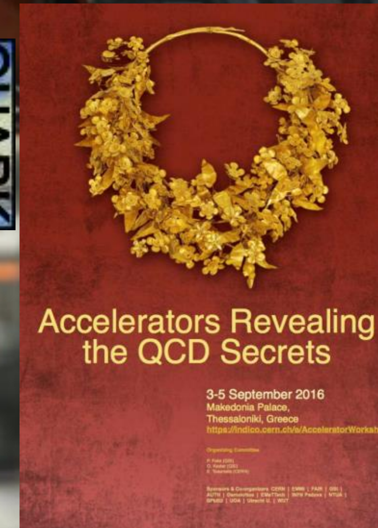
CERN

LHC
Status and perspectives

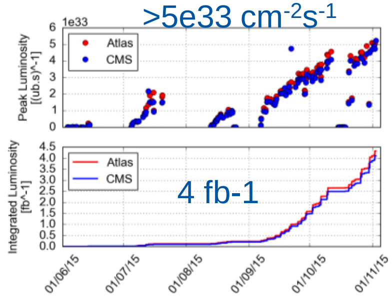


Mirko Pojer
Beams Department
Operation Group

With contributions from:
S. Danzeca, M. Hostettler, G. Iadarola, A. Lechner, J. Wenninger and many others

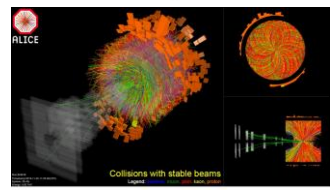
LHC RunII timeline

April '13 to Sep. '14



5th April

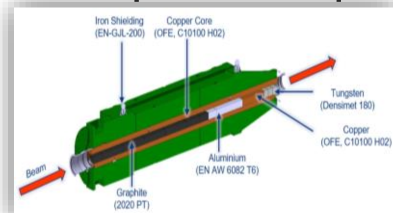
3rd June – First SB



...FINALLY, THE HIGHEST ENERGY
Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

IONS at the end

25th April-SPS dump



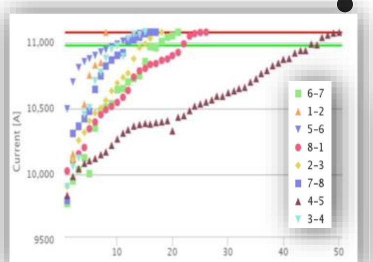
20th May-PS rot.

27th April – POPS down

Beam back

$\mathcal{L}$ >10^{34}cm^{-2}s^{-1}

2013-2014	Q3/2014-Apr2015	2015	2016

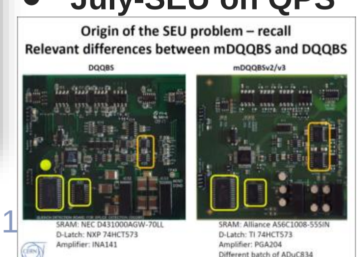


Dipole training campaign (6.5 TeV)

10th Apr.-Beam@6.5TeV

28th Oct.-record N_b

July-SEU on QPS



Physics restarts on Apr 23

14th April-LHC dump

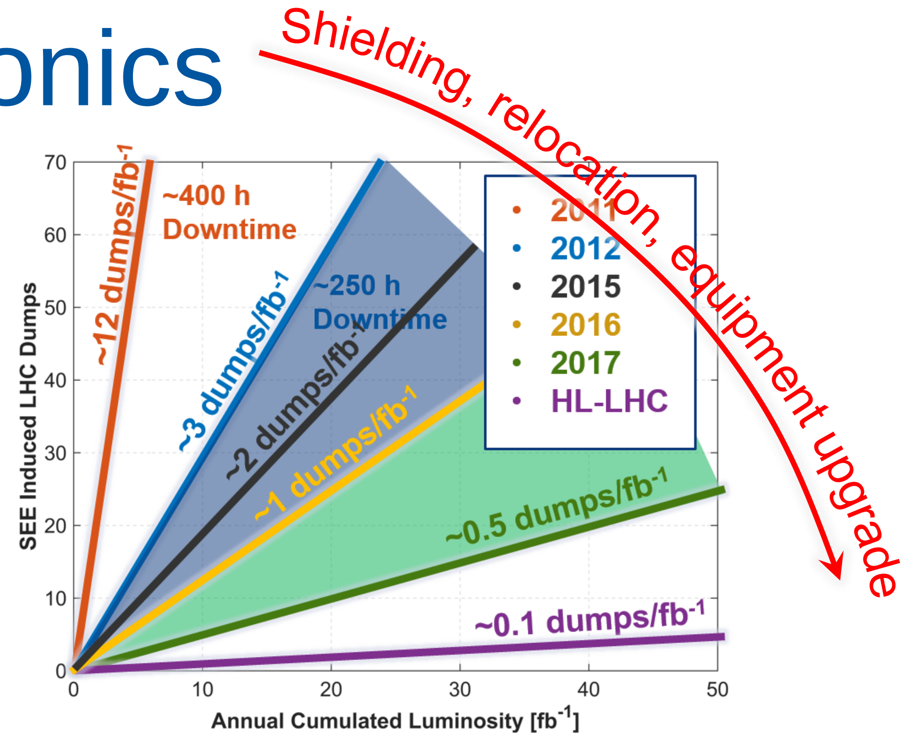
29th April-the weasel

Outline

- What we were prepared for…
- What we were not prepared for…the miserable April
- LHC performance in 2016
- Perspective for the rest of Run II and a look at HL-LHC

Radiation to Electronics

- R2E was "discovered" at the LHC in 2011 and "revamped" with the QPS SEU in 2015
- A lot of work and mitigation actions since the beginning (mitigation measures are balanced by increased cumulated dose…)
- Further measures are planned for HL-LHC
  - Remove all sensitive equipment from tunnel
    - PC powering through SC (HTS) links
    - QPS systems delocalized
  - Develop rad-hard electronics



Courtesy of S. Danzeca

QPS strategy → EPC strategy

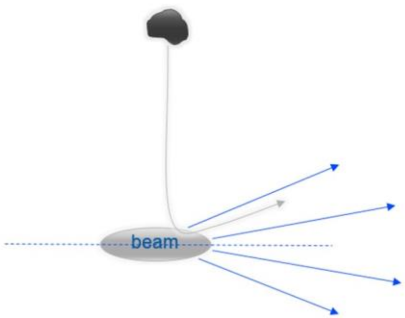
Equipment	Dumps 2012	Dumps 2015 (After TS2)	Predicted Dumps 2016 (35fb-1)	Predicted Dumps 2017 (45fb-1)
QPS	32	3	0-5	0-5
Power Converter	15	7	~25	0-10
Cryo	4	0	0	0
EN/EL	1	0	0	0
Vacuum	4	0	0	0
Collimation	1	0	0	0
RF	1	4*	[illegible]	[illegible]
Others (hidden)	-			
Total	3 /fb-			

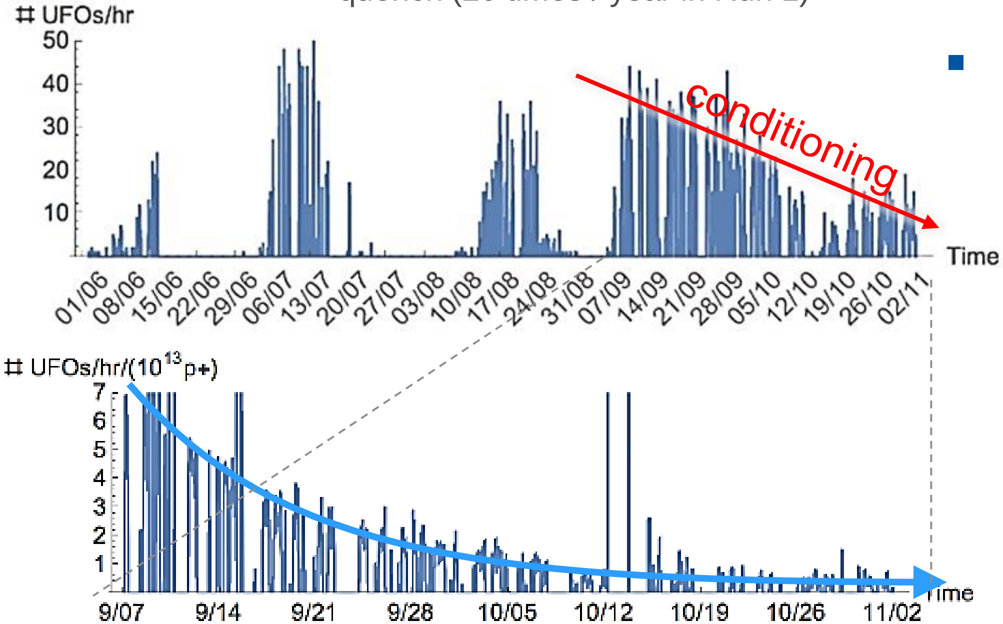
* To be confirmed

Surprise: only 3 radiation induced dumps till now!
Analyses are ongoing to interpret the lower than foreseen radiation level (might be due to reduced beam-gas)

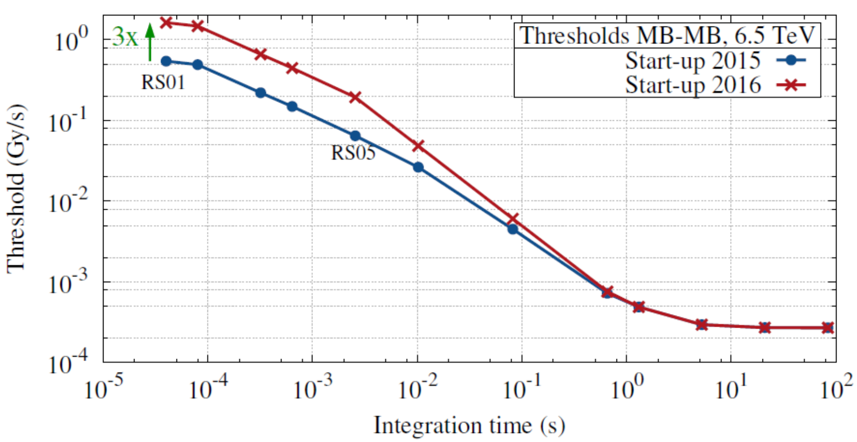
UFOs

- According to the most credited theory, the **Unidentified Falling Objects** are dust particles that, due to inelastic collisions with the beam, generate losses.
  - Identified already in Run I
  - If the induced losses are too high, the beams are dumped to avoid a magnet quench (20 times / year in Run 1)





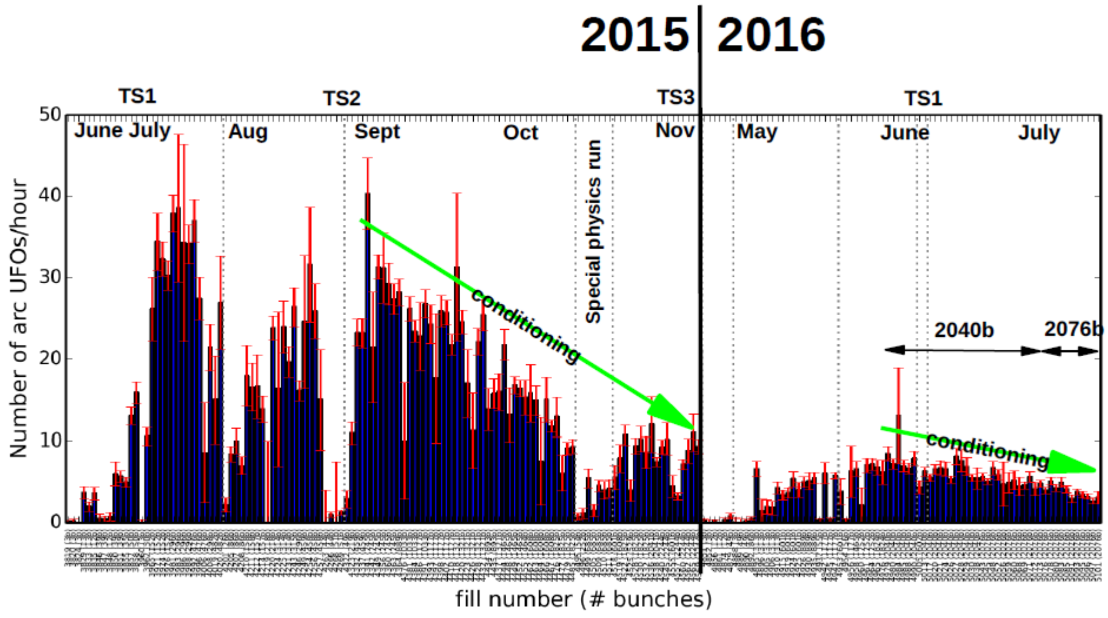
- **18 times, beams were dumped by UFOs in 2015, and we had 3 magnet quenches**
  - BLM thresholds have been several times adjusted, **balancing the risk of spurious dumps and the need for quench prevention**
  - A clear conditioning had been observed along the year



Strategy for 2016: increase BLM thresholds for short running sum

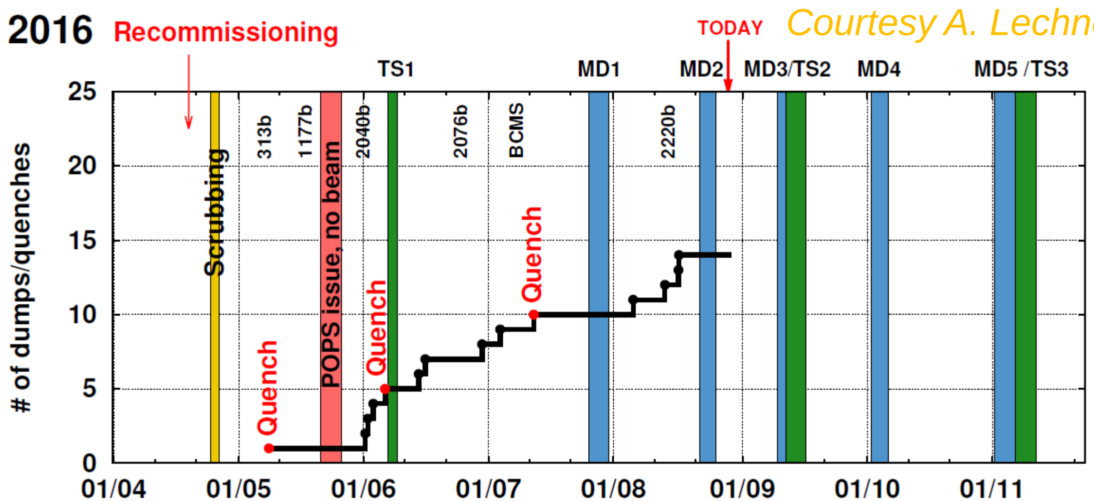
→ one could expect more quenches

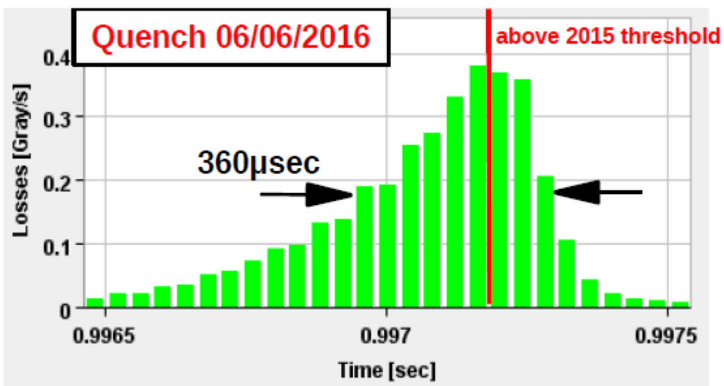
UFOs in 2016



- **Further conditioning has been observed this year**
- **11 BLM dumps (w/o quench), 3 quenches in 2016**
  - In 2 out of 3 cases we would have dumped with 2015 thresholds
  - It seems this would have not avoided the quenches (dump too late)

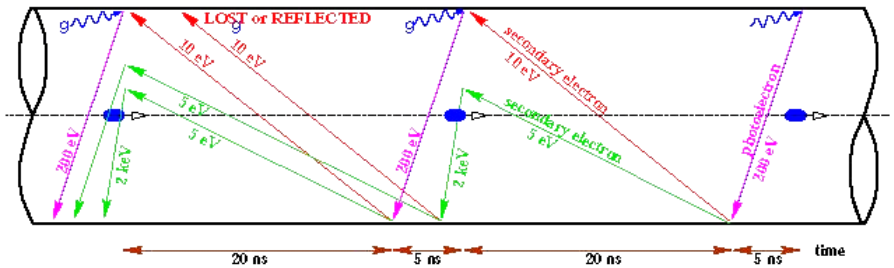
Courtesy A. Lechner (updated 29/08)



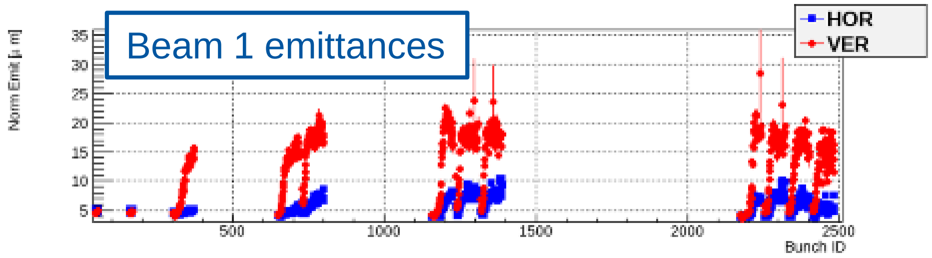


e-cloud

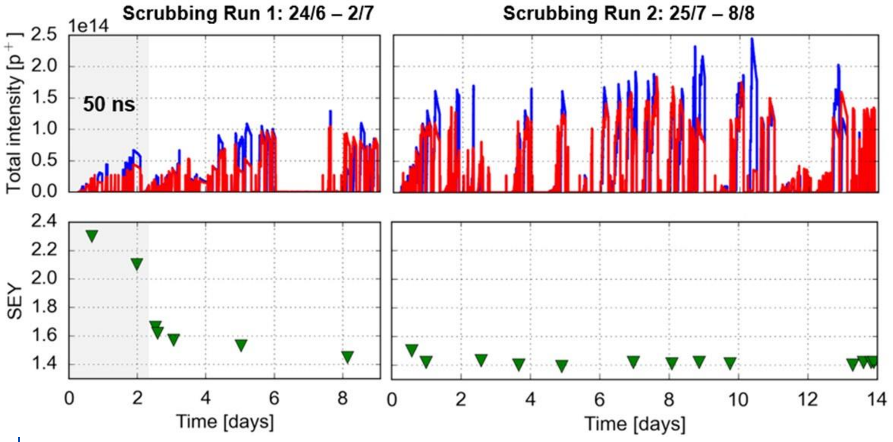
- **Electron cloud** effects
  - Vacuum pressure rise
  - Impact on beam quality (emittance growth, instabilities)
  - Excessive energy deposition → heat load on the cryogenics



Secondary emission yield [SEY] = ratio between emitted and impacting electrons
SEY>SEY_{th} ➔ avalanche effect (multipacting)
SEY_{th} depends on bunch spacing and population

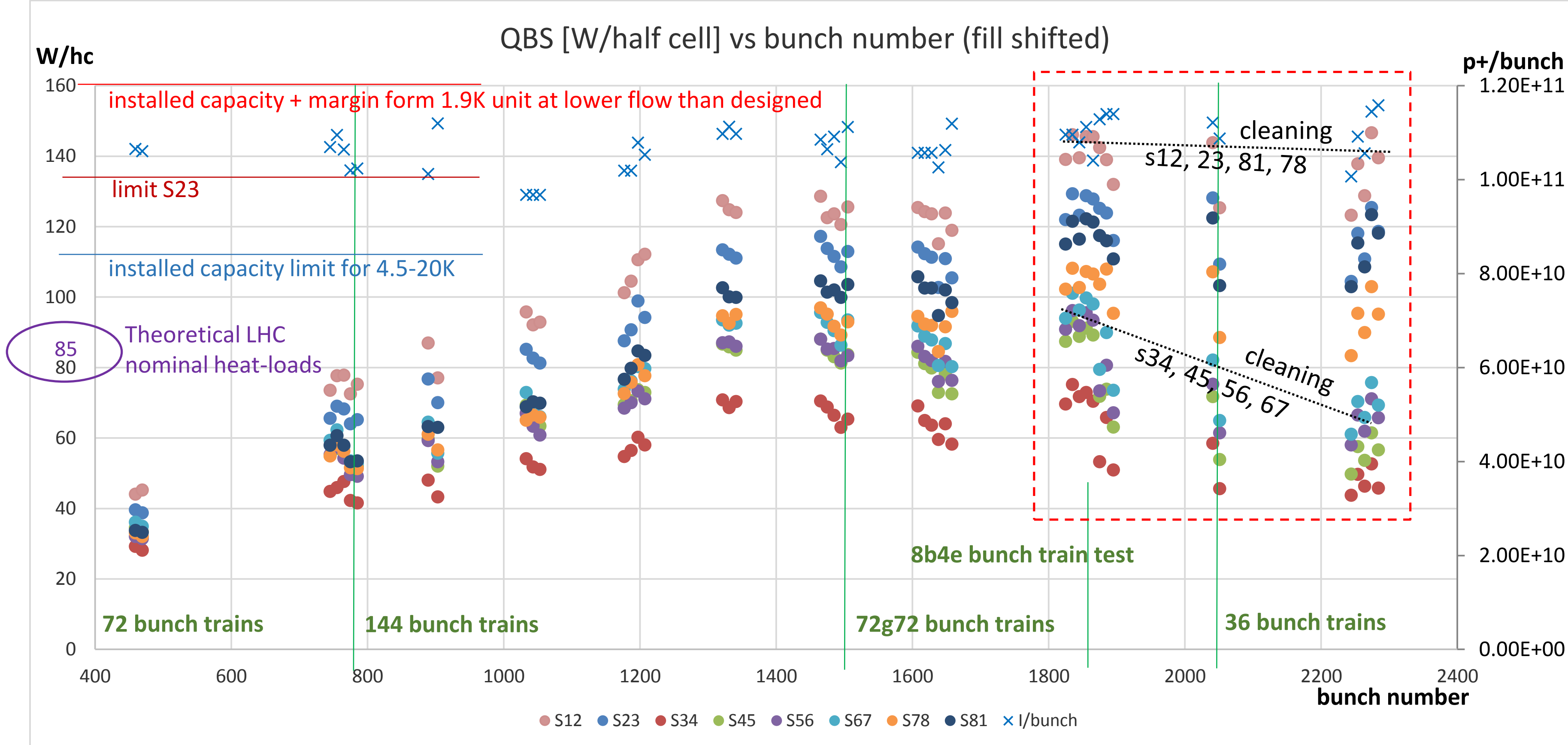


Chosen remedy: conditioning by beam-induced electron bombardment ("**scrubbing**") leading to a progressive reduction of SEY



Had to play with all parameters:
- High chromaticity and octupoles
- Optimized filling scheme to gain additional margin
- Increased longitudinal emittance blow-up on the ramp

e-cloud seen from cryogenics

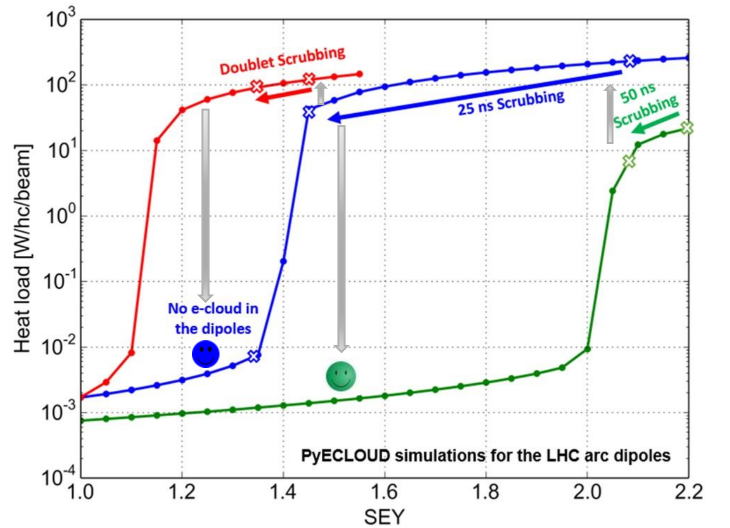


- After 2 months, significant reduction visible in all arcs (30% to 60% depending on the sector)
- Possible future strategy (e.g. after LS2):
  - Shorter scrubbing period, to achieve acceptable beam quality
  - Accumulate further electron dose in parallel with physics (but slower intensity ramp up to be expected)

Initial scrubbing strategy…modified!

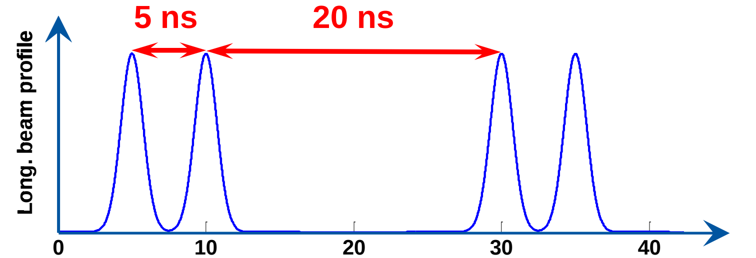
- Phase 1: re-establish 2015 conditions (4 days dedicated run) and intensity ramp-up (288b) phase 1 (~2000 bunches)

- Phase 2: scrubbing during Stable Beam

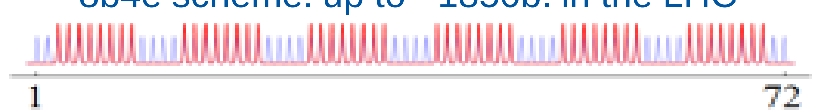


- Due to the issue with the SPS dump, phase 1 was reduced (1 day with limited bunches) and only partially reestablished the 2015 conditions.
- Scrubbing so far has been limited and only done with physics.

Doublet beam

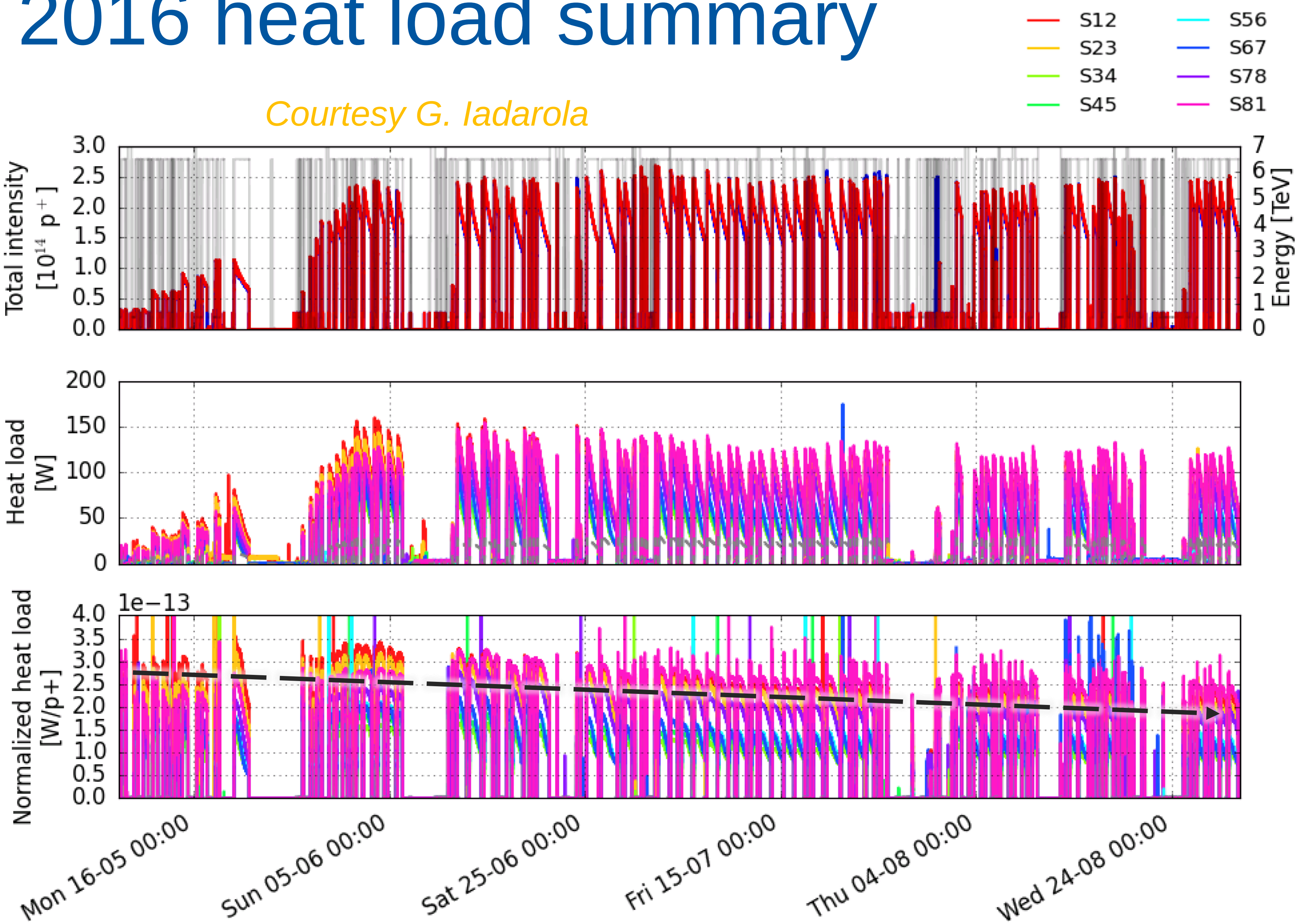


8b4e scheme: up to ~1850b. in the LHC



2016 heat load summary

Courtesy G. Iadarola



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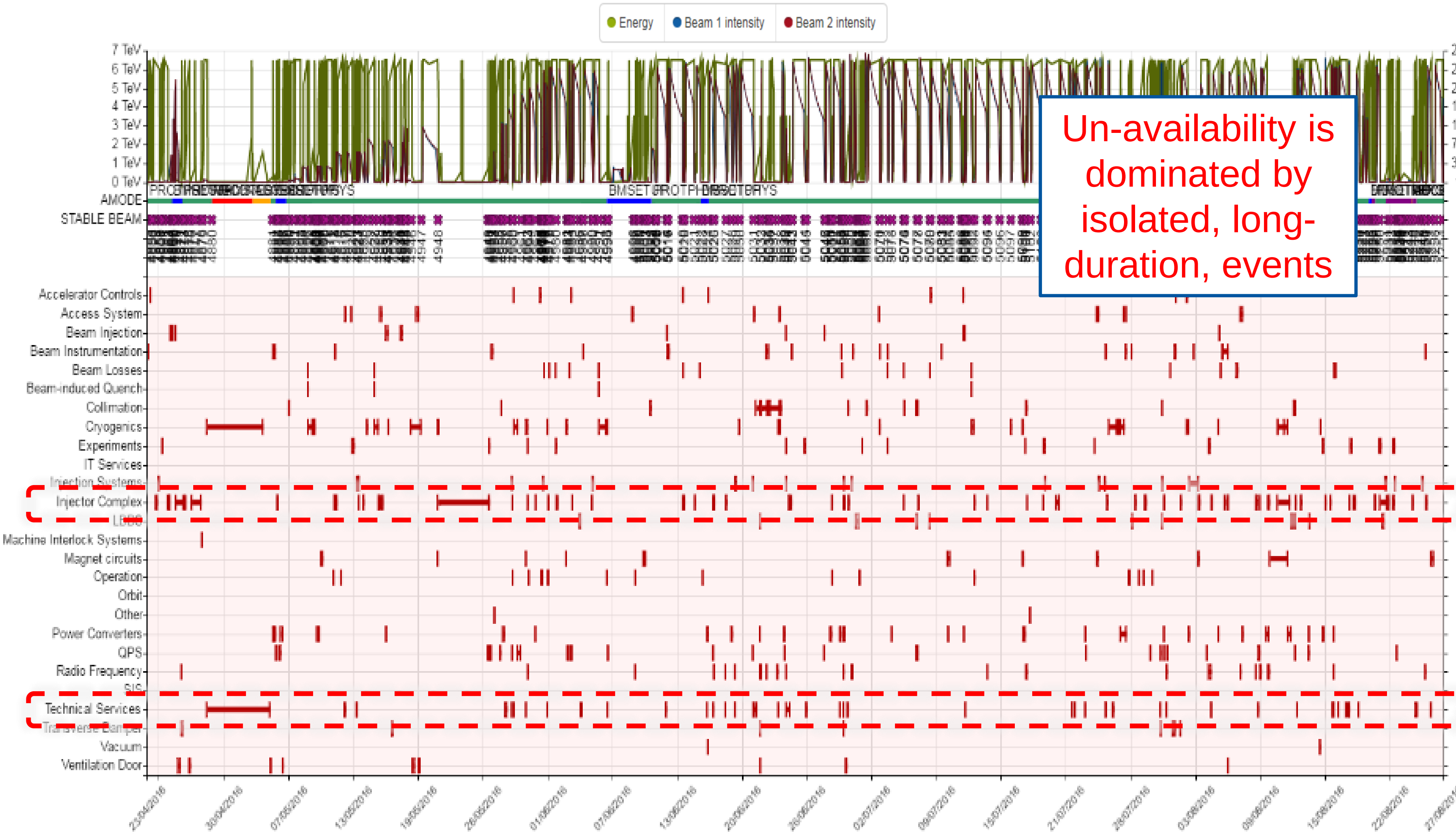
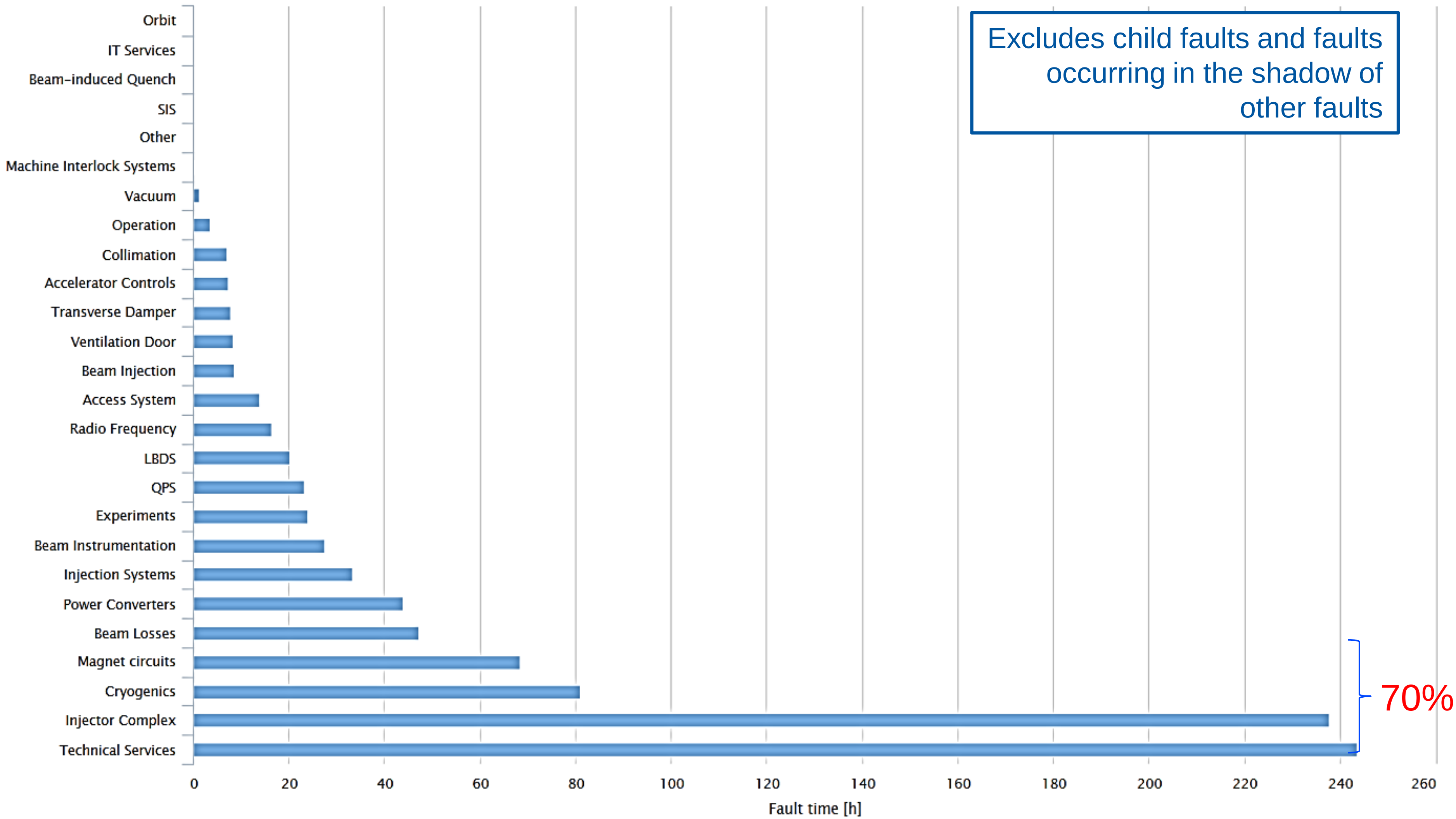
The LHC cardiogram

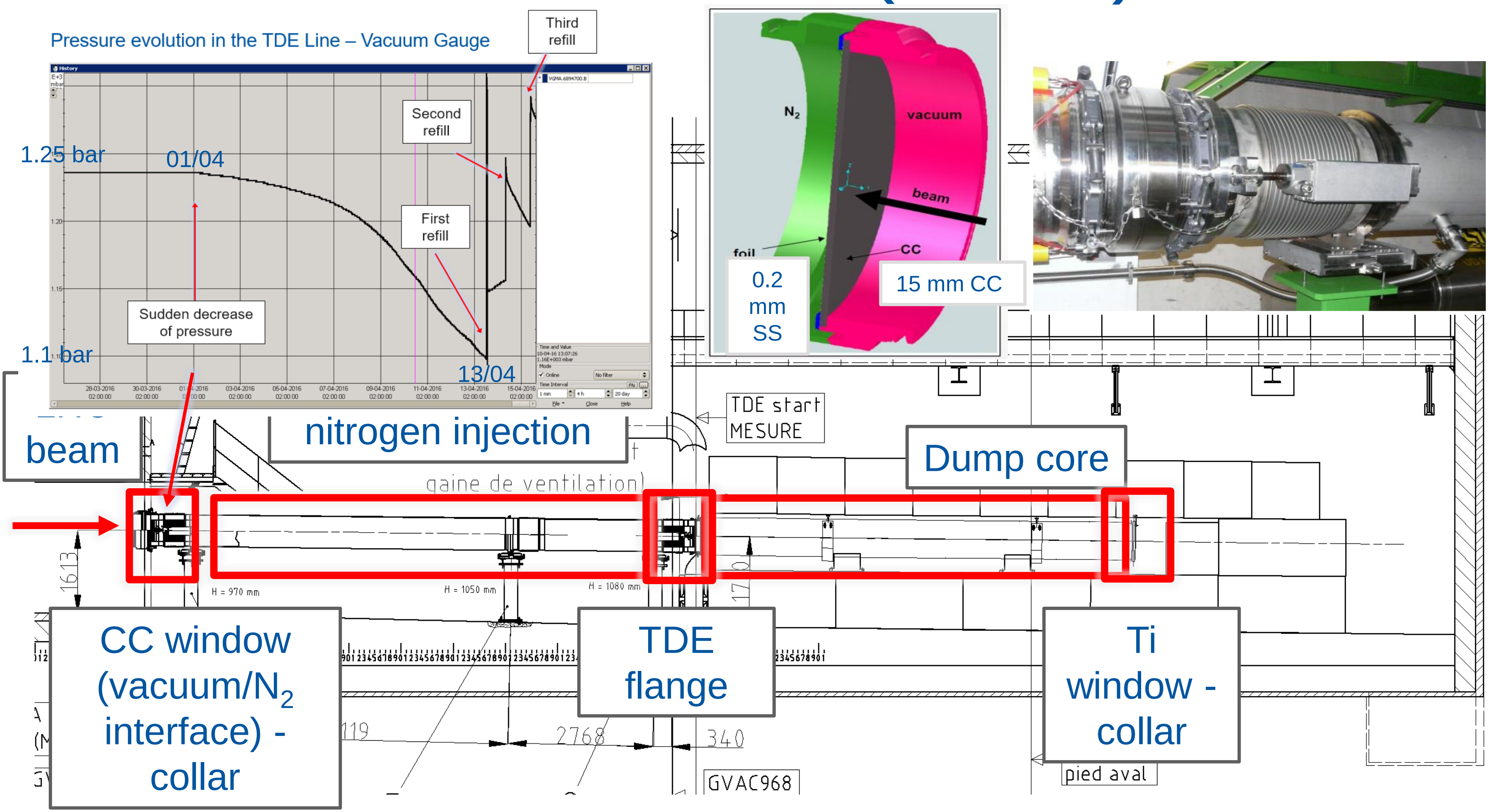
LHC beam status vs fault analysis (different downtime contributors shown)



Fault analysis by system



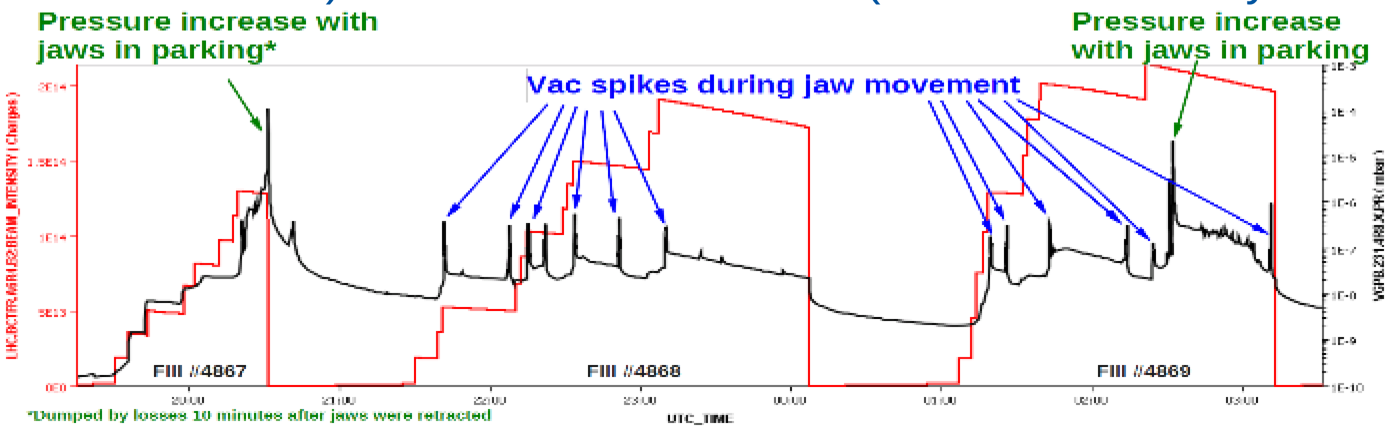
Leak on the B1 TDE (UD68)



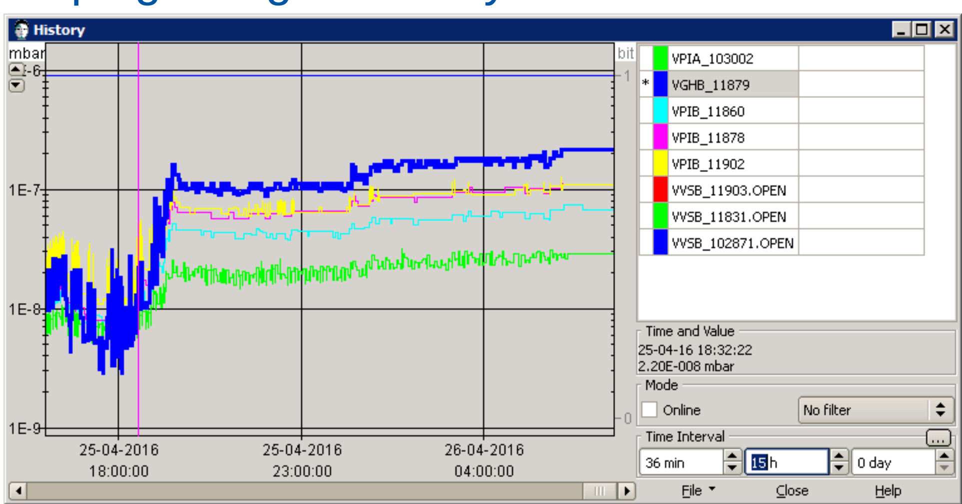
Problem observed on Apr. 13 and mitigated by adding a rack of N2 bottles. **Should be fixed during the EYETS 16/17.**

During scrubbing (25/04)…

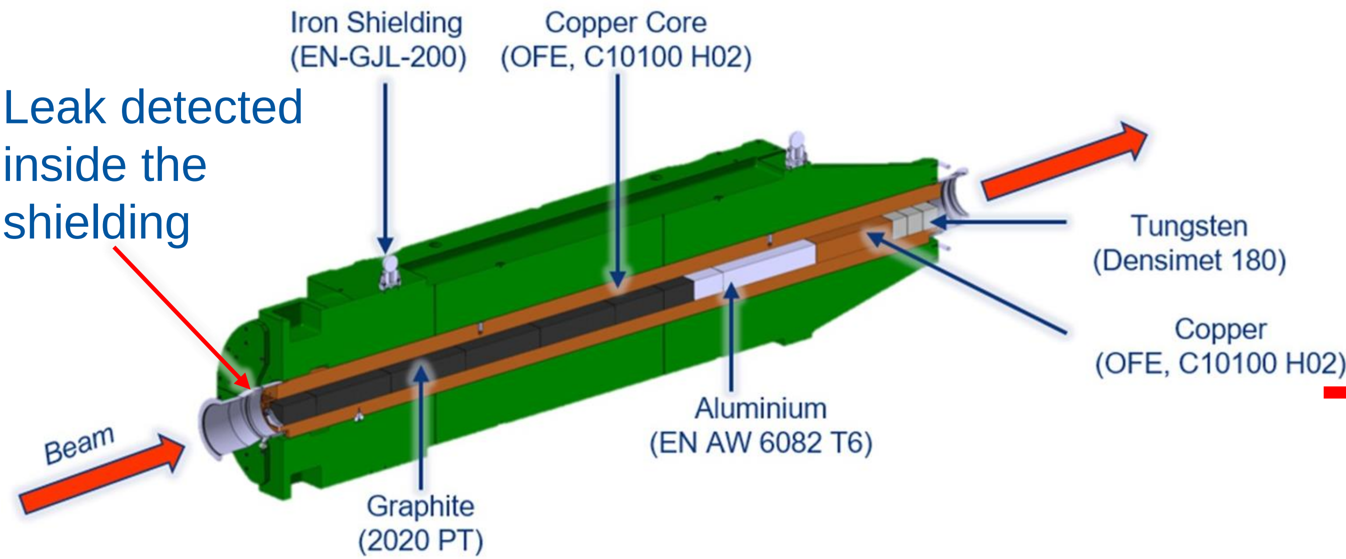
- During the LHC scrubbing, huge spikes in the TDI.4R8 (injection protection device) vacuum were observed (behaviour not fully understood)



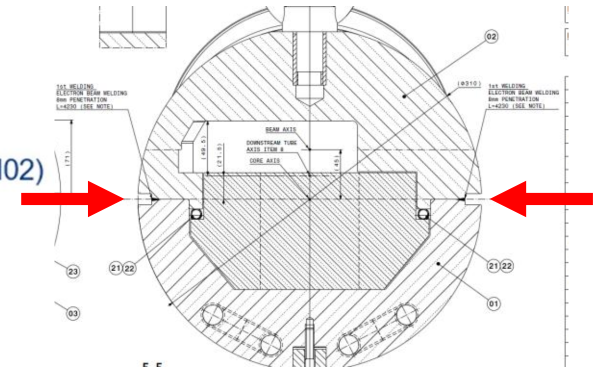
- Sudden loss of vacuum conditions on the SPS dump (TIDVG) after repetitive dumping of high intensity beams



During scrubbing (25/04)…



Probable leak on the longitudinal welding



- Due to the risk associated with high intensity dumps, a reduction of the operational intensity (# of bunches limited to 72 then 96) is in force, plus some operational precautions

- Reconditioning of the old dump ongoing
  - Heavy damages observed
- Order for a new dump launched

  (5 months!)

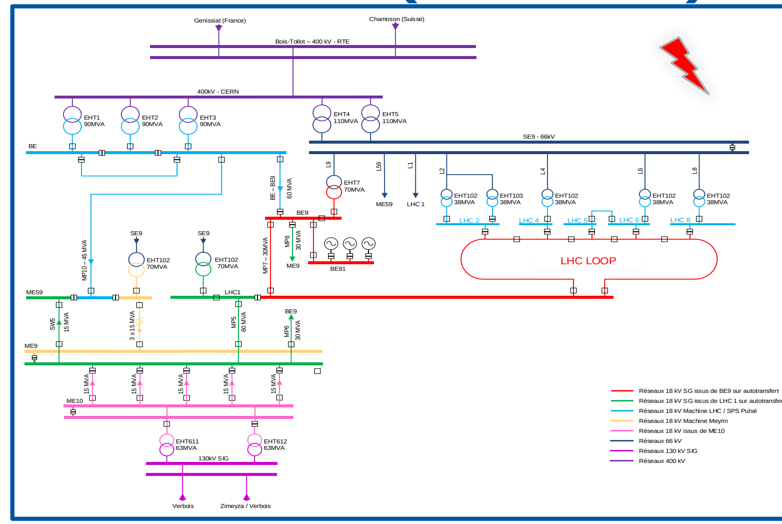
POPS incident on 27/04

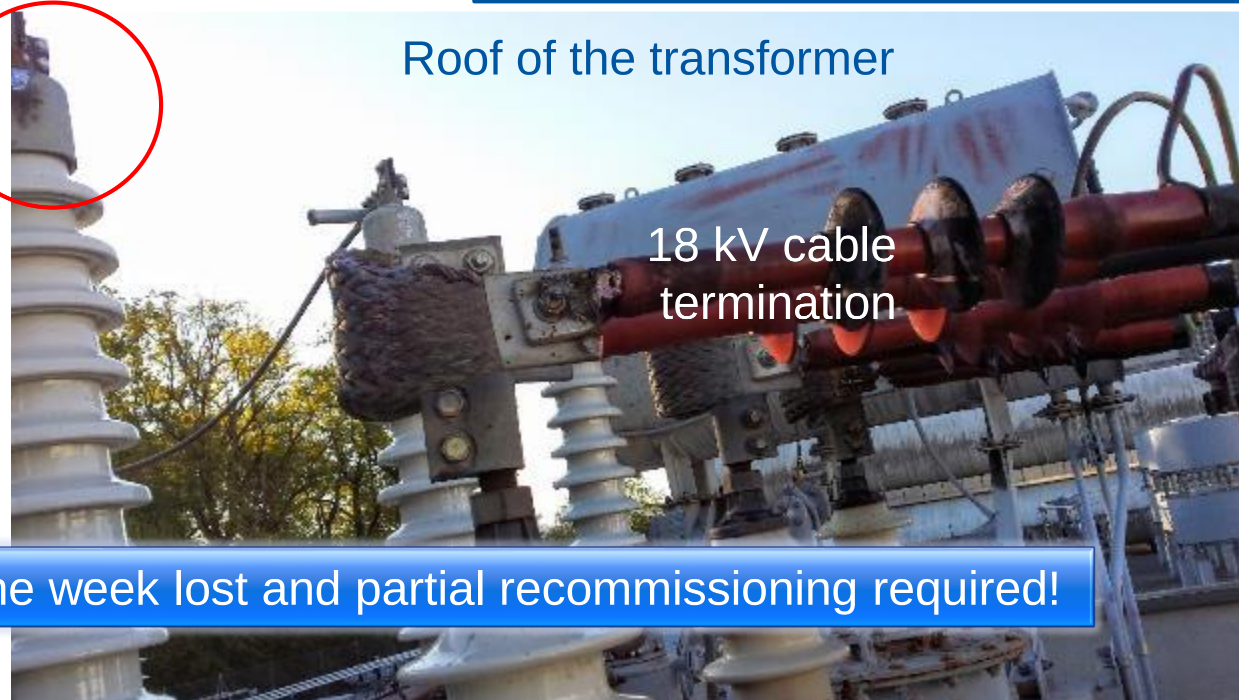
- During re-commissioning of POPS (=PS powering system), when charging with the magnets connected, two storage capacitors produced a short circuit
- The stored energy discharged through the short circuit, causing an explosion in the container
- Now working in degraded mode

Short circuited capacitors

The transformer short circuit (29/04)

A weasel was at the origin of a phase to ground fault on a 66/18 kV transformer, which generated a global power cut all over CERN: all machines stopped, all circuits tripped (excluding the CMS solenoid), cryogenics down everywhere.

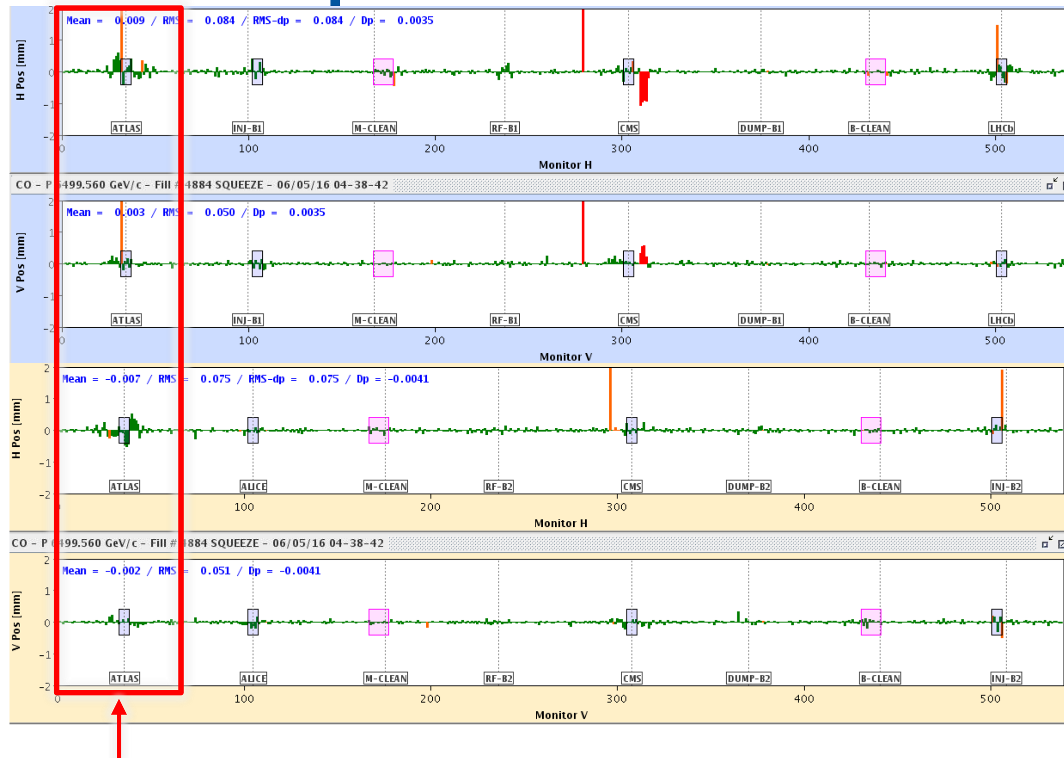




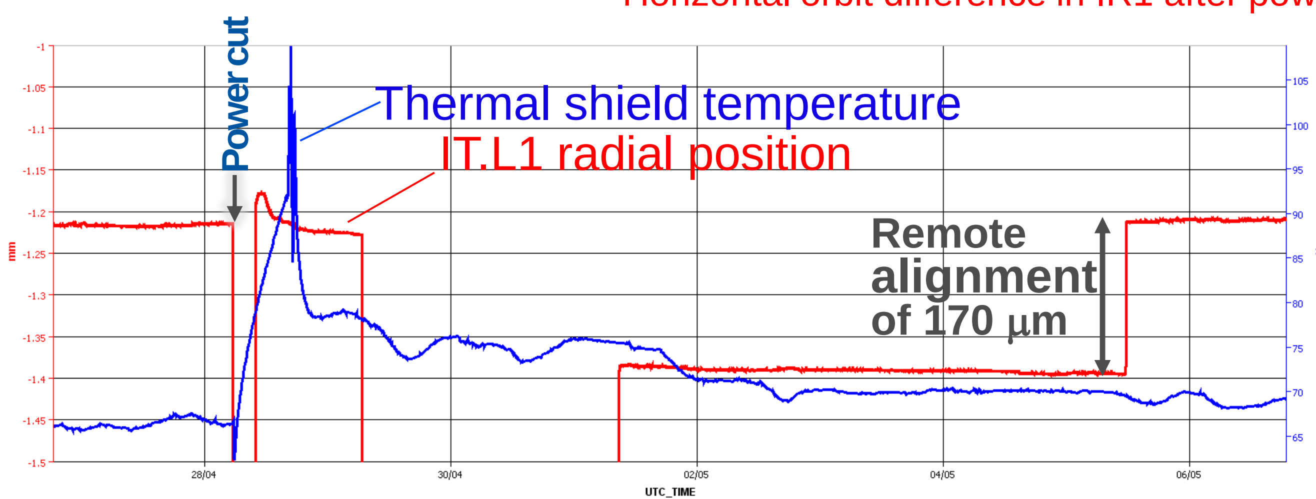
Almost one week lost and partial recommissioning required!

Consequences of the power cut

- After the power cut, an orbit drift was observed around point 1
- Investigations pointed to a shift of the radial position of Q1 magnet of the IT.L1
- The magnet was remotely realigned and orbit went back to nominal

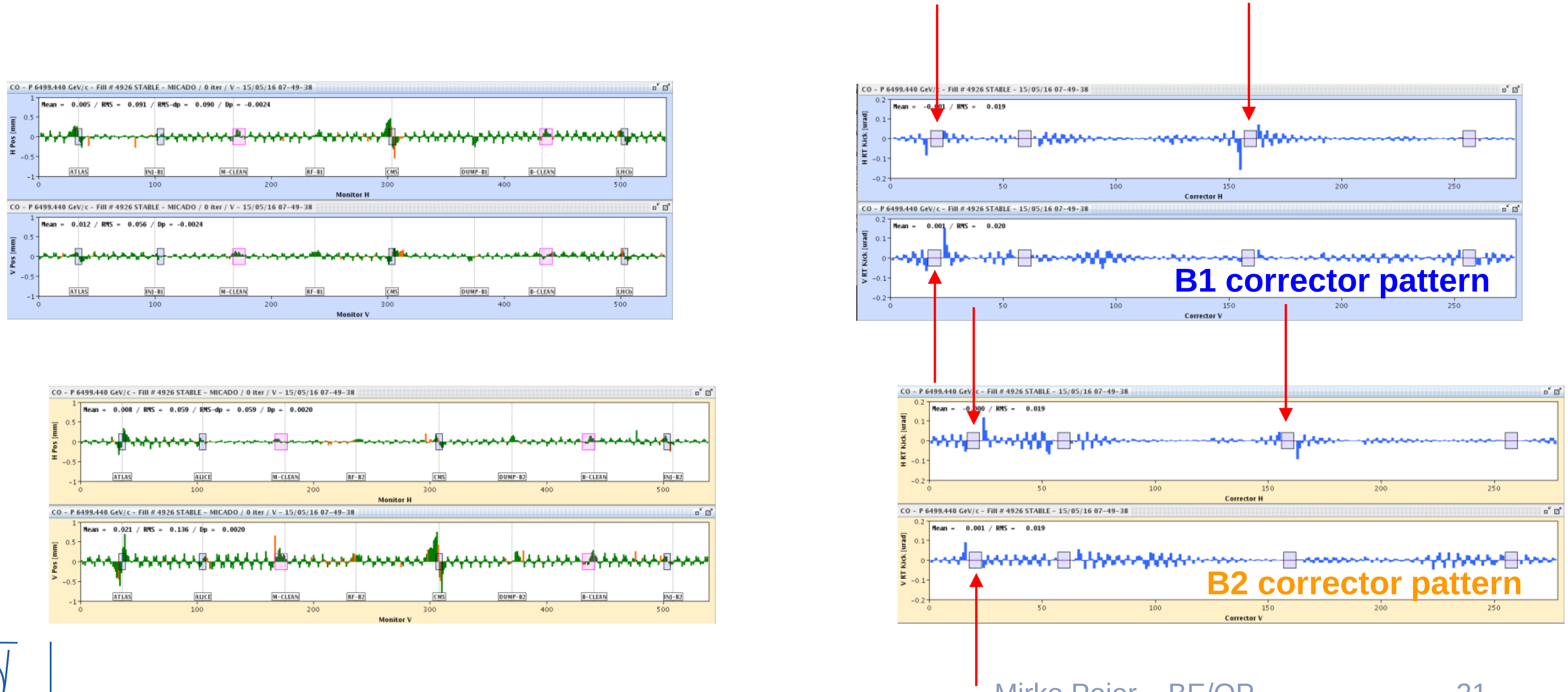


Horizontal orbit difference in IR1 after power cut



Orbit drifts in Stable Beams

- Continuous drifts of the orbit are observed in Stable Beams, which point in the direction of small IT movements (by planes), mainly in 1 & 5 (probably due to the high IT beta).
- The rms orbit drift reconstructed from the OFB corrections after 8-10 hours is typically in the range of 50-150 um (peak reaches ~1 mm in the triplets).
- ➢ We are obliged to continuously operate with OFB in SB!



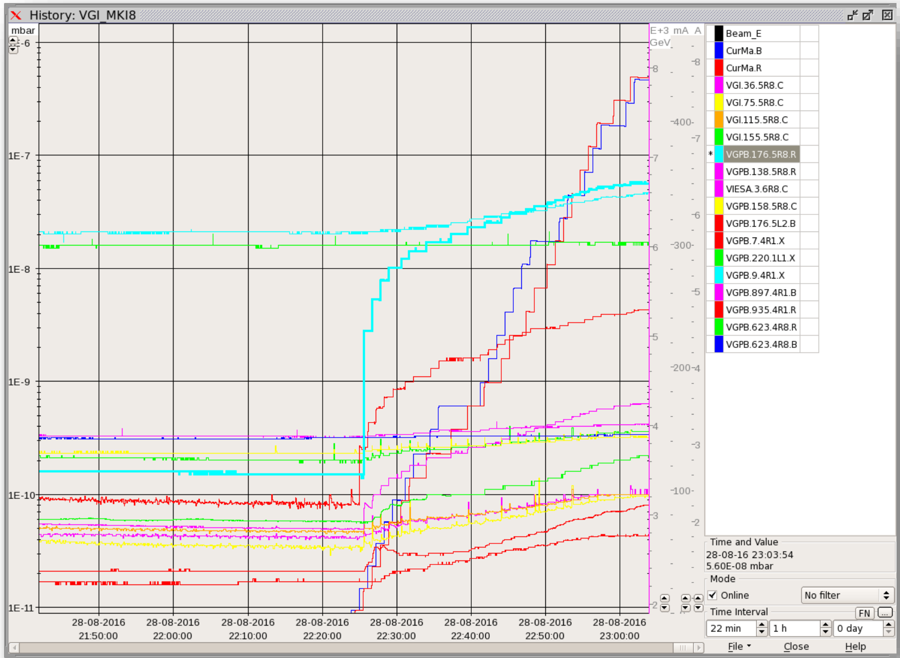
PS rotating machine fault (20/05)

- At the end of a normal access, conditions were set back to normal for beam in the PS
- A fire alarm was activated after restart: the fault was identified on the failure of 6kV circuit breaker of the rotating machine which did not close properly after access
- An electrical arc developed causing a short circuit
- The repair by the company was estimated in 2 weeks
- It was therefore decided to put POPS back in operation in a degraded mode (5oo6 capacitor banks)
- 5 days were lost in the degraded reconfiguration of POPS

B2 MKI (injection kicker) vacuum issue

- On the process to increase the number of bunches and particle per bunch, we realized to be limited by the vacuum interlock of the injection kicker
- Interlock raised from 6e-8 to 6.3e-8
  - each injection adds 2×10^{-9}
  - reaching a limit with bunch intensity of 1.15×10^{11}
  - risk of flash over
    - vacuum pressure increase suspected to be caused by e-cloud
    - mitigation in EYETS16-17

➢ This is presently the bottleneck for luminosity increase!



CERN

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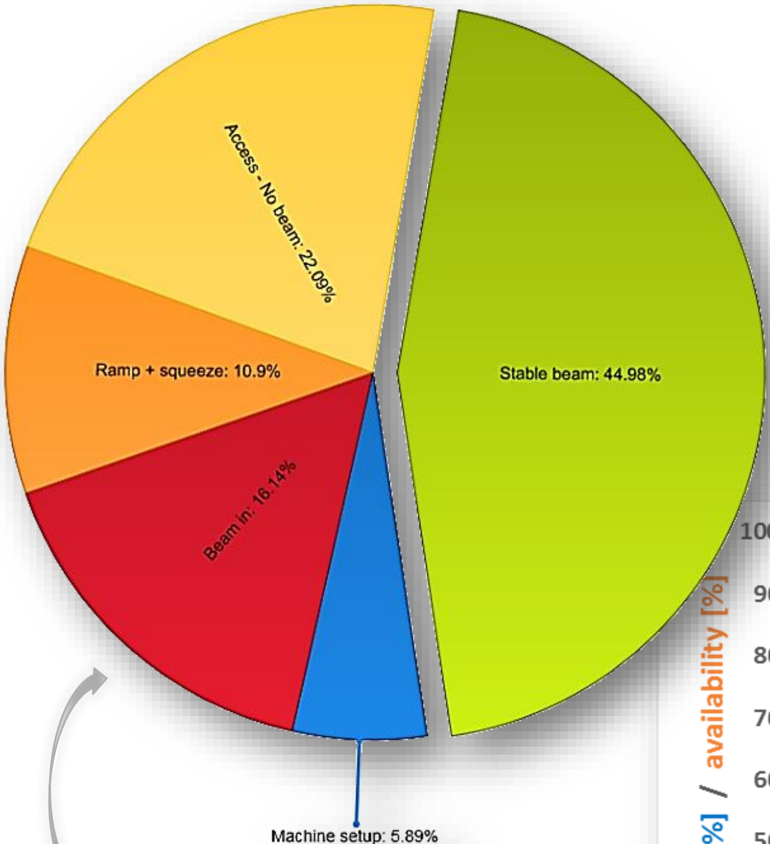
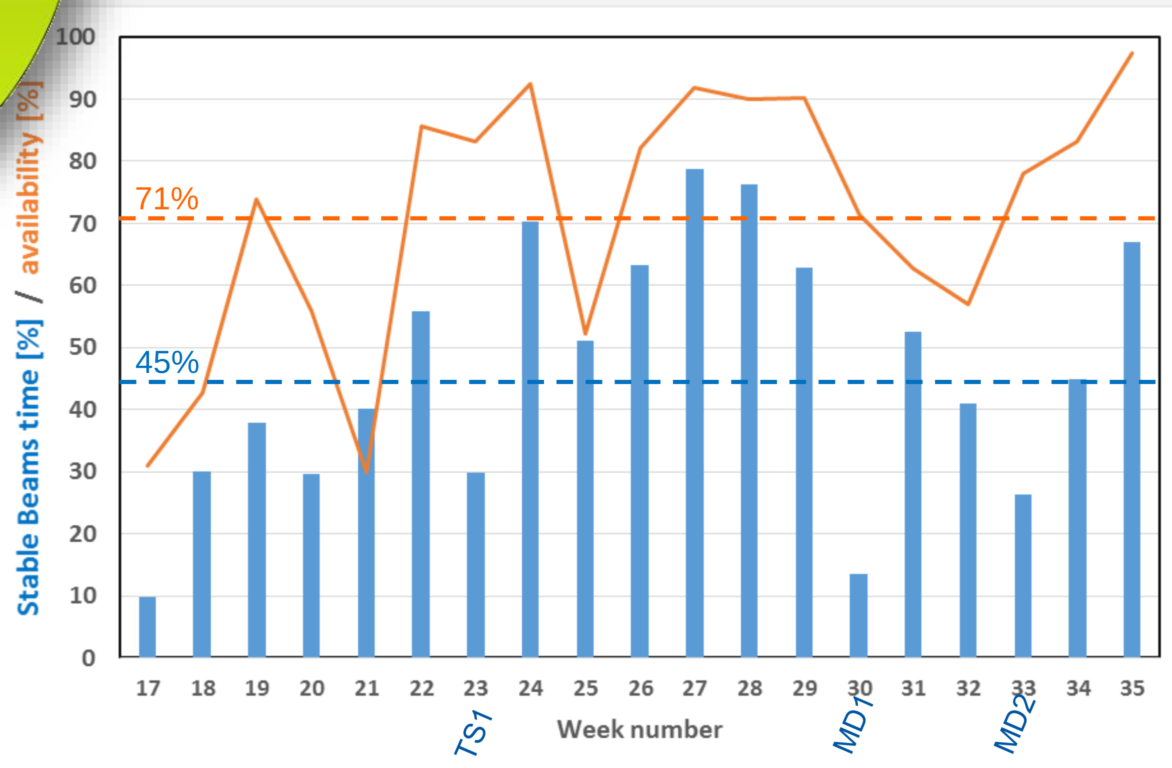
Stable Beams time and machine availability



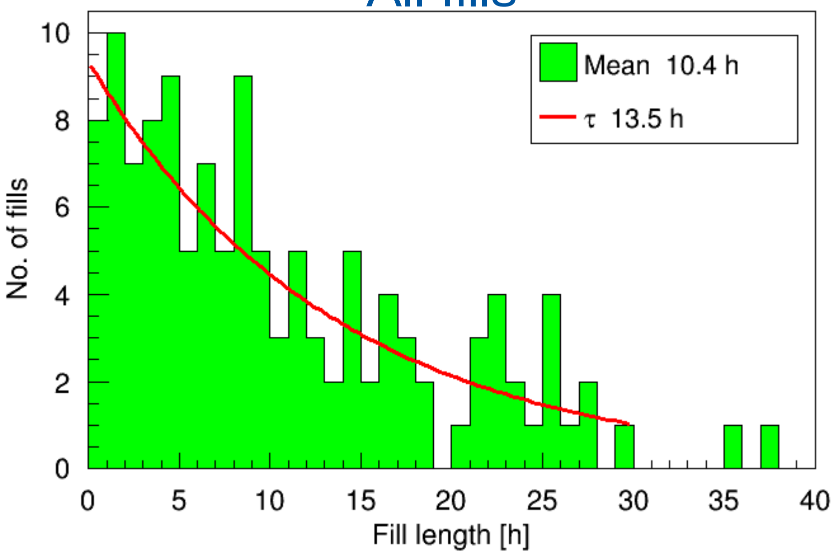
Time breakdown at the LHC
(April to August, with TS and MDs included)

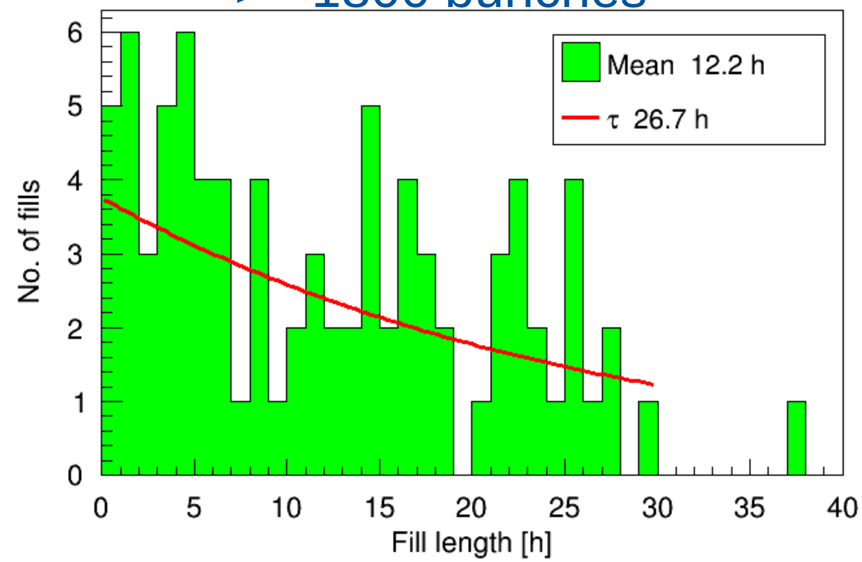
HL-LHC challenge: machine efficiency
→ target time spent in Stable Beams around 50%

- Very encouraging results from LHC in June-July in view of reaching this target



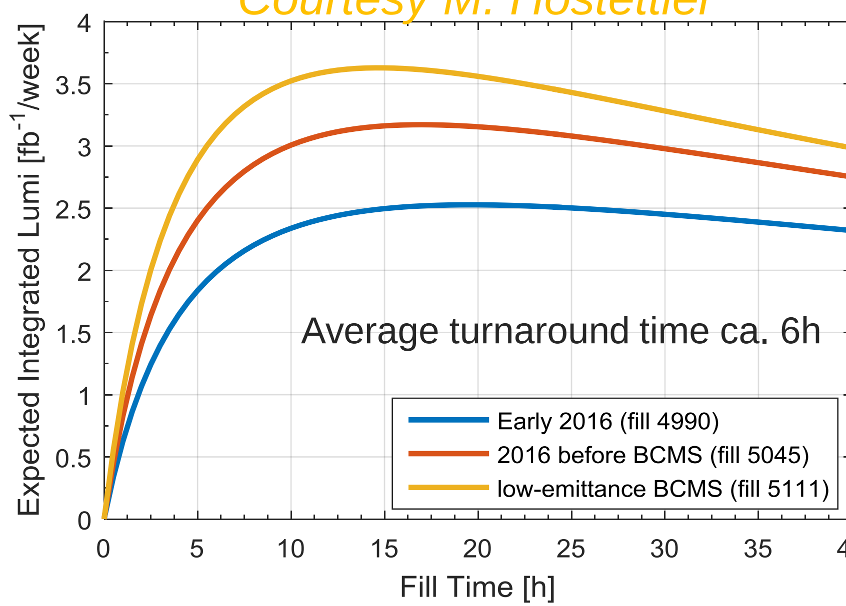
Fill length





- Fills with more than 1800 bunches: average is doubled wrt 2015 and run1
- ➢ HL-LHC considers an average fill length of ca10 hours

Courtesy M. Hostettler

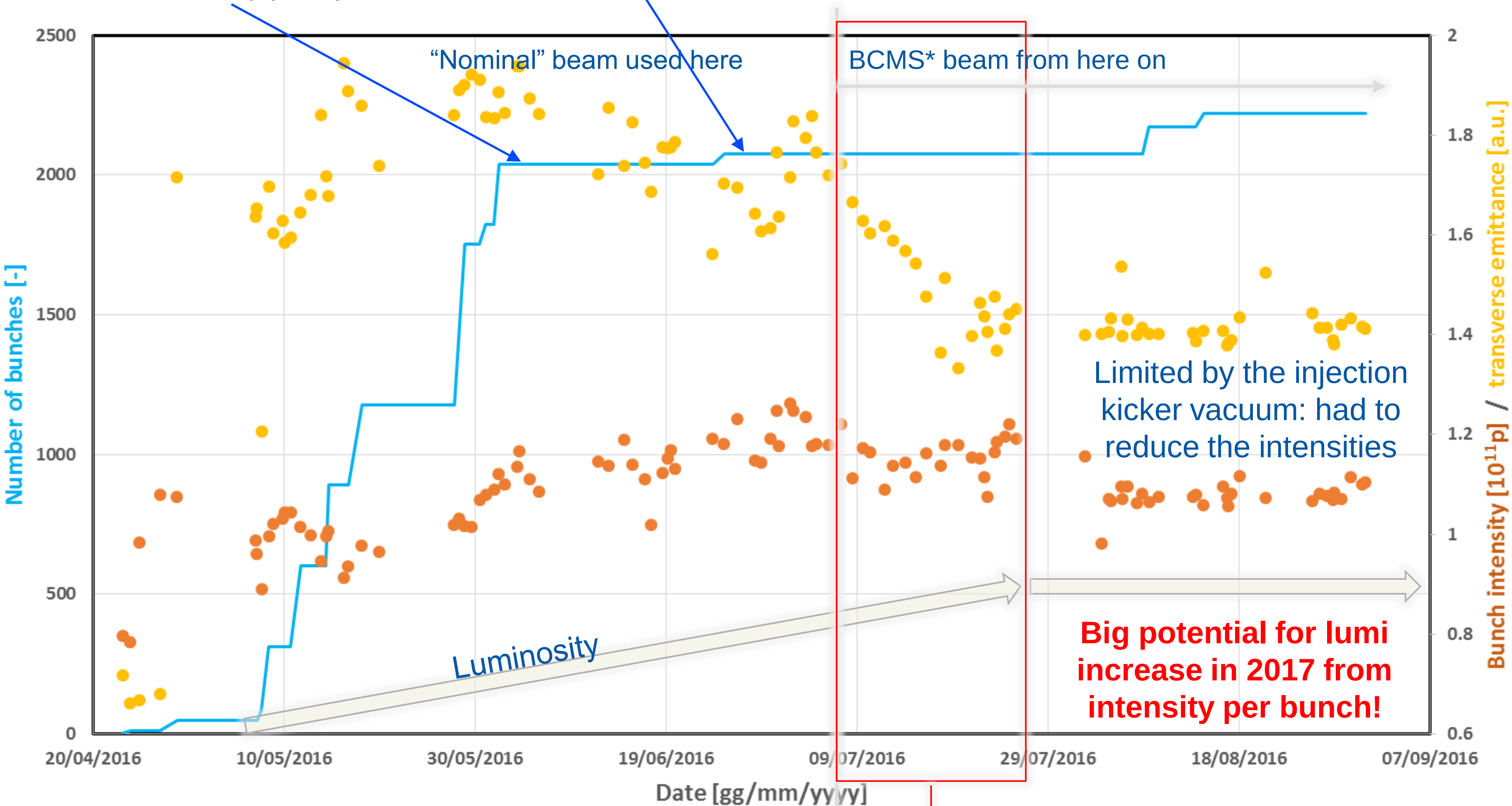


Pushing the performance

2040b with 72p per injection

2076b with 96p (=2*48b) per injection

Also adjusted batch spacing in SPS and LHC

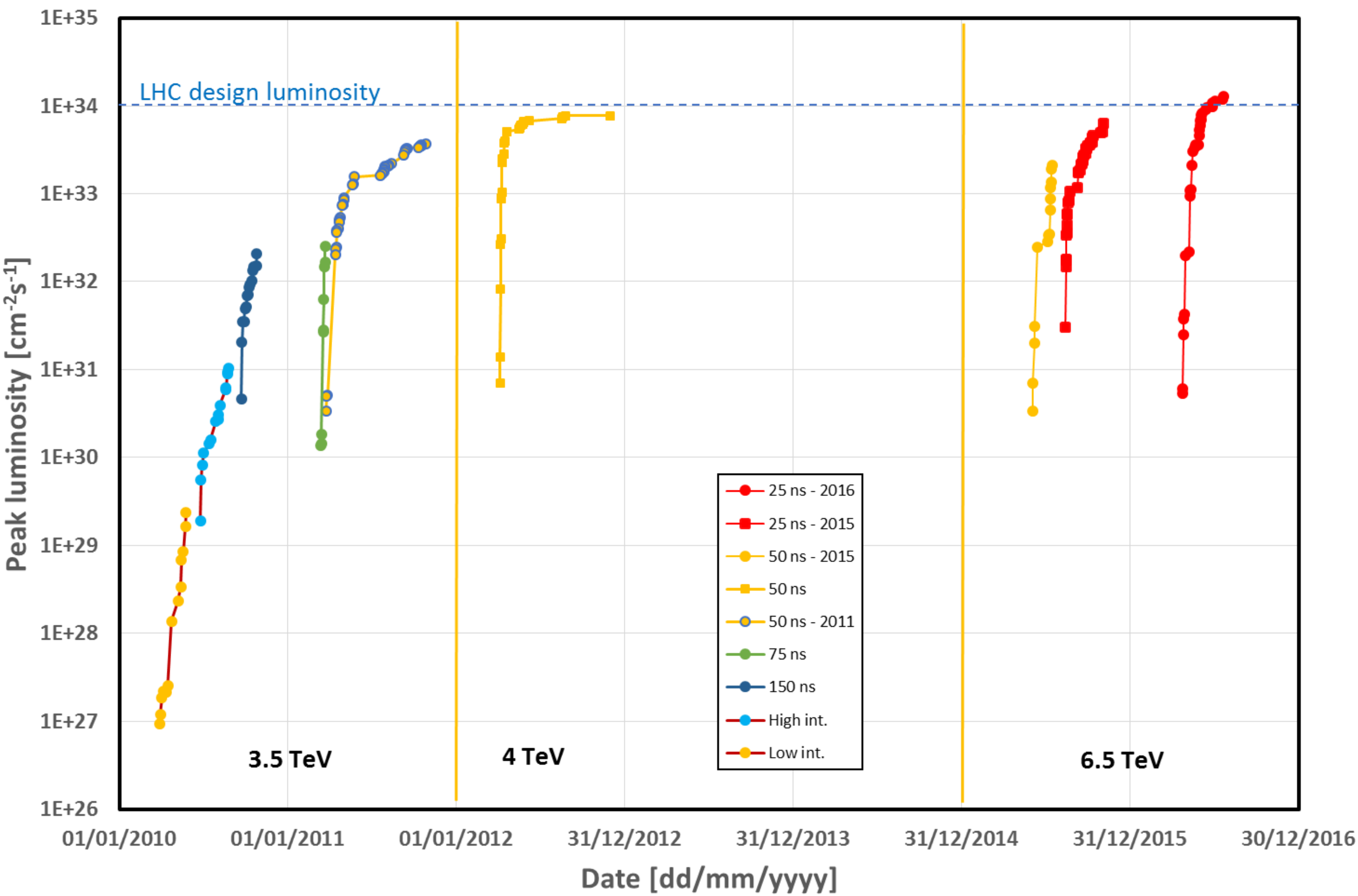


The BCMS beam was initially blown up to "nominal" emittances; progressively reduced

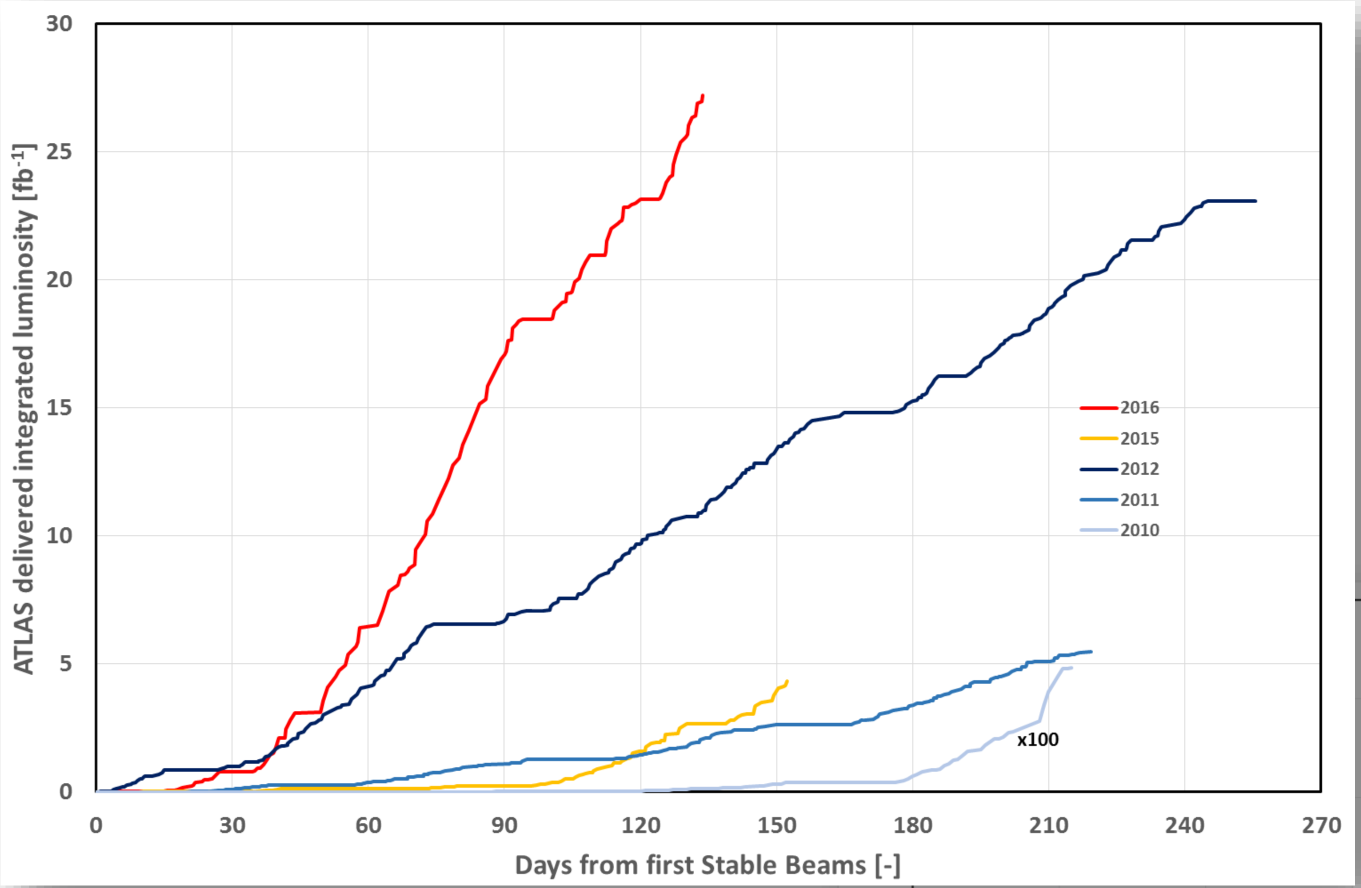
(*Bunch Compression Merging and Splitting)

Incredible flexibility of LHC and the injectors!

LHC reached its design luminosity

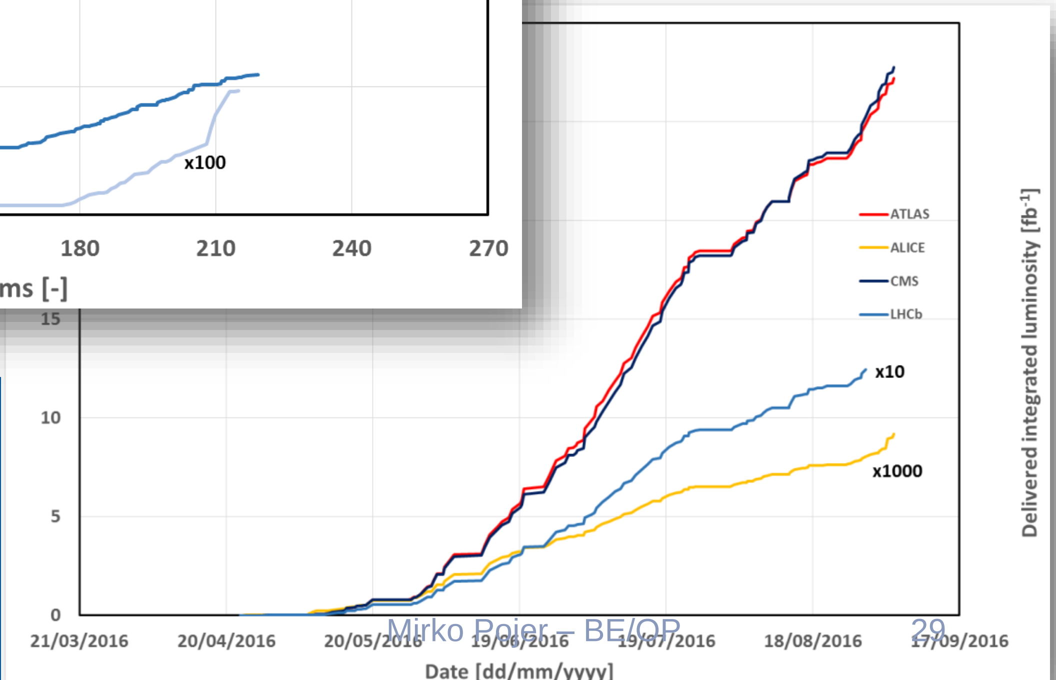


Integrated luminosities



2016 delivered integrated Luminosities
(update 30/08)

ATLAS: 27.2 fb^{-1}
ALICE: 9.2 pb^{-1}
CMS: 27.8 fb^{-1}
LHCb: 1.4 fb^{-1}



2016 parameters

Energy	6.5 TeV
Bunch spacing	25 ns
Bunch population	~1.1-1.2e11 p/b
Max bunches/injection	72/96
Max. number bunches	2220
Nc GPDs	2208
Beta* GPDs	40 cm
Crossing angle GPDs	185 μrad

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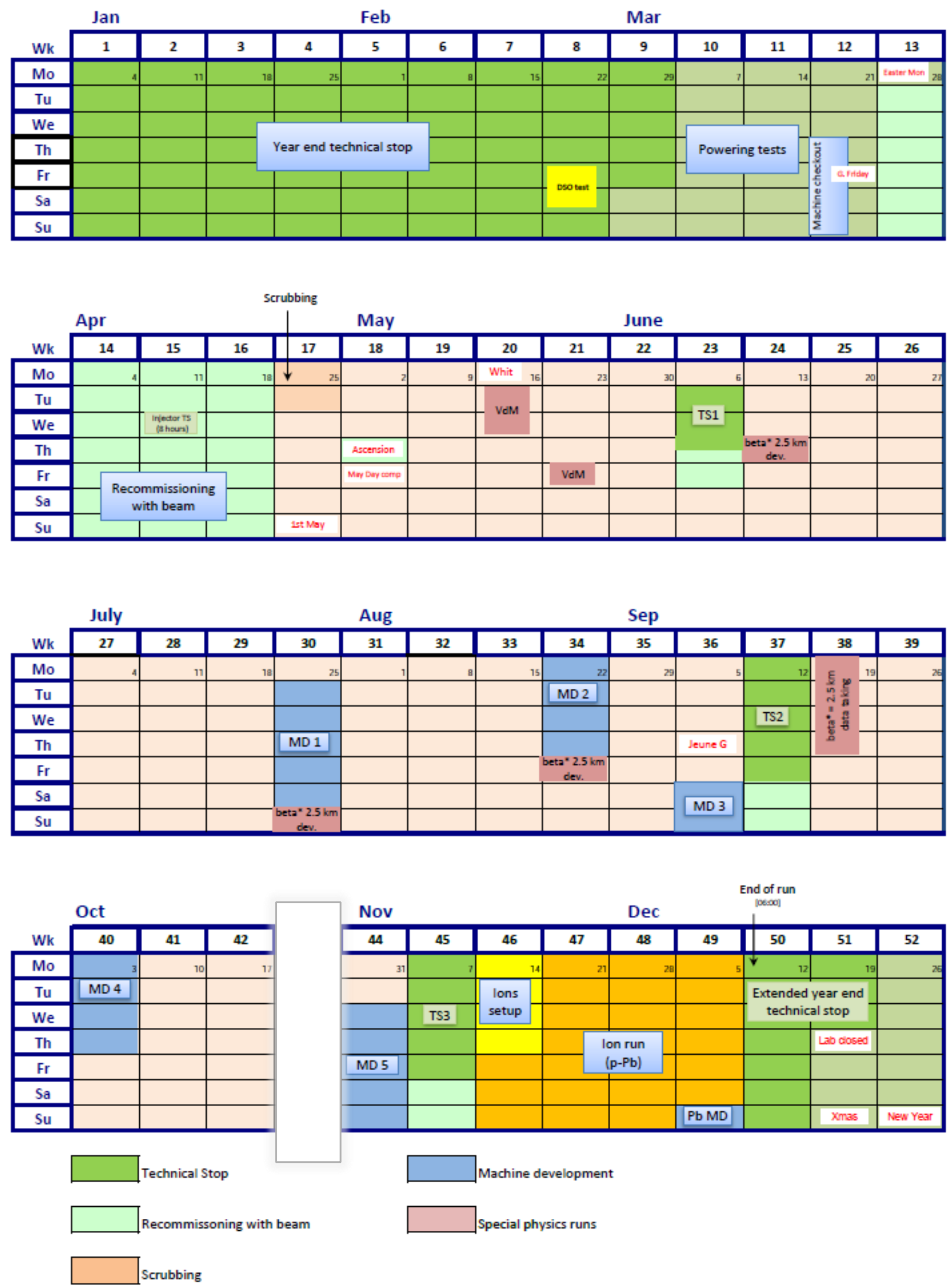
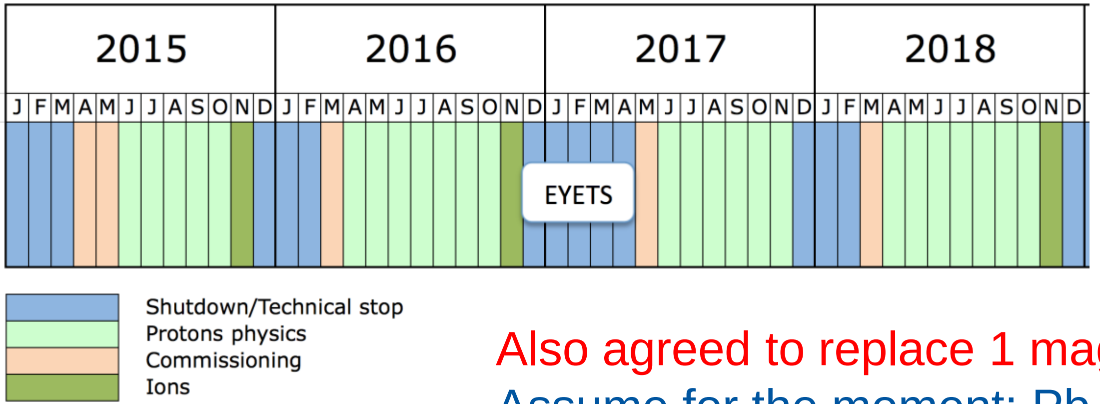
2016 breakdown

Phase	Days
Initial Commissioning	28
~~Scrubbing: 4 days initially and then as required during ramp up~~	2
Proton physics 25 ns	**146**
Special physics runs (high beta*; VdM)	10
Machine development	20
Technical stops	12
Technical stop recovery	6
Ion setup/proton-lead run	4 + 24
Total (including days already accountable as lost)	**252 days (37 weeks)**

About 1 month left for pp physics
Could gain an additional 5+ fb^{-1}



Run 2 objectives



EYETS –20 weeks – CMS pixel upgrade

Recently decided to anticipate EYETS by 1 week to allow for the training of 2 sectors to 7 TeV

Also agreed to replace 1 magnet → watch out for scrubbing!

Assume for the moment: Pb runs in 2016 and 2018

- Deliver 100+ fb-1 to GPDs, keep ALICE, LHCb, TOTEM and ALFA happy
- Keep pushing performance and availability

- Look forward to HL-LHC without compromising present performance:
  - ATS, beta* levelling, LRBB compensation, full de-tuning…
- Look forward to the post-LS2 LIU era and how to exploit the potential
- Prepare for (or go to) 7 TeV operation

2017 possible breakdown

Phase	Days
Initial Commissioning post EYETS	28
Scrubbing	7
Proton physics 25 ns	**163**
Special physics runs	8
Machine development	15
Technical stops	10
Technical stop recovery	4
Total	**235 days (34 weeks)**

2018 possible breakdown

Phase	Days
Initial Commissioning	21
Scrubbing	4
Proton physics 25 ns	**162**
Special physics runs	8
Machine development	22
Technical stops	15
Technical stop recovery	6
Ion setup/ion run	4 + 24
Total	**266 days (38 weeks)**

Guessing 2017/18 parameters

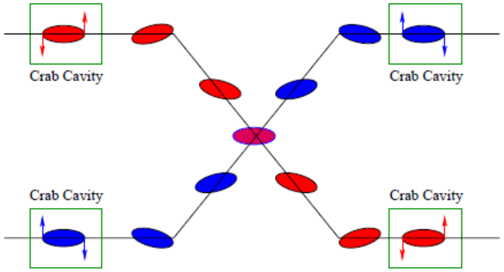
	Nominal	BCMS
Beta* (1/2/5/8)	0.4/10/0.4/3	0.4/10/0.4/3
Half crossing angle	-185/200/185/-250	-155/200/155/-250
Nc	2736	2448
Proton per bunch	1.25e11	1.25e11
Emittance into SB	3.2	2.3
Bunch length	1.25	1.25
Peak luminosity	~1.3e34	~1.6e34 *
Peak pile-up	~33	~47
Luminosity lifetime	~23	~17
150 days	38 fb^{-1}	43 fb^{-1}

* limited to ~1.7e34 by inner triplets (Laurent Tavian Evian 2012)

- Novel optics… flat beams, squeezing further
- Reduced crossing angle (LRBB limits)
- Maximizing number of bunches

Performance optimization of HL-LHC

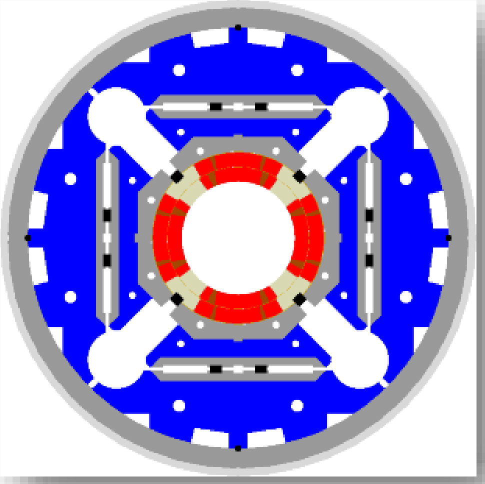
$$L = \frac{n_b \times N_1 \times N_2 \times \gamma \times f_{rev}}{4\pi \times \beta^* \times \varepsilon_n} \times F(\phi, \beta^*, \varepsilon, \sigma_s)$$



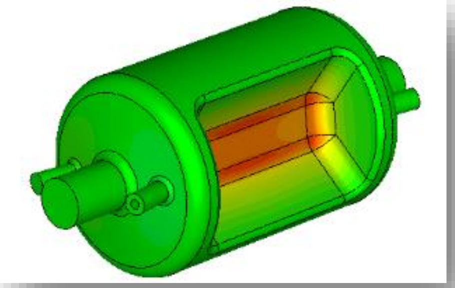
Maximize bunch intensities, minimize the beam emittance

LHC Injectors Upgrade

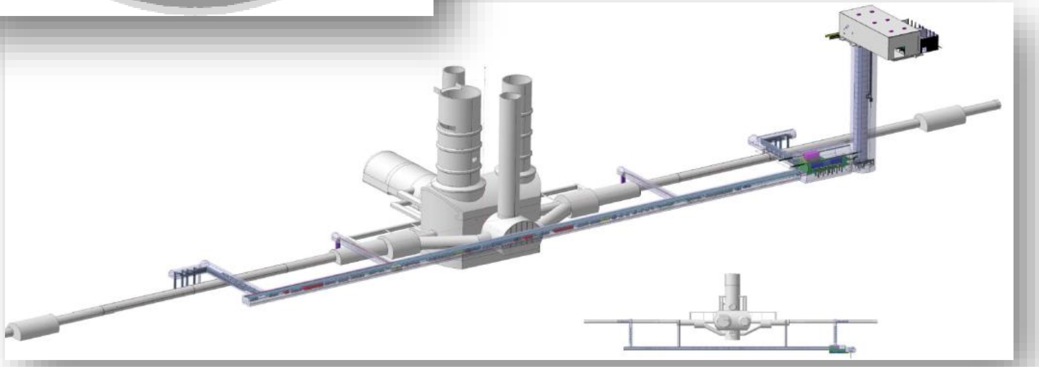
Minimize beam size



Compensate for ‘F’



Improve machine efficiency

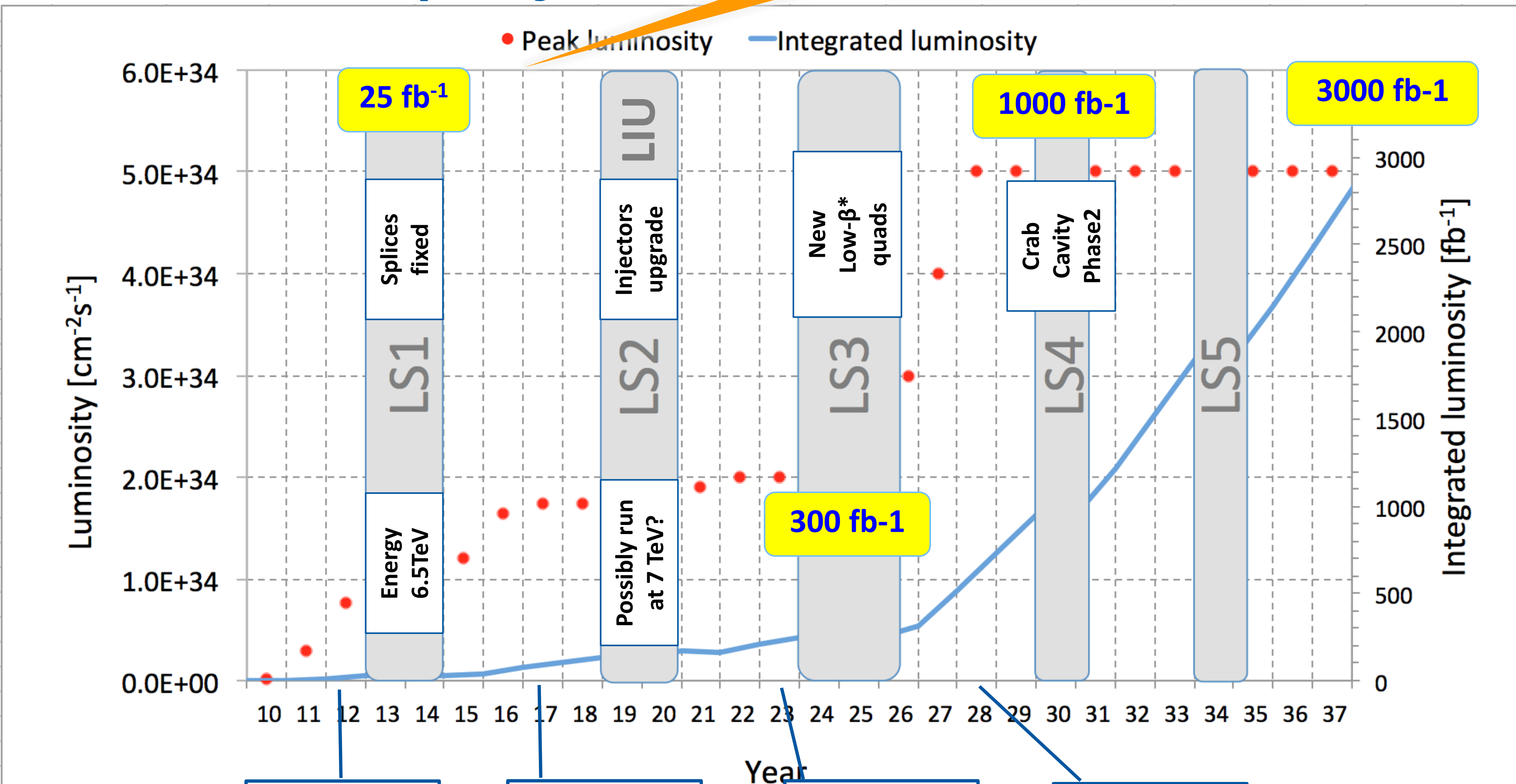


HL-LHC Parameters

Parameter	Nominal	HL-LHC	HL-LHC updated
Bunch population N_b [10^{11}]	1.15	2.2	2.2
Number of bunches	2808	2748	2748
Beam current [A]	0.58	1.12	1.12
Stored Beam Energy [MJ]	362	677	677
Full crossing angle [μrad]	285	590	512
Crossing angle with crab cavities [μrad]	285	0	150
Beam separation [σ]	9.9	12.5	12.5
Min β^* [m]	0.55	0.15	0.2
Normalized emittance ε_n [μm]	3.75	2.5	2.5
r.m.s. bunch length [m]	0.075	0.081	0.081
Virtual Luminosity (w/o CC) [10^{34} cm^{-2}s^{-1}]	1.2 (1.2)	21.3 (7.2)	13.8 (6.95)
Max. Luminosity [10^{34} cm^{-2}s^{-1}]	1	5.3	5.3
Levelled Pile-up/Pile-up density [evt. | evt./mm]	26/0.2	140/1.2	140/1.2

HL-LHC projections

Training of 2 sectors to 7 TeV before the EYETS 16/17



0.75 10^{34} $cm^{-2}s^{-1}$
50 ns bunch
high pile up ~40

1.6 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
high pile up ~40

1.6 -2.2 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
very high pile up > 60

5 10^{34} $cm^{-2}s^{-1}$ levelled
25 ns bunch
very high pile up ~140

Few concluding remarks

- The LHC (and the injector complex) performance have been outstanding in the past and present times
- After a wavering start-up, the objective of 2016 has been reached and will be most probably exceeded
- The foundations for a successful completion of the Run II are laid

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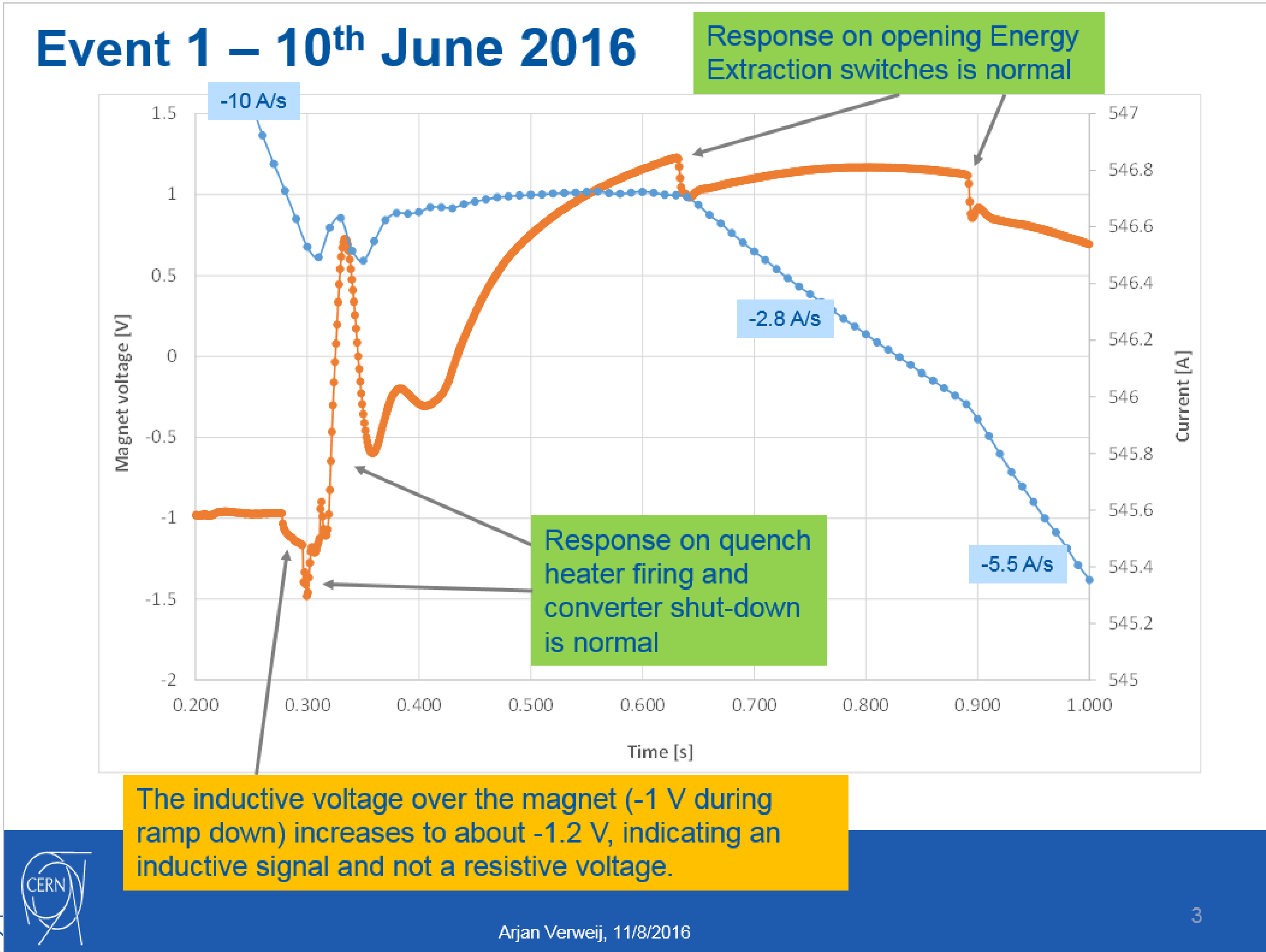
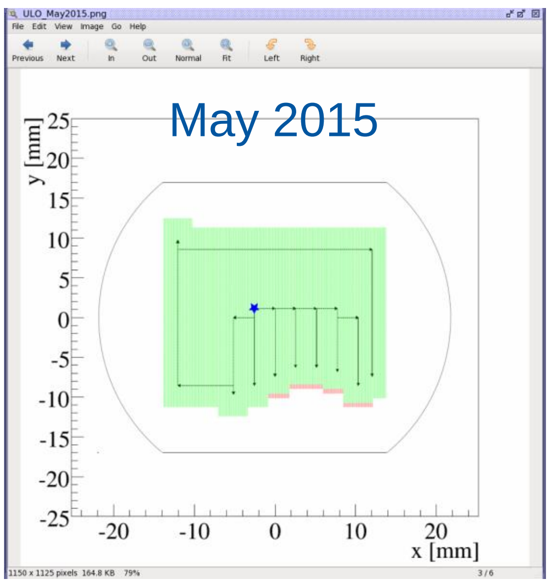
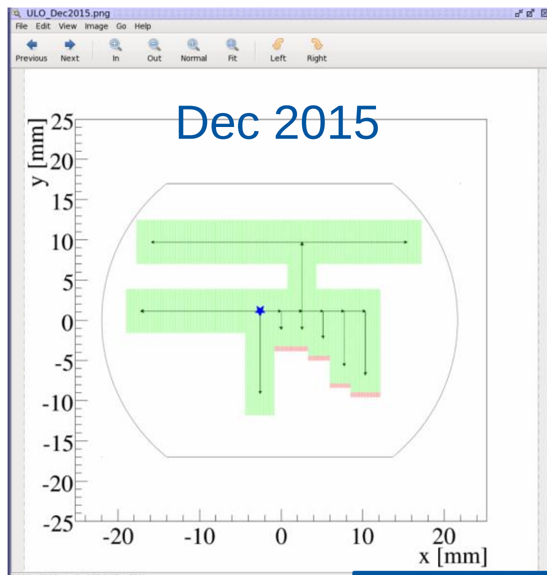
Dipole inter-turn short

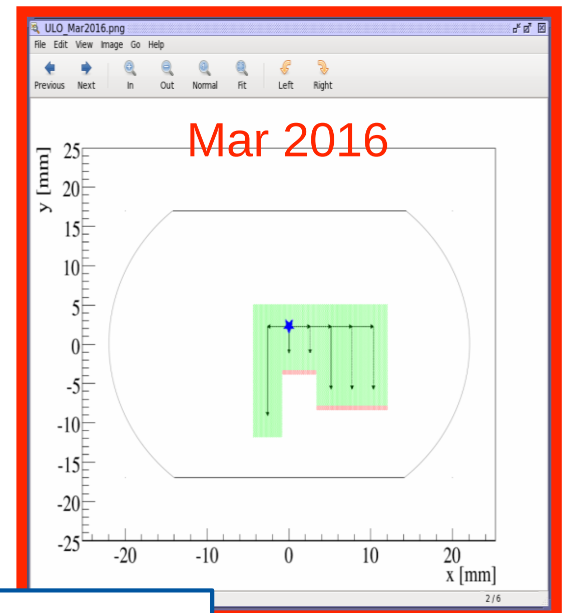


ULO scan

- The ULO is still there
- We bump around it with -3 mm (H) and +2 mm (V) offsets (last year -3 & +1 mm)
- Bump is included in all orbits







Looks similar to Dec 2015

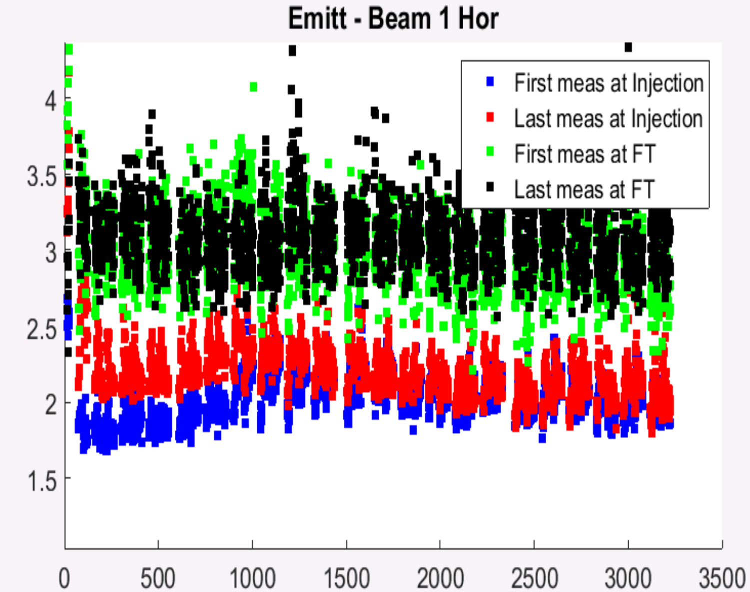
Aperture measurements

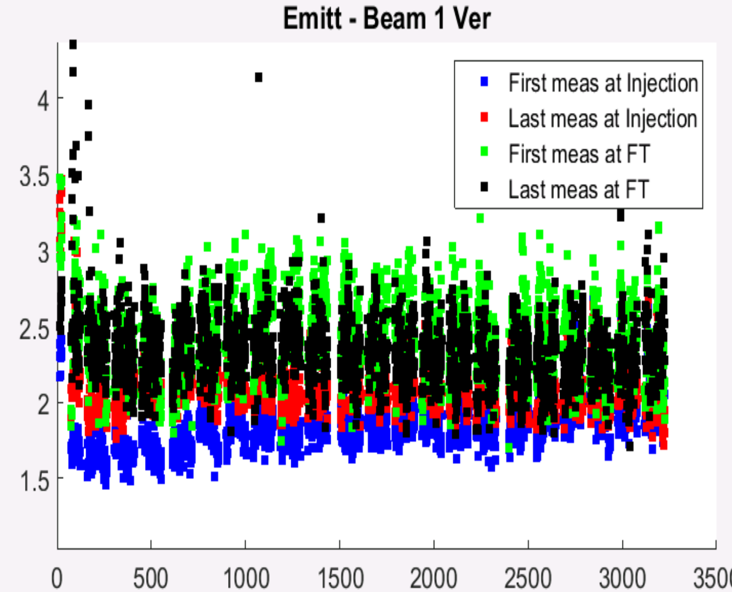
- Measurements to assess if there is any bottleneck in the machine in the different phases

	Beam / plane	Aperture (sigma)	Location
Injection	B1H	12.5-13.0	MBRC.4R8
	B1V	12.0-12.5	Q6.L4
	B2H	12.5-13.0	TCDQM.4L6.B2
	B2V	12.5-13.0	Q4.R6
Collision	B1H	11.5-12	Q3.R5
	B1V	~10	Q3.L1
	B2H	11.0-11.5	Q3.R1
	B2V	10.5-11.0	Q3.R1

At the limit for B1V, but considered acceptable

Emittance evolution





Green -> Beginning of FT

Black -> Before dump

Fill 5102

G. Trad