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LHC and LHC Upgrade

Acknowledgements: O. Brüning, M. Lamont, L. Rossi, J. Wenninger, F. Zimmermann and all the teams involved in LHC and LHC Injector operation

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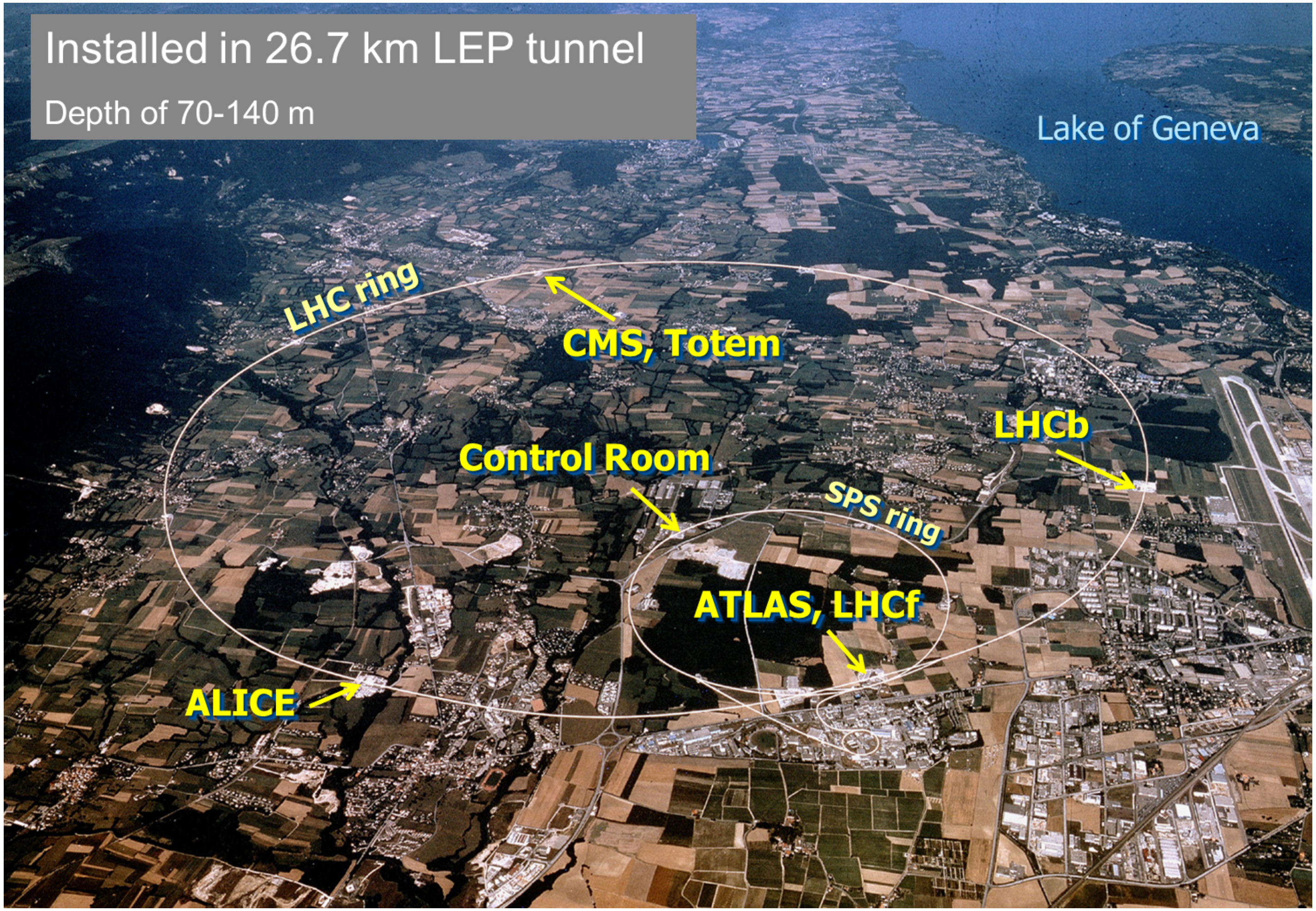
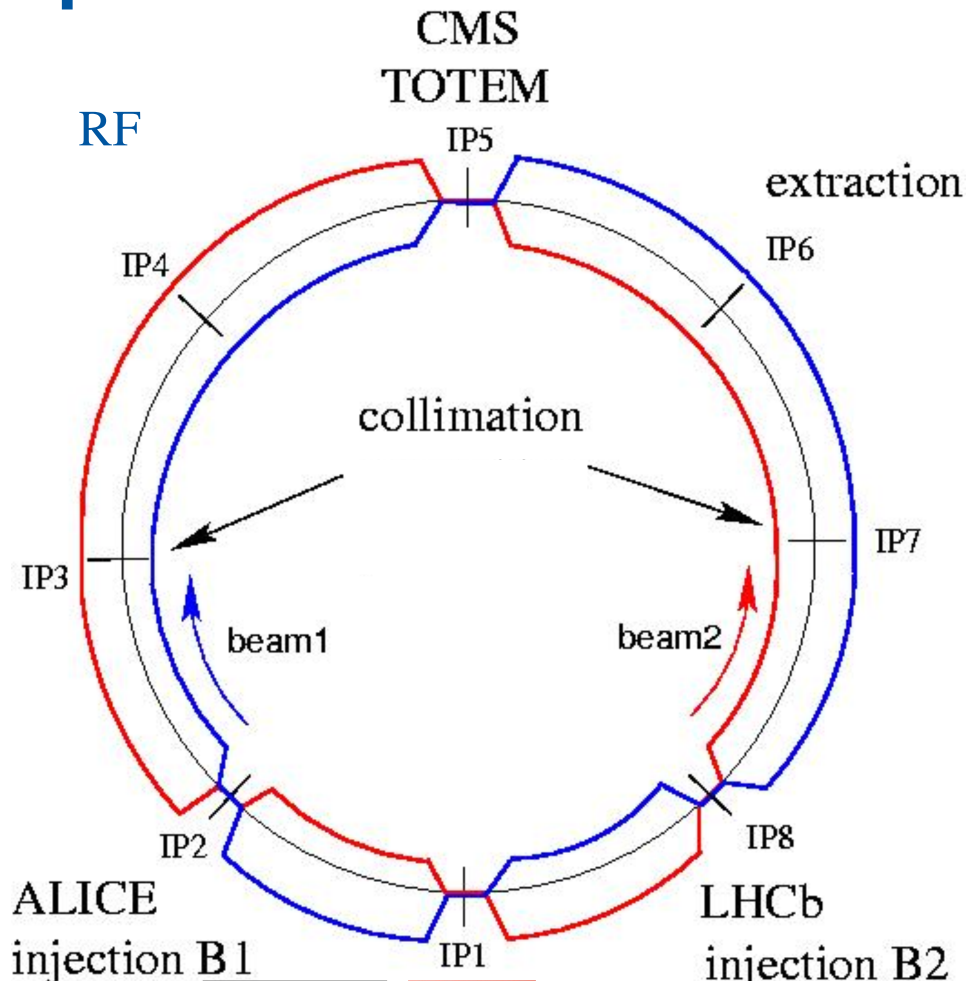
The Large Hadron Collider



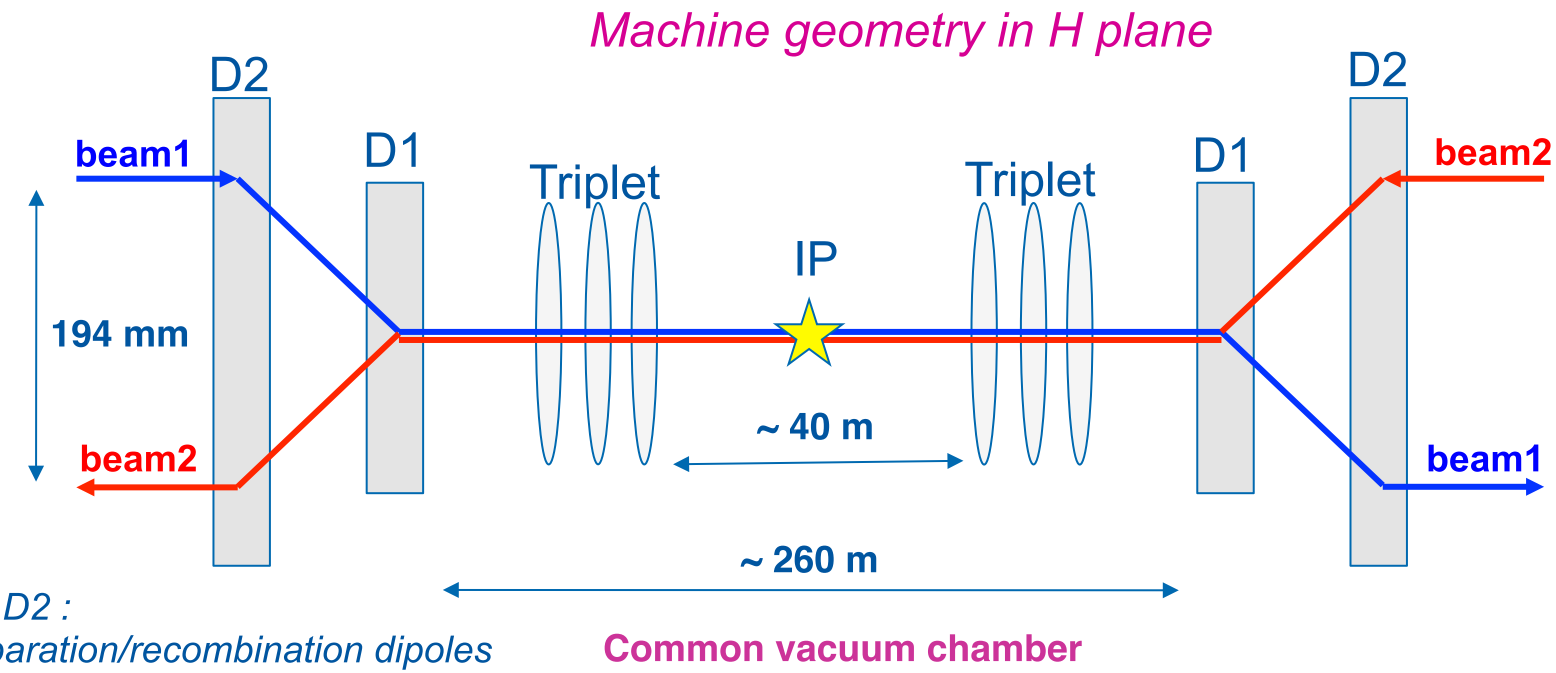
LHC layout and parameters

- Total length 26.57 km, in the former LEP tunnel.
- 8 arcs (sectors), ~2.8 km each.
- 8 long straight sections (700 m each).
- beams cross in 4 <u>points.</u>
- 2-in-1 magnet design with separate vacuum chambers → *p-p* (or ion/ion or p/ion) collisions.



Interaction regions geometry

- 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.



D1,D2 : separation/recombination dipoles

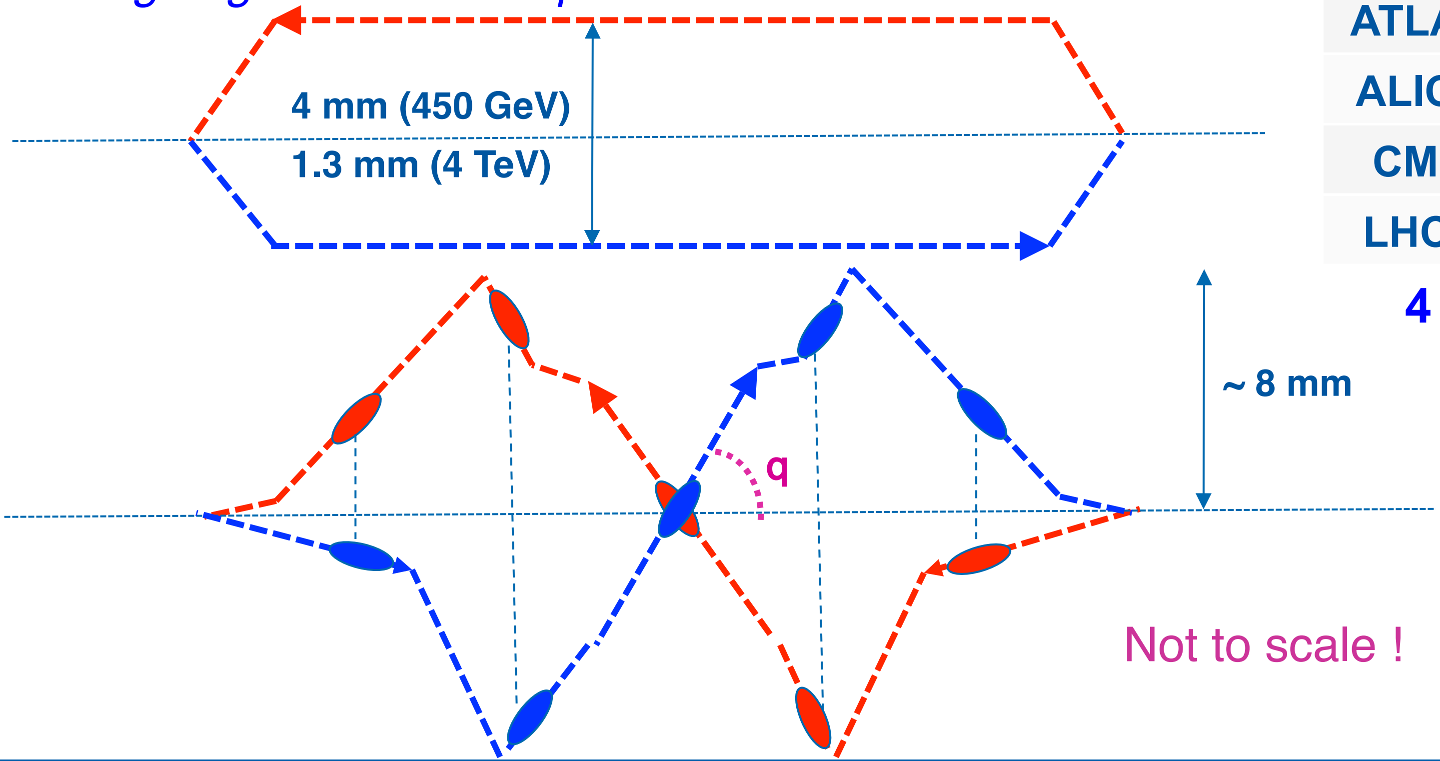
Separation and crossing

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.*

	a (mrad)
ATLAS	-145 / ver.
ALICE	145 / ver.
CMS	145 / hor
LHCb	90 / ver

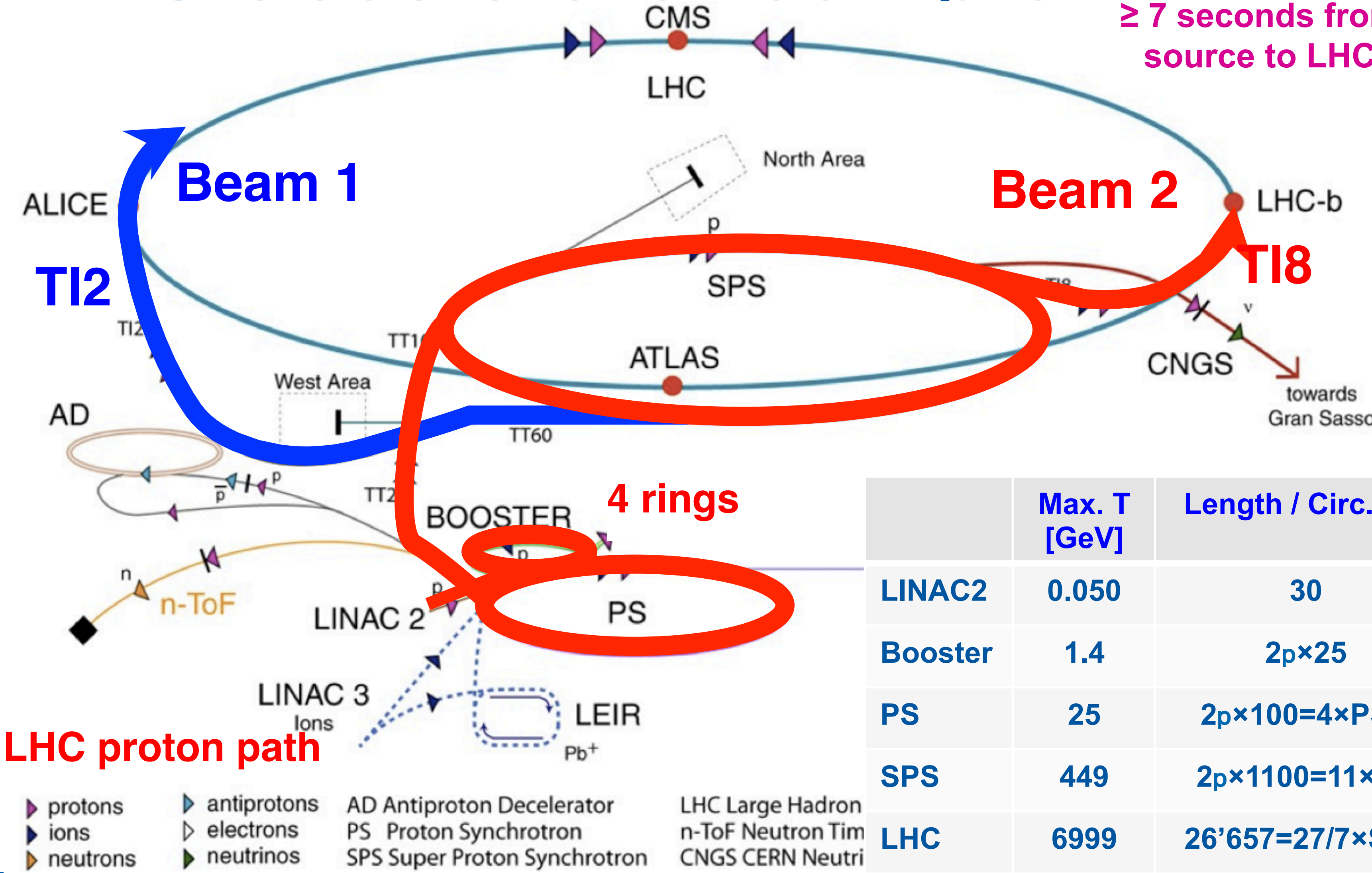
4 TeV / 2012 !



Not to scale !

LHC accelerator complex

≥ 7 seconds from source to LHC



	Max. T [GeV]	Length / Circ. (m)
LINAC2	0.050	30
Booster	1.4	2p×25
PS	25	2p×100=4×PSB
SPS	449	2p×1100=11×PS
LHC	6999	26’657=27/7×SPS

Two main drivers

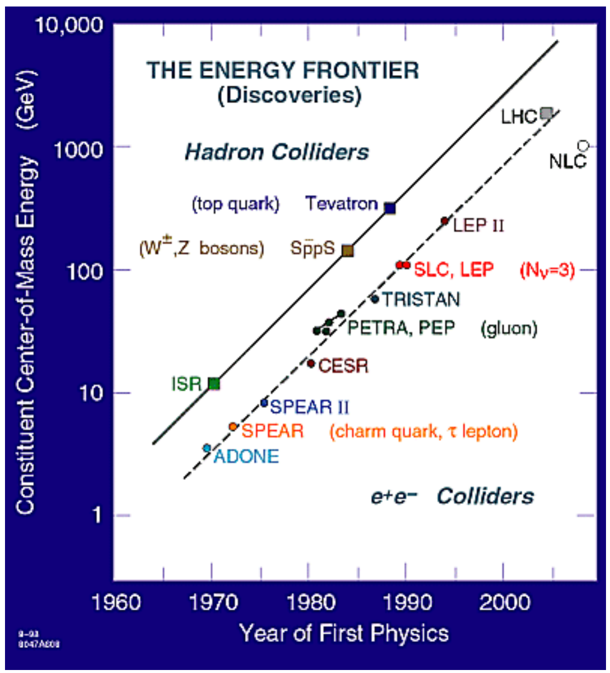
- More energy
- More luminosity

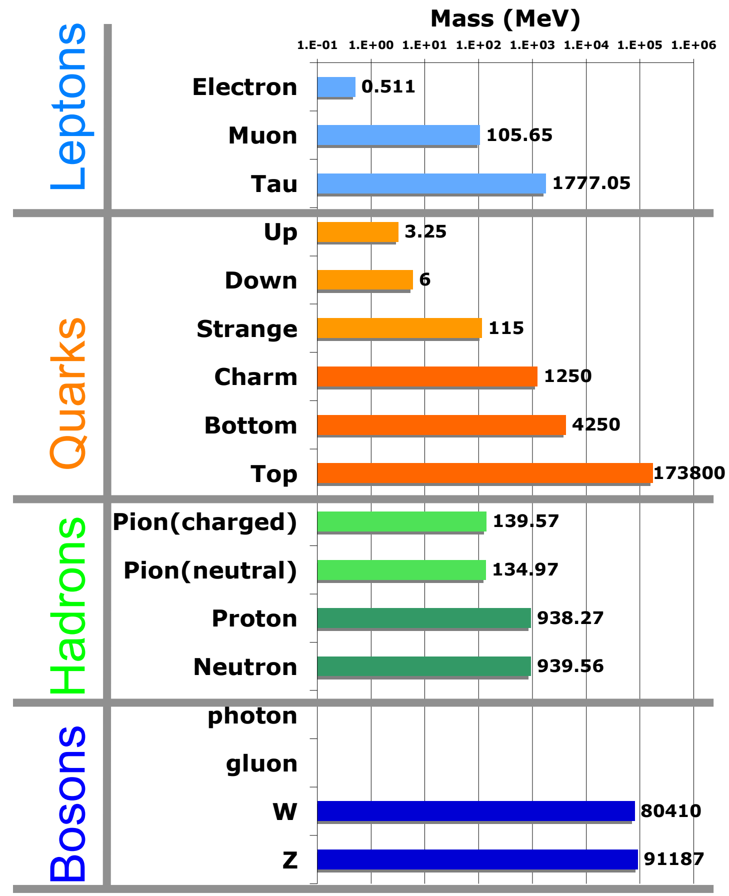
More energy

$$p \propto B\rho$$

- Large circumference: ~27 km
- Large bending fields: up to 8.3 T

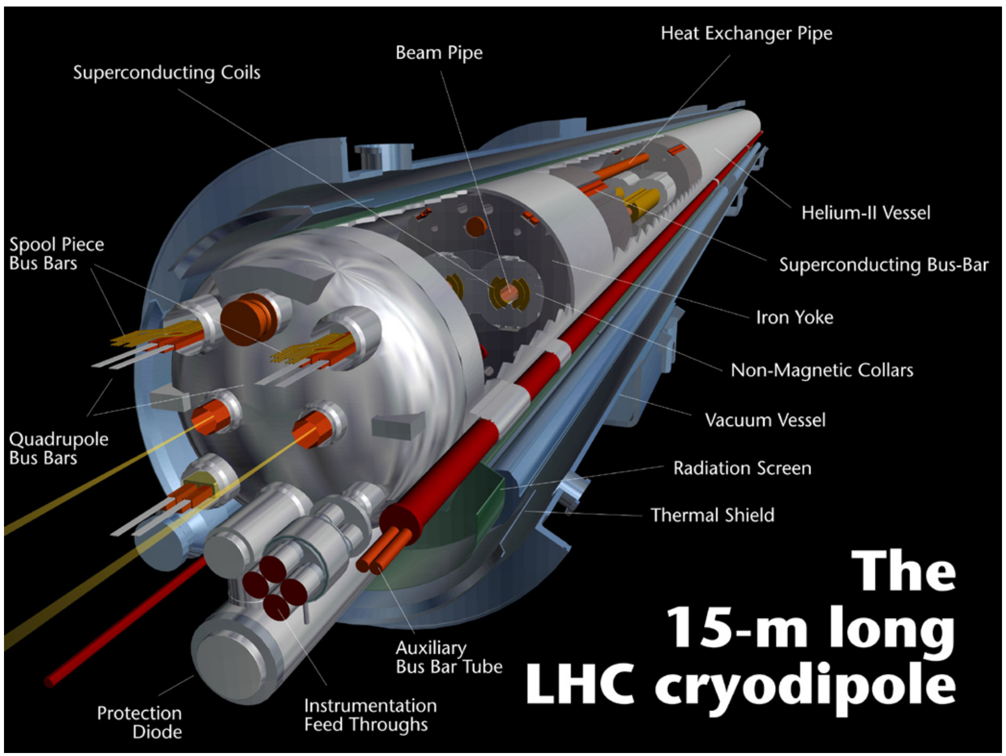
➔ p=7 TeV

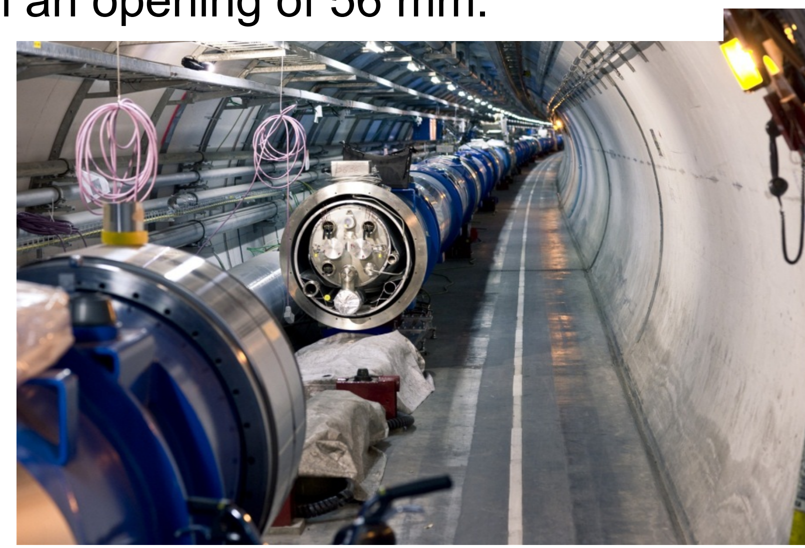




LHC dipole magnet

- 1232 dipole magnets.
- B field 8.3 T (11.8 kA) @ 1.9 K (super-fluid Helium) – after incident operated up to ~4.7 T ➔ interconnect consolidation during Long Shut-down 2013-2014
- 2 magnets-in-one design : two beam tubes with an opening of 56 mm.





- Operating challenges:
  - *Dynamic field changes at injection.*
  - *Very low quench levels (~ mJ/cm^3)*

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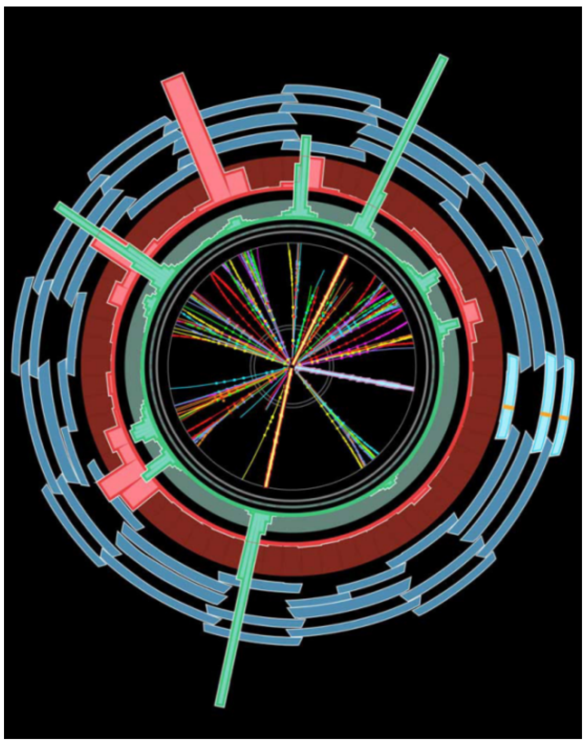
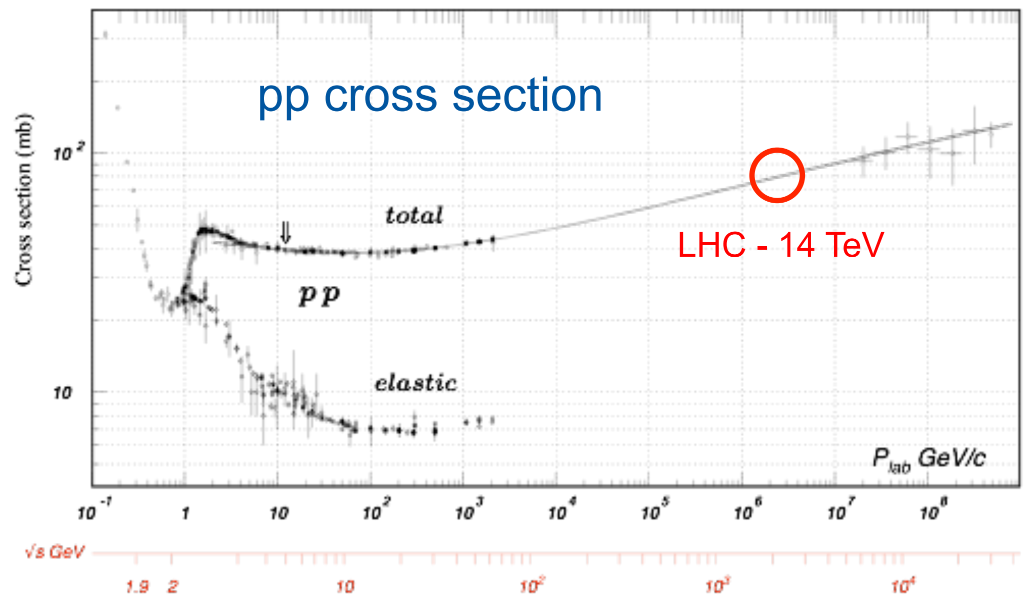
More luminosity

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





Luminosity

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

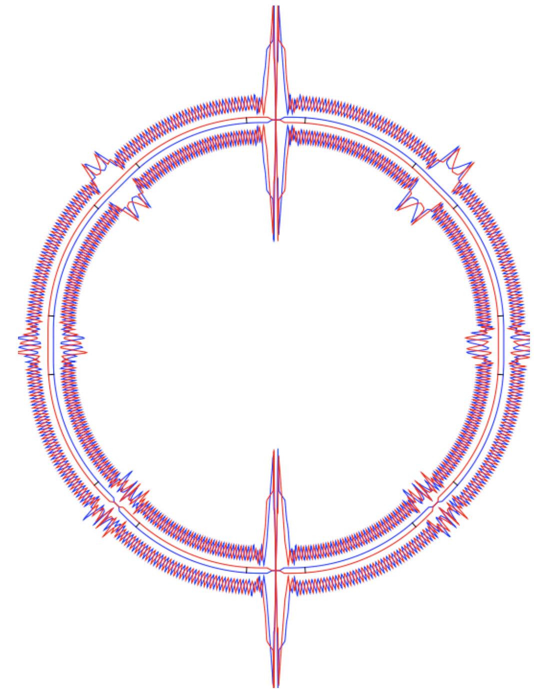
$$\sigma_x^* \sigma_y^* = \frac{\beta^* \varepsilon^*}{\gamma}$$

(Round beams)

- g = E/m, f is the revolution frequency (11.25 kHz) defined by the circumference (v~c!!)
- k is the number of colliding bunch pairs,
- N_b is the bunch population,
- s is the beam size at IP
- e* is the normalized emittance
- b* the betatron (envelope) function at the IP
- F is a reduction factor due to the crossing-angle

Beam size

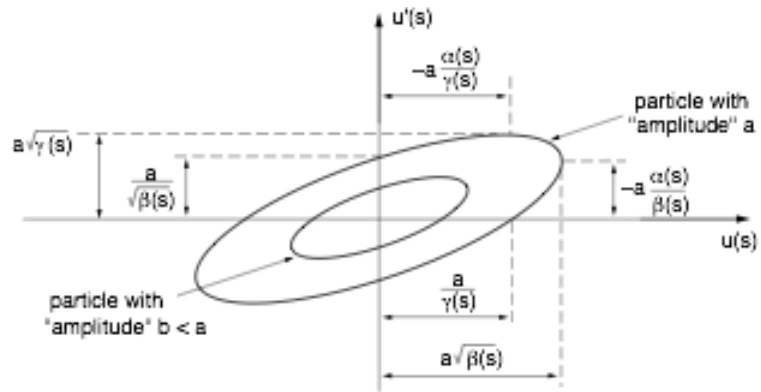
$$\sigma = \sqrt{\beta\varepsilon}$$



- b = optical function defined at each point of the machine by strength of the quadrupoles. b* is the value of the b function at the IP which is a focal point for the machine optics.

- e = emittance: phase space area. As we move around the machine the shape of the phase space ellipse will change as [illegible](s) but the area of the ellipse ([illegible][illegible]) does not change (Liouville). e shrinks naturally as we go up in energy (p_s increases, p_t doesn't) normalized emittance e*:

$$\varepsilon^* = \varepsilon\beta\gamma$$



- Ideally constant across the injector chain essentially defined at the proton source!!

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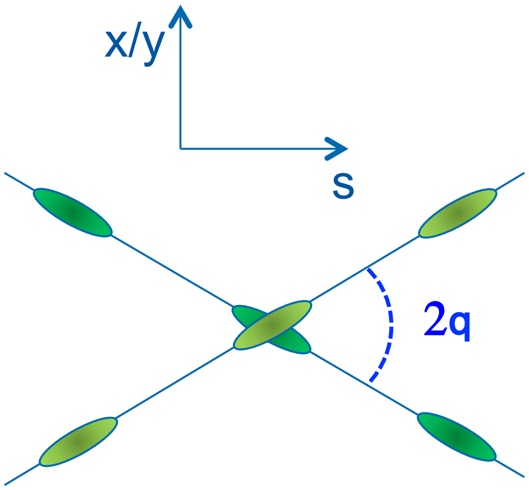
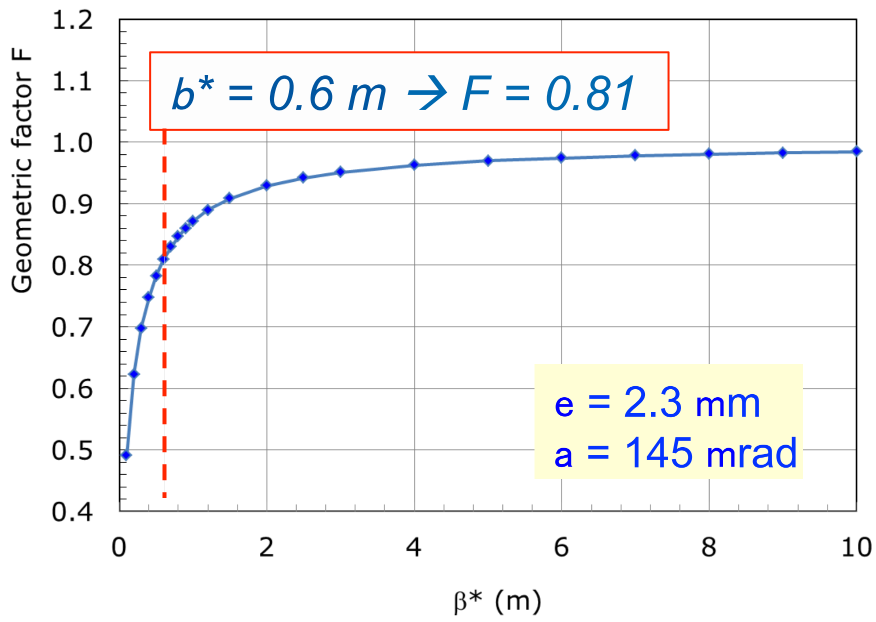
Crossing angle



- Drawbacks:
  - Due to the small beam size the luminosity geometric reduction factor due to bunch length s_s and crossing angle becomes significant for low b*

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



  - Reduction of the aperture
  - Long range beam-beam interactions
  - and others (e.g. synchro-betatron resonances,…)

Luminosity

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

$$\sigma_x^*\sigma_y^* = \frac{\beta^*\varepsilon^*}{\gamma}$$

<u>To maximize L:</u>

- **Many bunches (*k*) → tight bunch spacing**
- **Many protons per bunch (N_b)**
- **Small beam sizes $s^*_{x,y}$**

High beam "brightness" N_b/e^* (particles per phase space volume)

→ <u>Injector chain performance !</u>

Small envelope

→ <u>Strong focusing !</u>

- ***Small b****

Optics property

- ***Small emittance*** e^*

Beam property

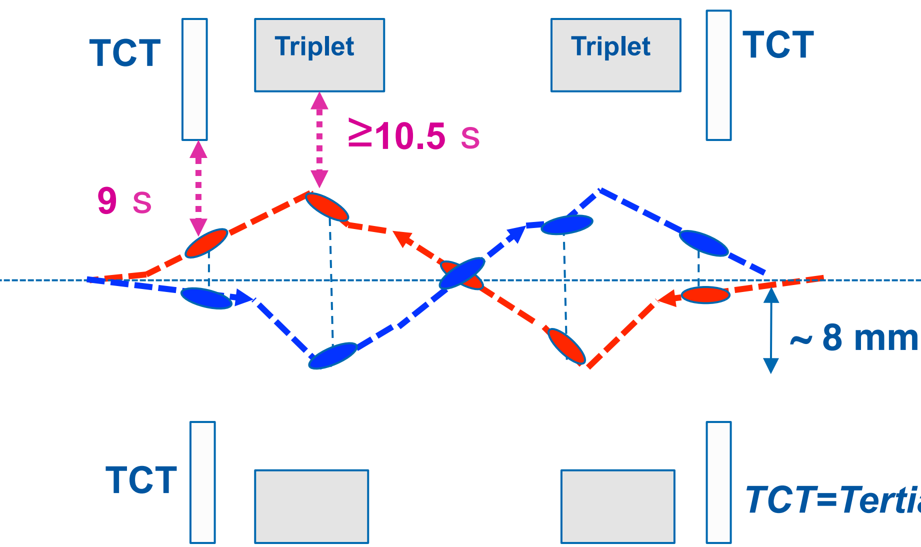
What limits b*?

Limits on b*

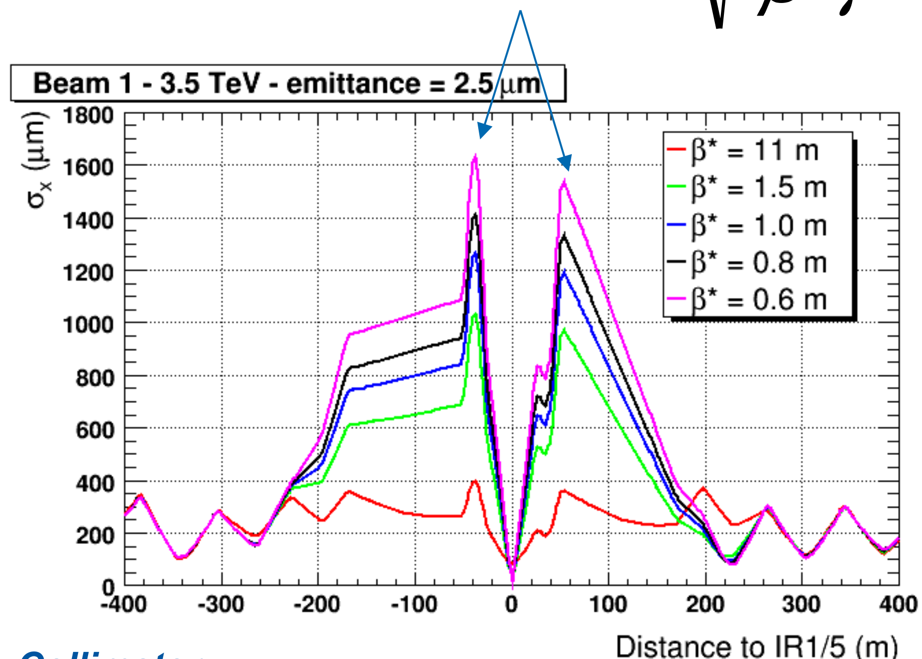
In the high luminosity IRs, the triplet quadrupoles define the ***machine aperture limit*** for squeezed beams, b* is constrained by:

- *the beam envelope,*
- *a margin TCT to triplet ,*
- *the **crossing angle***

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

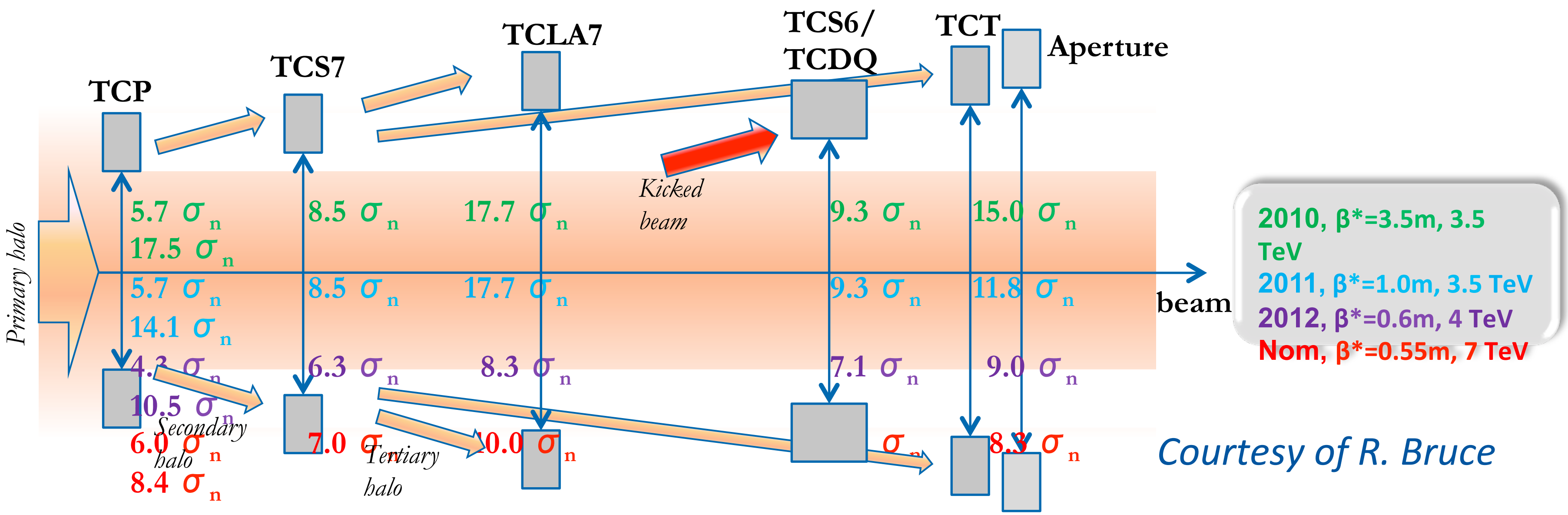


TCT=Tertiary Collimator



Implications on collimation system

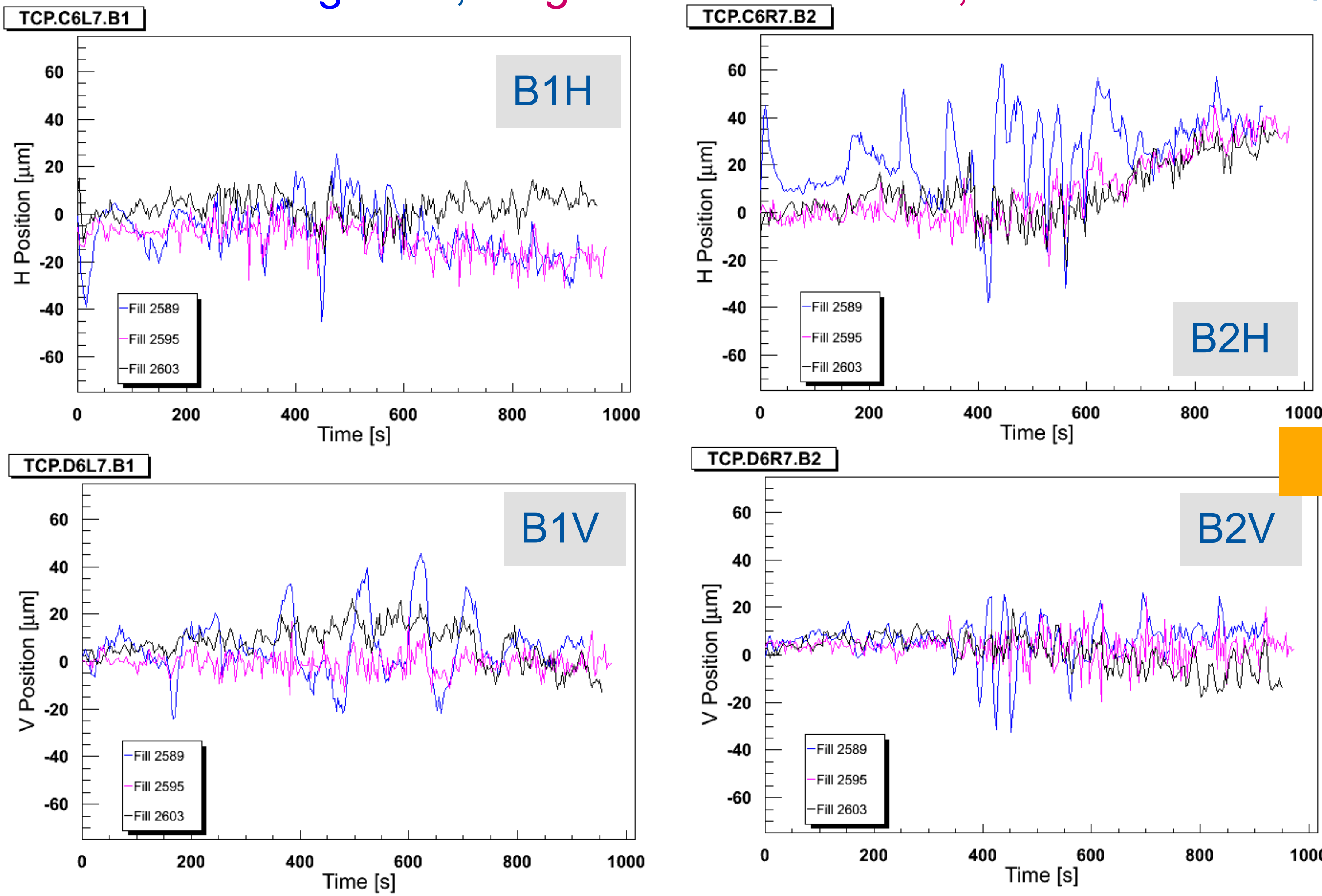
- Complex and high performance multi-stage collimation system.
- Collimation hierarchy has to be respected in order to achieve satisfactory protection and cleaning.
- Lower b* implies tighter collimator settings as well as alignment, beam sizes and orbit well within tolerance. We could do it only after having gained experience in orbit and optics controls and thanks to the small emittance delivered by the injectors.
- Smaller b* implies tighter collimator settings



Courtesy of R. Bruce

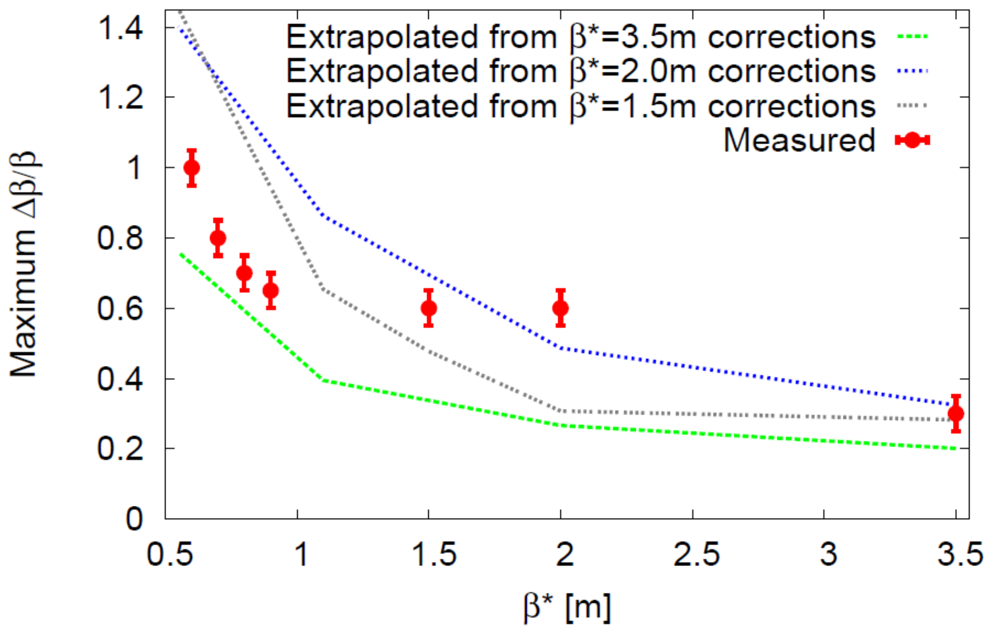
Implications on orbit control

Blue : before high BW, Magenta: OFB BW x10, Black: after 100% FF



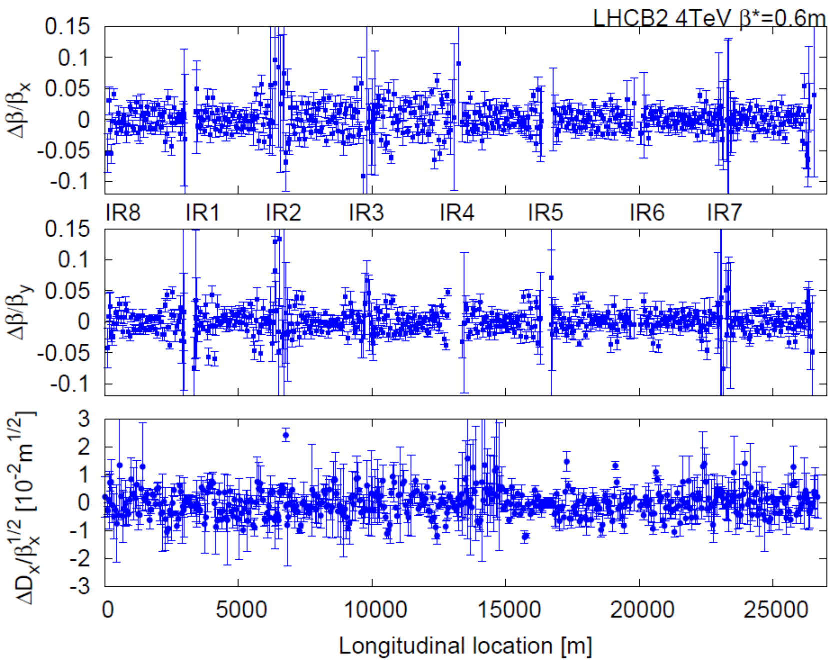
J. Wenninger

Implications on optics control



R. Tomas et al.

- Lower b* means enhancement of errors ➔ challenging



- …but proven to be feasible.

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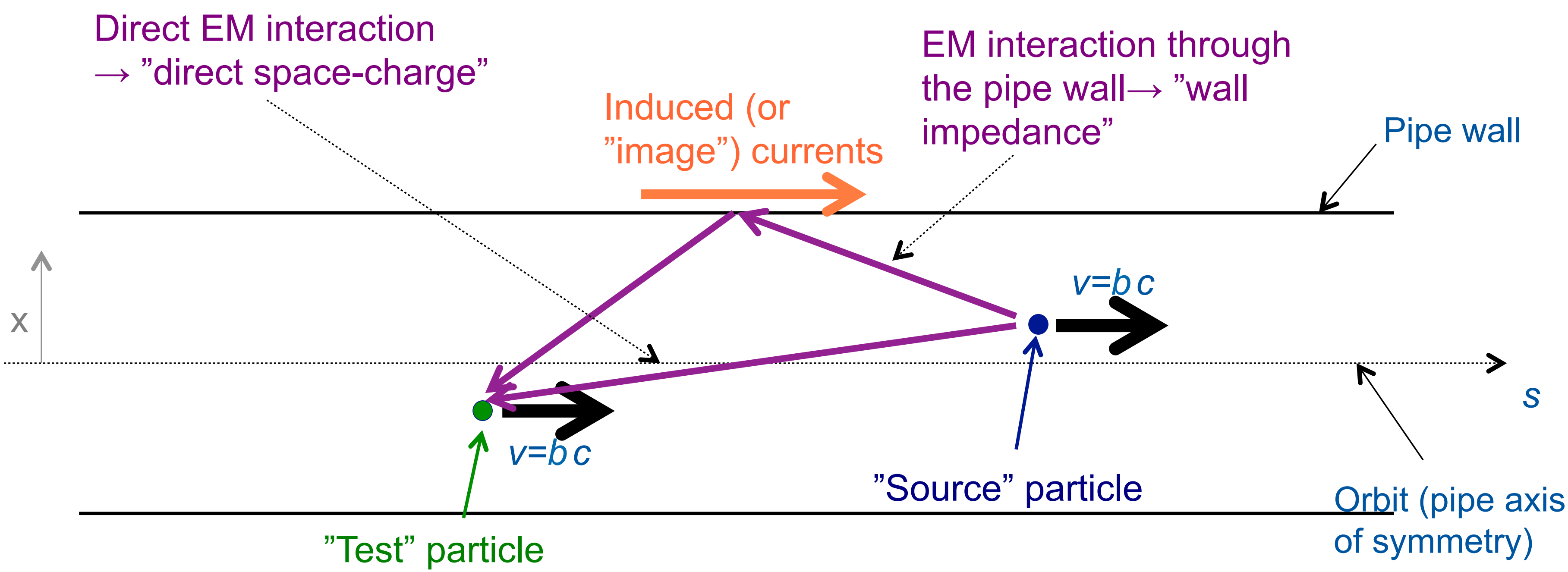
What limits the number and population of the bunches?

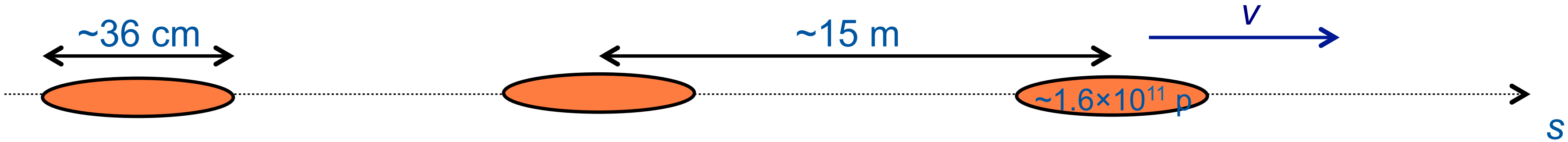
Wake fields and impedances

- Hight bunch population and tight bunch spacing make the beams prone to instabilities related to impedances i.e. to self-generated fields: electromagnetic (EM) fields created by a beam particle inside a structure (vacuum pipe, cavity, collimator, etc.), and felt by another particle.
- → results in an EM force, called wake field in time domain, beam-coupling impedance in frequency domain.

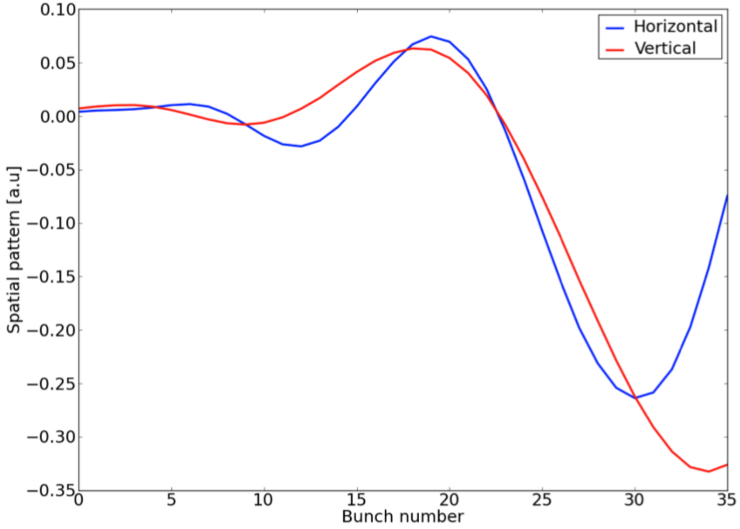


Instabilities

- Many bunches (up to 1380 with 50 ns spacing)



- Bunches can interact together (or even the head of each bunch can interact with the tail of the bunch) and in some cases begin to oscillate.
- Example with 36 bunches in the LHC: oscillation pattern along the bunch train (simulation result):



→ Coupled-bunch instabilities

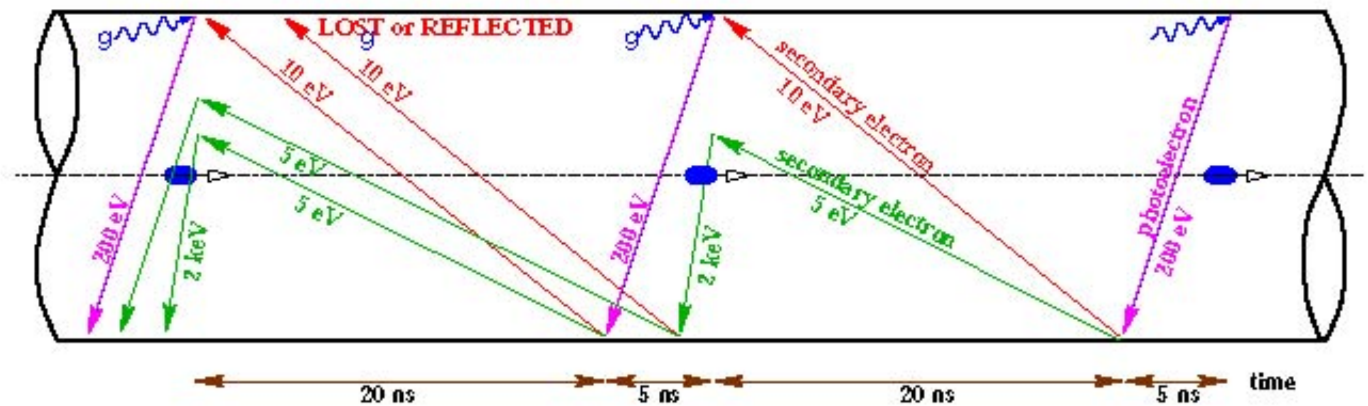
N. Mounet

Beam instabilities

- In 2012 instabilities have become more critical due to higher bunch intensity and tighter collimators settings. The LHC is one of the few machines where instabilities are more critical at high energy.
- Interplay between impedance (mostly due to collimators) and two-beams phenomena (mostly beam-beam) leading to (sometimes) conflicting requirements for the best settings of the machine in the various phase of the cycle
- 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.*
- Thanks to these cures achieved new record luminosities >7×10^{33} $cm^{-2}s^{-1}$ with:
  - High bunch intensity (~1.6×10^{11} p/bunch at injection)
  - Small emittance from the injectors

Electron cloud effects

F. Ruggiero

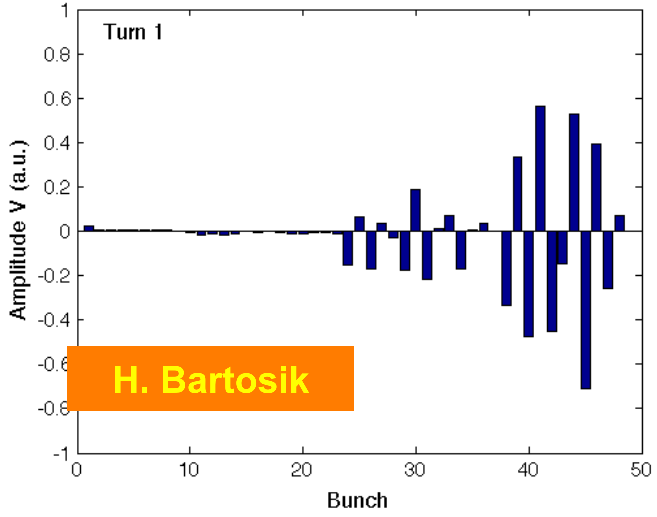


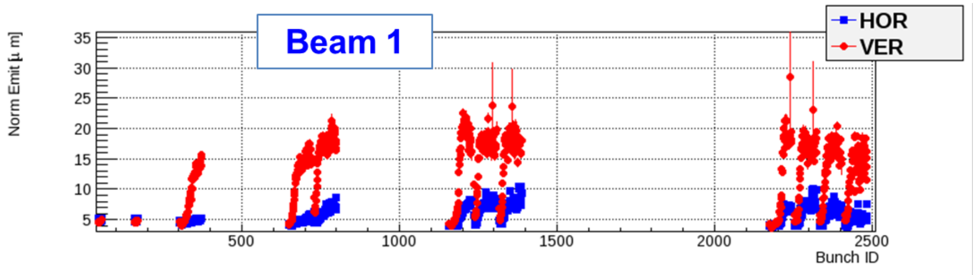
Secondary emission yield [SEY]
SEY>SEY_{th} ➔ avalanche effect (multipacting)
SEY_{th} depends on bunch spacing and population

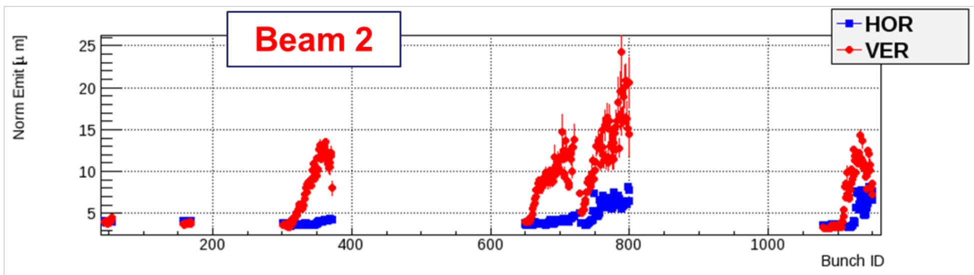
- Electron cloud effects occur **both in the warm and cold regions and their intensity increases rapidly for shorter bunch spacings. Observed in the LHC as soon as we started to inject bunch trains (150 ➔ 75 ➔ 50 ➔ 25 ns spacing):**
  - Vacuum pressure rise (interlock levels, beam losses…)
  - Single-bunch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

Electron cloud effects

- Fields induced by electrons act like wake fields (more complex) that couple different bunches along the train and head&tail of each bunch and have similar adverse effects on beam stability as impedances.

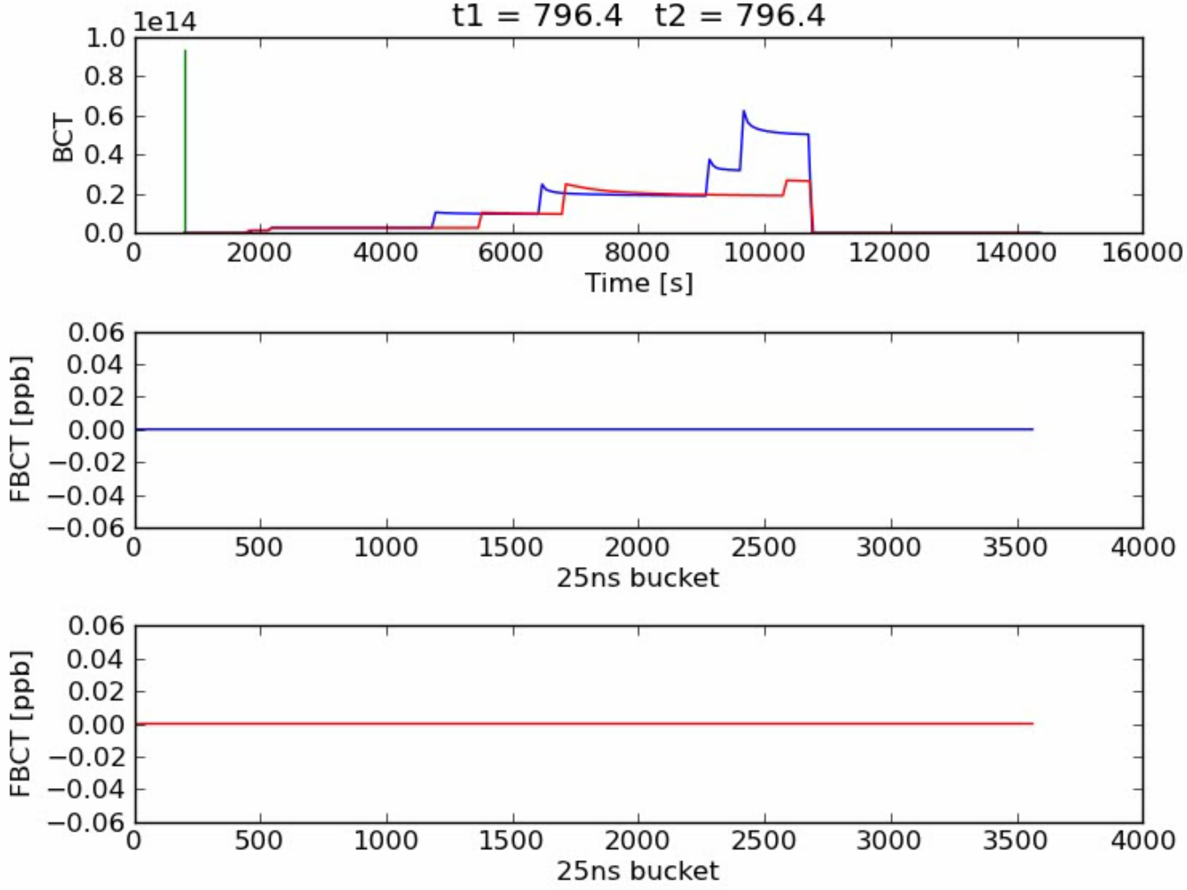






Electron cloud effects

2012 injection tests (10 July 2012)



Beam 1 ——— Beam 2 ———

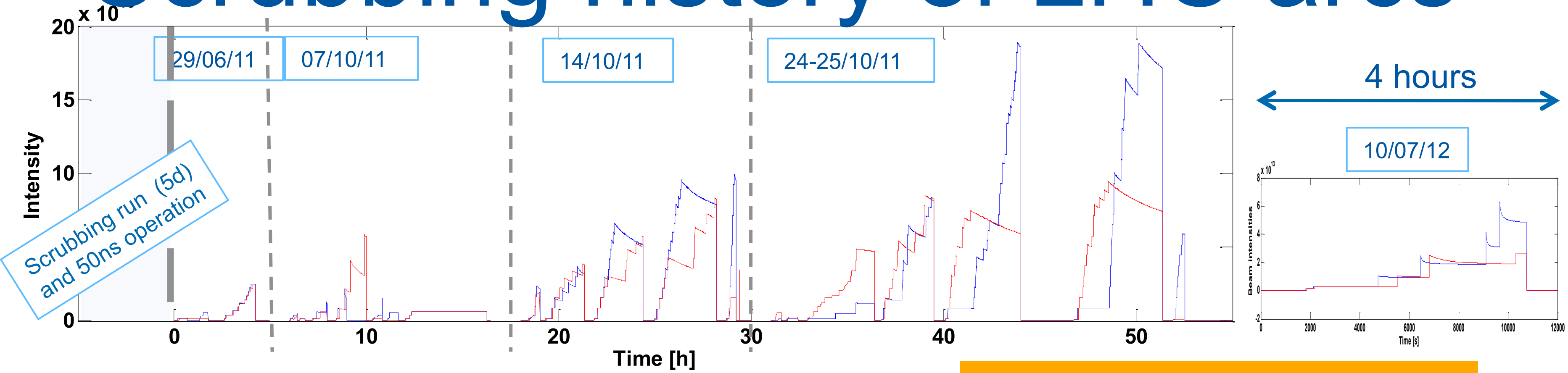
Bunch-by-bunch population Beam 1

Bunch-by-bunch population Beam 2

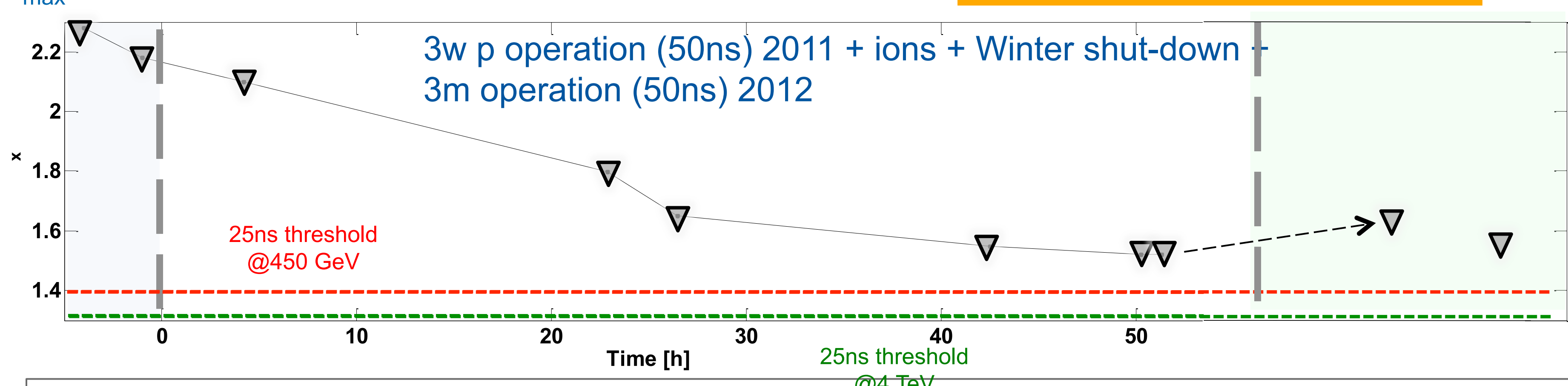
Cures for electron cloud effects

- At the time of the construction of the LHC:
  - NEG coating → would require activation to >200 ^{o}C → impractical
  - TiN coating: SEY > 1.3= SEY_{th} for 25 ns nominal operation
  - Conditioning by beam-induced electron bombardment ("scrubbing") leading to a progressive reduction of the SEY as a function of the accumulated electron dose → tested in the laboratory (on Cu surfaces) and in the SPS (Stainless Steel vacuum chambers) → Chosen strategy for the LHC operation with bunch trains
- More recently a-C coating has been successfully tested in the SPS showing SEY as low as 1.1

Scrubbing history of LHC arcs



G. Iadarola, G. Rumolo



- → d_{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

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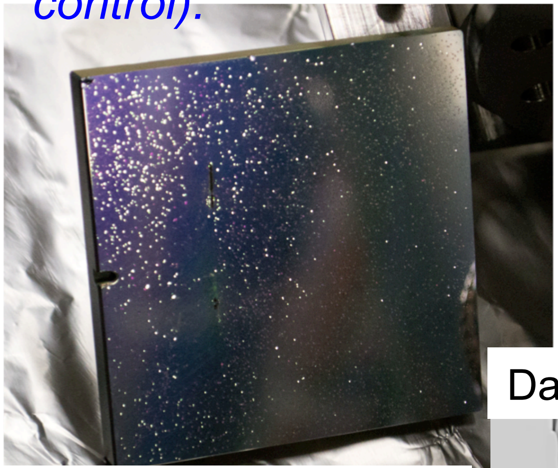
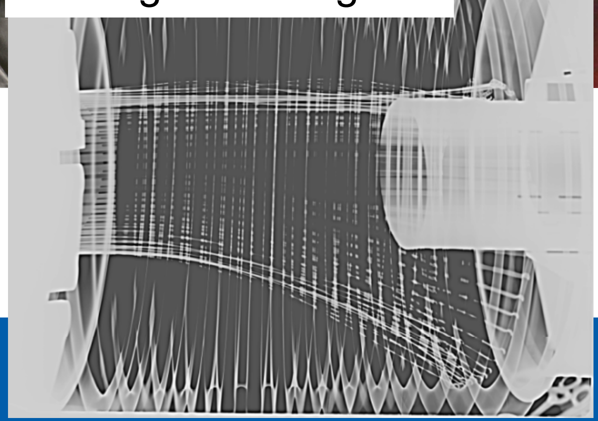
Heating damage

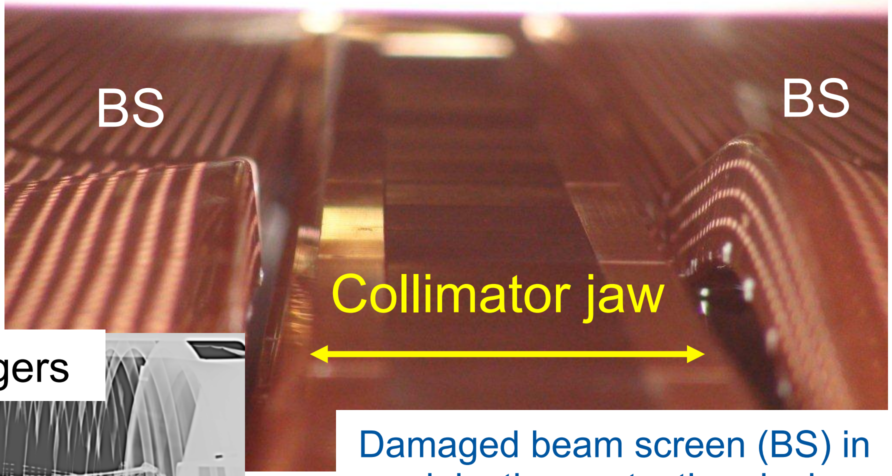
- High intensity beams may deposit large amounts of power via the EM fields they generate
  - *Design, manufacturing or installation errors may lead to damage of accelerator components.*
  - *So far they have not limited, could be fixed or mitigated (e.g. bunch length control).*



Damaged mirror of the synchrotron light telescope



Damaged RF fingers

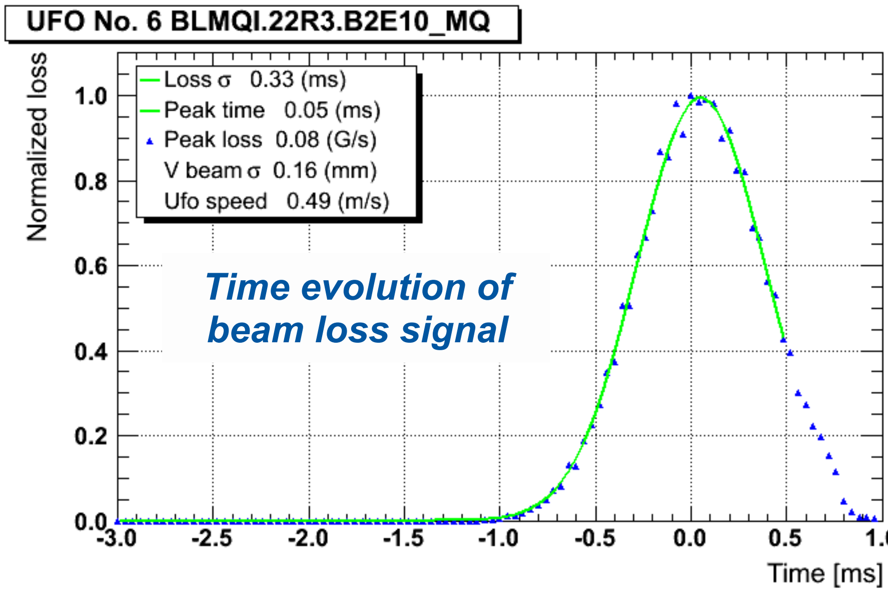


Damaged beam screen (BS) in an injection protection device

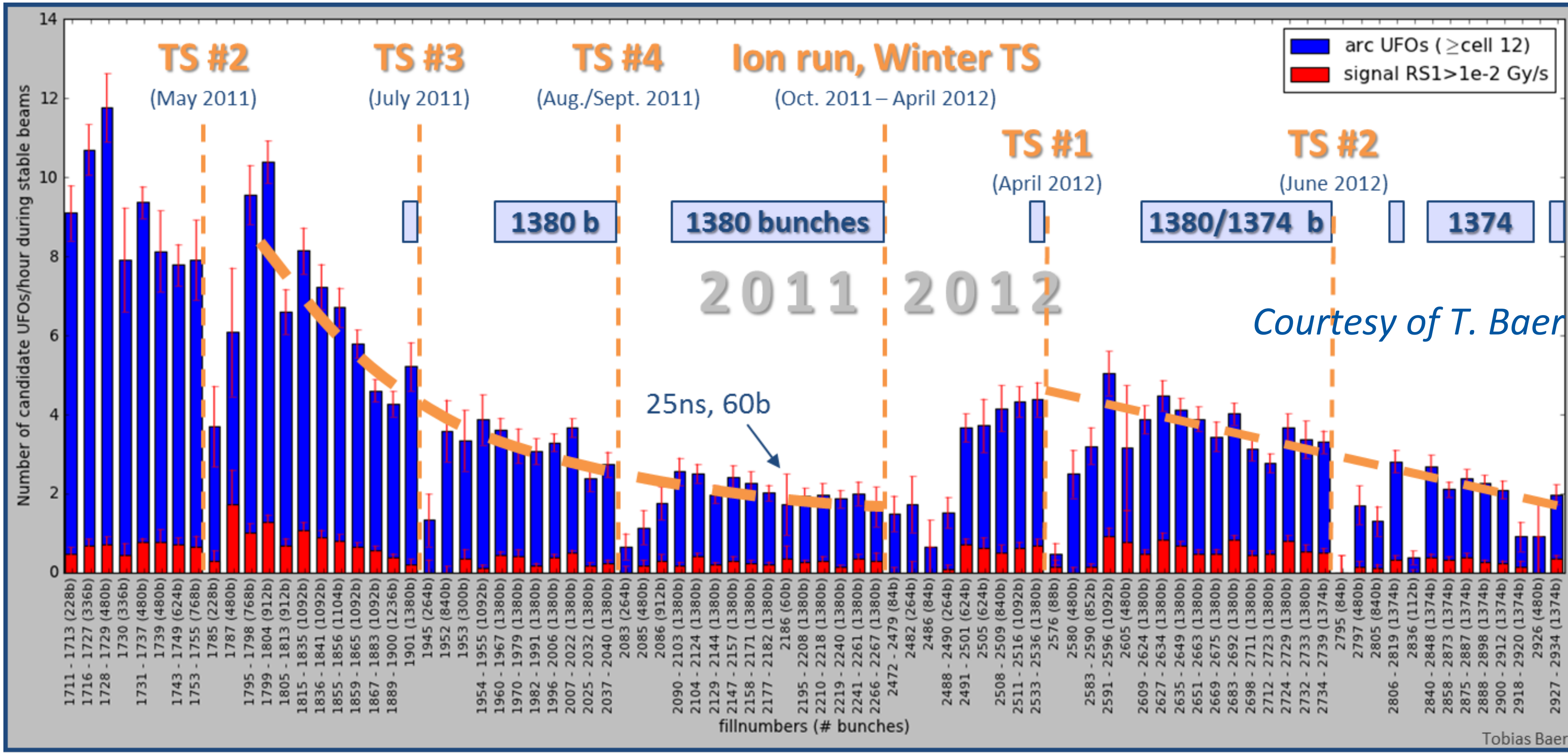
Other limitations

UFOs

- Very fast beam losses (time scale of ~millisecond) in the super-conducting regions of the LHC have been a surprise for the LHC – nicknamed UFOs (Unidentified Falling Object). If the loss is to high, the beams are dumped to avoid a magnet quench.
  - *2010: 18 beam dumps,*
  - *2011: 17 beam dumps,*
  - *2012: 15 beam dumps so far.*
- We are now certain that the UFOs are small (10's mm) dust particles falling into the beam.
  - *Triggered by the presence of the fields of the beam. Mechanism for removing the dust from the surface is not fully understood.*



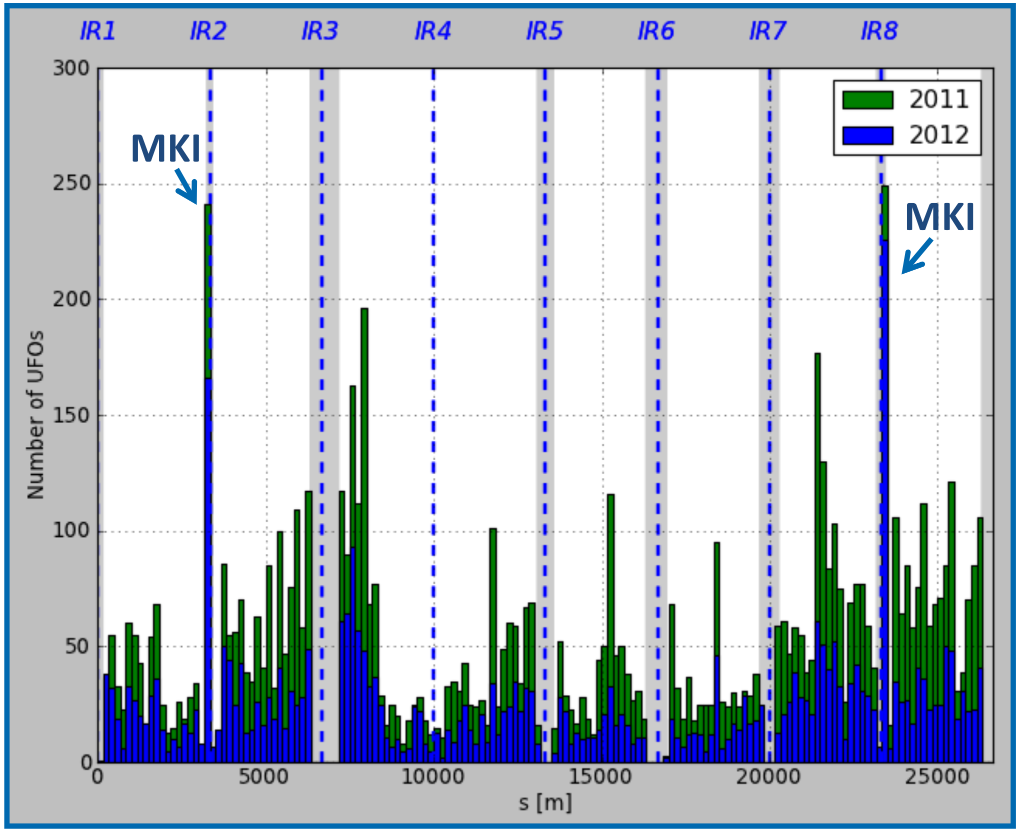
Arc UFO rate



- 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.

Spatial UFO distribution

Courtesy of T. Baer



- Spatial distribution around the ring very similar in 2011 and 2012.
- Many UFOs around injection kickers (MKIs).
  - *Al oxide particles produced during the machining of the inner ceramic tube of those fast kicker magnets.*
- Some arc cells with significantly increased number of UFOs.
  - *We do not know what dust is actually falling into the beam in the arc regions.*

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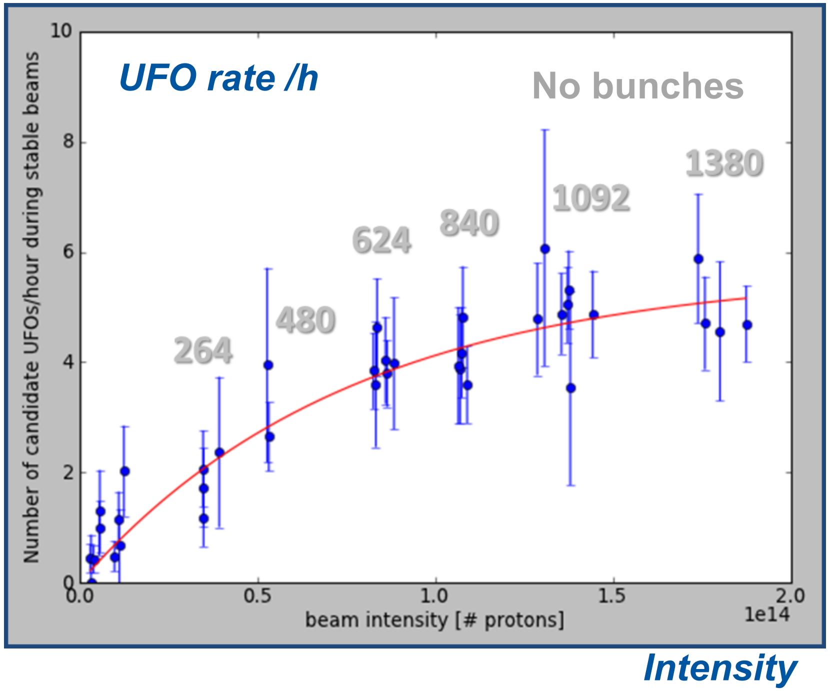
Intensity dependence and 7 TeV

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



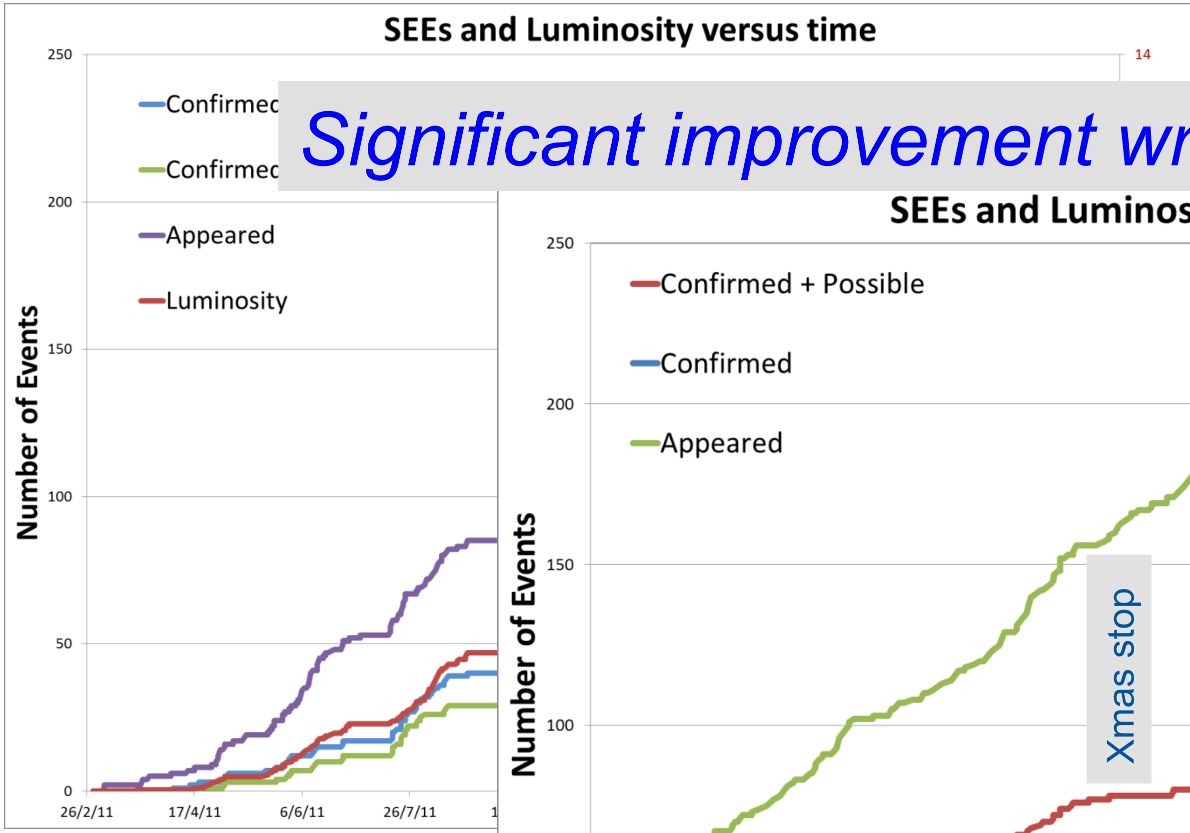
<u>At 7 TeV:</u>

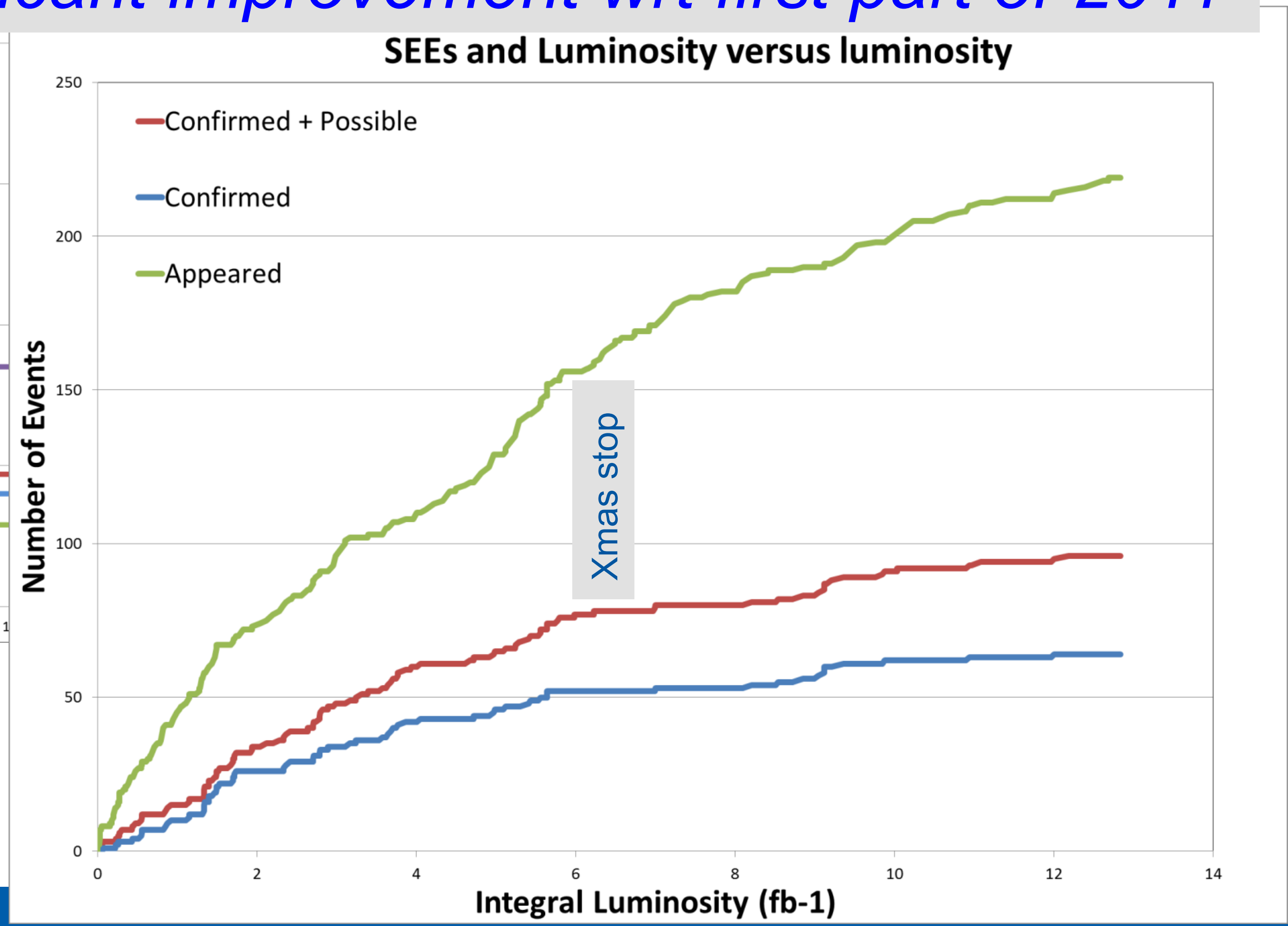
- The losses induced in the magnets by the UFOs will increase by a factor 3 (density at shower max in the magnets),
- The tolerable loss will go down by a factor 5 (higher B field),

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

Radiation to electronics (SEU)

Significant improvement wrt first part of 2011





Summary: 2010 to 2012

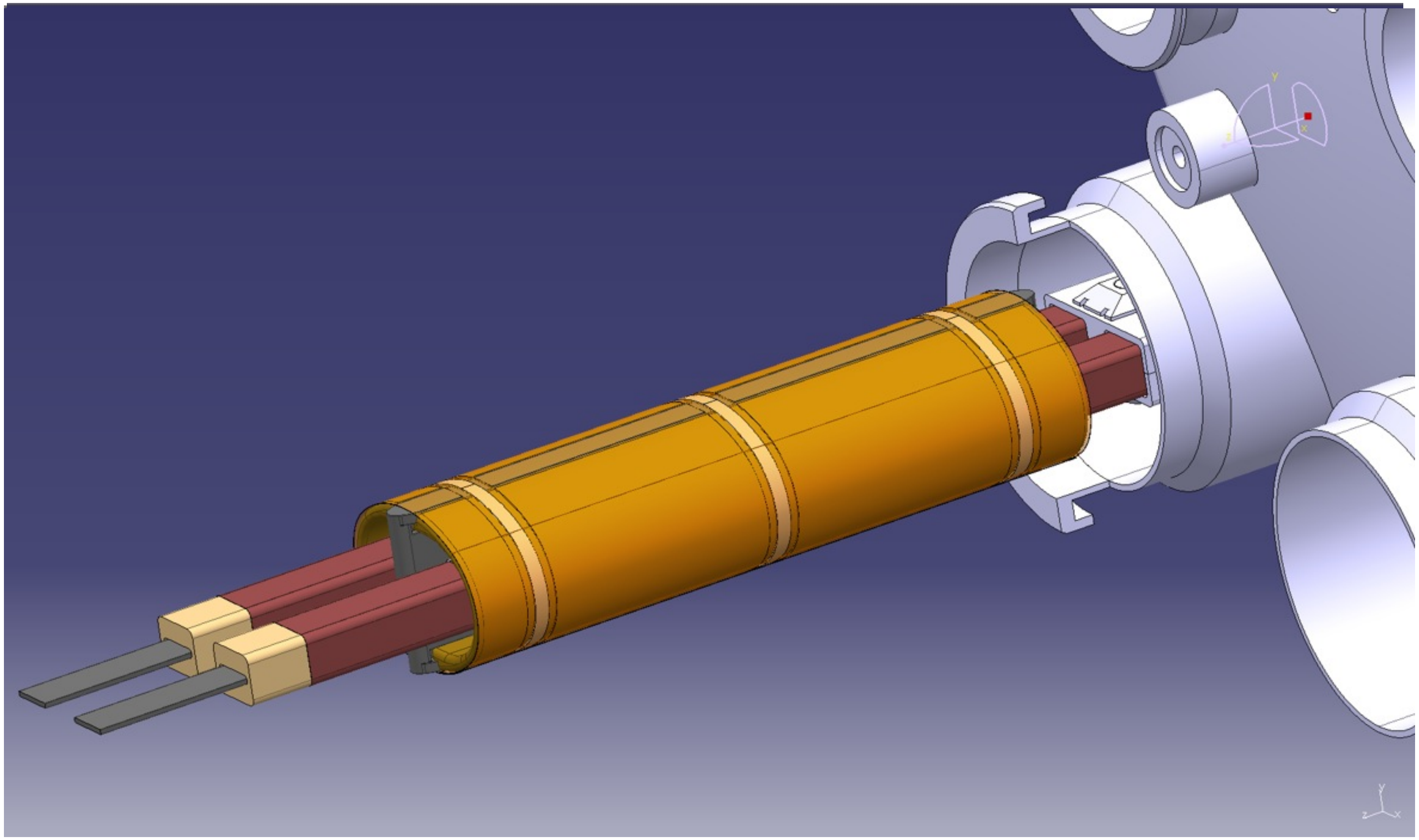
$$L = \frac{k N_b^{2} f \gamma}{4\pi \beta^{*} \varepsilon^{*}} F$$

- 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
e (mm rad)	2.4	2.4	2.5	3.75
b* (m)	3.5	1.5 → 1	0.6	0.55
L ($cm^{-2}s^{-1}$)	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

LS1 (2013-2014)
Prepare for 7 TeV!!

LS1 (2013-14) - Splice consolidation



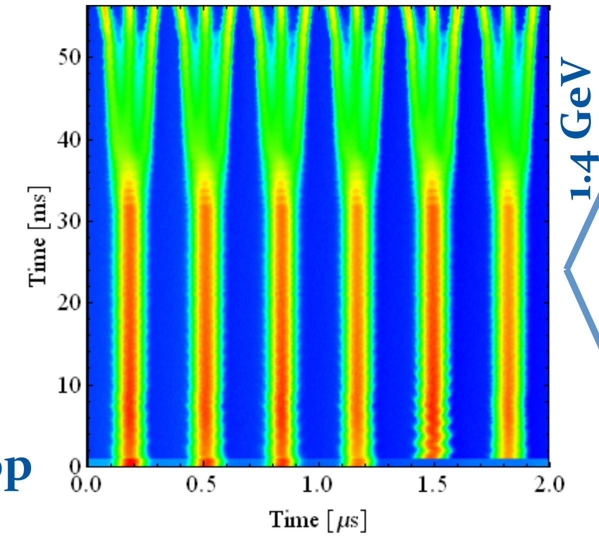
Phase III
Insulation between bus bar and to ground, Lorentz force clamping

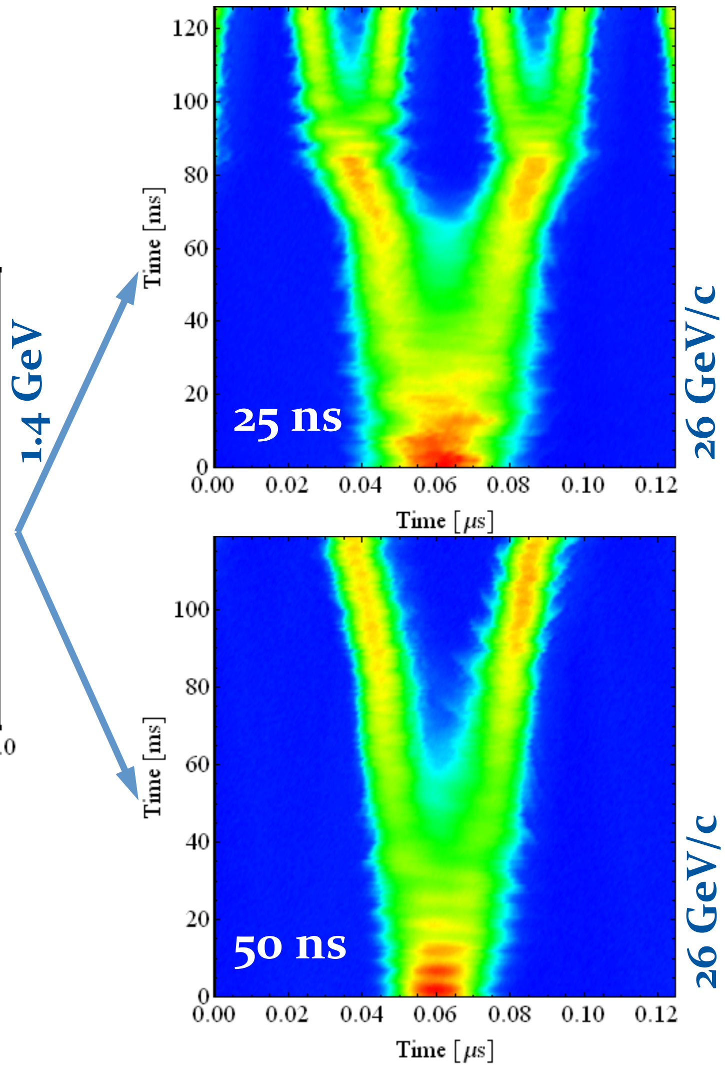
After LS1 (2015-17)
Physics at 7+7 TeV

Operational beams

- Established LHC beam generation scheme since 2000

1. Triple splitting on flat-bottom
2. Acceleration on *h* = 21
3. Double (50 ns) or quadruple (25 ns) splitting on flat-top





	25 ns	50 ns
Splitting ratio PS ejection/injection	12	6
Batch length from PS	72	36

H. Damerau

Key harmonic for acceleration *h* = 21, as bunch rotation cavities at *h* = 84/168

Batch compression and bunch merging

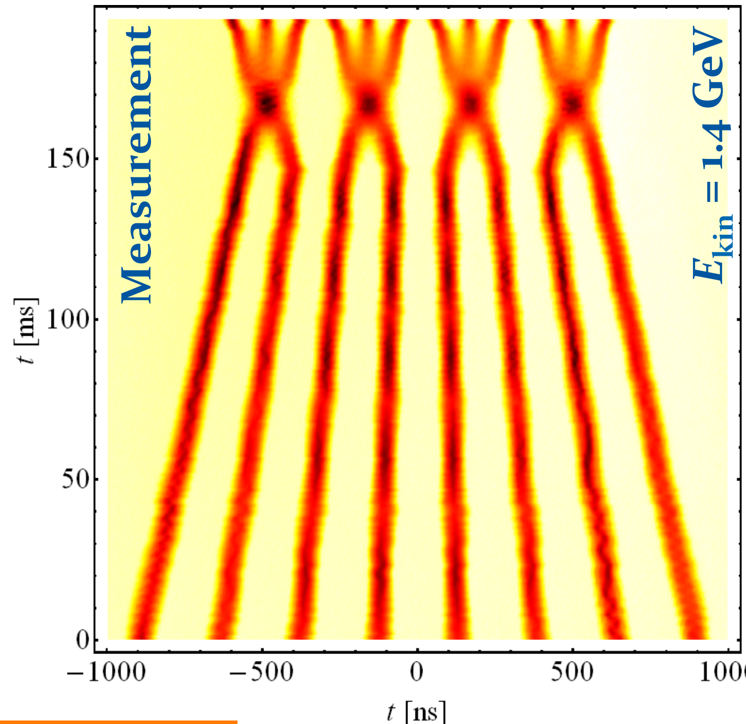
- **More evolved RF manipulations schemes from**

® **Most 'simple' scheme:** h = 9 → 10 → 11 → 12 → 13 → 14 → 7 → 21

	25 ns	50 ns
Splitting ratio PS ejection/injection	**6**	**3**
Batch length from PS	**48**	**24**

- **The "cake" coming from the PSB is divided in a smaller number of "slices"**
- **Shorter batch at PS extraction**

Pure h = 21



Pure h = 9

H. Damerau

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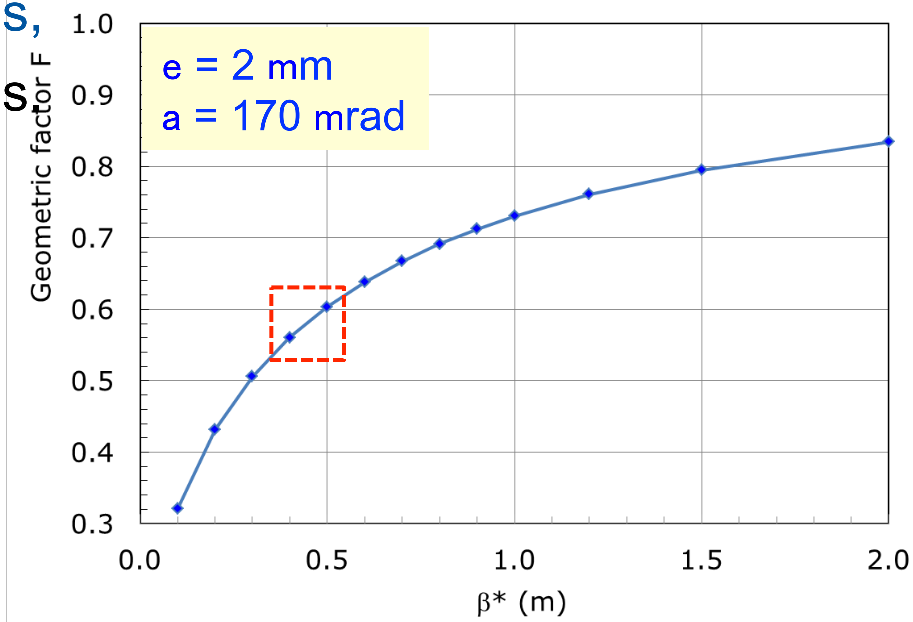
b* reach at 6.5+ TeV

- The b* reach depends on:
  - *The collimator settings and margins between collimators and with respect to apertures (we have a few scenarios…),*
  - *The beam type & emittance (25 ns / 50 ns) → crossing angle.*

- The range of minimum b* at 6.5+ TeV:
  - 0.4 m ≤ b* ≤ 0.5 m for 25 ns beams,
  - 0.3 m ≤ b* ≤ 0.4 m for 50 ns beams.

Loss of ~40-50% due to geometrical effect (crossing angle) !



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Luminosity at 6.5 TeV

3 out of many possible scenarios…

	k	N_b [10^{11} p]	e [mm]	b* [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!!!

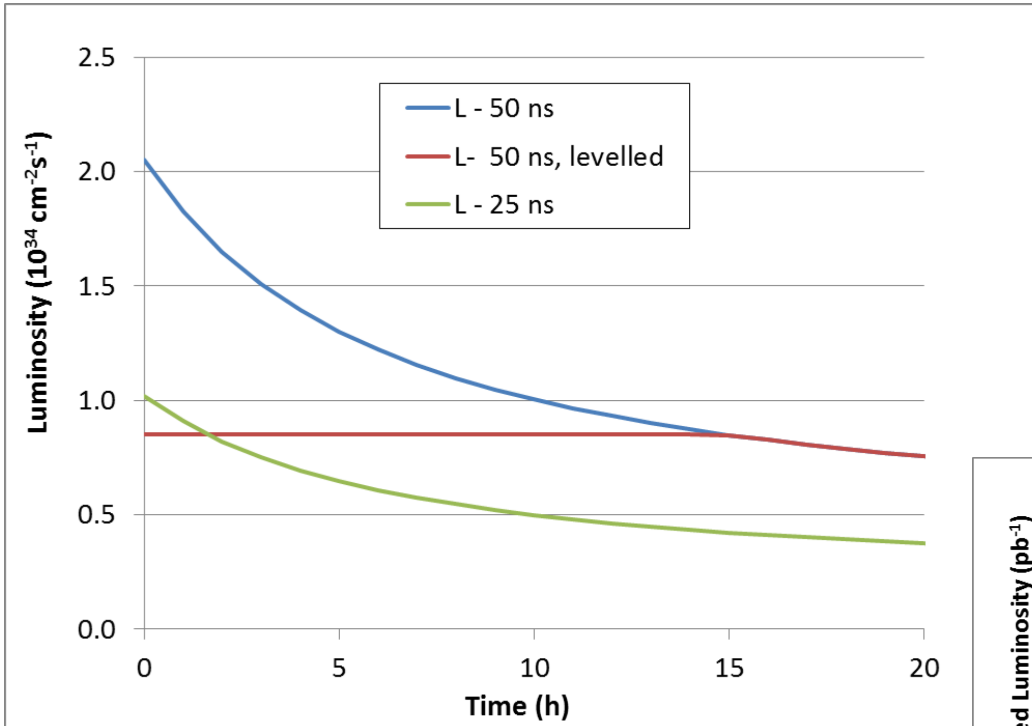
Int. L based on 120 days of production, 35% efficiency.

50 ns versus 25 ns

- 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 b*)*
  - *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, b* 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

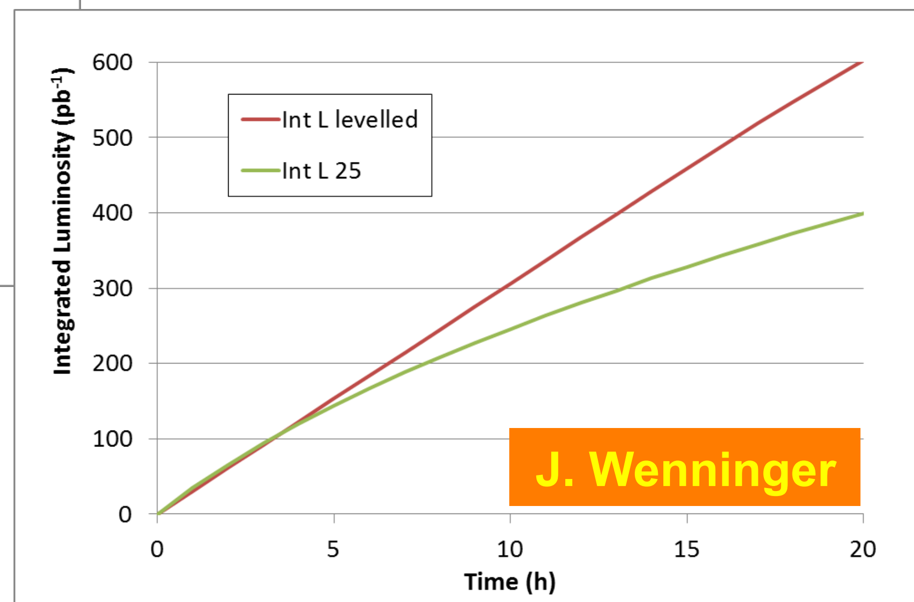
25 ns vs. 50 ns

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



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.

LHC & Injector Upgrade (2018 – onwards)

Ideas for the Upgrade

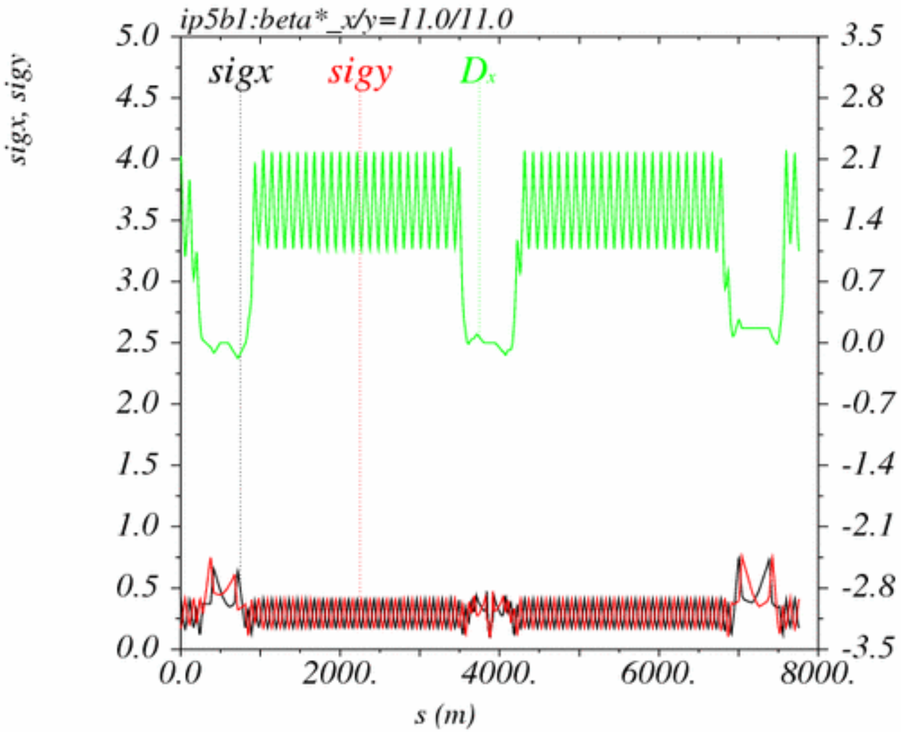
- Motivations:
  - Reduce statistical error by factor 3
  - Radiation damage limit of IR quadrupoles (~400 fb^{-1})

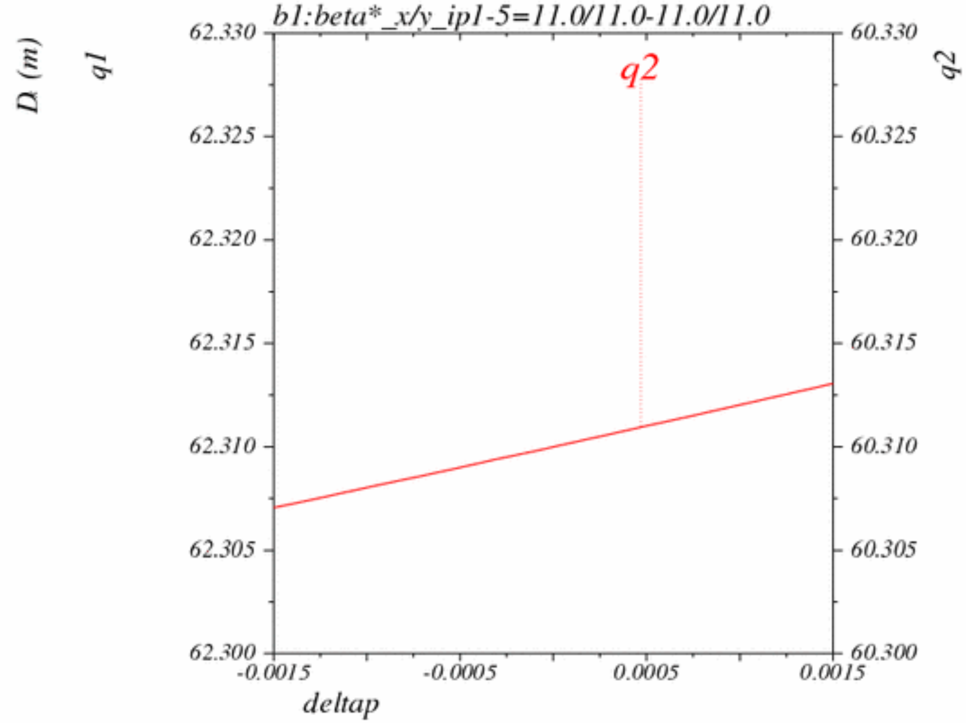
- Target (very ambitious) of the upgrade: 200 – 300 fb^{-1}/y (×10 today)

- 2010-2012 experience:
  - Head-on beam-beam limit higher than initially expected
  - Single bunch with > $3x10^{11}$ ppb with 2.5 mm emittance accelerated in the SPS
  - Low b* optics successfully tested in MD
  - Factor 2 higher peak luminosity with 50 ns spacing at the same current
  - Limit on total beam current in LHC due to several systems (RF, dump, vacuum, collimator robustness, machine protection, RP, …) at ultimate value (25 ns)
  - Expect more issues with 25 ns beam for electron cloud build-up

- Pile-up replaces beam-beam as HL-LHC constraint

Very low b* (10 cm)





IR4 IR5 IR6

Beam size [mm] and dispersion (IR4→IR6) at 3.5 TeV (for ge=3.5 mm)

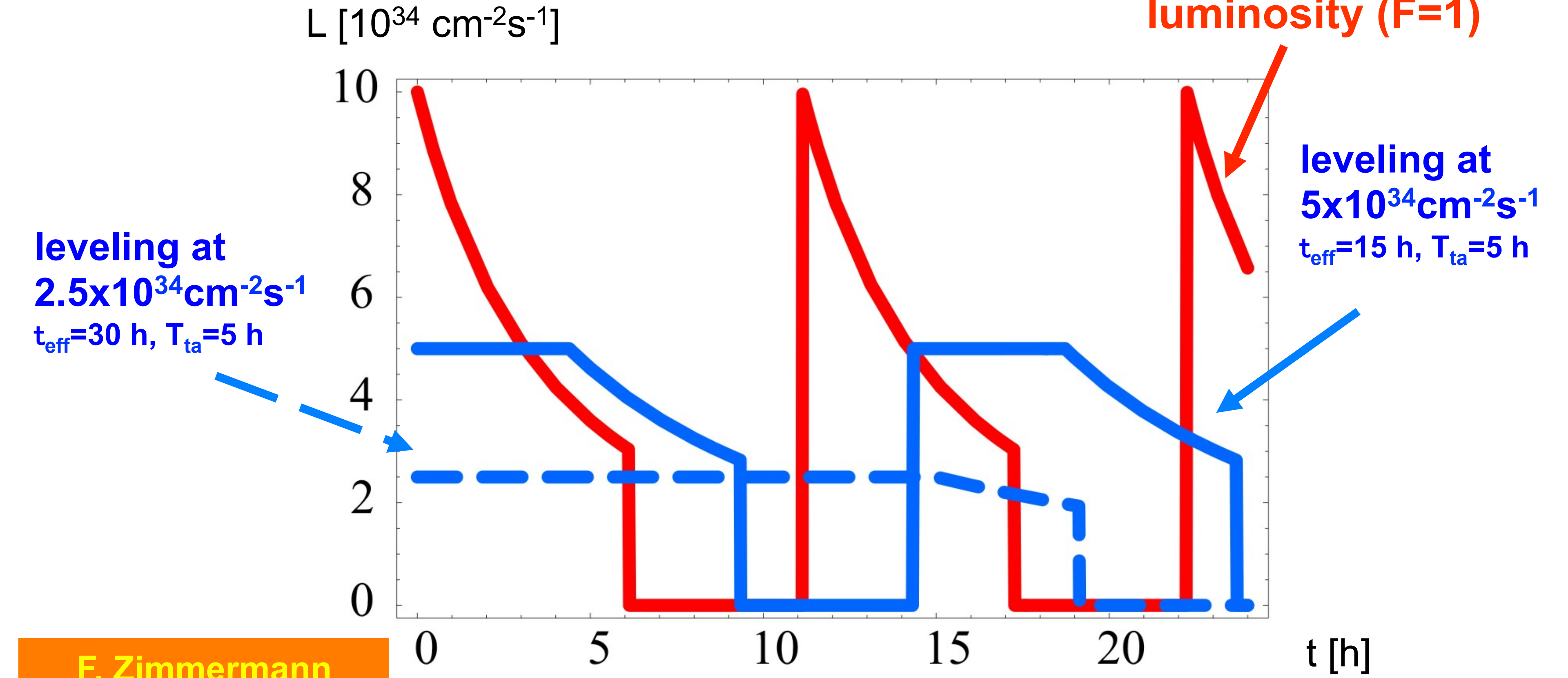
Tunes vs. d_p

ATS=Achromatic Telescopic Squeeze - S. Fartoukh

- …of course it requires larger aperture triplets

Ideas for the Upgrade

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

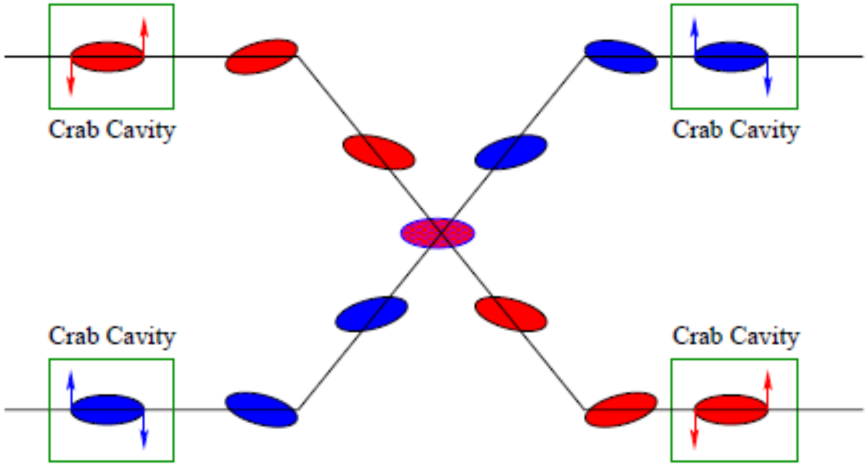


F. Zimmermann

Ideas for the Upgrade

- Operation at pile-up limit
  - ➔ choose parameters that allow higher than design pile-up
  - ➔ leveling mechanisms for controlling performance during run

- Preferred leveling mechanism: Crab Cavities (technology to be proven)



- Other tools for levelling:
  - dynamic β^* squeeze
  - transverse offsets at IP
  - crossing angle and Long-range and beam-beam wire compensators

O. Brü...g

HL-LHC Performance Estimates

Parameter	nominal	25ns	50ns
N	1.15E+11	**2.2E+11**	**3.5E**[illegible]
n_b	2808	2808	[illegible]
beam current [A]	0.58	**1.12**	[illegible]
x-ing angle [μrad]	300	[illegible]	[illegible]
beam separation [σ]	10	[illegible]	[illegible]
β^* [m]	0.55	[illegible]	[illegible]
ϵ_n [μm]	[illegible]	[illegible]	[illegible]
ϵ_L [eVs]	[illegible]	[illegible]	[illegible]
energy spread	[illegible]	[illegible]	[illegible]
bunch len[illegible]	[illegible]	[illegible]	[illegible]E-02
IBS h[illegible]	[illegible]	[illegible]	**20.7**
[illegible]	[illegible]	[illegible]	**13.2**
[illegible]	[illegible]	**2.7**	**2.9**
[illegible]	[illegible]	**0.35**	**0.33**
L[illegible]	[illegible]	**3.9E-03**	**5.0E-03**
Pe[illegible]	[illegible] 10^{34}	**9.0 10^{34}**	**7.9 10^{34}**
Virt[illegible]	1.2 10^{34}	**26 10^{34}**	**24 10^{34}**
Events [illegible]g	19	**171**	**340**

[illegible] (25ns) of [illegible] 10^{34} cm^{-2} s^{-1}

[illegible] 10^{34} cm^{-2} s^{-1} ('k' = 5)

Virtual luminosity (50ns) of L = 7.9 / 0.33 10^{34} cm^{-2} s^{-1}

= 24 10^{34} cm^{-2} s^{-1} ('k' = 10)

(Leveled to 5 10^{34} cm^{-2} s^{-1} and 2.5 10^{34} cm^{-2} s^{-1})

95 **95**

➔ requires between 148 and 400 fills per year to reach L_{int}=250 fb^{-1} per year!

➔ if pile-up < 100 ➔ $h = L_{int} / (L_{lev} \times \text{scheduled time})$

➔ h = 39% for L_{lev} = 5×10^{34} cm^{-2} s^{-1} @ 25ns, 250 fb^{-1} and 150 days

➔ h = 78% for L_{lev} = 2.5×10^{34} cm^{-2} s^{-1} @ 50ns, 250 fb^{-1} and 150 days

➔ h for 50ns significantly larger than 2011 LHC experience!

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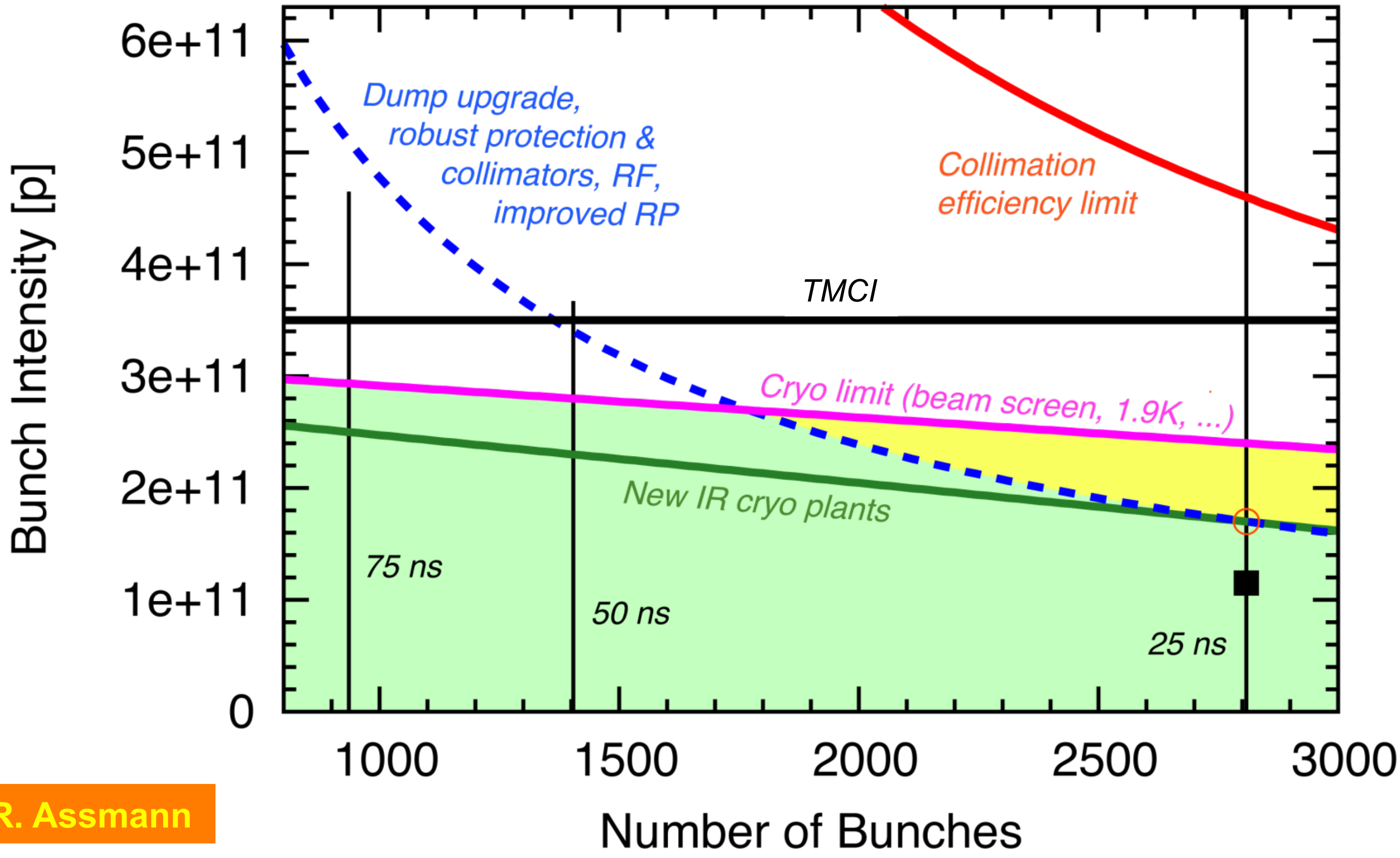
LHC limits

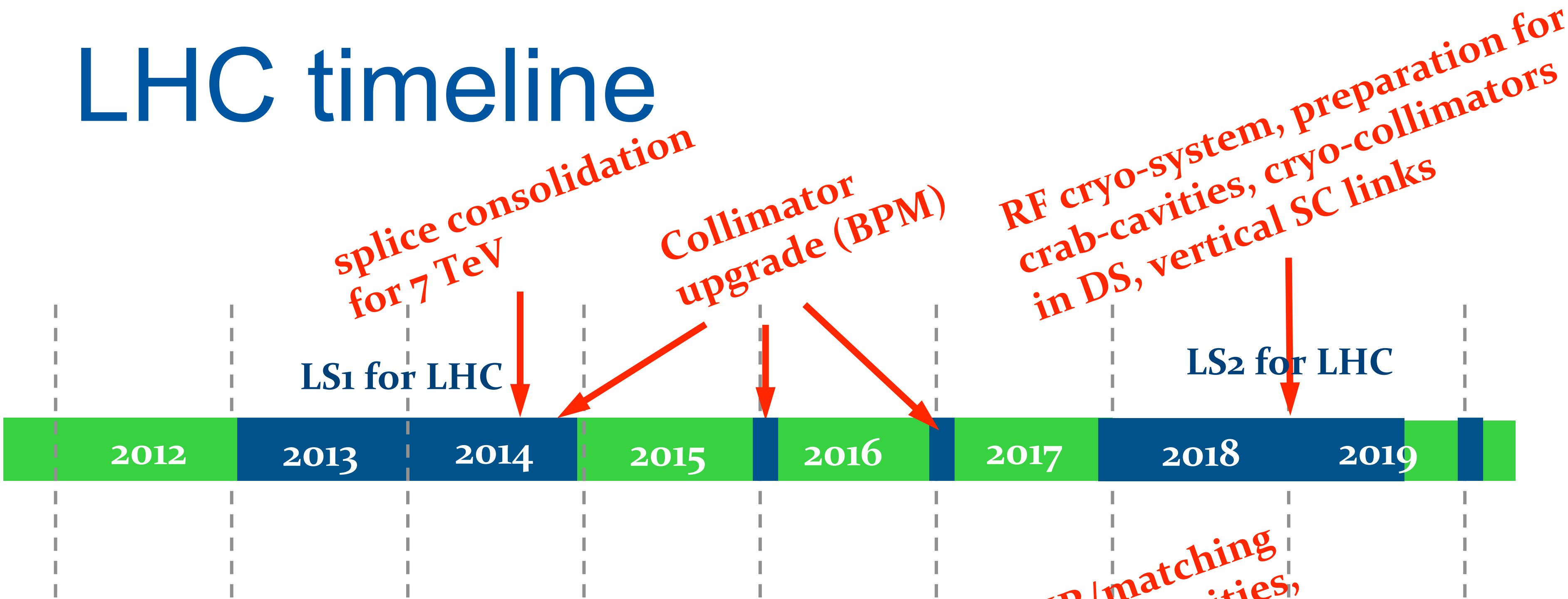


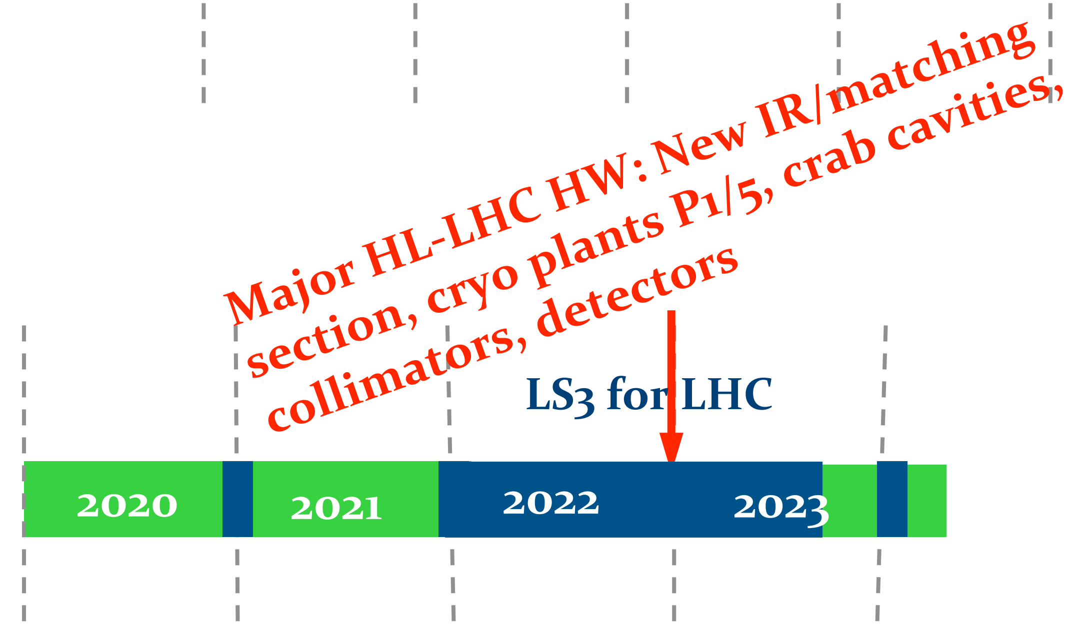
R. Assmann

Hardware for the Upgrade

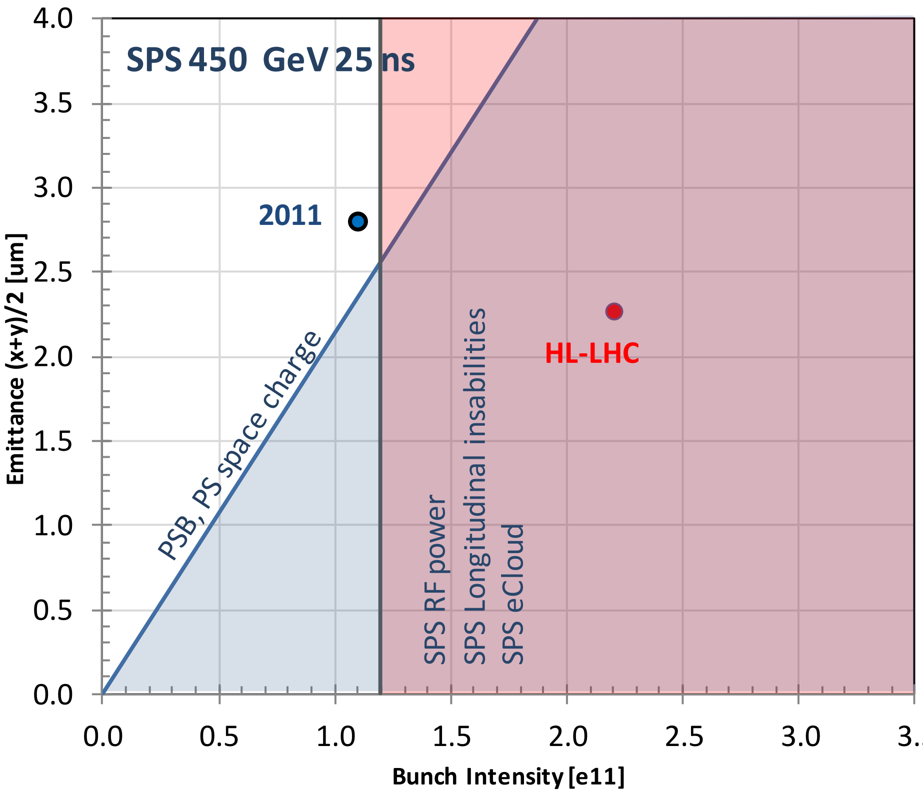
- New high field/larger aperture interaction region / matching section magnets
- Cryo-collimators and high field 11 T dipoles in dispersion suppressors
- New collimators (lower impedance)
- Additional cryo plants for P1, P4, P5
- Crab Cavities to take advantage of the small b*
- Single Event Upsets
  - SC links to allow power converters to be moved to surface
- Upgrade of the intensity in the Injector Chain

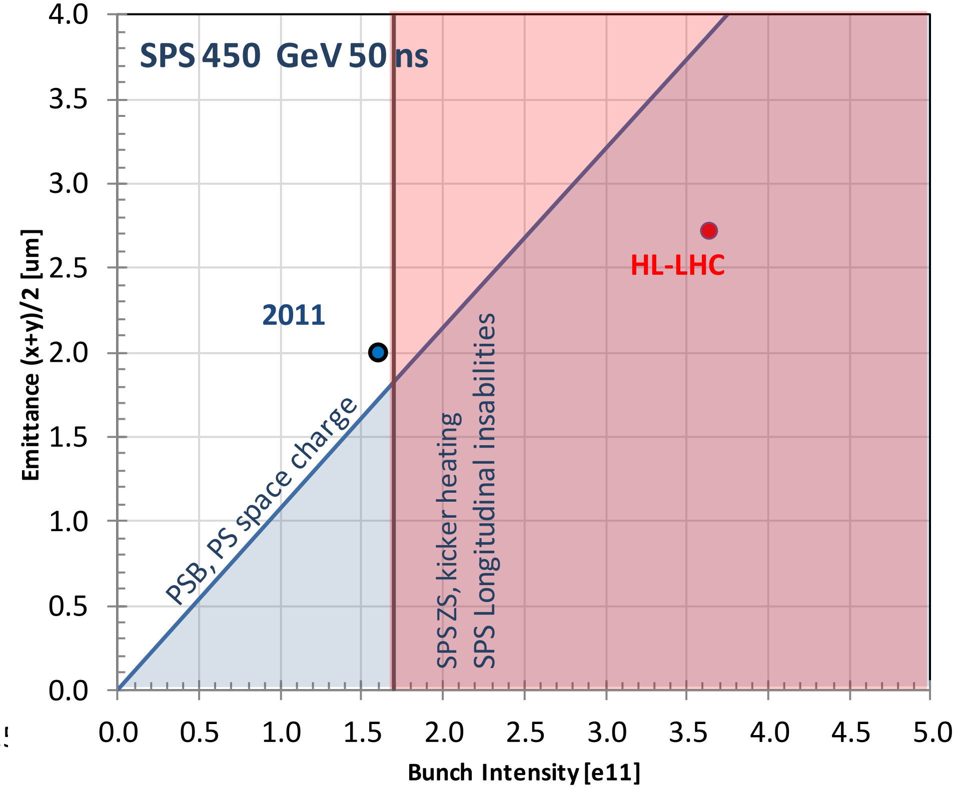
LHC timeline





2011 to post-LS2





B. Goddard

- 2011 was excellent: 1.5e11 with 2.0 um for 50 ns, around 1.1 e11 with 2.8 um for 25 ns, extracted from SPS
- Large improvement is required for either 25 or 50 ns beam!

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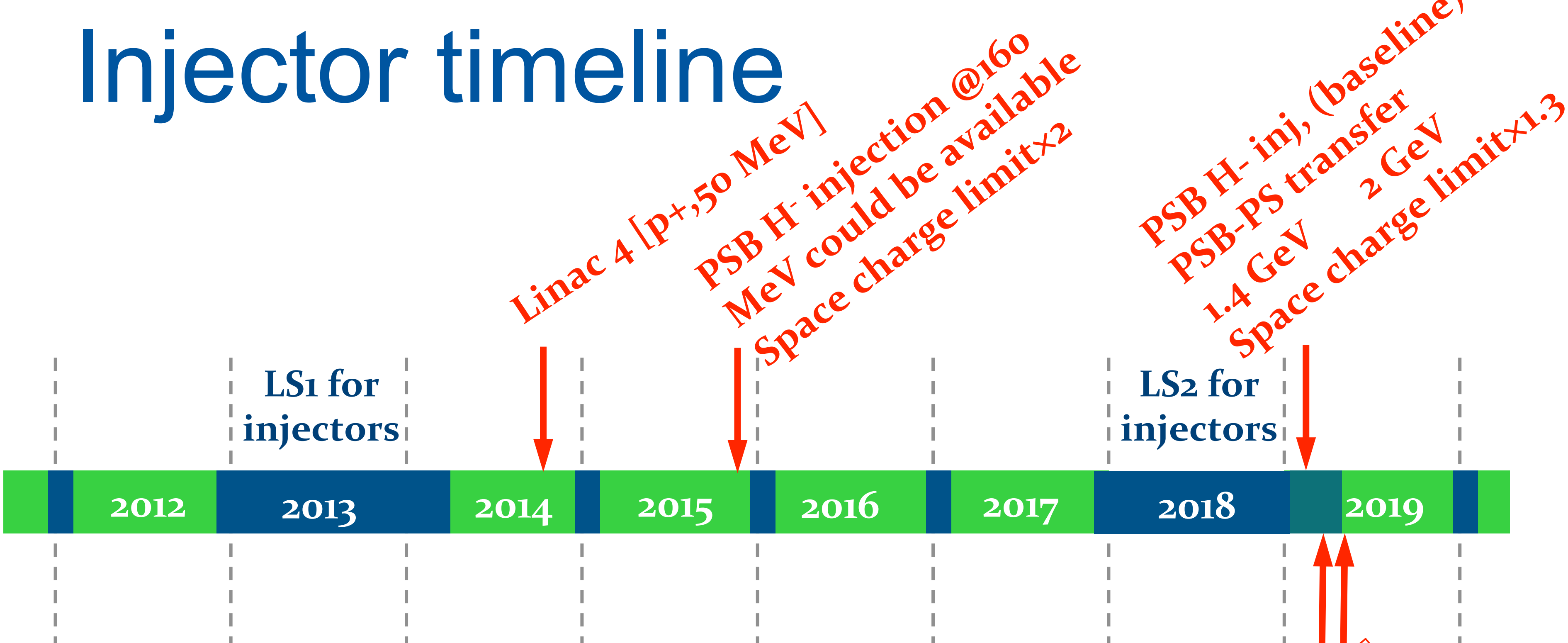
Injector timeline



Summary

- The progress in the performance of the LHC has been so far breath-taking
- This has been 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
- Luminosity performance and choice for the upgrade are now constrained by the acceptable detector pile-up

Thank you for your attention!!

… THAT THE LARGE HADRON COLLIDER HAS … ARTED WE CAN WATCH THE FIRST BLACK HOLES HANGING AROUND IN THE WILD

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