LHC Status and Plans

John Jowett, CERN

With thanks to G. Arduini for material and
many other colleagues at CERN,

European Strategy

- ***Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.***

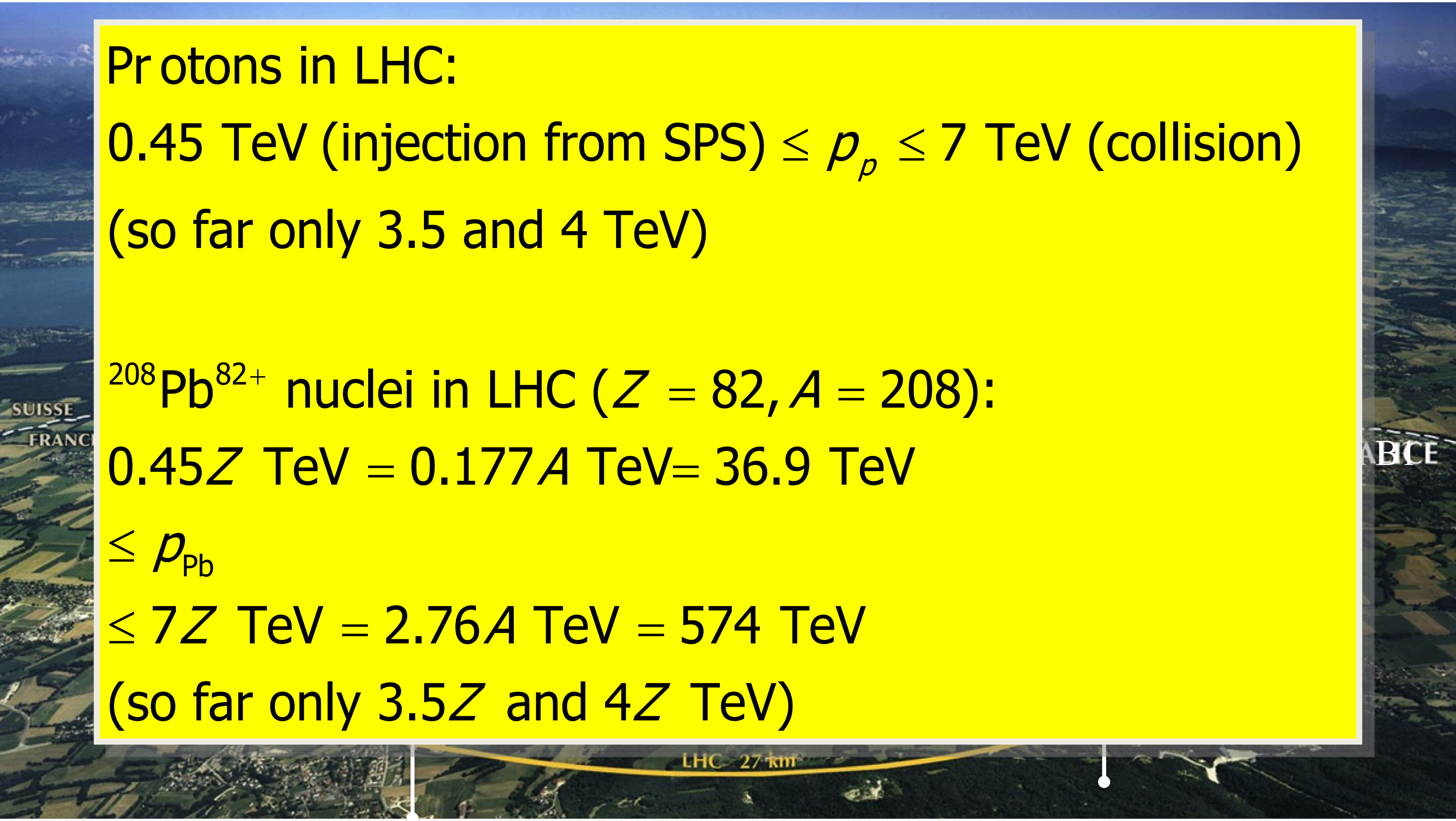
Plan of talk

- LHC generalities
- Performance with p-p
  - Achieved in Run 1
  - Expectations for Run 2, Run 3 and beyond, the HL-LHC
- Performance with Pb-Pb and p-Pb
  - Achieved in Run 1
  - Expectations for Run 2 and beyond, heavy ion HL-LHC

Cannot cover immense amount of detail, this will be an somewhat impressionistic selection of topics related to beam physics and operation.
See many other sources, eg, Chamonix 2014 workshop for more detail.

LHC GENERALITIES

The LHC



Protons in LHC:

0.45 TeV (injection from SPS) $\le p_p \le 7$ TeV (collision)

(so far only 3.5 and 4 TeV)

$^{208}\mathrm{Pb}^{82+}$ nuclei in LHC ($Z = 82, A = 208$):

$0.45Z$ TeV $= 0.177A$ TeV $= 36.9$ TeV

$\le p_{\mathrm{Pb}}$

$\le 7Z$ TeV $= 2.76A$ TeV $= 574$ TeV

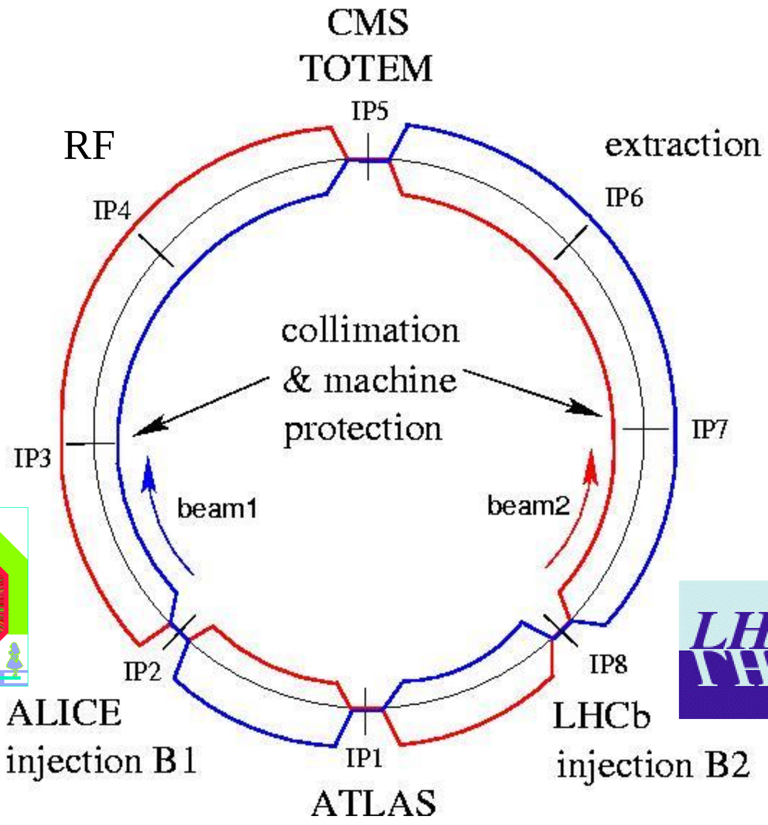
(so far only $3.5Z$ and $4Z$ TeV)

Annual run structure (typical)

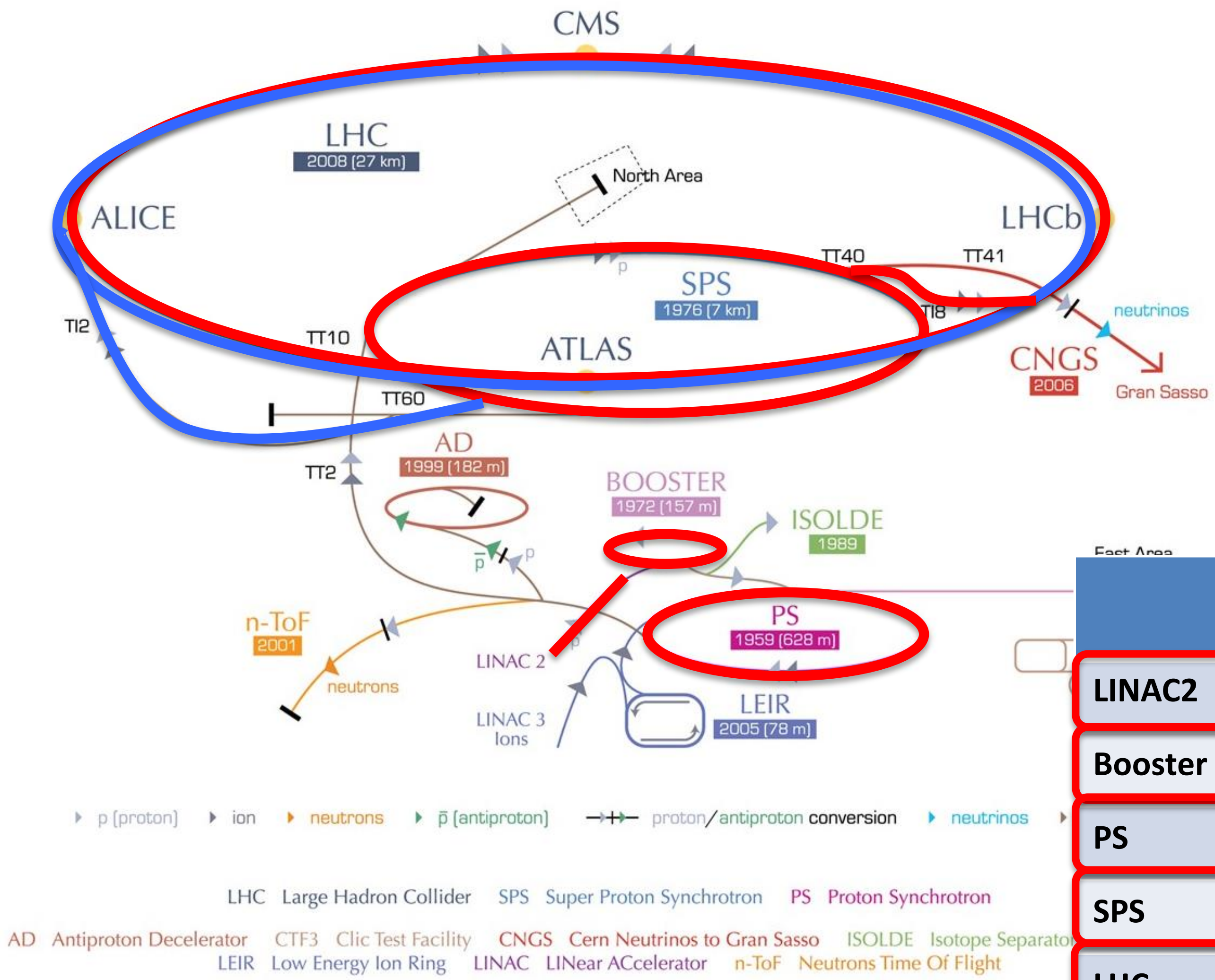
- Startup with proton-proton collisions, for ATLAS, ALICE, CMS, LHCb, ramp up performance
- Pattern of 1 month heavy-ion run at the end of each year
  - May include p-p at equivalent energy
  - Allows radiological cool-down before shutdowns
- ALICE, ATLAS, CMS for full heavy-ion programme
  - LHCb joins for p-Pb

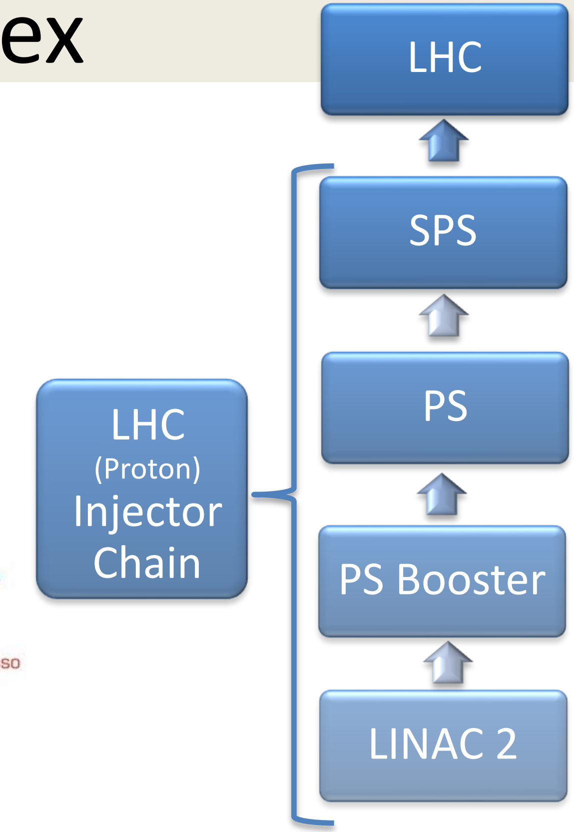
LHC layout

- Total length: ~26.7 km
  - 8 arcs (aka sectors): ~2.8 km each
  - 8 long straight sections: ~700 m each
- 2-in-1 magnet design with separate vacuum chambers ➔ coupled rings
  - p-p, ion/ion, or p/ion collisions
  - beams cross in 4 points



LHC Injector Complex




LHC

LHC (Proton) Injector Chain

SPS

PS

PS Booster

LINAC 2

	Max. En. (GeV)	Length / Circ. (m)
LINAC2	**0.050**	**30**
Booster	**1.4**	**157**
PS	**25**	**628=4 x PSB**
SPS	**449**	**6’911=11 x PS**
LHC	**7’000**	**26’657=27/7 x SPS**

Reminder: Luminosity of a hadron collider (1)

Event rate for process with given cross section $= \sigma L$

Particles removed from beam by collisions

$$\frac{dN_b}{dt} = -\sigma_{\text{tot}} L + \text{(other single beam physics)}$$

$$\sigma_{\text{tot}} = \begin{cases} 0.09 \text{ b (proton-proton)} \\ 520 \text{ b (Pb-Pb)} \end{cases}$$

al amplitude functions:

$= \beta_y^* = \beta^*$,

metric and normalised emittance:

$$\varepsilon_x^* = \varepsilon_y^* = \varepsilon^* = \frac{\varepsilon_n}{\sqrt{\gamma^2 - 1}}$$

$\Rightarrow$ Round beams at IP:

$$\sigma_x^* = \sigma_y^* = \sigma^* \square \sqrt{\frac{\beta^* \varepsilon_n}{\gamma}}$$

(N.B. LHC uses RMS emittances.)

- Parameters in luminosity
  - No. of particles per bunch N
  - No. of bunches per beam k_b
  - No. of bunches collliding at IP k_c
    - $(k_c < k_b)$
  - Relativistic factor γ
  - Normalised emittance ε_n
  - Beta function at the IP β^*
  - Crossing angle factor F
    - Full crossing angle θ_c
    - Bunch length σ_z
    - Transverse beam size at the IP σ^*

Reminder: Luminosity of a hadron collider (2)

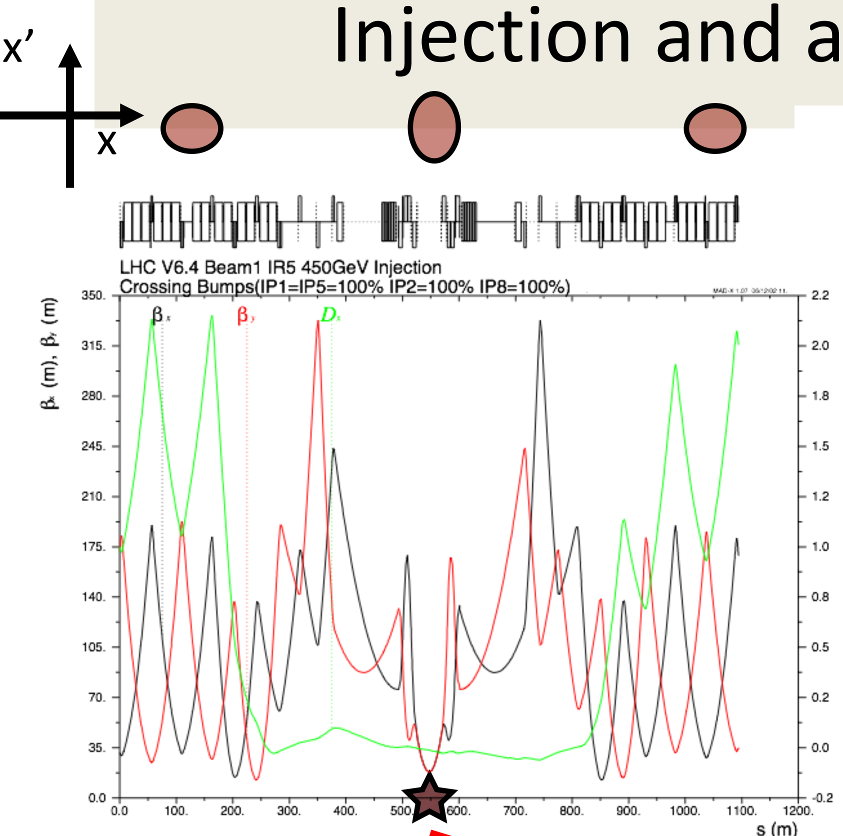
$$L = \frac{N_b{}^2 k_c f}{4\pi\sigma_x\sigma_y} F = \frac{N_b{}^2 k_c f_0 \gamma}{4\pi\,\varepsilon_n \beta^*} F(\theta_c)$$

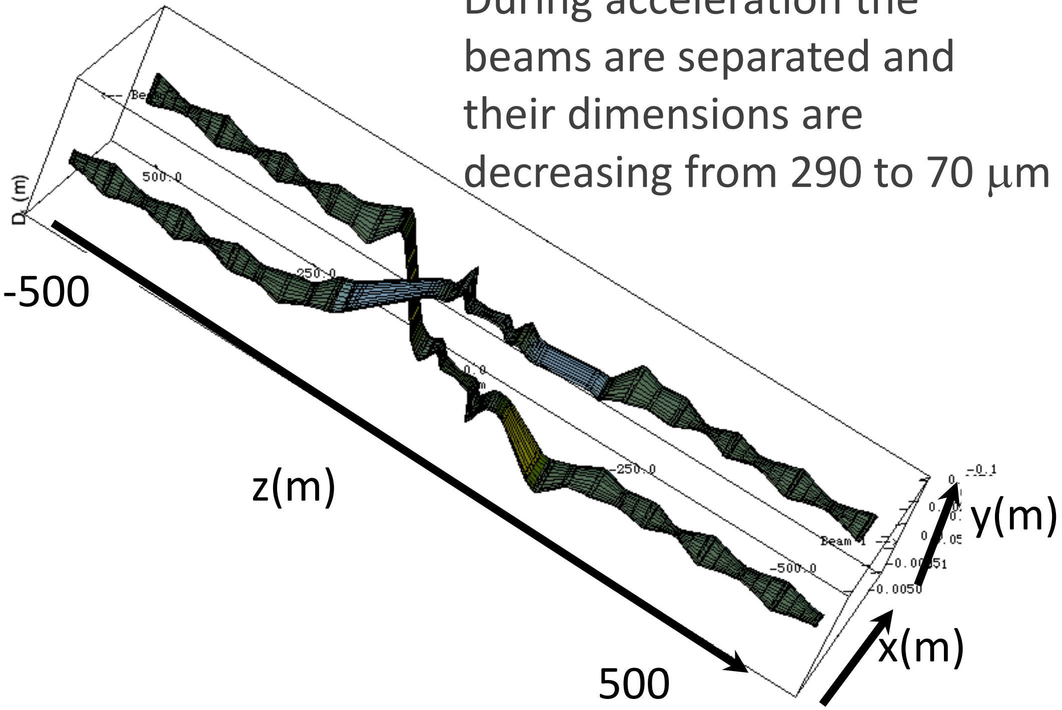
Hour glass factor: $F = 1 / \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$

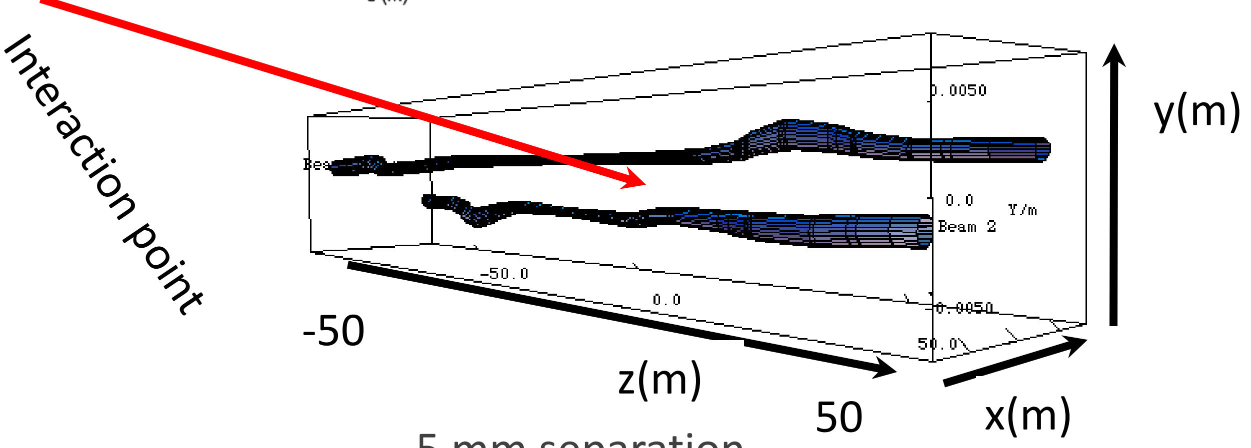
We want to collide many high intensity, low-emittance bunches, at an interaction point where the beam is focused down to a small point (at least as long as the number of events per bunch collision, the “pile-up” can be handled by the experiment).

Injection and acceleration IP5 (CMS)

During acceleration the beams are separated and their dimensions are decreasing from 290 to 70 μm

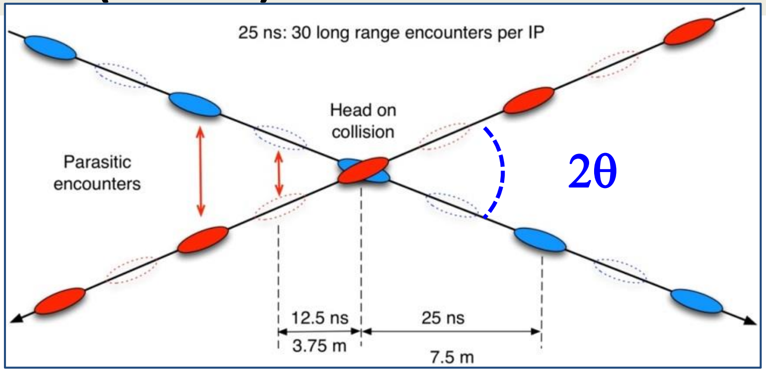


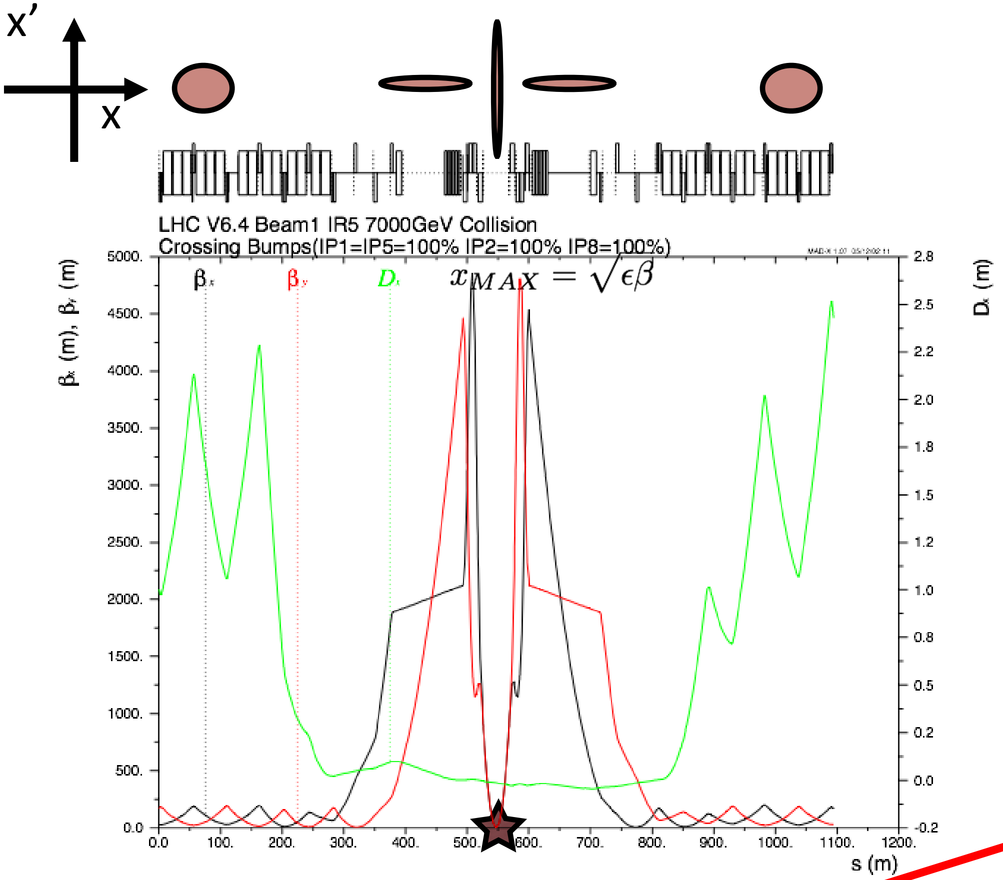


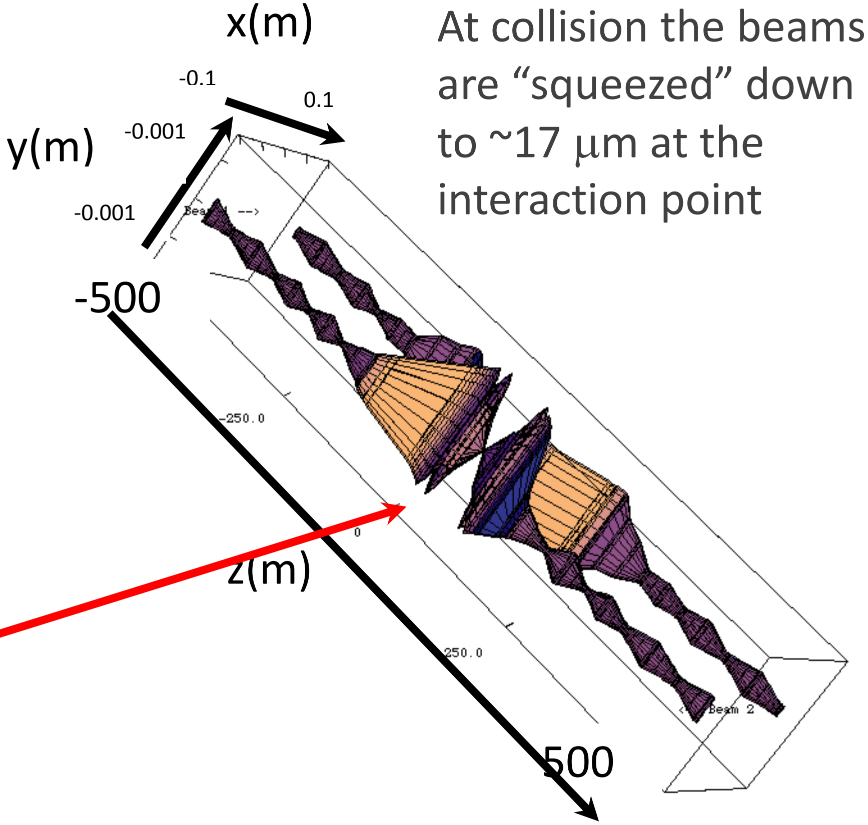


5 mm separation

Optics at collision IP5 (CMS)



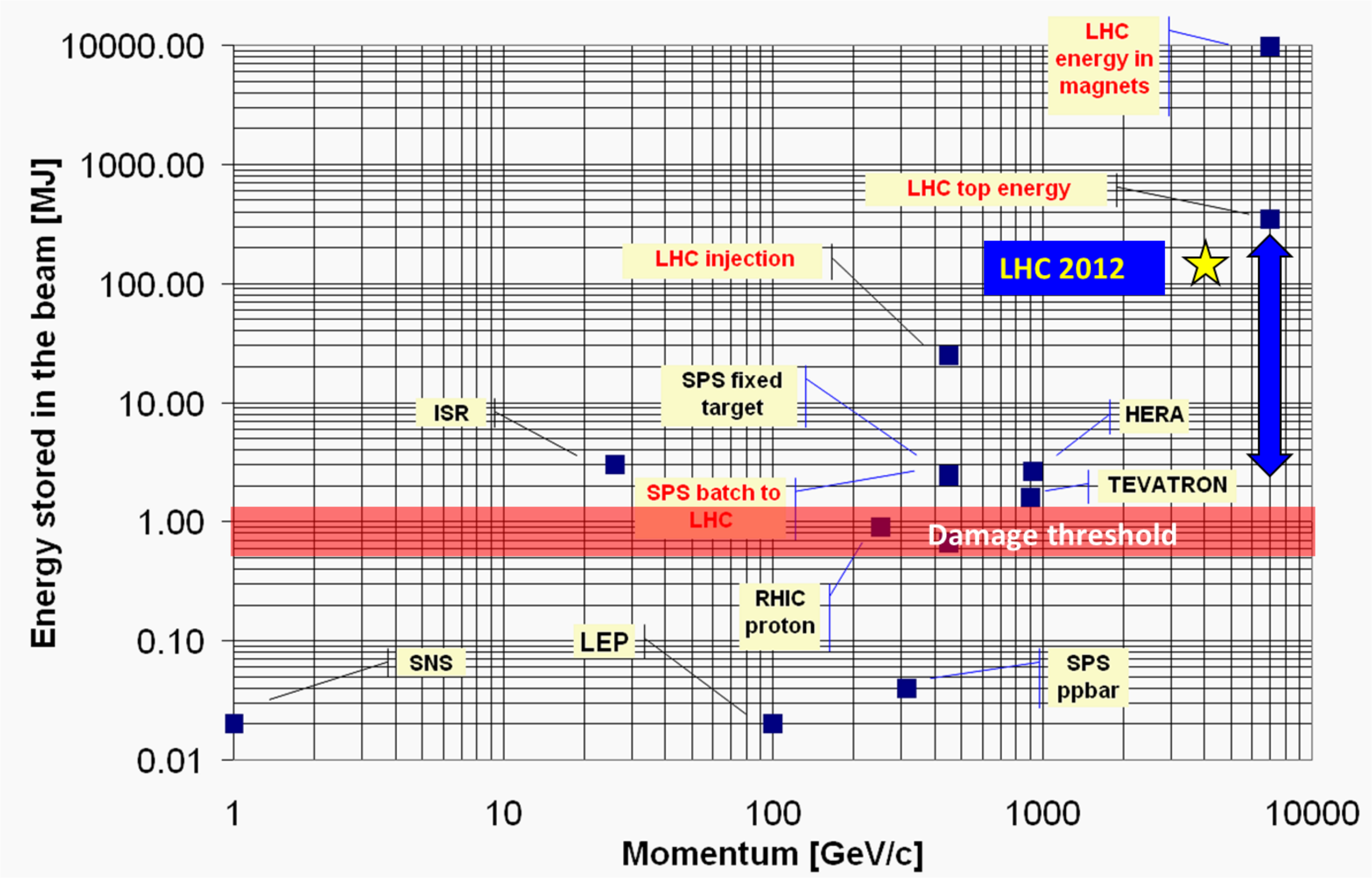




At collision the beams are "squeezed" down to ~17 μm at the interaction point

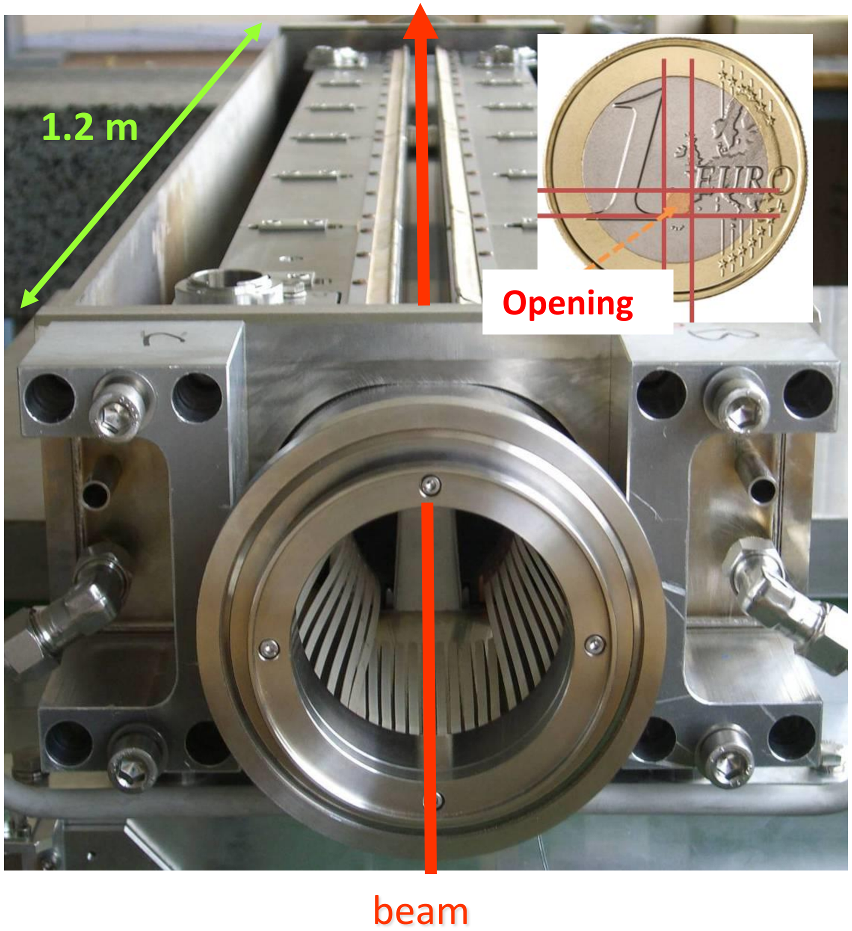
Stored energy

Design : 360 MJ – 4 TeV maximum : 150 MJ



Beam collimation

- To contain the large stored energy and intensity the LHC requires a large beam collimation system.

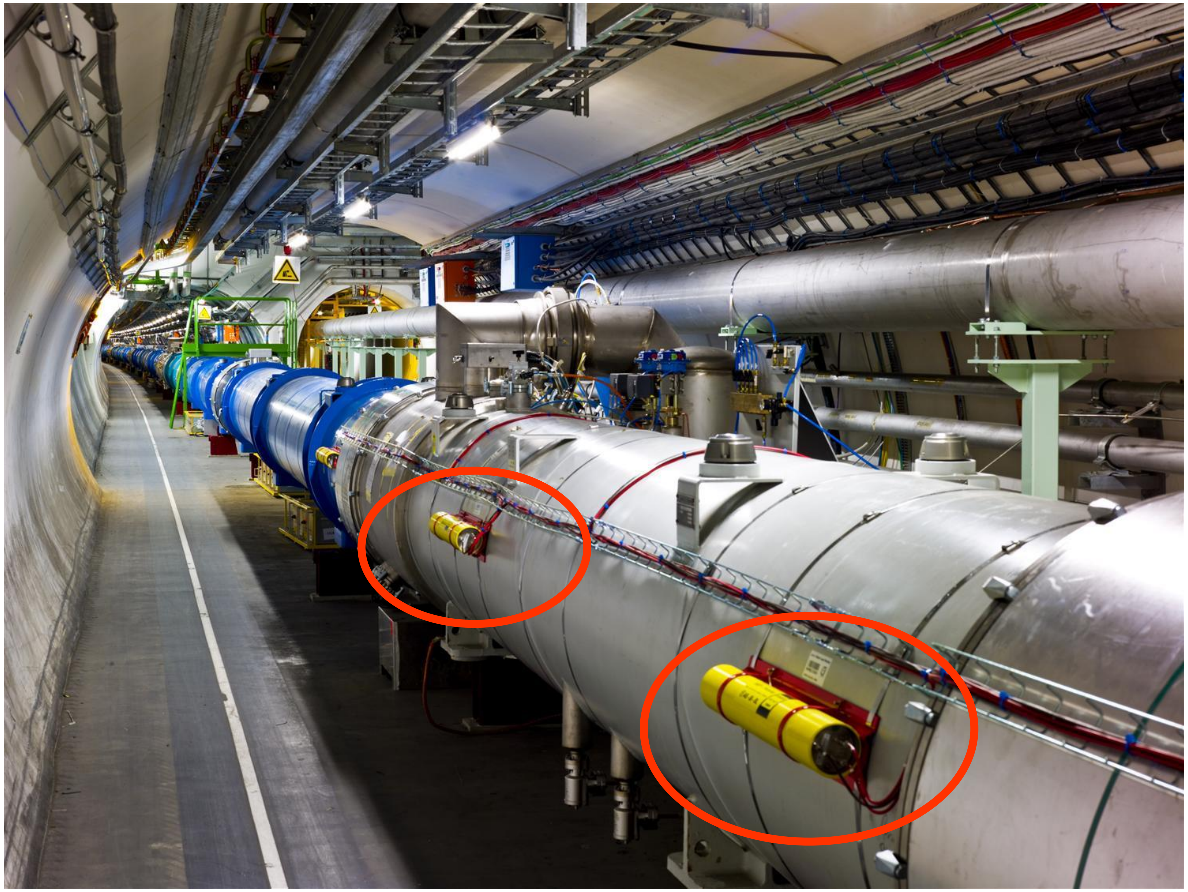


- Almost 100 collimators and absorbers,
- System designed to intercept ~99.99% of the protons lost from the beam.
- No magnet was quenched with beam at 3.5 / 4 TeV.
- Most collimators are made of Carbon to survive large beam loss (low Z material ➔ lower energy density).

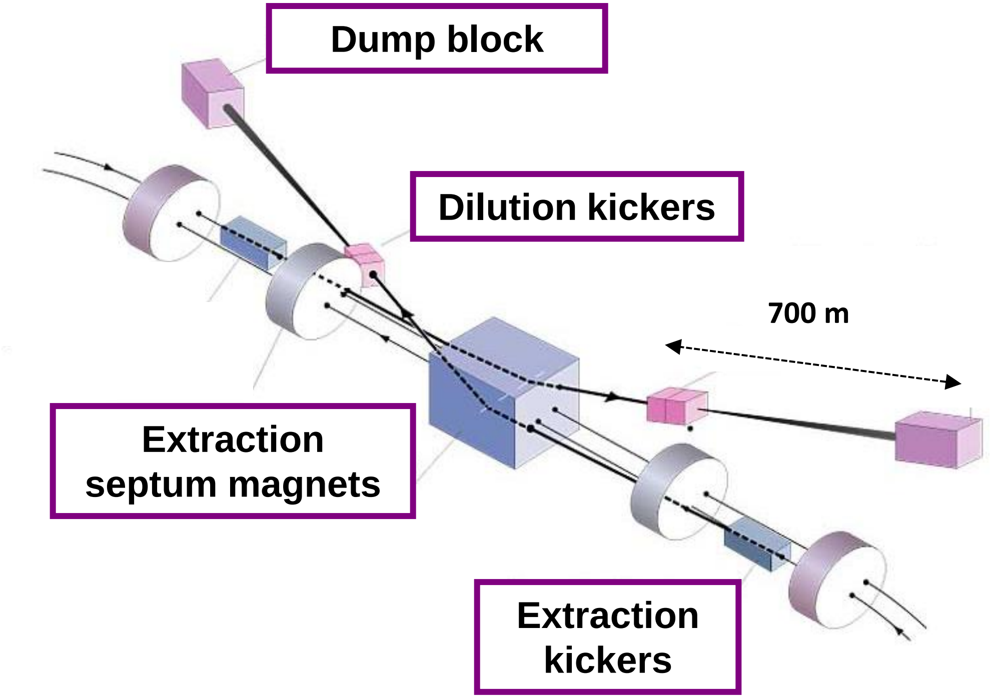
360 MJ in each beam vs. few mJ to quench a magnet

Beam loss monitoring

- ~3600 Ionization chambers distributed over the ring are used to detect abnormal loss of beam and if necessary to trigger a beam extraction to the dump !



Beam dumping system



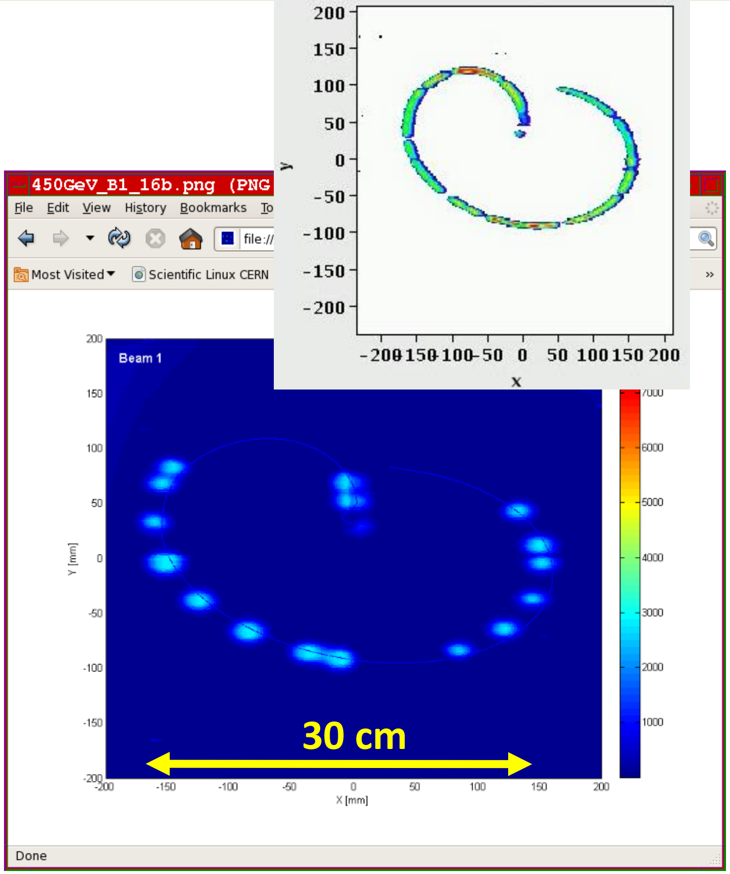
Dump block

Dilution kickers

700 m

Extraction septum magnets

Extraction kickers

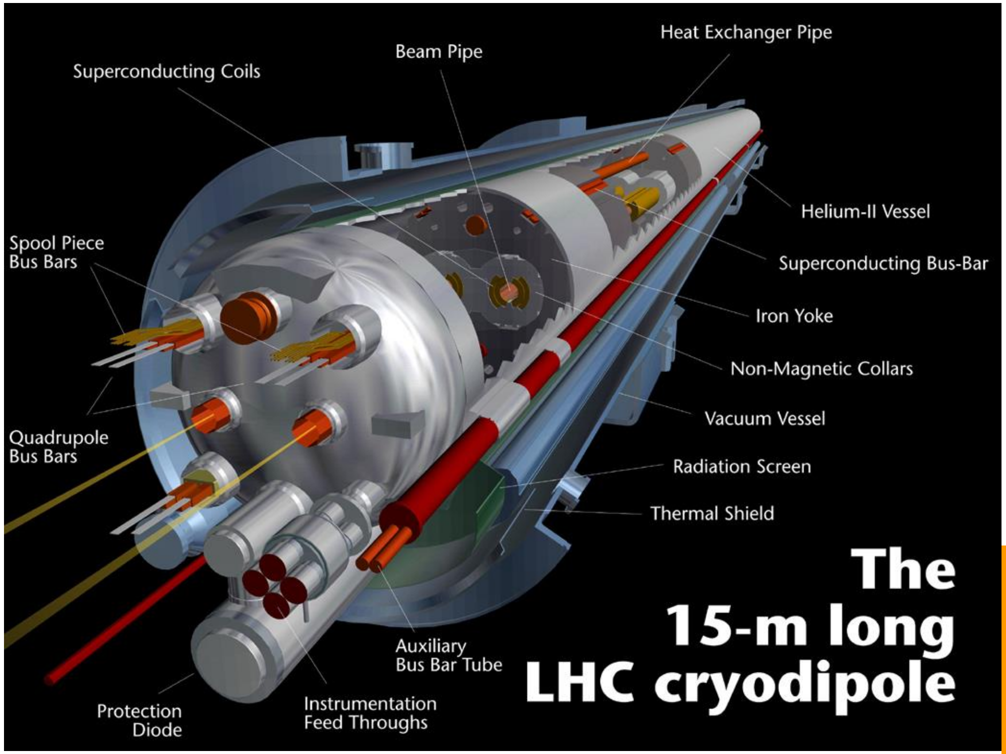


- The dump is the only LHC element capable of absorbing the nominal beam.
  - Beam swept over dump surface (lower power density).
  - Ultra-high reliability and fail-safe system.

PERFORMANCE WITH PROTON-PROTON COLLISIONS

Run 2: More energy

- 1232 Nb-Ti superconducting dipole magnets.
- 2 magnets-in-one design : two beam tubes with an opening of 50 mm
- 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 – huge campaign of work, now ending, circuits being tested and magnets trained now
- Many changes, upgrades, repairs, see Chamonix 2014 workshop for detail

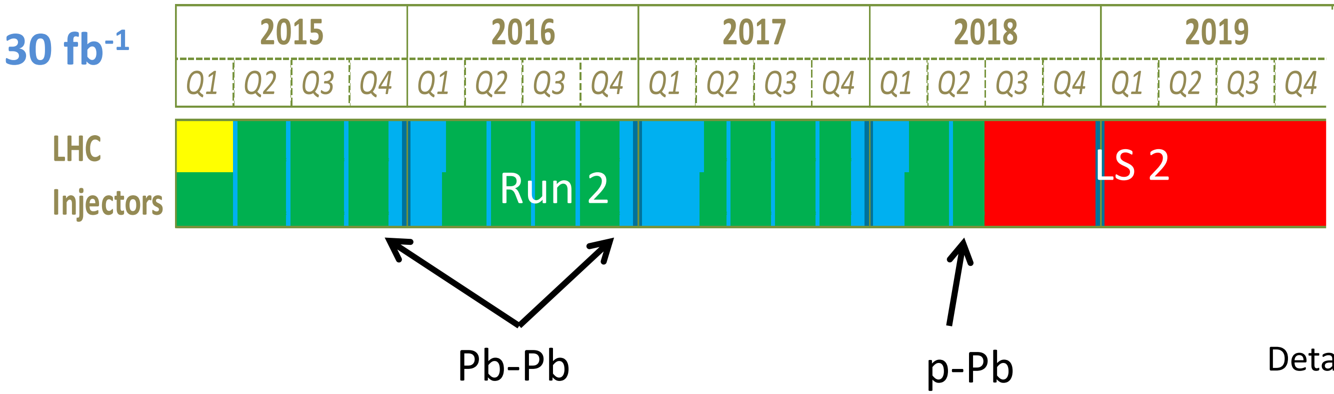


Operating challenges:

- **Dynamic field changes at injection.**
- **Very low quench (transition to normal conducting state) levels (~ mJ/cm^3)**

LHC Schedule for Run 2

- 🟩 Physics
- 🟥 Shutdown
- 🟨 Beam commissioning
- 🟦 Technical stop



Detail of heavy-ion runs may depend on physics community requests.

(Extended) Year End Technical Stop: (E)YETS

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators (December 2013)

Configuration and guidelines

- What we need is small β*, bright & stable beams, levelling (μ <=30)
- The main strategy is to concentrate on 6.5 TeV and 25 ns /2800b beam and to reduce complexity:
  - Relaxed β* of 80 cm (65 cm + ~2σ margin) for the startup.
  - BCMS scheme provides margin for emittance blow-up, but entails MPS constraints
  - Explore in 2015, produce in >=2016 !

Parameter	Value @ injection	Value @ collision
Energy [TeV]	0.45	6.5
β* (1/2/5/8) [m]	11 / 10 / 11 / 10	0.8 / 10 / 0.8 / 3
Half X-angle (1/2/5/8) [μrad]	-170 / 170 / 170 /170	-145* / 120 / 145* / -250
Tunes (H/V)	64.28 / 59.31	64.31 / 59.32
Separation (1/2/5/8) [mm]	2 / 2 / 2 / 3.5	0.55 / 0.55 / 0.55 / 0.55
Emittance (BCMS/standard) [μm]	≥ 1.3 / ≥ 2.4	≥ 1.7 / ≥ 2.7**
Bunch intensity [p]	≤ 1.3e11	≤ 1.2e11***
4 σ bunch length [ns]	1.2	1.25
Collimator settings	2012 (nominal)	2012 mm kept****

* Corresponding to 11 σ beam-beam separation. Room for increased angle if needed

** Assuming blowup from IBS only (M. Kuhn, Evian14). Much worse if scrubbing not successful (talk G. Iadarola)

*** Assuming 95% transmission

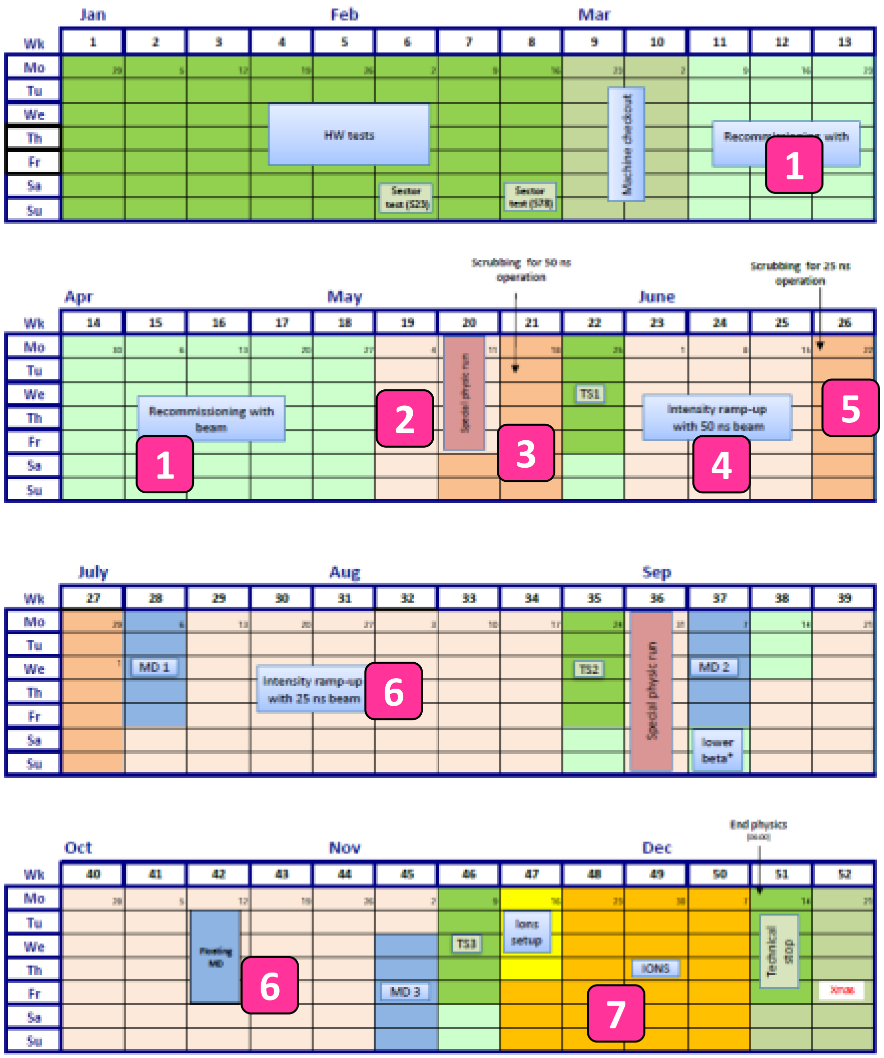
**** Room for increased margins for machine protection and impedance if needed

Main phases of current schedule

1. Low intensity commissioning (2 months)
2. First physics with a few isolated bunches, LHCf run + VdM
3. First scrubbing run (50 ns + 25ns)
4. 50 ns operation (up to 1380 bunches/beam) – produce 2012 like performance at 6.5TeV

   ~3 weeks
5. 25 ns (+doublet?) scrubbing run & e-cloud
6. 25 ns operation + special runs (β>=90m)

   ~90 days, potentially with two β* values
7. Ion run (2.56TeV? then 6.37TeV)



Initial (low intensity) beam commissioning

- What must be done before the first physics with 2-3 bunches:

☑ Establish the key beam commissioning steps

First threading, beam capture, orbit and optics corrections, IR bumps, aperture (β^*), polarities, energy ramp (combined ramp & squeeze), collisions, ..

☑ Commission with beam the key accelerator systems

FB systems, ADT, collimation (+BPMs), RF, injection, dump, diagnostics, ...

Many LS1 system changes! -> different to very fast 2012 re-commissioning

☑ Execute relevant machine protection commissioning

We want all MP-related systems in their final configs by the first stable Beam!

Complete beam validation of the given machine configuration.

Changes during run might become very time consuming, special runs already early on!

☑ Validate by measurements the machine configuration

The challenges of the Run II require new measurements compared to the standard commissioning of previous years!

☑ Already start preparing the scheduled β^* change planned for later in 2015

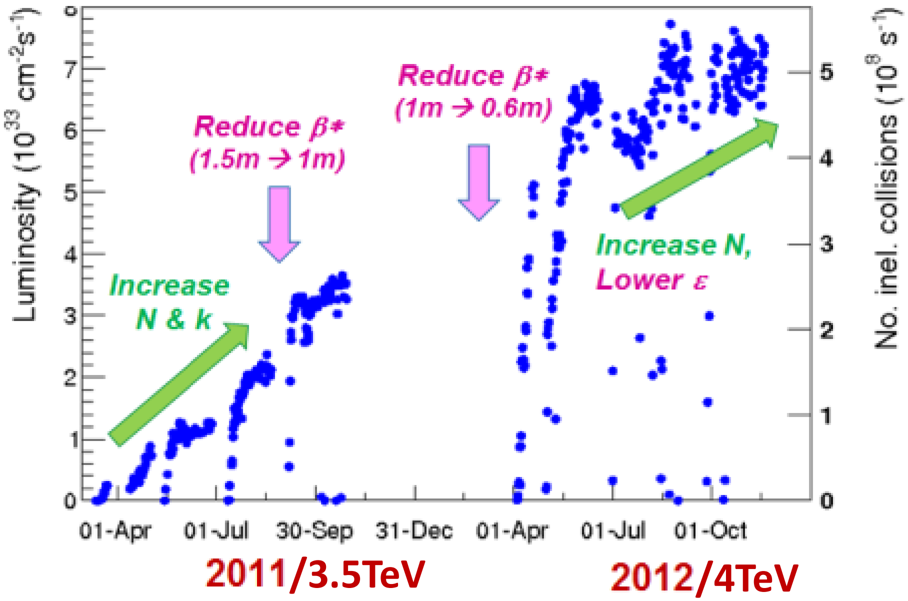
What can be done to speed up the optics re-commissioning?

M. Zerlauth, Chamonix 2014

Can we fit all that in 2 months?

Intensity ramp-up in run 1 and 2015 proposal

- **2011** intensity ramp up took ~9 effective weeks – **11** intensity steps
  - mixed bag of ‘debugging’-issues until reaching 480 bunches, > ~600 bunches ramp-up dictated by beam issues (losses and BLM thresholds, UFOs, heating, SEUs, instabilities,…).
- **2012** intensity ramp up took 2 weeks – **7** intensity steps.
- **2015 proposal:** 9 steps @ 50ns (50-> 1380?!), 11 steps @ 25ns (140->2800)
  - 50ns ramp up to establish run 1 conditions, first heating checks, e-cloud, feedback on BLM thresholds,…
  - Minimum of 3 fills with >20h of stable beams (strict in beginning to allow for debugging time)



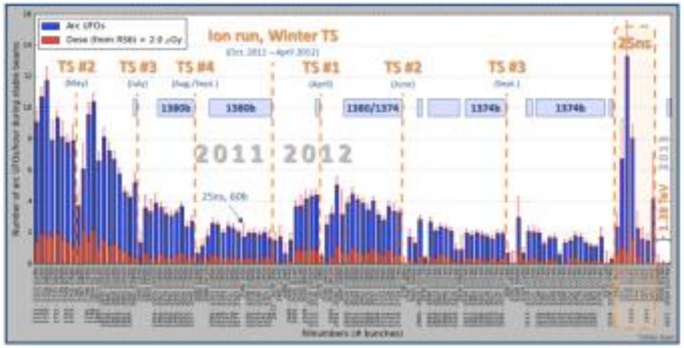
Intensity steps were defined by (r)MPP

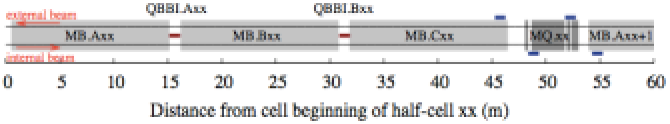
Towards lower β^*

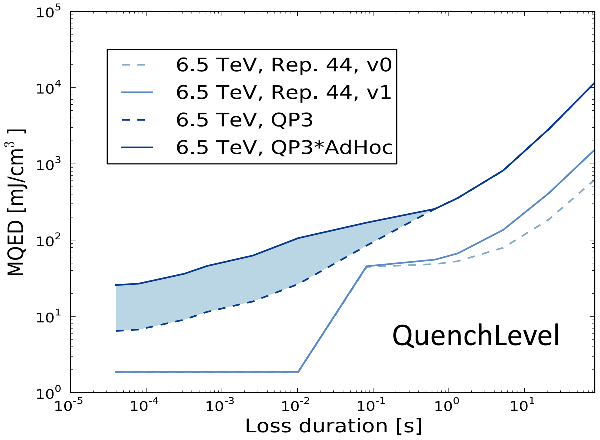
- A step towards lower β^* should be made in 2015 independently of a potential gain in integrated L !
  - Keep a margin of 3-4 weeks of operation after the change !
- A step to β^* ~60 cm should be possible from MP & collimation perspective as soon as we confirm:
  - The aperture (early commissioning),
  - The orbit & optics reproducibility.
    - With improved temperature stabilization of the BPM crates, we can hope for better reproducibility.
  - Impedance / stability aspects to be checked…
- A combined ramp & squeeze to ~3 m could be injected at this stage (if not done earlier) as a step towards higher efficiency.

UFOs vs BLM Thresholds

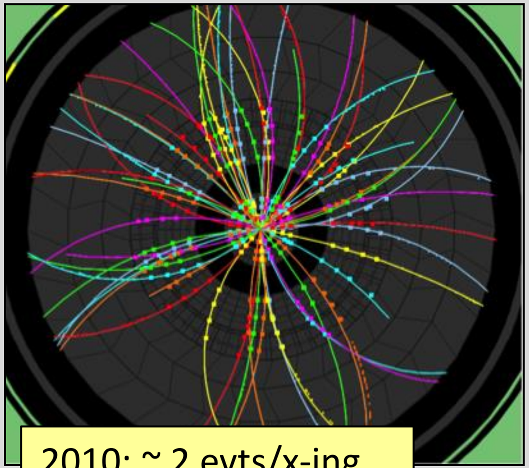
- Beam energy increases from 4 TeV to 6.5 TeV + operating at 25ns
  - energy-deposition per proton-particle collision increases ~2.4x;
  - quench level decreases 2-3x;
  - average UFO duration decreases due to smaller beam sizes;
  - Increased UFO rates at beginning of (25ns) run
- After LS1, in the arcs
  - no mitigation was possible to reduce UFO activity;
  - UFO-induced quenches and/or BLM triggers in the arcs are expected;
  - nonetheless the situation can be substantially improved through:
    - the relocation of BLMs for 100% coverage of sc magnets and to allow localizing and quantifying UFOs
    - and a refinement of BLM thresholds (based on quench tests) to avoid unnecessary triggers and quenches.



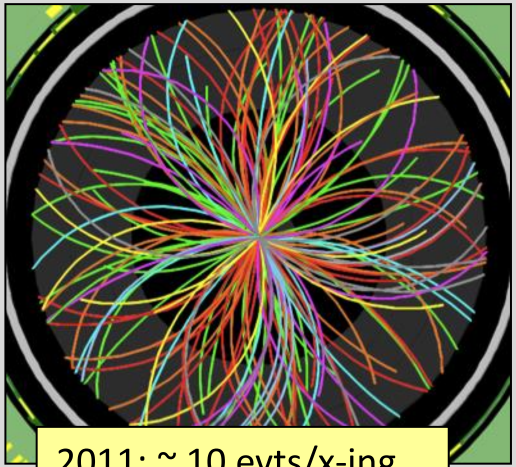




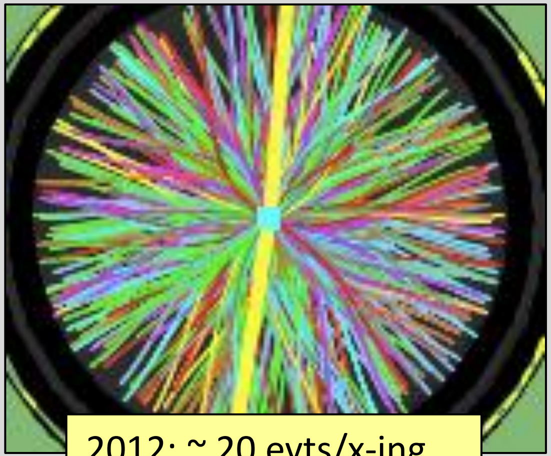
- ⇒ **The price of the high luminosity with fewer collisions: for each bunch crossing there are up to ~35 interactions (2012)**
- ⇒ **ATLAS & CMS were able to handle this pile-up !!**



2010: ~ 2 evts/x-ing

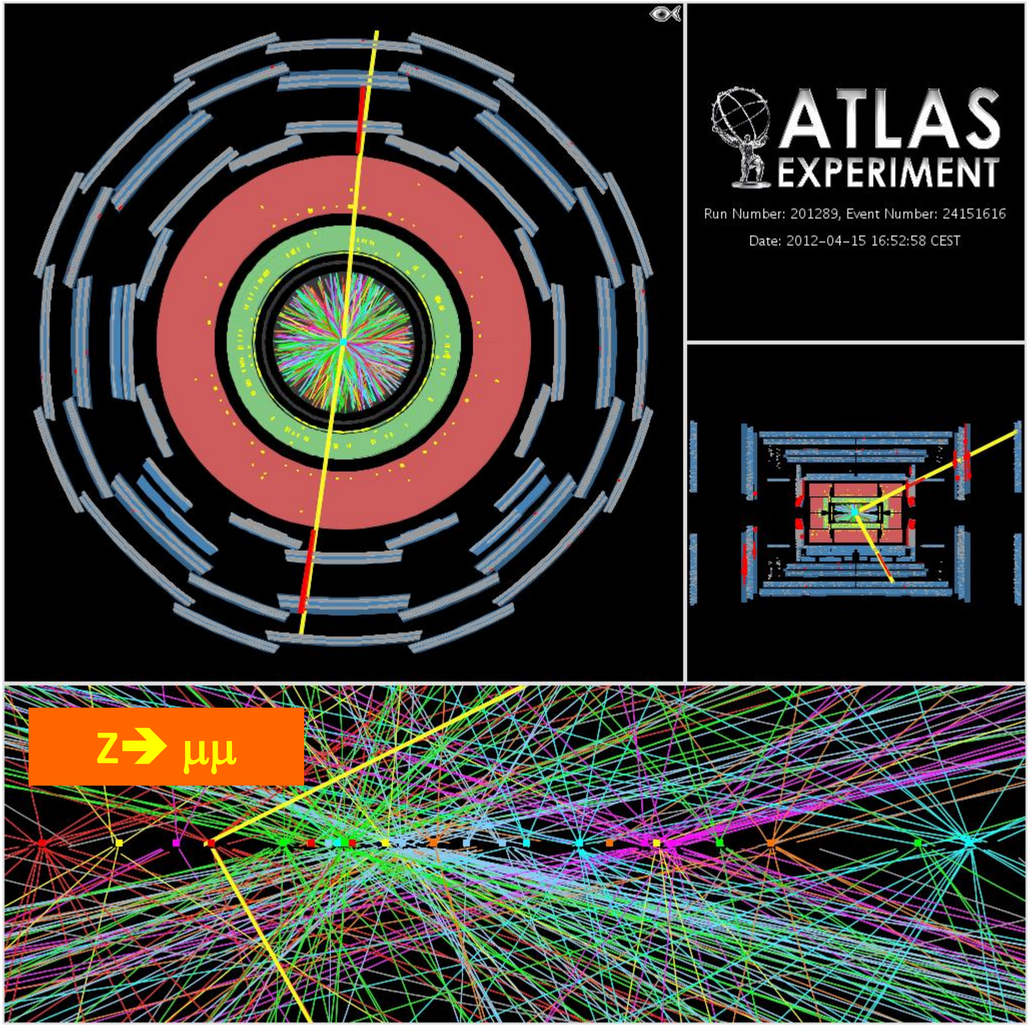


2011: ~ 10 evts/x-ing



2012: ~ 20 evts/x-ing

Pile-up density



- 25 reconstructed vertices – in a luminous region of 4.3 cm r.m.s. length
- Peaks of >40 events per bunch crossing observed with luminosities in the range of 7x10^{33} $cm^{-2}s^{-1}$
- Pile-up proportional to luminosity per bunch ➔ more bunches (i.e. 25 ns) is better

Best performance for Run II/III (β*=40 cm)

	N_{bcoll} $[10^{11}]$	ε^*_{coll} [μm]	# Coll. pairs IP1,5	B-B Sep [σ]	Full Xing angle [μrad]	L_{peak} $[10^{34}\ cm^{-2}s^{-1}]$	Max. Avg. Peak-pile-up density/Pile-up [ev./mm]/[ev./xing]
BCMS	1.24	1.65	2592	12	295	2.1	0.46/45
Standard	1.24	2.0	2736	12	320	1.8	0.46/45

- Limited by:
  - Inner triplet heat load due to collisions debris (**1.7×10^{34} $cm^{-2}\ s^{-1}$ ± 20%**)
  - Pile-up (here assumed to be 45 events/cross
  - → Will need levelling

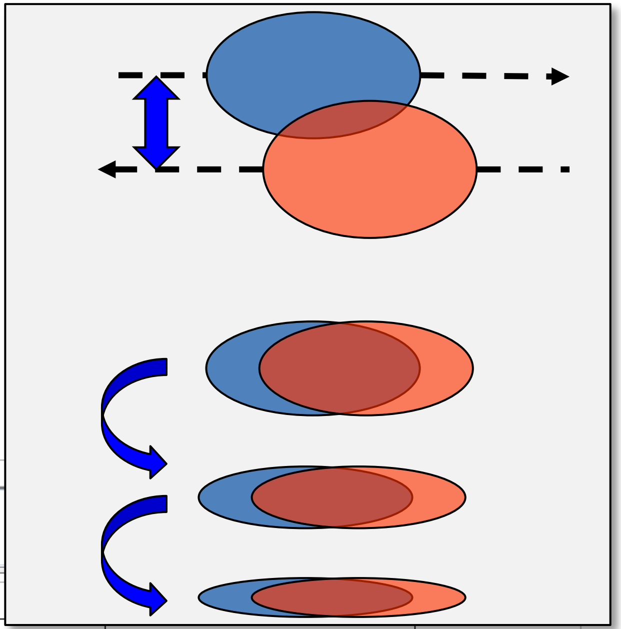
$$L = \frac{k N_b^{\ 2} f \gamma}{4\pi \boxed{\beta^*} \varepsilon^*} F$$

	L_{lev} $[10^{34}\ cm^{-2}s^{-1}]$	Lev. time [h]	Opt. Fill length [h]
BCMS	1.5	2.9	8
Standard	1.6	1.7	8.1

Expect to produce ~45-55 fb^{-1}/year

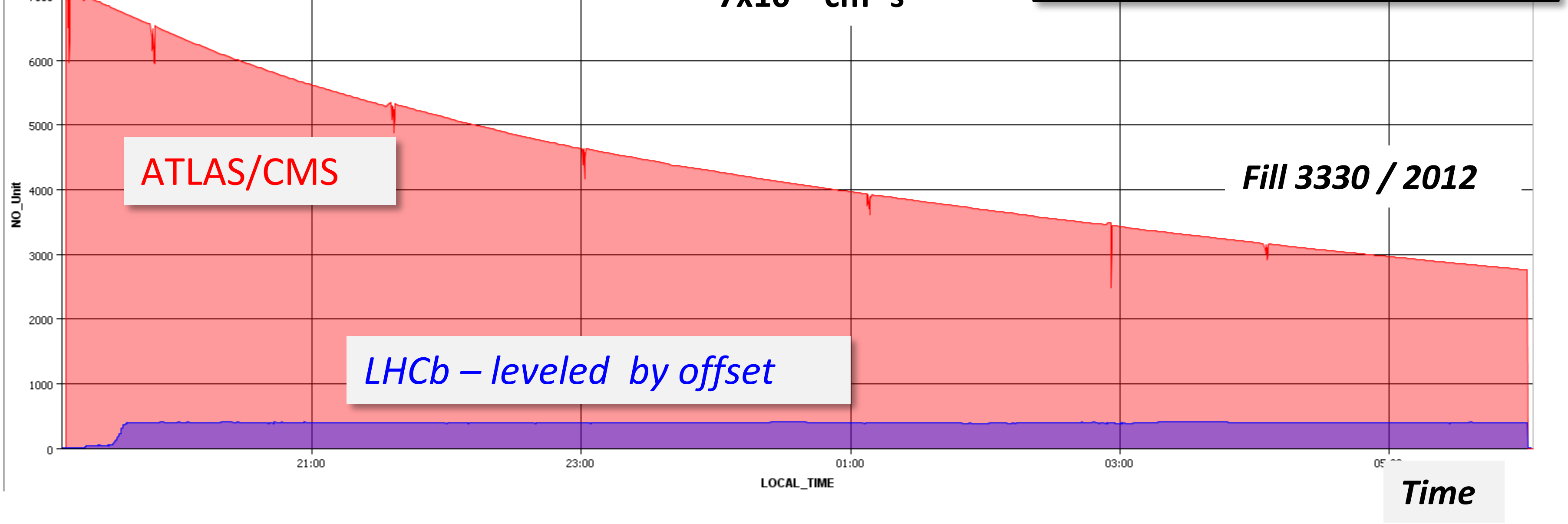
Levelling luminosities

- In run 1 we have levelled the luminosity of LHCb and ALICE by adjusting the offsets between the beams.
- In run 2 we are considering to level luminosities by adjusting β* (beam size at IP).
- Better / mandatory for beam stability.

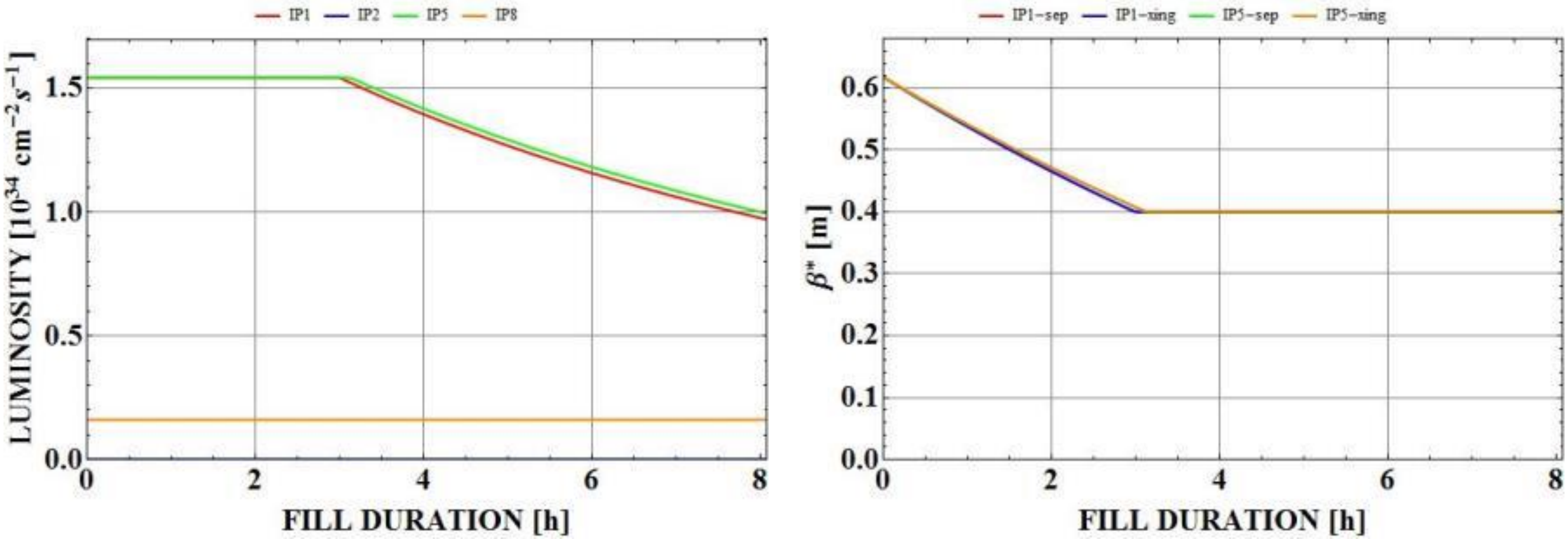


Timeseries Chart between 2012-11-25 19:08:02.097 and 2012-11-26 06:04:08.945 (LOCAL_TIME)

Luminosity



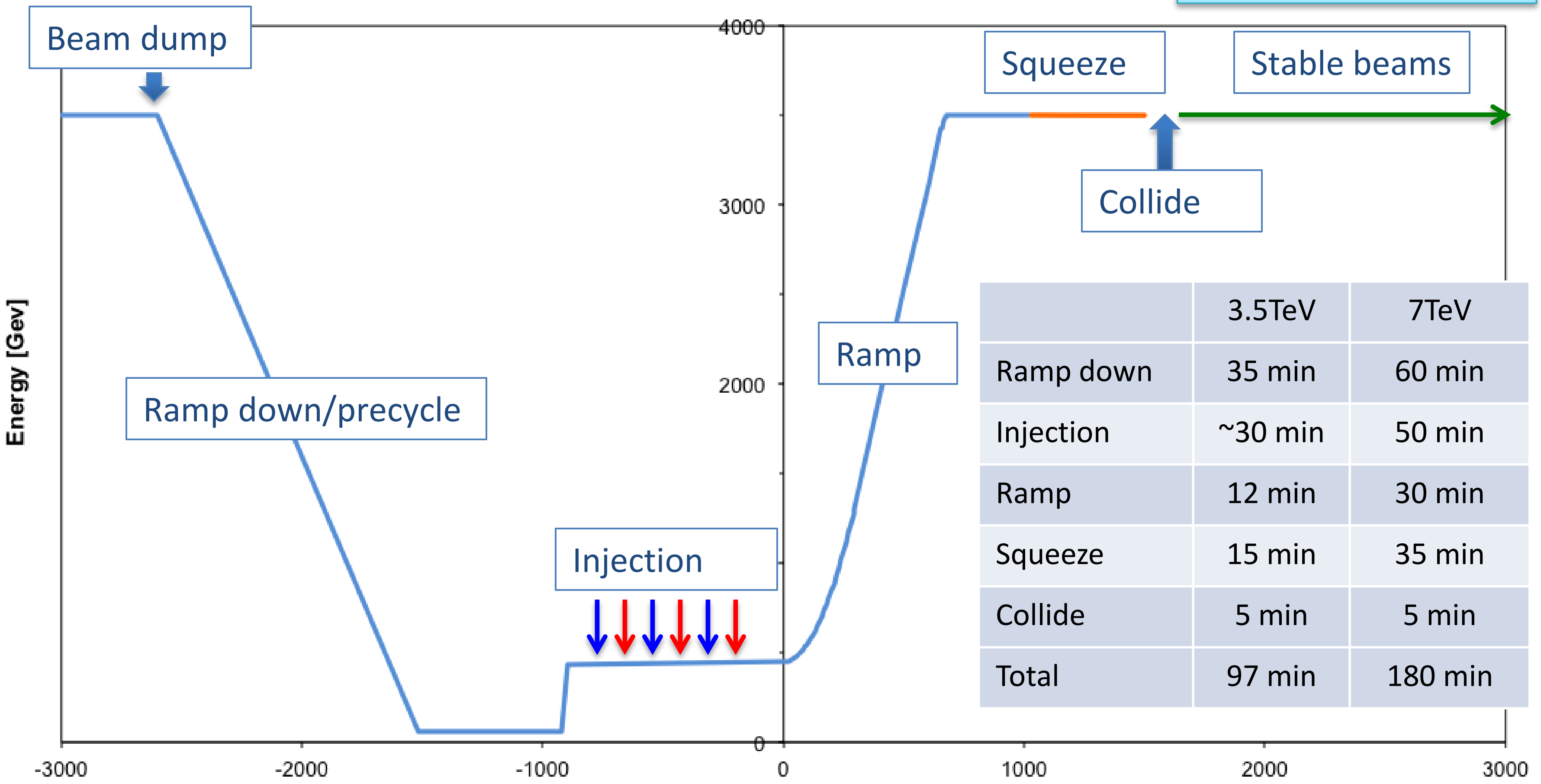
Best performance for Run II/III (β*=40 cm)



- Variation of the β* during the fill (β* levelling) is the most likely technique to be applied for luminosity levelling

Integrated Luminosity

M. Lamont @ Evian LHC Operation workshop



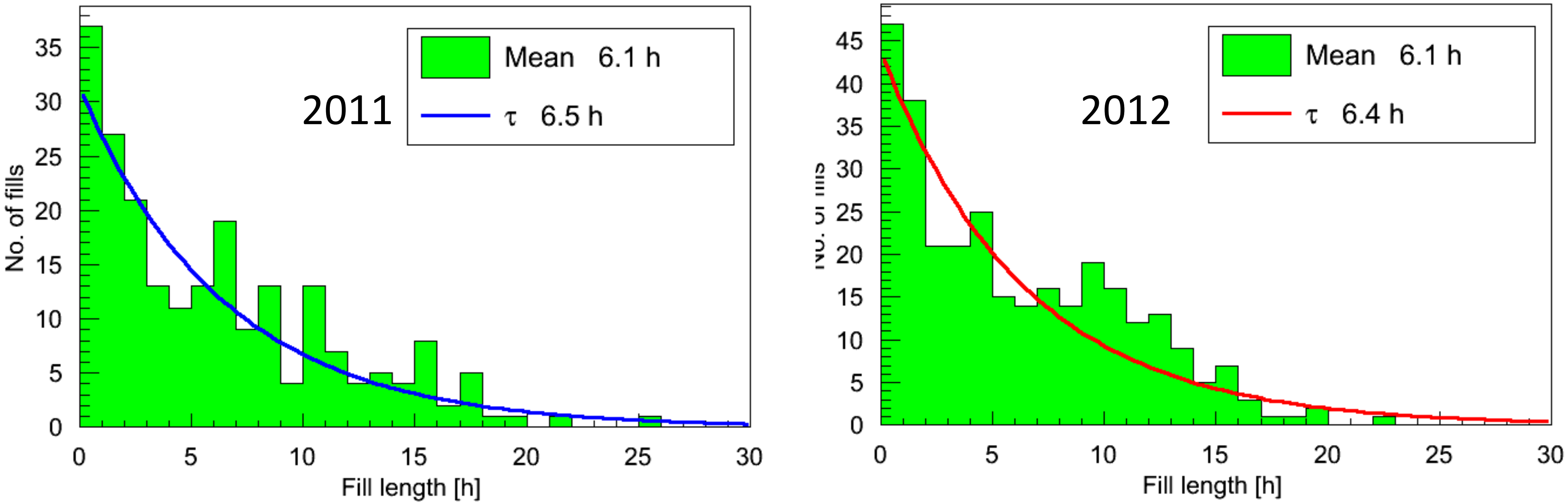
	3.5TeV	7TeV
Ramp down	35 min	60 min
Injection	~30 min	50 min
Ramp	12 min	30 min
Squeeze	15 min	35 min
Collide	5 min	5 min
Total	97 min	180 min

- ➔ Operational Turnaround time @ 3.5 TeV 2 - 3 hours! ➔ Efficiency!!!!
- ➔ Efficient operation requires a physics fill length >> operational Turnaround time
- ➔ HL-LHC: Leveling time ≈ 6-8 hours!

Integrated Luminosity

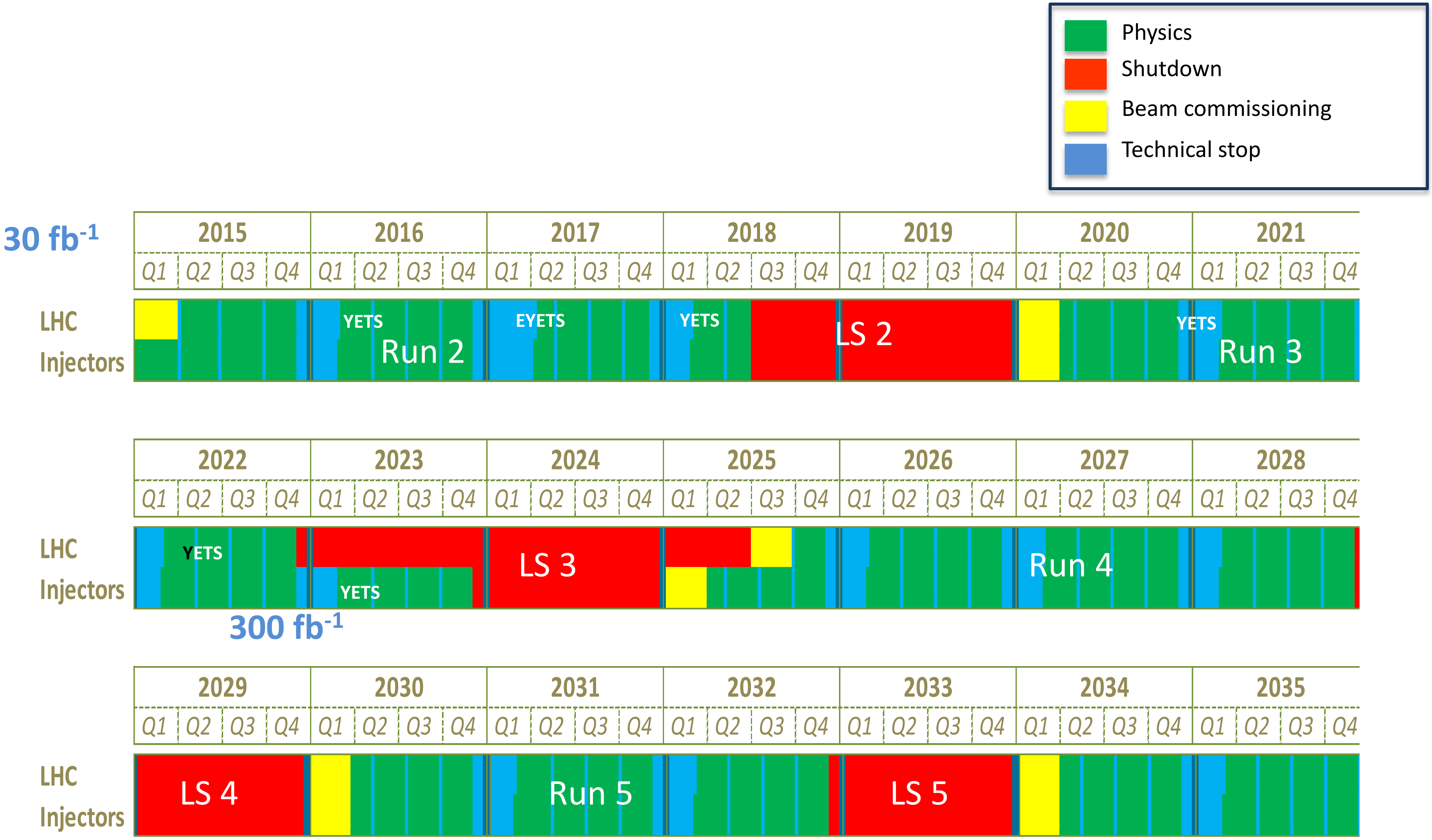
- Operation experience in 2011 and 2012

J. Wenninger @ Evian LHC Operation workshop



- Only ~30% of the fills are dumped by operation!
- HL-LHC will require significantly longer average fill length
- >> average Turnaround time and leveling time (about 10 hours)!!!!

LHC Schedule beyond LS1



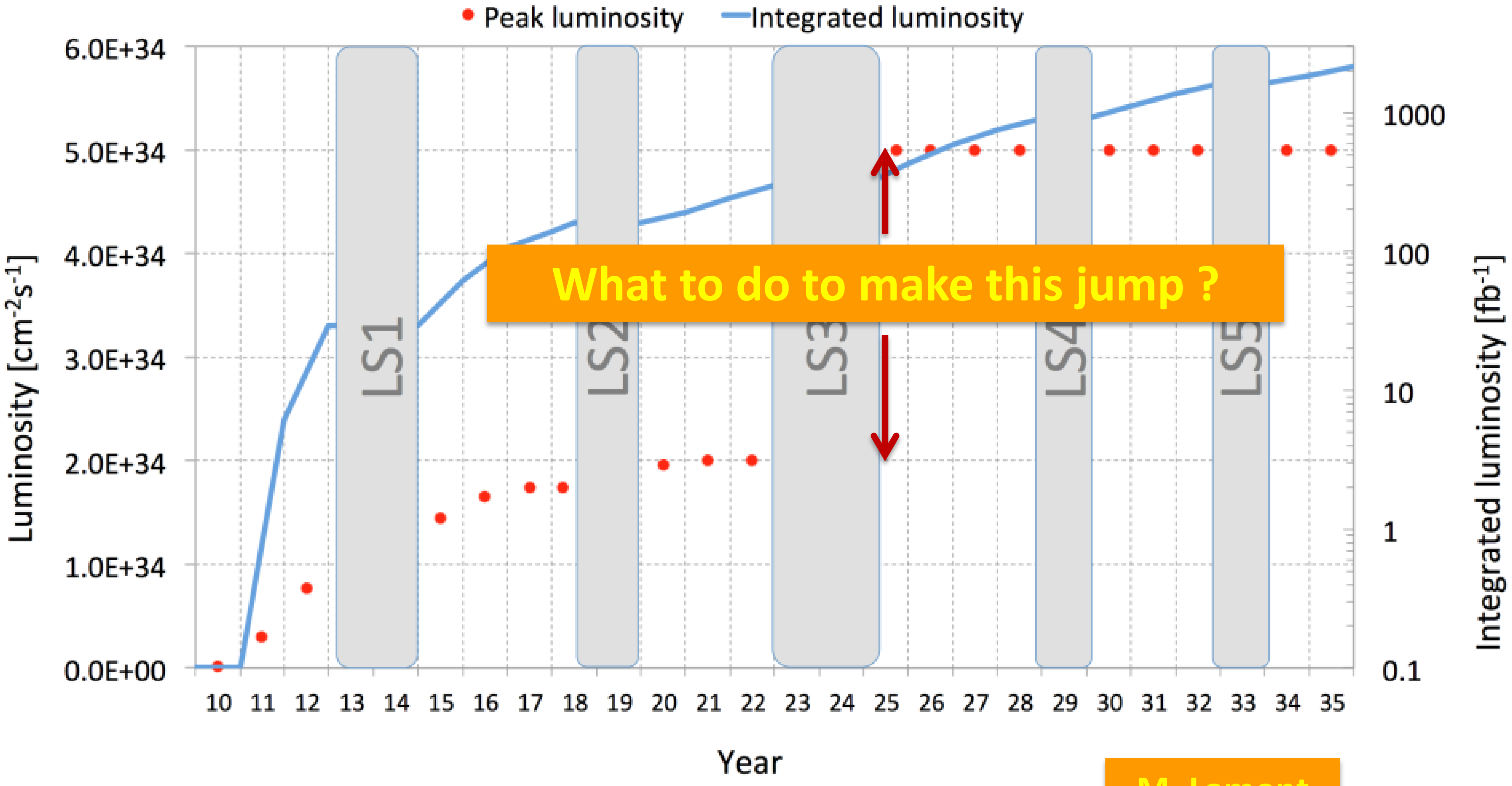
(Extended) Year End Technical Stop: (E)YETS

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators (December 2013)

HL-LHC Goals

- The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:
  - Prepare machine for reliable operation beyond 2025 and up to 2035
  - Devise beam parameters and operation scenarios for:
    - enabling a total integrated luminosity of **3000 fb^{-1}** ➔ **250 fb^{-1} to 300 fb^{-1} / year**,
    - design operation for pile-up **~ 140** (➔ peak luminosity of **5×10^{34} cm^{-2} s^{-1}**) compatibly with detector capabilities
    - design equipment for ‘ultimate’ performance of **7.5×10^{34} cm^{-2} s^{-1}**
- Ten times the luminosity reach of first 10 years of LHC operation!!

HL-LHC Goals

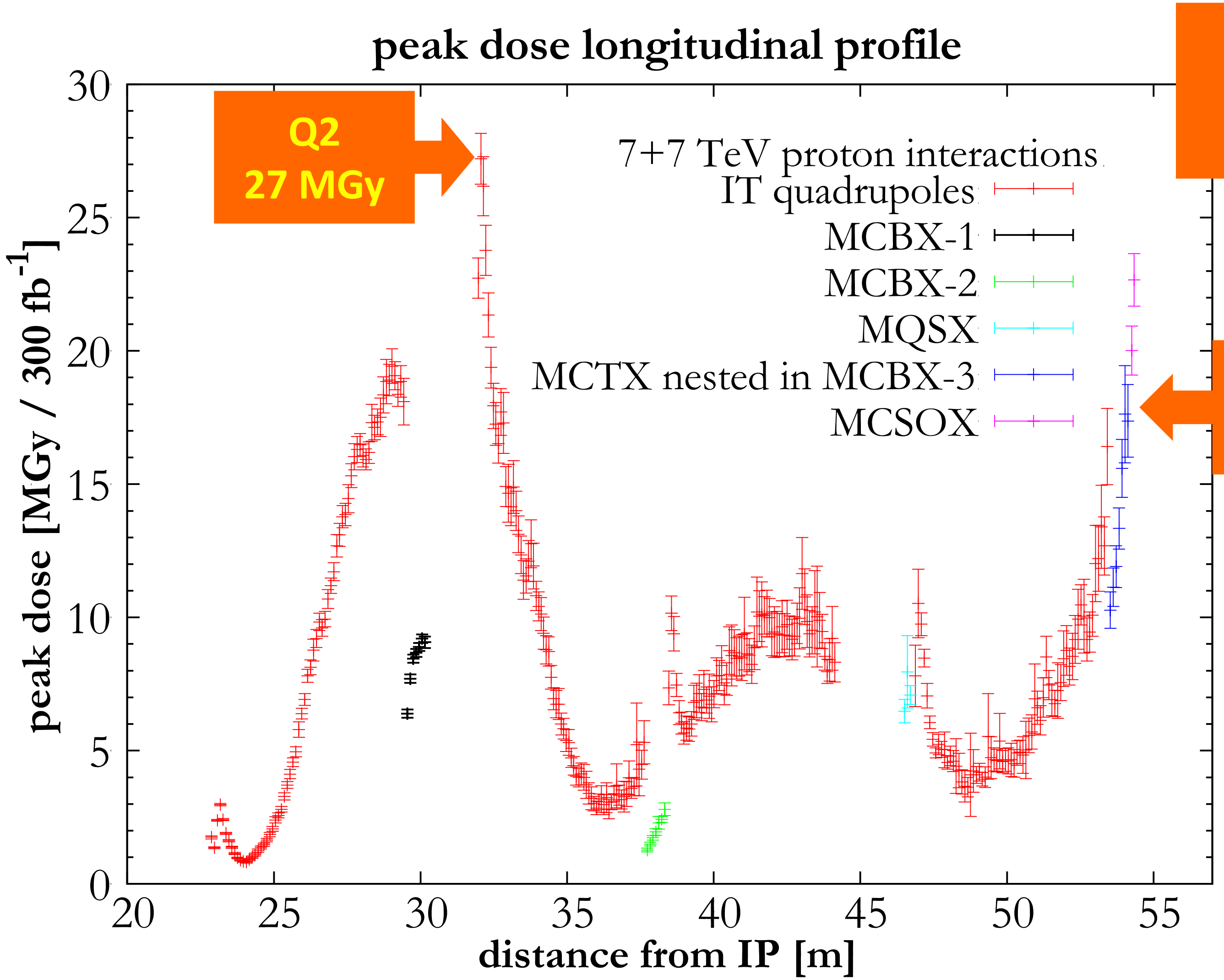


What to do to make this jump ?

M. Lamont

Radiation damage to triplet

F. Cerutti, N. Mokhov, L. Esposito,…



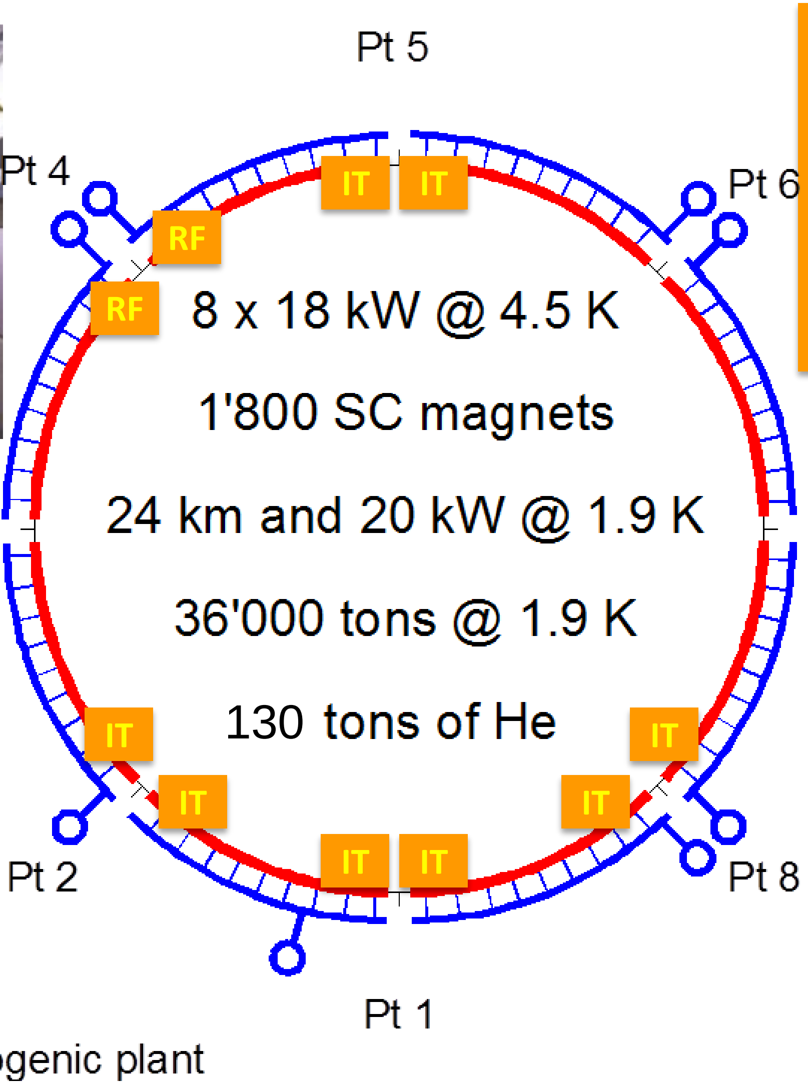
Q2
27 MGy

Cold bore insulation ≈ 35 MGy

MCBX3
20 MGy

Technical bottlenecks: Cryogenics

Cryo power limitation in Pt 4, interdependency of different systems with different cool-down time, reduced flexibility and no/little redundancy



8 x 18 kW @ 4.5 K

1'800 SC magnets

24 km and 20 kW @ 1.9 K

36'000 tons @ 1.9 K

130 tons of He

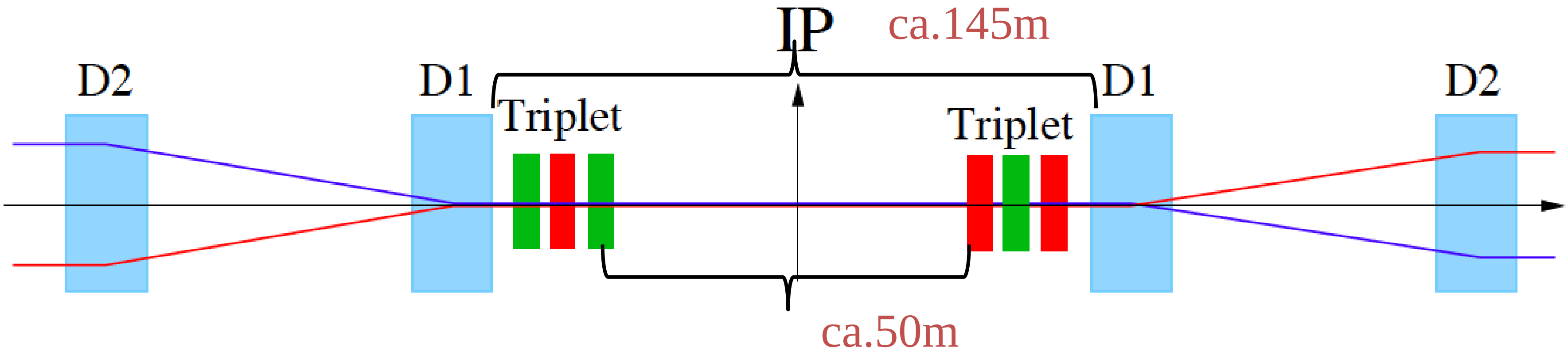
○ Cryogenic plant

Ingredients for the Upgrade

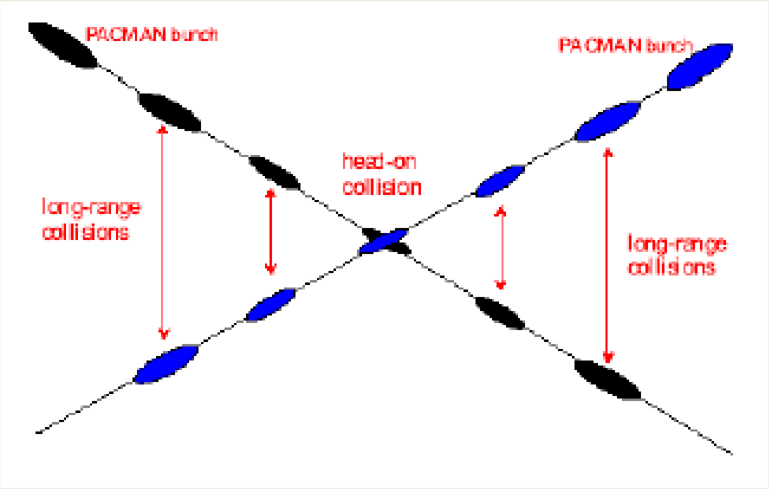
- Operation at pile-up/pile-up density limit by choosing parameters that allow higher than design pile-up:
  - maximize bunch intensities ➔ Injector Complex Upgrade
  - minimize the beam emittance ➔ Injector Complex Upgrade
  - maximize number of bunches (beam power) ➔ 25 ns
  - minimize beam size at the interaction point (constant beam power) ➔ LHC optics
  - compensate for luminosity reduction factor F ➔ crab cavities
  - Improve machine ‘Efficiency’ ➔ minimize the number of unscheduled beam aborts

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

HL-LHC Challenges: Crossing Angle I

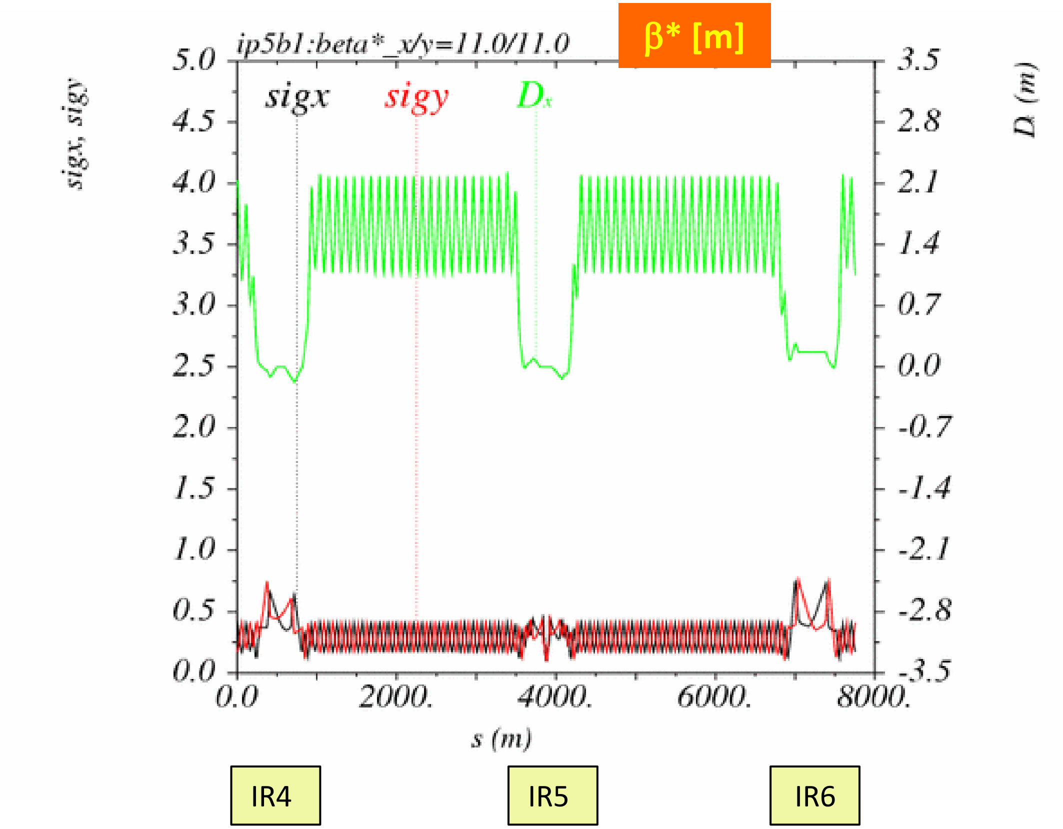


- Parasitic bunch encounters:
  - Operation with ~ 2800 bunches @ 25ns spacing ➔ approximately 30 unwanted encounters per Interaction Region (IR).
- Operation requires crossing angle
  - non-linear fields from long-range beam-beam interaction ➔ large beam separation at unwanted collision points
  - Separation of 10 -12 σ ➔ large triplet apertures for HL-LHC upgrade!!



Ingredients for the Upgrade

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



ATS=Achromatic Telescopic Squeeze - S. Fartoukh

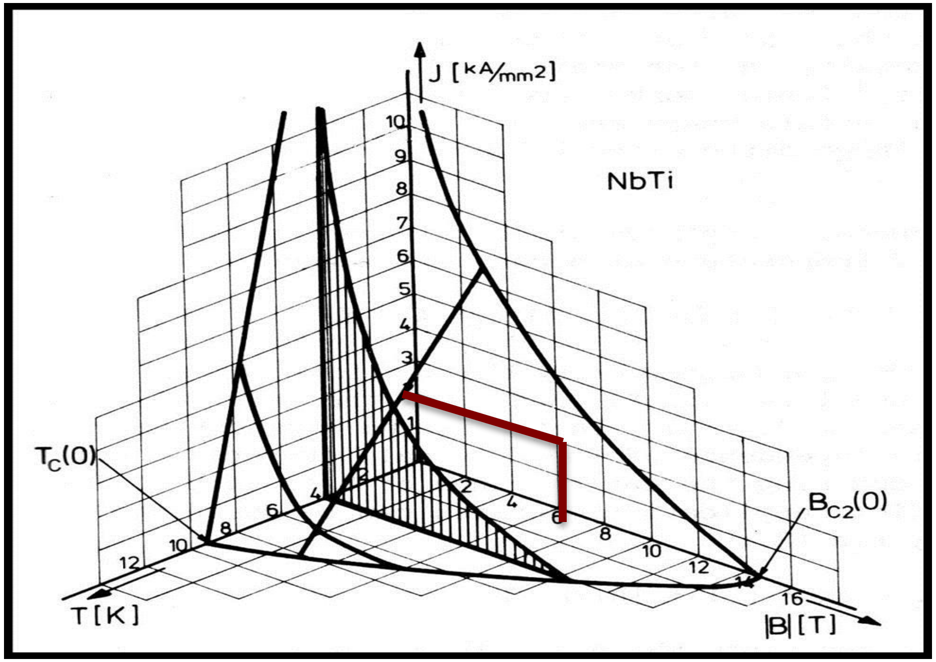
- …of course it requires larger aperture triplets

LHC Triplet Magnets

- Nominal LHC triplet: 210 T/m, 70 mm coil aperture
  - ca. 8 T @ coil
  - 1.8 K cooling with superfluid He (thermal conductivity)
  - current density of 2.75 kA / mm^2 = 2.75 x 10^5 A/cm^2
- At the limit of NbTi technology (HERA & Tevatron ca. 5 T @2kA/mm^2)

LHC Production in collaboration with USA and KEK

Critical Surface for NbTi

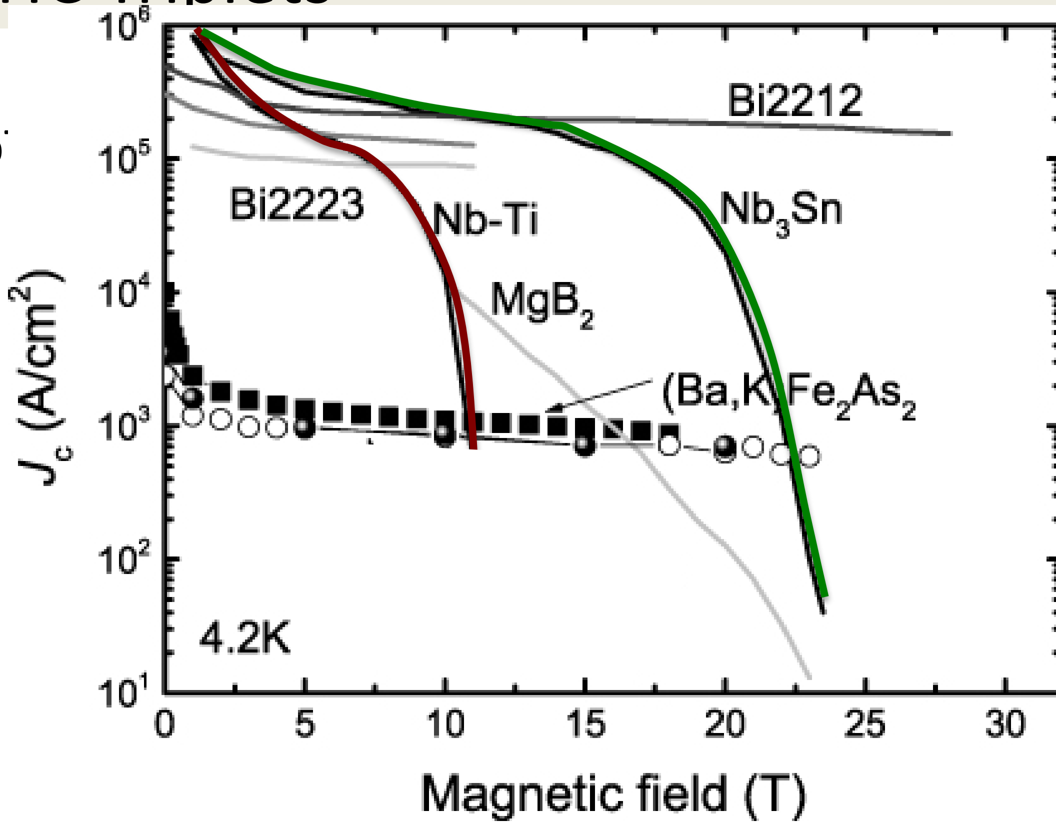


HL-LHC Triplets

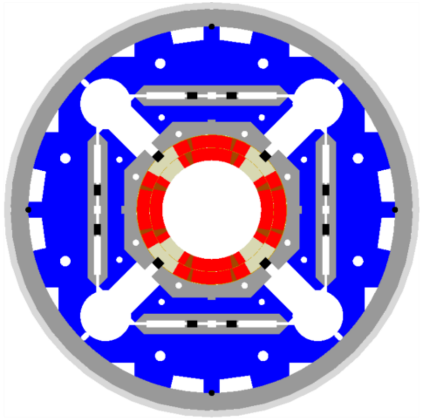
- LHC triplet: 210 T/m, 70 mm bore aperture ➔ 8 T @ coil (limit of Nb tech.)

- HL-LHC triplet: 140 T/m, 150 mm coil aperture (shielding, β* and crossing angle
- ➔ ca. 12 T @ coil ➔ 30% longer

- Requires Nb_3Sn technology
  - ceramic type material (fragile)
  - ca. 25 year development for this new magnet technology!
- US-LARP – CERN collaboration



US-LARP MQXF magnet design Based on Nb_3Sn technology

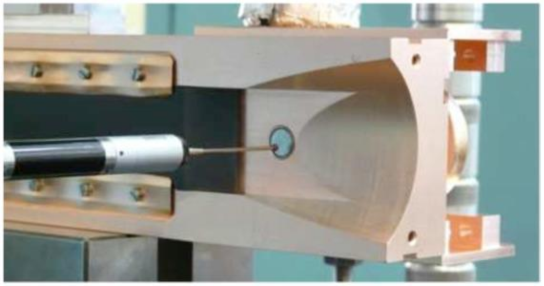


HL-LHC Challenges: Quench Protection

- Magnet quench ➔ beam abort ➔ several hours of recovery
- HL-LHC beam intensity > 1 A ➔ $7x10^{14}$ p/beam
- Quench level: $N_{lost} < 7\times10^{8}\ m^{-1} < 10^{-6}\ N_{beam}$
  - requires enhanced collimation
  - HL-LHC luminosity implies higher leakage from IP & requires additional collimators

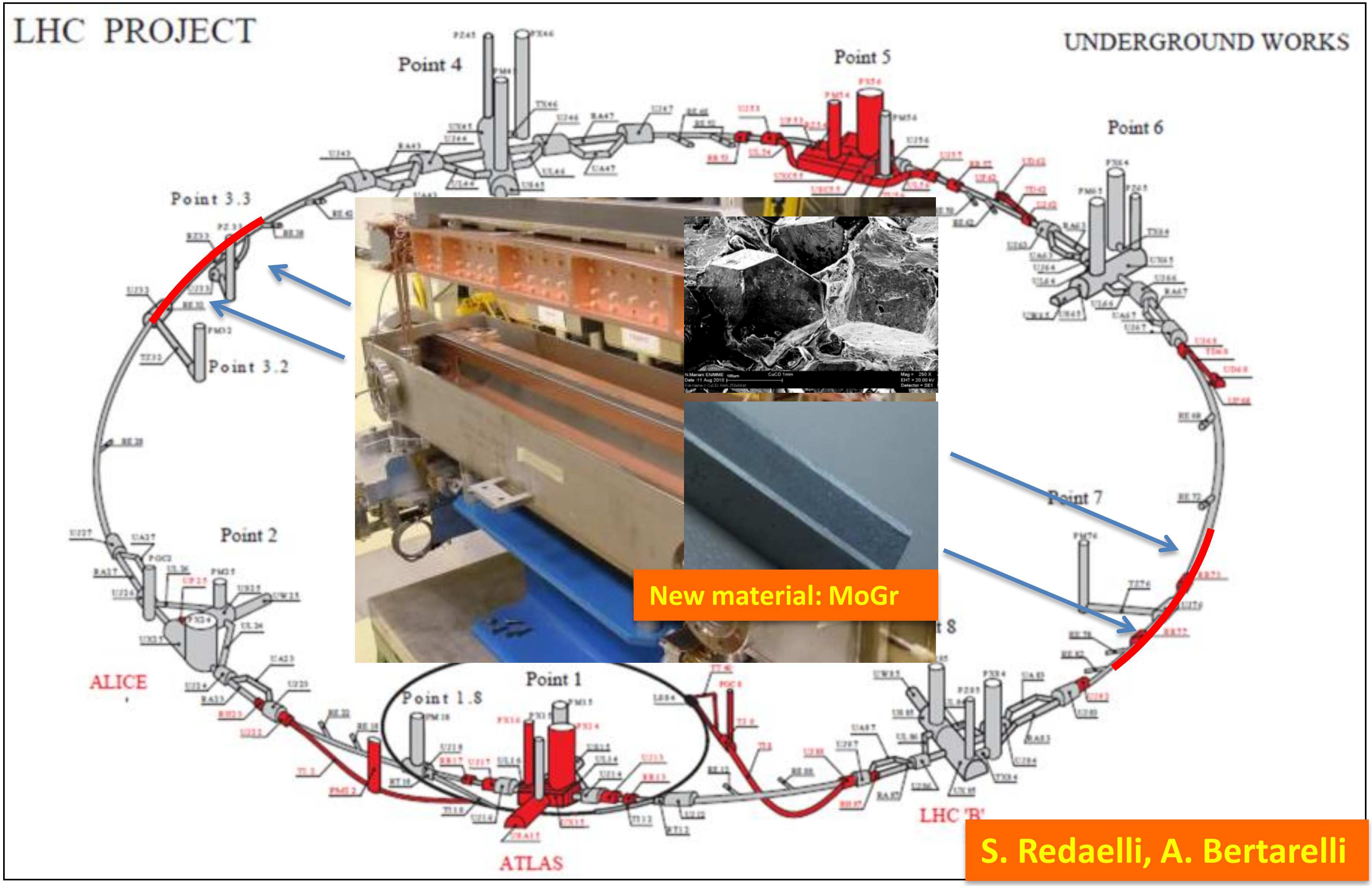
IR Collimation Upgrade

- Update of present collimation system during LS1:
  - Replace existing collimators
  - Reduce setup time (gain of factor ~100)
  - Improved monitoring



- For HL-LHC add dispersion suppressor collir
  - Eliminate off-momentum particles in a region w
  - Technology of choice for the DS collimators is warm with by-pass cryostat
  - Design completed with 4.5 m integration length.
  - Prototyping on-going
- Advanced collimation concepts being investigated for the future
  - Crystal collimation tests in SPS have been made and are being prepared in the LHC

Low impedance collimators



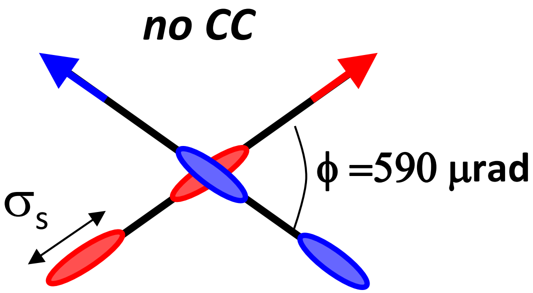
New material: MoGr

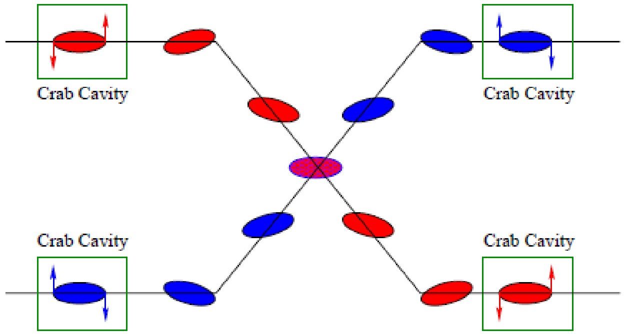
S. Redaelli, A. Bertarelli

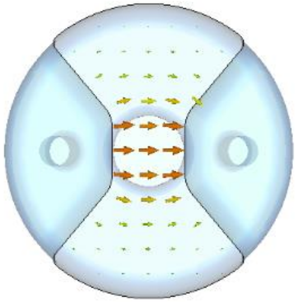
Crab-cavities

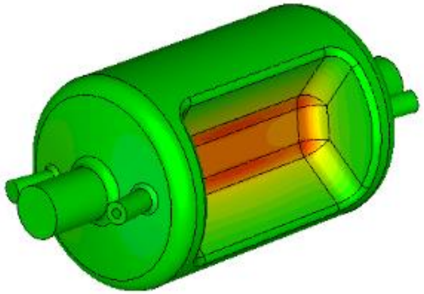
$$L = \frac{k N_b^{\,2} f \gamma}{4\pi \beta^* \varepsilon^*} \boxed{F}$$

- Crab-cavities (CC) are RF cavities used to deflec head and tail transversely to counteract the lum from the large crossing angles and small beam sizes at HL-LHC
  - To be installed on both sides of ATLAS and CMS





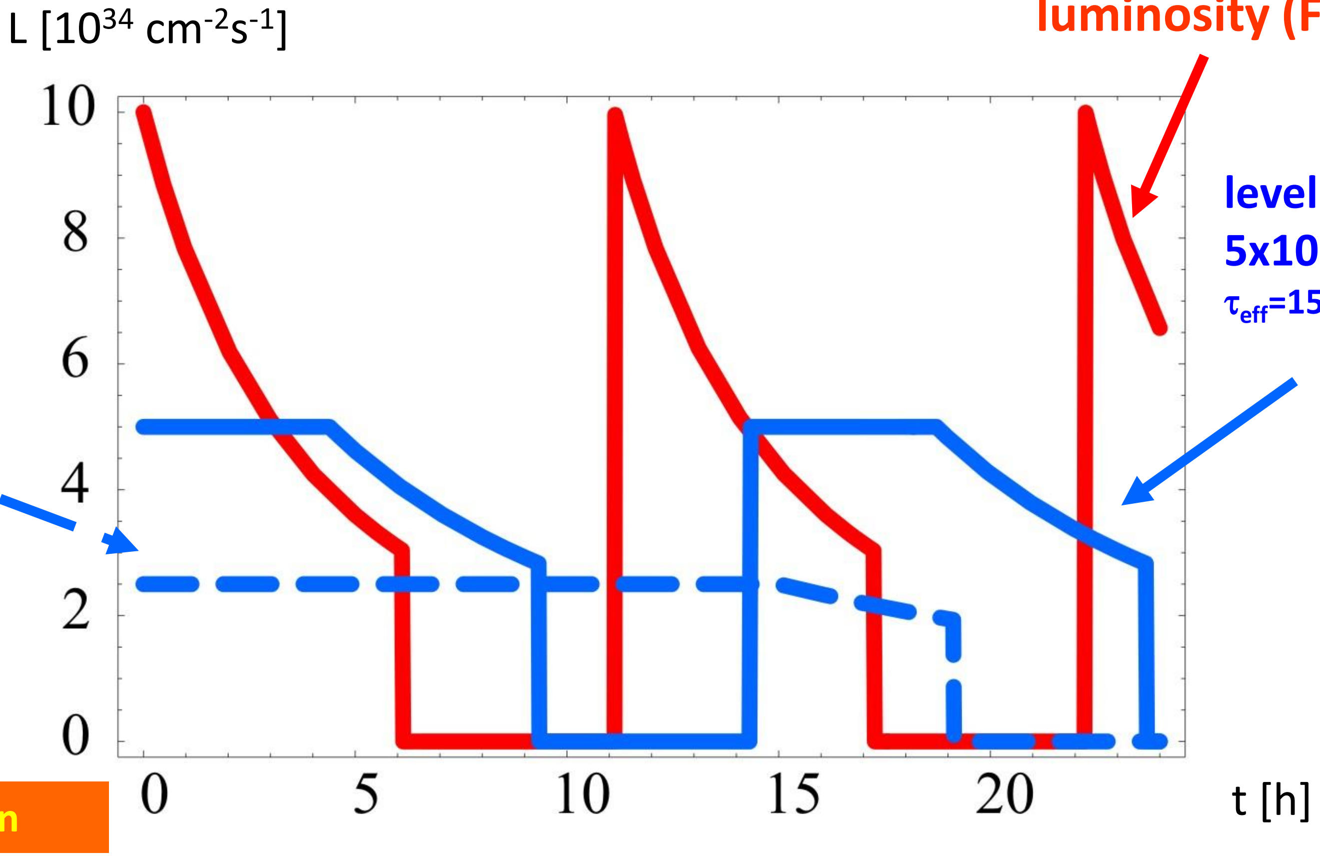




- CCs have never been used in a hadron machine - there are many challenges: noise on the beam, machine protection etc.

Ingredients for the Upgrade

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



Virtual peak luminosity (F=1)

leveling at $5\text{x}10^{34}$cm^{-2}s^{-1}

τ_{eff}=15 h, T_{ta}=5 h

leveling at $2.5\text{x}10^{34}$cm^{-2}s^{-1}

τ_{eff}=30 h, T_{ta}=5 h

F. Zimmermann

HL-LHC Performance Estimates

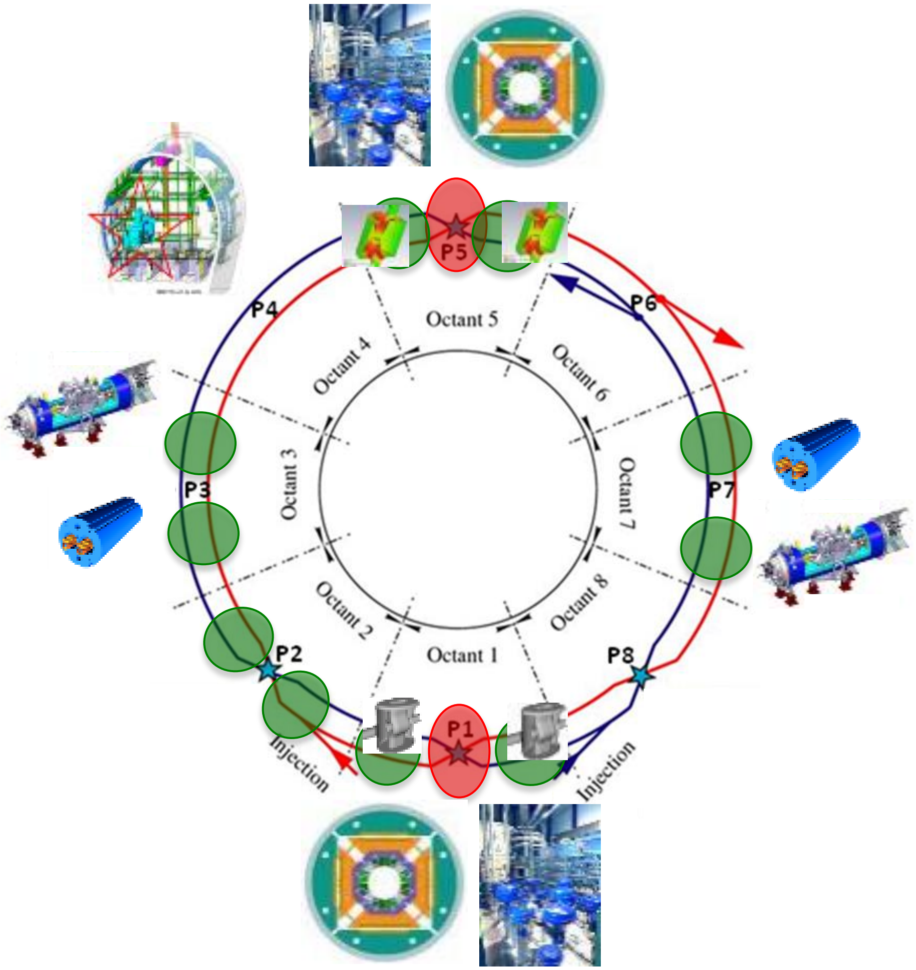
Parameter	Nominal	25ns – HL-LHC
Bunch population N_b [10^{11}]	1.15	2.2
Number of bunches	2808	2748
Beam current [A]	0.58	1.12
Crossing angle [μrad]	300	590
Beam separation [σ]	9.9	12.5
β^* [m]	0.55	0.15
Normalized emittance ε_n [μm]	3.75	2.5
ε_L [eVs]	2.51	2.51
Relative energy spread [10^{-4}]	1.20	1.20
r.m.s. bunch length [m]	0.075	0.075
Virtual Luminosity (w/o CC) [10^{34} cm^{-2}s^{-1}]	1.2 (1.2)	21.3 (7.2)
Max. Luminosity [10^{34} cm^{-2}s^{-1}]	1	5.1
Levelled Pile-up/Pile-up density [evt. / evt./mm]	26/0.2	140/1.25

Aim for ~250 fb^{-1}/y

ΔQ_{bb} ~ -0.01

Hardware for the Upgrade

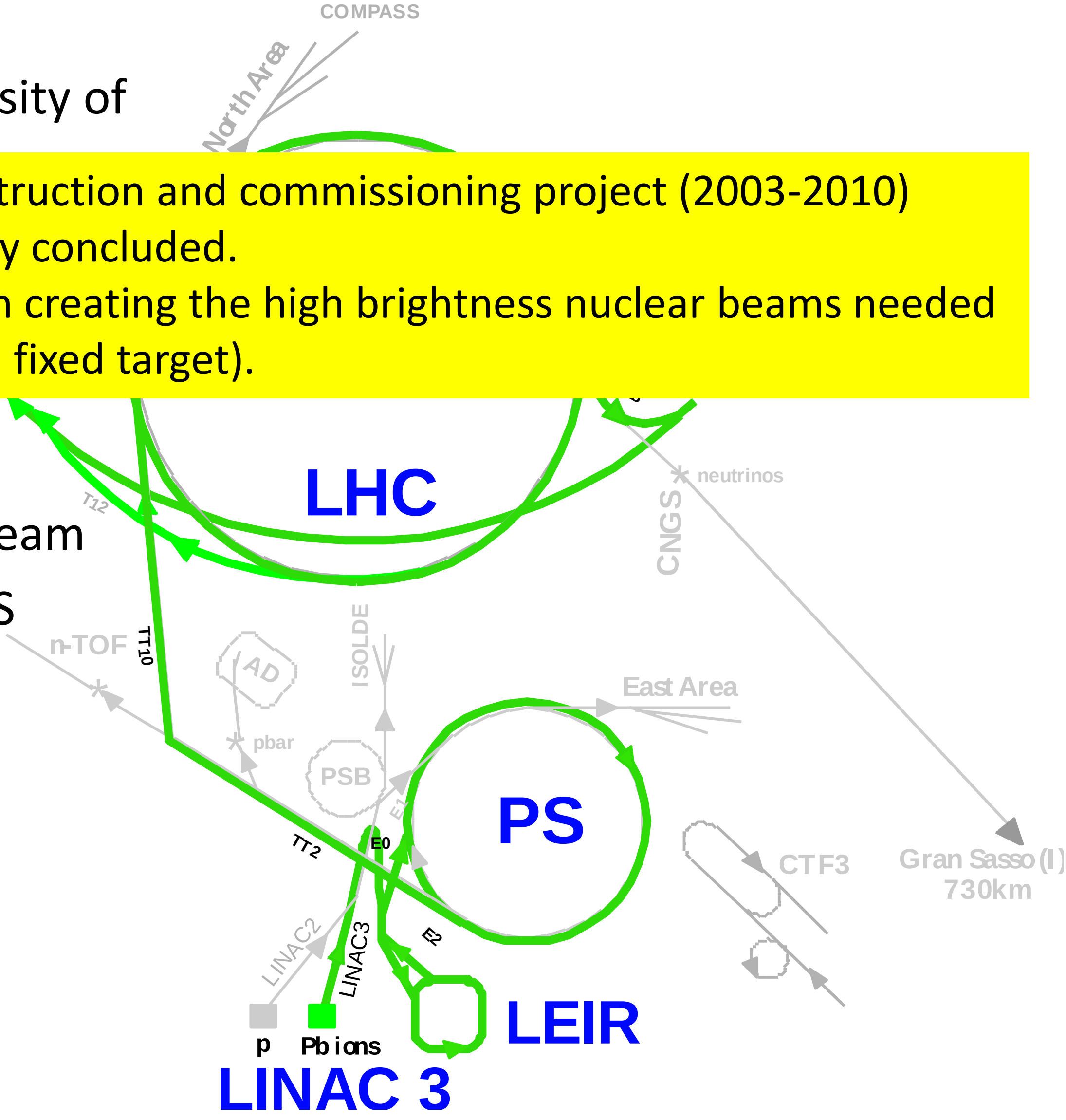
- Main modifications:
  - New high field/larger aperture interaction region magnets
  - Cryo-collimators and high field 11 T dipoles in dispersion suppressors to cope with higher intensity
  - Crab Cavities to take advantage of the small β^*
  - New collimators (lower impedance)
  - Additional cryo plants (P1, P4, P5)
  - SC links to allow power converters to be moved to surface



THE LHC AS A NUCLEUS-NUCLEUS COLLIDER

LHC Ion Injector Chain

- ECR ion source (2005)
  - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR inject
  - strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and cool Linac3 beam
  - Prepare bunch structure for PS
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)
  - Define filling scheme of LHC

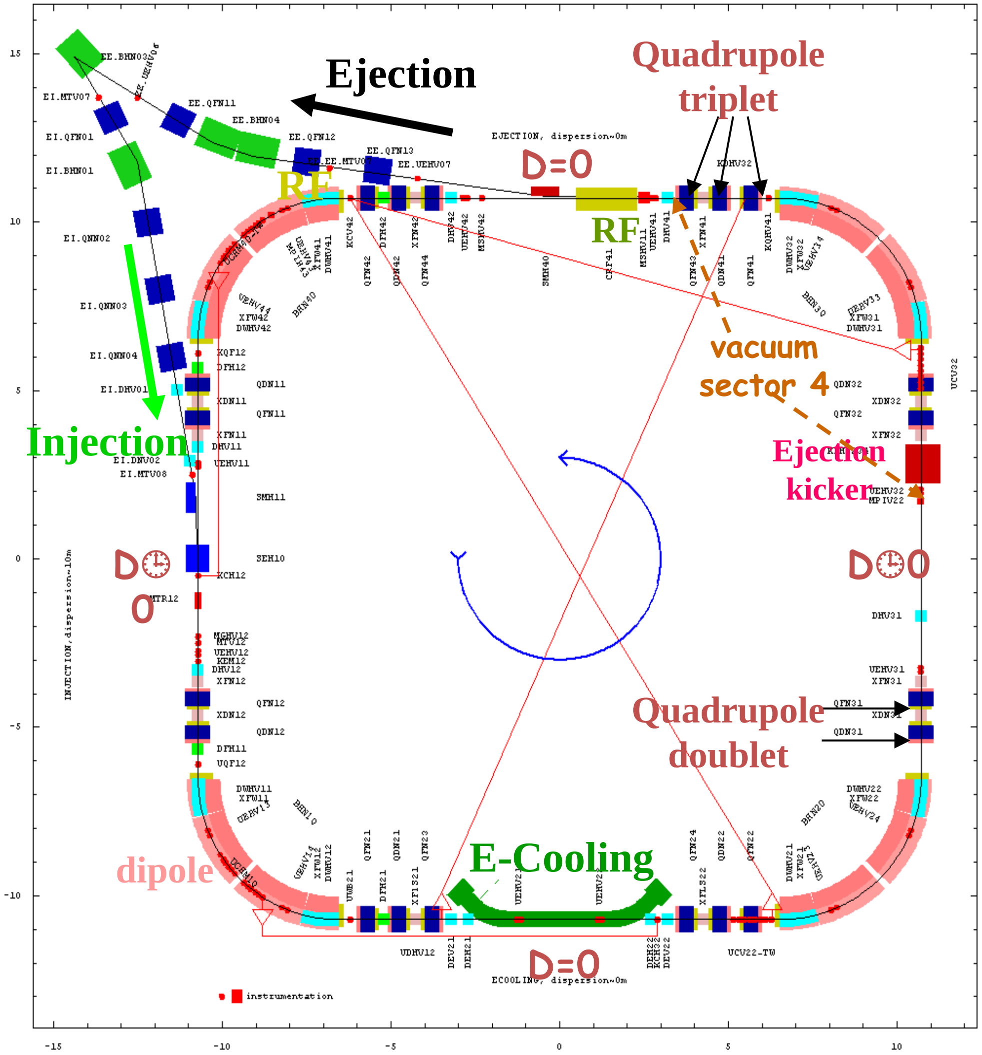


I-LHC construction and commissioning project (2003-2010) successfully concluded.

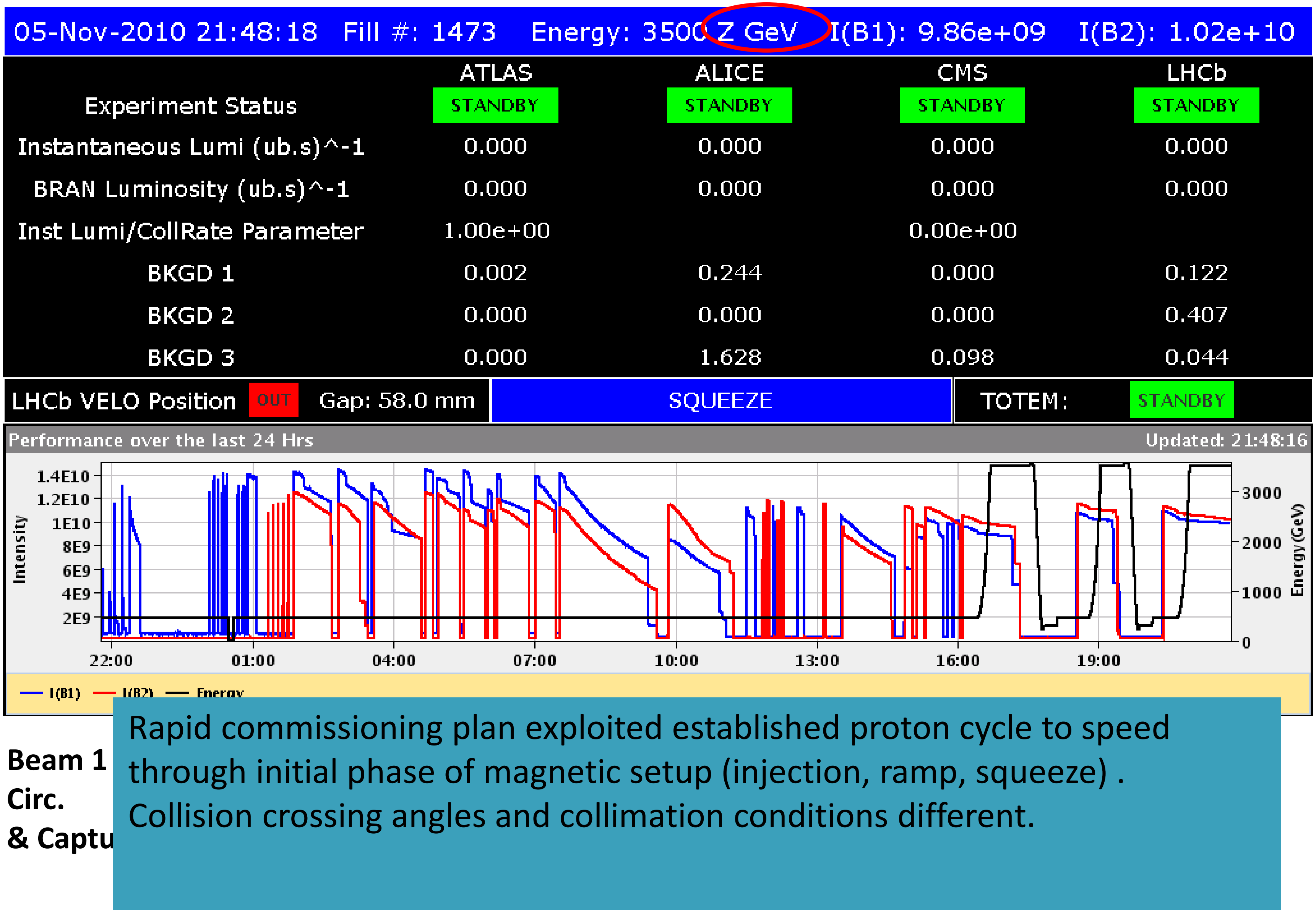
Vital role in creating the high brightness nuclear beams needed by LHC (vs. fixed target).

LEIR (Low-Energy Ion Ring)

- Prepares beams for LHC using electron cooling
- circumference 25p m (1/8 PS)
- Multiturn injection into horizontal+vertical+longitudinal phase planes
- Fast Electron Cooling : Electron current from 0.5 to 0.6 A with variable density
- Dynamic vacuum (NEG, Au-coated collimators, scrubbing)



2010 Heavy Ion Run: first 24 h, Thu-Fri 4-5 Nov



05-Nov-2010 21:48:18 Fill #: 1473 Energy: 3500 Z GeV I(B1): 9.86e+09 I(B2): 1.02e+10

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	STANDBY	STANDBY	STANDBY
Instantaneous Lumi (ub.s)^-1	0.000	0.000	0.000	0.000
BRAN Luminosity (ub.s)^-1	0.000	0.000	0.000	0.000
Inst Lumi/CollRate Parameter	1.00e+00		0.00e+00	
BKGD 1	0.002	0.244	0.000	0.122
BKGD 2	0.000	0.000	0.000	0.407
BKGD 3	0.000	1.628	0.098	0.044

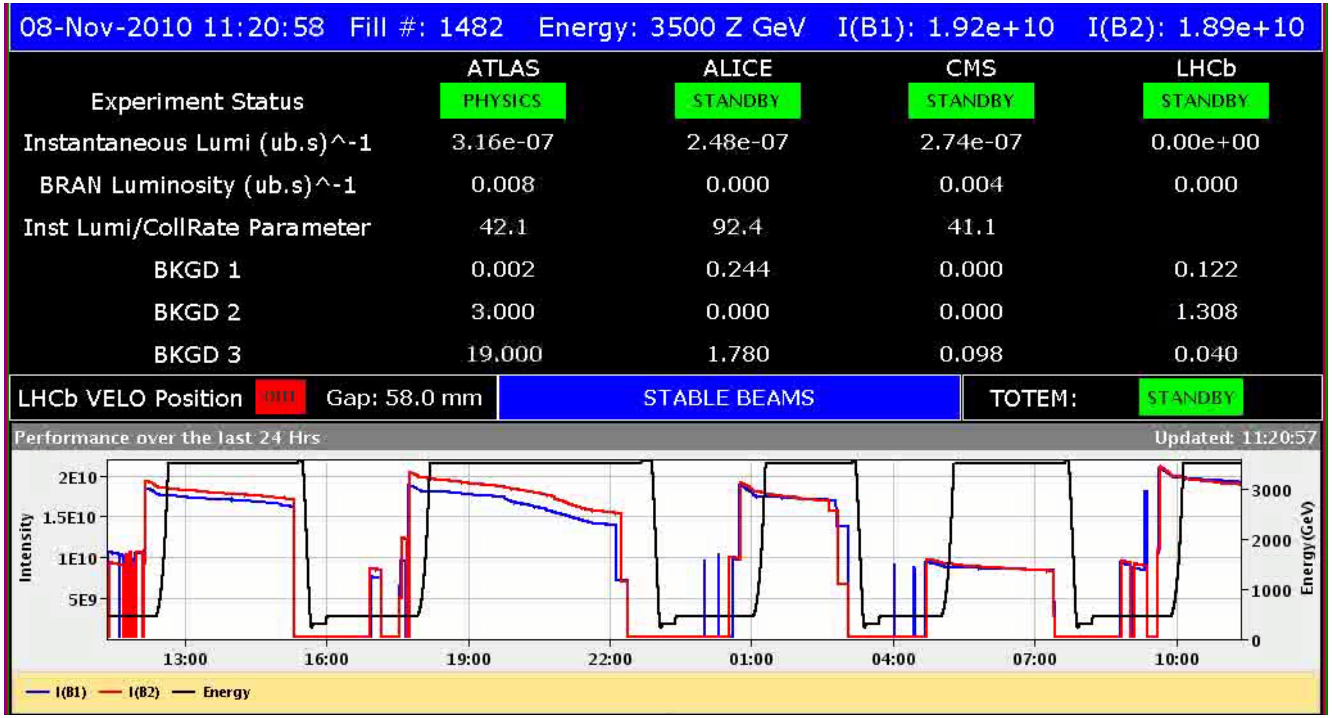
LHCb VELO Position OUT Gap: 58.0 mm SQUEEZE TOTEM: STANDBY

Performance over the last 24 Hrs Updated: 21:48:16

Beam 1
Circ.
& Captu

Rapid commissioning plan exploited established proton cycle to speed through initial phase of magnetic setup (injection, ramp, squeeze) . Collision crossing angles and collimation conditions different.

Monday morning: First Stable Beams for Pb-Pb



08-Nov-2010 11:20:58 Fill #: 1482 Energy: 3500 Z GeV I(B1): 1.92e+10 I(B2): 1.89e+10

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	STANDBY	STANDBY	STANDBY
Instantaneous Lumi (ub.s)^-1	3.16e-07	2.48e-07	2.74e-07	0.00e+00
BRAN Luminosity (ub.s)^-1	0.008	0.000	0.004	0.000
Inst Lumi/CollRate Parameter	42.1	92.4	41.1	
BKGD 1	0.002	0.244	0.000	0.122
BKGD 2	3.000	0.000	0.000	1.308
BKGD 3	19.000	1.780	0.098	0.040

LHCb VELO Position OUT Gap: 58.0 mm STABLE BEAMS TOTEM: STANDBY

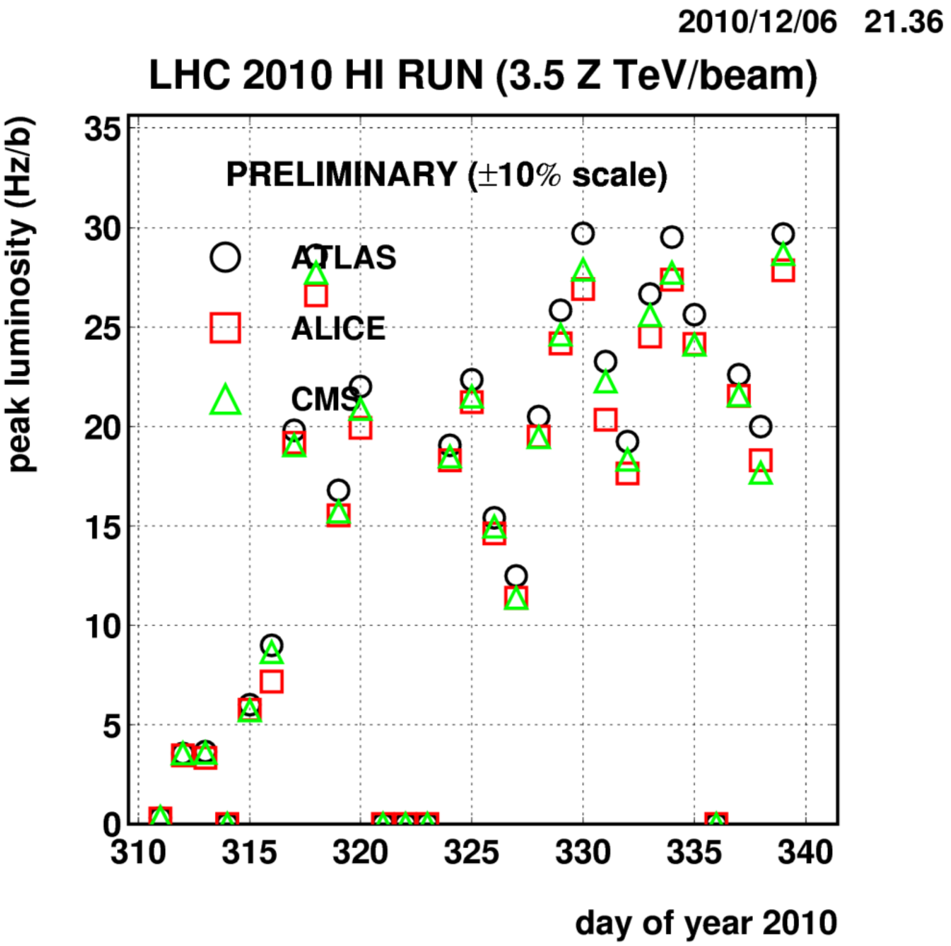
Performance over the last 24 Hrs Updated: 11:20:57

First stable beam with 2 bunches/beam (1 colliding)

Later same day, 5 bunches/beam, then increased on each fill: 17, 69, 121
Factor 100 in peak luminosity within 6 days.
Many interesting new RF manipulations in LHC in first 2 weeks.
Ion injectors exceeded design intensity/bunch by 70%.

Peak luminosity in fills

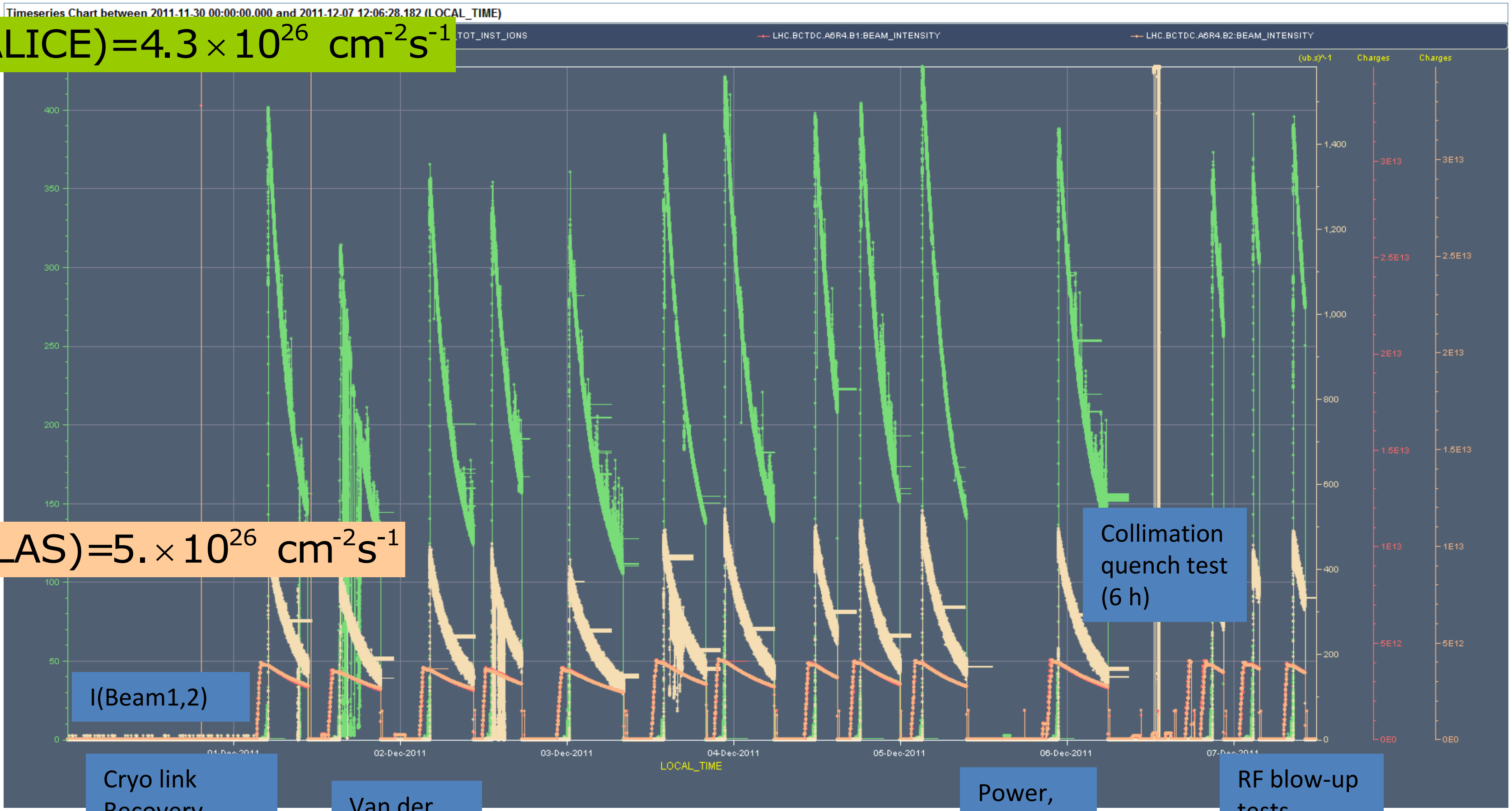
Interrupted twice by source refills (+ few days “parasitic” proton MD), some time to recover source performance (improvements for 2011).
Last few days: bunch number increased again to 137 with 8-bunches/batch from SPS.



2011 Pb-Pb run

- Aimed to increase integrated luminosity from ~10 μb^{-1} of 2010 to around 70 μb^{-1} by injecting trains of bunches from the SPS
- Final result was ~150 μb^{-1} in each of the 3 experiments
- But life became much more complicated because of intensity decay along trains due to combination of intra-beam scattering, space-charge and RF noise effects at injection in the SPS

Intensity and luminosity ~final week



$L(\text{ALICE})=4.3\times10^{26}\ \text{cm}^{-2}\text{s}^{-1}$

$L(\text{ATLAS})=5.\times10^{26}\ \text{cm}^{-2}\text{s}^{-1}$

I(Beam1,2)

Collimation quench test (6 h)

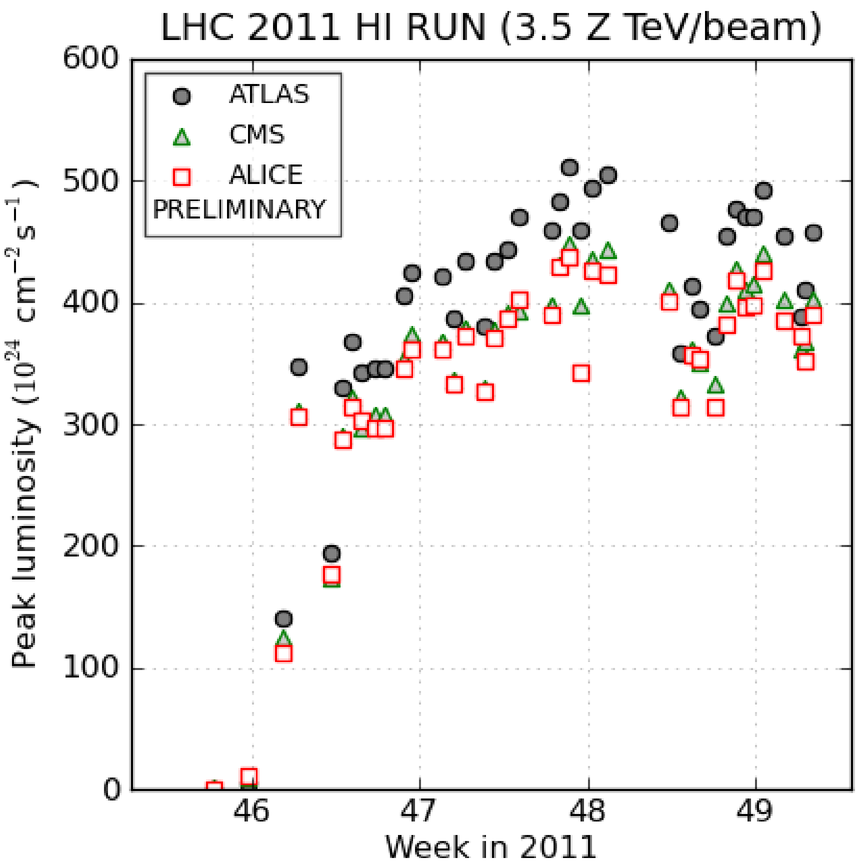
Cryo link Recovery ELQA Powering tests

Van der Meer scans

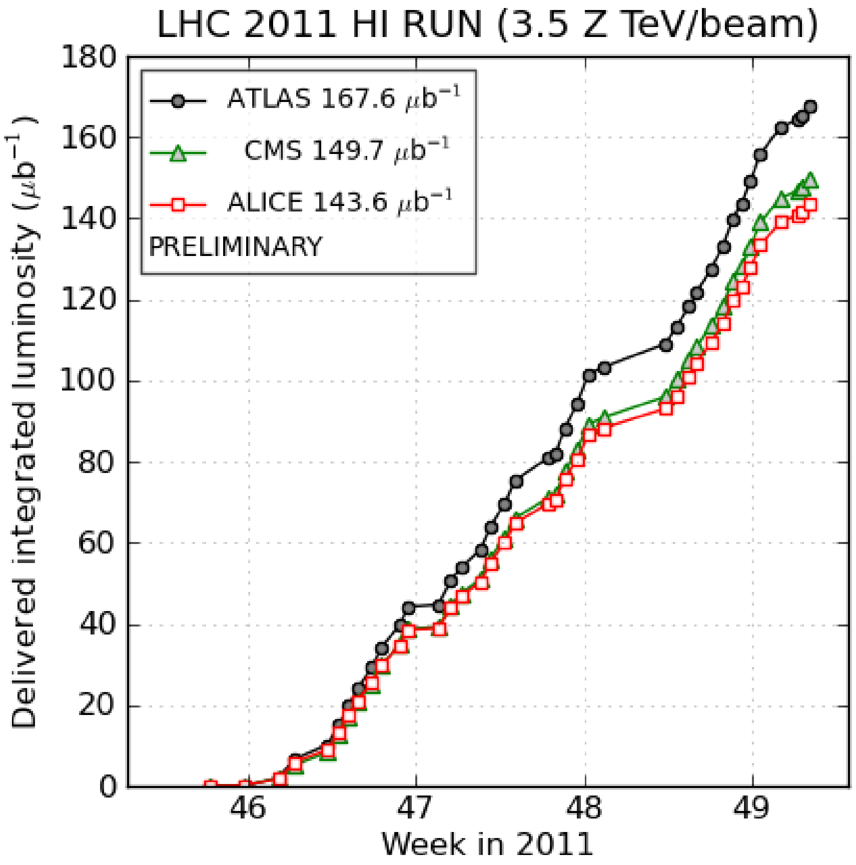
Power, cryo

RF blow-up tests

HI2011 final luminosity



(generated 2011-12-20 08:08 including fill 2351)



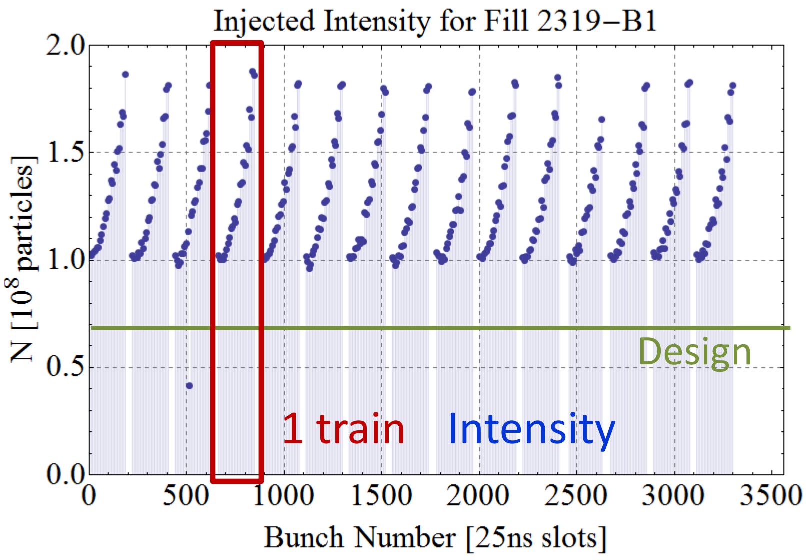
(generated 2011-12-20 08:08 including fill 2351)

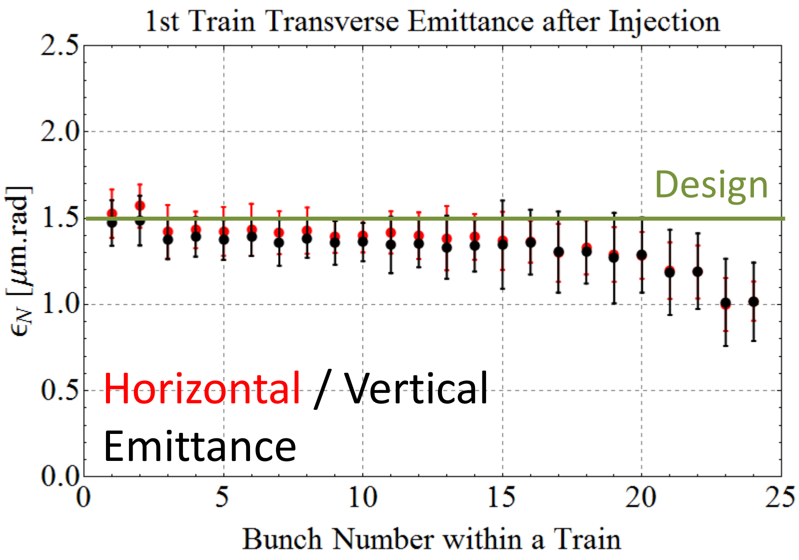
What limits the luminosity we can achieve?

- Limits for Pb-Pb include new effects that do not affect p-p
  - (Some p-p effects are no problem for Pb-Pb/)
- Intra-beam scattering (multiple small-angle Coulomb scattering within bunch) blows up beam emittance, especially at low energy (and in SPS) and may cause intensity losses, stronger for high charge
- Losses in collimation process (more complicated nuclear physics …)
- Ultraperipheral electromagnetic interactions of colliding nuclei (completely new in LHC, describe in following)

Bunch-by-Bunch Differences after Injection in the LHC

E = 450 Z GeV

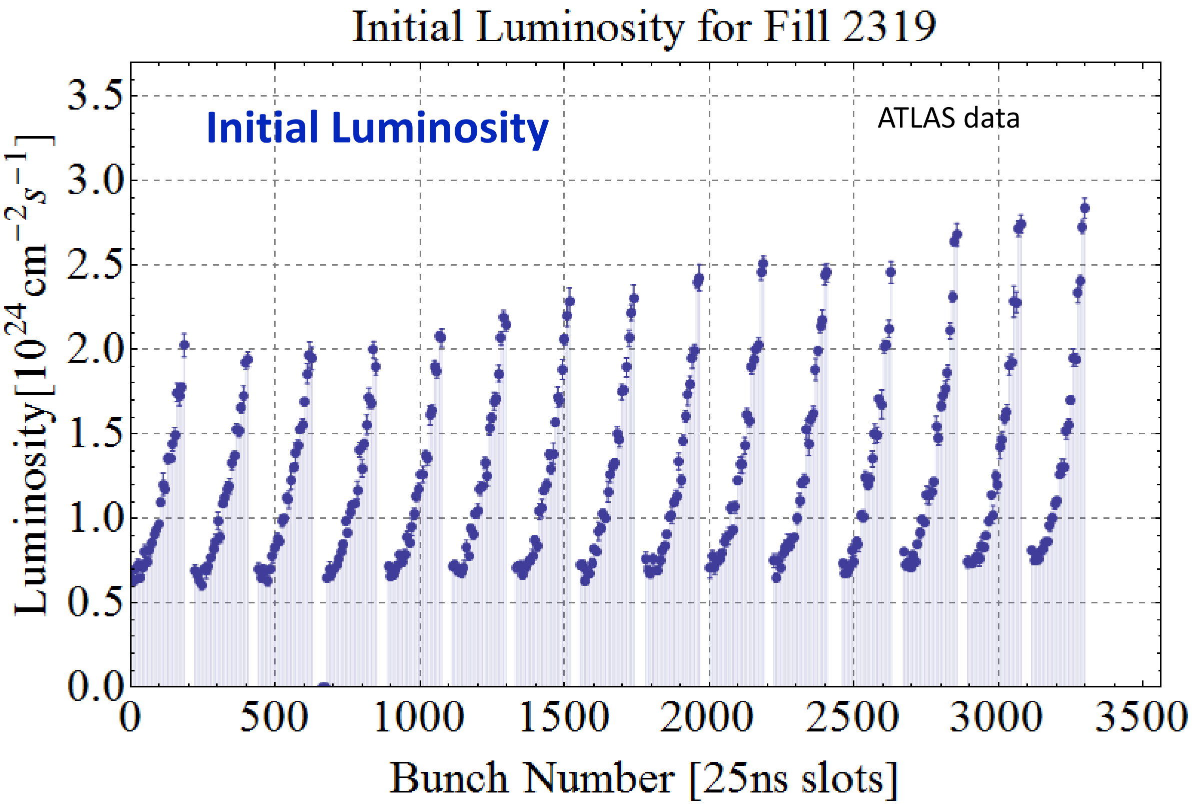




- Structure within a train (1st to last bunch):
  - increase: - intensity
    - bunch length
  - decrease: emittance.
- IBS, space charge, RF noise … at the injection plateau of the SPS:
  - while waiting for the 12 injections from the PS to construct a LHC train.
- First injections sit longer at low energy → strong IBS, → emittance growth and particle losses.

Bunch-by-Bunch Luminosity

E = 3.5Z TeV



Implications for any experiment using heavy-ion beams ?

Electromagnetic processes in Pb-Pb collisions

$$\text{BFPP1:}\quad {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \longrightarrow {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + e^{+},$$
$$\sigma = 281\ \mathrm{b},\quad \delta = 0.01235$$

$$\text{BFPP2:}\quad {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \longrightarrow {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{80+} + 2e^{+},$$
$$\sigma \approx 6\ \mathrm{mb},\quad \delta = 0.02500$$

$$\text{EMD1:}\quad {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \longrightarrow {}^{208}\mathrm{Pb}^{82+} + {}^{207}\mathrm{Pb}^{82+} + n\ ,$$
$$\sigma = 96\ \mathrm{b},\quad \delta = -0.00485$$

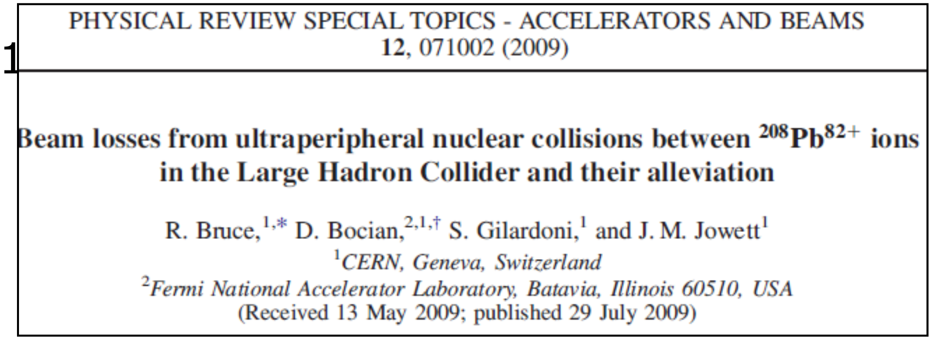
$$\text{EMD2:}\quad {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \longrightarrow {}^{208}\mathrm{Pb}^{82+} + {}^{206}\mathrm{Pb}^{82+} + 2n\ ,$$
$$\sigma = 29\ \mathrm{b},\quad \delta = -0.00970$$

Each of these makes a secondary beam emerging from the IP with rigidity change

$$\delta = \frac{1 + \Delta m / m_{\mathrm{Pb}}}{1 + \Delta Q / Q} - 1$$

Hadronic cross section is 8 b (so much less power in debris).

Discussed since Chamonix 2003 …

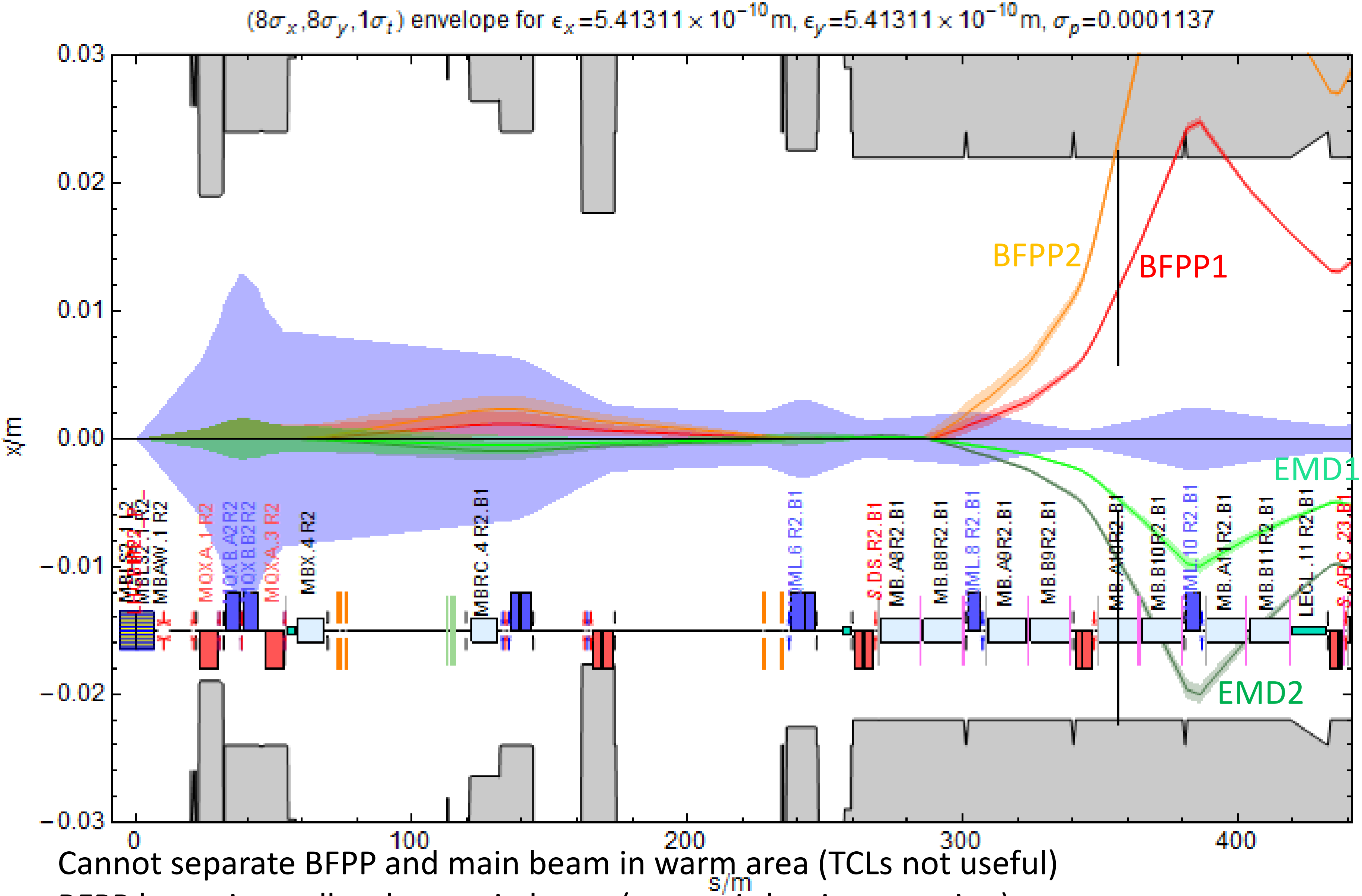


PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS
12, 071002 (2009)

Beam losses from ultraperipheral nuclear collisions between ${}^{208}\mathrm{Pb}^{82+}$ ions in the Large Hadron Collider and their alleviation

R. Bruce,[1,*] D. Bocian,[2,1,†] S. Gilardoni,[1] and J. M. Jowett[1]
[1]*CERN, Geneva, Switzerland*
[2]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
(Received 13 May 2009; published 29 July 2009)

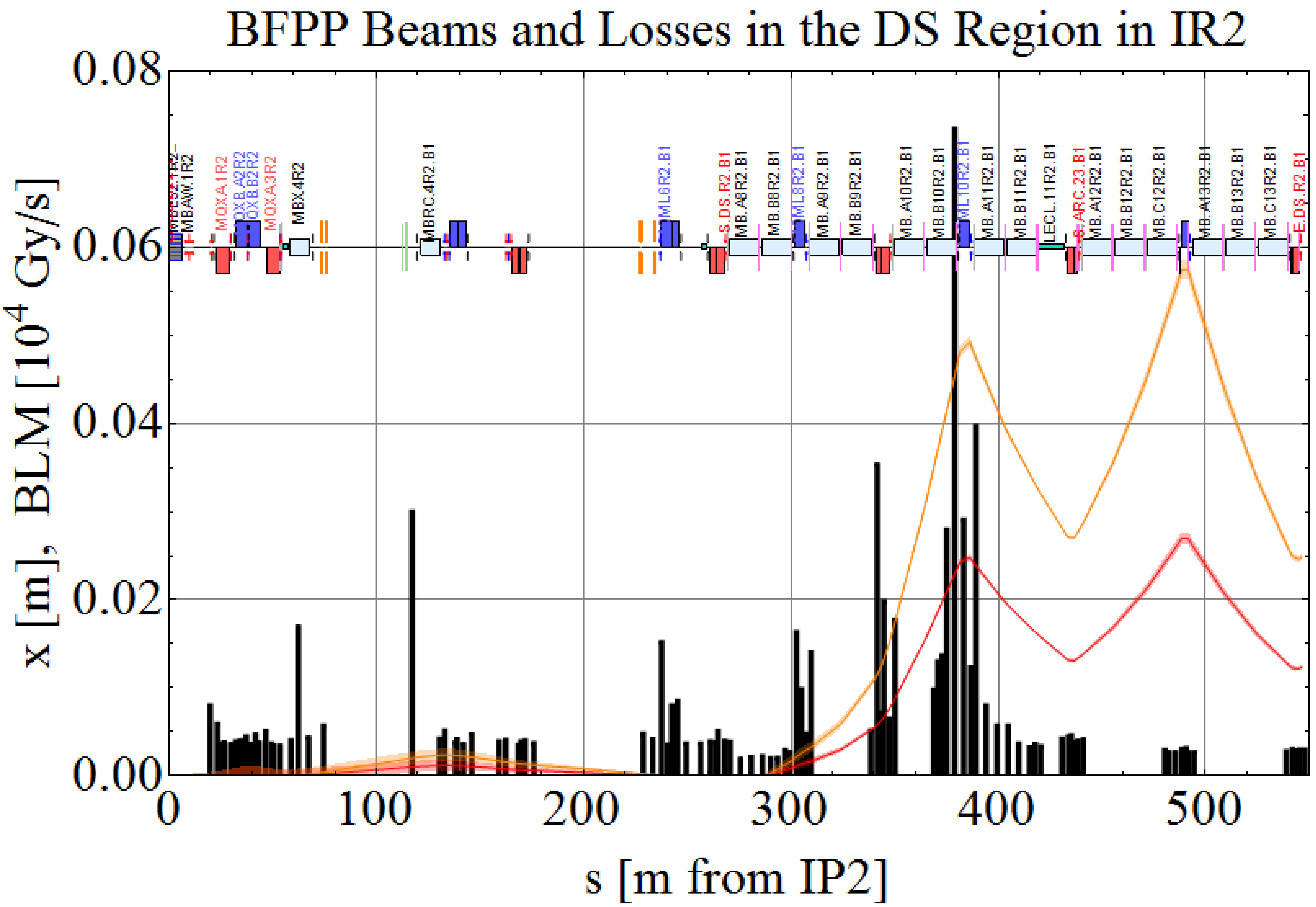
Secondary beams from Beam 1 in IR2



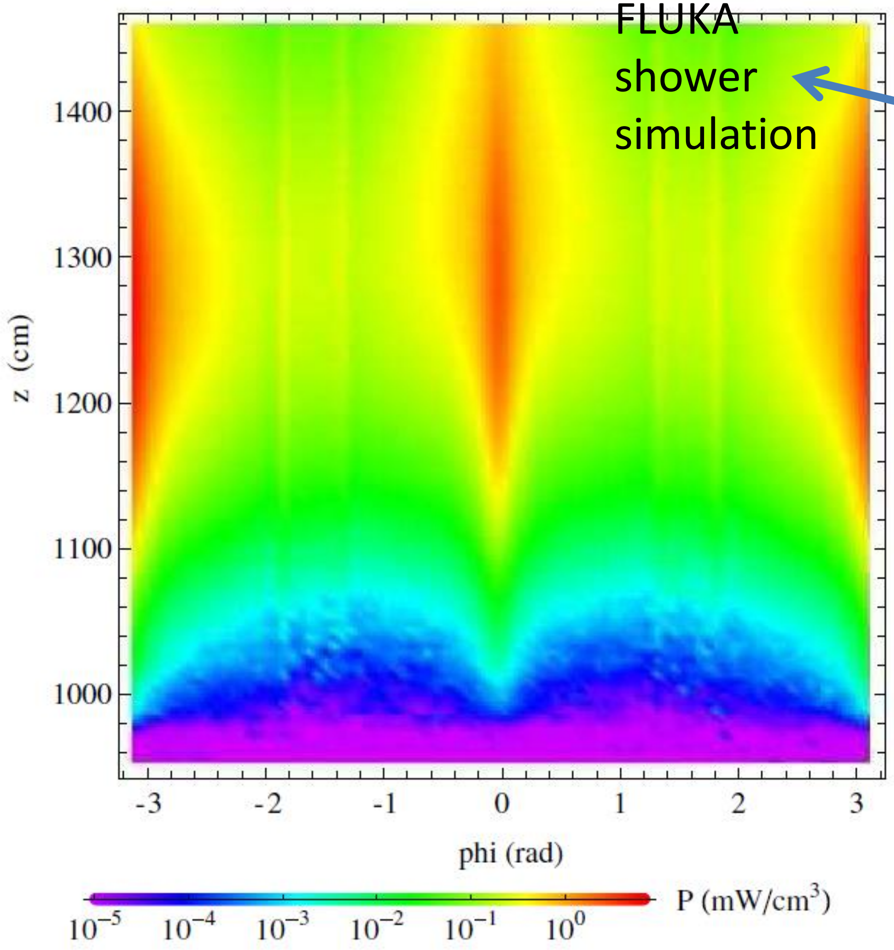
Cannot separate BFPP and main beam in warm area (TCLs not useful)

BFPP beam is smaller than main beam (source is luminous region).

2011 Pb-Pb operation



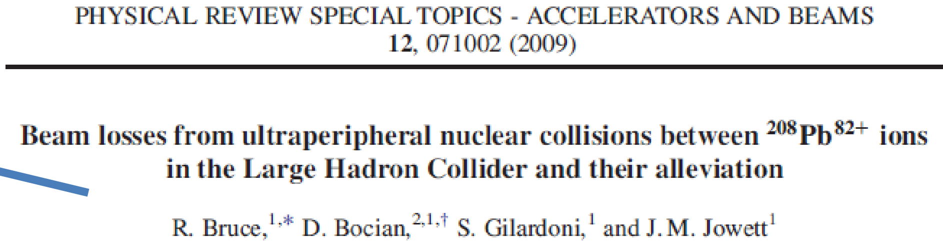
Power density in superconducting cable



FLUKA shower simulation

FIG. 7. (Color) The heating power from beam losses caused by BFPP in the inner layer of the coil of an LHC main dipole as simulated with FLUKA. The power density was averaged over the width of the cable and is shown as a function of azimuthal angle ϕ and longitudinal coordinate z, with $z = 0$ in the beginning of the magnet. The beam loss is centered around $z = 1206$ cm and $\phi \approx -3.11$ rad.

Newer FLUKA studies – see talk by A. Lechner



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS
12, 071002 (2009)

Beam losses from ultraperipheral nuclear collisions between $^{208}\mathrm{Pb}^{82+}$ ions in the Large Hadron Collider and their alleviation

R. Bruce,[1,*] D. Bocian,[2,1,†] S. Gilardoni,[1] and J. M. Jowett[1]

Maximum power density in coil at 7 Z Te

P = 15.5 mW/cm^3 at design luminosity.

For upgrade luminosity, expect

$P \approx$ 93 mW/cm^3

See other talks!

c.f. quench limit (latest from A. Verweij)

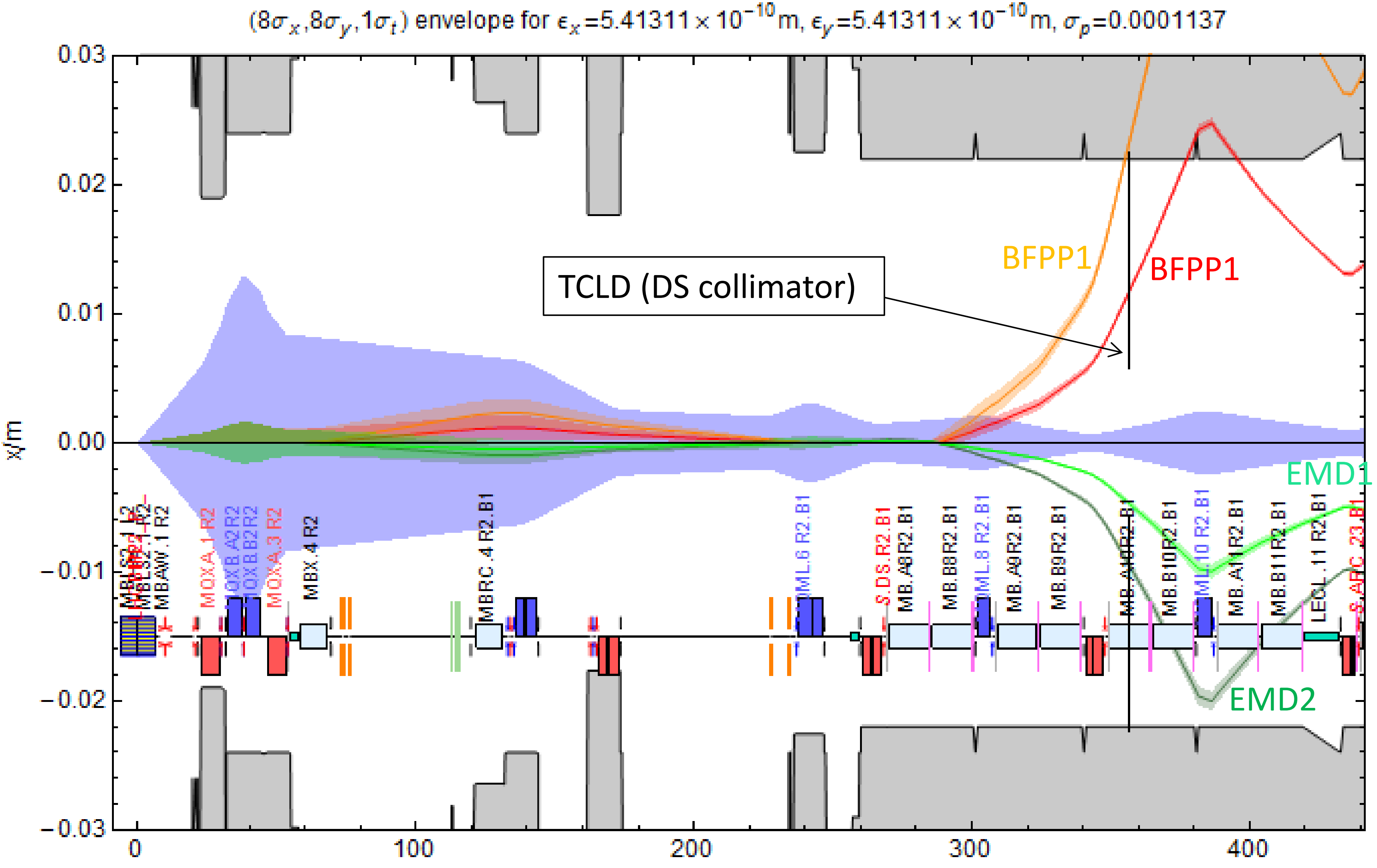
200 mW/cm^3 at 4 Z TeV

40-50 mW/cm^3 at 7 Z TeV

(higher than used previously)

Nevertheless, expect to quench MB and possibly MQ!

Secondary beams from Beam 1 in IR2 (horizontal plane)



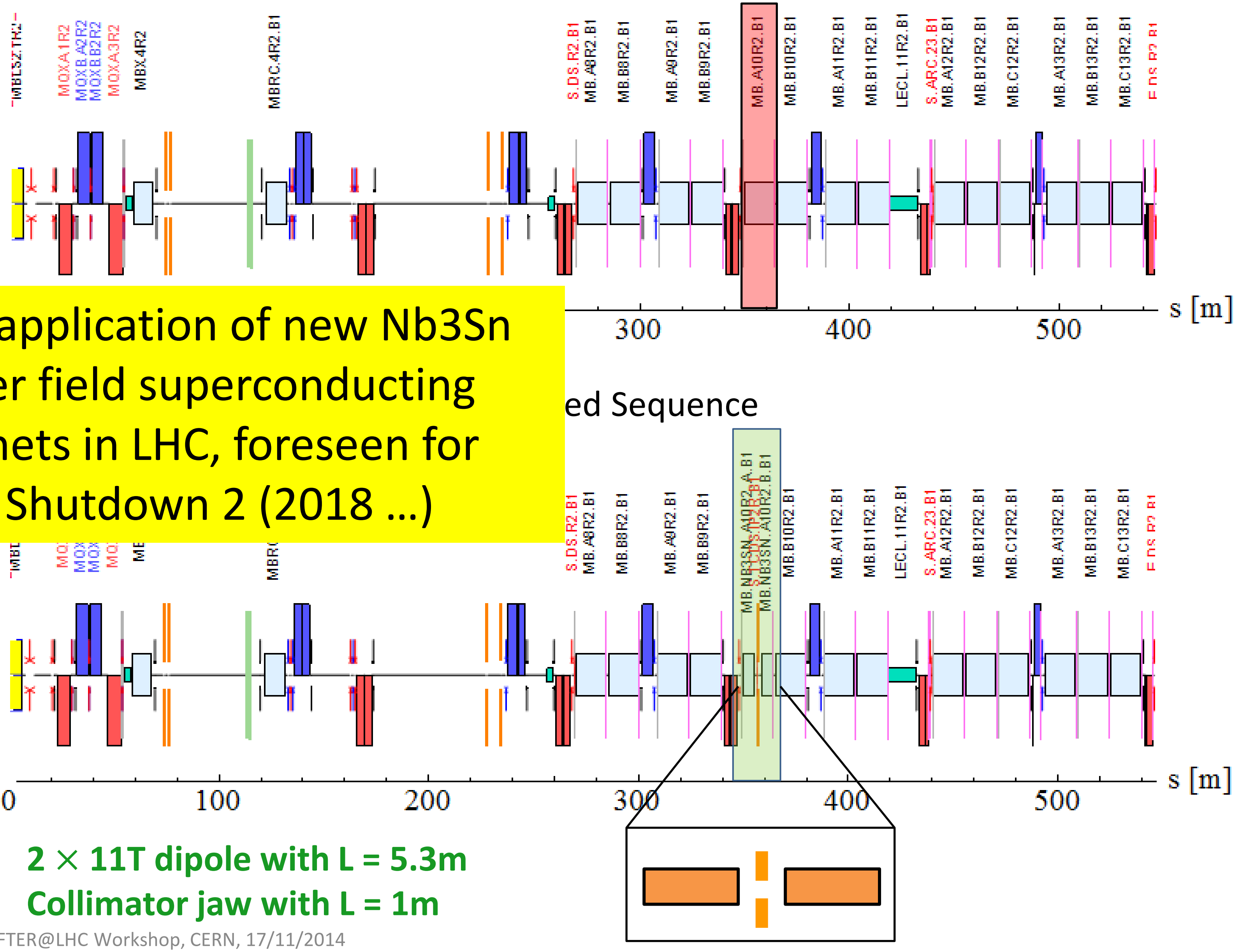
Cannot separate BFPP and main beam in warm area (TCLs not useful)

BFPP beam is smaller than main beam (source is luminous region).

DS collimator installation in IR2

Magnet to be replaced **MB.A10R2**

Nominal Beam Line

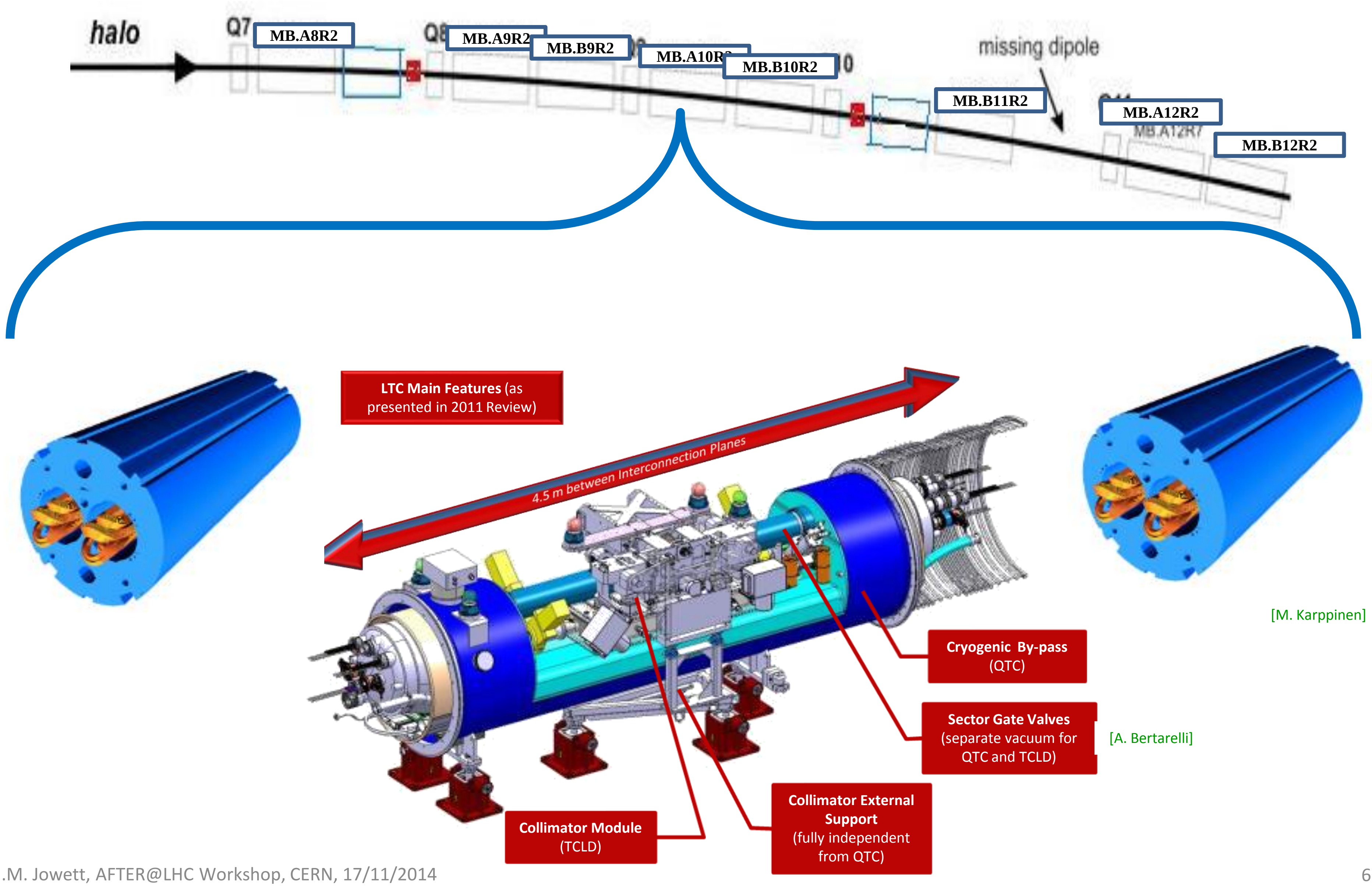


First application of new Nb3Sn higher field superconducting magnets in LHC, foreseen for Long Shutdown 2 (2018 …)

2 × 11T dipole with L = 5.3m
Collimator jaw with L = 1m

Integrated technological solution for point 2

(same solution deployable in IP 7 in case of need)



LTC Main Features (as presented in 2011 Review)

Cryogenic By-pass (QTC)

Sector Gate Valves (separate vacuum for QTC and TCLD)

Collimator External Support (fully independent from QTC)

Collimator Module (TCLD)

[M. Karppinen]

[A. Bertarelli]

ATLAS and CMS ?

- ATLAS and CMS also take high-luminosity Pb-Pb
- The same problem of BFPP losses exists in the DSs around IP1 and IP5
    - Details of loss locations somewhat different
    - Highest BLM signals from BFPP in 2011 were right of IP5
    - We have some scope for mitigation using the orbit bump method tested in 2011 (will be made operational for Run 2 anyway) - **backup slides**

Collimation of heavy ions

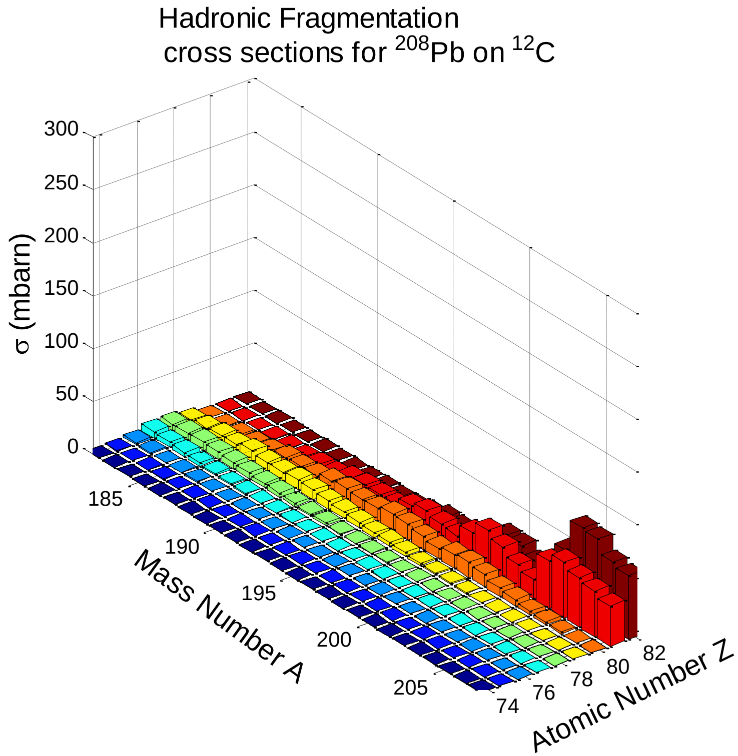
- LHC proton collimation principle:
  - Errant protons encounter primary collimator and are diffractively scattered to larger betatron oscillation amplitude, cleaned by secondary collimators
- Collimation of heavy ions is very different from protons
  - Nuclear interactions (hadronic fragmentation, EM dissociation) in primary collimator material.
  - Staged collimation principle does not work.
  - Single stage system, reduced collimation efficiency

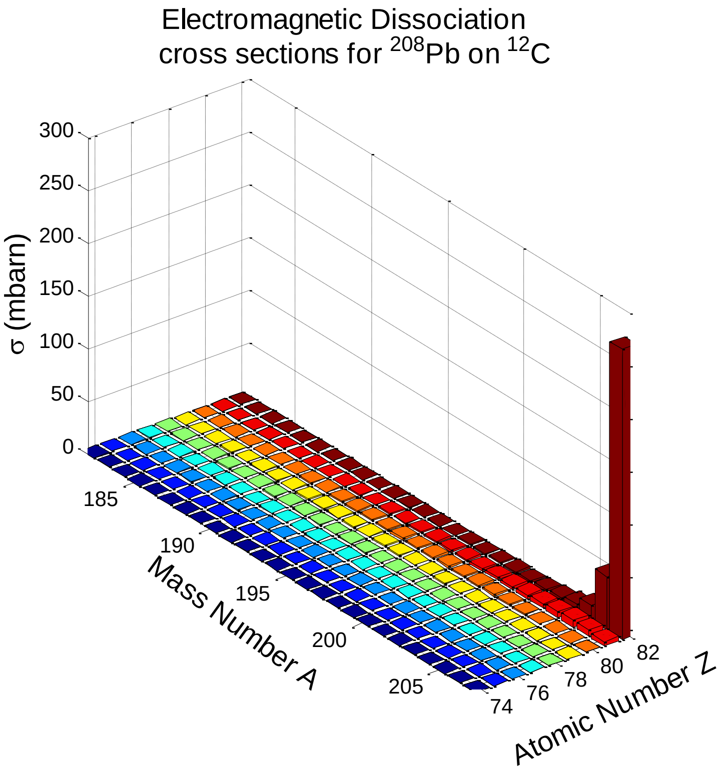
Collimation system cleans beam halo

LHC design (primarily for p beam) principle: diffractive scattering of errant particles on primary collimator towards absorption in secondary collimators
Nuclear physics different for heavy ions!

Hadronic fragmentation:
Large variety of daughter nuclei, specific cross sections

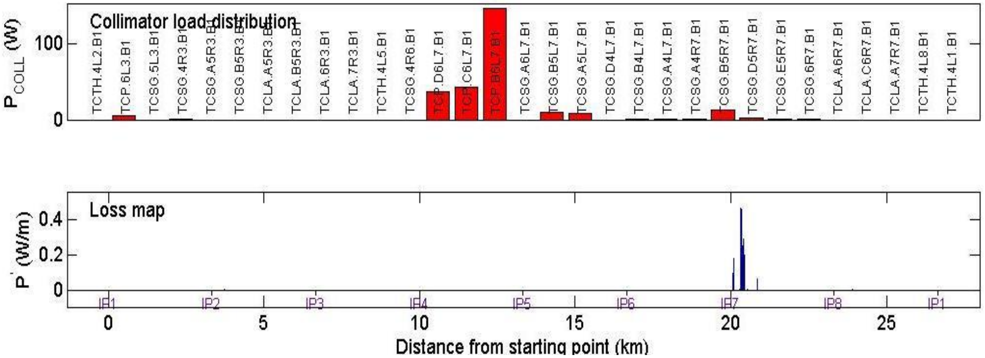
Electromagnetic dissociation:
Mainly loss of 1 (59%) or 2 (11%) neutrons → ^{207}Pb, ^{206}Pb


Hadronic Fragmentation
cross sections for ^{208}Pb on ^{12}C


Electromagnetic Dissociation
cross sections for ^{208}Pb on ^{12}C

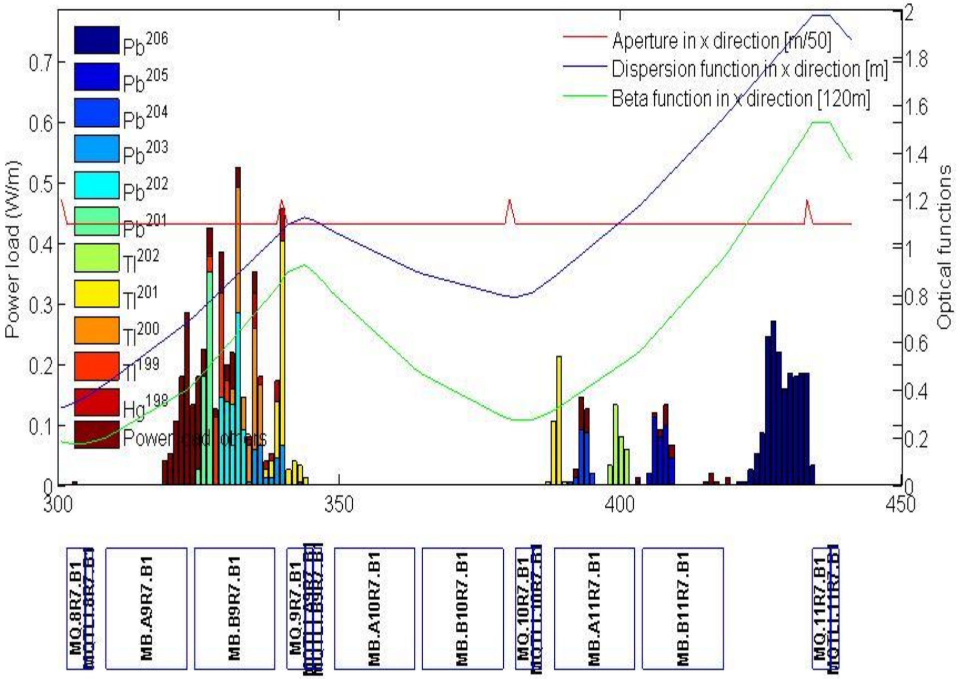
Beam1, betatron collimation E=3.5 Z TeV, β^* =3.5m, 12min lifetime

TCP IR7	5.7 σ	TCP IR3	12 σ
TCSG IR7	8.5 σ	TCSG IR3	15.6 σ
TCLA IR7	17.7 σ	TCLA IR3	17.6 σ
		TCTs	15 σ



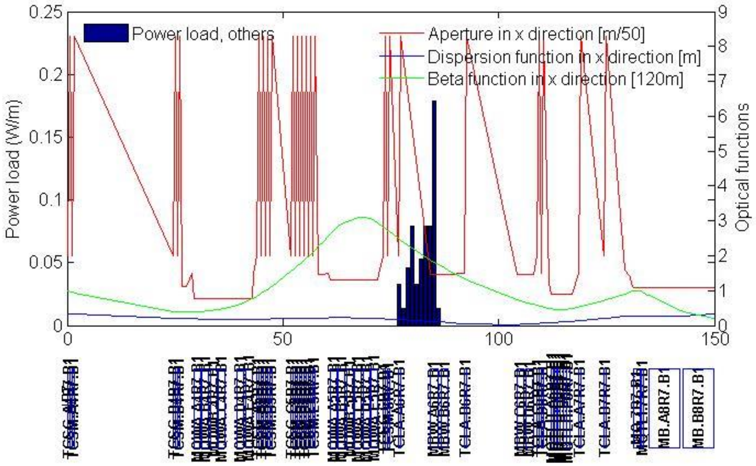
Σ aperture hits/Σ collimator hits=
η= 0.033

Isotopic loss map, DS.R7



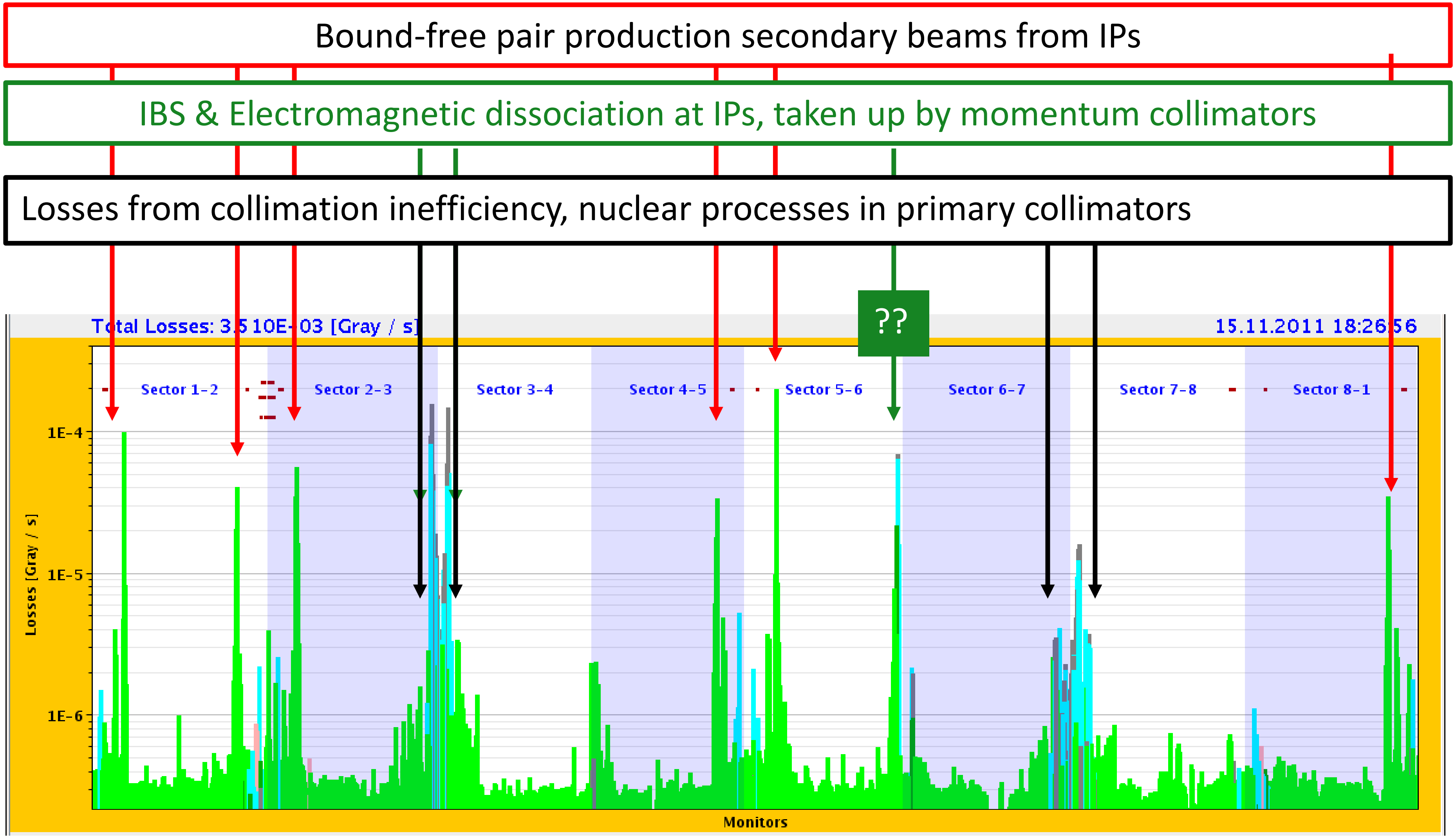
Max load on TCP.B6L7.B1=122W

Some losses before DS



From G. Bellodi

Steady-state losses during Pb-Pb Collisions in 2011

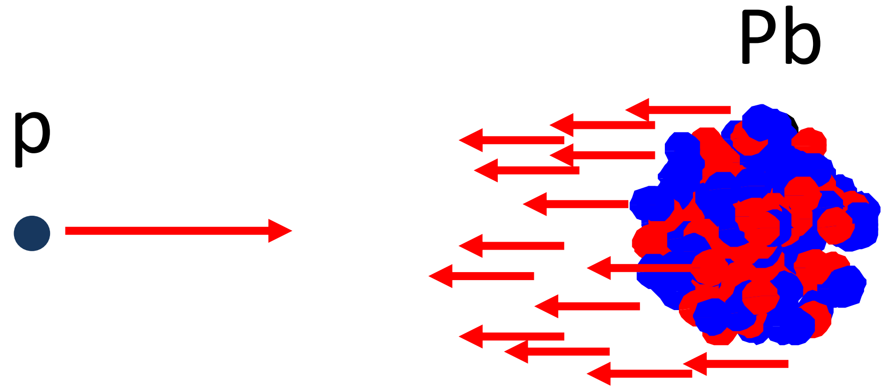


Bound-free pair production secondary beams from IPs

IBS & Electromagnetic dissociation at IPs, taken up by momentum collimators

Losses from collimation inefficiency, nuclear processes in primary collimators

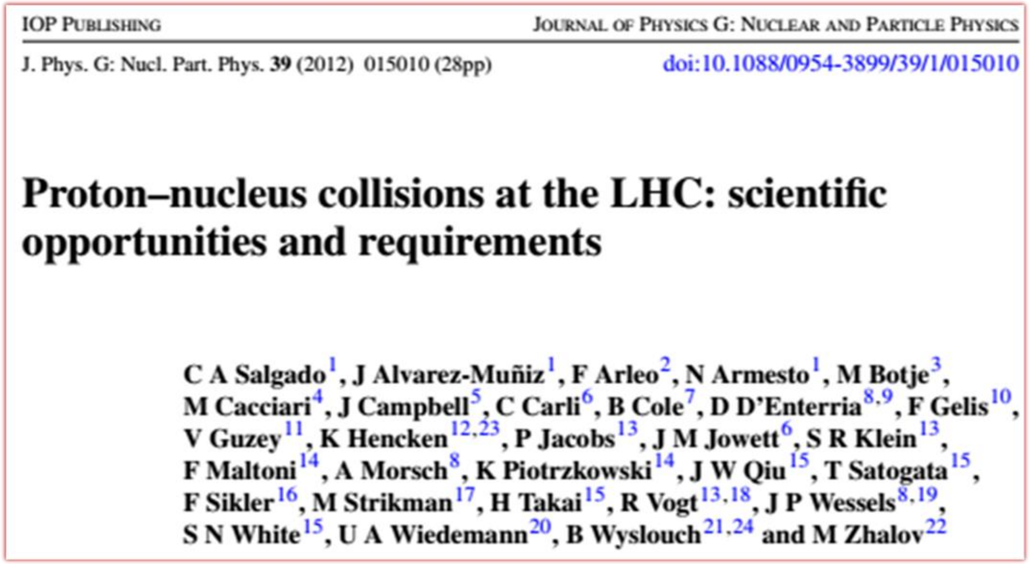
Beam loss monitors in the full LHC Ring



LHC AS A PROTON-NUCLEUS COLLIDER

History of proton-nucleus collisions at LHC (1)

- Long considered desirable by experiments but never included in baseline design of LHC
- 2003: RHIC finds a way to collide deuterons and gold nuclei but this way is not open to LHC …
- 2005 CERN workshop on pA in LHC
  - Predicted that p-Pb in LHC could work (despite RHIC …)
  - Physics case written up much later



IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **39** (2012) 015010 (28pp) doi:10.1088/0954-3899/39/1/015010

Proton–nucleus collisions at the LHC: scientific opportunities and requirements

C A Salgado[1], J Alvarez-Muñiz[1], F Arleo[2], N Armesto[1], M Botje[3], M Cacciari[4], J Campbell[5], C Carli[6], B Cole[7], D D'Enterria[8,9], F Gelis[10], V Guzey[11], K Hencken[12,23], P Jacobs[13], J M Jowett[6], S R Klein[13], F Maltoni[14], A Morsch[8], K Piotrzkowski[14], J W Qiu[15], T Satogata[15], F Sikler[16], M Strikman[17], H Takai[15], R Vogt[13,18], J P Wessels[8,19], S N White[15], U A Wiedemann[20], B Wyslouch[21,24] and M Zhalov[22]

History of proton-nucleus collisions at LHC (2)

- 2006 First paper at European Particle Accelerator Conference, in Edinburgh (!)
- Early 2011, LHC Chamonix workshop – go-ahead given for feasibility tests on LHC
- Preparation of LHC systems during 2011
- 31/10/2011 successful feasibility test
- Early 2012, after high Pb-Pb luminosity in Nov 2011, experiments *really* want p-Pb comparison data
- 13/9/2012 Successful pilot collision run (one night) yields new physics
- Full 1 month run postponed to early 2013 to allow more p-p data taking before long shutdown
- Jan-Feb 2013 first full physics run

Relation between Beam Momenta

- LHC accelerates protons through the momentum range

$$0.45\ \text{TeV (injection from SPS)} \le p_p \le 7\ \text{TeV (collision)}$$

  - p_p is measure of magnetic field in main bending magnets
- The two-in-one magnet design of the LHC fixes the relation between momenta of beams in the two rings (equal “*magnetic rigidity*”)

$$p_{\mathrm{Pb}} = Z p_{\mathrm{p}}$$

where $Z = 82$, $A = 208$ for fully stripped Pb in LHC

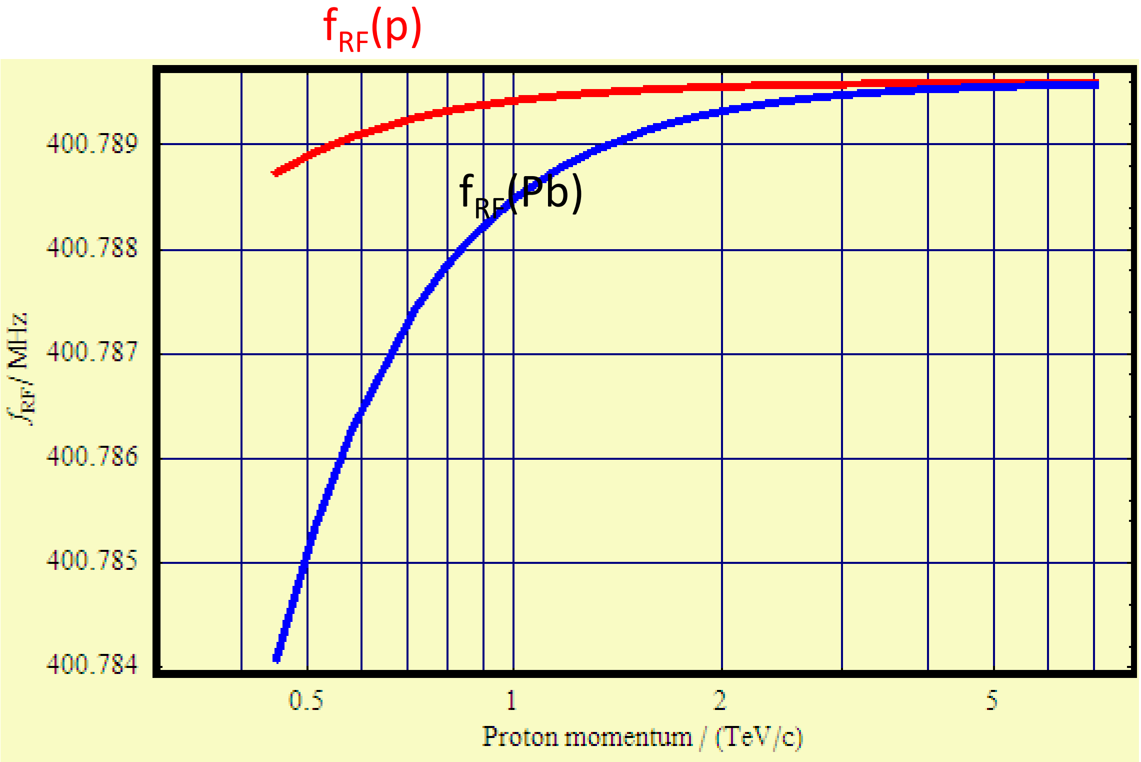
RF Frequency for p and Pb in LHC

Revolution time of a general particle, mass *m*, charge *Q*, is

$$T\left(p_{\mathrm{p}}, m, Q\right) = \frac{C}{c}\sqrt{1+\left(\frac{mc}{Qp_{\mathrm{p}}}\right)^2} \quad \text{and RF frequency} \quad f_{\mathrm{RF}} = \frac{h_{\mathrm{RF}}}{T\left(p_{\mathrm{p}}, m, Q\right)}$$

where the harmonic number $h_{\mathrm{RF}} \in \mathbb{N}$, $h_{\mathrm{RF}} = 35640$ in LHC

RF frequencies needed to keep p or Pb on stable *central* orbit of constant length *C* are different at low energy.



No problem in terms of hardware as LHC has independent RF systems in each ring.

Distorting the Closed Orbit

- Additional degree of freedom: adjust length of closed orbits to compensate different speeds of species.
  - Done by adjusting RF frequency

$$T\left(p_{\mathrm{p}},m,Q\right)=\frac{C}{c}\sqrt{1+\left(\frac{mc}{Qp_{\mathrm{p}}}\right)^{2}}\,(1+\eta\delta)$$

where $\delta=\dfrac{(p-Qp_{\mathrm{p}})}{Qp_{\mathrm{p}}}$ is a fractional momentum deviation and

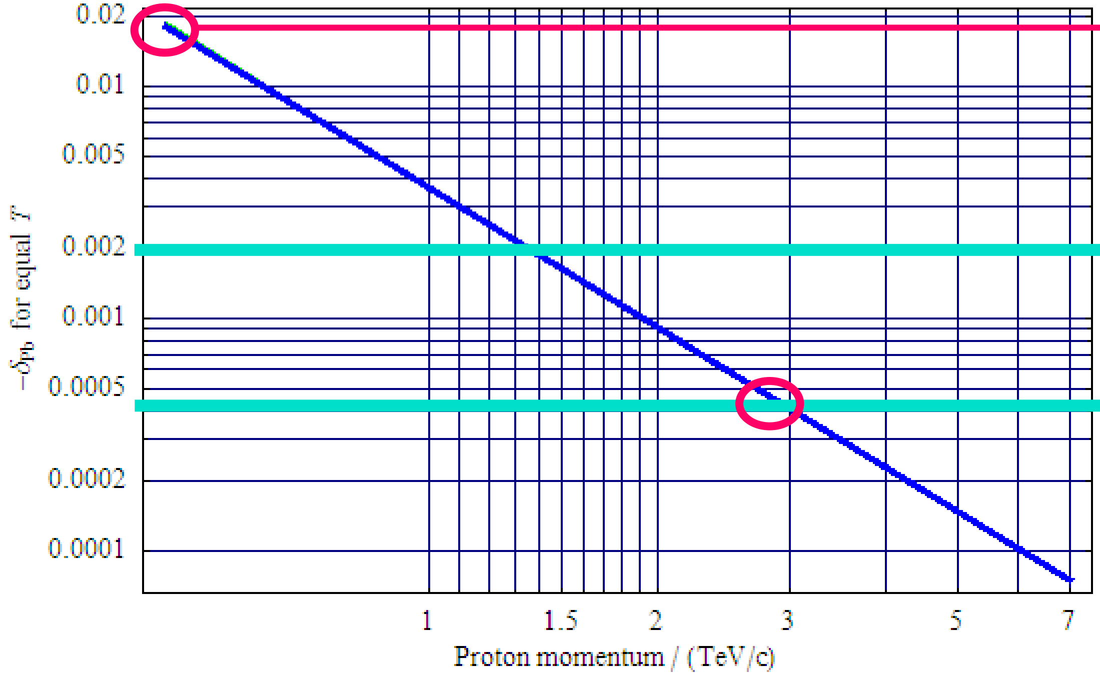
the phase-slip factor $\eta=\dfrac{1}{{\gamma_T}^{2}}-\dfrac{1}{\gamma^{2}}$, $\quad\gamma=\sqrt{1+\left(\dfrac{Qp_{\mathrm{p}}}{mc}\right)^{2}}$, $\quad\gamma_T=55.8$ for LHC optics.

Moves beam on to off-momentum orbit, longer for $\delta>0$.

Horizontal offset given by dispersion: $\Delta x=D_x\left(s\right)\delta$.

Momentum offset required through ramp

Minimise aperture needed by $\delta_{\mathrm{p}} = -\delta_{\mathrm{Pb}} = \frac{c^2 {\gamma_T}^2}{4p_{\mathrm{p}}^2}\left(\frac{m_{\mathrm{Pb}}^2}{Z^2} - m_{\mathrm{p}}^2\right).$



2% - would move beam by 35 mm in QF!!

Limit with pilot beams

Limit in normal operation
(1 mm in arc QD)

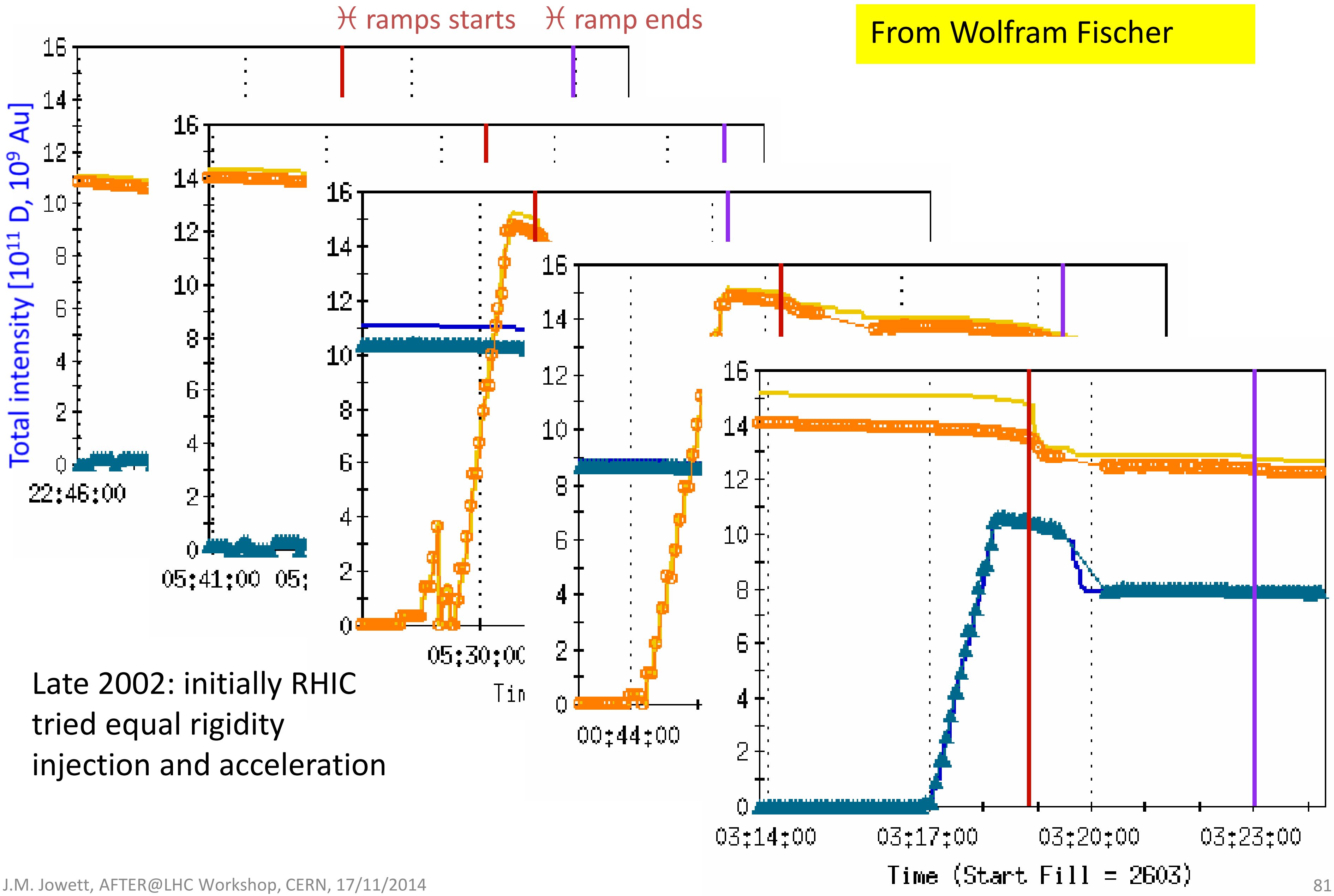
Revolution frequencies must be equal for collisions at top energy.

Lower limit on beam energy for p-Pb collisions, *E*=2.7 Z TeV.

RF frequencies must be unequal for injection, ramp!

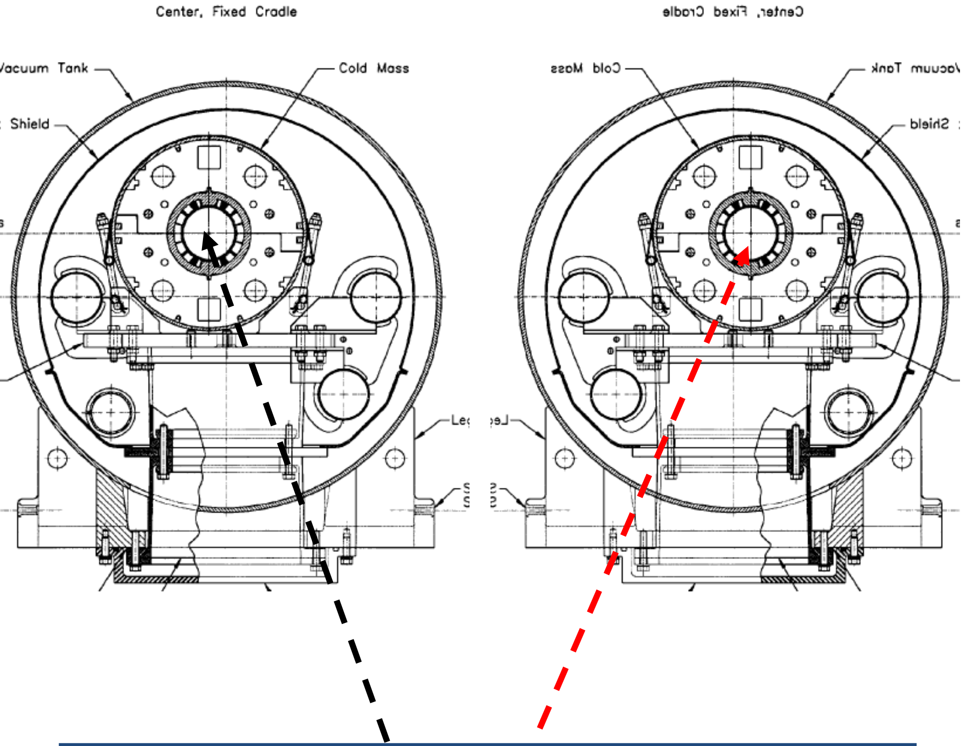
RHIC D-Au injection and ramp $(B\rho)_d = (B\rho)_{Au}$

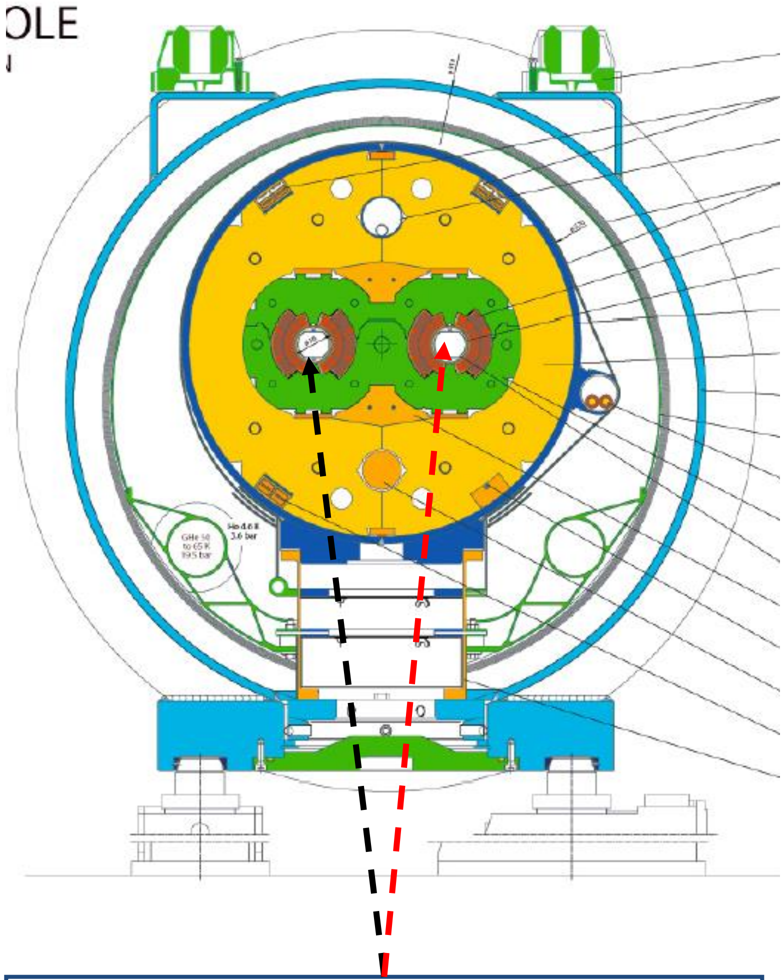
From Wolfram Fischer



Late 2002: initially RHIC tried equal rigidity injection and acceleration

Critical difference between RHIC and LHC





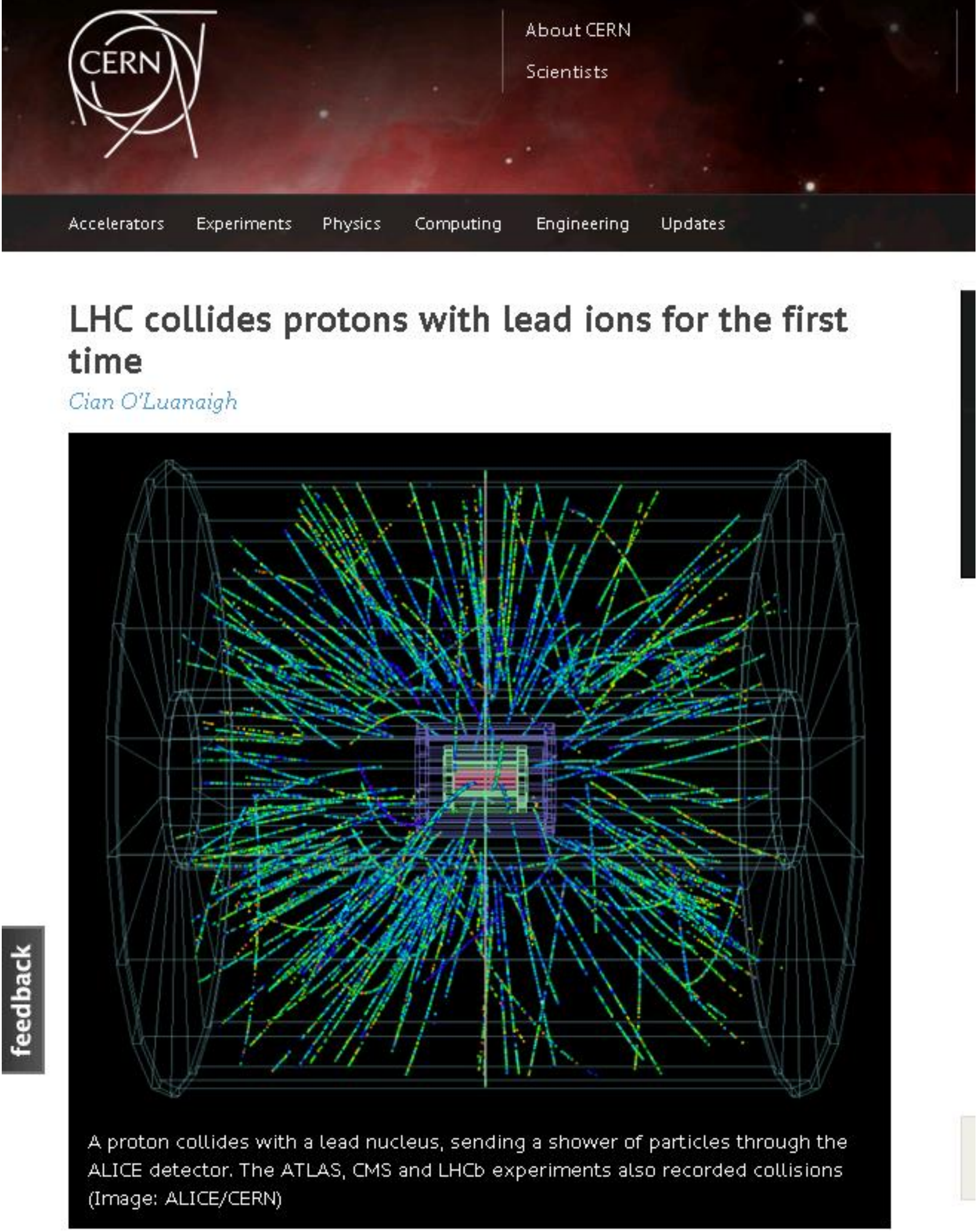
RHIC: Independent bending field for the two beams – they abandoned equal-rigidity and switched to equal-frequency D-Au.

LHC: Identical bending field in both apertures of
two-in-one dipole – no choice

Outline of p-Pb physics cycle (Pb-p similar)

- Inject p beam in Ring 1, f_{RF1} for p
- Inject Pb beam in Ring 2, f_{RF2} for Pb
- Ramp both beams on central orbits
  - Orbit feedback decouples RF frequencies
- Bring f_{RF} together to lock, beams are slightly off central orbits
- RF re-phasing to position collision point
- Squeeze
- Change ALICE crossing angle to collision configuration
- Collide

At injection the proton beam makes 8 more revolutions per minute than the Pb beam



LHC collides protons with lead ions for the first time

Cian O'Luanaigh

A proton collides with a lead nucleus, sending a shower of particles through the ALICE detector. The ATLAS, CMS and LHCb experiments also recorded collisions (Image: ALICE/CERN)

Single pilot fill, night of 13-14 September 2012

Injection and ramp of p and Pb beams with unequal revolution frequencies.
RF frequencies locked, collision points moved to experiments.

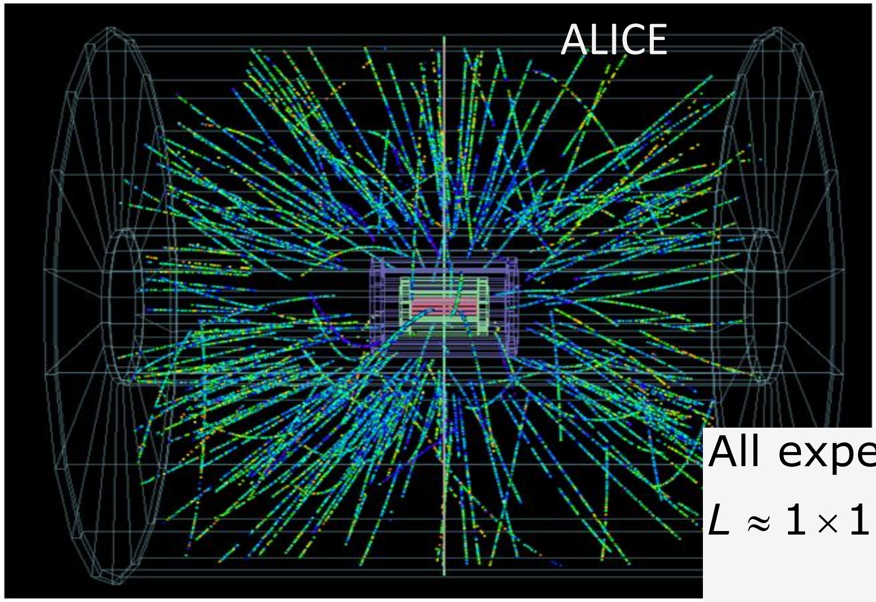
Setup of collimation, declaration of Stable Beams with unsqueezed optics.

4 hours physics, 2 more hours with IPs displaced by +- 0.5 m.

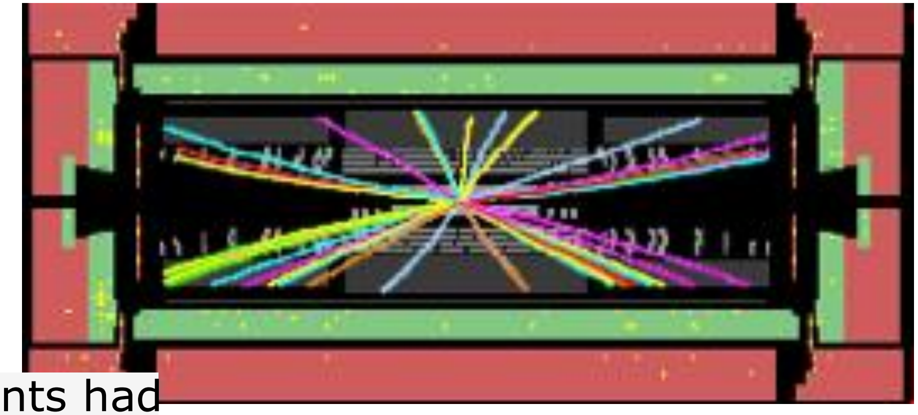
Largest increase of centre-of-mass energy in history of accelerators.

+ *unexpected physics discoveries*

Collisions in all experiments



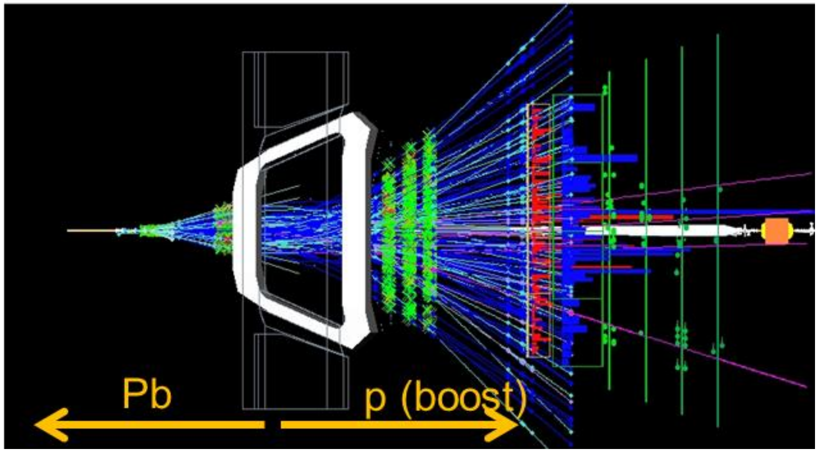
ATLAS

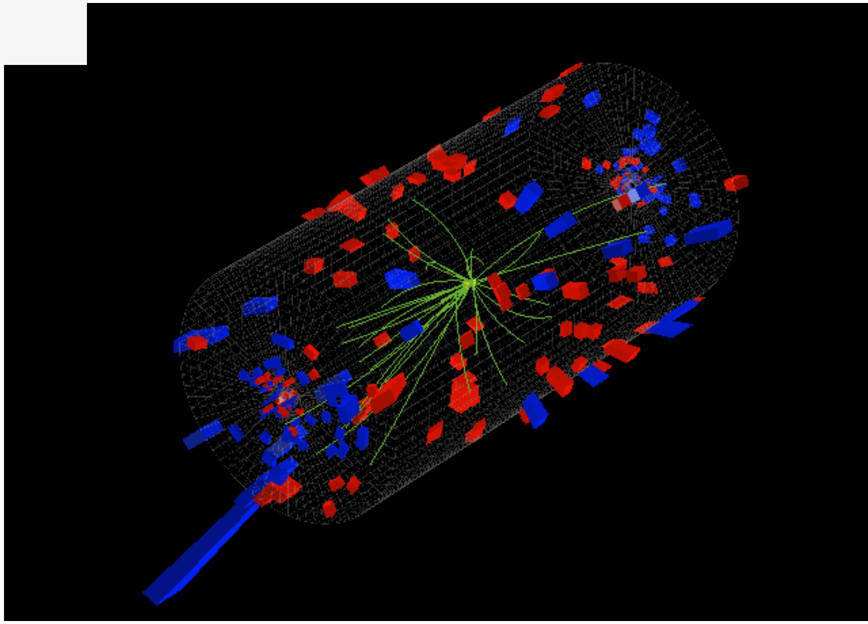


All experiments had

$L \approx 1 \times 10^{26}$ $\text{cm}^{-2}\text{s}^{-1}$

LHCb



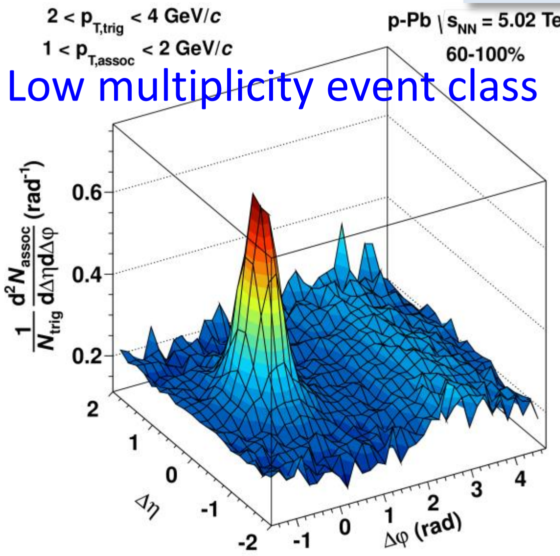


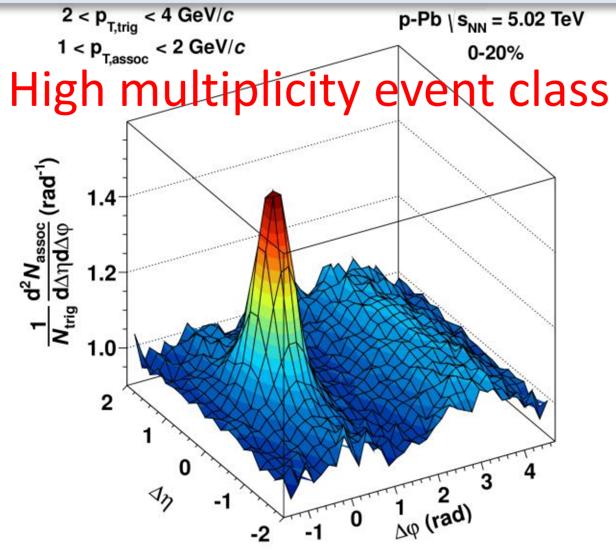
CMS

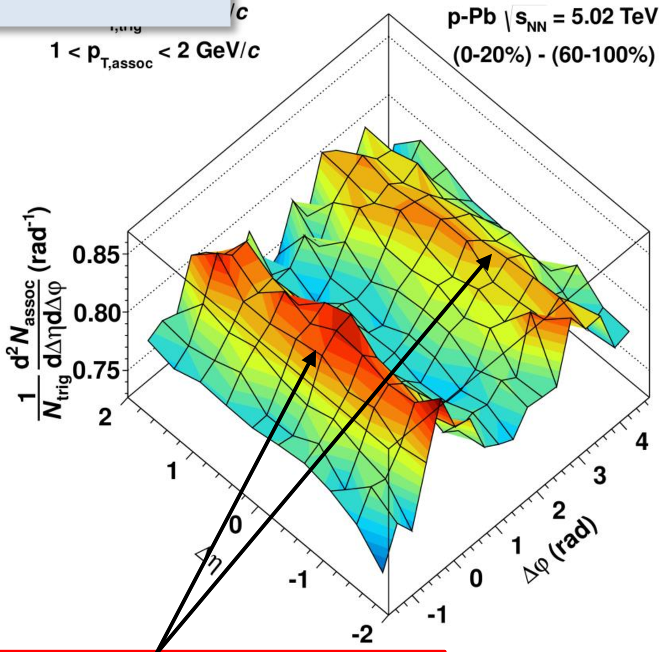
Correlations in pA: subtracting low-mult from the high-mult…

- A double-ridge structure appears, with remarkable properties:
  - Can be expressed in terms of $v_{2,3}$, Fourier coefficients of single particle azimuthal distribution, with $V_{2,3}$ increasing with p_T and v_2 also with multiplicity
  - **Same yield near and away side for all classes of p_T and multiplicity: suggest common underlying process**
  - Width independent of yield
  - No suppression of away side observed (its observation at similar x-values at RHIC is considered a sig
  - In agreement wi

Similar results published by CMS (first) and ATLAS.


Low multiplicity event class

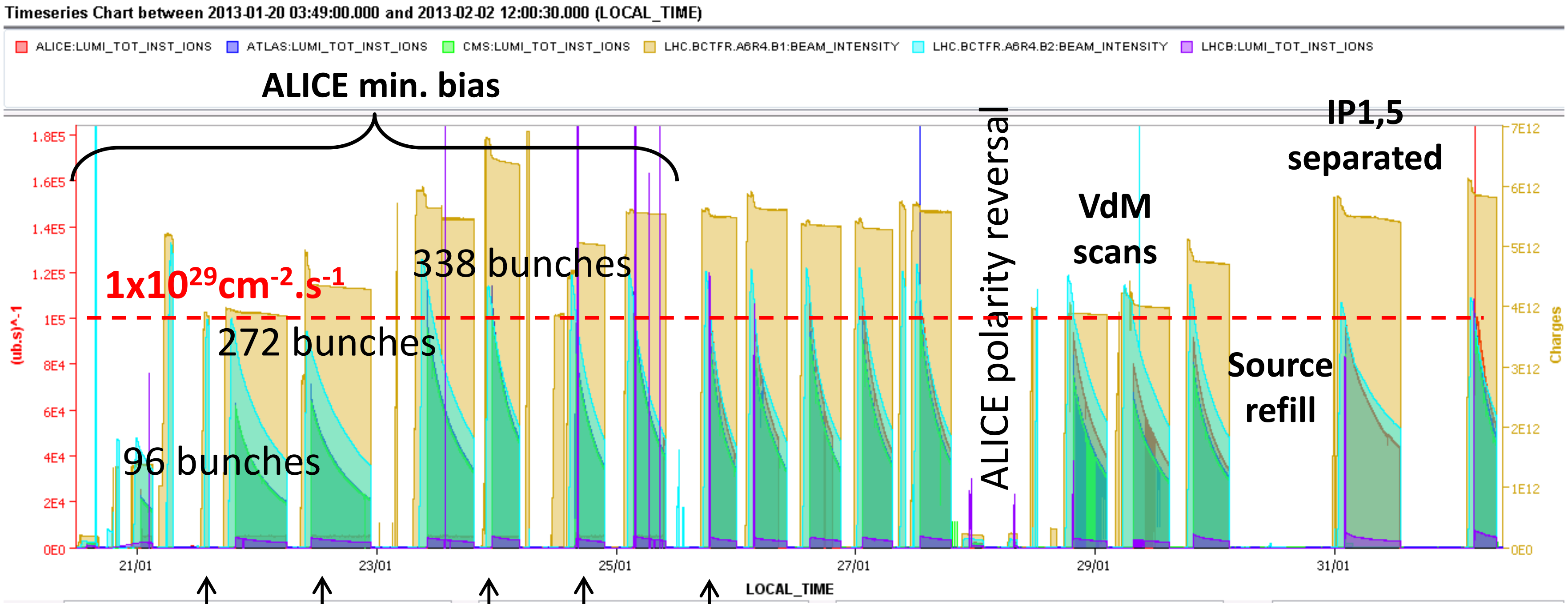

High multiplicity event class



Double-ridge structure

P. Giubellino, Evian Dec 2012

Reminder: p-Pb luminosity production in 2013



Increase of BLM monitor factor (losses during cogging)

Problem of losses during cogging solved

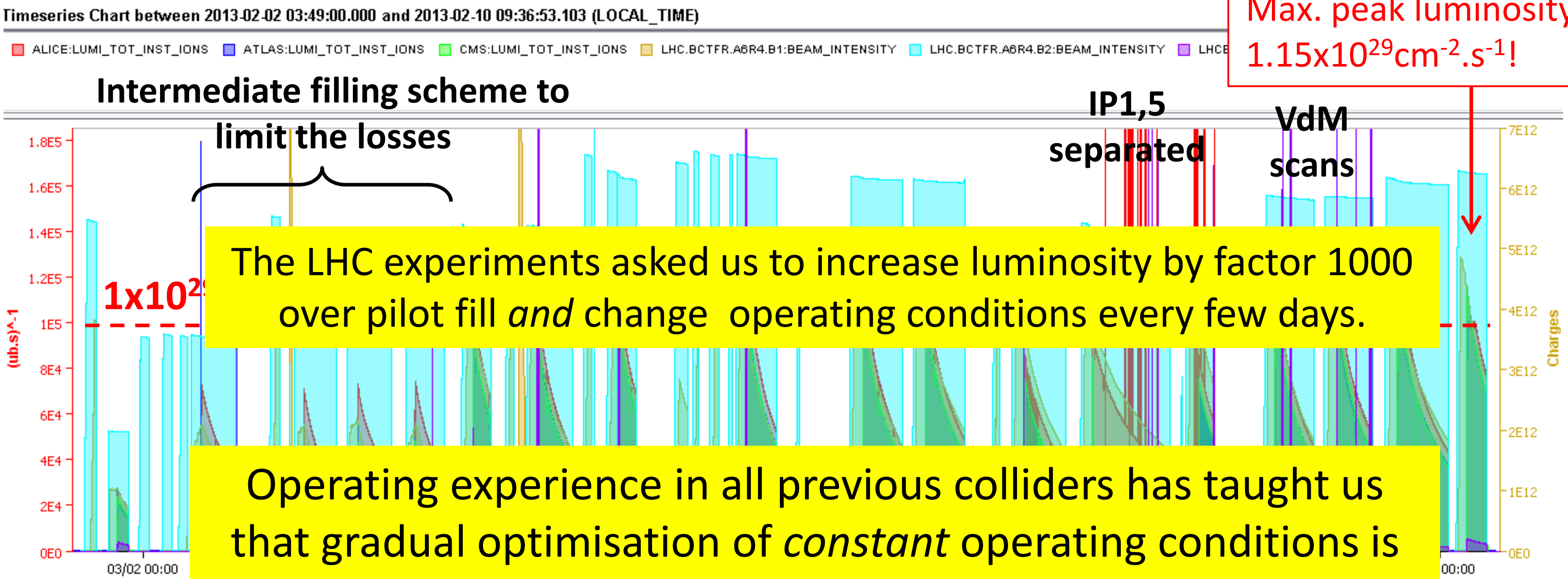
TOTEM Roman Pots moved in

ALFA Roman Pots moved in

Longitudinal blow up ON

R. Versteegen

Reminder: Pb-p luminosity production in 2013



Intermediate filling scheme to limit the losses

1x10²

IP1,5 separated

VdM scans

Max. peak luminosity $1.15\mathrm{x}10^{29}\mathrm{cm}^{-2}.\mathrm{s}^{-1}$!

The LHC experiments asked us to increase luminosity by factor 1000 over pilot fill *and* change operating conditions every few days.

Operating experience in all previous colliders has taught us that gradual optimisation of *constant* operating conditions is the path to high luminosity.

Increase of BLM monitor factor (losses end of ramp + squeeze)

Increase bandwidth of orbit feedback

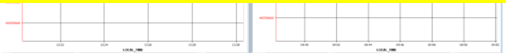
sses at the start of the ramp), rematch injection energy to the SPS

Co
tri

Nevertheless we fulfilled all requests, thanks to the quality of the LHC, meticulous planning and some judicious risk-taking (with performance, I hasten to add).

So we do not need to fear “complicated” physics requests.

es



Peak performance in p-Pb runs

	2012 pilot	**2013 production**
$E\,/\,(Z\ \mathrm{TeV})$	4	4
k_c	(8,8,8,8)	(296,288,296,39)
β*/m	(11,10,11,10)	(0.8,0.8,0.8,2.0)
γε(p)/ μm	1.7	2
γε(Pb)/ μm	1.2	1.5
N_{bp}	1.2×10^{10}	1.6×10^{10}
$N_{b\mathrm{Pb}}$	7×10^{7}	12×10^{7}
$L\,/\,(10^{29}\,\mathrm{cm}^{-2}\mathrm{s}^{-1})$	0.001	(1.12,1.01,1.16,0.05)

- Some numbers are averages because of the wide distribution of individual bunch parameters.
- Sets of four values correspond to the interaction points IP1(ATLAS), IP2(ALICE), IP5(CMS), IP8 (LHCb).

Design Baseline and Performance Achieved

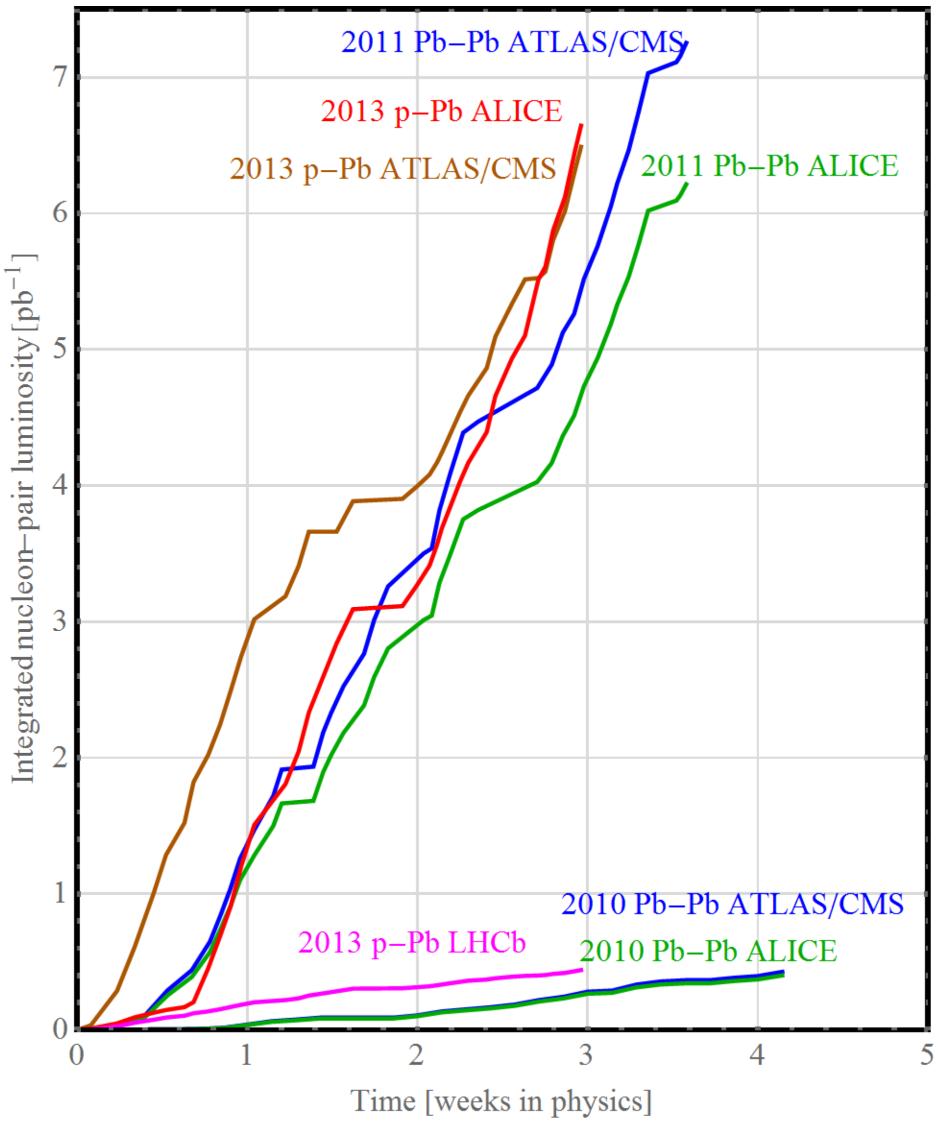
“p-Pb not part of baseline”

	Pb-Pb				p-Pb	
	Baseline	**Injection 2011**	**Collision 2011**	**Injection 2013**	**physics case paper**	**2013**
Beam Energy [Z GeV]	7000	450	3500	450	7000	4000
No. Ions per bunch $[10^8]$	0.7	1.24 ± 0.30	1.20 ± 0.25	1.67 ± 0.29	0.7	$\mathbf{1.40 \pm 0.27}$
Transv. normalised emittance $[\mu\mathrm{m.rad}]$	1.5	---	1.7 ± 0.2	$\mathbf{1.3 \pm 0.2}$	1.5	---
RMS bunch length $[\mathrm{cm}]$	7.94	8.1 ± 1.4	9.8 ± 0.7	8.9 ± 0.2	7.94	9.8 ± 0.1
Peak Luminosity $[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1	---	$\mathbf{0.5}$	---	115	110

$= 2 \times$ design scaled with E^2

Integrated nucleon-nucleon luminosity in Run 1

Goal of the first even p-Pb run was to match the integrated nucleon-nucleon luminosity for the preceding Pb-Pb runs.



Future runs and species

Charges Z_1, Z_2 in rings with magnetic field set for protons of momentum p_p : colliding nucleon pairs have:

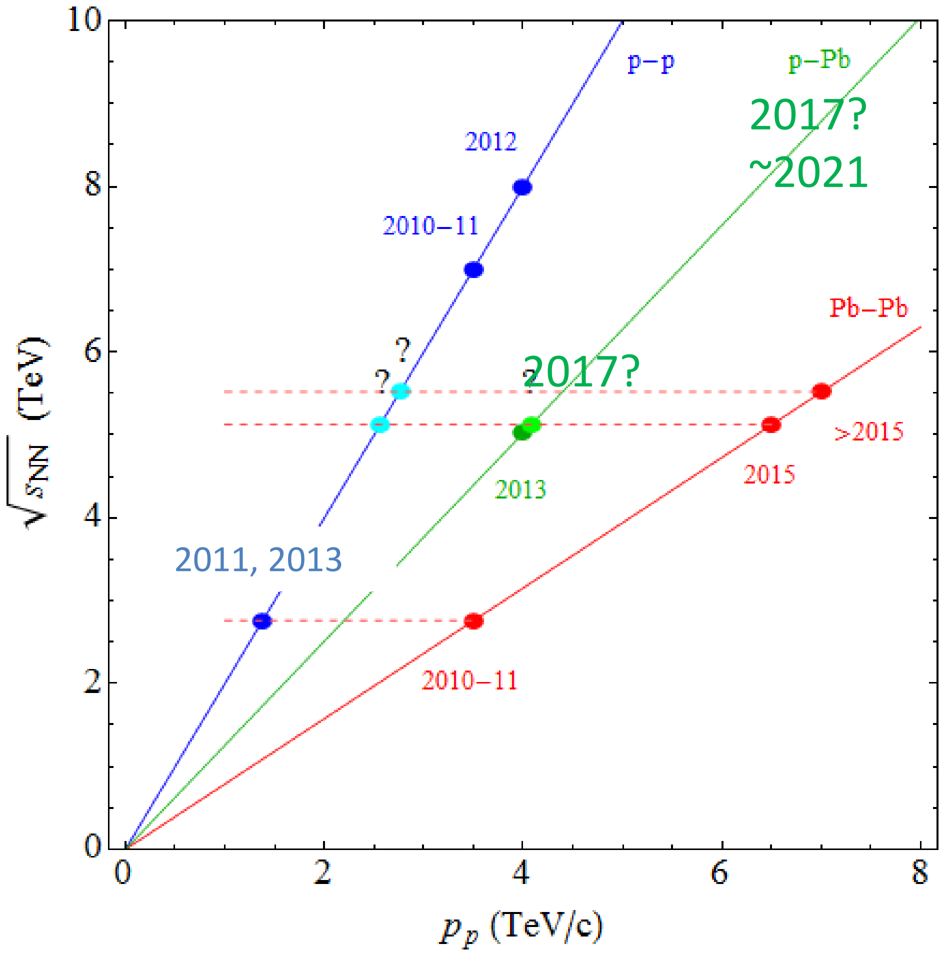
$$\sqrt{s_{NN}} \approx 2c\, p_p \sqrt{\frac{Z_1 Z_2}{A_1 A_2}}, \qquad y_{NN} = \frac{1}{2}\log\frac{Z_1 A_2}{A_1 Z_2}$$

Mainly Pb-Pb operation with p-Pb roughly every 3rd year.

More efficient to do p-Pb at same p_p energy as preceding p-p but may need to lower it to an equivalent CM energy.

Reference data in p-p also required at equivalent CM energies, should ideally track integrated Pb-Pb luminosity.

Lighter species not considered for now.



HL-LHC Performance Goals for Pb-Pb collisions

With upgrade of Pb injectors, etc, indicative parameter goals:

ALICE upgrade integrated luminosity goal for post-2018 period

$\int L\, dt = 10\ \mathrm{nb}^{-1}$ $=10 \times$ (first phase)

equivalent to $\int L_{NN}\, dt = 0.43\ \mathrm{fb}^{-1}$ nucleon-nucleon luminosity.

Annual integrated luminosity (1 month run) $\approx 1.5\ \mathrm{nb}^{-1}$

Peak luminosity $L \approx 6 \times 10^{27}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} = 6 \times$ design

Up to $k_b = 912$ bunches with mean intensity $N_b = 2.2 \times 10^8$ Pb.

Stored energy in beam: W $\approx$ 18 MJ $=$ 4.8 $\times$ design

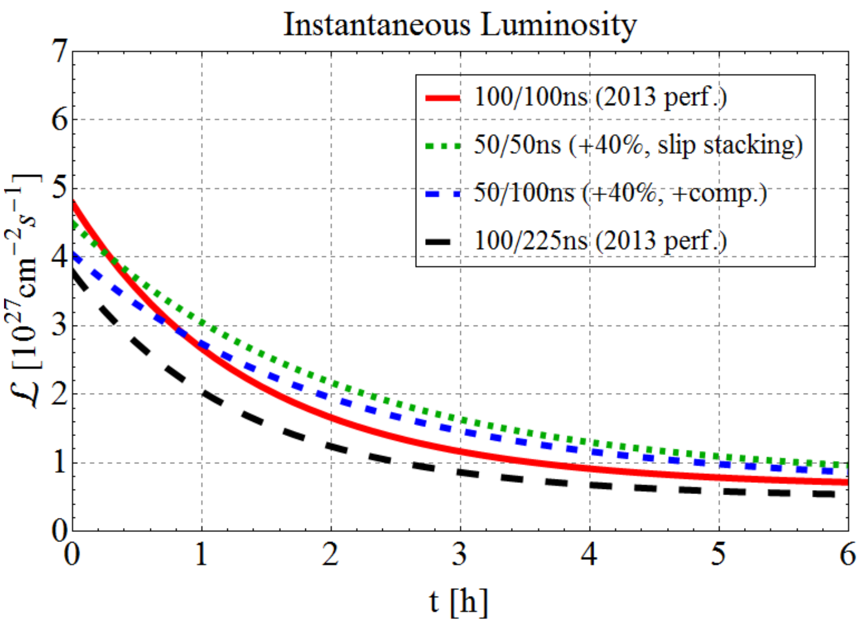
Power in BFPP1 beam: $P_{\mathrm{BFPP1}} = 155$ W

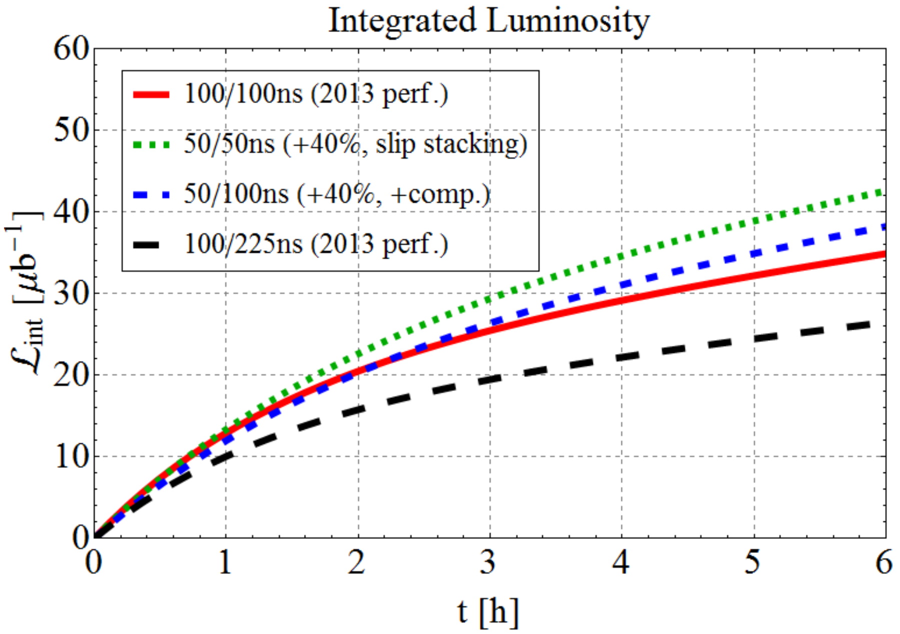
Power in EMD1 beam: $P_{\mathrm{EMD1}} = 53$ W

ATLAS and CMS also taking luminosity (high burn-off).
Levelling strategies may reduce peak luminosity but we must aim for high intensity.
Comparison data: p-Pb runs at high luminosity may become comparable to Pb-Pb (on one side of IP).

Luminosity Evolution for main Upgrade Scenarios

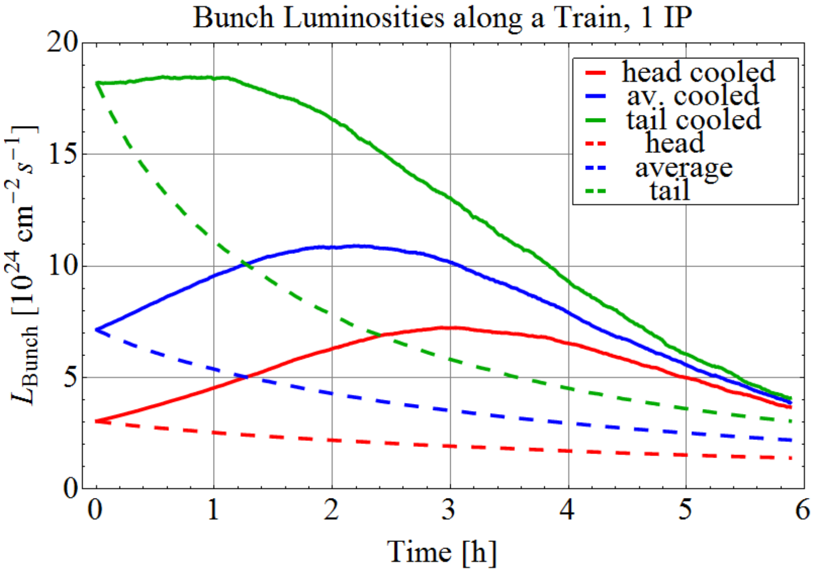
Takes into account different initial bunch luminosities and bunch luminosity decay times.

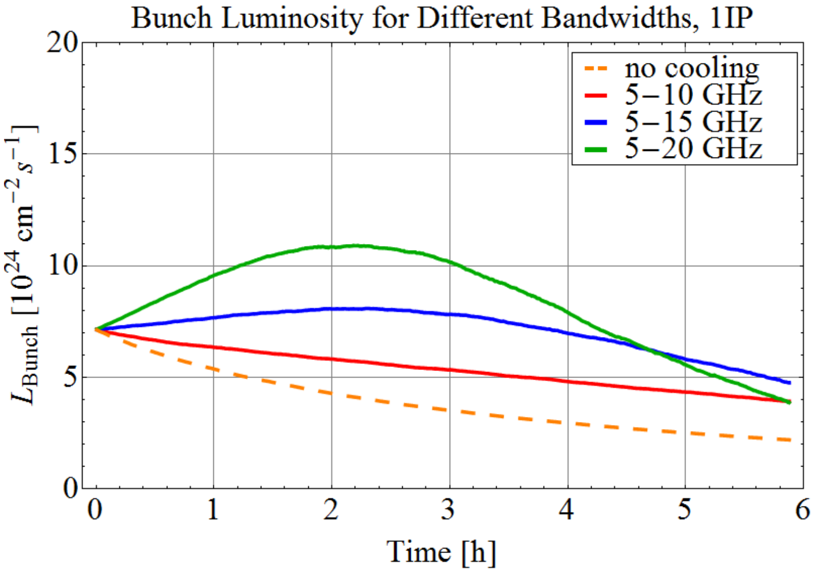




Scenario	**L_{int} after 3h [μb^{-1}]**	**L_{int} after 5h [μb^{-1}]**	**L_{int} in run with 30×5h**	
100/225ns	19	25	0.8 nb^{-1}	Present
100/100ns	25	32	1.0 nb^{-1}	**Baseline**
50/50ns	29	39	1.2 nb^{-1}	Slip Stacking
50/100ns	26	35	1.1 nb^{-1}	Batch compression

Stochastic Cooling Simulations, Pb beam at 7 *Z* TeV


Bunch Luminosities along a Train, 1 IP


Bunch Luminosity for Different Bandwidths, 1IP

- IBS horizontal growth time ≈ 8h.
- Radiation damping time ≈ 13h
  → radiation damping not included in the simulations on this slide.

- Assuming a stochastic cooling system with a 5-20GHz bandwidth and average 2013 Pb bunches [4]:

$$T_{\text{cool}} = \frac{N_b C_{\text{LHC}}}{4\sigma_z W}\left[\frac{M+U}{(1-\tilde{M}^{-2})^2}\right] \approx 1.8\,\text{h}$$

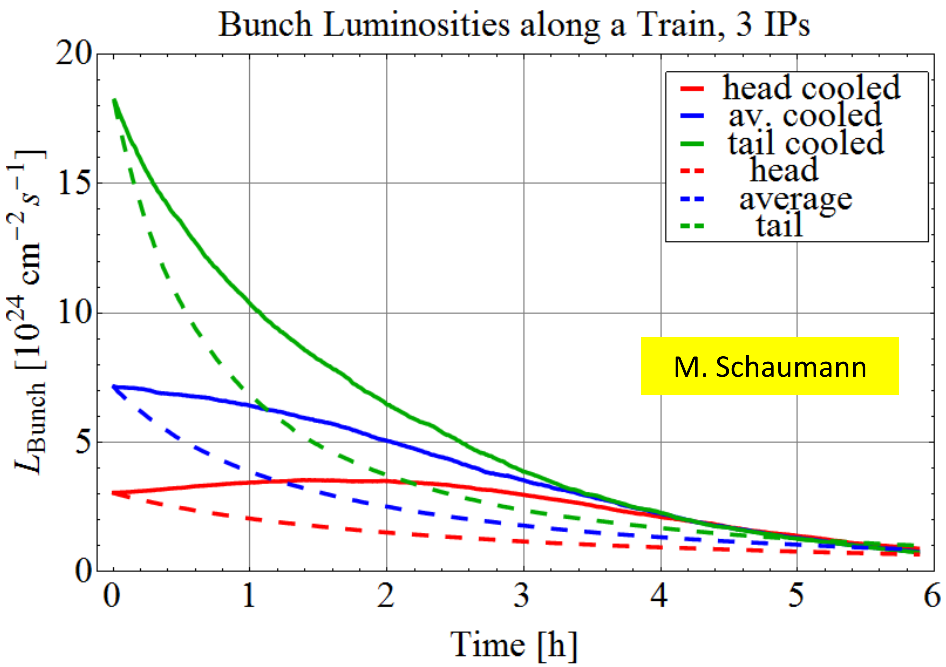
- First estimate for RMS voltage per cavity (assuming a system with 16 cavities as in RHIC):

$$V_{cavity} = 2\,\text{kV}$$

- Integrated luminosity could be increased by a factor 2.
- Larger bandwidth and higher upper frequency, lead to higher integrated luminosity.

M. Schaumann

ALICE, ATLAS, CMS illuminated



As demonstrated, particularly with U-U collisions, at RHIC, a transverse stochastic cooling system is the ultimate luminosity upgrade and essentially **eliminates the beam halo.**

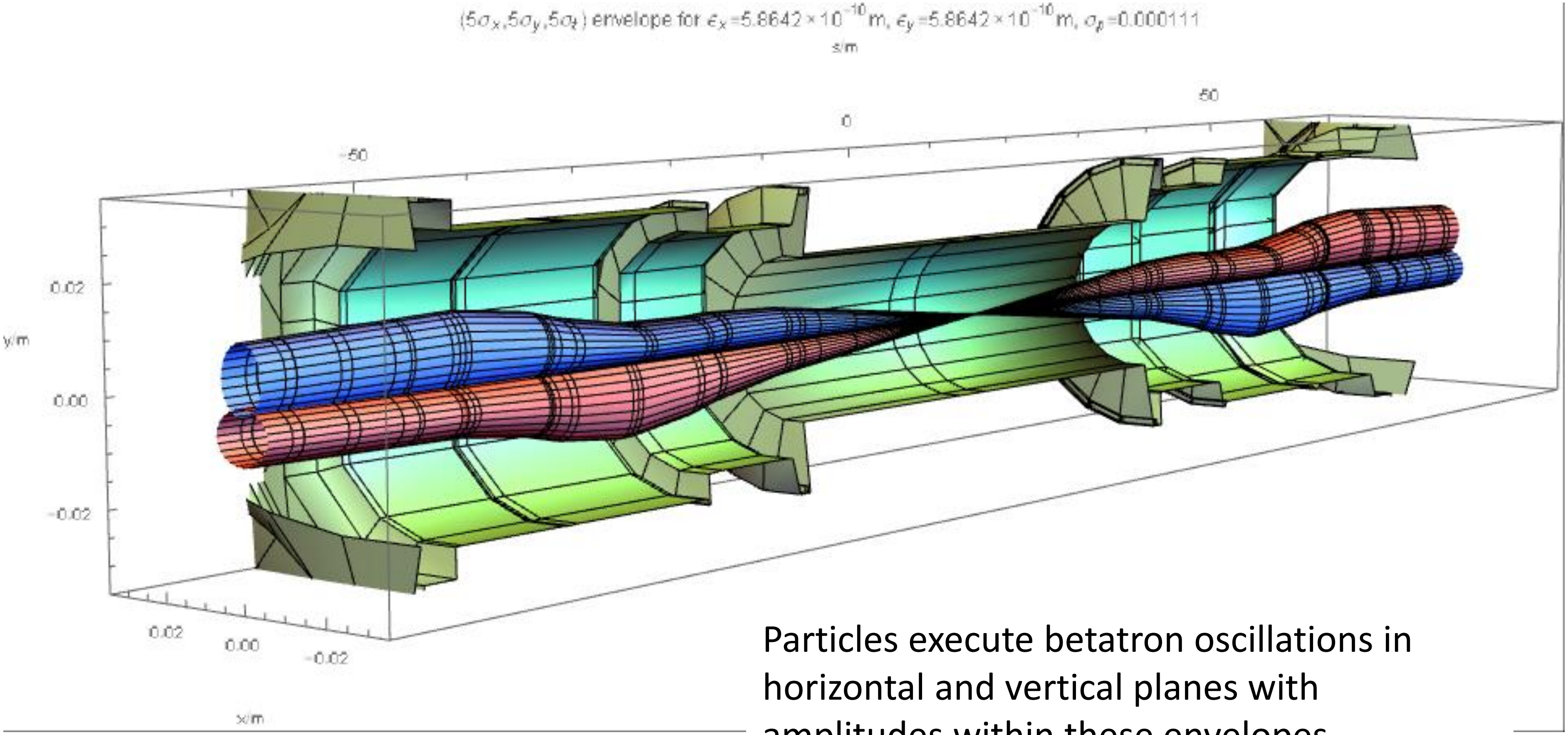
At present, this is only a feasibility study and would work for Pb beams only.

Concluding remarks

- The progress in the performance of the LHC has been breathtaking so far
  - Some of the (beam dynamics) challenges that had to be faced have been outlined
  - With Run II we will explore high energies and operation with 25 ns proton beams (not trivial). Aim for 300 fb^{-1} by the end of Run III
  - In Run II we will also explore Pb-Pb collisions, in high burn-off regime, approaching quench limit of magnets
- Luminosity performance and choices for p-p upgrade are now constrained by the acceptable detector pile-up/pile-up density
  - To reach 3000 fb^{-1} by ~2035 we are pushing even further the above challenges…
  - Several Technologies/Techniques are being developed to provide margin for the achievement of these challenging parameters
- Push Pb-Pb and p-Pb luminosity each year

BACKUP SLIDES

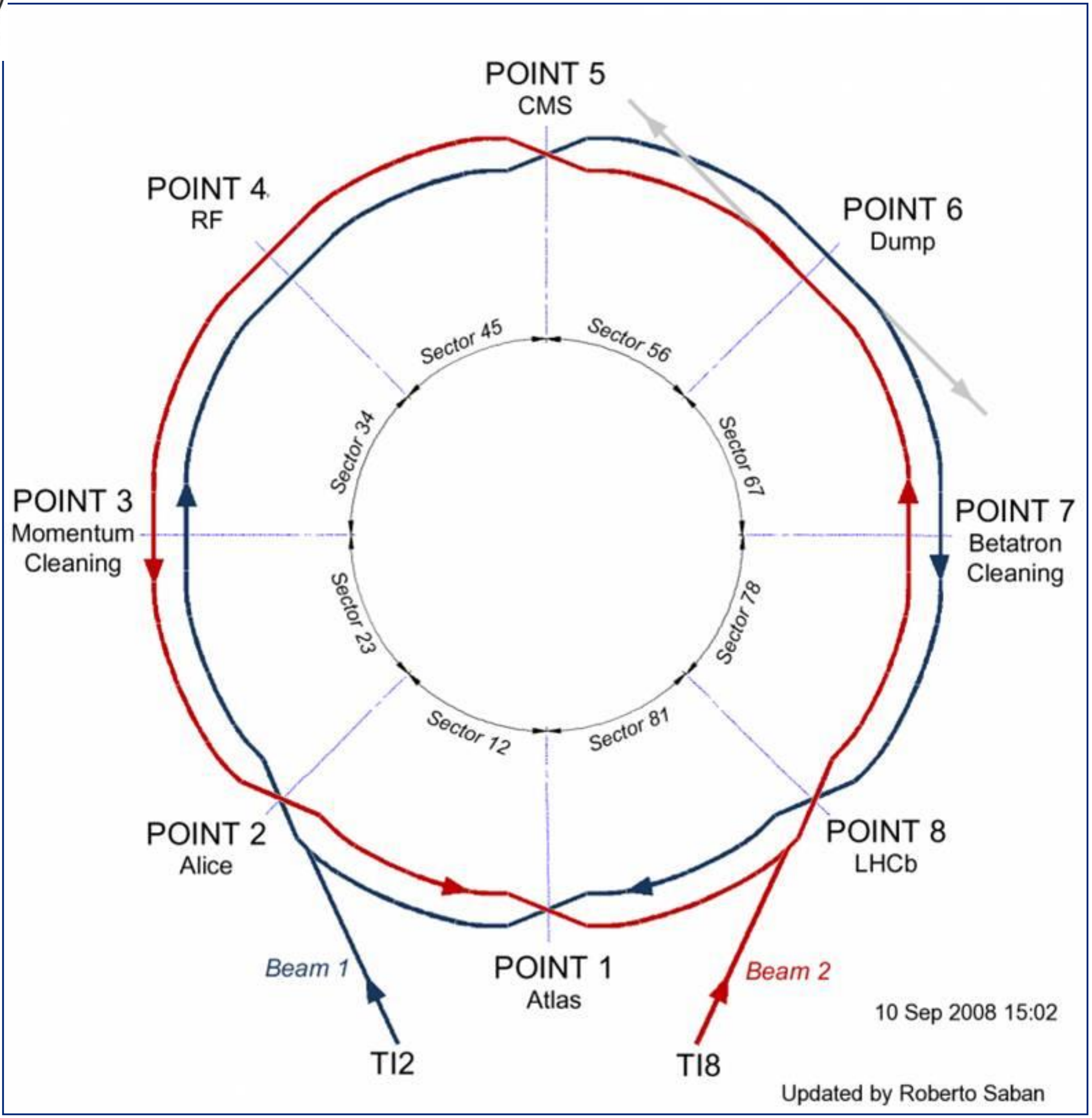
Collision beam envelopes (5σ) around ATLAS (Run 1)



Particles execute betatron oscillations in horizontal and vertical planes with amplitudes within these envelopes.

π/2 phase advance across interaction region.

LHC orientation



10 Sep 2008 15:02

Updated by Roberto Saban

Three large and highly capable heavy-ion physics experiments:

ALICE
ATLAS
CMS

LHCb takes p-Pb collisions, not Pb-Pb

LHC Pb Injector Chain:
Design Parameters for luminosity 10^{27} cm^{-2} s^{-1}

	ECR Source →	**Linac 3** $\xrightarrow{4}$	**LEIR** →	**PS** $\xrightarrow{13,12,8}$	**SPS** $\xrightarrow{12}$	**LHC**
Output energy	**2.5 KeV/n**	**4.2 MeV/n**	**72.2 MeV/n**	**5.9 GeV/n**	**177 GeV/n**	**2.76 TeV/n**
^{208}Pb charge state	**27+**	**27+ → 54+**	**54+**	**54+ → 82+**	**82+**	**82+**
Output Bρ [Tm]		2.28 → 1.14	4.80	86.7 → 57.1	1500	23350
bunches/ring			2 (1/8 of PS)	4 (or 4x2)[4]	52,48,32	592
ions/pulse	$9\ 10^{9}$	$1.15\ 10^{9}$ 1)	$9\ 10^{8}$	$4.8\ 10^{8}$	$\leq 4.7\ 10^{9}$	$4.1\ 10^{10}$
ions/LHC bunch	**$9\ 10^{9}$**	**$1.15\ 10^{9}$**	**$2.25\ 10^{8}$**	**$1.2\ 10^{8}$**	**$9\ 10^{7}$**	**$7\ 10^{7}$**
bunch spacing [ns]				100 (or 95/5)[4]	100	100
ε*(nor. rms) [μm][2]	**~0.10**	**0.25**	**0.7**	**1.0**	**1.2**	**1.5**
Repetition time [s]	0.2-0.4	0.2-0.4	3.6	3.6	~50	**~10'fill/ring**
ε_{long} per LHC bunch[3]			0.025 eVs/n	0.05	0.4	1 eVs/n
total bunch length [ns]			200	3.9	1.65	1

Stripping foil

[1] 50 eμA$_e$ x 200 μs Linac3 output after stripping

[2] Same physical emittance as protons,

$$\varepsilon^* \equiv \varepsilon_n = \sqrt{\gamma^2 - 1}\,\varepsilon_{x,y}$$ is □ invariant in ramp.

Historical energy jumps

$\sqrt{s_{\mathrm{NN}}}$ is the centre-of-mass energy per colliding nucleon pair

Collision type	Before	$\sqrt{s_{\mathrm{NN}}}$ / GeV	After	$\sqrt{s_{\mathrm{NN}}}$ / GeV	Jump
e^+e^-	any		any		2-3
pp,$\bar{p}$p	PS, AGS	7.1	ISR	52	7.3
pp,$\bar{p}$p	ISR	59	S$\bar{p}$pS	540	9.0
pp,$\bar{p}$p	S$\bar{p}$pS	540	Tevatron	1960	3.6
pp,$\bar{p}$p	Tevatron	1960	LHC (pp)	7000	3.6
DIS (e/μ)*p*	E665 (μp)	29.7	HERA (ep)	314	10.6
AA	RHIC (Au-Au)	200	LHC(Pb-Pb)	2760	13.8
(p/d)*A*	RHIC (d-Au)	200	LHC(p-Pb)	5023	25.1

This was the largest factor of increase in the energy of a given type of collision ever achieved in the history of particle accelerators.