LHC Performance in Run 2 and Beyond

Mike Lamont for the LHC team

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 to 40 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

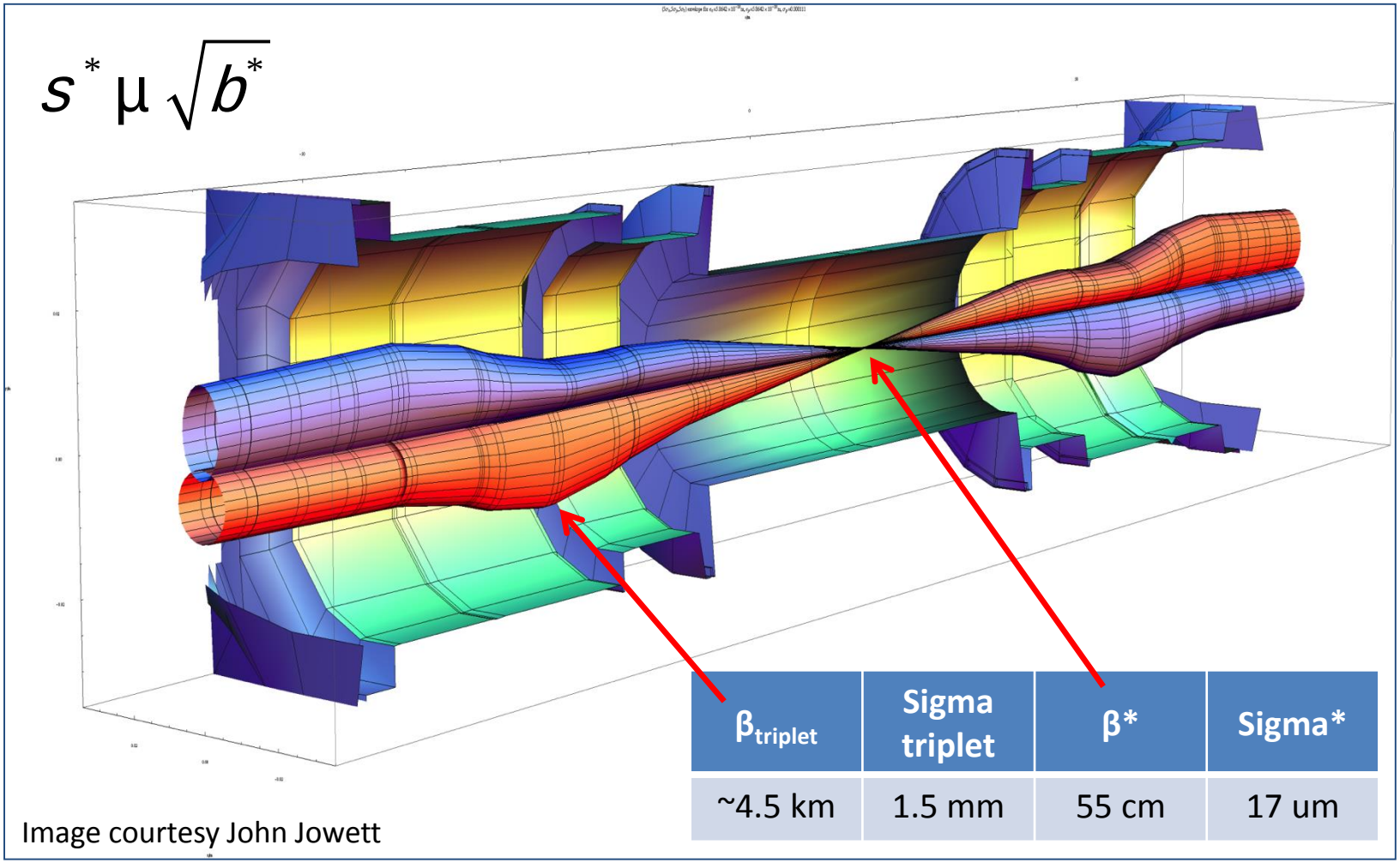
Nominal LHC bunch structure

- 25 ns bunch spacing
- ~2800 bunches
- Nominal bunch intensity: 1.15 x 10^{11} protons per bunch

26.7 km 2800 bunches

Beta*

- Lower beta* implies larger beams in the triplet magnets
- Aperture concerns dictate caution



$\beta_{triplet}$	Sigma triplet	β*	Sigma*
~4.5 km	1.5 mm	55 cm	17 um

Image courtesy John Jowett

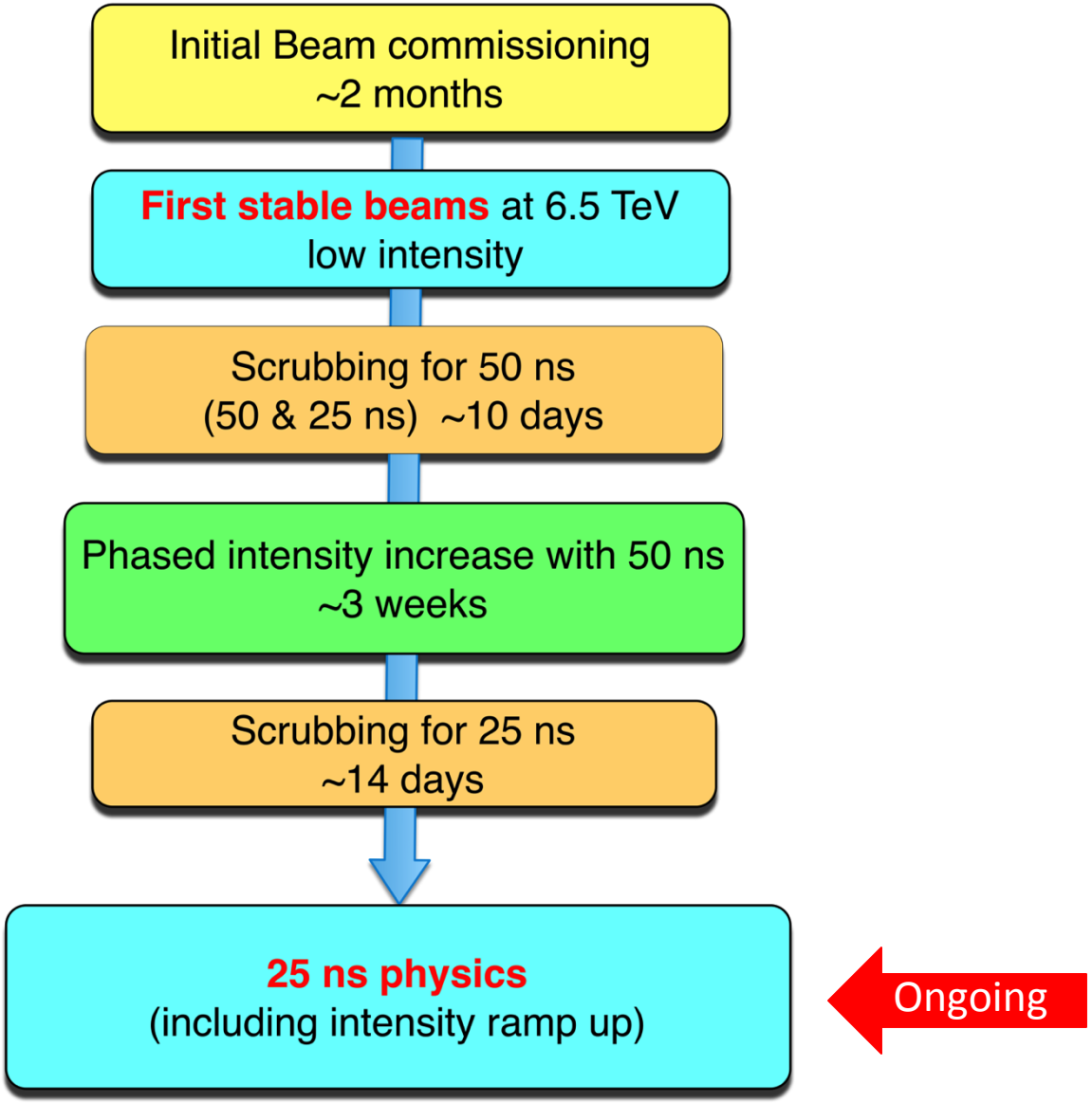
2015: beta* in IPs 1 and 5

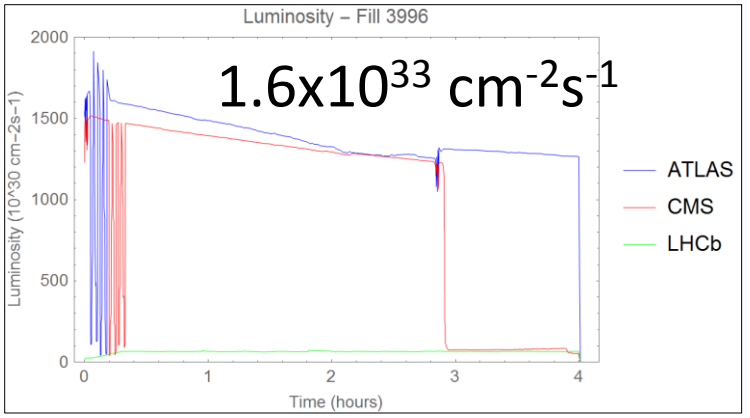
- Start-up: **β*= 80 cm – (very) relaxed**
  - 2012 collimator settings
  - 11 sigma long range separation-> crossing angle
  - Check aperture, orbit stability… looking good

- Ultimate in 2015 and Run 2: **β*= 40 cm**
  - Possible reduction later in the year

$$\mathcal{L} \propto \frac{1}{\beta^*}$$

2015 commissioning strategy





5th April
first beam

10th April: 6.5 TeV for the first time

July 14th: 476b (50 ns)

APRIL

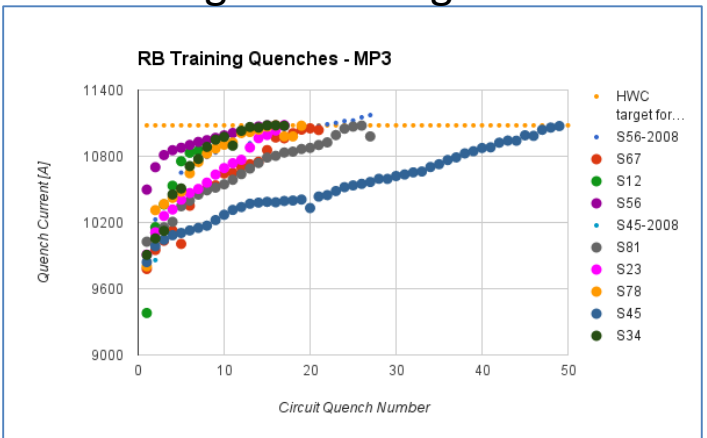
MAY

JUNE

JULY

AUGUST

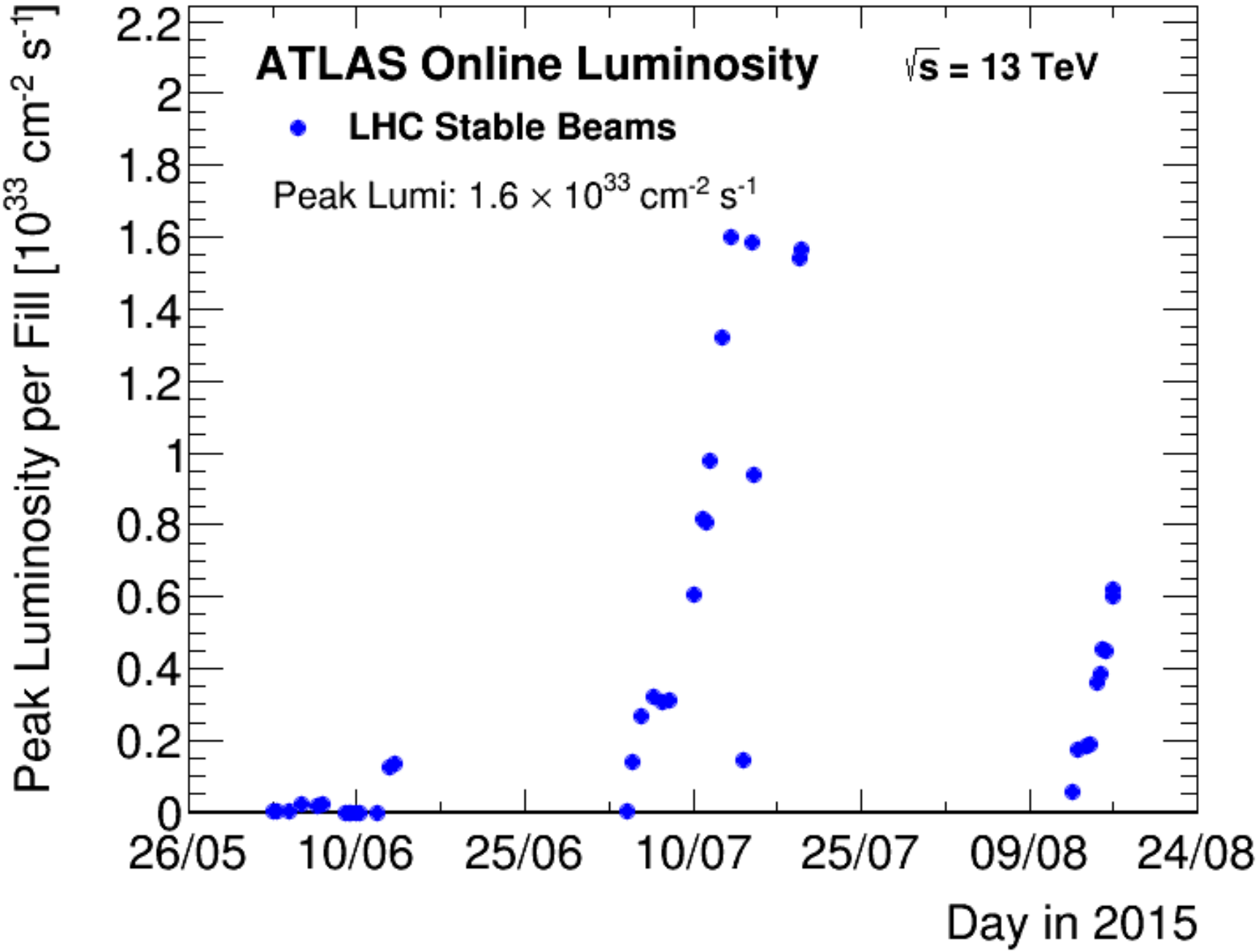
Finish magnet training



3rd June: First Stable Beams

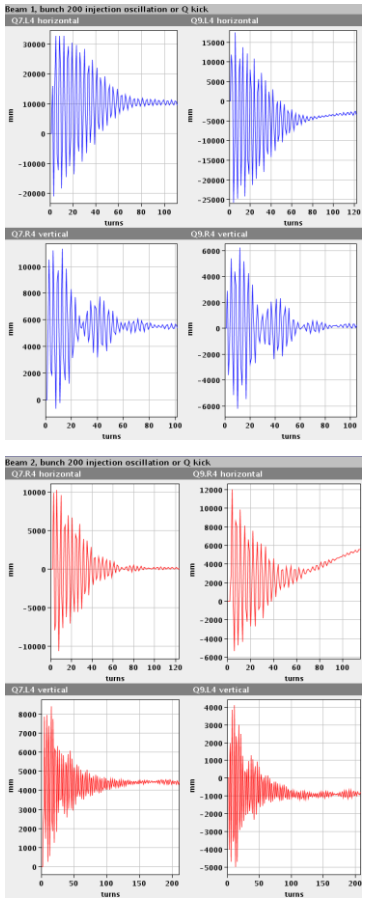
25 ns
219 bunches

2015


ATLAS Online Luminosity
√s = 13 TeV
LHC Stable Beams
Peak Lumi: 1.6 × 10^33 cm^-2 s^-1
Peak Luminosity per Fill [10^33 cm^-2 s^-1]
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
26/05
10/06
25/06
10/07
25/07
09/08
24/08
Day in 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!

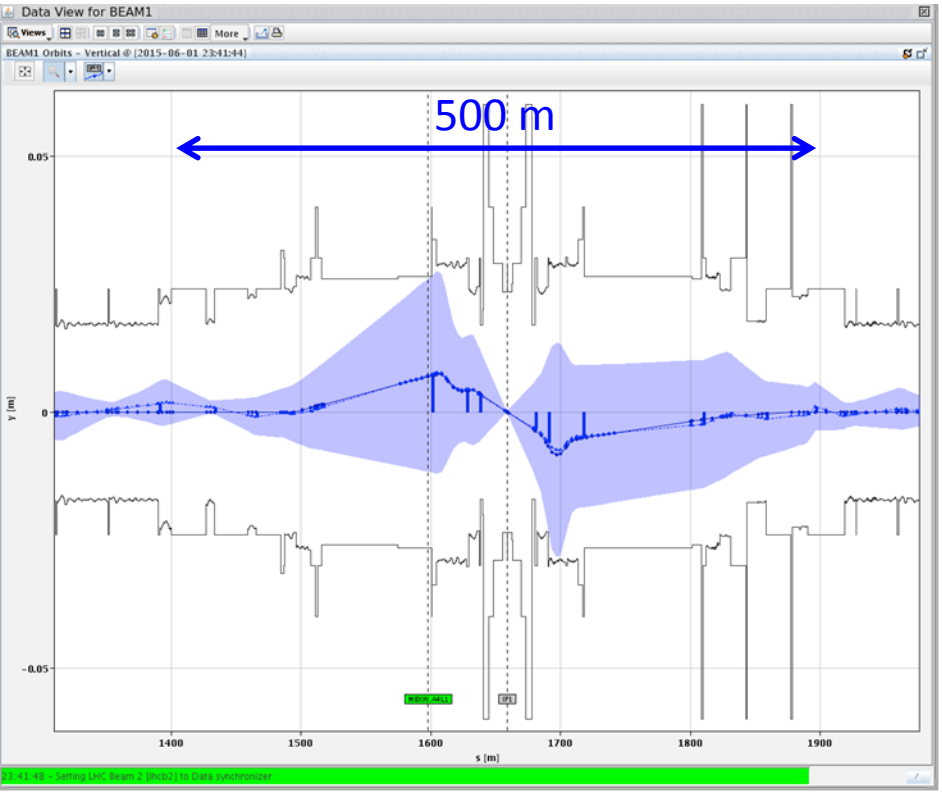


Initial commissioning 2/2

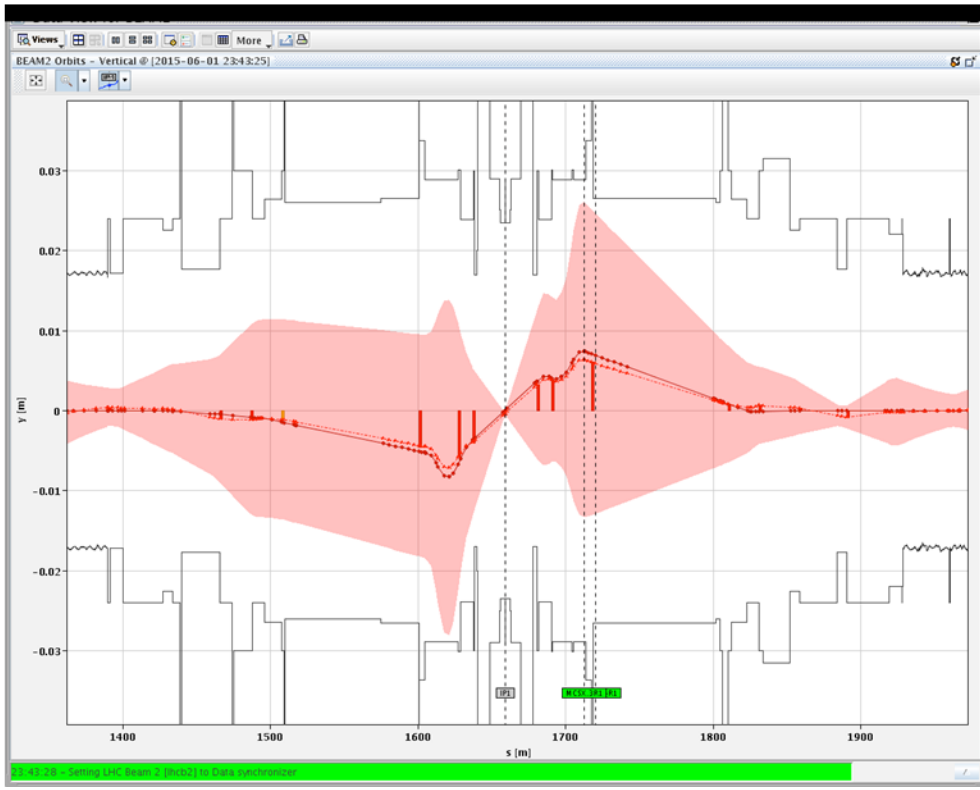
- Magnetically reproducible as ever
- Optically good, corrected to excellent
- Aperture is fine and compatible with the collimation hierarchy.
- Magnets behaving well at 6.5 TeV
  - 11 additional training quenches
- Operationally things well under control
  - Injection, ramp, squeeze etc.

Aperture

Carefully checked with beam



IP1 – B1

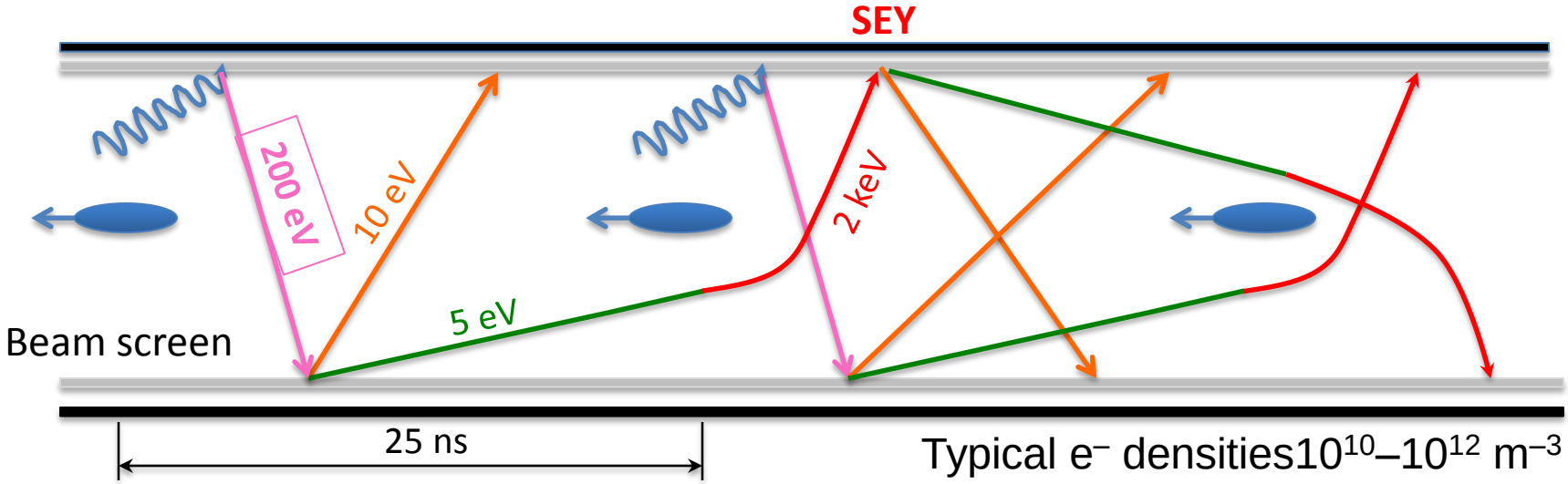


IP1 – B2

Electron cloud

- Electron clouds are the result of an avalanche-like process, when electrons from gas ionization or photoemission are accelerated in the electromagnetic field of the beam and hit the beam chamber walls with energies of few hundreds of eV, producing more electrons.
- The electron impacts on the wall cause molecule desorption as well as heat load for the cryogenic system in cold regions.
- High electron densities in the beam chamber lead to oscillations and blow up of the particle bunches due to the electromagnetic interaction between electrons and protons.

25 ns & electron cloud



Possible consequences:

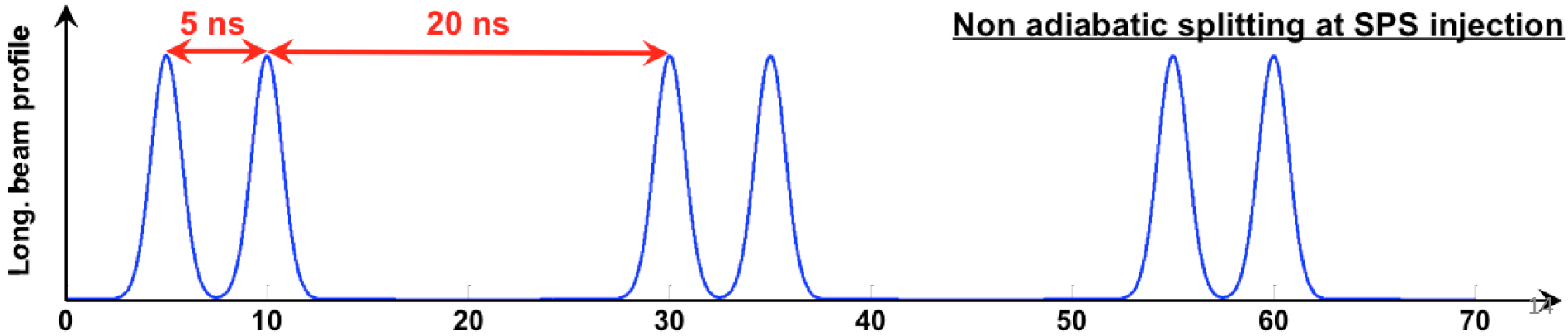
- instabilities, emittance growth, desorption – bad vacuum
- excessive energy deposition in the cold sectors

Electron bombardment of a surface has been proven to reduce drastically the **secondary electron yield (SEY)** of a material. This technique, known as **scrubbing**, provides a mean to suppress electron cloud build-up.

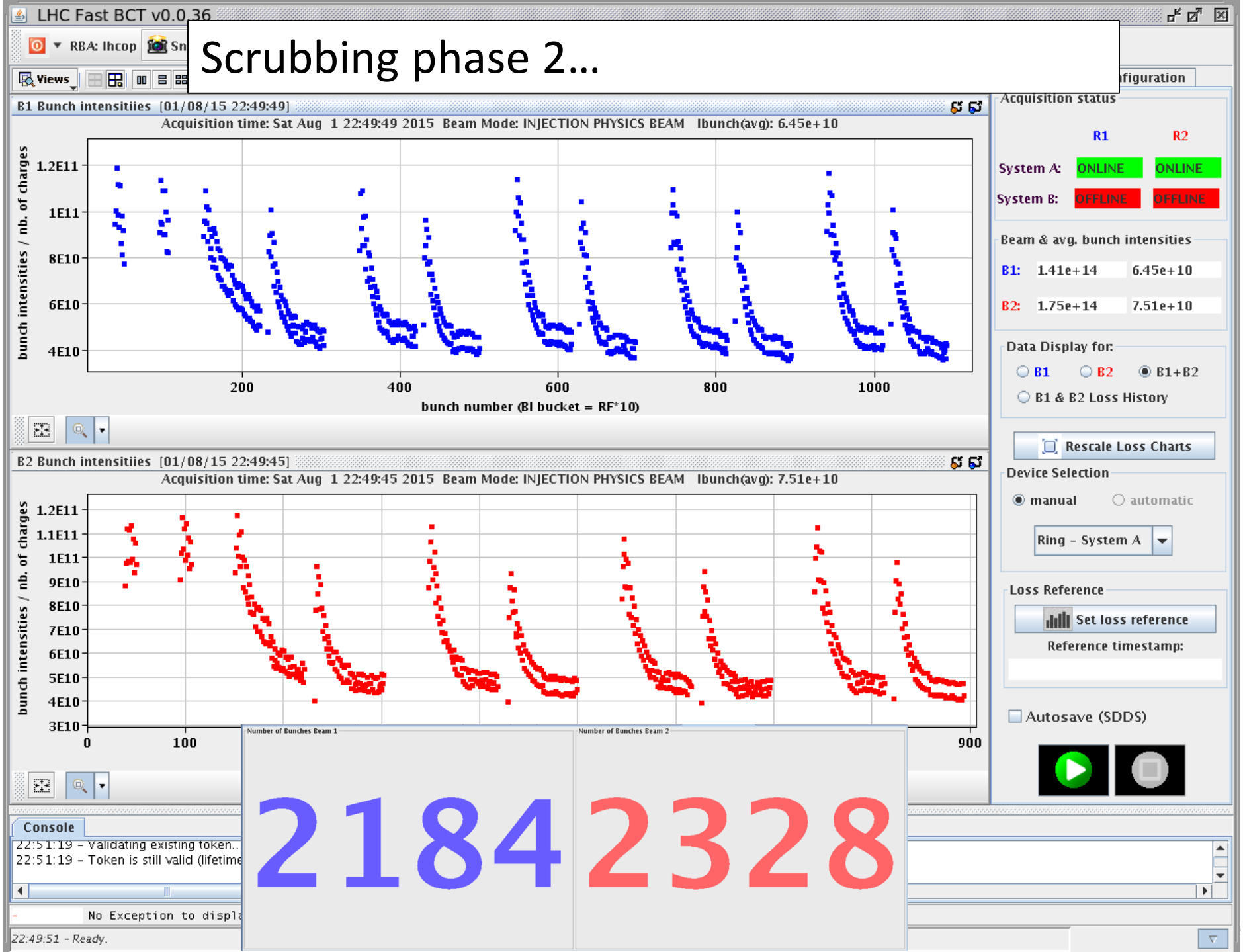
Electron cloud significantly worse with 25 ns

Scrubbing 2015

- More scrubbing than in 2012 was mandatory
- 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

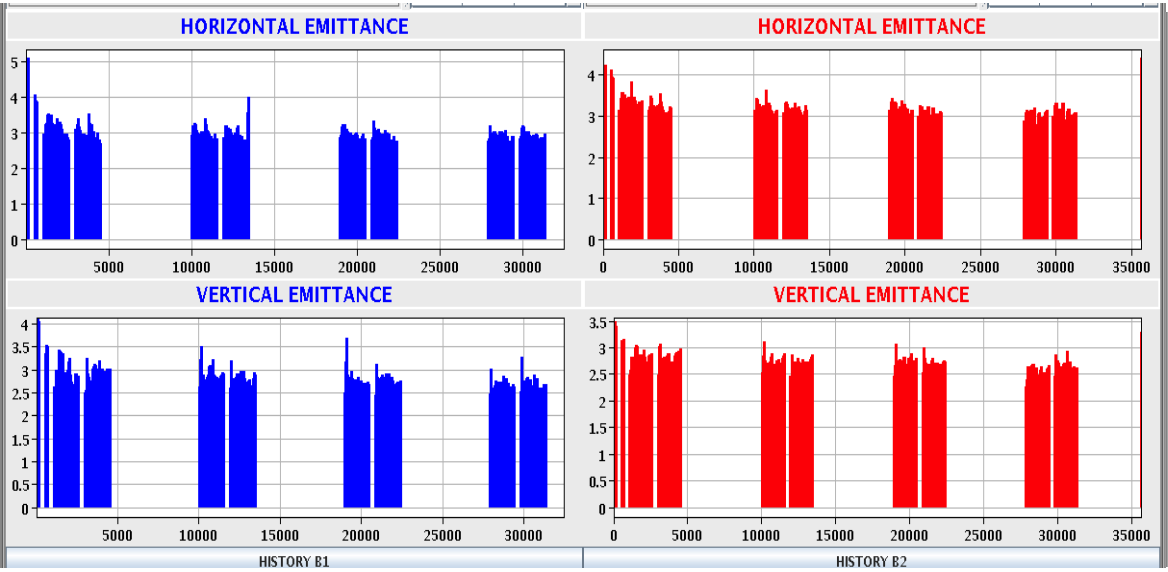


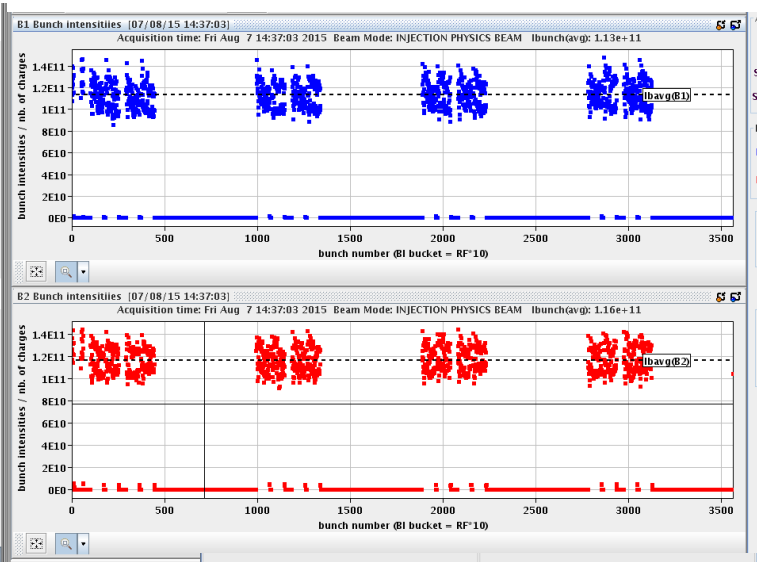
Scrubbing phase 2…



25 ns scrubbing - exit

- Use of doublet beam difficult – more 25 ns scrubbing required
- Present beam quality at 450 GeV OK for up to ~1500 bunches
- To be confirmed with ramps to 6.5 TeV
- Limitations from injection protection devices and injection kickers ~1200 bunches…





1176 1176


Present challenges
RedBull

50 ns: 476 bunches – 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 board in B29R2
4000	Ramp 2.0 TeV	476			UFO with quench at ULO
4001	69s	476	1.4	<0.1	QPS board in B11.L1
4003	Ramp 2.2 TeV	476			UFO at ULO
4006	10m	476	1.6	0.79	QPS board in B16R1
4008	2h34m	298	0.9	7.86	QPS board 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

25 ns: early days

Fill	Stable beams /Lost	bunches	Peak Lumi $cm^{-2}s^{-1}$	Int Lumi pb^{-1}	dumped by
41xx	Collisions	8	-	-	**Earth fault S78**
41yy	Squeeze	8	-	-	**Earth fault S78**
4201	**2h40m**	26	5.9e31	0.5	Water leak
4204	Flat top	86	-	-	Instability
4205	**9h57m**	86	1.732	5.2	Programmed dump
4207	**4h24m**	86	1.6e32	2.6	Electrical glitch
4208	**5h12m**	86	1.9e32	3.0	**UFO (plus quench)**
4210	**1h17m**	158	3.6e32	1.5	BPM interlock
4211	**1h55m**	158	3.8e32	1.8	BPM interlock
4212	**1h4m**	158	4.5e32	1.7	Cryogenics glitch
4214	**5h16m**	158	4.5e32	7.4	Power converter trip
4219	**6m**	219	6.0e32	0.1	RF trip
4220	**>8h30m**	219	6.22e32	>16.6	

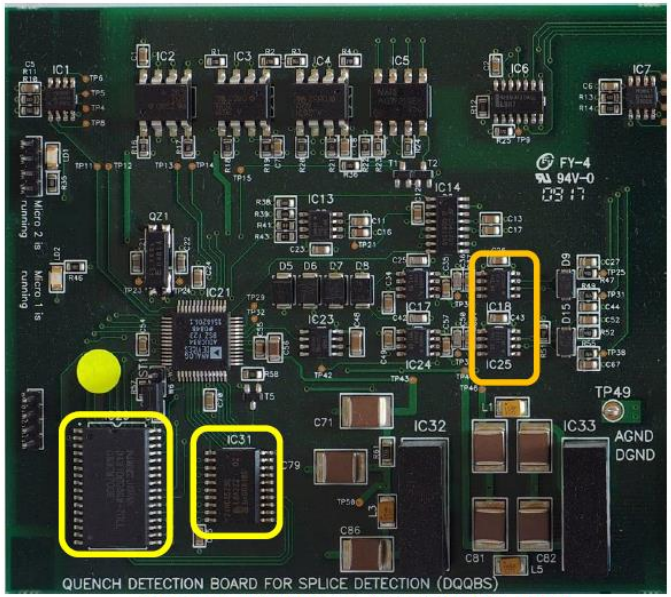
Main issues

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
  - Appear to be suppressed by local warm-up of beam screen
- Earth faults (not intensity related)
  - RCS.A78B2 - 154 sextupole correctors on main dipoles
  - Main dipoles A78

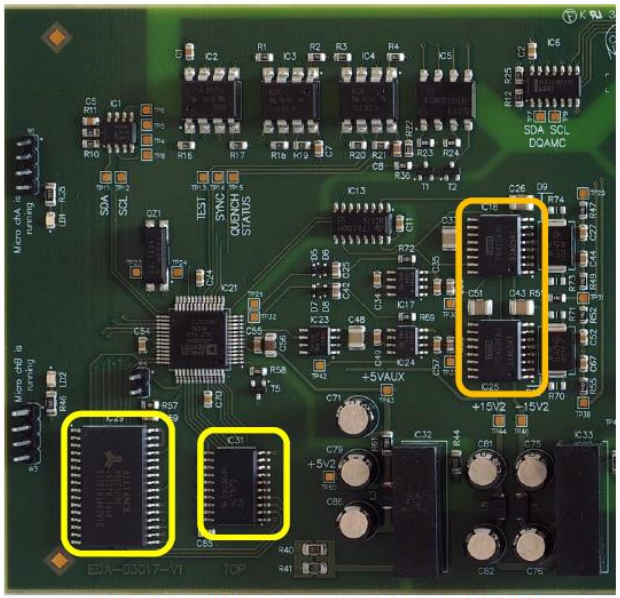
Origin of the SEU problem – recall
Relevant differences between mDQQBS and DQQBS

DQQBS



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

mDQQBSv2/v3

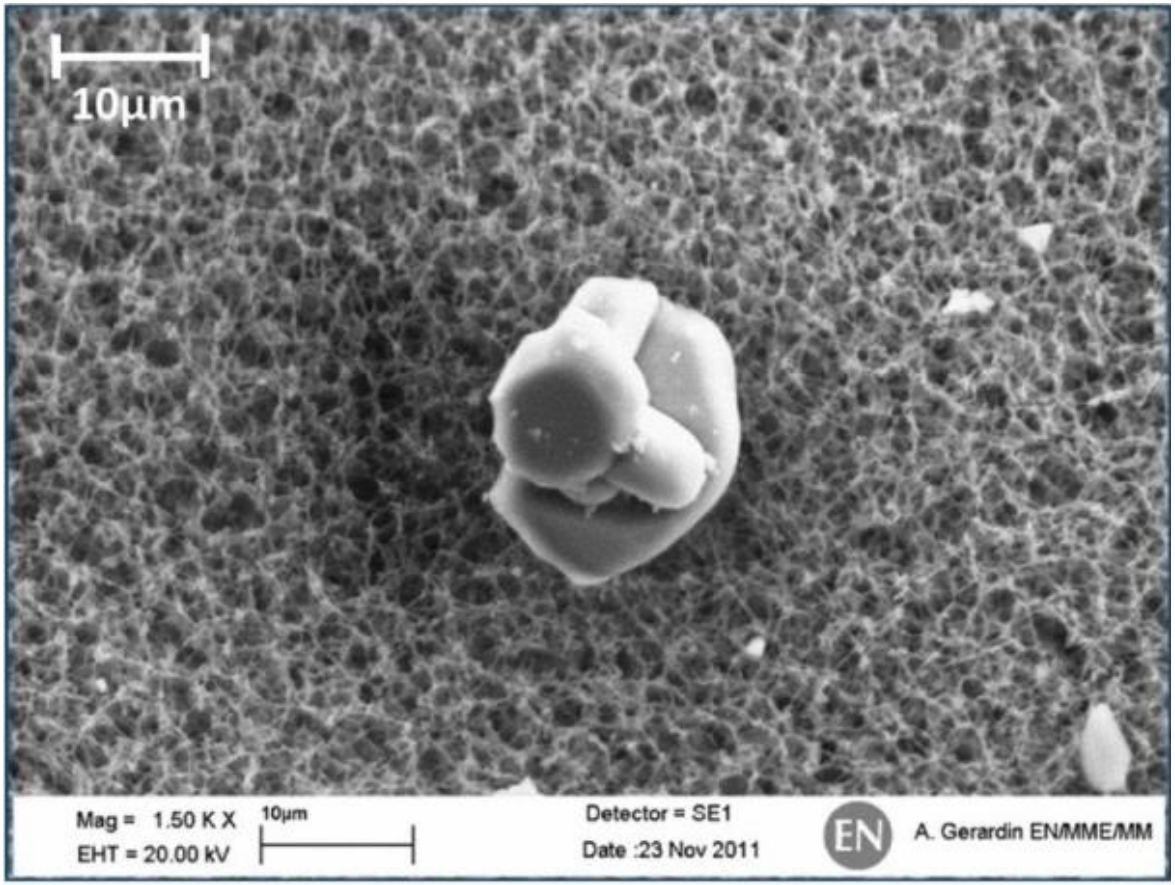


SRAM: Alliance AS6C1008-55SIN
D-Latch: TI 74HCT573
Amplifier: PGA204
Different batch of ADuC834

- 1268 modified boards used for special tests (CSCM) during circuit re-commissioning.
- **Should have come out**
- To be replaced during upcoming technical stop

UFOs

A nice picture of some dust



T. Baer CERN-THESIS-2013-233

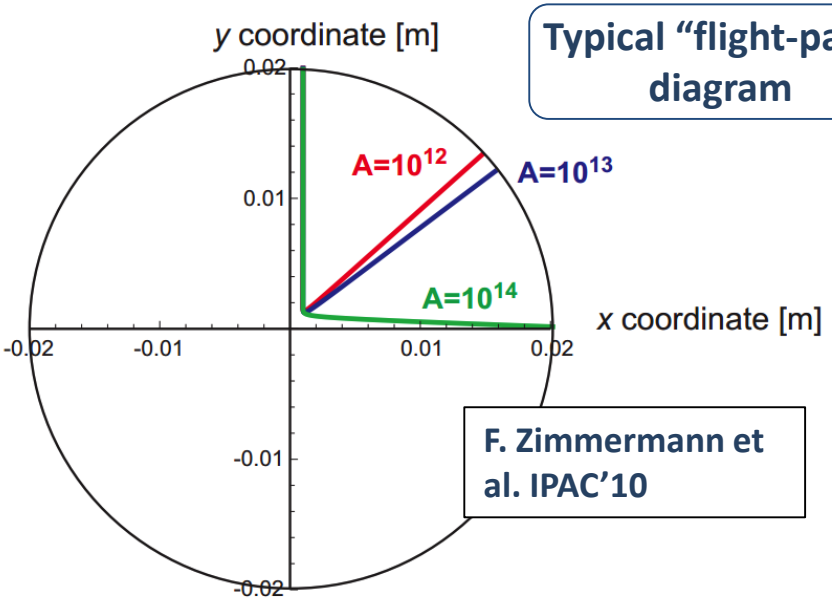
Accepted interpretation of a UFO event:

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!**



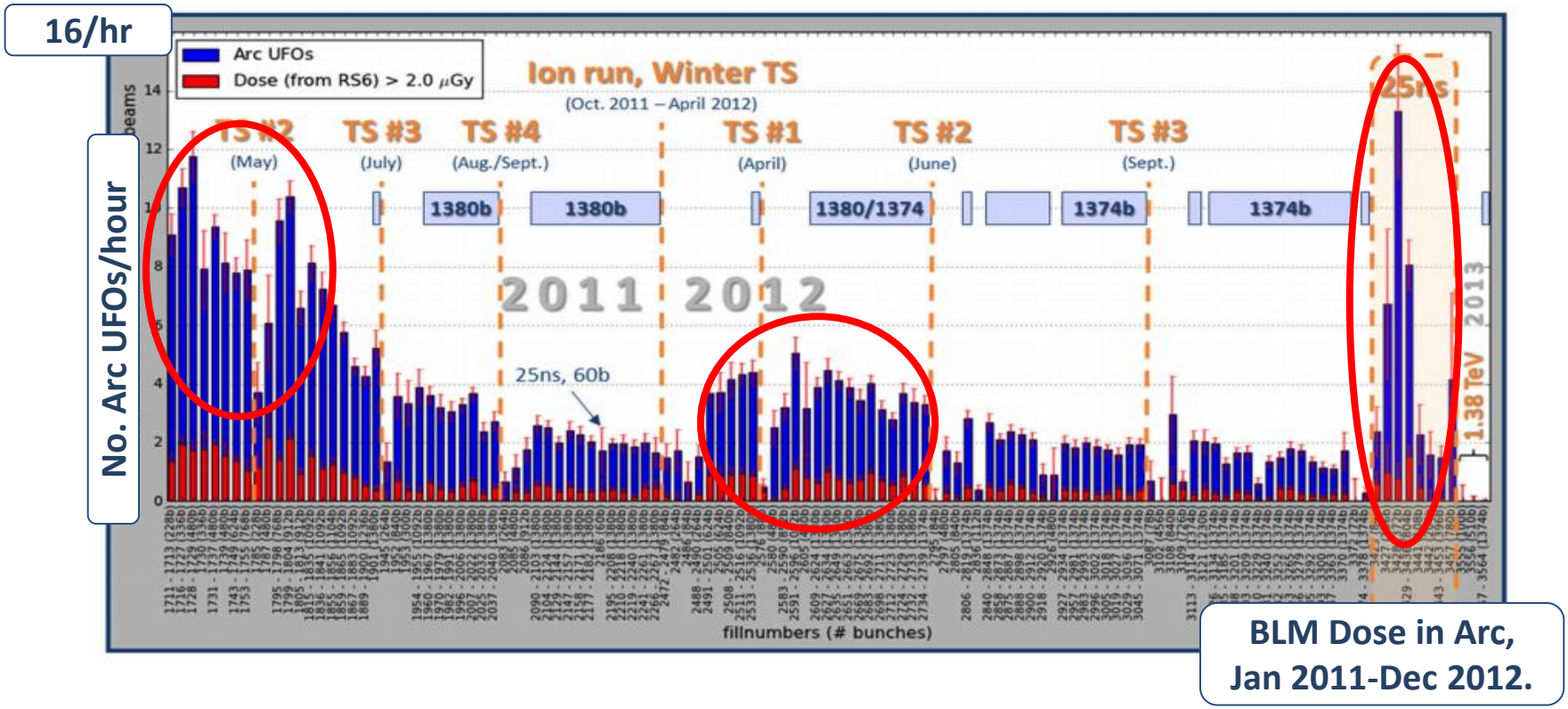
Typical "flight-path" diagram

F. Zimmermann et al. IPAC'10

UFO simulation for a given mass, A.

UFOs - strategy

- **No. of UFO events** have been seen to **exceed 10+/hour** with notable increases after long shutdowns and or with a decrease in bunch spacing



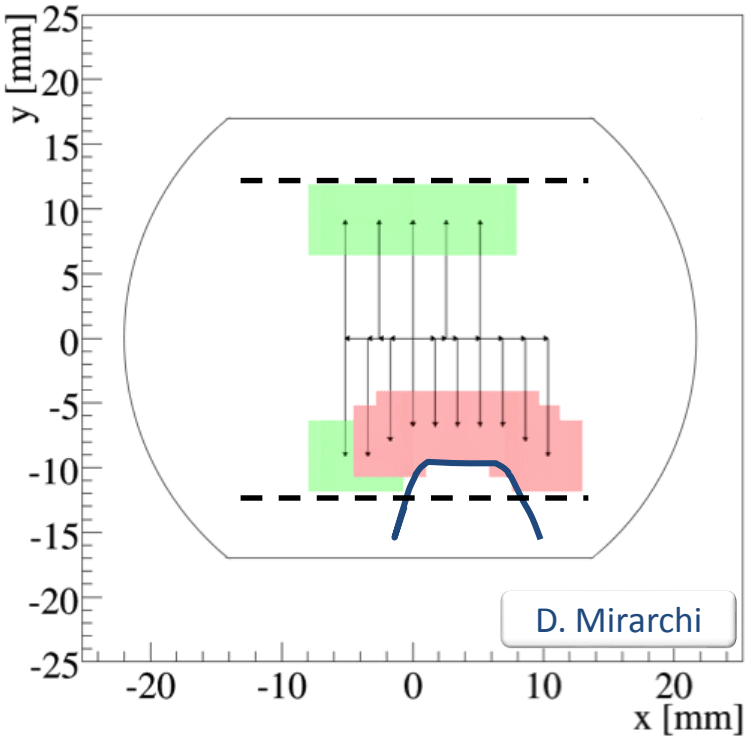
BLM Dose in Arc, Jan 2011-Dec 2012.

- Beam loss monitor thresholds have been set judiciously
- Essentially relying on conditioning
- Other variables: total beam intensity, beam size, defender bunches

Aperture restriction in 15R8

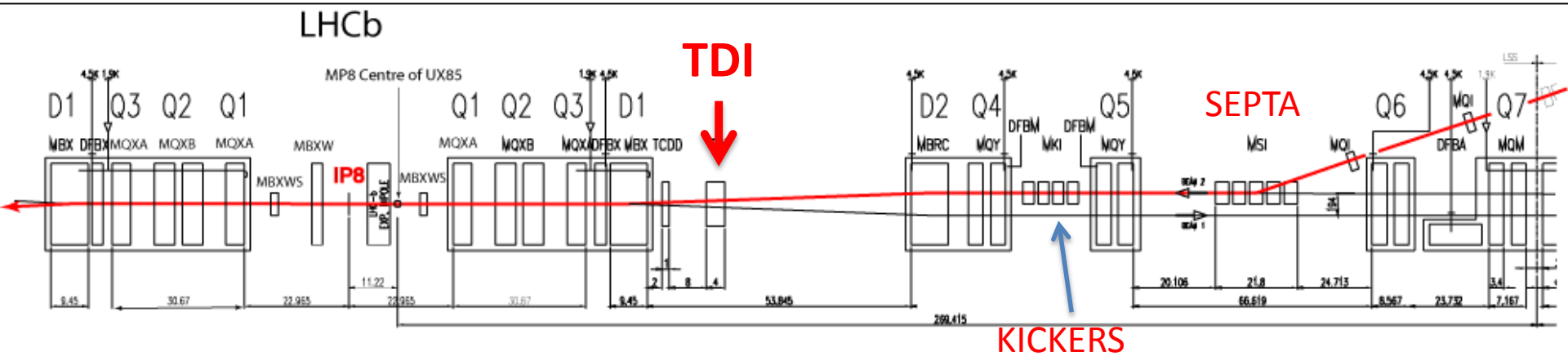
ULO (Unidentified Lying Object)

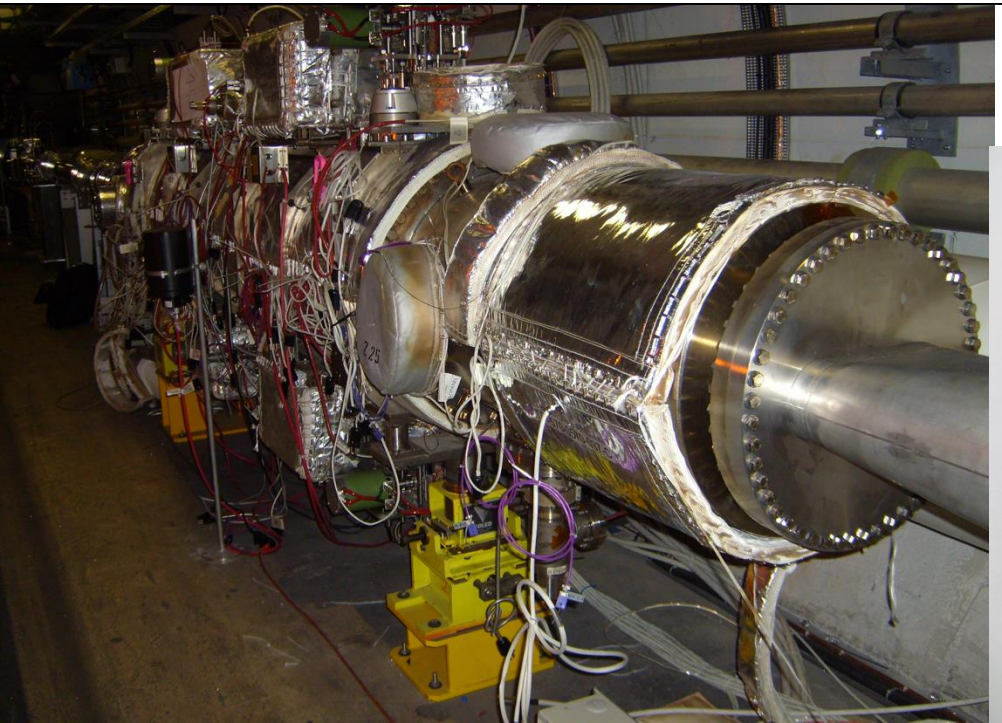
- Aperture restriction measured at injection and 6.5 TeV
- Presently running with orbit bumps
  - -3 mm in H, +1 mm in V, to optimize available aperture
- Behaviour with higher intensities looks OK
- UFOs, DUFOs, MUFOs!



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

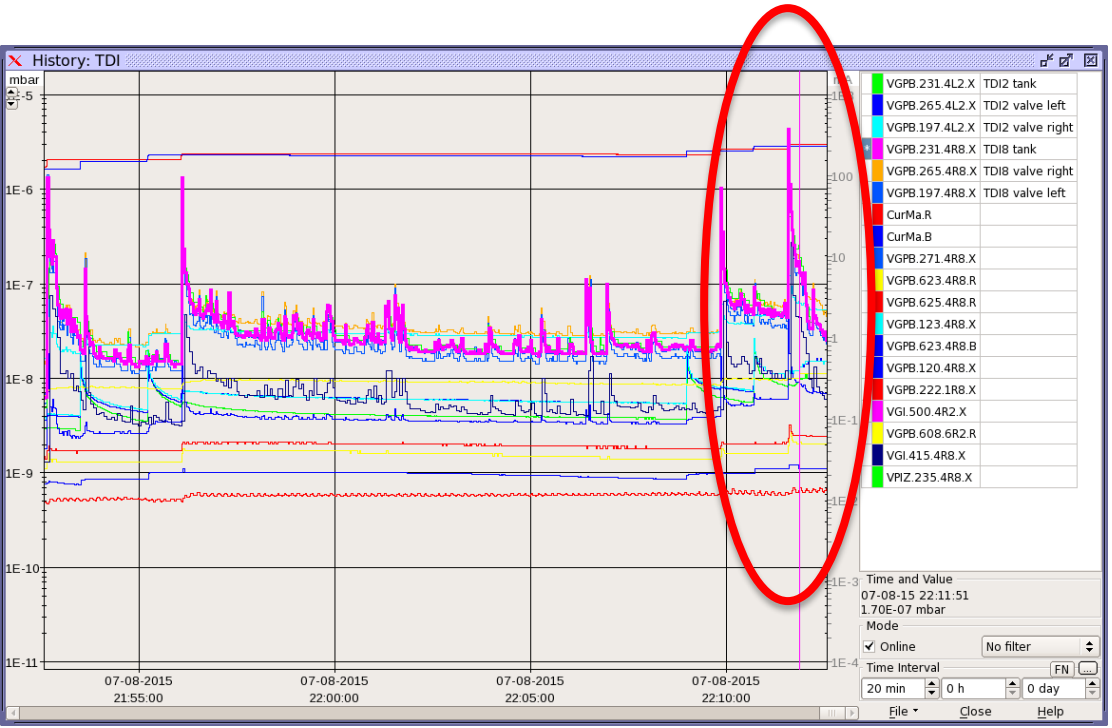
- TDI hBN block cannot withstand temperatures higher than 450 °C (B_2O_3 reactant melting temperature)
- Limitation on number of injection to avoid potential damage (maximum allowed temperature = 400 °C)

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

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

TDI beam 2 - vacuum

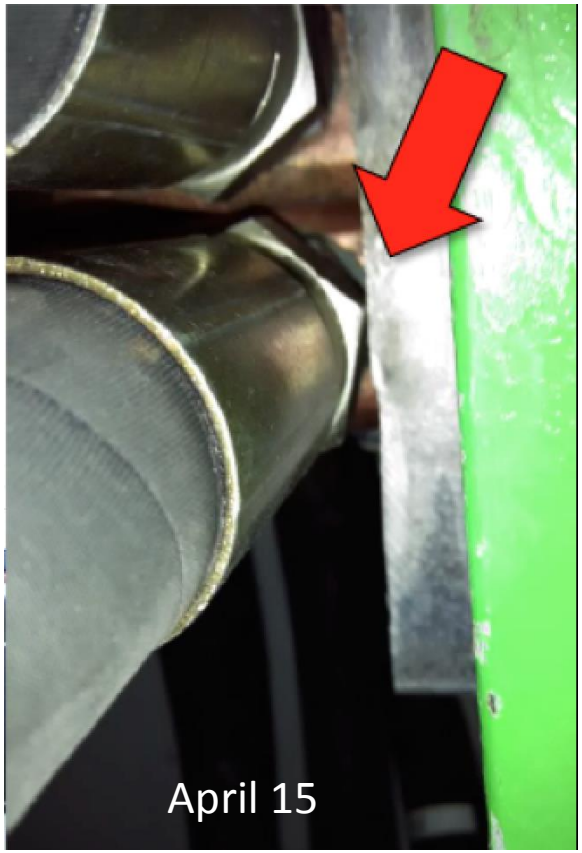
- In addition during scrubbing, heating and outgassing of TDI right of point 8 has been observed
  - Vacuum spikes up to and above interlock limits



- Investigations of mitigation measures in progress
- For the moment we are assuming a (soft) limit of around 1200 bunches

Earth faults earlier in the year

RB.A78 – contact between water cooled cables and protection covers



RB.A34

March 15

The short is very likely caused by a small metallic debris, bridging the half moon with the diode tube.

A. Verweij, LMC, 25/3/2015

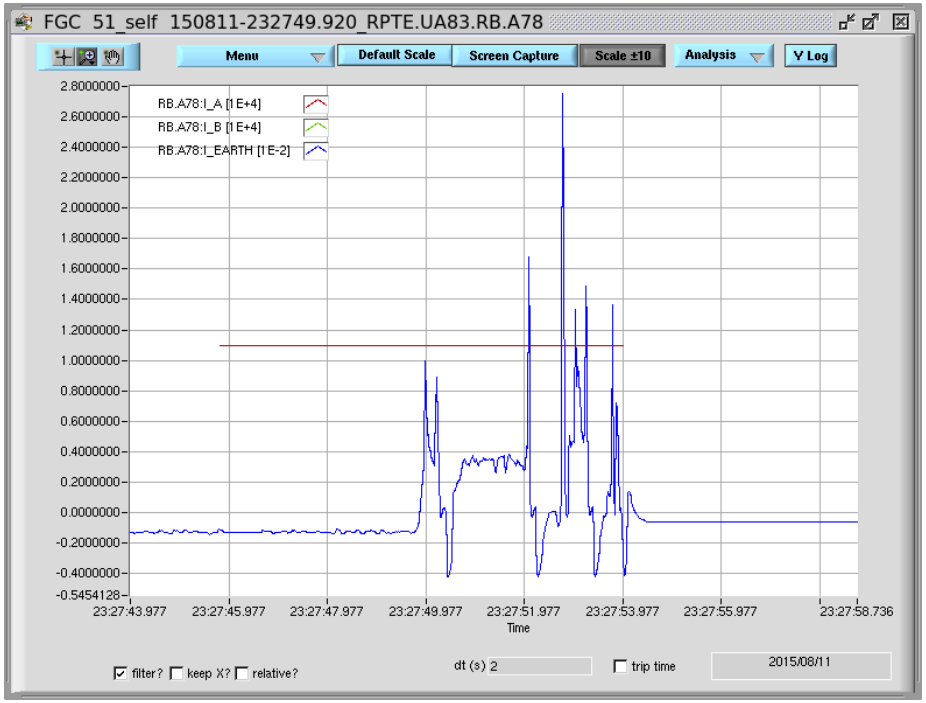
Earth faults - more recently

- Had to condemn a circuit of 154 sextupole correctors (RCS.A78B2)
- Last week 2 re-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



Earth current detected by power converter…

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

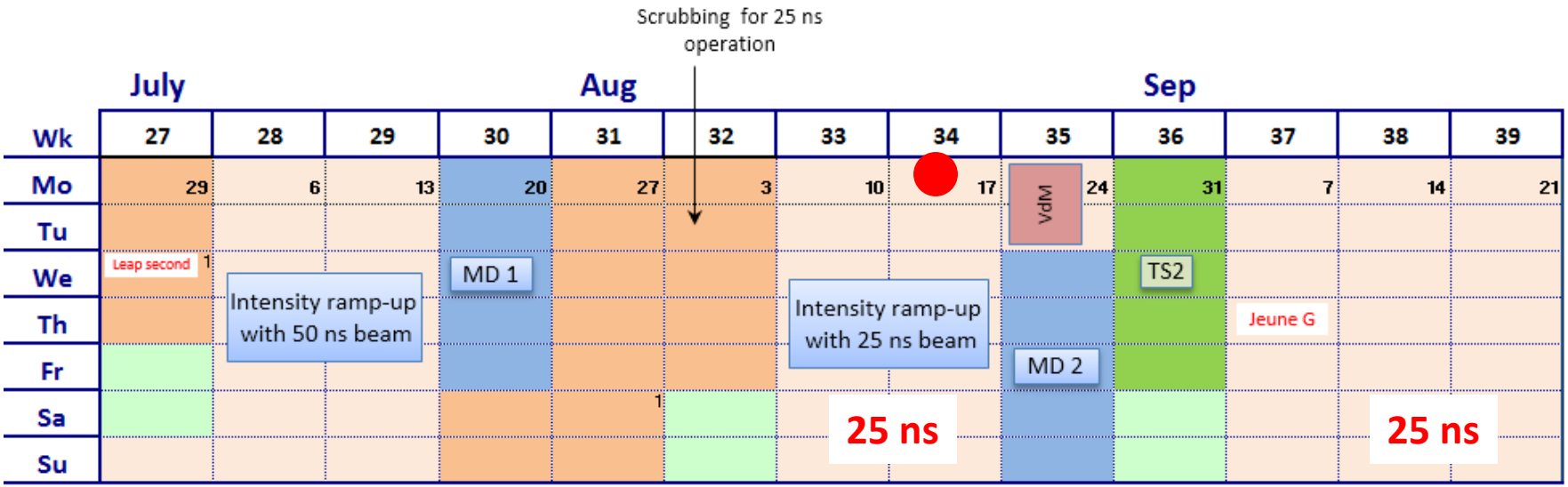
To summarize

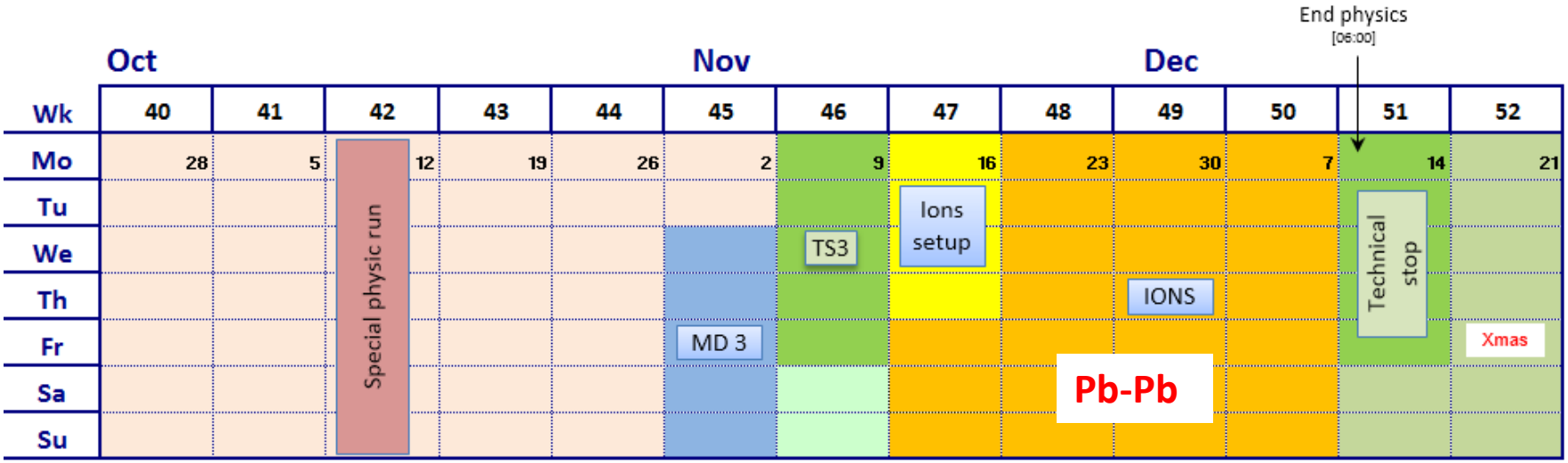
- QPS – to be fixed soon
- E-cloud – to work with – it will get better
- UFOs – to work though
- ULO – hope it stays quiet
- Earth faults – worry
- TDI – to live with
  - limitations from BN blocks
  - TDI.R8 looks to be compromised already

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

So after we've got back in the boat…

Q3/Q4 2015 - latest





25 ns - incoming

- 2 weeks ramp-up before MD2/TS2
  - 1 week in: 218 bunches
  - Might get to 400/700 bunches
- 7 weeks contiguous proton-proton operation
  - Special run to be scheduled (~5 days – not included in the 7 weeks)

2015 performance - comments

- Time is limited
- Scrubbing for 25 ns is not complete
  - Wrestle with electron cloud above ~1500 bunches
- TDI.R8 will provide a soft limit of around 1200 bunches
  - Will be pushed
- Luminosity potential could be increased by a judicious choice of beam and beta*
  - Low emittance (BCMS scheme) and an intermediate beta* (60 cm) are being considered.

2015: ATLAS and CMS performance

- Beta* = 80 cm, or ~60 cm
- Nominal bunch population
- Nominal emittance into collisions, or lower
- **>> Assume Injection limit for 25 ns: max colliding bunches 1200**

- **Moderate availability plus need for intensity ramp-up**

	Nc	Beta *	ppb	EmitN	Lumi [$cm^{-2}s^{-1}$]	Days (approx)	Int lumi	Pileup
50 ns	476	80	1.1e11	1.8	1.6e33	14	0.1 fb^{-1}	27
2015.1	1200	80	1.2e11	3.5	3.6e33	50	~2.3 fb^{-1}	21
2015.2	1200	60	1.2e11	2.3	5.6e34	47	~3.4 fb^{-1}	33

Detailed limitations lead to a modest total for the year
Still getting to grips with the issues…

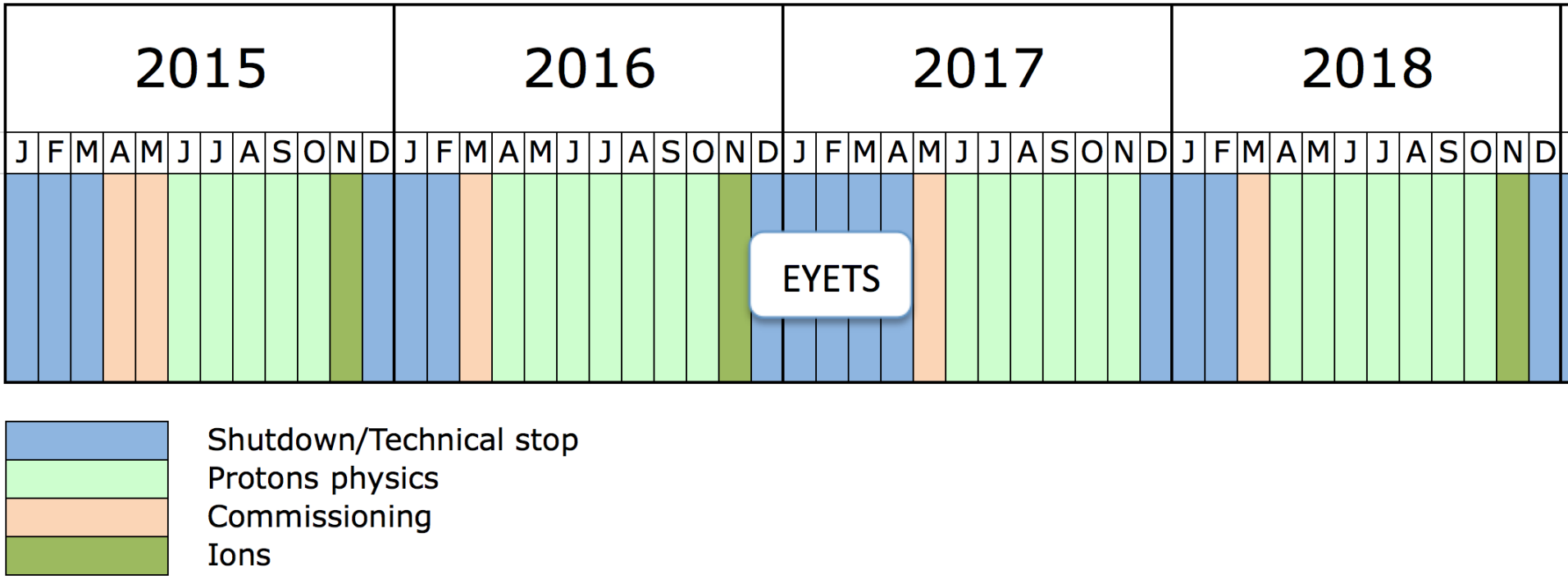
LHCb & ALICE

- LHCb (pile-up limited) will also suffer if the number of bunches is limited.
- ALICE – 5e29 to 2e30 $cm^{-2}s^{-1}$ - min. impact

LHCb	Levelled lumi [$cm^{-2}s^{-1}$]	Days (approx)	Int lumi fb^{-1}	Pileup
25 ns	4e32	50	0.5	1.1
25 ns (1200b)	2e32	50	0.3	1.2

- 30% physics efficiency (~36% in 2012)

Run 2



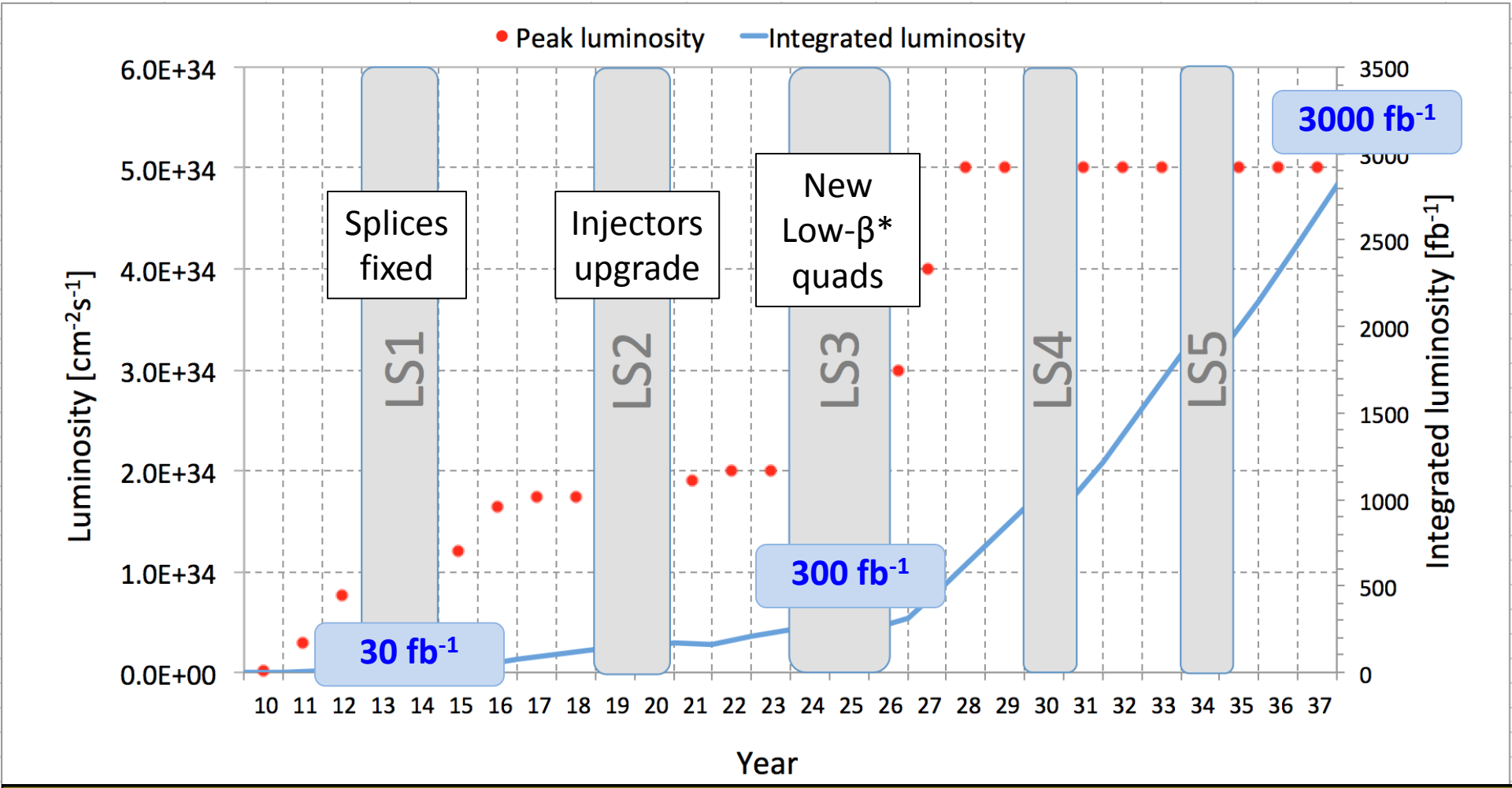
- EYETS – Extended Year End Technical Stop – 19 weeks – CMS pixel upgrade
- Start LS2 at the end of 2018

Run 2 performance

- Start 2016 in production mode
  - 6.5 TeV, machine scrubbed for 25 ns operation
  - Beta* = 40 cm in ATLAS and CMS
  - New injection protection absorbers
  - Peak lumi limited to 1.7e34 by inner triplets
  - Reasonable availability assumed – usual caveats apply – really need to gain experience with 25 ns operation

	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	36
2018	1.5	160	36

And beyond



LHC is highest-E, highest-L operational collider → full exploitation ($\sqrt{s}$ ~ 14 TeV, 3000 fb^{-1}) is mandatory:

FG EPS 15

Conclusions

- 6.5 TeV/fundamentals look good
- Commissioning and scrubbing went well
- Still picking up some hang-over from LS1
  - Quench protection system
  - Earth faults
  - Injection protection devices
  - ULO
- Electron cloud and UFOs will slow progress
- Injection will impose limits on number of bunches

2015 will be a short year for proton physics but should lay foundations for production for the rest of Run 2 and beyond