CERN

The Large Hadron Collider: status and plans

Roberto Losito, CERN

Outlook

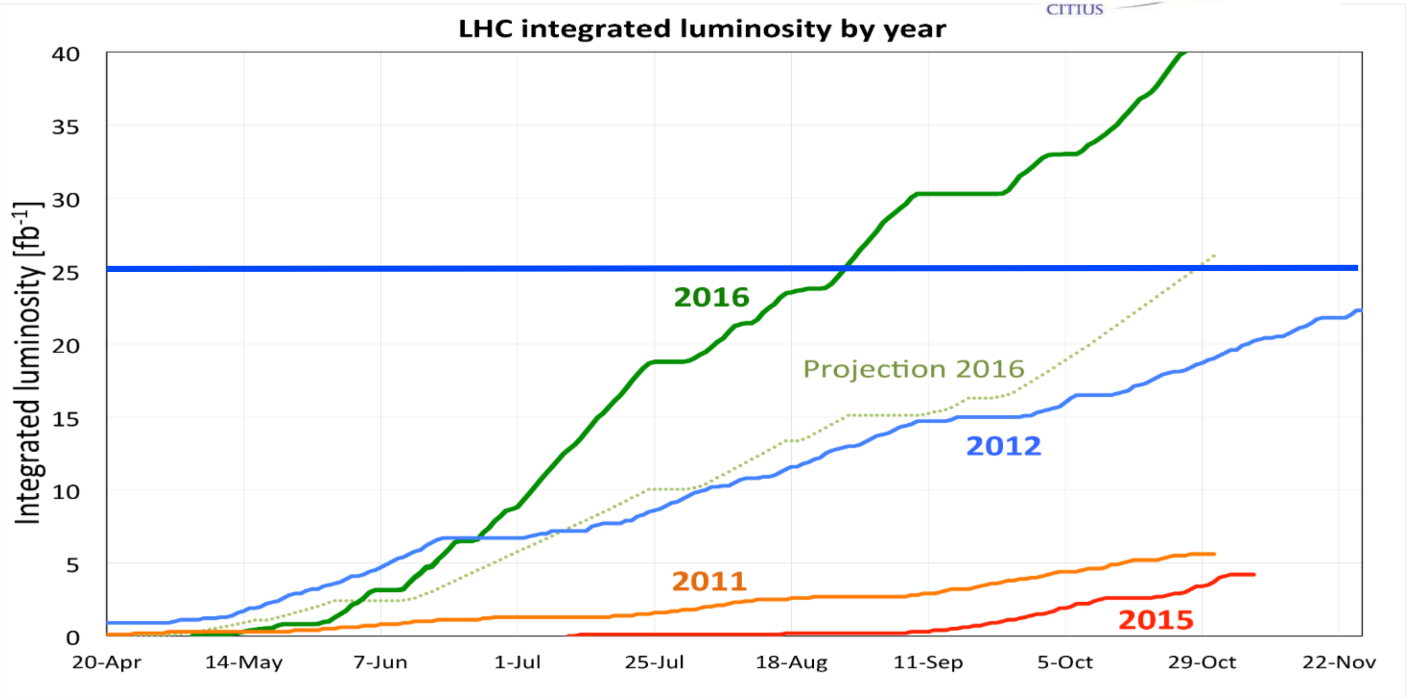
- 2016 Operation and limitations
- Upgrades during EYETS
- Scenarios for 2017 (and Beyond…)

The glorious past

2011: 3.5 TeV
2012: 4 TeV
2015/16: 6.5 TeV

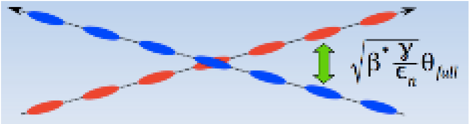
Peak luminosity > 1.35 x 10^{34} $cm^{-2}s^{-1}$

about 40 fb^{-1} in both ATLAS and CMS ☺



Main highlights of 2016

- Stable operation with high intensity beams
  - Control of e-cloud through the 8b+4e scheme



- Beta* reduced to 40 cm
  - Crossing angle correspondingly reduced: no fundamental limit reached

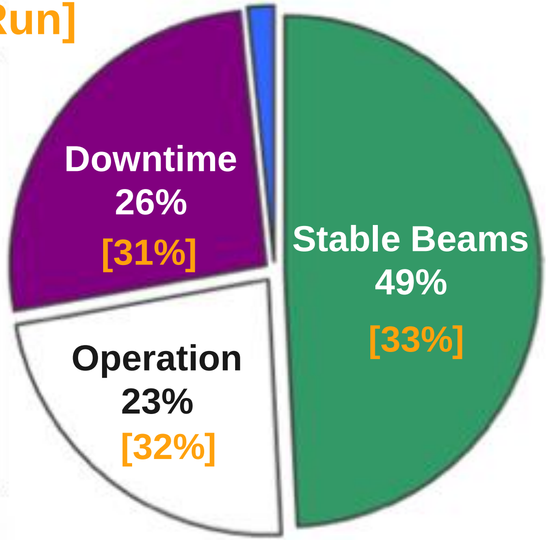
- Deployed routine operation with high brightness beam for high luminosity (Batch-Compression-Merging-and-Splitting, BCMS)

- Settings optimized (Q, Q’, octupoles, feedback) → **better beam quality, e-cloud minimised**

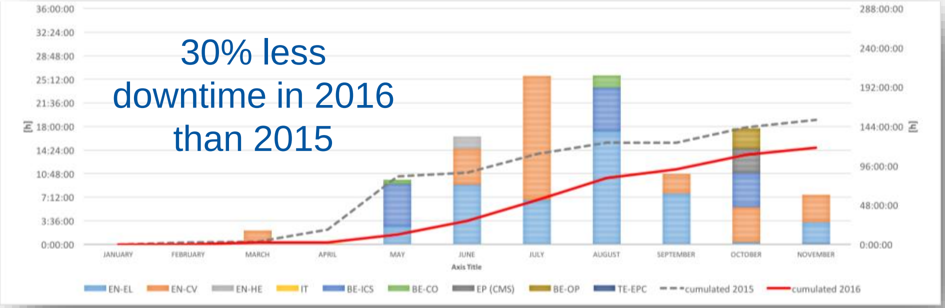
2016 Availability

Remarkable availability:

- **Increased** operational efficiency
- **Enhanced** system availability
- **New** pre-cycle strategy



Downtime of technical infrastructures



Non-availability of beams from the injector complex is the largest source of LHC downtime

LHC Limitations in 2016

SPS beam-dump

Nb of bunches per injection limited to 96

Total number of bunches: 2200

LHC Injection kickers

Outgassing from ceramic

Bunch population limited to around 1.1 x 10^{11}

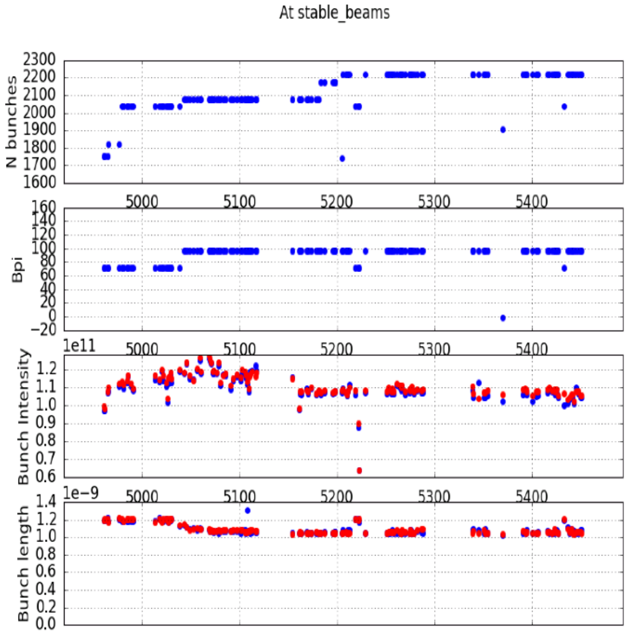
Electron cloud

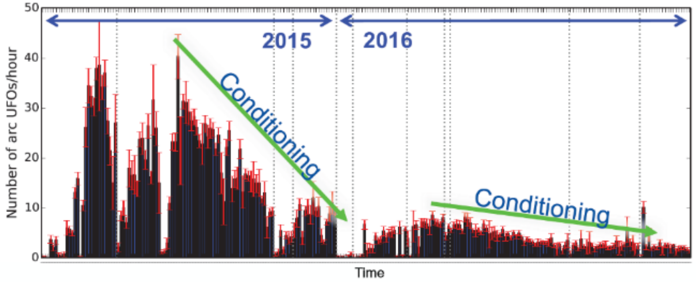
Still significant heat-load within cryogenic limits

Dynamics – well handled by cryogenics feed-forward – no impact on operations in the present conditions

UFOs

Frequency has happily conditioned down





SPS Beam Dump

The SPS internal beam dump developed a vacuum leak in April 2016

- Operation possible with limited number of bunches
  - 96 BCMS or 144 normal

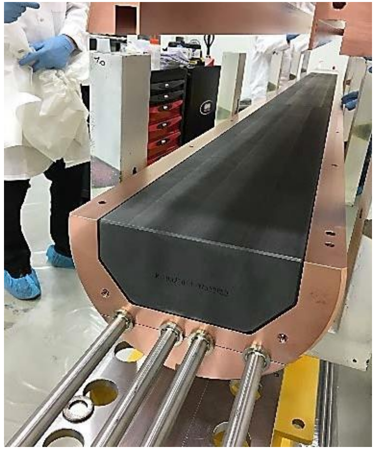
Crash program to develop an improved version

- Simplify manufacturing
- Overcome historical vacuum limitations by improving cooling of (no more aluminum)

SPS new beam dump: assembly (TIDVG#4)

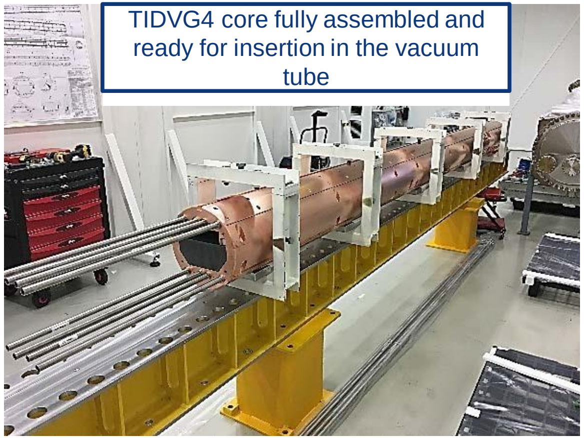
- The dump core has been assembled at CERN in January 2017
- 3.5 m graphite, 40 cm CuCrZr and 40 cm Inermet (Tungsten)

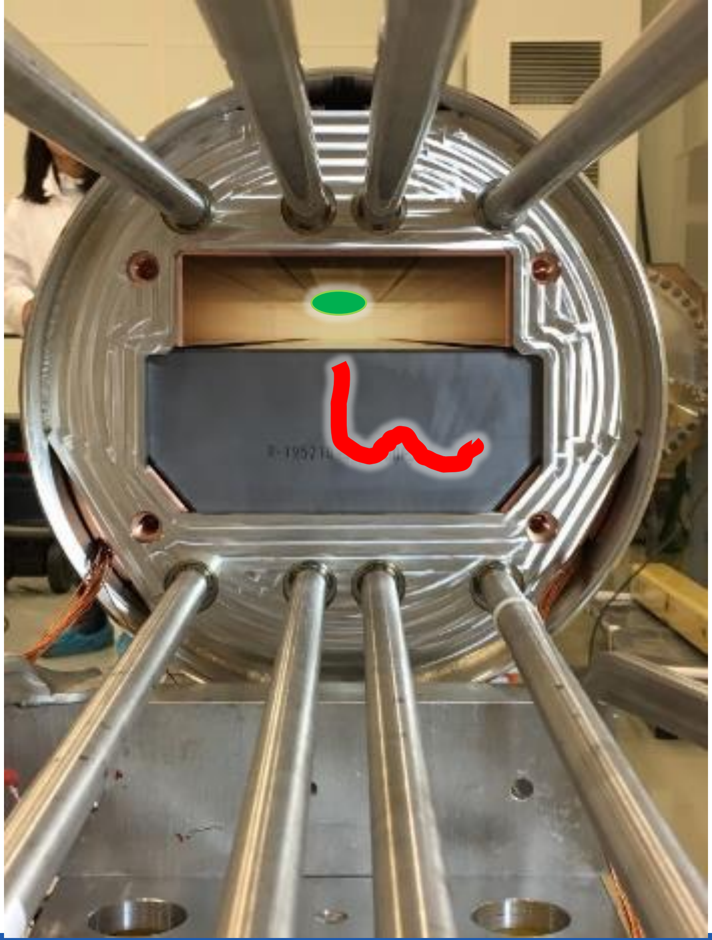
Graphite inside the CuCrZr core



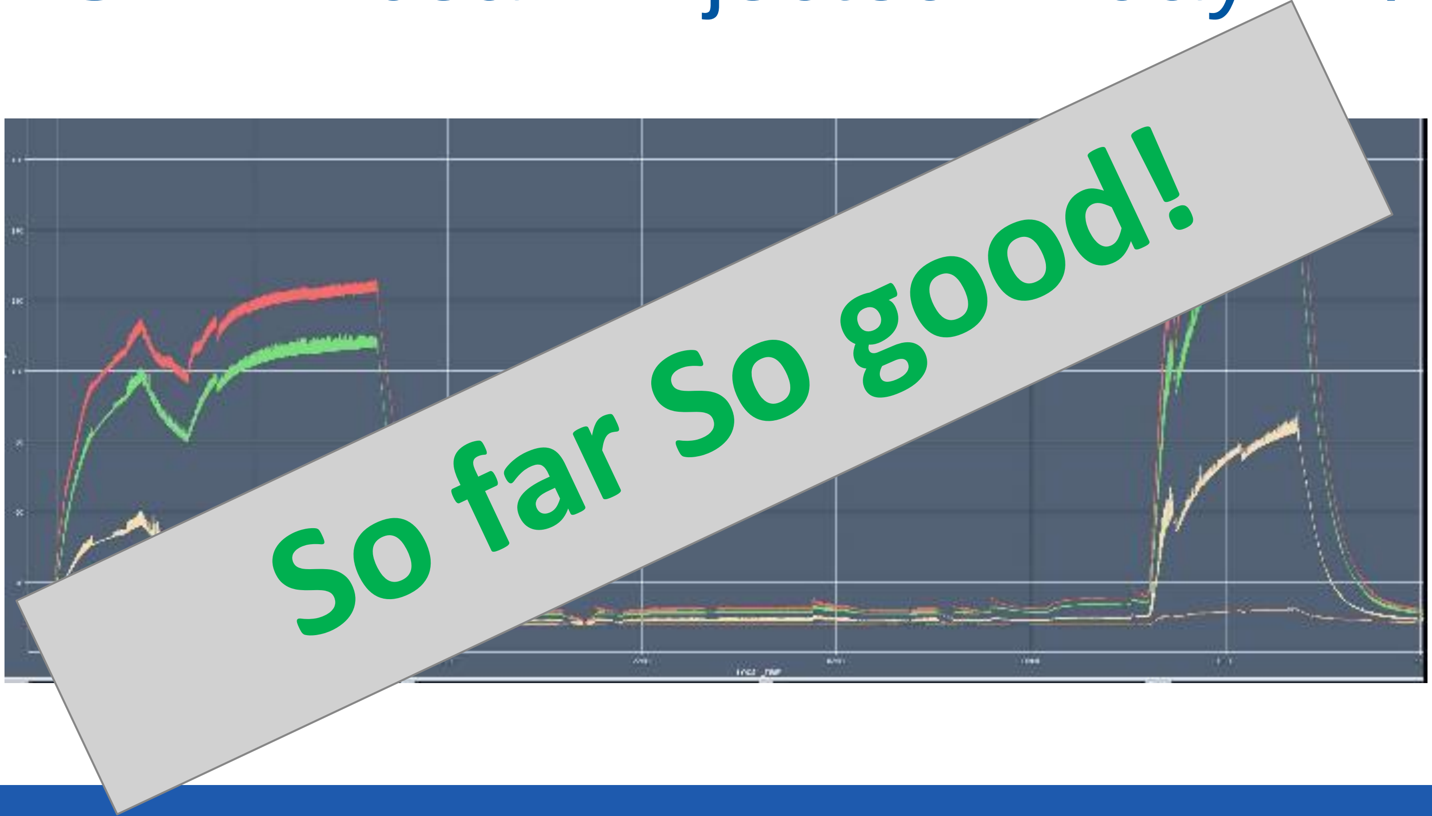
Medium/high-Z absorber

TIDVG4 core fully assembled and ready for insertion in the vacuum tube

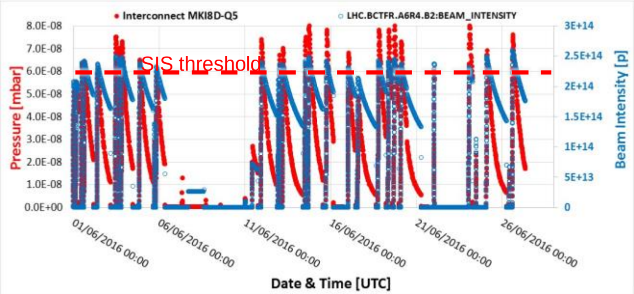


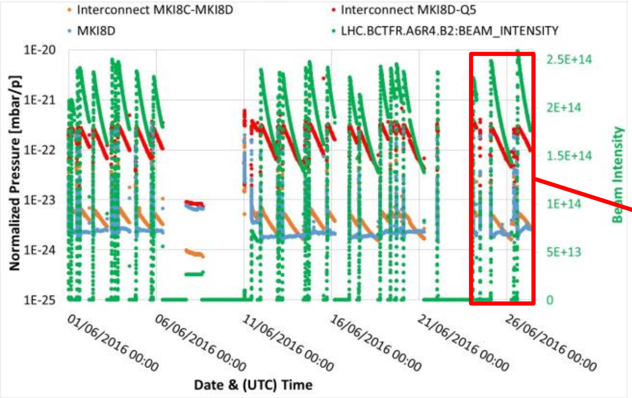


SPS – 1st beam injected Friday 21/04



Electron Cloud around MKI8D/2D





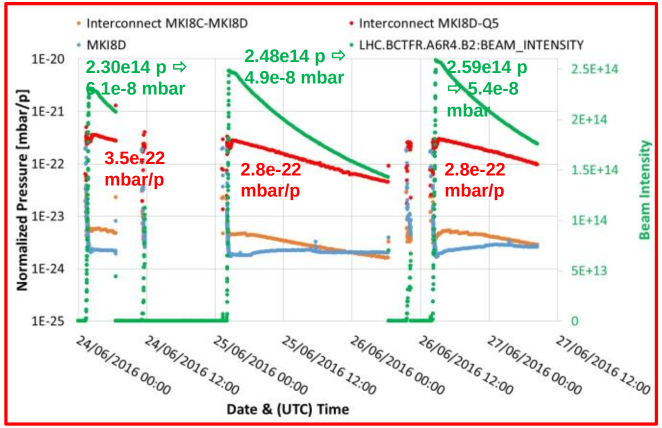
Dynamic pressure rise, c.f. no beam:

- Factor of ~20 in most MKI8 interconnects
- BUT **factor of ~1000 in MKI8D-Q5 interconnect**
- Factor of ~10 in MKI tanks

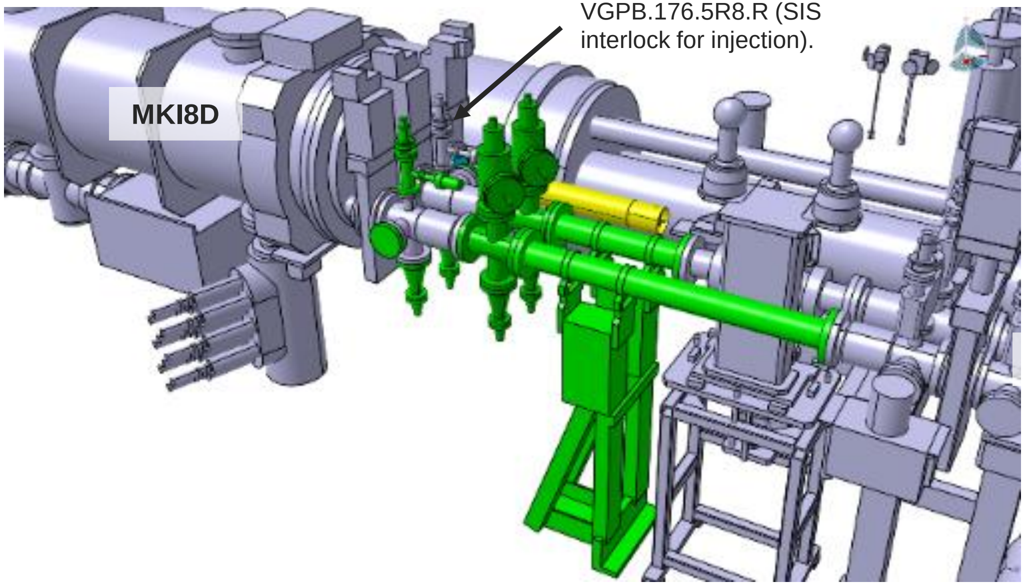
Fill 5038
25ns, 72bpi
B2 – 3 injections missing

Fill 5043 (2x48).
25ns_2076b_2064_1717_1767_96bpi_23inj

Fill 5045 (2x48).
25ns_2076b_2064_1717_1767_96bpi_23inj (design luminosity !)



MKI8D/2D Vacuum Upgrade



EYETS - Two new NEG cartridges of 400 l/s each now integrated in new modules of vacuum sector I5R8 and I5L2 respectively.

- **The upgrade will locally increase the pumping speed by factor ~2 to 3 and hence maintain the dynamic pressure increase in the MKI8D-Q5 interconnect well below the interlock threshold (5e-8 mbar) up to the nominal number of 25 ns bunches.**

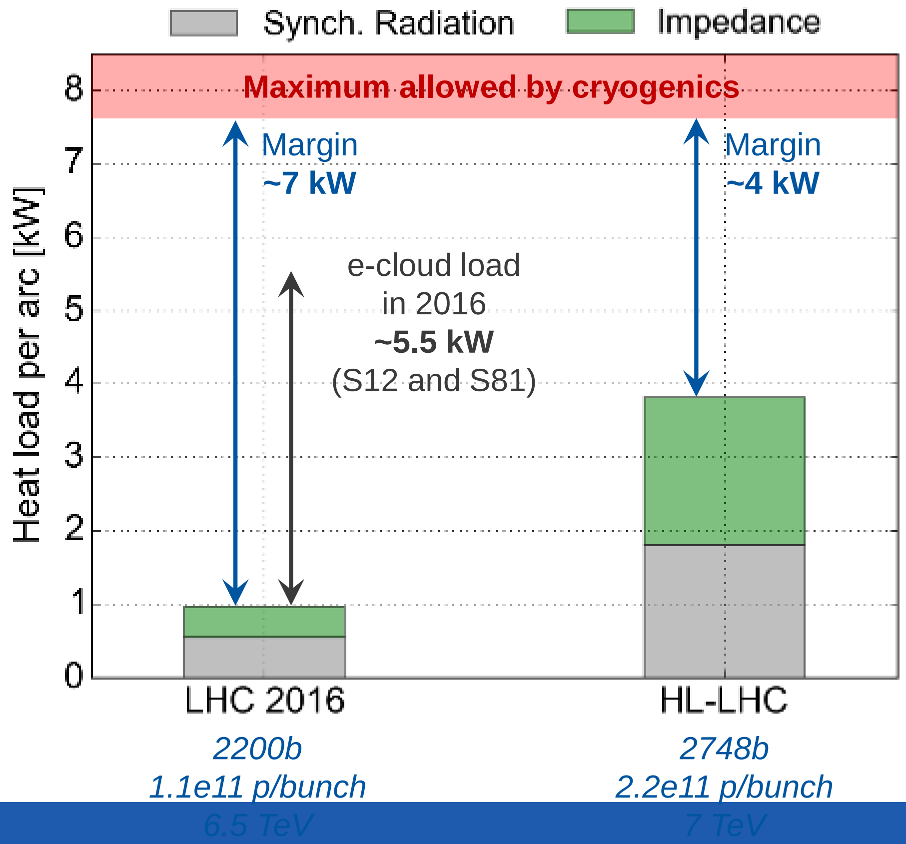
Expected to allow increasing bunch intensity from 1.1 x 10^{11} to 1.3 x 10^{11}

- Long Term mitigation being investigated: **Cr_2O_3 coating could lower the SEY from 10 to ~1.4** and is expected to **increase the surface flashover voltage**

Electron Cloud

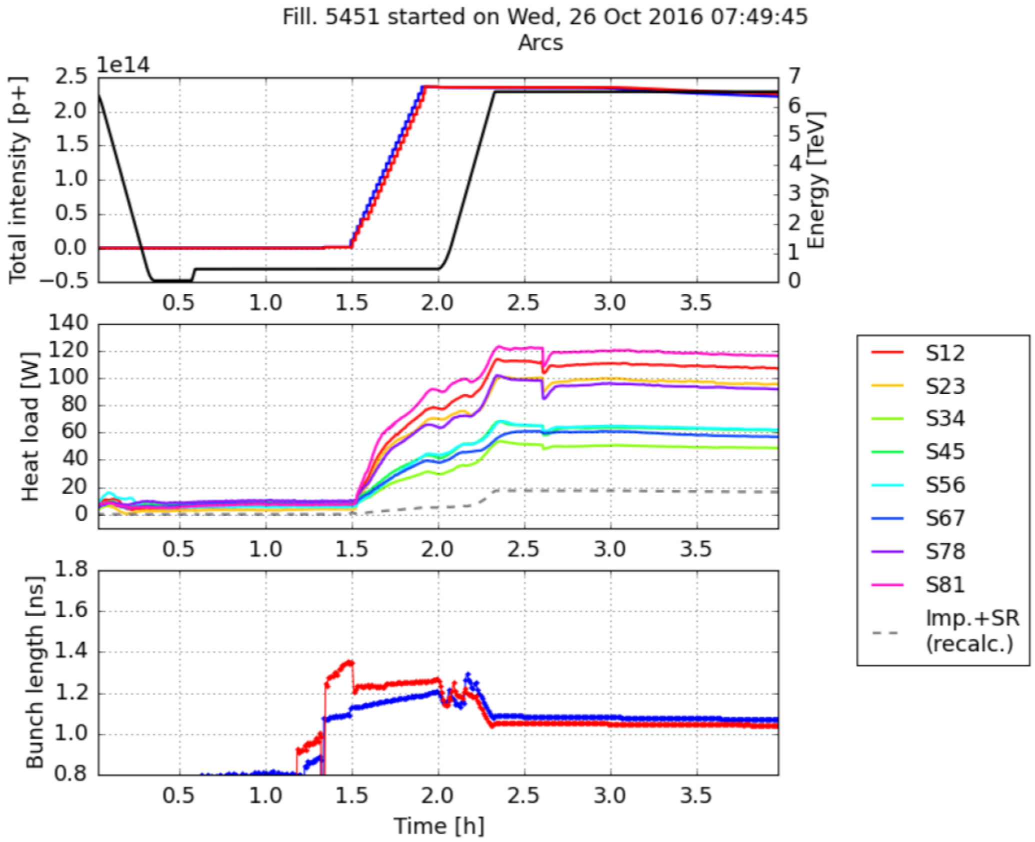
- **Breakthroughs**
  - Cryogenic feedforward
  - MDs with specific beam patterns, e.g. 8b+4e beams

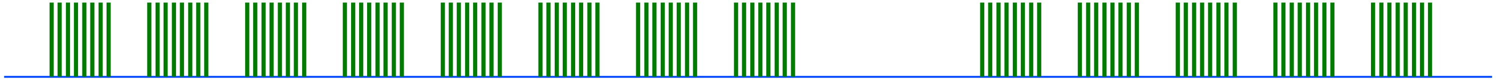
- **Issues remaining**
  - Mechanism not yet reproduced in laboratory
  - Different behavior in the different sectors



E-cloud

- Heat load very different in different sector
- Origin of difference is not understood



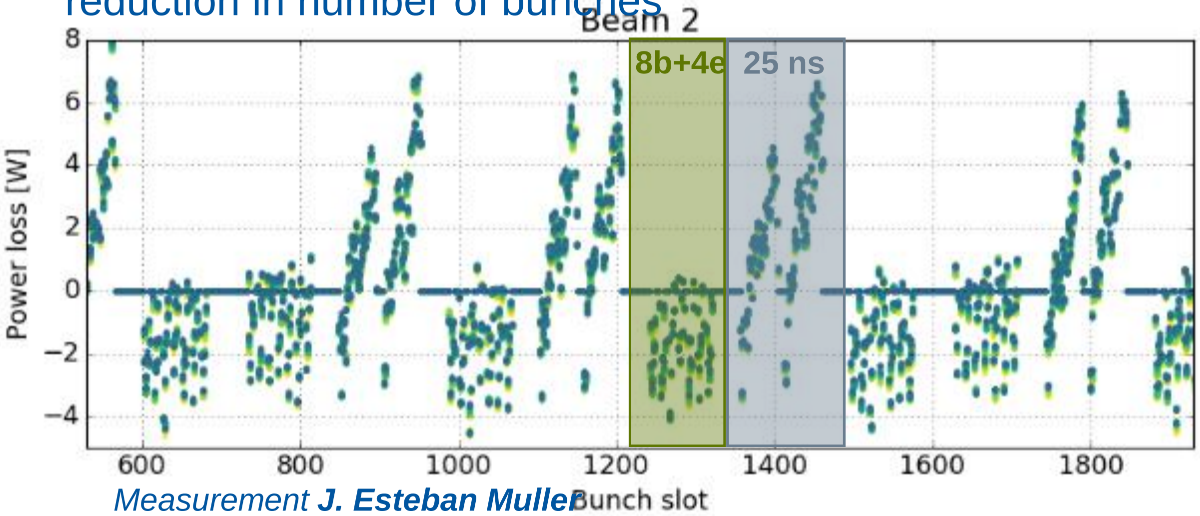


8b+4e scheme: Filling pattern designed to suppress the e-cloud (but ~30% less bunches)

- e-cloud suppression **proved experimentally** at the LHC in 2015
- In 2016 MD we tested **mixed filling schemes** combining std. 25ns and 8b+4e trains

→ **Promising:** obtained 40% reduction on e-cloud heat load against 15% reduction in number of bunches

Heat load per arc [kW]



*Measurement **J. Esteban Muller***

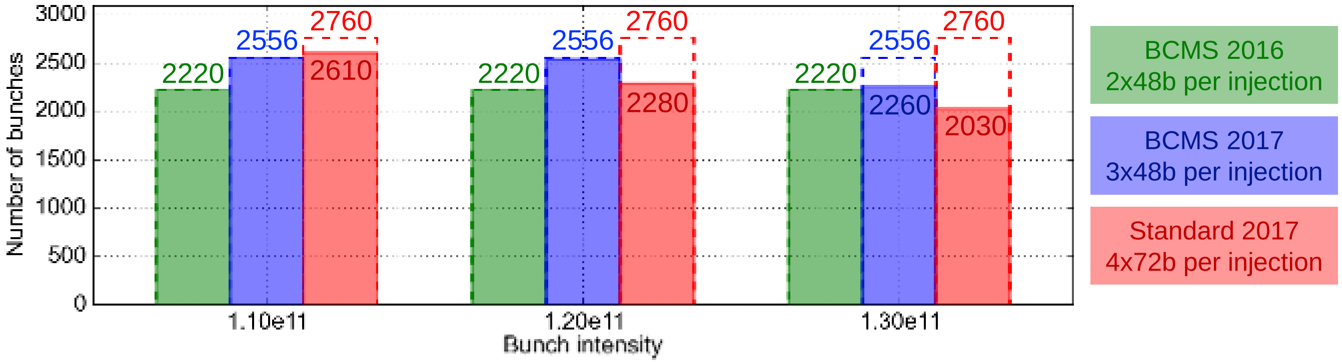
Heat load estimates: BCMS vs standard

"Standard 2017", 2760b., 4x72b per injection

→ Cryo capacity **limit is already reached** for a bunch intensity of **1.1×10^{11} p/bunch**

→ For larger bunch intensity the standard scheme is limited to a **number of bunches** that is even **lower than BCMS**

Dashed bars: max. allowed by filling scheme, **Full bars:** max. allowed by heat load limit



Standard scheme (lower brightness) **does not really allow for a larger number of bunches!**

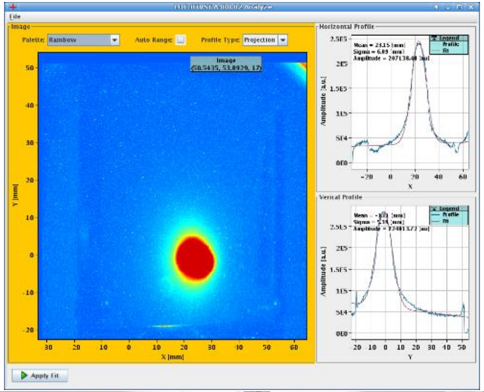
→ **BCMS** seems to be the **natural choice for 2017-18**, but probably **we will not see more conditioning than in 2016**

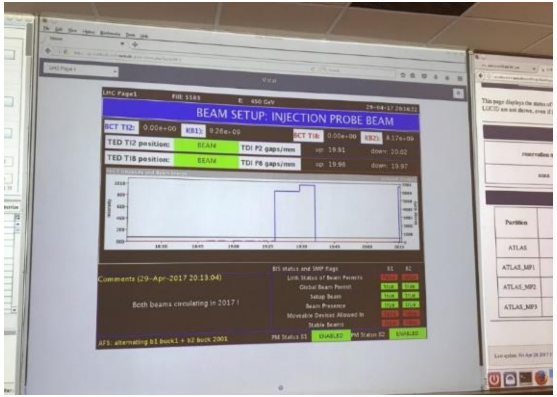
  → Not much impact on Run 2 performance but concerns for Run 3 and HL-LHC

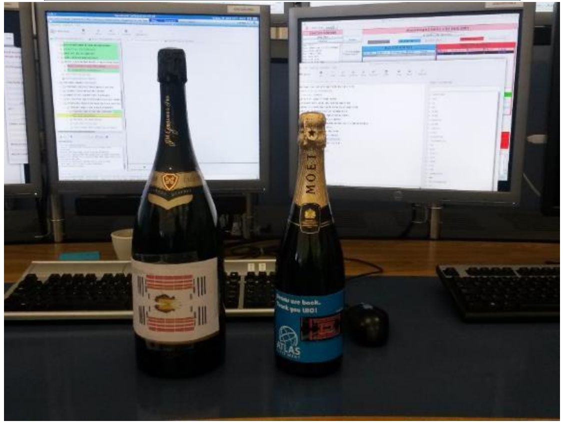
  → A period with long bunch trains (4x72b) could be envisaged if this scheme shows to be promising during the scrubbing run

2017 (and beyond) Scenarios

2017: beams are back in LHC from Friday 29th April







2017 scenarios

	Nominal	BCMS	BCMS+
Beta* (1/5) [cm]	40	40	33
Half crossing angle [urad]	185	150	170
No. of colliding bunches	2748	2544	2544
Proton per bunch	1.1e11	1.2e11	1.2e11
Emittance into SB [um]	~3.2	~2.3	~2.3
Bunch length [ns]	1.05	1.05	1.05
Peak luminosity [$cm^{-2}s^{-1}$]	~1.1e34	~1.7e34	~1.8e34
Peak pile-up	~28	~48	~52
Luminosity lifetime [h]	~24	~15	~14

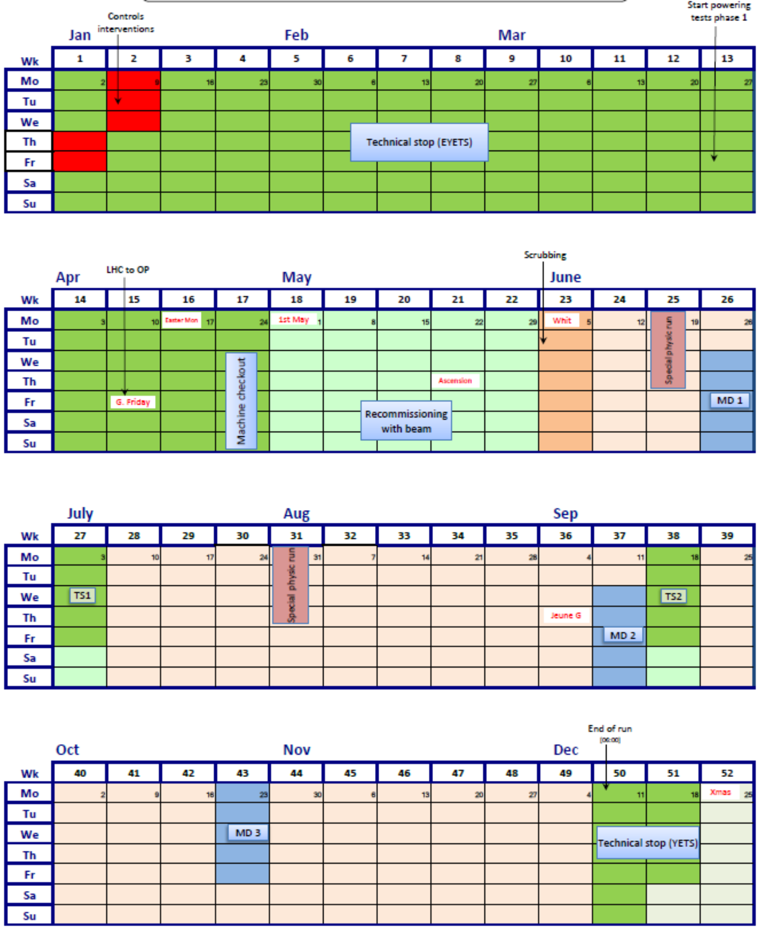
2017 plans: 45fb^{-1}

- Keep pushing performance and **availability (~50%)**
- BCMS beams (Smaller emittance though cycle; lower electron cloud heat load; faster intensity ramp-up; lower total beam current; lower losses; better for R2E... pile-up ?) **=> maximize integrated luminosity**
- Starting with ATS optics; β^* = 40 cm and later towards 33 cm

  (would deploy HL-LHC optics and open up the exploration of its possibilities)

  => expect to reach 1.7 to 1.9 10^{34} cm^{-2} s^{-1}

  (inner triplet cooling limit ?)
- No Ions !!!



Increasing Energy?

LHC Energy Exploitation

Full Energy Exploitation of the LHC mandate – Chair: Oliver Bruning

Main scope and goal:

Part of a general study that is divided into 3 parts:

I. Implications for pushing the LHC to 7 TeV (nominal energy) → **report 2017**
II. Implications for pushing the LHC to 7.7 TeV (ultimate energy) → **report 2018**
III. Implications and feasibility for pushing the LHC beam energy beyond ultimate by replacing some of the LHC magnets with 11T magnets → **report for the ESPP**

Part I :

Time required for training all magnets to 7TeV

→ provide robust data to the management for estimating the performance reach if the LHC is pushed to 7TeV before LS2

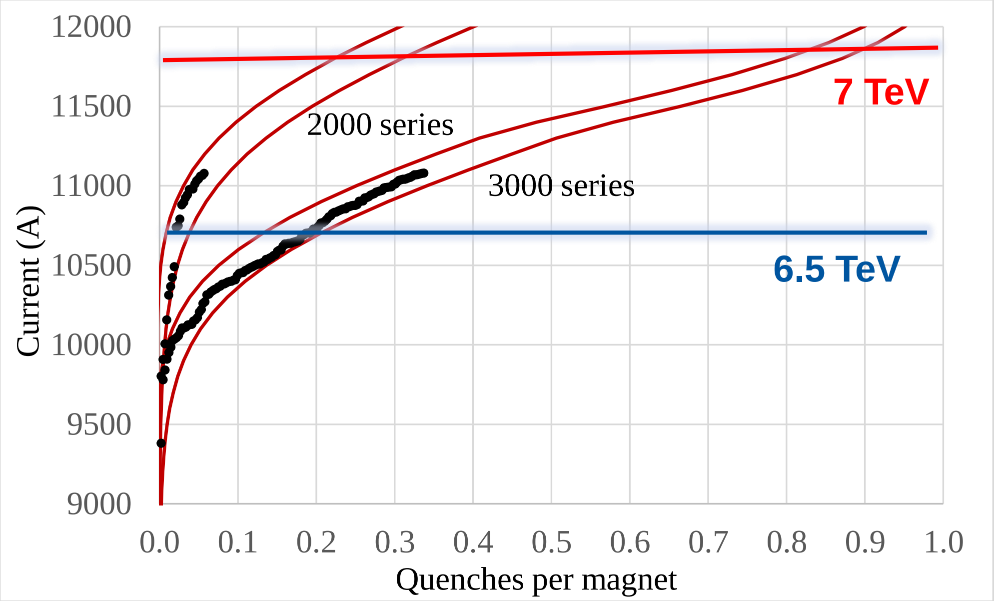
Perform training campaigns in S34 and S45 before EYETS 16/17

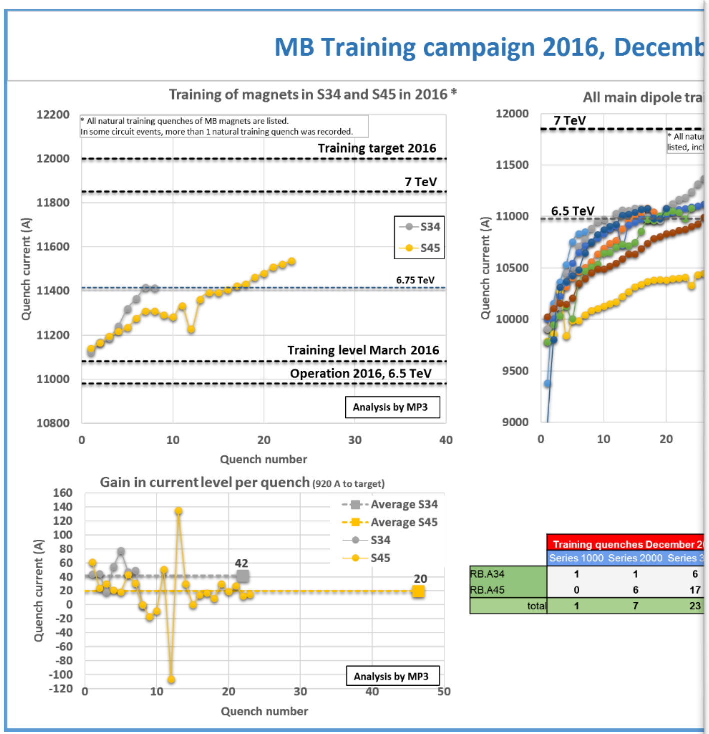
→ Explore if there are any ‘unforeseen’ obstacles when training a large fraction of the machine to 7TeV

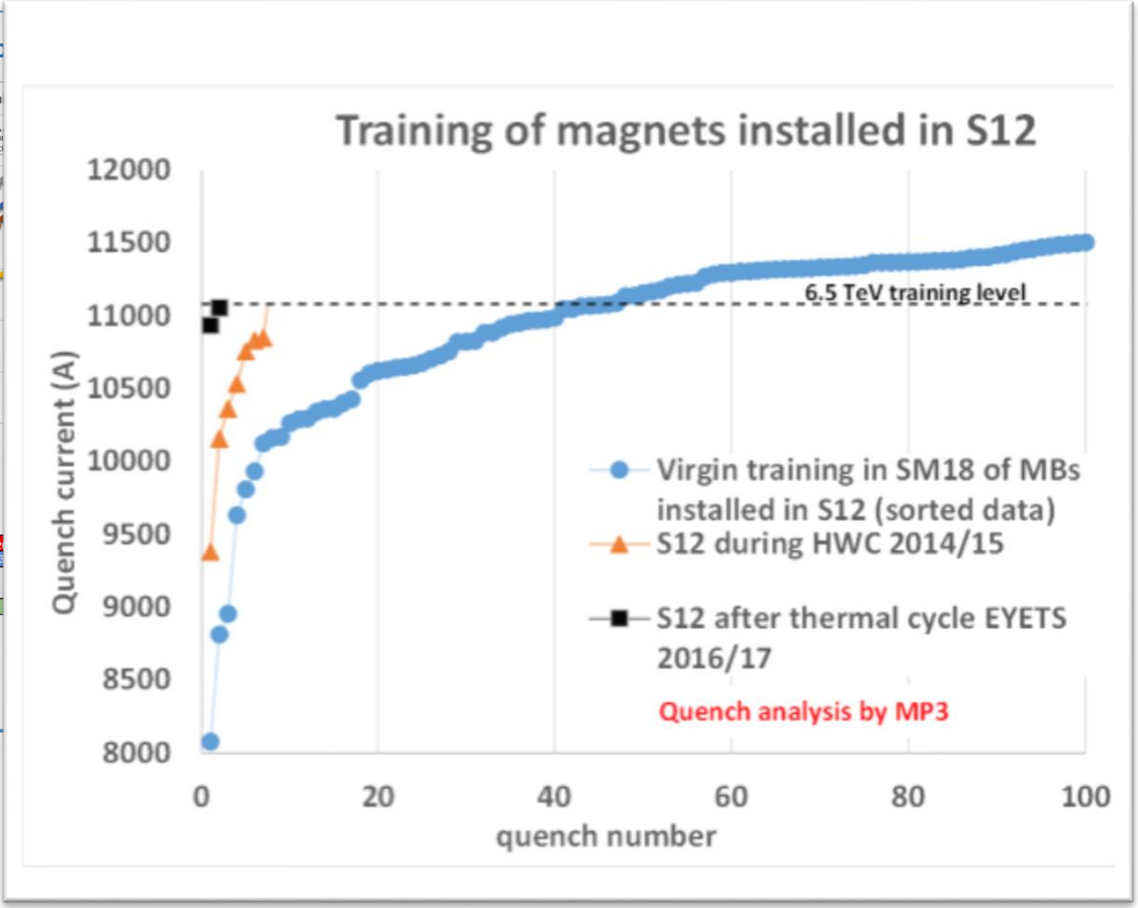
Training Quenches analysis for 7 TeV operation

- Training quenches follow a statistical model

- Need data from machine to make realistic estimates




MB Training campaign 2016, Decemb
Training of magnets in S34 and S45 in 2016 *
* All natural training quenches of MB magnets are listed.
In some circuit events, more than 1 natural training quench was recorded.
Training target 2016
7 TeV
S34
S45
6.75 TeV
Training level March 2016
Operation 2016, 6.5 TeV
Analysis by MP3
Quench current (A)
Quench number
All main dipole trai
7 TeV
6.5 TeV
Gain in current level per quench (920 A to target)
Average S34
Average S45
S34
S45
42
20
Analysis by MP3
Quench current (A)
Quench number
Training quenches December 2
Series 1000 Series 2000 Series 3
RB.A34 1 1 6
RB.A45 0 6 17
total 1 7 23

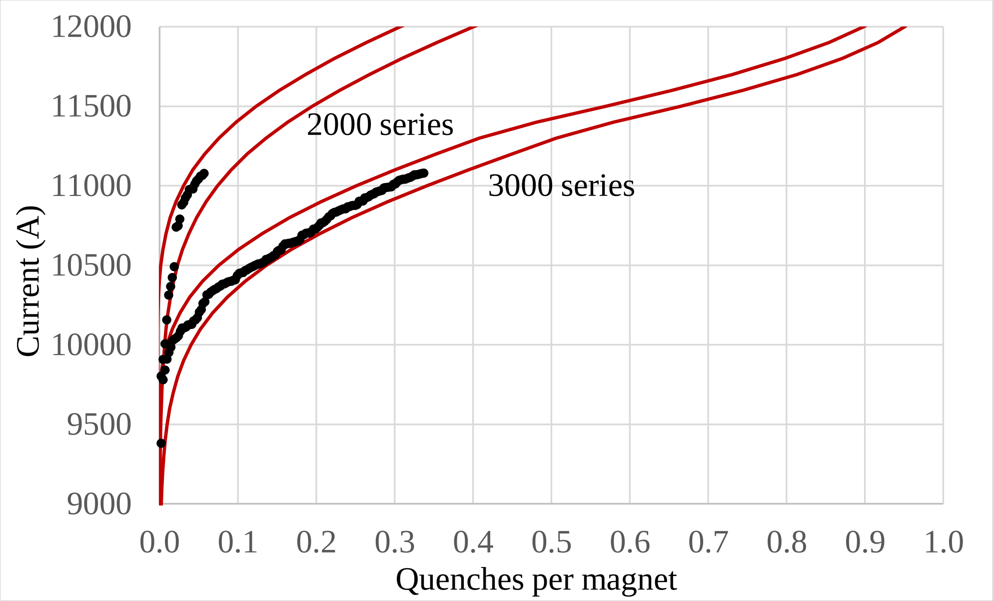

Training of magnets installed in S12
6.5 TeV training level
Virgin training in SM18 of MBs installed in S12 (sorted data)
S12 during HWC 2014/15
S12 after thermal cycle EYETS 2016/17
Quench analysis by MP3
Quench current (A)
quench number

Training Quenches extrapolation for 7 TeV operation

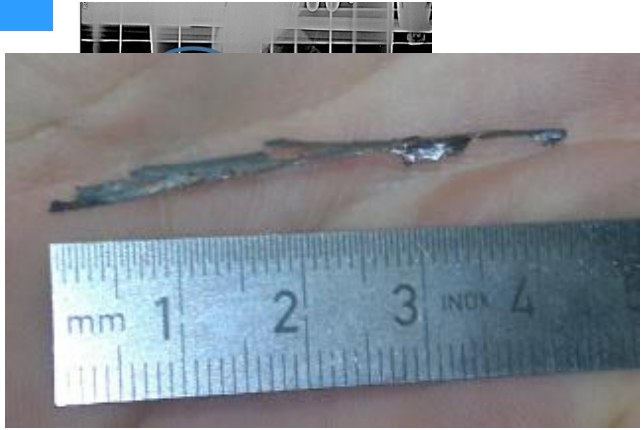
- Magnets from different production show different behavior

- *Expect need for ~600 Quenches (~35 days)*

- *Consequence of non recoverable Earth Fault ~ 3 months stop*



LHC Energy Exploitation



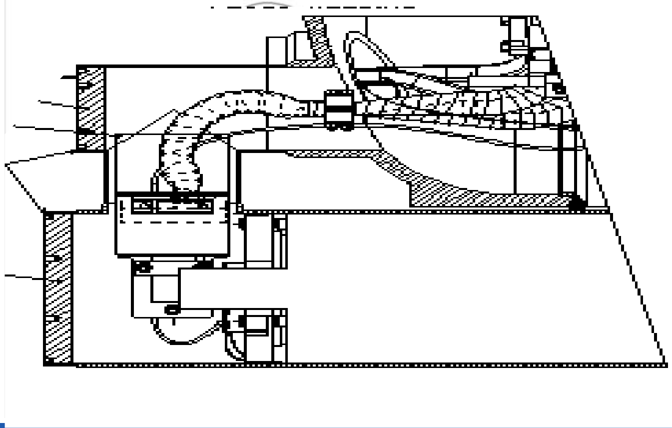
Unforeseen obstacles:

Short in the diode box following a training quench:

=> released energy during quench at high energy is capable of displacing debris that has collected in the diode box

=> Second incident during training in ca. 252 quenches but had also 5-6 shorts before LS1)

Earth Fault Burner:
Solution that removed two shorts
But no guarantee that this method will always work



Beam energy : **Run 2 @ 13 TeV c.m.**

NO change of beam energy in 2017 and 2018

Goal is to prepare the LHC to run at 14 TeV during Run 3.

Preference to make the change in energy in a single step.

Study how to reinforce the insulation (and to clean) during LS2 the electrical part connecting the dipole bypass diode. Powering tests before and during LS2 should be defined

Working group was set up after Chamonix'17 workshop:
How to clean?, How long ?, How much ?

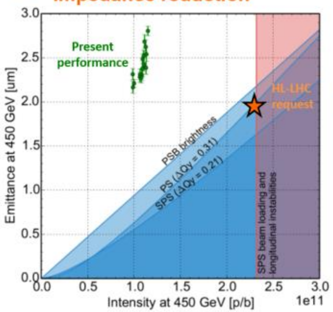
Budget allocated in the new MTP

LIU & HL-LHC

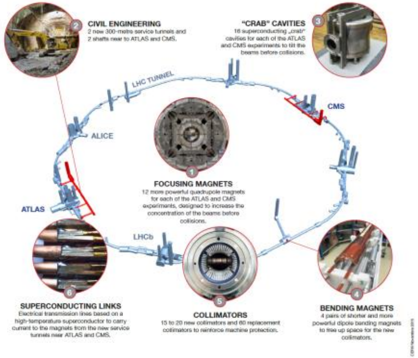
LIU & HL-LHC project

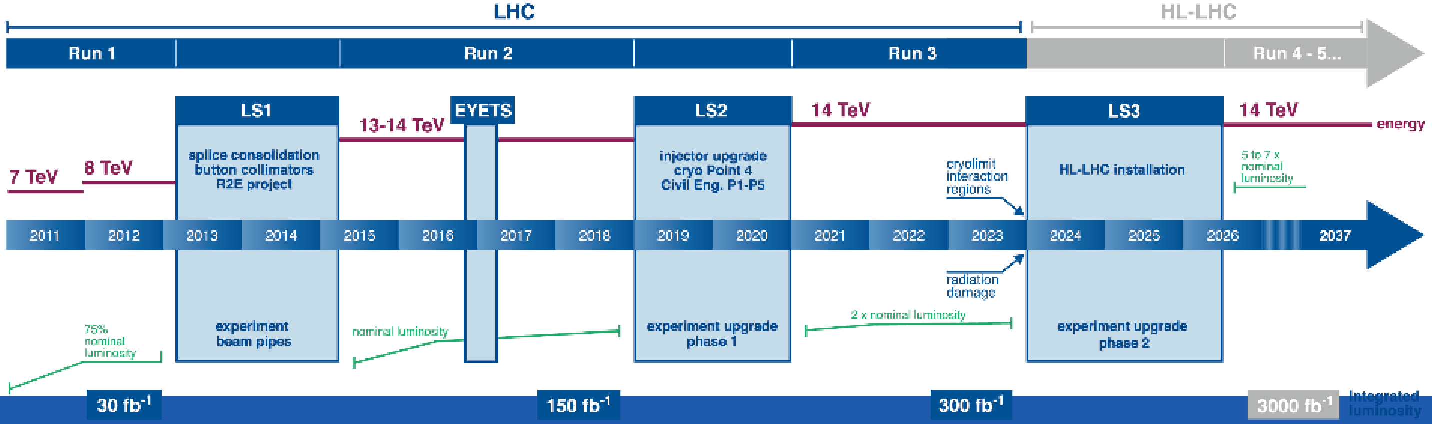
formal approval by CERN Council (June 2016)

LIU performance reach for protons with SPS impedance reduction



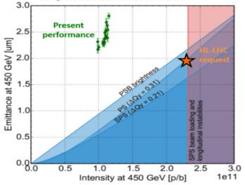
	$\mathcal{N}$ (x 10^{11} p/b)	ε (μm)
LIU Baseline	2.3	2.2
HL-LHC	2.3	2.1





LIU and HL-LHC outlook - PROTONS

LIU performance reach for protons with SPS impedance reduction



	$\mathcal{N}$ (x 10^{11} p/b)	ε (μm)
LIU Baseline	2.3	2.2
HL-LHC	2.3	2.1

Baseline and beam parameters - protons

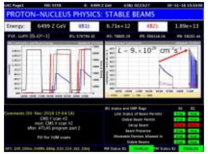
HL-LHC

- The present **baseline is compatible with the integrated luminosity goal** (250 fb^{-1}/year, luminosity levelled at $5x10^{34}$ $cm^{-2}s^{-1}$) relying on LIU to deliver bunches with **$2.3x10^{11}$ p/bunch**
- Several **options** are being studied to **further increase performance** (BCMS+, 80b trains, dynamic crossing angle to further push β*) and for **risk mitigation** (flat beams, 8b+4e, 200 MHz main RF)

LIU

- The **baseline upgrades** (including SPS impedance reduction, following C&S Review 2015) allow reaching **beam parameters compatible with HL-LHC requirements**
- Main **risk factors** (PS longitudinal instabilities and SPS losses at low energy) are being investigated in order to define **suitable mitigation measures**

LIU and HL-LHC outlook - IONS



Baseline and beam parameters - ions

HL-LHC

- The **baseline upgrade meets the goal of accumulating 2.85 nb^{-1}** in each Pb-Pb run (with 3 experiments; 10nb-1 before LS4). This relies on the injectors providing beams with **50 ns** bunch spacing and bunch intensities of **1.9×10^8 ions/bunch**
- Specific **upgrades on the collimation system**, i.e. new collimators in the dispersion suppressors of IR2 and IR7, will be **implemented in LS2**

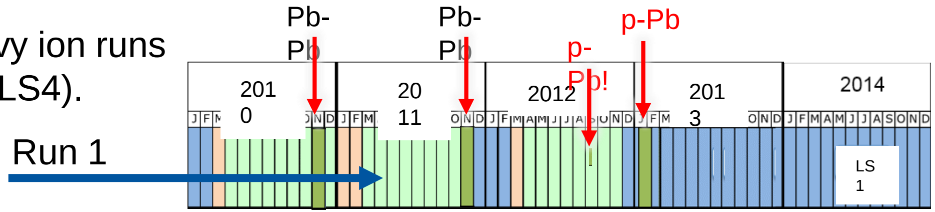
LIU

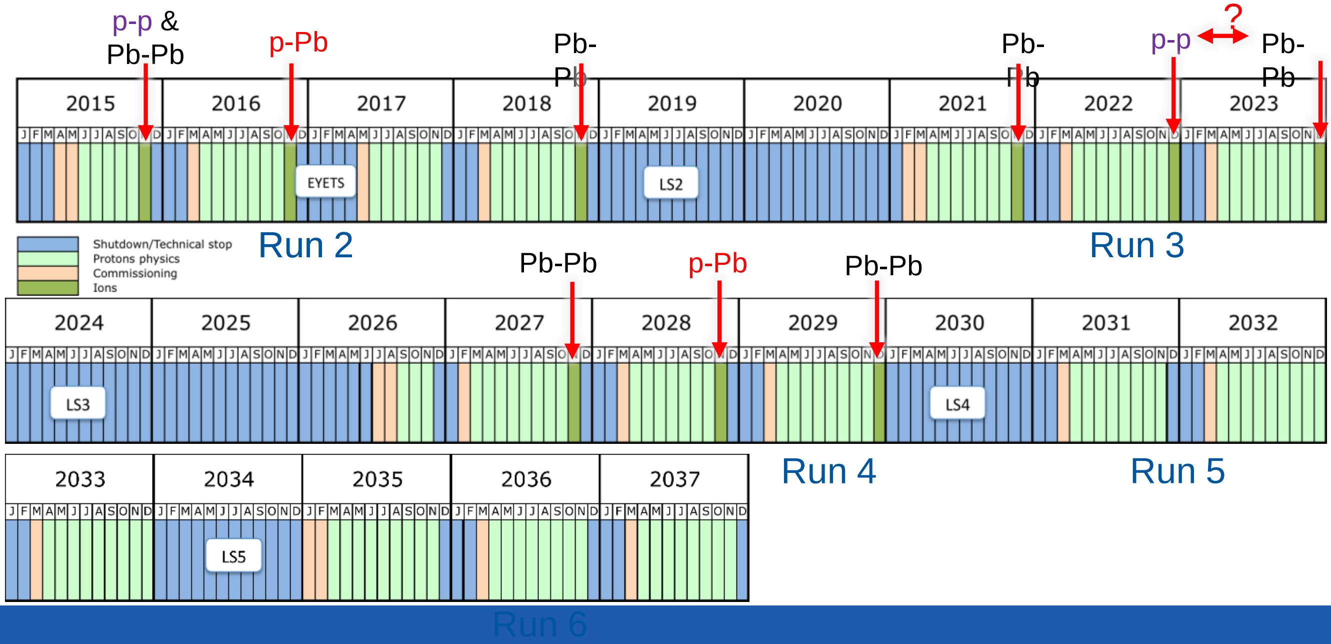
- Ion **chain restarted earlier in 2016** to allow for extended period for **studies** and machine **optimization → doubled intensity per PS batch** injected in the LHC
- **Earlier start** of ion chain **requested also for 2018**
- This performance together with the implementation of **momentum slip-stacking** in the SPS after LS2 (new low-level RF), allows meeting the **HL-LHC requirement.**
- Investigate **swapping 2021 ion run with 2023 p-p reference** to have more time to commission SPS slip-stacking

LHC heavy-ion runs, past & future

LHC :12 ~one month heavy ion runs between 2010 and 2030 (LS4).

Five done already.



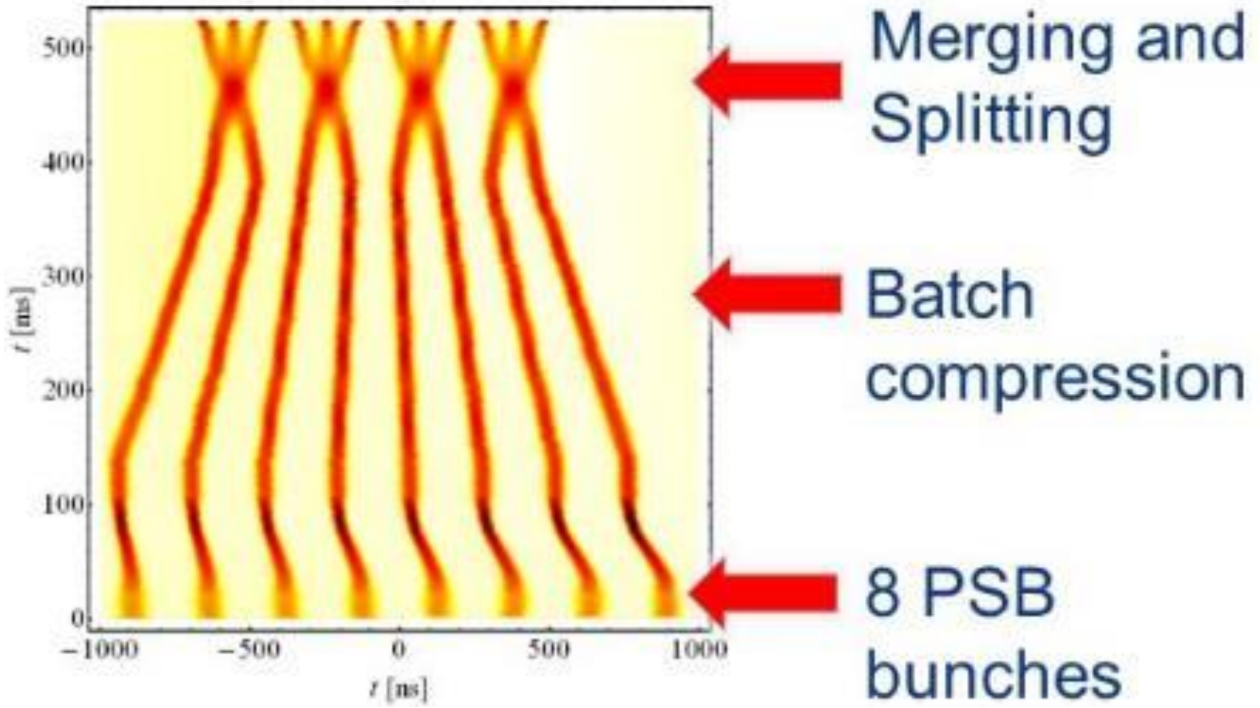


Conclusions

- LHC is performing well
  - Excellent availability
  - Luminosity beyond nominal and increasing
  - Strategies to further push the limits under investigations
  - LIU and HL-LHC projects formally approved by CERN Council

Spare Slides

BCMS = Batch Compression Merging and Splitting



2017 special runs ?

- 5 TeV pp reference run (for Pb-Pb and p-Pb physics analysis)
  - LHCC should recommend if to do at end of 2017 or end of 2018 just before the ion run
  - LHCC should define the duration: 7-10 days or 4-5 days of stable days

- High β* run at low energy (900 GeV/2 TeV ?)

  (TOTEM and ATLAS(ALFA)

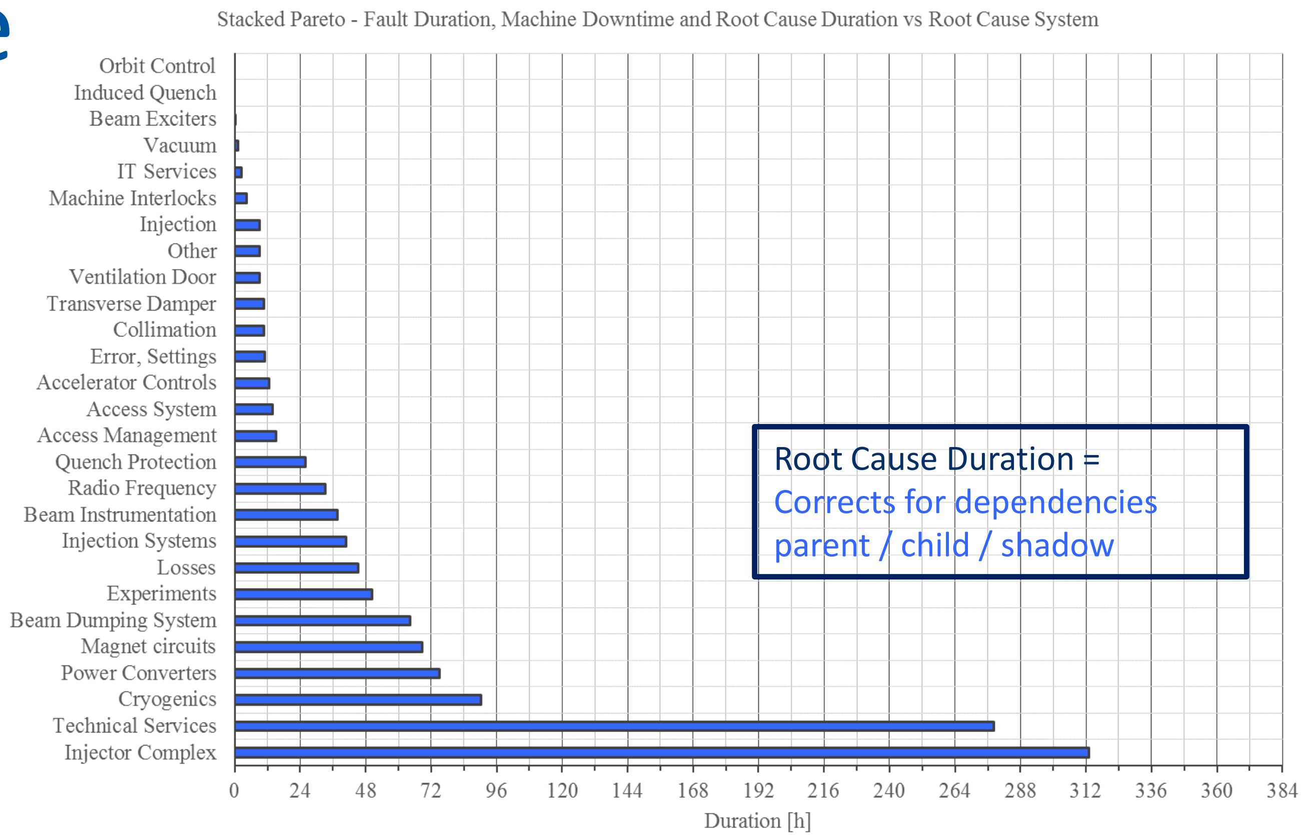
  - 2018 or Run 3 ?
  - To schedule 1 day of machine time in 2017 to investigate possibilities ?

- 90 m-like β* run with maximum luminosity

  (TOTEM and ATLAS(ALFA)

  - LHCC: 2018 ? Duration : ~1-2 weeks including setup

Downtime

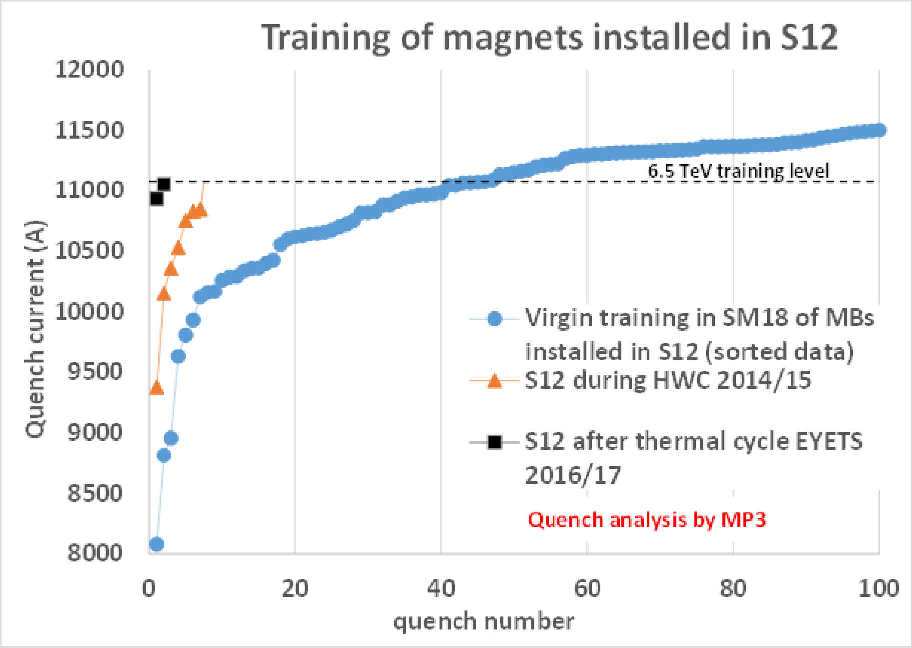


Root Cause Duration =
Corrects for dependencies
parent / child / shadow

LHC Powering tests

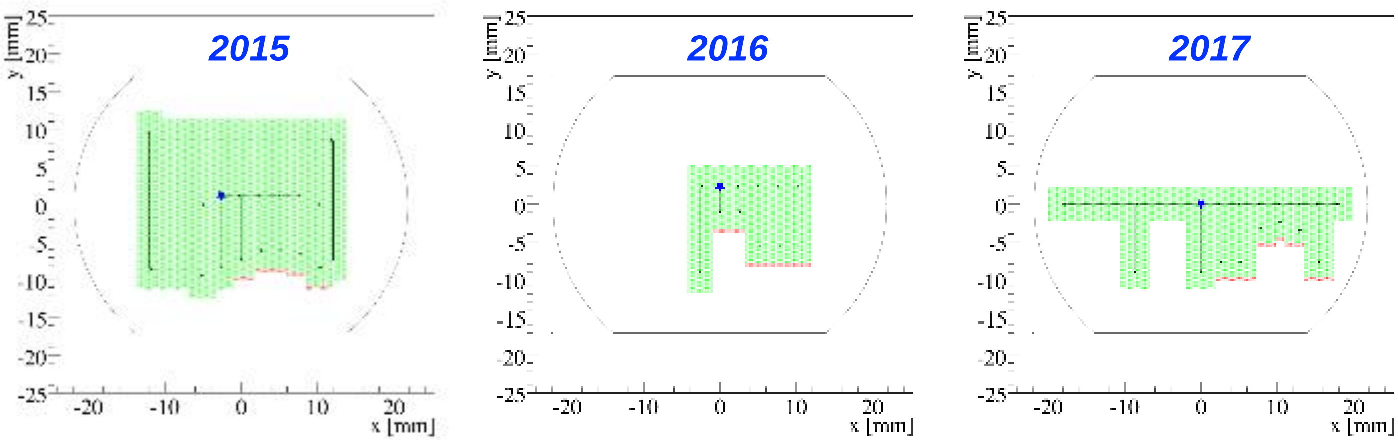
The main circuits are commissioned in the 8 sectors

- No training quench in the 7 sectors
- **In sector 1-2, two training quenches during last weekend: 10935 A, 11055 A**



2017 ULO with pilots

Preliminary measurements performed with pilot orbit (within 24h from first injection)

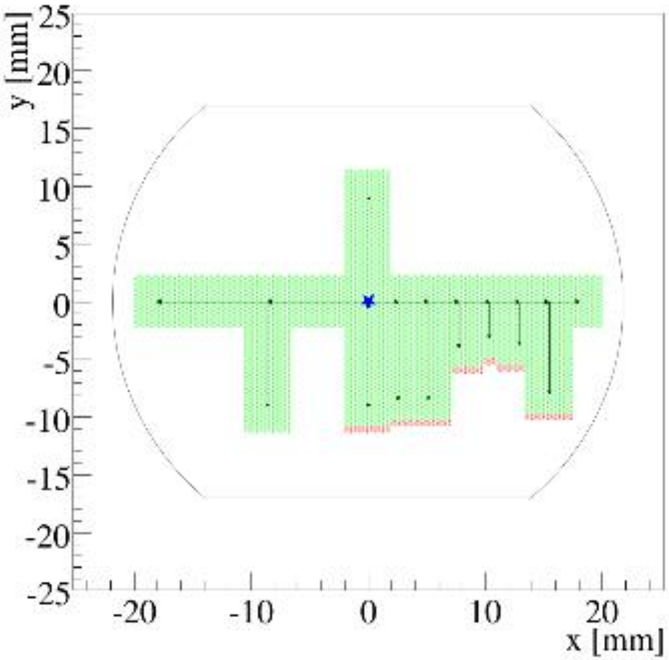


ULO moved to the external side of the machine, supported also by the fact that:

- ✓ **Almost no losses are observed**, except on the first complete turn
- ✓ **Few spikes in these first days of operations**, during beam manipulations

Final assessment with reference orbit

Measurements performed with reference nominal orbit (done the 9th of May)



Proposed **fixed bump:**
H = -2 mm
V = 0 mm

Consistent results obtained with respect to first measurements with pilot orbit

Energy/Current/Field for LHC Dipoles

Energy [TeV]	Current [A]	Field [T]
6.5	10980	7.73
7	11820	8.83
7.56	12840	9