LHC Run 2 experience and prospects

Mike Lamont for the LHC team

Thanks to everyone for the material!

LHC - 2015

- Target energy: 6.5 TeV
  - looking good after a major effort
- Bunch spacing: 25 ns
  - strongly favored by experiments – pile-up
- Beta* in ATLAS and CMS: 80 cm

Energy

- Lower quench margins
- Lower tolerance to beam loss
- Hardware closer to maximum (beam dumps, power converters etc.)

25 ns

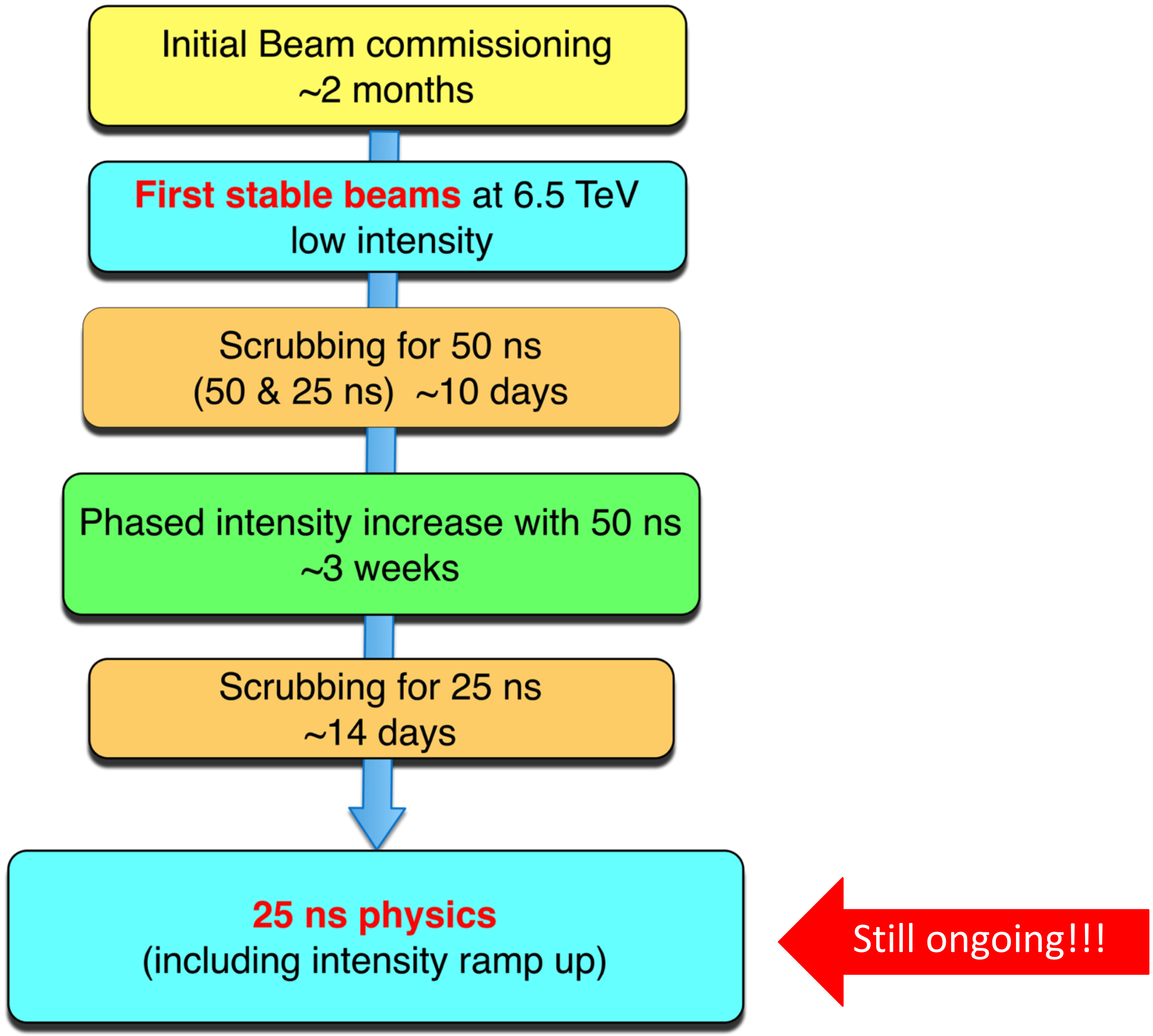
- Electron-cloud
- UFOs
- More long range collisions
- Larger crossing angle, higher beta*
- Higher total beam current
- Higher intensity per injection

2015: beta* in IPs 1 and 5

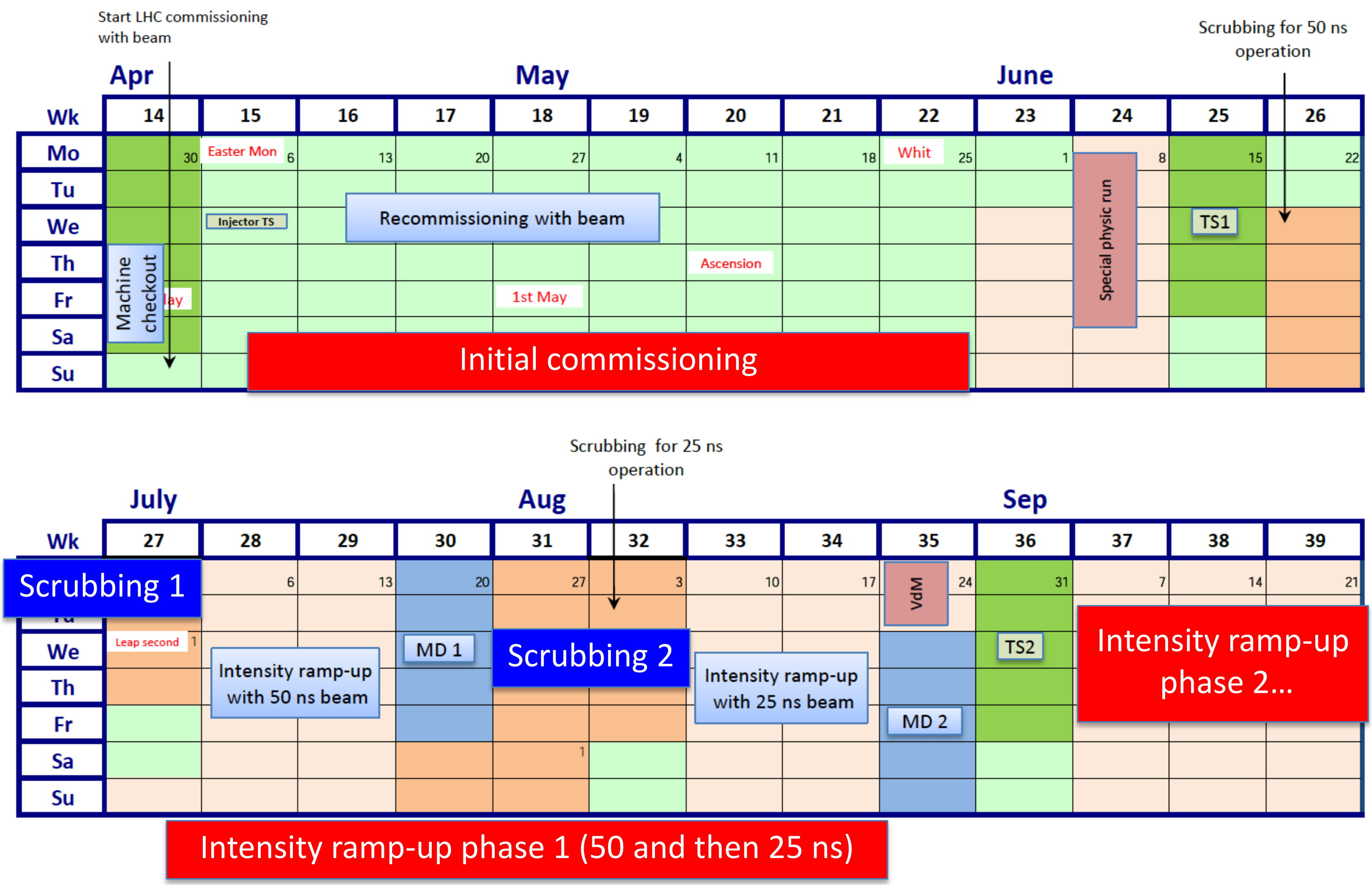
- Start-up: **β^*= 80 cm – relaxed**
  - 2012 collimator settings
  - 11 sigma long range separation-> crossing angle
  - Aperture, orbit stability… looking good

- Target in Run 2: **β^*= 40 cm**
  - Validated during machine development in 2015
  - To be used from the start in 2016

2015 commissioning strategy

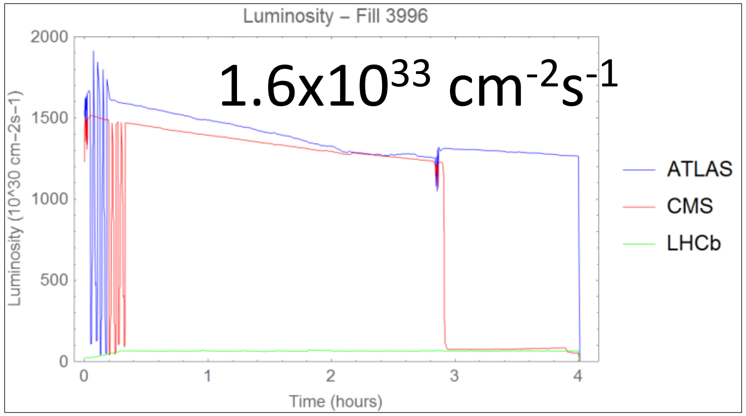


2015 schedule Q2/Q3



5th April
first beam

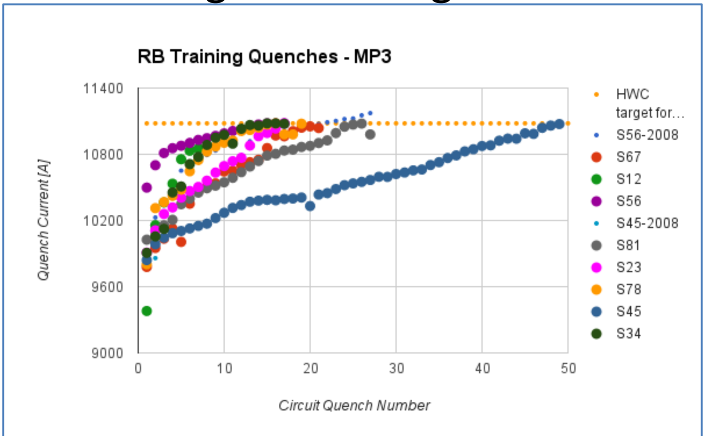
10th April: 6.5 TeV for the first time



July 14th: 476b (50 ns)

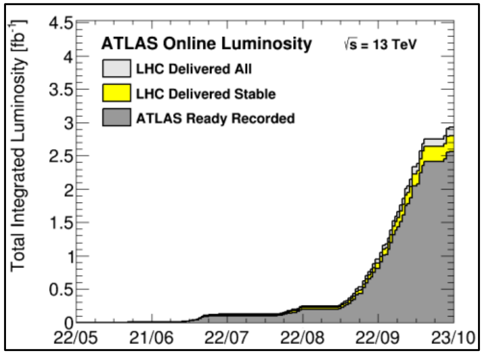
APRIL | MAY | JUNE | JULY | AUGUST…

Finish magnet training



3rd June: First Stable Beams

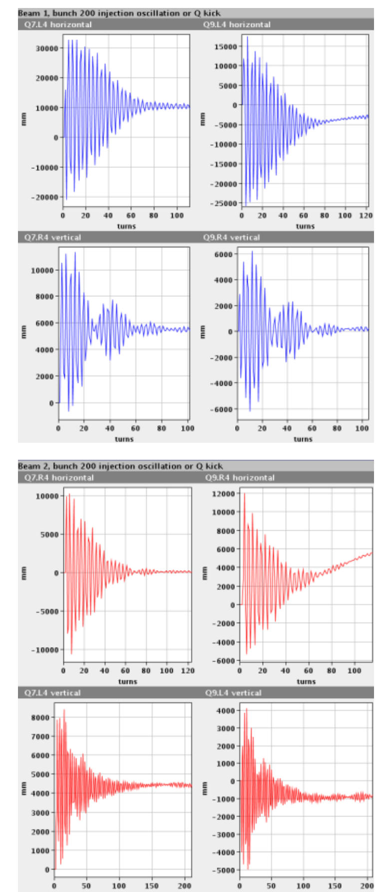
25 ns ramp-up



2015

Initial commissioning 1/2

- **A lot of lessons learnt from Run 1**
- Excellent and improved system performance:
  - Beam Instrumentation
  - Transverse feedback
  - RF
  - Collimation
  - Injection and beam dump systems
  - Vacuum
  - Machine protection
- Improved software & analysis tools
- Experience!

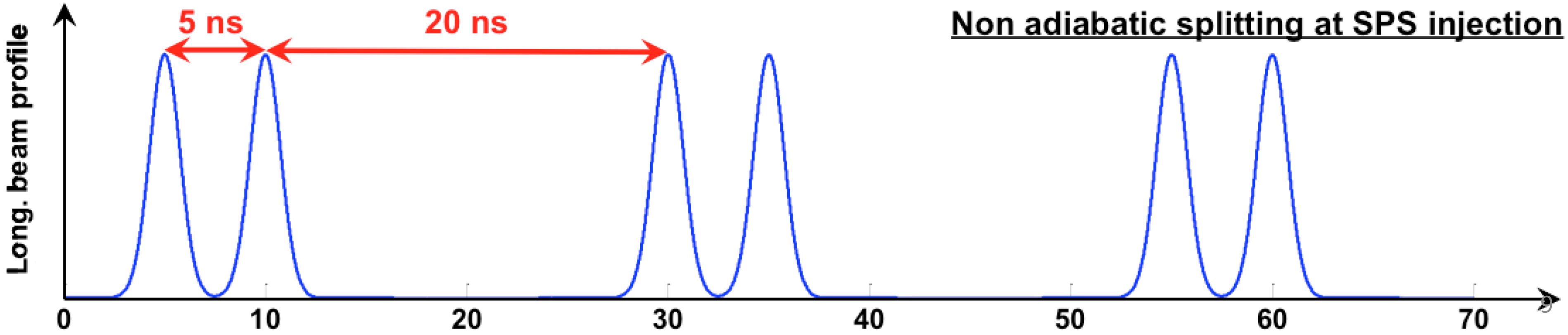


Initial commissioning 2/2

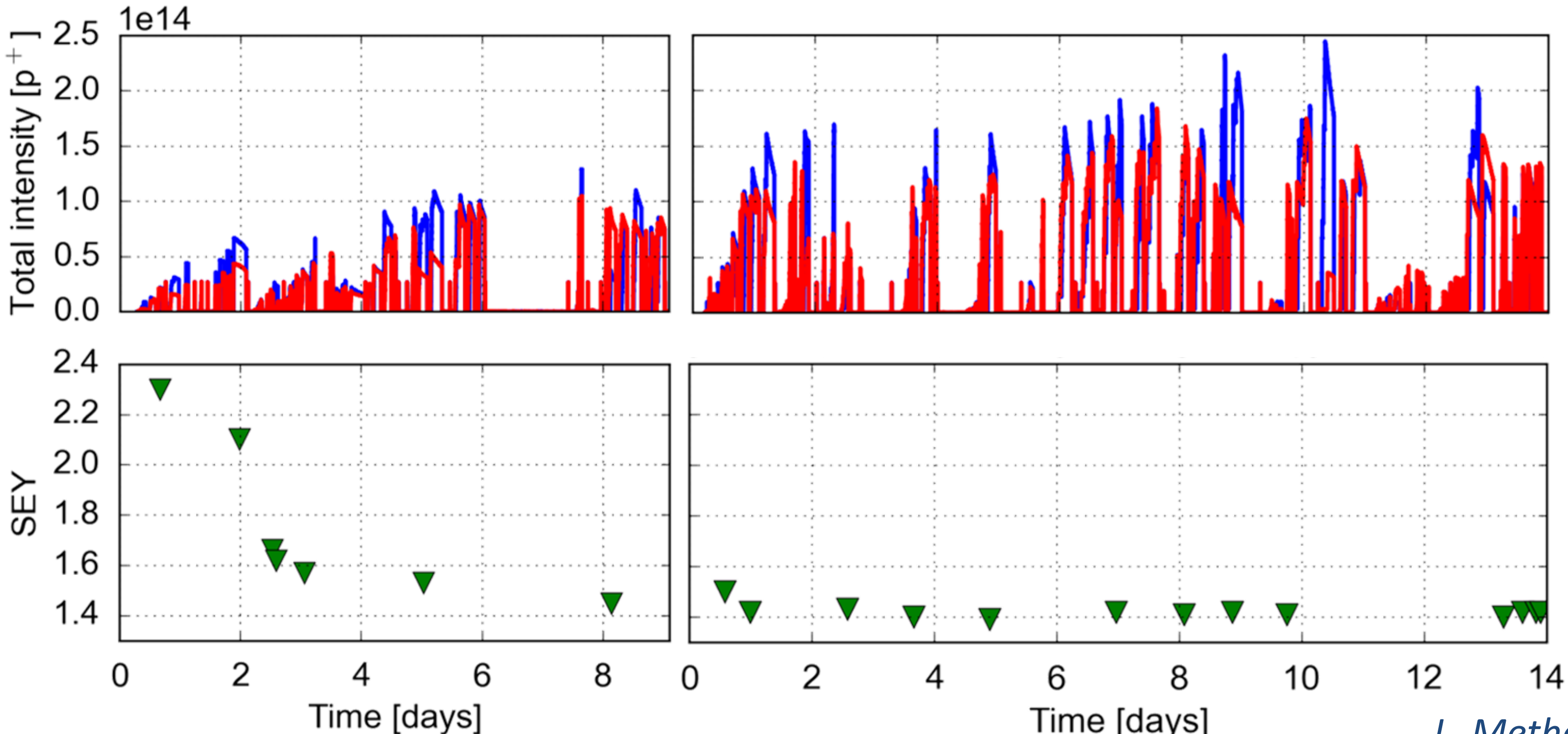
- Magnetically reproducible as ever
- Optically good, corrected to excellent
- Aperture is fine and compatible with the collimation hierarchy.
- Magnets behaving well at 6.5 TeV
  - 4 additional training quenches during operation
- Operationally things well under control
  - Injection, ramp, squeeze etc.

Scrubbing 2015

- Knew that e-cloud would be a lot worse with 25 ns, concerted scrubbing campaign anticipated
- Doublet scrubbing beam looked attractive…
- A two stage scrubbing strategy was pursued:
  - Scrubbing 1 (50 ns and 25 ns) to allow for operation with 50 ns beams at 6.5 TeV
  - Scrubbing 2 (25 ns and doublet) to allow for operation with 25 ns beams at 6.5 TeV



Scrubbing for 25 ns operation

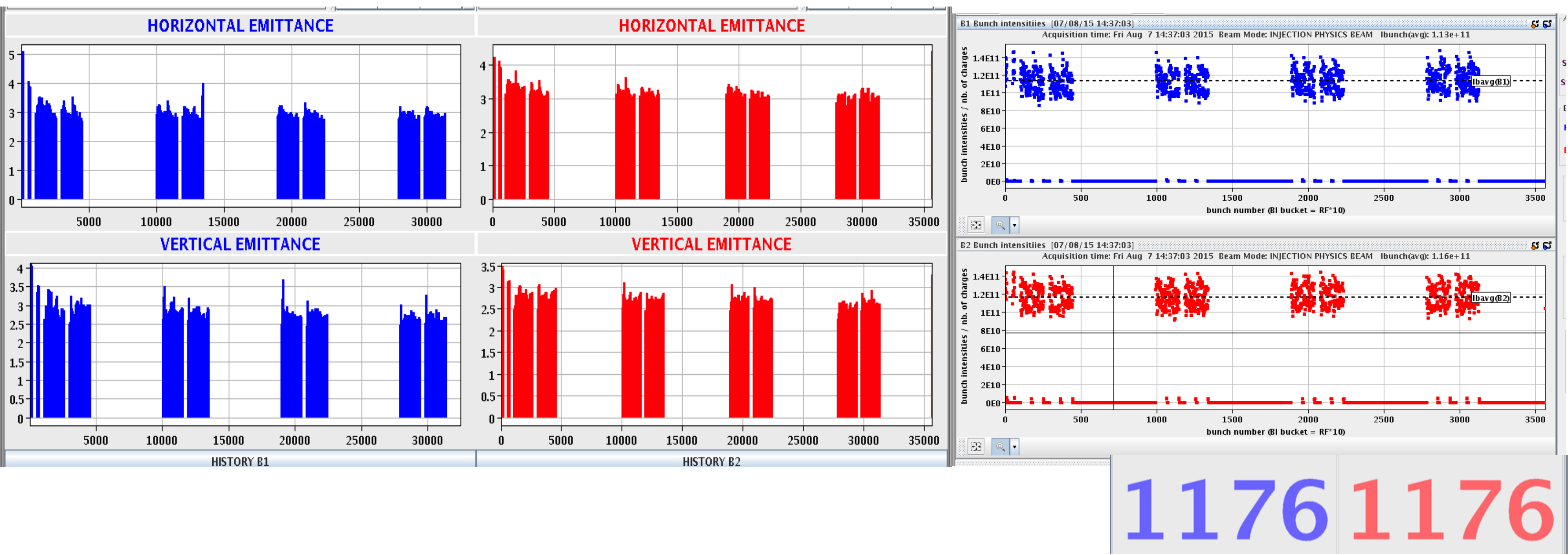


L. Mether

- During (1+2) weeks of scrubbing, regularly filled the machine with up to ~2500 bunches with 25 ns spacing
- Main limitations: vacuum spikes at TDI8, pressure rise in MKIs, time required by cryogenics to handle transients on beam screen temperatures
- Reduction of the SEY could be inferred from heat load measurements and confirmed by steadily improving beam quality

25 ns scrubbing run - exit

- Use of doublet beam proved difficult – more 25 ns scrubbing required before its effective use
- **Still significant electron cloud (but reasonable beam quality up to around 1500 bunches)**
- **Subsequently the cryogenics system has had to wrestle with the additional heat load**



Initial 50 ns ramp-up – mid July

Fill	Stable beams /Lost	bunches	Peak Lumi 10^{33} $cm^{-2}s^{-1}$	Int Lumi pb^{-1}	dumped by
3992	5h18m	476	1.4	22.16	QPS RB.A81
3994	Top of ramp	476			UFO 10L3
3995	Flat top	476			UFO with quench, 34L8
3996	4h4m	476	1.6	20.23	QPS SEU in B29R2
4000	Ramp 2.0 TeV	476			UFO with quench at ULO
4001	69s	476	1.4	<0.1	QPS SEU in B11.L1
4003	Ramp 2.2 TeV	476			UFO at ULO
4006	10m	476	1.6	0.79	QPS SEU in B16R1
4008	2h34m	298	0.9	7.86	QPS SEU in B29R2
4013	Ramp 6.1 TeV	476			RCS.A78B2 earth fault
4015	Ramp 6.2 TeV	476			RCS.A78B2 earth fault
4018	Flat-top	476			UFO 12L6
4019	31m	476	1.5	2.3	UFO 15L2

Initial 25 ns ramp-up – end August

Fill	Stable beams /Lost	bunches	Peak Lumi $cm^{-2}s^{-1}$	Int Lumi pb^{-1}	dumped by
4224	10m	315	8.3e32		Cryo MSR8
4225	2h23m	315	7.7e32		Cryo MSR8
4228	Squeeze	315			QPS SEU
4230	Adjust	315			RF trip
4231	5h26m	315	6.9e32	11.1	QPS SEU S34
4237	Flattop	315			QPS SEU L1
4243	4h23m	315	8.3e32	12.1	BPMS low intensity
4246	10h25m	296 (50 ns)	1.05e33	27.0	OP dump
4249	19m	459	8.9e32	1.0	QPS SEU S81
4252	Ramp	459			QPS SEU
4254	37m	458	9/9e32	2.1	Cryo comms
4256	2h18m	458	1.0e33	7.7	UFO 19R2
4257	19m	458	9.6e32	1.1	QPS SEU

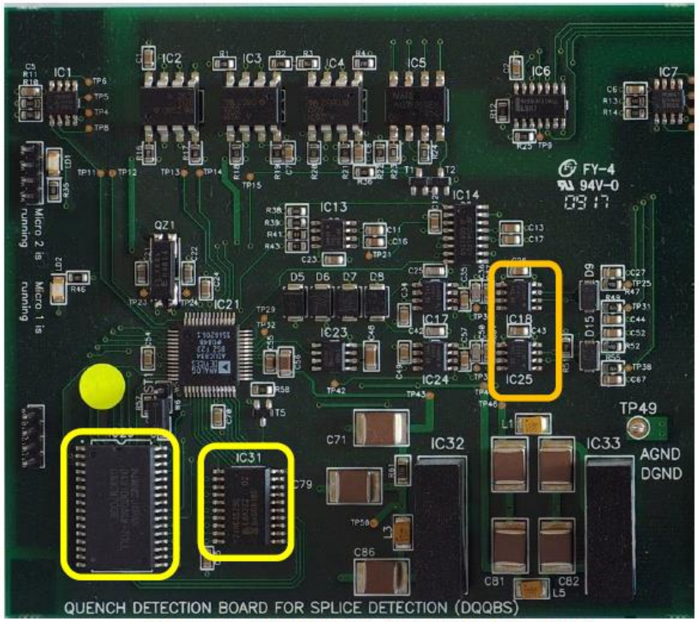
Main issues

Intensity ramp-up designed to flush out **intensity related issues** – successful in that regard

- Quench Protection System (QPS)
  - Non radiation hard components
- Unidentified Falling Objects (UFOs)
  - Distributed around the ring
- UFOs at the ULO
- Earth faults (not intensity related)
  - RCS.A78B2 - 154 sextupole correctors on main dipoles
  - Main dipoles A78 – intermittent fault

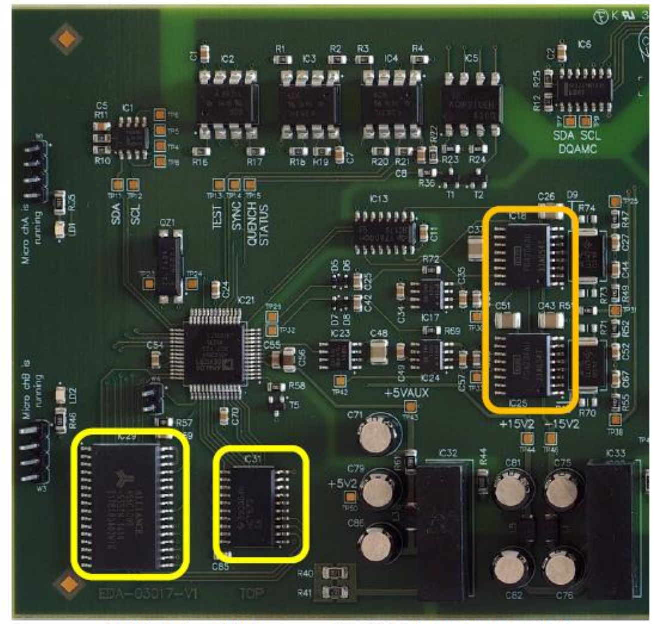
Origin of the SEU problem – recall
Relevant differences between mDQQBS and DQQBS

DQQBS



SRAM: NEC D431000AGW-70LL
D-Latch: NXP 74HCT573
Amplifier: INA141

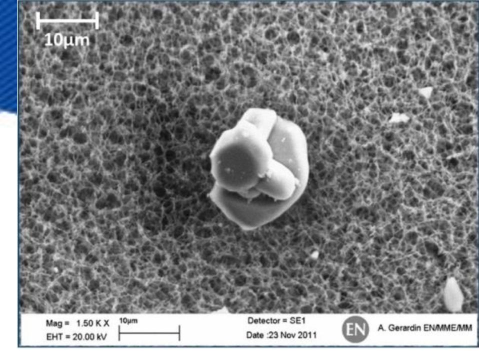
mDQQBSv2/v3



SRAM: Alliance AS6C1008-55SIN
D-Latch: TI 74HCT573
Amplifier: PGA204
Different batch of ADuC834

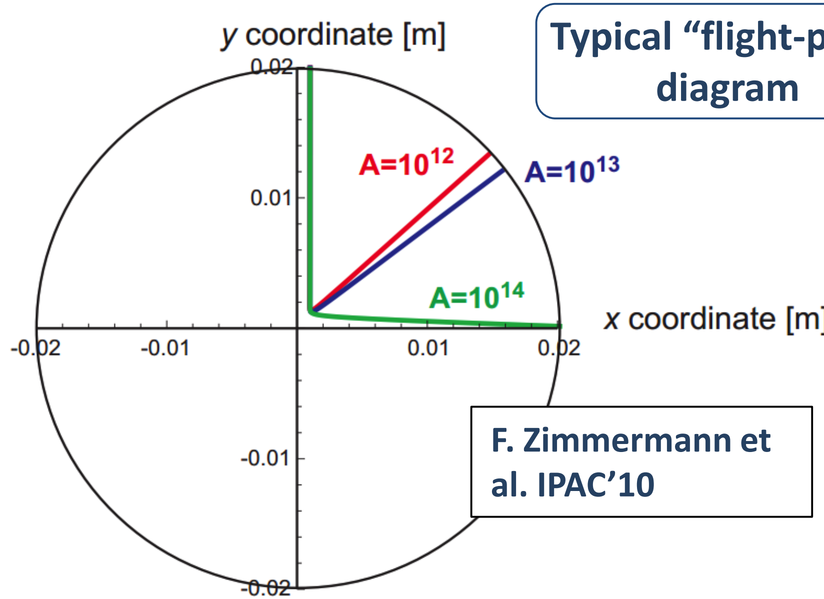
- 1268 modified boards used for special tests during circuit re-commissioning.
- **Replaced during 2nd technical stop – no problems since!**

Accepted interpretation of a UFO event:



1. A **macroparticle (dust) falls** from the top of the beam screen
2. The **macroparticle is subsequently ionized** due to elastic collisions with the beam
3. The now positively charged **macroparticle is subsequently repelled away** from the beam
4. For the duration of the UFO-to-beam interactions, there may be **significant losses due to inelastic collisions, resulting in a beam dump and or magnet quench!**

Typical "flight-path" diagram

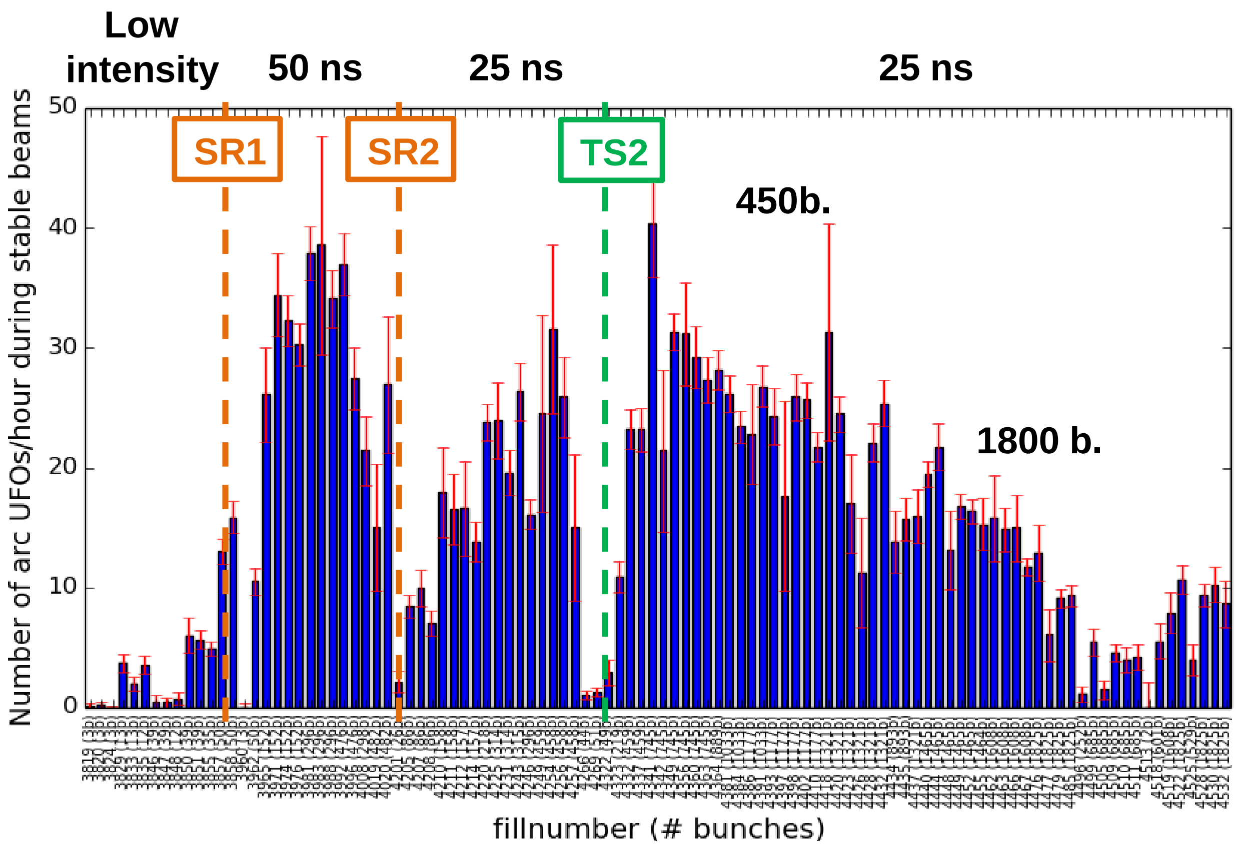


F. Zimmermann et al. IPAC'10

UFO simulation for a given mass, A.

UFOs 2015

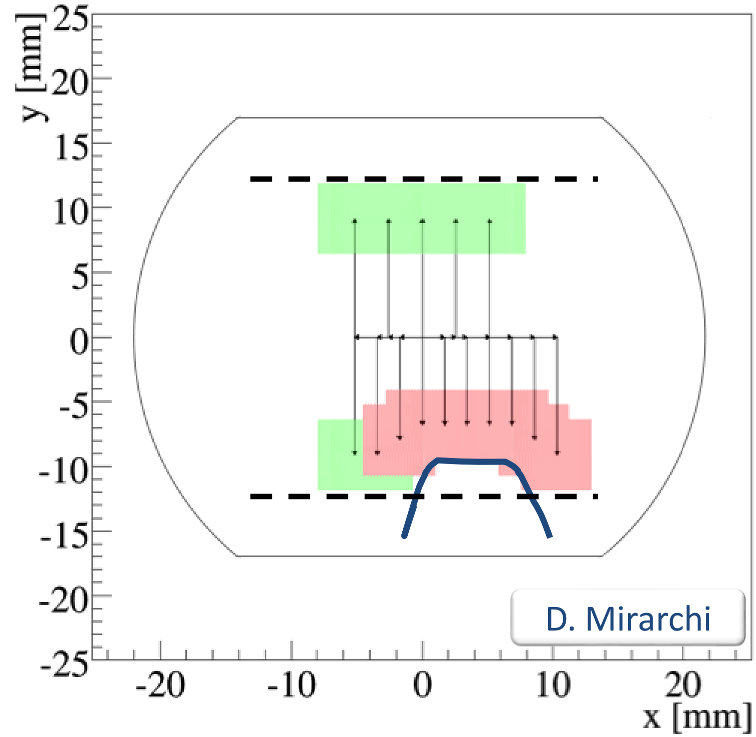
- Beam loss monitor thresholds have been set judiciously
- Over the last month ~24% of the fills which reached stable beams were dumped by a UFO (9 dumps / 38 fills)
- **Happily, conditioning is observed (as in Run 1)**



G. Papotti

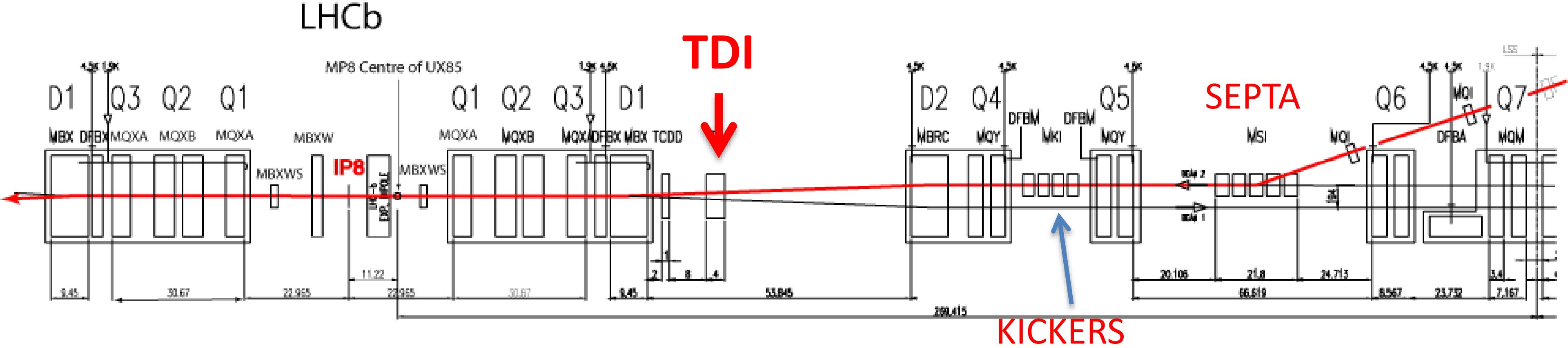
Aperture restriction in 15R8
ULO (Unidentified Lying Object)

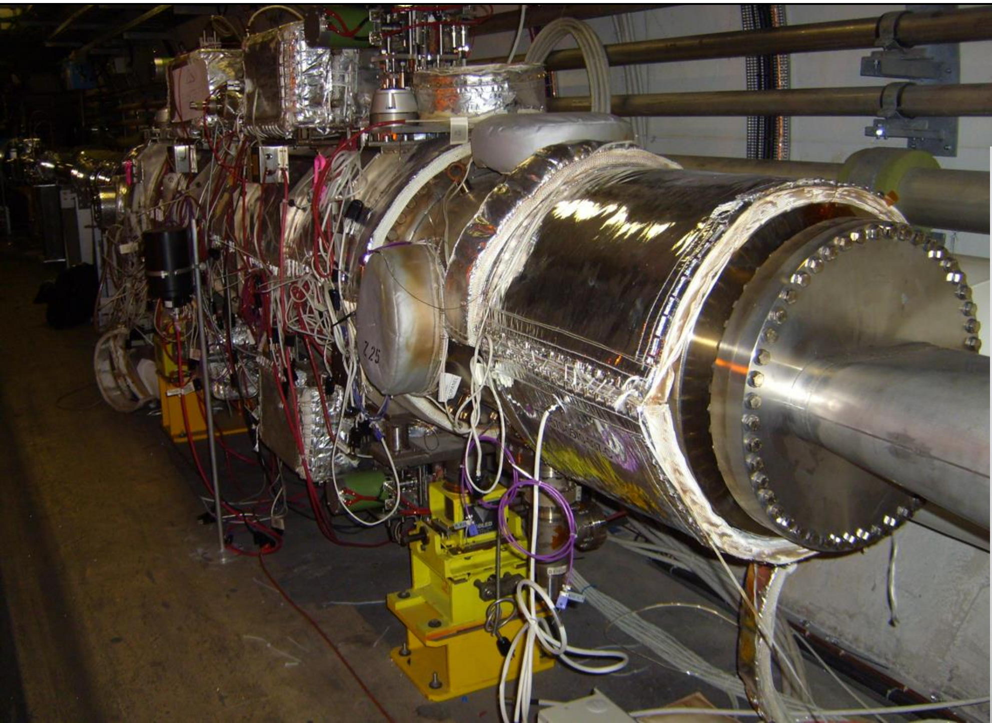
- Aperture restriction measured at injection and 6.5 TeV
- Presently running with orbit bumps
  - -3 mm in H, +1 mm in V, to optimize available aperture
- Behaviour with higher intensities looks OK
- UFOs, DUFOs, MUFOs!
  - but quiet recently



TDI (Injection protection devices)

TDI: movable vertical absorbers – 4.2 m in length – down stream of injection kickers





- Main blocks: hex-boron-nitride
- However during bake-out tests…

TDI.R8

- TDI hBN block cannot withstand temperatures higher than 450 °C
  - B_2O_3 reactant melting temperature
- Limitation on number of injections to avoid potential damage
- In addition, heating and outgassing of TDI.R8 has been observed

Limits of ~2 PS batches per injection (144b) from the injection protection absorbers reduced the maximum number of bunches to around 2400

BN block to be replace with graphite in YETS – temporary limitation

Earth faults - August

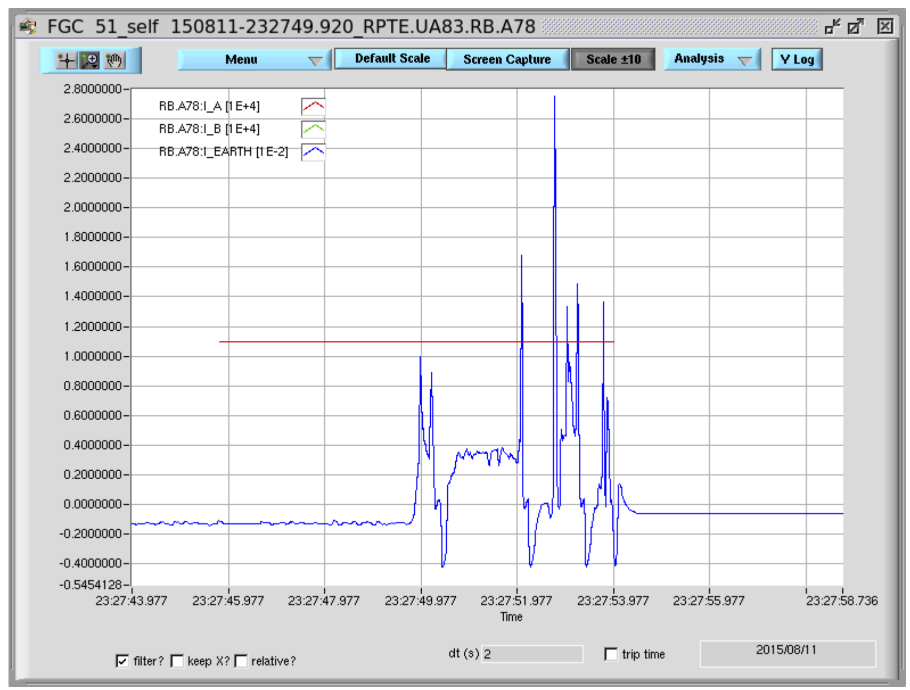
- Had to condemn a circuit of 154 sextupole correctors (RCS.A78B2)
- 3 occurrences of an intermittent earth fault in the main dipole chain in sector 78

05:36 Wed 8th July

18:33 Mon 10th August

23:27 Tues 11th August →

- 11,000 A
- 3 - 4 seconds
- 40 – 50 mA



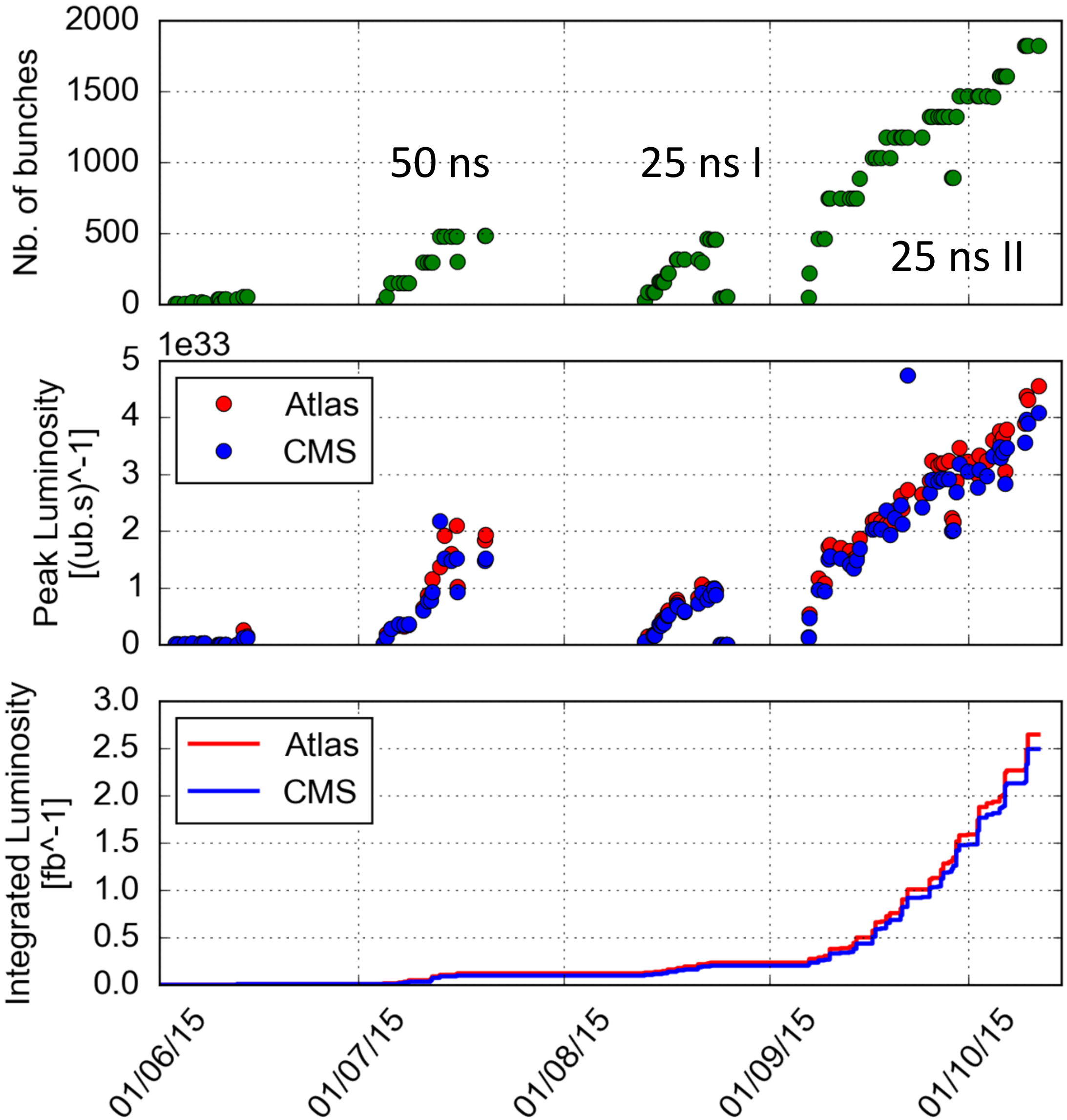
Earth current detected by power converter…

Intensity ramp-up phase 1 - summary

- QPS – radiation to electronics issue resolved
- UFOs – conditioning
- ULO – hope it stays quiet, scan next week
- Earth faults – background worry
- Issue with injection absorbers
  - to live with until year end technical stop

Painful for 2015 – a commissioning year – but they shouldn't be long term issues for Run 2

25 ns ramp-up - phase 2



Operating with e-cloud 1/2

- Beam stable through the cycle with:
  - high chromaticity
  - high octupoles
  - high transverse damper gain
  - Change of working point at 450 GeV
- Defining issue has been cryogenics having to deal with the heat load
  - Transients at injection, ramp, beam dump
  - Working close to cooling power limit
  - Huge effort by cryogenics team
    - including careful optimization of beam screen temperature regulation

Operating with e-cloud 2/2

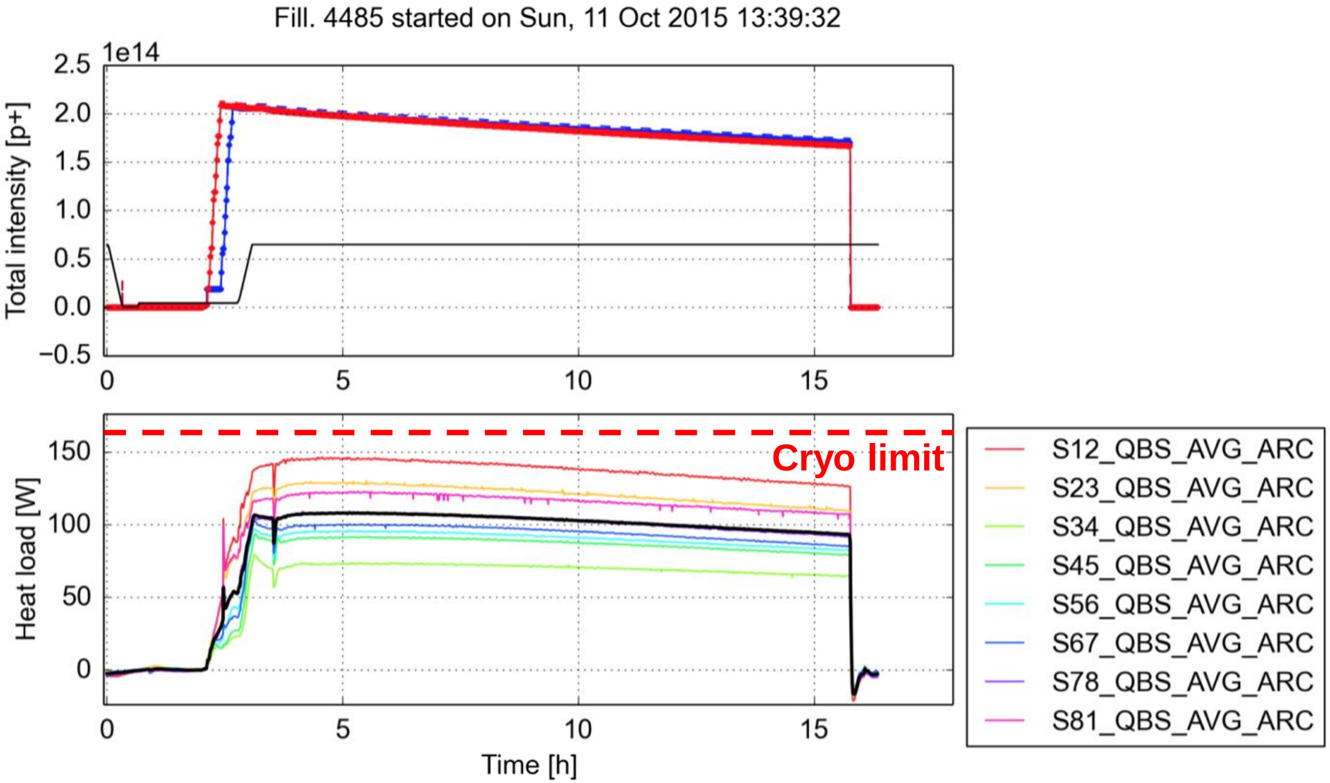
- Moderate bunch population
- Patient ramp-up in number of bunches
  – Small quantum of 144 bunches
- Bunch configuration
  – 72b-gap-72b reducing heat load for a given number of bunches
  – 8b4e tested

For more details: **Giovanni Iadarola** Joint Session W2-WP9 on Wednesday

Intensity ramp-up with 25 ns beams: heat loads

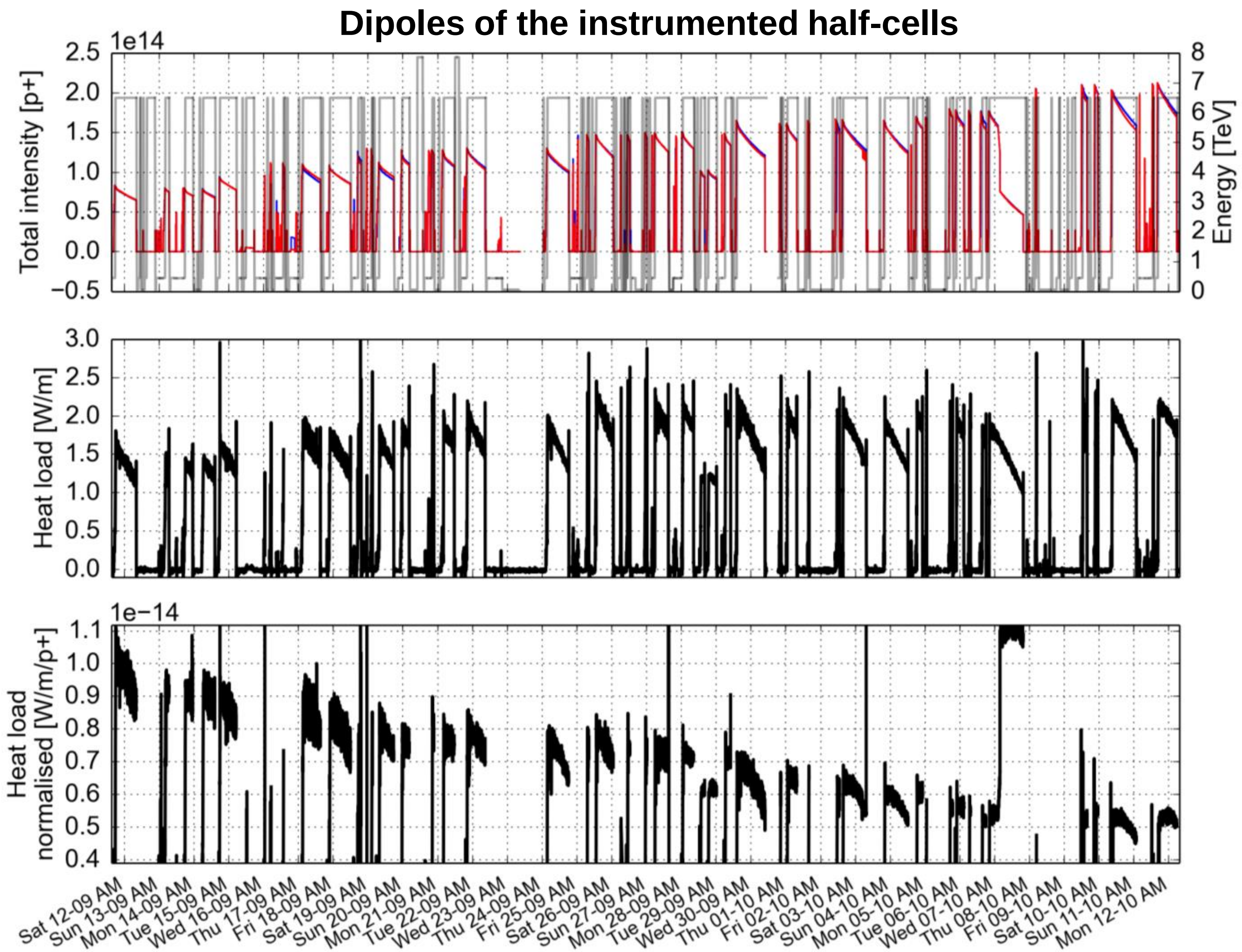
Now running with 2041 bunches per beam

Close to the margin of available cryogenics cooling capacity



Intensity ramp-up with 25 ns beams: heat loads

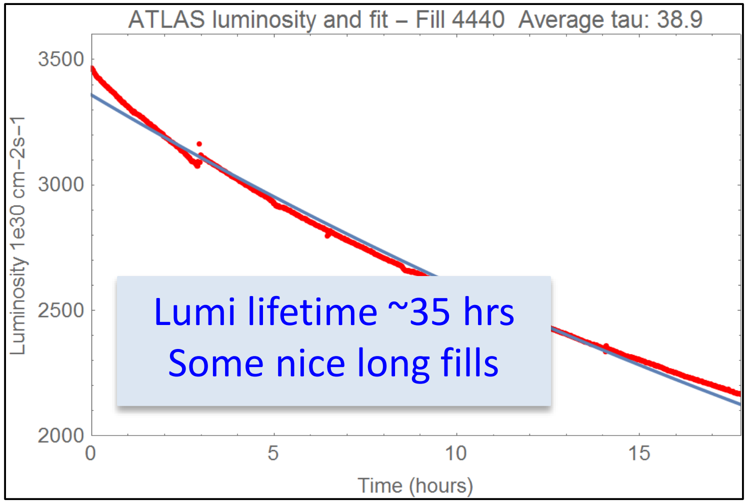
However scrubbing is observed operating with physics fills at 6.5 TeV

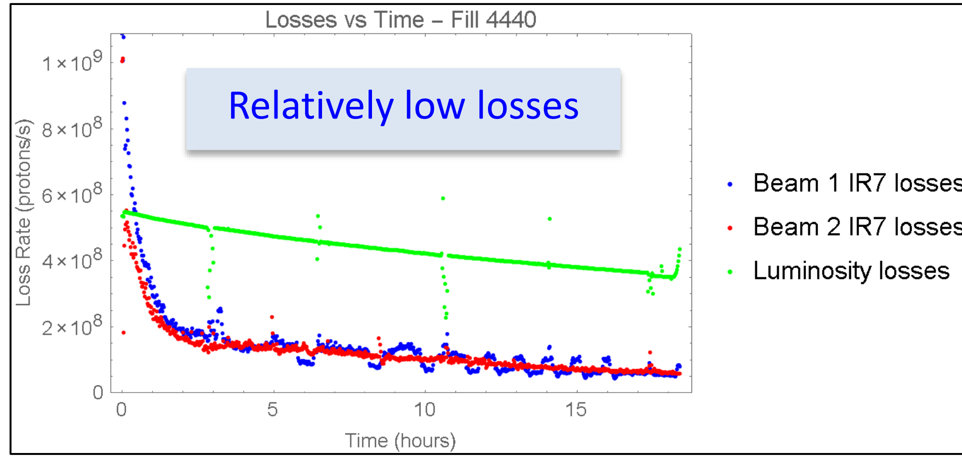


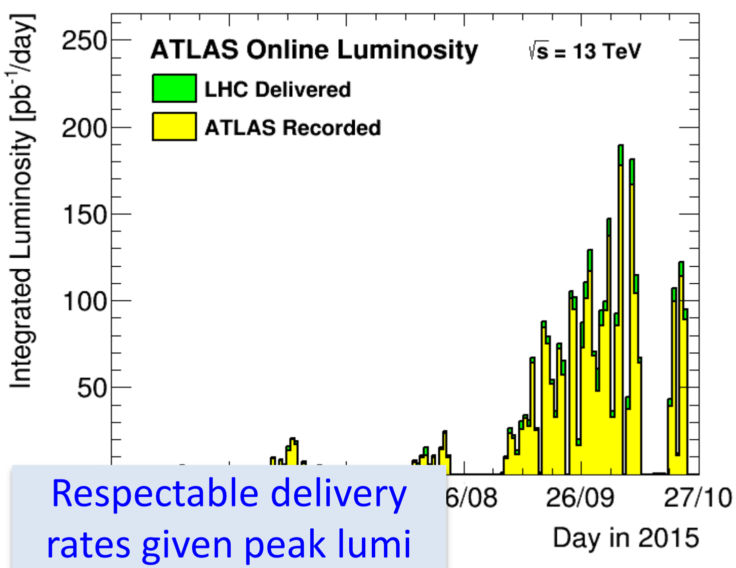
Performance 2015

- Excellent transmission through cycle
- Acceptable emittance growth through ramp, squeeze (~35%)
  - No instabilities (with ADT, high Q’ etc. - studies continue)
- Stable beams
  - benign conditions: low LRBB, low HOBB
  - good luminosity lifetimes
  - low losses (cf. 2012) even with high chromaticity and octupoles
  - synchrotron radiation damping
    - Some gentle horizontal emittance growth
    - Vertical: ~zero growth or even decreasing
    - Bunch length shortening -> reduction factor

Performance







Peak luminosity: ~4.5x10^{33} cm^{-2}s^{-1}

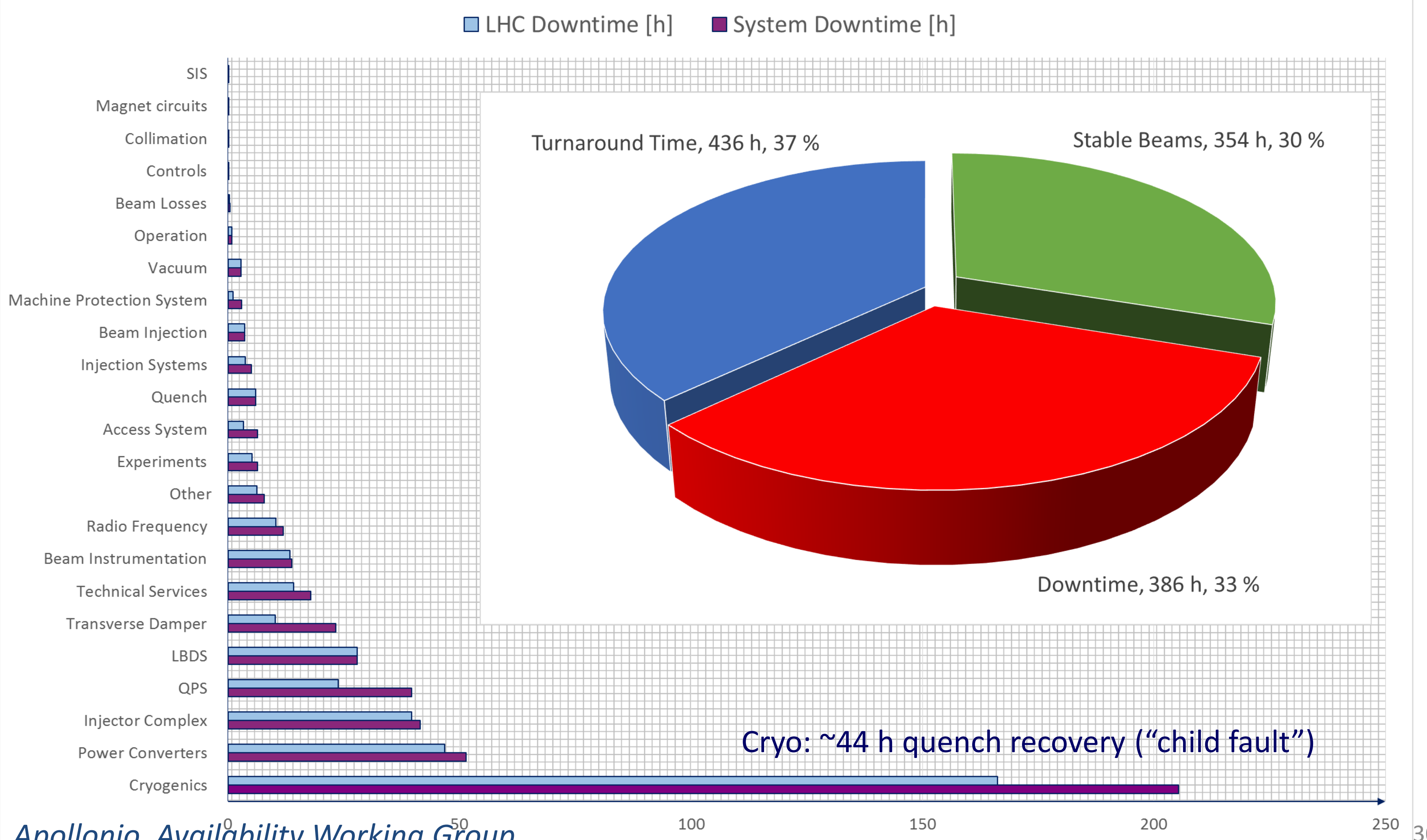
CMS

Maximum Luminosity Delivered in one Fill	217.56 pb^{-1}	Fill 4467
Maximum Luminosity Delivered in one Day	185.38 pb^{-1}	Day 283
Maximum Luminosity Delivered in one Week	677.51 pb^{-1}	Week 39
Maximum Luminosity Delivered in one Month	1430.41 pb^{-1}	Month 10
Maximum Colliding Bunches	1813	Fill 4476
Longest Time in Stable Beams for one Fill	22.83 hours	Fill 4467
Longest Time in Stable Beams for one Day	17.65 hours	Day 280
Longest Time in Stable Beams for one Week	75.13 hours	Week 39
Longest Time in Stable Beams for one Month	194.48 hours	Month 9

Integrated for the year ~3 fb^{-1} with a week to go

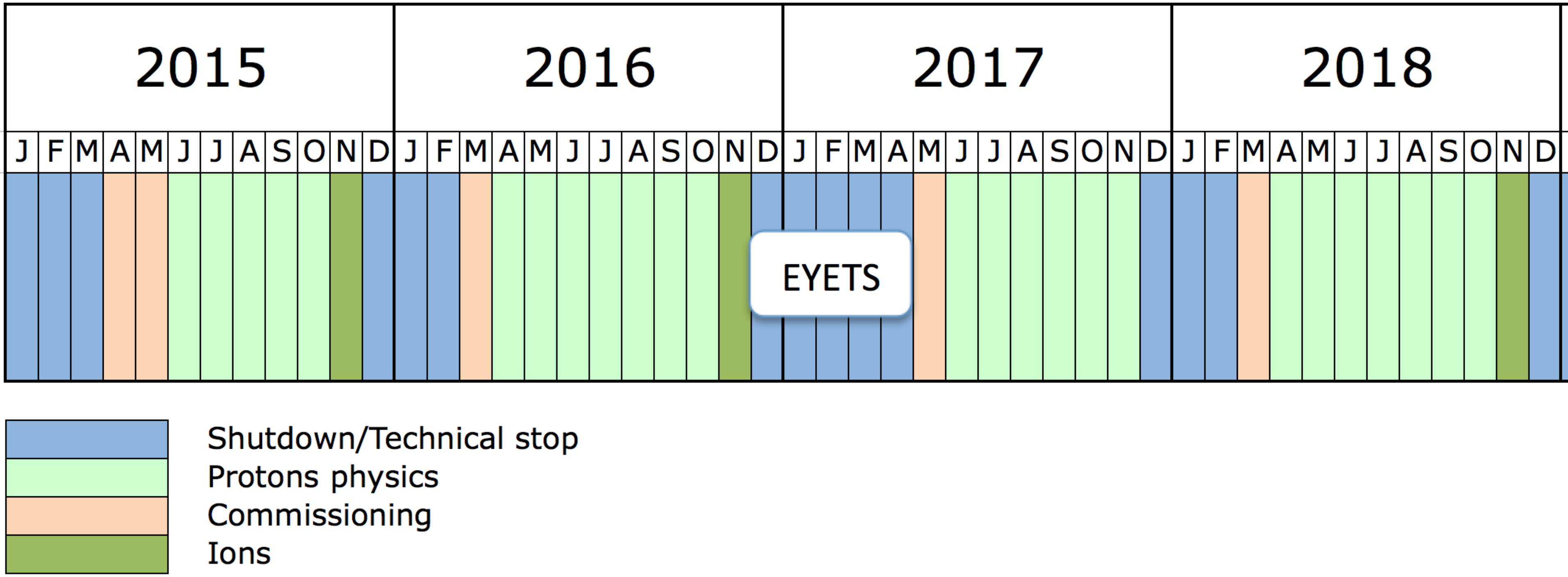
Availability

During intensity ramp-up with 25 ns beams, 450 to 1800 bunches
Stable beam fraction 30%, cf. 35% in 2012



A. Apollonio, Availability Working Group

Run 2



- EYETS – Extended Year End Technical Stop – 19 weeks – CMS pixel upgrade
- Start LS2 at the end of 2018

Run 2 performance

- 2016 – production year
  - 6.5 TeV
  - Not fully scrubbed for 25 ns
    - Re-establish present conditions, good for operations up to ~2000 bunches, continue pushing
  - Beta* = 40 cm in ATLAS and CMS
  - Peak luminosity limited to ~1.7e34 by inner triplets
  - Reasonable availability assumed – usual caveats apply

	Peak lumi E34 $cm^{-2}s^{-1}$	Days proton physics	Approx. int lumi [fb^{-1}]
2015	~0.5	65	3
2016	1.2	160	30
2017	1.5	160	35
2018	1.5	160	35

Conclusions

- 6.5 TeV fundamentals look good
- Picked up some hang-over from LS1
  - QPS; earth faults; injection protection devices; ULO…
- Commissioning and scrubbing went well
  - Still have significant electron cloud – has slowed progress
- At the end of the day, the LHC is operational at 13 TeV with 25 ns beam - this might regarded as an achievement for all involved!
- **Should stress the sophistication, performance of all key systems and the continuing push for understanding**

2015 has been short year for proton physics but has laid foundations for production for the rest of Run 2 and beyond

HL-LHC

- Availability!
- Radiation to electronics
  – Continue to take seriously
- Electron cloud after long shutdowns
  – scrubbing; intensity ramp-up; beam stability
- Beam dynamics
  – Instabilities – see 2012
  – Beam loss in collision with high bunch population – see 2012 compared with 2015

LHC Page1

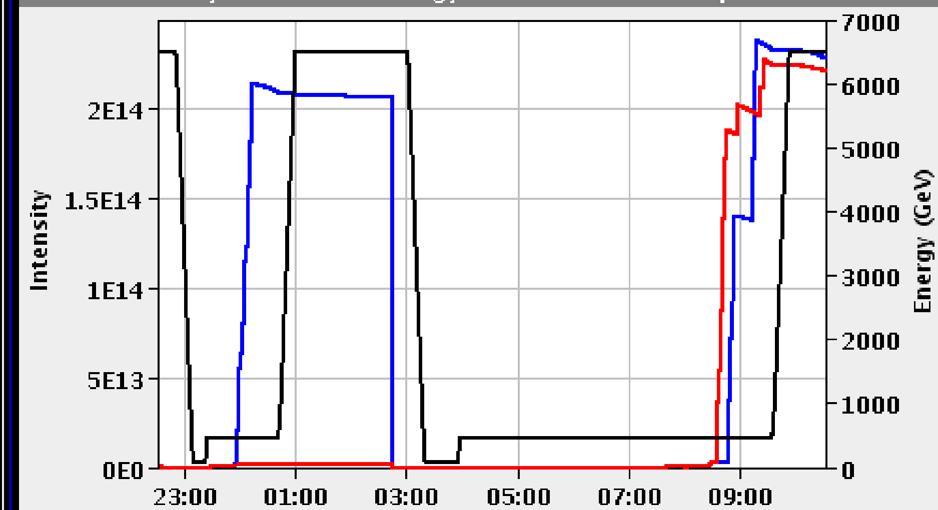
LHC Page1 | Fill: 4536 | E: 6500 GeV | t(SB): 00:00:21 | 26-10-15 10:31:08

PROTON PHYSICS: STABLE BEAMS

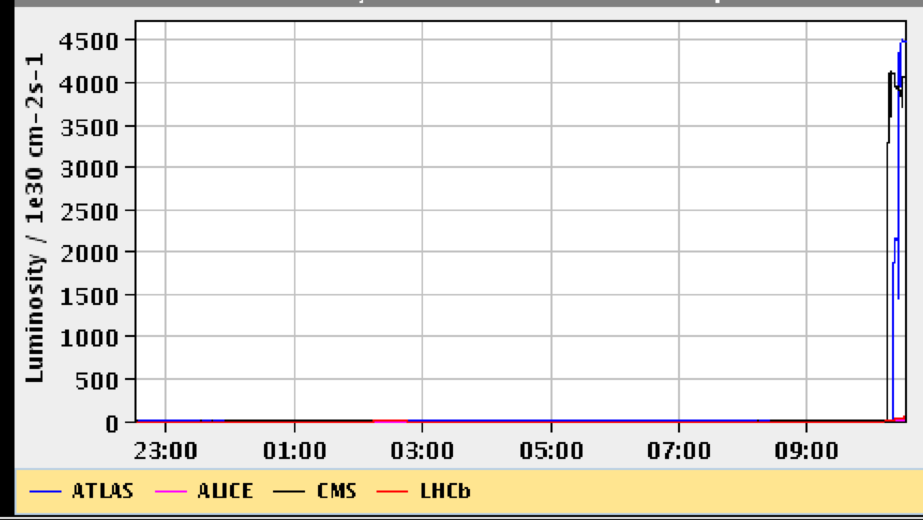
Energy:	6500 GeV	I(B1):	2.26e+14	I(B2):	2.20e+14

Inst. Lumi [(ub.s)^-1]	IP1: 4489.82	IP2: 5.19	IP5: 4071.14	IP8: 48.43

FBCT Intensity and Beam Energy Updated: 10:31:08



Instantaneous Luminosity Updated: 10:31:08



Comments (26-Oct-2015 10:30:46)

2041 b for physics

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 25ns_2041b_2029_1666_1710_144bpi17inj_sp | PM Status B1 ENABLED | PM Status B2 ENABLED