ultra-High Efficiency

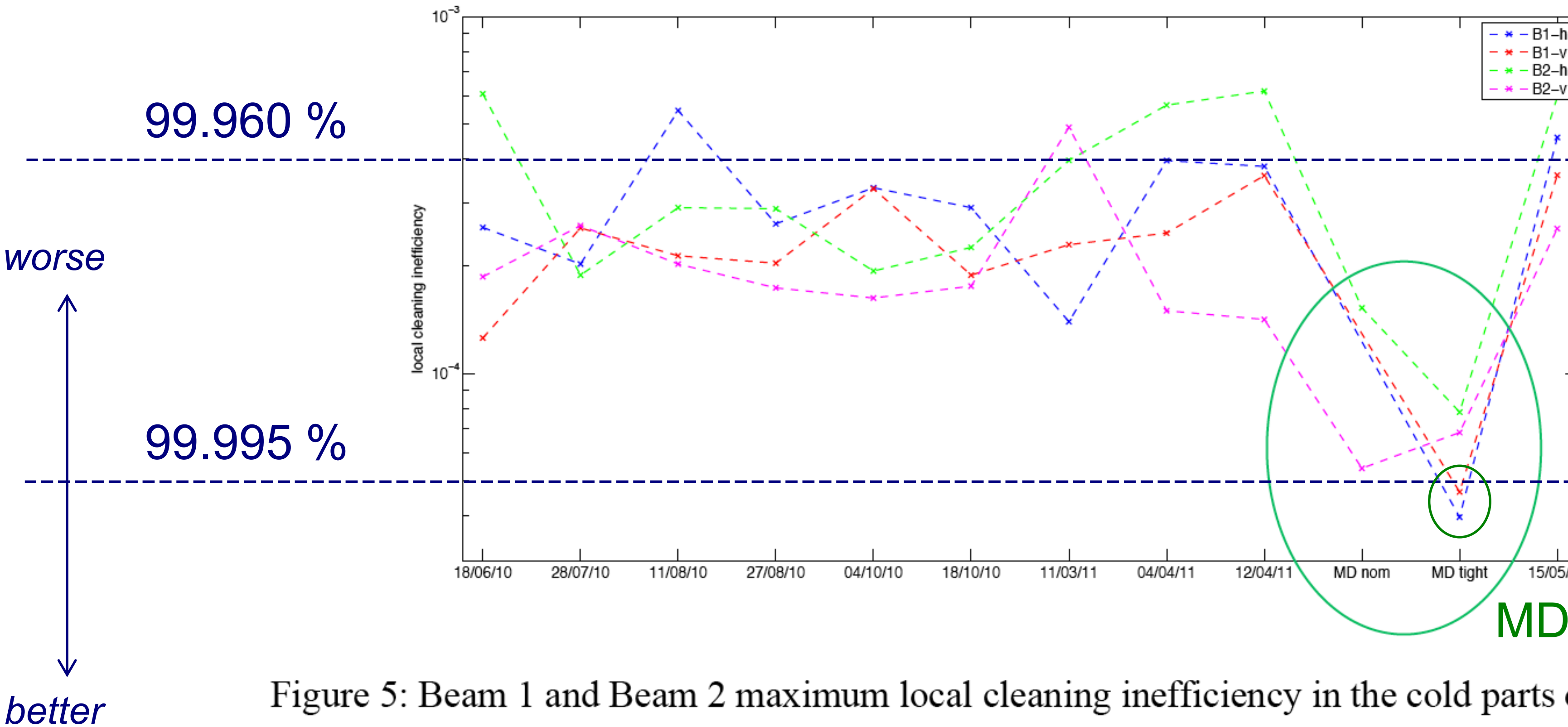
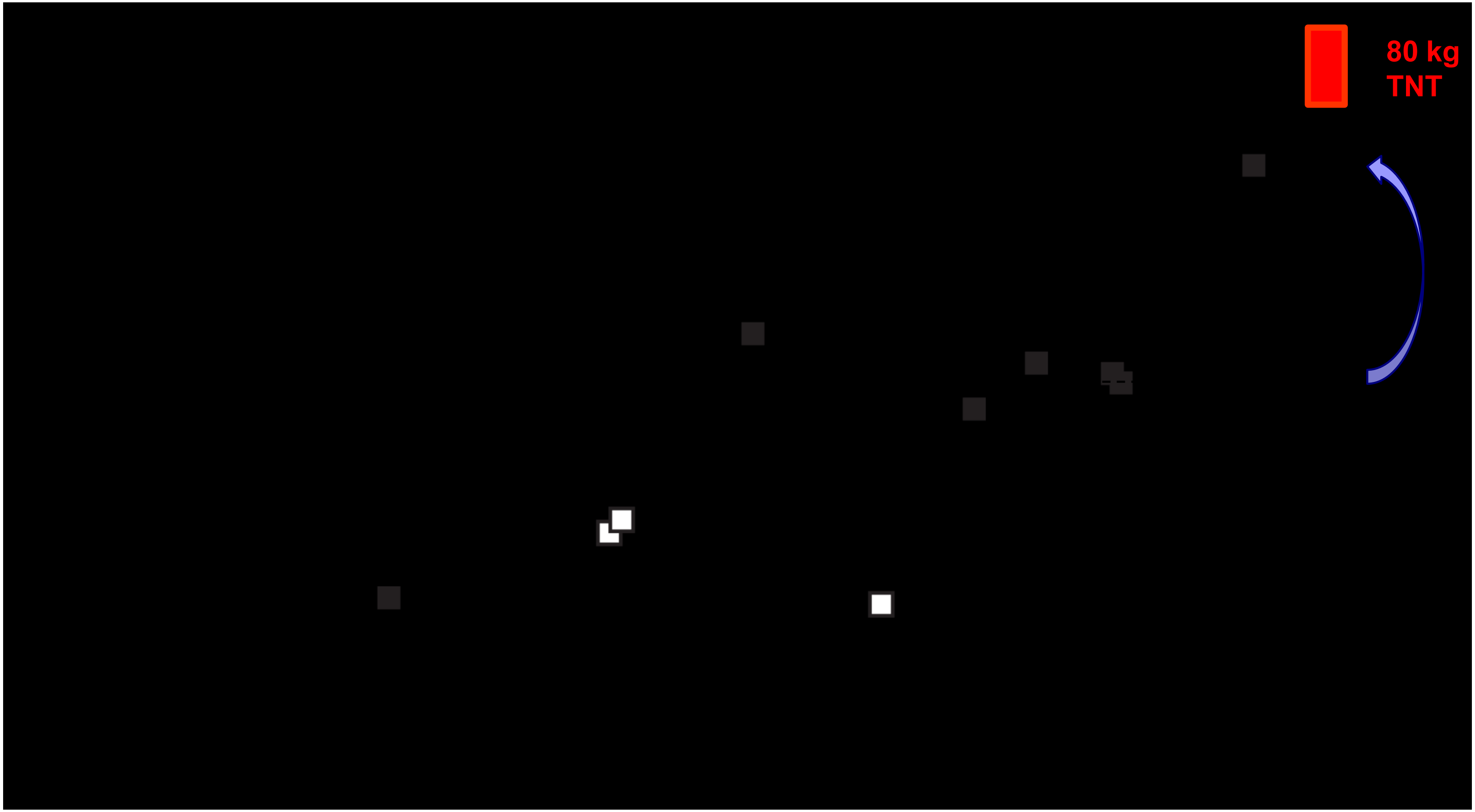


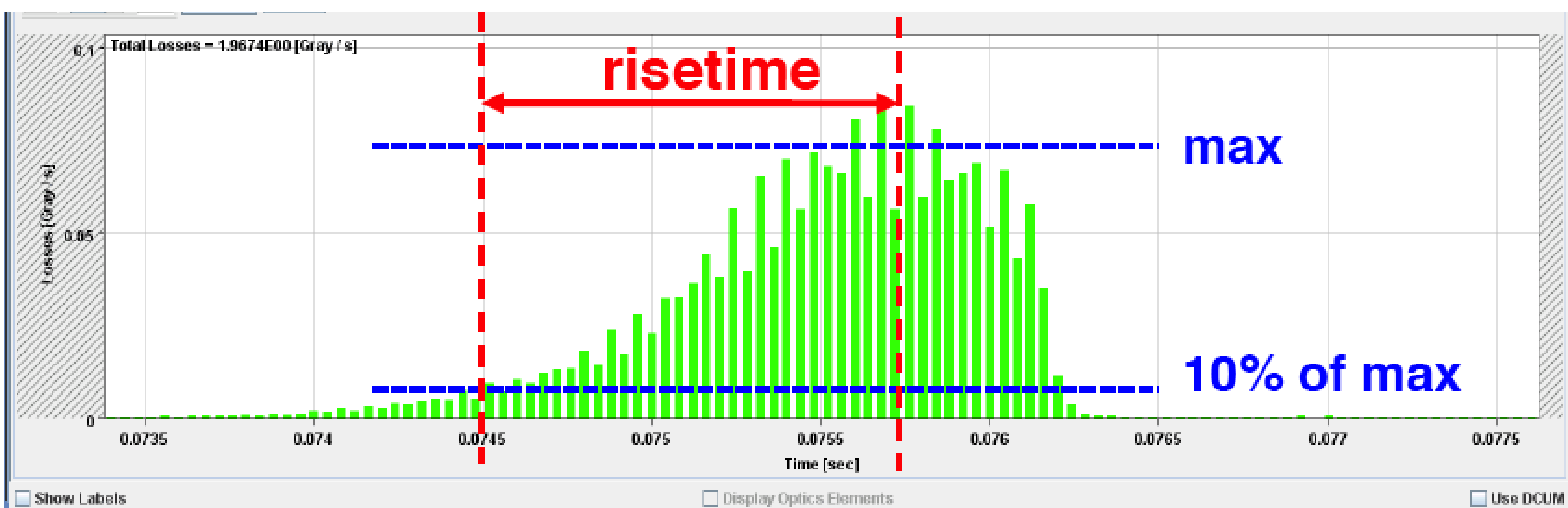
Figure 5: Beam 1 and Beam 2 maximum local cleaning inefficiency in the cold parts of the LHC at 3.5TeV over about one year operation. The results from this MD are contained in the second and third sets of points from the right, where a clear decrease can be observed.

Achieved Stored Energy: 80 MJ



UFO - Unidentified Falling Object

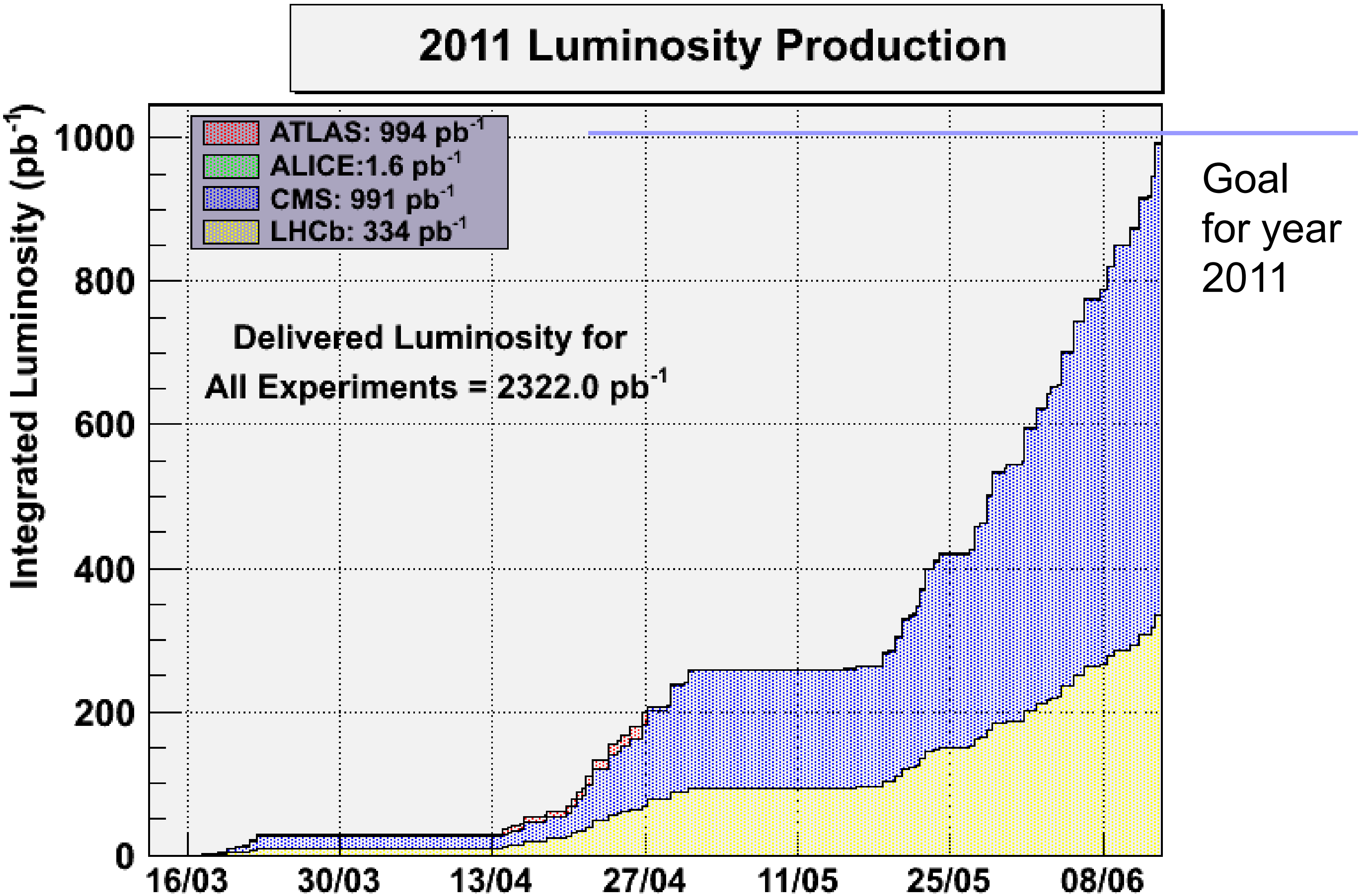
- Sudden local losses, in the middle of SC sections: collimators cannot intercept the loss.
- No quench, but preventive dump (very diluted shower).
- Rise time on the ms scale.
- Working explanation: dust particles falling into beam creating scatter losses and showers propagating downstream.



Achievements and parameters

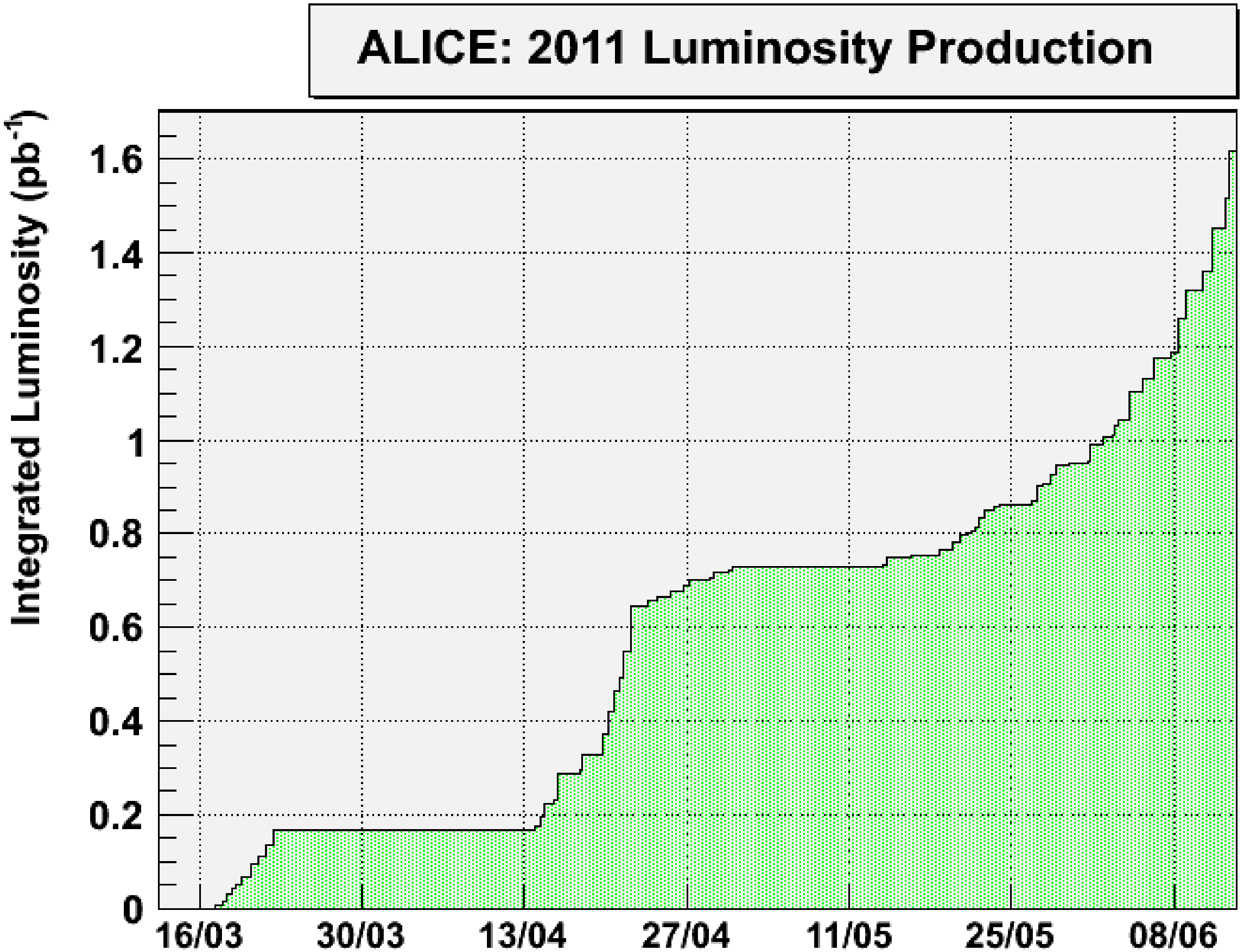
- Status June 16
  - Highest luminosity per fill: 46.61 pb^{-1}
  - Highest luminosity in 1 day: 56.33 pb^{-1}
  - Production in a week: 229.64 pb^{-1}
  - Average bunch intensity: 1.2e11 (slightly lowered)
  - Typical luminosity: 1.1e33 (slightly lowered)
  - Number of bunches/beam: 1092
  - β^*: 1.5 m

2011 Luminosity Production I

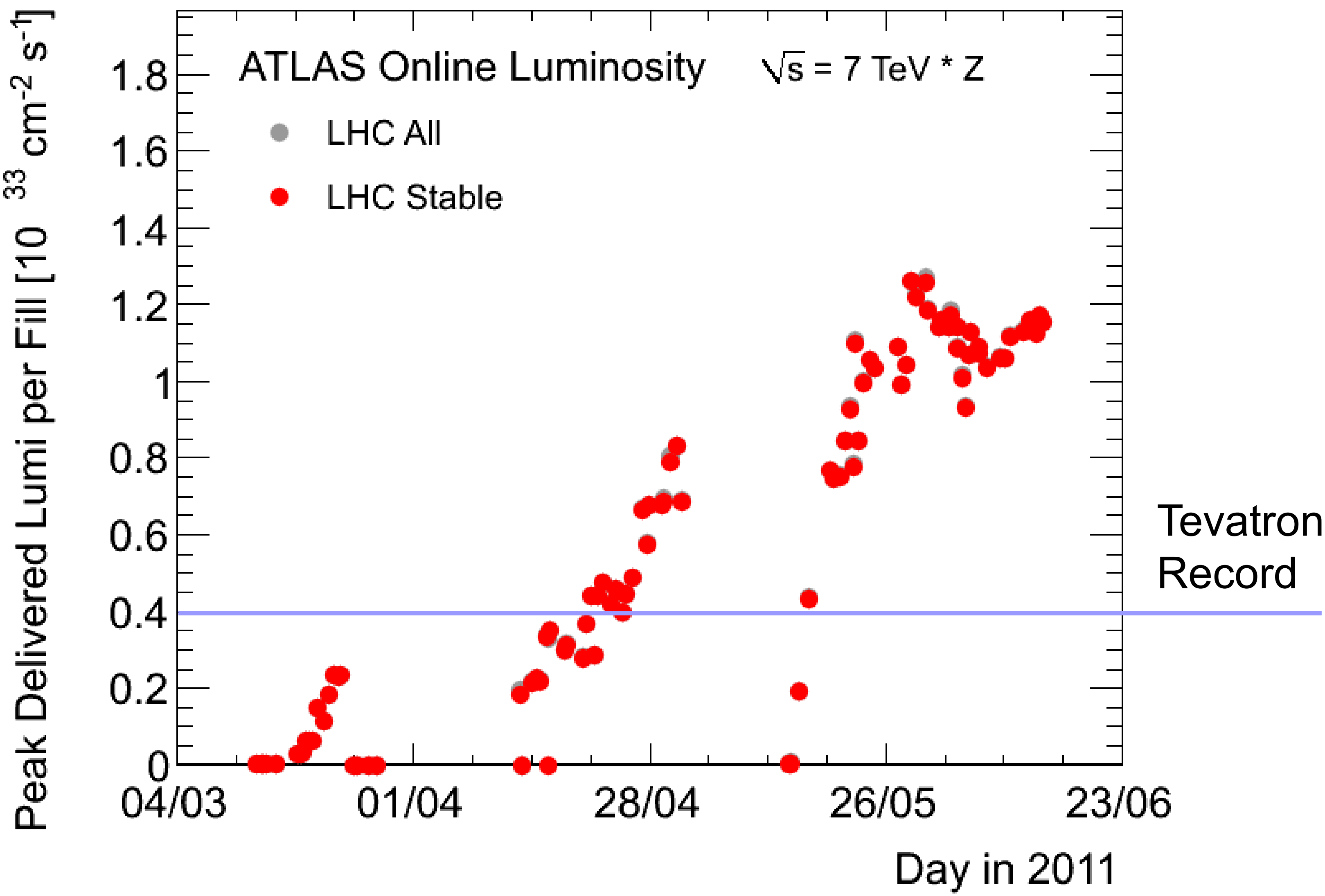


Goal for year 2011

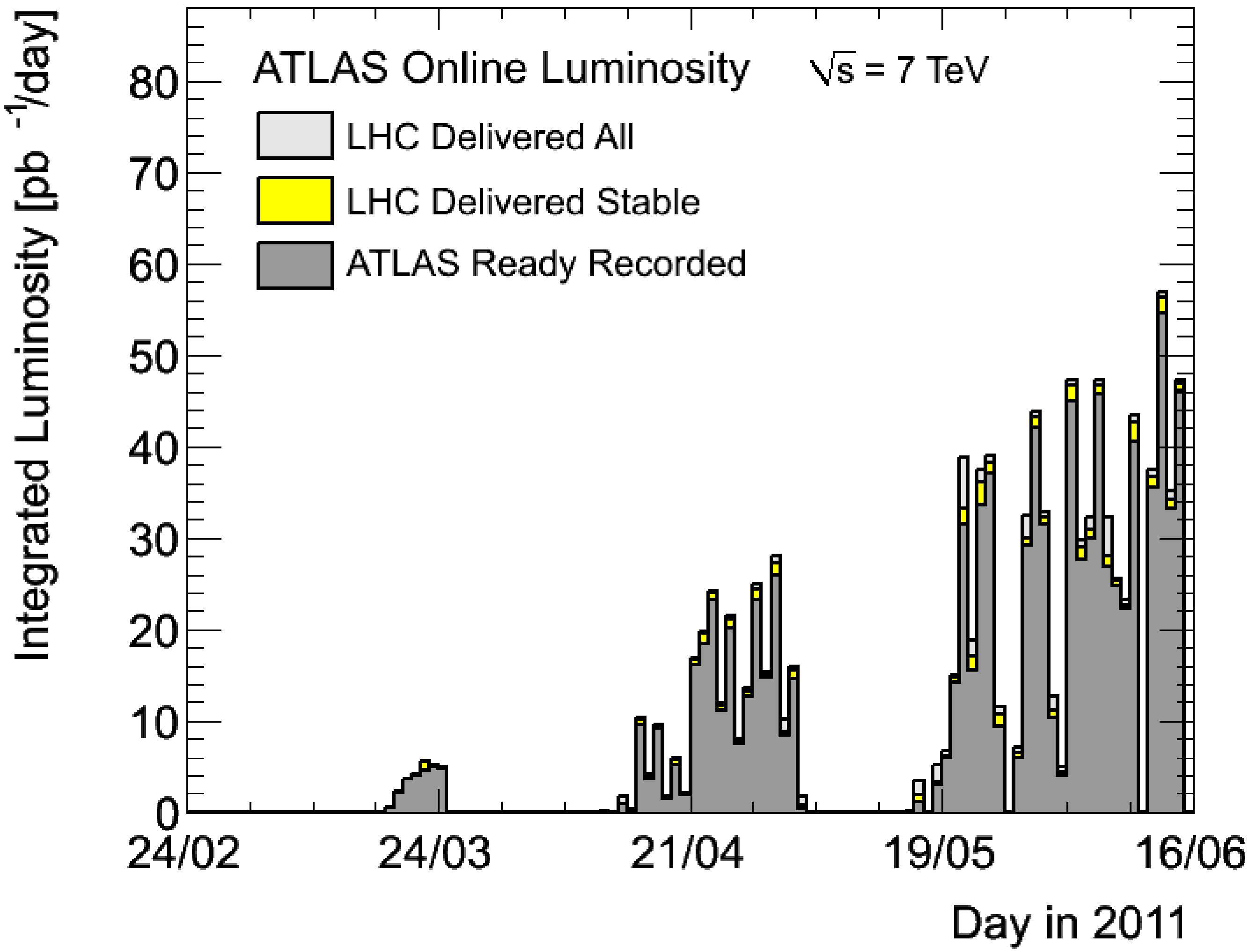
2011 Luminosity Production II



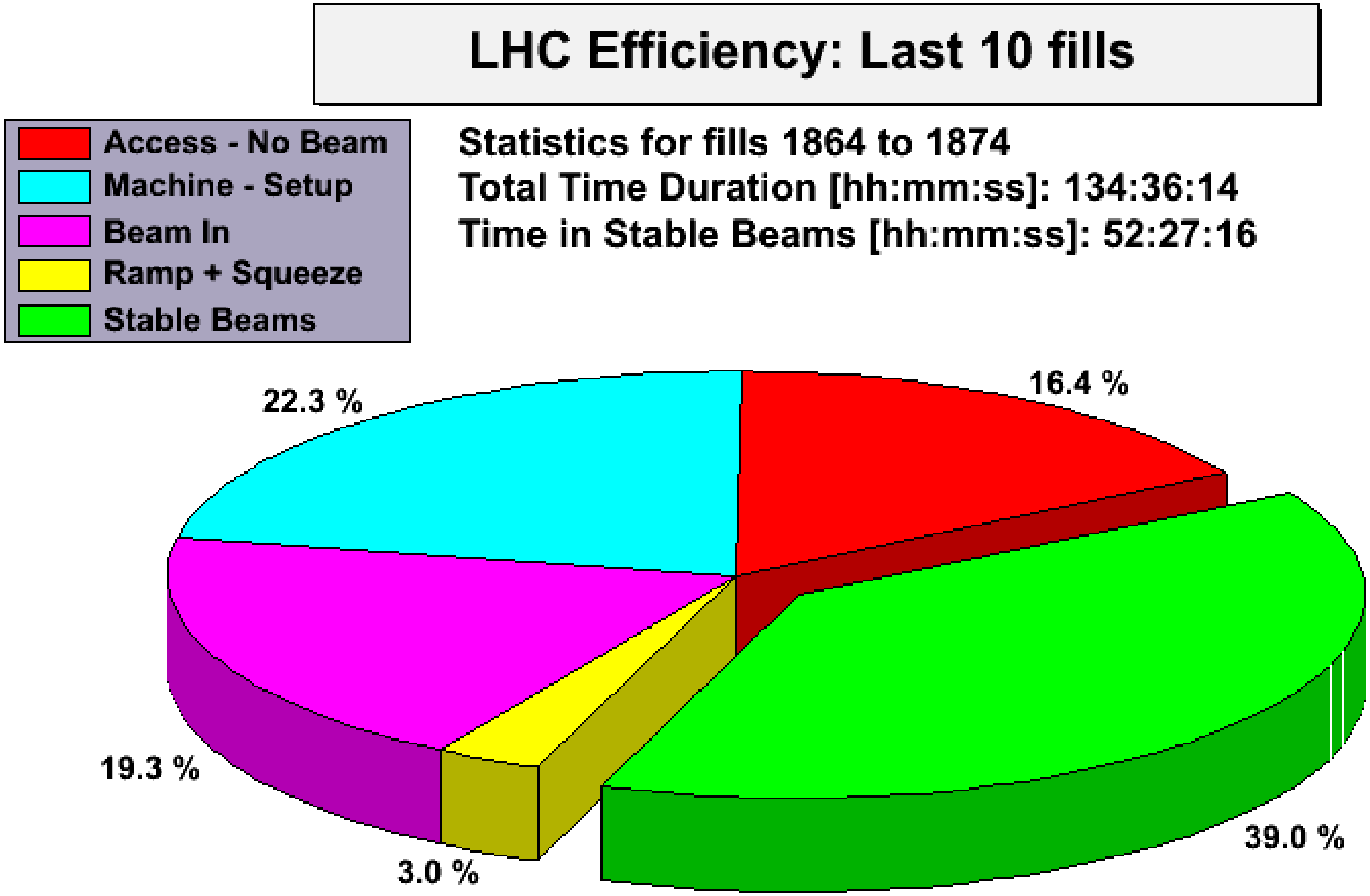
Peak Luminosity (Recorded in ATLAS)



Luminosity per Day (Recorded in ATLAS)



Efficiency


LHC Efficiency: Last 10 fills
Access - No Beam
Machine - Setup
Beam In
Ramp + Squeeze
Stable Beams
Statistics for fills 1864 to 1874
Total Time Duration [hh:mm:ss]: 134:36:14
Time in Stable Beams [hh:mm:ss]: 52:27:16
22.3 %
16.4 %
19.3 %
3.0 %
39.0 %

Future

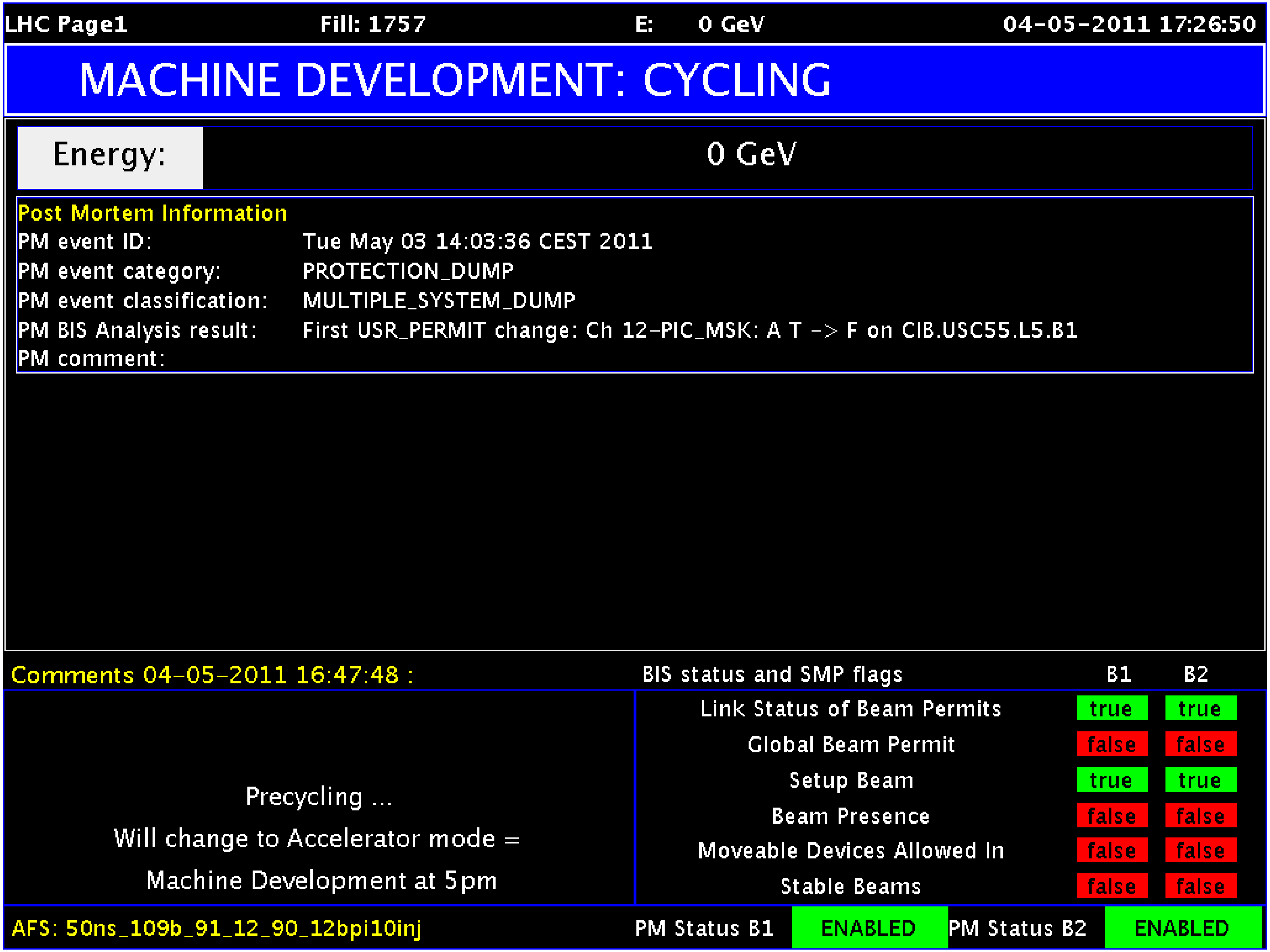
Machine Development Lessons…

- MD's prove excellent performance potential of LHC:
  - **No head-on beam-beam limit encountered with 3 times nominal brightness**. Total tune shift: **0.03** with ATLAS/CMS collisions.
  - **ATS** injection optics with **different integer tunes** fine to 3.5 TeV.
  - Collimation system reached **tighter settings with better cleaning efficiency**. Limited by setup accuracy and stability.
  - Collimation **reached 500 kW primary beam loss without quench**.
  - Impedance and **instabilities under control**.

R. Assmann
F. Zimmermann
G. Papotti

Getting busy…

1st LHC MD Period Started Last Wednesday



Beam-beam limit

- Collided high intensity beams (**1.7 E11**) and small emittances (smaller than **1.5 um**) in IP1 and IP5.
- In final attempt reduced vertical tune to end up below 10th order after putting beams in collision. No more blowup observed, **tune shifts per IP in excess of 0.015** (with initial emittance below 1.2 um).
- **No limit found for head-on beam-beam effects for the intensities investigated so far** (no long range yet).

factor ~5 above design

5 times higher luminosity than design?

CERN-ATS-Note-2011-029 MD

19 May 2011

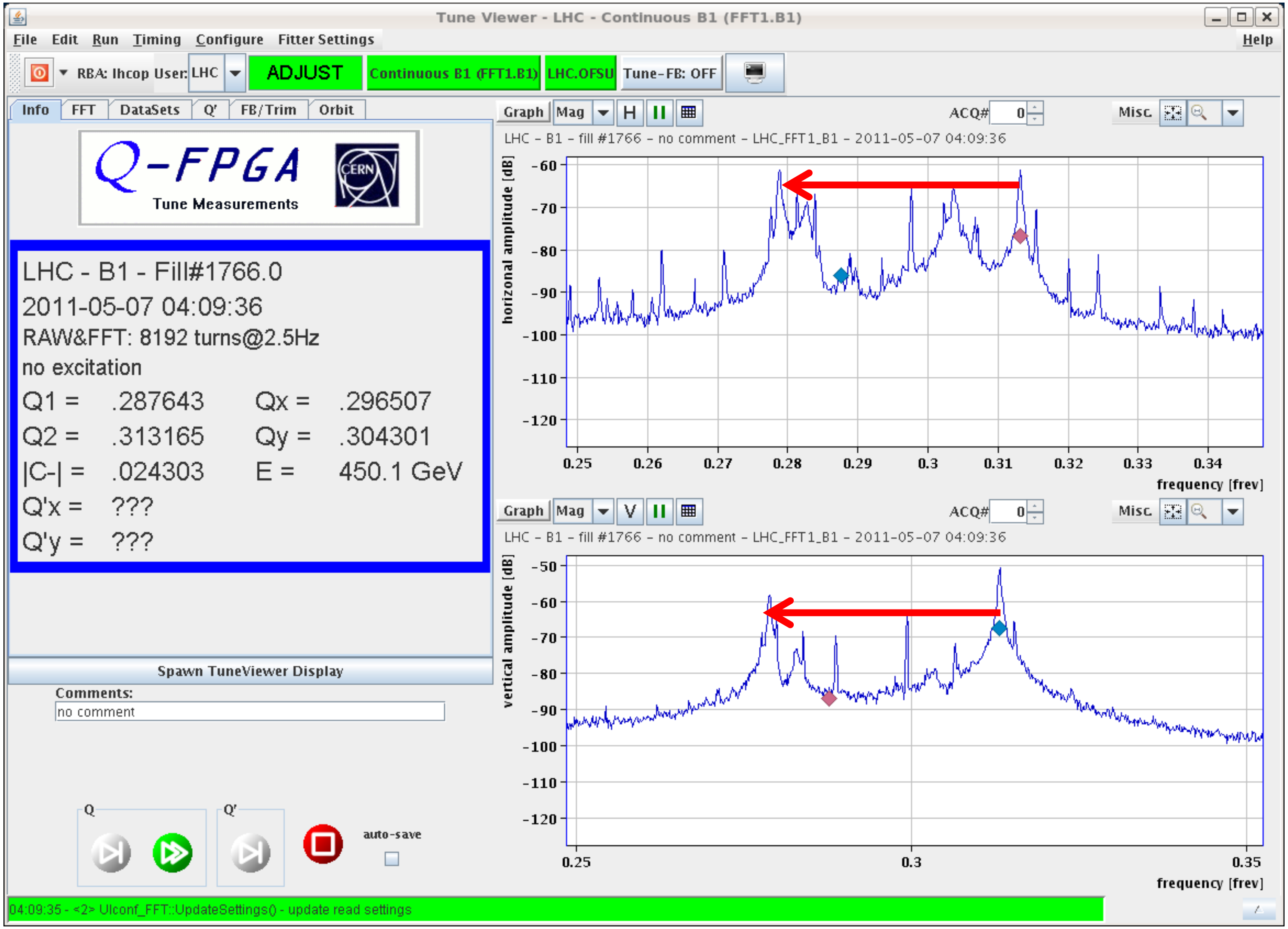
Werner.Herr@cern.ch

Head-on beam-beam tune shifts with high brightness beams in the LHC

Participants:
R. Alemany, X. Buffat, R. Calaga, K. Cornelis, M. Fitterer, R. Giachino, W. Herr, A. McPherson, R. Miyamoto, G. Papotti, T. Pieloni, S. Redaelli, F. Roncarolo, M. Schaumann, R. Suykerbuyk, G. Trad
CERN, CH-1211 Geneva 23
S. Paret
LBNL, U.S.A.

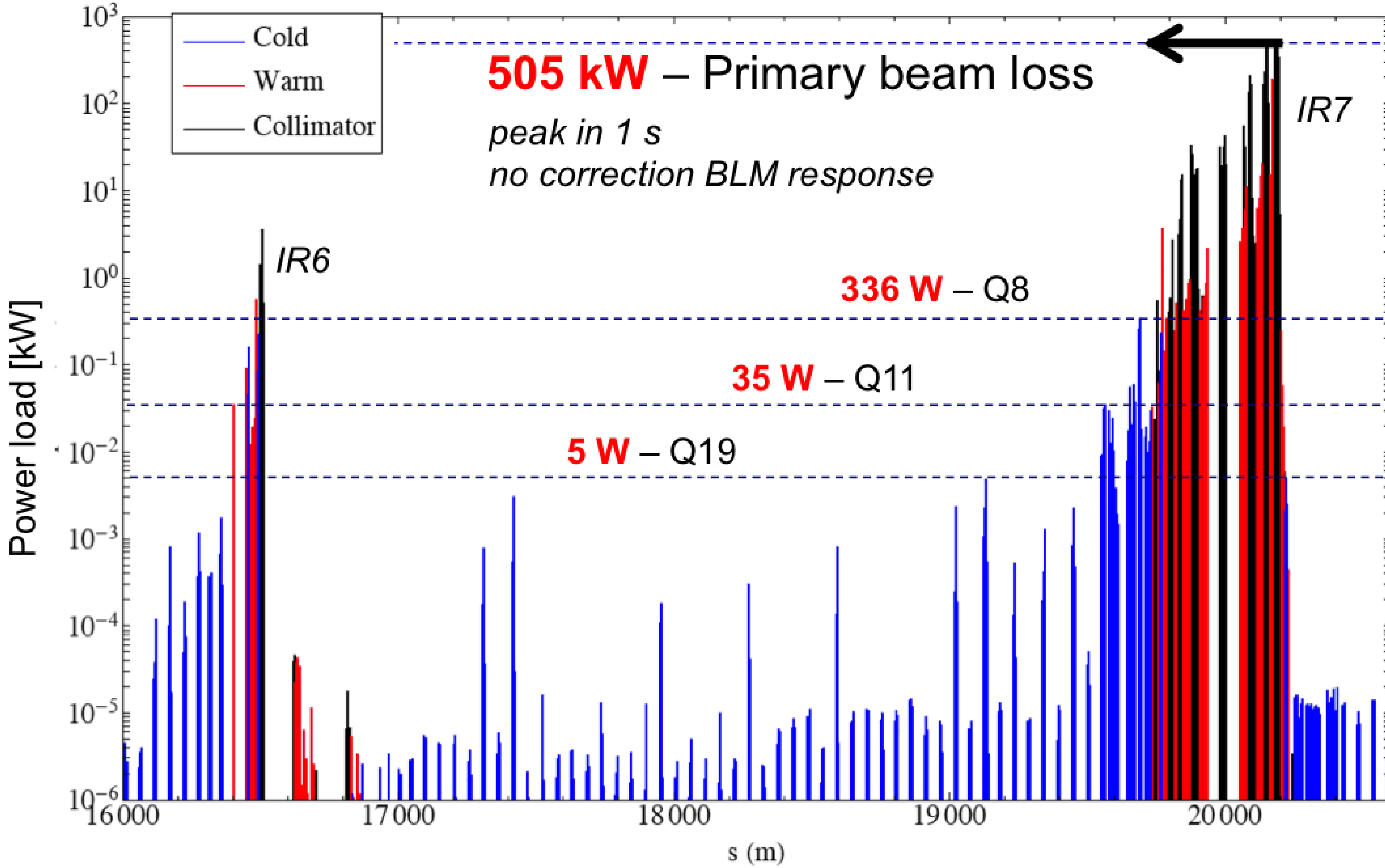
Keywords: LHC, beam-beam

B1: IP1, IP5, 450 GeV, tune shift > 0.015 per IP



R. Assmann

Collimation: Leakage into SC Magnets



3.5 TeV operational collimator settings (not best possible)

No quench of any magnet!

CERN-ATS-Note-2011-036 MD

2011-05-24

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Summary of MD on nominal collimator settings

R.W. Assmann, R. Bruce, F. Burkart, M. Cauchi, D. Deboy, L. Lari, E. Metral, N. Mounet, S. Redaelli, A. Rossi, B. Salvant, G. Valentino, D. Wollmann

Keywords: Collimator settings, collimator impedance

	TCP IR7	TCSG IR7	TCLA IR7	TCSG IR6	TCDQ IR6
2010 settings	5.7	8.5	17.7	9.3	10. - 10.6
Nominal	5.7	6.7	9.7	7.2	7.7
Tight B1	4.0	6.0	8.0	7.0	7.5
Tight B2	4.0	5.0	7.2	6.2	6.7

Settings in nominal beam sigma at 3.5 TeV

Settings in mm at 3.5 TeV for tightest collimator settings achieved (beam 1)

R. Assmann

(In) Efficiency Reached *(Coll → SC Magnet)*

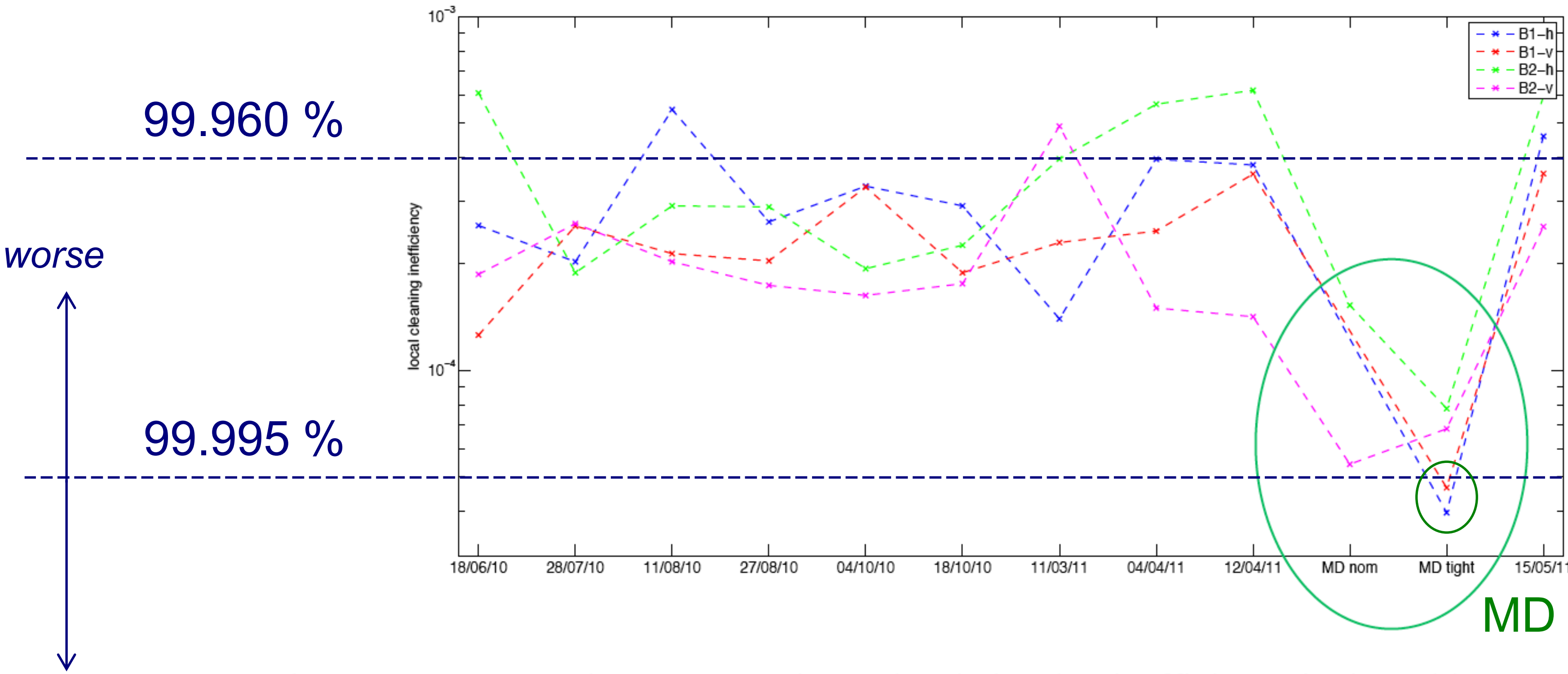
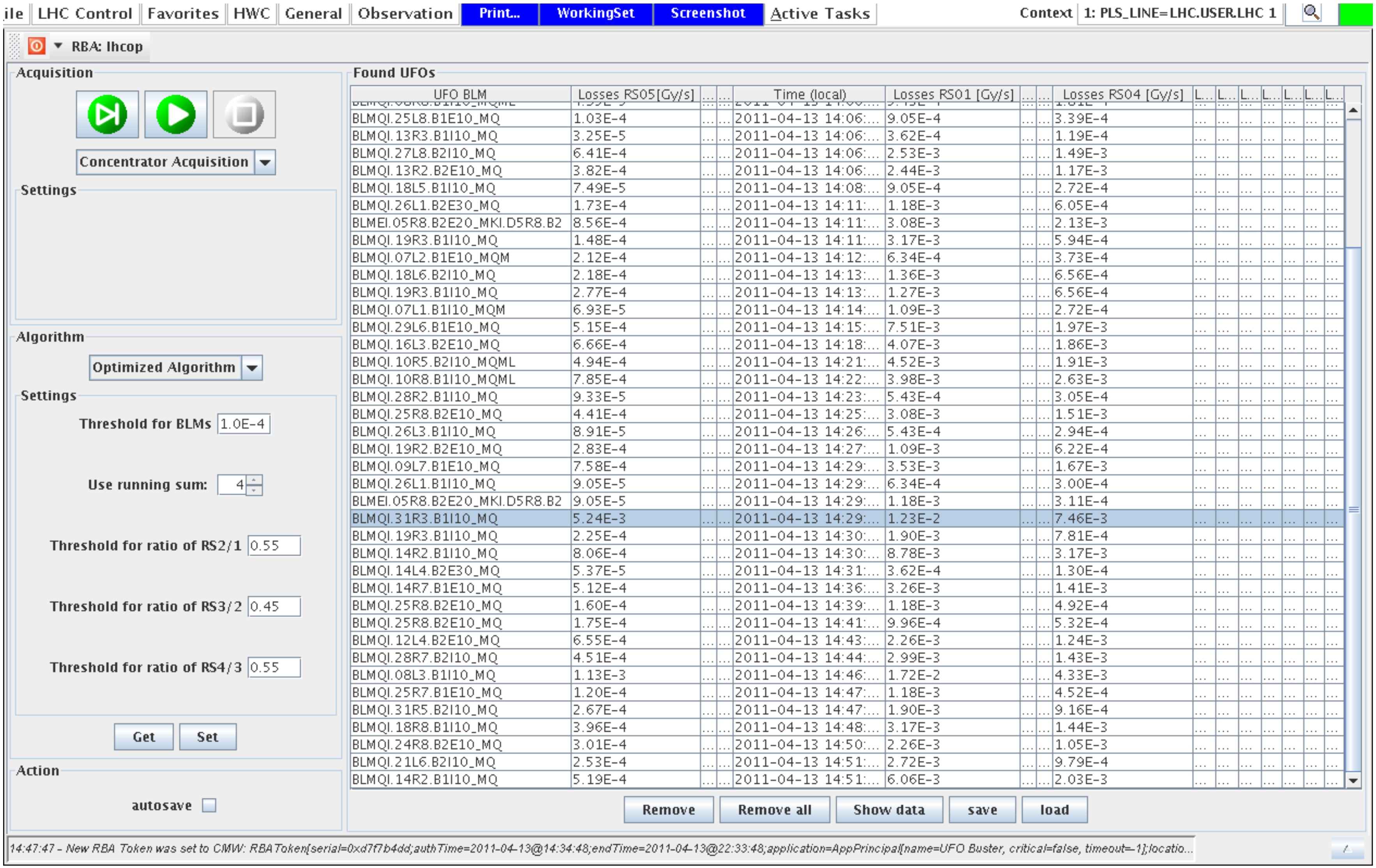


Figure 5: Beam 1 and Beam 2 maximum local cleaning inefficiency in the cold parts of the LHC at 3.5TeV over about one year operation. The results from this MD are contained in the second and third sets of points from the right, where a clear decrease can be observed.

UFO’s: 90 in 90 minutes



UFO BLM	Losses RS05[Gy/s]	...	...	Time (local)	Losses RS01 [Gy/s]	...	...	Losses RS04 [Gy/s]	L...	L...	L...	L...	L...	L...	L...
BLMQI.25L8.B1E10_MQ	1.03E-4	...	...	2011-04-13 14:06:...	9.05E-4	...	...	3.39E-4	...	...	...	...	...	...	...
BLMQI.13R3.B1I10_MQ	3.25E-5	...	...	2011-04-13 14:06:...	3.62E-4	...	...	1.19E-4	...	...	...	...	...	...	...
BLMQI.27L8.B2I10_MQ	6.41E-4	...	...	2011-04-13 14:06:...	2.53E-3	...	...	1.49E-3	...	...	...	...	...	...	...
BLMQI.13R2.B2E10_MQ	3.82E-4	...	...	2011-04-13 14:06:...	2.44E-3	...	...	1.17E-3	...	...	...	...	...	...	...
BLMQI.18L5.B1I10_MQ	7.49E-5	...	...	2011-04-13 14:08:...	9.05E-4	...	...	2.72E-4	...	...	...	...	...	...	...
BLMQI.26L1.B2E30_MQ	1.73E-4	...	...	2011-04-13 14:11:...	1.18E-3	...	...	6.05E-4	...	...	...	...	...	...	...
BLMEI.05R8.B2E20_MKI.D5R8.B2	8.56E-4	...	...	2011-04-13 14:11:...	3.08E-3	...	...	2.13E-3	...	...	...	...	...	...	...
BLMQI.19R3.B1I10_MQ	1.48E-4	...	...	2011-04-13 14:11:...	3.17E-3	...	...	5.94E-4	...	...	...	...	...	...	...
BLMQI.07L2.B1E10_MQM	2.12E-4	...	...	2011-04-13 14:12:...	6.34E-4	...	...	3.73E-4	...	...	...	...	...	...	...
BLMQI.18L6.B2I10_MQ	2.18E-4	...	...	2011-04-13 14:13:...	1.36E-3	...	...	6.56E-4	...	...	...	...	...	...	...
BLMQI.19R3.B1I10_MQ	2.77E-4	...	...	2011-04-13 14:13:...	1.27E-3	...	...	6.56E-4	...	...	...	...	...	...	...
BLMQI.07L1.B1I10_MQM	6.93E-5	...	...	2011-04-13 14:14:...	1.09E-3	...	...	2.72E-4	...	...	...	...	...	...	...
BLMQI.29L6.B1E10_MQ	5.15E-4	...	...	2011-04-13 14:15:...	7.51E-3	...	...	1.97E-3	...	...	...	...	...	...	...
BLMQI.16L3.B2E10_MQ	6.66E-4	...	...	2011-04-13 14:18:...	4.07E-3	...	...	1.86E-3	...	...	...	...	...	...	...
BLMQI.10R5.B2I10_MQML	4.94E-4	...	...	2011-04-13 14:21:...	4.52E-3	...	...	1.91E-3	...	...	...	...	...	...	...
BLMQI.10R8.B1I10_MQML	7.85E-4	...	...	2011-04-13 14:22:...	3.98E-3	...	...	2.63E-3	...	...	...	...	...	...	...
BLMQI.28R2.B1I10_MQ	9.33E-5	...	...	2011-04-13 14:23:...	5.43E-4	...	...	3.05E-4	...	...	...	...	...	...	...
BLMQI.25R8.B2E10_MQ	4.41E-4	...	...	2011-04-13 14:25:...	3.08E-3	...	...	1.51E-3	...	...	...	...	...	...	...
BLMQI.26L3.B1I10_MQ	8.91E-5	...	...	2011-04-13 14:26:...	5.43E-4	...	...	2.94E-4	...	...	...	...	...	...	...
BLMQI.19R2.B2E10_MQ	2.83E-4	...	...	2011-04-13 14:27:...	1.09E-3	...	...	6.22E-4	...	...	...	...	...	...	...
BLMQI.09L7.B1E10_MQ	7.58E-4	...	...	2011-04-13 14:29:...	3.53E-3	...	...	1.67E-3	...	...	...	...	...	...	...
BLMQI.26L1.B1I10_MQ	9.05E-5	...	...	2011-04-13 14:29:...	6.34E-4	...	...	3.00E-4	...	...	...	...	...	...	...
BLMEI.05R8.B2E20_MKI.D5R8.B2	9.05E-5	...	...	2011-04-13 14:29:...	1.18E-3	...	...	3.11E-4	...	...	...	...	...	...	...
BLMQI.31R3.B1I10_MQ	5.24E-3	...	...	2011-04-13 14:29:...	1.23E-2	...	...	7.46E-3	...	...	...	...	...	...	...
BLMQI.19R3.B1I10_MQ	2.25E-4	...	...	2011-04-13 14:30:...	1.90E-3	...	...	7.81E-4	...	...	...	...	...	...	...
BLMQI.14R2.B1I10_MQ	8.06E-4	...	...	2011-04-13 14:30:...	8.78E-3	...	...	3.17E-3	...	...	...	...	...	...	...
BLMQI.14L4.B2E30_MQ	5.37E-5	...	...	2011-04-13 14:31:...	3.62E-4	...	...	1.30E-4	...	...	...	...	...	...	...
BLMQI.14R7.B1E10_MQ	5.12E-4	...	...	2011-04-13 14:36:...	3.26E-3	...	...	1.41E-3	...	...	...	...	...	...	...
BLMQI.25R8.B2E10_MQ	1.60E-4	...	...	2011-04-13 14:39:...	1.18E-3	...	...	4.92E-4	...	...	...	...	...	...	...
BLMQI.25R8.B2E10_MQ	1.75E-4	...	...	2011-04-13 14:41:...	9.96E-4	...	...	5.32E-4	...	...	...	...	...	...	...
BLMQI.12L4.B2E10_MQ	6.55E-4	...	...	2011-04-13 14:43:...	2.26E-3	...	...	1.24E-3	...	...	...	...	...	...	...
BLMQI.28R7.B2I10_MQ	4.51E-4	...	...	2011-04-13 14:44:...	2.99E-3	...	...	1.43E-3	...	...	...	...	...	...	...
BLMQI.08L3.B1I10_MQ	1.13E-3	...	...	2011-04-13 14:46:...	1.72E-2	...	...	4.33E-3	...	...	...	...	...	...	...
BLMQI.25R7.B1E10_MQ	1.20E-4	...	...	2011-04-13 14:47:...	1.18E-3	...	...	4.52E-4	...	...	...	...	...	...	...
BLMQI.31R5.B2I10_MQ	2.67E-4	...	...	2011-04-13 14:47:...	1.90E-3	...	...	9.16E-4	...	...	...	...	...	...	...
BLMQI.18R8.B1I10_MQ	3.96E-4	...	...	2011-04-13 14:48:...	3.17E-3	...	...	1.44E-3	...	...	...	...	...	...	...
BLMQI.24R8.B2E10_MQ	3.01E-4	...	...	2011-04-13 14:50:...	2.26E-3	...	...	1.05E-3	...	...	...	...	...	...	...
BLMQI.21L6.B2I10_MQ	2.53E-4	...	...	2011-04-13 14:51:...	2.72E-3	...	...	9.79E-4	...	...	...	...	...	...	...
BLMQI.14R2.B1I10_MQ	5.19E-4	...	...	2011-04-13 14:51:...	6.06E-3	...	...	2.03E-3	...	...	...	...	...	...	...

Single Event Upset (SEU)

- Primary ion beam losses are intercepted at the collimators
- Several features contribute to more severe ion loss problems
  - Nuclear physics: Ion dissociation and fragmentation reduce cleaning efficiency by factor ~100 when compared to protons (predicted since years, now confirmed).
    - Collimation upgrade (DS collimators) will solve this.
  - Ion beam lifetimes factor ~3-6 lower than for proton beams
    - Not yet understood
- Effects are clearly seen in Radmon monitors
- And in the equipment!
  - "QPS OK" lost on Q9.L7, communication to quench detector → Single Event Upset ("SEU"). Upgraded firmware in dispersion suppressors of LSS7.
  - "QPS OK" lost on Q9.R7 and Q9.L7, FIP communication → SEU? No work-around available at the moment

Achievements and parameters

- Status June 16
  - Highest luminosity per fill: 46.61 pb^{-1}
  - Highest luminosity in 1 day: 56.33 pb^{-1}
  - Production in a week: 229.64 pb^{-1}
  - Average bunch intensity: 1.2e11 (slightly lowered)
  - Typical luminosity: 1.1e33 (slightly lowered)
  - Number of bunches/beam: 1092
  - β^*: 1.5 m
- Immediate improvements:
  - Number of bunches/beam: 1380 (2 steps of 144b)
- Medium term improvements:
  - Increase bunch charge: up to 2e11?
  - Decrease emittance: down to 1 mm?
  - Go to 25 ns spacing: up to 2808 b

This Year

- Reached so far 1 fb^{-1}
- Official 2010 goal has been achieved.
- Weekly production: 200 – 250 pb^{-1}
- 16 weeks ahead
  - 4-5 fb^{-1} total are not excluded if we can keep running like now (no failure, …)
  - Plus any additional gains from MD results…

LHC: Longer Term Future

- 2010 – 2012: Physics run at 3.5 TeV
- 2013 – 2014: Shutdown: Repair of interconnects
- 2014 – 2017: Physics run at 6.5/7 TeV
- 2017 – 2018: Shutdown

- Long term:
  - HL-LHC upgrade — 2023? 5-10 times higher luminosity, same beam energy
  - HE-LHC upgrade — higher beam energy, magnets do not exist yet…

Overall Strategy >2016 (Dates Indicative)

2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	etc.
														Increase Beam Energy to 16.5 TeV					
				New interaction region (β^* to 0.2m, luminosity leveling)															
Increase beam brightness																			
Ultimate				**HL-LHC**										**HE-LHC**					
$2.3\ 10^{34}$				**$5\ 10^{34}$**										**$2\ 10^{34}$**					
$\leq 100\ fb^{-1}/yr$				**$\leq 200\ fb^{-1}/yr$**										**$\leq 100\ fb^{-1}/yr$**					

HE-LHC

"First Thoughts on a Higher-Energy LHC"

Ralph Assmann, Roger Bailey, Oliver Brüning, Octavio Dominguez Sanchez, Gijs de Rijk, Miguel Jimenez, Steve Myers, Lucio Rossi, Laurent Tavian, Ezio Todesco, Frank Zimmermann

Abstract:
We report preliminary considerations for a higher-energy LHC ("HE-LHC") with about 16.5 TeV beam energy and 20-T dipole magnets. In particular we sketch the proposed principal parameters, luminosity optimization schemes, the new HE-LHC injector, the magnets required, cryogenics system, collimation issues, and requirements from the vacuum system.

Table of Contents:

Provisional parameter list for LHC energy upgrade 33 TeV centre-of-mass energy

	nominal LHC	HE-LHC
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40
#bunches / beam	2808	1404
bunch population [10^{11}]	1.15	1.29
initial transverse normalized emittance [μm]	3.75	3.75 (x), 1.84 (y)
number of IPs contributing to tune shift	3	2
maximum total beam-beam tune shift	0.01	0.01
IP beta function [m]	0.55	1.0 (x), 0.43 (y)
full crossing angle [μrad]	285 (9.5 $\sigma_{x,y}$)	175 (12 σ_{x0})
stored beam energy [MJ]	362	479
SR power per ring [kW]	3.6	62.3
longitudinal SR emittance damping time [h]	12.9	0.98
events per crossing	19	76
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0
beam lifetime [h]	46	13
integrated luminosity over 10 h [fb^{-1}]	0.3	0.5

Thanks for your attention…