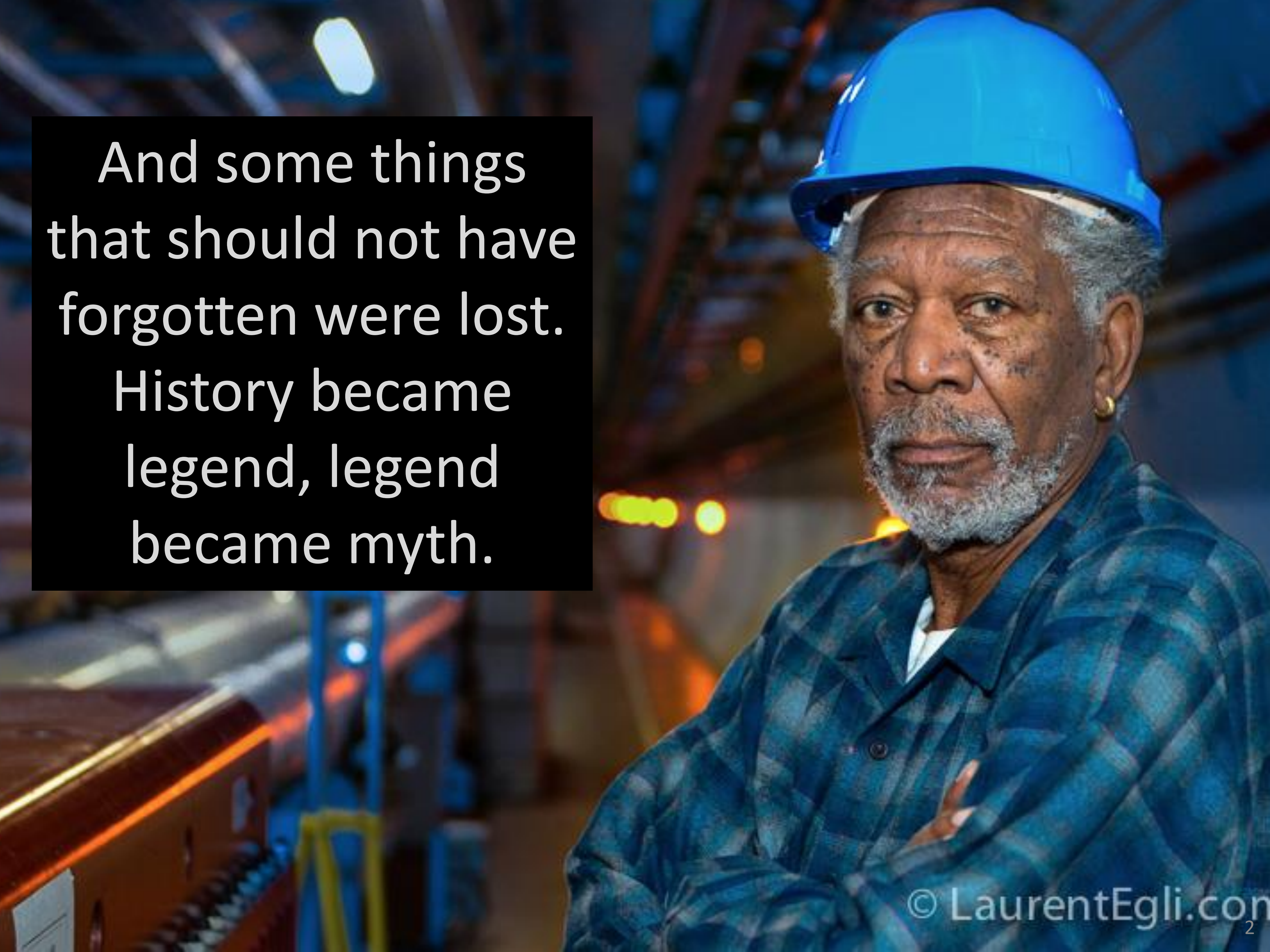
LHC: Past, Present and Future

A mythical river journey

And some things that should not have forgotten were lost. History became legend, legend became myth.



Myth

A traditional story, esp. one that involves gods and heroes and explains a cultural practice or natural phenomenon.

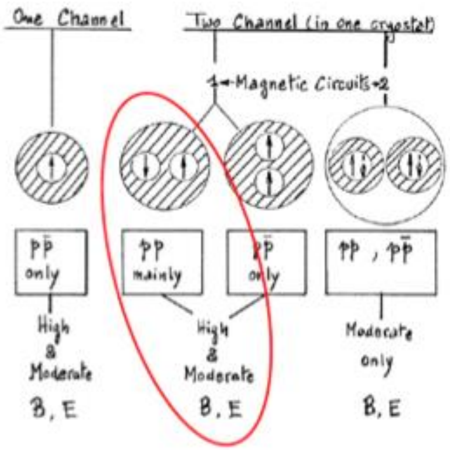
- Conception
- Birth
- Initiation
- Descent into the underworld
- Trial and Quest with the possibility of Hubris followed by Nemesis
- Withdrawal from community for meditation and preparation
- Resurrection and rebirth
- Ascension, apotheosis, and atonement

Repeat as required

And they often involve rings…

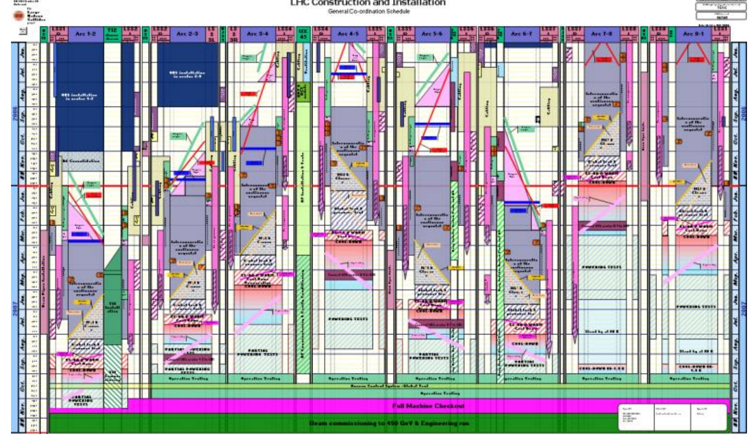
The offing was barred by a black bank of clouds, and the tranquil waterway leading to the uttermost ends of the earth flowed sombre under an overcast sky-seemed to lead into the heart of an immense darkness.

Conception

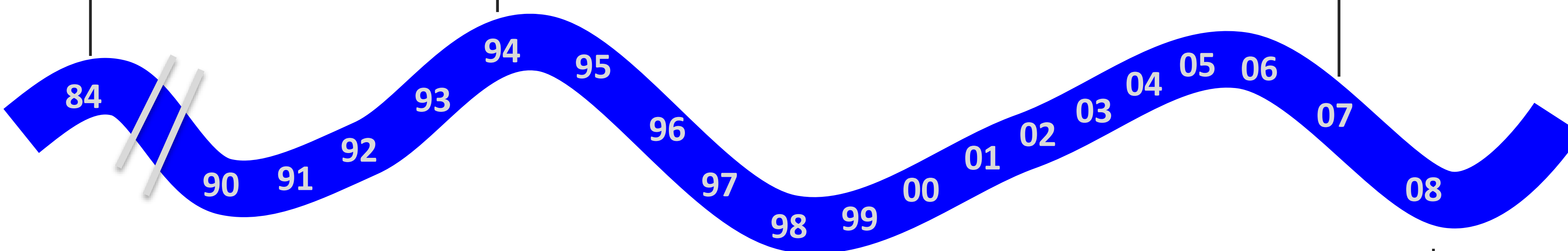


Initiation

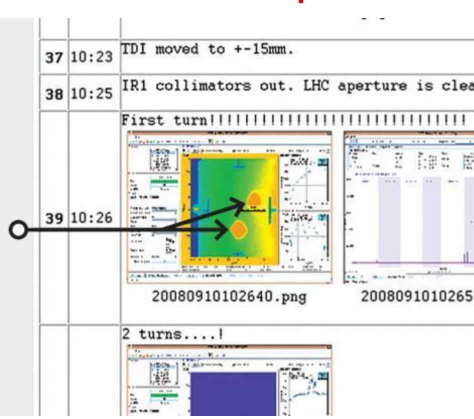
LHC approved by the Elders



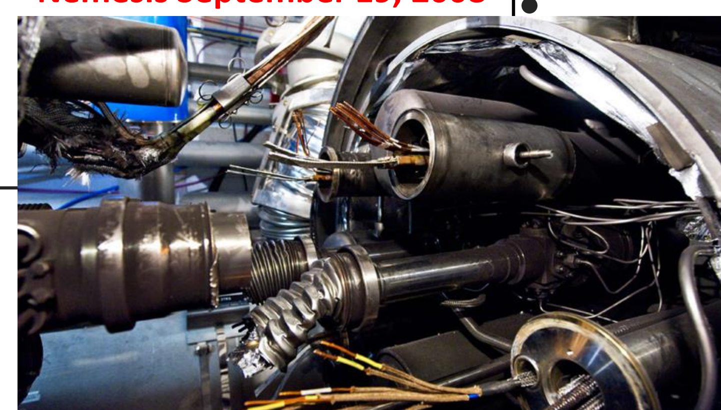
Birth – overdue

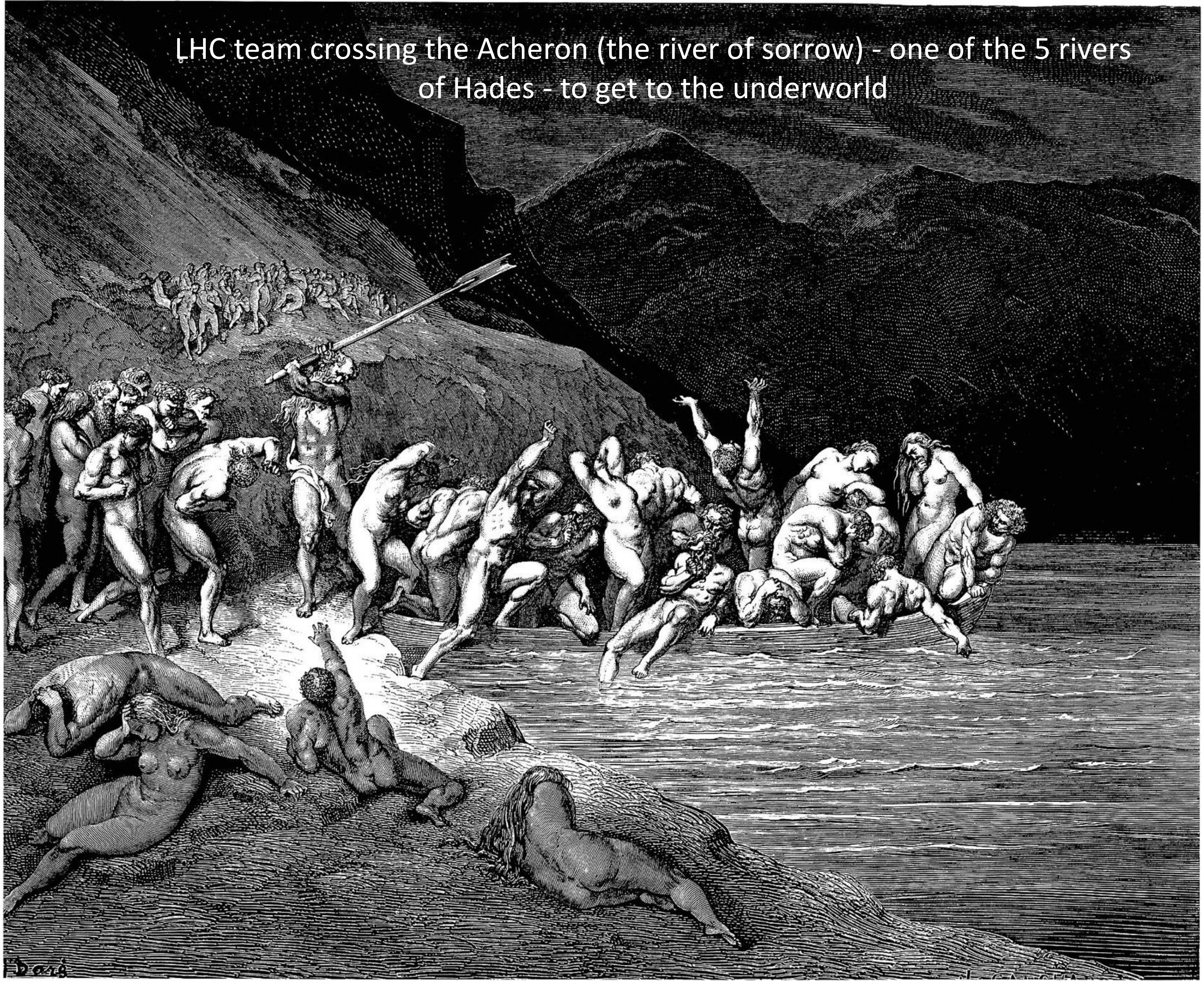


Possible hubris September 10, 2008

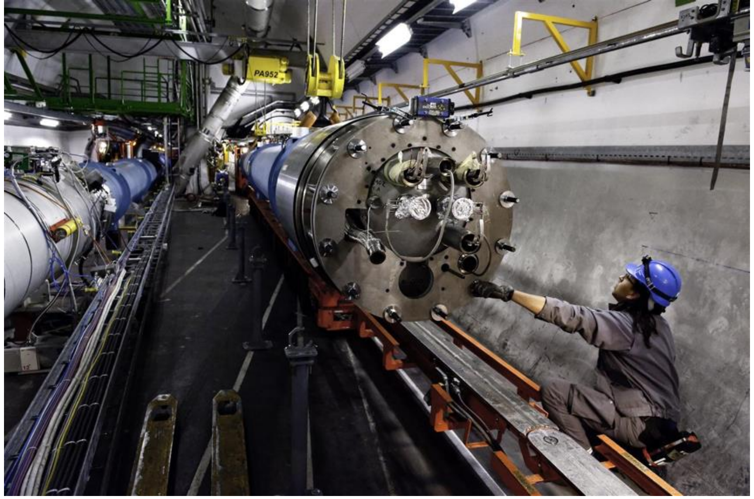


Nemesis September 19, 2008





LHC team crossing the Acheron (the river of sorrow) - one of the 5 rivers of Hades - to get to the underworld



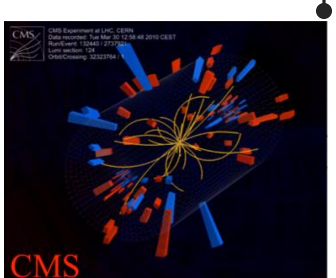
Trial/descent in the underworld I

November 29, 2009

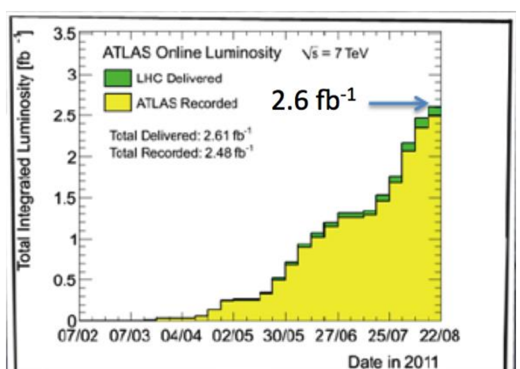
Resurrection and rebirth

2009 2010 2011 2012 2013

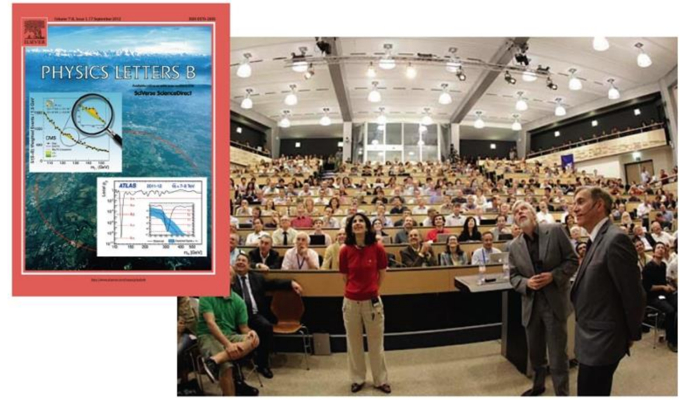
March 30, 2010
First collisions at 3.5 TeV



Ascension



Apotheosis and atonement



4 July, 2012

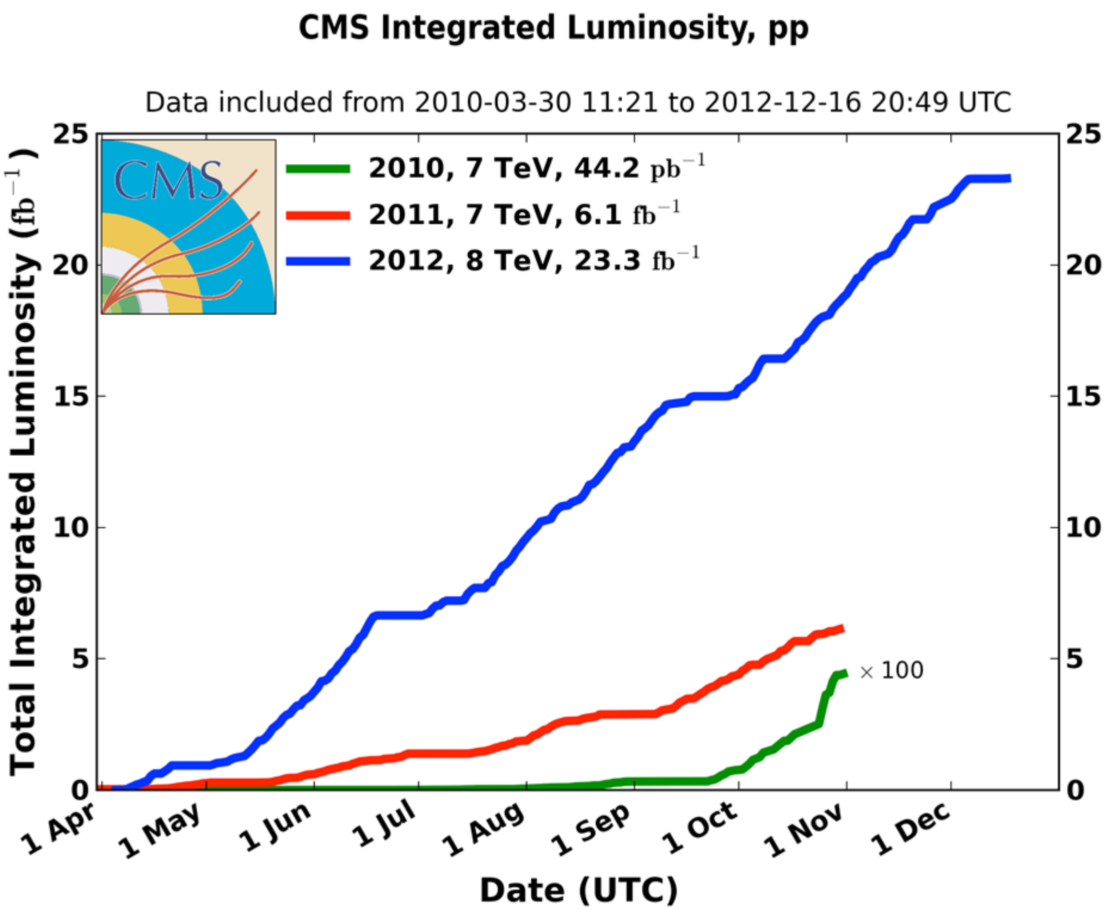
Heroic subplot

And let us not forget Fortuna

- Late
- Over budget
- Blew it up after 9 days
- Costly, lengthy repair
- Rival coming up fast on the outside
- Had to run at half energy
- And yet…


WE FOUND A NEW PARTICLE
WE FOUND A NEW PARTIC

Integrated luminosity 2010-2012



- 2010: **0.04 fb^{-1}**
  - 7 TeV CoM
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - 7 TeV CoM
  - Exploring the limits
- 2012: **23.3 fb^{-1}**
  - 8 TeV CoM
  - Production

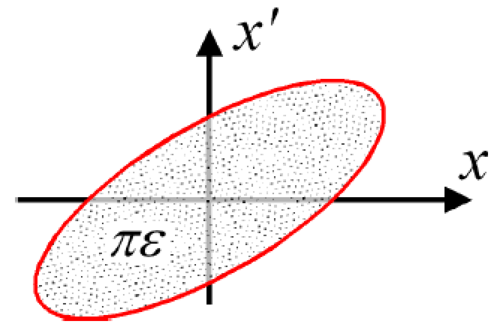
It was not all luck

Luminosity

$$L = \frac{N^2 k_b f}{4\pi\sigma_x^*\sigma_y^*}F = \frac{N^2 k_b f\gamma}{4\pi\varepsilon_n\beta^*}F$$

N	**Number of particles per bunch**
k_b	**Number of bunches**
f	Revolution frequency
σ*	**Beam size at interaction point**
F	Reduction factor due to crossing angle
ε	Emittance
ε_n	**Normalized emittance**
β*	**Beta function at IP**

Round beams, beam 1 = beam 2

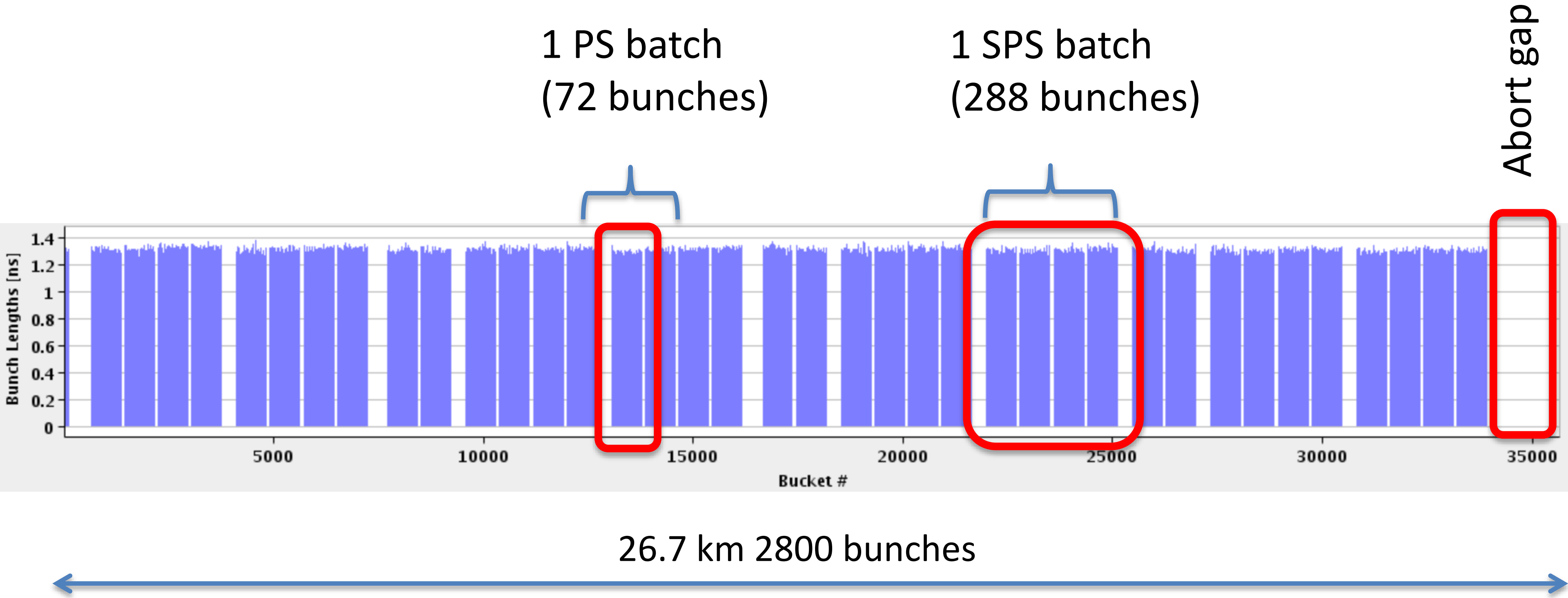


$$\sigma^* = \sqrt{\beta^*\varepsilon}$$

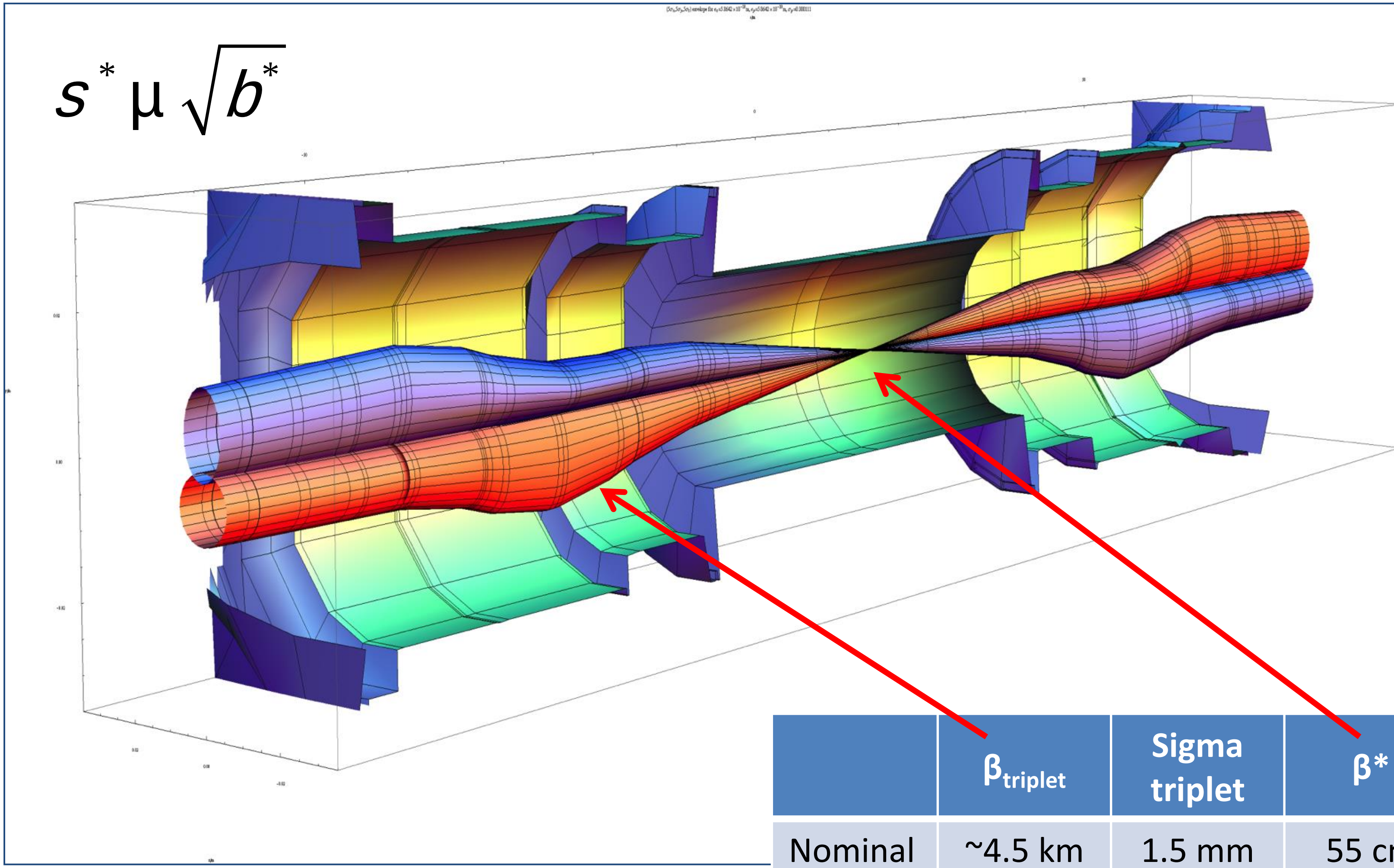
$$\varepsilon_n = \beta\gamma\varepsilon$$

Nominal LHC bunch structure

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



Squeeze in ATLAS



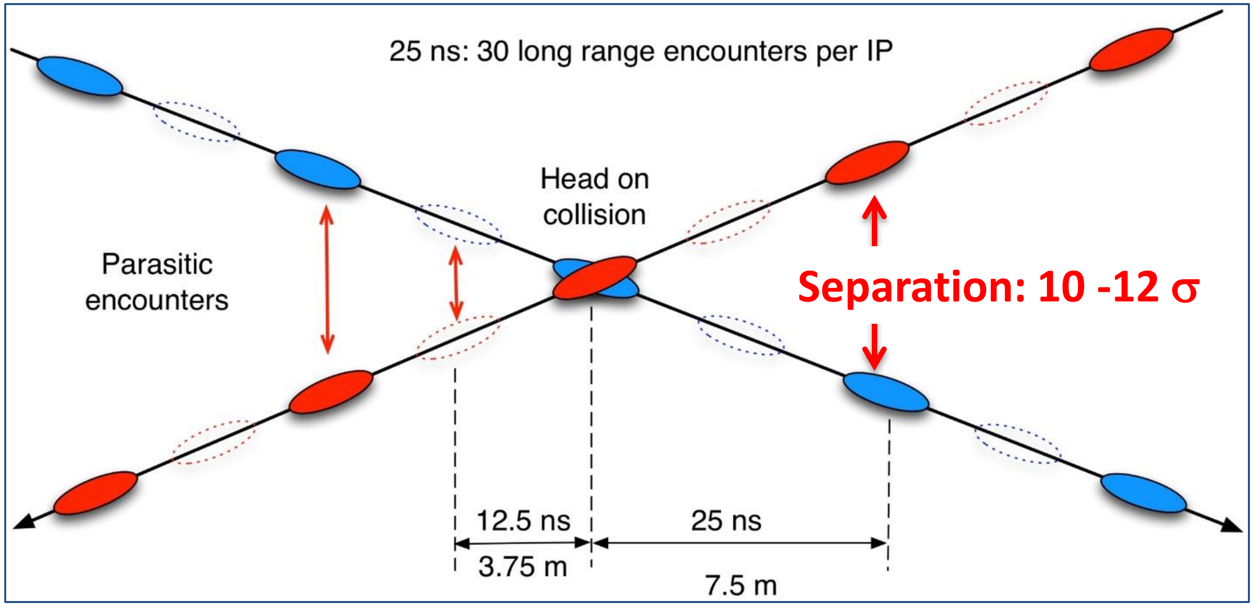
$$s^* \mu \sqrt{b^*}$$

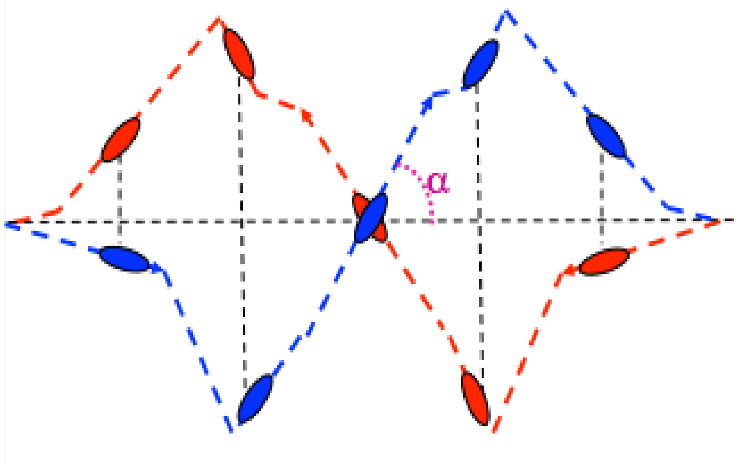
	$\beta_{triplet}$	Sigma triplet	β*	Sigma*
Nominal	~4.5 km	1.5 mm	55 cm	17 um
HL-LHC	~20 km	2.6 mm	15 cm	7 um

Image courtesy John Jowett

Crossing angle

work with a crossing angle to avoid parasitic collisions.





geometric luminosity reduction factor:

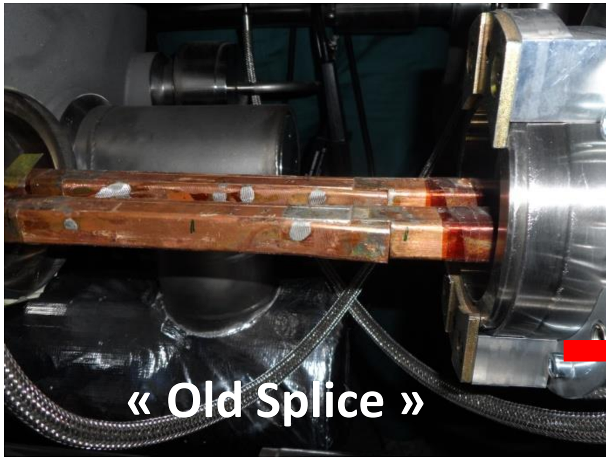
$$F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

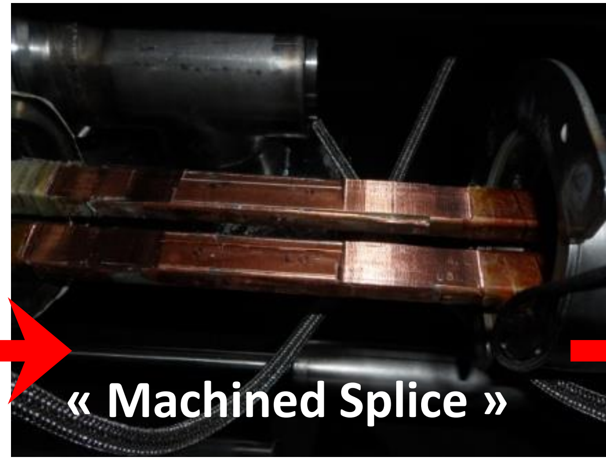
Peak performance Run 1

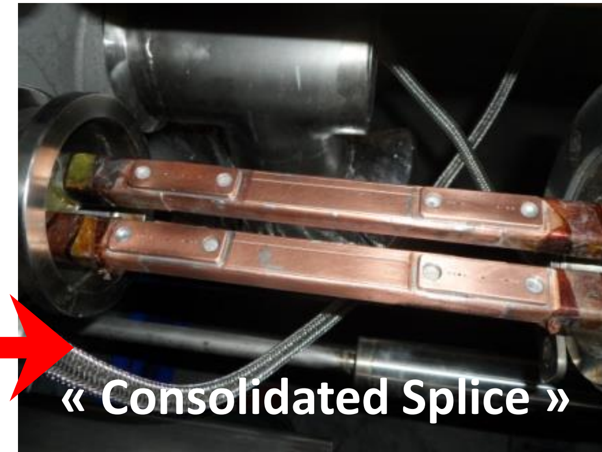
	2010	2011	2012	Nominal
Bunch spacing [ns]	150	50	50	25
No. of bunches	368	1380	1380	2808
beta* [m] ATLAS and CMS	3.5	1.0	0.6	0.55
Max **bunch intensity** [protons/bunch]	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
Normalized emittance [micron]	~2.0	~2.4	~2.5	3.75
Peak luminosity [$cm^{-2}s^{-1}$]	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}	1.0×10^{34}

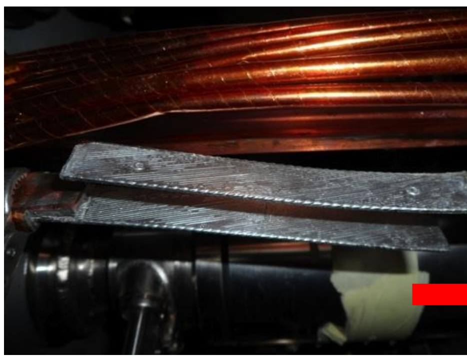
End of Run 1 – back into the underworld

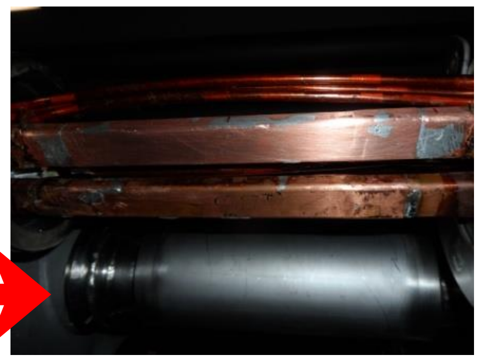

25R7 / 27R7
metabo

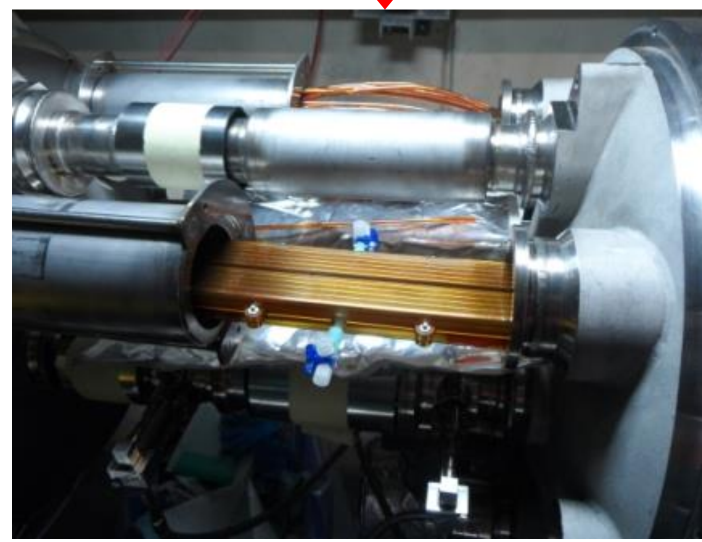

« Old Splice »


« Machined Splice »


« Consolidated Splice »


« 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…

Hopefully doing an Achilles on the LHC

Rubens

Achilles being dipped into the Styx to render him invincible.


Run 2

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

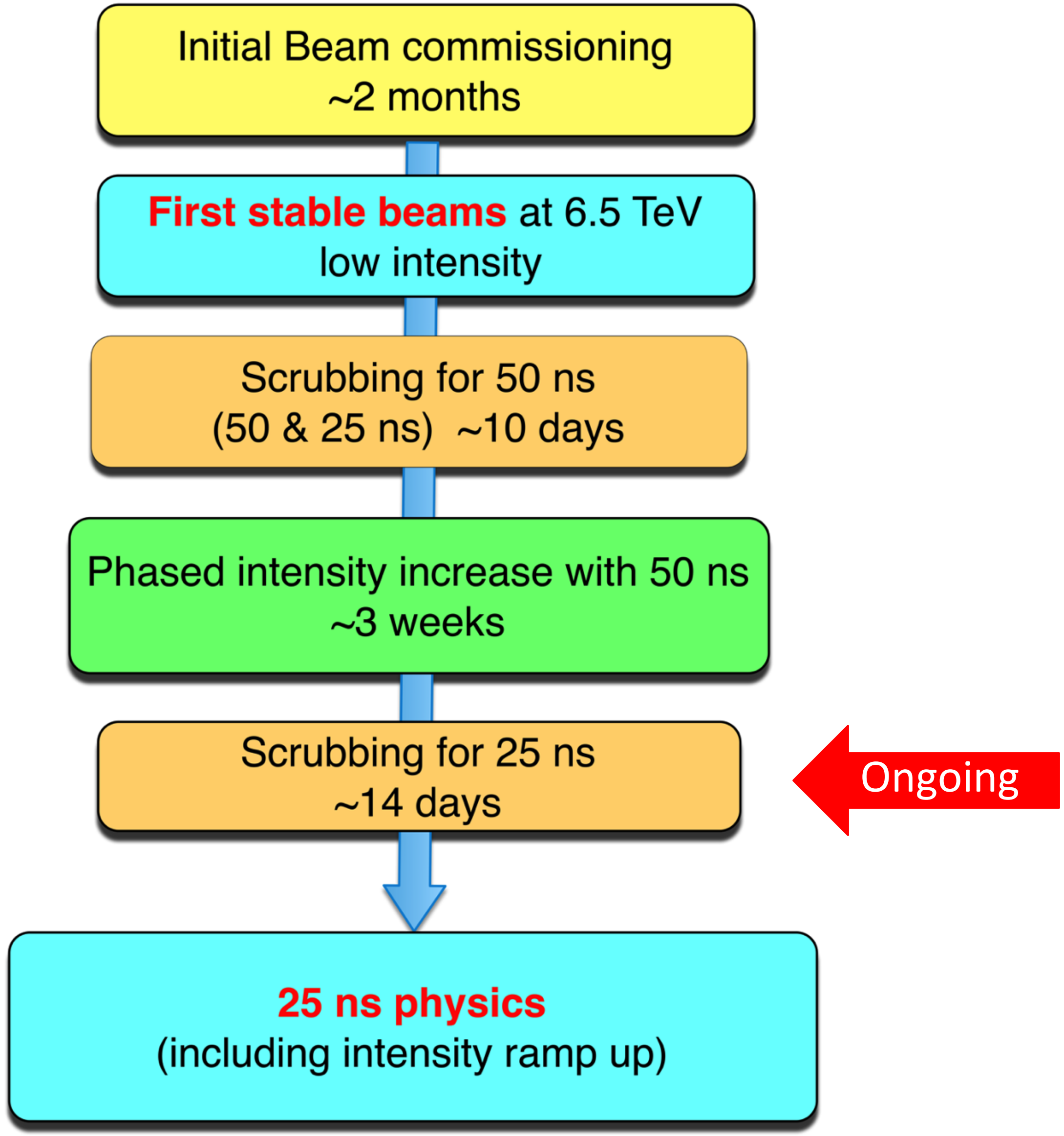
2015: beta* in IPs 1 and 5

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

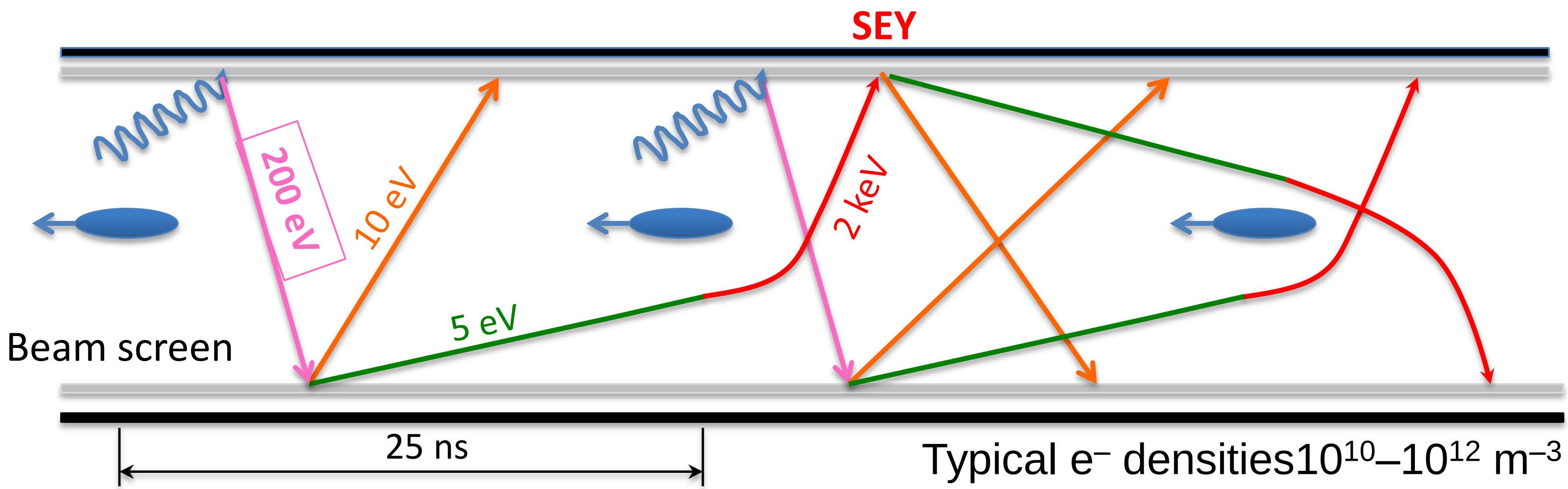
- Ultimate in 2015 and Run 2: **β*= 40 cm**
  - Possible reduction later in the year

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

2015 commissioning strategy



25 ns & electron cloud



Possible consequences:

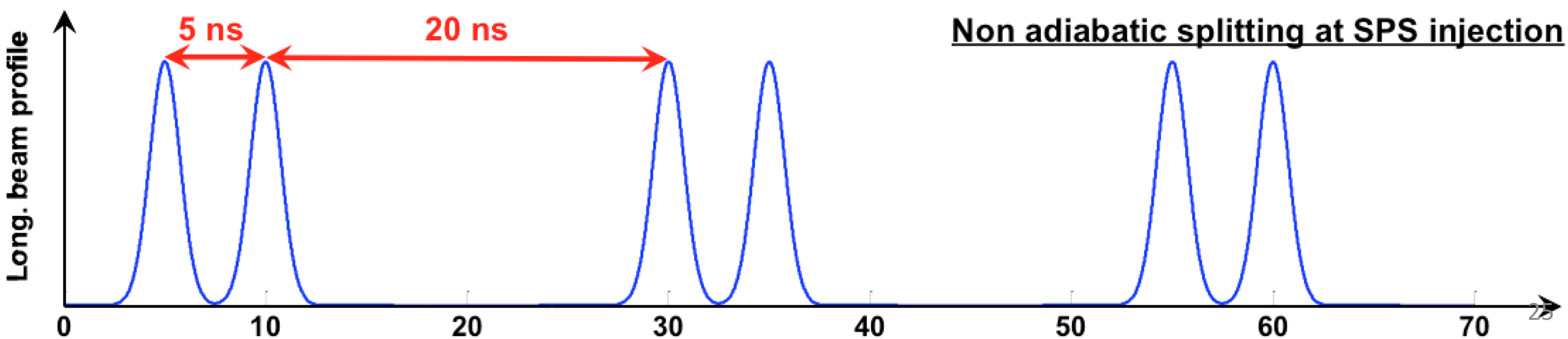
- instabilities, emittance growth, desorption – bad vacuum
- excessive energy deposition in the cold sectors

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

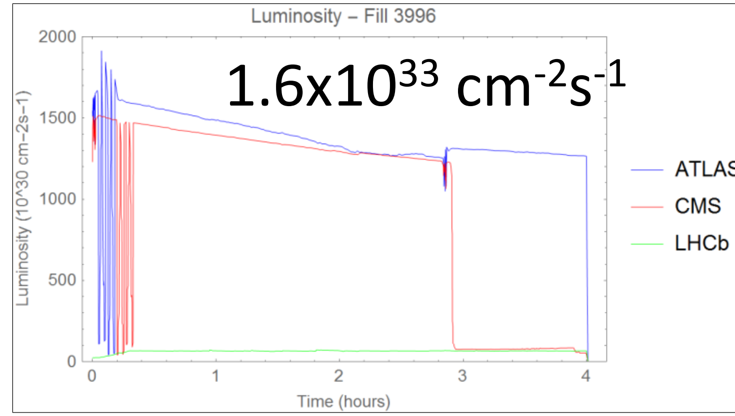
Scrubbing 2015

- More scrubbing than in 2012 is mandatory
- Doublet scrubbing beam looks attractive
- A two stage scrubbing strategy is foreseen:
  - 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



5th April first beam

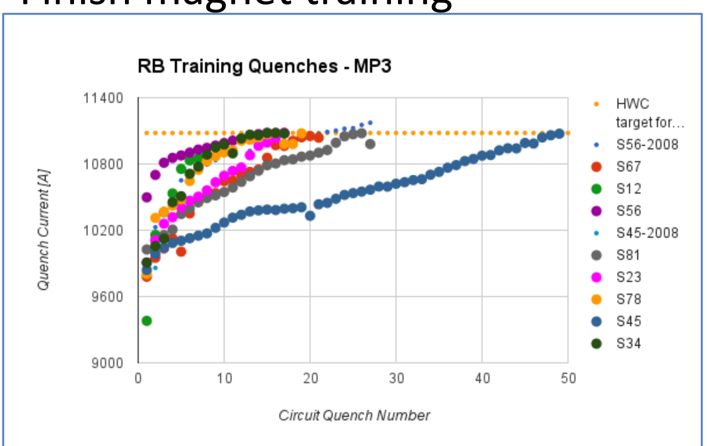
10th April: 6.5 TeV for the first time



July 14th: 476 bunches

APRIL MAY JUNE JULY

Finish magnet training

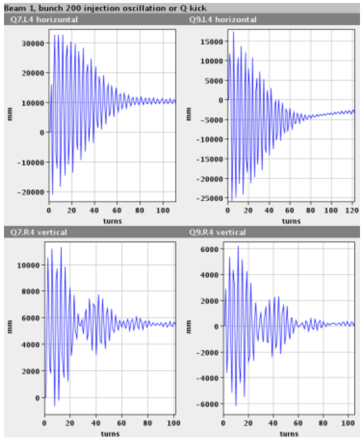


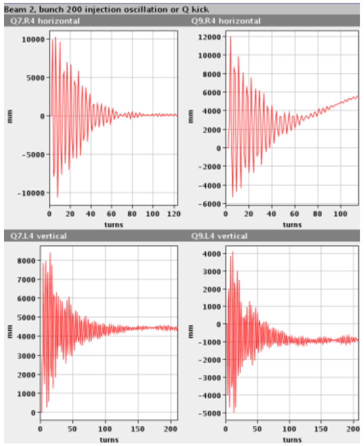
3rd June: First Stable Beams

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!



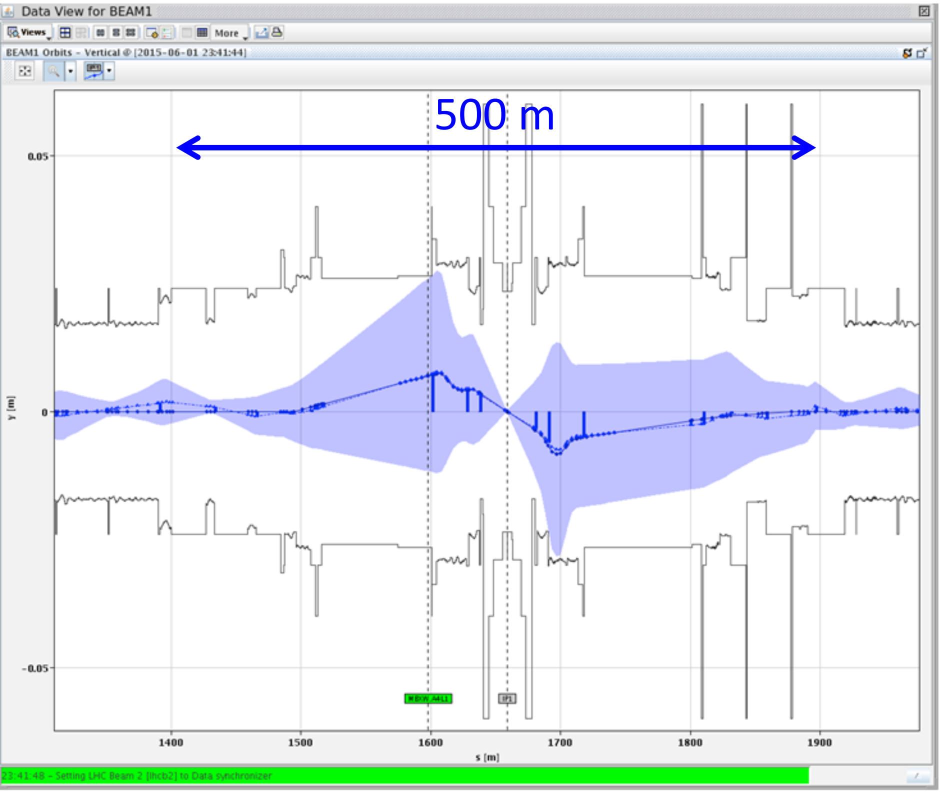


Initial commissioning 2/2

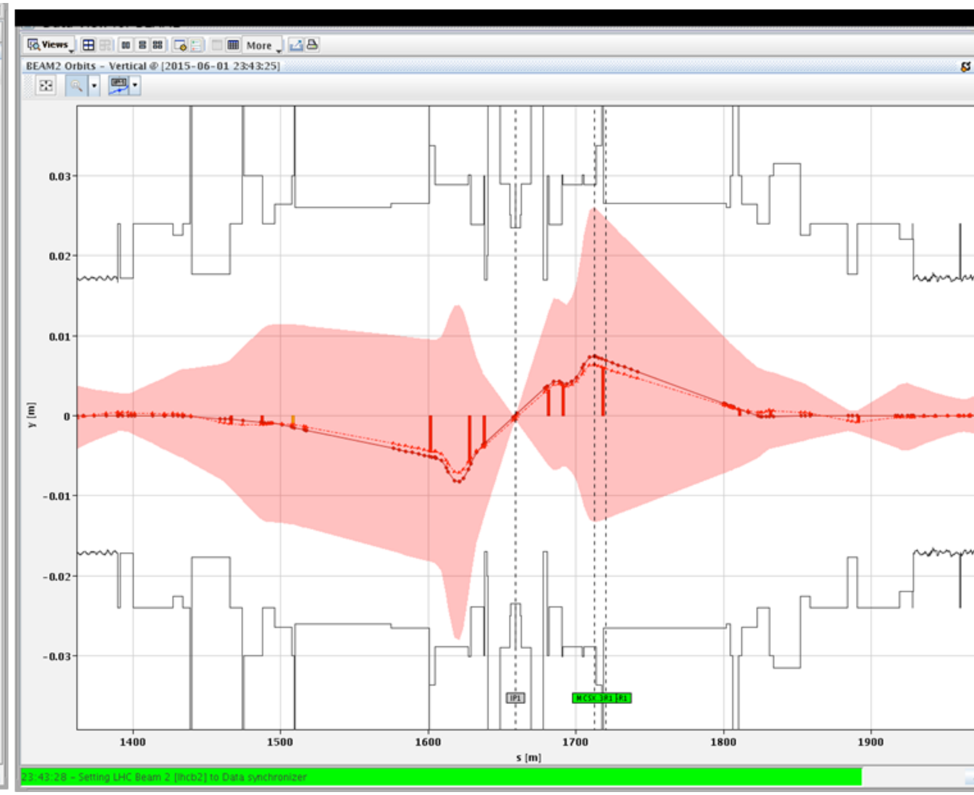
- Magnetically reproducible as ever
- Optically good, corrected to excellent
- Aperture is fine and compatible with the collimation hierarchy.
- Magnets behaving well at 6.5 TeV
  - 11 additional training quenches
- Operationally things well under control
  - Injection, ramp, squeeze etc.

Aperture

Carefully checked with beam



IP1 – B1

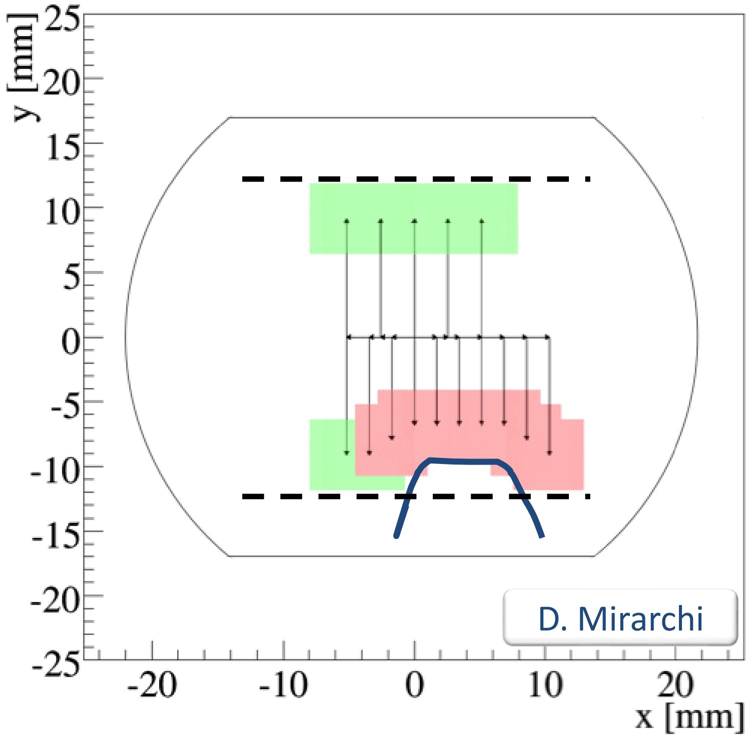


IP1 – B2

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!



Present challenges

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			Trip of **RCS.A78B2**
4015	Ramp 6.2 TeV	476			Trip of **RCS.A78B2**
4018	Flat-top	476			**UFO** 12L6
4019	**31m**	476	1.5	2.3	**UFO** 15L2

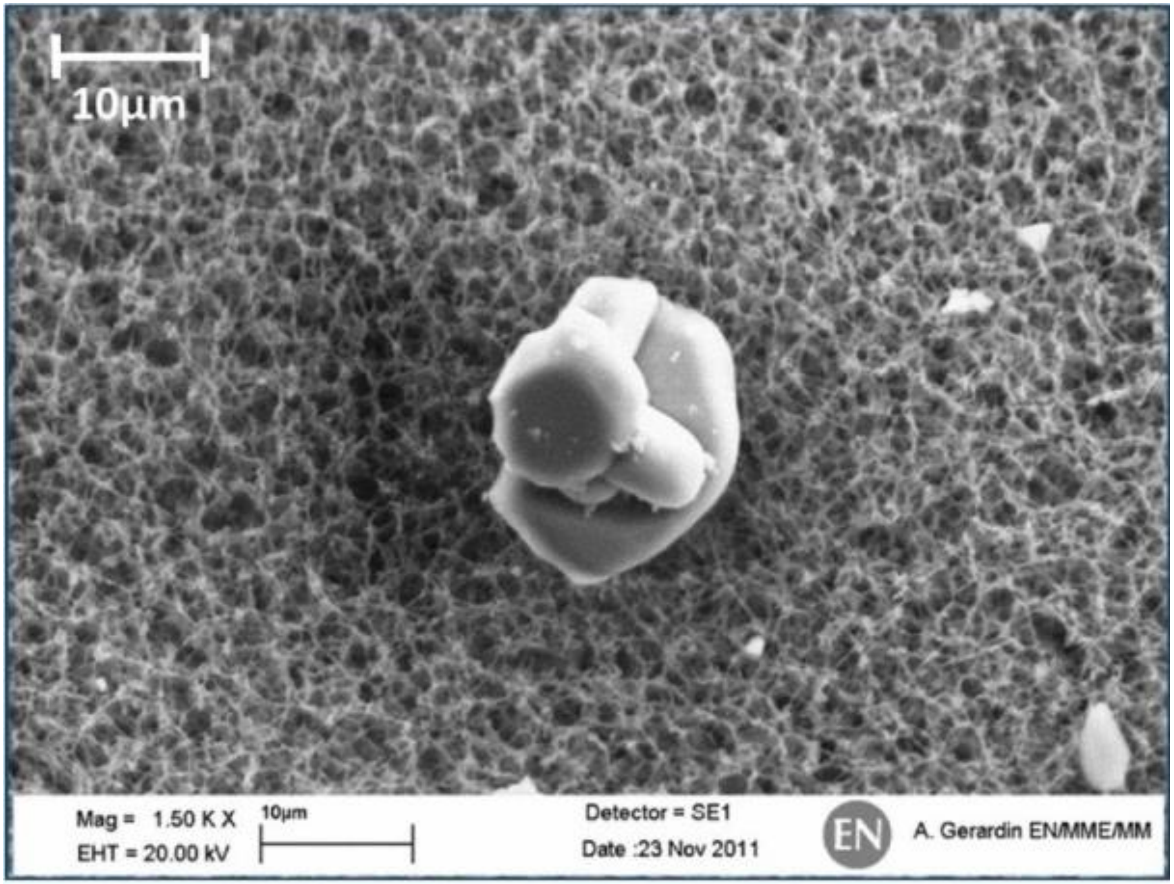
Main issues

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

- 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 fault(s)
  - RCS.A78B2 - 154 sextupole correctors on main dipoles
  - will operate without them

UFOs

A nice picture
of some dust



T. Baer CERN-THESIS-2013-233

Accepted interpretation of a UFO event:

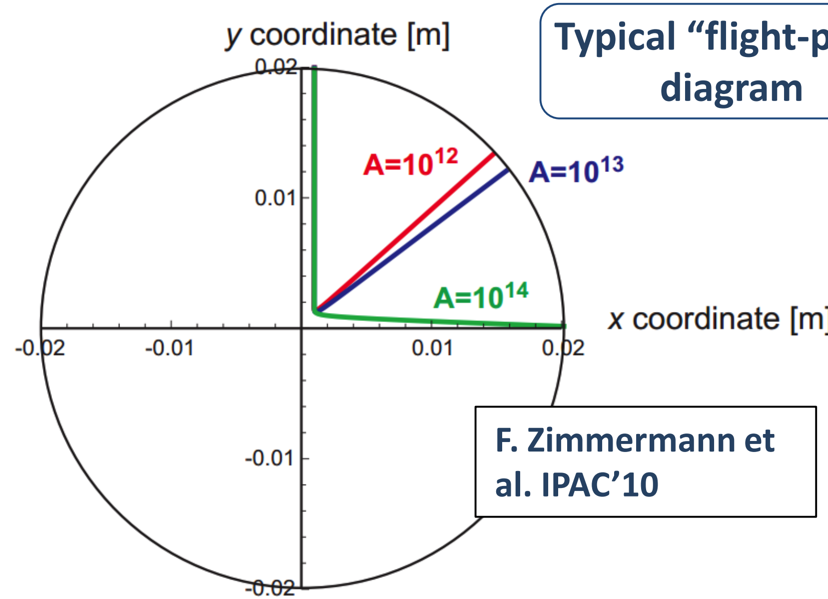
1. A **macroparticle (dust) falls** from the top of the beam screen

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

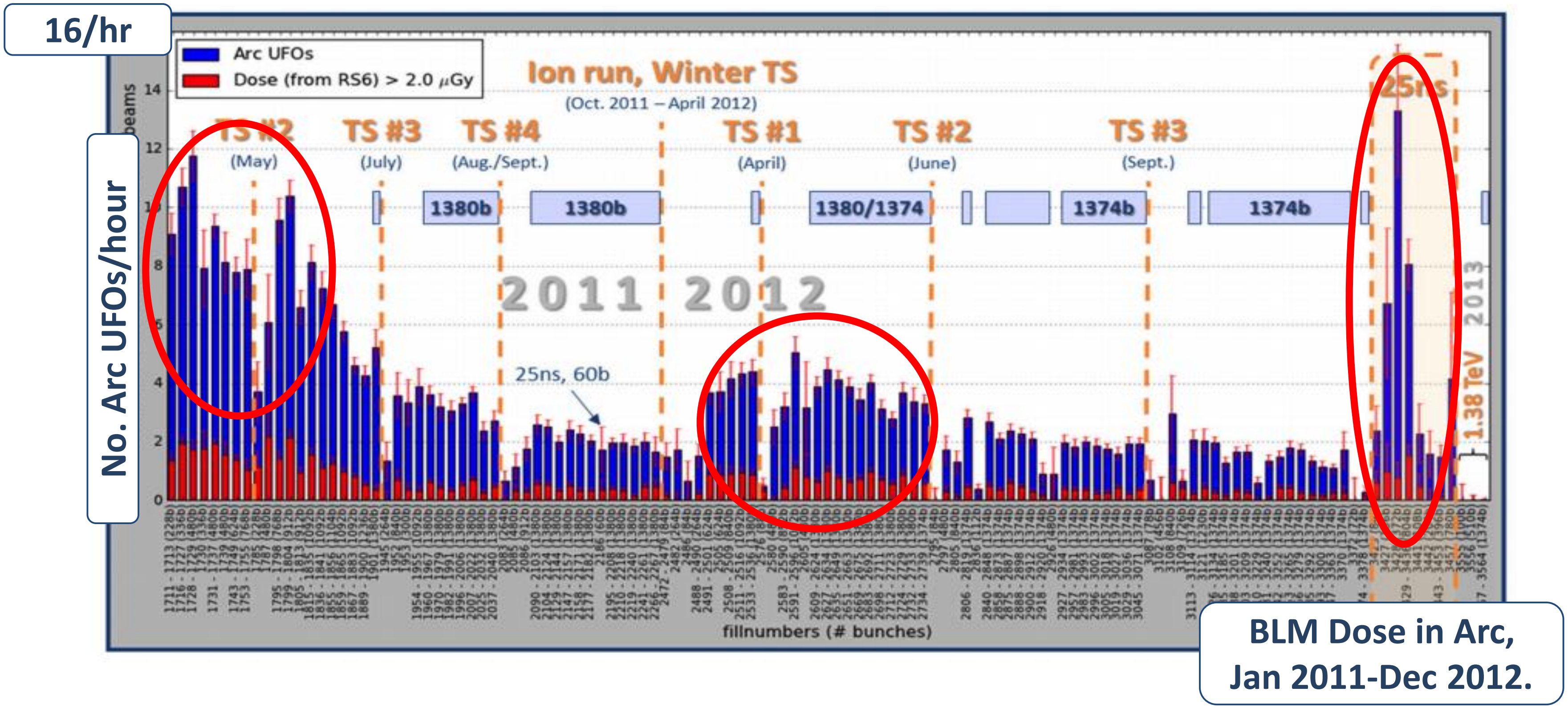


F. Zimmermann et al. IPAC'10

UFO simulation for a given mass, A.

UFOs - strategy

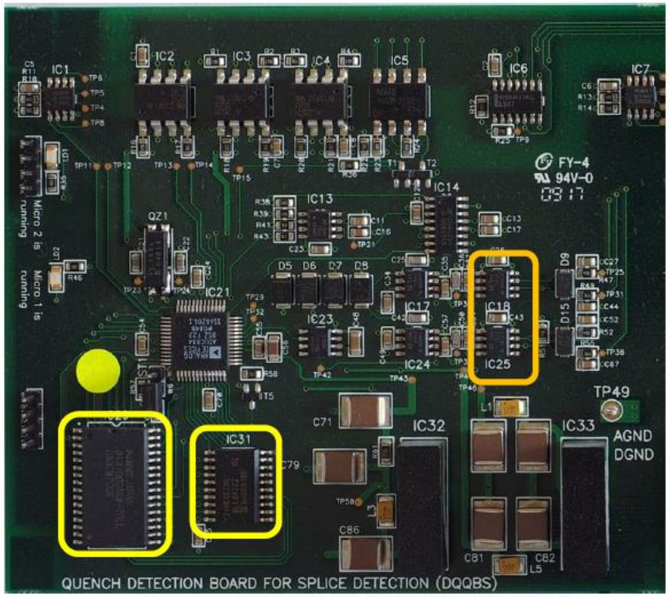
- **No. of UFO events** have been seen to **exceed 10+/hour** with notable increases after long shutdowns and or with a decrease in bunch spacing



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

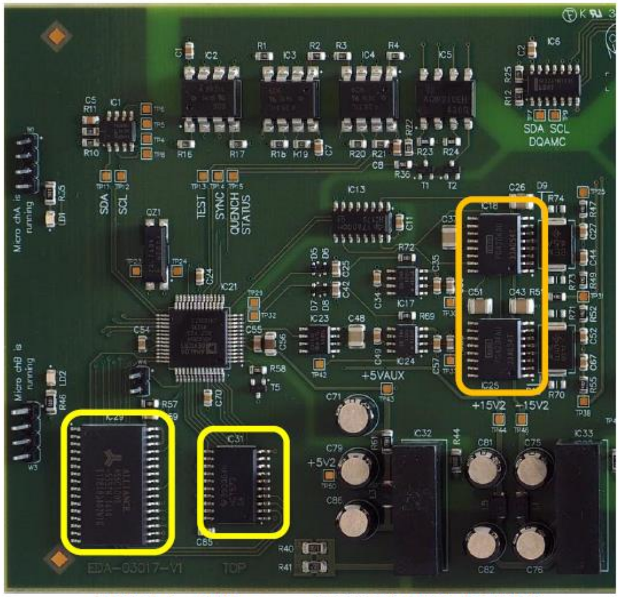
Origin of the SEU problem – recall
Relevant differences between mDQQBS and DQQBS

DQQBS



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

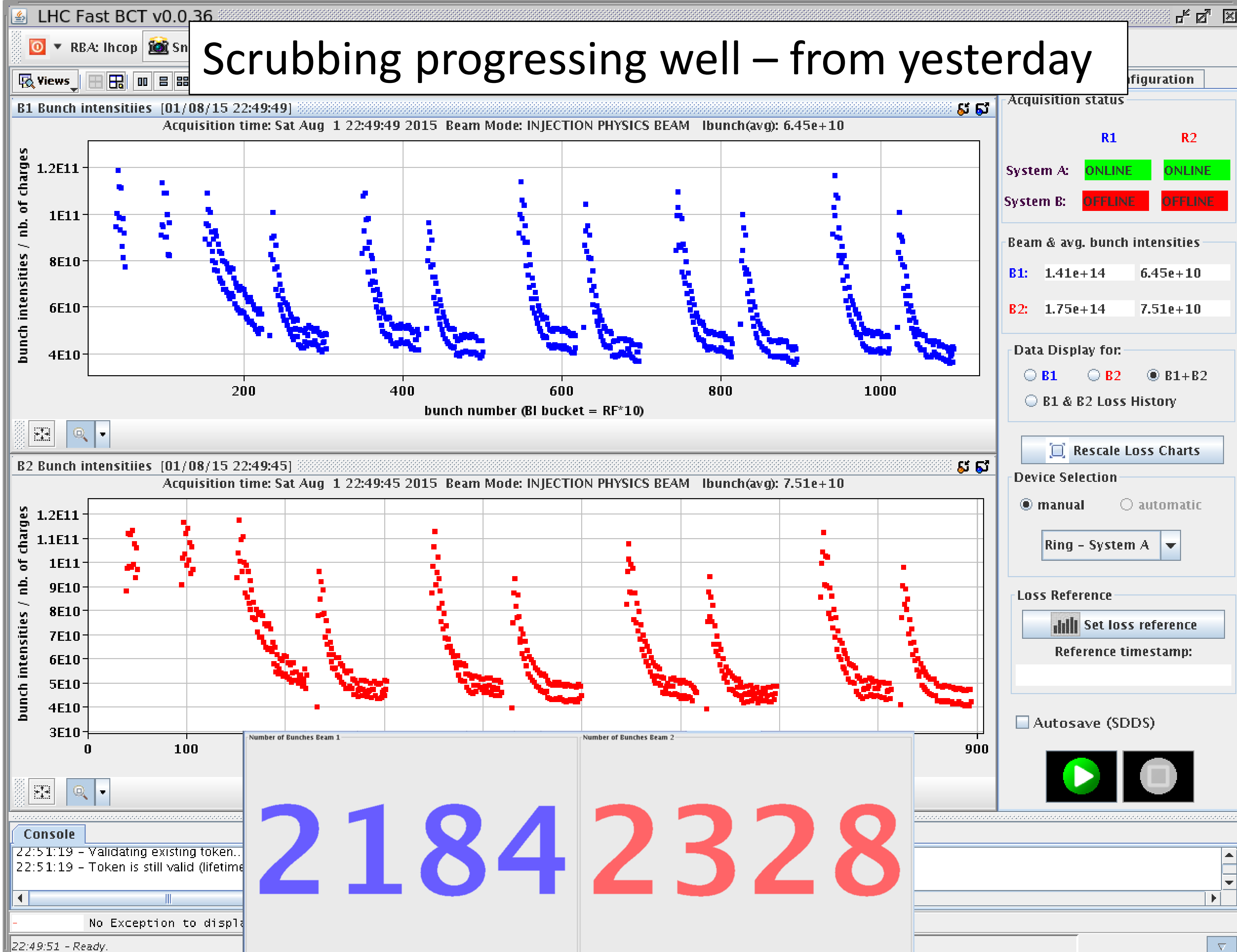
mDQQBSv2/v3



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

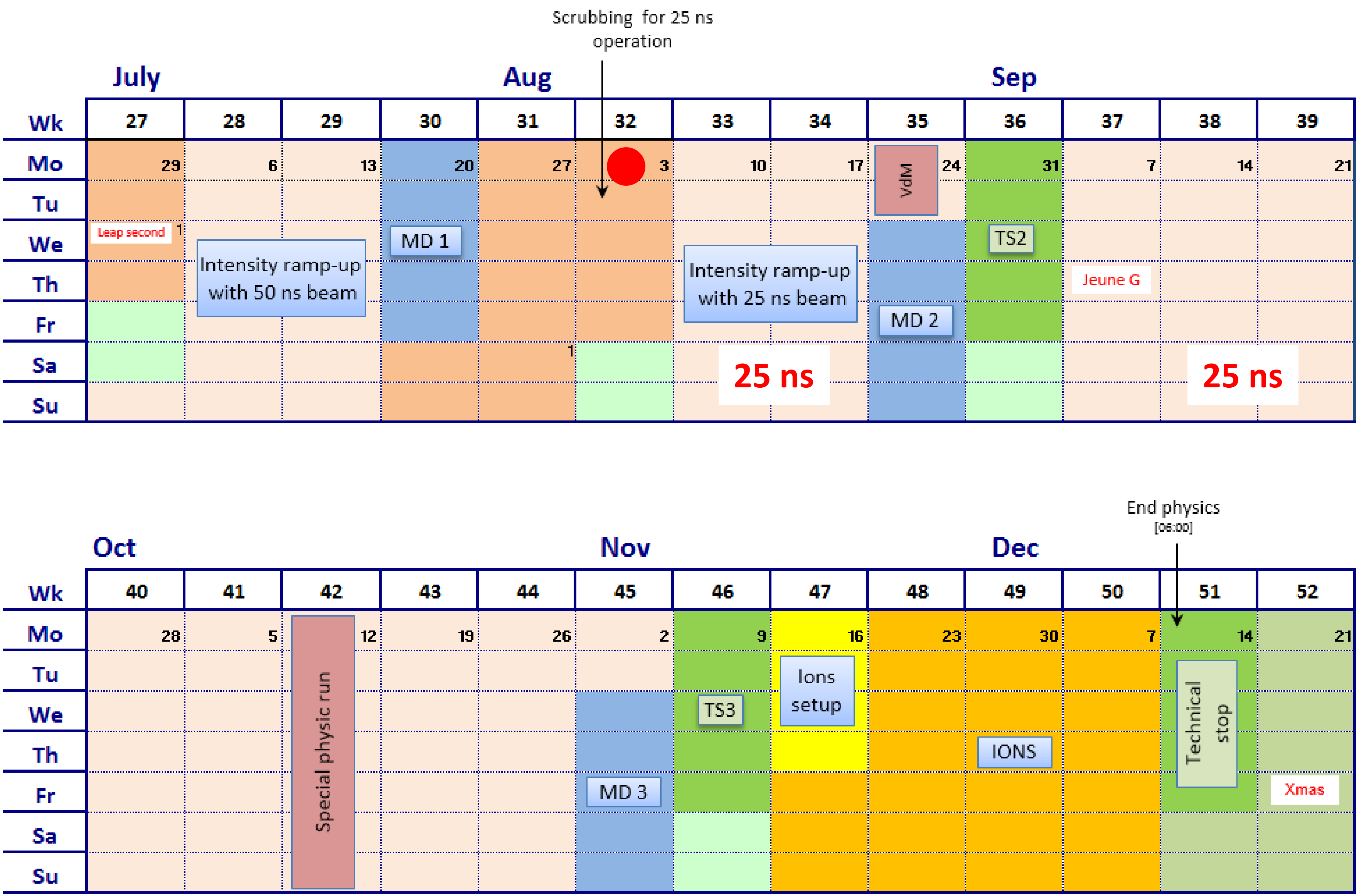
- 1268 modified boards used for special tests (CSCM) during circuit re-commissioning.
- **Should have come out**
- To be replaced during upcoming technical stop

Scrubbing progressing well – from yesterday




So after we’ve got back in the boat…

Q3/Q4 2015 - latest



2015: ATLAS and CMS performance

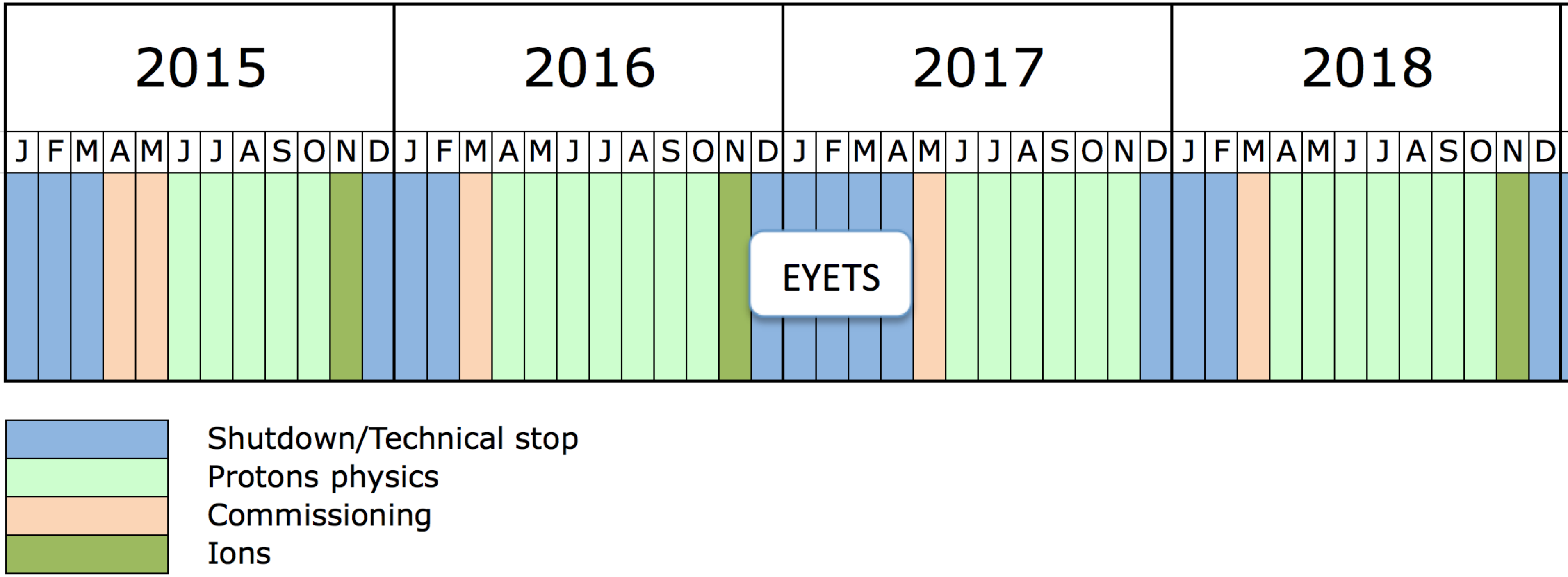
- Beta* = 80 cm, possible reduction later in year (count 4 days + ramp-up)
- Nominal bunch population
- Reasonable emittance into collisions
- Injection limit for 25 ns: max colliding bunches 2376

- **Moderate availability plus need for intensity ramp-up (UFOs!)**

	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	2376	80	1.2e11	3.1	7.0e33	33	~4 fb^{-1}	21
2015.2	2376	40	1.2e11	3.1	1.2e34	28	~4 fb^{-1}	35

Official GPD luminosity target for the year was 10 fb^{-1}
Now on the challenging side – let’s say 5 to 8 fb^{-1}

Run 2



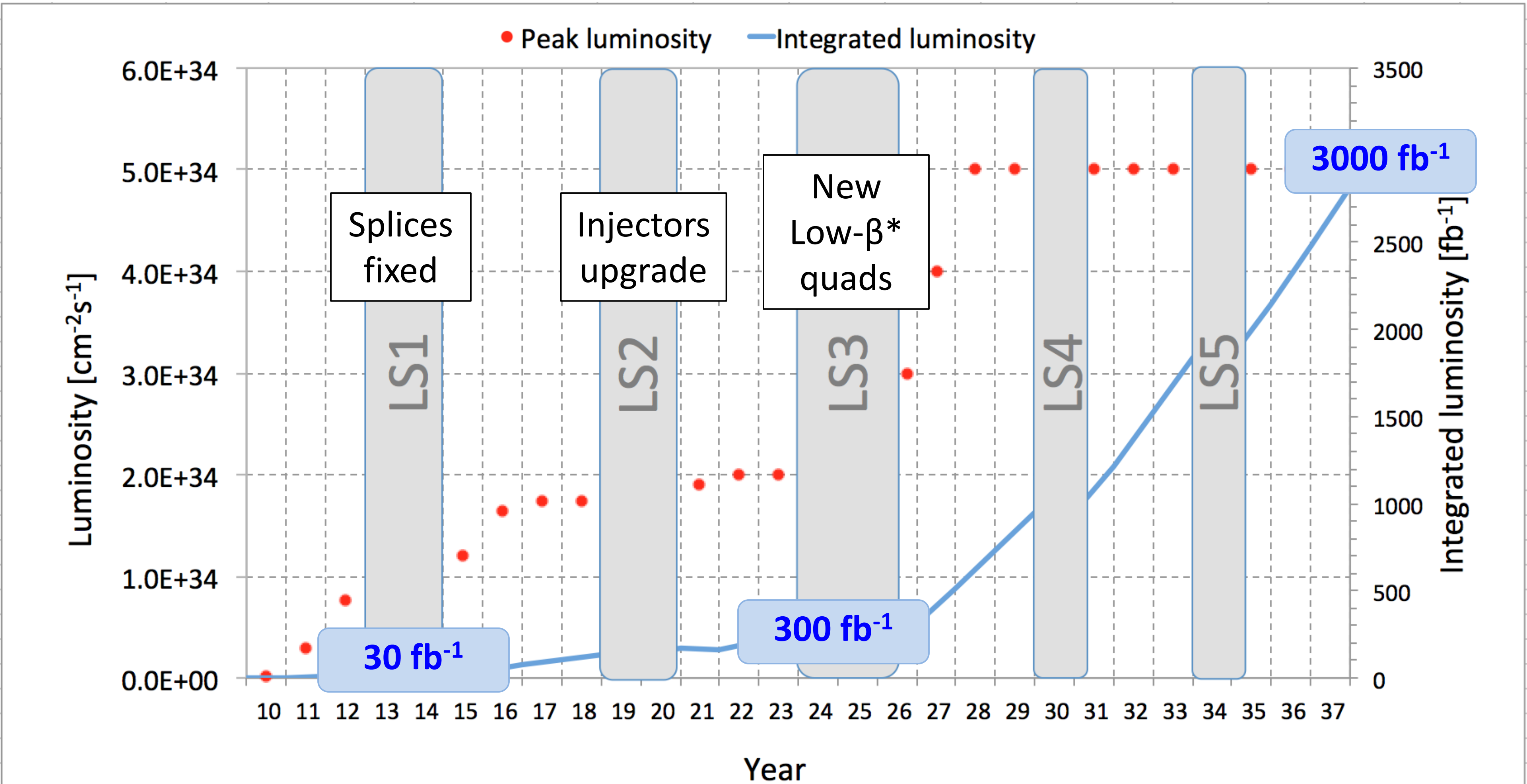
- EYETS – Extended Year End Technical Stop – 19 weeks – CMS pixel upgrade
- Start LS2 at the end of 2018

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	65	5 - 8
2016	1.5	160	35
2017	1.7	160	45
2018	1.7	160	45

And beyond



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

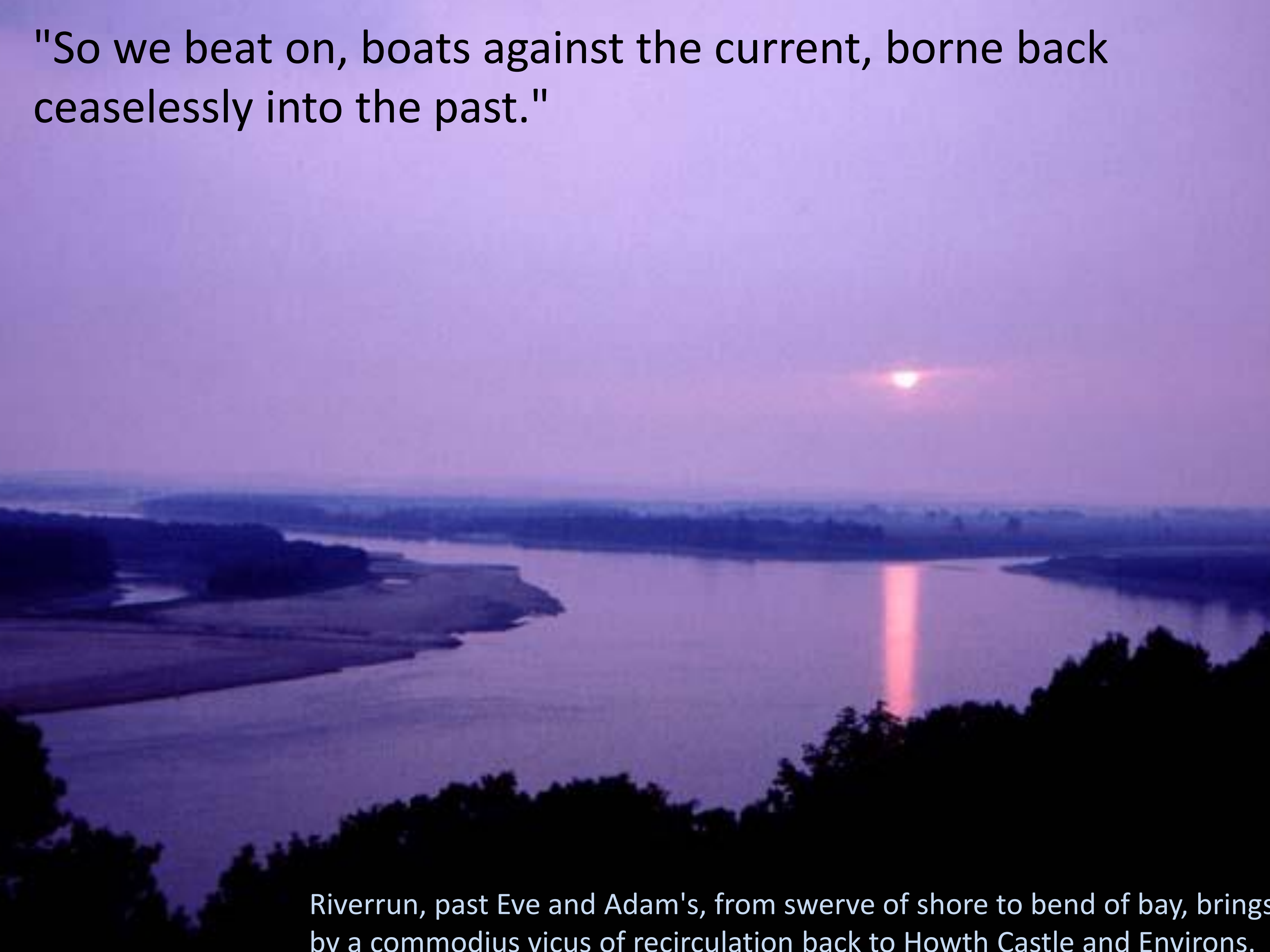
FG EPS 15

Conclusions

- 6.5 TeV/fundamentals looks good
- Commissioning and scrubbing going well
- Still picking up some hang-over from LS1
  - QPS
  - Earth faults (recent loss of RCS.A78B2)
  - Injection protection devices
  - ULO
- Electron cloud and UFOs could slow progress

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

"So we beat on, boats against the current, borne back ceaselessly into the past."



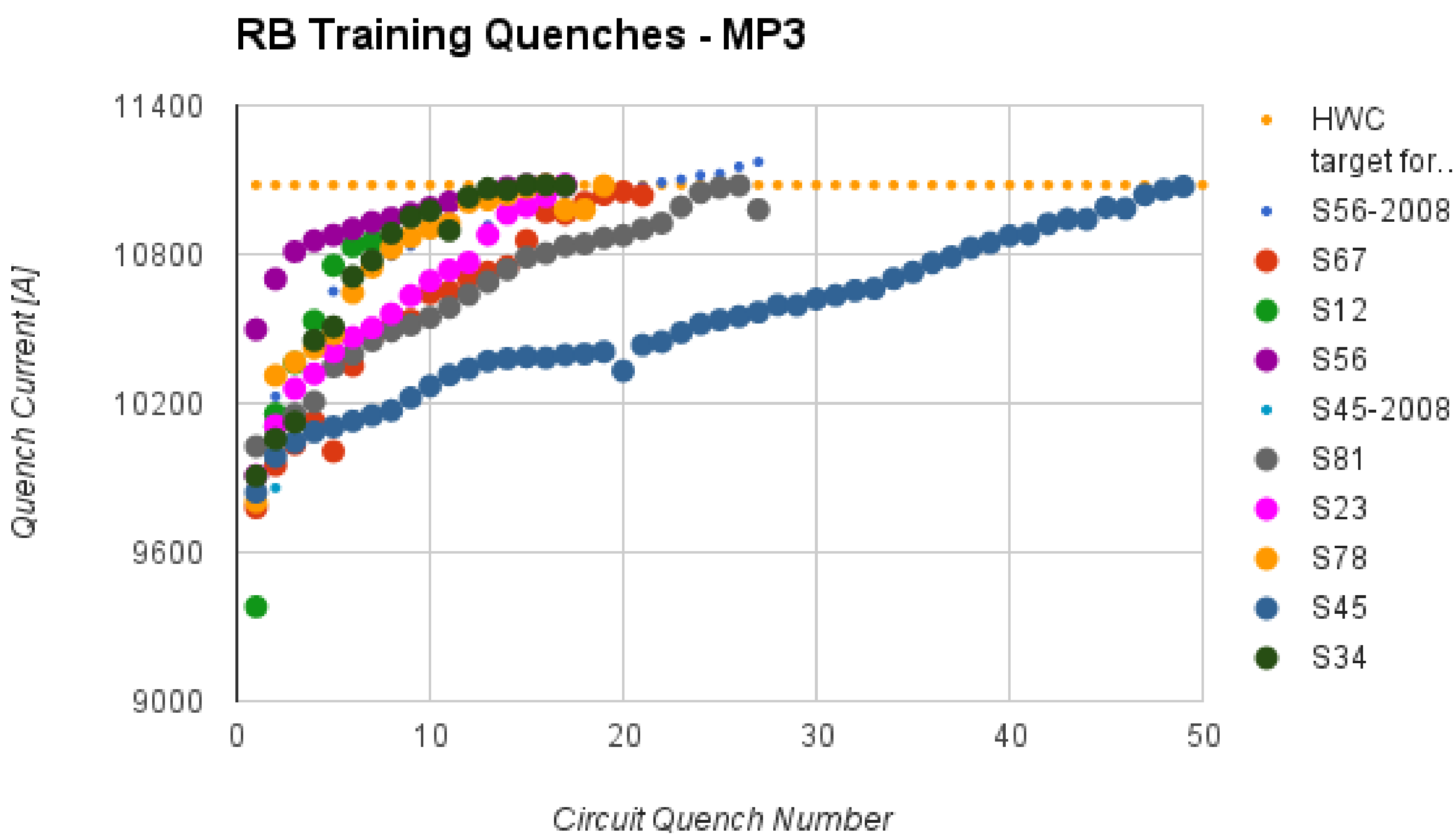
Riverrun, past Eve and Adam's, from swerve of shore to bend of bay, brings by a commodius vicus of recirculation back to Howth Castle and Environs.

Could, of course, just be a bunch of animals having fun!

RESERVE

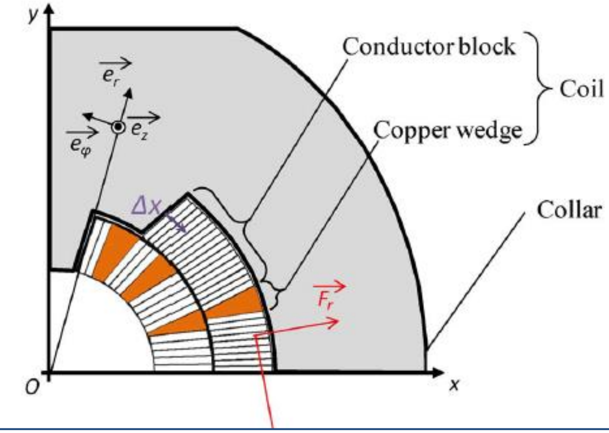
Dipole training 1/2

- 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.

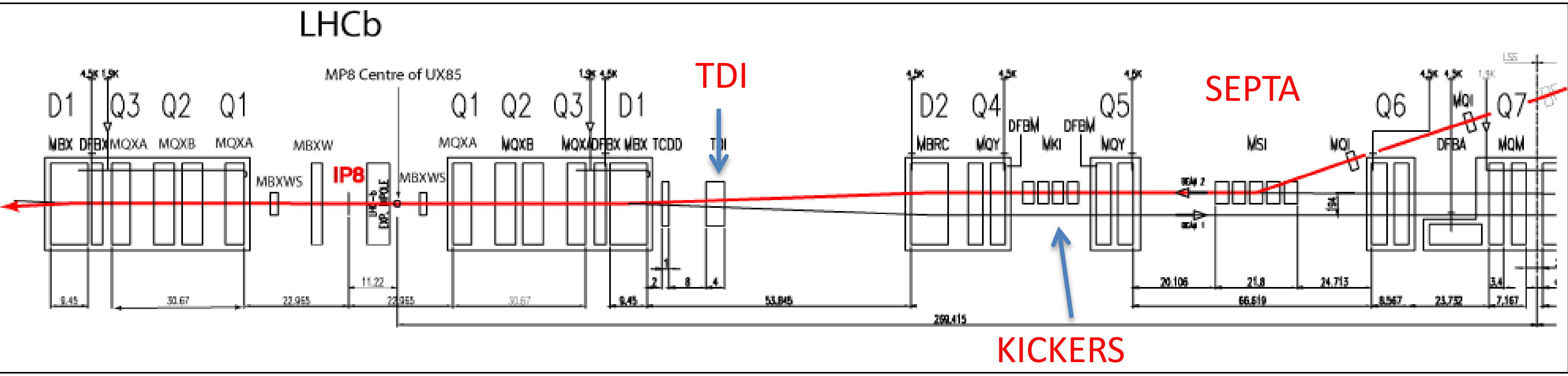
#MQ: Number of magnet training quenches in a sector.

#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

TDI limitations

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



- Main blocks: h-BN
- However during bake-out tests…

TDI Limits

- TDI hBN block cannot withstand temperatures higher than 450 °C (B_2O_3 reactant melting temperature) ➔ limit the maximum number of bunches which can hit the TDI (maximum allowed temperature = 400 °C)

Beam type	Bunch/Doublet intensity	Emittance (um rad)	Bunch/Doublet spacing (nsec)	Bunches/Doublets per batch	1 batch	2 batches	3 batches	4 batches
Standard 25 nsec	1.20E+11	2.6	25	72	*72 (1.8 usec)* 206 deg C	*144 (3.8 usec)* 352 deg C	*216 (5.8 usec)* 483 deg C	*288 (7.8 usec)* 606 deg C
BCMS	1.30E+11	1.3	25	48	*48 (1.2 usec)* 239 deg C	*96 (2.6 usec)* 408 deg C	*144 (4.0 usec)* 560 deg C	
50 nsec	1.20E+11	1.5	50	36	*36 (1.8 usec)* 160 deg C	*72 (3.8 usec)* 277 deg C	*108 (5.8 usec)* 378 deg C	*144 (7.8 usec)* 473 deg C
Doublet(*)	1.60E+11	4	25	72	*72 (1.8 usec)* 212 deg C	*144 (3.8 usec)* 363 deg C		

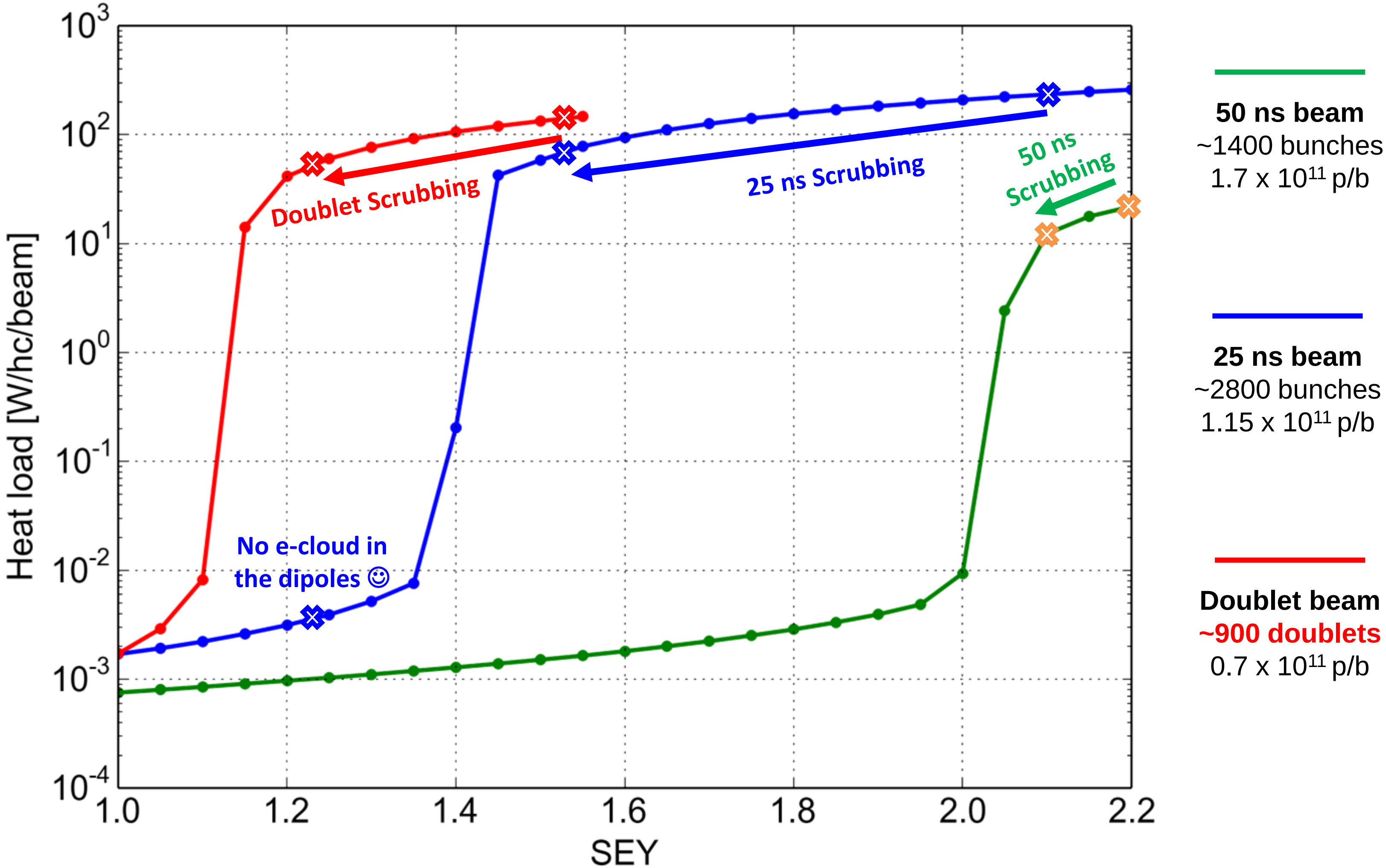
J. Uythoven
A. Lechner

New limits of ~2 PS batches per injection from the injection protection absorbers will reduce the maximum number of bunches to around 2400

Scrubbing: Goal and strategy

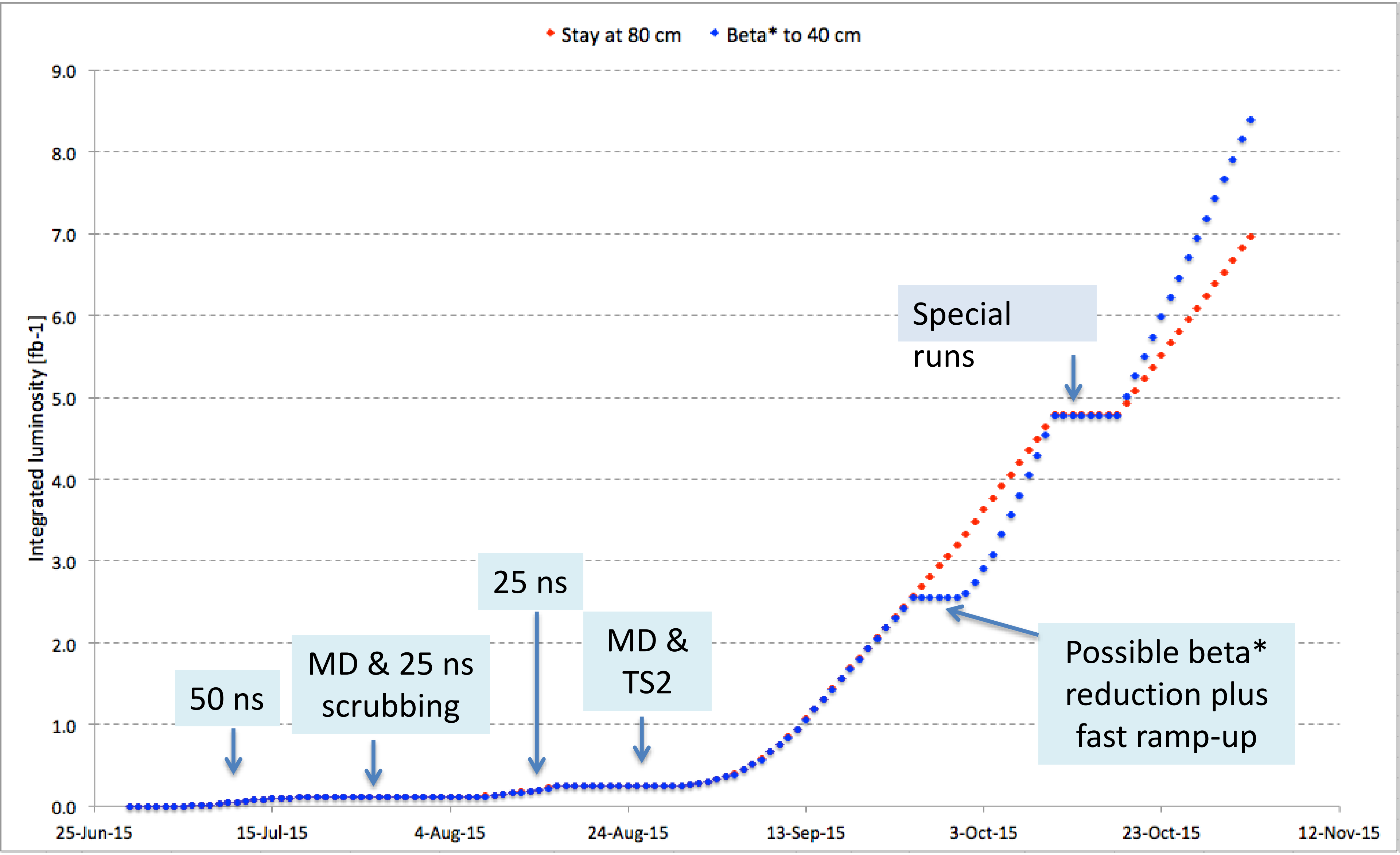
Goal: accumulate e⁻ dose on the beam chambers to mitigate e-cloud effects with 50 ns and 25 ns beams

Strategy: gradually increase the e⁻ flux (50 ns → 25 ns → doublets) while keeping under control vacuum, heat loads and beam degradation



Giovanni Iadarola and Giovanni Rumolo

Day by day projection



Including intensity ramp-ups and steadily increasing physics efficiency