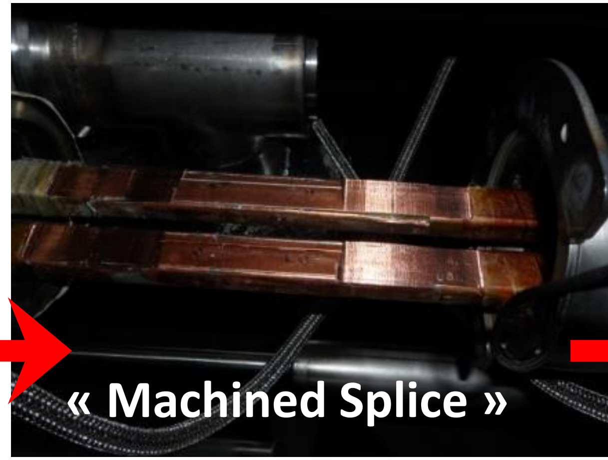
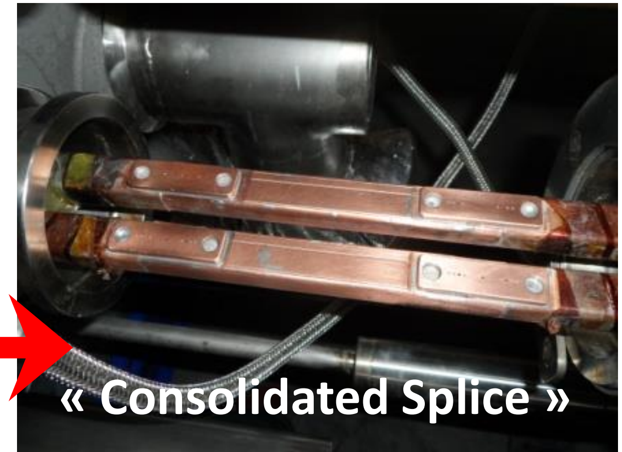
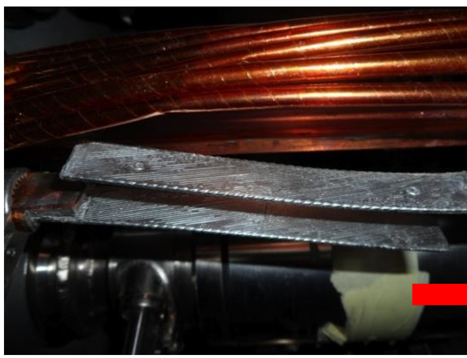
The LHC in Run 2: status and plans

Mike Lamont for the LHC team

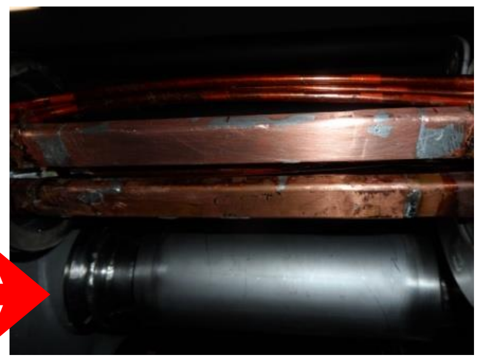
LS1 - descent into the underworld again



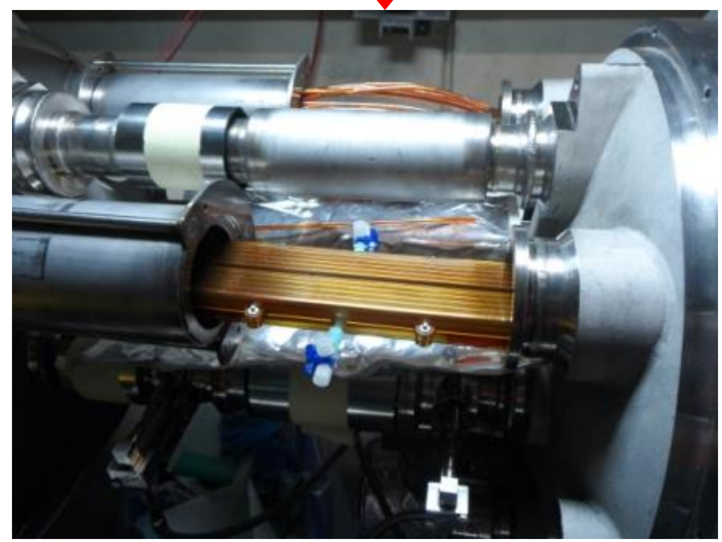




« Cables »



« New Splice »



« Insulation box »

- Total interconnects in the LHC:
  - 1,695 (10,170 high current splices)
- Number of splices redone: ~3,000 (~ 30%)
- Number of shunts applied: > 27,000

And a lot more besides…

Superconducting Magnets and Circuits Consolidation (SMACC)

Monumental effort

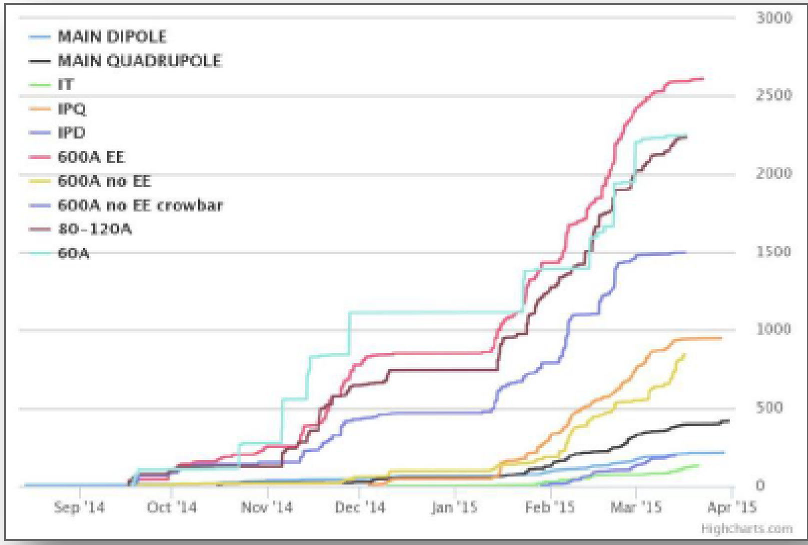
- Over 350 persons involved
- Including preparation: ~1,000,000 working hours
- No serious accidents!

Jean-Philippe Tock

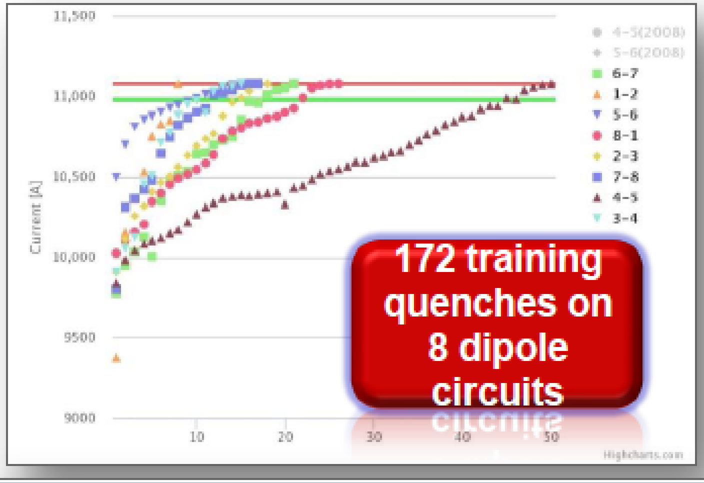
Collaborations with NTUA (Athens), WUT (Wroclaw) and support of DUBNA

SMACC project : Closure of the last interconnection – 18.06.2014
Activity led by A Musso (TE-MSC)

The LHC powering tests overview



Powering tests were completed at 8 am on Friday April 03rd



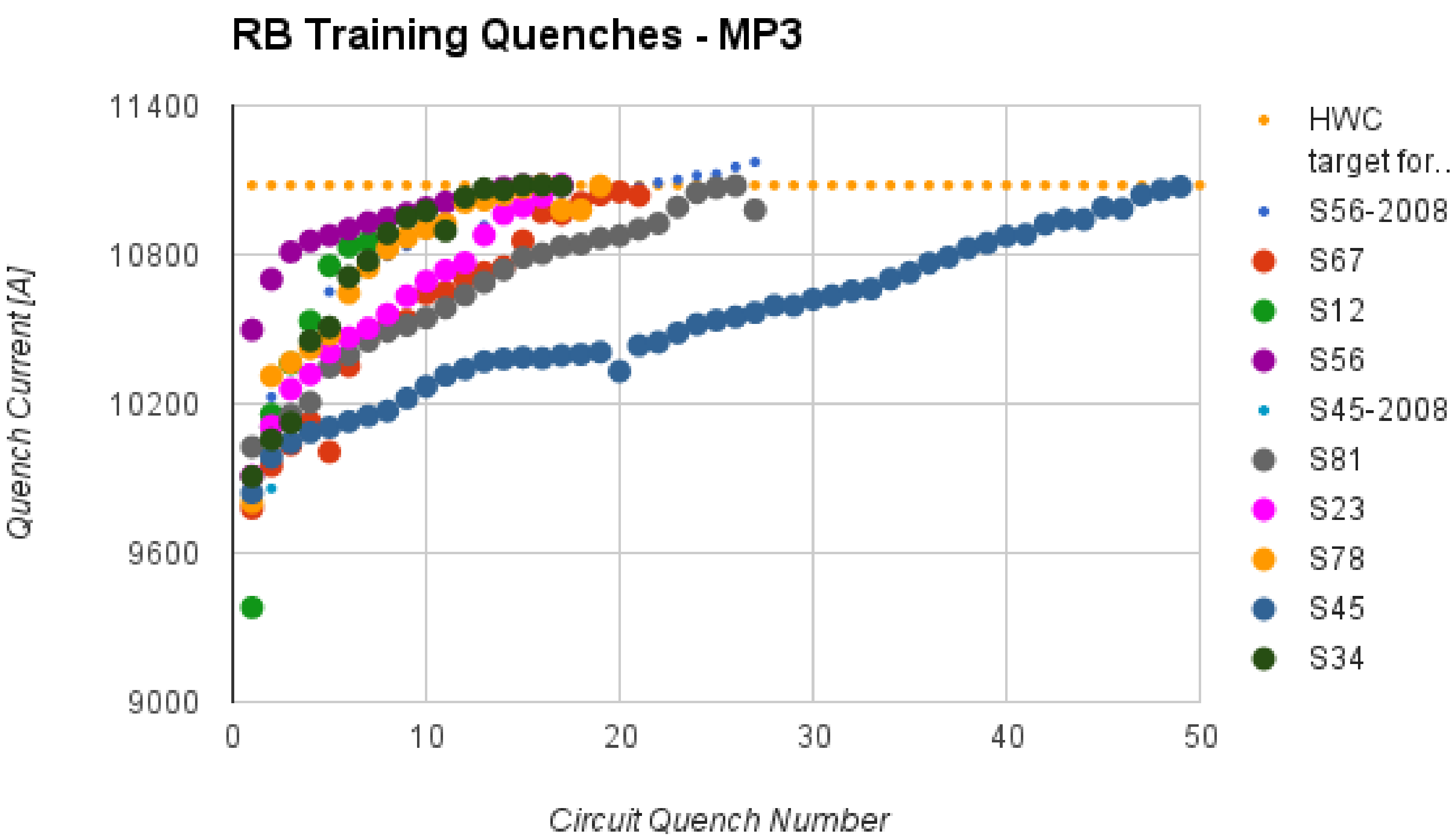
Circuit	Status	#M Firm 1	#M Firm 2	#M Firm 3	#MQ Firm 1	#MQ Firm 2	#MQ Firm 3	#MQ total	#CQ total
RB.A12	11080 A reached	50	95	9	2	1	4	7	7
RB.A23	11080 A reached	56	58	40	0	2	15	17	17
RB.A34	11080 A reached	44	81	29	1	7	8	16	16
RB.A45	11080 A reached	48	44	62	-	3	48	51	49
RB.A56	11080 A reached	28	42	84	0	0	18	18	17
RB.A67	11080 A reached	57	36	61	0	1	21	22	21
RB.A78	11080 A reached	53	40	61	2	10	7	19	19
RB.A81	11080 A reached	64	24	66	0	3	26	29	26

Since September 15th 2014:

1566 superconducting circuits commissioned through execution and analysis of **more than 10.000 test steps** (~13.800 test steps including re-execution)

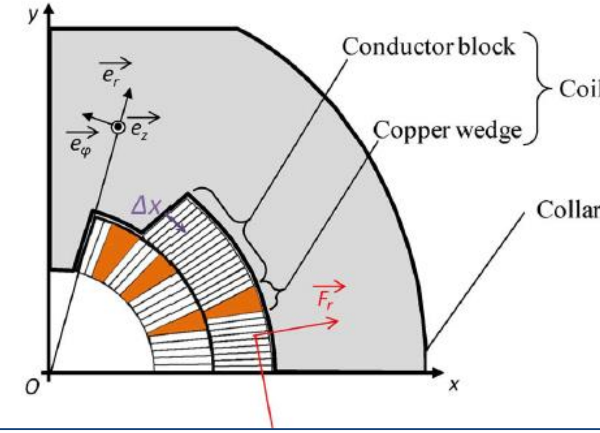
Dipole training 1/2

- 154 dipoles per sector, powered in series
- Ramp the current until single magnet quenches - "training quench"
- Usually quench 3 – 4 other dipoles at the same time
- Cryogenics recovery time: 6 – 8 hours



Dipole training 2/2

Training: frictional energy released during conductor motion



Campaign summary

Training quenches during HWC 2014-2015 occurring until I_PNO+100 A has been reached for the first time									
Circuit	Status	#M Firm 1	#M Firm 2	#M Firm 3	#MQ Firm 1	#MQ Firm 2	#MQ Firm 3	#MQ total	#CQ total
RB.A12	11080 A reached	50	95	9	2	1	4	7	7
RB.A23	11080 A reached	56	58	40	0	1	15	16	16
RB.A34	11080 A reached	44	81	29	1	5	8	14	14
RB.A45	11080 A reached	48	44	62	0	3	48	51	49
RB.A56	11080 A reached	28	42	84	0	0	15	15	14
RB.A67	11080 A reached	57	36	61	0	1	20	21	20
RB.A78	11080 A reached	53	40	61	2	8	6	16	16
RB.A81	11080 A reached	64	24	66	0	3	26	29	26
	Total:	400	420	412	5	22	142	169	162

#M: Number of magnets in a sector.

#MQ: Number of magnet training quenches in a sector.

#CQ: Number of circuit quenches in a sector.

- All magnets have been trained to well over 7 TeV in SM18 before installation
- Extensive re-training in situ was not expected

7 TeV?

- Assume all 412 firm 3 dipoles need re-training
  - Some will required more than 1 re-training quench
- Firm 2 (~5% to 6.5 TeV) and firm 1 (~ 1% to 6.5 TeV) will also play a part
- Detailed analysis ongoing
  - Clearly hundreds more t-quenches required
  - Could type test 1 sector in 2015 YETS…

The essential feeling at the moment is:
let's get the machine running at 6.5 TeV first

LHC - 2015

- Target energy: 6.5 TeV
  - looking good
- Bunch spacing: 25 ns
  - strongly favored by experiments (pile-up limit around 50)
- Beta* in ATLAS and CMS: 80 to 40 cm

Energy

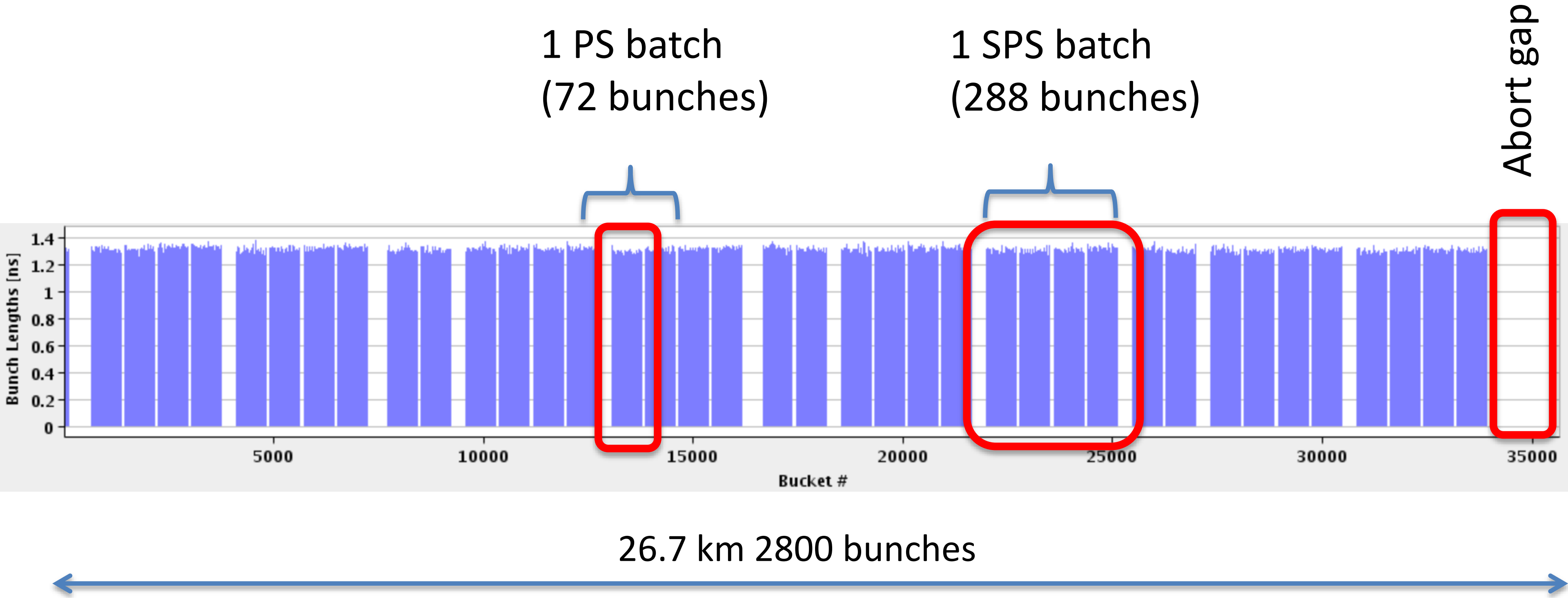
- Lower quench margins
- Lower tolerance to beam loss
- Hardware closer to maximum (beam dumps, power converters etc.)

25 ns

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

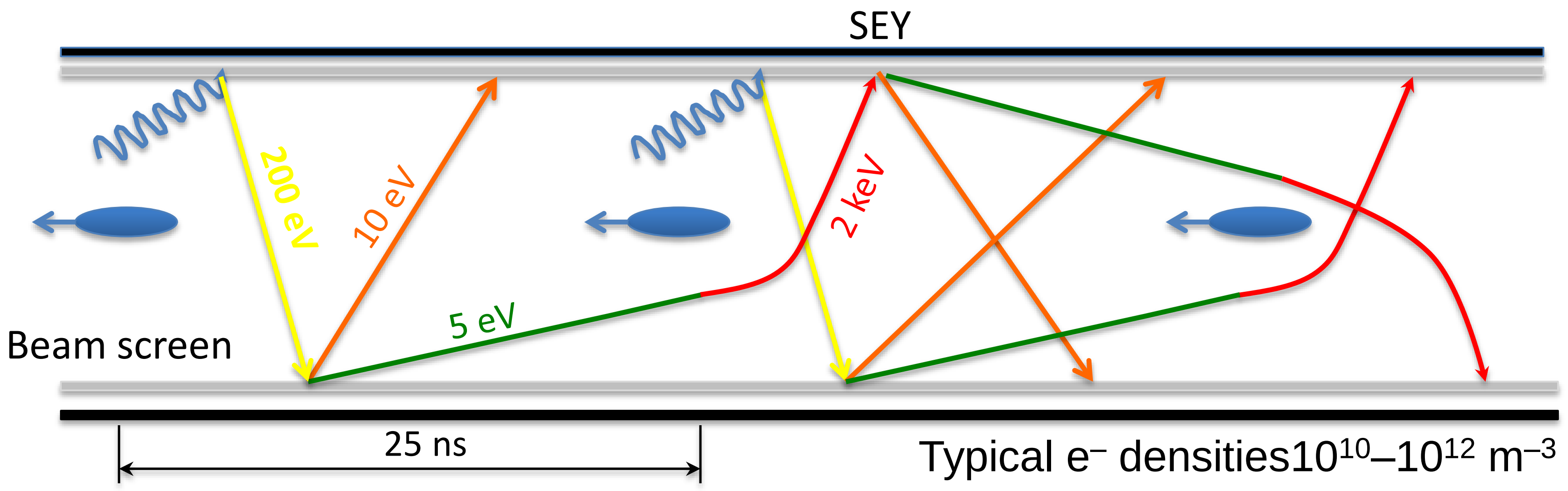
LHC bunch structure - 2015

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



New limits of ~2 PS batches per injection from the injection protection absorbers – will reduce the maximum number of bunches to around 2500

25 ns & electron cloud



Possible consequences:

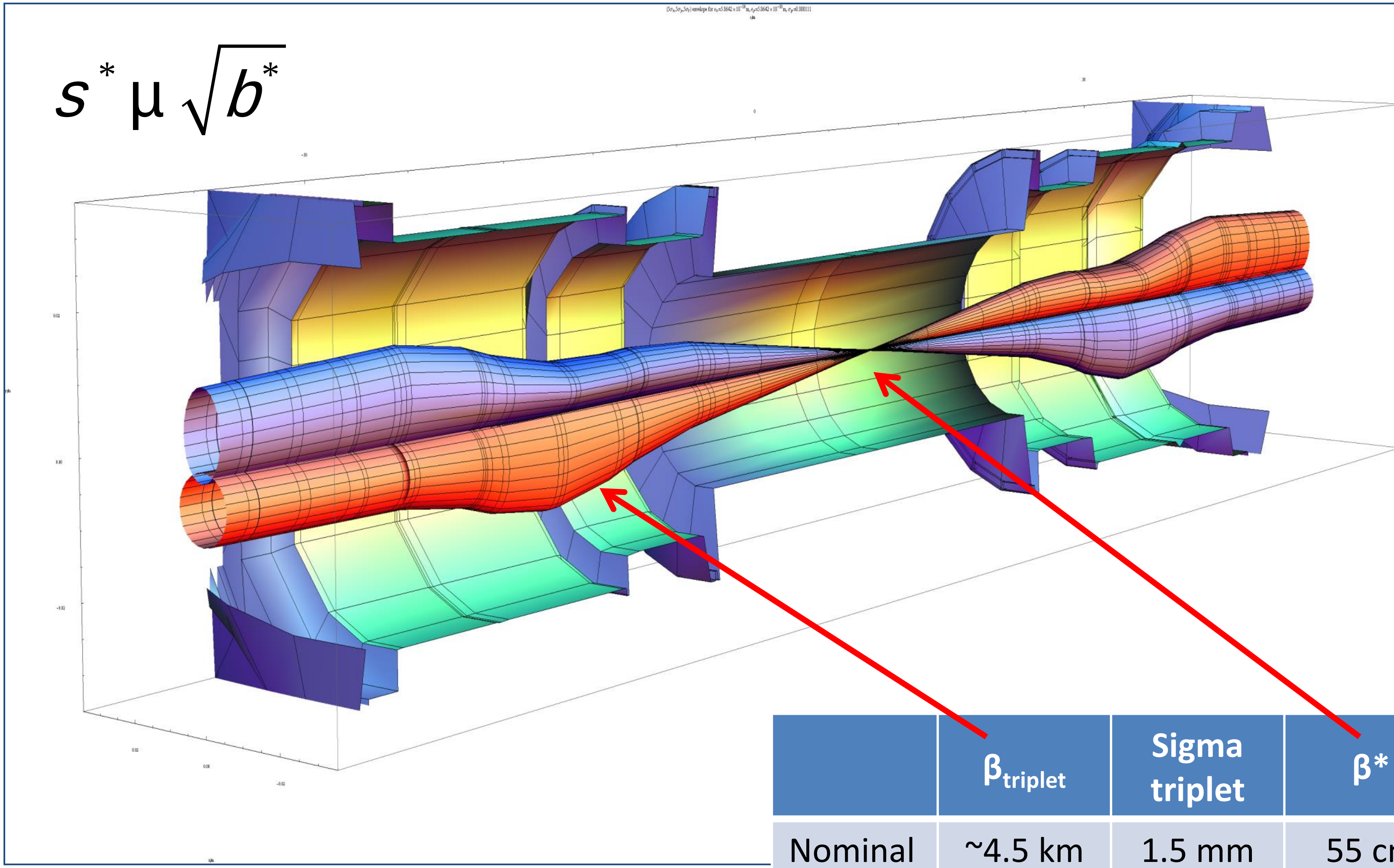
- instabilities, emittance growth, desorption – bad vacuum
- excessive energy deposition in the cold sectors

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

Squeeze in ATLAS

$$s^* \mu \sqrt{b^*}$$

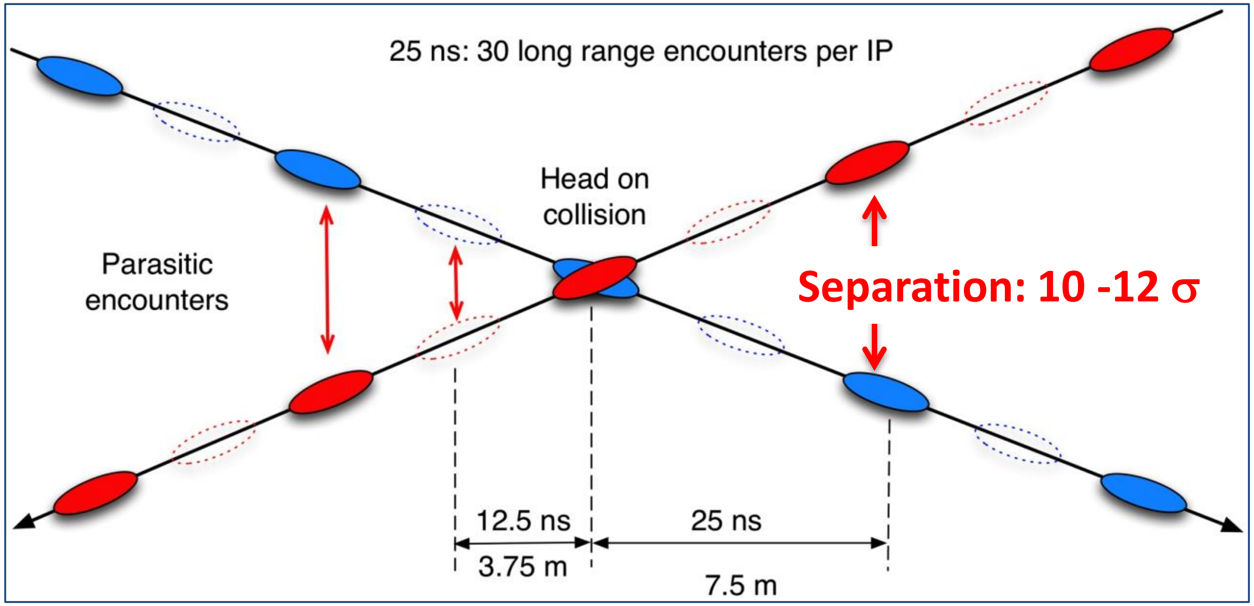


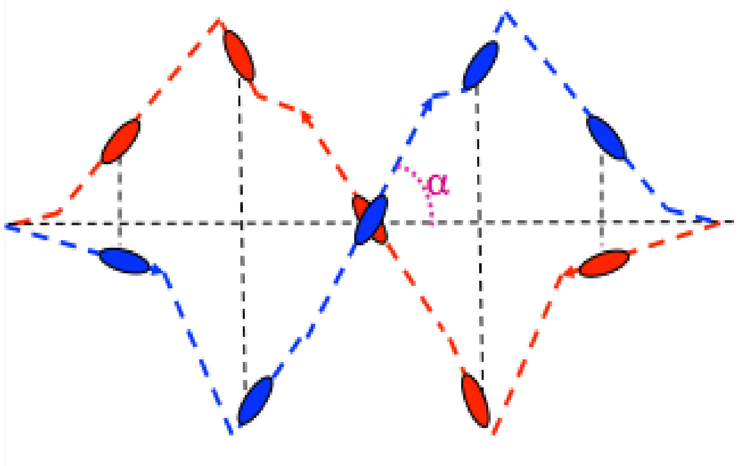
	$\beta_{triplet}$	Sigma triplet	β*	Sigma*
Nominal	~4.5 km	1.5 mm	55 cm	17 um
HL-LHC	~20 km	2.6 mm	15 cm	7 um

Image courtesy John Jowett

Crossing angle

work with a crossing angle to avoid parasitic collisions.





geometric luminosity reduction factor:

$$F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

2015: beta* in IPs 1 and 5

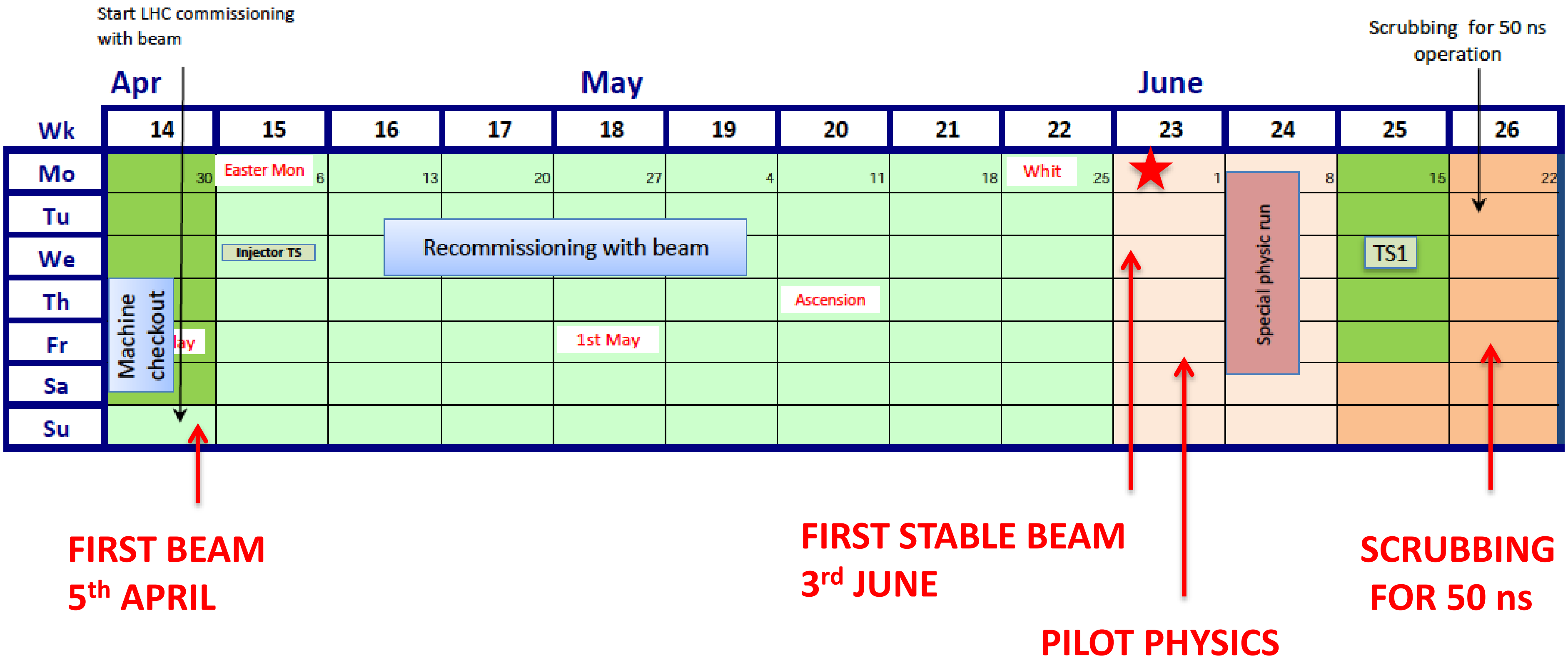
- Many things have changed. Start carefully and push performance later.
- Start-up: **β*= 80 cm – (very) relaxed**
  - 2012 collimator settings
  - 11 sigma long range separation
  - Aperture, orbit stability… checks ongoing
- Ultimate in 2015: **β*= 40 cm**
  - **Possible reduction later in the year**

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

2015 commissioning strategy

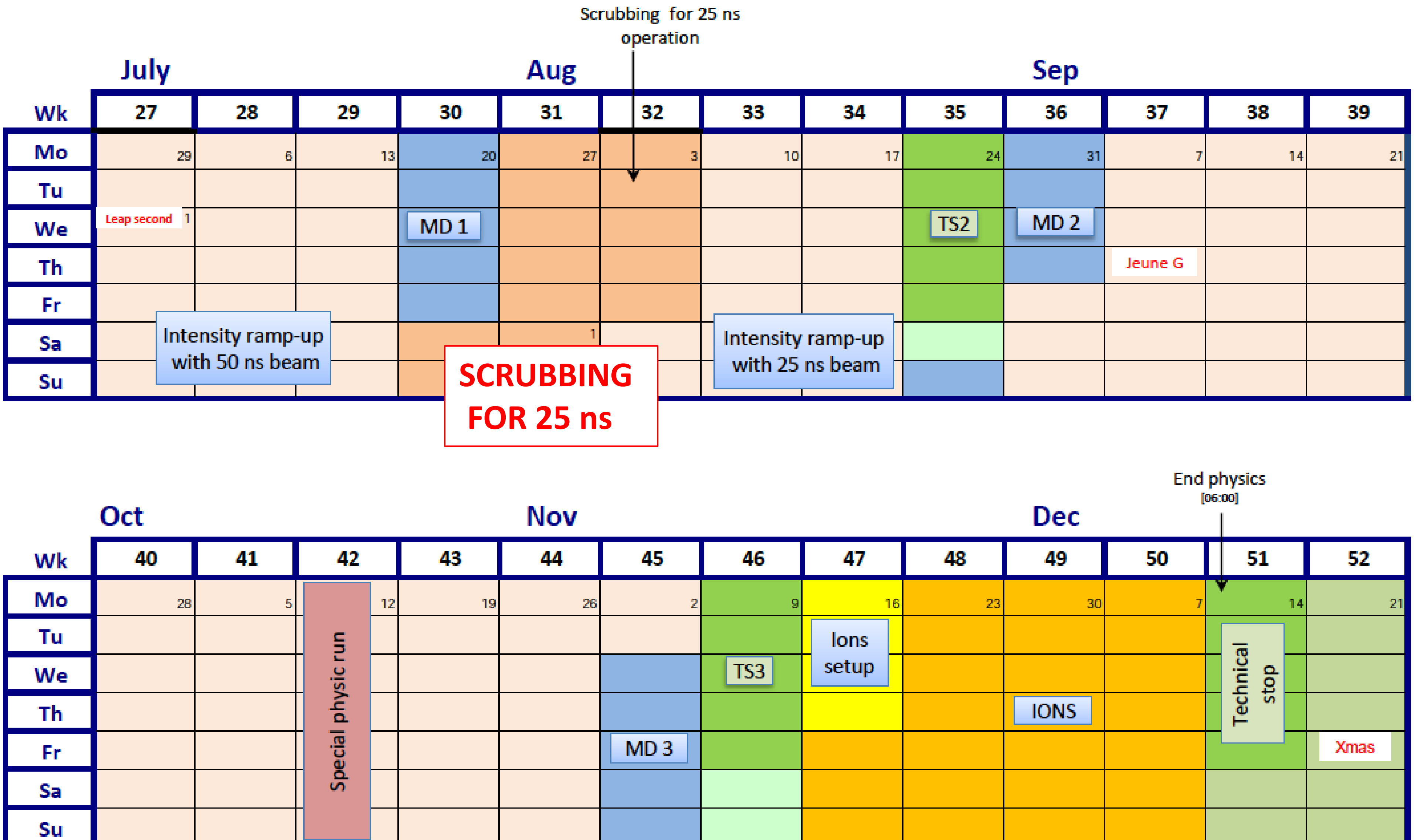
- **Low intensity commissioning of full cycle – 8 weeks**
- Pilot physics – low number of bunches
- Special physics run: LHCf and luminosity calibration
- Scrubbing for 50 ns
- Intensity ramp-up with 50 ns
  - Characterize vacuum, heat load, electron cloud, losses, instabilities, UFOs, impedance
- Scrubbing for 25 ns
- Ramp-up 25 ns operation with relaxed beta*
- Possibly commission lower beta*
- 25 ns operation

2015 Q2



- 8 weeks beam commissioning
- Pilot physics – up to at least 40 bunches per beam
- 5 days special physics at beta* = 19 m (VdM, LHCf, TOTEM & ALFA)
- Start technical stop – 15th June

Q3/Q4 2015



Scrubbing for 25 ns operation
July
Aug
Sep
Wk
27
28
29
30
31
32
33
34
35
36
37
38
39
Mo
Tu
We
Th
Fr
Sa
Su
29
6
13
20
27
3
10
17
24
31
7
14
21
Leap second
1
MD 1
TS2
MD 2
Jeune G
Intensity ramp-up with 50 ns beam
SCRUBBING FOR 25 ns
Intensity ramp-up with 25 ns beam
End physics [06:00]
Oct
Nov
Dec
40
41
42
43
44
45
46
47
48
49
50
51
52
28
5
12
19
26
2
9
16
23
30
7
14
21
Special physic run
TS3
Ions setup
IONS
MD 3
Technical stop
Xmas

2015 – latest schedule

Phase	Days
Initial Commissioning	57
Scrubbing	23
Special physics run 1 (LHCf/VdM)	5
Proton physics 50 ns	**9 + 21**
Proton physics 25 ns	**70**
Special physics run 2 (TOTEM/VdM)	7
Machine development (MD)	15
Technical stops	15
Technical stop recovery	3
Ion setup/Ion run	4 + 24
Total	**253 (36 weeks)**

Schedule - comments

- Picked up some 4 weeks delay from:
  - Powering tests/quench training overrun
  - Earth fault resolution
- Proton-proton physics down to 70 days
  - Decrease in beta*to be reviewed after gaining some experience (although considerable progress made during commissioning)
- Ion program unaffected
  - Proton-proton reference data will be difficult to squeeze in

Commissioning

- **System commissioning with beam**
  - Collimation
  - Beam dump
  - Feedbacks
  - Beam instrumentation
  - Machine protection
  - RF
  - Transverse damper
  - Injection
- **Machine characterization**
  - Optics measurement and correction
  - Magnetic machine
- **Operations**
  - High intensity injection
  - Ramp to 6.5 TeV
  - Squeeze

Injection - probe

Ramp - probe

Flat-top - probe

Squeeze - probe

Injection - nominal

Ramp - nominal

Flat-top - nominal

Squeeze - nominal

Collide & validation

Complete
Ongoing

Milestones

Circulating beam	Sunday 5th April
Ramp to 6.5 TeV	Friday 10th April
First 13 TeV collisions	Wednesday 20th May
First Stable beams	Wednesday 3rd June

Working throughout with:

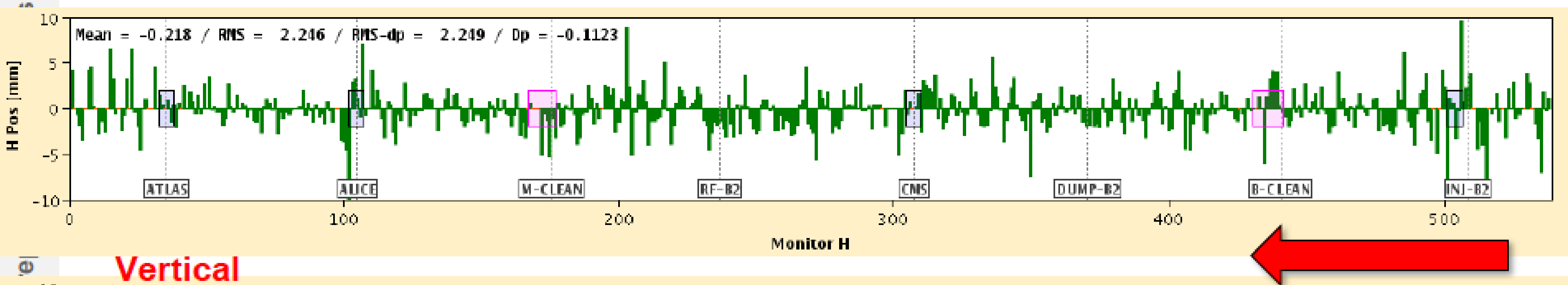
- **probes (5e9 protons per bunch) or**
- **1 or 2 nominals (1.2e11 protons per bunch)**

THIS IS NOT BAD!

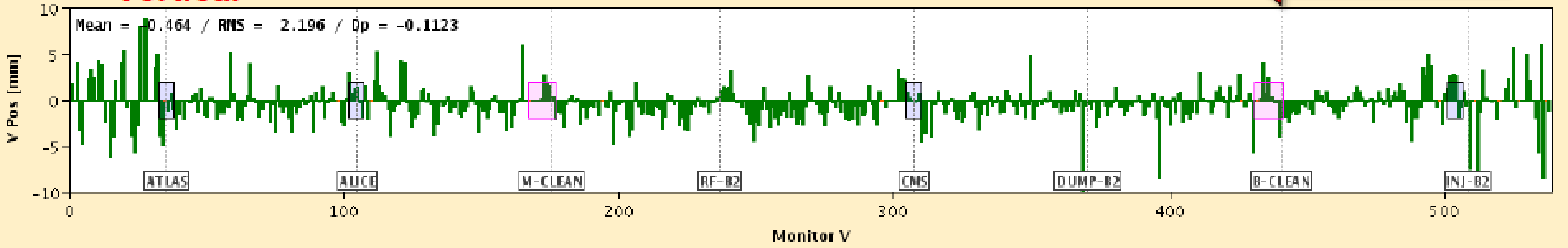
Threading – Easter Sunday

- Threading of B2 started at 10:12, ended 10:41.
  - *Followed by 1 hour of work to establish a closed orbit and circulate more than 25 turns.*
- Threading of B1 started at 11:54, ended 12:26.
  - *Almost immediately obtained a closed orbit and more than 25 turns.*

Horizontal



Vertical

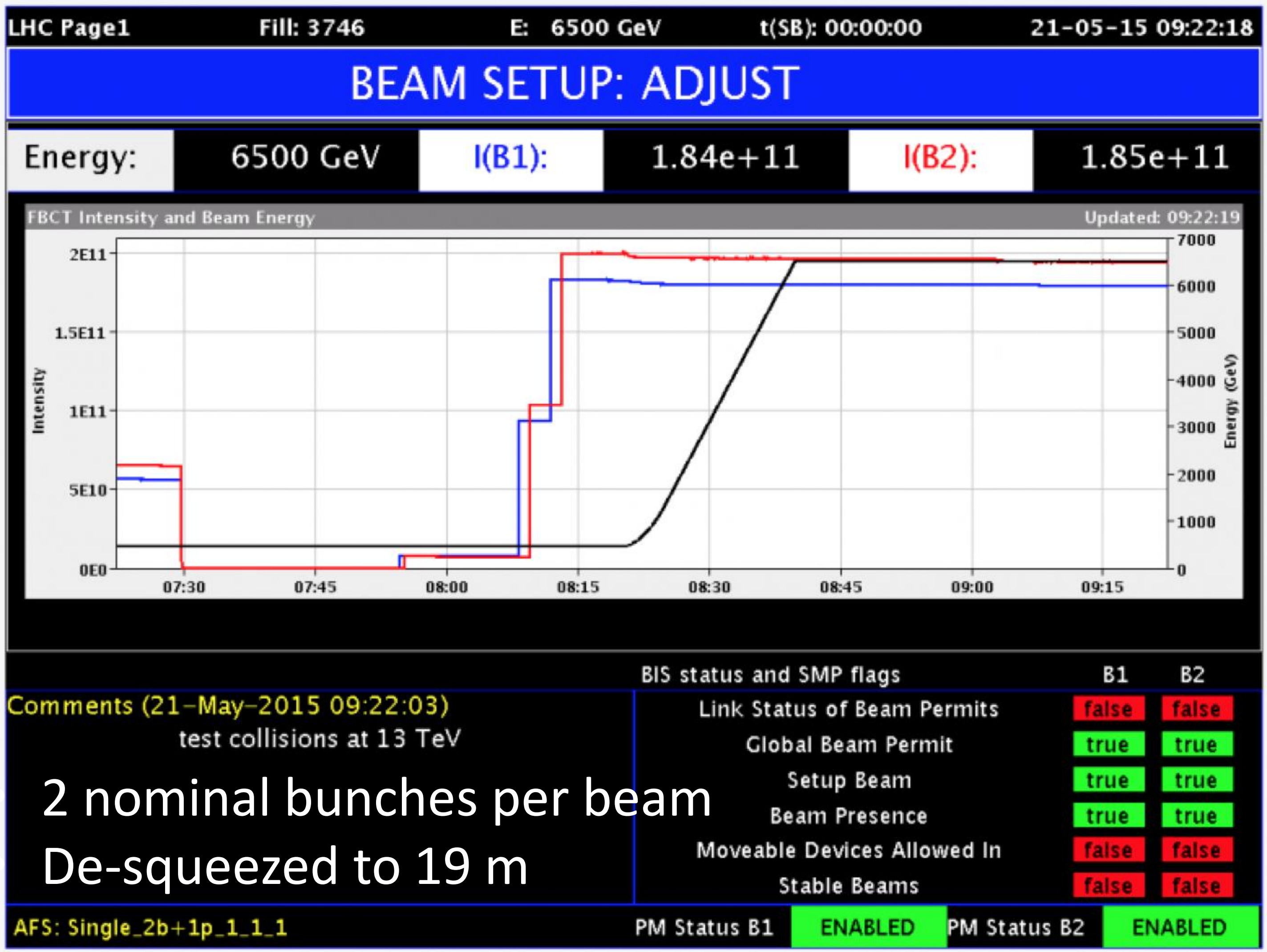


6.5 TeV for the first time

01:03 10th April

First images of collisions at 13 TeV

by Cian O'Luanaigh



- 2 nominal bunches per beam
- De-squeezed to 19 m

Test collisions continue today at 13 TeV in the Large Hadron Collider (LHC) to prepare the detectors ALICE, ATLAS, CMS, LHCb, LHCf, MOEDAL and TOTEM for data-taking, planned for early June (Image: LHC page 1)

Of note 1/2

- It’s not a new machine – 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!

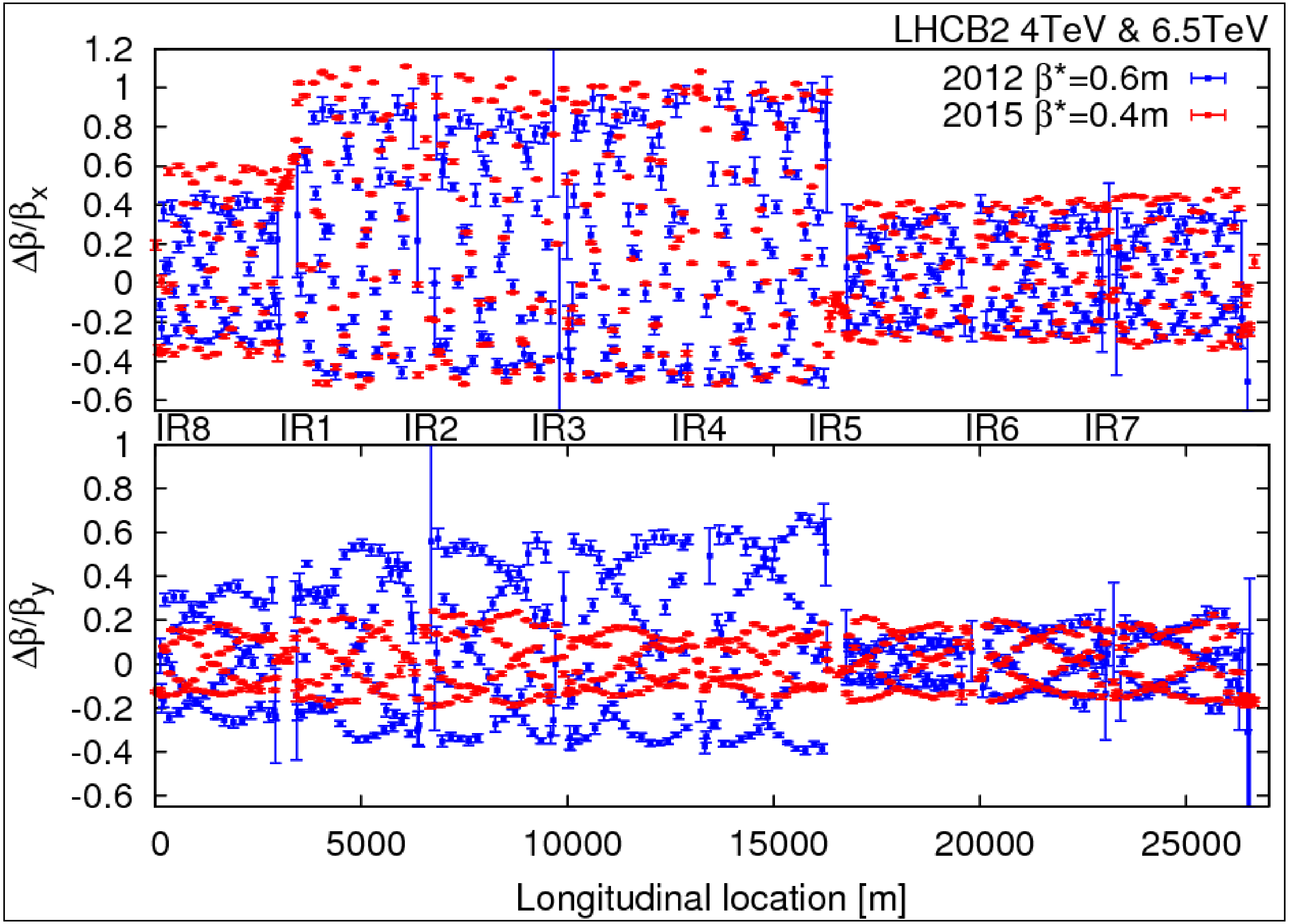
Of note 2/2

- Magnetically reproducible as ever
- Optically good, corrected to excellent
- Behaving well at 6.5 TeV
  – One additional training quench so far
- Operationally well under control
  – Injection, ramp, squeeze, de-squeeze

Still have to face the intensity ramp-up

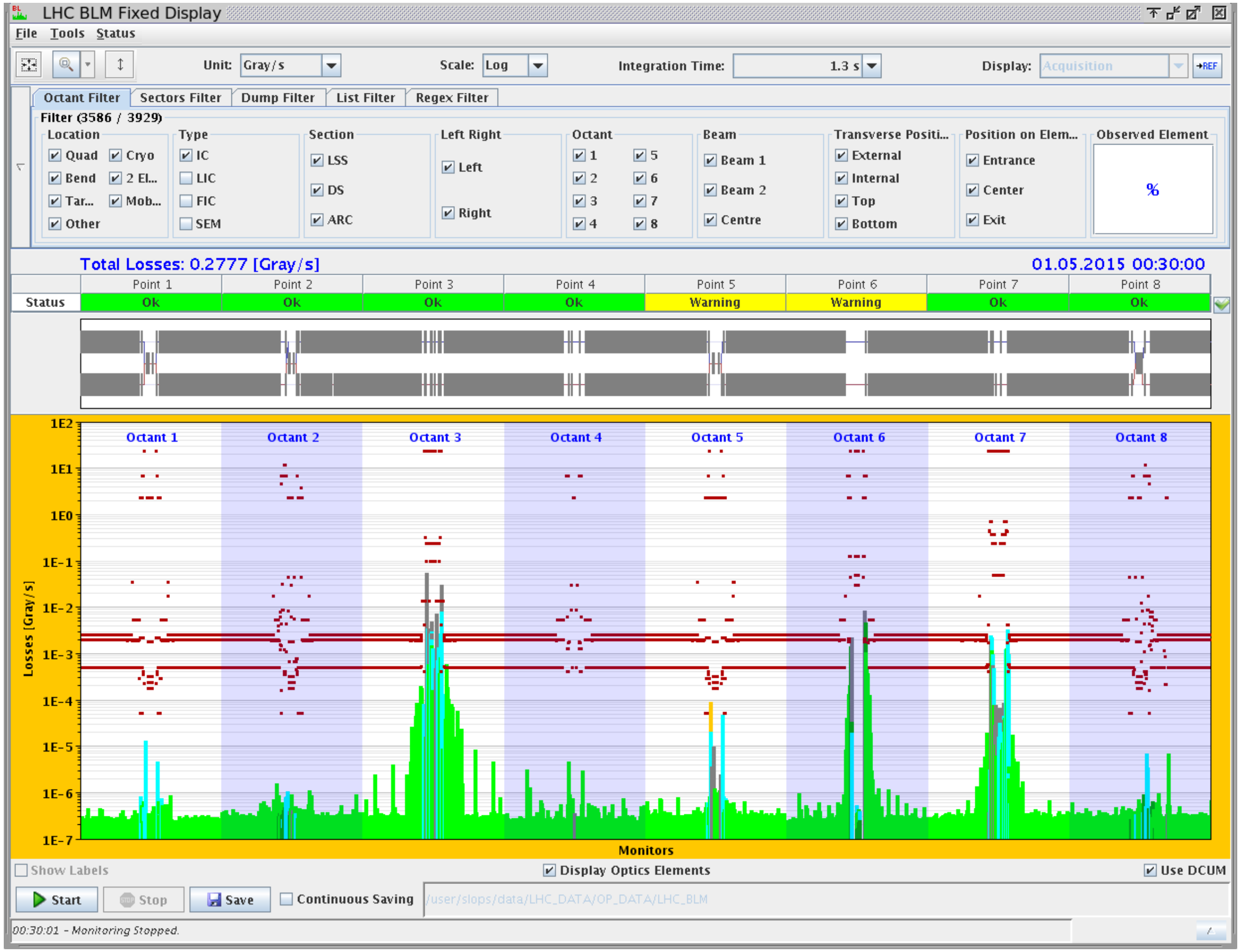
- UFOs, e-cloud, vacuum, beam induced heating, instabilities

Optics - 40 cm



Rogelio and OMC team

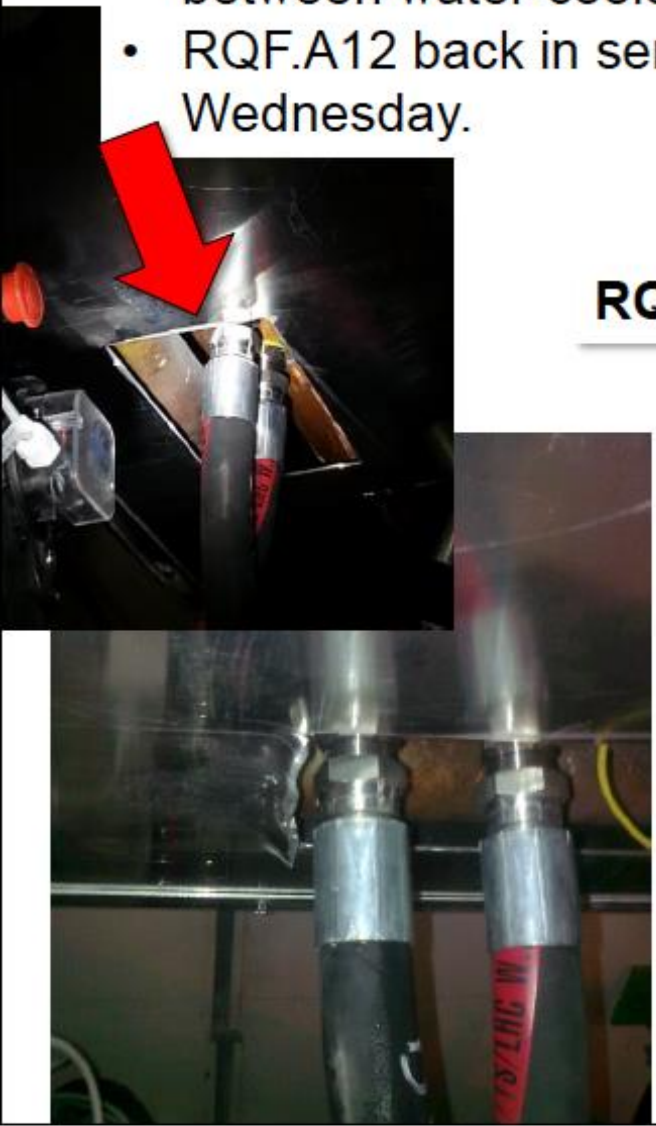
Off momentum loss map 6.5 GeV



Novel features of collimation system – BPM equipped tertiary collimators, automatic beam based set-up

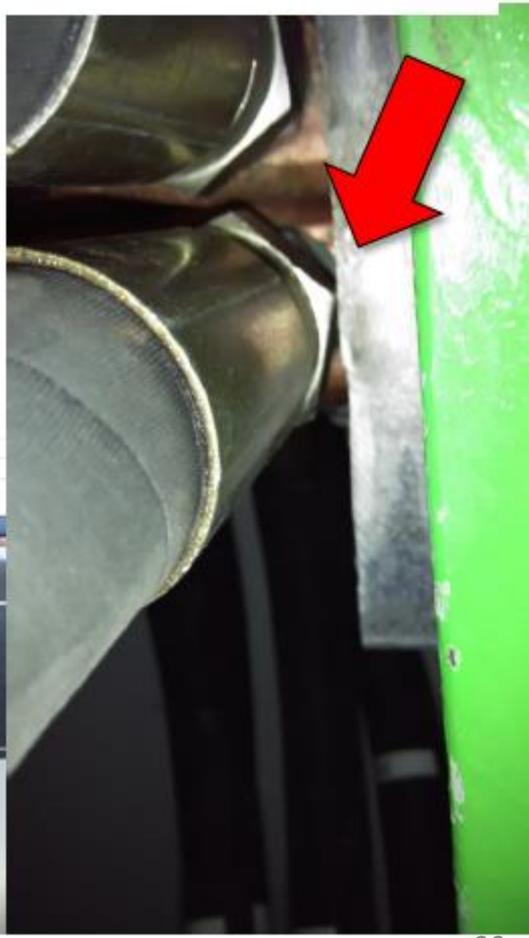
Of course we've had a few issues…

- RQF.A12 and RB.A78 earth faults were both traced to contacts between water-cooled cables and (metallic) protection covers.
- RQF.A12 back in service Tuesday, reconnection of RB.A78 on Wednesday.

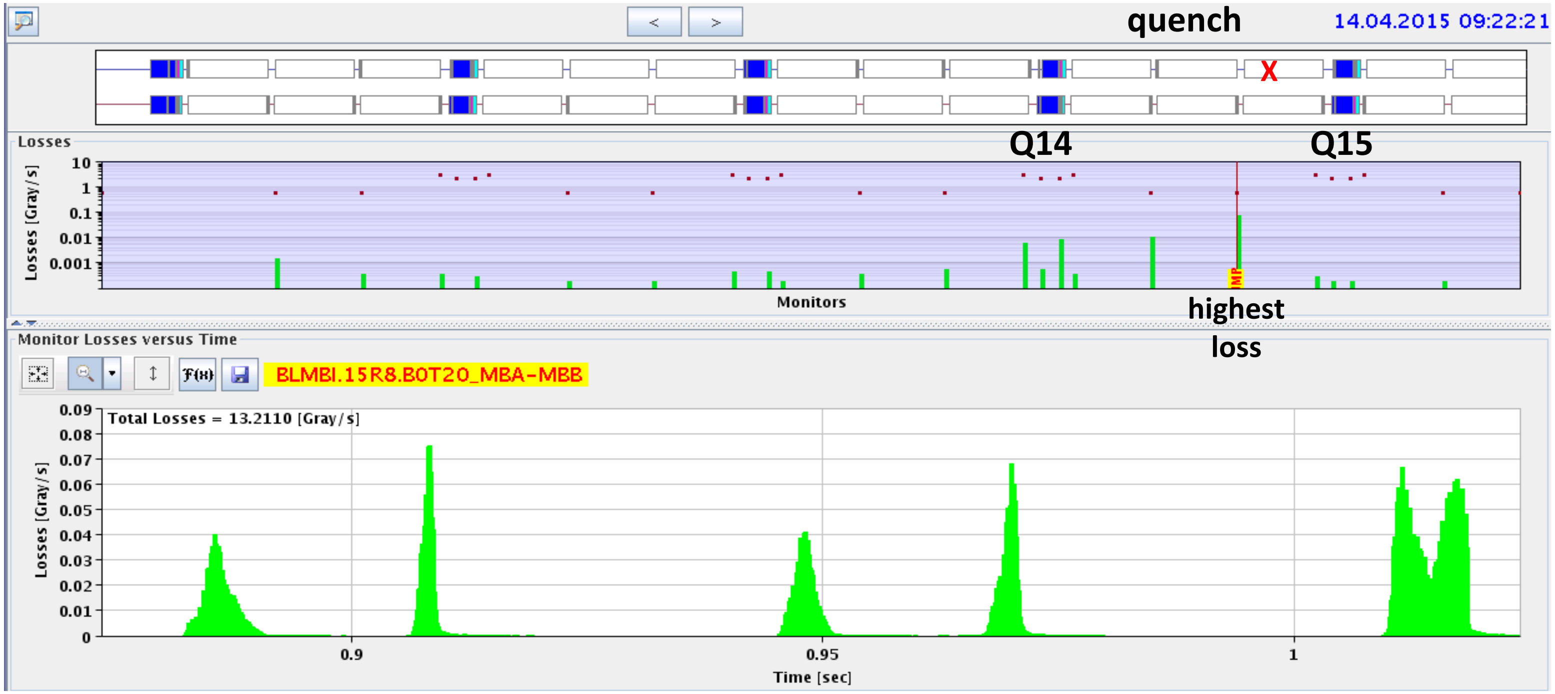


RQF.A12

RB.A78



MUFOs in 15R8

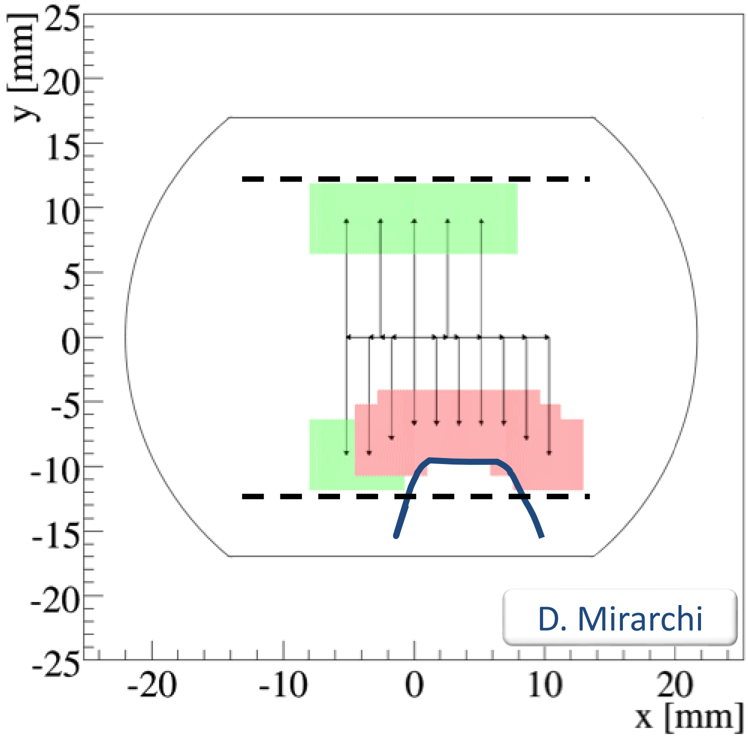


- Multiple loss events after a short time at 6.5 TeV compatible with particles falling into the beam
  - loss patterns point to a specific position in the middle of a dipole magnet
  - Quenched twice, numerous BLM triggered dumps…

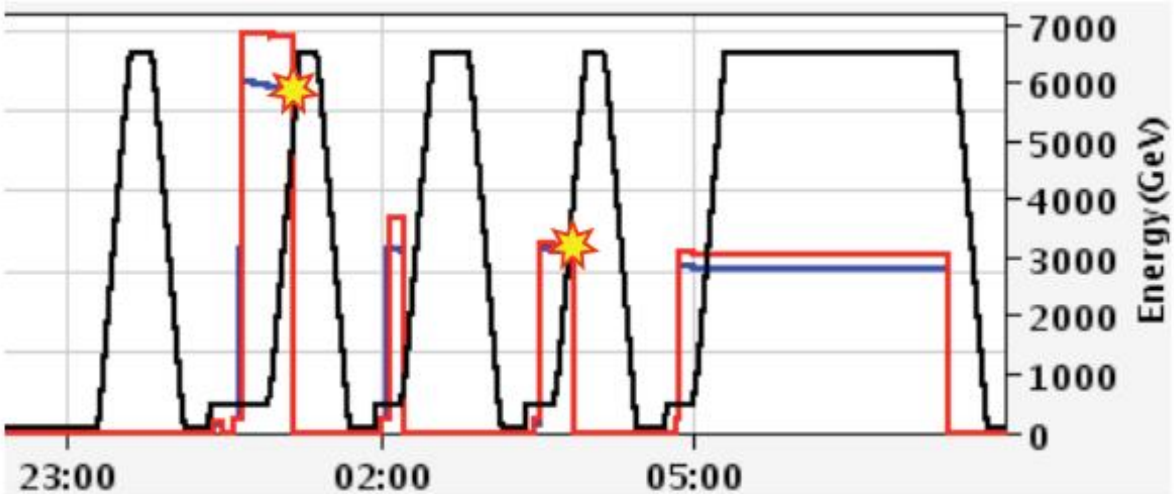
Aperture restriction in 15R8

ULO (Unidentified Lying Object)

- Aperture restriction measured at injection and 6.5 TeV
- Presently running with orbit bumps
  - -3 mm in H, +1 in V, to optimize available aperture
  - aperture probably not limiting for operation
- Behaviour with higher intensities and bunch trains still unknown
- MUFOs went away but last week



UFO in 15R8 are back



Dump 1: 5.1 TeV with 2 bunches
Dump 2: 4.3 TeV with 1 bunch

Somewhat worrying

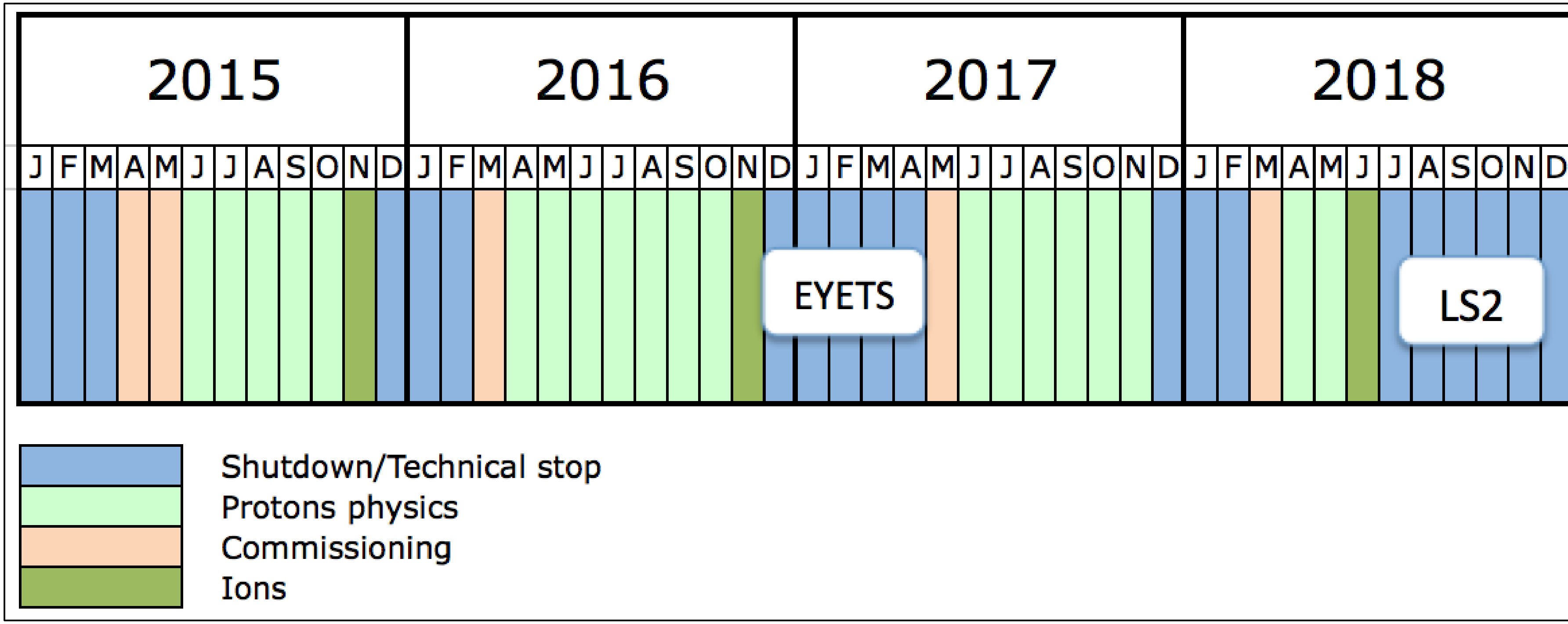
2015: ATLAS and CMS performance

- Conservative beta* to start
- Nominal bunch population
- Reasonable emittance into collisions
- Assume same machine availability as 2012

	Nc	Beta *	ppb	EmitN	Lumi [$cm^{-2}s^{-1}$]	Days (approx)	Int lumi	Pileup
50 ns	1300	80	1.2e11	2.5	4.8e33	21	~1 fb^{-1}	25
2015.1	2448	80	1.2e11	3.1	7.1e33	35	~4 fb^{-1}	21
2015.2	2448	40	1.2e11	3.1	1.2e34	30	~5 fb^{-1}	35

Official GPD luminosity target for the year was 10 fb^{-1}
Now on the challenging side – let's say 5 to 10 fb^{-1}

Run 2



- EYETS – Extended Year End Technical Stop – 19 weeks – CMS pixel upgrade
- **Mid-year 2018 stop will be pushed towards year end (not yet official)**

Run 2 performance

- Aim to 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 – full injection
  - Peak lumi limited to 1.7e34 by inner triplets

	Peak lumi E34 $cm^{-2}s^{-1}$	Days proton physics	Approx. int lumi [fb^{-1}]
2015	1.2	70	5 - 10
2016	1.5	160	35
2017	1.7	160	45
2018	1.7	40	10

Conclusions

- Looking good at 6.5 TeV
  - Impressive progress so far
  - Fabulous job done in LS1 and during powering tests
  - Lot of lessons learnt in Run 1
- Next challenge - higher intensity and e-cloud
- Fundamentals look sound, no show stoppers for the moment
  - Some irritants – resolution cost time
- 2015 will be a short year for proton physics but lay foundations for production for the rest of Run 2

It takes a remarkable effort by a large number of teams to prepare and exploit the LHC.