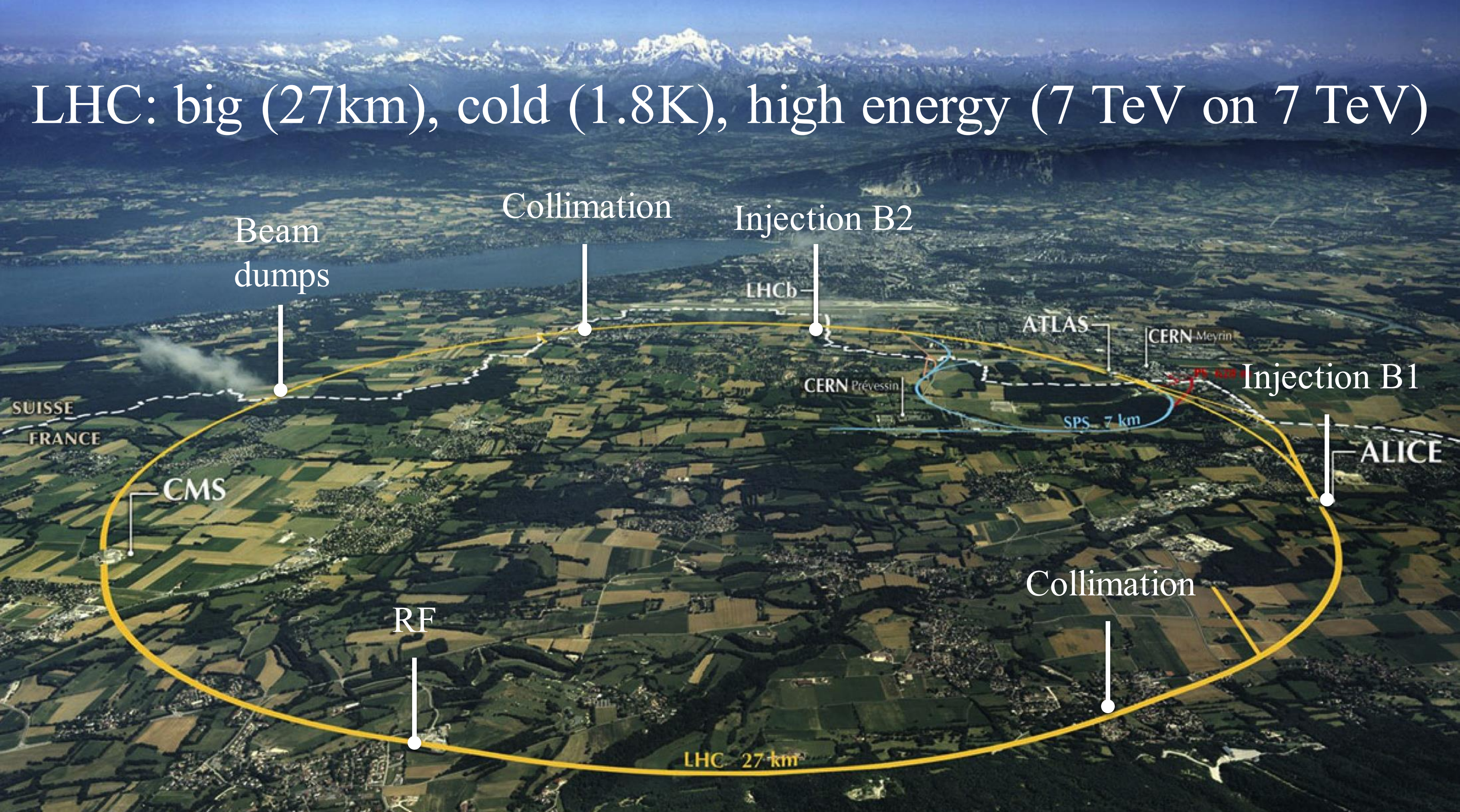
High Luminosity LHC

LHC and its Upgrade: HL-LHC

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Oliver Brüning, CERN

LHC: big (27km), cold (1.8K), high energy (7 TeV on 7 TeV)

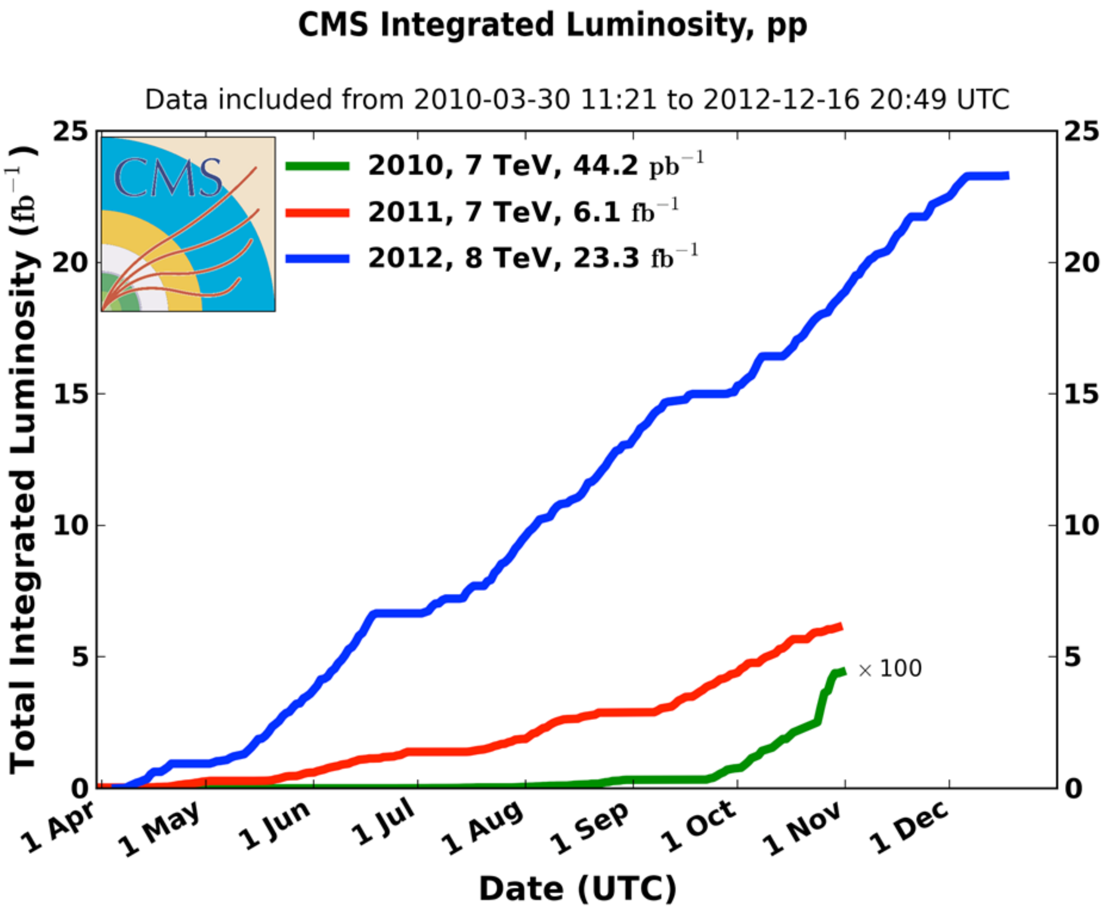


1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
4000 Beam loss monitors

150 tonnes Helium, ~90 tonnes at 1.8 K
140 MJ stored beam energy in 2012
370 MJ design and > 500 MJ for HL-LHC!
830 MJ magnetic energy per sector at 6.5 TeV
➔ ≈ 10 GJ total @ 7 TeV

High Luminosity LHC

RunI Operation with 50ns bunch spacing (2010-2012)



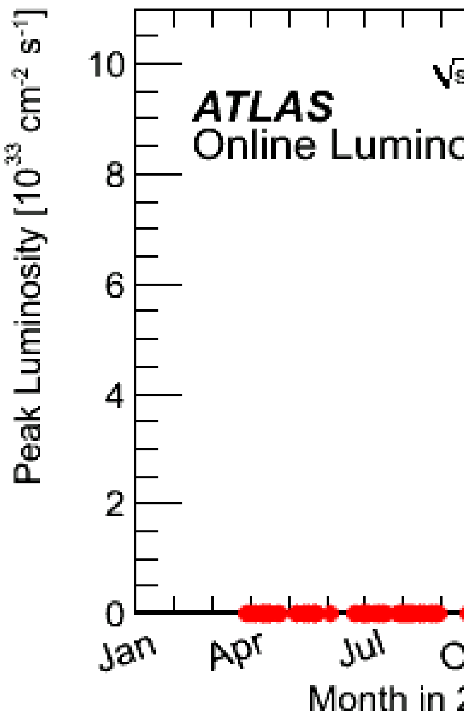
× 15

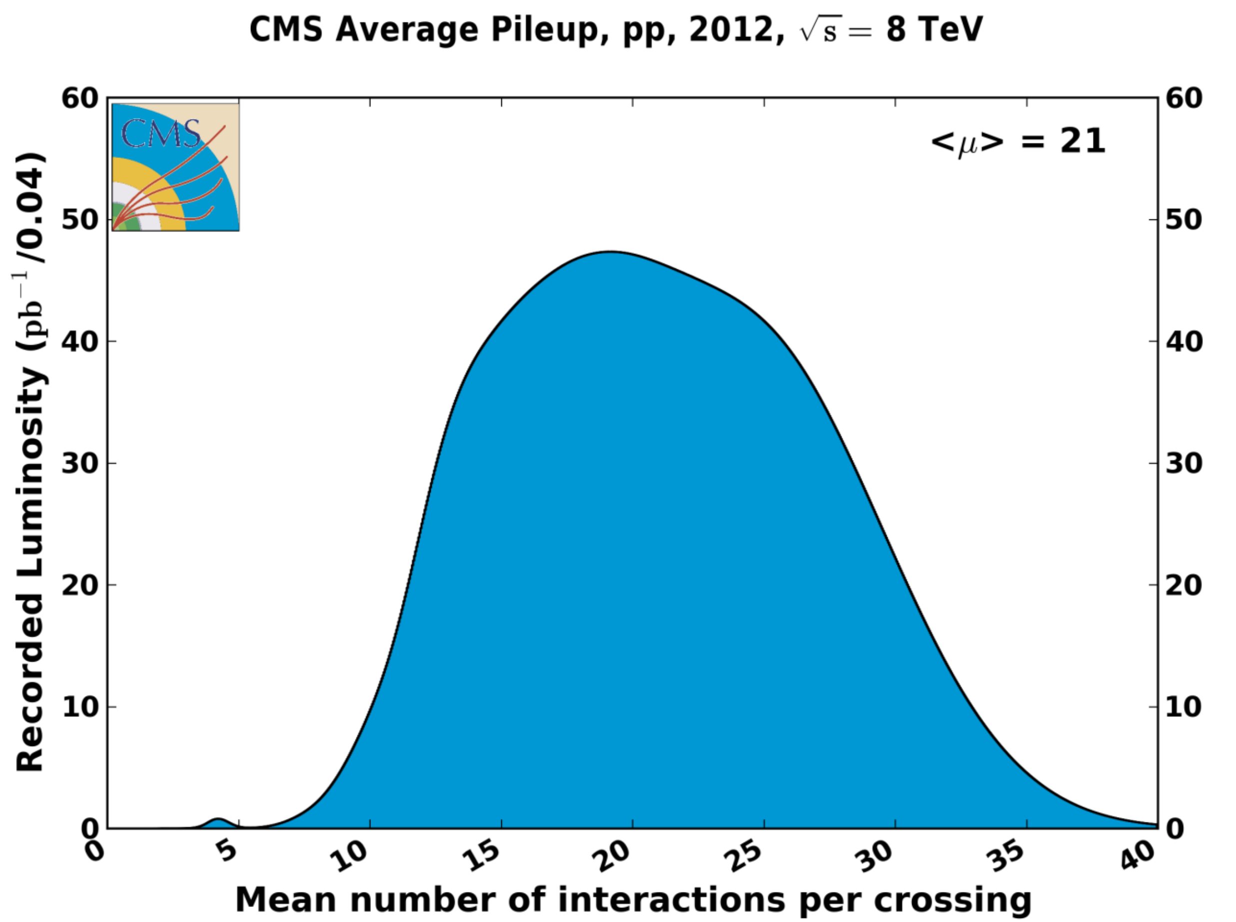
- 2010: **0.04 fb^{-1}**
  - 7 TeV CoM
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - 7 TeV CoM
  - Exploring the limits
- 2012: **23.3 fb^{-1}**
  - 8 TeV CoM
  - Production

× 4

➔ × 60 in 2 years!

75% of nominal L @ 60% energy and half intensity ➔ Higgs Discovery!



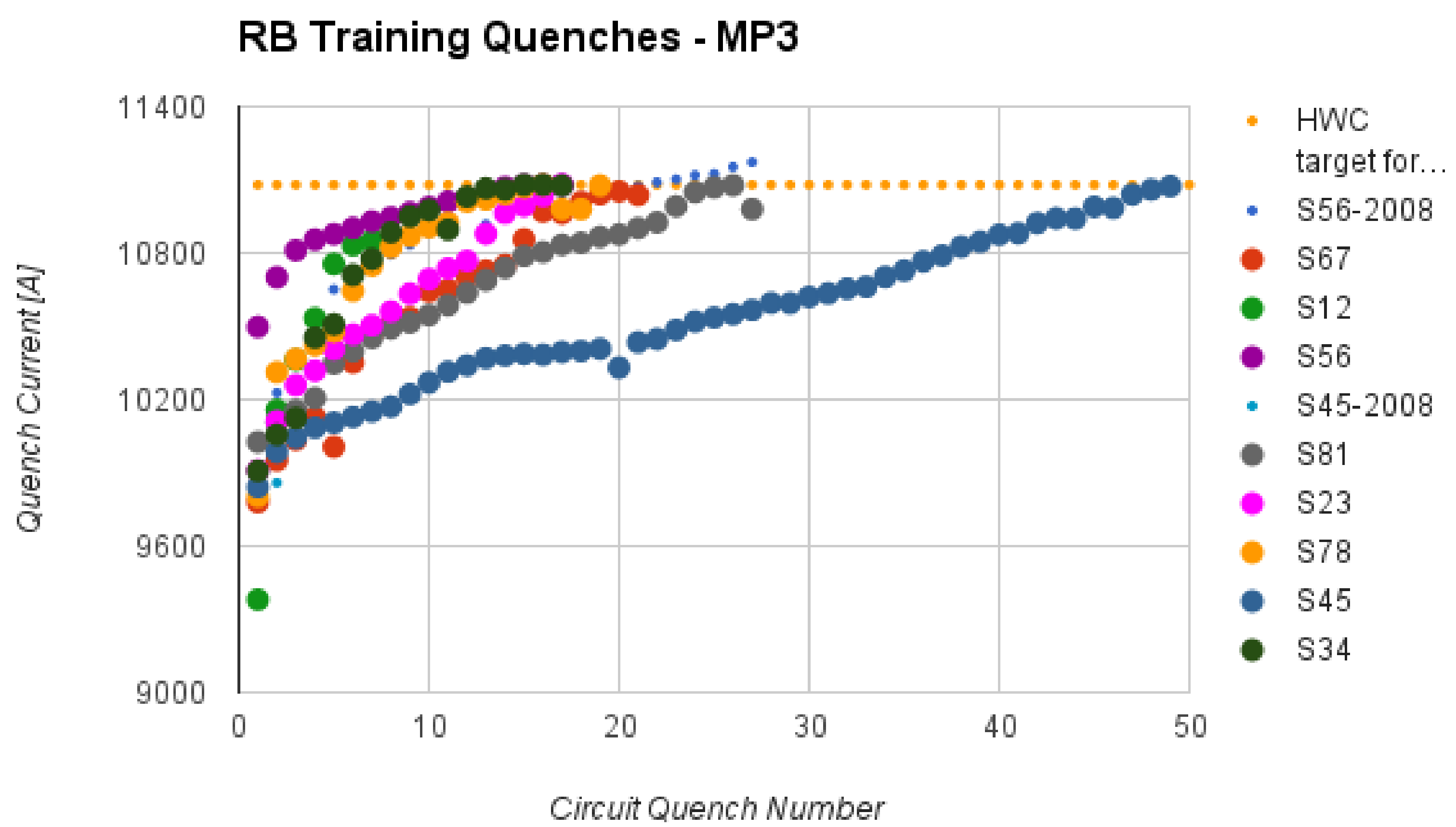


➔ Request to change to 25ns operation for 2015 (smaller lumi / bunch)!

➔ Electron cloud for operation

Long Shutdown I from 2013-2014:

Memory loss of magnets and re-training!



RunII: Operation with 50ns bunch spacing

- Typical teething problems for commissioning a new machine:
  - ULO: Unidentified Lying Object (ca. 3mm x 1mm)
  - Earth Faults: RCS78 & RB78
  - Vacuum issues limiting intensity (MKI had to be re-conditioned due to vacuum opening – B2)
- Overall good startup and smooth performance ramp up with 50ns bunch spacing

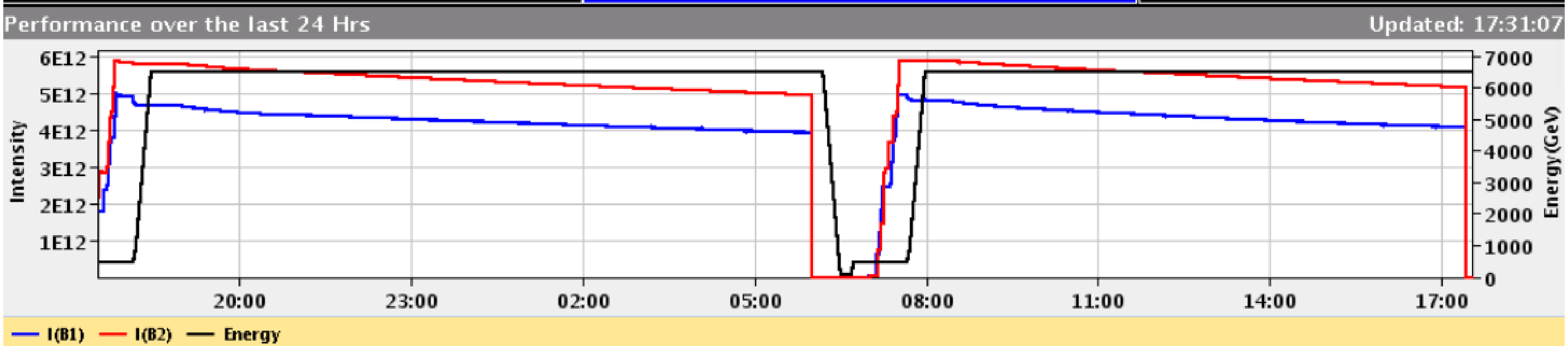
➔Optics measurements and machine validation

High Luminosity LHC

A nice day at the LHC: 50ns & low intensities

14-Jun-2015 17:31:07	Fill #: 3858	Energy: 6502 GeV	I(B1): 0.00e+00	I(B2): 0.00e+00
	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	STANDBY	STANDBY	STANDBY
Instantaneous Lumi [(ub.s)^-1]	0.008	0.000	0.177	0.000
BRAN Luminosity [(ub.s)^-1]	0.0	0.0	0.0	0.0
Fill Luminosity (nb)^-1	3496.834	0.000	3279.892	191.862
BKGD 1	0.170	0.036	0.806	0.141
BKGD 2	0.000	0.000	3.384	3.144
BKGD 3	0.250	0.023	1.610	0.054

LHCb VELO Position OUT Gap: 58.0 mm | RAMP DOWN | TOTEM: PHYSICS



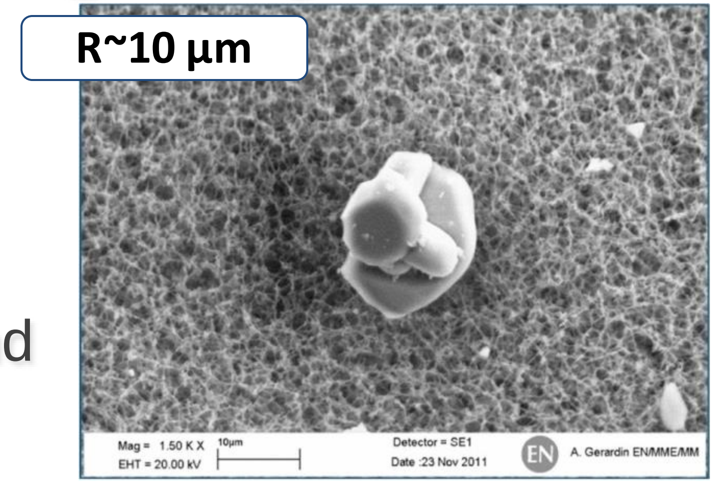
50 bunches @ 50ns per beam ➔ Two OP programmed dumps. About 20 hours in stable beams.

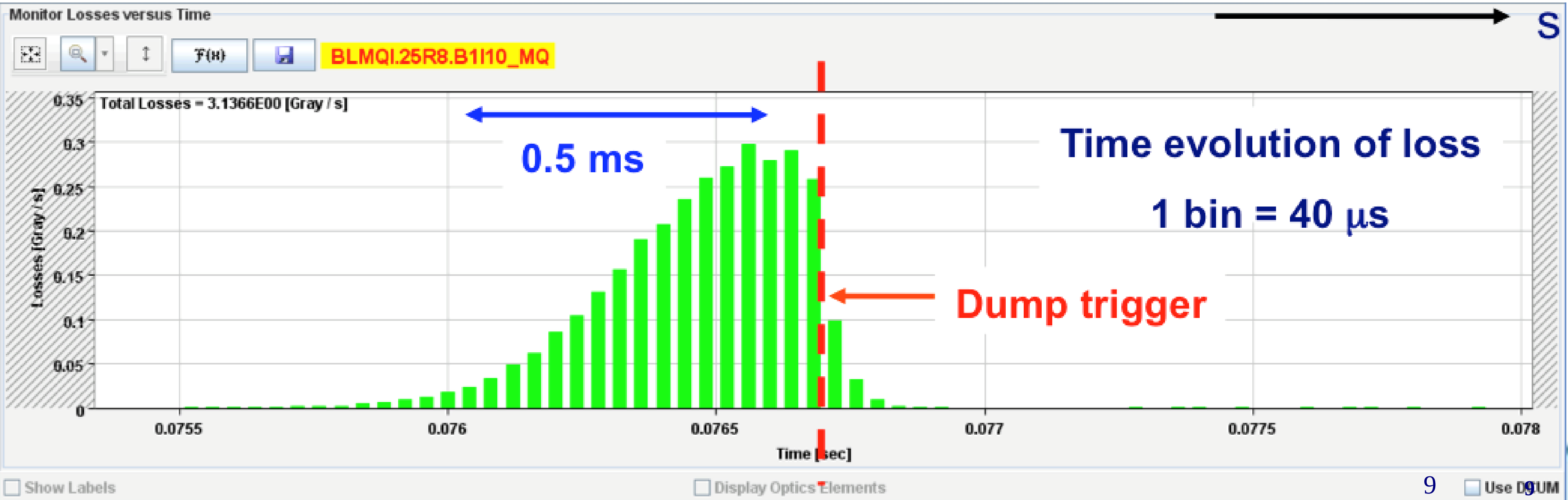
RunII Startup: 25ns bunch spacing

- Unidentified Falling Objects (UFOs)
- Electron-cloud effects (heating & instability)
- Cryo instability with 144+ bunch trains due to transients ➔ electron cloud!
- QPS R2E problem ➔ showed that when possible, all electronics should be removed from the tunnel!
- Problems from equipment heating (e.g. TDI ➔ deformation, coating damage?
- (CMS solenoid – oil contamination of cooling circuit)

UFOs – Unidentified Falling Objects:

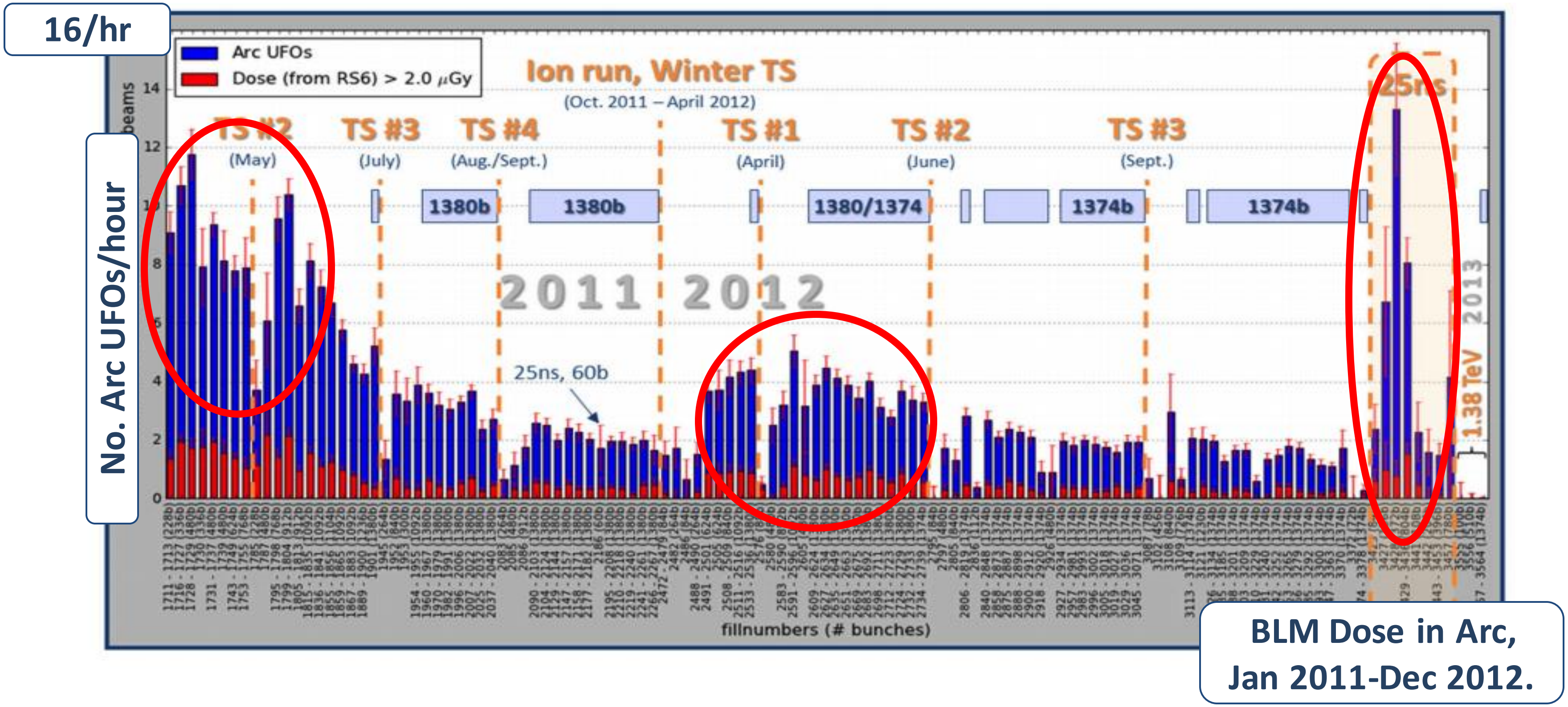
- Sudden local loss
- Rise time of the order of 1 ms.
- Potential explanation: dust particles falling into beam creating scatter losses and showers propagating downstream
- Distributed around the ring – arcs, inner triplets, IRs
- Even without quench, preventive dumps by QPS





UFOs – RunI Observations:

- **No. of UFO events** have been seen to **exceed 10+/hour** with notable increases after long shutdowns (beam energy), decreasing bunch spacing, total current

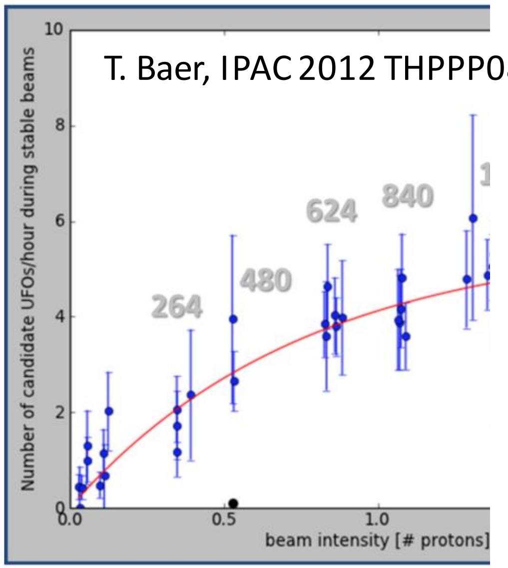


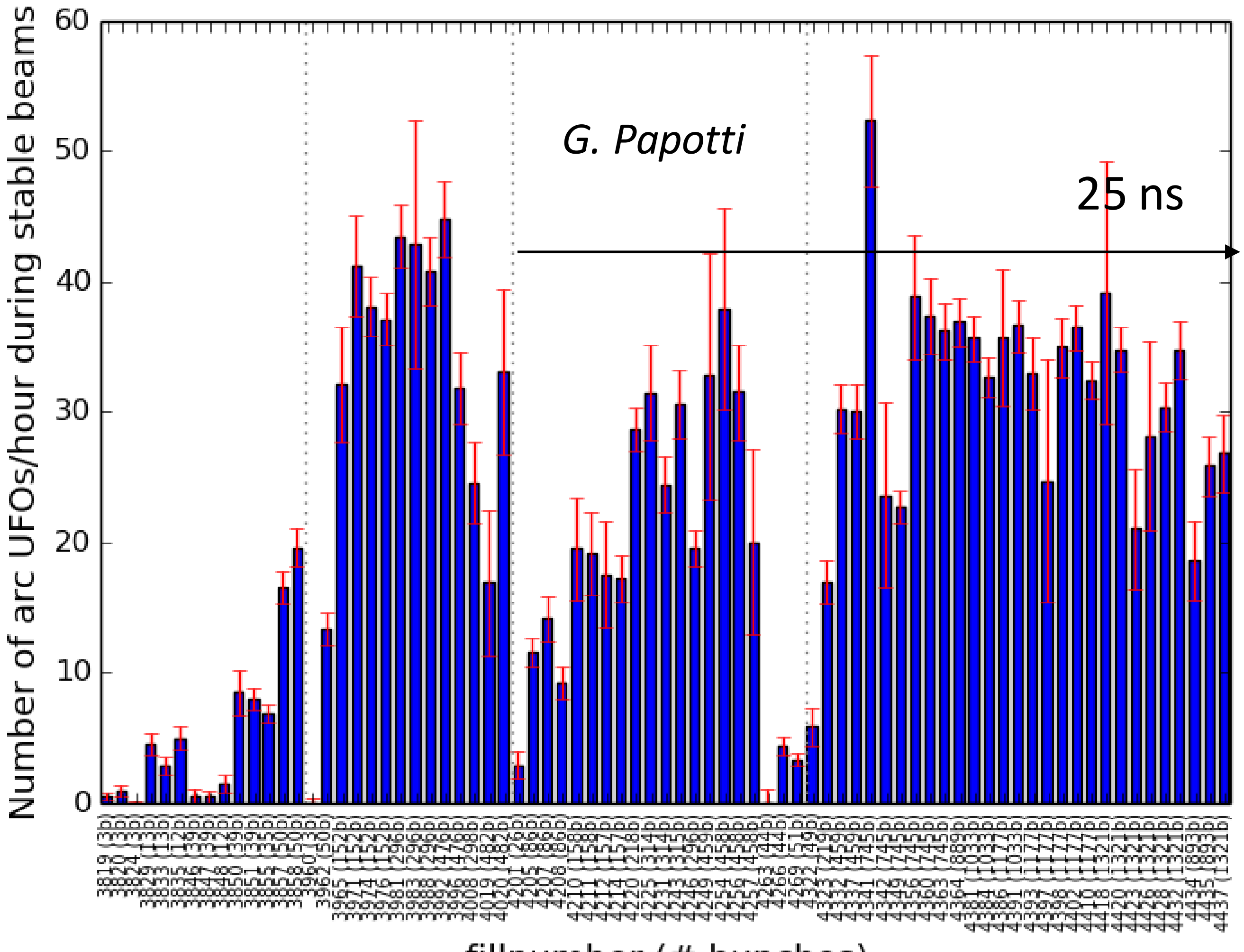
- Beam loss monitor thresholds have been set judiciously
- Essentially relying on conditioning

High Luminosity LHC

RunII Startup: UFO rates (September)

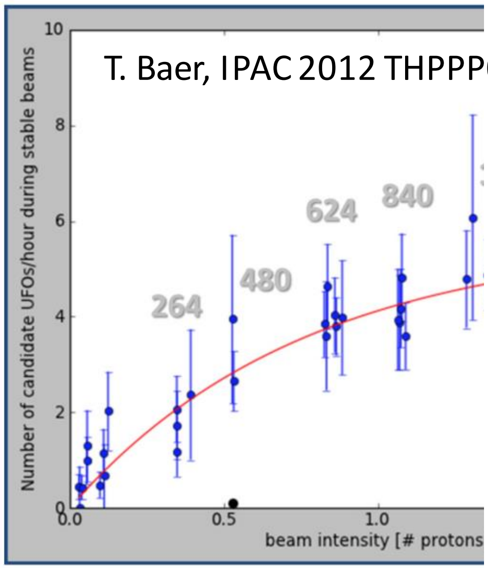
- There are many UFOs, a significant number > 1% of threshold
- In 2 fills we observed UFOs > 90% of threshold !

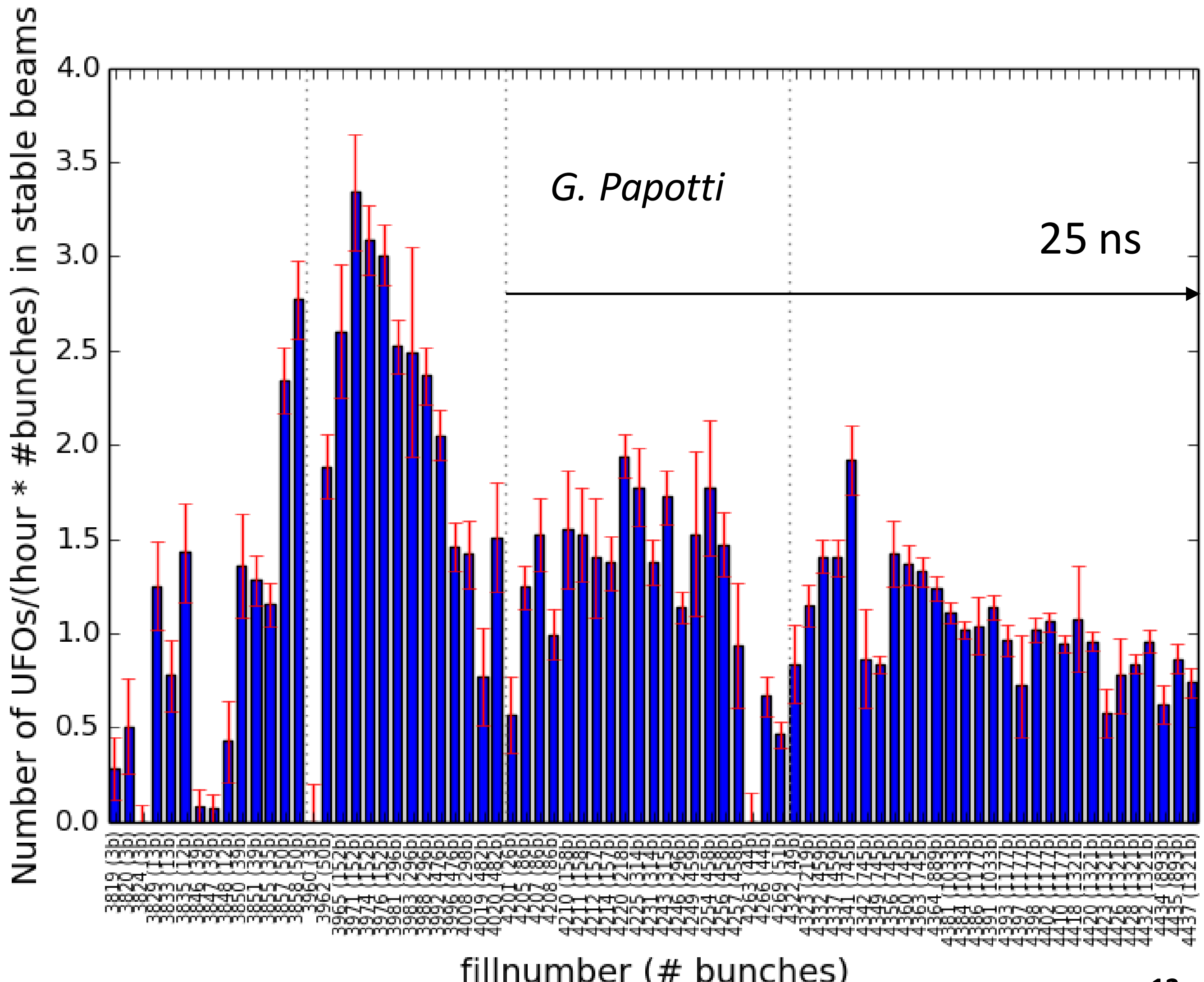




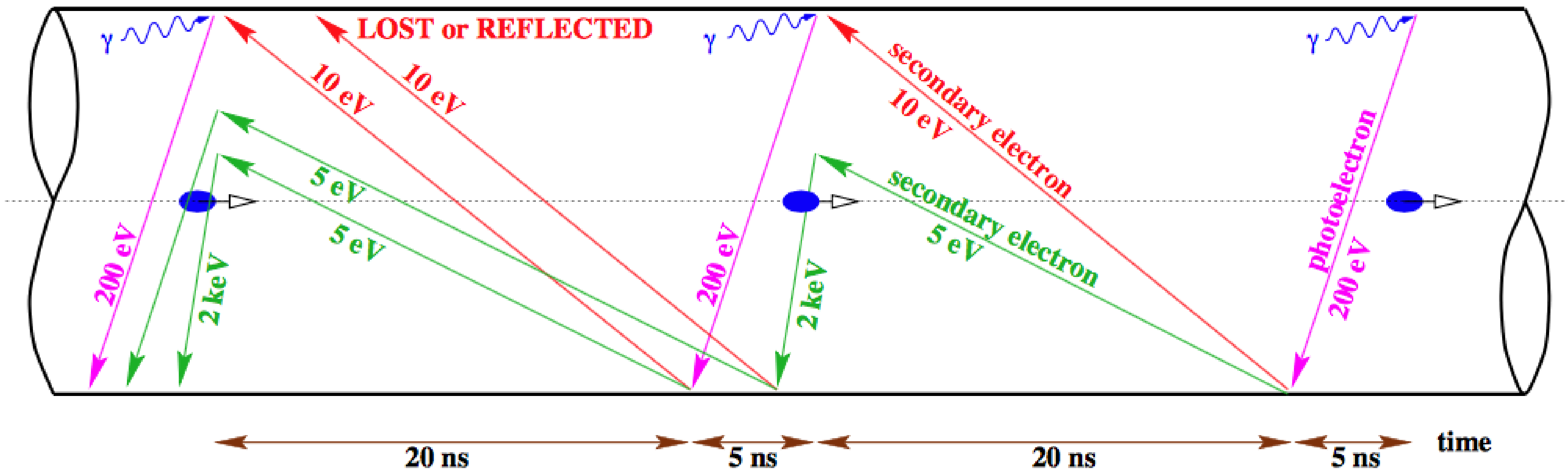
RunII Startup: UFO rates (September)

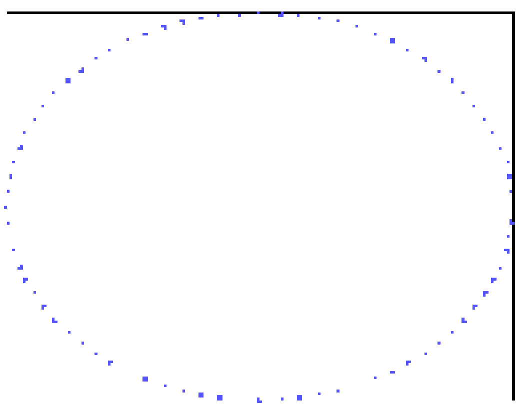
- Slight signs of conditioning when normalizing the rate by the total number of bunches, but still a major concern!





Electron Cloud in the LHC:





Heat load on the LHC beam screen

Beam instability via e-cloud coupling

No issue for 50ns bunch spacing

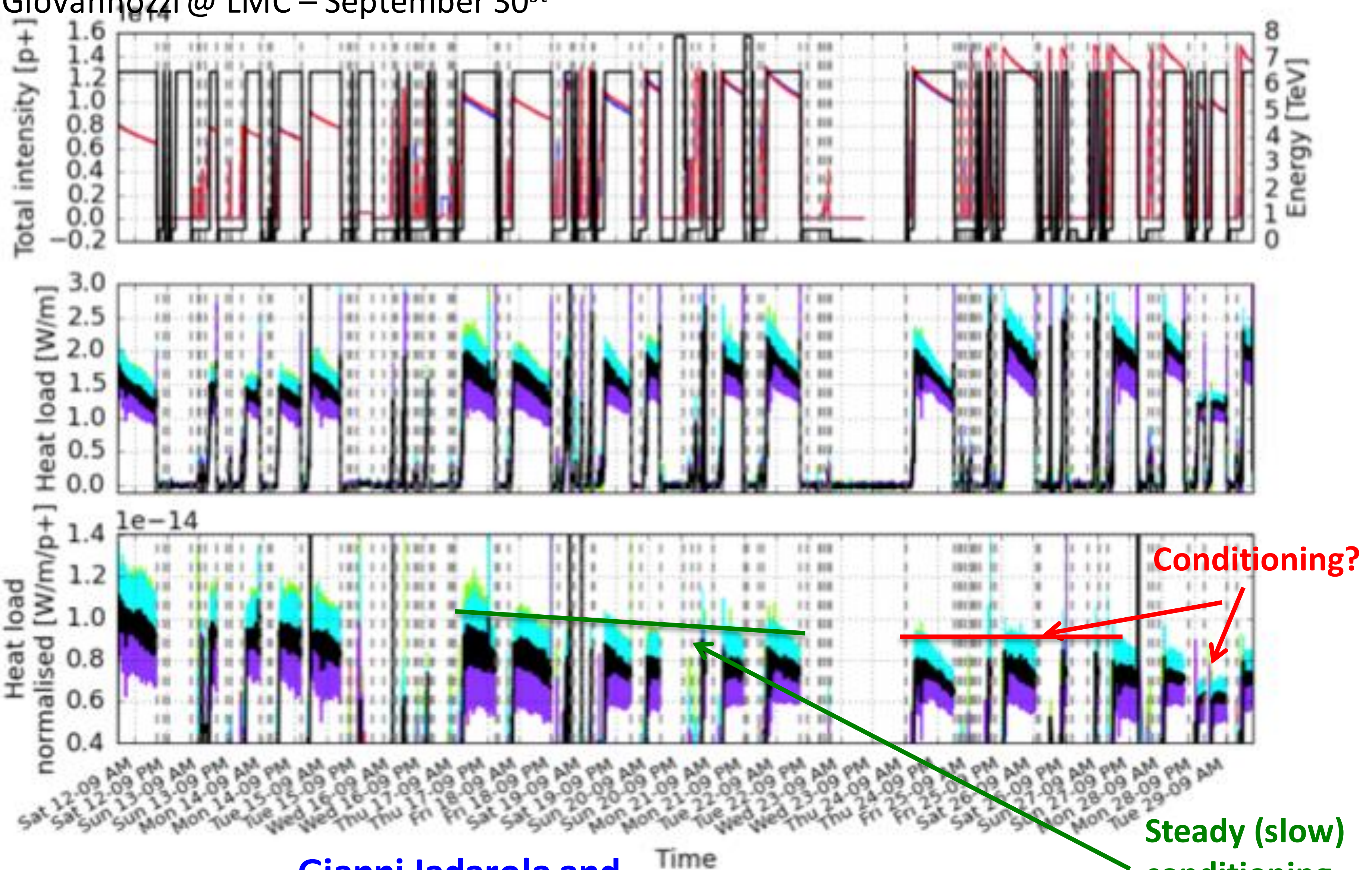
Sever problem for 25ns bunch spacing

Effect depends on SEY of surface

surfaces can be conditioned through e-cloud bombardment ➔ beam scrubbing

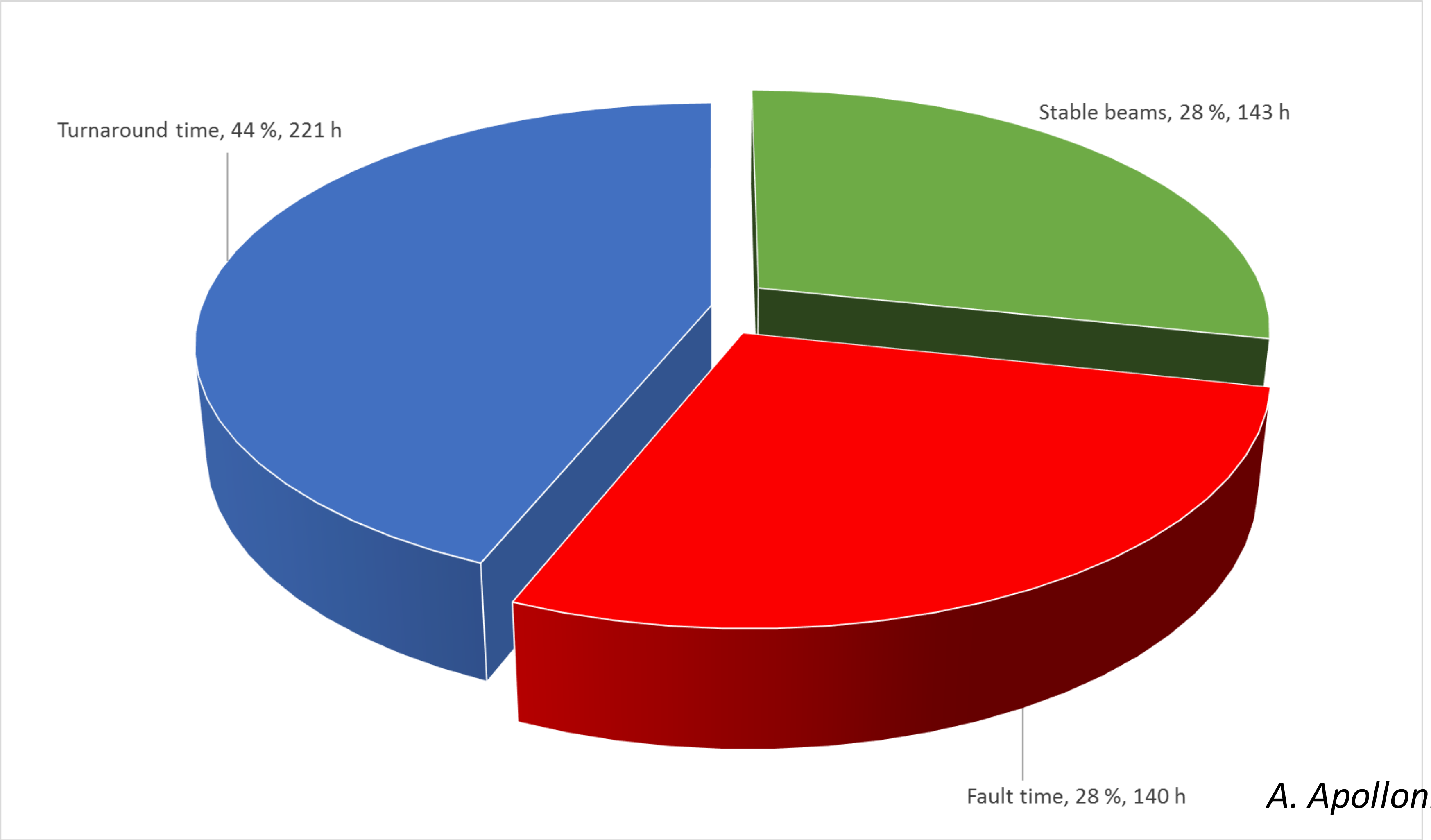
Scrubbing with 25ns: Heat Load Evolution

M. Giovannozzi @ LMC – September 30st



Gianni Iadarola and e-cloud team

Overall Physics Efficiency after TS2:



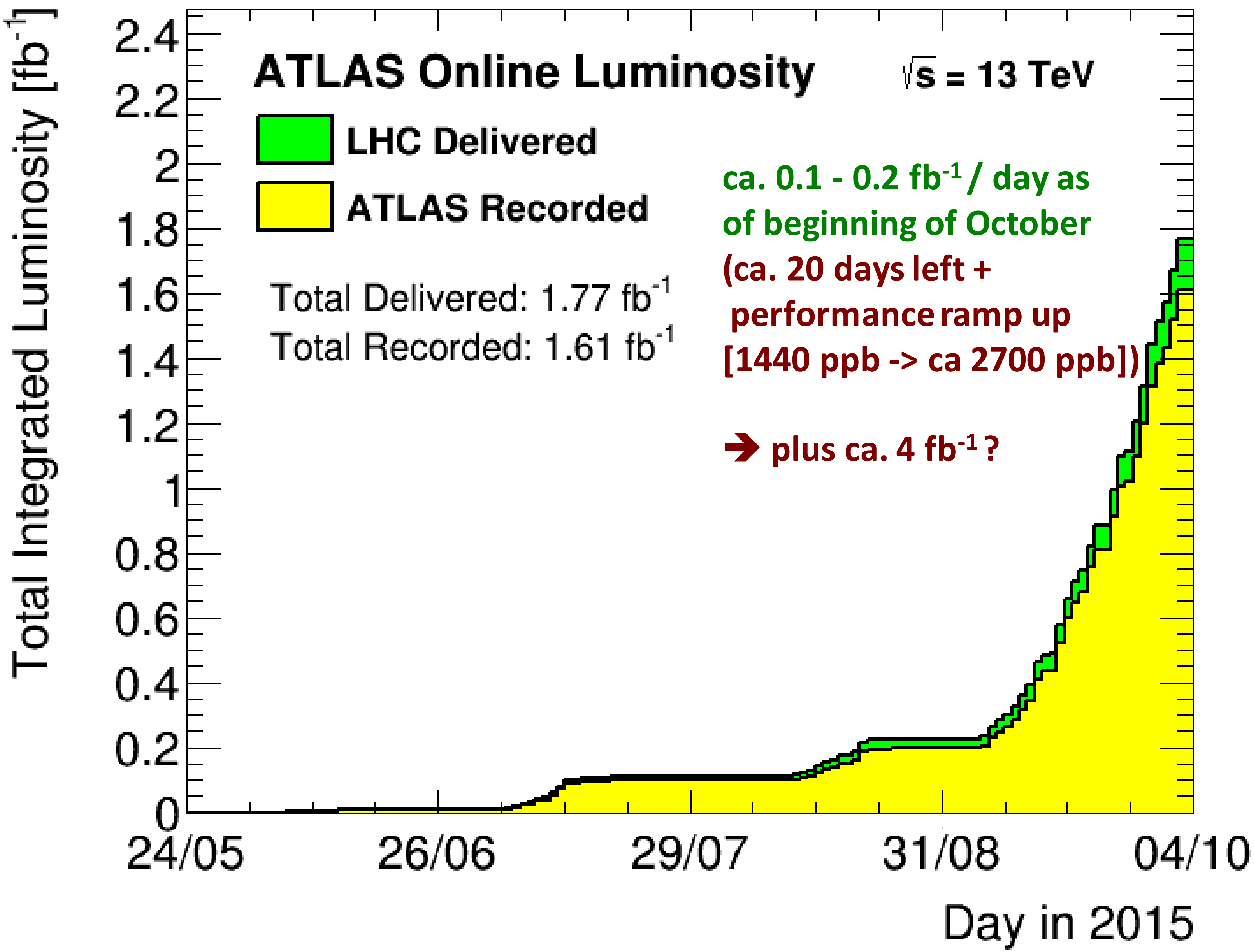
A. Apollonio

- **Slightly better after the removal of radiation sensitive QPS cards**
- **Good weeks of LHC operation feature up to 40% in Stable beams for physics**

➔ But HL-LHC requires Efficiency of ≥ 50%!! ➔ need to demonstrate long fills!

Intensity ramp up

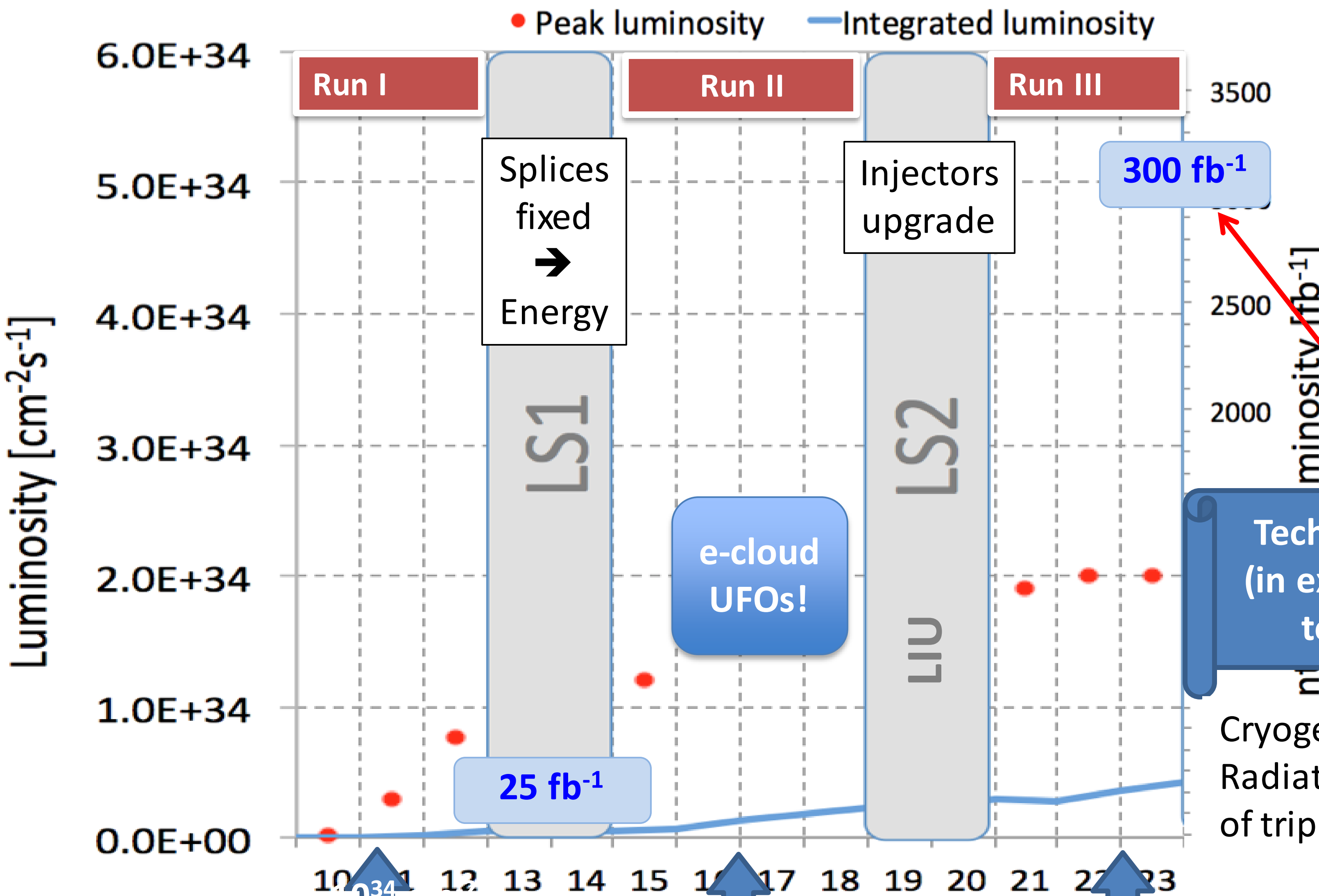
ATLAS Data



ca. 0.1 - 0.2 fb^{-1} / day as of beginning of October (ca. 20 days left + performance ramp up [1440 ppb -> ca 2700 ppb])

➔ plus ca. 4 fb^{-1} ?

Performance Projections over 10 years:



Technical limits (in experiments, too) like :

Cryogenic limit & Radiation Damage of triplet magnets

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

1.5 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
high pile up ~40

1.5 -2.2 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
very high pile up > 60

Goal of High Luminosity LHC (HL-LHC):

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

Prepare machine for operation beyond 2025 and up to **2035**

Devise beam parameters and operation scenarios for:

enabling at total integrated luminosity of **3000 fb^{-1}**

implying an integrated luminosity of **250 fb^{-1} per year**,

design oper. for μ δ **140** (➔ peak luminosity of **5 10^{34} cm^{-2} s^{-1}**)

> Ten times the luminosity reach of first 10 years of LHC operation!!

High Luminosity LHC

LHC Limitations and HL-LHC Challanges:

- Technical bottle necks (e.g. cryogenics) → New addit. Equipment
- Insertion magnet lifetime and aperture:

  → New insertion magnets and low-β with increased aperture

- Geometric Reduction Factor: → SC Crab Cavities

  → New technology and a first for a hadron storage ring!

- Performance Optimization: Pileup density → luminosity levelling

  → devise parameters for virtual luminosity >> target luminosity

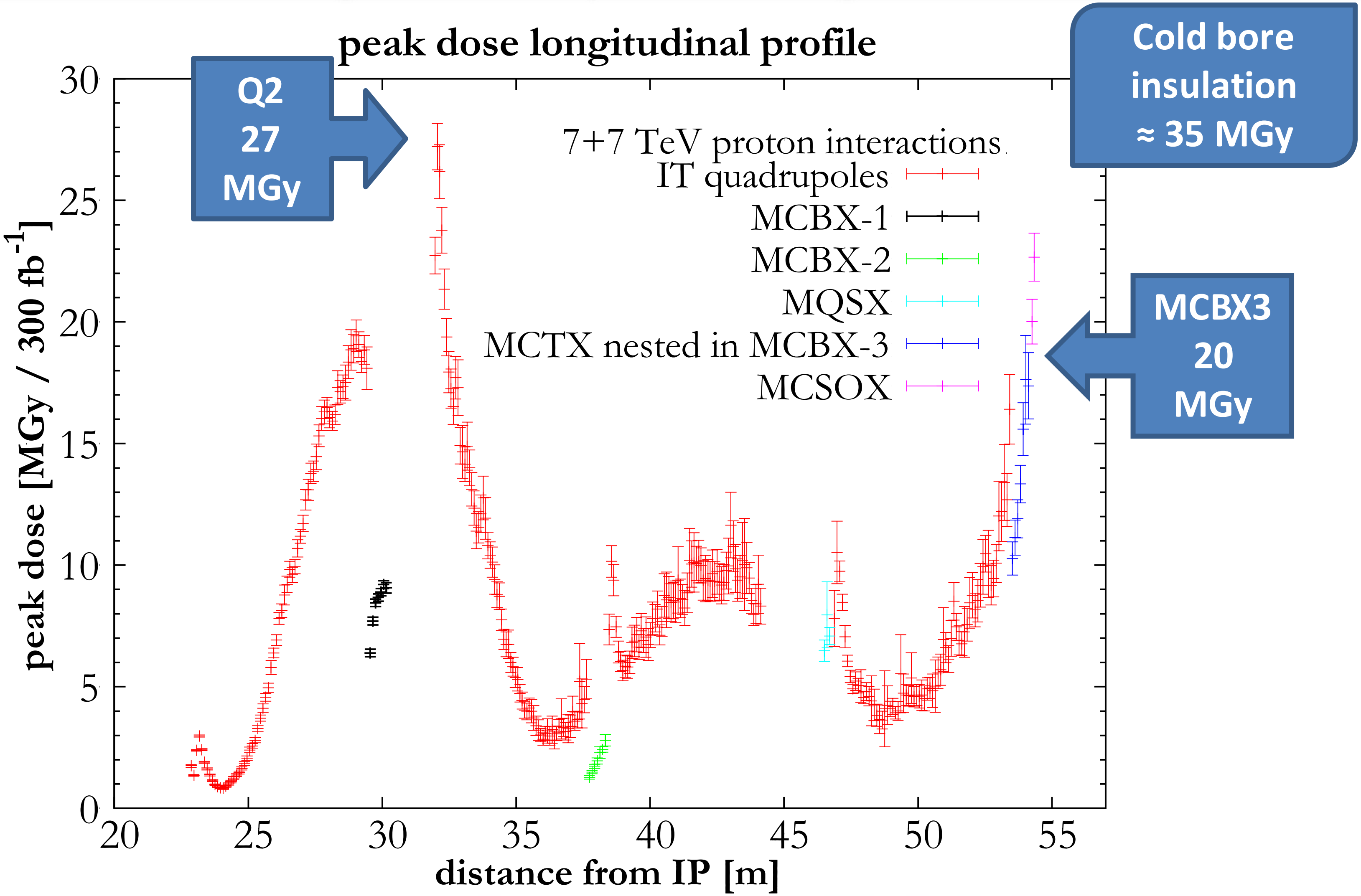
- Beam power & losses → additional DS (cold region) collimators
- Machine effciency and availability:

  # R2E → removal of all electronics from tunnel region

  # e-cloud → beam scrubbing (conditioning of surface)

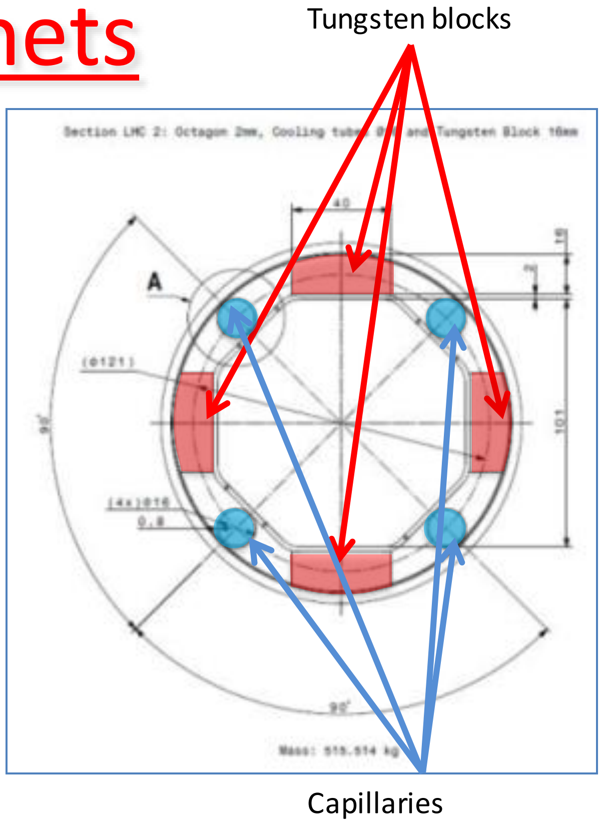
  # UFOs → beam scrubbing (conditioning of surface)

HL-LHC technical bottleneck:
Radiation damage to triplet magnets at 300 fb^{-1}



HL-LHC technical bottleneck:
Radiation damage to triplet magnets

Need to replace existing triplet magnets with radiation hard system (shielding!) such that the new magnet coils receive a similar radiation dose @ 10 times higher integrated luminosity!!!!!



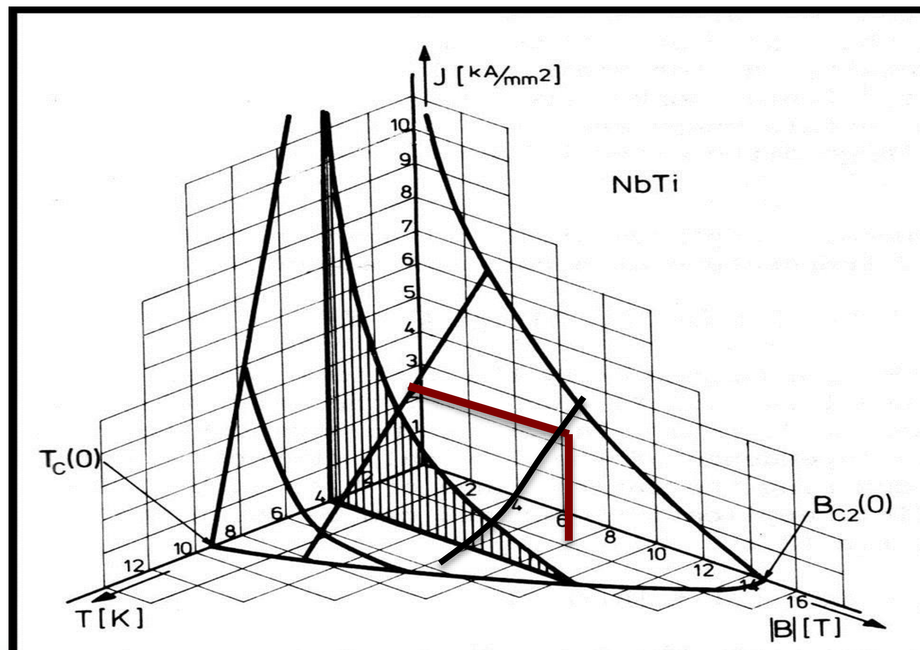
- ➔ Upgraded Cryogenics for Cooling
- ➔ Requires larger aperture!
  - ➔ New magnet technology to reach gradient @ higher aperture

HL-LHC Upgrade Ingredients: Triplet Magnets

- Nominal LHC triplet: 210 T/m, 70 mm coil aperture
  - ➔ ca. 8 T @ coil
  - ➔ 1.8 K cooling with superfluid He (thermal conductivity)
  - ➔ current density of 2.75 kA / mm^2
- At the limit of NbTi technology (HERA & Tevatron ca. 5 T @ 2kA/mm^2)!!!

LHC Production in collaboration with USA and KEK

Critical Surface for NbTi



HL-LHC Magnets:

- LHC triplet:

  210 T/m, 70 mm bore aperture

  ➔ 8 T @ coil (limit of NbTi tech.)
- **HL-LHC triplet:**

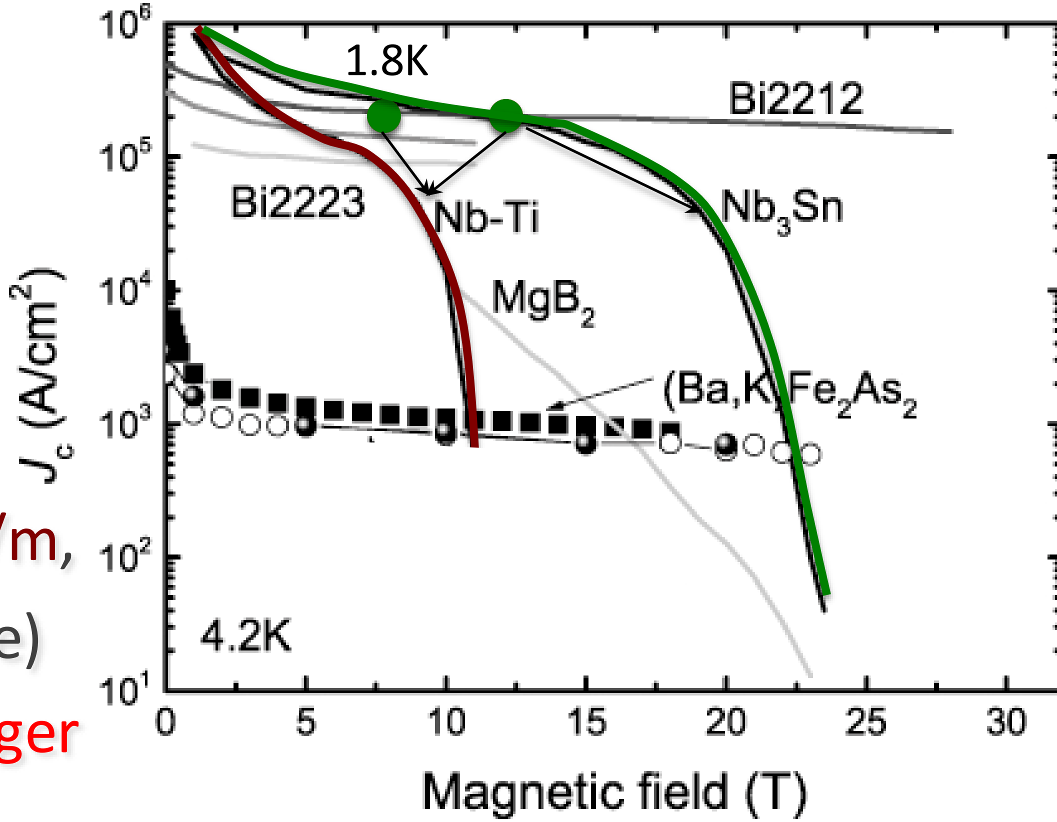
  150 mm coil aperture ➔140 T/m,

  (shielding, β^* and crossing angle)

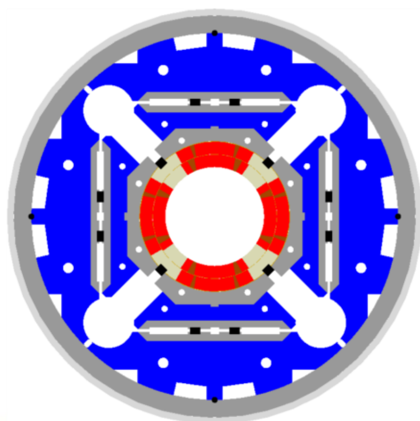
  ➔ ca. 12 T @ coil ➔ 30% longer
  - Requires Nb_3Sn technology

    ➔ brittle material (fragile)

    ➔ ca. 25 year development for this new magnet technology!
  - US-LARP – CERN collaboration



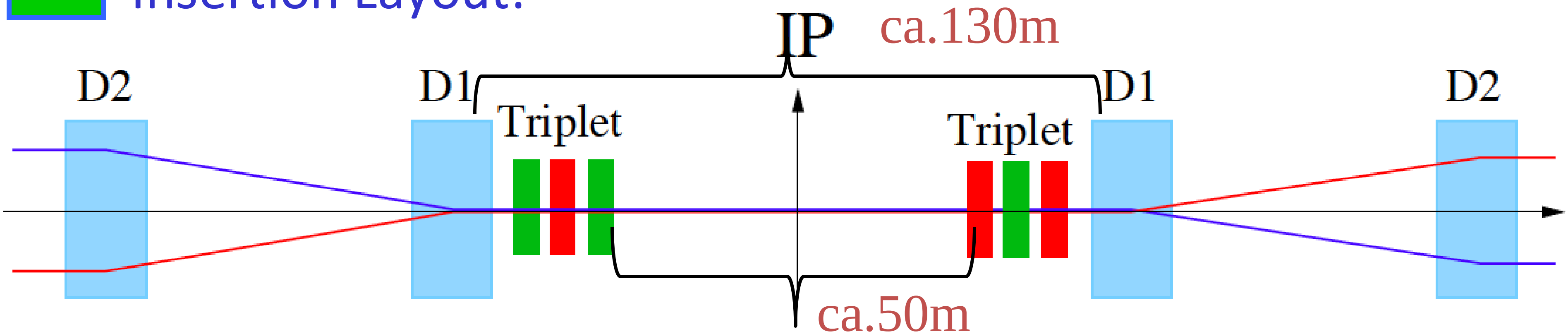
US-LARP MQXF magnet design Based on Nb_3Sn technology



High Luminosity LHC

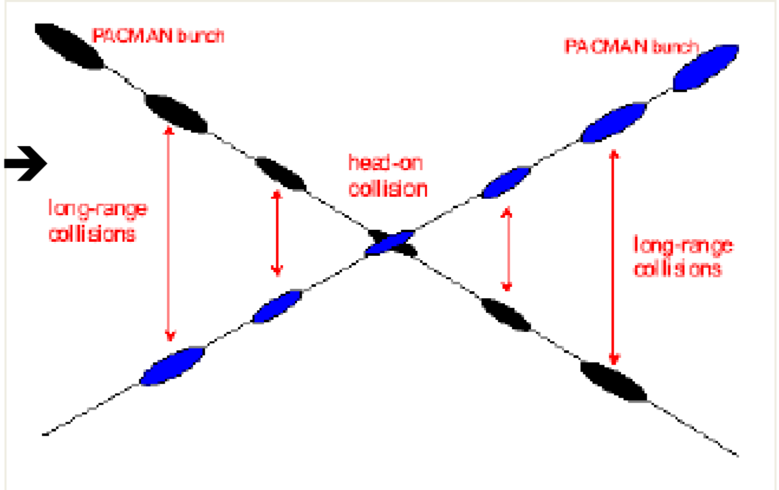
HL-LHC Interaction Region: Crossing Angle

Insertion Layout:



Parasitic bunch encounters:

Operation with ca. 2800 bunches @ 25ns spacing ➔
approximately 30 unwanted collision per Interaction Region (IR).



➔ Operation requires crossing angle

➔ Increases with decreasing β^*

non-linear fields from long-range beam-beam interaction:

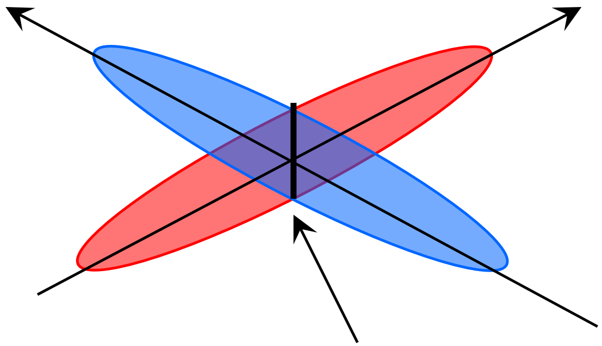
efficient operation requires large beam separation at unwanted collision points

➔ Separation of 10 -12 σ ➔ large triplet apertures for HL-LHC upgrade!!

High Luminosity LHC

LHC Challenges: Crossing Angle II

geometric luminosity reduction factor:



large crossing angle:

- ➔ reduction of long range beam-beam interactions
- ➔ reduction of beam-beam tune spread and resonances
- ➔ reduction of the mechanical aperture
- ➔ increase of effective beam cross section at IP
- ➔ reduction of luminous region
  - ➔ reduction of instantaneous luminosity
  - ➔ inefficient use of beam current!

HL-LHC Upgrade Ingredients: Crab Cavities

Geometric Luminosity Reduction Factor:

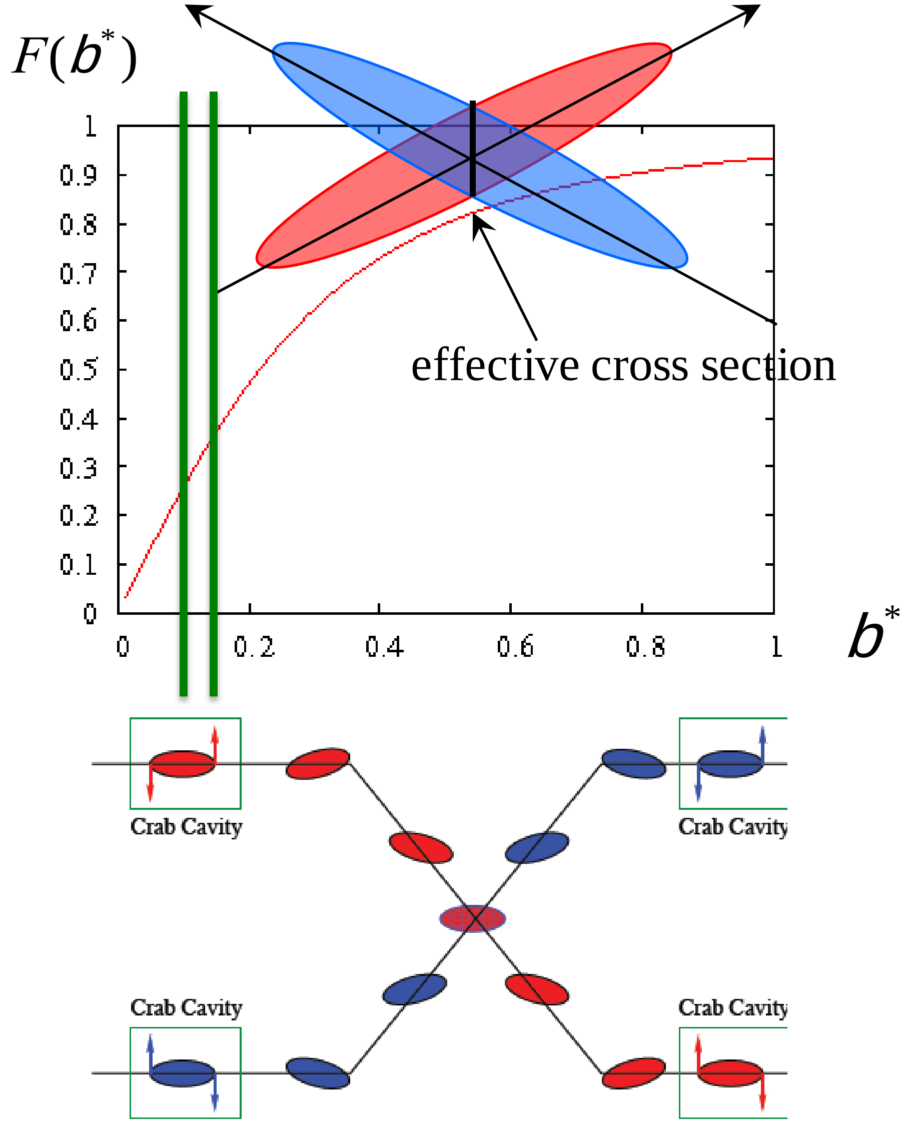
Crab Cavities:

- Reduces the effect of geometrical reduction factor
- Independent for each IP

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

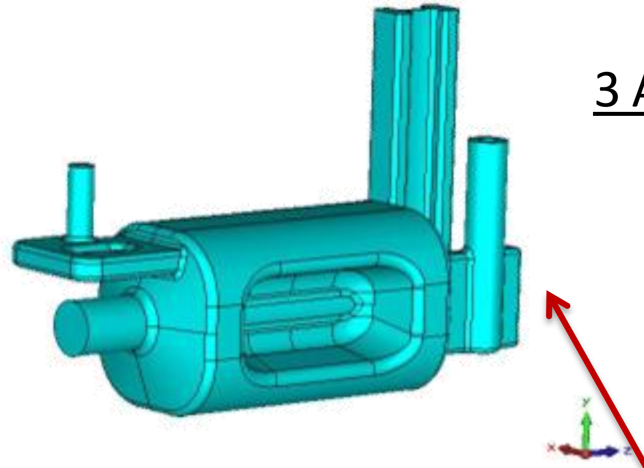
- Noise from cavities to beam?!?
- Challenging space constraints:

  ➔ requires novel compact cavity design

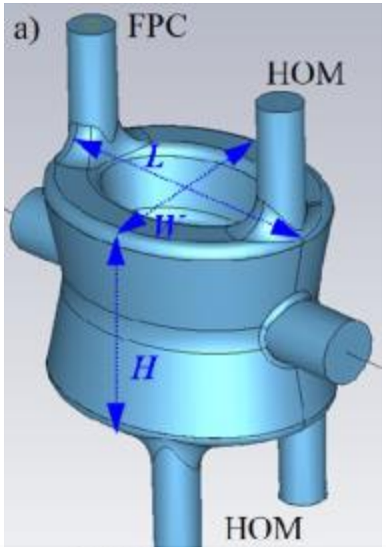


Latest cavity designs toward accelerator

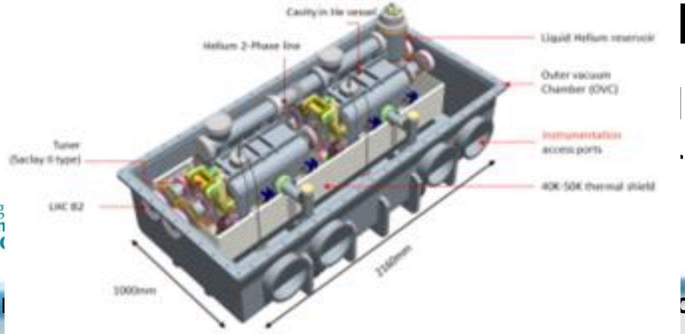
3 Advanced Design Studies with Different Coupler concepts



RF Dipole: Waveguide or waveguide-coax couplers



All 3 Prototypes exceeded Design Specifications!
Review: Concentrate on two designs in order to be Ready for test installation in SPS in 2016/2017 TS



: Coaxial couplers with
ent ar

Present baseline: 4 cavity/cryomod
TEST in SPS under preparation for 2017 / 2018

LHC Challenges: Beam Power

- Unprecedented beam power:

Worry about beam losses:

Failure Scenarios → Local beam Impact

→ Equipment damage

→ Machine Protection

Lifetime & Loss Spikes → Distributed losses

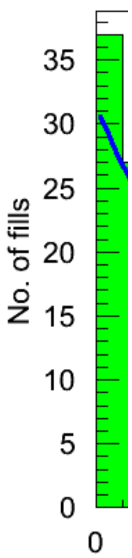
→ Magnet Quench

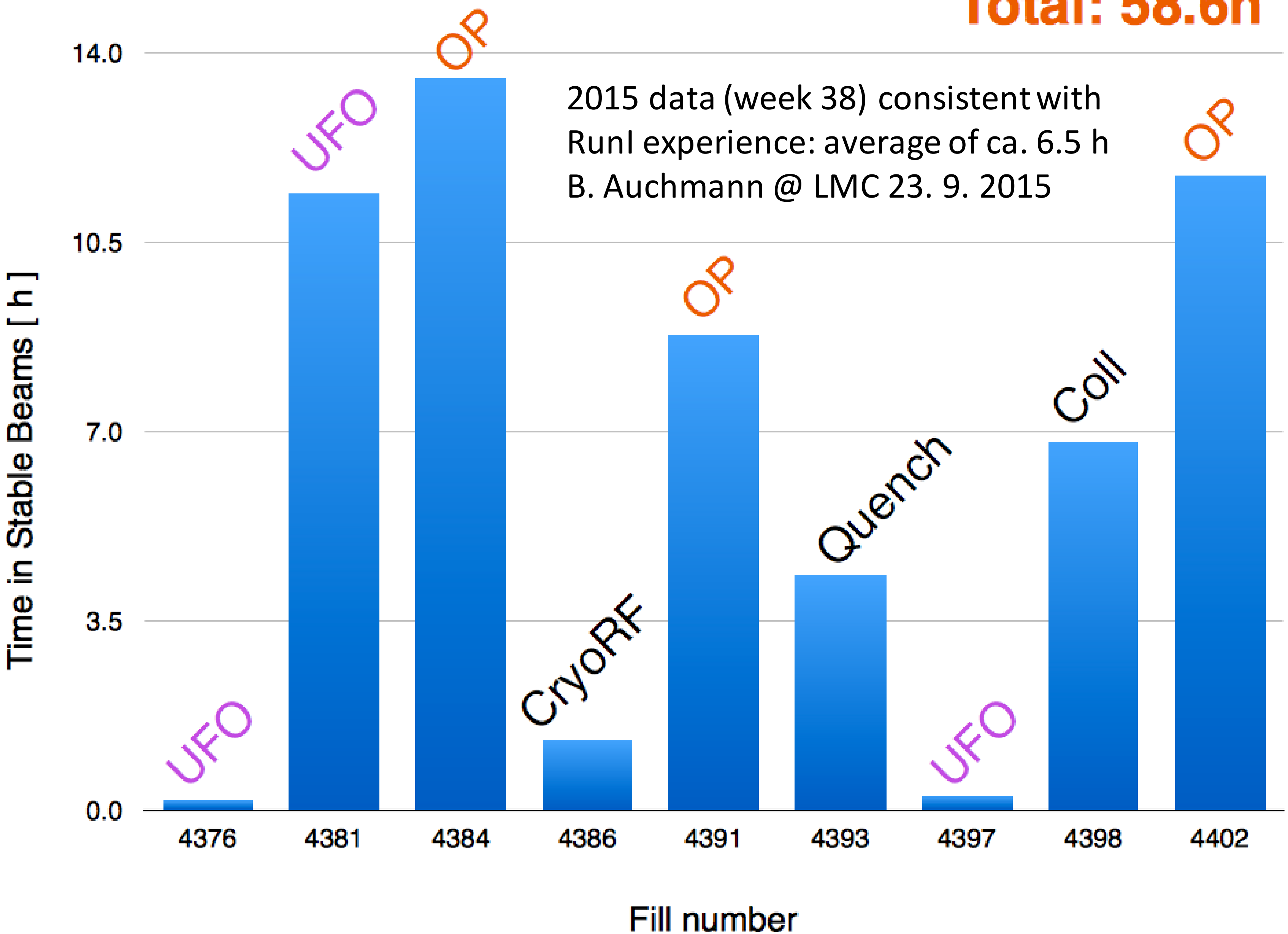
→ R2E and SEU

→ Machine efficiency

HL-LHC Challenge: Machine Efficiency

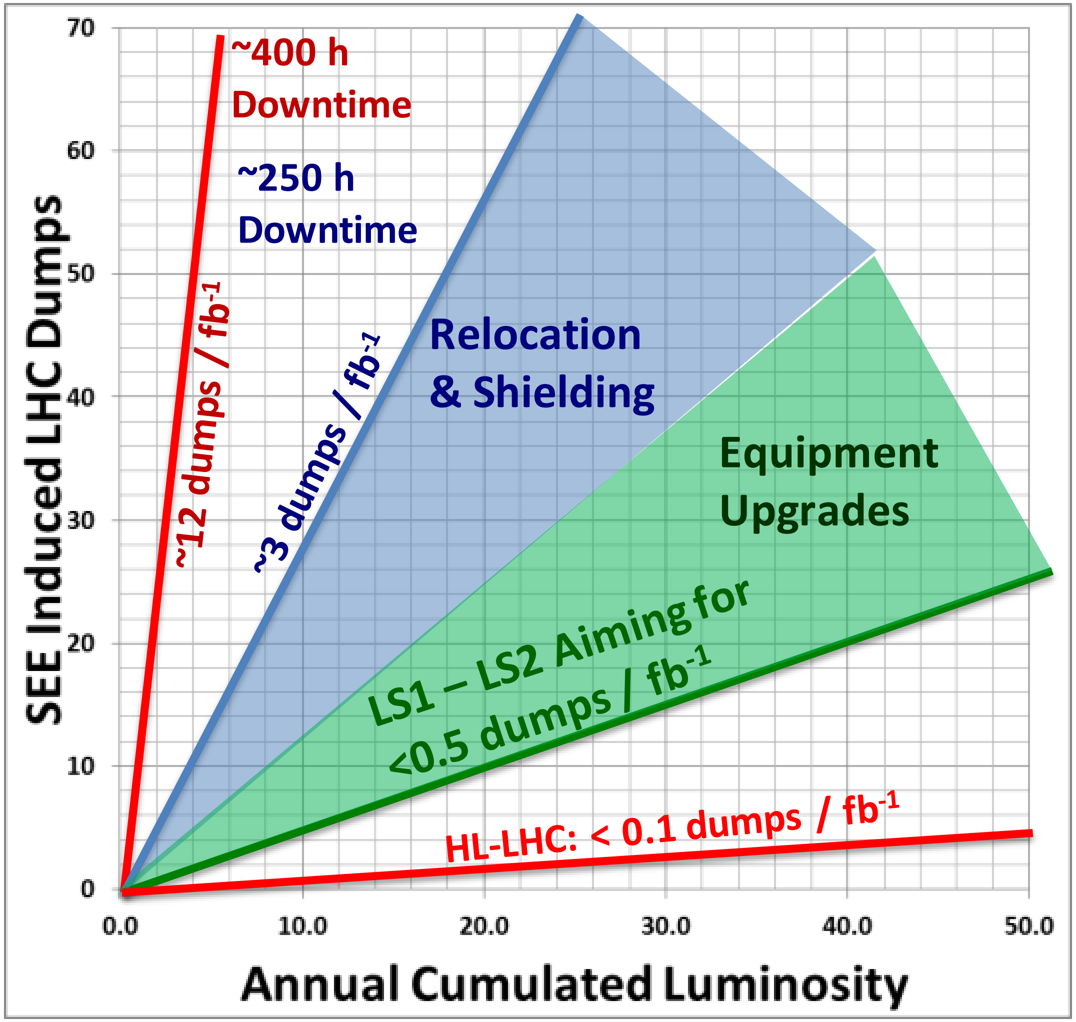
Total: 58.6h





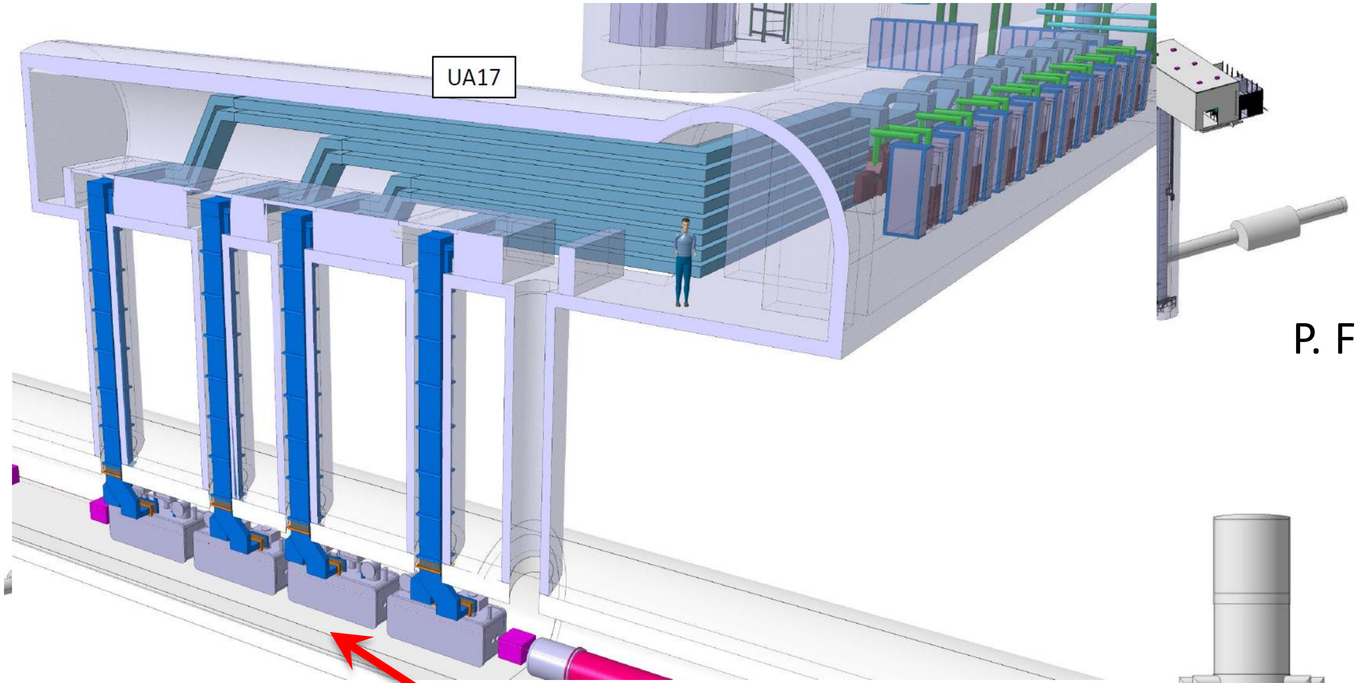
2015 data (week 38) consistent with RunI experience: average of ca. 6.5 h
B. Auchmann @ LMC 23. 9. 2015

R2E SEU Failure Analysis - Actions

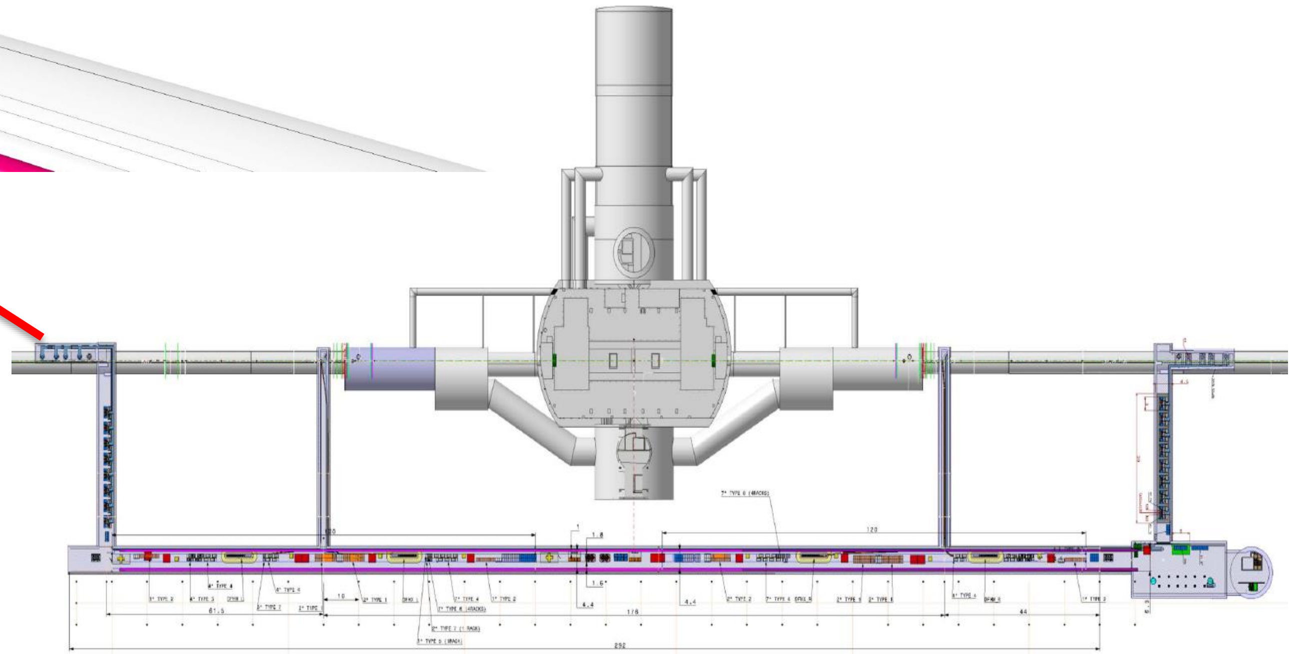


- **2008-2011**
  - Analyze and mitigate all safety relevant cases and limit global impact
- **2011-2012**
  - Focus on equipment with long downtimes; provide shielding
- **LS1 (2013/2014)**
  - Relocation of power converters
- **LS1 – LS2:**
  - Equipment Upgrades
- **LS3 -> HL-LHC**
  - Remove all sensitive equipment from underground installations

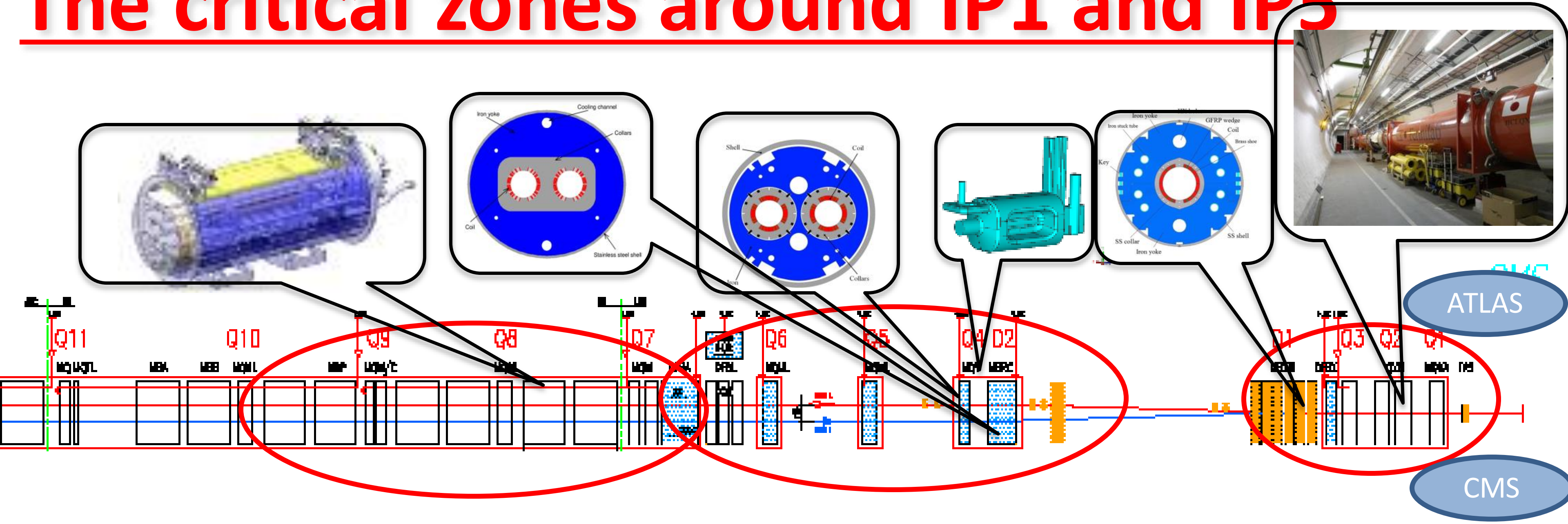
IR1 & IR5 Underground Civil Engineering:



P. Fessia, HL-LHC TDR



The critical zones around IP1 and IP5



3. For collimation we also need to change the DS in the continuous cryostat: 11T Nb_3Sn dipole

2. We also need to modify a large part of the matching section e.g. Crab Cavities & D1, D2, Q4 & corrector

1. New triplet Nb_3Sn required due to:
- -Radiation damage
- -Need for more aperture

Changing the triplet region is not enough for reaching the HL-LHC goal!

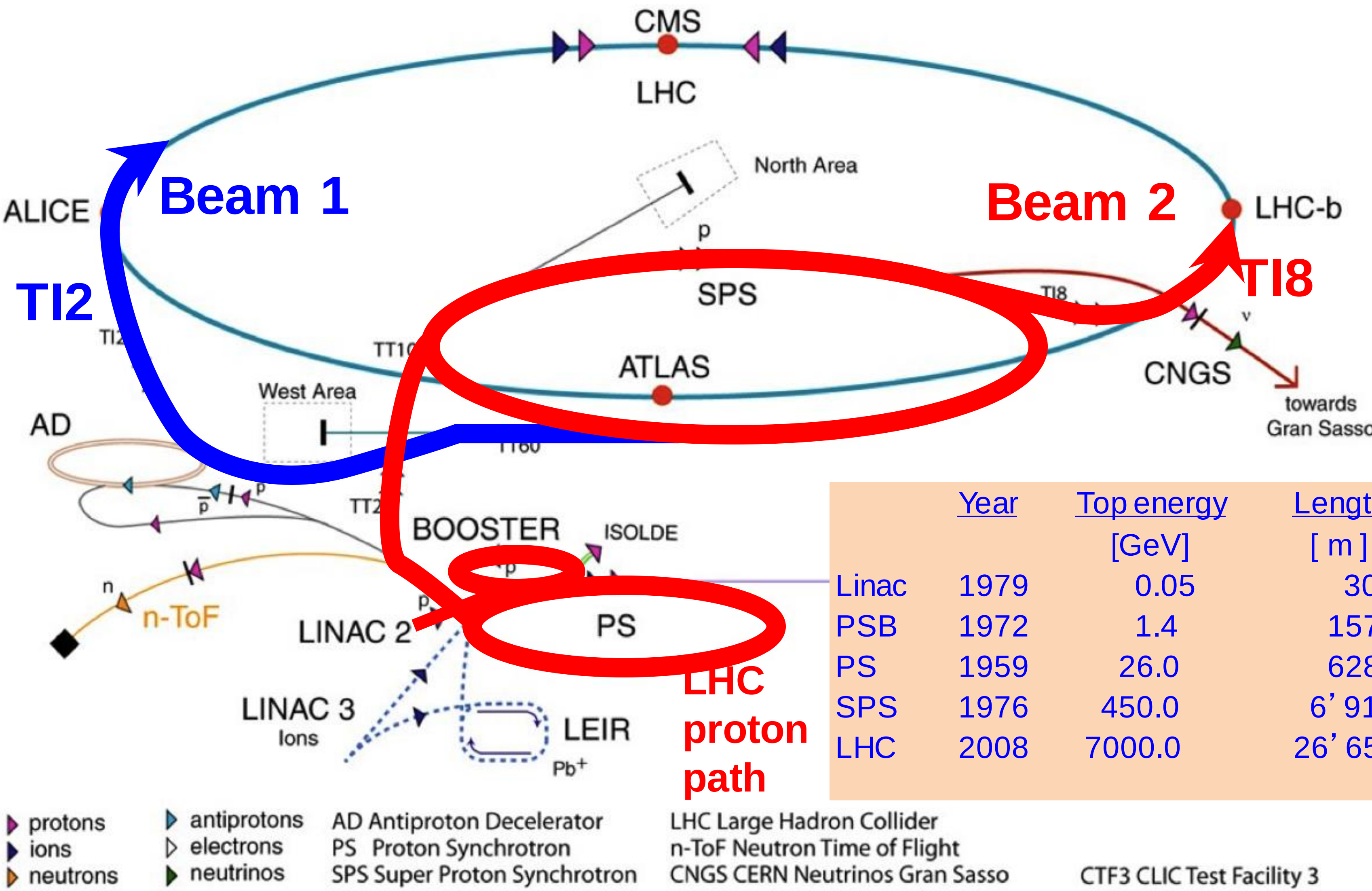
→ **More than 1.2 km of LHC !!**

→ **Plus technical infrastructure (e.g. Cryo, Powering & new caverns)!!**

High Luminosity LHC

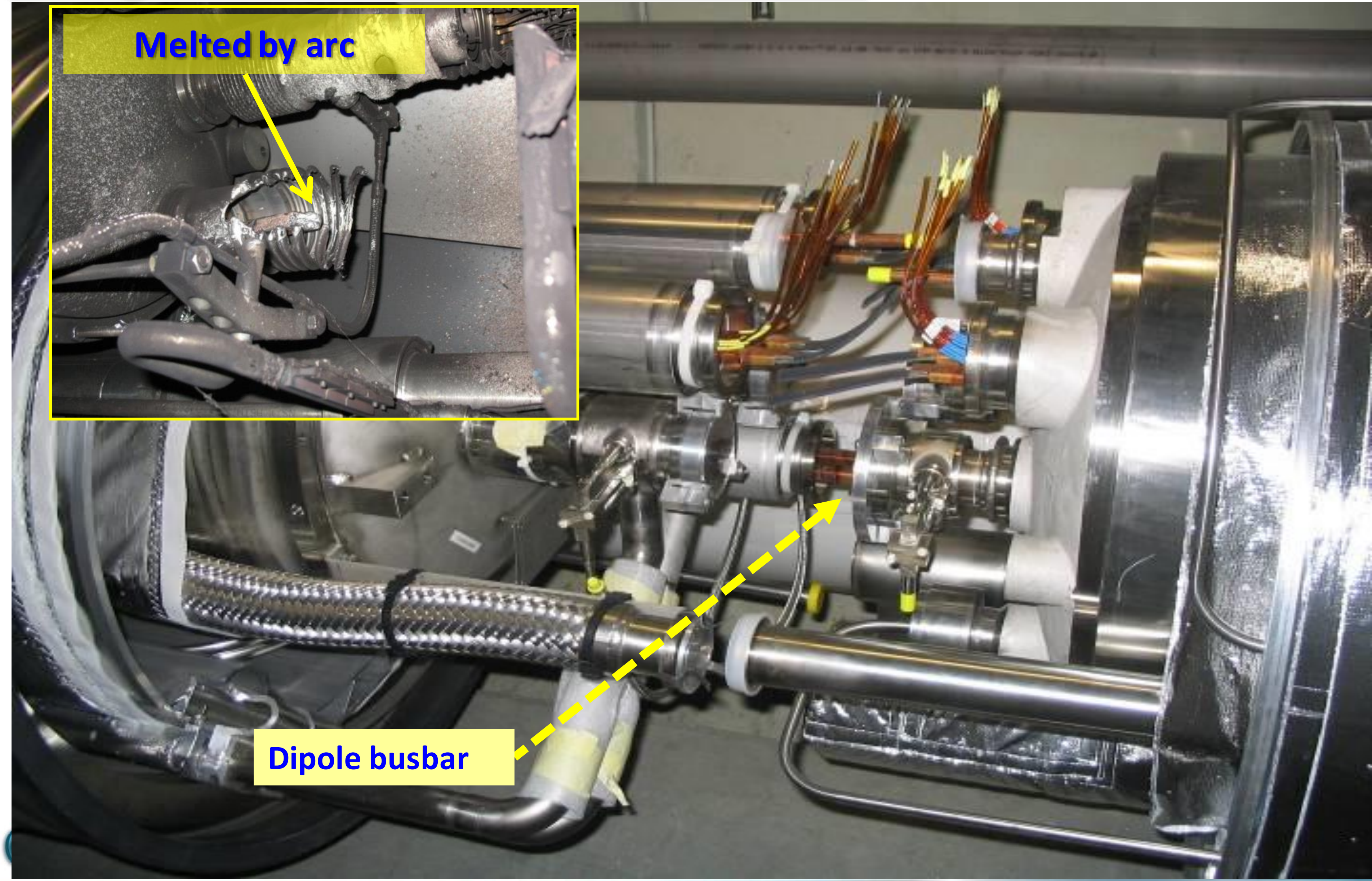
Reserve Transparencies

The LHC is NOT a Standalone Machine:



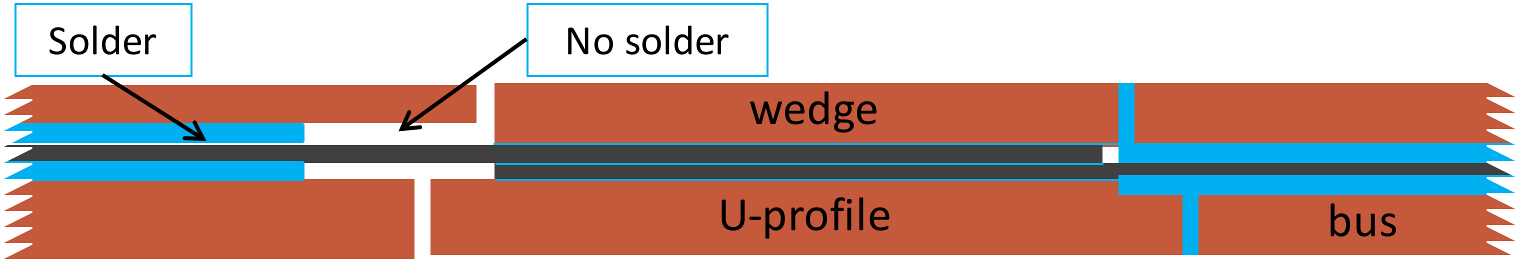
	Year	Top energy [GeV]	Length [m]
Linac	1979	0.05	30
PSB	1972	1.4	157
PS	1959	26.0	628
SPS	1976	450.0	6’911
LHC	2008	7000.0	26’657

Magnet Interconnections:



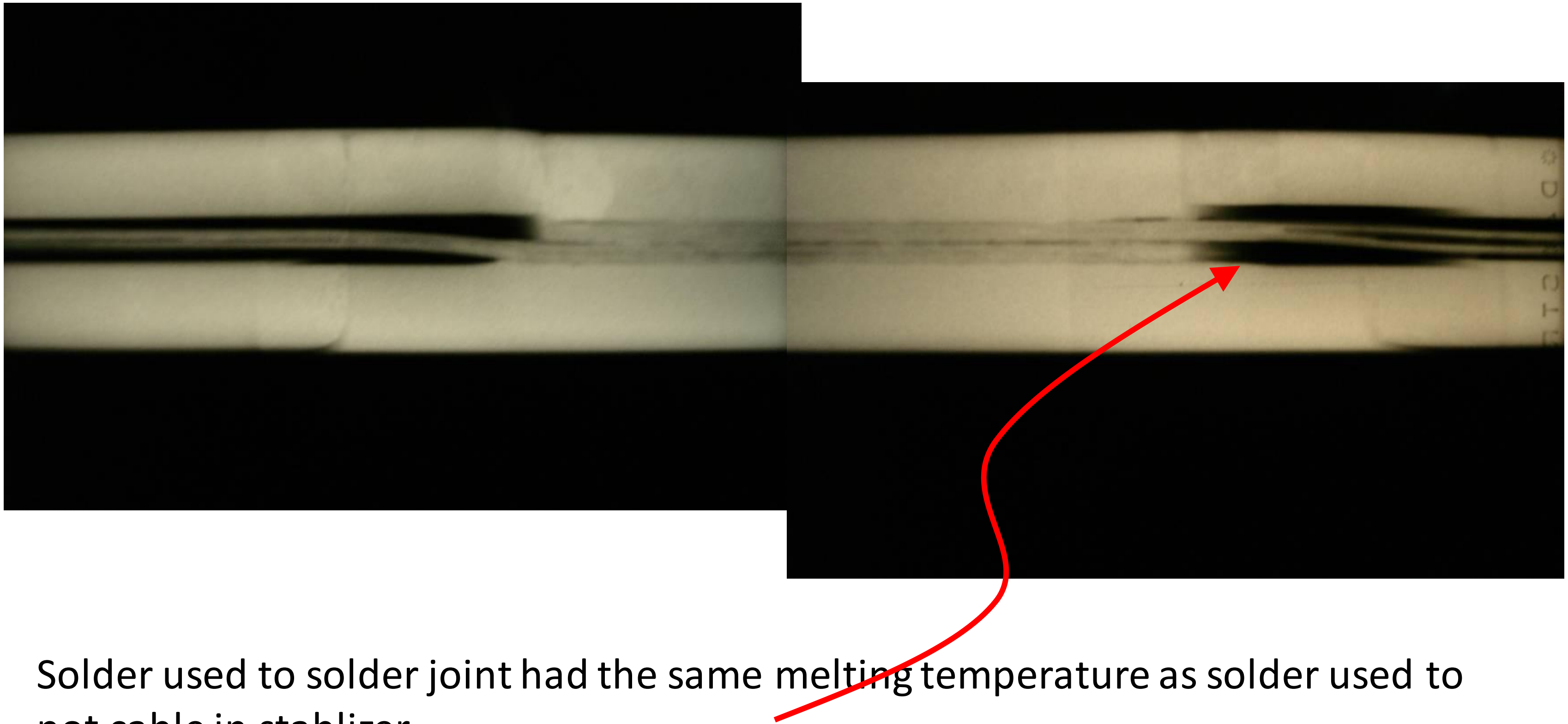
Joint quality

During repair work in the damaged sector, inspection of the joints revealed systematic voids caused by the welding procedure.



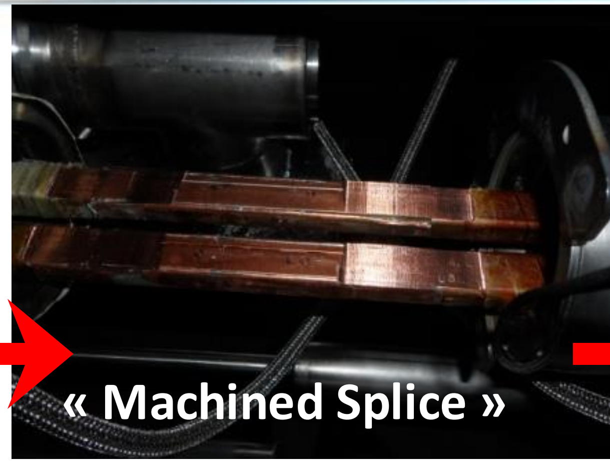
Extensive simulations and measurements in the lab have show that there is potential for thermal run away in case of a bus-bar quench

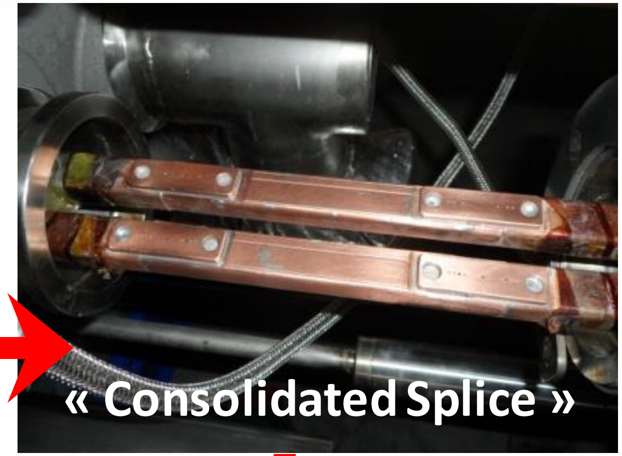
Joint Quality:

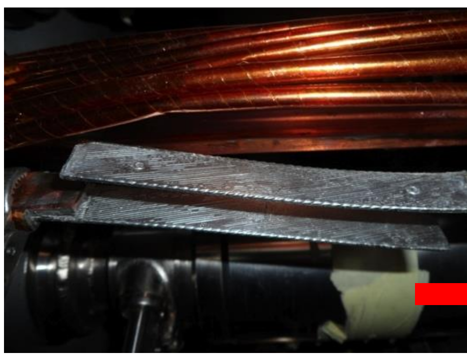


Solder used to solder joint had the same melting temperature as solder used to pot cable in stablizer

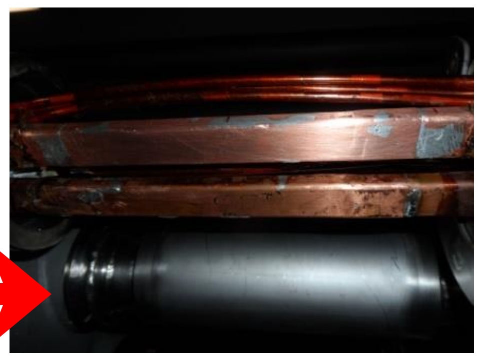
⇒ **Solder wicked away from cable**



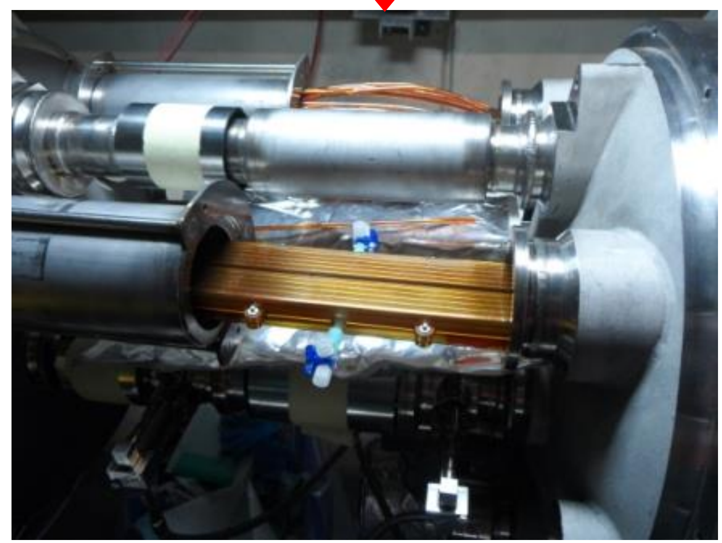




« Cables »



« New Splice »



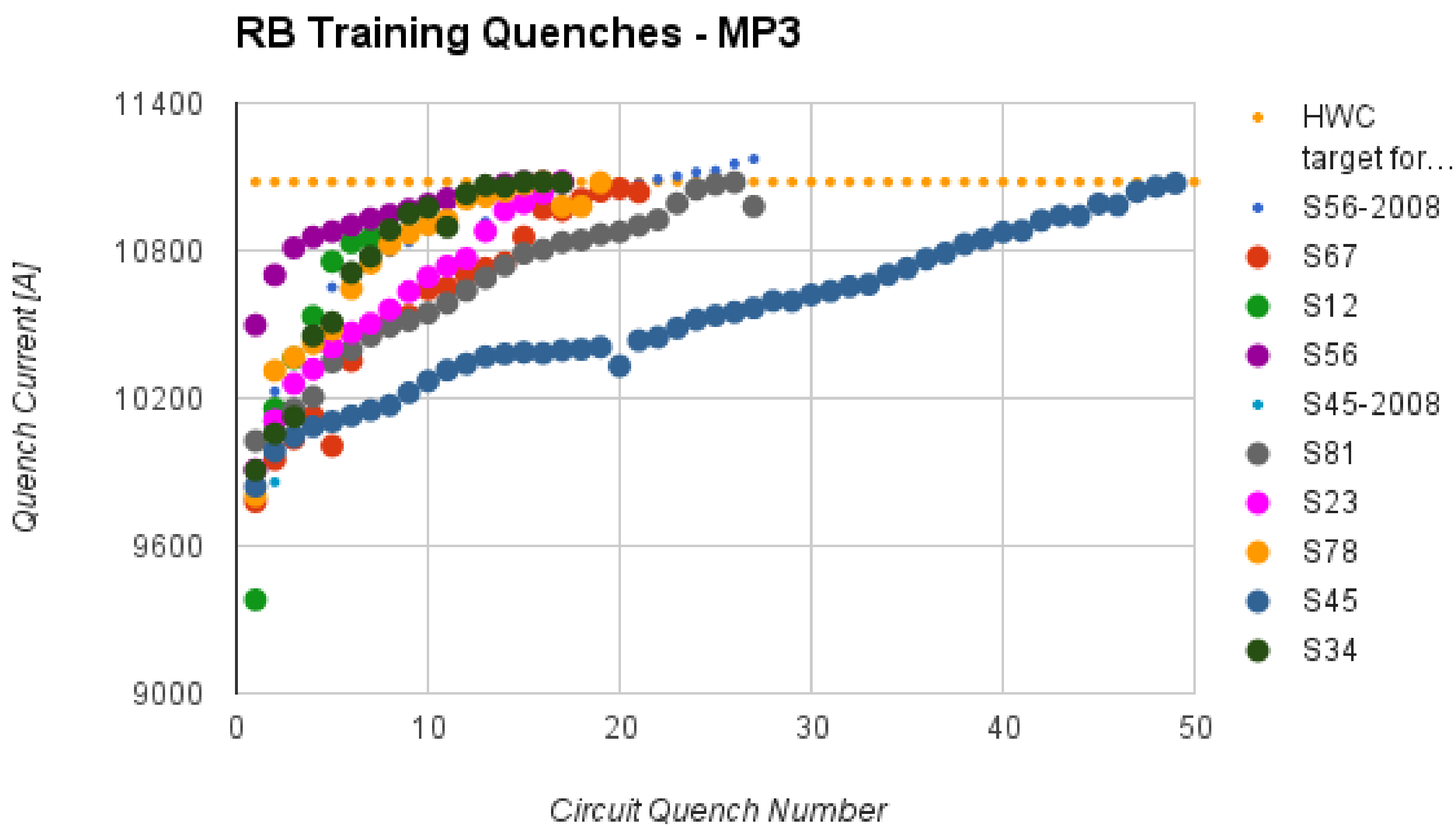
« Insulation box »

- 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

Long Shutdown 1: LS1

Hardware Commissioning: Dipole training

- 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
- RB34 earth fault ➔ controlled burn off using capacitive discharge



LHC RunII Goals and Plans for 2015

- Target energy: 6.5 TeV
  - looking good after a major effort

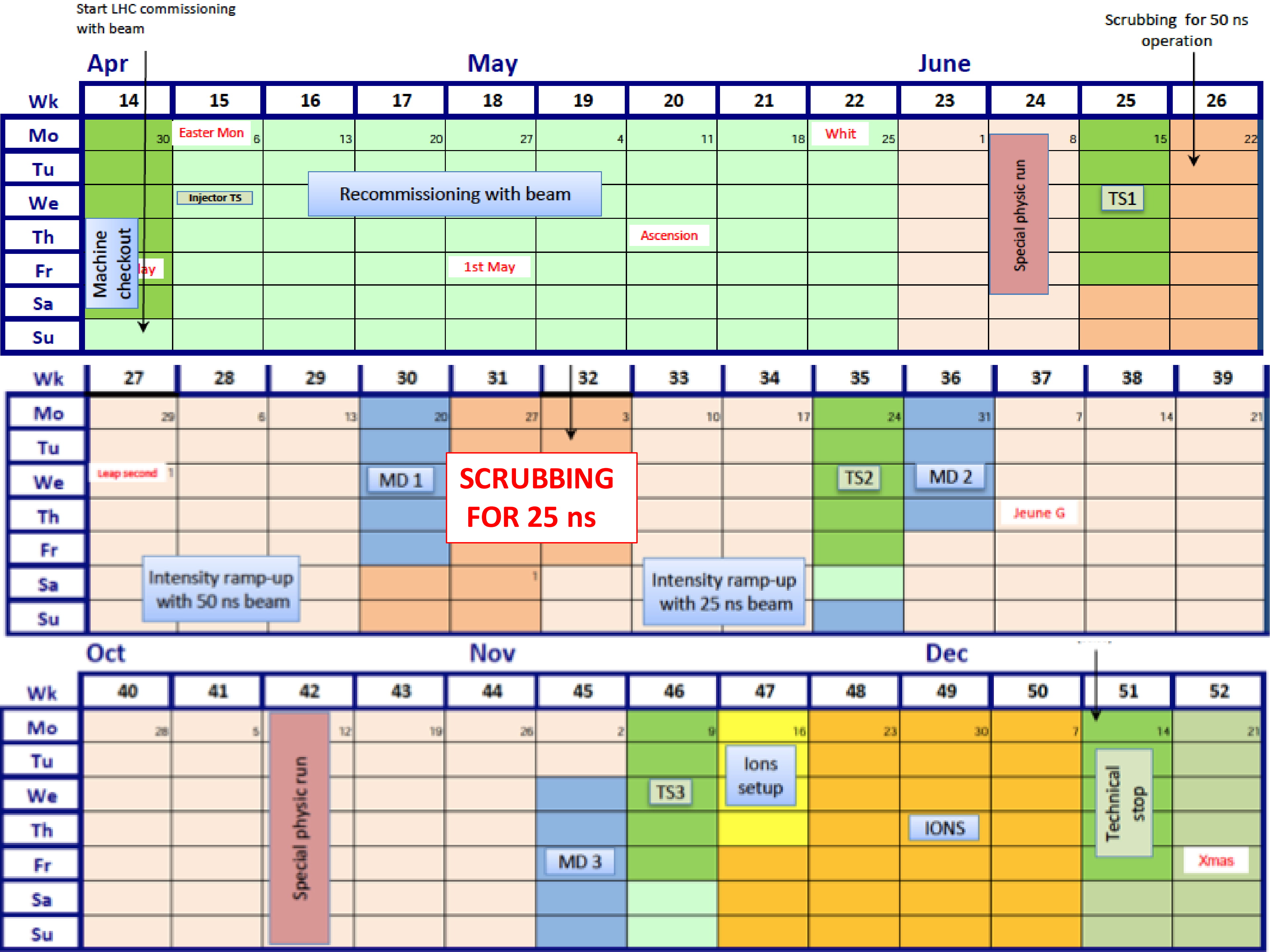
    (magnet detraining [up to 50 training quenches] & intermittent earth fault in B8R5 and other circuits)
- Bunch spacing: 25 ns
  - strongly favored by experiments – pile-up
  - Requires careful conditioning (scrubbing) with beam (time) [e-cloud & UFO]
- β^* in ATLAS and CMS: 80 [to 40 cm]

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 β^*
- Higher total beam current
- Higher intensity per injection

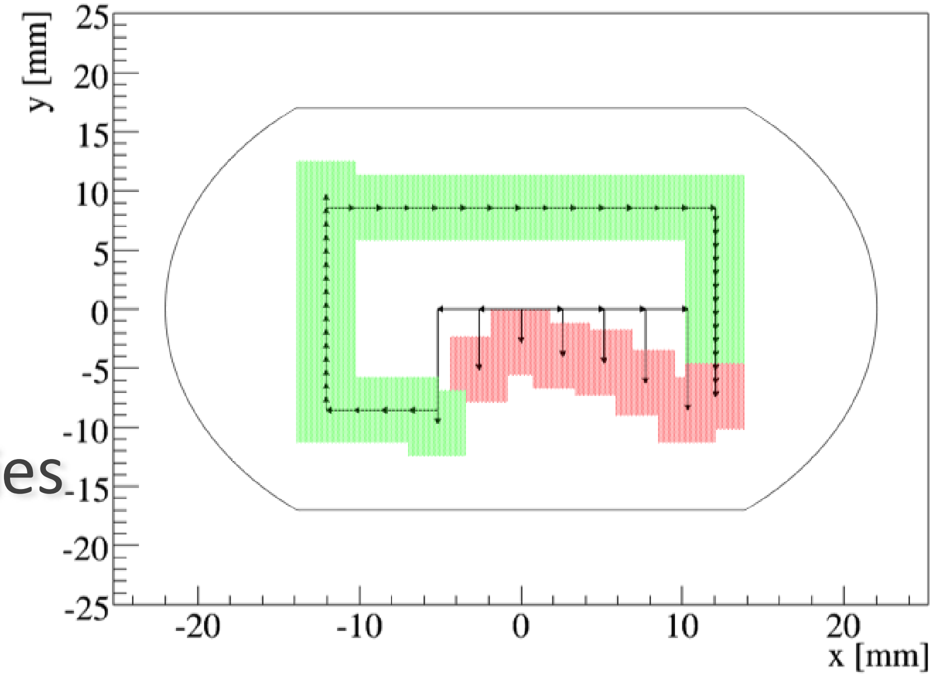


Start LHC commissioning with beam
Scrubbing for 50 ns operation
Apr
May
June
Wk
14
15
16
17
18
19
20
21
22
23
24
25
26
Mo
Tu
We
Th
Fr
Sa
Su
30
Easter Mon
6
13
20
27
4
11
18
Whit
25
1
8
15
22
Injector TS
Recommissioning with beam
Machine checkout
Ascension
1st May
Special physic run
TS1
Wk
27
28
29
30
31
32
33
34
35
36
37
38
39
29
6
13
20
27
3
10
17
24
31
7
14
21
Leap second
1
MD 1
SCRUBBING FOR 25 ns
TS2
MD 2
Jeune G
Intensity ramp-up with 50 ns beam
Intensity ramp-up with 25 ns beam
Oct
Nov
Dec
Wk
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
Ions setup
TS3
IONS
MD 3
Technical stop
Xmas

ULO (Unidentified Lying Object)

Aperture restriction in 15R8

- 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
- Behavior with higher intensities looks OK



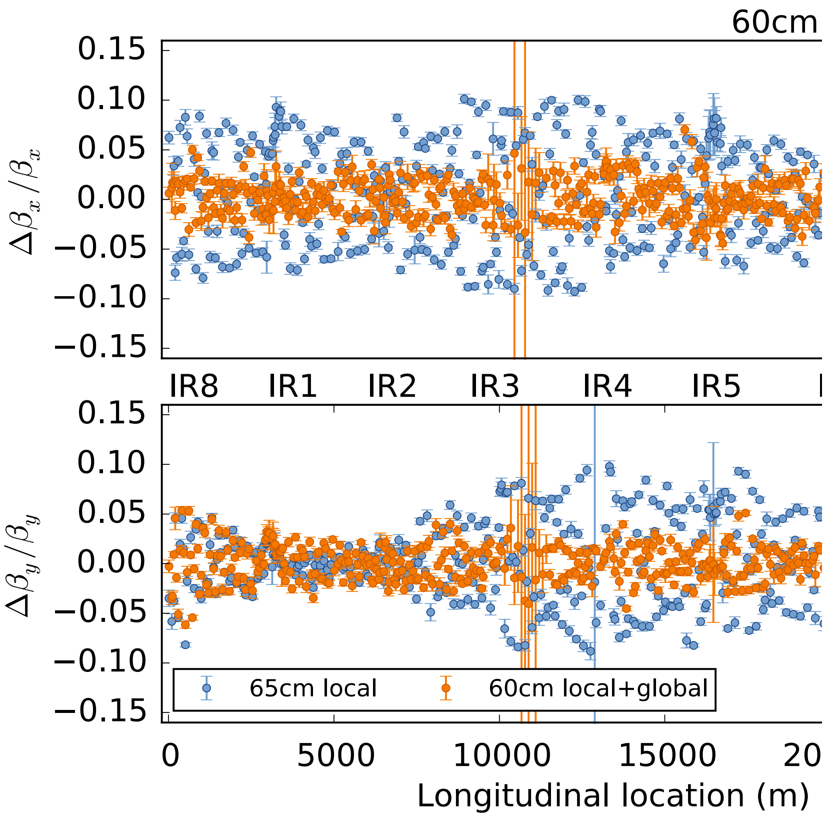
D. Pascal, 27.4. LHC morning meeting

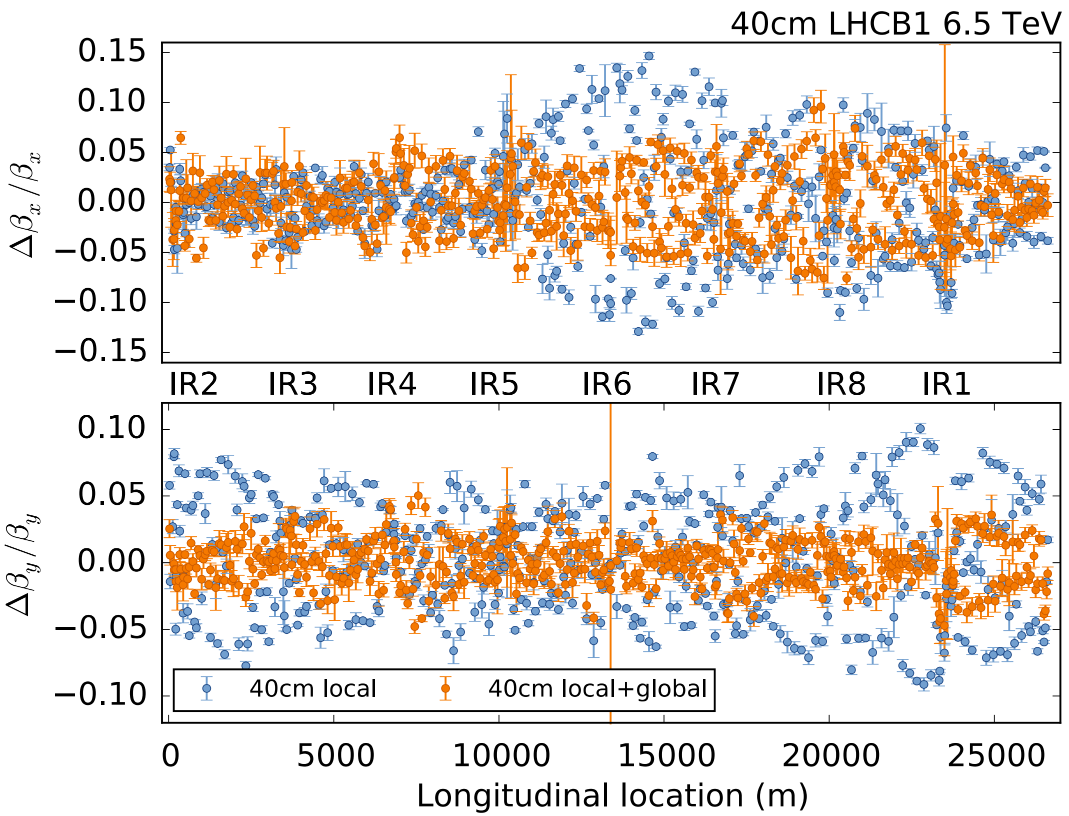
Optics measurements:

- New magnet transfer function commissioning to 6.5 TeV (from 4TeV in RunI)
- New machine cycle wrt RunI
- Measured optics on and off-momentum at 80cm, 70cm and 65 cm with collision tunes.

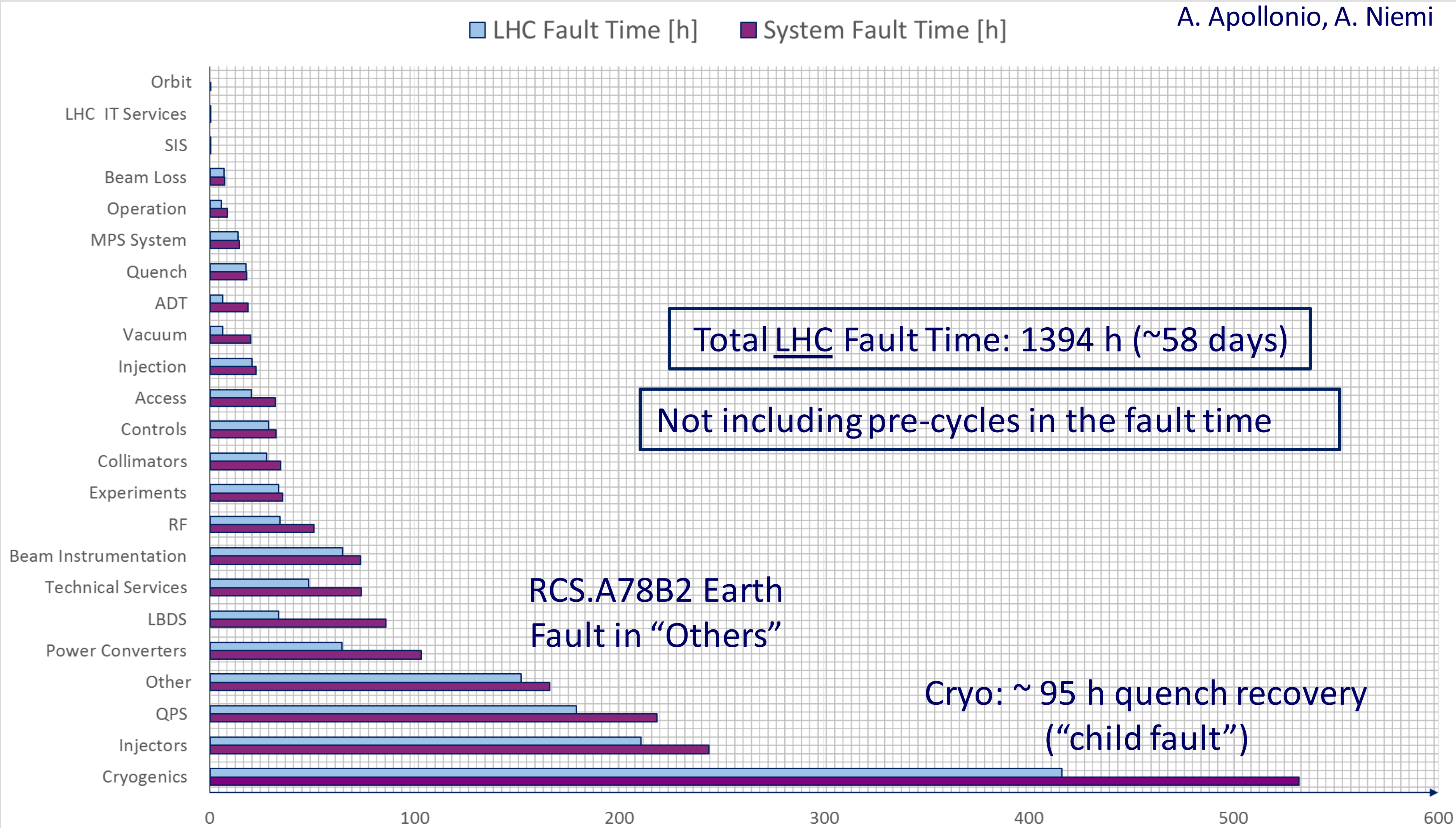
➔ global beta-beat < 10%, at IP1/5 < 5%

R. Tomas - OMT, 20.5. LHC morning meeting



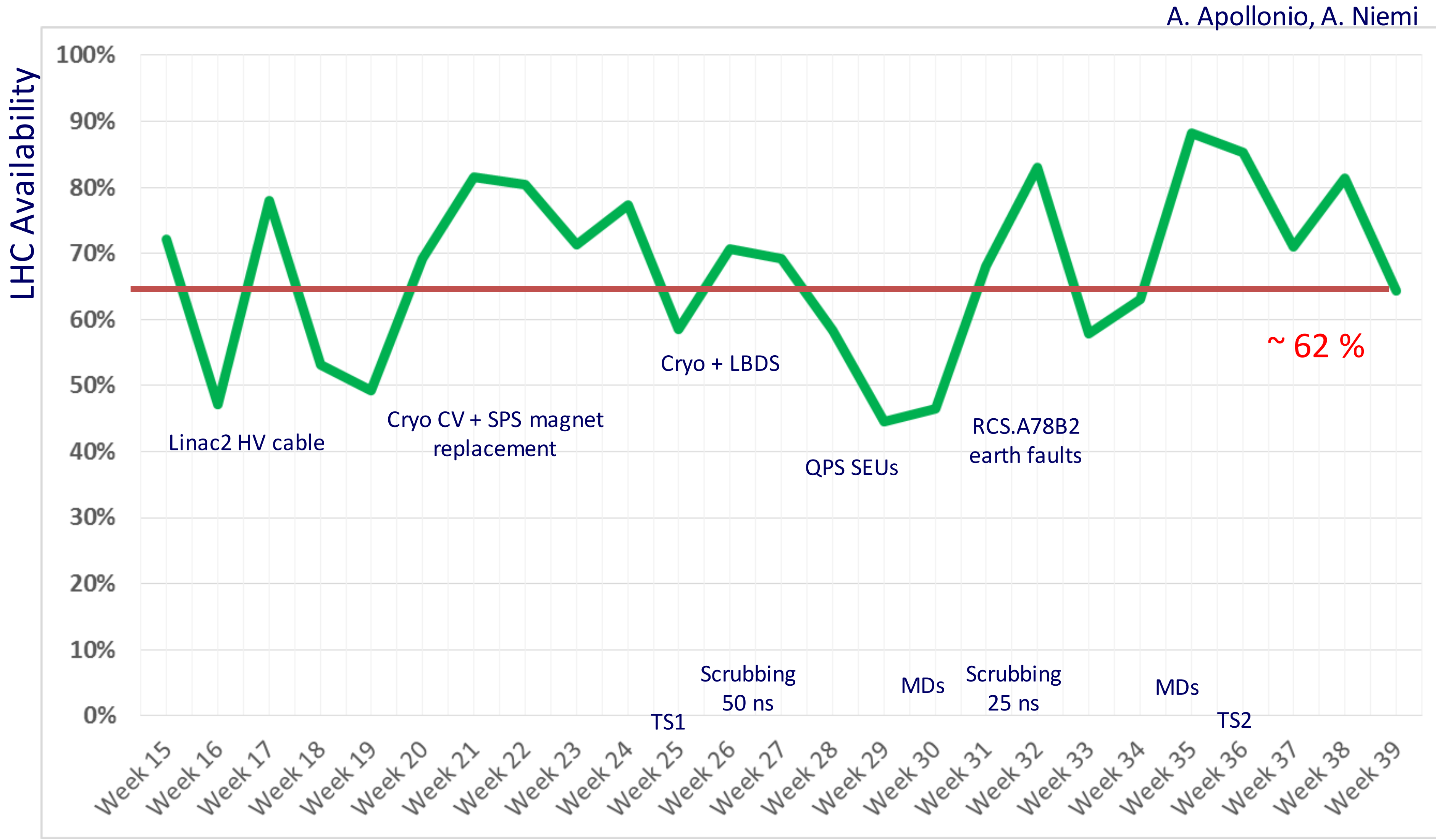


Fault Time in 2015 up to 27th September



- **Over a period with approximately 150 days of scheduled operation ➔ ca. 38% fault time**

Overall Machine Availability:

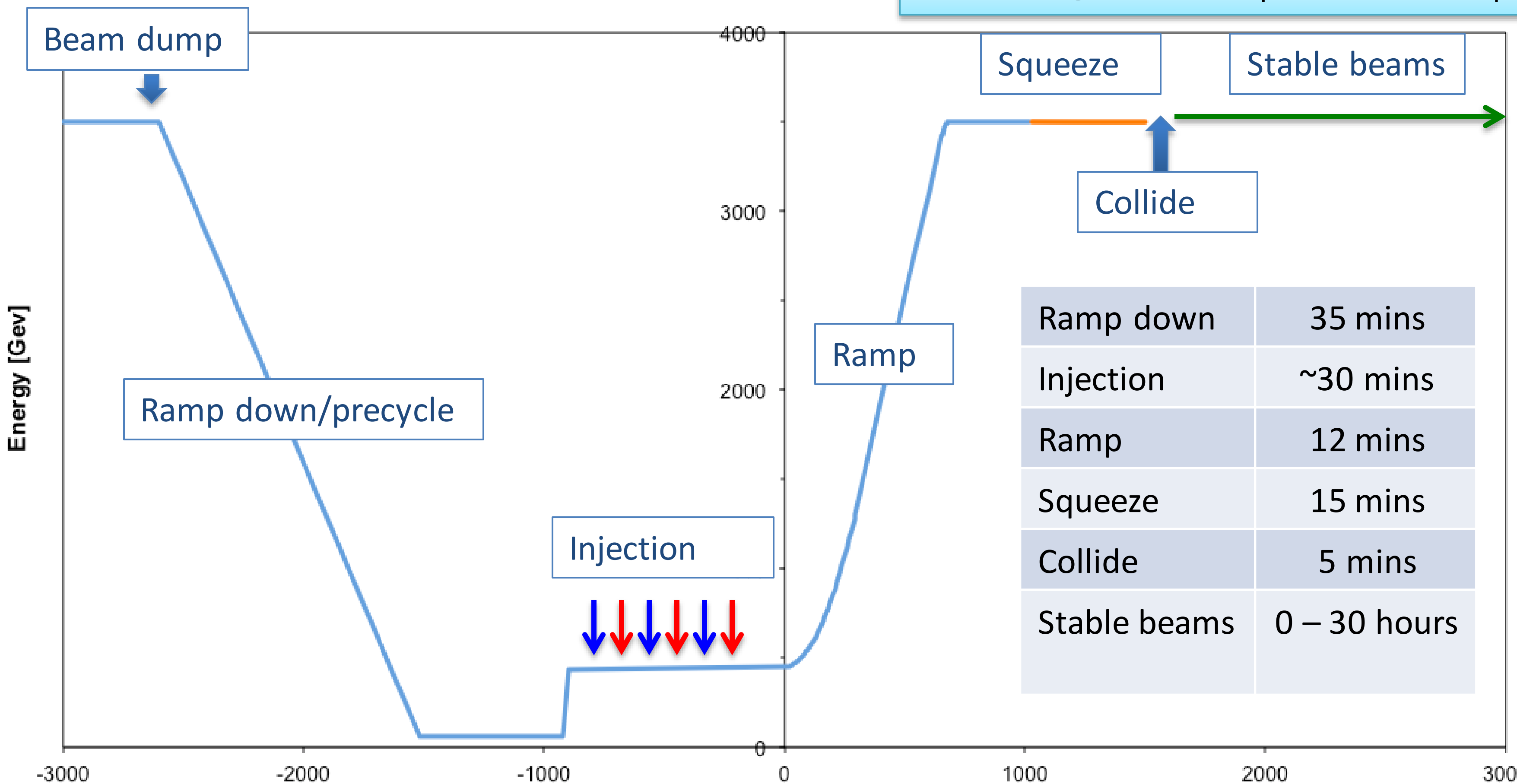


- Not including pre-cycles due to faults in the unavailability

HL-LHC Challenge: Machine Efficiency

Nominal LHC Operation Cycle:

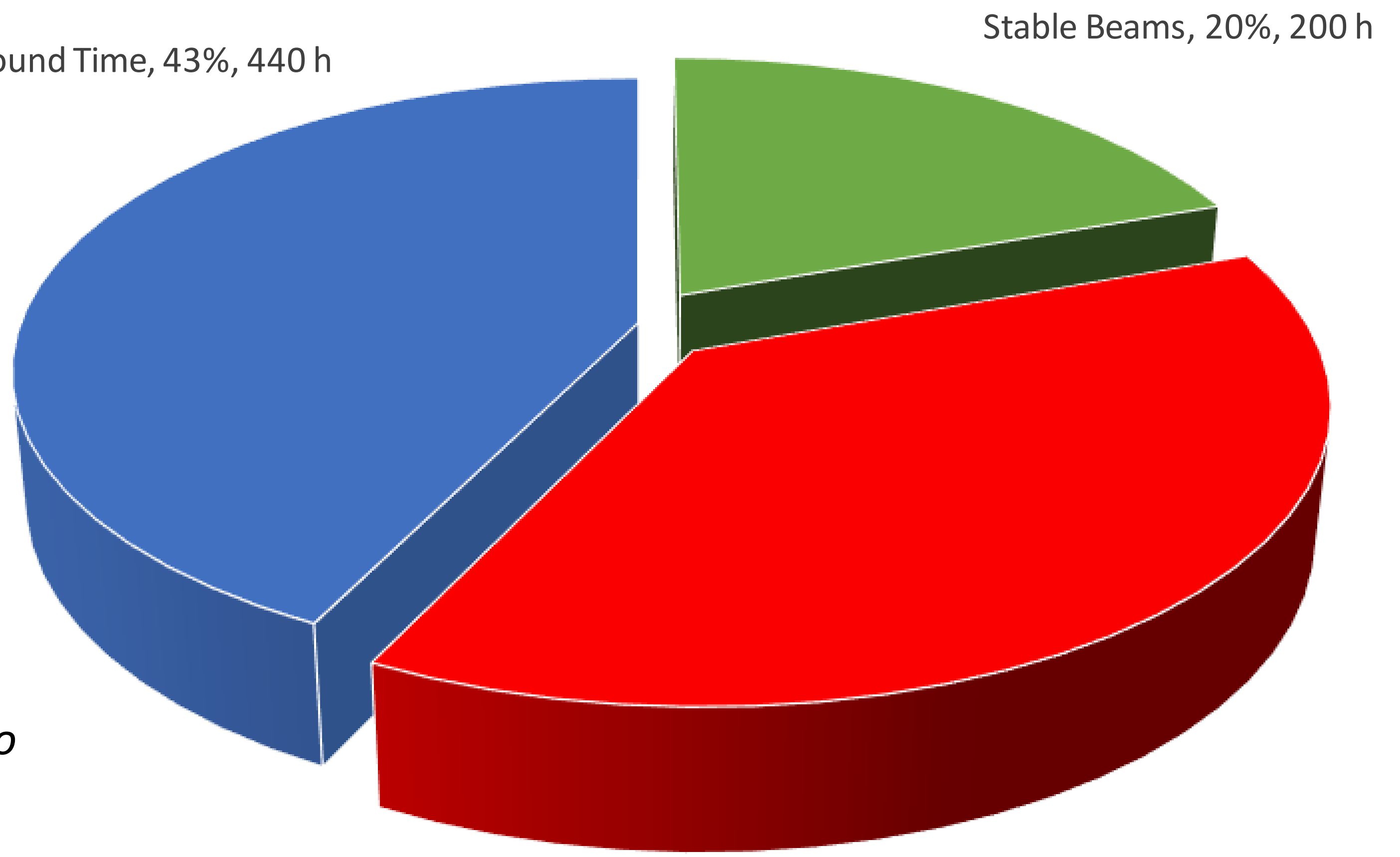
M. Lamont @ Evian LHC Operation workshop



Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

→ Operational Turn around time of 2 - 3 hours → Efficiency = time in physics / scheduled time

Overall Machine Efficiency:



Includes beam measurements and tests

A. Apollonio

- **Total 43 days allocated for physics run**
- **End of RunI (50ns) : 36.5% (A. McPherson @ Evian 2012); HL-LHC: 50%**

2015: ATLAS and CMS performance outlook

- 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!)**

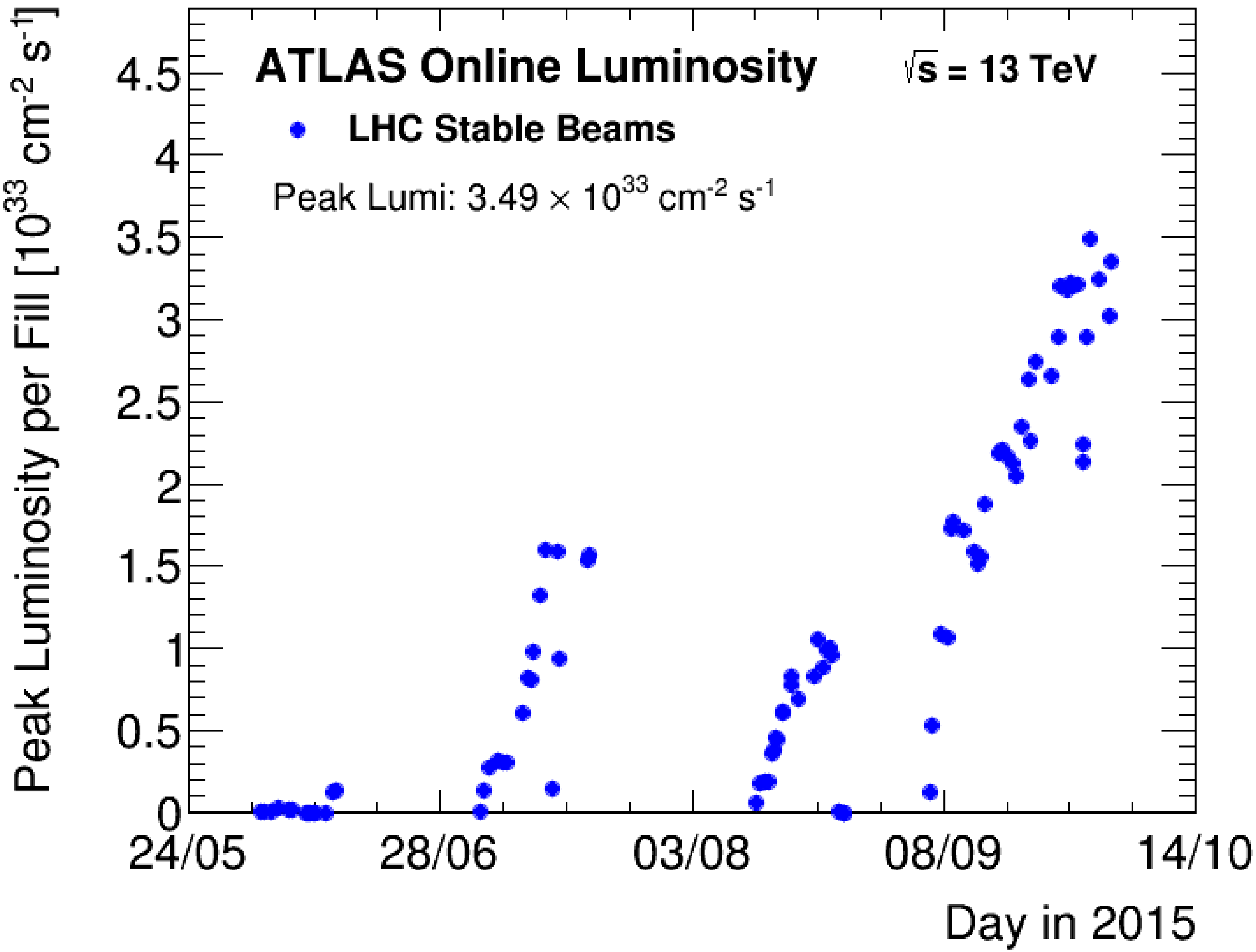
	Nc	Beta *	ppb	EmitN	Lumi [$cm^{-2}s^{-1}$]	Days (approx)	Int lumi	Pileup
50 ns	476	80	1.1e11	1.8	1.6e33	14	0.1 fb^{-1}	27
2015.1	2376	80	1.2e11	3.1	7.0e33	33	~3 fb^{-1}	21
2015.2	2376	40	1.2e11	3.1	1.2e34	28	~4 fb^{-1}	35

Official luminosity target for the year was 10 fb^{-1}

Now even 5 fb^{-1} seems to be on the challenging side (QPS, Cryo)

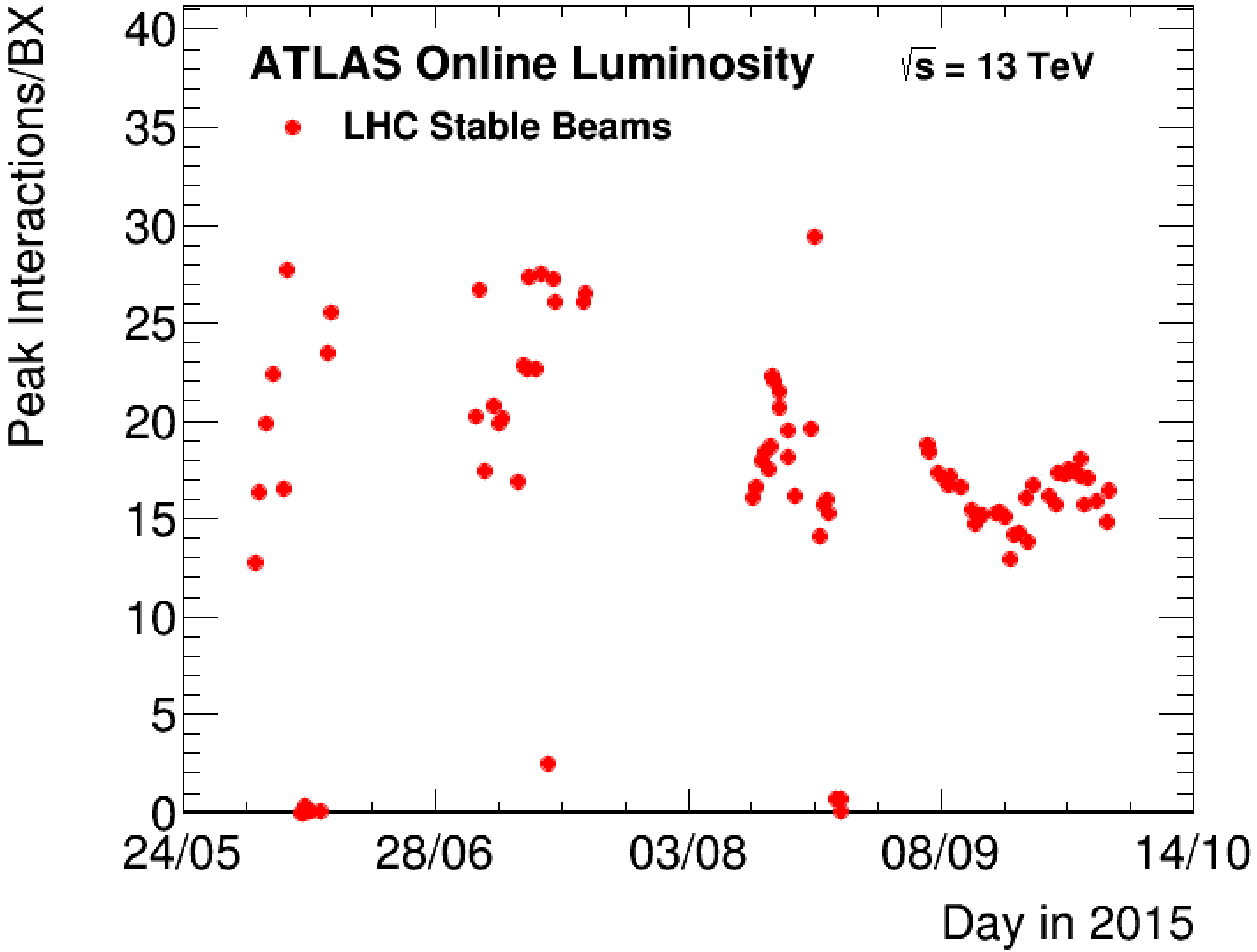
Intensity ramp up

ATLAS Data



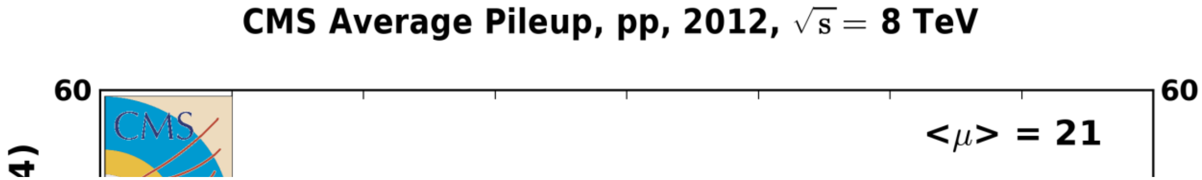
Intensity ramp up

ATLAS Data



HL-LHC Challenge: Event Pileup Density

Vertex Reconstru



HL-LHC Performance Optimization:

Use leveling techniques for keeping average

Pileup around 140 events per bunch crossing

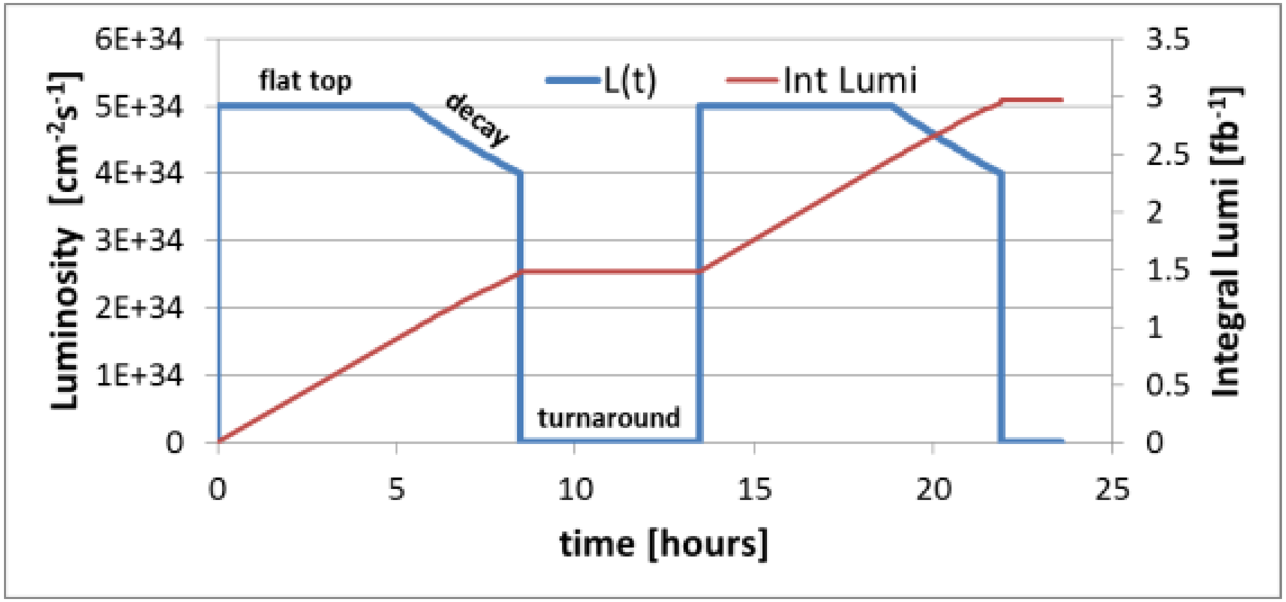
➔ level luminosity at 5 10^{34} cm^{-2} s^{-1}

➔ $\langle\mu\rangle = 140$; $\mu_{peak} = 280$ @ 25ns bunch spacing

High Luminosity LHC

LHC Upgrade Goals: Performance optimization

- Levelling:

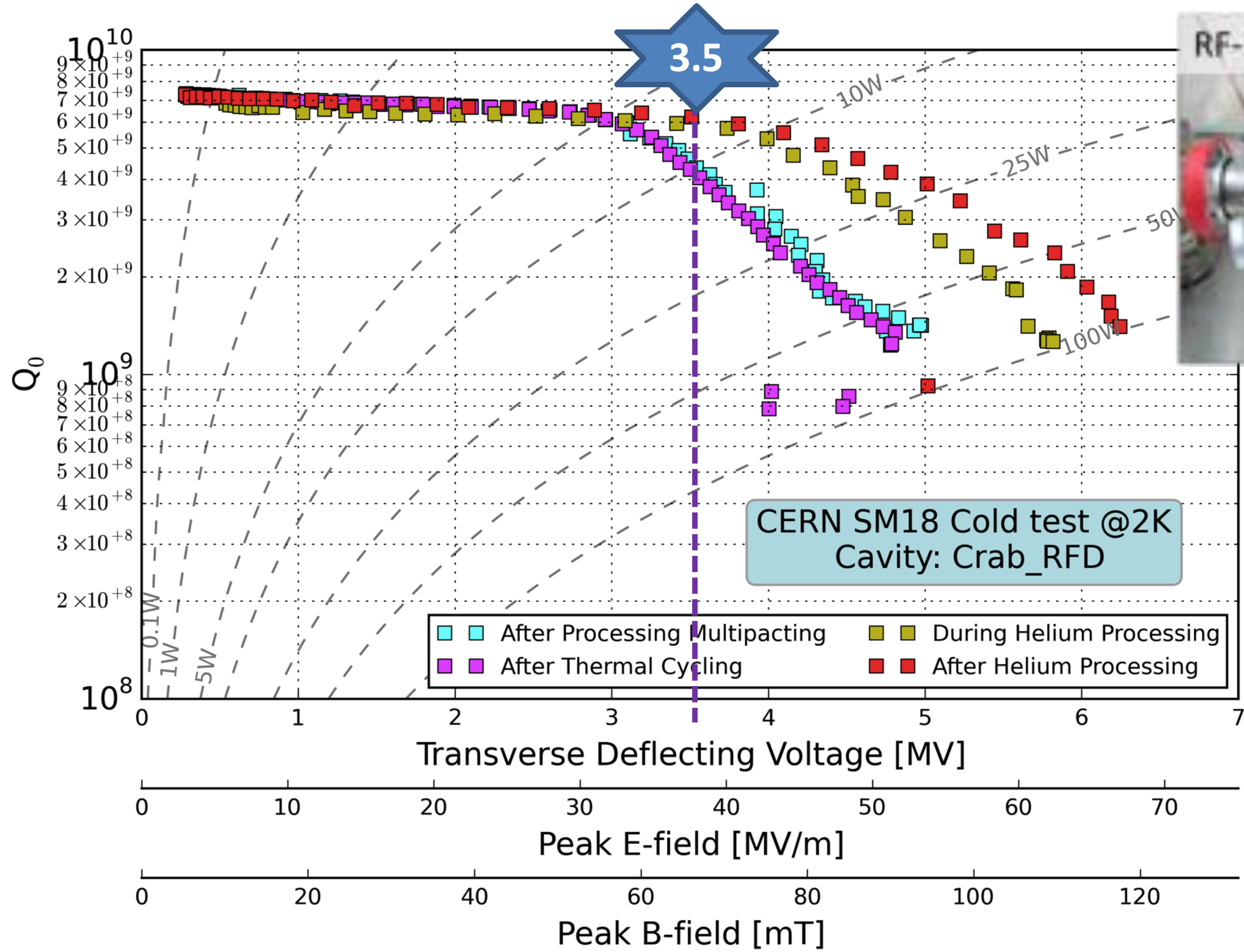


- Luminosity limitation(s):
  - Even Pileup in detectors
  - Debris leaving the experiments and impacting in the machine (magnet quench protection)
  - Triplet Heat Load

High Luminosity LHC

And excellent first results: RF Dipole

Recent results from Measurements @ CERN

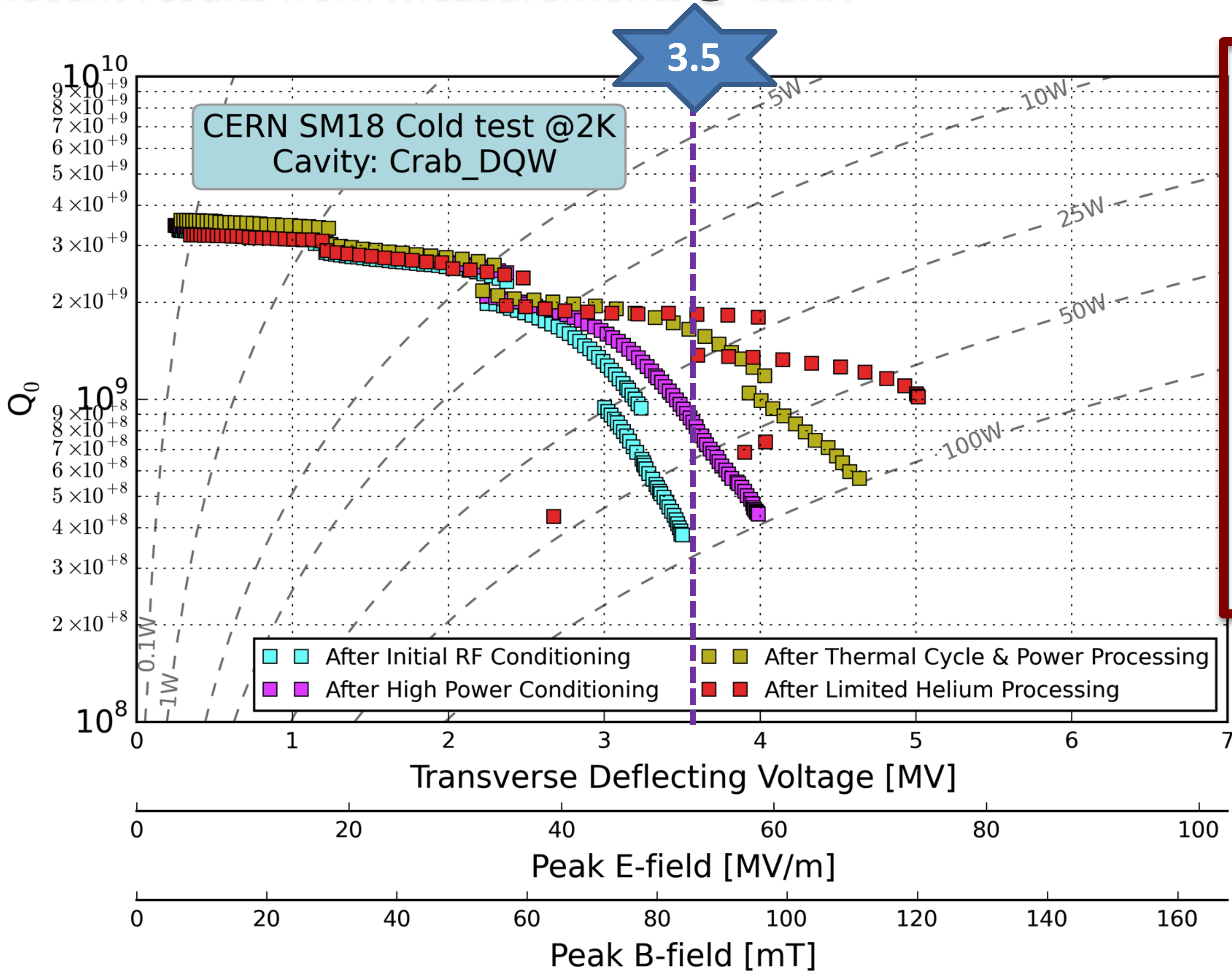


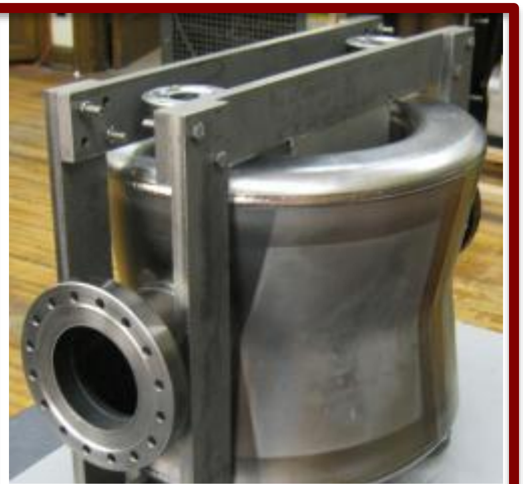
Initial goal was 3.5 MV however ΔV > 5-6 MV would ease integration

High Luminosity LHC

And excellent first results: DQW

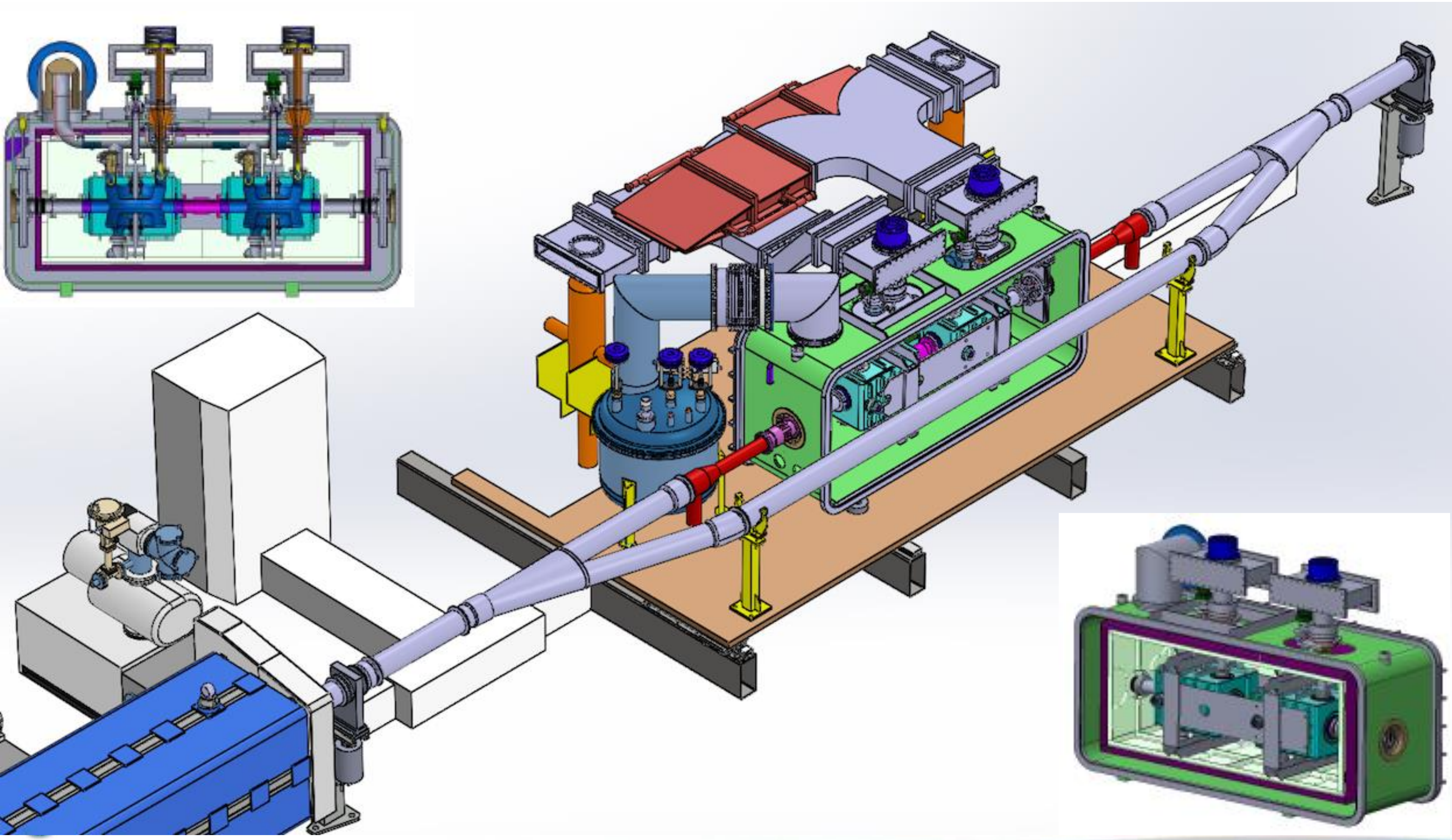
Recent results from Measurements @ CERN





DQWR prototype (17-Jan-2013) [BNL]

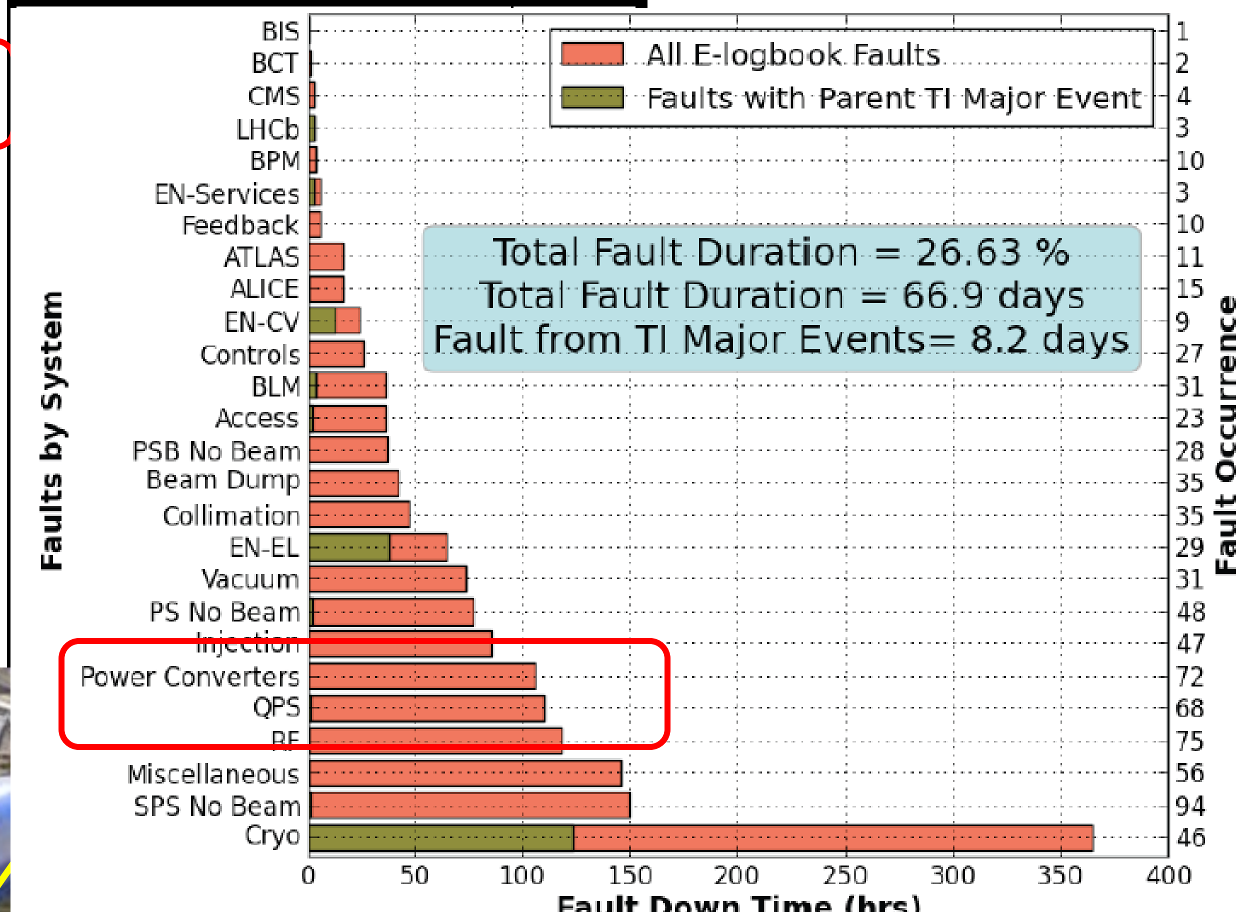
SPS beam test: a critical step for Crab Cavities (profiting of the EYETS 2016- 2017):



Intervention rate & time: QPS boxes

Dump Cause	#
Beam: Losses	58
Quench Protection	56
Power Converter	35
Electrical Supply	26
RF + Damper	23
Feedback	19
BLM	18
Vacuum	17
Beam: Losses (UFO)	15
Cryogenics	14
Collimation	12

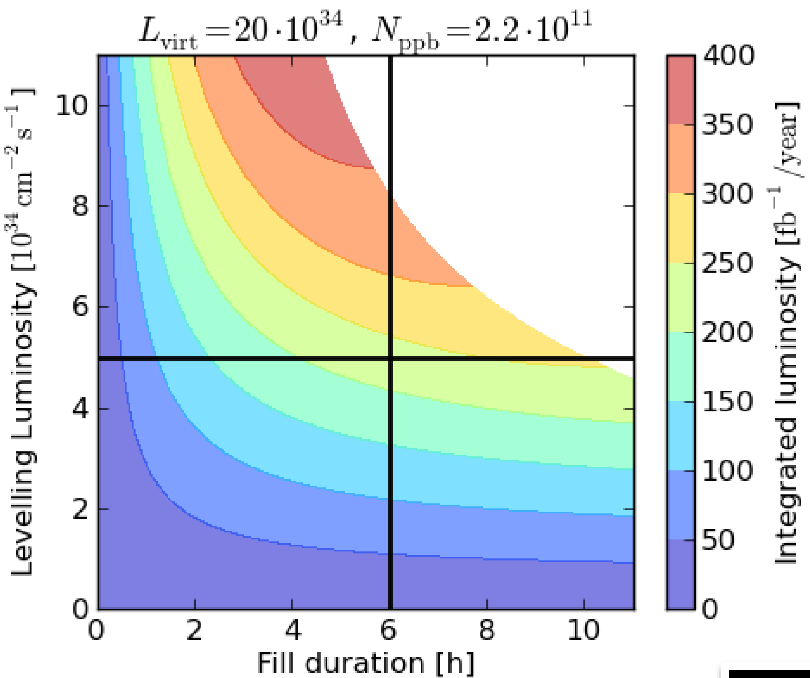
Dump Cause	#



Consolidation of infrastructure !
But also new paradigme: remove as much as possible from the tunnel

Efficiency for ∫Ldt:

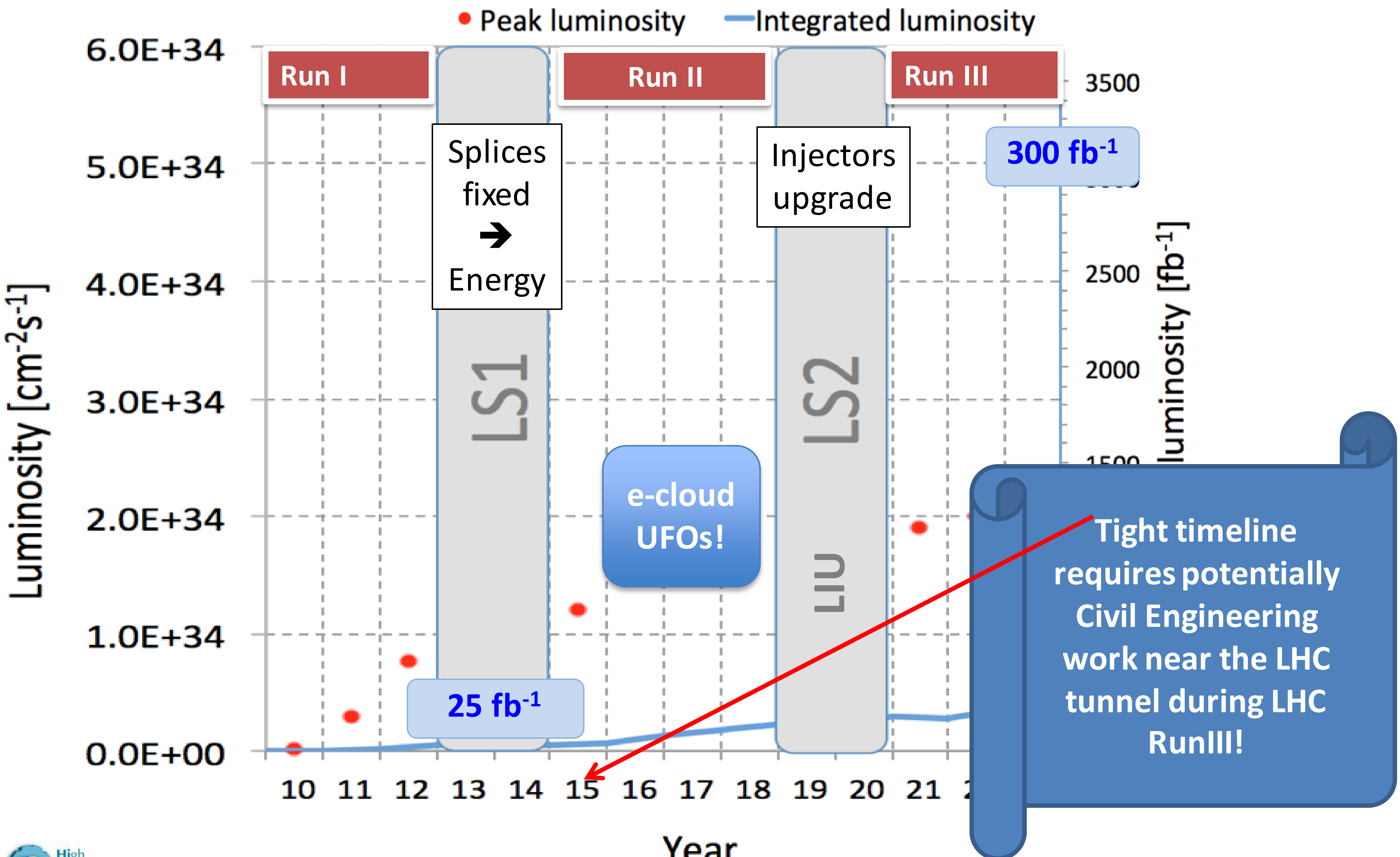
- All assumptions are based on forecast for the operation cycle:



$\eta \geq 50\%$

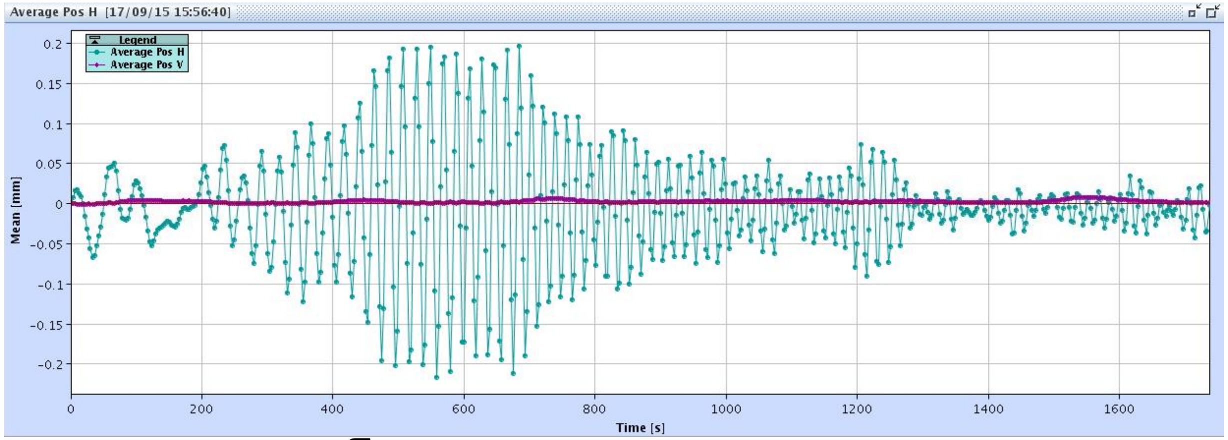
High reliability and availbility are key goals

Performance Projections up to HL-LHC:



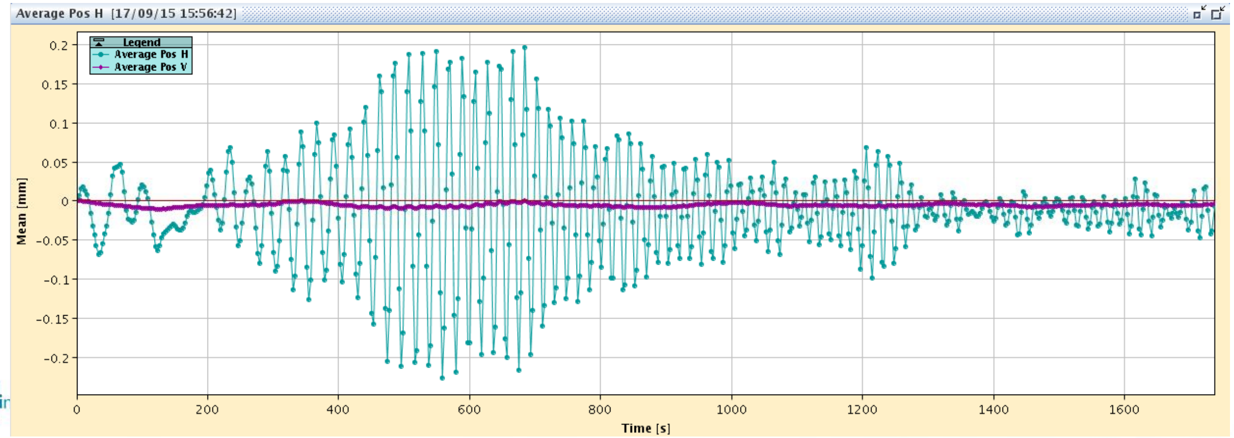
Vibrations and Earthquake detections

- LHC radial orbit change between **01:45** and **02:15 (23:45-24:15 UTC)**. LHC at injection energy. Radial amplitude is large (3 times larger than Costa Rica event, 200 microns).
- Roughly 1 hour after the 8.3M quake, which roughly fits a simple estimate based on a distance of 12’000 km at a speed of 4 km/s.



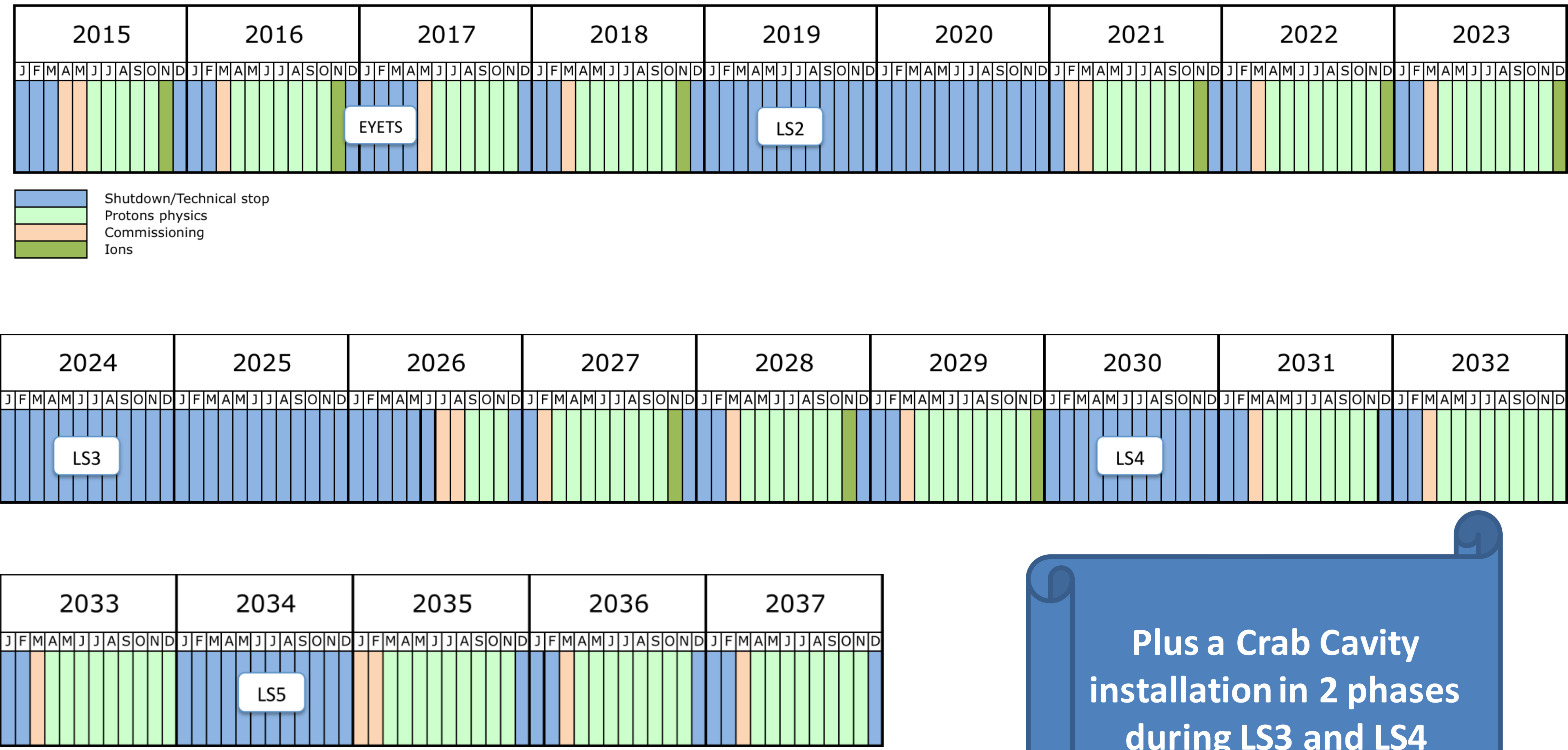
Period is ~ 25 seconds.

Peak excursions of +/- 200μm



J. Wenninger
08/10/2015

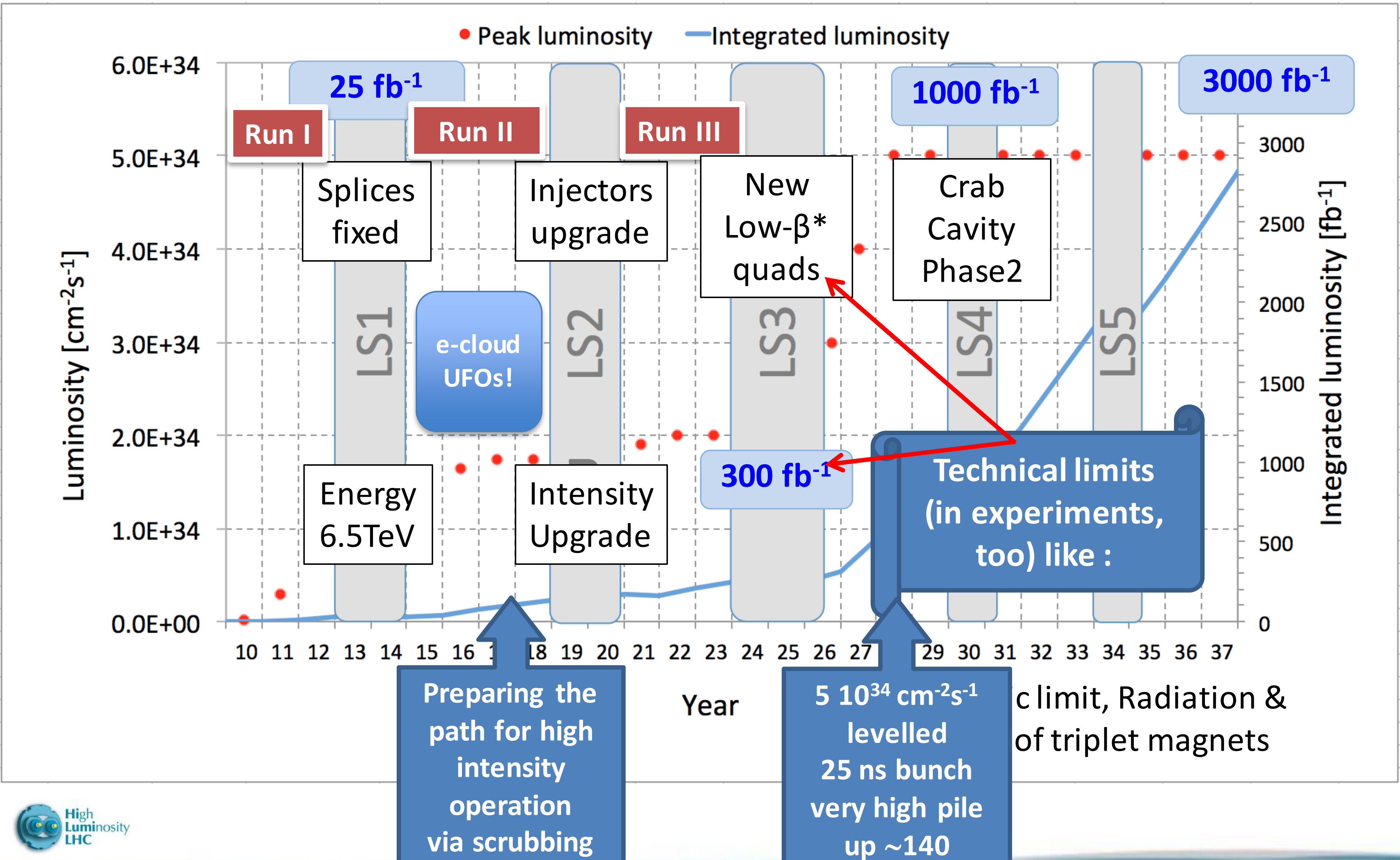
New Schedule: → HL-LHC CE during LS2



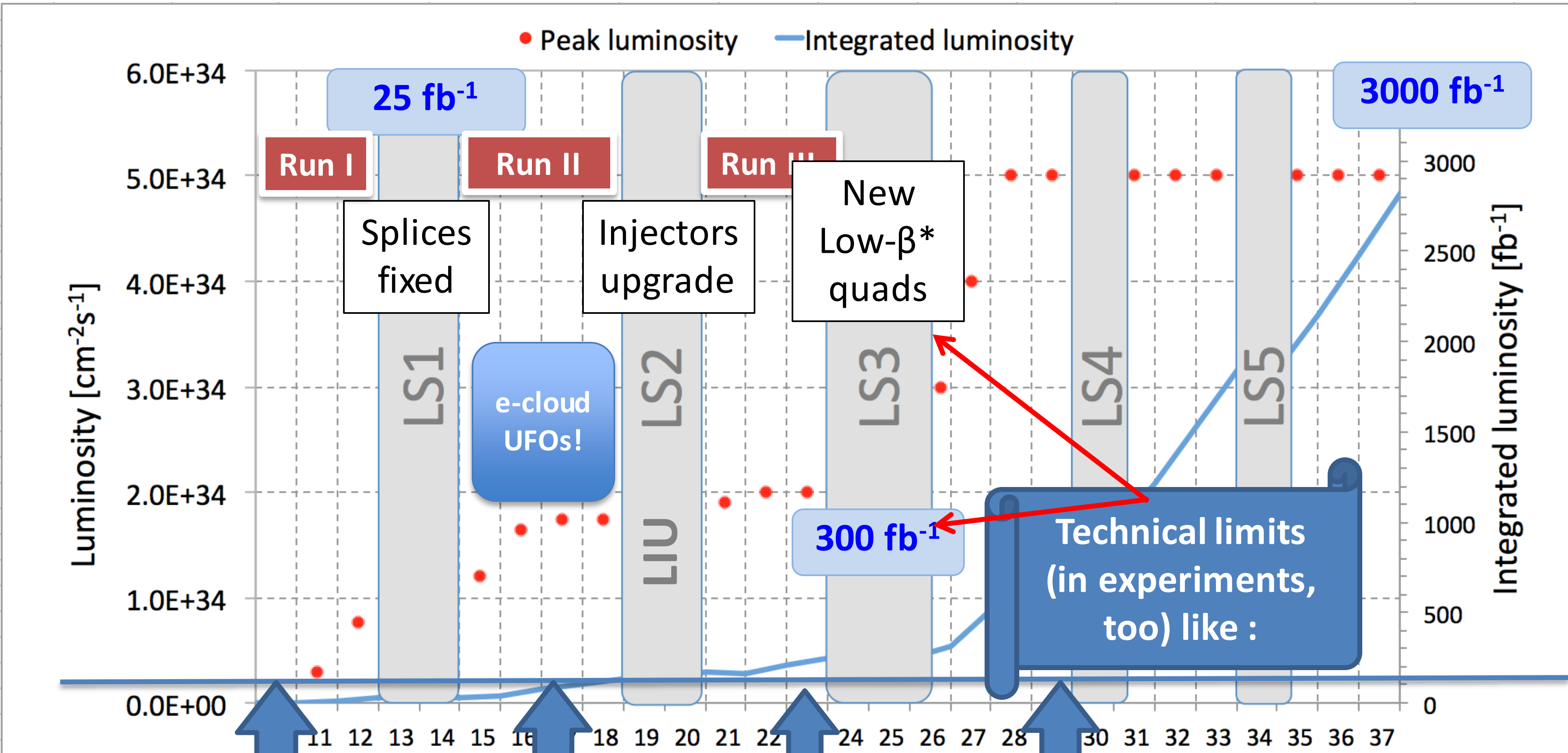
Plus a Crab Cavity installation in 2 phases during LS3 and LS4

High Luminosity LHC

Performance Projections for HL-LHC:



Performance Projections up to HL-LHC:



Technical limits (in experiments, too) like : ...mit, Radiation & triplet magnets

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

$1.5\ 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch
high pile up ~40

$1.5 - 2.2\ 10^{34}\ cm^{-2}s^{-1}$
25 ns bunch
very high pile up > 60

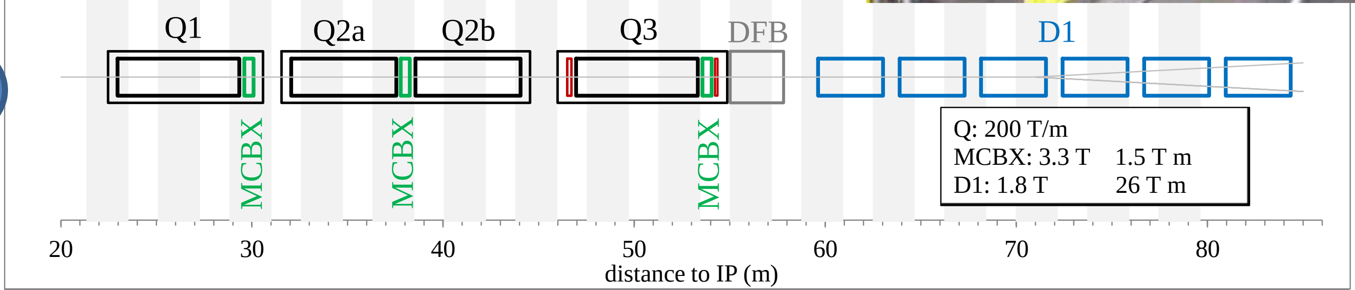
$5\ 10^{34}\ cm^{-2}s^{-1}$ levelled
25 ns bunch
very high pile up ~140

High Luminosity LHC

New Interaction Region lay out

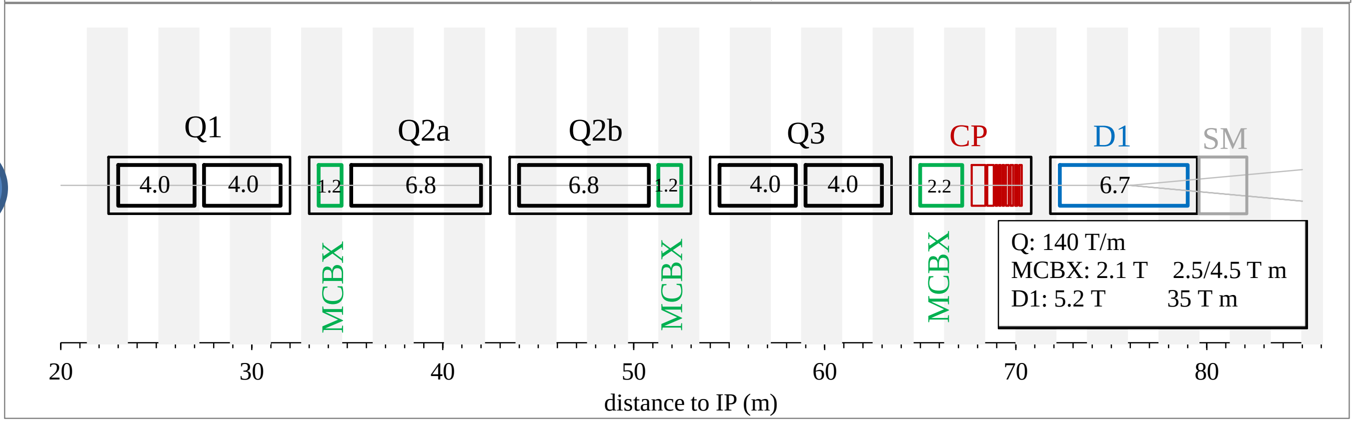
Longer Quads; Shorter D1 (thanks to SC)

ATLAS CMS



LHC

ATLAS CMS



HL LHC

Thick boxes are magnetic lengths -- Thin boxes are cryostats

High Luminosity LHC