Under the LHC Bonnet

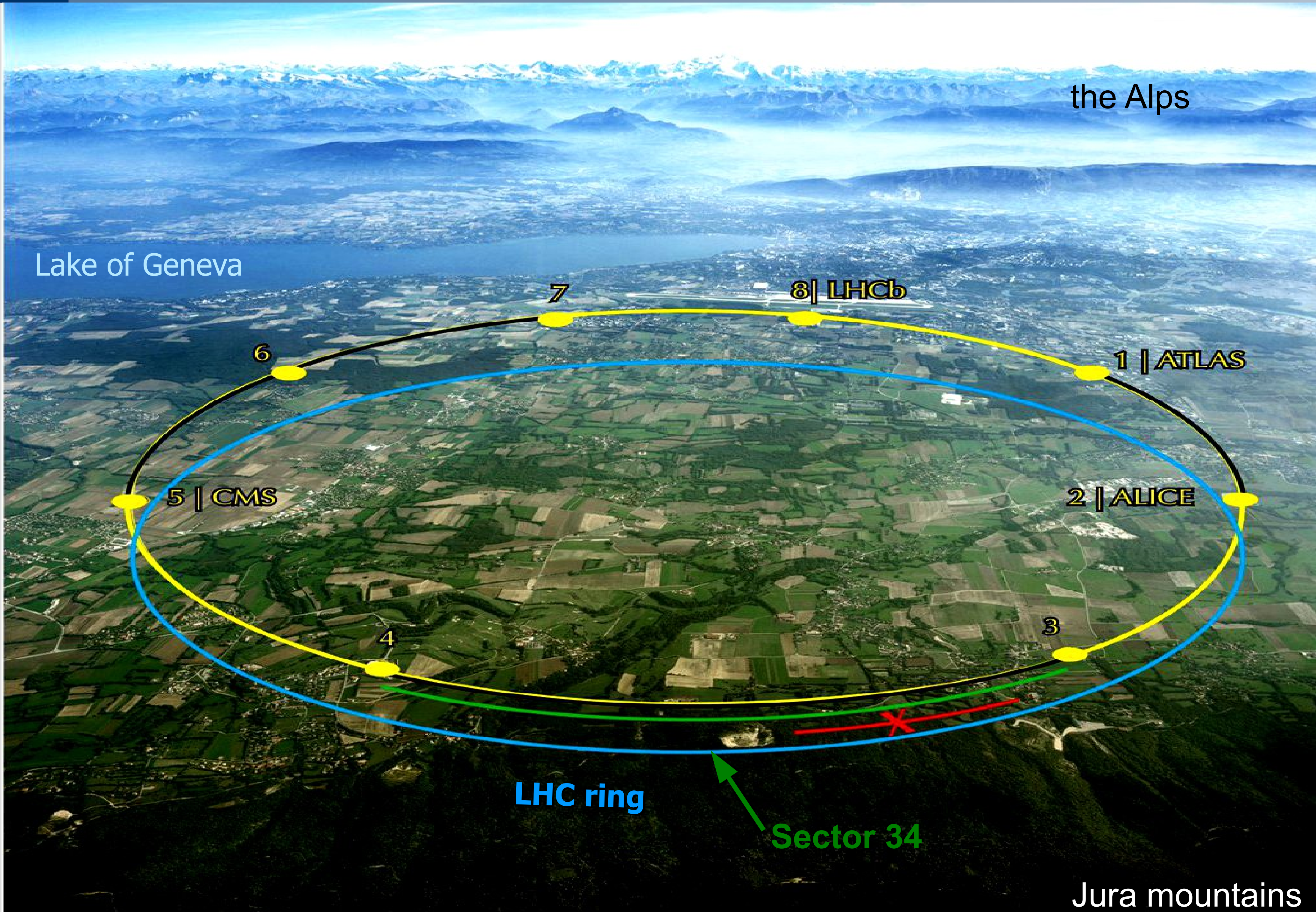
Commissioning with Beam in 2010

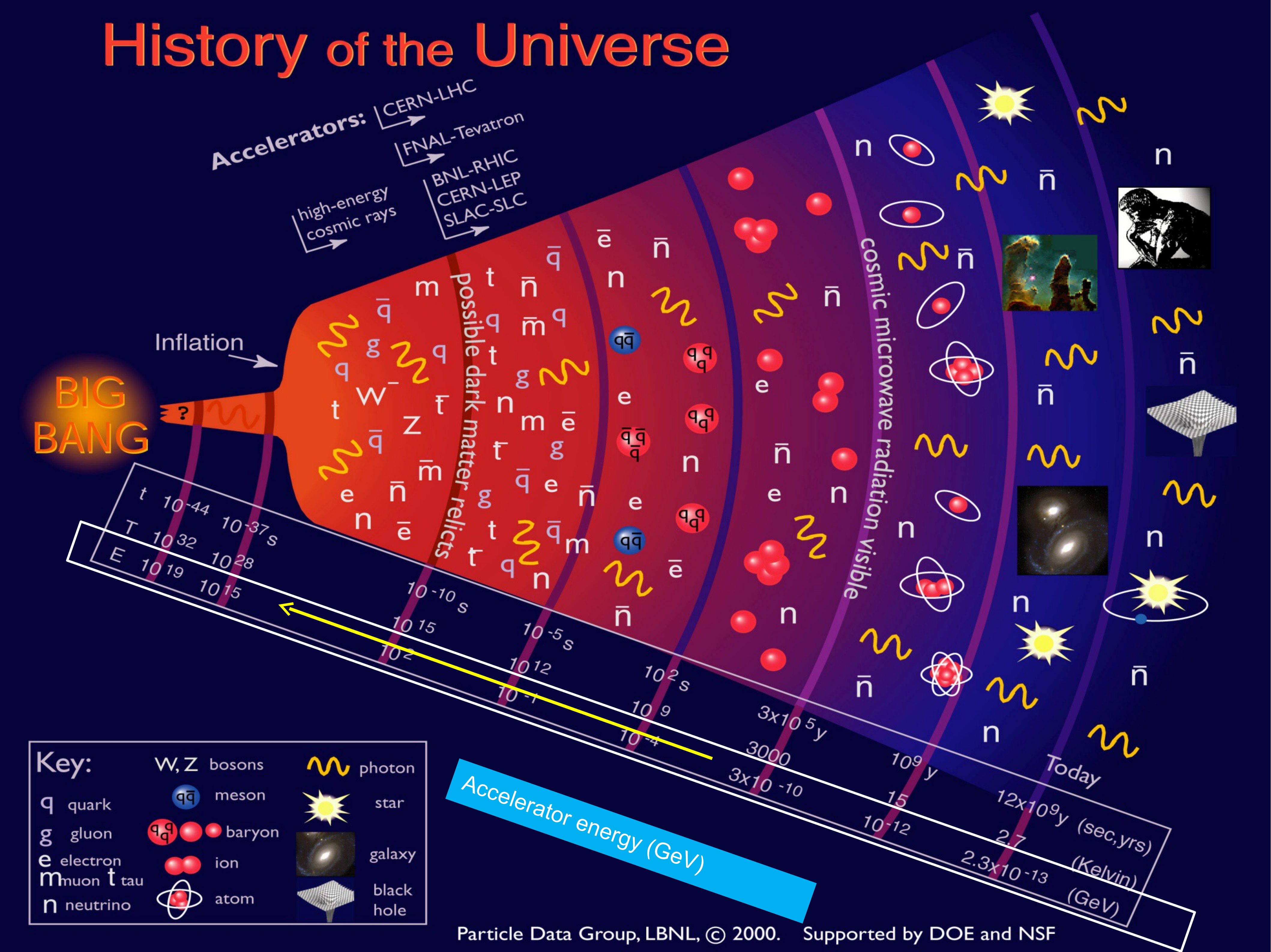
An impression by Ralph J. Steinhagen, CERN

Overview

- Part I - LHC Commissioning with Circulating Beam
  - Milestones of 60 hours of LHC Beam
  - 'The September 19th Incident in LHC Sector 34'
  - Analysis, consolidation and response measures
- Part II – Re-Commissioning with Beam in 2010
  - Some impression on operation with
    - Proton beams
    - Ions beams
  - Some selected “puzzles” we are working on...

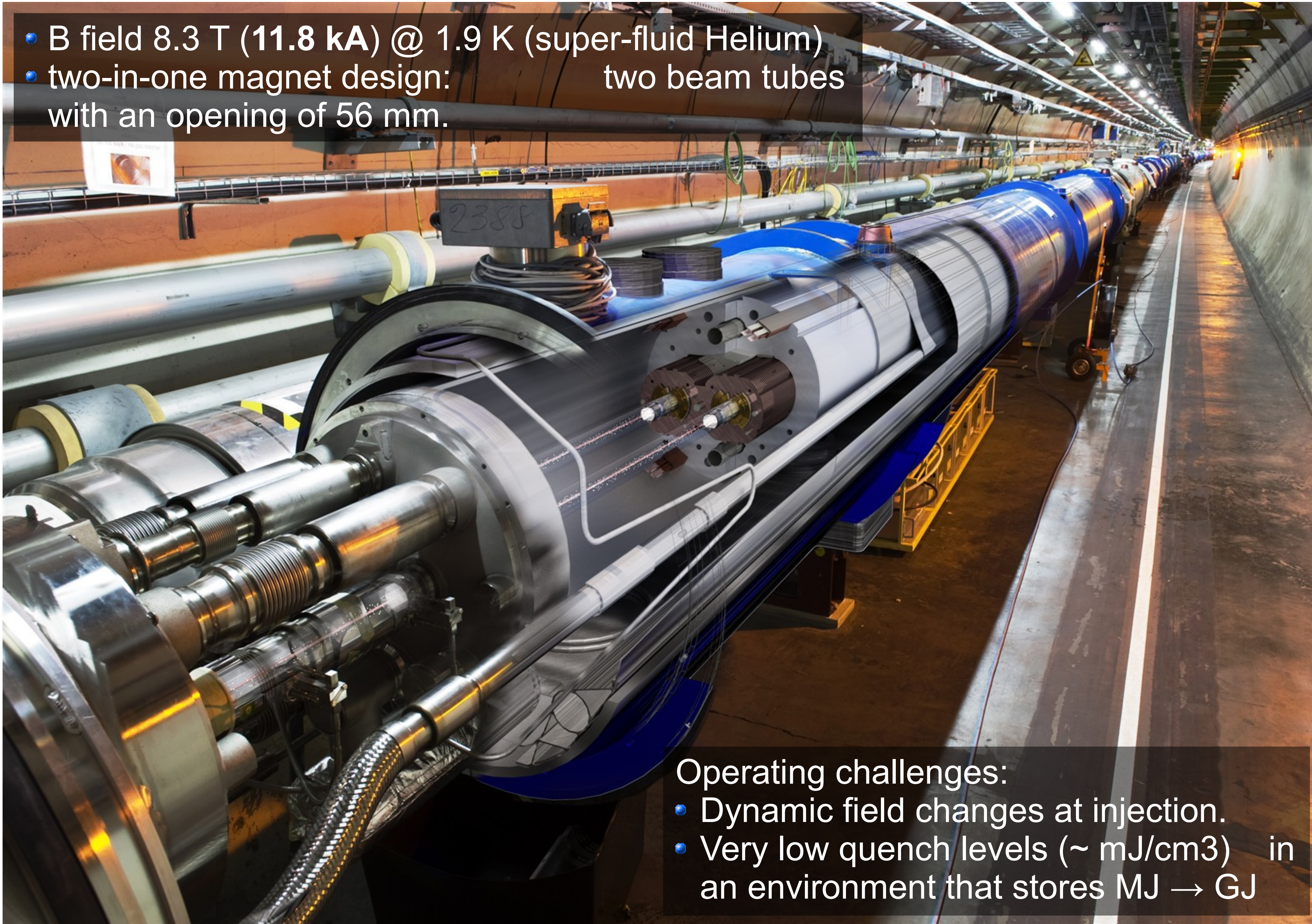
The Large Hadron Collider LHC
Installed in the LEP tunnel, 27 km, Depth of 70-140 m



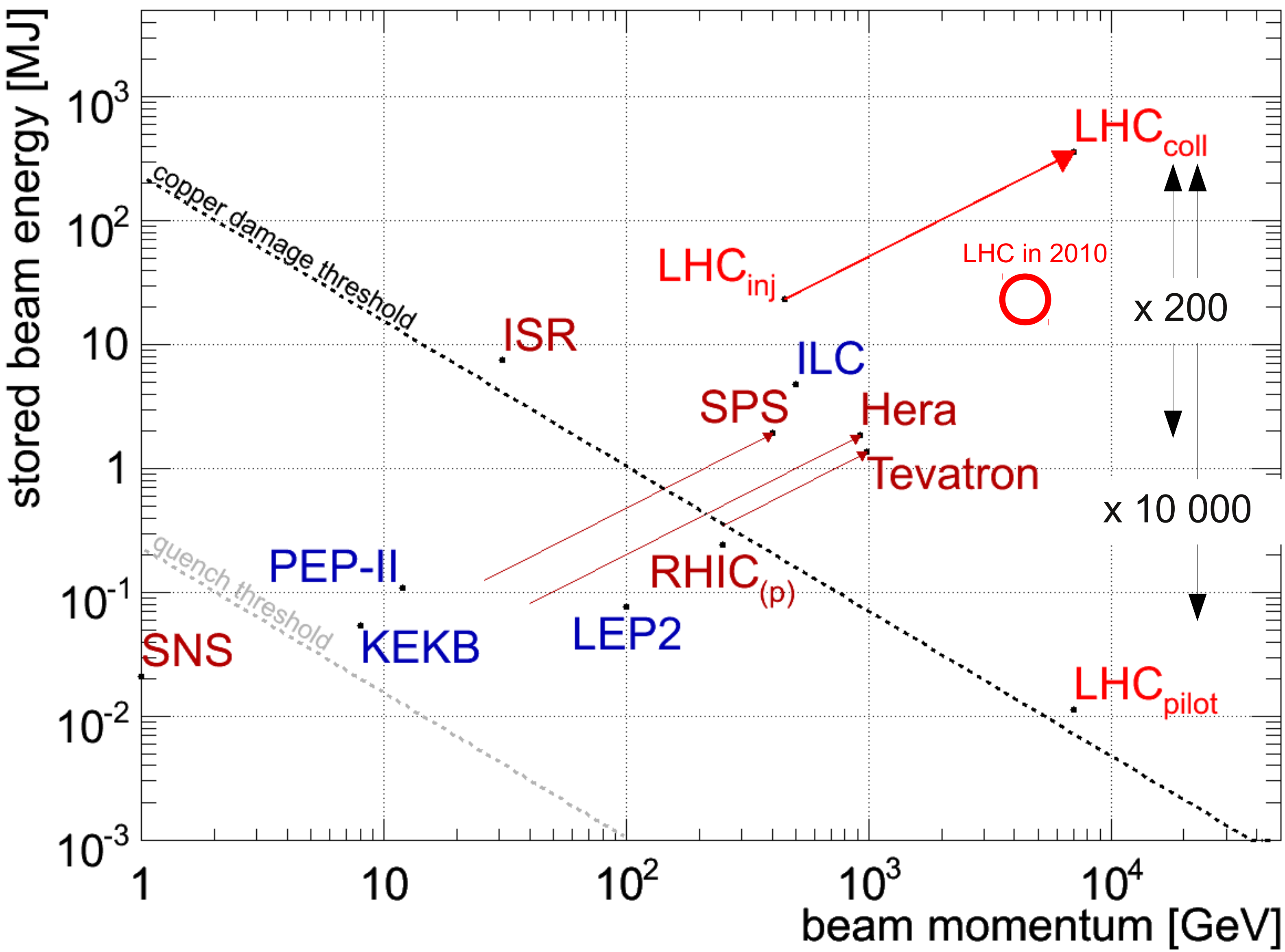

History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10 -44 10 -37 s 10 -10 s 10 -5 s 10 2 s 3x10 5 y 10 9 y Today 12x10 9 y (sec,yrs)
T 10 32 10 28 10 15 10 12 10 9 3000 15 2.7 (Kelvin)
E 10 19 10 15 10 2 10 -1 10 -4 3x10 -10 10 -12 2.3x10 -13 (GeV)
Accelerator energy (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

27 km Circumference – 1232 LHC dipole magnet

- B field 8.3 T (**11.8 kA**) @ 1.9 K (super-fluid Helium)
- two-in-one magnet design: two beam tubes with an opening of 56 mm.



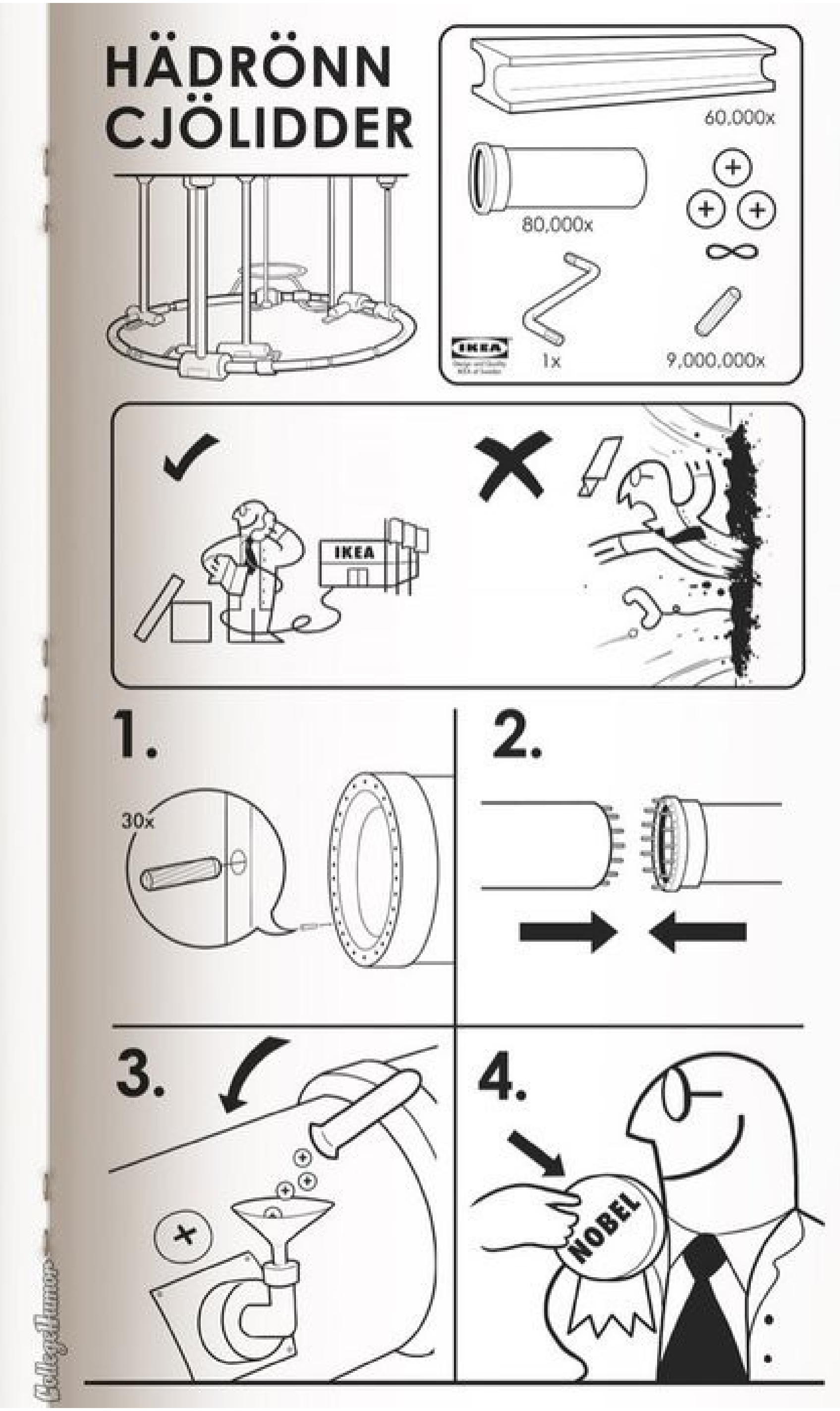
Operating challenges:
- Dynamic field changes at injection.
- Very low quench levels (~ mJ/cm3) in an environment that stores MJ → GJ



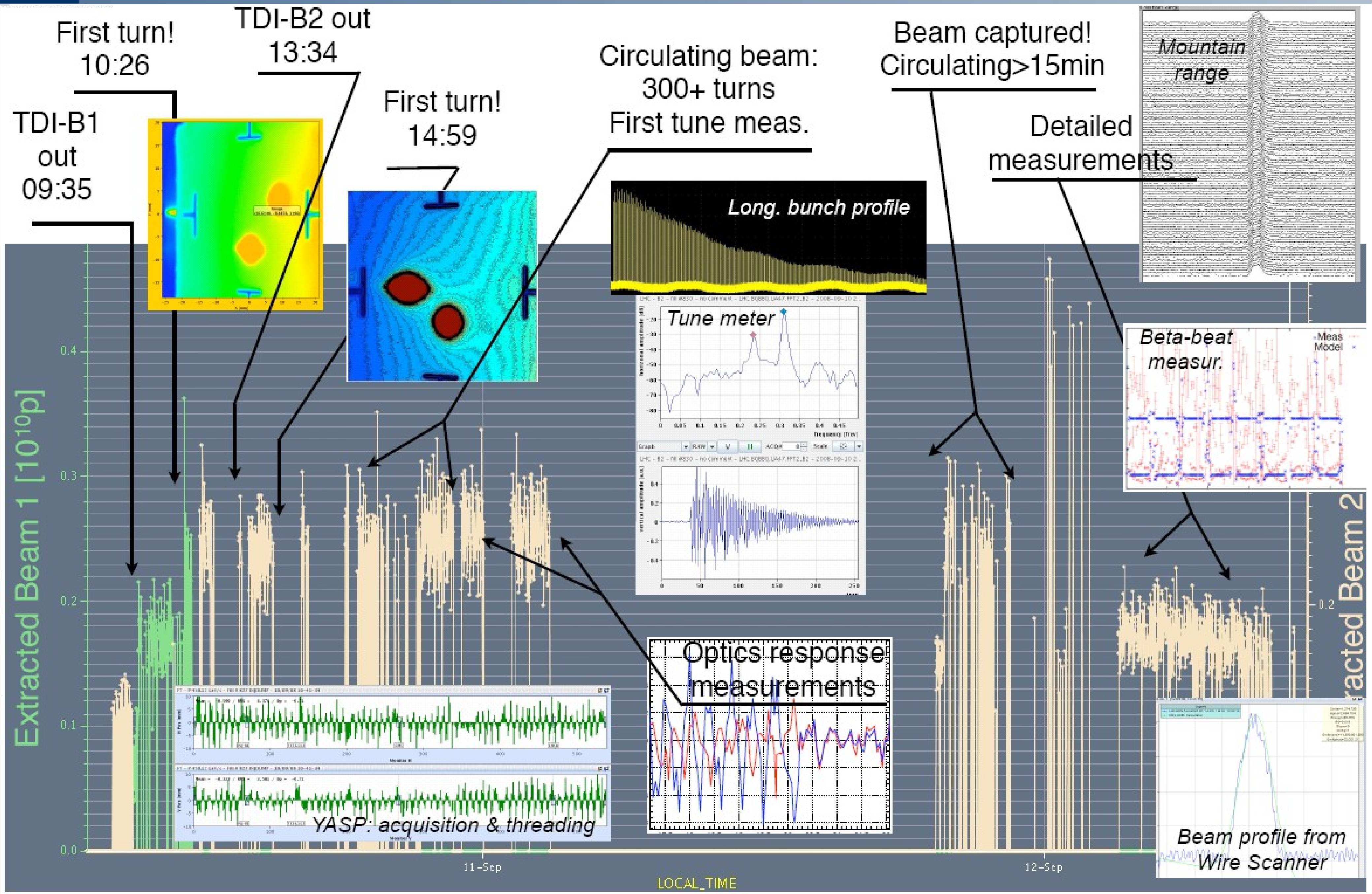
- LHC requires respect and vigilant treatment ...not much margin to err

see Chamonix XIV: “Damage levels - Comparison of Experiment and simulation” and PAC'05 for details

It all looks so easy...



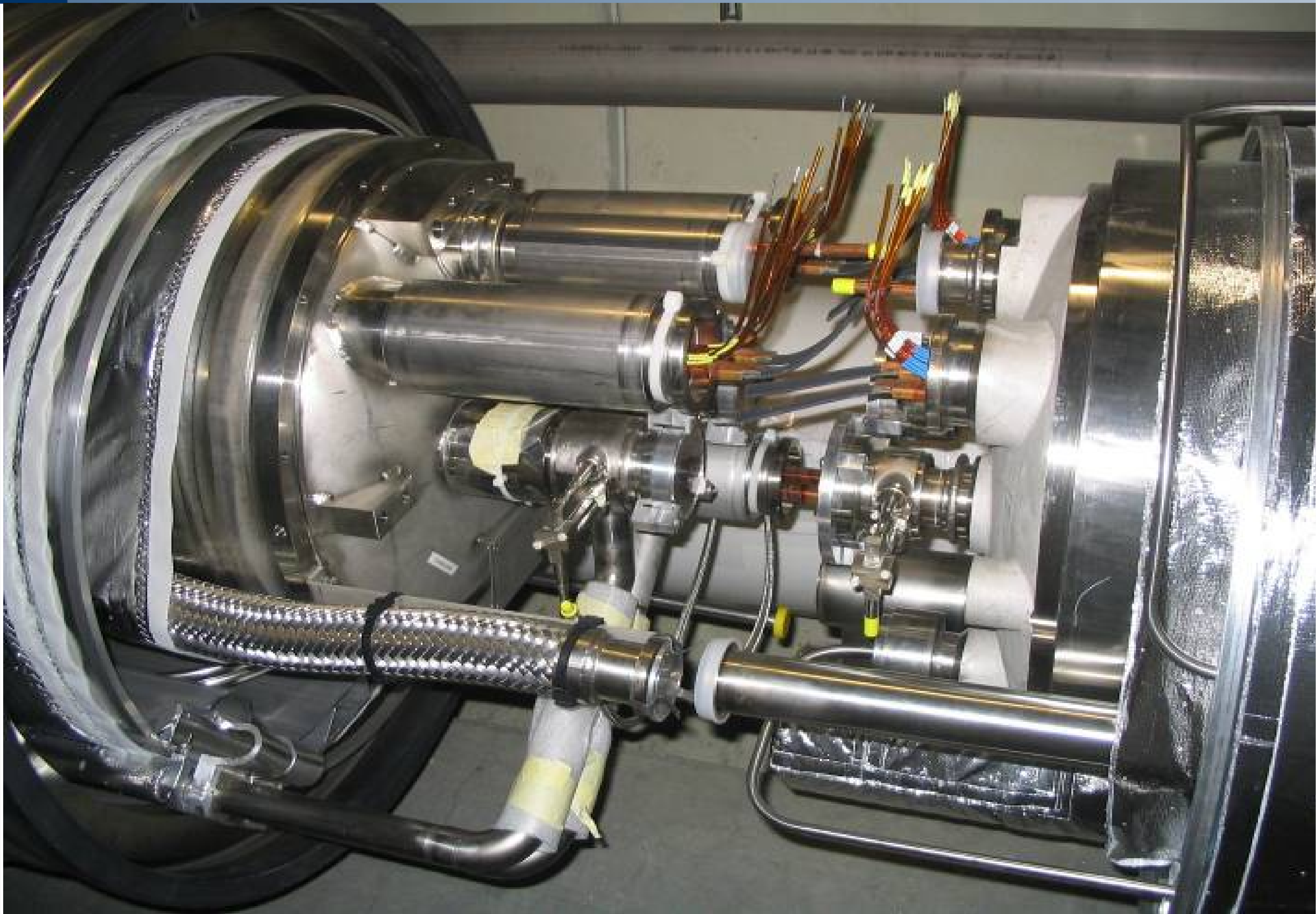
10th September 2008
Milestones of 50 Hours of LHC Beam Operation



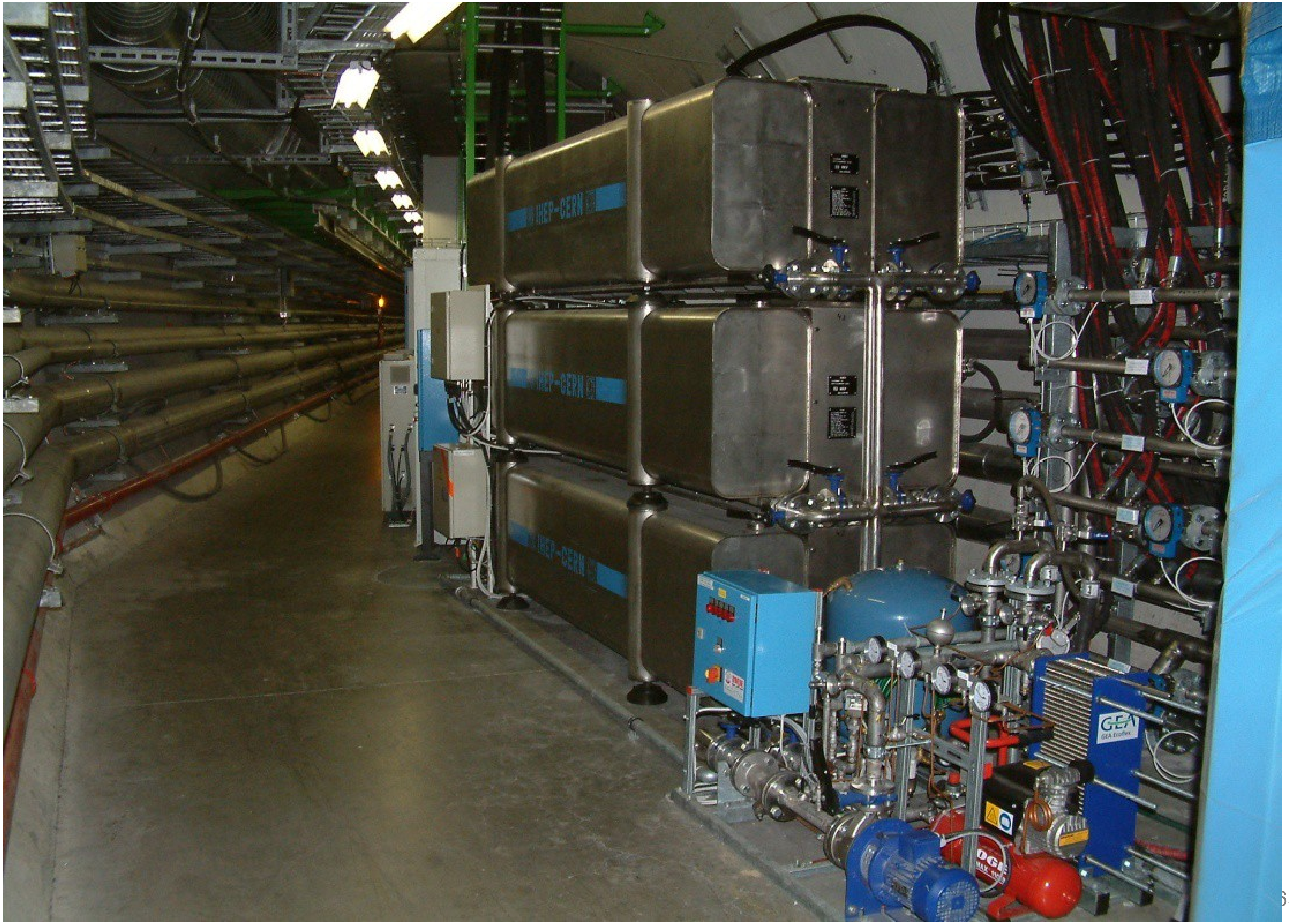
10th of September 2008 – CERN Control (Show) Room

Three fantastic days, all went like a dream with beam…

Risk without Beam:
While preparing the last sector for to 5 TeV operation ...

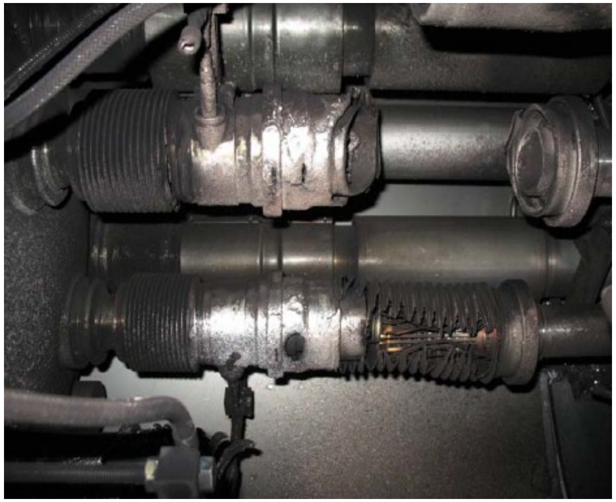


Dump Resistors



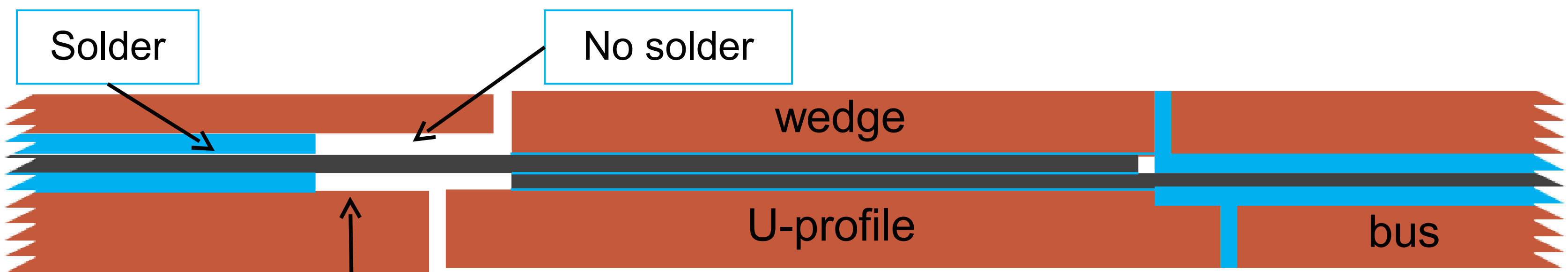
19th September 2008 – 11:18:36.798 - Impressions

QQBI.27R3

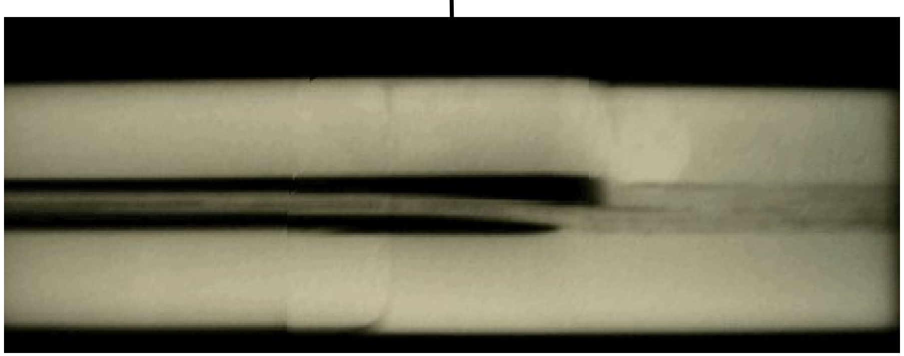


Magnet Interconnection

- The copper stabilizes the bus bar in the event of a cable quench (=bypass for the current while the energy is extracted from the circuit).
  - Protection system in place in 2008 not sufficiently sensitive.
- A copper bus bar with reduced continuity coupled to a superconducting cable badly soldered to the stabiliser can lead to a serious incident.

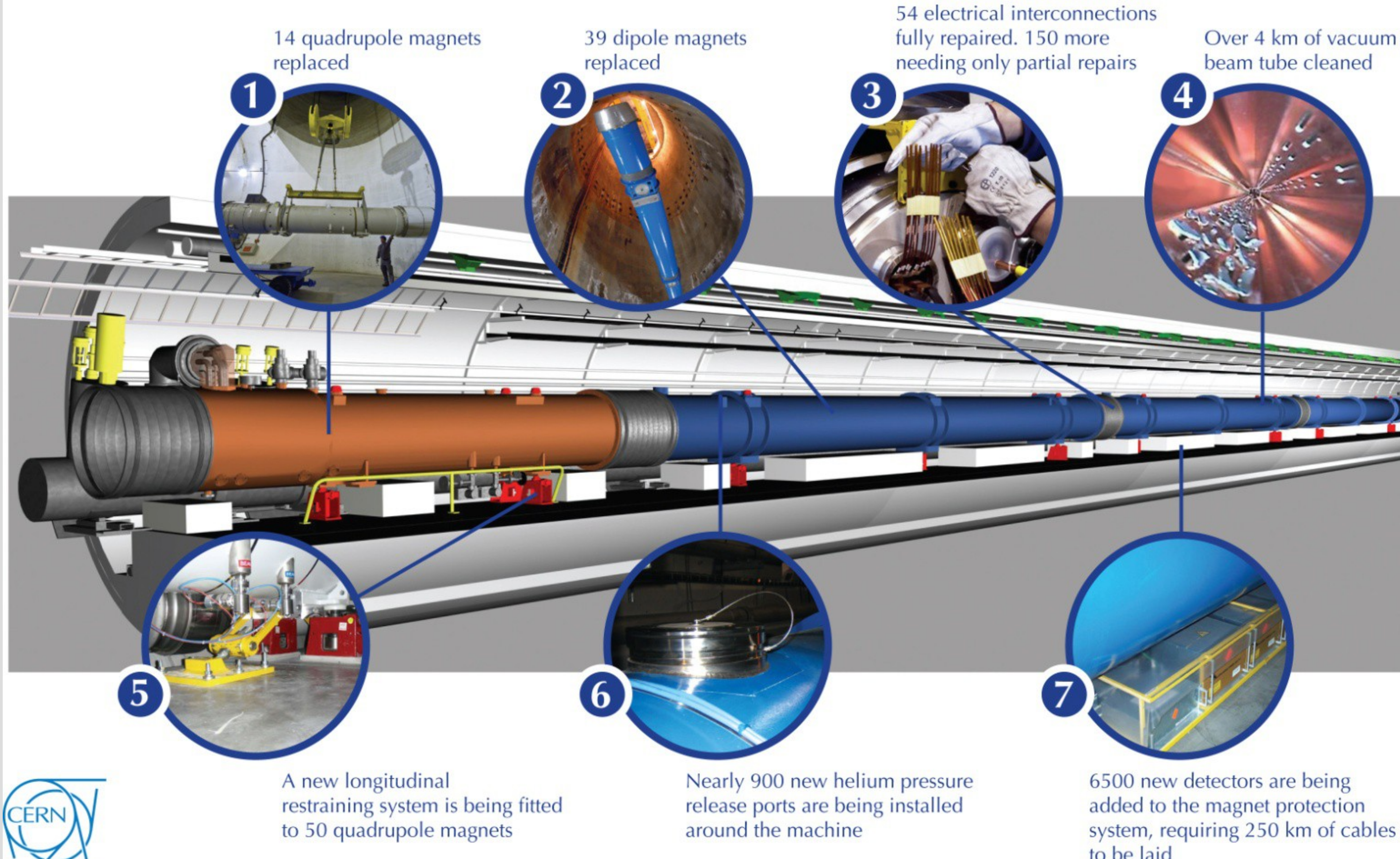


X-ray of joint



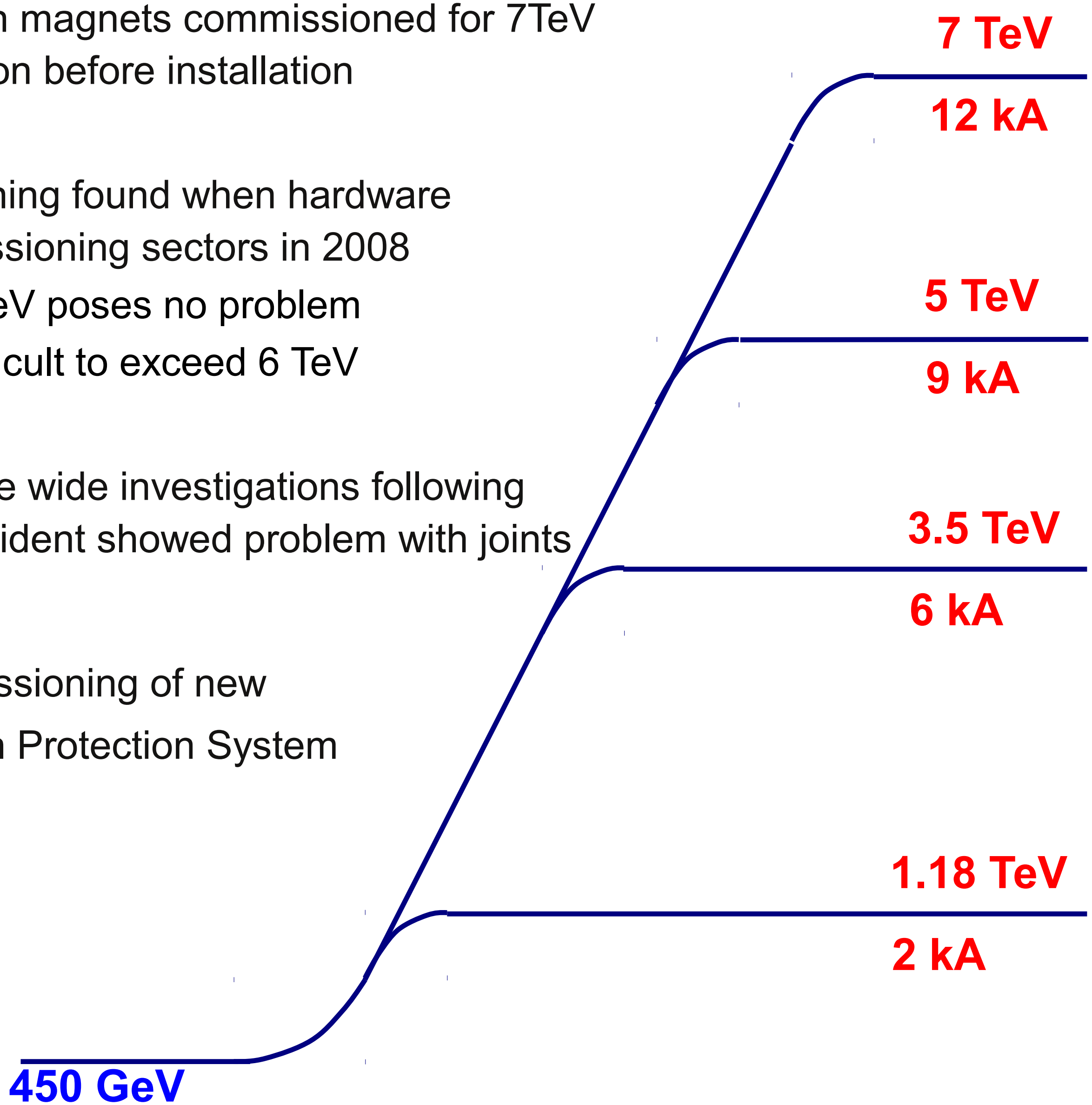
- Typical joint resistances: 0.3 nΩ @1.9K (100 µΩ @300K)
- During repair, inspection of the joints revealed systematic voids caused by the welding procedure.

LHC repair and consolidation



LHC target energy: the way down

- All main magnets commissioned for 7TeV operation before installation
- De-training found when hardware commissioning sectors in 2008
  - 5 TeV poses no problem
  - Difficult to exceed 6 TeV
- Machine wide investigations following S34 incident showed problem with joints
- Commissioning of new Quench Protection System (nQPS)



When	Why
2002-2007	Design
Summer 2008	De-training
Late 2008 Spring 2009	Joints
Nov. 2009	nQPS

Steve Myer's Conclusion during the Chamonix Workshop:

"A ship in harbour is safe, but that is not what ships are built for.", **John Augustus Shedd**, *Salt from My Attic, 1928*

LHC 2009 → 2010 Re-Commissioning

- Clear priorities
  - Re-commission the repaired sectors and new more sensitive quench protection system with beam
  - lay the foundations for 2011 and the delivery of 1 fb^{-1}
    ↔ competitive high-energy-physics (Tevatron)
    - peak luminosity target 10^{32} $cm^{-2}s^{-1}$
  - Gain solid operational experience of injecting, ramping, squeezing and establishing stable beams
  - Steady running at or around 1 MJ for an extended period
  - Perform a safe, phased increase in intensity with validation and a running period at each step

November 2009
After 14 month of Repair, Consolidation and HW Re-Commissioning

- Great relief on November 20th when both beams circulated again
- November 29th reaching 1.2 TeV for the first time:

CHENNAI

THE HINDU • TUESDAY, DECEMBER 1, 2009

Atom-smasher sets world record

GENEVA: The "Big Bang" experiment at CERN near Geneva scored a world record on Monday by accelerating beams to the highest energy ever achieved in a particle collider, the research centre announced. Scientists at CERN, the European Organisation for Nuclear Research, said the achievement marked a major milestone on the way to tests next year which they hope will unlock secrets of the origins and make-up of the universe.

The energy of the twin beams circulated around 27 km tunnels deep underground went, at 1.18 trillion electric volts (TeV), well past the previous highest — just under 1 TeV — in a collider at the U.S. Fermi National Accelerator Laboratory.

The achievement in the Large Hadron Collider (LHC) came 10 days after the world's largest scientific experiment was restarted following an accident soon after its launch in September 2008.

"We are still coming to …

HIGH-ENERGY FEAT: *Scientists celebrate at CERN on Monday.* – PHOTO: AFP

… Swiss border — leaves some way to go before the real "Big Bang" experiments can begin.

The object of these is to smash particles together at a force of some 7 TeV and create conditions one billionth …

… around the world.

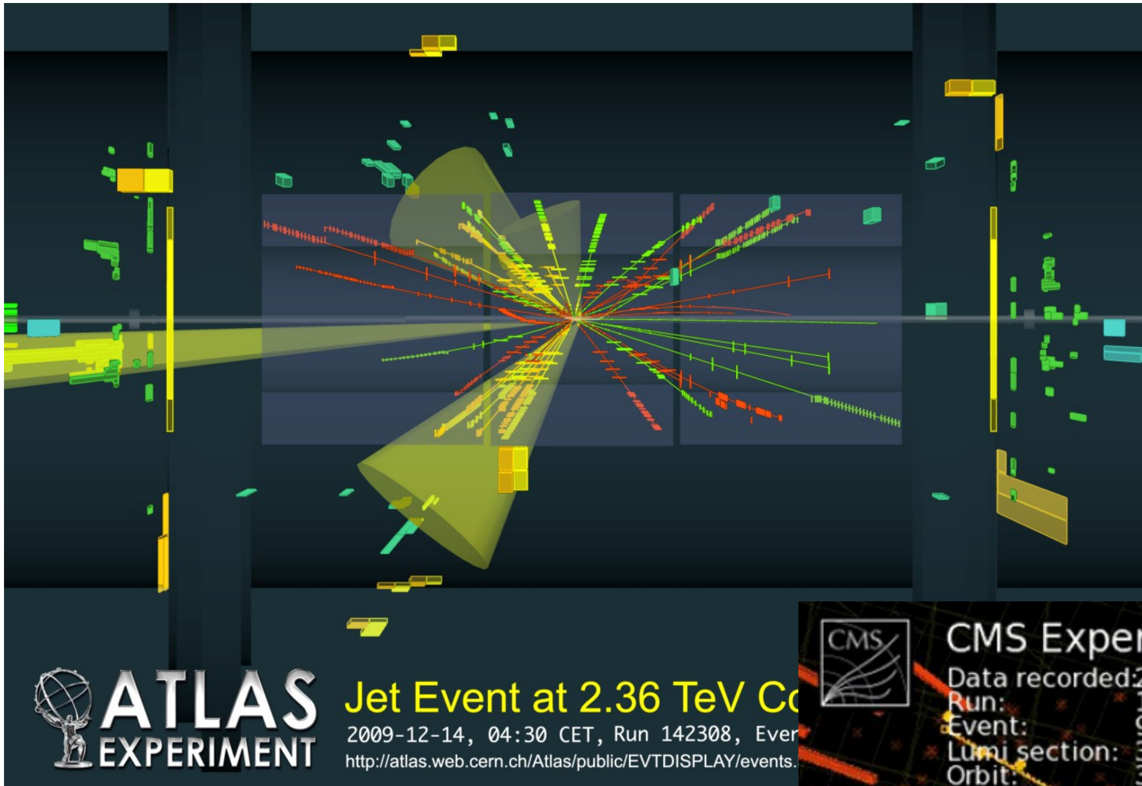
Scientists hope to learn how matter, and what is called anti-matter, was created and whether the so-called "Higgs Boson" — which Scottish physicist Peter Higgs …

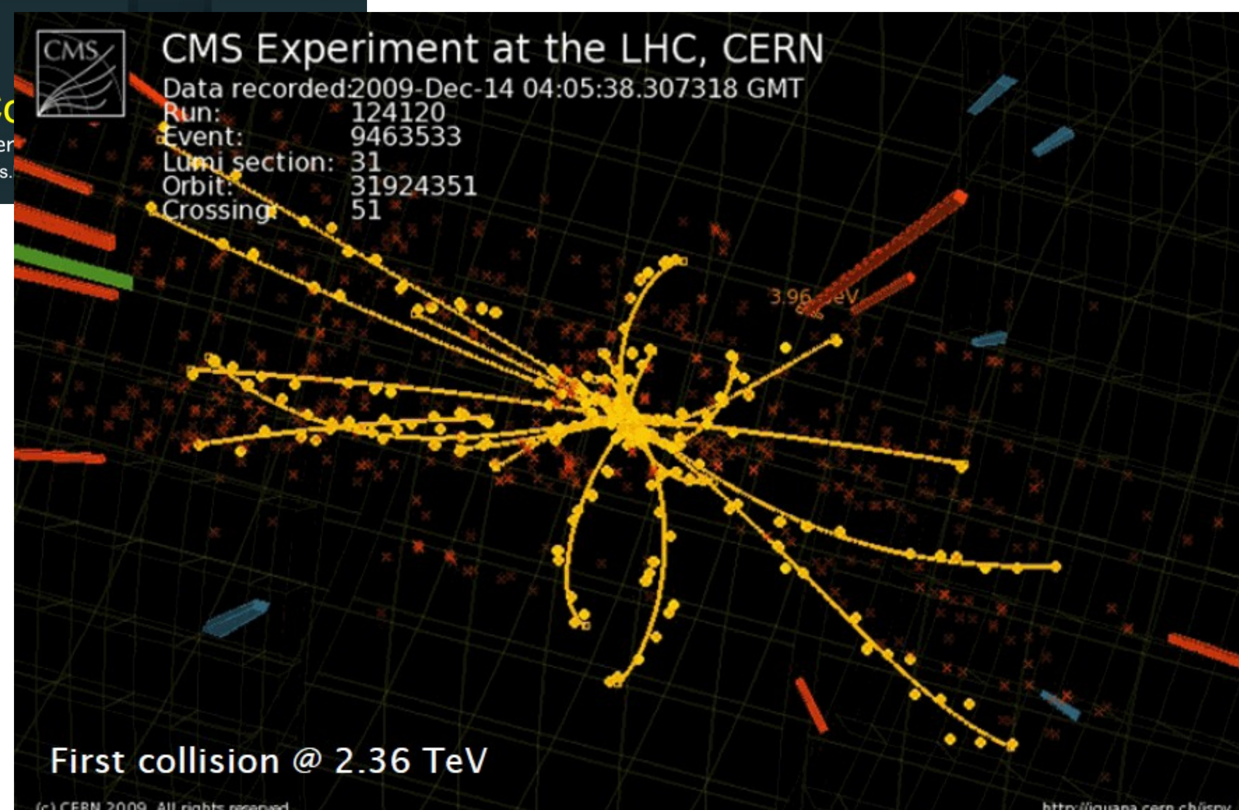
… continuing to take it step by step, and there is a lot to do before we start physics in 2010. I'm keeping my champagne on ice until then."

Over the next few weeks, scientists will move into a …

- Systems commissioned at forced pace – aim to check as much as possible
  - Our most optimistic plan became true !!
  - Gained experience with the new, and much more sensitive QPS system

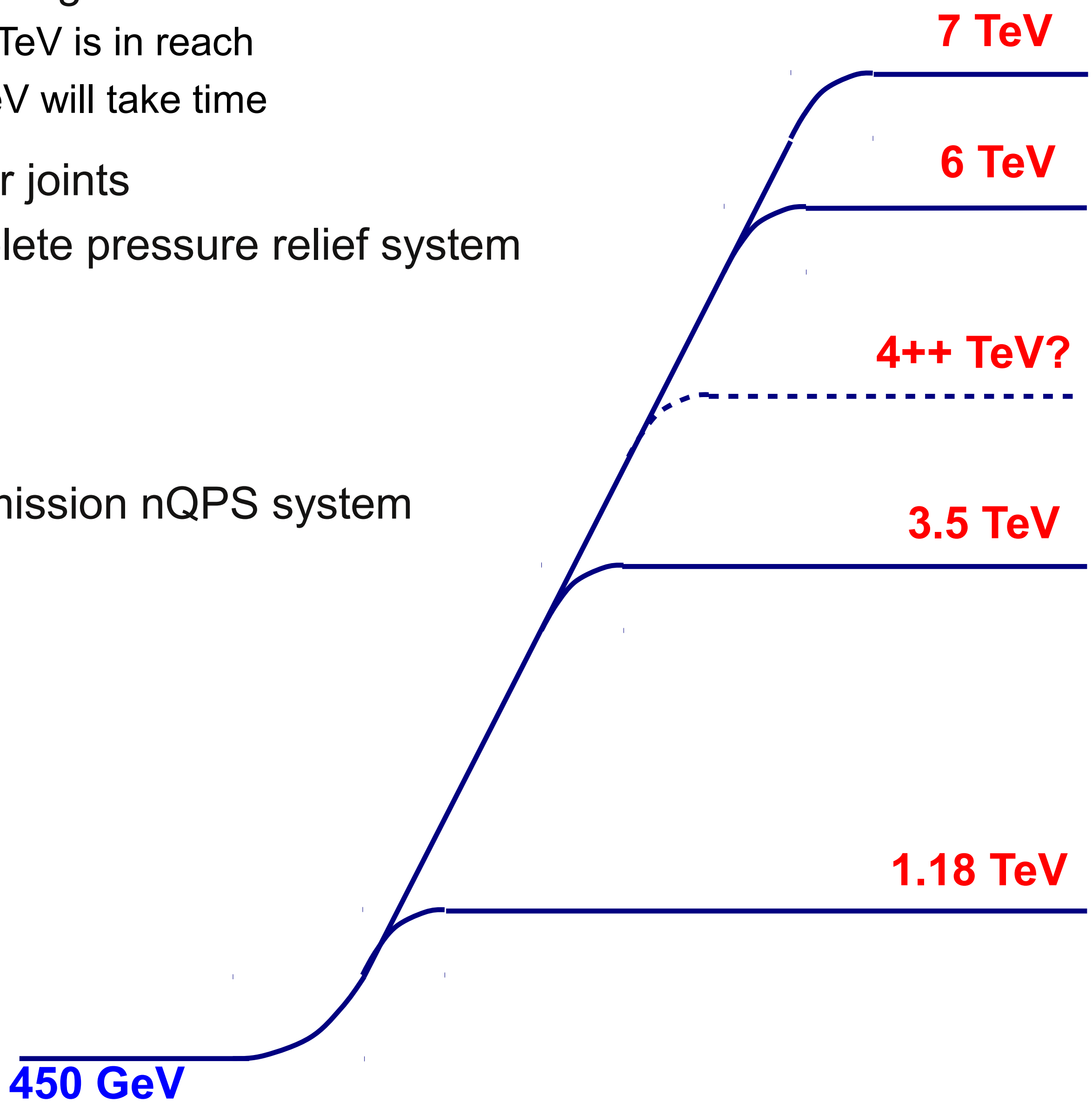
1.2 TeV Collisions





LHC target energy: the way up

- Train magnets
  - 6.5 TeV is in reach
  - 7 TeV will take time
- Repair joints
- Complete pressure relief system
- Commission nQPS system



When	What
2014 ?	Training
2013	Stabilisers
2011	Chamonix
2010	nQPS
2009	

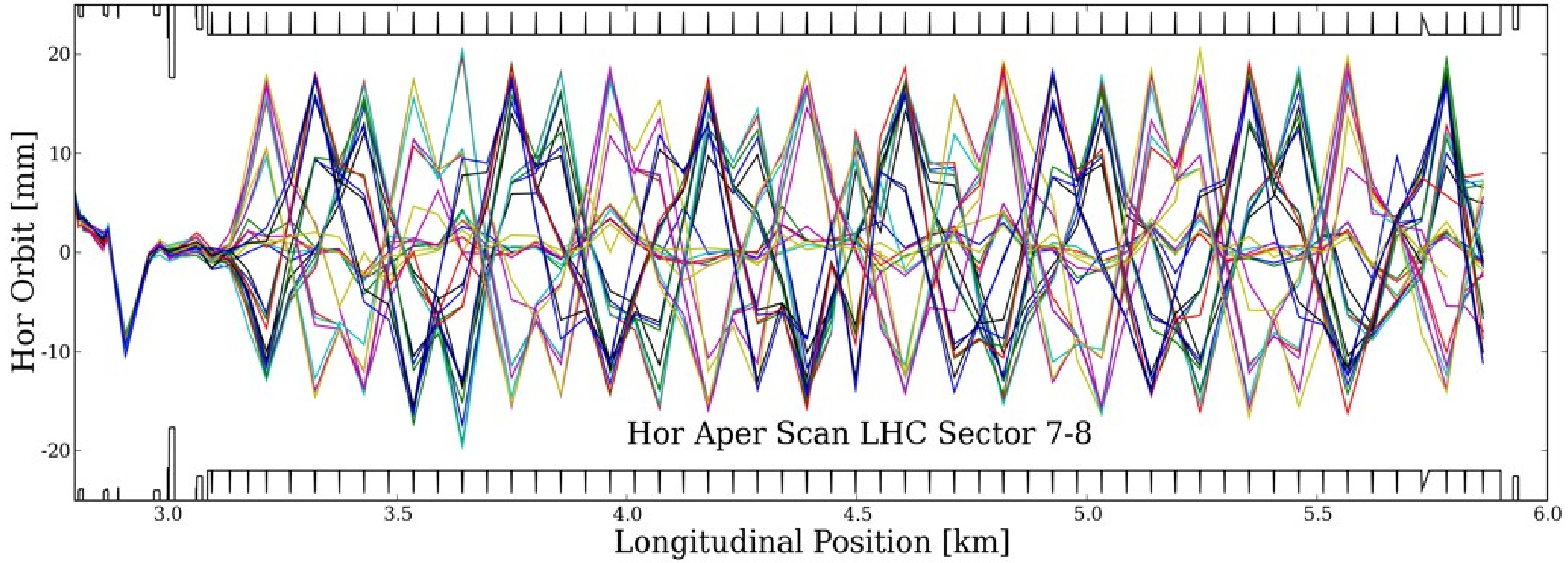
Milestones - 2010

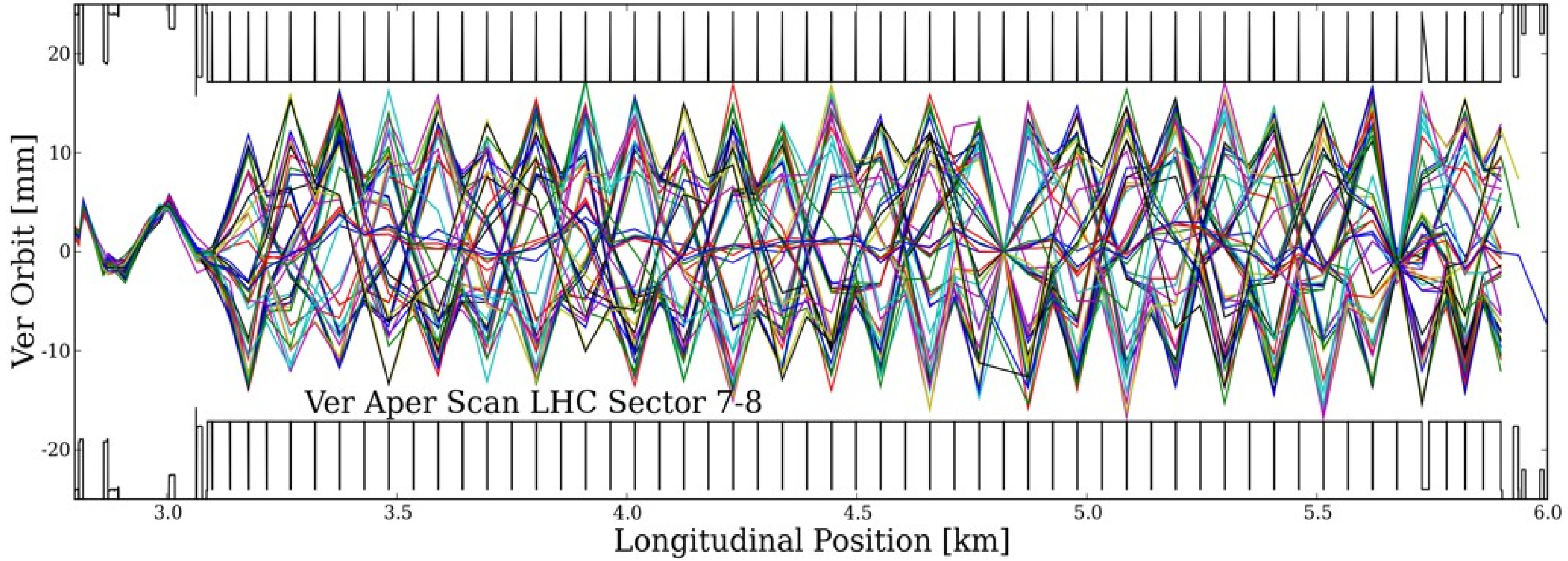
Date	Achieved	
Feb 28	Restart with beam.	
Mar 30	First collisions at 7 TeV centre of mass.	Luminosity ~ 2 10^{27} cm-2 s-1
Apr 01	Start squeeze commissioning.	Regular physics runs 2 on 2 bunches of 1010 Un-squeezed 1 colliding pairs per experiment Rates around 100Hz
Apr 07	Squeeze to 2 m in points 1 and 5.	
Apr 09	Single nominal bunch of 1.1 1011 stable at 450GeV.	
Apr 13	Squeeze to 2 m in point 8.	
Apr 16	Squeeze to 2m in point 2.	
April 24	First stable beams at 7 TeV, 3 on 3, squeeze to 2m.	Luminosity ~ 2 10^{28}cm-2 s-1

Milestones reached 2010 (to August)

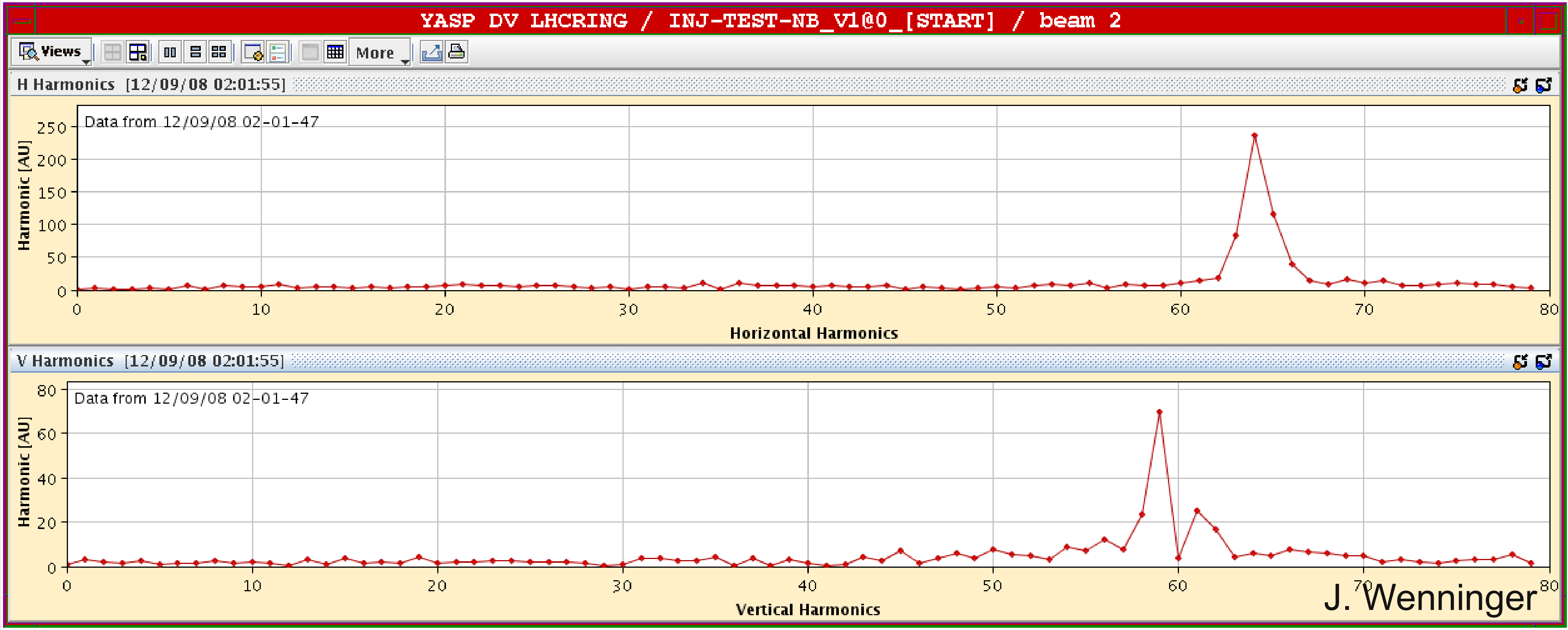
Date	Achieved	
May	Increase bunch intensity to 2 1010, Increase kb.	Regular physics runs
May 24	13 on 13, 8 colliding pairs per experiment.	Luminosity ~ 3 10^{29}cm-2 s-1
June	Increase bunch intensity to nominal, squeeze to 3.5m.	Machine development
June 25	First stable beams at 7 TeV, 3 on 3 nominal bunch.	Luminosity ~ 5 10^{29}cm-2 s-1
July 15	13 on 13, 8 colliding pairs, 9 1010 / b	Luminosity ~ 1.5 10^{30}cm-2 s-1
July 30	25 on 25, 16 colliding pairs, 9 1010 / b	Luminosity ~ 3 10^{30}cm-2 s-1
Aug 19	48 on 48, 36 colliding pairs 1 5 and 8, 9 1010 / b	Luminosity ~ 6 10^{30}cm-2 s-1
Aug	Stable running period to consolidate operation and MP 50x50, 11 1010 / b	~2-3 MJ per beam Luminosity ~ 1 10^{31}cm-2 s-1

- <u>A great relief</u> : the aperture was very good – no buckled bellows & Co.



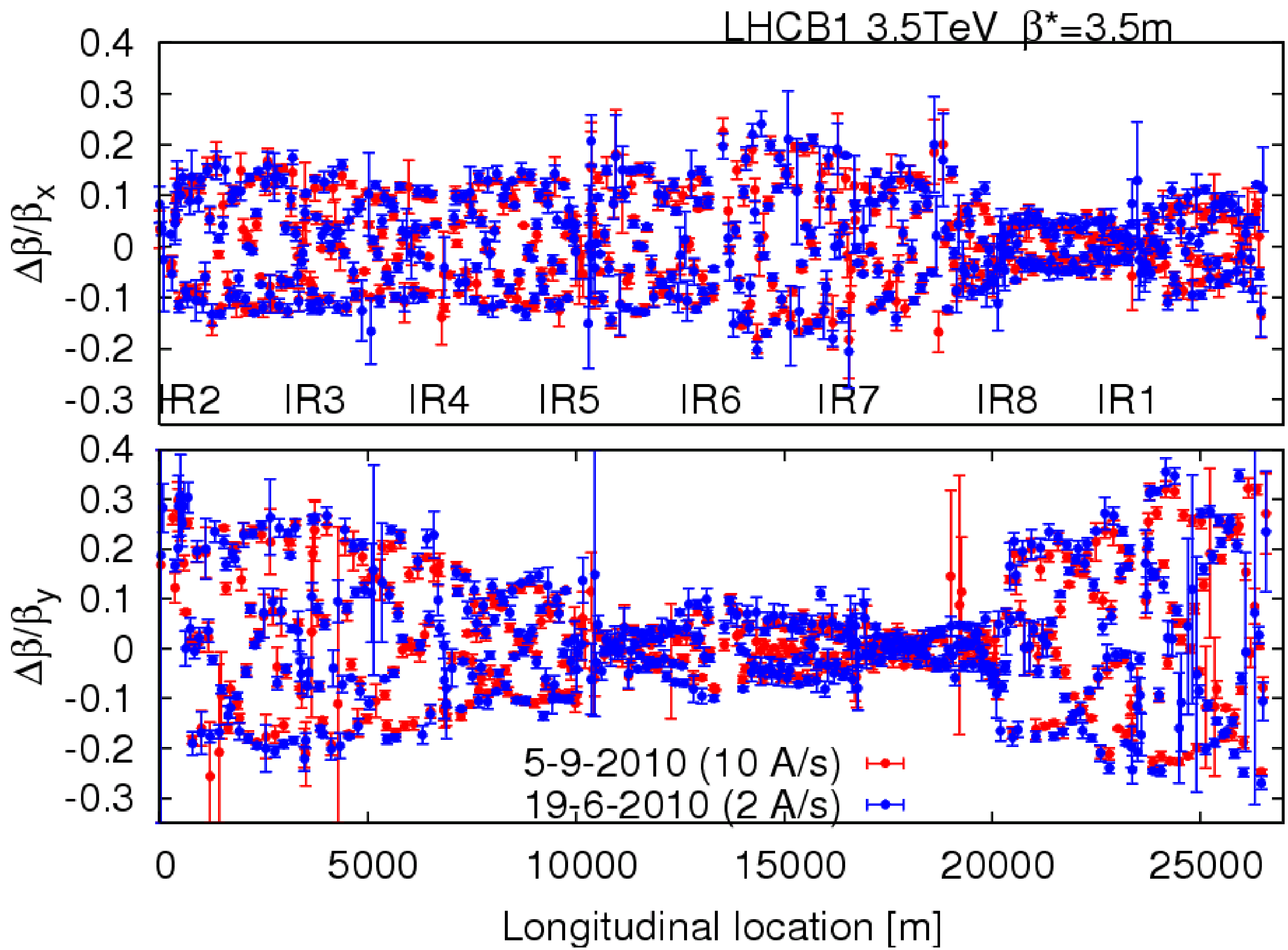


- Something probably measured only rarely during an accelerator's life-time:
  - Integer tunes: $Q_x = 64$ & $Q_y = 59$



Optics

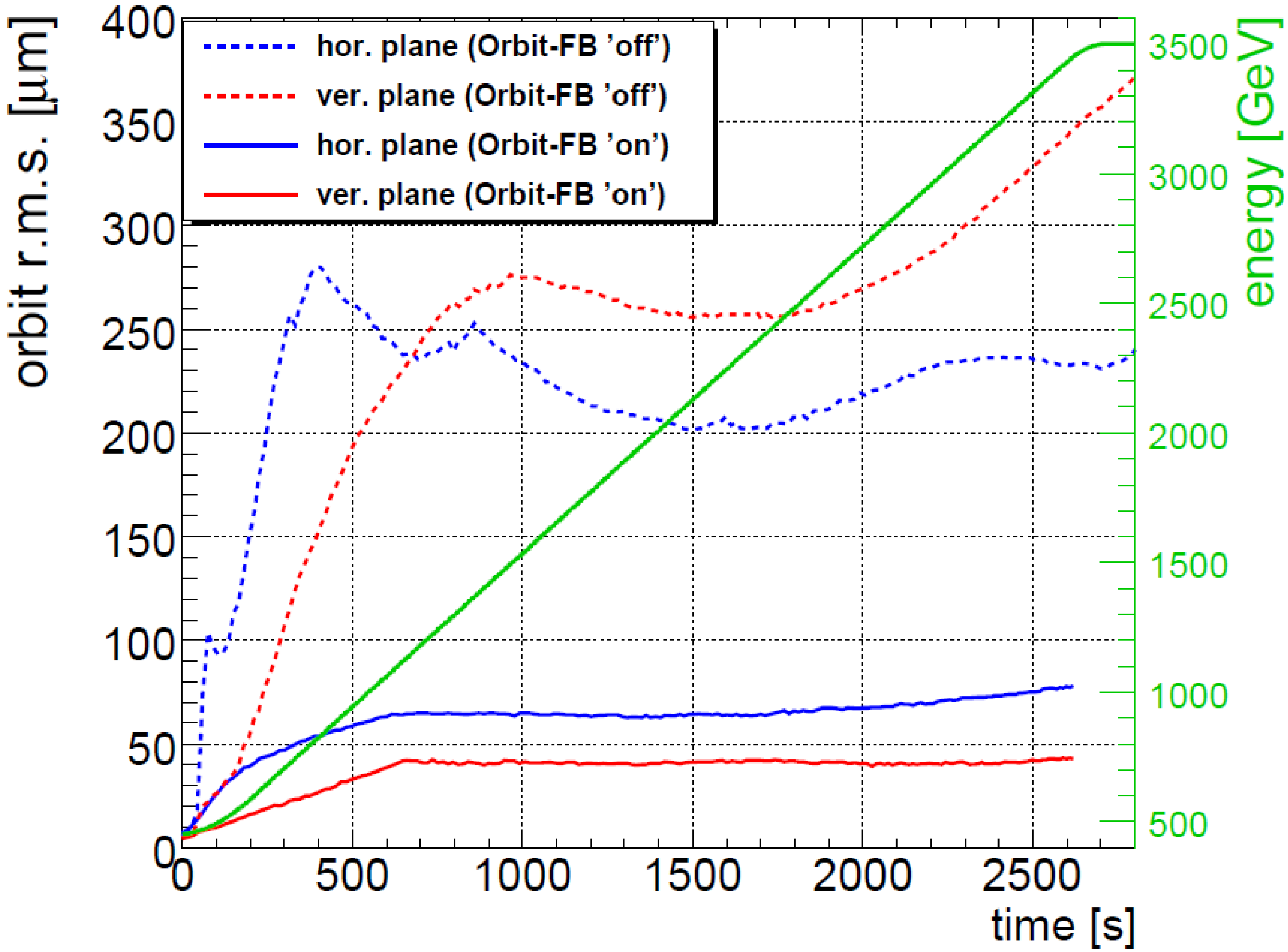
- Stunningly stable optics after three month



R. Tomas et al.

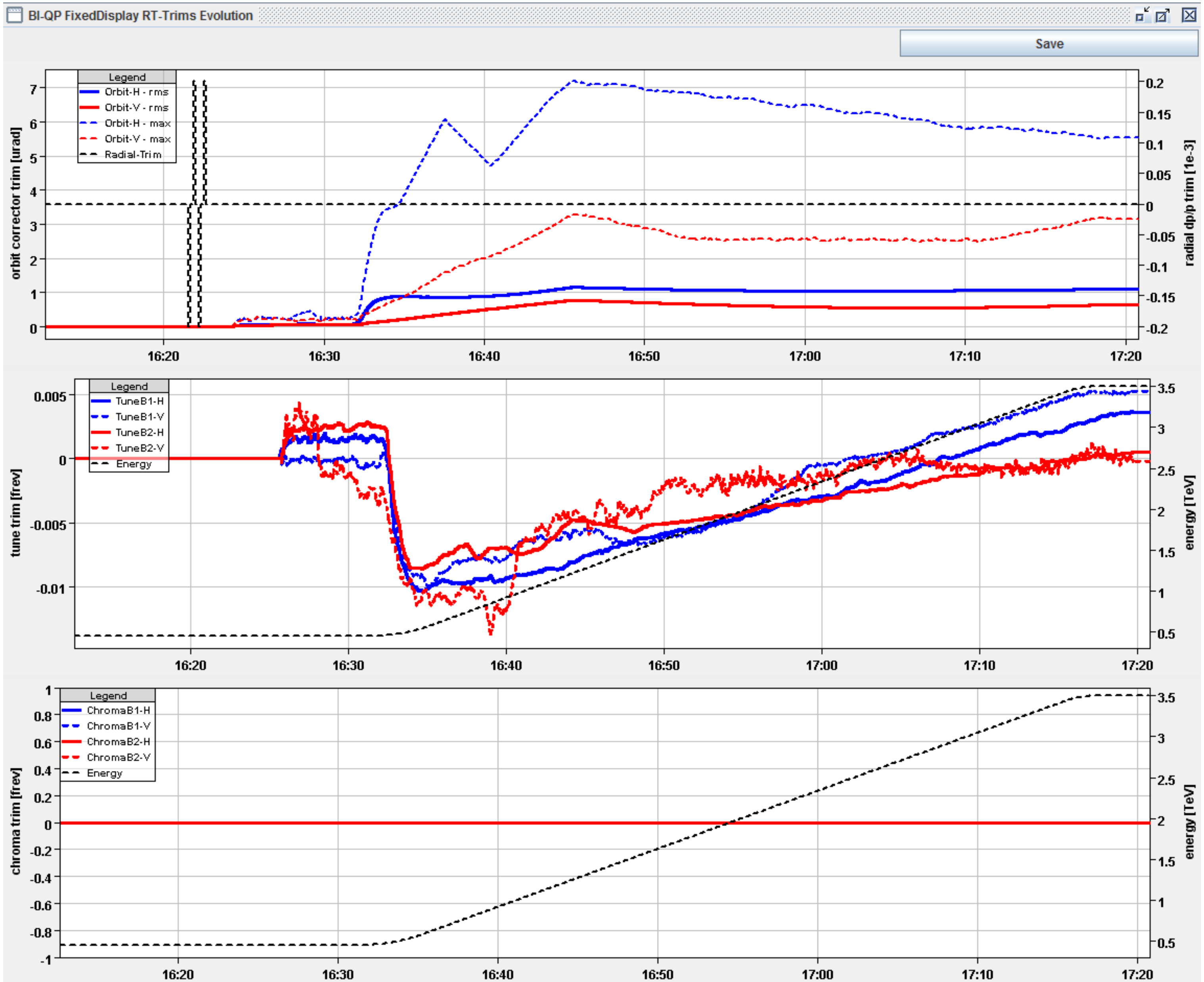
Orbit Feedback Performance during the Ramp

Orbit stability in the ramp: ≤ 80 µm rms



- The LHC only operates reliably with both orbit and tune FBs (ramp and squeeze).
  - Ramp and squeeze essentially without losses !!!!

Feedback in Action : Ramp



Fill 1309

29.08.2010

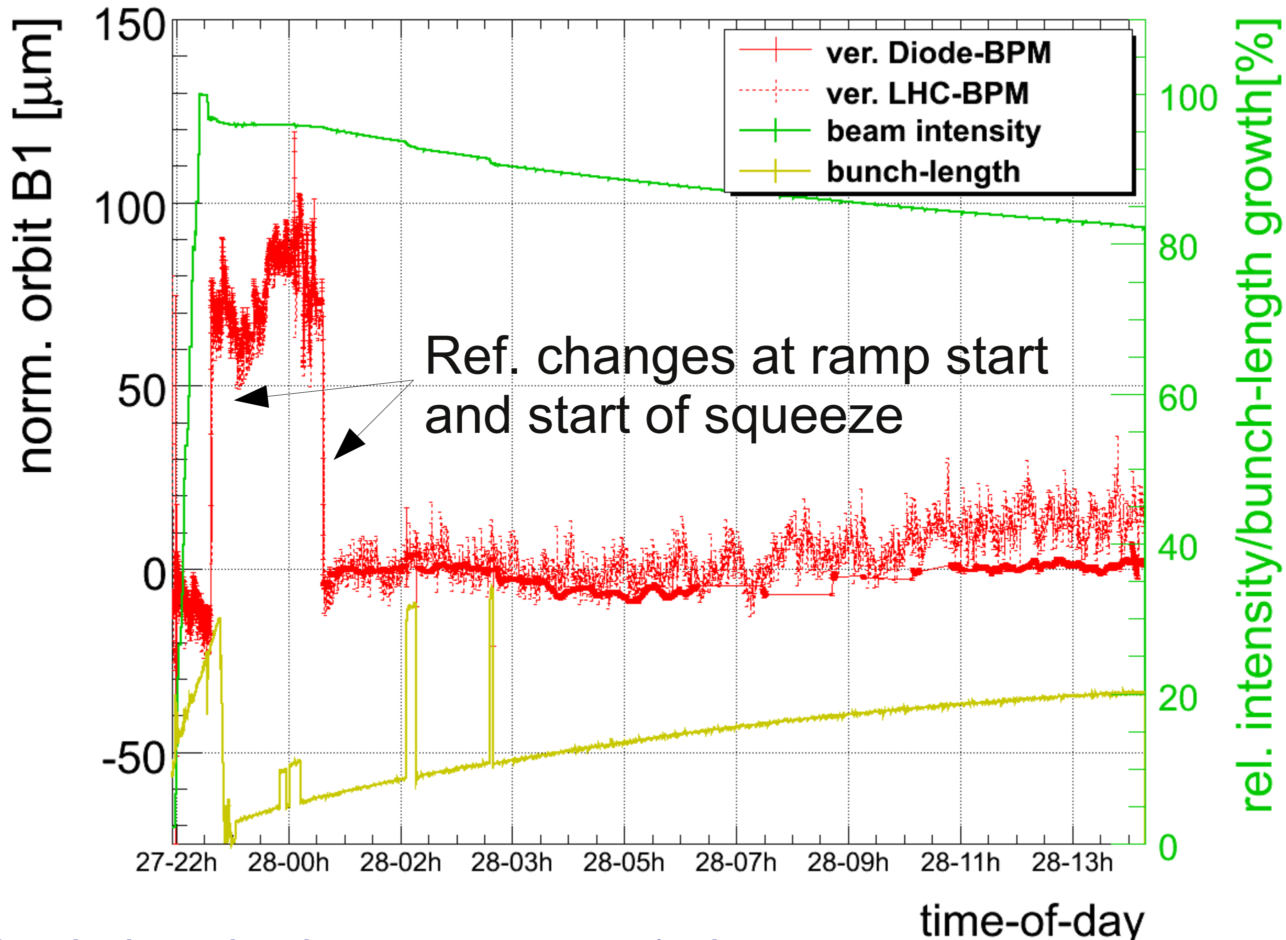
OFB trims (µrad)

QFB trims

Energy (TeV)

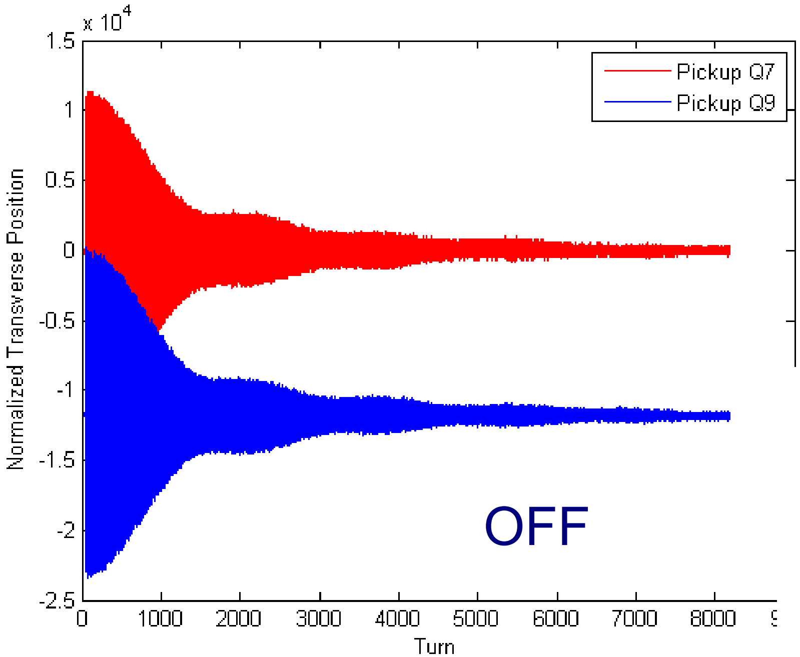
Orbit Stability during one LHC Fill

- Injection probe-beam, injection physics beam, ramp, squeeze, stable physics
  - Stability at one reference pick-up in LSS4

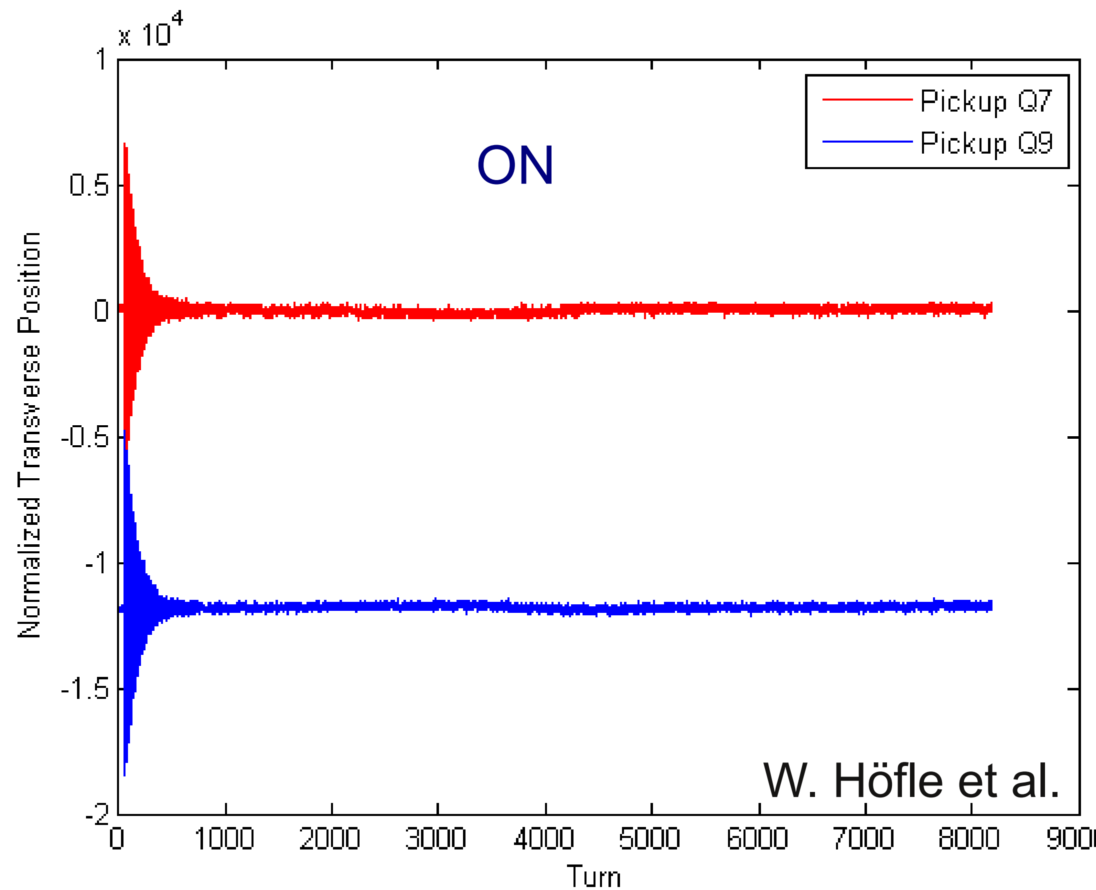


- Orbit stability during physics < 5 µm over 15 hours

Transverse Dampers



Crucial to keep emittance growth under control



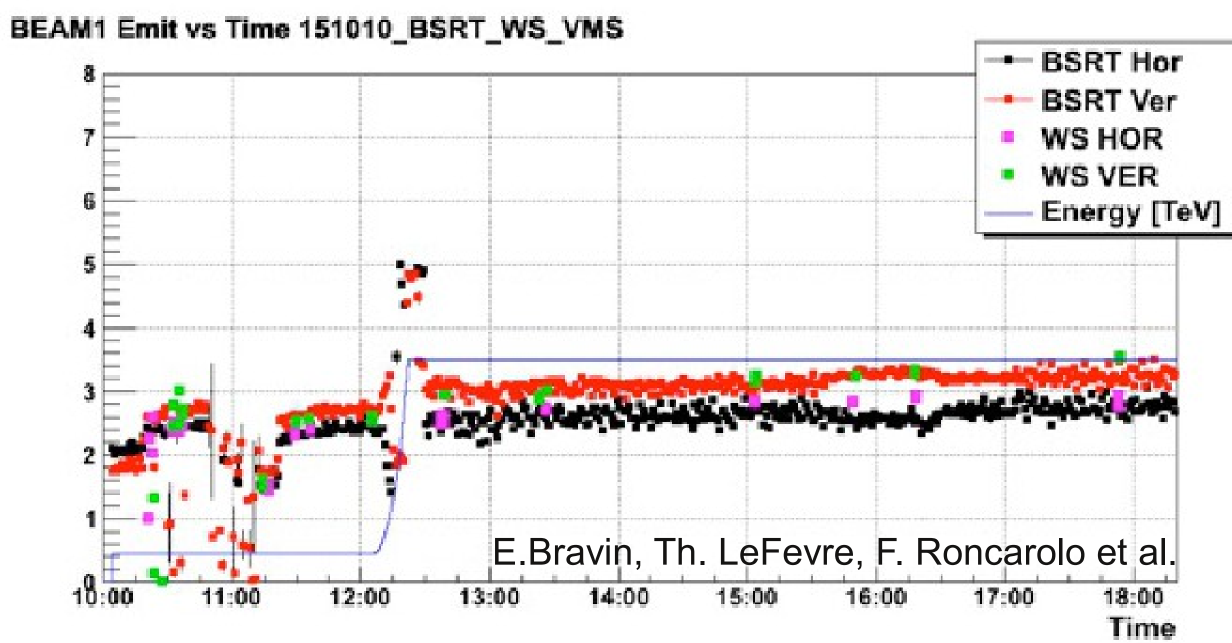
Already operational through the cycle – including stable beams

Protons visible by eye

- Excellent performance of the beam instrumentation has largely contributed to the fast progress.

- At the LHC momentum and magnetic fields are sufficiently strong for the protons to emit visible light that can be used to image the beams in real-time.

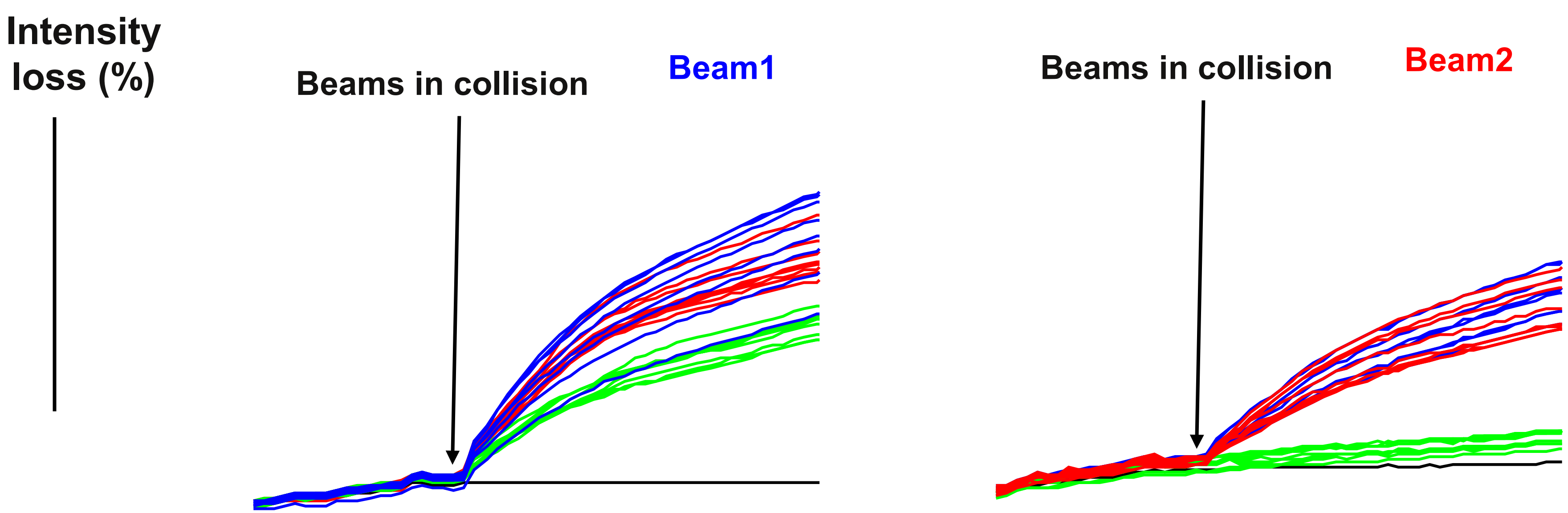
  The energy loss per turn is 7 keV at 7 TeV.



Beam-Beam Interaction I/II
Head-On

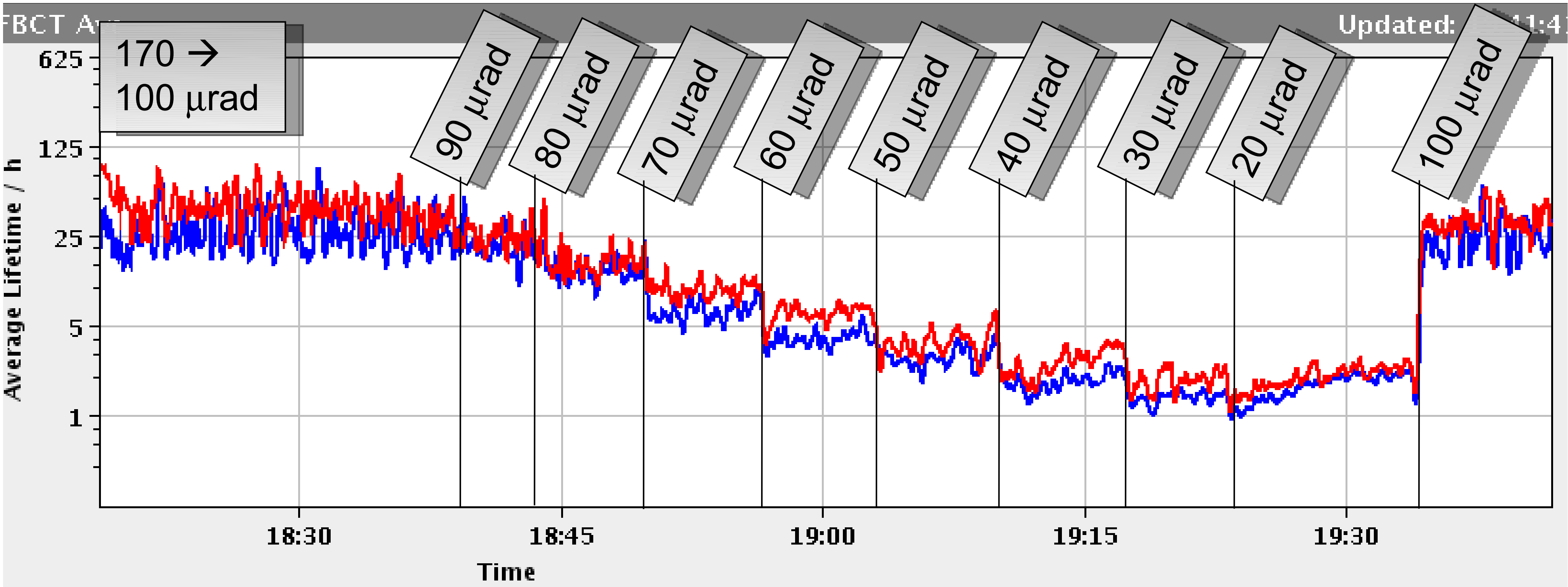
- Effects of the beam-beam force are visible on the lifetime of the various bunches.
  - sensitive to tune working point → cured by tune split and/or transverse damper
  - Lots of numerology

- black	witness bunches (zero collisions);
- red	bunches colliding in IP 1 5 and 2 (3 collisions);
- blue	bunches colliding in IP 1 5 and 8 (3 collisions);
- green	bunches colliding in IP 2 and 8 (2 collisions).



Beam-Beam Interaction II/II
Long-Range Beam-Beam – Lifetime versus crossing angle

- Test with 3 batches of 8 bunches each, spacing 150 ns at injection
  - up to 6 long range interactions per bunch.

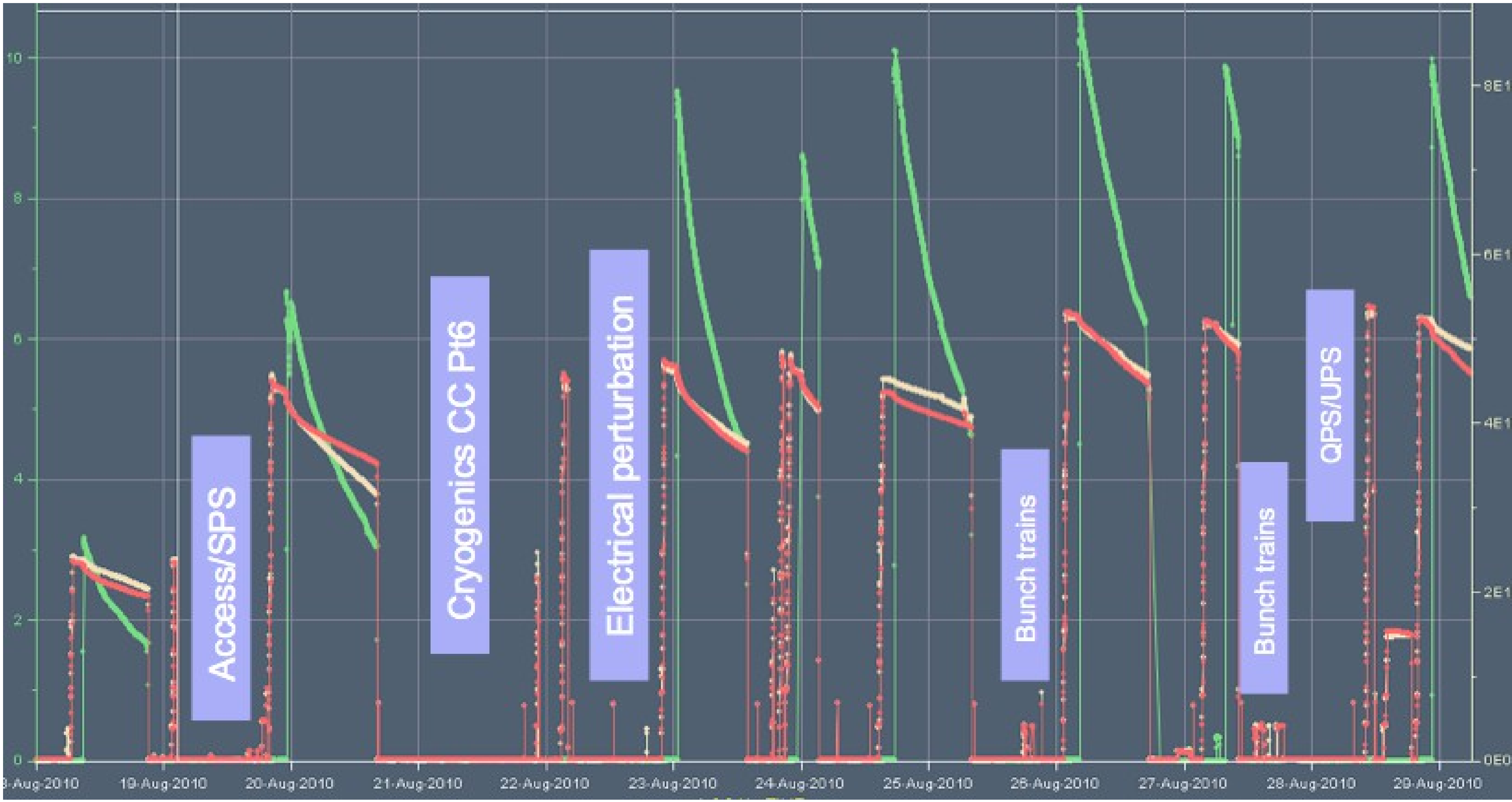


- At injection the minimum crossing angle with 150 ns trains is 100 µrad
  - Using nominal value of 170 µrad to gain experience (aperture not a problem).

Beam current during fill 25/08/2010

Mike Lamont: *"Quite frankly: we're dreaming…"*

Two weeks in August

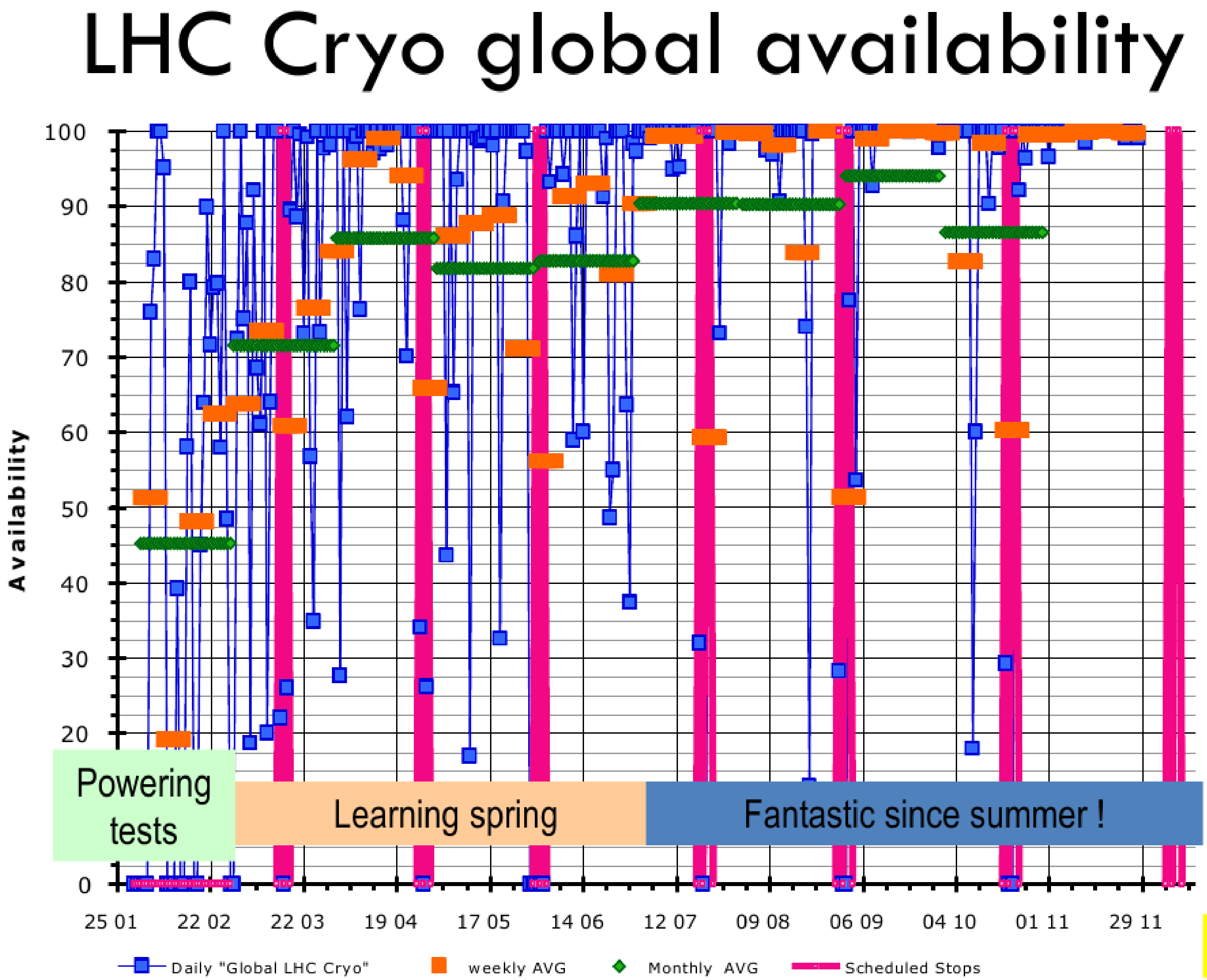


25b | ← 48b → | ← 50b →

August: Operational Reliability and Routine are starting to settle in....

August	Fill	Bunches	Stable	nb-1	EOF
18	1293	25x25	12h01	93	Programmed dump
19/20	1295	48x48	14h43	238	Programmed dump
22/23	1298	48x48	13h07	280	fast beam loss event Q22.R3.
24	1299	48x48	3h18	87	RD1.R2 trip.
24/25	1301	50x50	14h17	345	EOF studies
26	1303	50x50	13h07	369	fast beam loss event Q25.R5.
27	1305	50x50	3h30	118	EOF studies
28/29	1308	50x50	13h42	335	Programmed dump
29/30	1309	50x50	11h18	312	Programmed dump

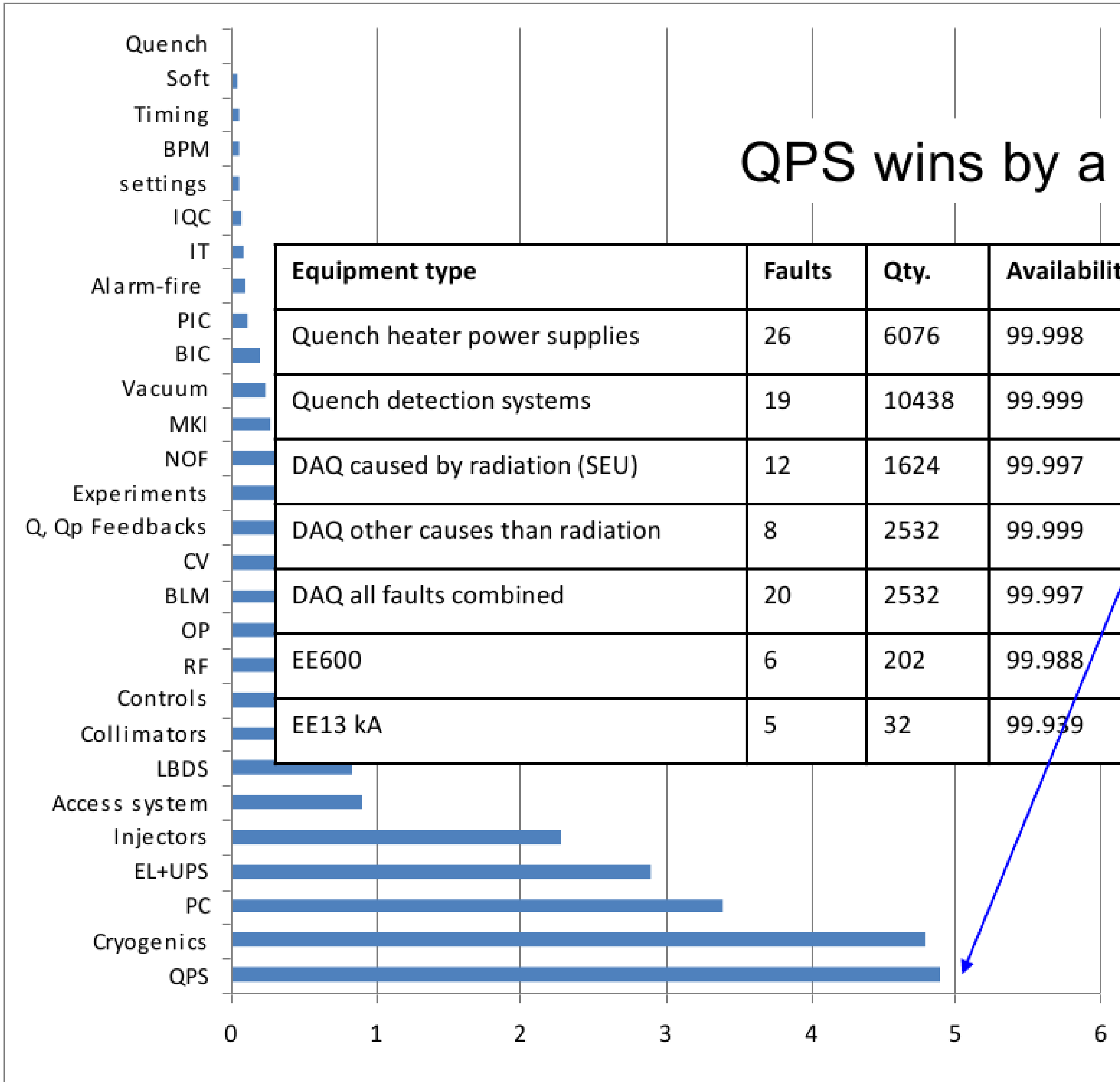
Results for 2010 above expectations, thanks as well to periodic technical stops



S. Claudet

Perturbations: clogging sub-atm circuits-CV891-instrumentation-Shaft seals-VFD/MB-24V

All LHC Faults Downtime Distribution

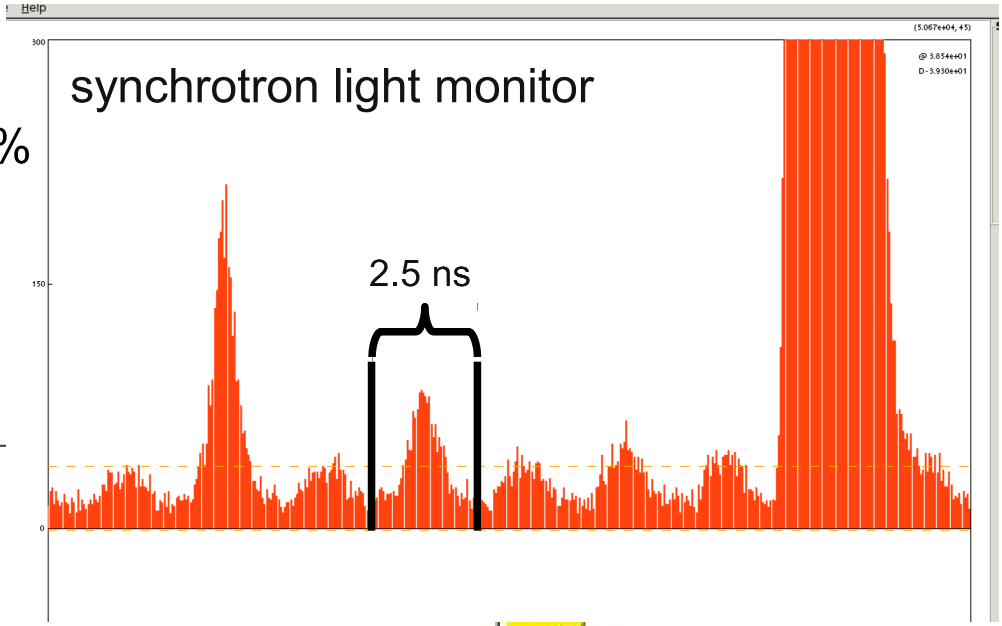


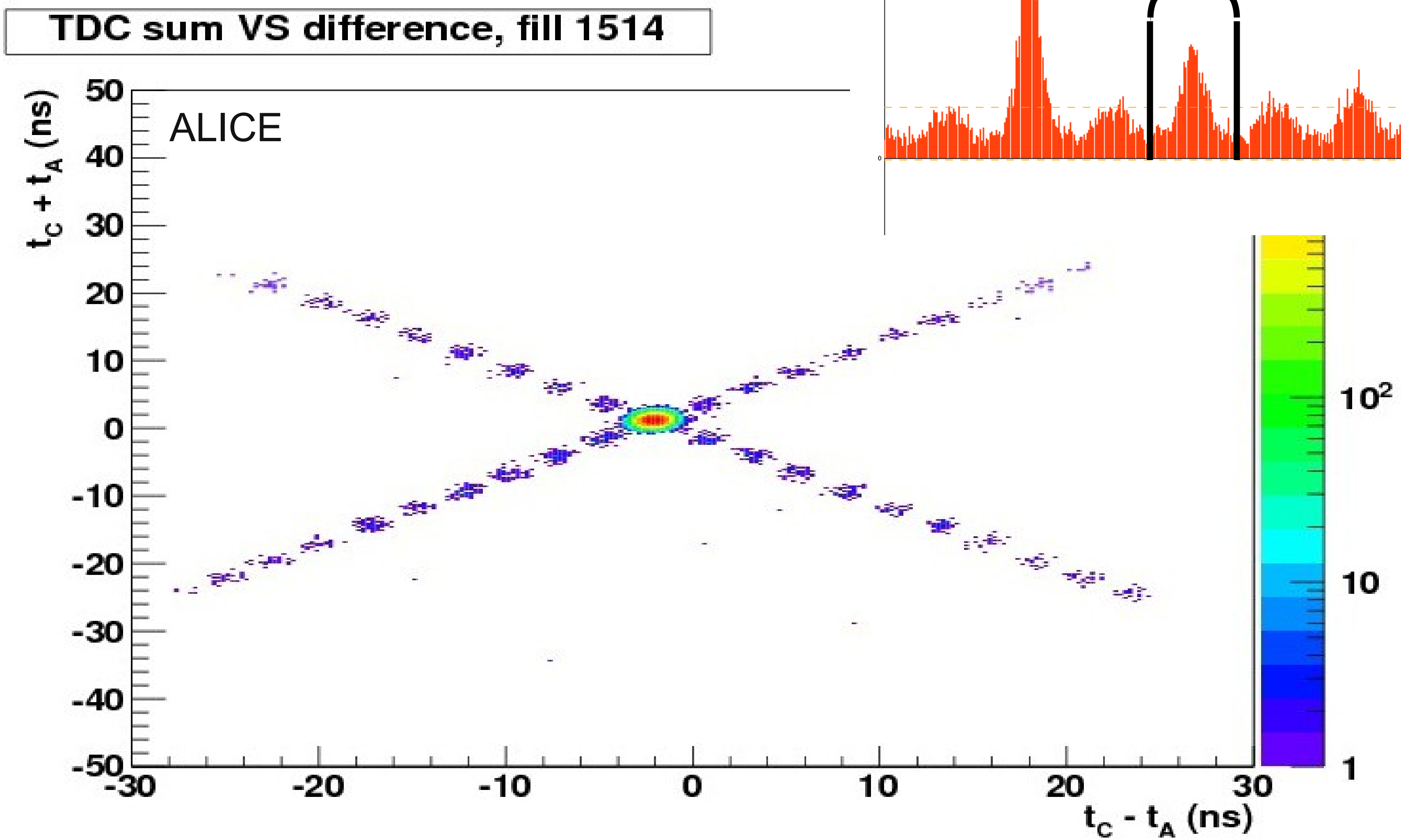
QPS wins by a neck…

Equipment type	Faults	Qty.	Availability[1] [%]	MTBF [hours]
Quench heater power supplies	26	6076	99.998	1145760
Quench detection systems	19	10438	99.999	3362135
DAQ caused by radiation (SEU)	12	1624	99.997	828240
DAQ other causes than radiation	8	2532	99.999	1936980
DAQ all faults combined	20	2532	99.997	774792
EE600	6	202	99.988	206040
EE13 kA	5	32	99.939	39168

R. Denz

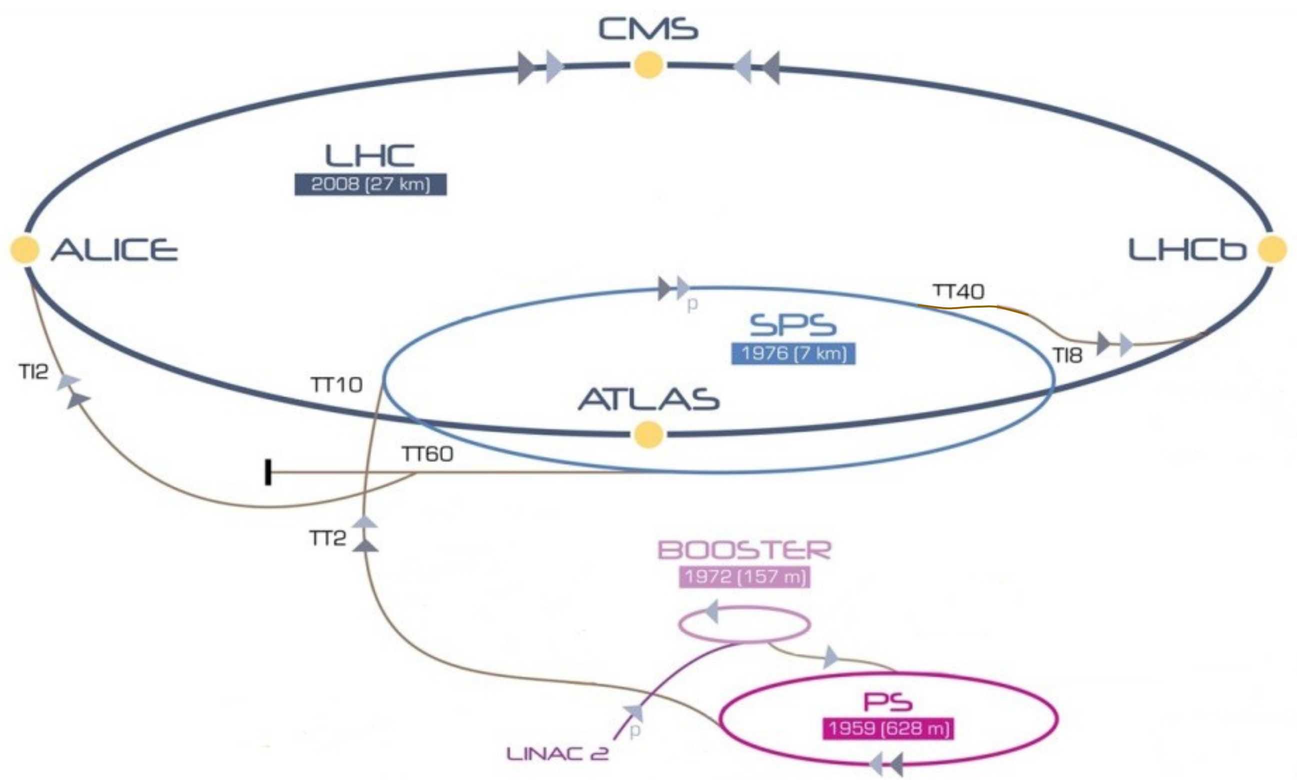
- For the time being a non-issue
  - need to revisit if becomes larger than 5%





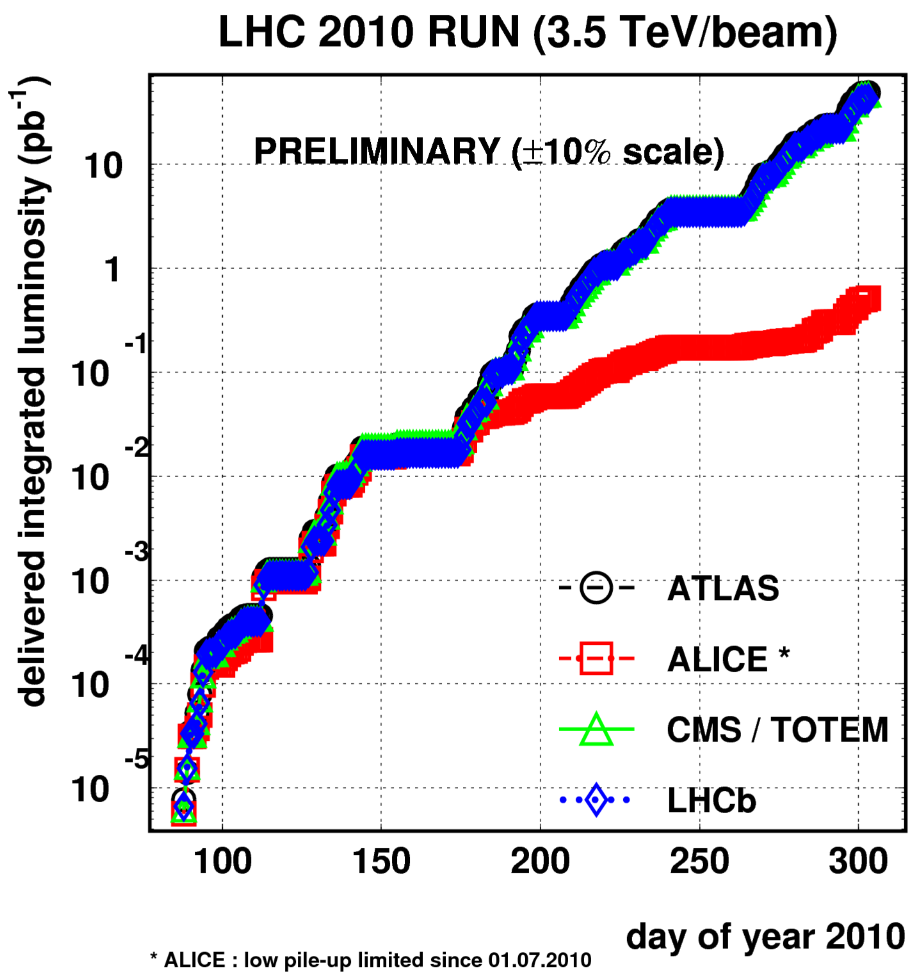
Emittance and Bunch Charge Improvements

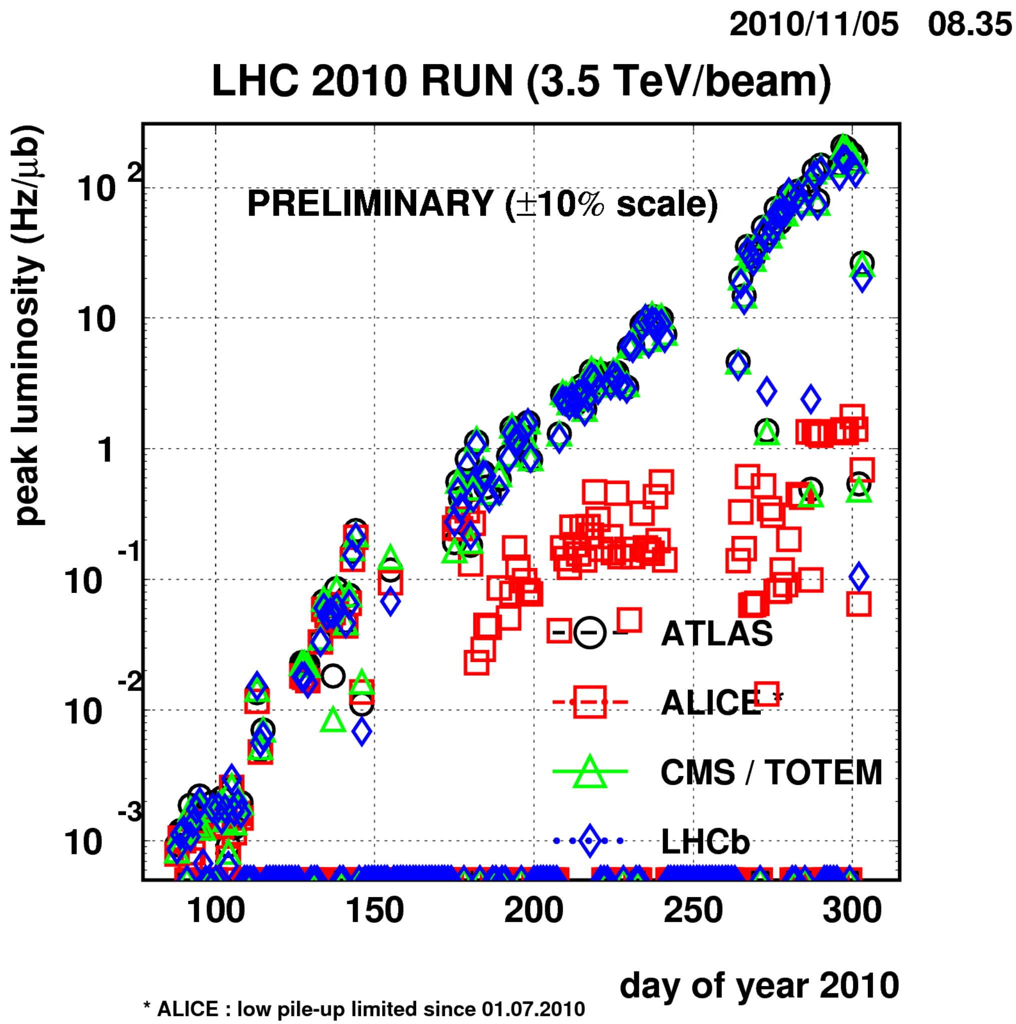
- Injected emittance reduced to less than 1.5 µm (nominal 3.5 µm).
  - Lower for 50, 75 and 150 ns than 25 ns.
  - Impact on beam-beam observed – curable
- Presently we aim to inject beams with emittances of ~2 µm.
  - routinely start collisions with ε ~2.5 µm (B1 better than B2).
  - Since Luminosity ~ 1/emittance → ~30% gain of luminosity.
- In addition, injector already can already produce above nominal bunch intensities → LHC future looks bright



Proton Performance in 2010

- Integrated delivered proton luminosity ~ 48 pb^{-1}/experiment
- Record peak Luminosity of $2 \cdot 10^{32}$ $cm^{-2}s^{-2}$





plots at: http://cern.ch/lpc

LHC Operation with Ions

Hadron Collider switches to heavy ions, tinfoilers wet pants again

Also: *Reg* hack in large-red-button LHC control room incident

By **Lewis Page** • **Get more from this author**

Posted in Physics, 8th November 2010 13:52 GMT

Particle-punishing boffins at the Large Hadron Collider - the most outrageously powerful matter-rending apparatus and largest machine of any kind assembled by the human race - have switched ammunition. The colossal superconductor massdriver cannons of the LHC are now firing "fully stripped" ultrahypervelocity lead projectiles rather than comparatively insubstantial hydrogen ones.

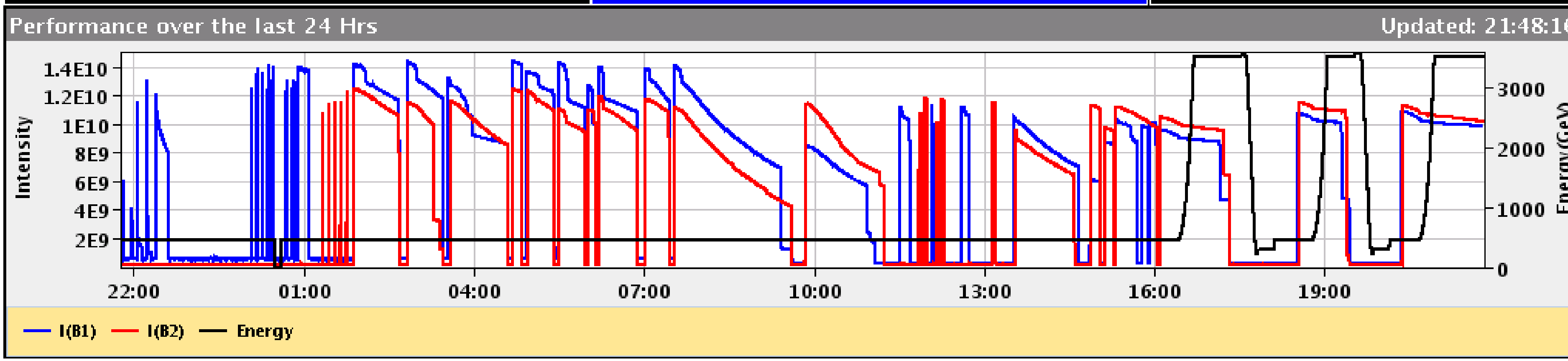
Acknowledgements to:
John Jowett
Mike Lamont
Walter Venturini
Matteo Solfaroli Camillocci

Ion Commissioning: Thursday & Friday

05-Nov-2010 21:48:18 Fill #: 1473 Energy: 3500 Z GeV I(B1): 9.86e+09 I(B2): 1.02e+10

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	STANDBY	STANDBY	STANDBY
Instantaneous Lumi (ub.s)^-1	0.000	0.000	0.000	0.000
BRAN Luminosity (ub.s)^-1	0.000	0.000	0.000	0.000
Inst Lumi/CollRate Parameter	1.00e+00		0.00e+00	
BKGD 1	0.002	0.244	0.000	0.122
BKGD 2	0.000	0.000	0.000	0.407
BKGD 3	0.000	1.628	0.098	0.044

LHCb VELO Position OUT Gap: 58.0 mm SQUEEZE TOTEM: STANDBY



Beam 1 Inj., Circ. & Capture

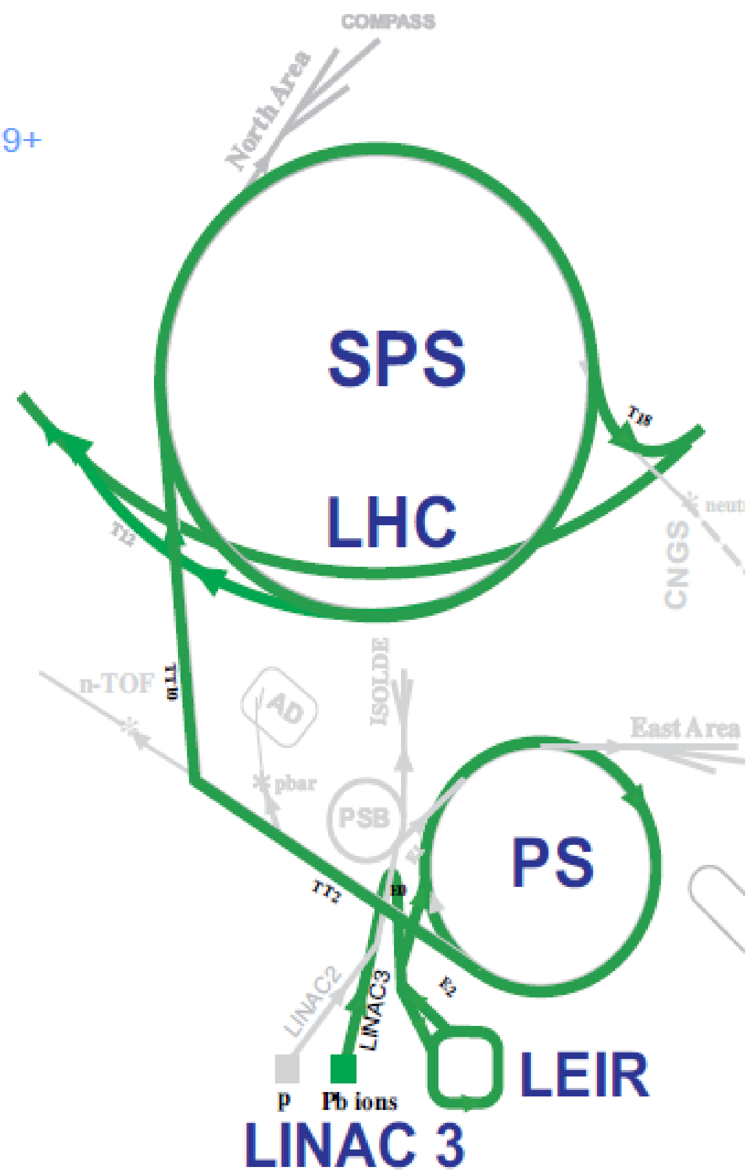
Beam 2 Inj., Circ. & Capture

Optics Checks
BI Checks
Collimation Checks

First Ramp
Collimation Checks
Squeeze

Lead Ion Injector Chain
“We are standing on the shoulder of giants”

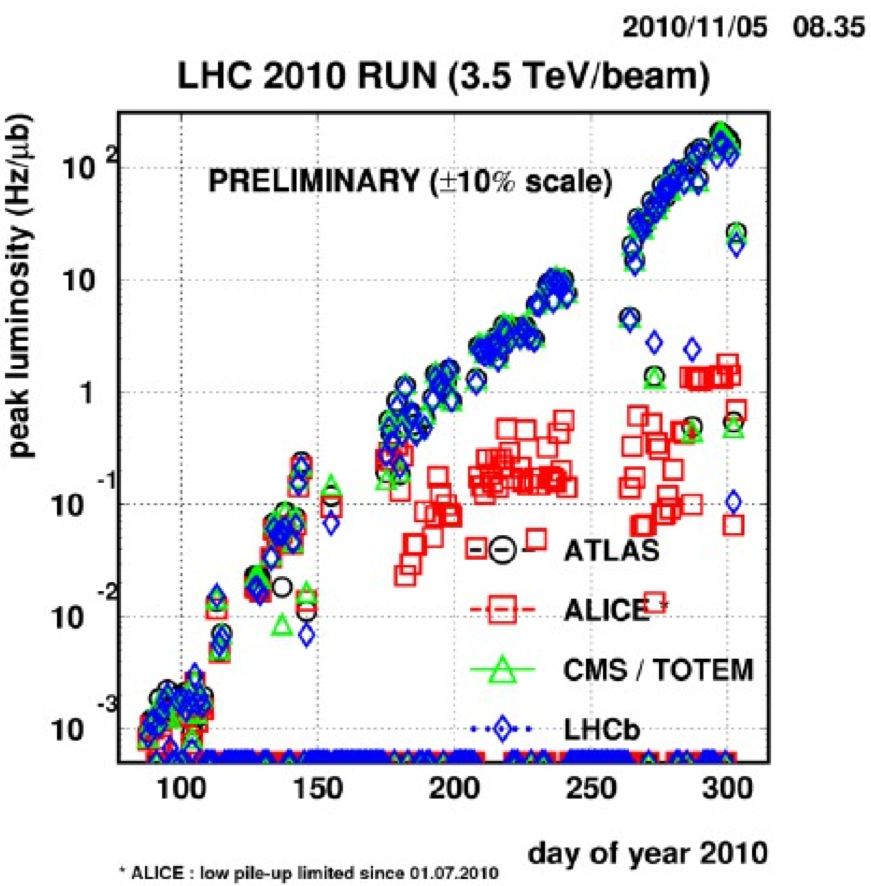
- ECR ion source (2005)
  - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR injection energy
  - strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and cool Linac 3 beam
  - Prepare bunch structure for PS
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)
  - Define filling scheme

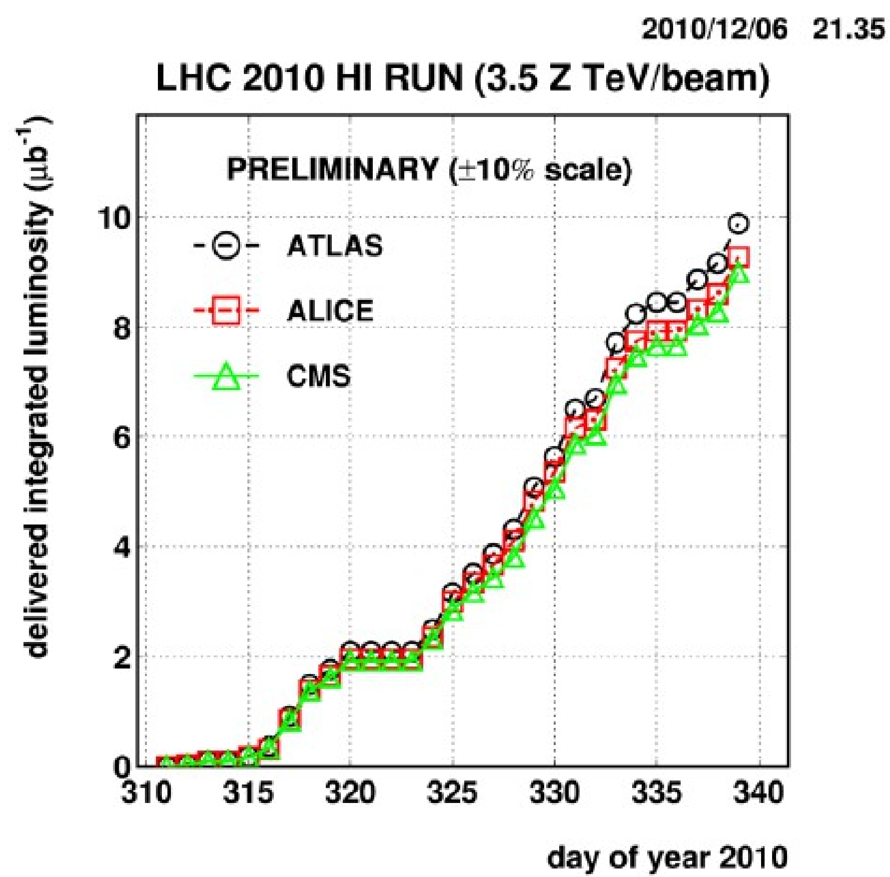


→ achieved 70% more than nominal bunch intensities!!

Performance of Ion Operation

- LHC Mode change: Large Hardron Collider → Large Hardron Collider
- Hours spent in stable beams in 2010:
  - 851 hours of protons out of 7 months, 1 apr - 31 oct
  - 223 hours of ions out of 1 month , 8 nov - 6 dec

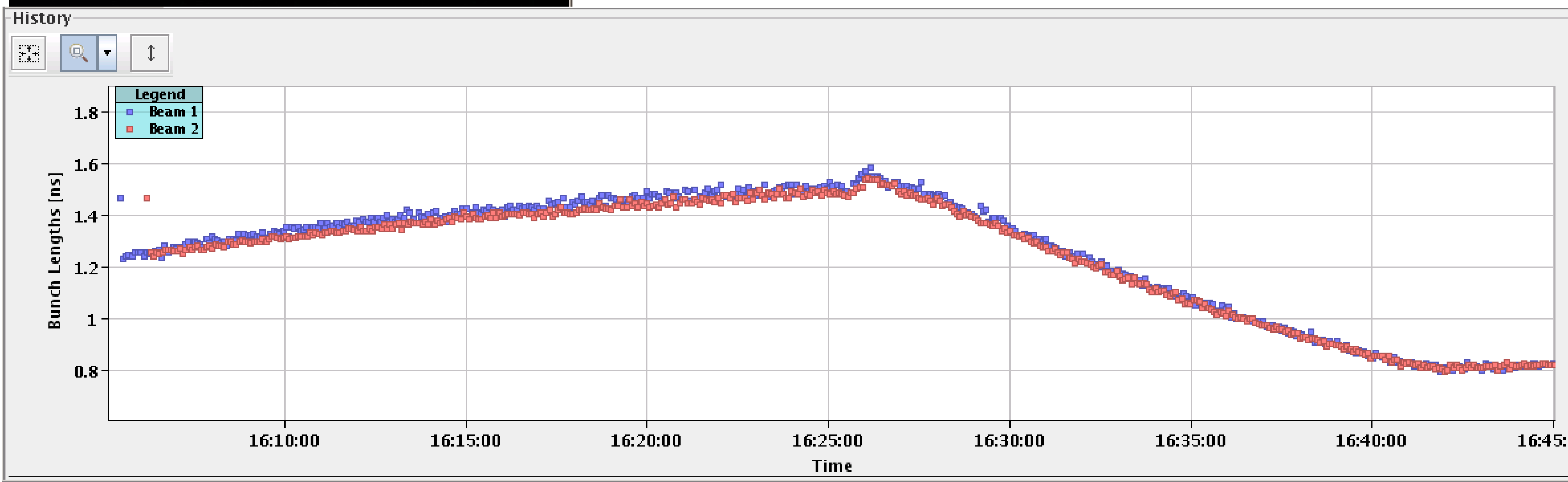




Friday afternoon: first ramp – no losses

World first: observation of synchrotron light from nuclei

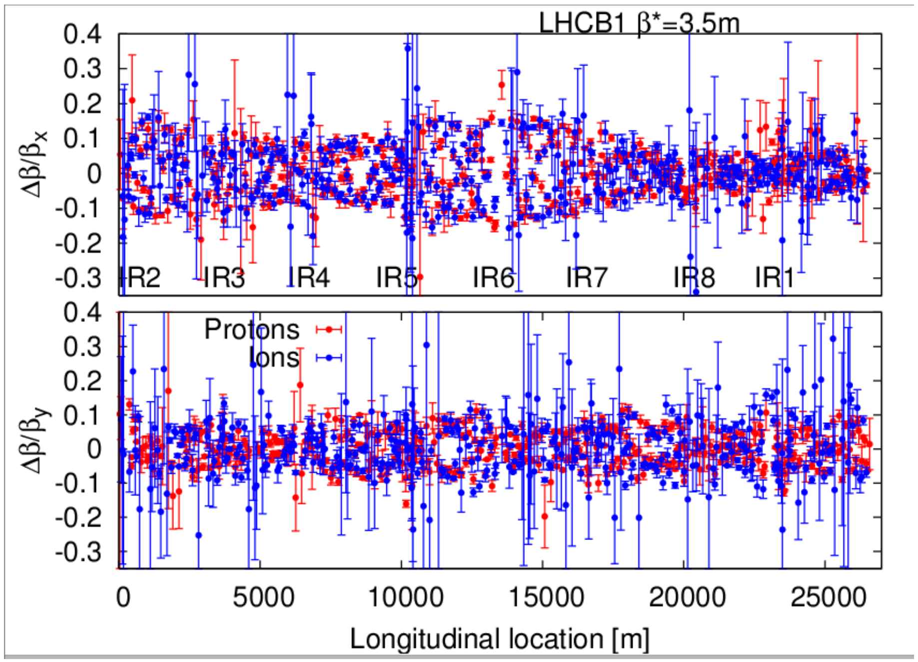
Appears around 0.55 Z TeV (later if filtered)

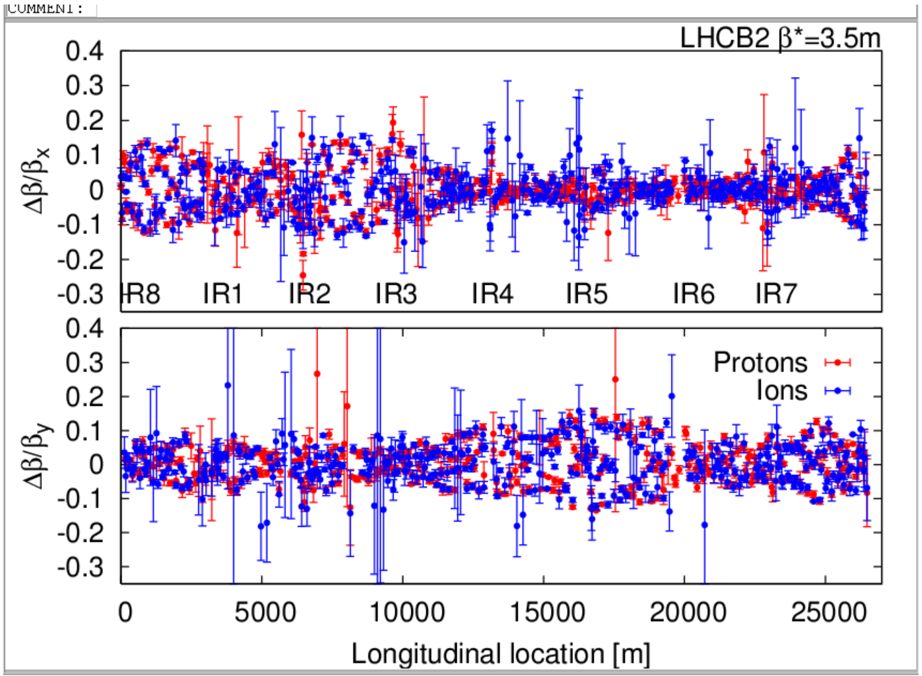


Bunch length increasing at injection (IBS), down during the ramp, increasing again at 3.5 TeV (IBS)

Optics measurements at 3.5 Z TeV, squeezed

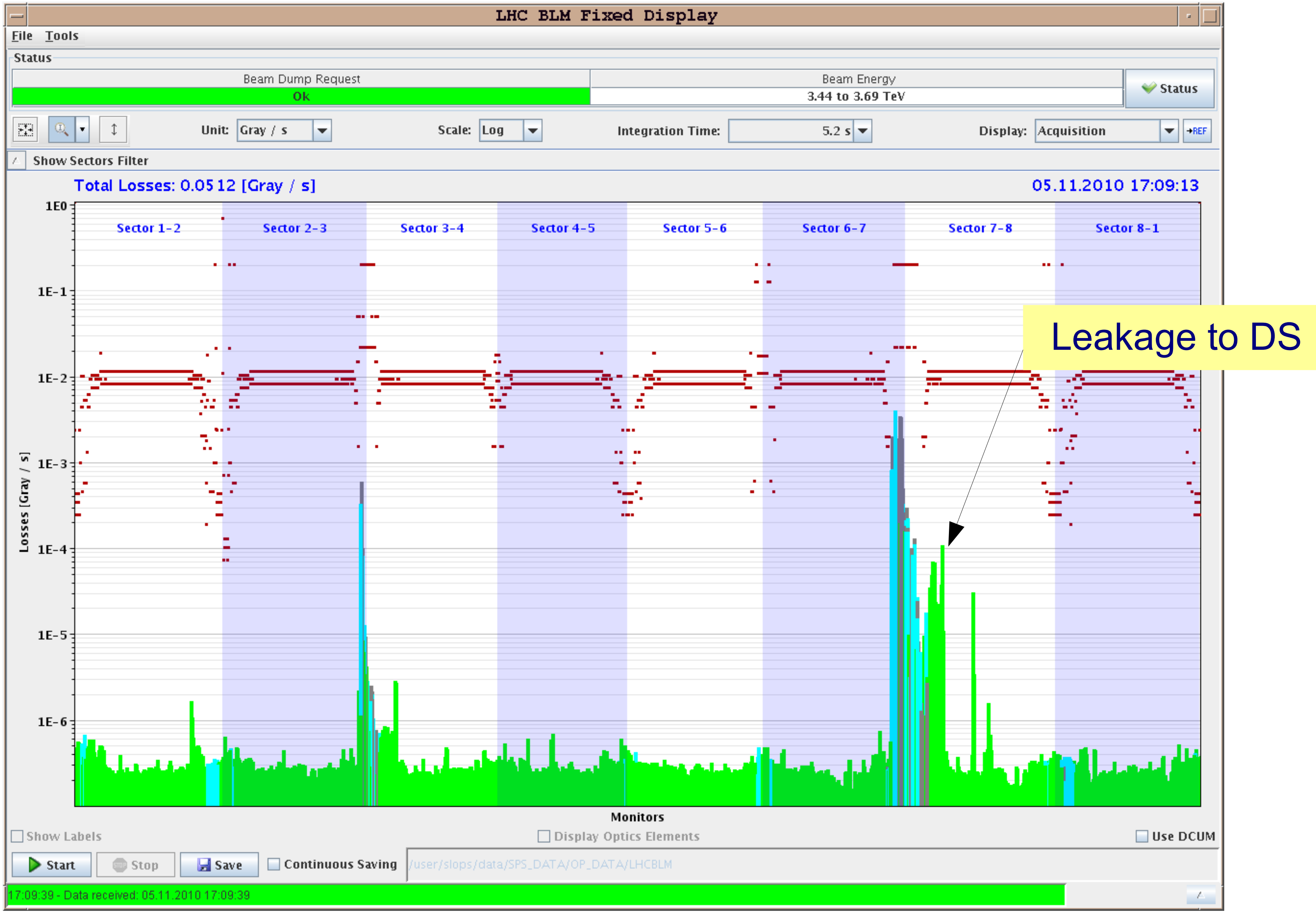
- Very similar to protons





R. Tomas et al.

Betatron Loss Maps with Ions – 450 GeV



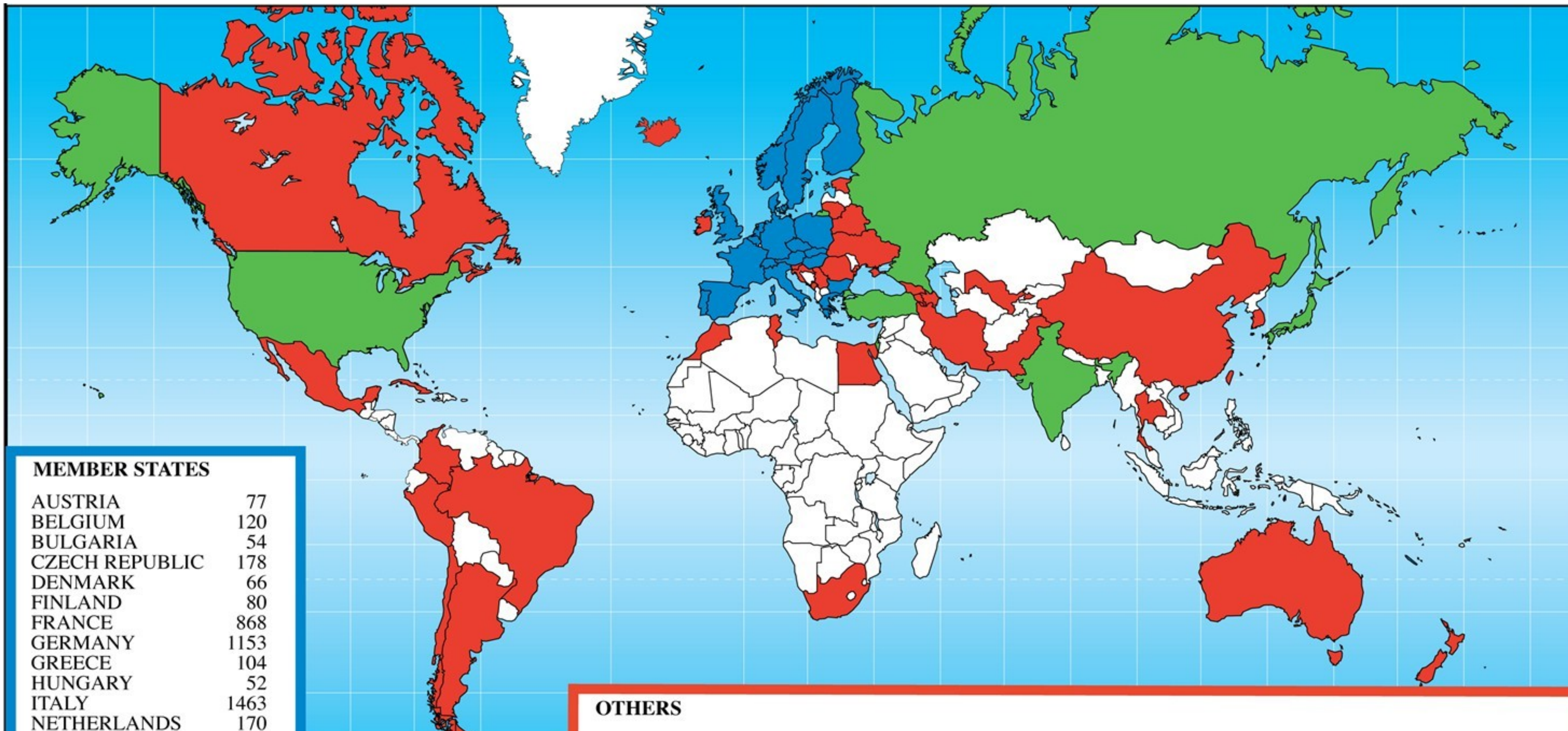
Ions - conclusions

- Very swift commissioning period leveraging proton set-up to the maximum.
  - pushing though 2 – 17 – 69 toward 120 bunches per beam
  - Peak luminosity around 6 x 10^{24} $cm^{-2}s^{-1}$ with 69 bunches
- Injectors are giving us 70% beyond design single-bunch intensity, some consequences…
  - Significant IBS growth and de-bunching at injection, seems to be in reasonable agreement with theory
- Emittance blow-up in physics is not too bad, but mostly not IBS
- Collimation of heavy ions is complicated
  - Simulations roughly right but do not show all details – need considerable effort for refinement … and counter-measures in future

Courtesy John Jowett

CERN grew beyond it's original Mission...

- LHC's success was not an accident, but a result of a combined, high-quality, and meticulous preparation prior to and after the 10th of September.
  It did <u>not</u> jump out of the ground but has a fine pedigree all across the world...



MEMBER STATES

AUSTRIA	77
BELGIUM	120
BULGARIA	54
CZECH REPUBLIC	178
DENMARK	66
FINLAND	80
FRANCE	868
GERMANY	1153
GREECE	104
HUNGARY	52
ITALY	1463
NETHERLANDS	170
NORWAY	73
POLAND	191
PORTUGAL	122
SLOVAKIA	55
SPAIN	311
SWEDEN	71
SWITZERLAND	362
UNITED KINGDOM	732

6302

OBSERVER STATES

INDIA	91
ISRAEL	49
JAPAN	204
RUSSIA	901
TURKEY	60
USA	1618

2923

OTHERS

ARGENTINA	8	CROATIA	18	MALTA	2	THAILAND	1
ARMENIA	16	CUBA	4	MEXICO	33	TUNISIA	1
AUSTRALIA	17	CYPRUS	8	MONTENEGRO	1	UKRAINE	17
AZERBAIJAN	1	EGYPT	3	MOROCCO	6	UZBEKISTAN	1
BELARUS	19	ESTONIA	9	NEW ZEALAND	8		
BRAZIL	77	GEORGIA	10	PAKISTAN	15		
CANADA	141	ICELAND	1	PERU	1		
CHILE	2	IRAN	15	ROMANIA	59		
CHINA	78	IRELAND	14	SERBIA	20		
CHINA (TAIPEI)	53	KOREA	64	SLOVENIA	17		
COLOMBIA	9	LITHUANIA	5	SOUTH AFRICA	8		

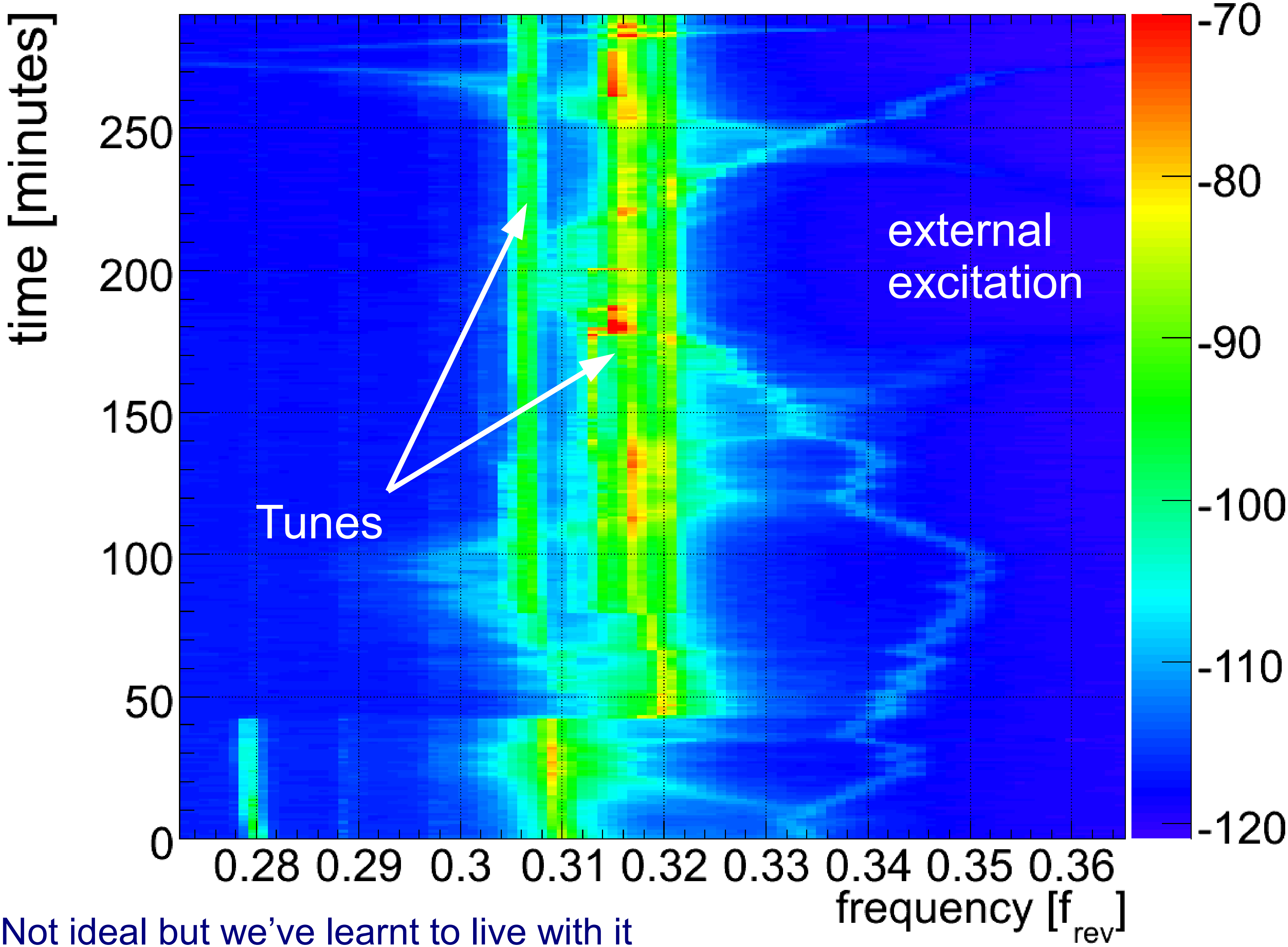
762

Issues, Issues, Issues...

- LHC commissioning was not without any faults and problems
- Most of the problems were addressed at a fast pace
- Some need some revisiting next year

- Following slides contain some assorted examples

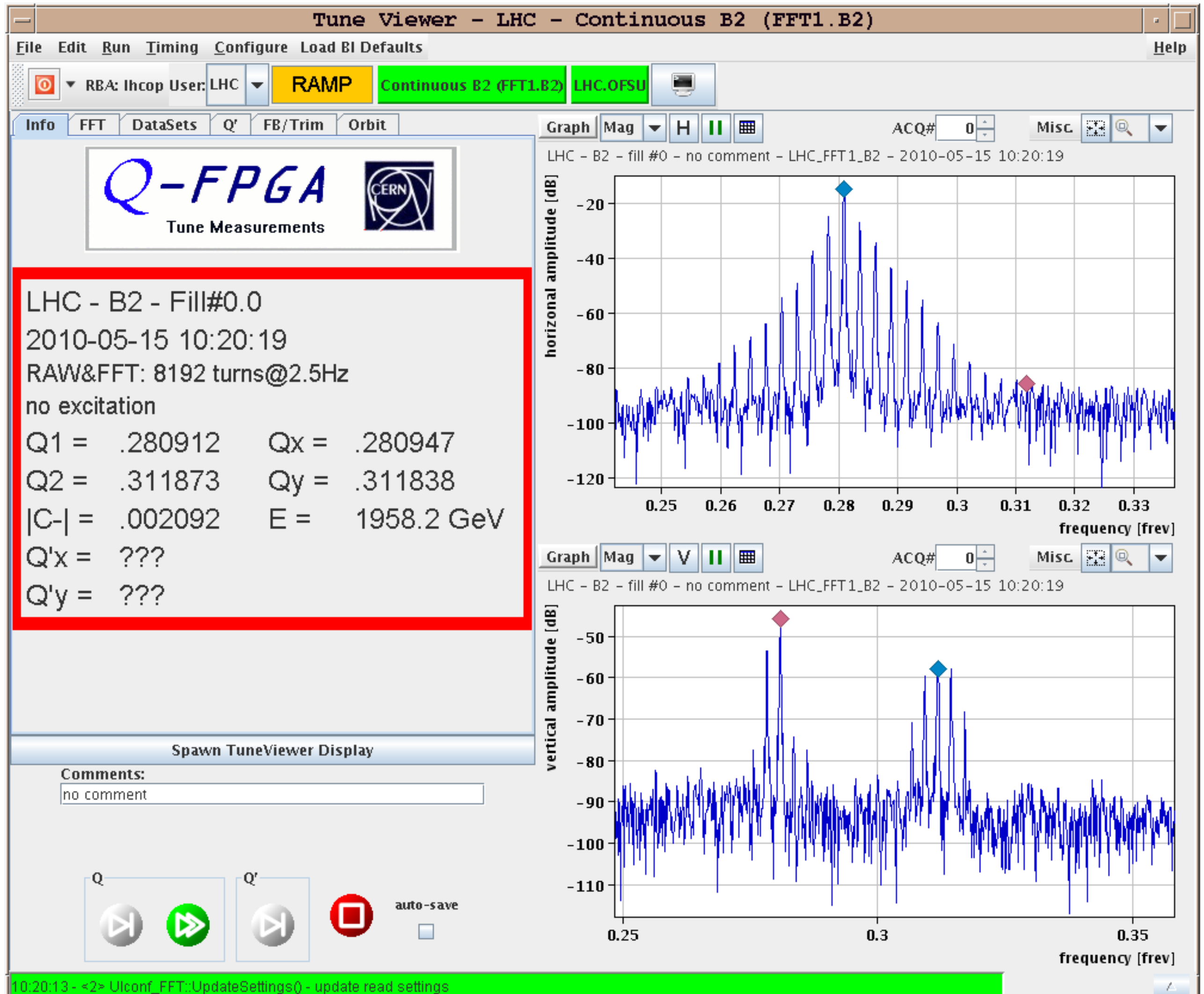
The Hump – Source is still unknown



Not ideal but we've learnt to live with it

Tune Christmas Trees in May

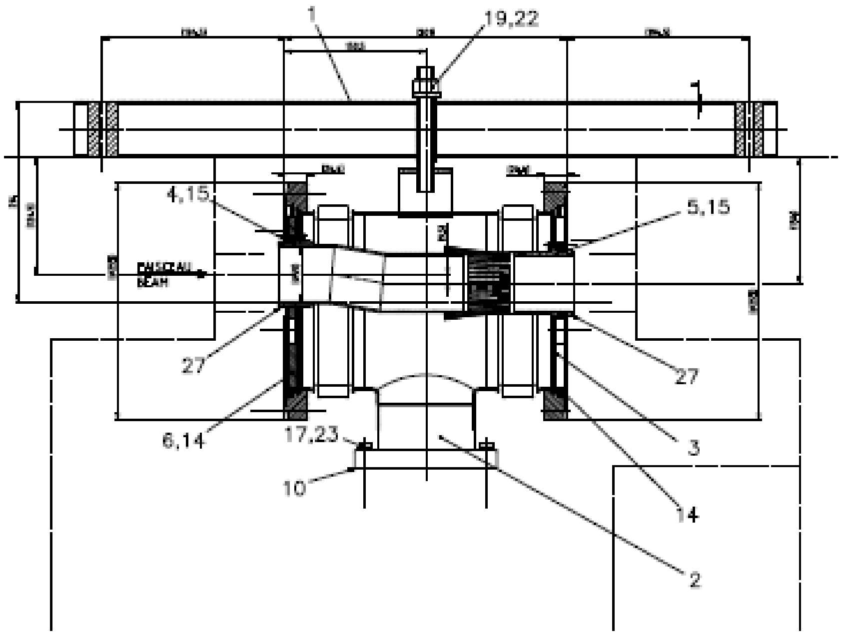
- Impedance measurement in agreement with estimates (dominated by collimators)
- What happend when we got ultra-short bunches for the first time:

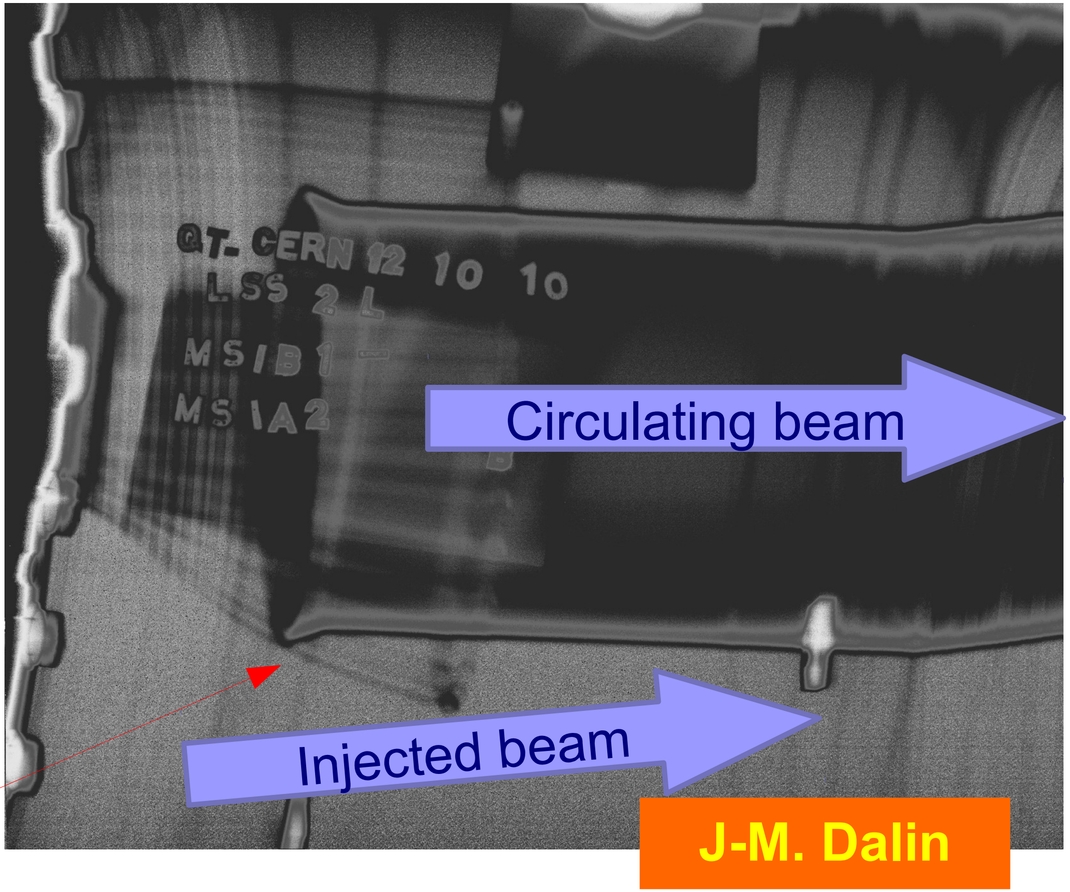


- Not an issue: easily cured by Landau Damping (non-linear field ↔ Octupoles)

Injection Septa Interconnection Repair

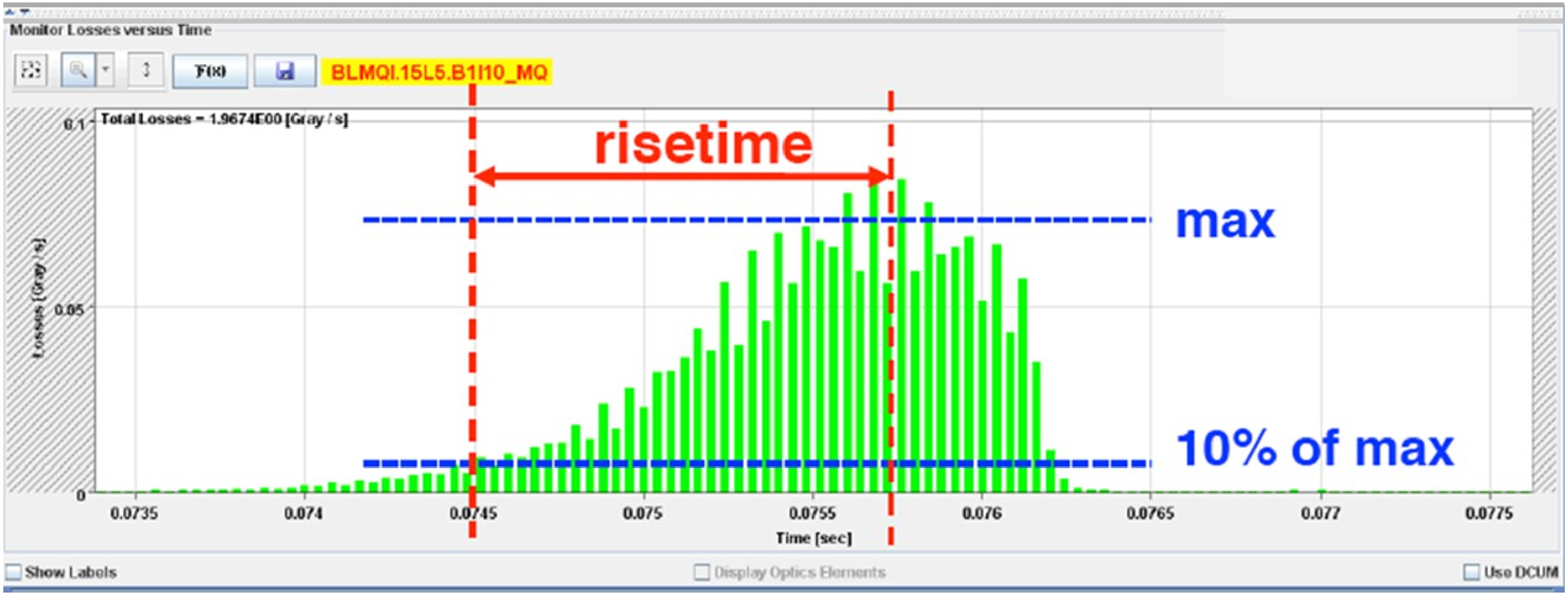
- Injection is becoming more critical:
  - Injected beams have now some damage potential.
  - Losses at injection collimators become more critical
- Radiation survey and X-ray showed aperture restriction at the transition between the injection septa due to a non-conformity in the mounting of the interconnection





RF fingers

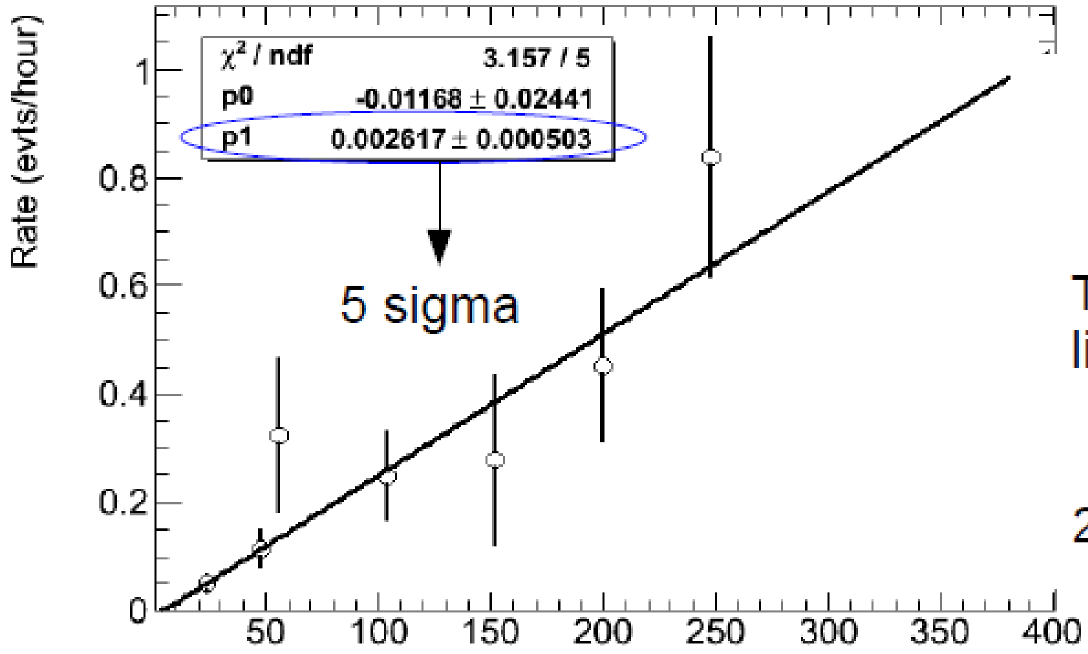
- Sudden local losses have been recorded.
  No quench, but preventive dumps (raised level).
  - Rise time partly < 1 ms.
  - Pot explanation: dust particles falling into beam → thus 'UFO'
    - However: seen these only at 3.5 TeV and never at 450 GeV



UFO: intensity dependence

Beam loss monitor thresholds have been raised a the appropriate timescales

Logging data mined for events not above threshold



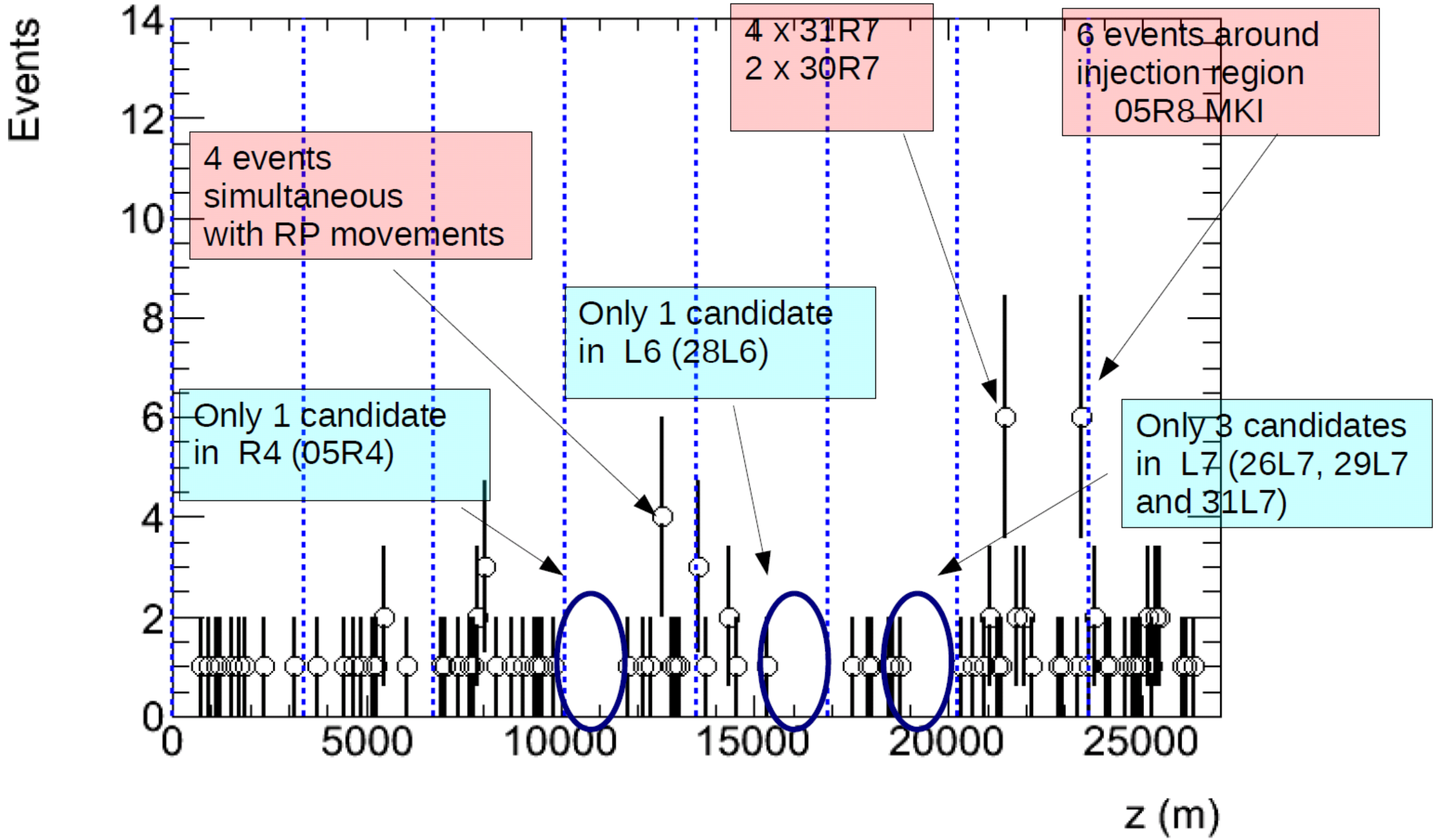
<u>"UFO" Rate</u>

The UFO rate seems to increase linearly with intensity:

Extrapolating
2000 Bunches => ~ 5.2 evts/hour

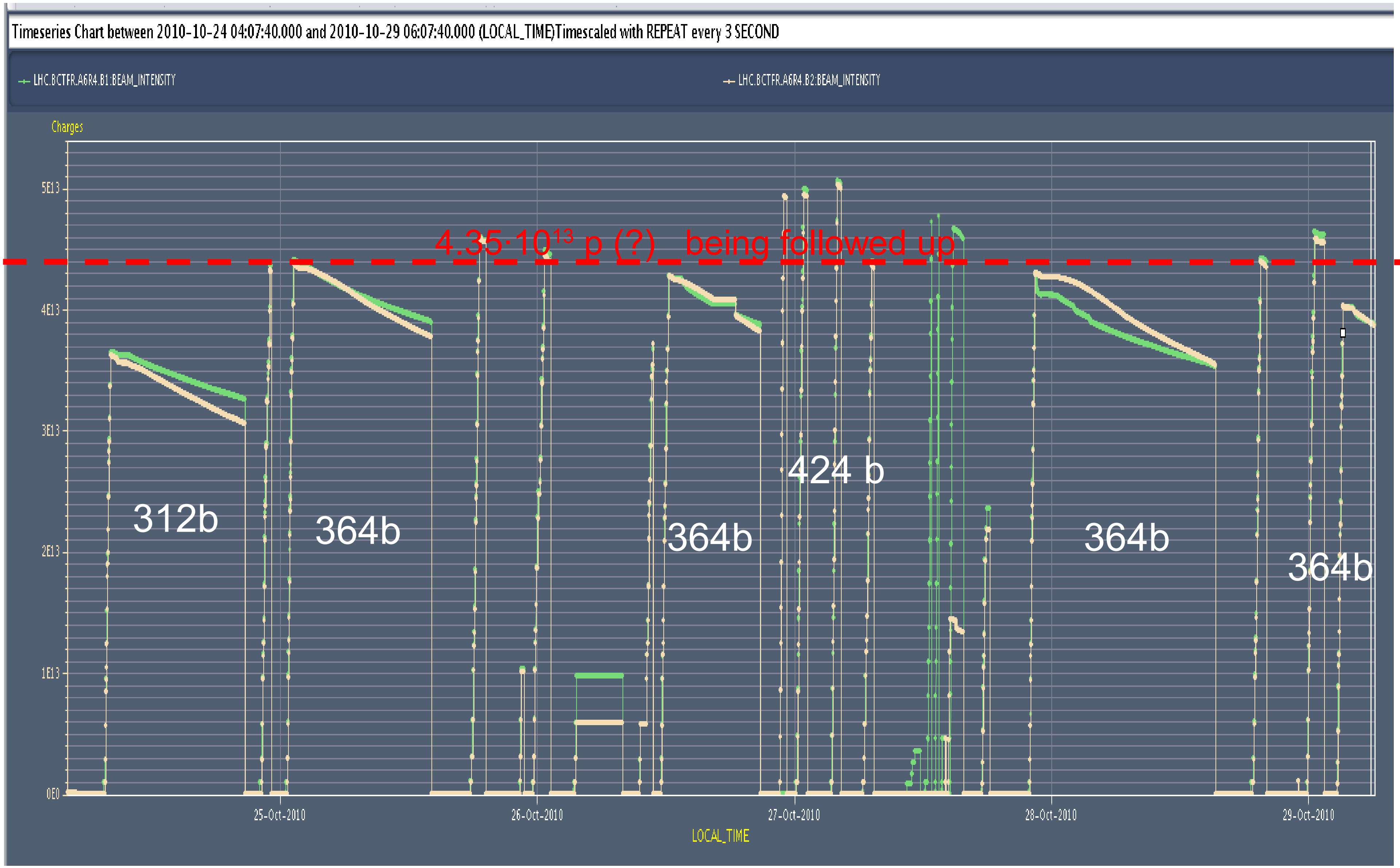
E. Nebot for the BLM team

UFO Landing Landing Sites in the LHC



E. Nebot for the BLM team

Intensity Reach 150 ns



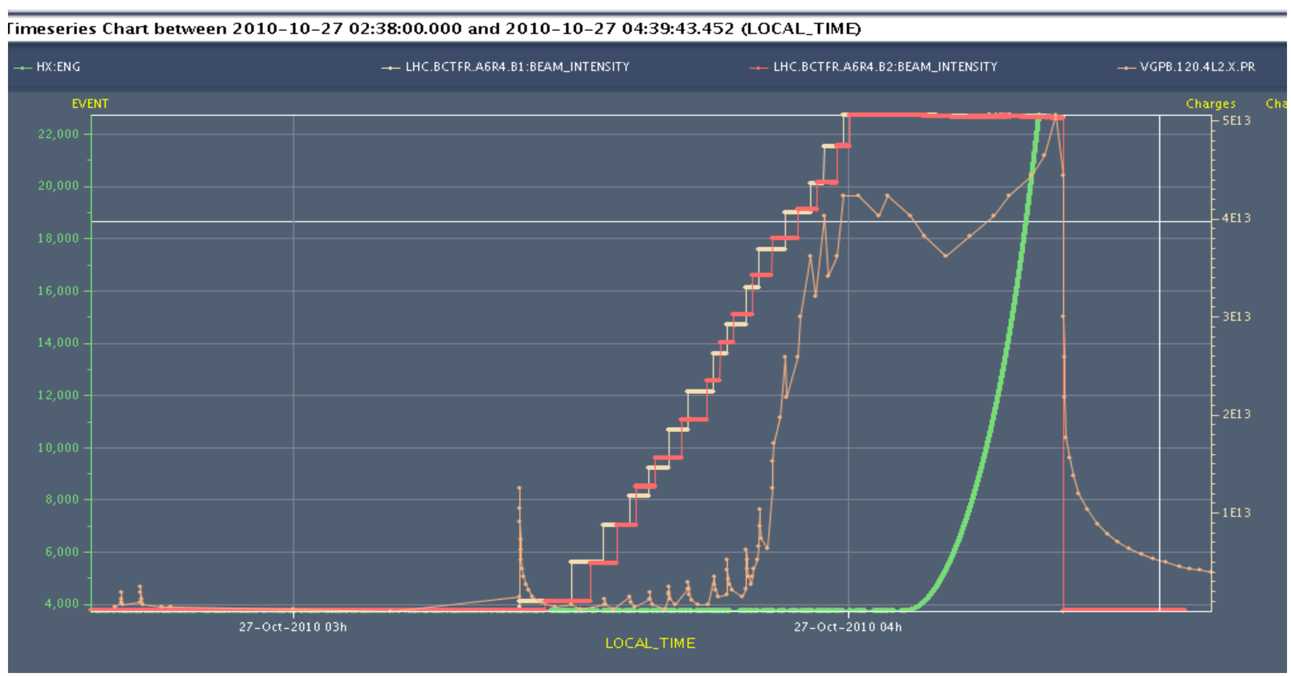
Stored energy reached at 3.5 TeV: **28.0 MJ**

Stored energy at 3.5 TeV in stable beams: **24.4 MJ**

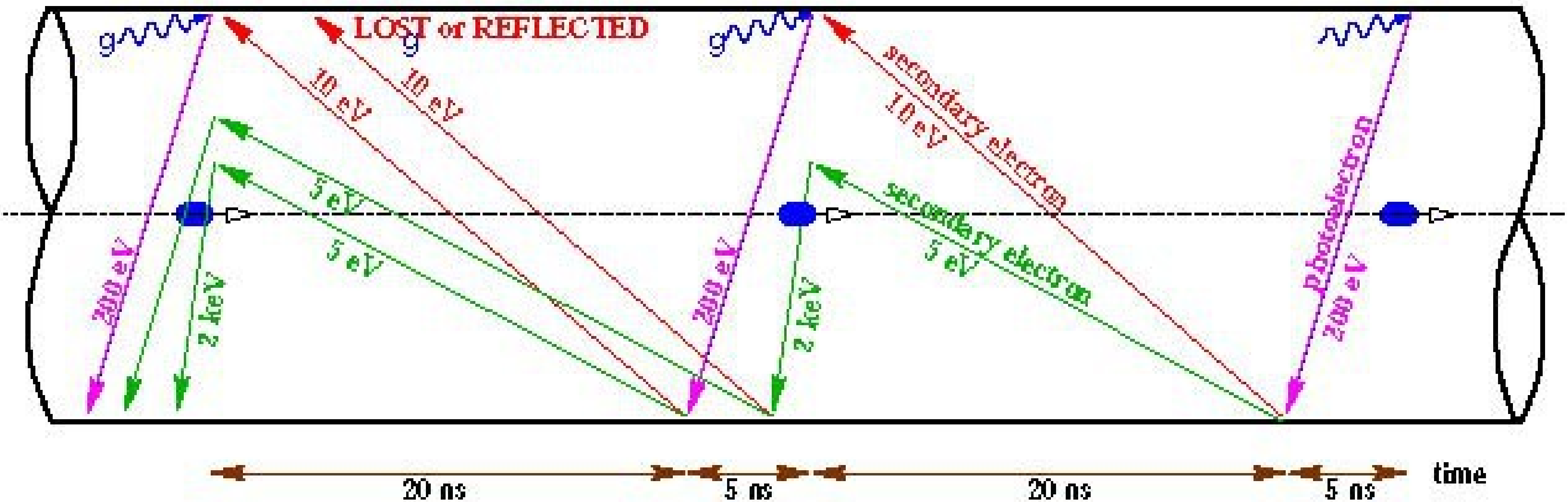
Ralph Assmann

Vacuum Pressure Rise

- Pressure rise seen in common beam pipe regions
- Particularly unbaked warm-cold transitions
- Two effects:
  - electron cloud driven by closely space passage of b1 and b2 bunches
  - synchrotron radiation induced desorption
- Region +/- 58 m of IP1 equipped with solenoids
  - worked well – classic cure for electron cloud
- Cleaning observed

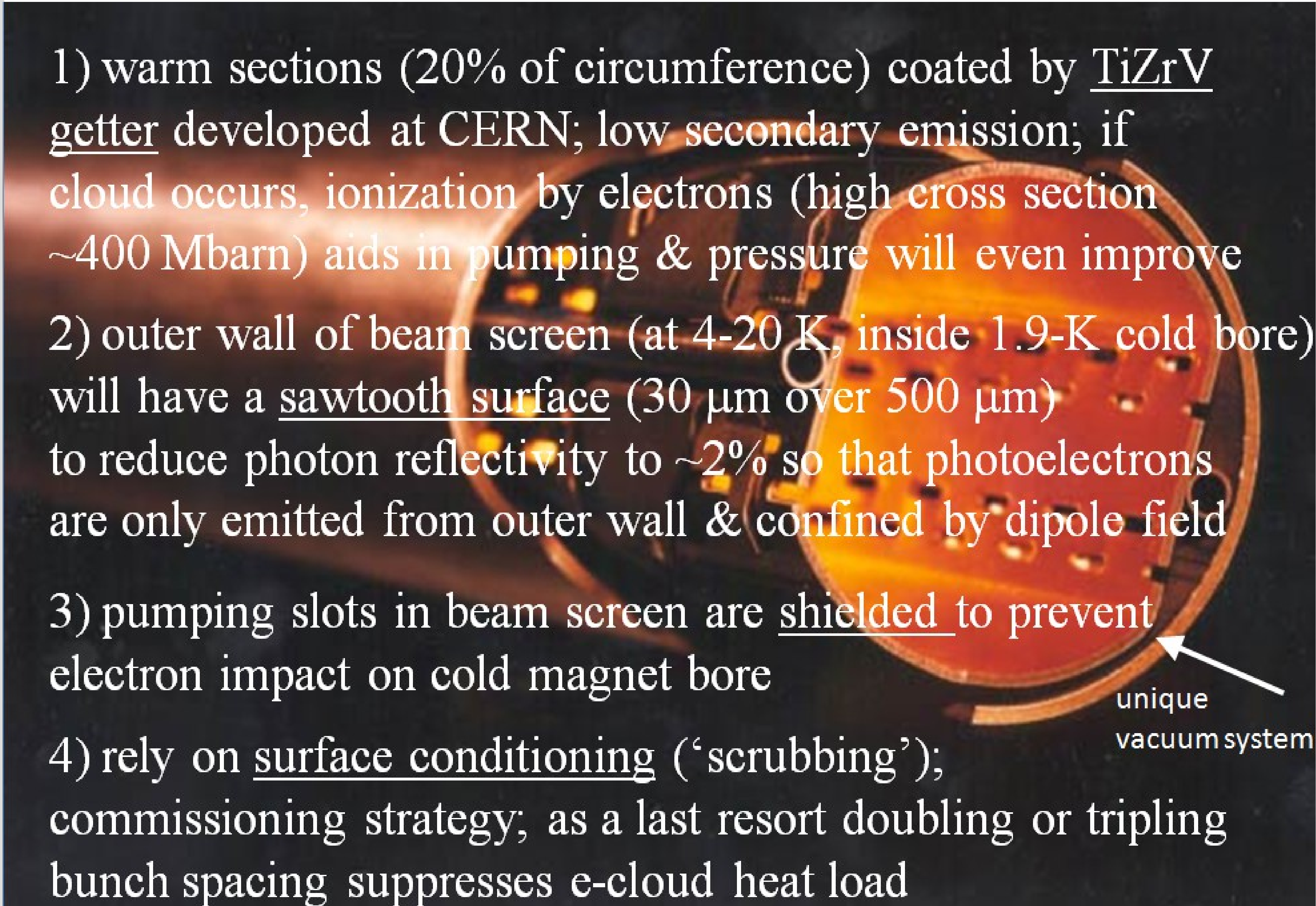


Schematic of e-Cloud Buid up in LHC Arc Beam Pipe, due to Photoemission and secondary Emission



[F. Ruggiero]

LHC Strategy against Electron-Cloud



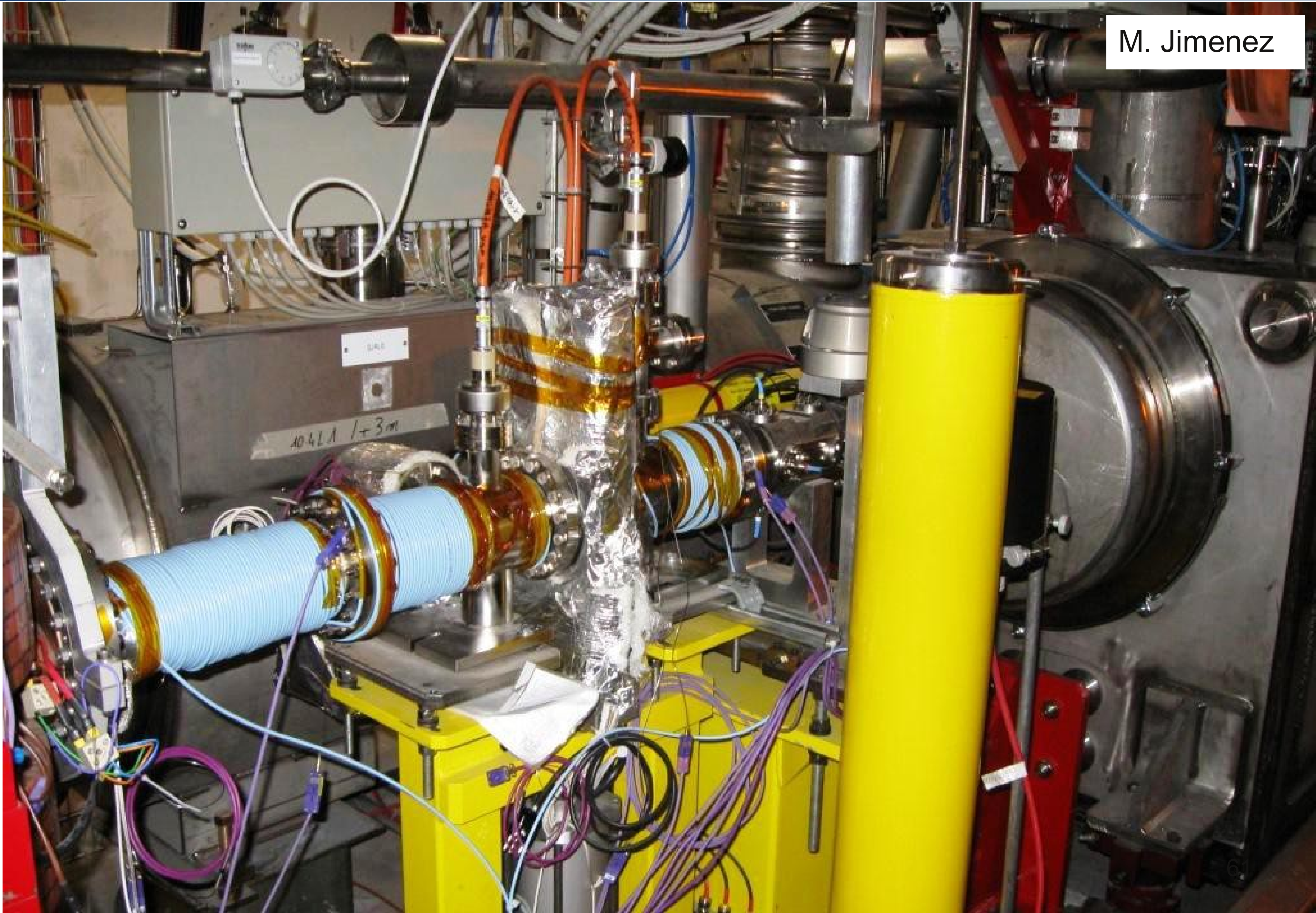
1) warm sections (20% of circumference) coated by TiZrV getter developed at CERN; low secondary emission; if cloud occurs, ionization by electrons (high cross section ~400 Mbarn) aids in pumping & pressure will even improve

2) outer wall of beam screen (at 4-20 K, inside 1.9-K cold bore) will have a sawtooth surface (30 µm over 500 µm) to reduce photon reflectivity to ~2% so that photoelectrons are only emitted from outer wall & confined by dipole field

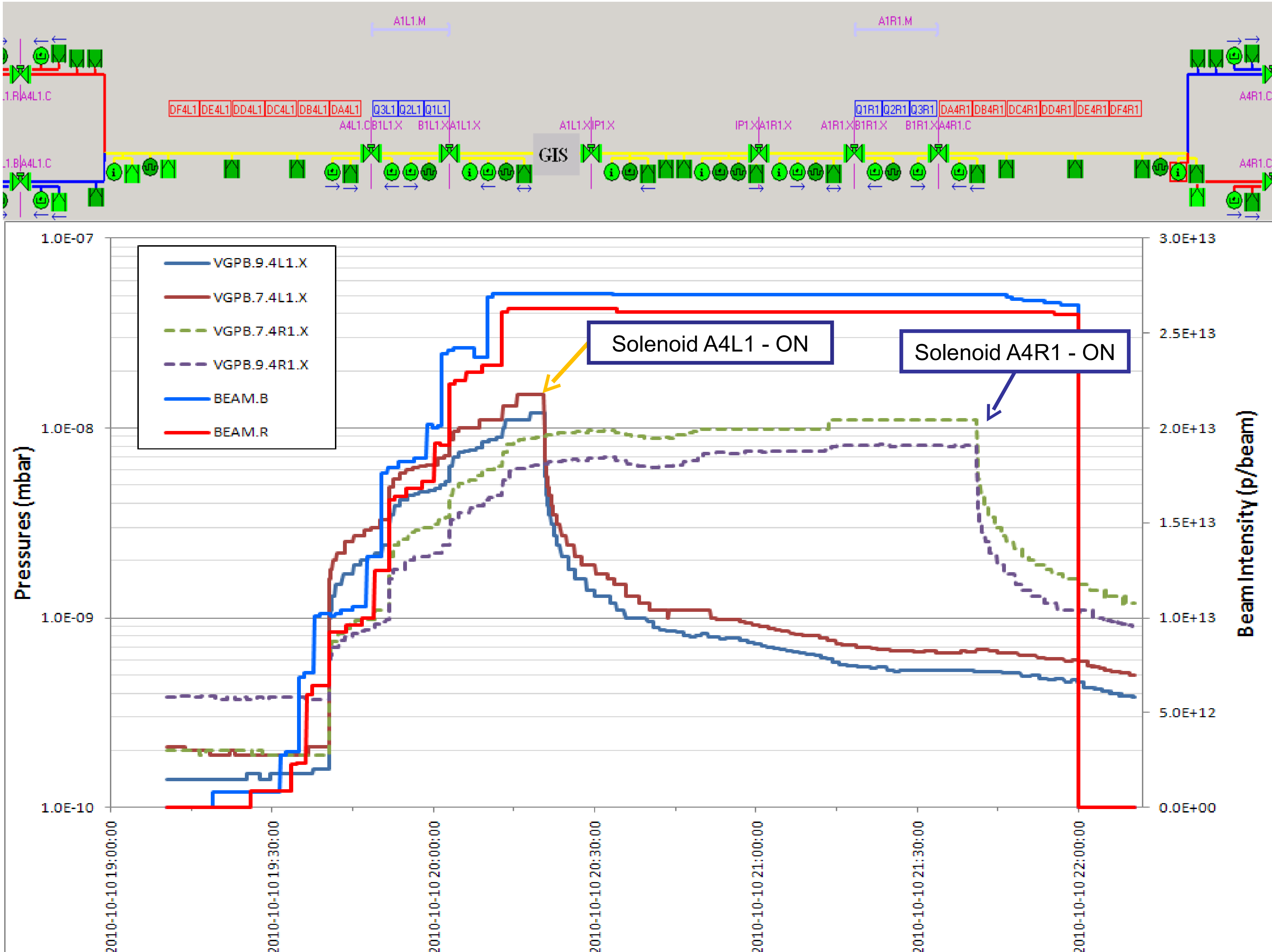
3) pumping slots in beam screen are shielded to prevent electron impact on cold magnet bore

4) rely on surface conditioning ('scrubbing'); commissioning strategy; as a last resort doubling or tripling bunch spacing suppresses e-cloud heat load

Solenoids between DFBX and D1 in IR1L



Vaccum Pressure in IR1



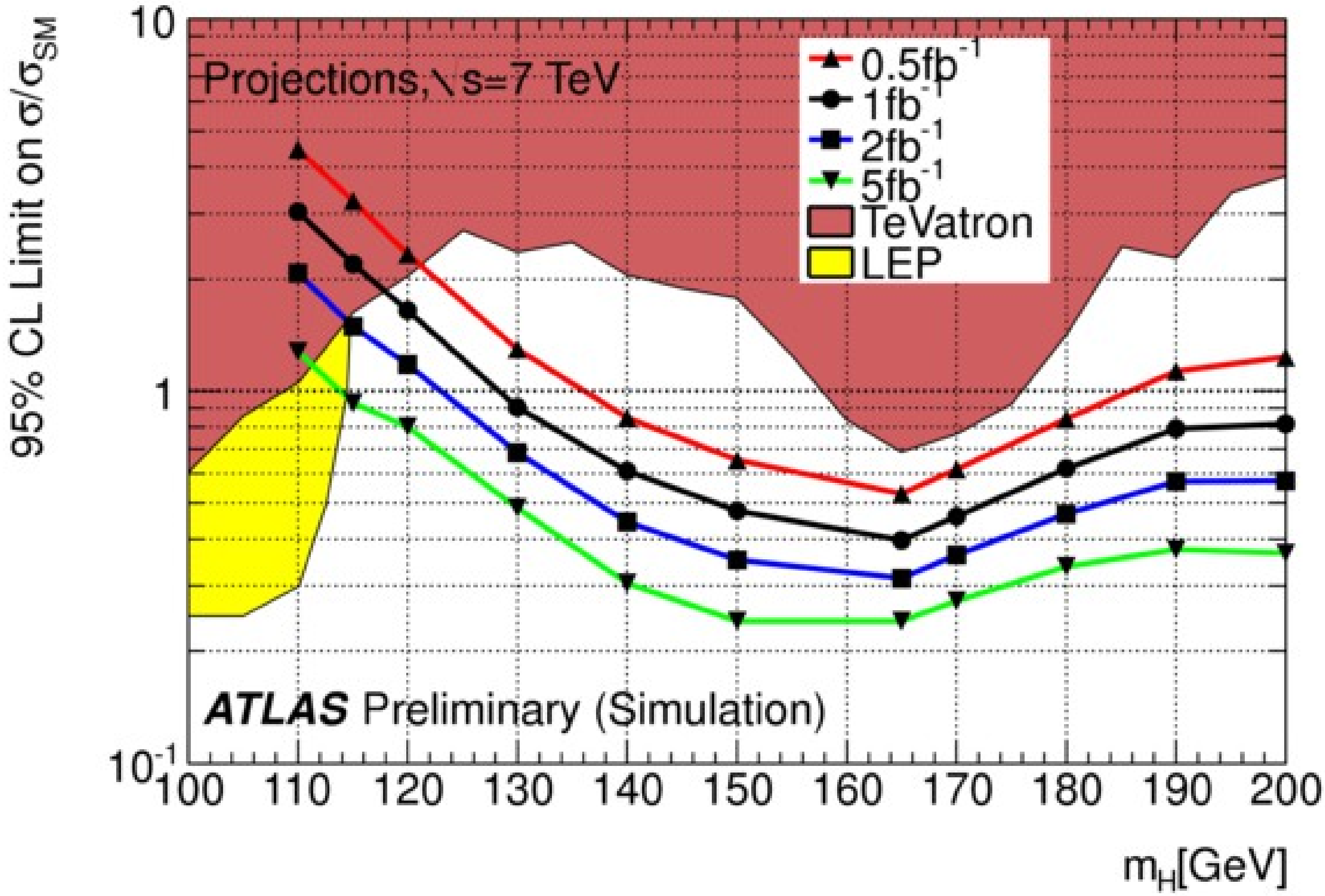
Conclusions

- Very successful period of initial commissioning
  - No real physics operation but got a good idea on how 2010 could look like
  - Re-established and solidified physics that has been discovered over the last 50 years at Tevatron, RHIC, ….
- All key systems performed remarkably well
  - Some commissioning still required, issues still to be addressed
- Performance with beam (losses, lifetimes, luminosity, emittance growth etc.) is very encouraging.
- Moving towards a MJ culture.
- 2011: smooth running with 10s MJ
  - re-establish 2010 performance
  - a bit of scrubbing (e-cloud mitigation)
  - Move LHC status from 'commissioning' to 'physics operation'
  - > 1 fb^{-1}, cranking up intensities: 75 ns bunch trains (50 ns?), ~900 bunches

LHC has taken off

Thank You for your Attention!

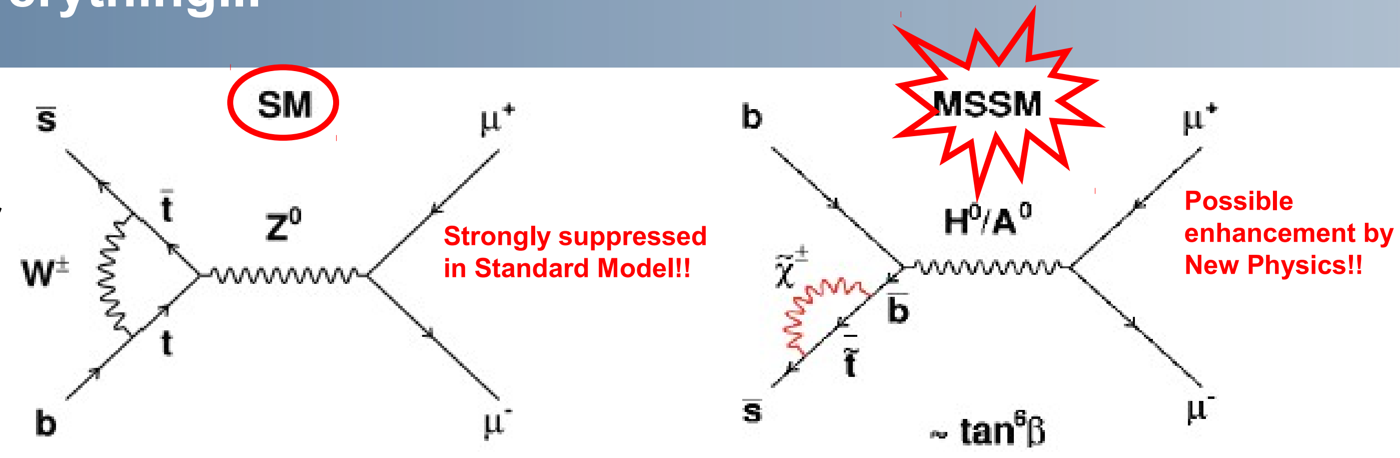
ATLAS: Preliminary Projections

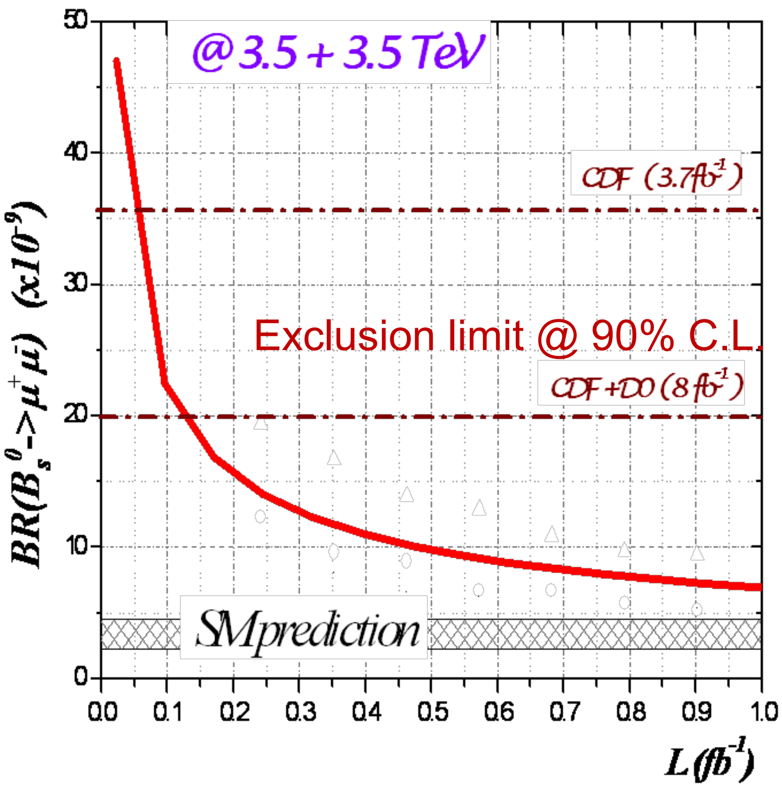


- $5fb^{-1}$ enough to close gap with LEP at 7 TeV
  - Expected 3σ observation from 123 to 550 GeV with
  - ATLAS estimates from a very conservative analysis at 7TeV

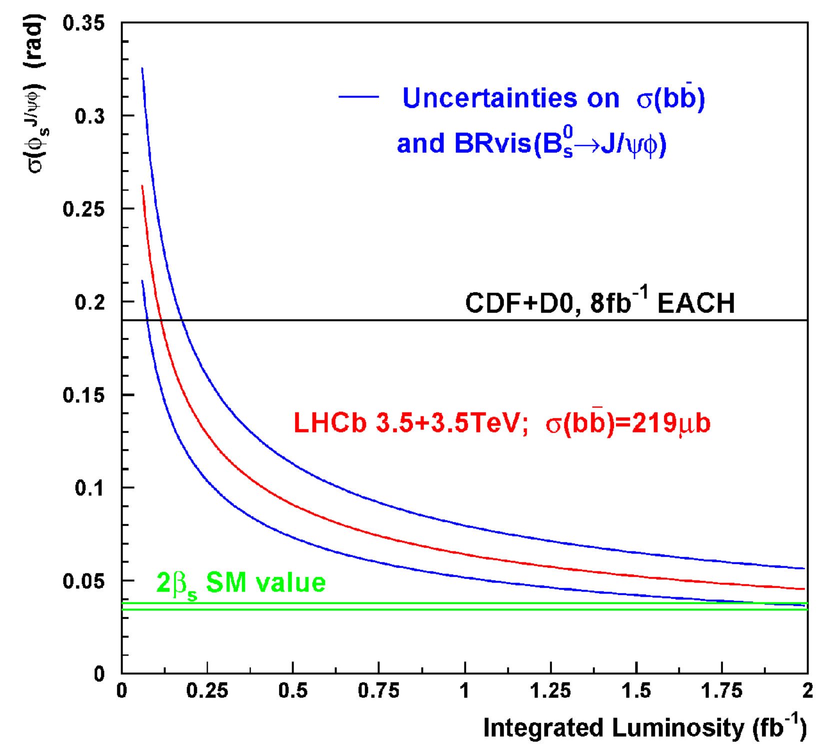
But Higgs is not everything...

- Beauty also counts
- LHCb expectations for





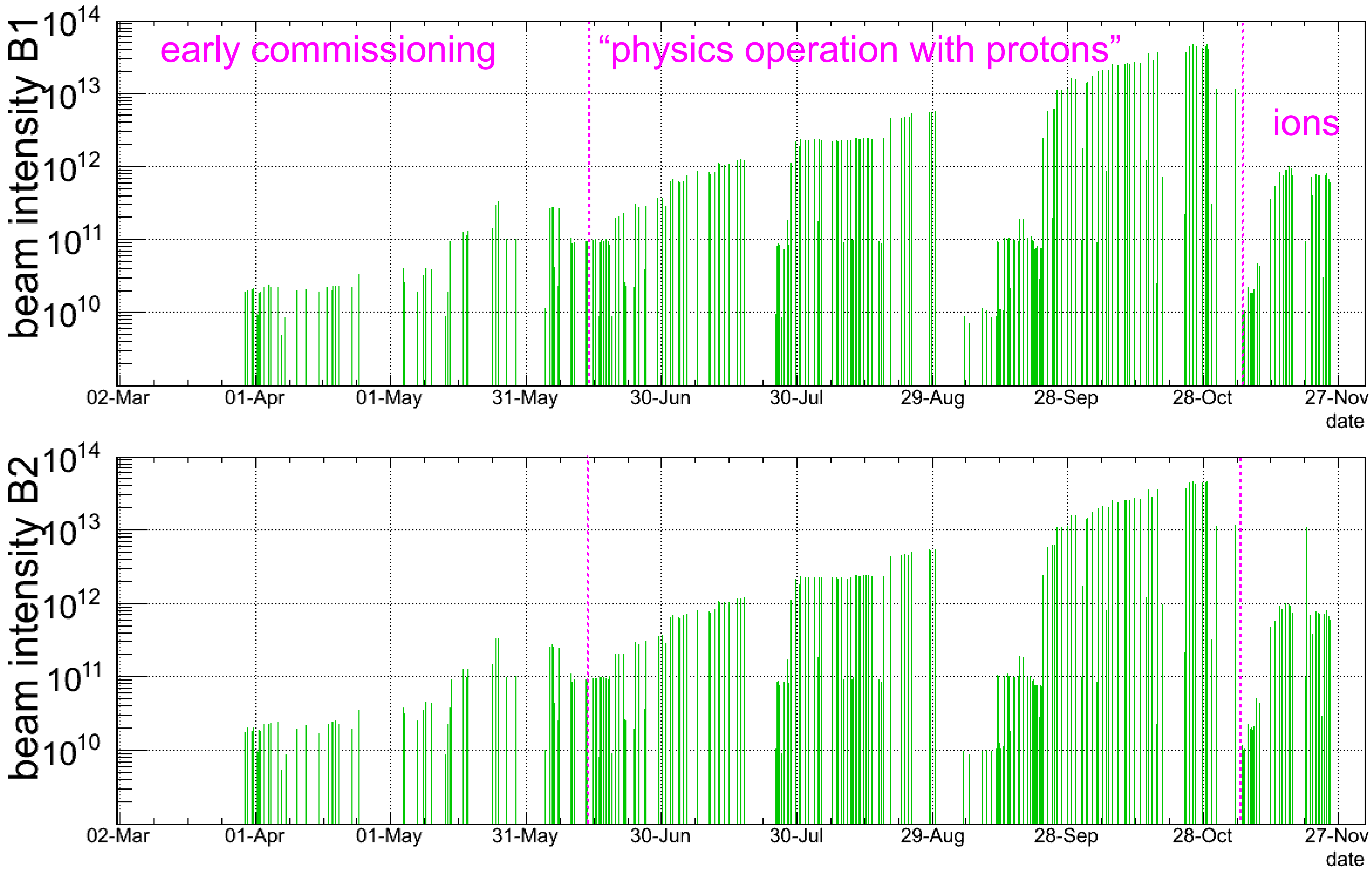
And the B_s equivalent of the "B_d CKM angle (B factories)"



Courtesy Massimiliano Ferro-Luzzi

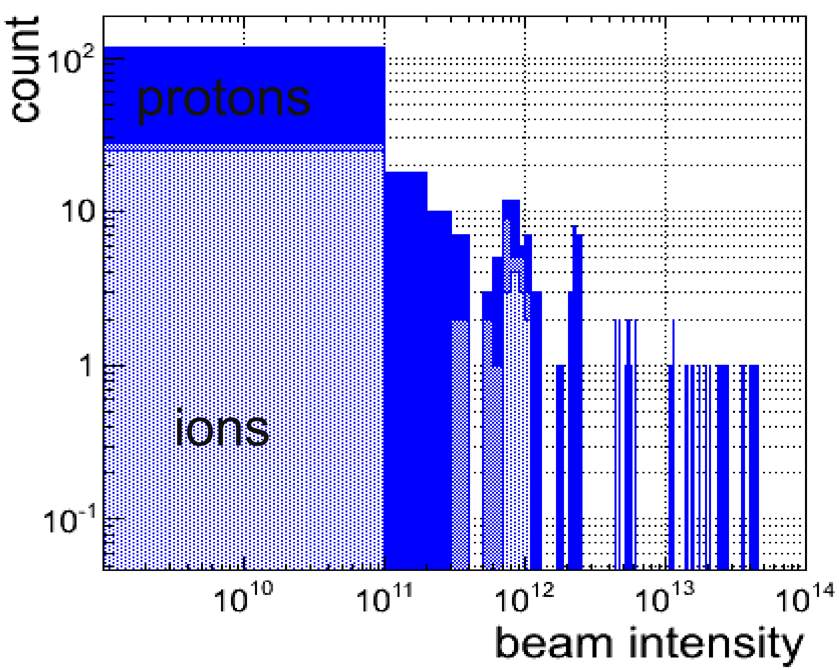
Q/Q'-Stability and Feedback Performance

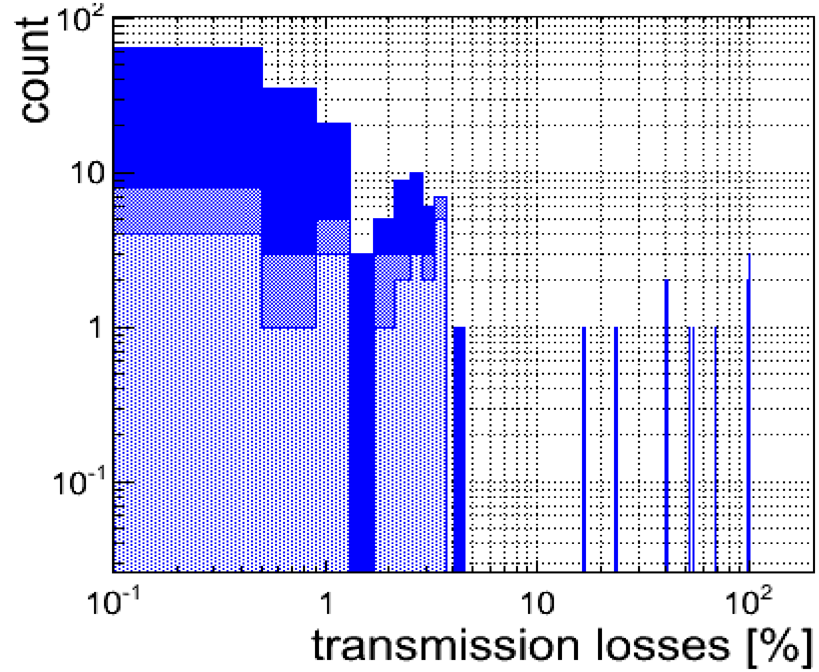
- Analysed a total of 275 ramps, excluded most of early ramps in 2009

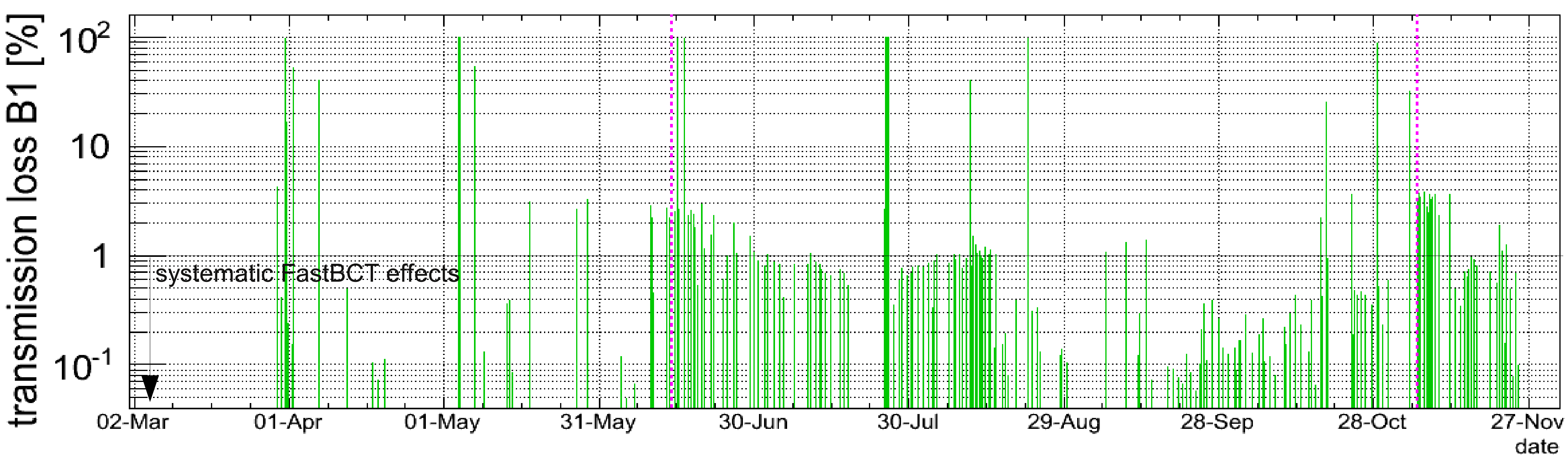


Maximum Intensity and Transmission Loss during the Ramp Beam 1

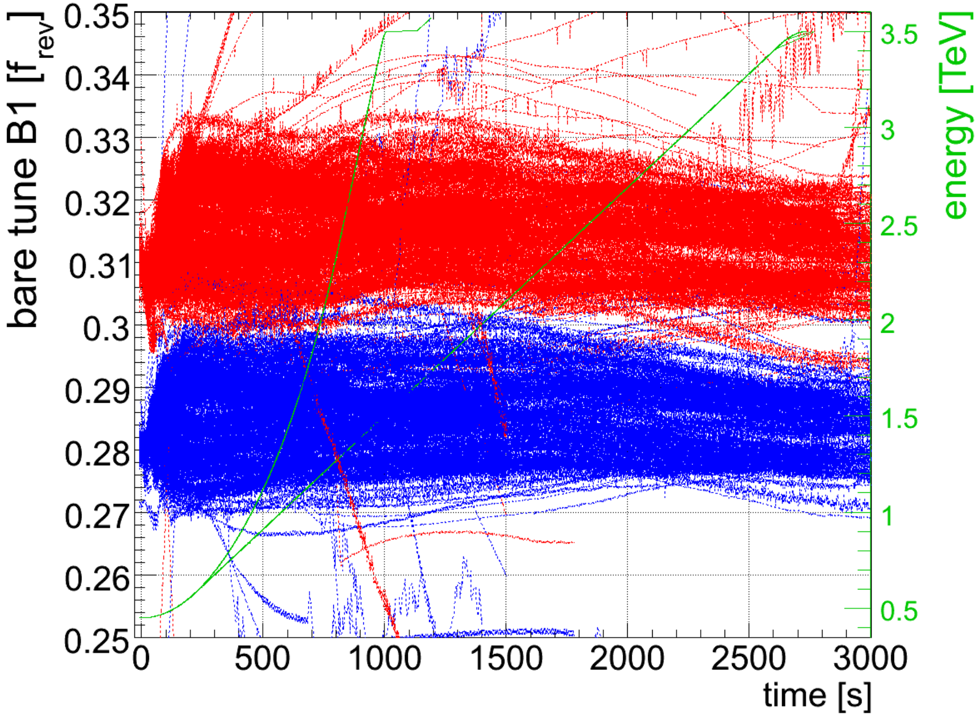
- Most losses when switching mode of operation (single bunch → trains → ions)

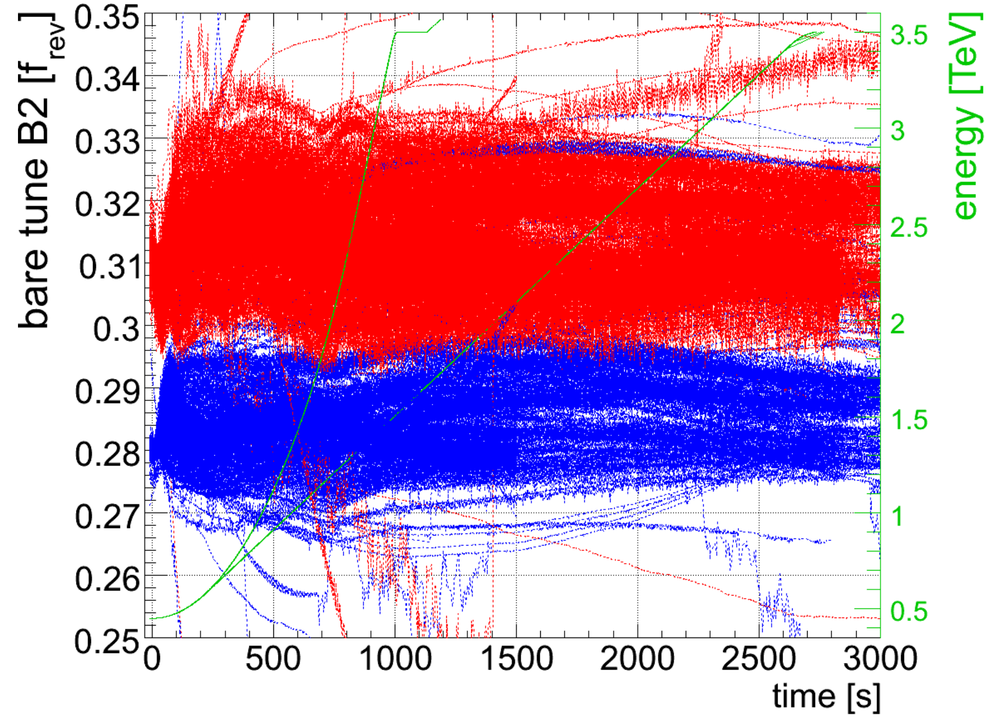






- Ramp dynamics and variations are compensated/absorbed by Tune-FB





- … 56 lost due to low-order (3^{rd},4^{th},C^{-}) resonance crossing without Tune-FB
- … 150 exceeding ΔQ=±0.01 tolerance
- … all above nominal ΔQ=±0.0015 limit

- … 83 lost due to low-order (3^{rd},4^{th},C^{-}) resonance crossing without Tune-FB
- … 157 exceeding ΔQ=±0.01 tolerance
- … all above nominal ΔQ=±0.0015 limit

Beam 2 - RF Capture
Thursday 11th – Late Evening

once QPS, cryo and power systems have been fixed:

- Re-cycled LHC, re-corrected tune, orbit, …, switched on RF

- Beam circulated for more than 10 minutes (life-time > 1 h)
  - forced beam abort → first emergency beam dump test
- Commissioning driven by RF team from SR4.
  - CCC could only watch the longitudinal profile monitor!