



LHC on the March - 20-22 November 2012 IHEP, Protvino



LHC STATUS & PLANS (INCLUDING UPGRADE)



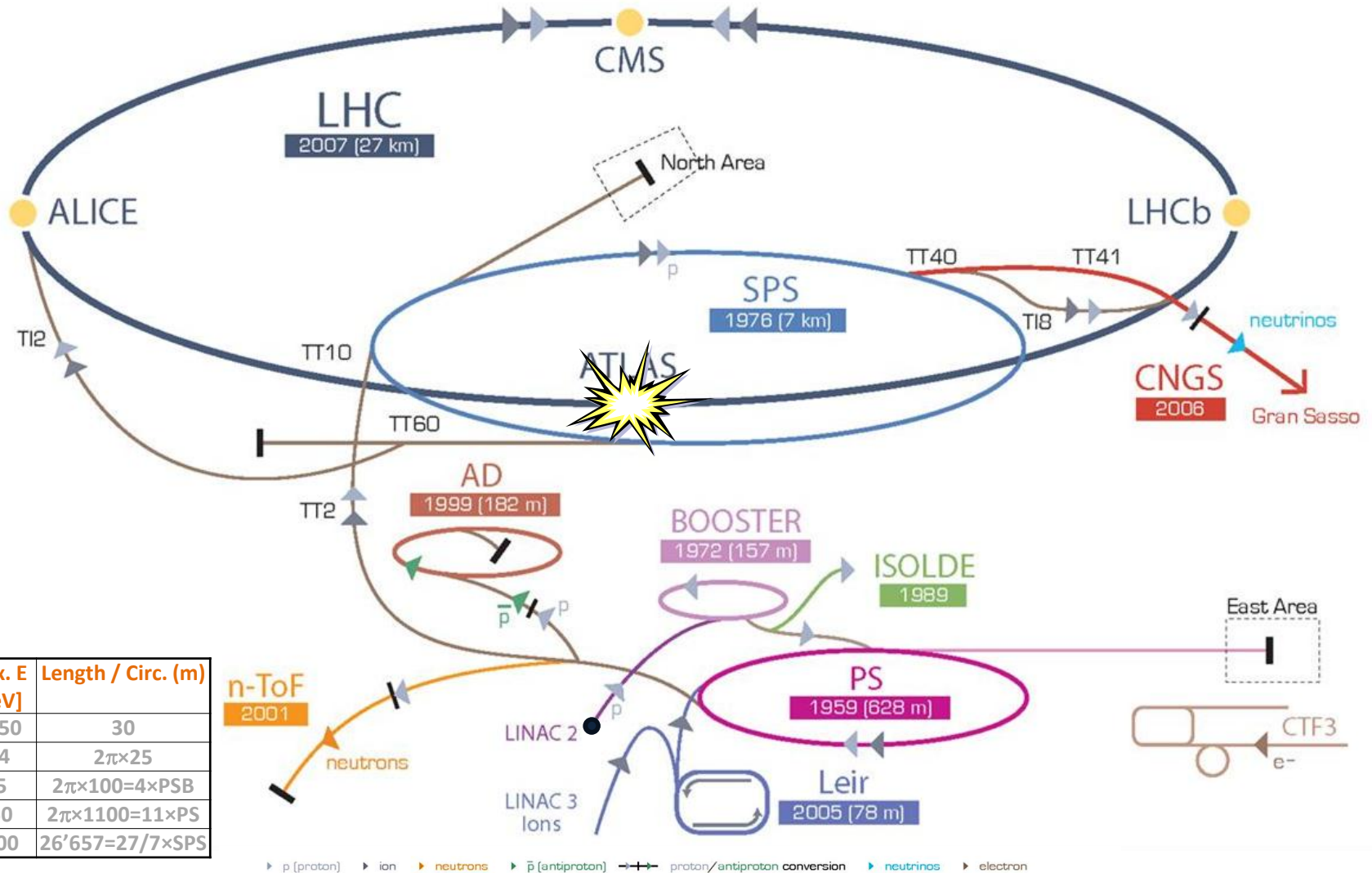
MIRKO POJER – BEAMS DEPARTMENT/OP GROUP

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



- ☐ Setting the scene
- ☐ Motivation for an upgrade
- ☐ Machine performance
- ☐ Upgrades

CERN'S PARTICLE ACCELERATOR CHAIN



	Max. E [GeV]	Length / Circ. (m)
LINAC2	0.050	30
Booster	1.4	$2\pi \times 25$
PS	25	$2\pi \times 100 = 4 \times \text{PSB}$
SPS	450	$2\pi \times 1100 = 11 \times \text{PS}$
LHC	7000	$26'657 = 27/7 \times \text{SPS}$

▶ p [proton] ▶ ion ▶ neutrons ▶ \bar{p} [antiproton] ↔ proton/antiproton conversion ▶ neutrinos ▶ electron

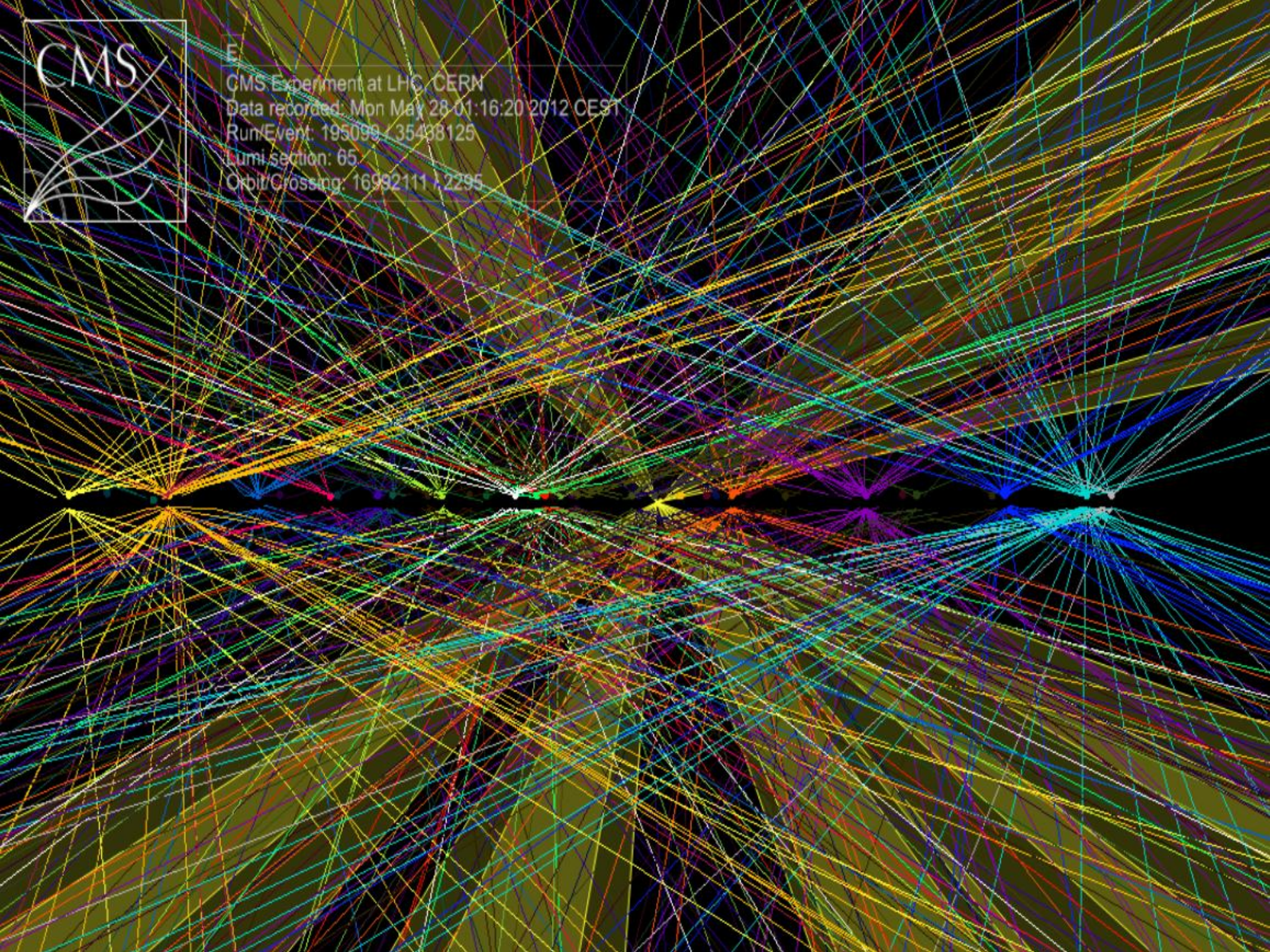


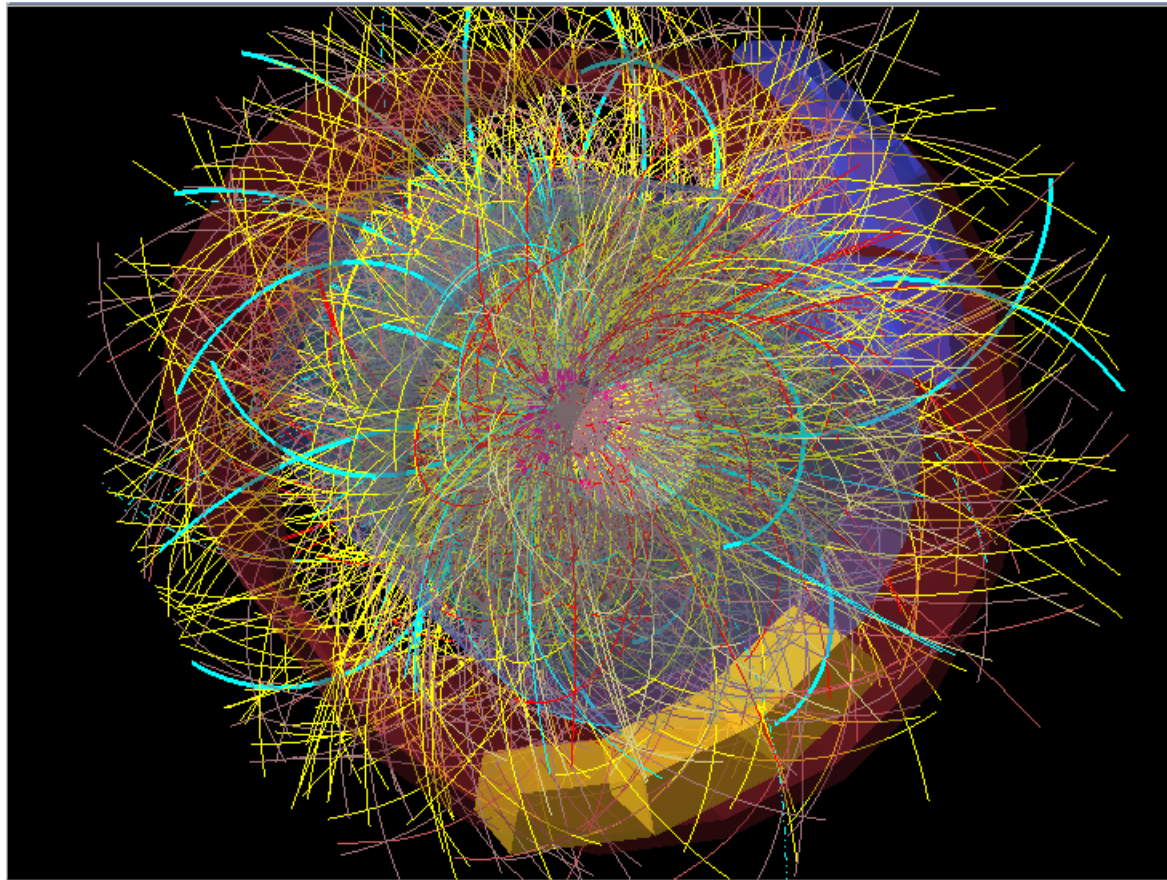


	2012
Collision energy: 7+7 TeV	4+4 TeV
Number of bunches: 2808	1374
Number of particles per bunch: 1.15×10^{11}	$1.7e^{11}$
Circulating beam current: 0.58 A	0.42 A
Stored energy per beam: 360 MJ	150 MJ
Peak luminosity in IP1 and IP5: $10^{34} \text{ cm}^{-2}\text{s}^{-1}$	$7.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
<p>⇒ 30-50 collisions per crossing; 10^9 collisions per second</p> <p>⇒ Big challenge for the detectors and for the acquisition and analysis of data</p>	



E
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295

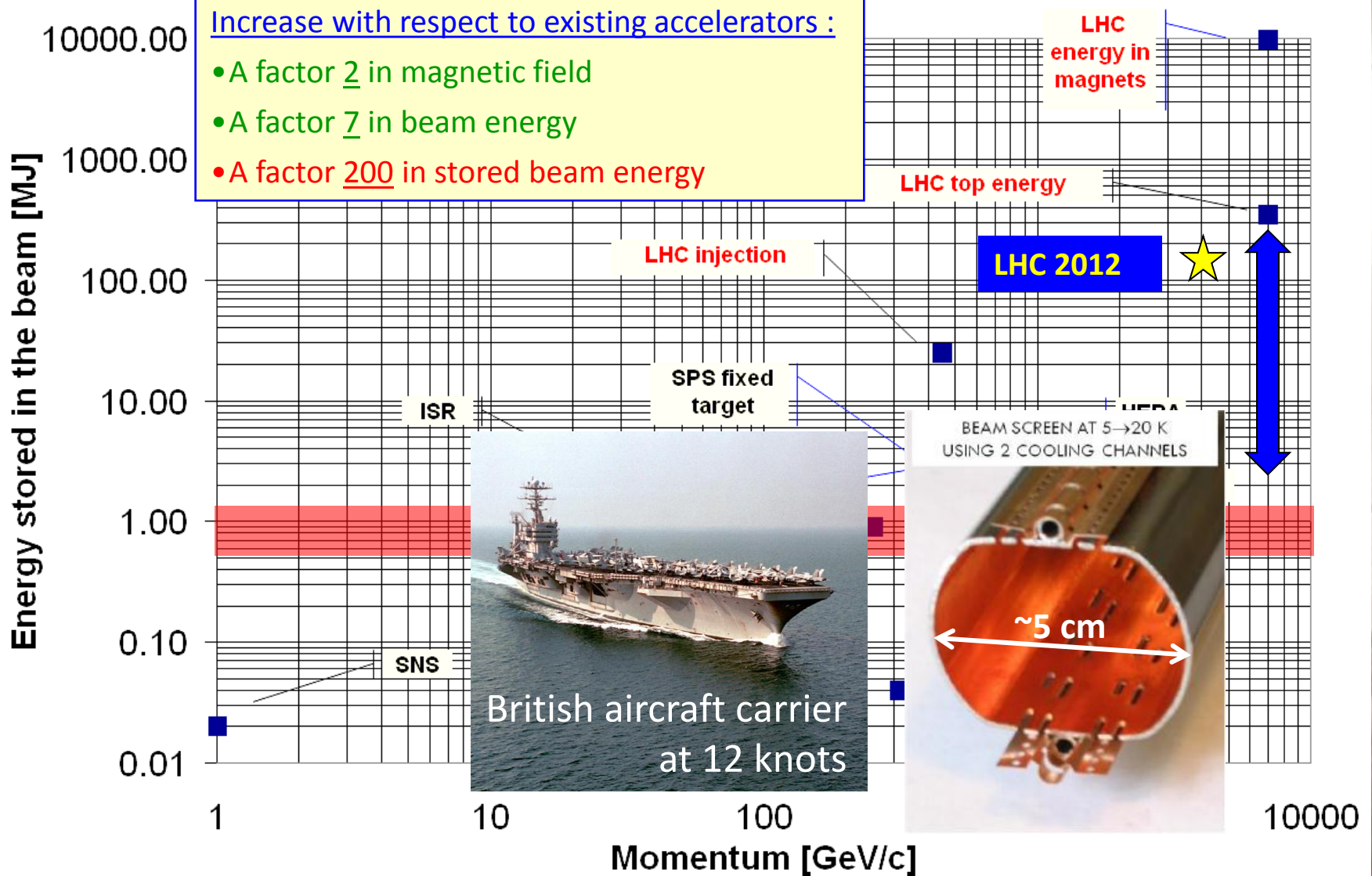




The experiments are producing ~15 Millions Gigabytes of data per year
(~ 5 millions DVDs!)

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

THE LHC CHALLENGES...



1232 15-m-long/30-ton-weight dipole magnets
+
3700 multipole corrector magnets

392 quadrupole magnets
+
2500 multipole correctors

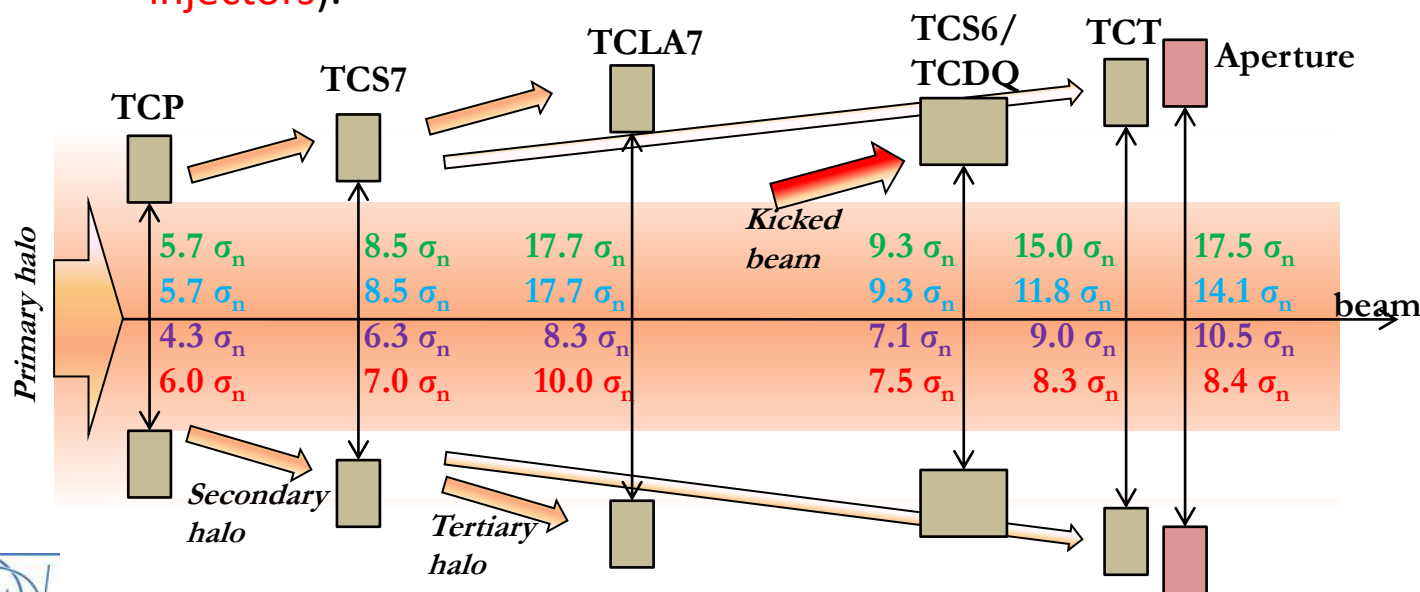
Thousands of BLMs and BPMs

8 Inner Triplet assembly

quench protection, power converters for orbit correctors and instrumentation (beam, vacuum + cryogenics)



- ❑ 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/cm³).
- ❑ 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, $\beta^*=3.5\text{m}$, 3.5 TeV
 2011, $\beta^*=1.0\text{m}$, 3.5 TeV
 2012, $\beta^*=0.6\text{m}$, 4 TeV
 Nom, $\beta^*=0.55\text{m}$, 7 TeV

R. Bruce

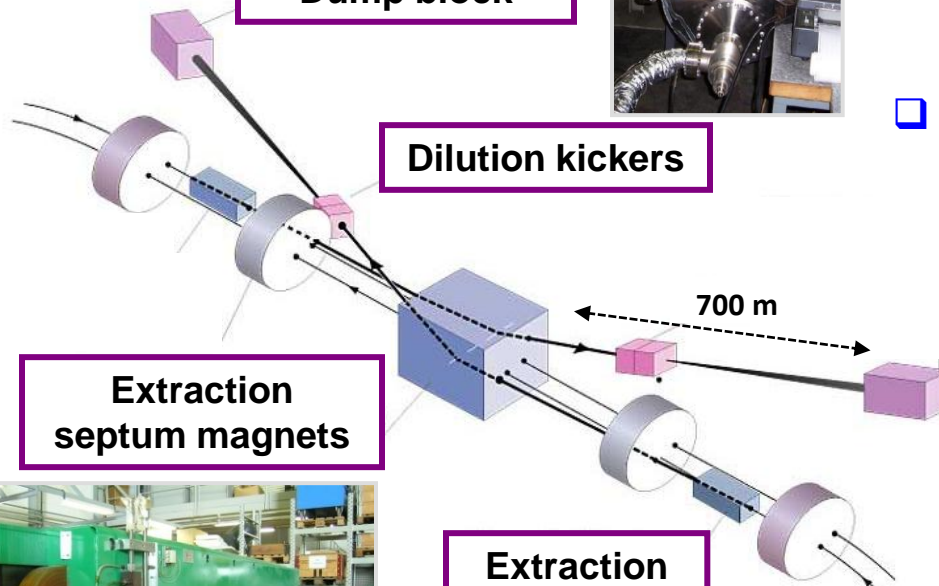
THE BEAM DUMPING SYSTEM



Dump block



Dilution kickers



Extraction septum magnets



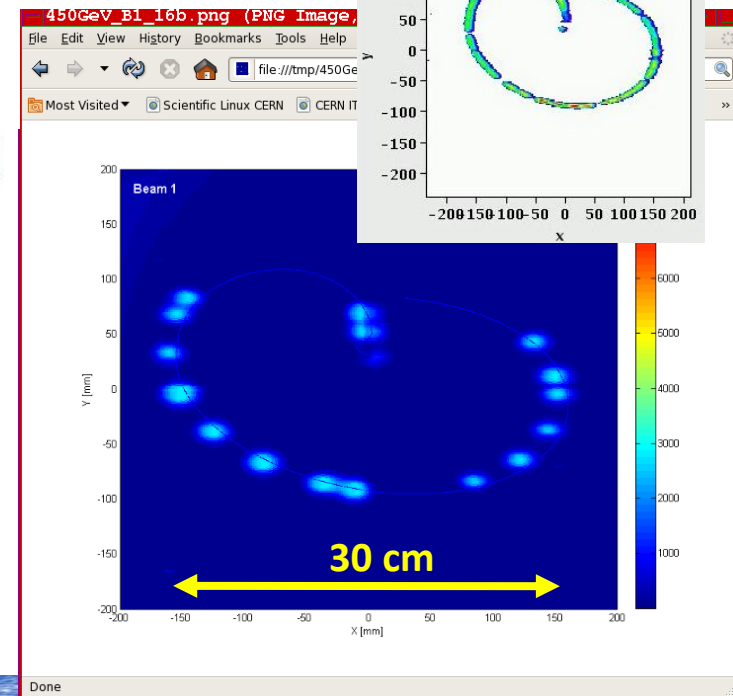
Extraction kickers



- The dump is the only LHC element capable of absorbing the nominal beam.

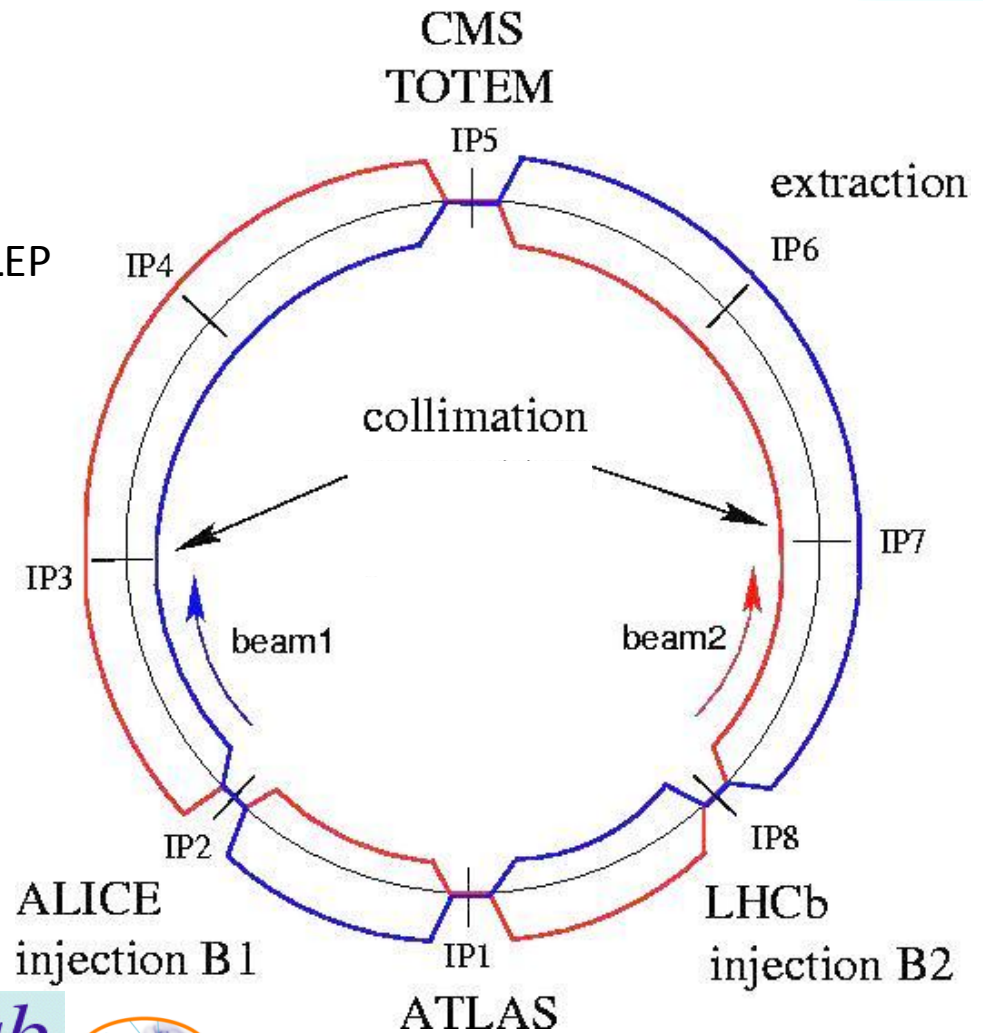
Beam swept over dump surface (power load).

- Ultra-high reliability and fail-safe system.

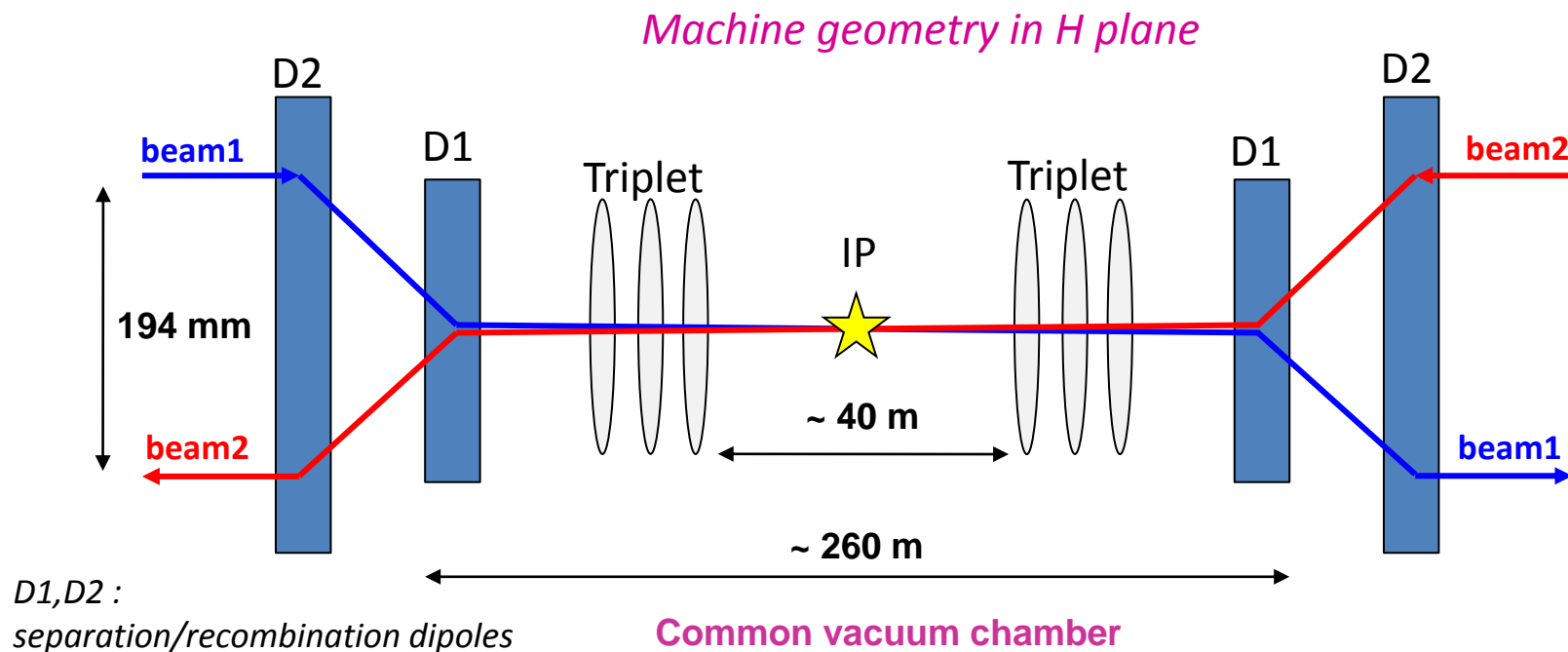




- Total length 26.57 km, in the former LEP tunnel.
- 8 arcs (sectors), ~3 km each.
- 8 long straight sections (700 m each).
- beams cross in 4 points.
- 2-in-1 magnet design with separate vacuum chambers → p - p collisions.



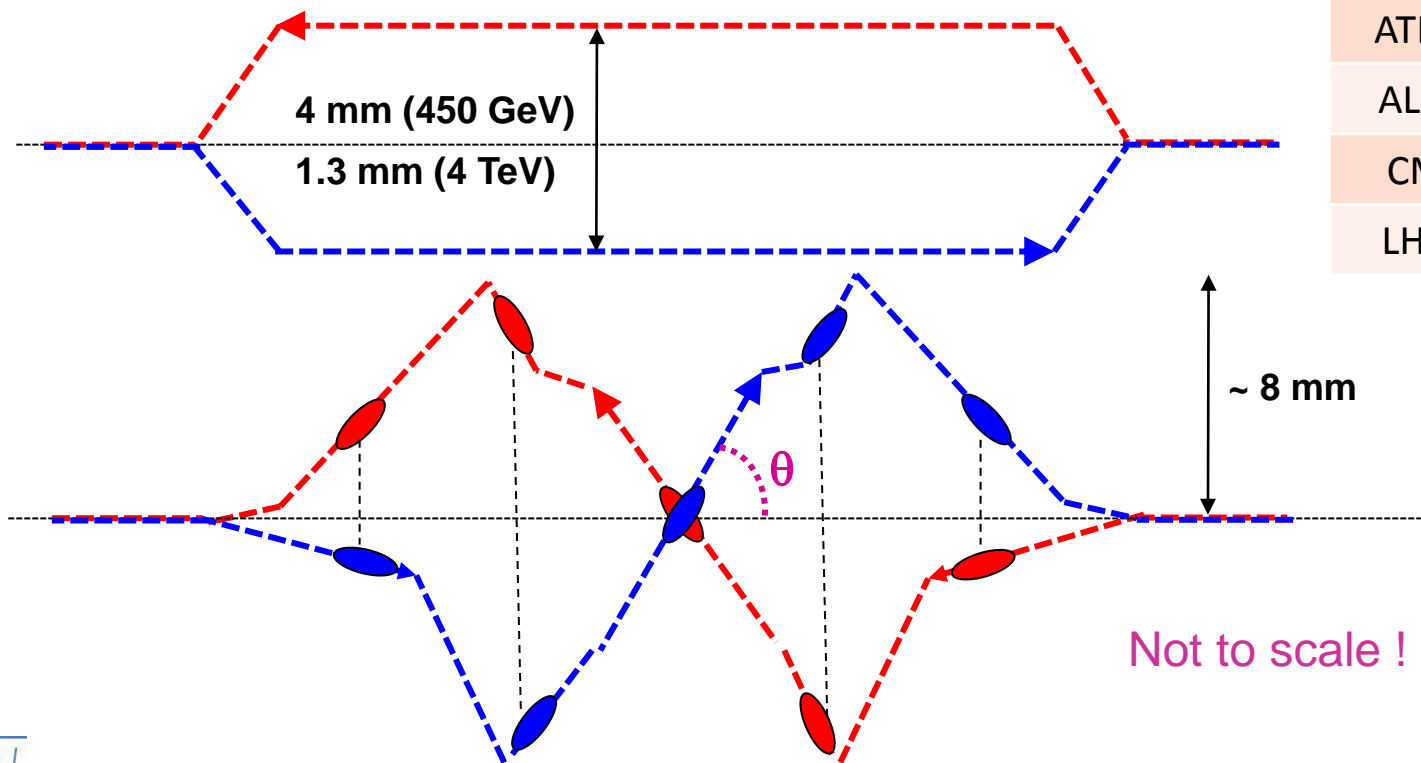
- In the IRs, the beams are first combined into a single common vacuum chamber and then re-separated in the horizontal plane
- The beams move from inner to outer bore (or vice-versa),
- The triplet quadrupoles are used to focus the beam at the IP.





□ 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 (μ rad)
ATLAS	-145 / ver.
ALICE	145 / ver.
CMS	145 / hor.
LHCb	90 / ver.

(4 TeV / 2012)

- ☐ Setting the scene
- ☐ Motivation for an upgrade
- ☐ Machine performance
- ☐ Upgrades

TWO MAIN DRIVERS



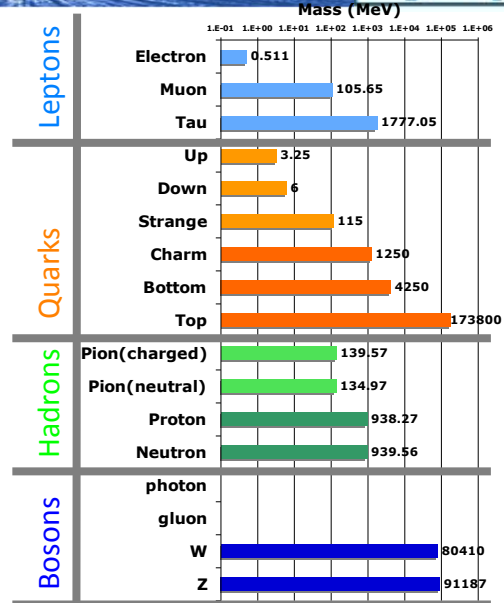
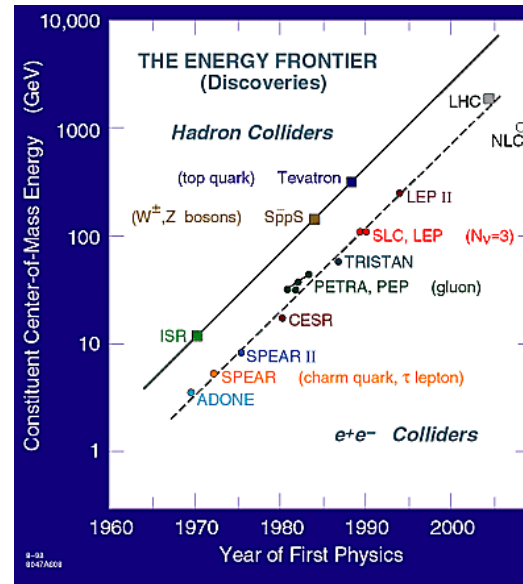
More energy

$$p \propto B\rho$$

- Larger circumference
- Larger bending fields
(~27 km/ 8.3 T --> p=7 TeV)

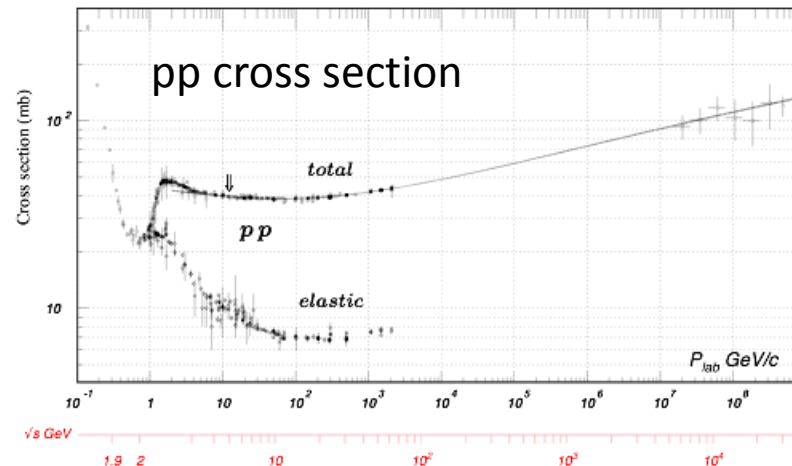
→ Needs new technology!!

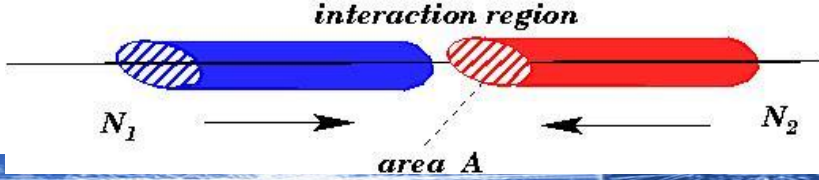
(HE-LHC)



More luminosity

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





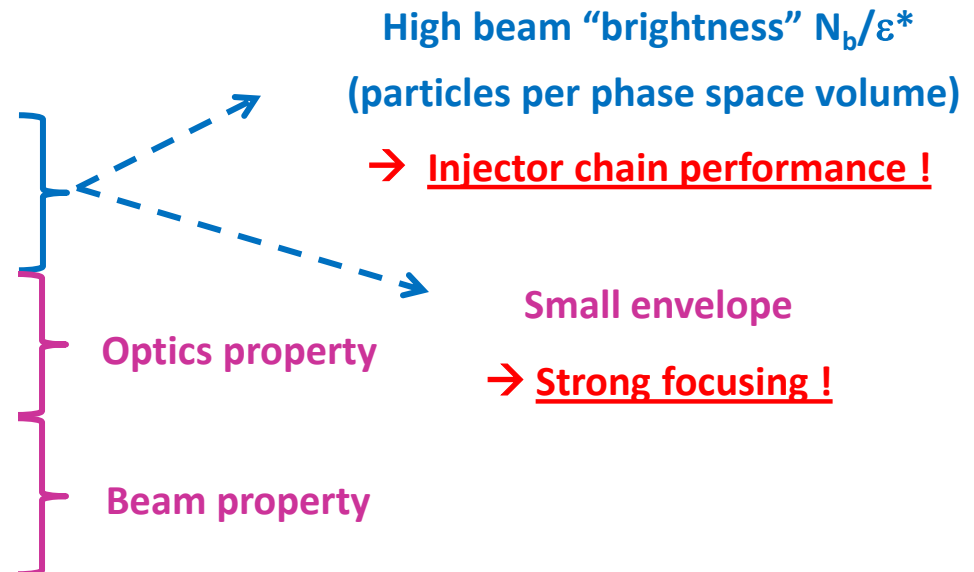
$$L = \frac{k N_b^2 f}{4\pi \sigma_x^* \sigma_y^*} F = \frac{k N_b^2 f \gamma}{4\pi \beta^* \varepsilon^*} F$$

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

- $\gamma = E/E_0$,
- 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^***

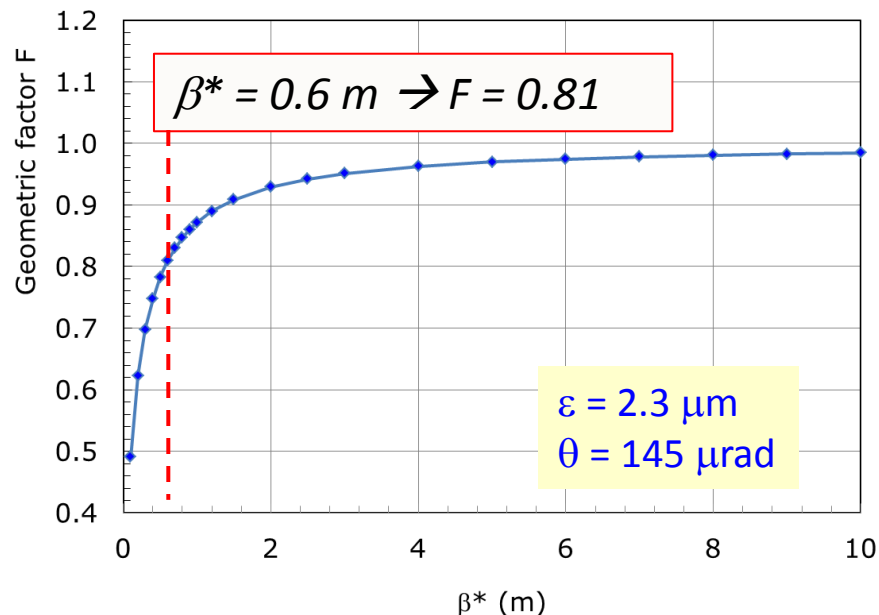
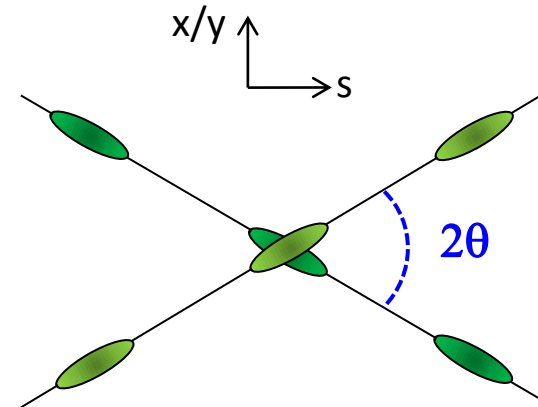


LUMINOSITY GEOMETRIC REDUCTION FACTOR AND CROSSING ANGLE



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

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



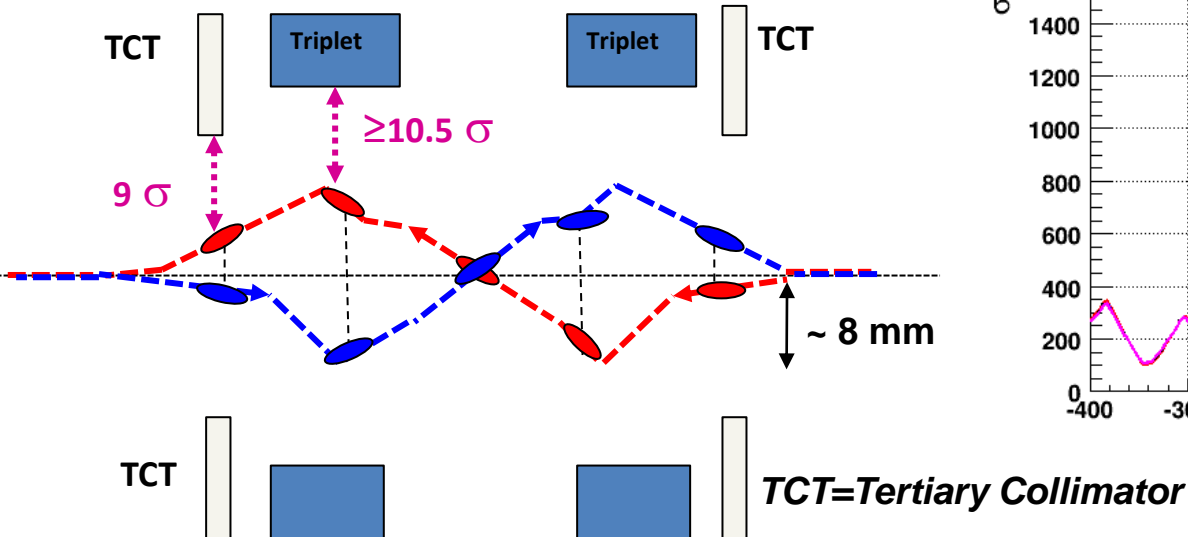
- Will get even stronger at 6.5-7 TeV.
- Could fix with 'Crab cavities' (see **HL-LHC** later).
 - Reduction of the aperture
 - Long range beam-beam interactions
 - and others (e.g. synchro-betatron resonances,...)

- In the high luminosity IRs, the triplet quadrupoles define the machine aperture limit for squeezed beams, β^* is constrained by:

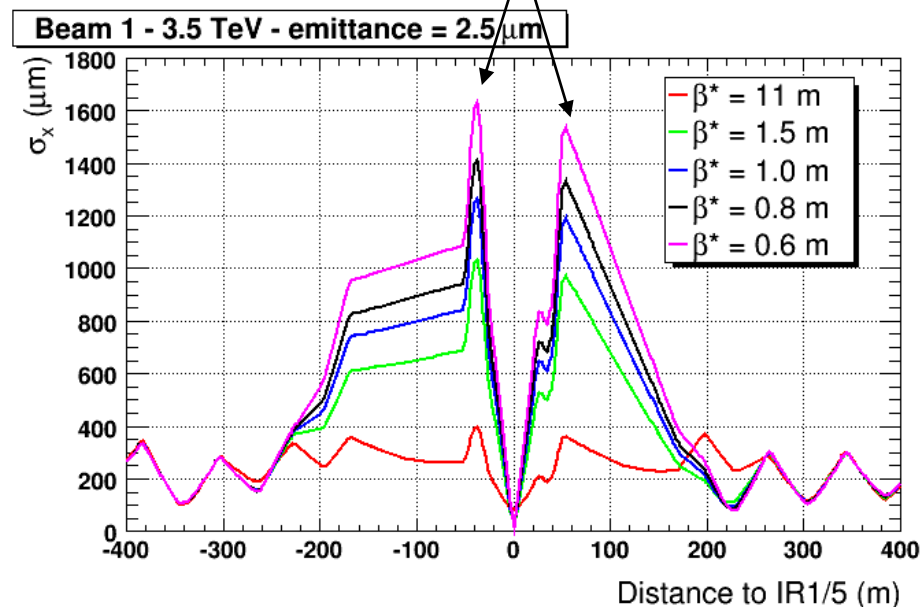
- the beam envelope,
- the margin between TCT and triplet,
- the crossing angle

- → need larger aperture ITs

(HL-LHC)

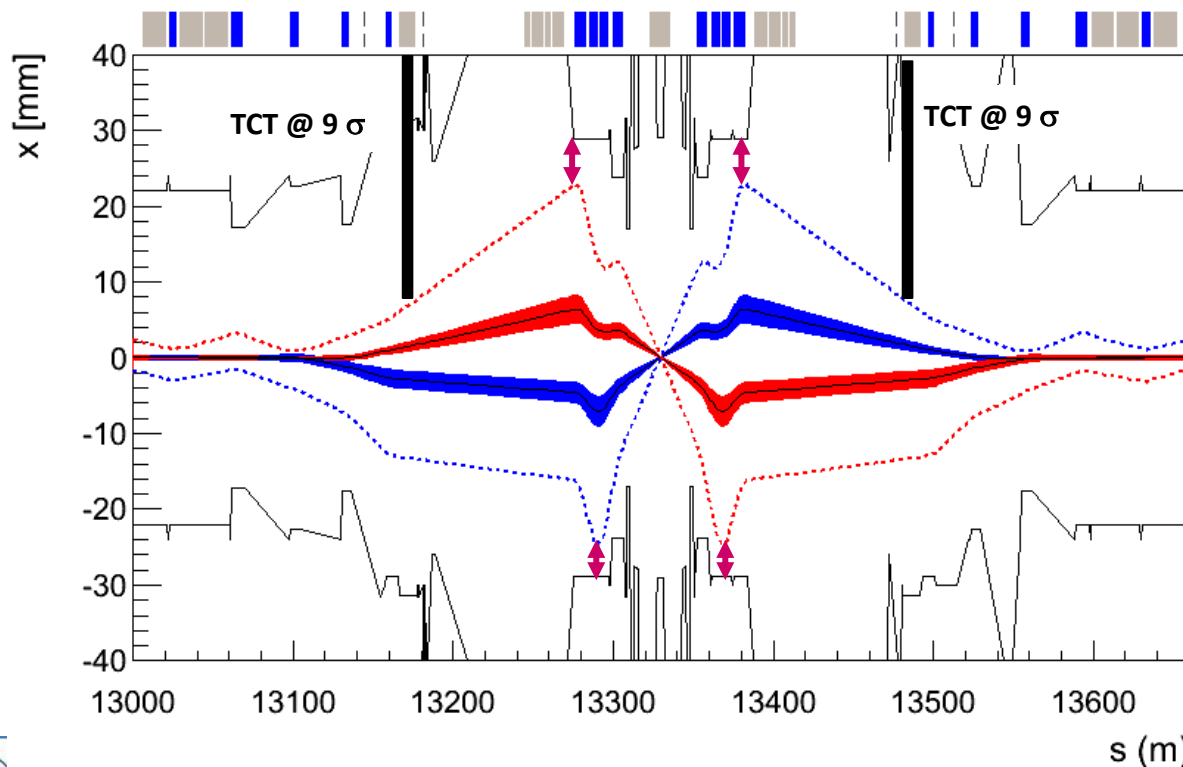


$$\sigma_{\text{triplet}} \propto \sqrt{\frac{\varepsilon}{\beta^* \gamma}}$$



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

IR5 H plane



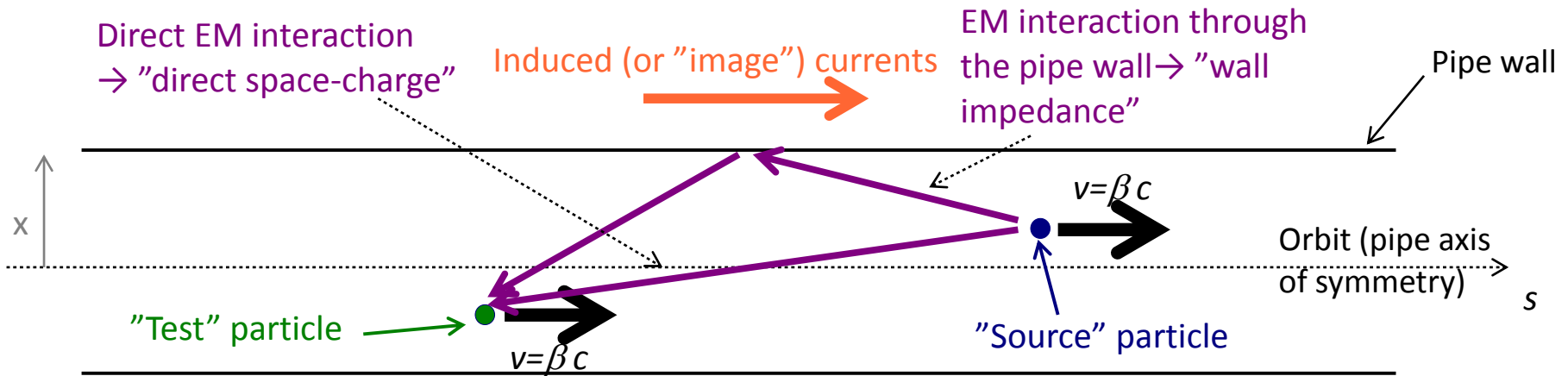
- 1σ beam envelopes
- 9σ extreme beam envelopes
- ↕ 1.5σ margin to triplet

**emittance = $3.5 \mu\text{m}$,
 $\beta^* = 0.6\text{m}$**

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**
 - results in an EM force, called **wake field** in time domain, **beam-coupling impedance** in frequency domain.

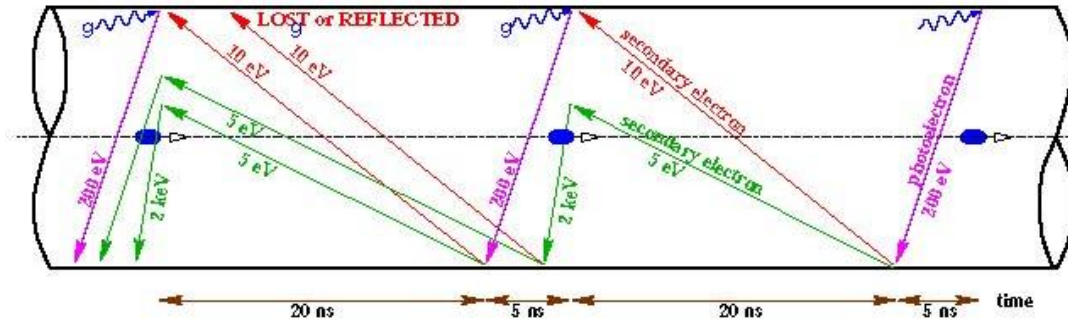


- In 2012 instabilities have become more critical due to higher bunch intensity and tighter collimators settings.
- Cures:
 - Transverse feedback ('damper') that measures the oscillations and sends corrective deflections,
 - Non-linear magnetic fields (sextupoles, octupoles, beam-beam) that produce a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

WHAT LIMITS THE NUMBER AND POPULATION OF THE BUNCHES?



F. Ruggiero



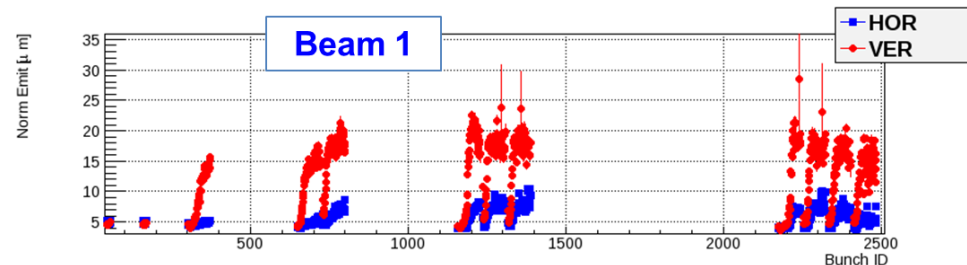
Secondary emission yield [SEY]

$SEY > SEY_{th} \rightarrow$ 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 \rightarrow 75 \rightarrow 50 \rightarrow 25 ns spacing):

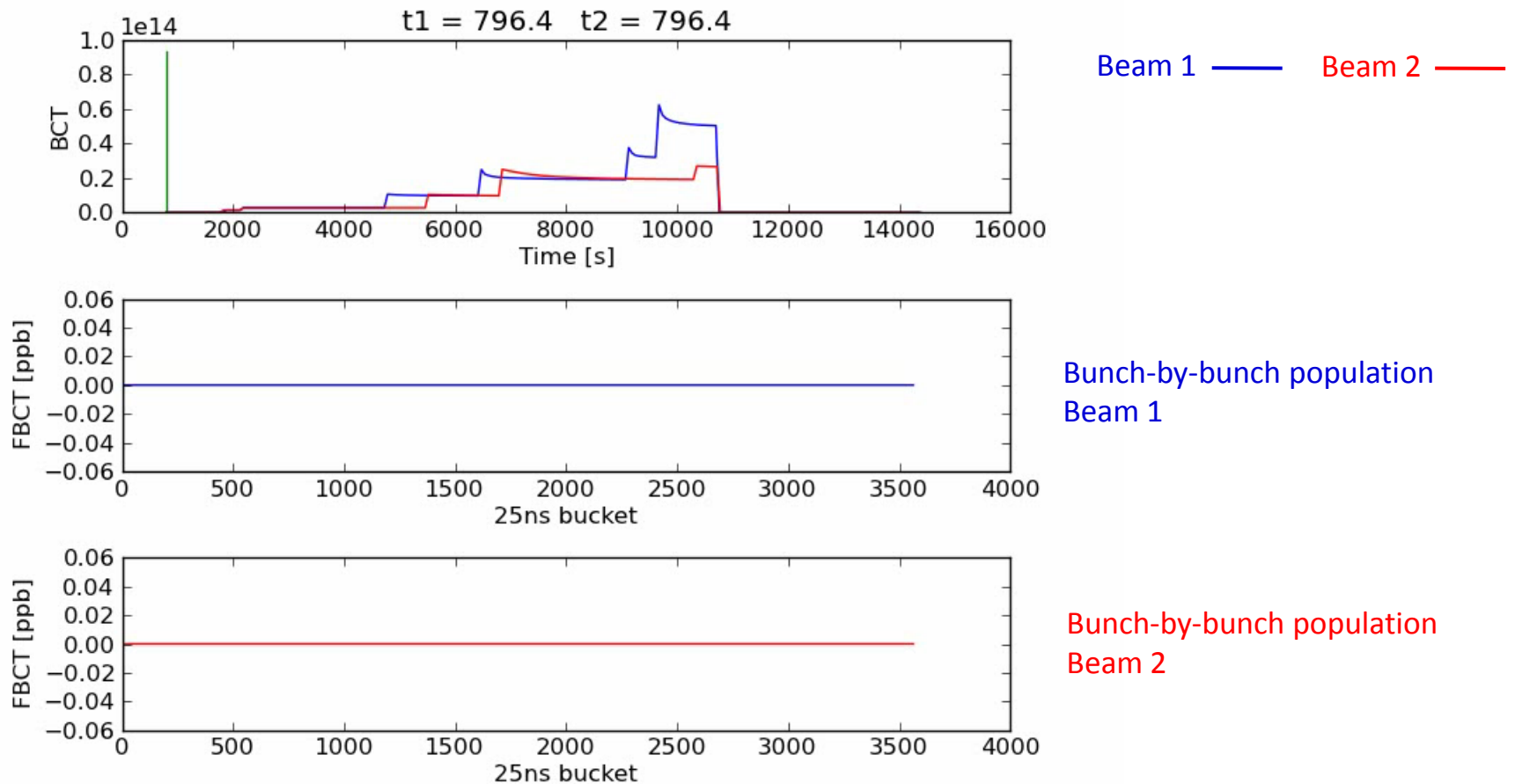
- Vacuum pressure rise (interlock levels, beam losses...)
- Single-bunch and multi-bunch instabilities \rightarrow beam size growth
- Incoherent beam size growth
- Heat load on the cryogenics



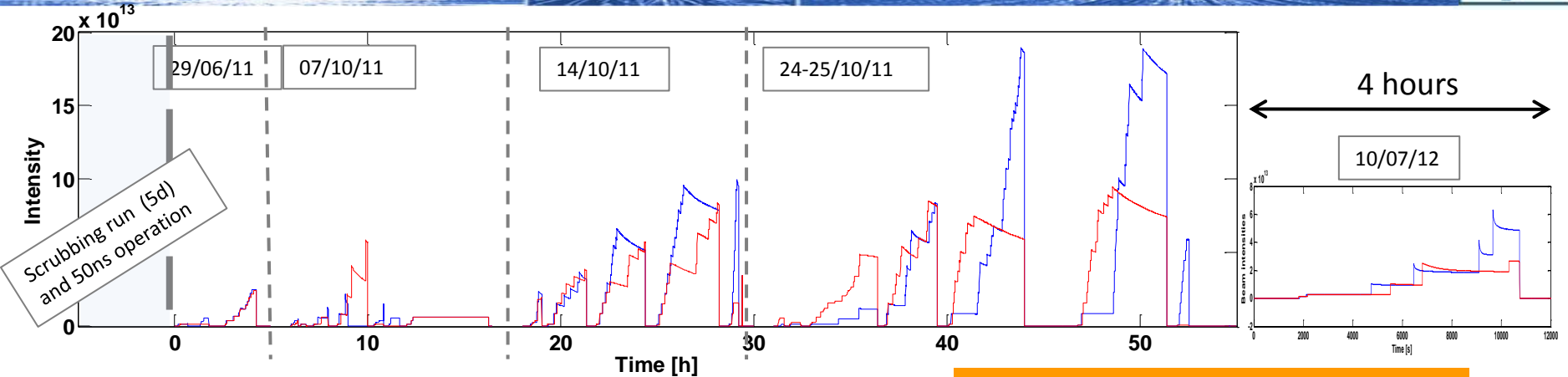
❑ Chosen remedy: **conditioning by beam-induced electron bombardment** ("scrubbing") leading to a progressive reduction of the SEY

2012 injection tests (10 July 2012)

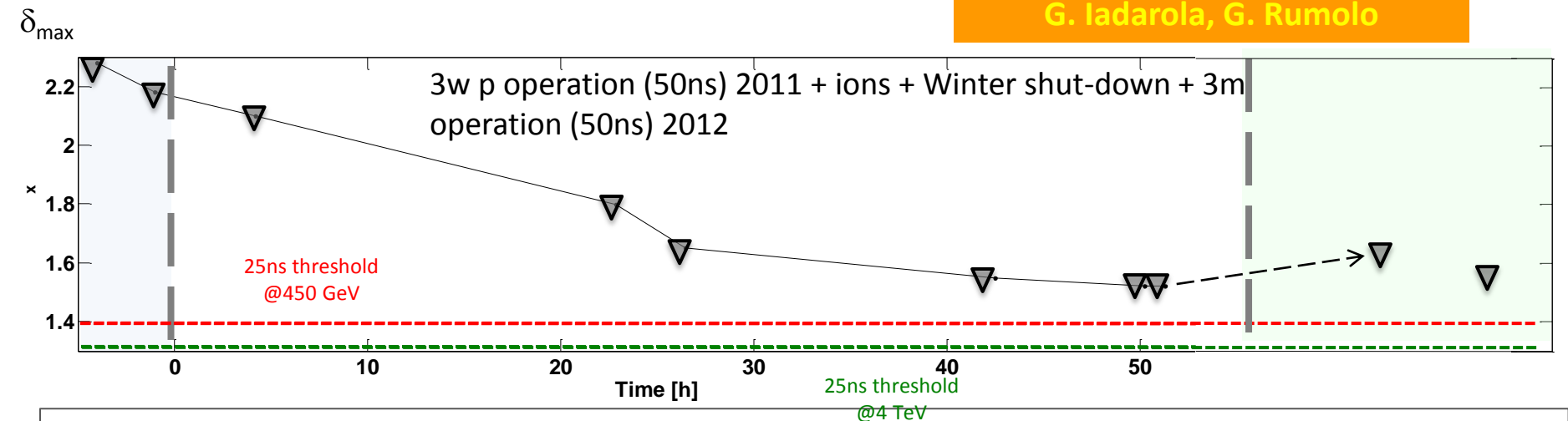
G.Rumolo



SCRUBBING HISTORY OF LHC ARCS

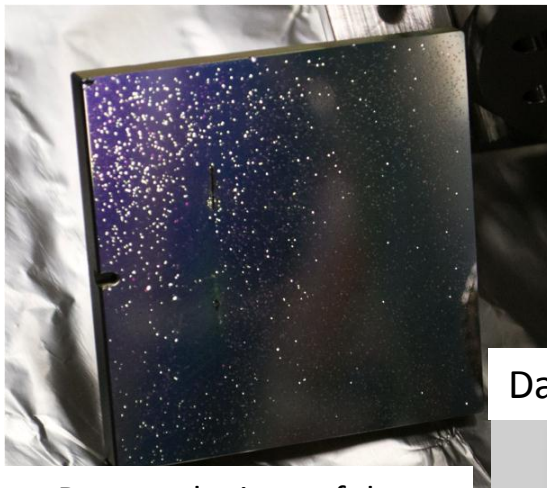


G. Iadarola, G. Rumolo



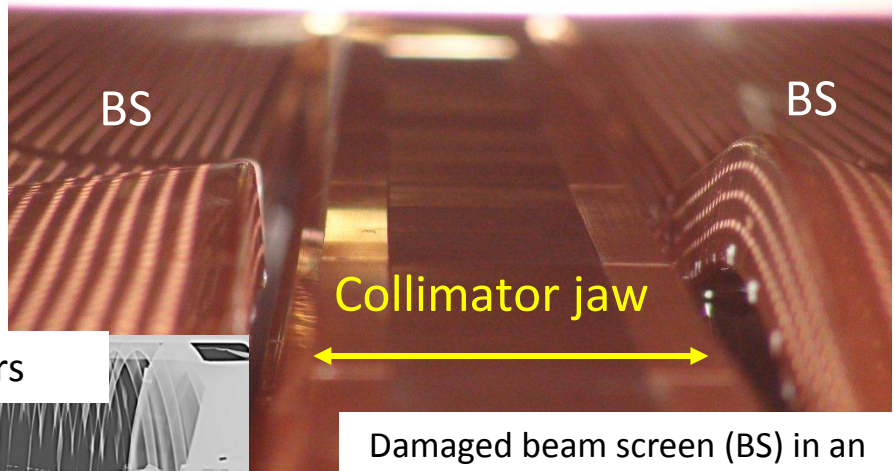
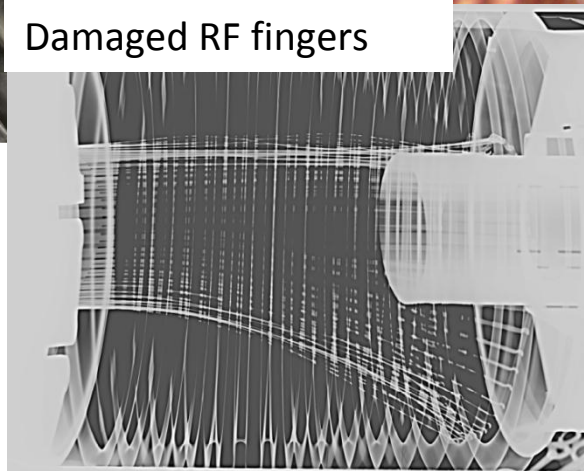
- δ_{\max} decreased from the initial **2.1 to 1.52** in the arcs after approximately 50h machine time with 25ns beams in 2011. **Expect ~2 weeks of scrubbing at 450 GeV for operation at 25 ns.**
- Slightly higher (**1.65**) in 2012, but rapidly decreased to **1.55** after 4h beam time

- 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 RF fingers



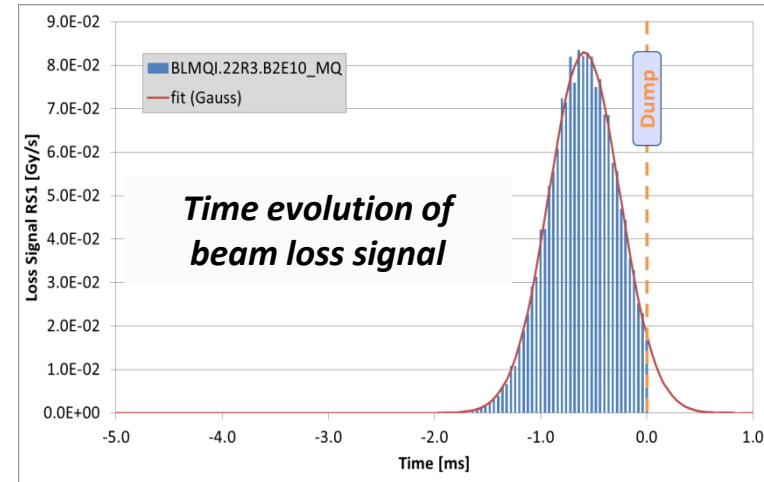
Damaged beam screen (BS) in an injection protection device

UFOs = UNIDENTIFIED FALLING OBJECTS



- Small (10's μm) dust particles falling into the beam, generating very fast beam losses. If the losses are too high, the beams are dumped to avoid a magnet quench

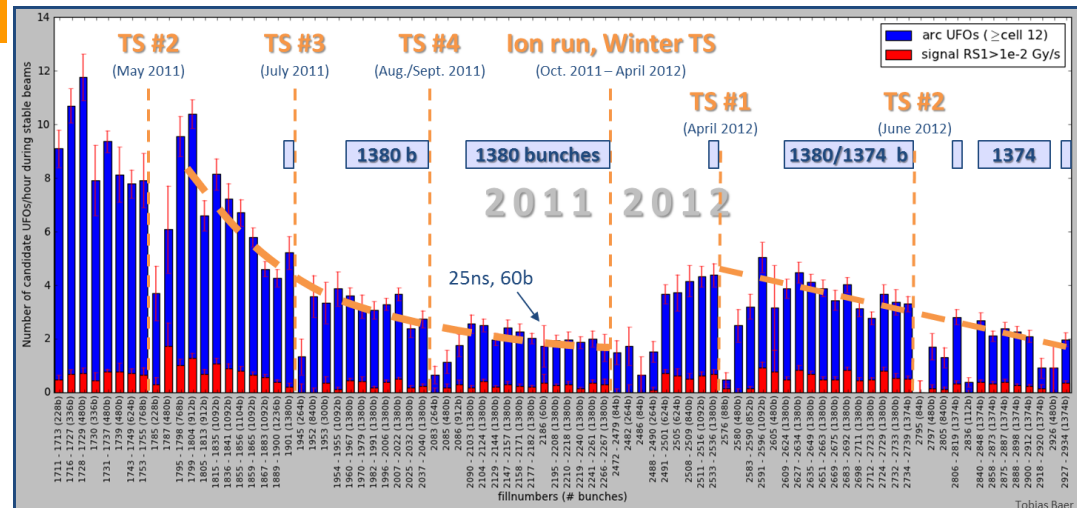
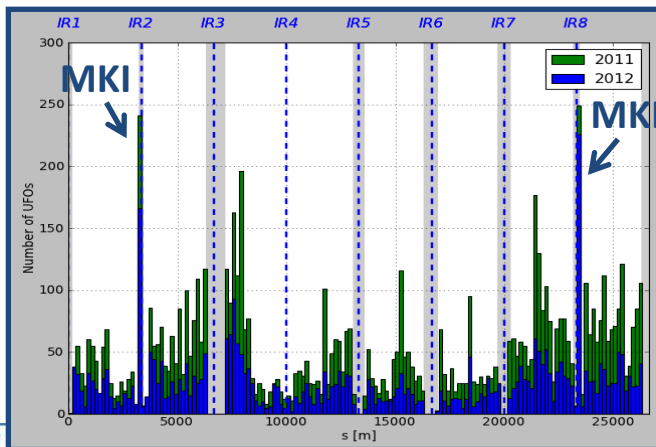
- 2010: 18 beam dumps,
- 2011: 17 beam dumps,
- 2012: 15 beam dumps so far



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.

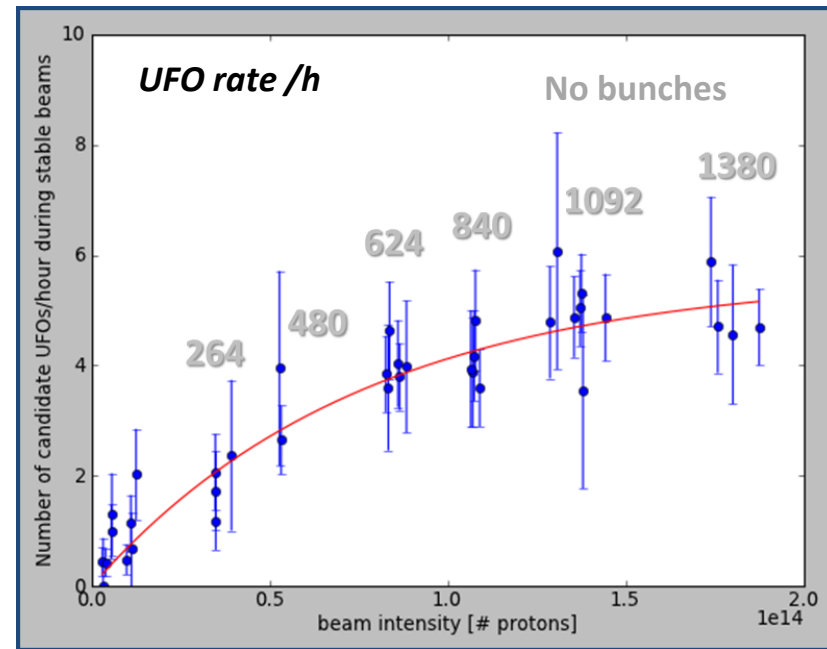
T. Baer



- ❑ The rate of events increases with beam intensity.
- ❑ A large increase was observed with 25 ns beams – to be confirmed this year.

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),



T. Baer

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

- 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



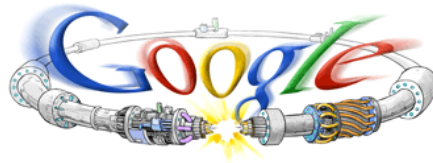
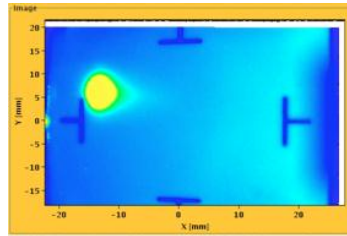
- ☐ Setting the scene
- ☐ Motivation for an upgrade
- ☐ Machine performance
- ☐ Upgrades

THE LHC TIMELINE



August 2008

First Injection tests



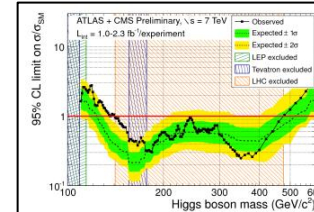
September, 10 2008

Both beams circulating



November 29, 2009

Beams back



December, 2011

3.6e33, 5.6 fb⁻¹

June, 28 2011

1380 bunches

1380

Energy: 4 TeV

March, 2012

4 TeV

2008

2009

2010

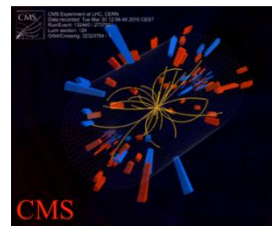
2011

2012

September, 19 2008

Incident

Accidental release of 600 MJ stored in one sector of LHC dipole magnets

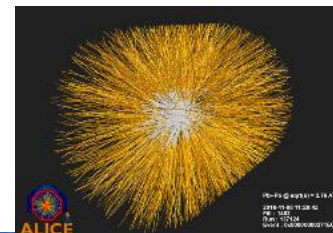


March 30, 2010

First collisions at 2-3.5 TeV

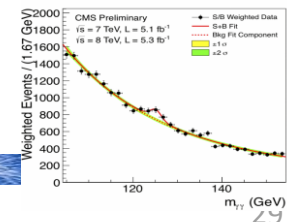
November 2010

Ion run



July 4, 2012

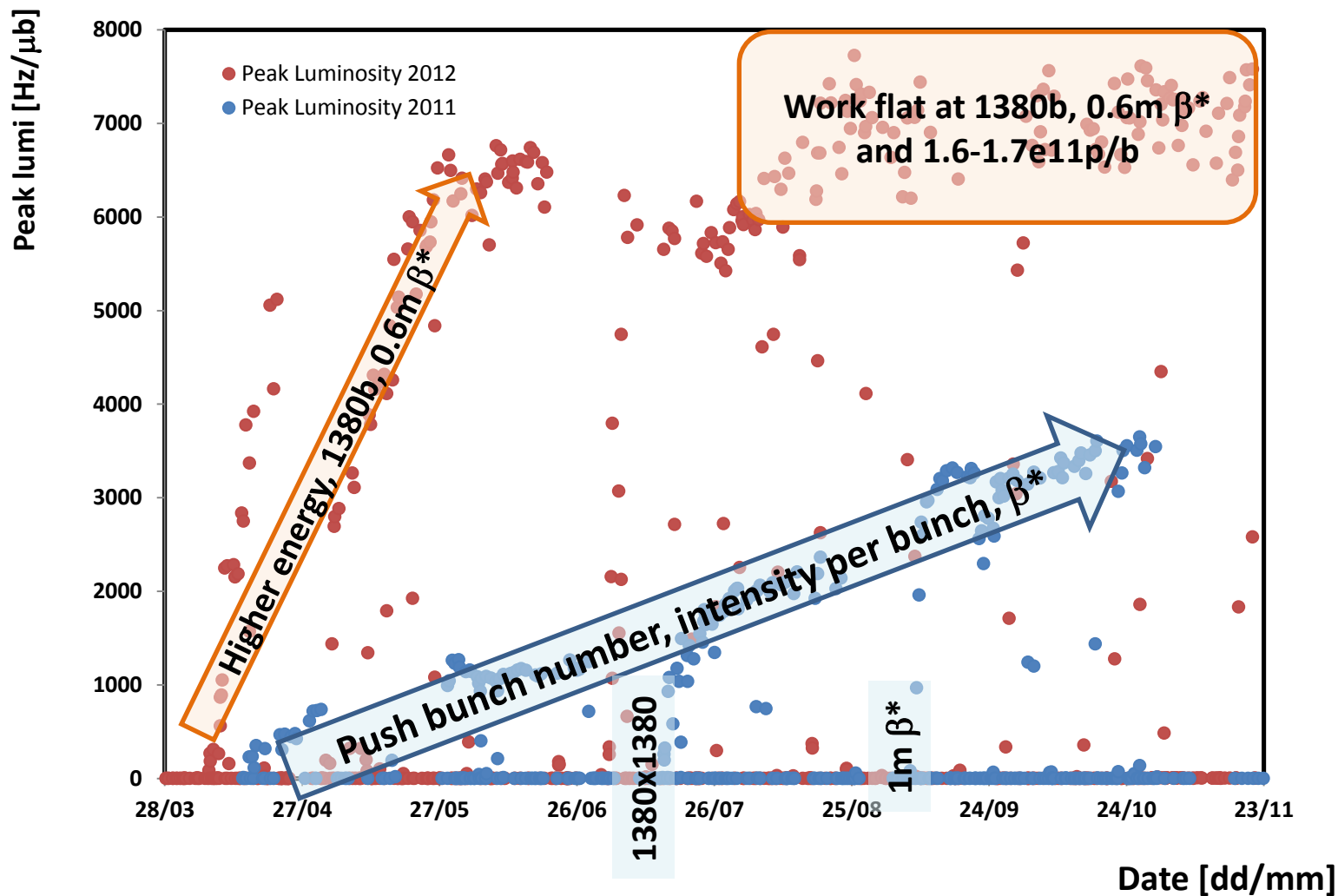
Higgs boson search update



22/11/2012

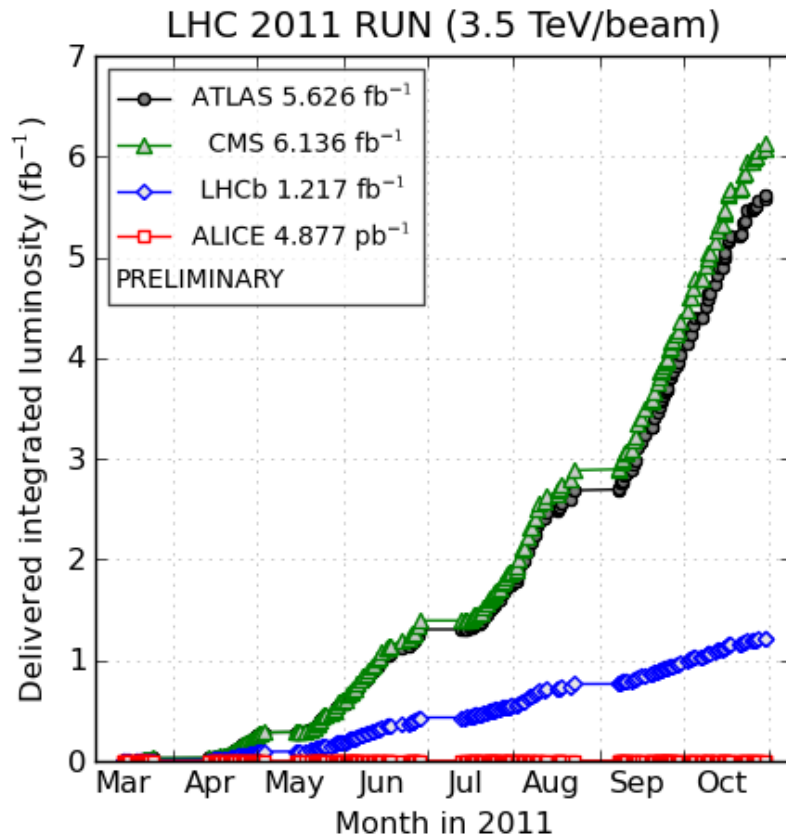
Mirko Pojer – LHC on the March - 20-22 November 2012 IHEP, Protvino



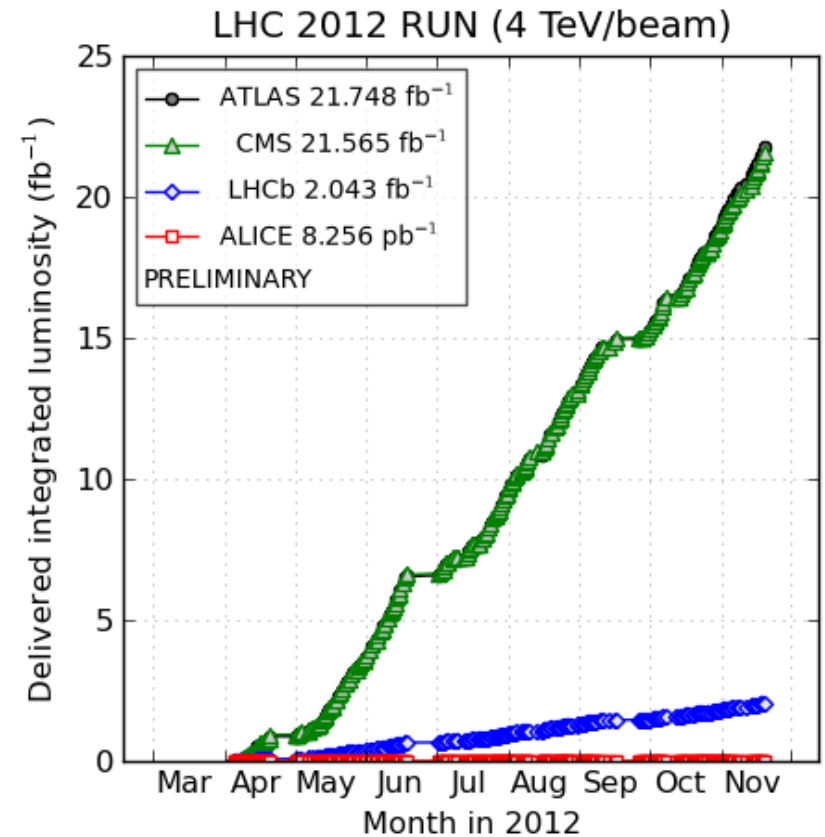


2011: target was 1 fb⁻¹; ~6 obtained

2012: target was 15-20 fb⁻¹; ~22 obtained so far



(generated 2012-06-21 00:39 including fill 2267)



(generated 2012-11-20 01:27 including fill 3300)

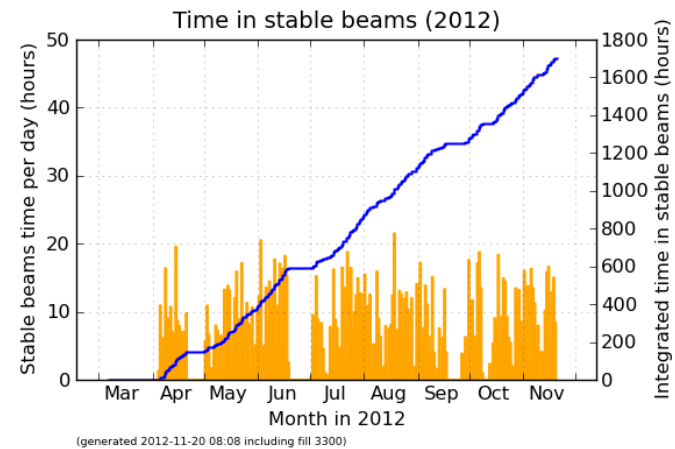
2012 – so far

LHC Run Efficiency

Mode: Proton Physics
Fills: 2469 – 3304 [700 Fills]
SB Time: 68 days 22 hrs 32 mins



Access - No beam : 13.8% Machine setup : 27.29%
Beam in : 14.78% Ramp + squeeze : 8% Stable beams: 36.12%

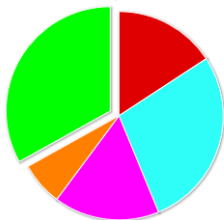


- Average fill length of ~6 hours
- Fill length determined mostly by 'failures'.
- Only ~30% of fills are dumped by operation.

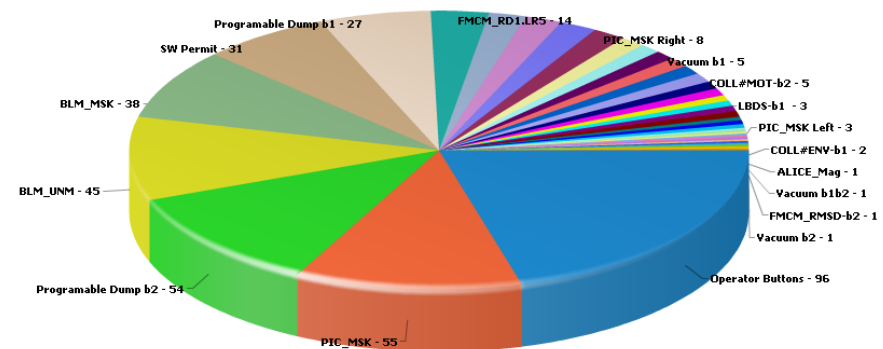
2011

LHC Run Efficiency

Mode: Proton Physics
Fills: 1613 – 2261 [475 Fills]
SB Time: 53 days 1 hrs 10 mins



Access - No beam : 15.78% Machine setup : 28.01%
Beam in : 16.37% Ramp + squeeze : 6.74% Stable beams: 33.09%



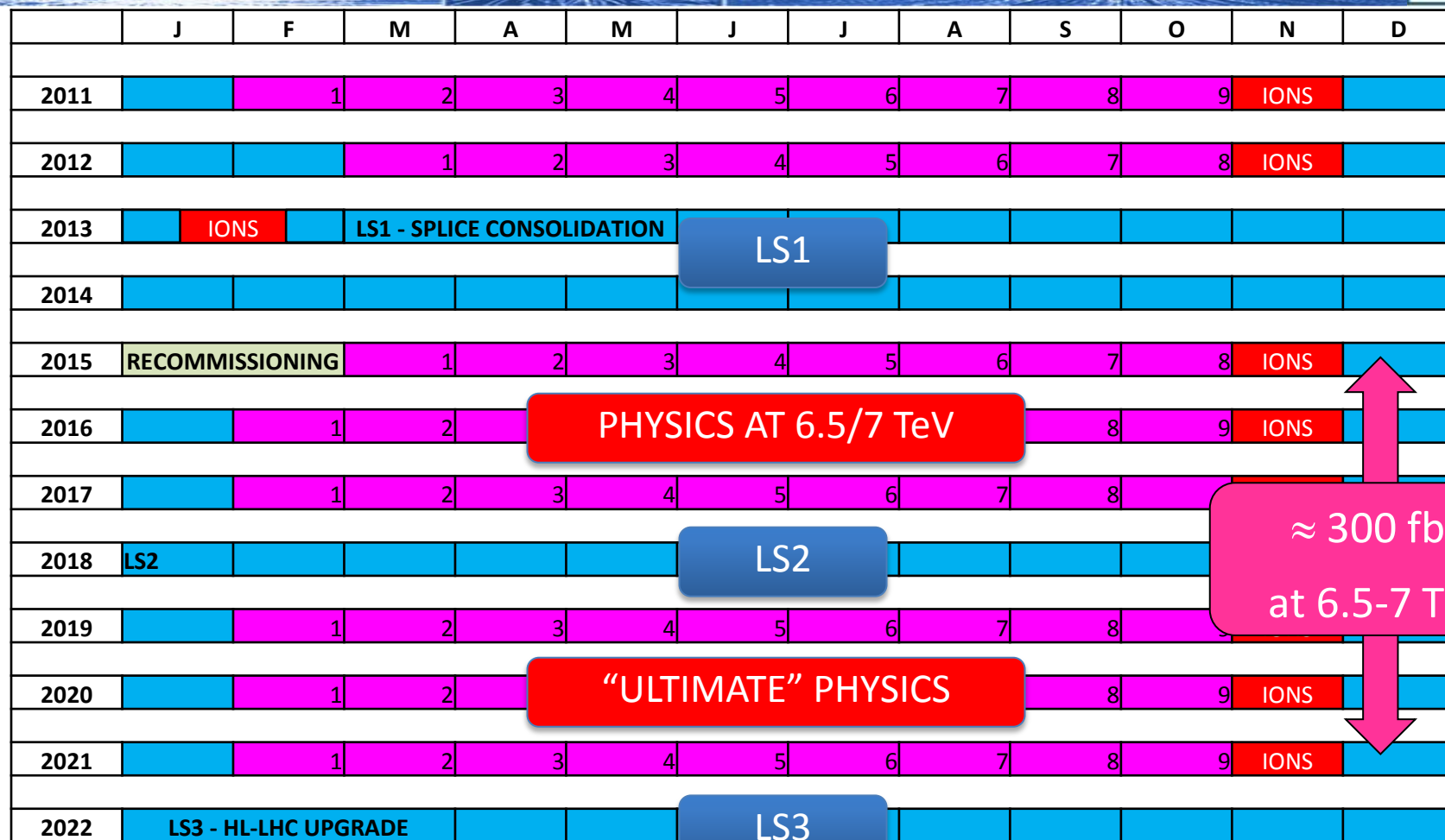
Dumps above injection energy per system



□ Impressive progress in performance. Doomed to level off...

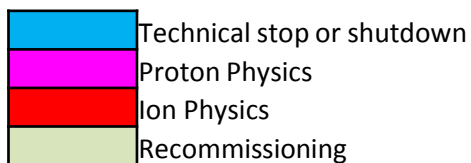
Parameter	2010	2011	2012	Nominal
Energy (TeV)	3.5	3.5	4.0	7.0
N (10^{11} p/bunch)	1.2	1.45	1.6	1.15
k (no. bunches)	368	1380	1380	2808
Bunch spacing	150	75 / 50	50	25
Stored energy (MJ)	25	112	140	362
ε ($\mu\text{m rad}$)	2.4	2.4	2.5	3.75
β^* (m)	3.5	1.5 \rightarrow 1	0.6	0.55
L ($\text{cm}^{-2}\text{s}^{-1}$)	2×10^{32}	3.5×10^{33}	7.6×10^{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

- ☐ Setting the scene
- ☐ Motivation for an upgrade
- ☐ Machine performance
- ☐ Upgrades



$\approx 300 \text{ fb}^{-1}$

 at 6.5-7 TeV



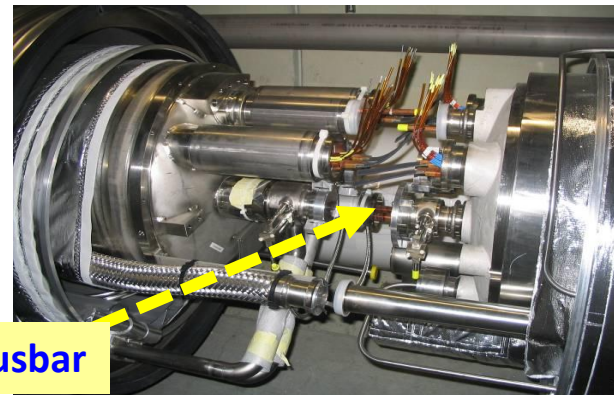
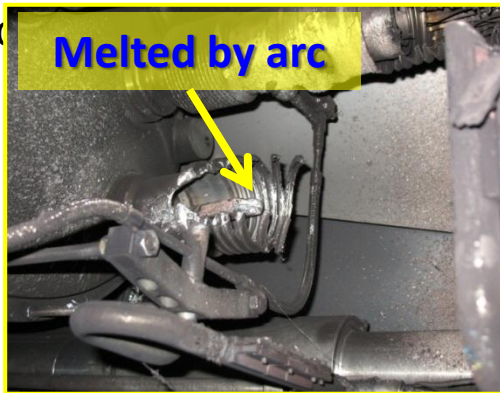
HL-LHC

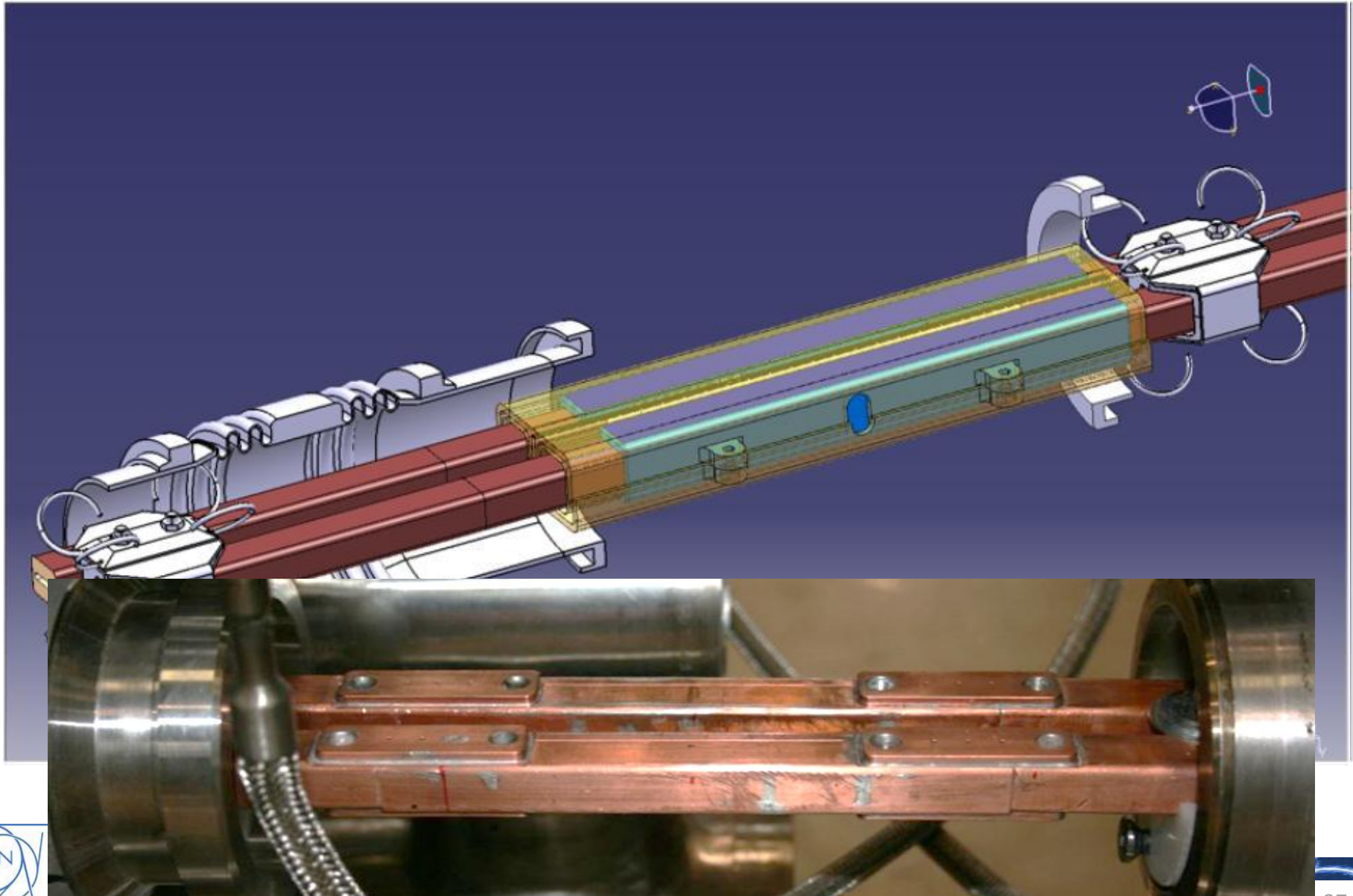


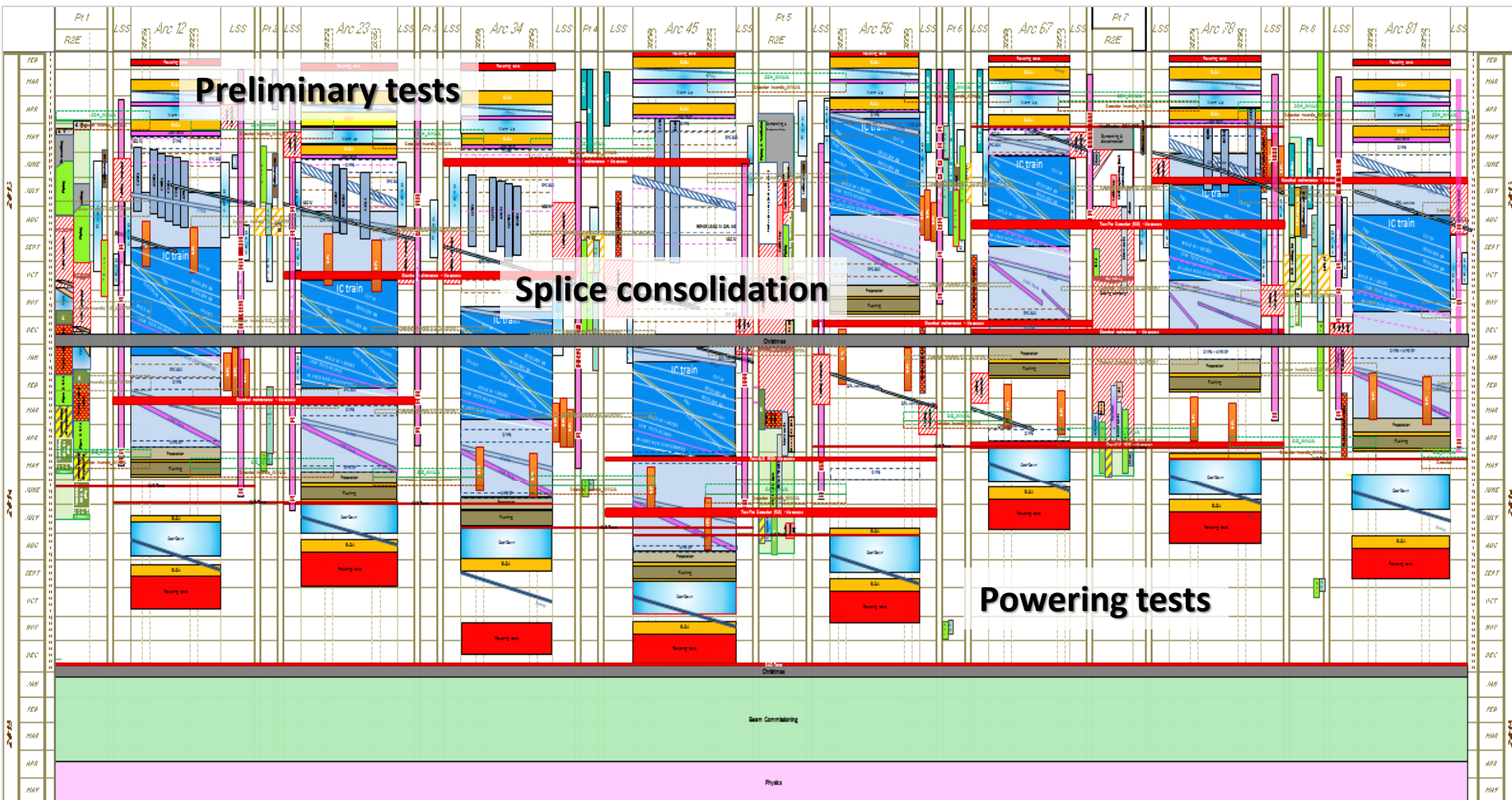
OBJECTIVE OF LS1 FOR LHC: PREPARE THE MACHINE FOR 6.5/7 TeV

- ❑ 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 4 quadrupole magnets
- ❑ Consolidate faulty circuits
- ❑ R2E mitigation actions → relocate electronics in 3 points
- ❑ Install collimators with integrated button BPMs (tertiary collimators and a few secondary collimators)

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



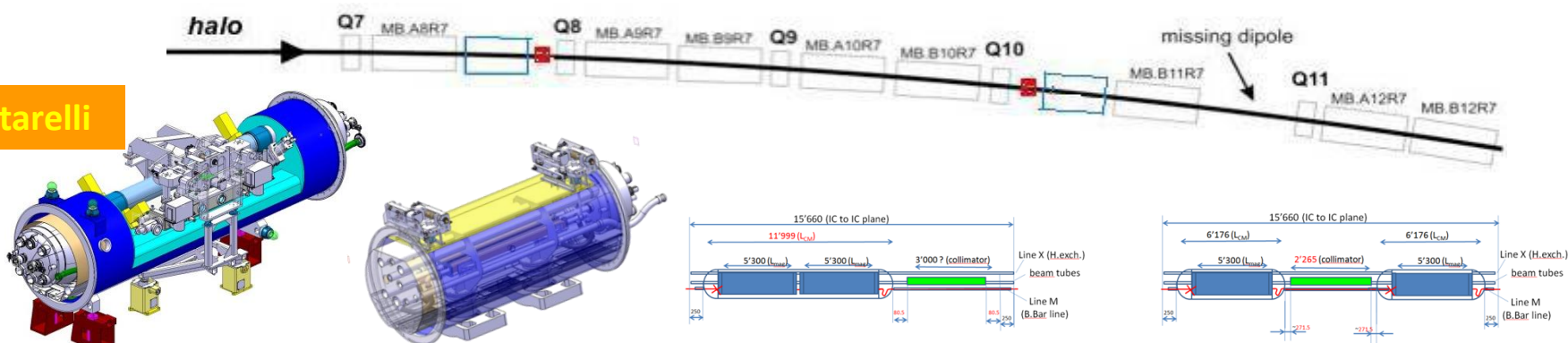




K. Foraz

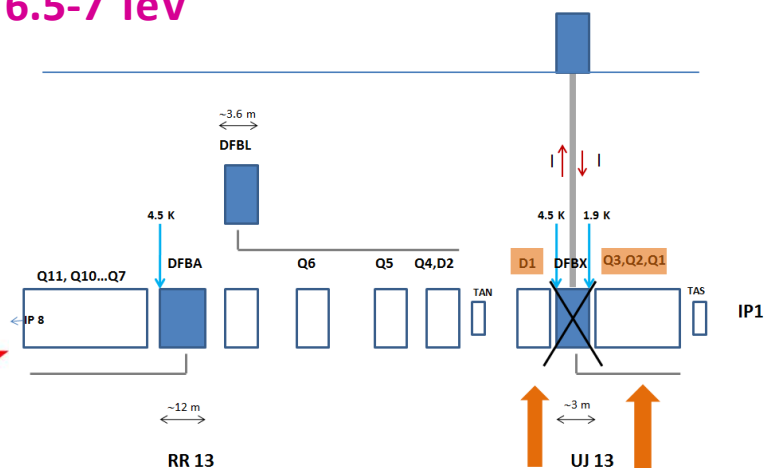
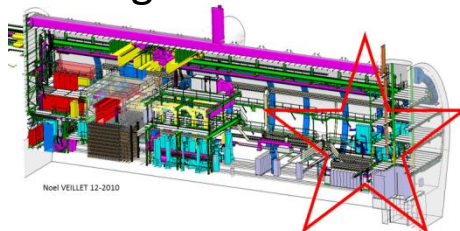
- To avoid off-momentum protons on SC dipoles, DS cryo-collimation with 11 T in 1 IP; priority NOT yet established: IP1, IP5 or IP2 ? **Review in Spring 2013**

A. Bertarelli



Luminosity $\approx 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at 6.5-7 TeV

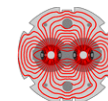
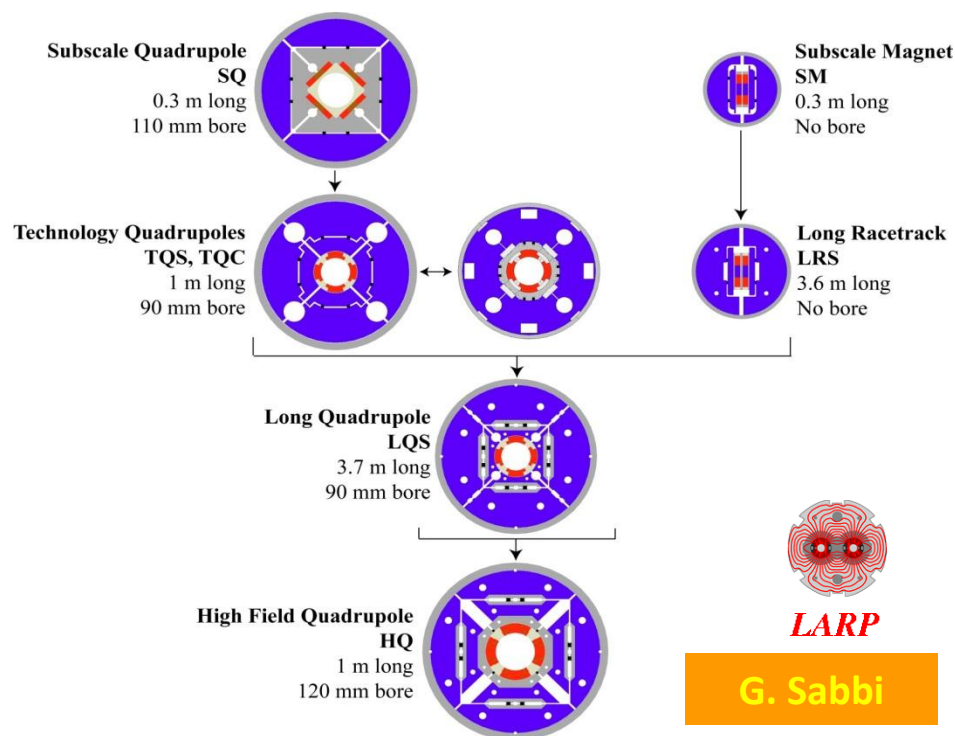
- Vertical SC links in P1, P5 (IT and stand-alone)
- Cryogenics P4 \Rightarrow separation between SC magnets and RF cavities cooling circuit
- Improve triplet cooling
- Some beam diagnostics
- Some collimators
- **Major injectors upgrade** (LINAC4, 2GeV PS Booster, SPS coating, ...)



- ❑ **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



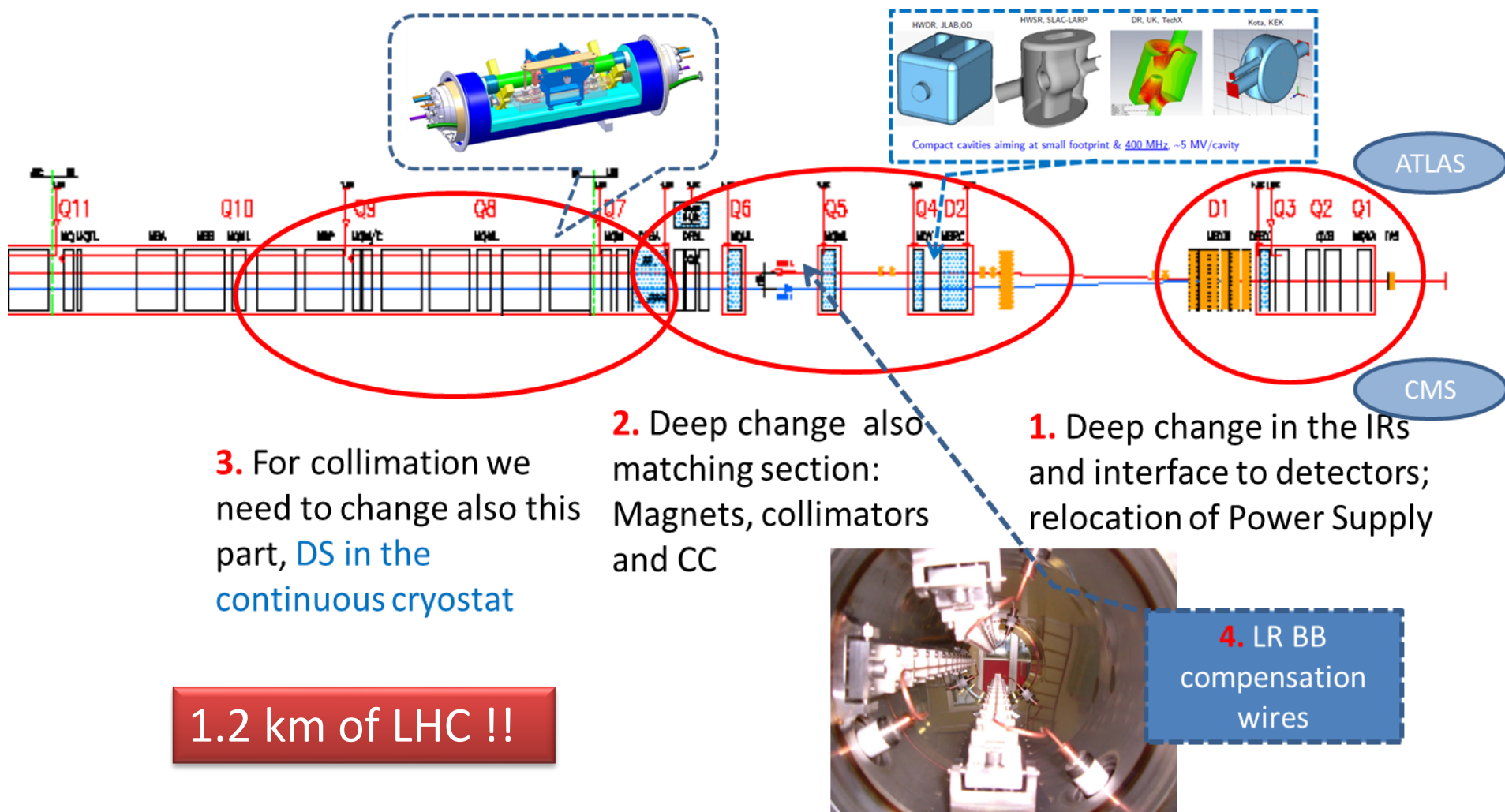
The HiLumi LHC Design Study (a sub-system of HL-LHC) is cofunded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404

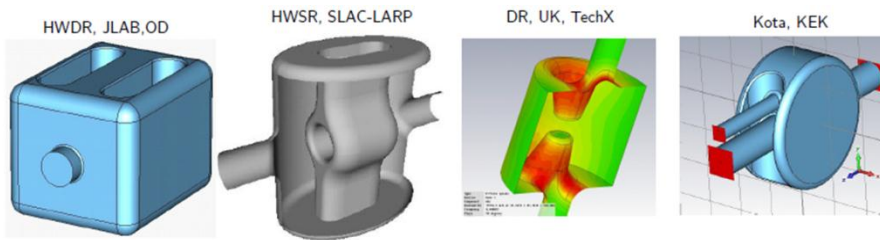


LARP

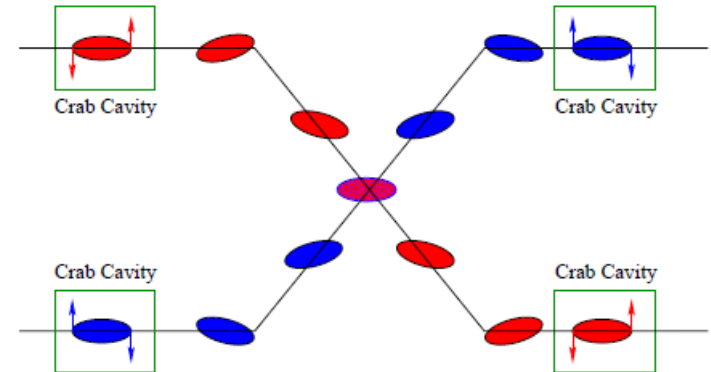
G. Sabbi

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





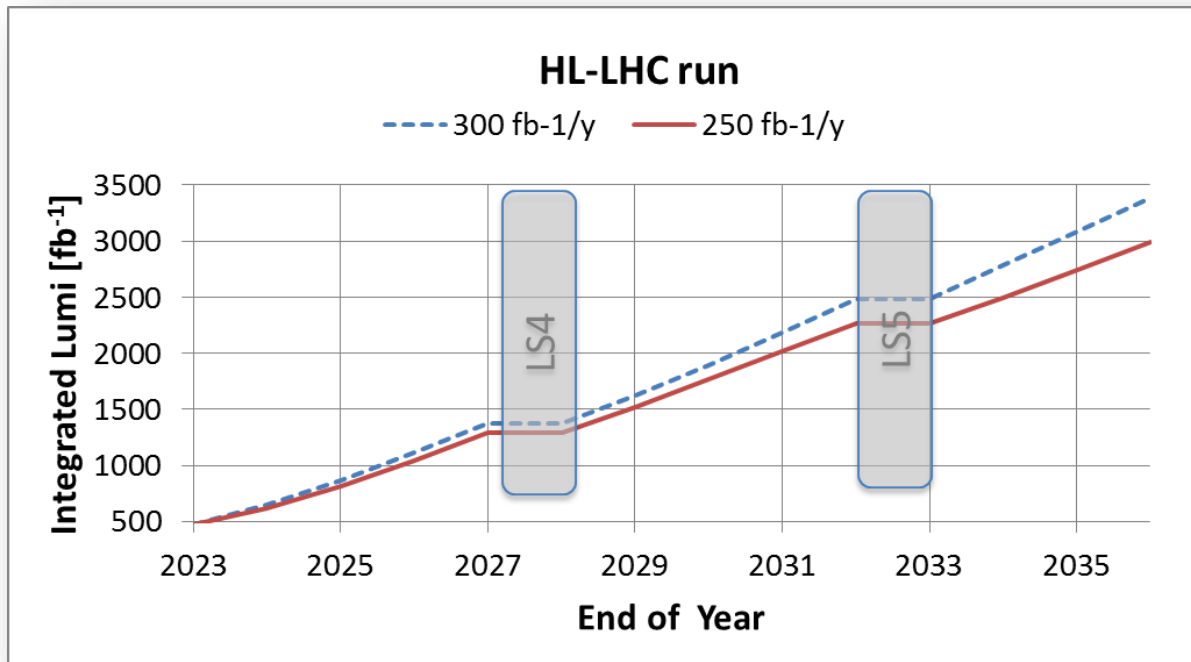
Compact cavities aiming at small footprint & [400 MHz](#), ~5 MV/cavity



- ❑ 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 $5 \cdot 10^{34}$ 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**



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



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
θ_c [μ rad]	300	475	445	480	430
β^* [m]	0.55	0.15	0.15	0.15	0.15
ϵ_n [μ m]	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
$L_{\text{peak virtual}}$	1	20	22.7	14.3	19.5
Pileup $L_{\text{lev}}=5L_0$	19	95	190	95	190
Eff. [†] 150 days	=	0.62	0.61	0.66	0.67

baseline



- ❑ The progress in the performance of the LHC has been so far breath-taking
- ❑ The LHC is performing incredibly well (even better than expected) and 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



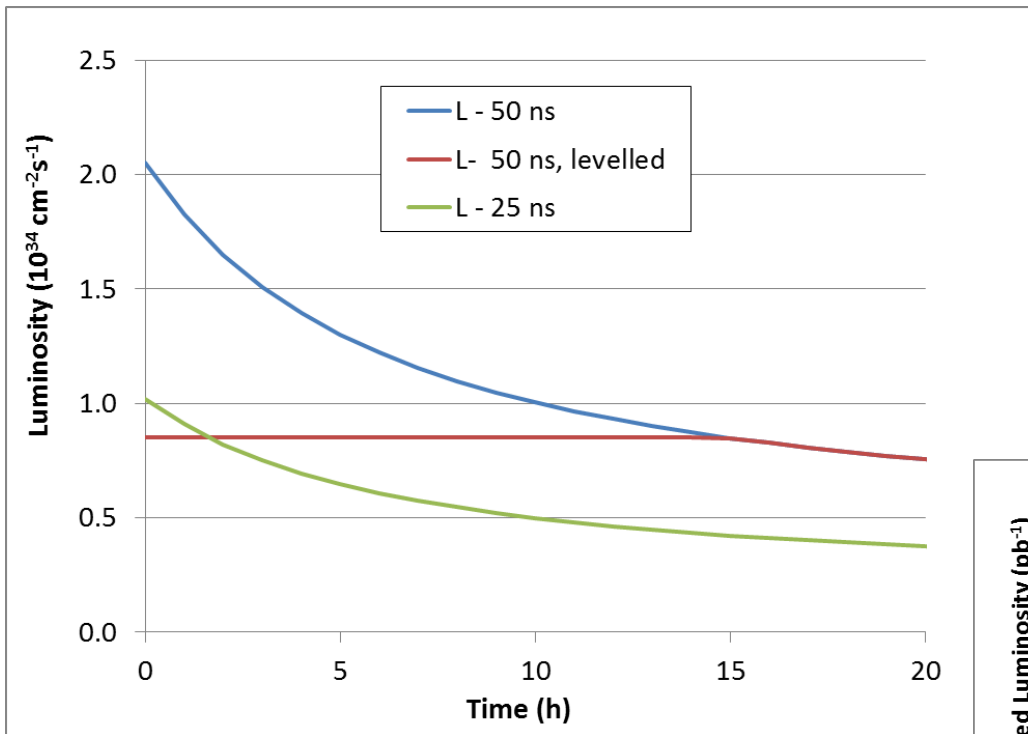
3 out of many possible scenarios...

	k	N_b [10^{11} p]	ε [μm]	β^* [m]	L [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	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

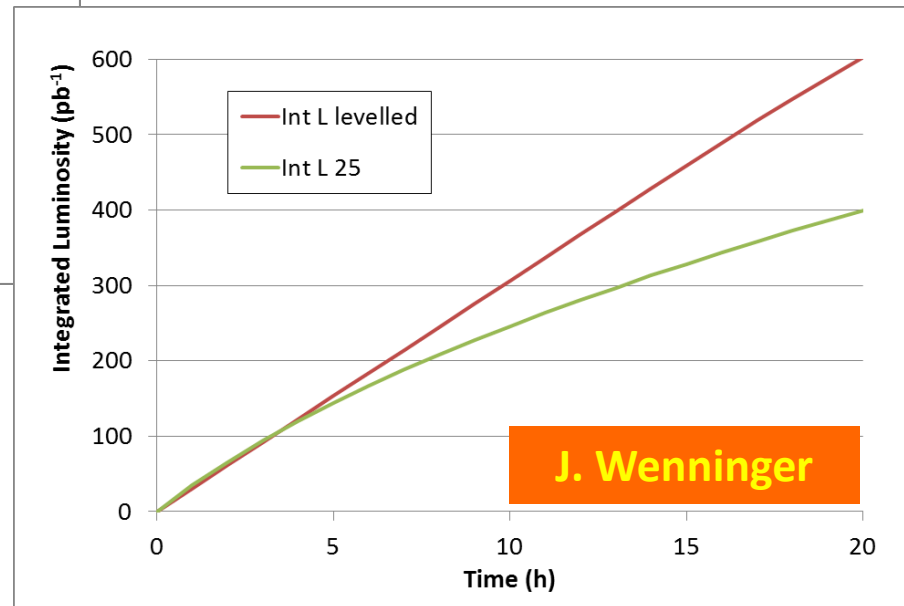
Main challenge emittance preservation!!!

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



Standard 25 ns and 50 ns with levelling

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

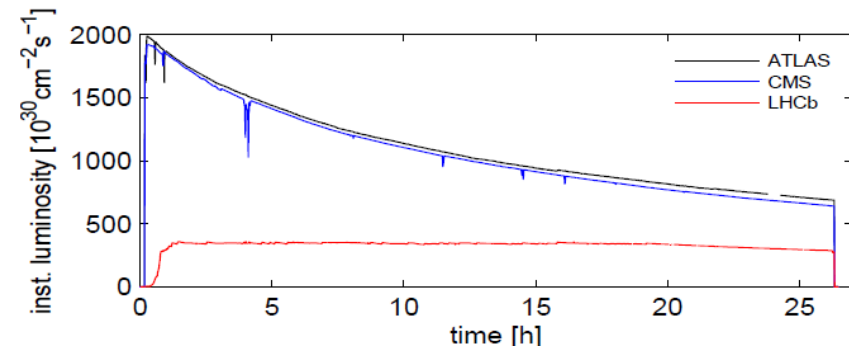
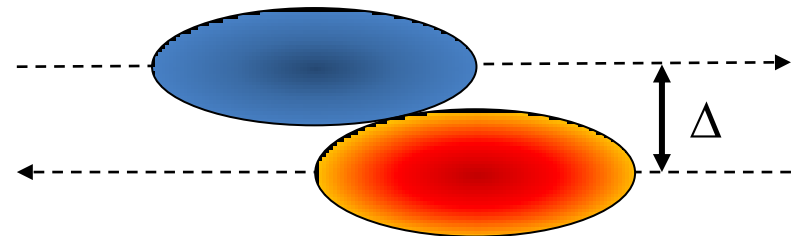
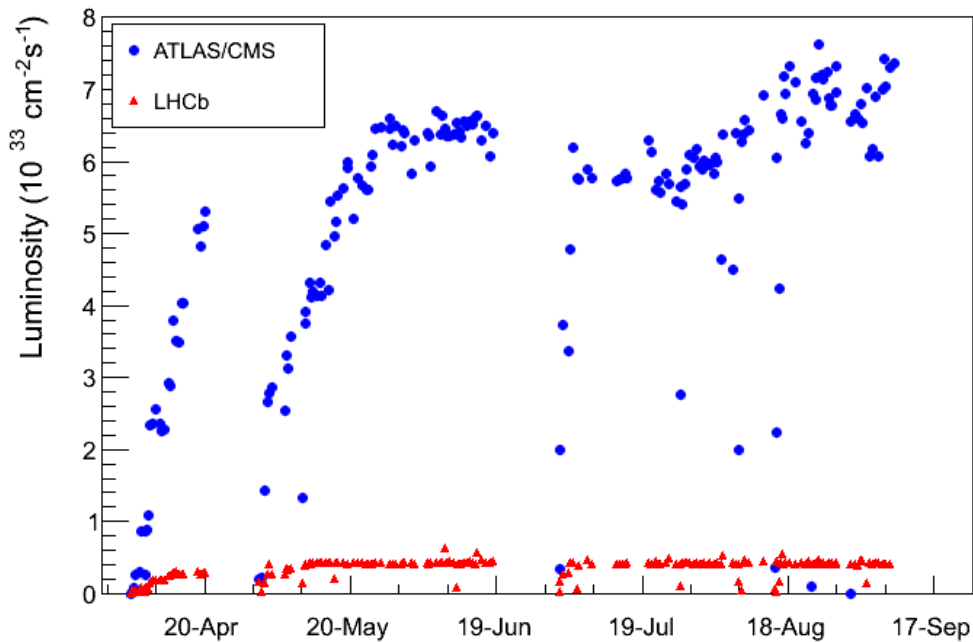


- Low emittance 25 ns provides higher performance due to higher luminosity for same or lower pile-up.

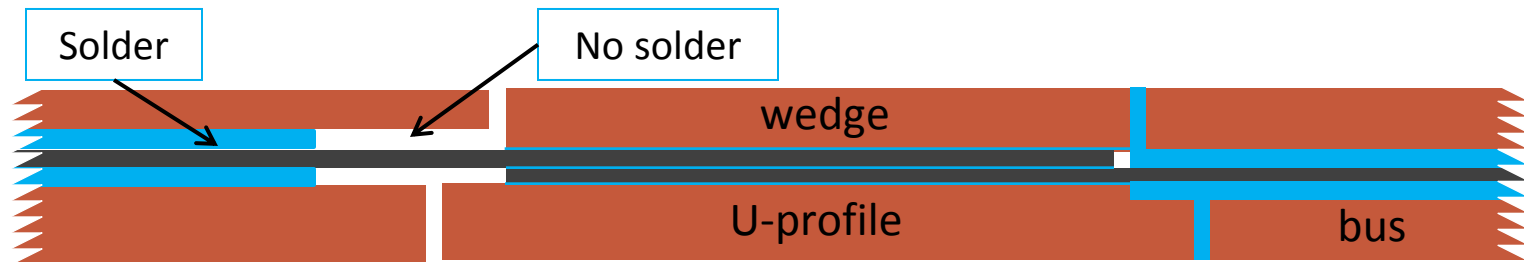


- ❑ 50 ns beam remains very attractive for high luminosity after LS1:
 - *Similar peak (levelling) and integrated luminosities due to higher brightness from injectors*
 - *Lower total current and stored energy*
 - *Less / no e-clouds,*
 - *Less beam induced heating ?*
 - *Less long-range collisions (lower 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

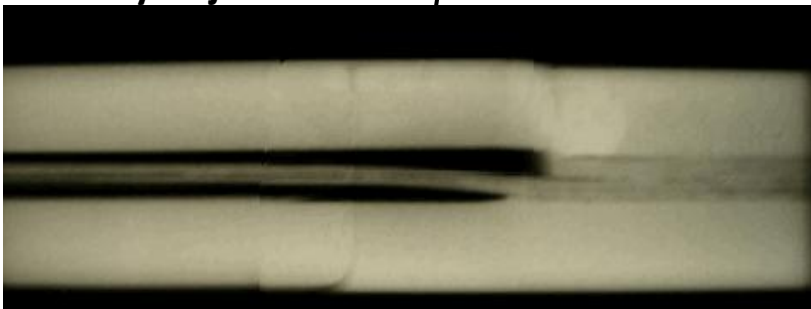
- The LHCb luminosity is limited to $4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ (detector limitations on rate and pileup).
- The transverse offset D between beams is adjusted regularly while colliding to maintain a constant luminosity – **luminosity levelling**.



- ❑ 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.

ATLAS
STANDBY

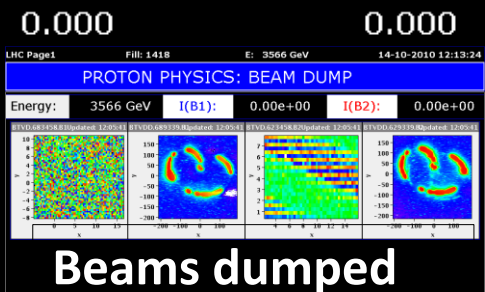
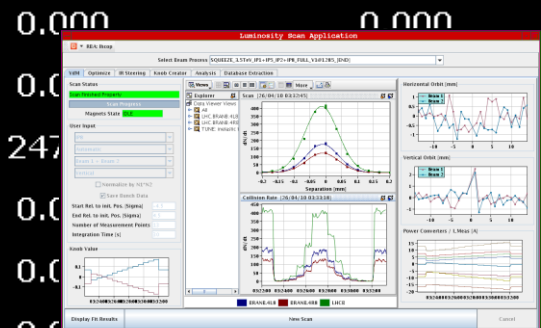
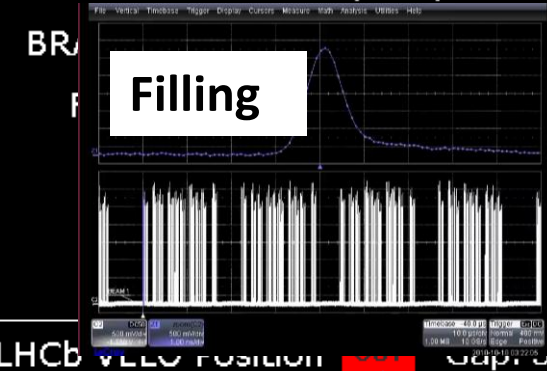
ALICE
STANDBY

CMS
STANDBY

LHCb
STANDBY

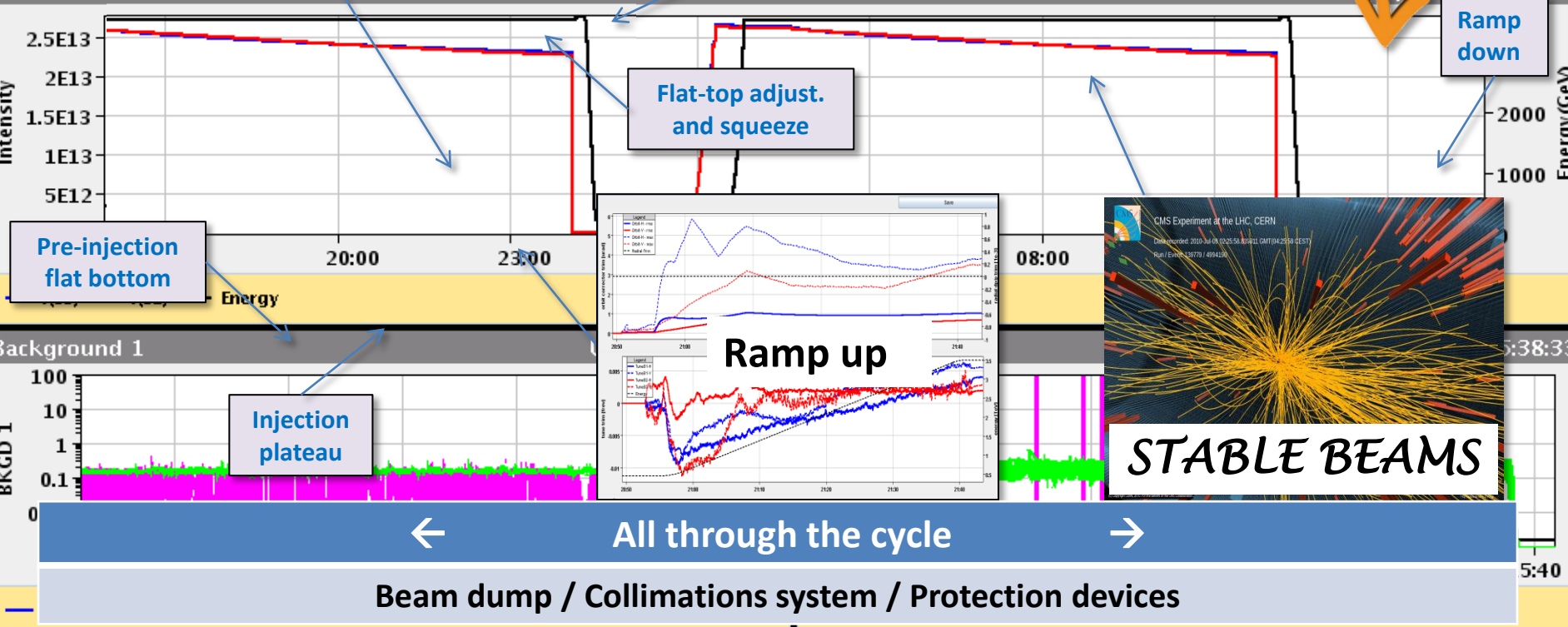
Experiment Status

Instantaneous Lumi (ub.s)⁻¹



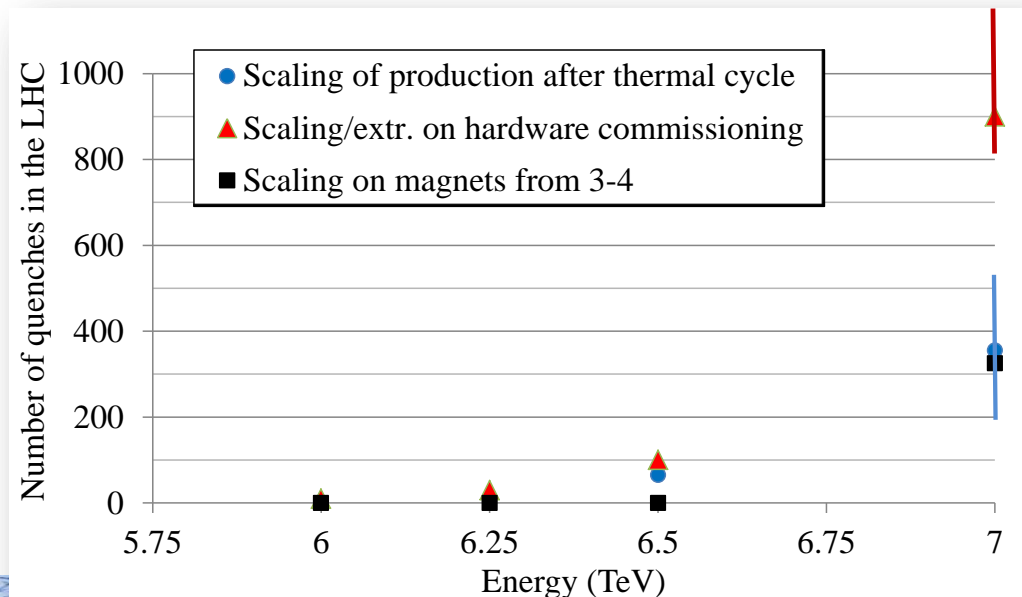
Beams in collision

Performance over the last 24 Hrs





- ❑ 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

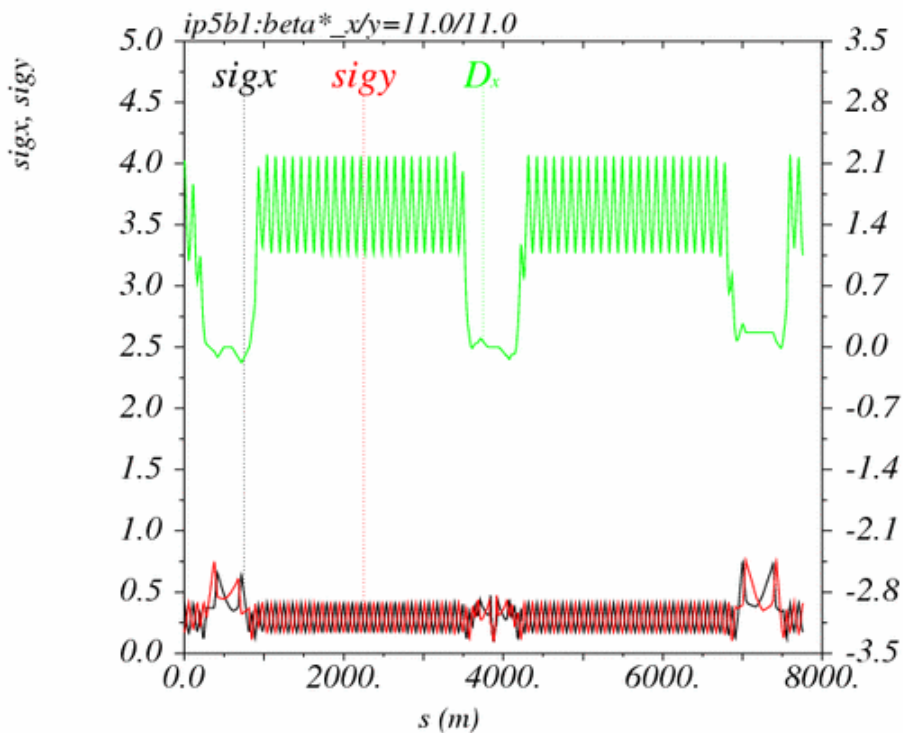


- New ideas and concepts will be implemented in the PS to produce beams with higher intensity and smaller emittance.
- Possible beams after LS1 (not yet demonstrated).

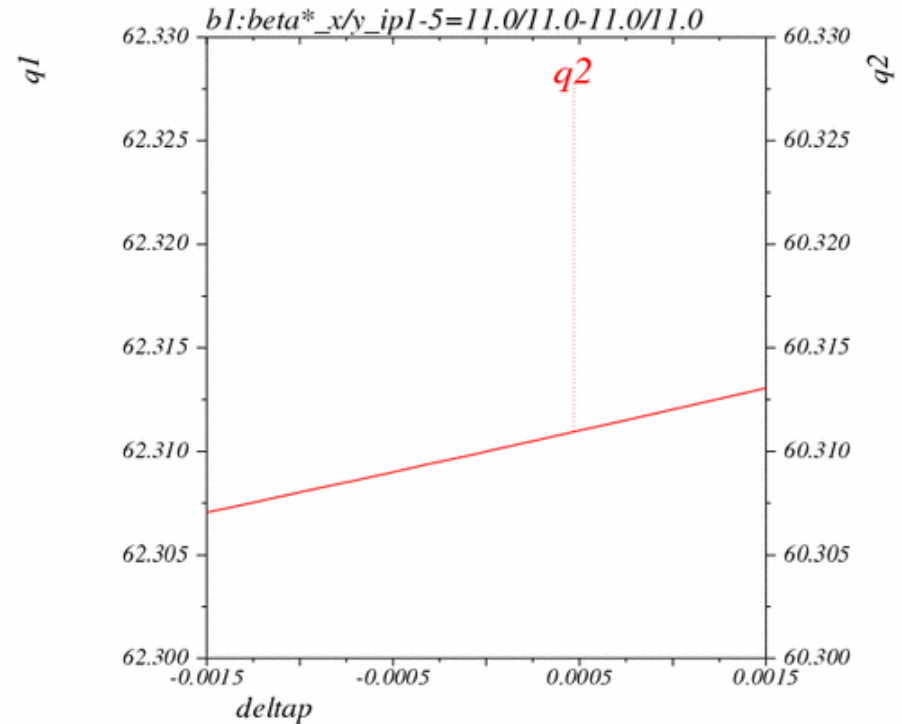
		Nominal			
		50 ns	50 ns	25 ns	25 ns
PS ejection	Bunches / train	32	24	48	72
SPS ejection	Bunch intensity	$1.7 \cdot 10^{11}$	$1.7 \cdot 10^{11}$	$1.15 \cdot 10^{11}$	$1.2 \cdot 10^{11}$
	Emittance [μm]	1.5	1.2	1.4	2.8
No bunches in LHC		~1340	~1300	~2600	2808
Relative luminosity		2	2.4	1.85	1
Relative 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 $\sim +0.6 \mu\text{m}$).



IR4 IR5 IR6
Beam size [mm] and dispersion (IR4→IR6)
at 3.5 TeV (for $\gamma\epsilon=3.5 \mu\text{m}$)



Tunes vs. δ_p

ATS=Achromatic Telescopic Squeeze - S. Fartoukh

☐ ...of course it requires larger aperture triplets

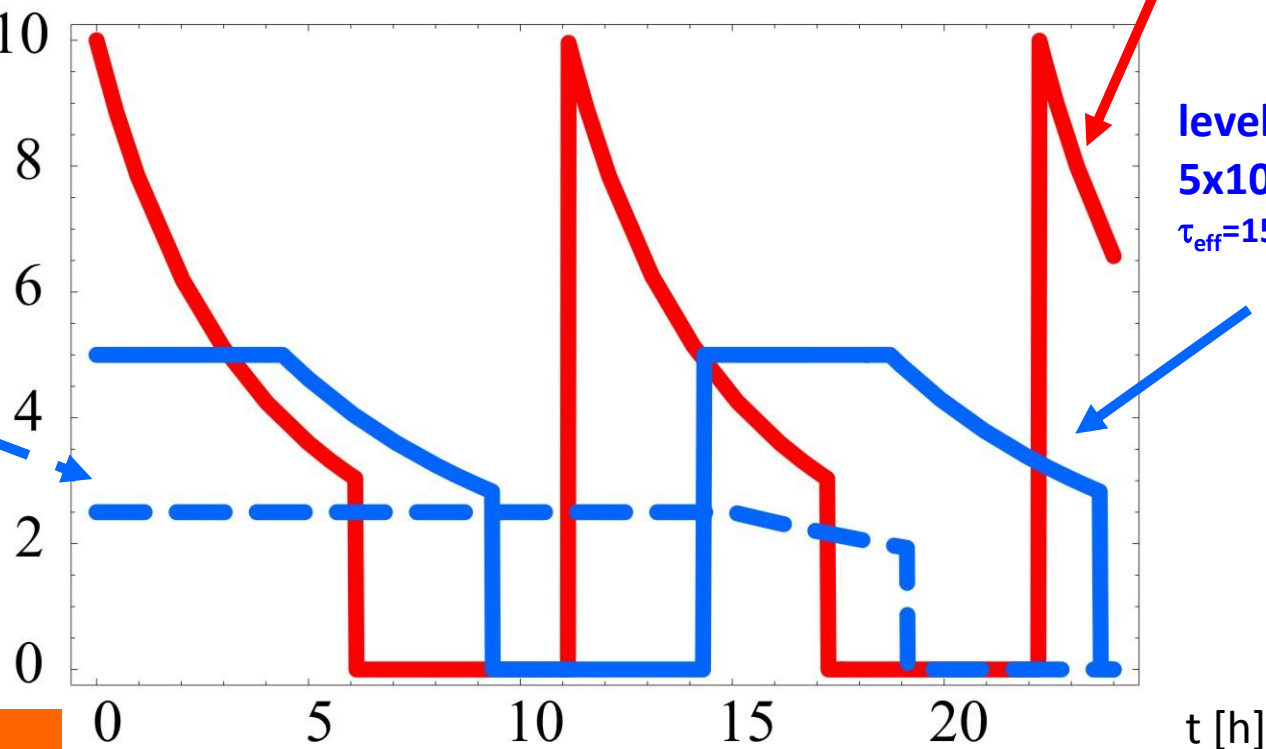
$$L = \frac{k N_b^2 f \gamma}{4 \pi \beta^* \varepsilon^*} F$$

$L [10^{34} \text{ cm}^{-2} \text{ s}^{-1}]$

Virtual peak
luminosity ($F=1$)

leveling at
 $2.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
 $\tau_{\text{eff}}=30 \text{ h}, T_{\text{ta}}=5 \text{ h}$

leveling at
 $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
 $\tau_{\text{eff}}=15 \text{ h}, T_{\text{ta}}=5 \text{ h}$



F. Zimmermann

THE “SUPER” MAGNETS

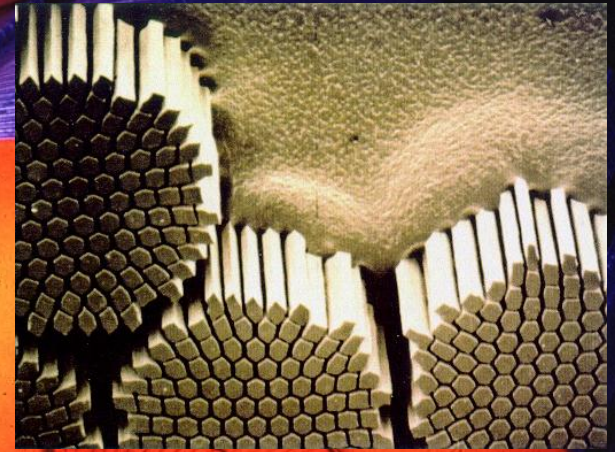


1500 tones (7000 km)
of top quality SC
cables

15000 MJ of magnetic
energy

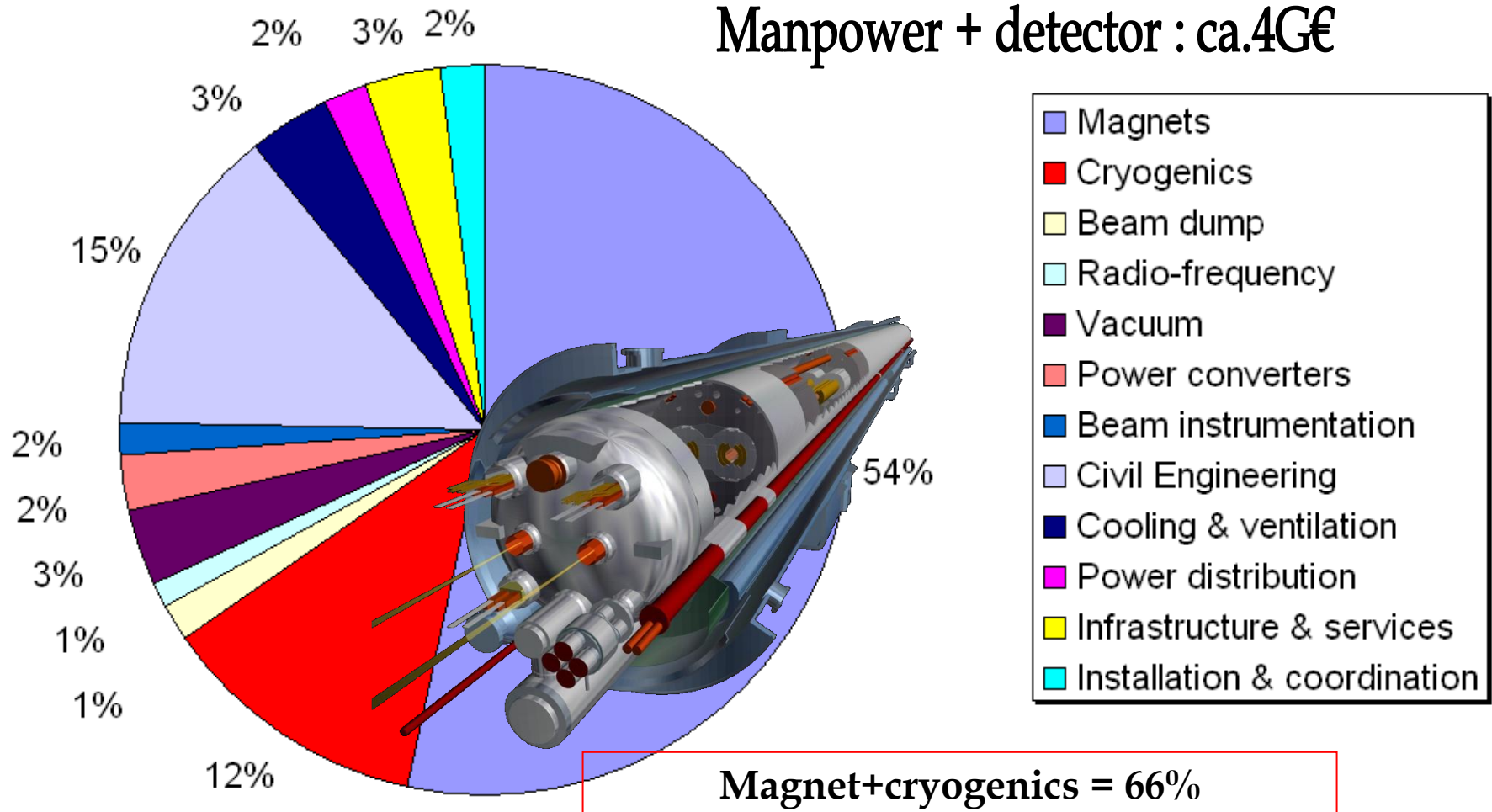
1800 HTS Leads
11 kW@1.9 K

1800 Power Converter
from 60 A to 24 kA

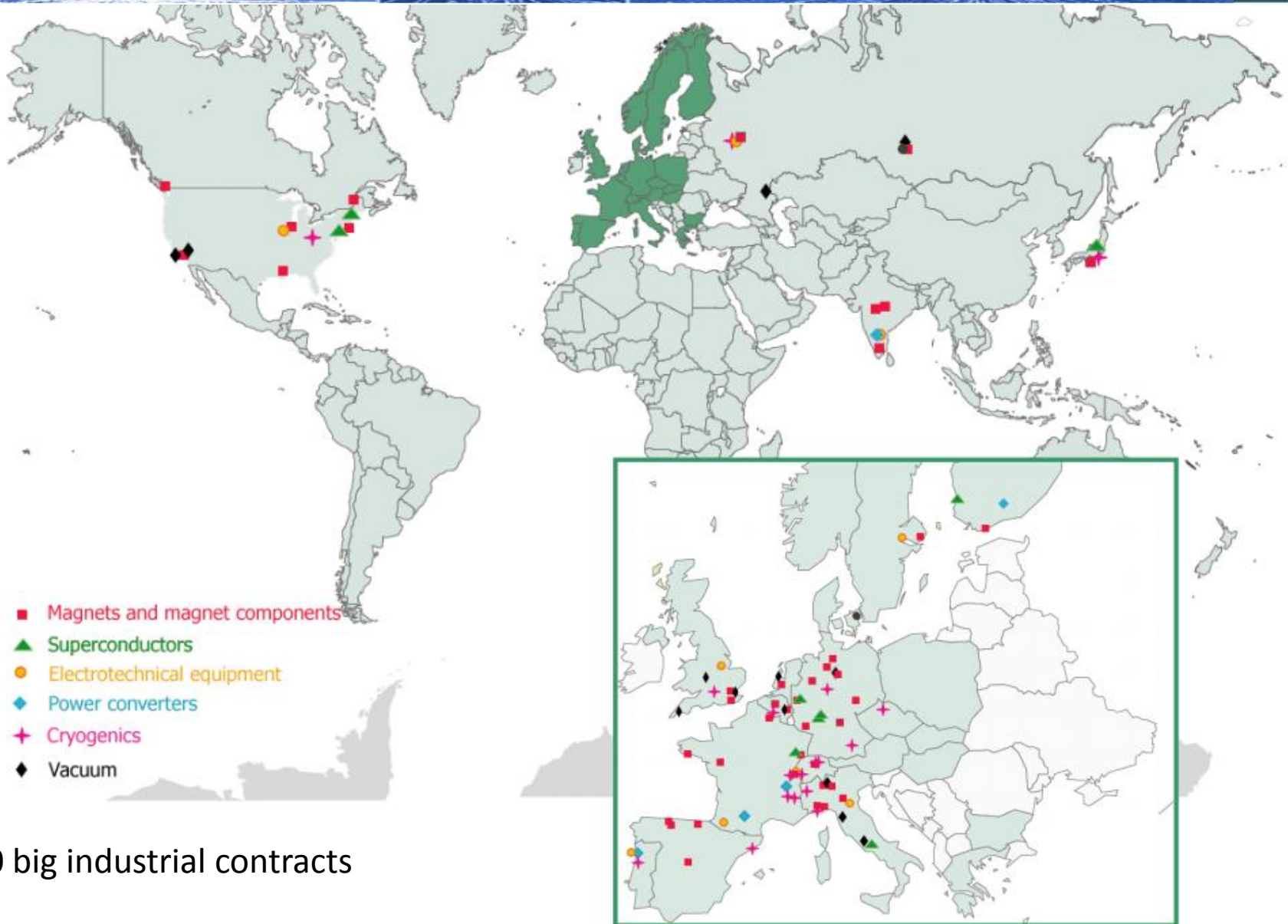


LHC Machine: 2.2 G€ (material+external work)

Manpower + detector : ca.4G€



AN INTERNATIONAL JOINT VENTURE



90 big industrial contracts

Or what you can do with 2.9 MJ

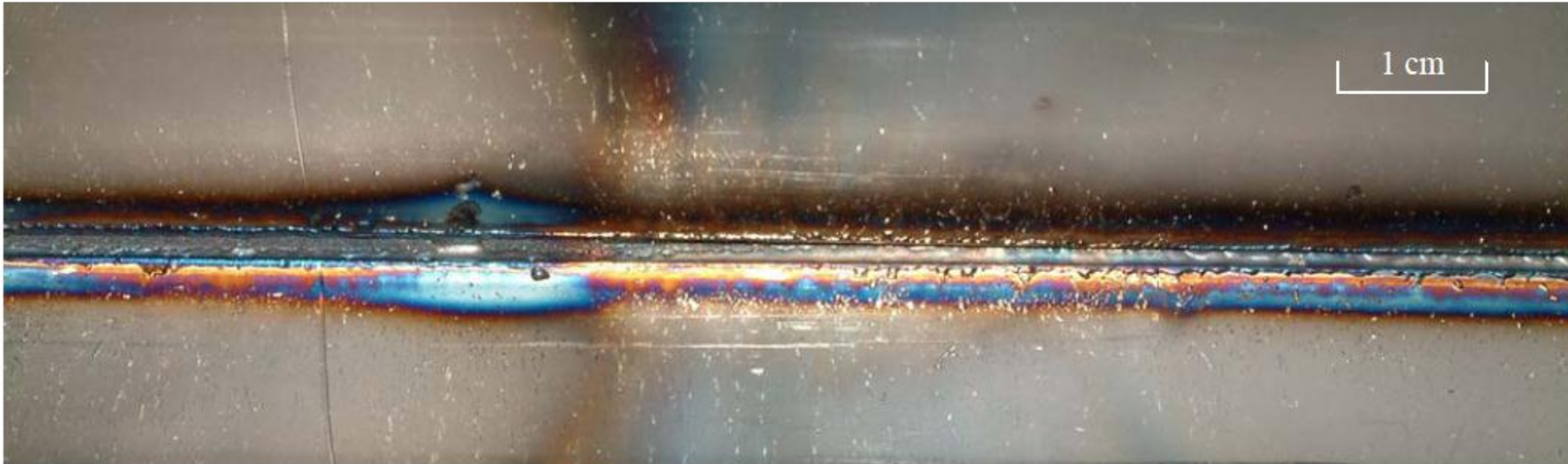


Figure 4. Damage observed on the inside of the vacuum chamber, on the beam impact side. A groove approximately 110 cm long due to removed material was clearly visible, starting at about 30 cm from the entrance.

During high intensity extraction on 25/10/04 an incident occurred in which the vacuum chamber of the TT40 magnet QTRF4002 was badly damaged. The beam was a 450 GeV full LHC injection batch of $3.4 \cdot 10^{13}$ p+ in 288 bunches, and was extracted from SPS LSS4 with the wrong trajectory

Approx equivalent to 48 bunches of $1 \cdot 10^{11}$ at 3.5 TeV

We need an extremely reliable system (HW and SW) to protect the machine in case of problems and this system mainly relies on the BIS, the LBDS and the collimators.