Barcelona, May 13th -18th, 2013

LHC STATUS & PLANS (INCLUDING UPGRADE)

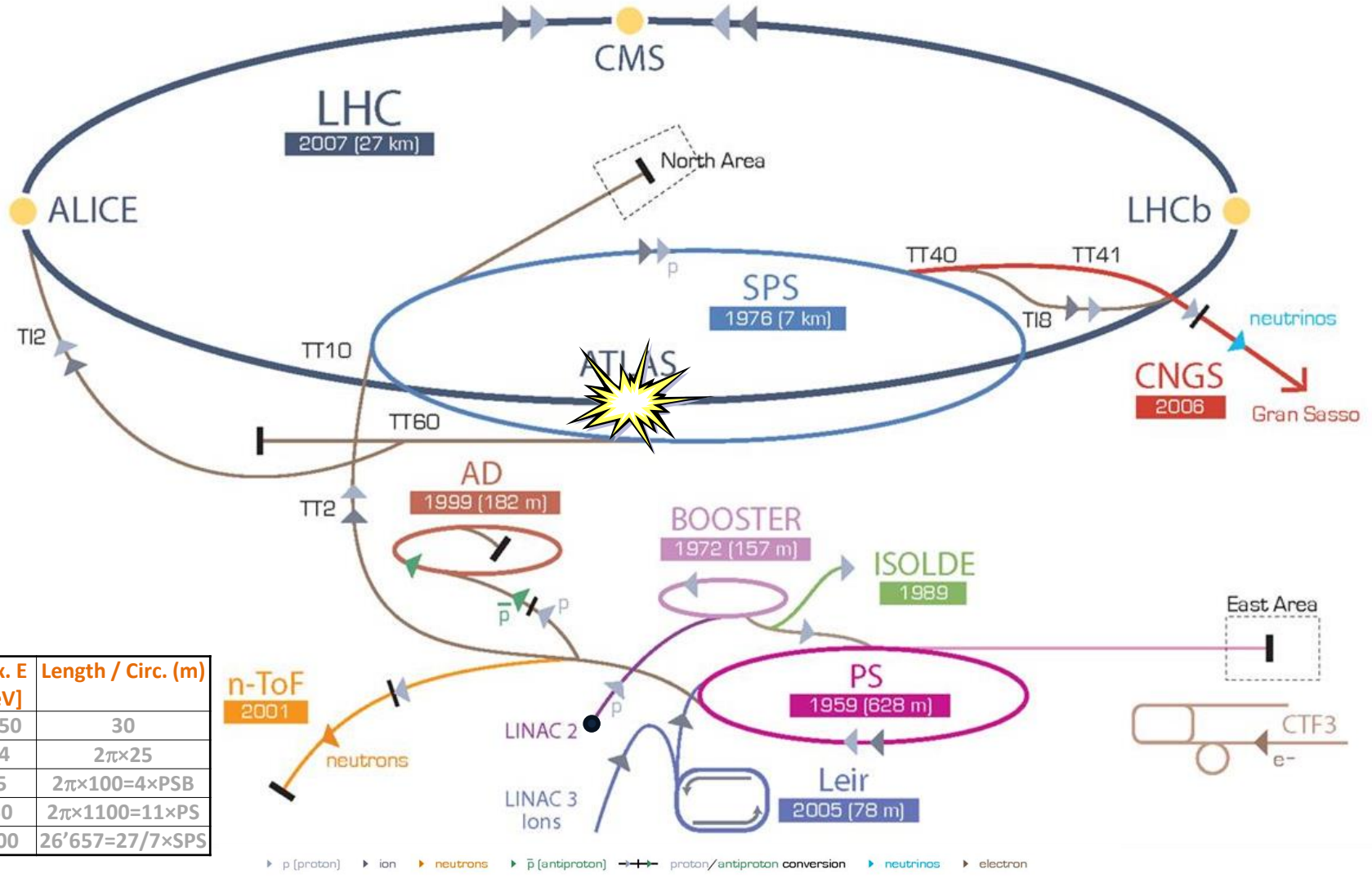
MIRKO POJER – BEAMS DEPARTMENT/OP GROUP
on behalf of the LHC Operation Team

Acknowledgements: G. Arduini, J. Wenninger, M. Lamont, L. Rossi and all colleagues from OP

OUTLINE

- Setting the scene
- What limits machine performance?
- LHC run I
- LS1 and future upgrades

CERN'S PARTICLE ACCELERATOR CHAIN



	Max. E [GeV]	Length / Circ. (m)
LINAC2	0.050	30
Booster	1.4	2π×25
PS	25	2π×100=4×PSB
SPS	450	2π×1100=11×PS
LHC	7000	26'657=27/7×SPS

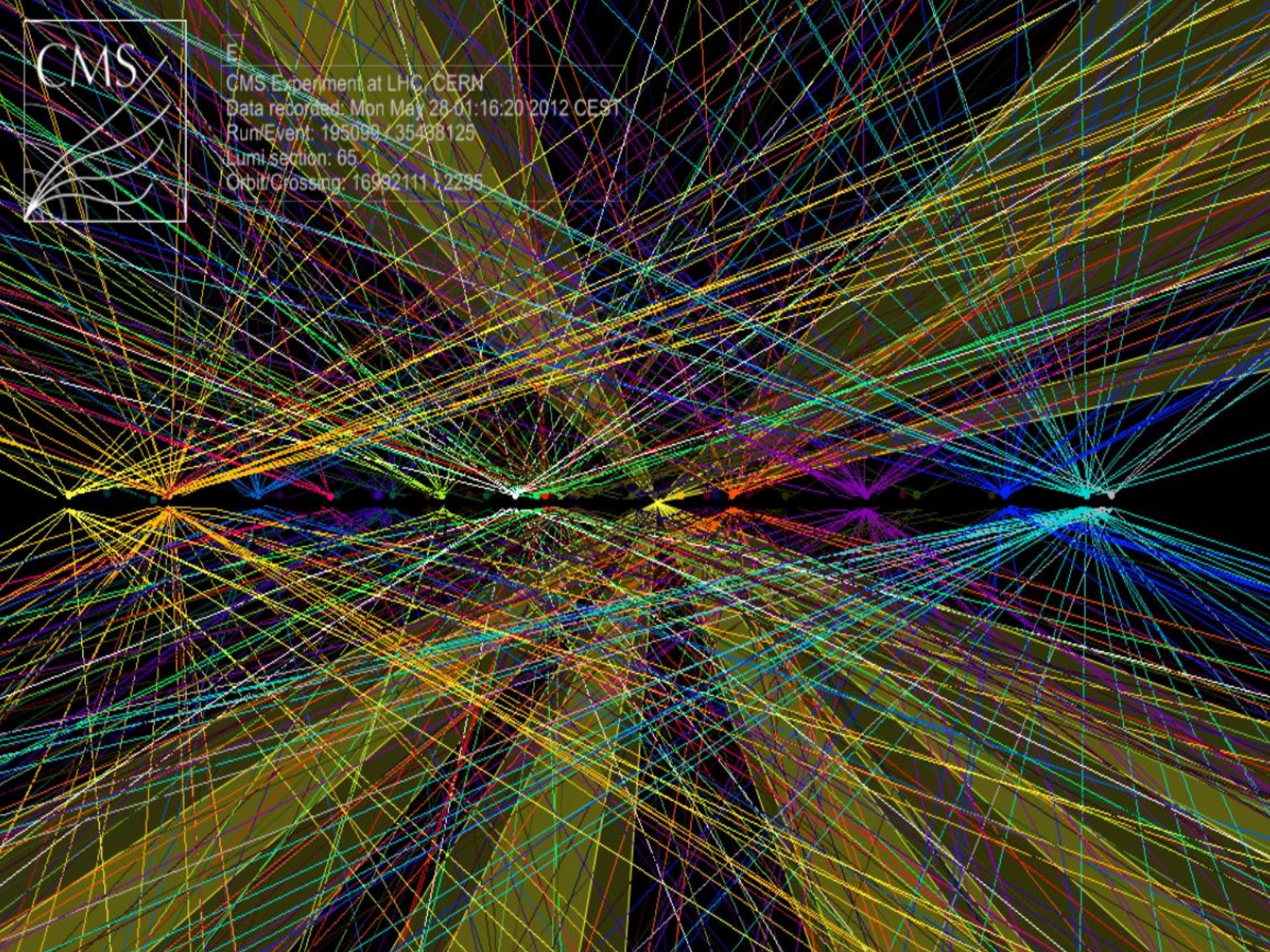
LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron
AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

THE NOMINAL MACHINE PARAMETERS

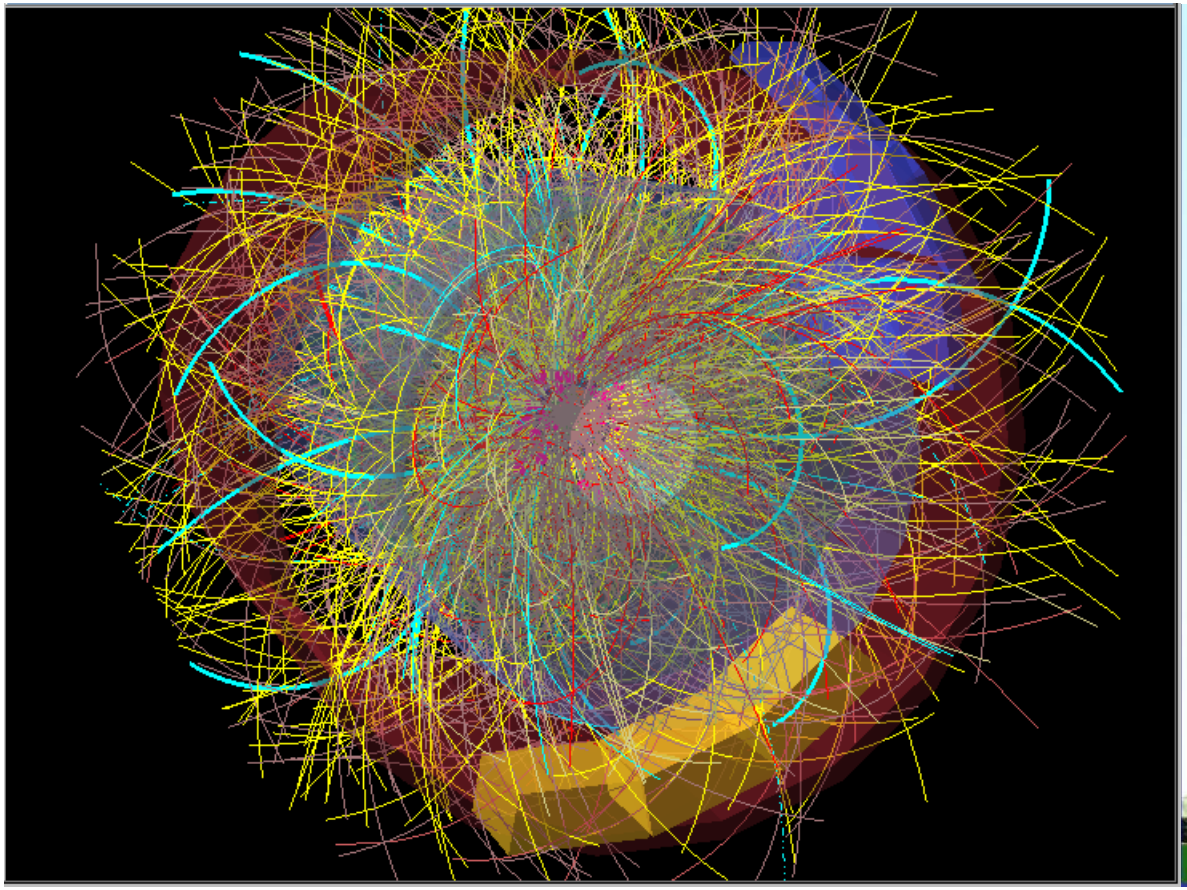
		2012
Collision energy:	**7+7 TeV**	4+4 TeV
Number of bunches:	**2808**	1374
Number of particles per bunch:	**1.15×10^{11}**	1.7e11
Circulating beam current:	**0.58 A**	0.42 A
Stored energy per beam:	**360 MJ**	150 MJ
Peak luminosity in IP1 and IP5:	**10^{34} cm^{-2}s^{-1}**	$7.7*10^{33}$ cm^{-2}s^{-1}

⇒ **30-50 collisions per crossing; 10^9 collisions per second**

⇒ **Big challenge for the detectors and for the acquisition and analysis of data**


CMS
E
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35488125
Lumi section: 65
Orbit/Crossing: 16982111 / 2295

THE CHALLENGE OF DATA MINING



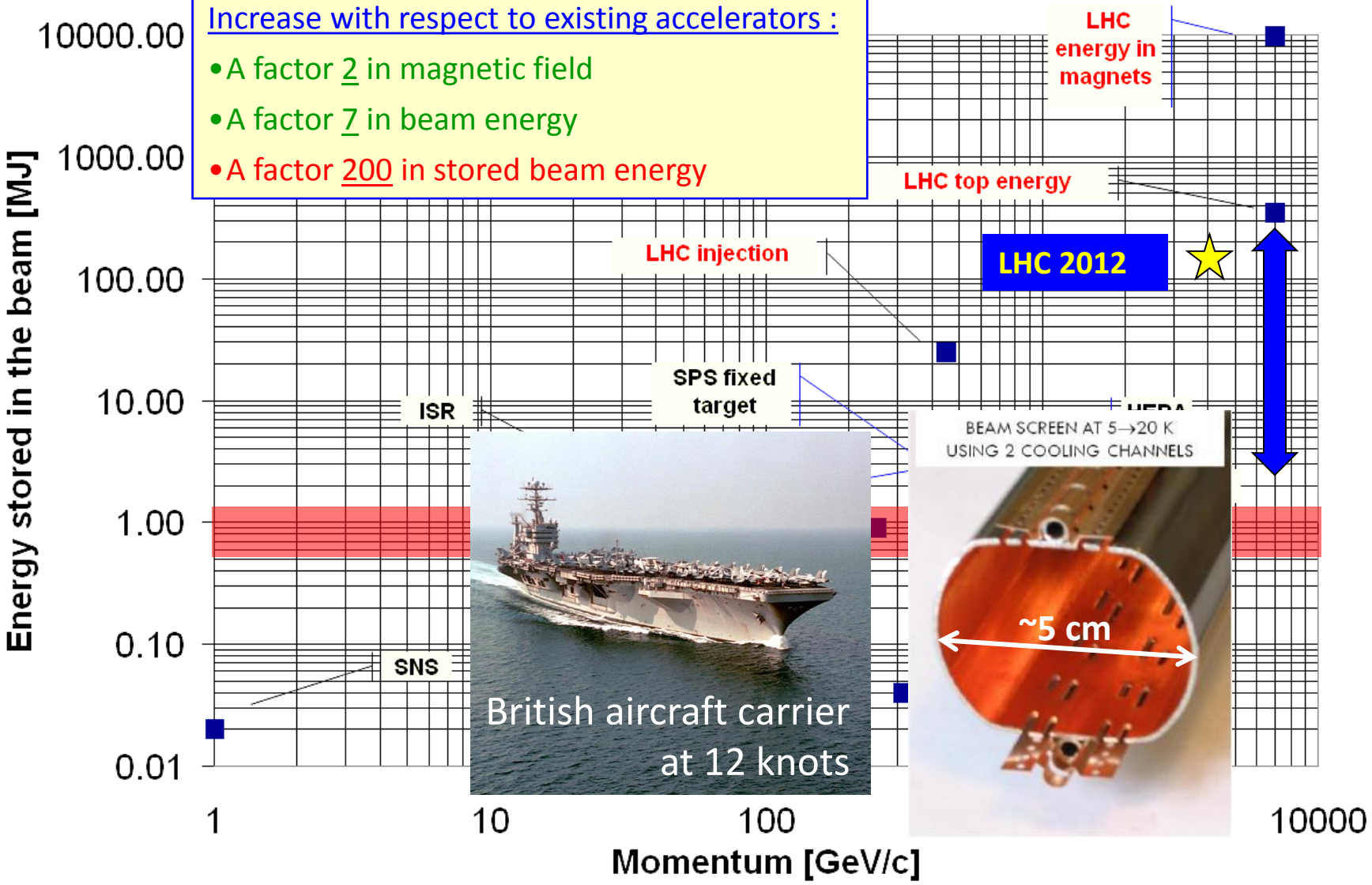
The experiments are producing ~15 Millions Gigabytes of data per year (~ 5 millions DVDs!)

The analysis of all these data demands for a computational power of ~100,000 new generation processors

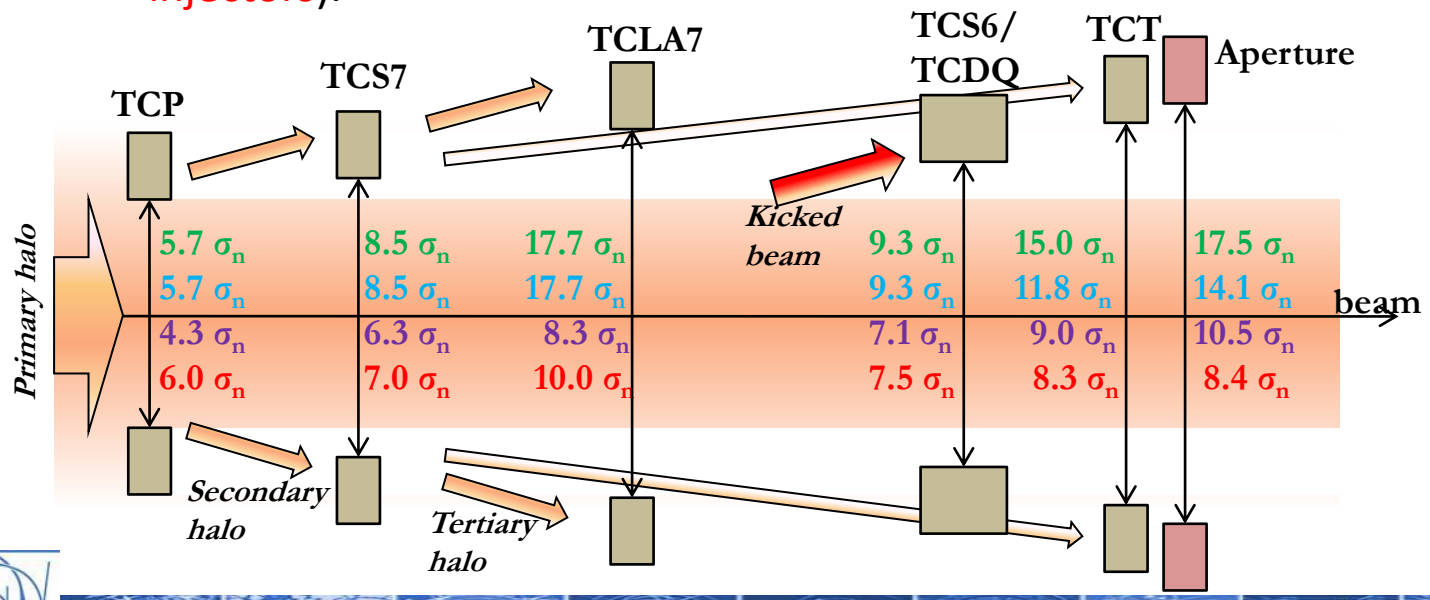
THE LHC CHALLENGES…

Increase with respect to existing accelerators :

- A factor 2 in magnetic field
- A factor 7 in beam energy
- A factor 200 in stored beam energy



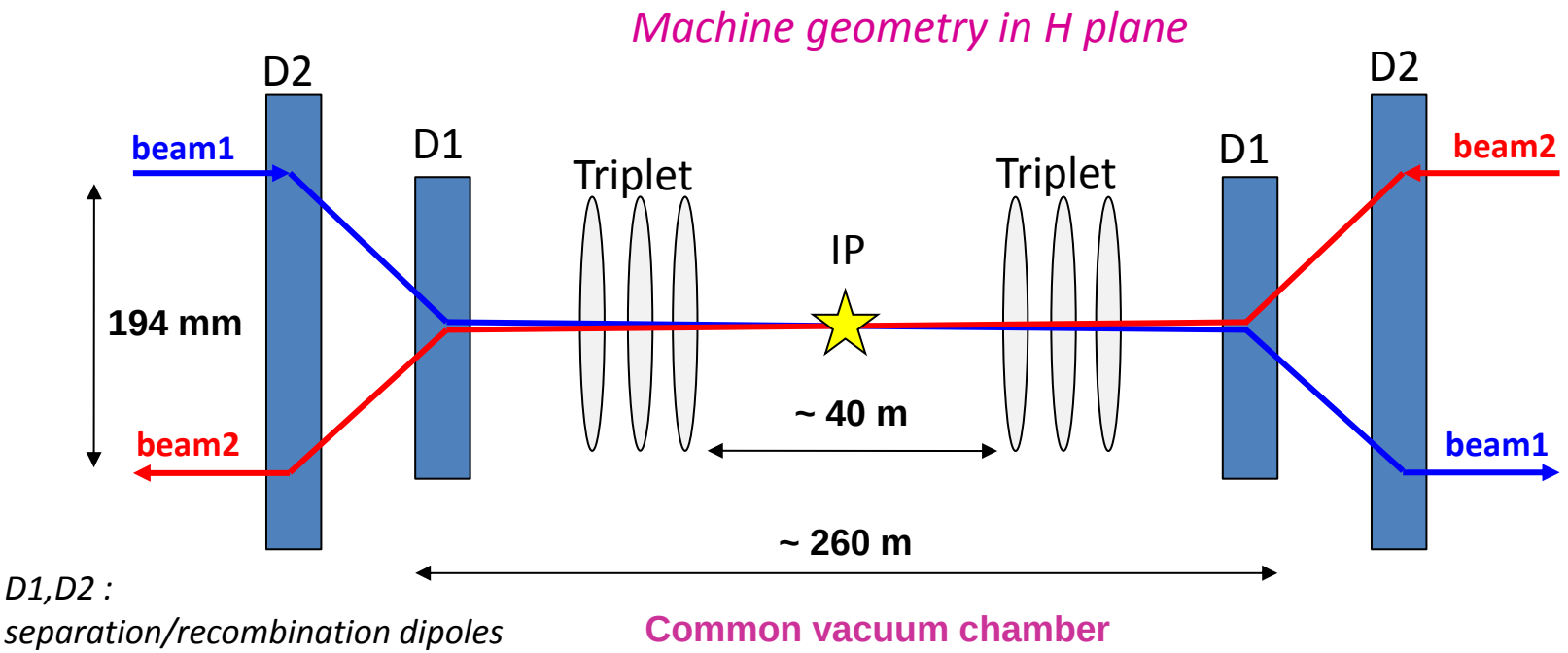
- To operate at nominal performance the LHC requires a large and complex (multi-stage) collimation system
  - Previous colliders used collimators mostly for experimental background conditions; the LHC can only run with collimators (magnets with quench limits of few mJ/cm^3).
- Collimation hierarchy has to be respected in order to achieve satisfactory protection and cleaning.
- Lower β* implies tighter collimator settings as well as alignment, beam sizes and orbit well within tolerance (gained experience and small emittance by the injectors).



2010, β*=3.5m, 3.5 TeV
2011, β*=1.0m, 3.5 TeV
2012, β*=0.6m, 4 TeV
Nom, β*=0.55m, 7 TeV

R. Bruce

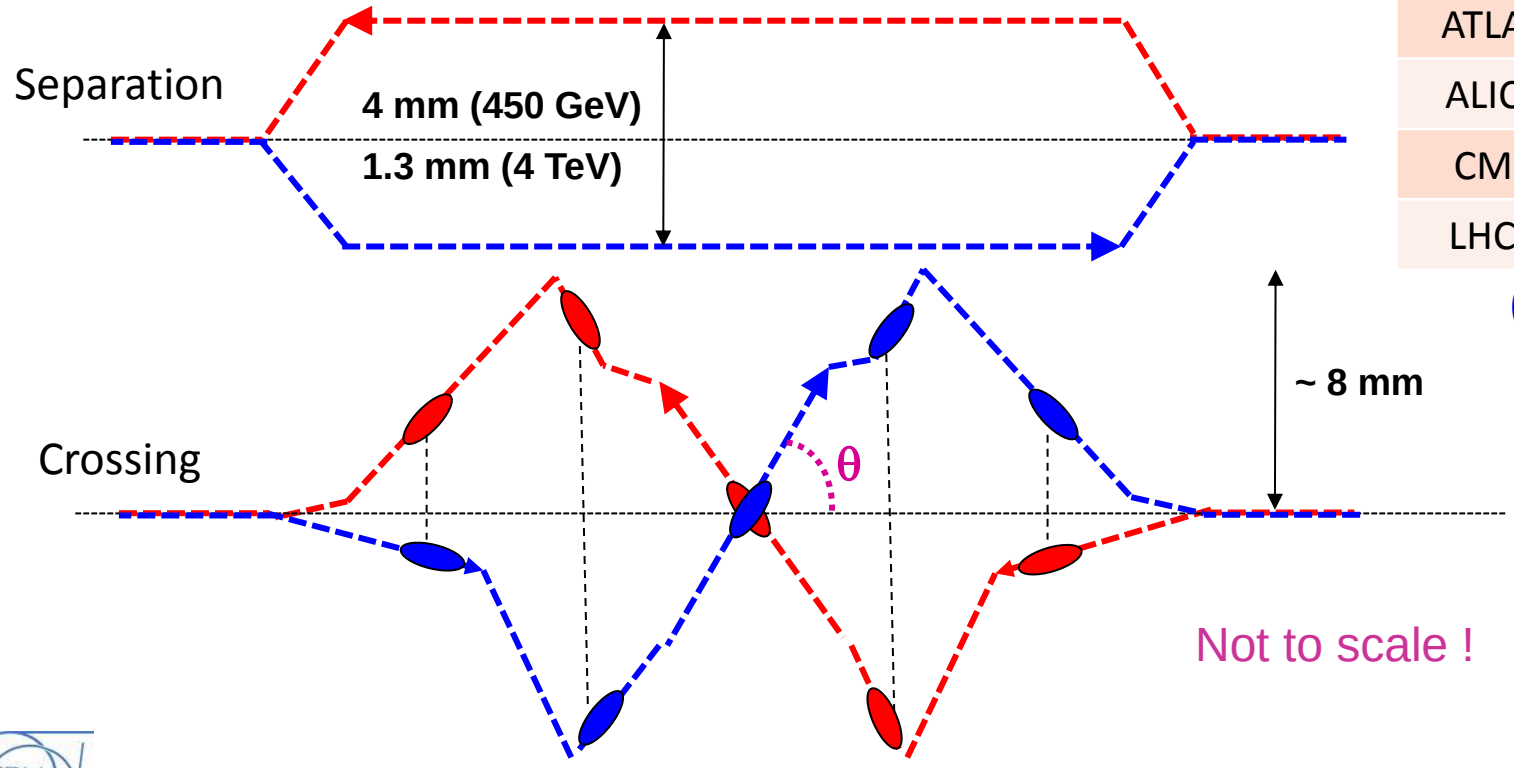
- In the IRs, the beams are first combined into a single common vacuum chamber and then re-separated in the horizontal plane
- The beams move from inner to outer bore (or vice-versa),
- The triplet quadrupoles are used to focus the beam at the IP.



- Because of the tight bunch spacing and to prevent undesired parasitic collisions in the region where the beams circulate in the common vacuum chamber:
  - Parallel separation in one plane (mostly effective at the IP), which is collapsed to 0 when the beams are colliding,
  - Crossing angle in the other plane.

	θ (μrad)
ATLAS	-145 / ver.
ALICE	145 / ver.
CMS	145 / hor.
LHCb	90 / ver.

(4 TeV / 2012)



- Setting the scene
- What limits machine performance?
- LHC run I
- LS1 and future upgrades

TWO MAIN DRIVERS TO PERFORMANCE IMPROVEMENT

- More energy

$$p \propto B\rho$$

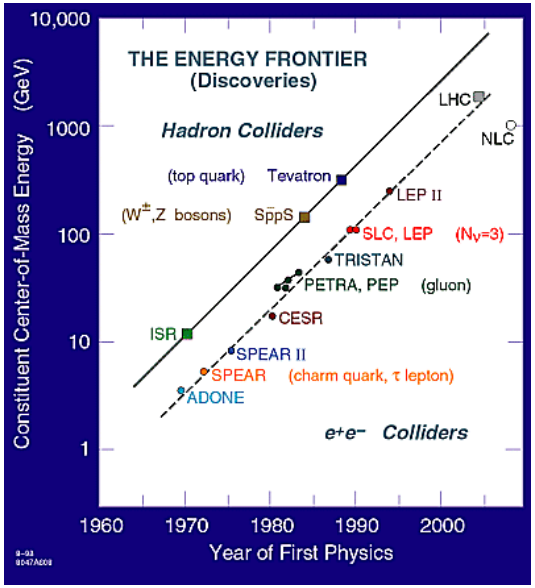
  - Larger circumference
  - Larger bending fields

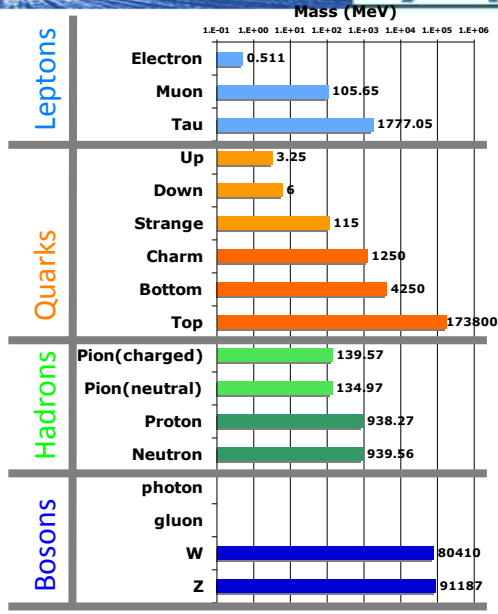
    (~27 km/ 8.3 T --> p=7 TeV)

→ **Needs new technology!!**

(HE-LHC)

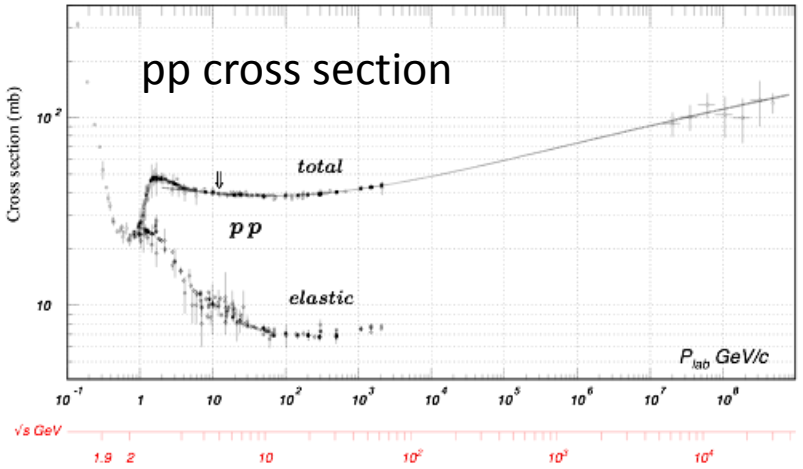
(TLEP)

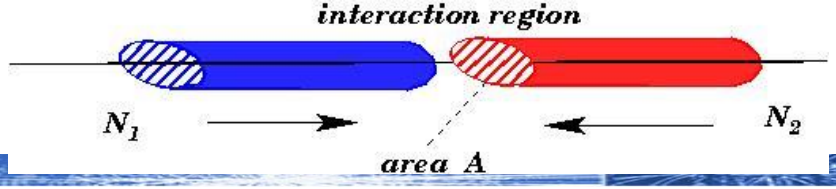




- More luminosity

$$\frac{dN_{event}}{dt} = L\sigma_{event}$$





LUMINOSITY

$$L = \frac{kN_b^{\,2} f}{4\pi\sigma_x^* \sigma_y^*} F = \frac{kN_b^{\,2} f \gamma}{4\pi \beta^* \varepsilon^*} F$$

$$\sigma_x^* \sigma_y^* = \frac{\beta^* \varepsilon^*}{\gamma} \quad \textit{(Round beams)}$$

- $\gamma = E/E_0$,
- f is the revolution frequency (11.25 kHz)
- k is the number of colliding bunch pairs,
- N_b is the bunch population,
- σ is the beam size at IP
- ε^* is the normalized emittance
- β^* the betatron (envelope) function at the IP
- F is a reduction factor due to the crossing-angle

To maximize L:

- **Increase the energy (γ)**
- **Many bunches (k) → tight bunch spacing**
- **Many protons per bunch (N_b)**
- **Small beam sizes $\sigma^*_{x,y}$**
- ***Small β^****
- ***Small emittance ε^****

High beam "brightness" N_b/ε^*
(particles per phase space volume)
→ **Injector chain performance !**

Optics property

Small envelope
→ **Strong focusing !**

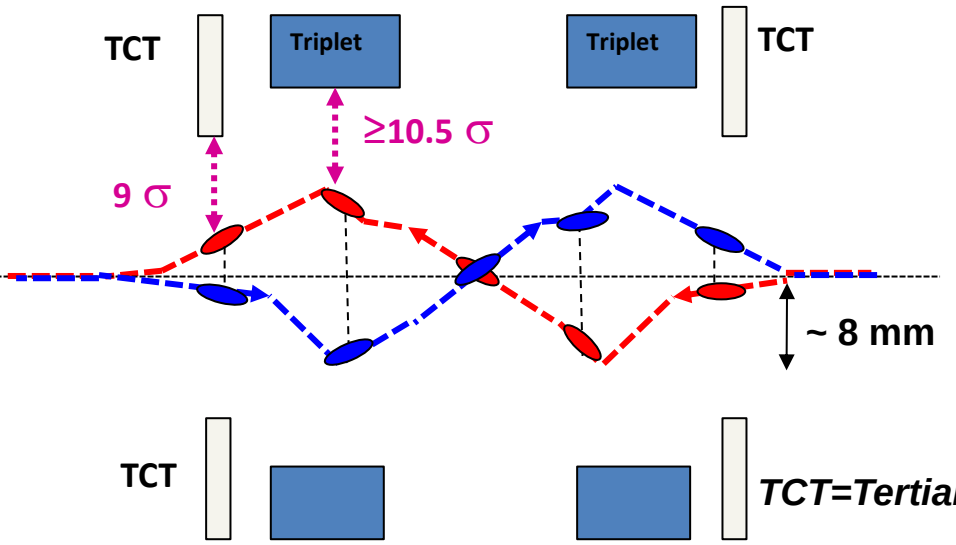
Beam property

WHAT LIMITS β*?

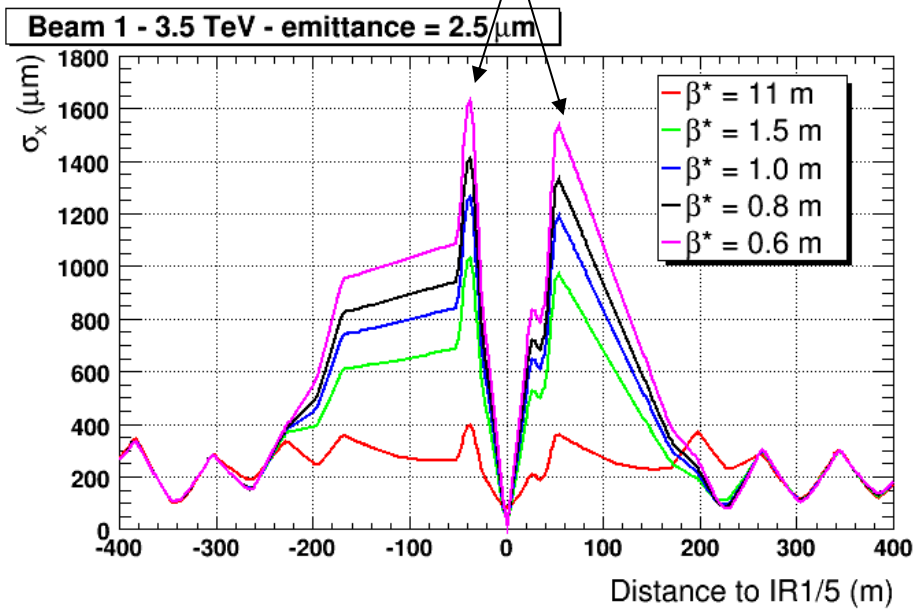
- In the high luminosity IRs, the triplet quadrupoles define the machine aperture limit for squeezed beams; β* is constrained by:
  - the beam envelope,
  - the margin between TCT and triplet,
  - the crossing angle
- → **need larger aperture ITs**

(HL-LHC)

$$\sigma_{triplet} \propto \sqrt{\frac{\varepsilon}{\beta^* \gamma}}$$

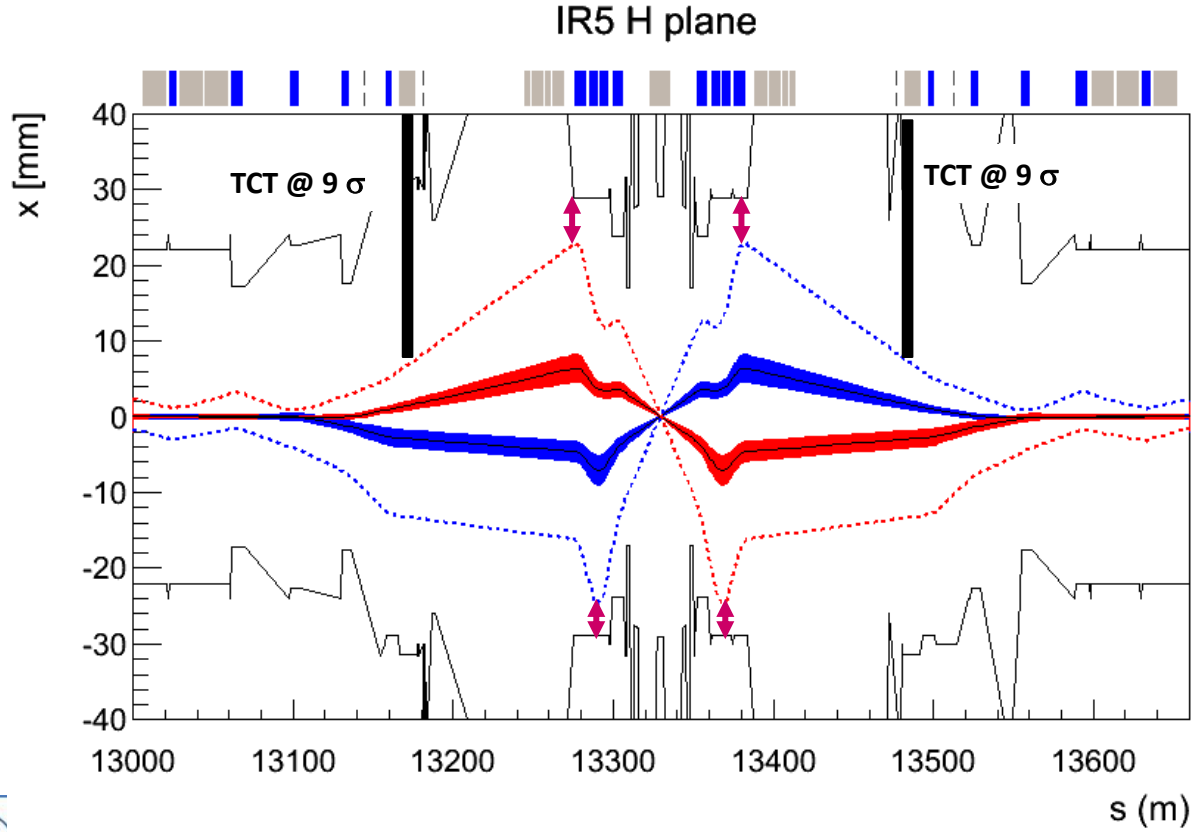


TCT=Tertiary Collimator



β* EVOLUTION

Date	β* (m)	Reason
Startup 2011	1.5	Interpolation of aperture measurement at 450 GeV
Sept. 2011	1.0	Aperture measurement at 3.5 TeV
2012	0.6	4 TeV and tighter collimator settings



1σ beam envelopes

9σ extreme beam envelopes

1.5σ margin to triplet

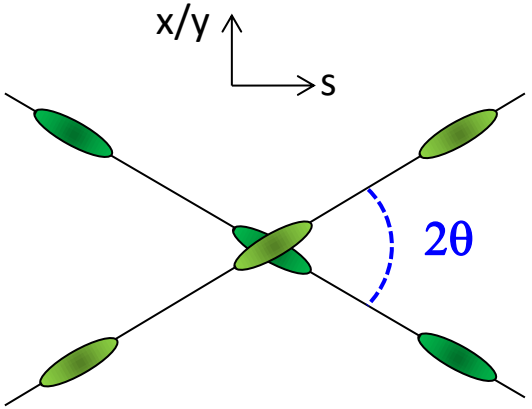
emittance = 3.5 μm,

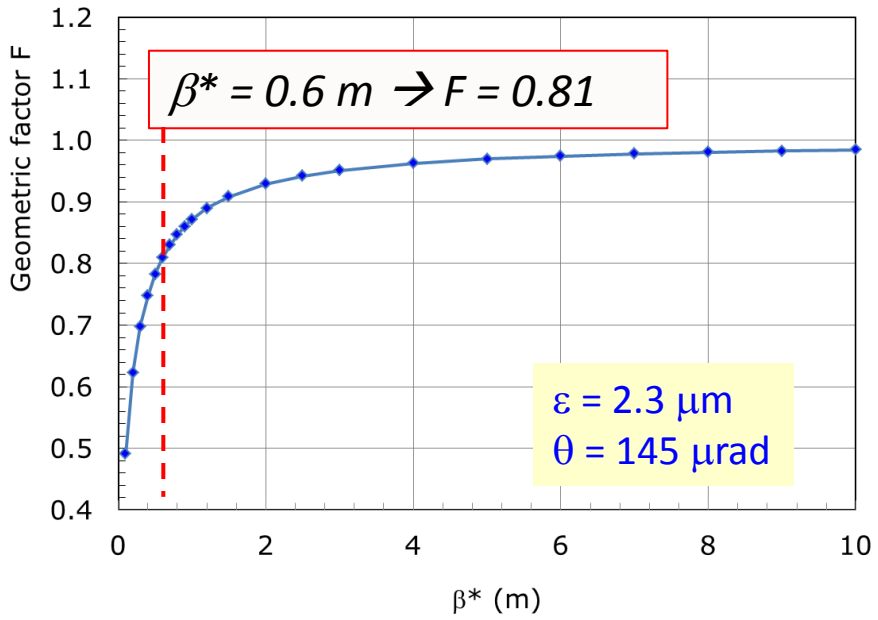
β* =0.6m

LUMINOSITY GEOMETRIC REDUCTION FACTOR AND CROSSING ANGLE

- With small beam size, the luminosity geometric reduction factor due to bunch length σ_s and crossing angle becomes significant for low β^*

$$F = \frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_{x/y}}\tan\theta\right)^2}}$$

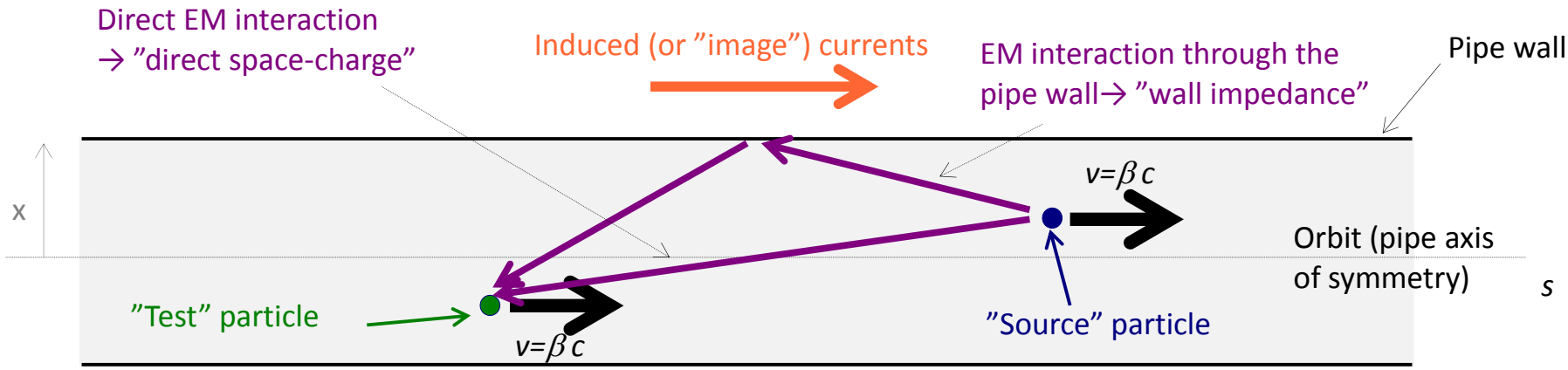




- *Will get even stronger at 6.5-7 TeV.*
- *Could fix with 'Crab cavities'*
  *(see **HL-LHC** later).*
  - Reduction of the aperture
  - Long range beam-beam interactions
  - and others (e.g. synchro-betatron resonances,…)

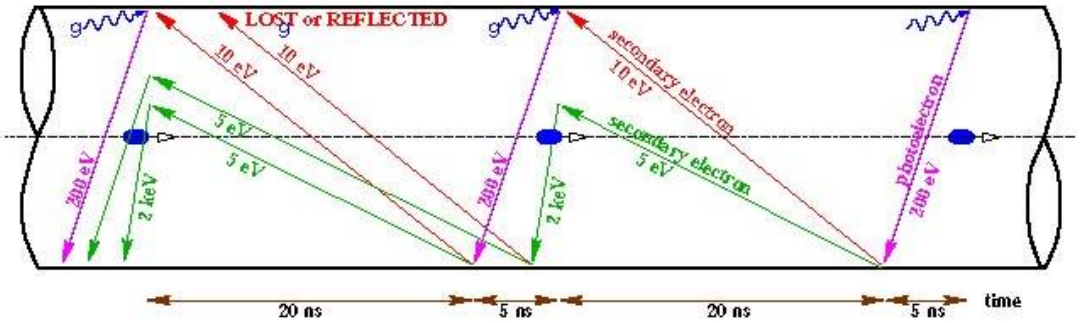
WHAT LIMITS THE NUMBER AND POPULATION OF THE BUNCHES?

- High bunch population and tight bunch spacing make the beams prone to instabilities related to impedances i.e. to **self-generated fields**
  - **wake field** in time domain, **beam-coupling impedance** in frequency domain.



- In 2012 instabilities have become more critical due to higher bunch intensity and tighter collimators settings.
- Cures:
  - Transverse feedback (‘damper’) that measures the oscillations and sends corrective deflections,
  - Non-linear magnetic fields (sextupoles, octupoles, beam-beam) that produce a frequency spread among particles – kill coherent motion.

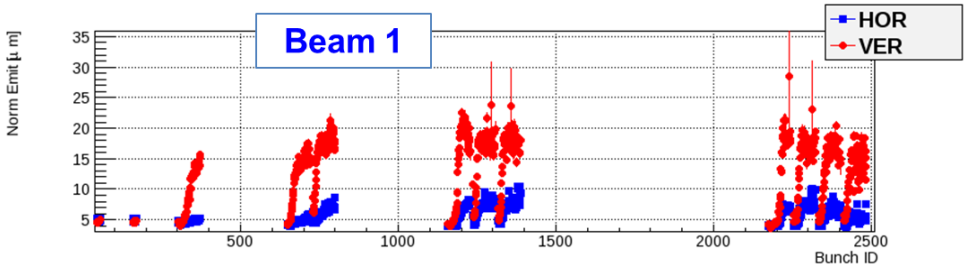
WHAT LIMITS THE NUMBER AND POPULATION OF THE BUNCHES?



F. Ruggiero

Secondary emission yield [SEY]
SEY>SEY$_{th}$ → avalanche effect (multipacting)
SEY$_{th}$ depends on bunch spacing and population

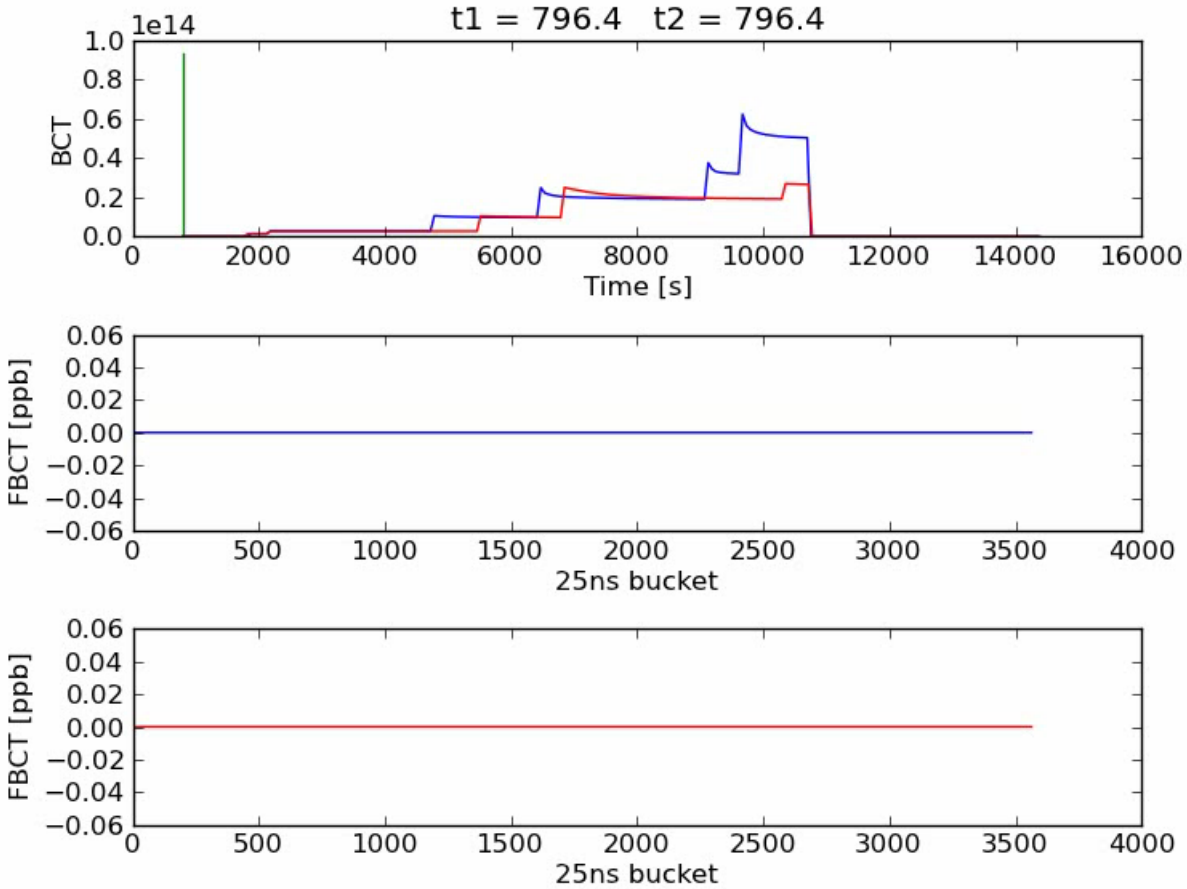
- **Electron cloud** effects occur both in the warm and cold regions and their intensity increases rapidly for shorter bunch spacing. Observed in the LHC as soon as we started to inject bunch trains (150 → 75 → 50 → 25 ns spacing):
  - Gas desorption from walls and vacuum pressure rise (interlock levels, beam losses…)
  - Single-bunch and multi-bunch instabilities
  - Incoherent beam size growth
  - Excessive energy deposition on walls
    → Heat load on the cryogenics



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

2012 injection tests (10 July 2012)

G.Rumolo



Beam 1 Beam 2

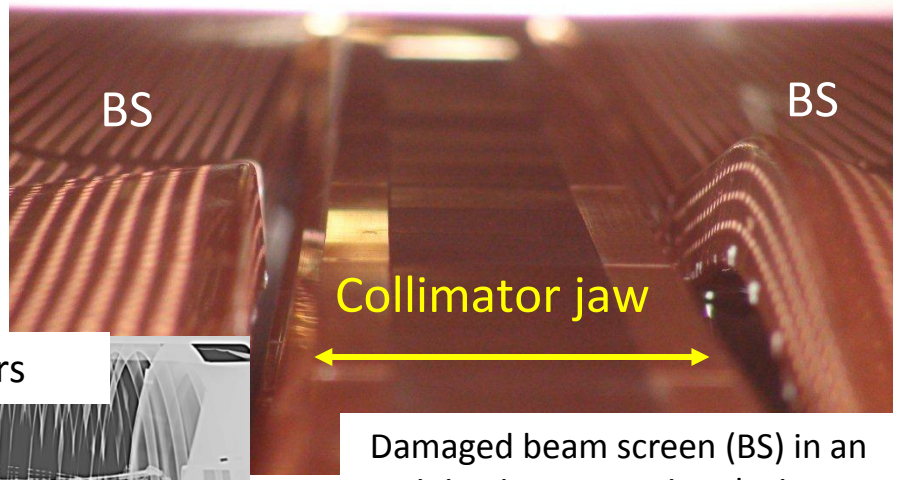
Bunch-by-bunch population
Beam 1

Bunch-by-bunch population
Beam 2

HEATING DAMAGE

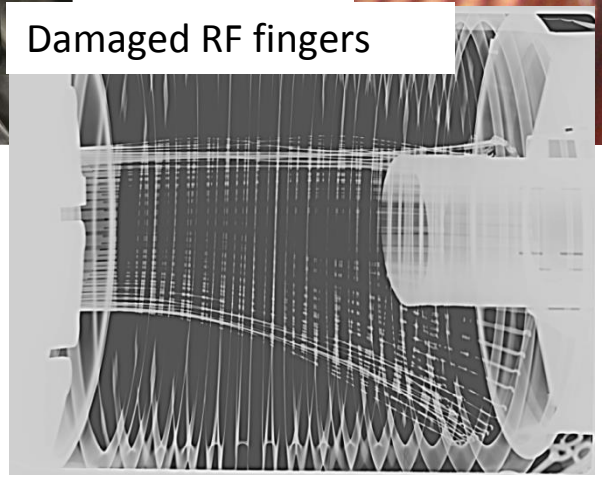
- High intensity beams may deposit large amounts of power via the EM fields they generate
  - Design, manufacturing or installation errors may lead to damage of accelerator components.
  - So far they have not limited, could be fixed or mitigated (e.g. bunch length control).

Damaged mirror of the synchrotron light telescope



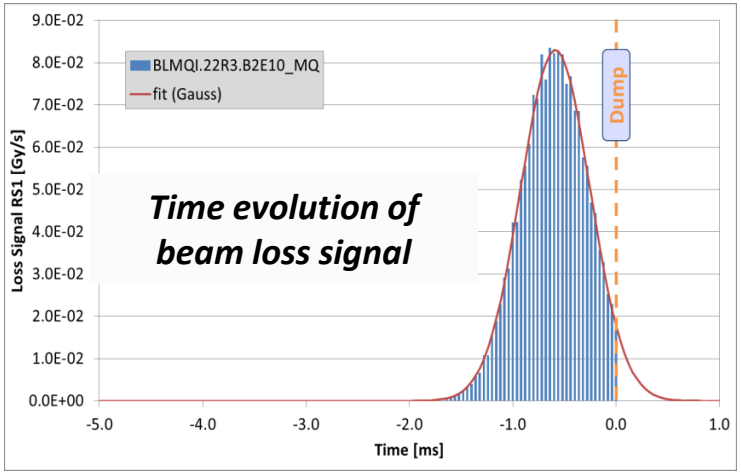
Damaged beam screen (BS) in an injection protection device

Damaged RF fingers



UFOs = UNIDENTIFIED FALLING OBJECTS

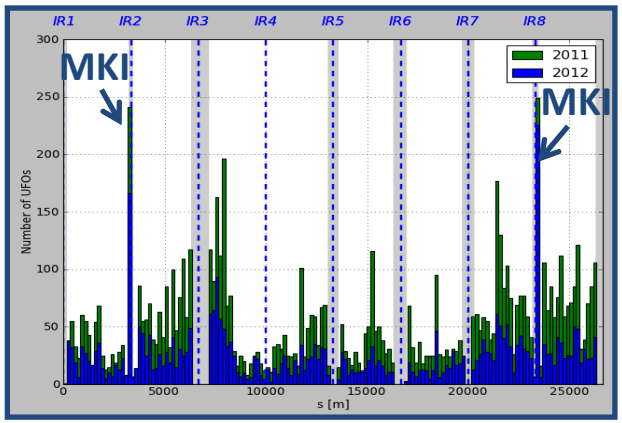
- Small (10's μm) dust particles falling into the beam, generating very fast beam losses. Beams are dumped to avoid a magnet quench.
  - 2010: 18 beam dumps,
  - 2011: 17 beam dumps,
  - 2012: 15 beam dumps

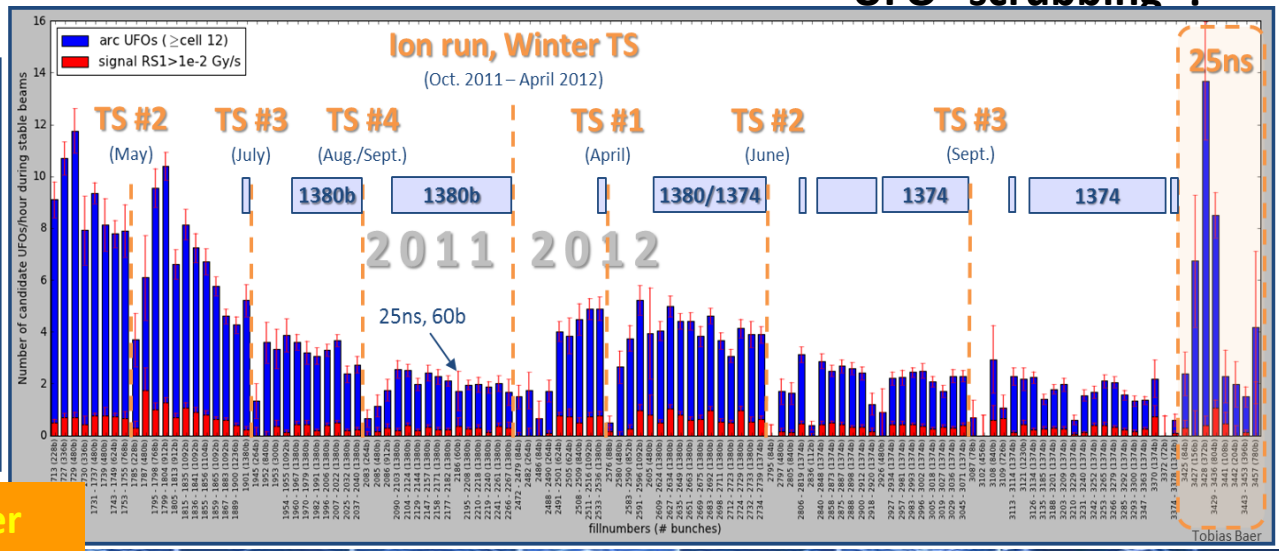


2011: Decrease from **≈10 UFOs/hour** to **≈2 UFOs/hour**

2012: Initially, about **2.5 times higher** UFO rate compared to October 2011. **UFO rate decreased** since then to 2011 level. Up to **10 times** increased UFO rate with 25ns

UFO "scrubbing"?

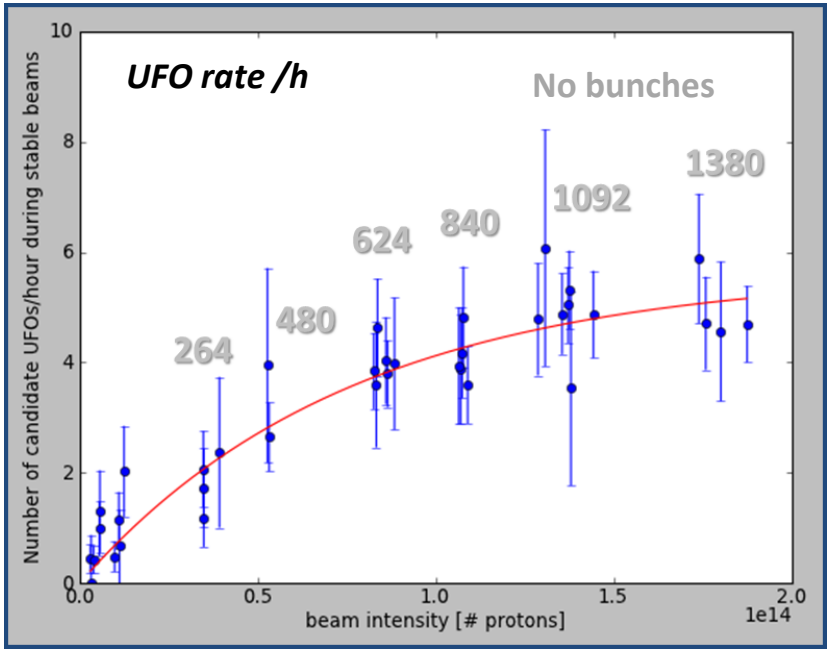




T. Baer

UFO: INTENSITY DEPENDENCE AND 7 TEV

- The rate of events increases with beam intensity.
- A large increase was observed with 25 ns beams



T. Baer

At 7 TeV

- The losses induced in the magnets by the UFOs will increase by a factor 3 (density at shower max in the magnets),
- The tolerable loss will go down by a factor 5 (higher B field),

→ scaling the rate and amplitudes of 2012 one predicts at least one beam dump per DAY !! Could become a serious issue !!

EFFECT OF RADIATION ON ELECTRONICS (R2E)

- Tunnel electronics suffers from beam loss induced single event errors (especially QPS, power converter and cryogenics)

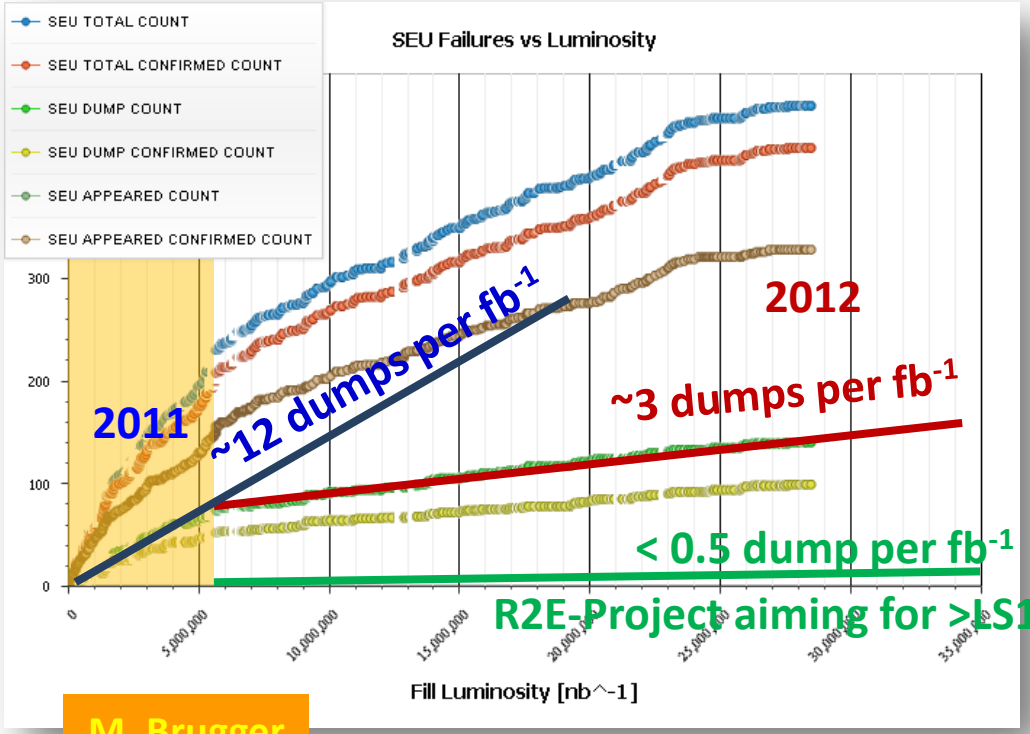
- **Mitigation**:
  - **Equipment relocation, sometimes to surface.**
  - **Additional shielding.**
  - **More error robust firmware.**

- 2011 Christmas mitigation actions served to reduce the SEUs by a factor 3

- A massive campaign of relocation and shielding is planned for LS1

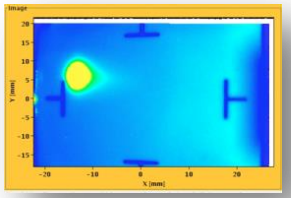
Several shielding campaigns prior the 2011 Run + Relocations 'on the fly' + Equipment Upgrades

2011/12 xMasBreak 'Early' Relocation + Additional Shielding + Equipment Upgrades

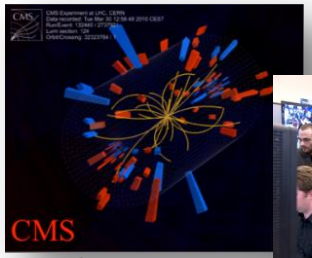


- Setting the scene
- What limits machine performance?
- LHC run I
- LS1 and future upgrades

THE LHC TIMELINE



August 2008
First Injection tests



March 30, 2010
First collisions at 2·3.5 TeV

Ju
13

1380

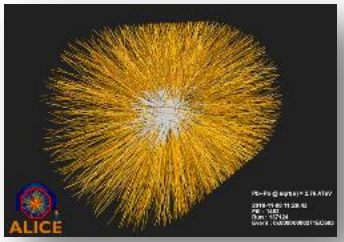
September, 10 2008
Both beams circulating

2008 | 2009 | 2010 | 2011 | 2012

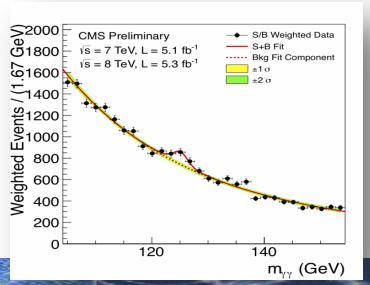
September, 19 2008
Incident
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

November 29, 2009
Beams back

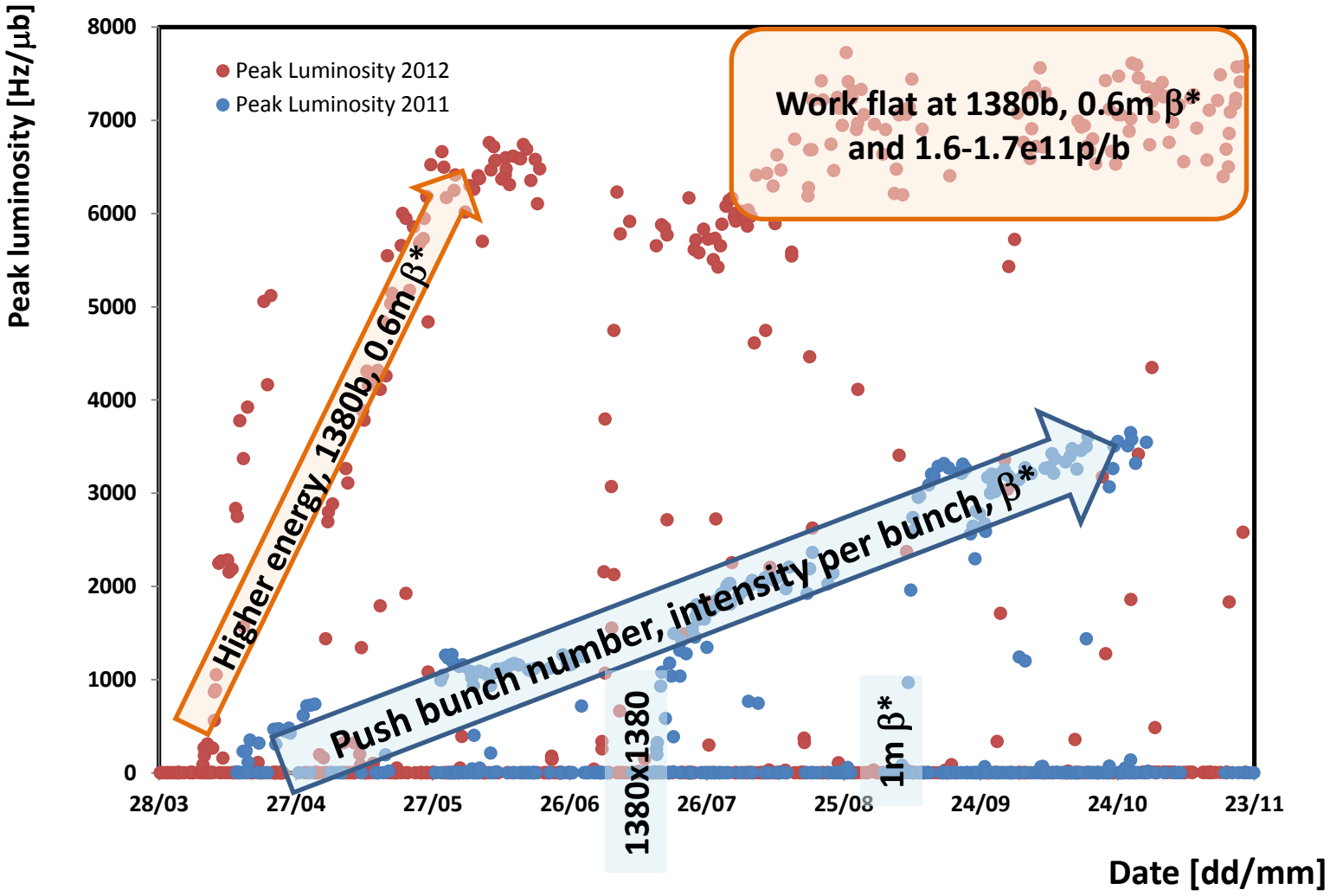
November 2010
Ion run



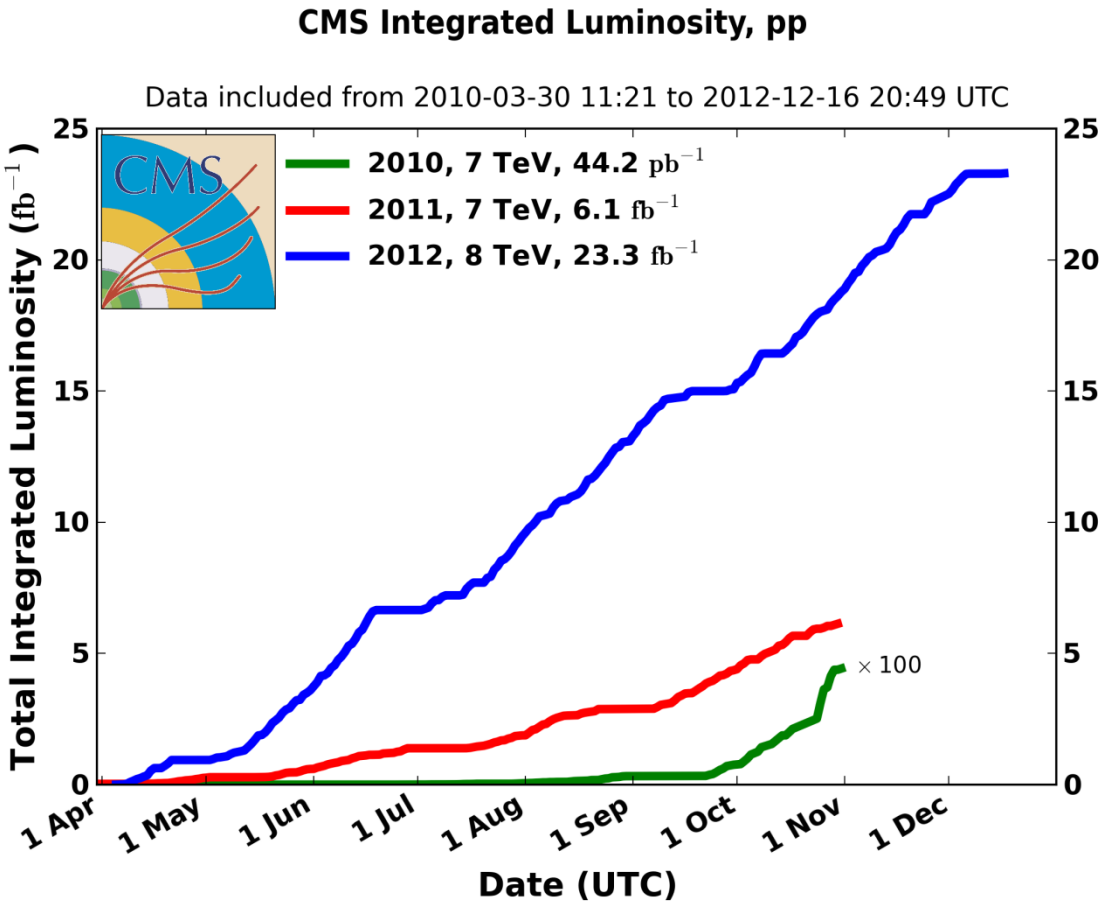
July 4, 2012
Higgs boson search update



PEAK LUMINOSITY PERFORMANCE



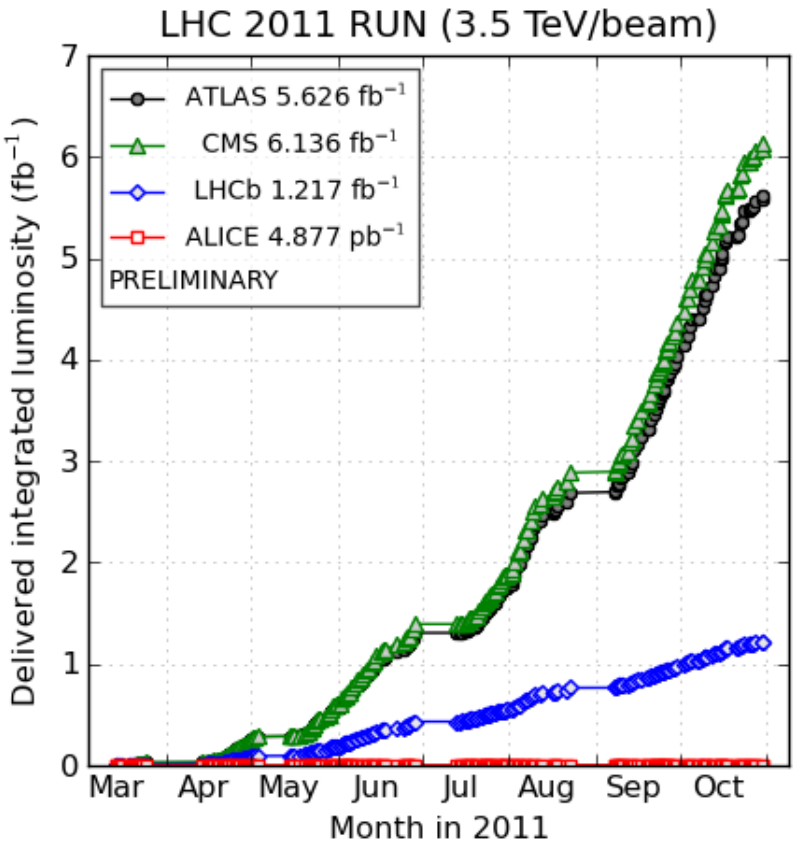
INTEGRATED LUMINOSITY 2010-2012



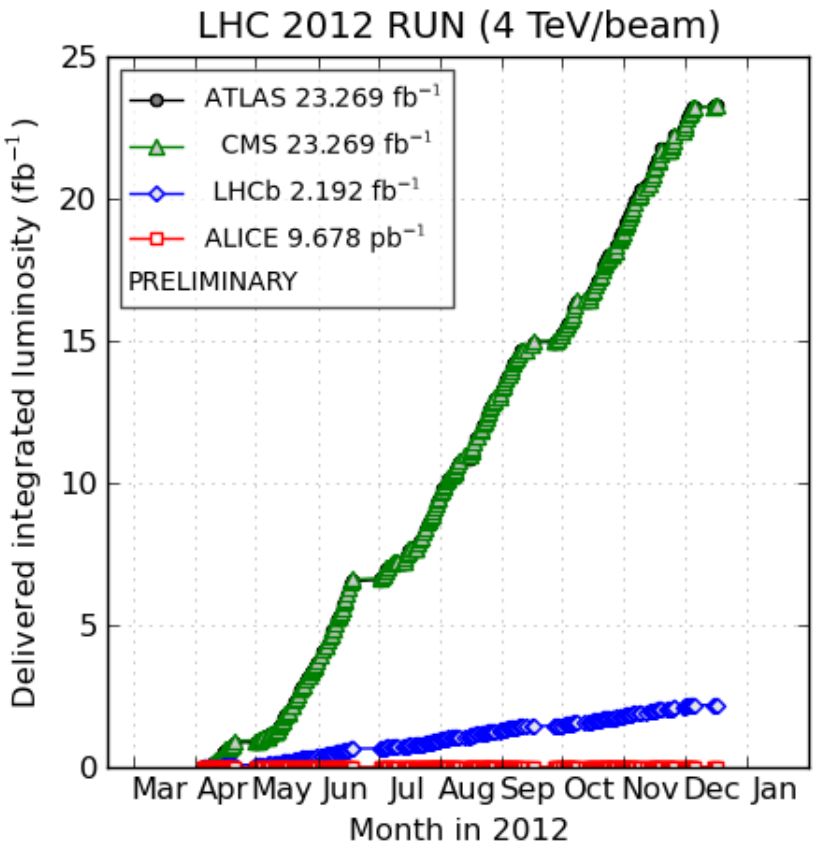
- 2010: **0.04 fb^{-1}**
  - $\sqrt{s}$ = 7 TeV
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - $\sqrt{s}$ = 7 TeV
  - … exploring the limits
- 2012: **23 fb^{-1}**
  - $\sqrt{s}$ = 8 TeV
  - … production

INTEGRATED LUMINOSITY FOR ALL: 2012 VS 2011

2011: target was 1 fb^{-1}; ~6 obtained



2012: target was 15-20 fb^{-1}; ~23 obtained

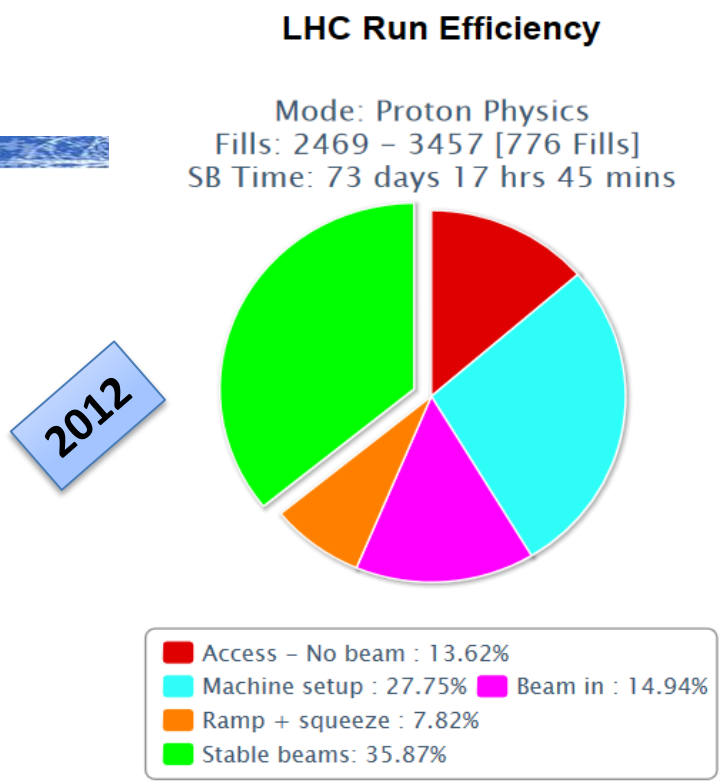


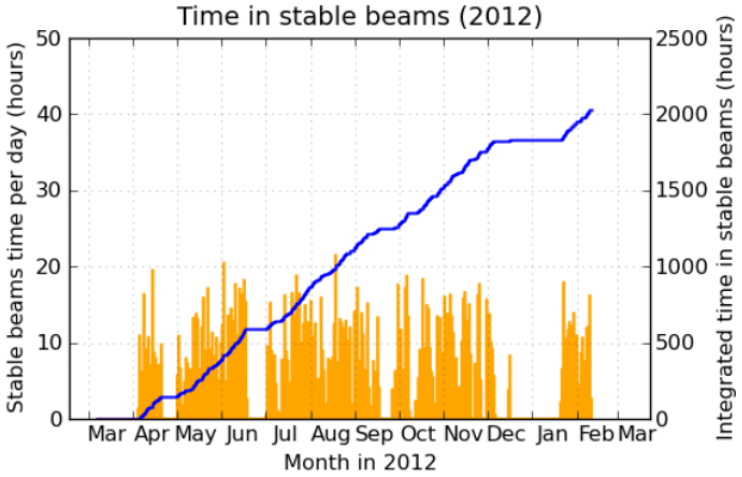
SUMMARY: 2010 TO 2012

- Impressive progress in performance. Doomed to level off…

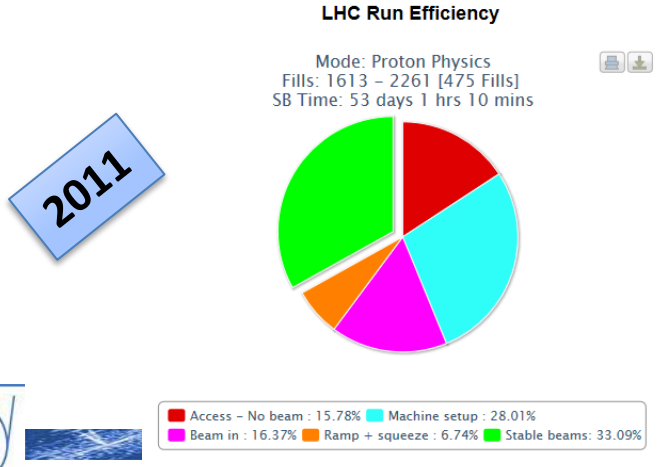
Parameter	2010	2011	2012	Nominal
Energy (TeV)	3.5	3.5	4.0	7.0
N (10^{11} p/bunch)	1.2	1.45	1.6-1.7	1.15
k (no. bunches)	368	1380	1374	2808
Bunch spacing	150	75 / 50	50	25
Stored energy (MJ)	25	112	140	362
ε (μm rad)	2.4	2.4	2.5	3.75
β^* (m) (high lumi experiments)	3.5	1.5 → 1	0.6	0.55
L ($cm^{-2}s^{-1}$)	2×10^{32}	3.5×10^{33}	7.73×10^{33}	10^{34}
Beam-beam parameter/IP	-0.0054	-0.0065	-0.0069	-0.0033
Average Pile-up @ beg. of fill	8	17	38	26

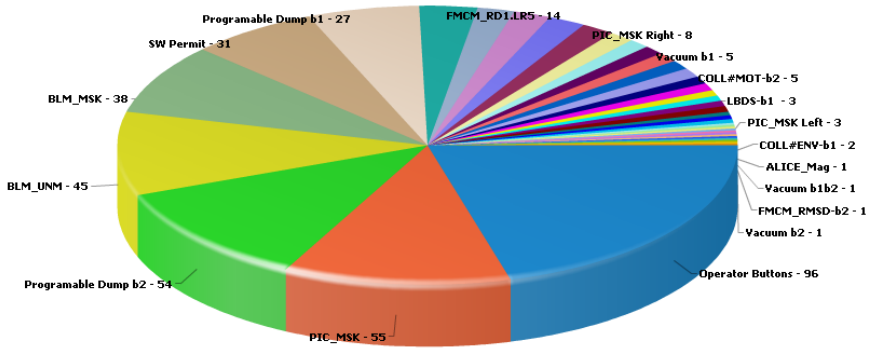
MACHINE AVAILABILITY





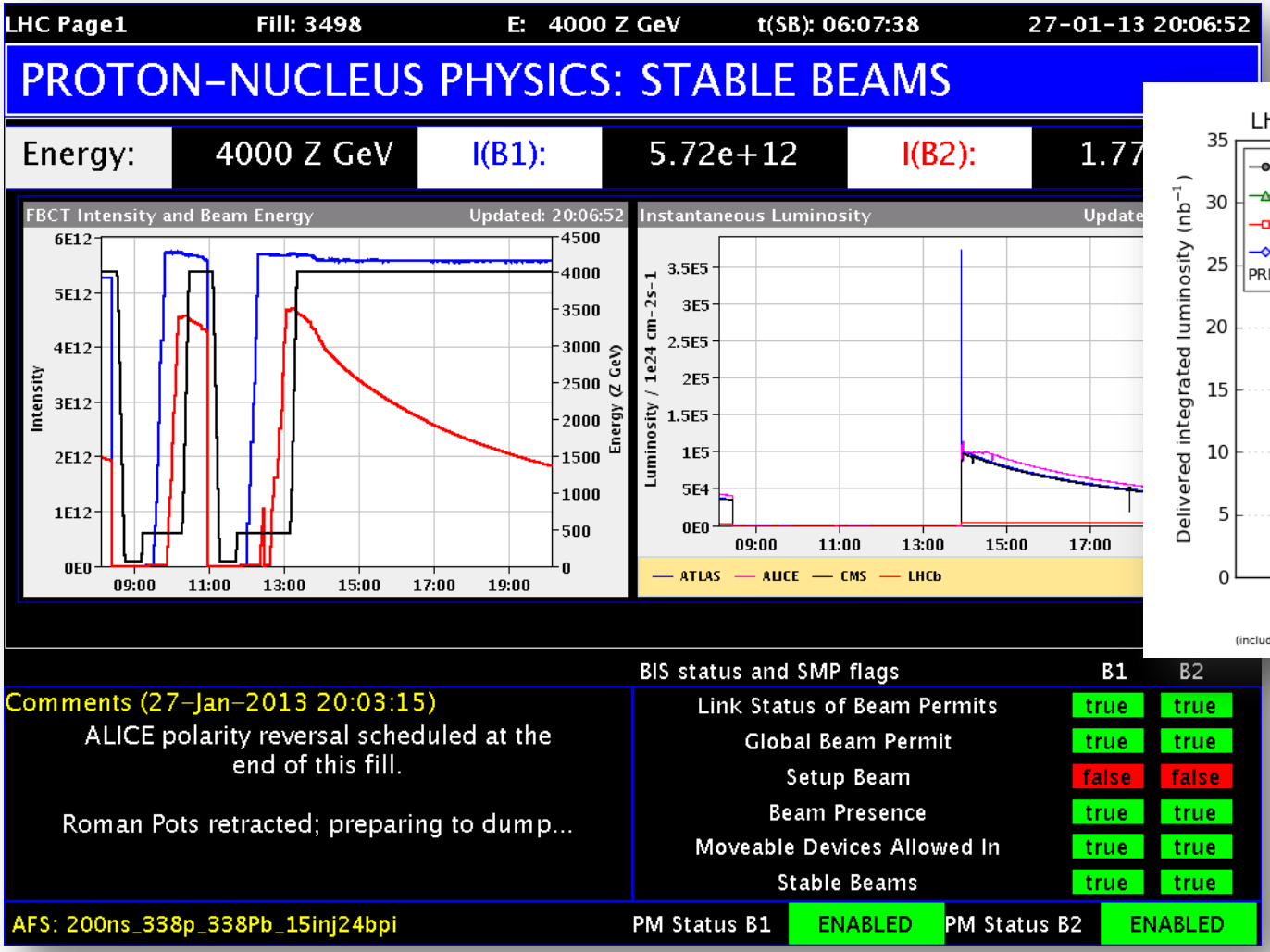
- **Average fill length of ~6 hours**
- **Fill length determined mostly by 'failures'**
- **Only ~30% of fills dumped by operation**

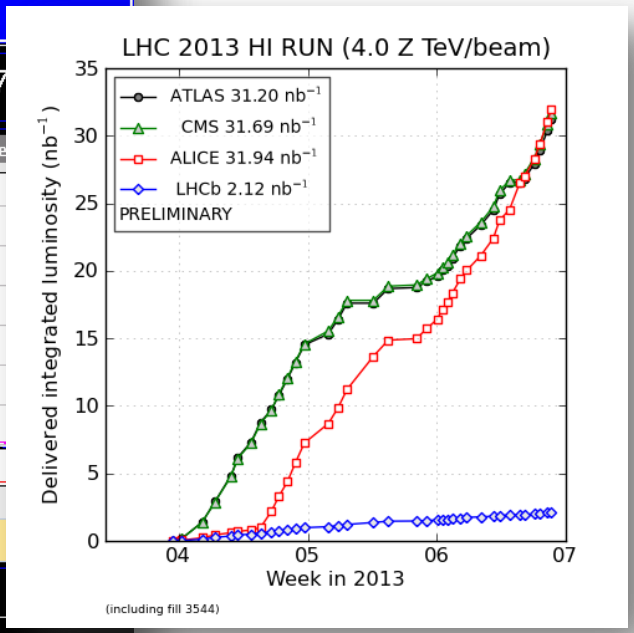




Dumps above injection energy per system

PROTON-LEAD





Extreme flexibility of the machine, with many changes of polarity/specimen.

Without forgetting the high beta run and all other MD activities…

WHAT WE LEARNT

Beam

- **Excellent single beam lifetime** – vacuum
- **Excellent magnetic field quality**
- Low tune modulation, low power converter ripple, low RF noise
- **Beam-Beam**
  - Head-on is not a limitation
  - Long range taken reasonably seriously
- **Collective effects** – had some fun here:
  - Single and coupled bunch instabilities

Optics

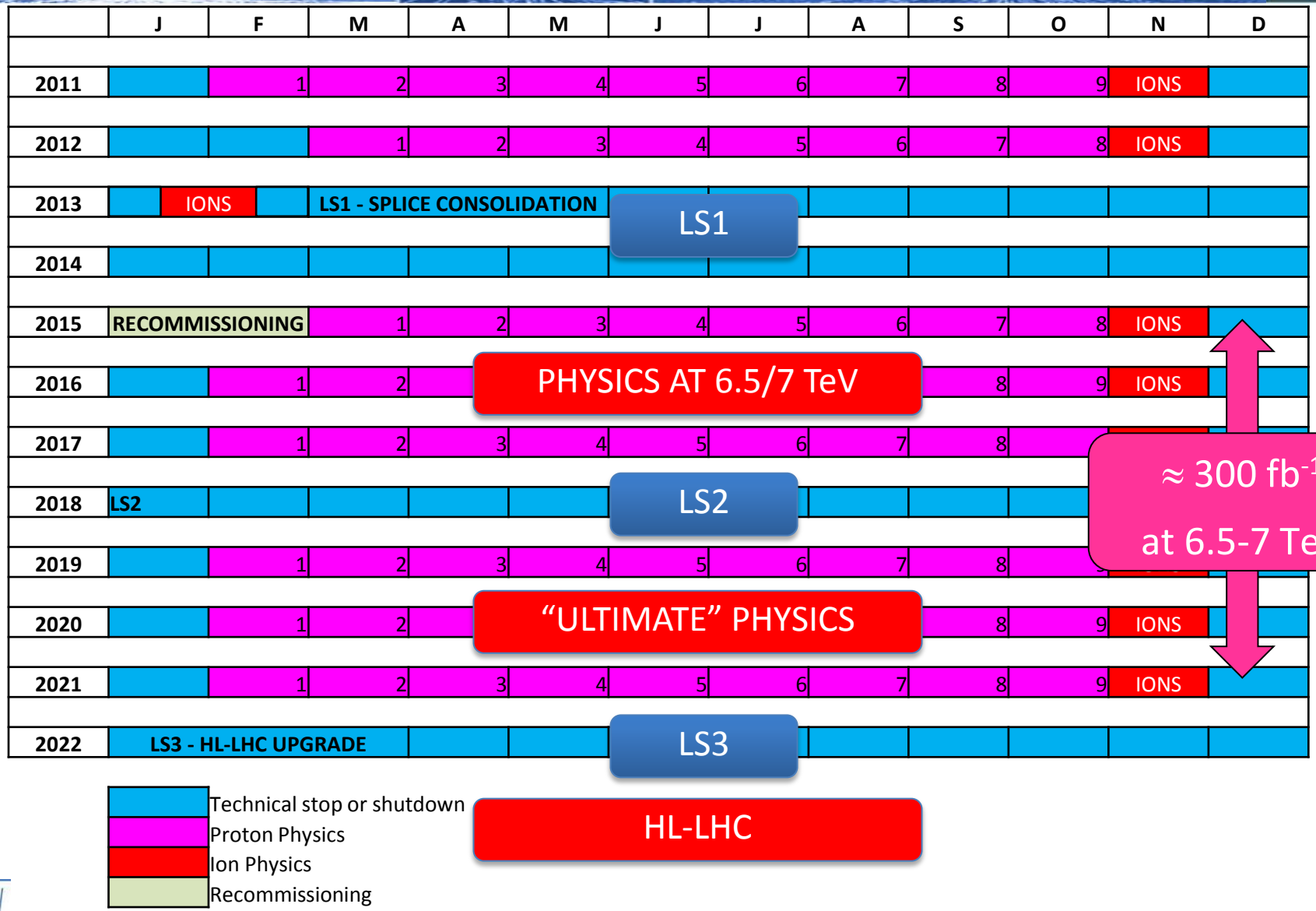
- **Linear optics**: remarkably close to model, corrected to excellent
- **Very good magnetic model**
  - including dynamic effects
- **Better than expected aperture**
  - tolerances, alignment
- **β^* reach established and exploited**
  - aperture, collimation, optics

Operational robustness

- **Machine remarkably reproducible**
  - optics, orbit, collimator set-up, tune…
- Pre-cycle, injection, 450 GeV, ramp, squeeze, collide:
  - good lifetime throughout the whole process (on the whole)
- **Superb performance of machine protection**
  - Rigorous machine protection follow-up, qualification, and monitoring

- Setting the scene
- What limits machine performance?
- LHC run I
- LS1 and future upgrades

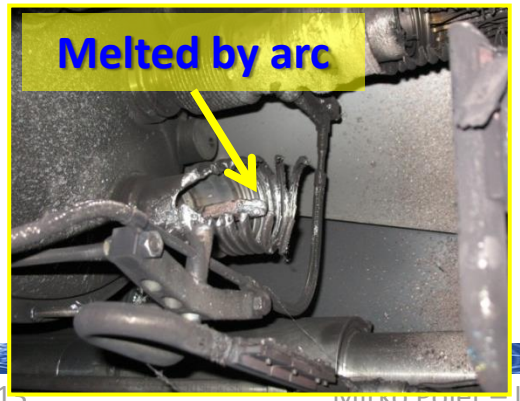
10 YEAR PLAN

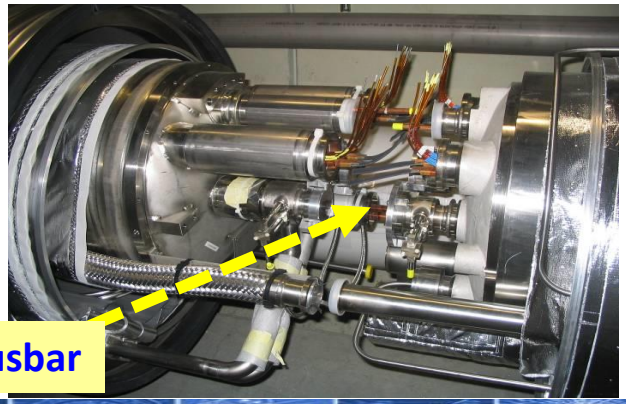

J F M A M J J A S O N D
2011 1 2 3 4 5 6 7 8 9 IONS
2012 1 2 3 4 5 6 7 8 IONS
2013 IONS LS1 - SPLICE CONSOLIDATION
LS1
2014
2015 RECOMMISSIONING 1 2 3 4 5 6 7 8 IONS
2016 1 2 PHYSICS AT 6.5/7 TeV 8 9 IONS
2017 1 2 3 4 5 6 7 8
2018 LS2
LS2
2019 1 2 3 4 5 6 7 8
2020 1 2 “ULTIMATE” PHYSICS 8 9 IONS
2021 1 2 3 4 5 6 7 8 9 IONS
2022 LS3 - HL-LHC UPGRADE
LS3
≈ 300 fb-1
at 6.5-7 TeV
Technical stop or shutdown
Proton Physics
Ion Physics
Recommissioning
HL-LHC

OBJECTIVE OF LS1 FOR LHC: PREPARE THE MACHINE FOR 6.5/7 TEV

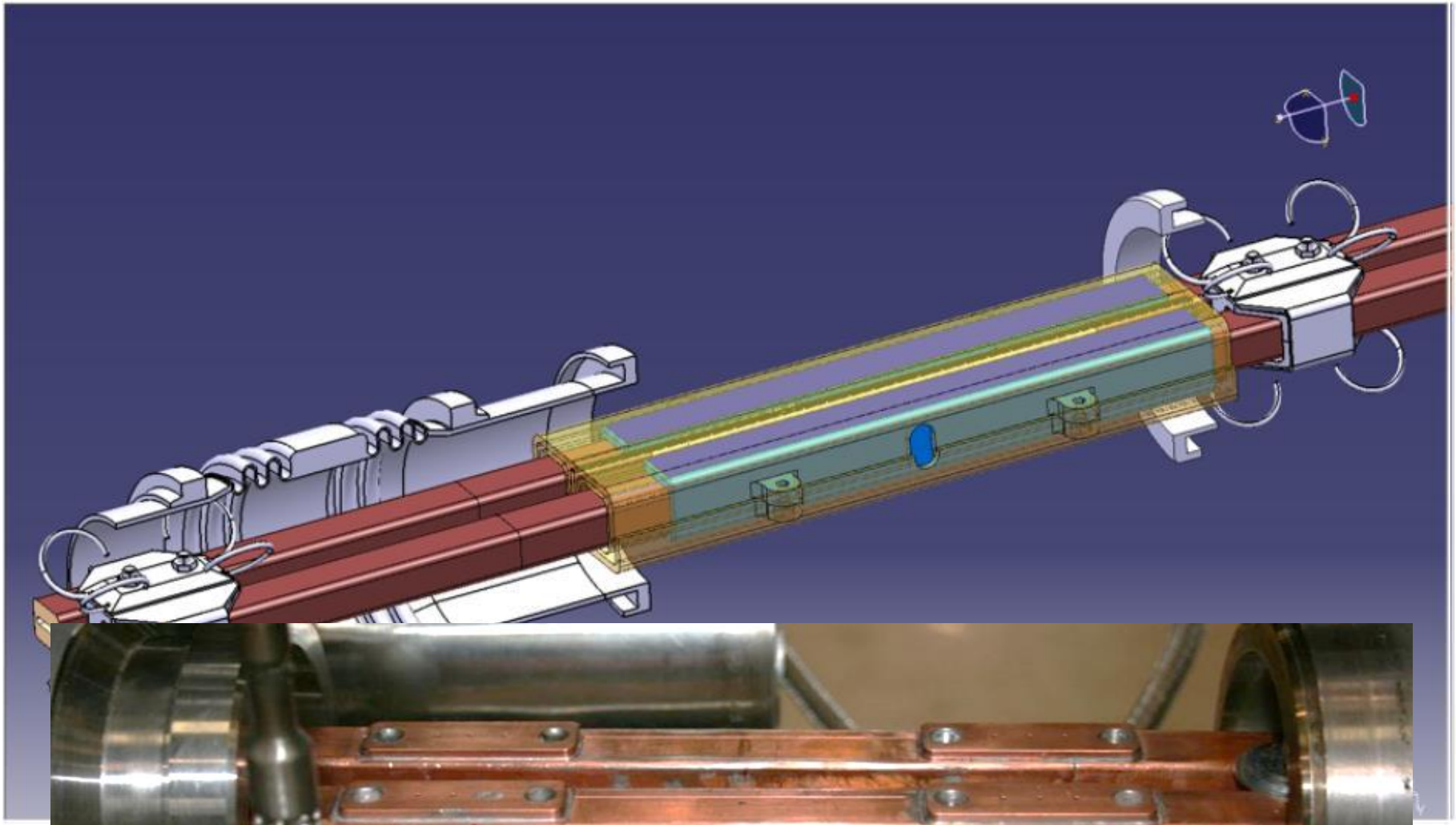
- Consolidate the 13 kA splices with the approved design of shunt and insulation (re-measure all at warm and re-solder defective ones)
  - open 1695 interconnections and redo ~1500 splices
- Install missing DN200 valves, as completion of the compensatory measures in case of major incident
  - 3.5/8 sectors = 612 Valves
- Replace weak magnets (weak insulation, faulty quench heaters, wrong beam screen, missing correctors)
  - 15 dipole and 3 quadrupole magnets
- Consolidate faulty circuits
- R2E mitigation actions → relocate electronics in 3points
- Install collimators with integrated button BPMs (tertiary collimators and a few secondary collimators)

Luminosity ≈ 10^{34} $cm^{-2}s^{-1}$ at 6.5-7 TeV

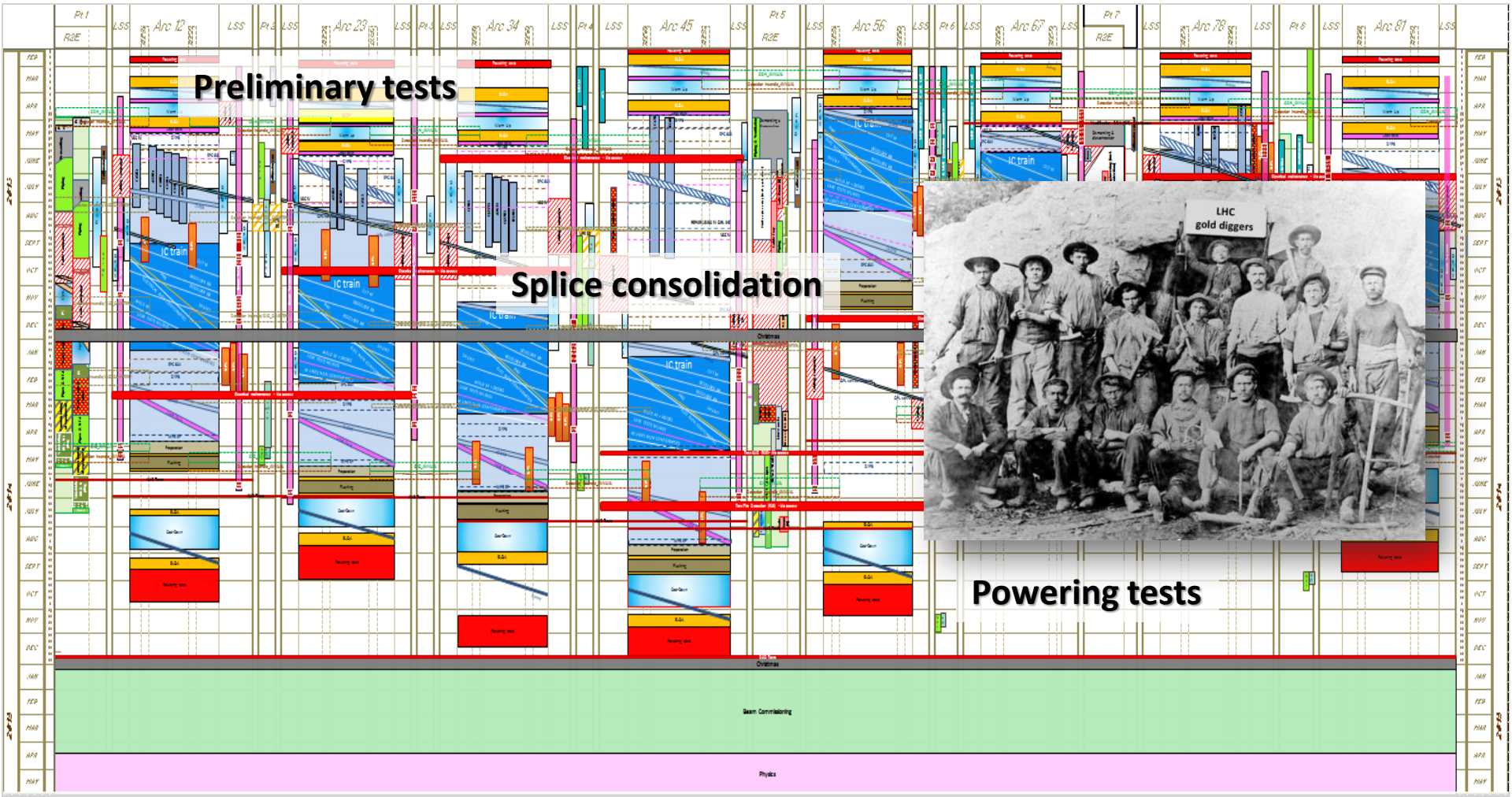




SPLICE CONSOLIDATION



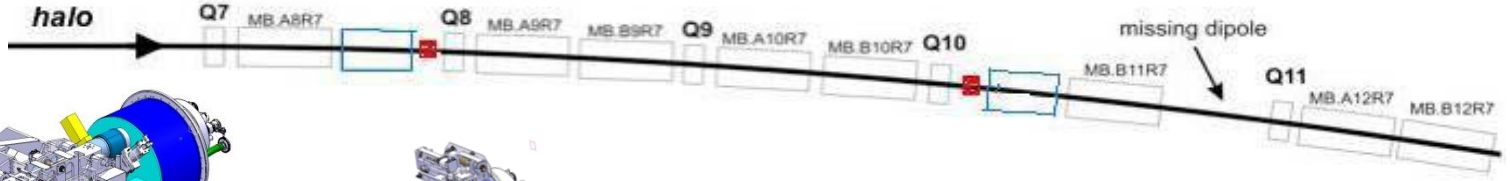
LS1 PLANNING

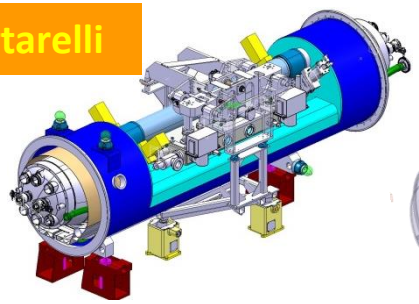


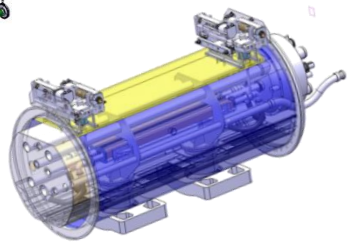
K. Foraz

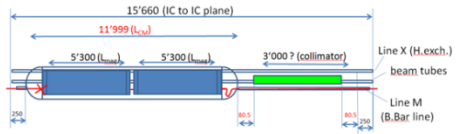
- To avoid off-momentum protons on SC dipoles, DS cryo-collimation with 11 T in 1 IP; priority NOT yet established: IP1,IP5 or IP2 ?

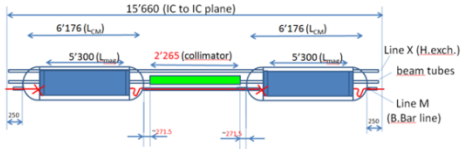
A. Bertarelli





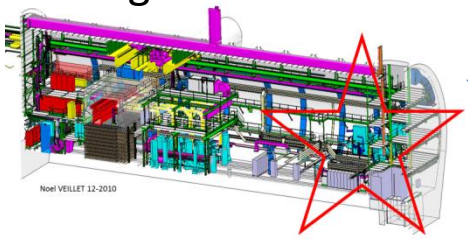


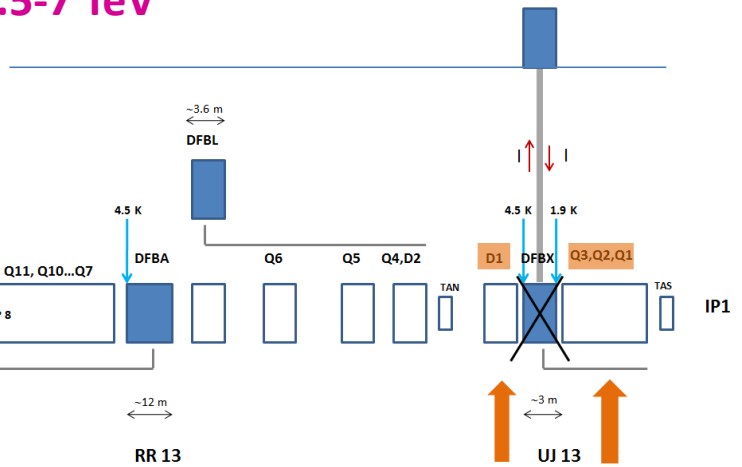




Luminosity ≈ 2×10^{34} $cm^{-2}s^{-1}$ at 6.5-7 TeV

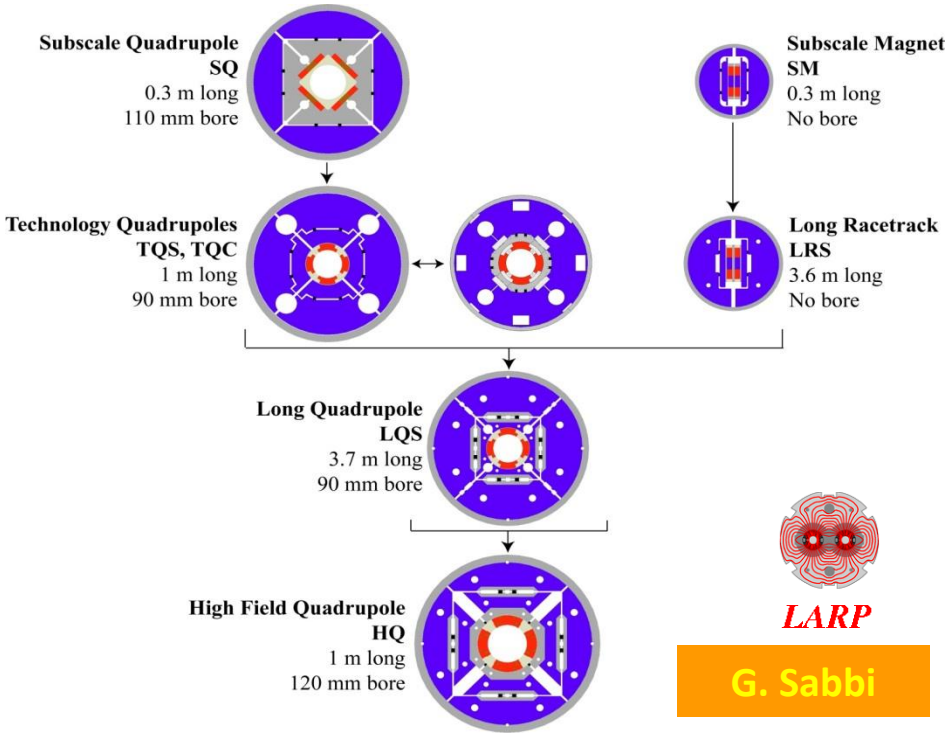
- Vertical SC links in P1, P5 (IT and stand-alone)
- Cryogenics P4 ⇒ separation between SC magnets and RF cavities cooling circuit
- Improve triplet cooling
- Some beam diagnostics
- Some collimators





- **Major injectors upgrade** (LINAC4, 2GeV PS Booster, SPS coating, …)

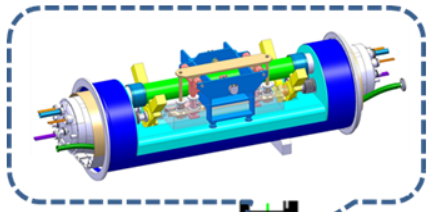
- **Triplets + D1-D2**
- TAS + Exp-interfaces
- New cryo in IP1-IP5 with **separation Arc-IR**
- New MS magnets (Q4-Q5) and correctors
- CC cavities with its local cryo
- Vertical links for all new magnets IP1-IP5
- New collimators
- Diagnostics & wigglers

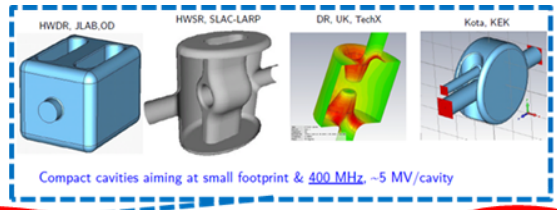


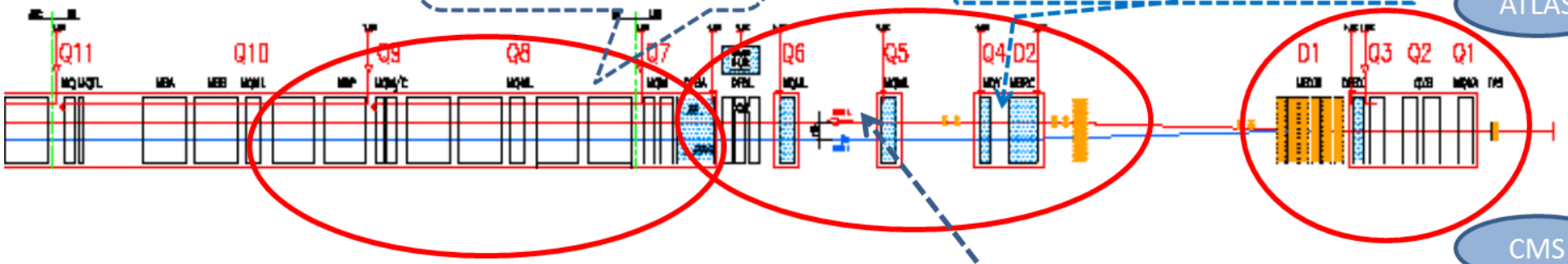
High Luminosity LHC

The HiLumi LHC Design Study (a sub-system of HL-LHC) is cofunded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404

CHANGING 300X2 M BOTH ATLAS & CMS (+LHC-B & ALICE …)



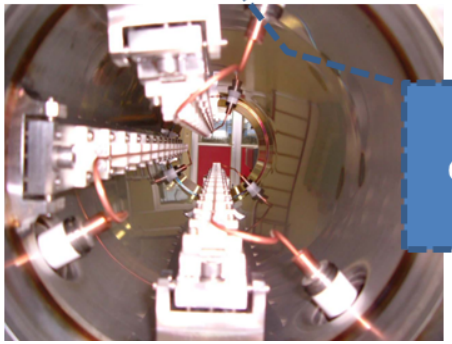




3. For collimation we need to change also this part, DS in the continuous cryostat

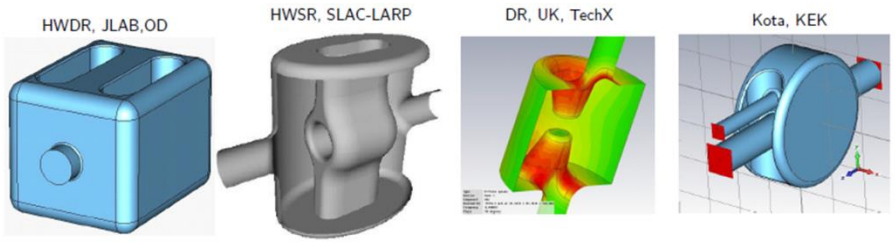
2. Deep change also matching section: Magnets, collimators and CC

1. Deep change in the IRs and interface to detectors; relocation of Power Supply

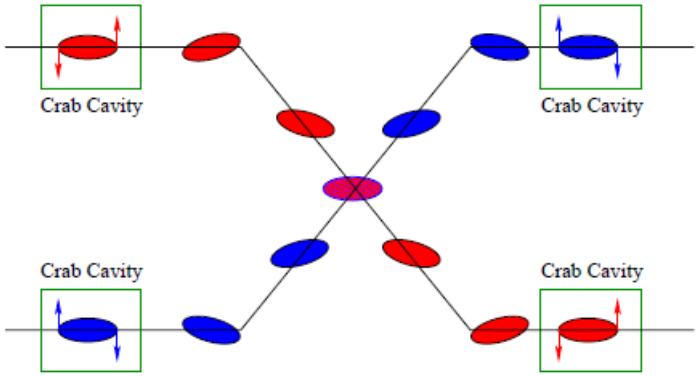


4. LR BB compensation wires

1.2 km of LHC !!

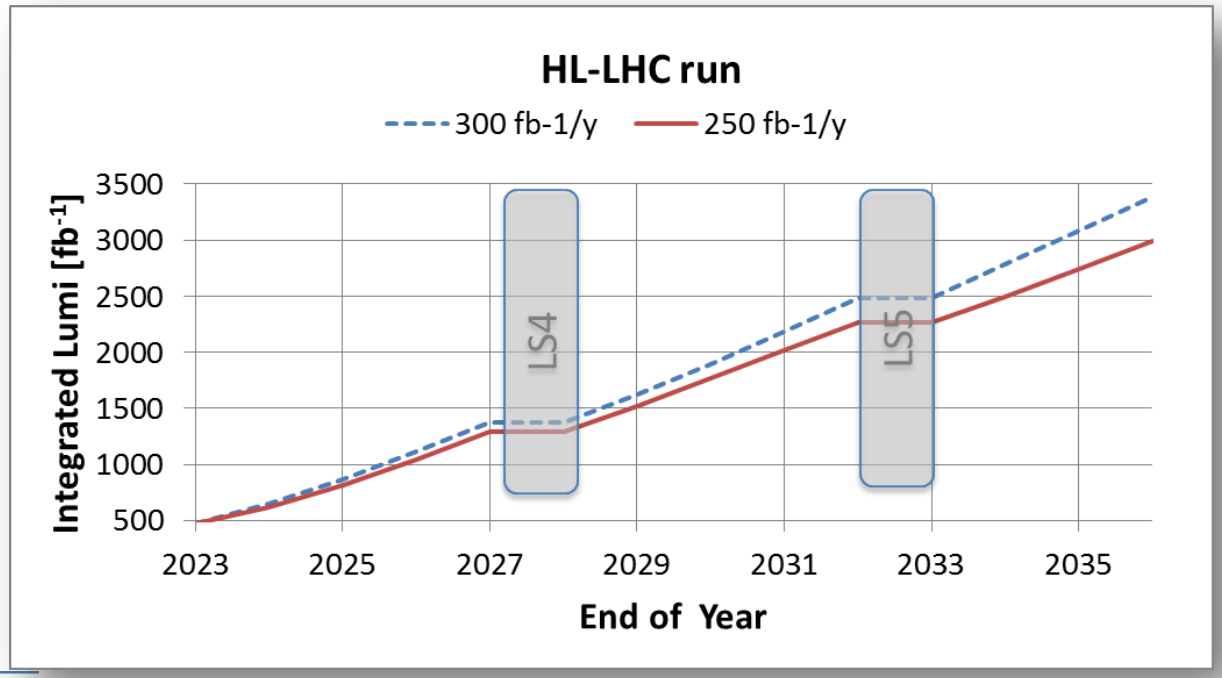


Compact cavities aiming at small footprint & 400 MHz, ~5 MV/cavity



- RF crab cavity deflects head and tail in opposite direction so that collision is effectively “head on” and then luminosity is maximized
- Crab cavity maximizes the lumi and can be used also for luminosity leveling: if the lumi is too high, initially you don’t use it, so lumi is reduced by the geometrical factor. Then they are slowly turned on to compensate the proton burning
- Other tools for levelling:
  - dynamic b* squeeze
  - transverse offsets at IP
  - crossing angle and Long-range and beam-beam wire compensators

- To push the performance above the ultimate, **to 5 10^{34} or more**
  - If pile up allows it. Today we have 30-35, experiments design upgrade for 140 evt/crossing average with a max of 200/crossing)
  - If energy deposition by collision debris in the nearest SC magnets (low.β triplet quads) allows it
- **Use of lumi levelling** to maximize integrated luminosity for a given max lumi.
- **Final goal is : 3000 fb^{-1} by 10-12 years**



High Luminosity LHC

The HiLumi LHC Design Study (a sub-system of HL-LHC) is cofunded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404

TARGET PARAMETERS

Parameter	Nom. 25 ns	Target 25 ns	Target 50 ns	LIU 25 ns	LIU 50 ns
N_b [10^{11}]	1.15	2.0	**3.3**	1.7	2.5
n_b	2808	2808	1404	2808	1404
I [A]	0.56	**1.02**	0.84	0.86	0.64
θc [μrad]	300	475	445	480	430
β* [m]	0.55	**0.15**	**0.15**	**0.15**	**0.15**
ε_n [μm]	3.75	**2.5**	**2.0**	**2.5**	**2.0**
ε_s [eV s]	2.5	2.5	2.5	2.5	2.5
IBS h [h]	111	25	**17**	25	**10**
IBS l[h]	65	21	**16**	21	**13**
Piwinski	0.68	2.5	2.5	2.56	2.56
F red.fact.	0.81	0.37	0.37	0.37	0.36
b-b/IP[10^{-3}]	3.1	3.9	**5**	3	**5.6**
L_{peak}	1	7.4	8.4	5.3	**7.2**
Crabbing	no	**yes**	**yes**	**yes**	**yes**
$L_{peak\ virtual}$	1	20	22.7	14.3	19.5
Pileup $L_{lev}=5L_0$	19	95	190	95	190
Eff.†150 days	=	0.62	0.61	0.66	0.67

baseline

CONCLUSIONS

- The progress in the performance of the LHC has been breath-taking
- The LHC is performing incredibly well (even better than expected) an this is possible thanks to the quality of the design, construction and installation and to the thorough preparation in the injectors which are delivering beams well beyond nominal parameters
- A solid upgrade program is in a very mature state, even if the final parameters will depend on the capacity of the experiments to manage pile-up

Thank you for the attention!

Reserve slides

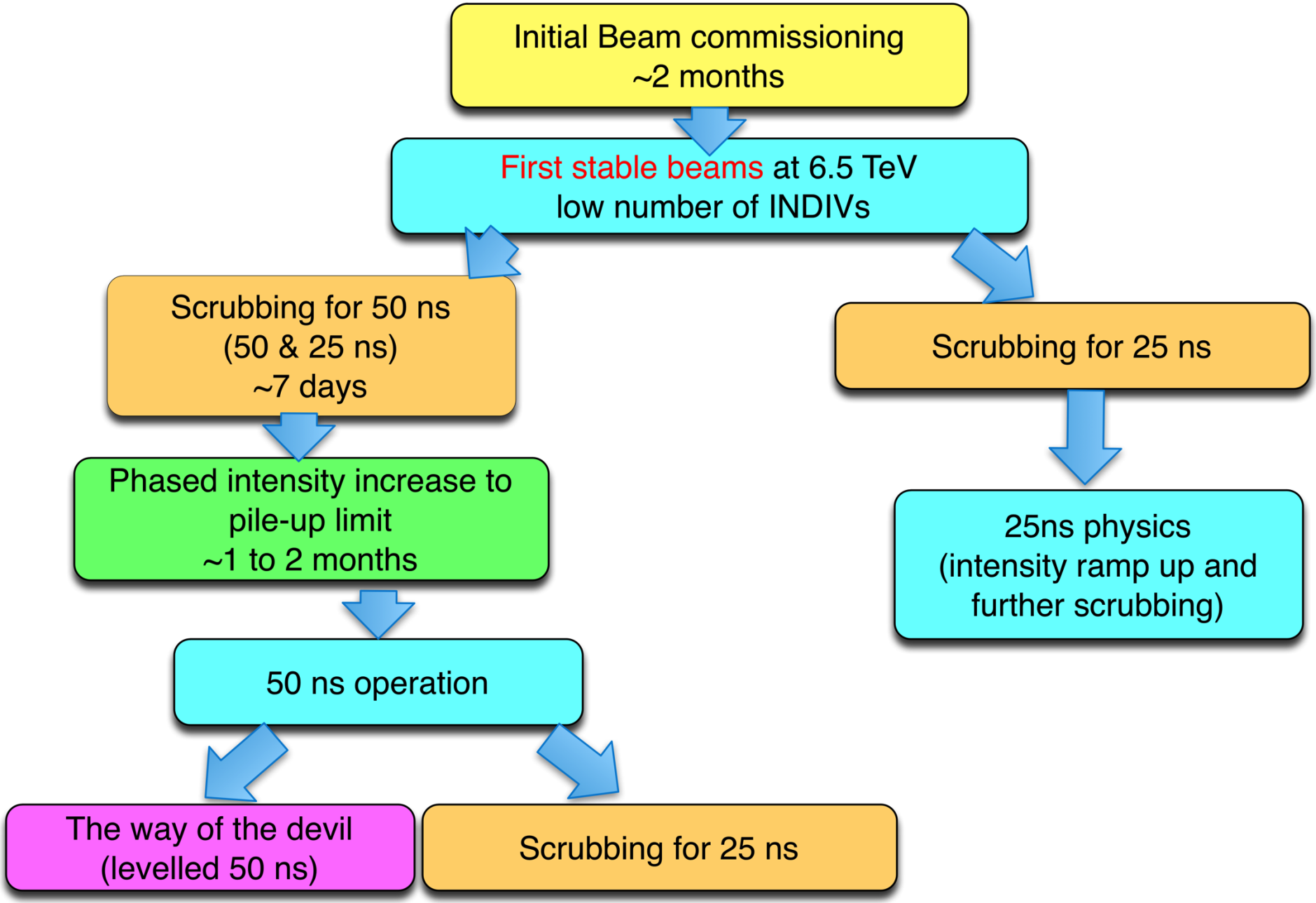
3 out of many possible scenarios…

	k	N_b [10^{11} p]	ε [μm]	β* [m]	L [10^{34} cm^{-2}s^{-1}]	Pile-up	Int. L [fb^{-1}]
50 ns	1380	1.70	1.5	**0.4**	2.05	104*	~30
25 ns low emit	2600	1.15	1.4	**0.4**	1.73	47*	~50
25 ns standard	2800	1.20	2.8	**0.5**	1.02	25	~30

(*) leveled down to a pile-up of ~40

Main challenge emittance preservation!!!

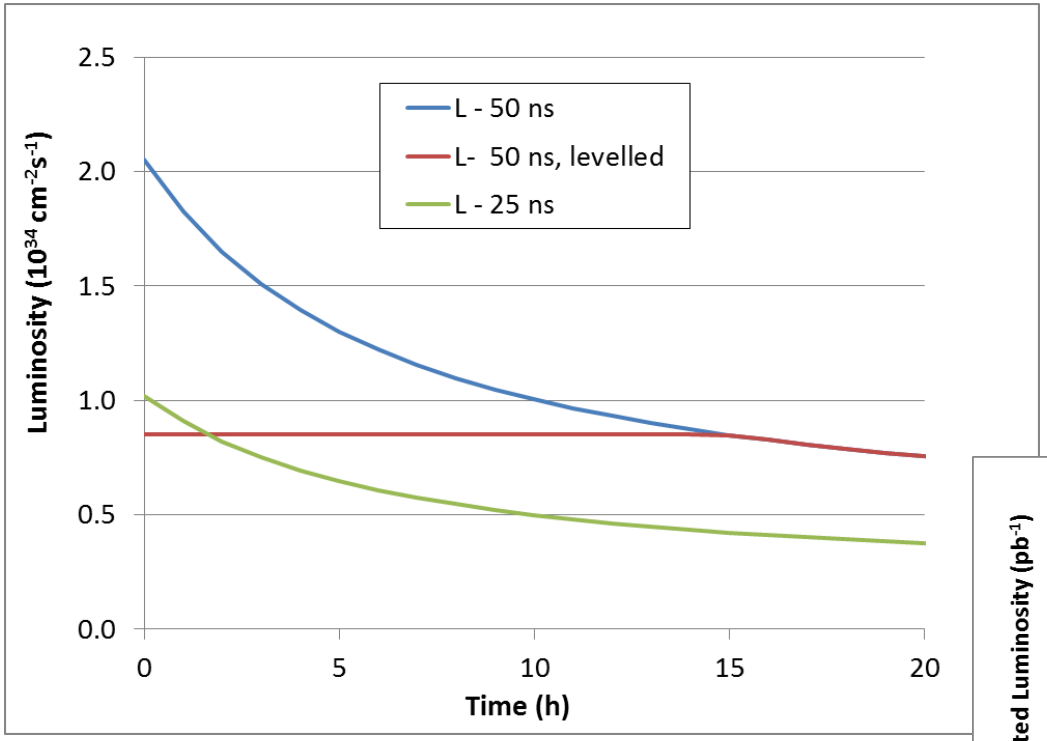
Int. L based on 120 days of production, 35% efficiency.


Initial Beam commissioning
~2 months
First stable beams at 6.5 TeV
low number of INDIVs
Scrubbing for 50 ns
(50 & 25 ns)
~7 days
Scrubbing for 25 ns
Phased intensity increase to
pile-up limit
~1 to 2 months
25ns physics
(intensity ramp up and
further scrubbing)
50 ns operation
The way of the devil
(levelled 50 ns)
Scrubbing for 25 ns

50 vs 25 ns

	50 ns	25 ns
GOOD	• Lower total beam current • Higher bunch intensity • Smaller emittance	• **Lower pile-up**
BAD	• **High pile-up** • Need to level • Pile-up stays high • High bunch intensity – instabilities…	• More long range collisions: larger crossing angle; higher β^* • Larger emittance • Electron cloud: need for scrubbing; emittance blow-up; • Higher UFO rate • Higher injected bunch train intensity • Higher total beam current

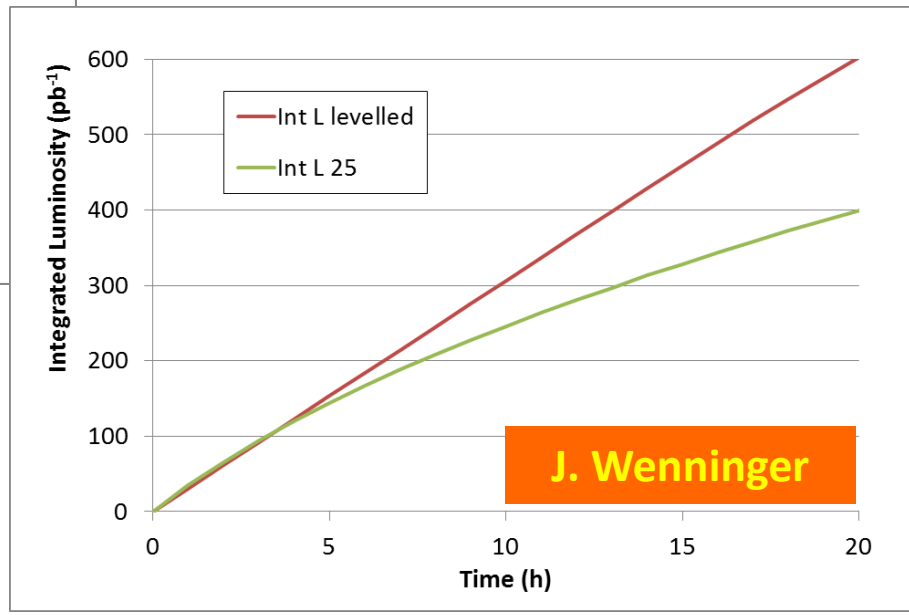
25 ns vs. 50 ns



Standard 25 ns and 50 ns with levelling

- Equivalent in integrated luminosity for fill lengths up to 5-6 hours.

- Low emittance 25 ns provides higher performance due to higher luminosity for same or lower pile-up.



- 50 ns beam remains very attractive for high luminosity after LS1:
  - *Similar peak (levelling) and integrated luminosities due to higher brightness from injectors*
  - *Lower total current and stored energy*
  - *Less / no e-clouds,*
  - *Less beam induced heating ?*
  - *Less long-range collisions (lower crossing angle and β^*)*
  - *Fewer UFOs? Saw a worrying rate of UFOs with 25 ns beams…TBC.*
  - *But at the price of higher pile-up.*
- To limit pile-up, β^* levelling is mandatory in ATLAS and CMS with 50 ns beams (and to some extent with small emittance 25 ns).
  - *Possibly squeeze with colliding beams – good for beam stability !!*
- It is realistic to assume that we start with 50 ns beams, and switch to 25 ns to operate the experiments at lower pile-up

PERFORMANCE FROM THE INJECTORS IN 2012

Design report with 25 ns:
- **1.15 x 10^{11} ppb**
- **Normalized emittance 3.75 μm**

Bunch spacing [ns]	Protons per bunch [ppb]	Norm. emittance H&V [μm] Exit SPS
50	1.7 x 10^{11}	1.8
25	1.2 x 10^{11}	2.7

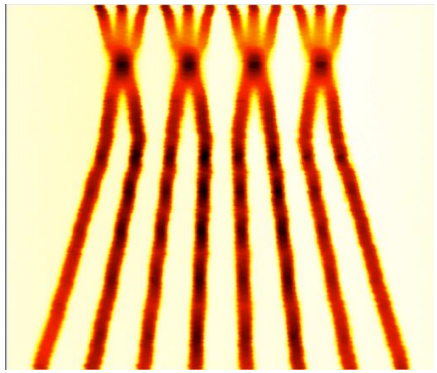
N.B. the importance of 50 ns in the performance so far.
This at the expense of high pile-up.
(And they are in the process of re-inventing themselves again)

BEAM FROM INJECTORS LS1 TO LS2

LIU team

		Bunch intensity [10^{11} p/b]	Emittance [mm.mrad] Exit SPS	Into collisions
25 ns ~nominal	2760	1.15	2.8	3.75
25 ns BCMS	2520	1.15	1.4	1.9
50 ns	1380	1.65	1.7	2.3
50 ns BCMS	1260	1.6	1.2	1.6

BCMS = Batch Compression and (bunch) Merging and (bunch) Splitting



Batch compression & triple splitting in PS

β* & CROSSING ANGLE

- β* reach depends on:
  - available aperture
  - collimator settings
  - required crossing angle which in turn depends on
    - emittance
    - bunch spacing

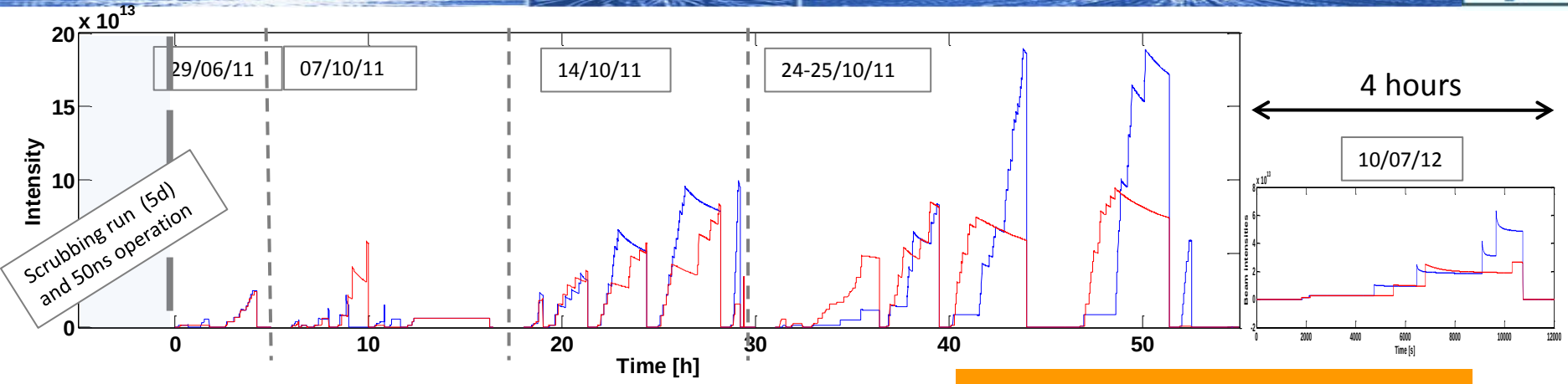
- β* reach at 6.5 TeV

- Pessimistic scenario:
  - ➡ β* = 70cm at 25ns
  - ➡ β* = 57cm at 50ns
- Optimistic scenario:
  - ➡ β* = 37cm at 25ns
  - ➡ β* = 30cm at 50ns

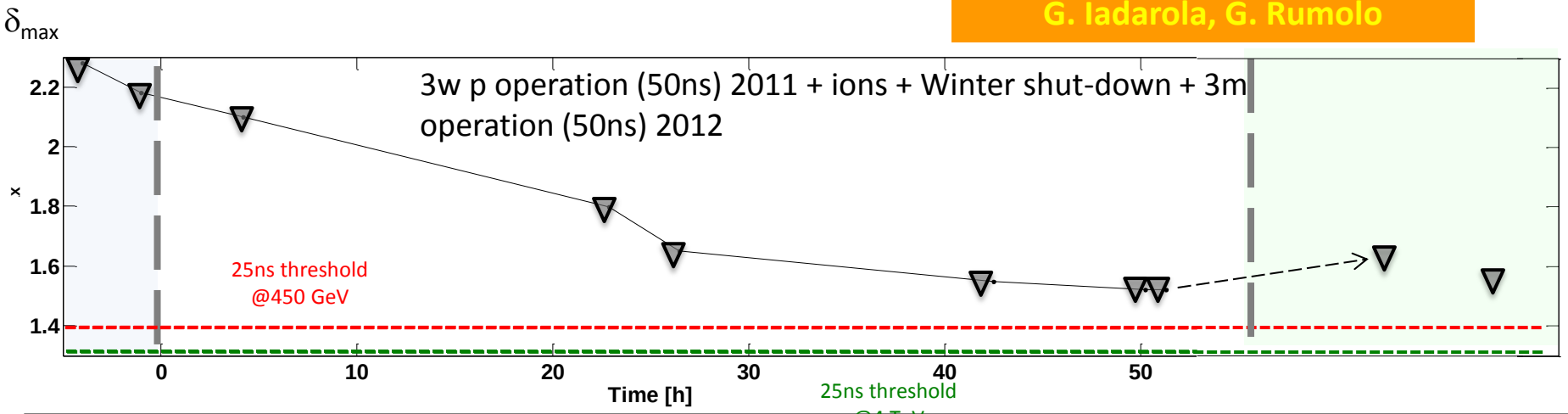
B. Salvachua

03-14-2013 Mirko Pojer – LHCP 2013 - 13-18 May 2013, Barcelona 53

SCRUBBING HISTORY OF LHC ARCS



G. Iadarola, G. Rumolo



→ δ_{max} decreased from the initial **2.1 to 1.52** in the arcs after approximately 50h machine time with 25ns beams in 2011. Expect ~2 weeks of scrubbing at 450 GeV for operation at 25 ns.

→ Slightly higher (**1.65**) in 2012, but rapidly decreased to **1.55** after 4h beam time

- New ideas and concepts will be implemented in the PS to produce beams with higher intensity and smaller emittance.
- Possible beams after LS1 (not yet demonstrated).

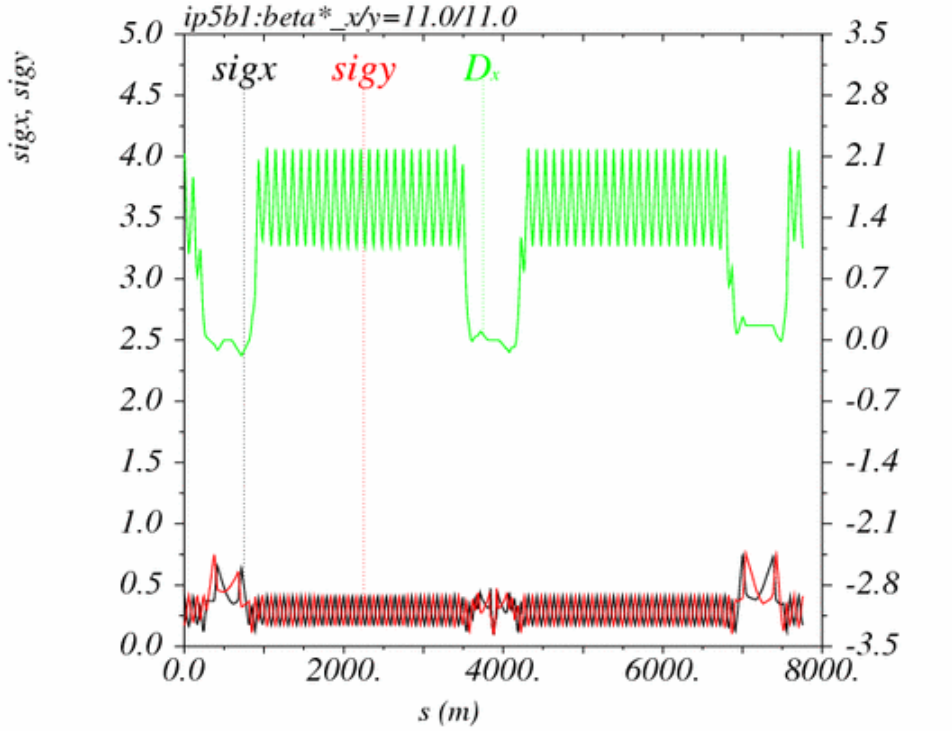
Nominal

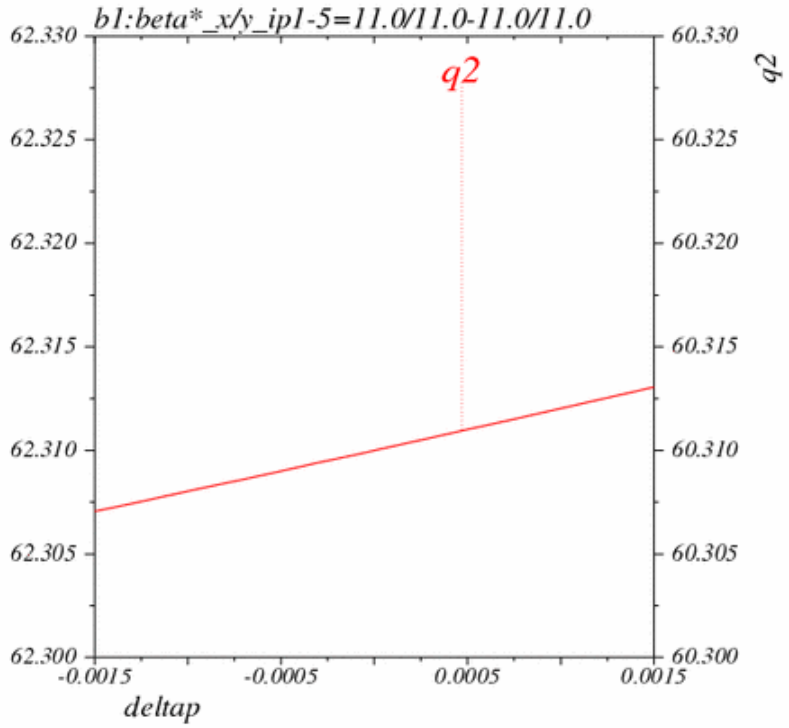
		50 ns	50 ns	25 ns	25 ns
PS ejection	Bunches / train	32	24	48	72
SPS ejection	Bunch intensity	$1.7 \cdot 10^{11}$	$1.7 \cdot 10^{11}$	$1.15 \cdot 10^{11}$	$1.2 \cdot 10^{11}$
	Emittance [μm]	1.5	1.2	**1.4**	2.8
No bunches in LHC		~1340	~1300	~2600	2808
Relative luminosity		2	2.4	1.85	1
Relative pile-up		4.1	5.2	2	1

H. Damerau

- The quoted emittance values (and luminosities) do not include any blowup in the LHC (presently ~ +0.6 μm).

VERY LOW B* (10 CM)





IR4 IR5 IR6

Beam size [mm] and dispersion (IR4→IR6) at 3.5 TeV (for $\gamma\varepsilon$=3.5 μm)

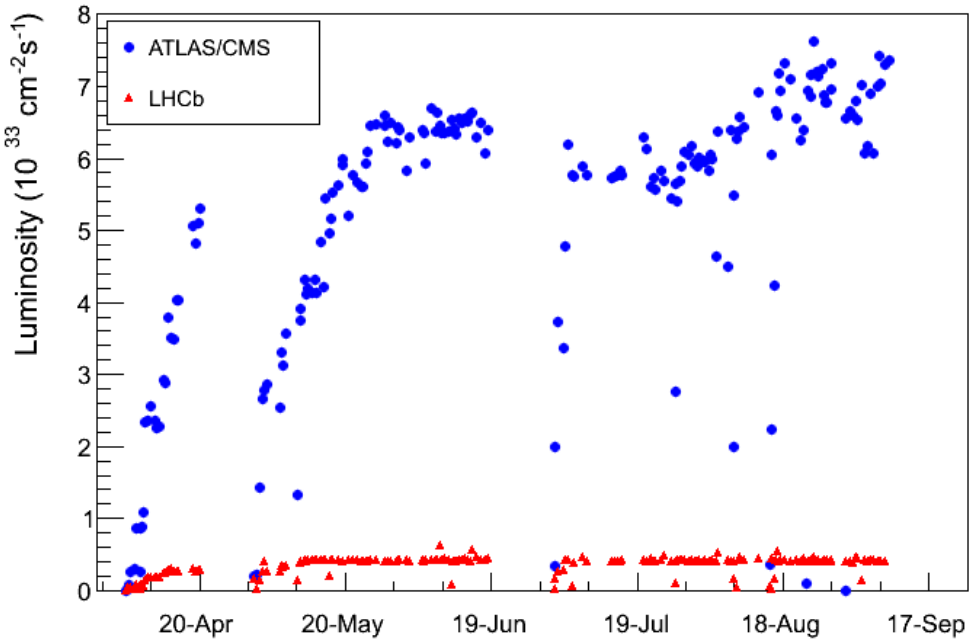
Tunes vs. δ_p

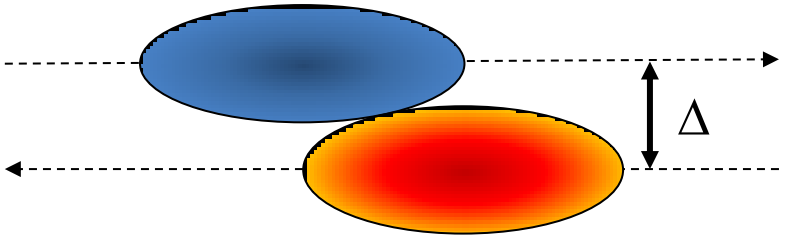
ATS=Achromatic Telescopic Squeeze - S. Fartoukh

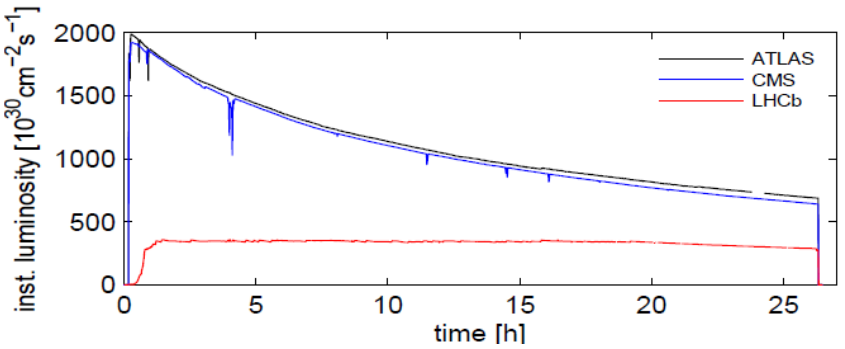
- …of course it requires larger aperture triplets

LHCb versus ATLAS/CMS

- The LHCb luminosity is limited to 4×10^{32} $cm^{-2}s^{-1}$ (detector limitations on rate and pileup).
- The transverse offset D between beams is adjusted regularly while colliding to maintain a constant luminosity – luminosity levelling.

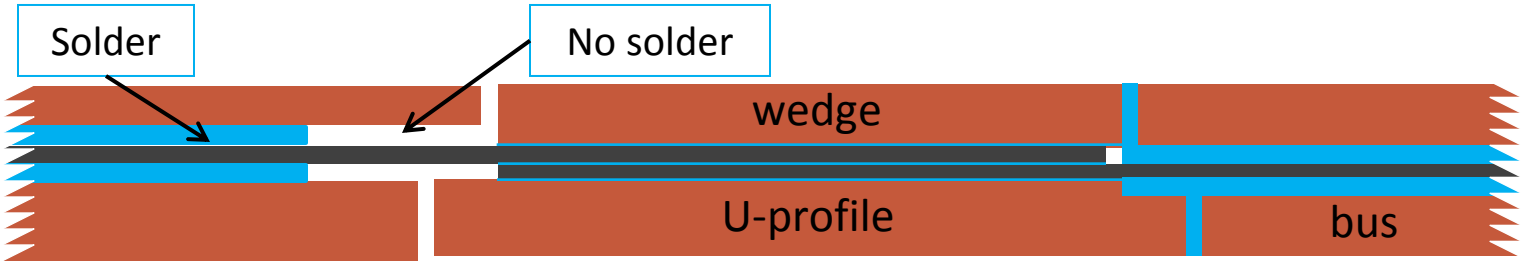




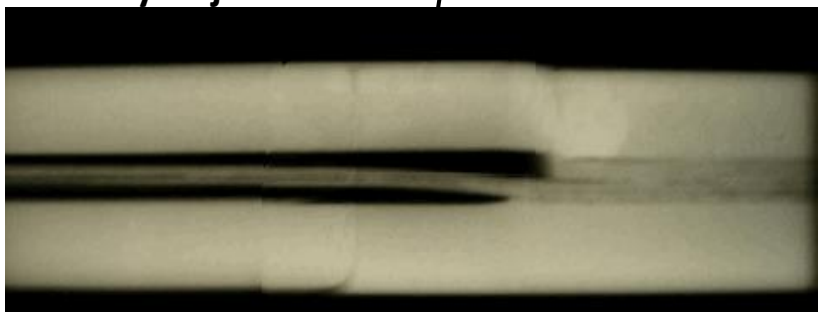


- The copper stabilizes the bus bar in the event of a cable quench (=bypass for the current while the energy is extracted from the circuit).

- A copper bus bar with reduced continuity coupled to a badly soldered superconducting cable can lead to a serious incident.

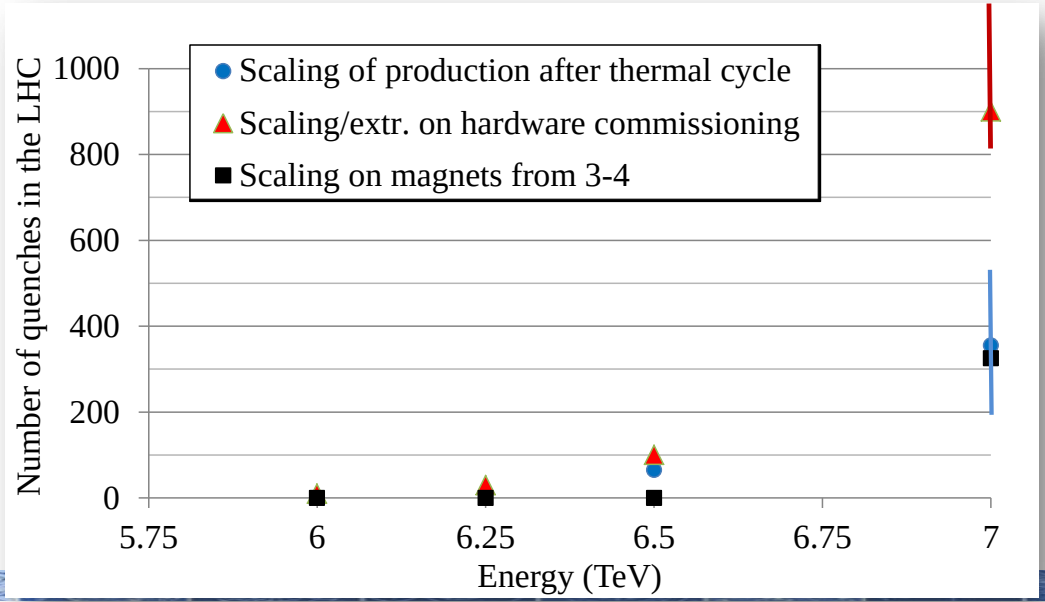


X-ray of joint



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

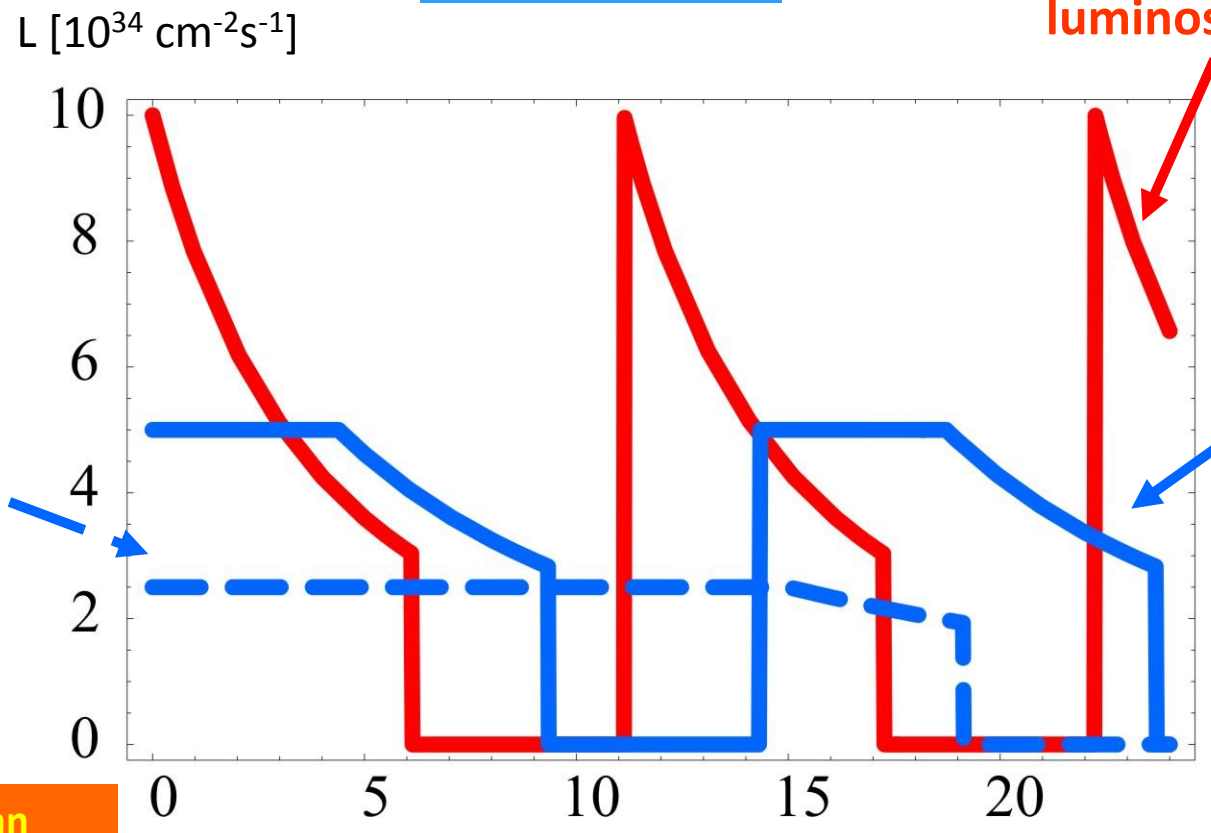
- In 2008 attempts to commission the first LHC sector to 7 TeV revealed a problem on the magnets from one manufacturer.
  - *The magnets that had been trained on test stands started to quench again.*
  - *The number of quenches increased rapidly beyond 6.5 TeV.*
- Extrapolations showed that the number of training quenches required to reach 7 TeV is too large.
  - *Time and risk to the magnets.*
- For those reasons we will most likely restart at **6.5 TeV**, or slightly above depending on time and experience during the re-commissioning.



E. Todesco

$$L = \frac{k N_b^{\,2} f \gamma}{4\pi \beta^* \varepsilon^*} F$$

Virtual peak luminosity (F=1)



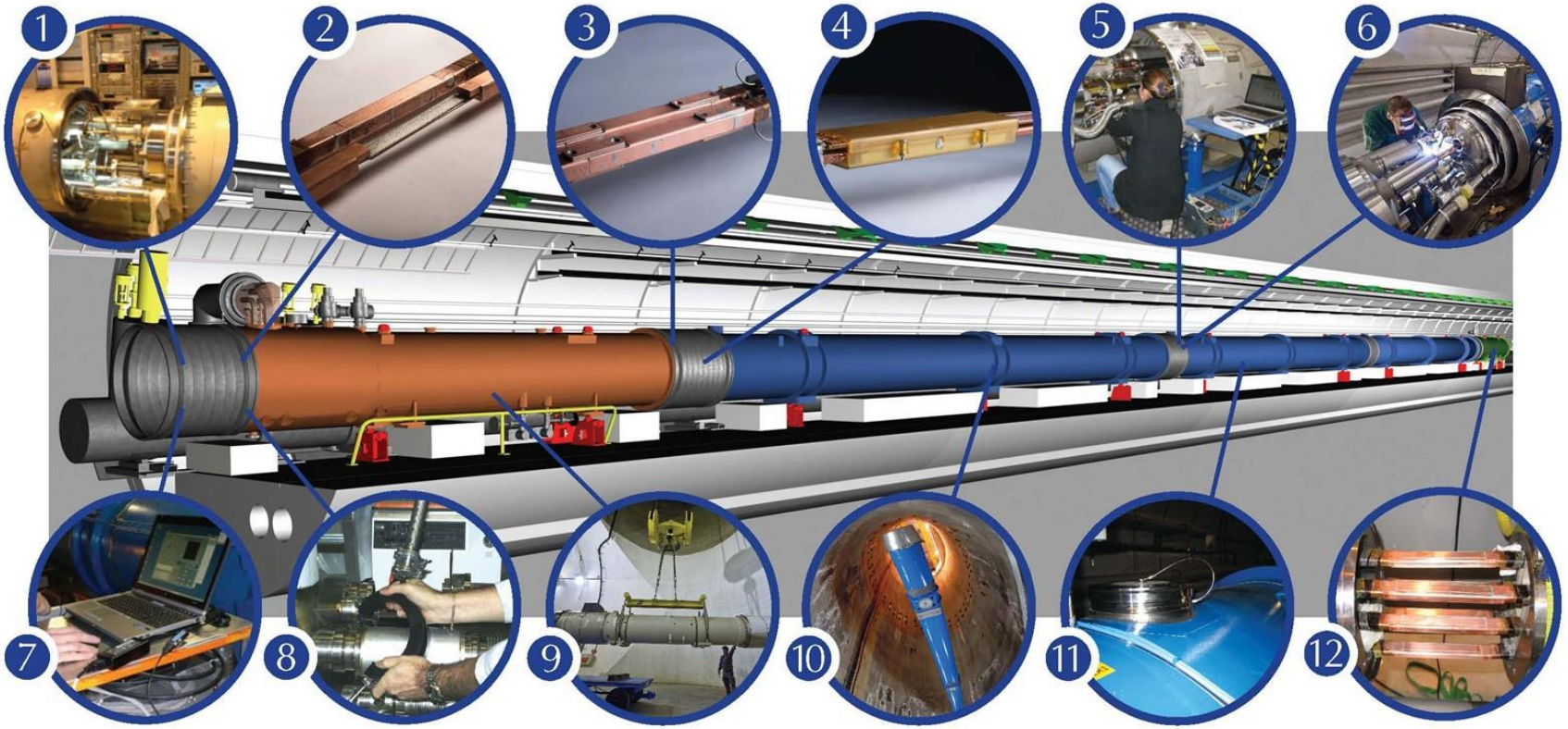
leveling at 2.5×10^{34} cm^{-2}s^{-1}
τ_{eff}=30 h, T_{ta}=5 h

leveling at 5×10^{34} cm^{-2}s^{-1}
τ_{eff}=15 h, T_{ta}=5 h

F. Zimmermann

The main 2013-14 LHC consolidations

1. 1695 Openings and final reclosures of the interconnections
2. Complete reconstruction of 1500 of these splices
3. Consolidation of the 10170 13kA splices, installing 27 000 shunts
4. Installation of 5000 consolidated electrical insulation systems
5. 300 000 electrical resistance measurements
6. 10170 orbital welding of stainless steel lines



7. 18 000 electrical Quality Assurance tests
8. 10170 leak tightness tests
9. 4 quadrupole magnets to be replaced
10. 15 dipole magnets to be replaced
11. Installation of 612 pressure relief devices to bring the total to 1344
12. Consolidation of the 13 kA circuits in the 16 main electrical feedboxes