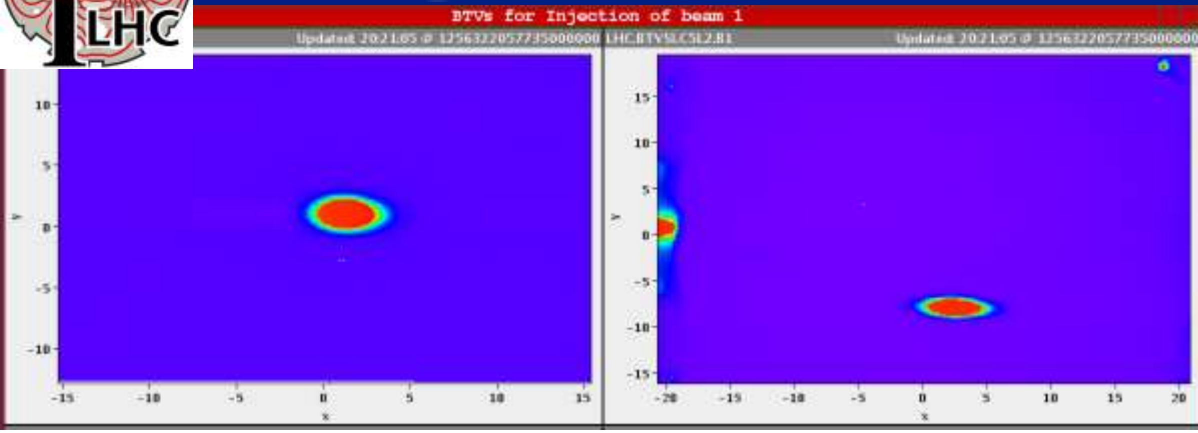
Heavy and Light Nuclear Collisions in the LHC

John Jowett, CERN

Plan of talk

- LHC as a heavy-ion collider
  - LHC orientation
  - Injectors
  - Design parameters, performance limits
- HI2010 run
  - Plan, performance different, limits
- Future runs
  - Higher performance with Pb-Pb
  - Hybrid collisions p-Pb
  - Lighter ions
  - Deuterons

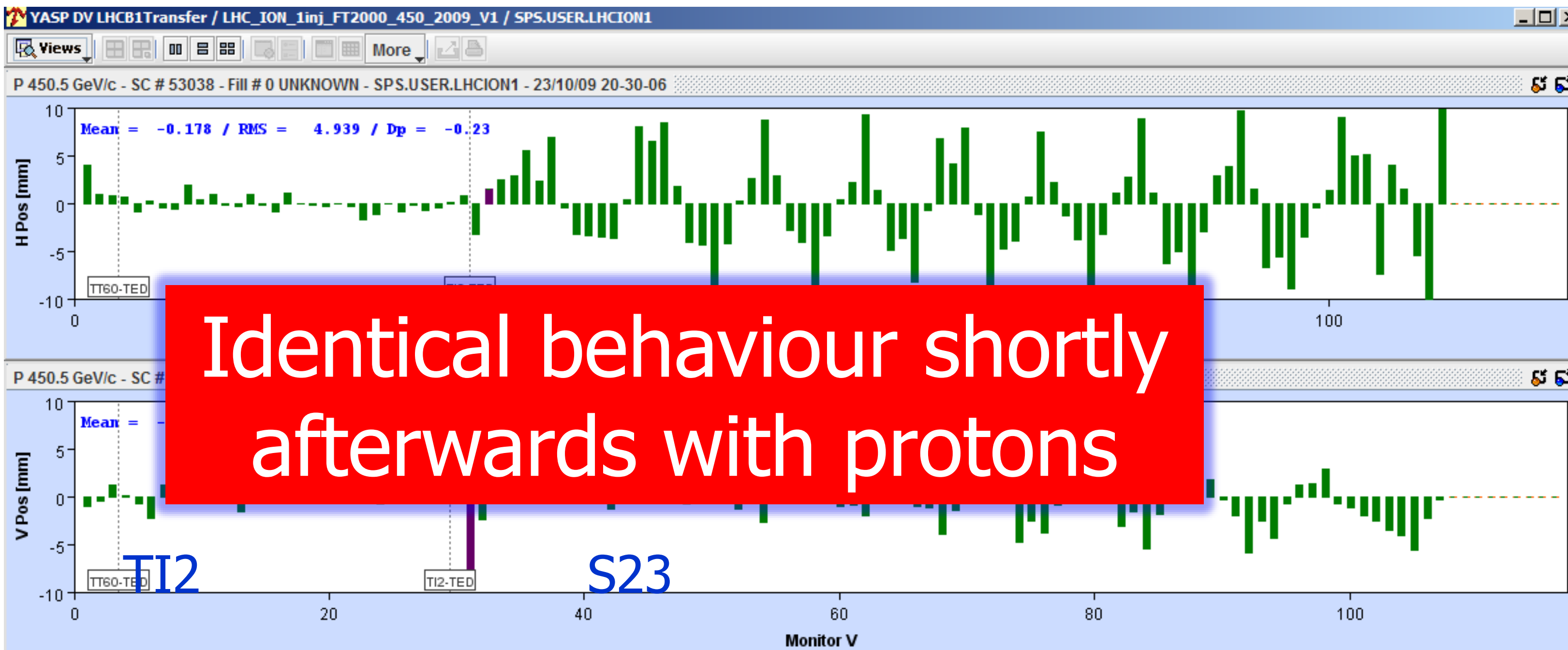
Prologue: First Pb nuclei in LHC in 2009



First beam to re-awaken LHC after the September 2008 incident

Injection region screens

TI2/Sector 2-3 – first trajectory



Identical behaviour shortly afterwards with protons

LHC AS A HEAVY-ION COLLIDER

Luminosity of a hadron collider

$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F(\theta_c)$$

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

- Parameters in luminosity
  - Number of particles per bunch N
  - Number of bunches per beam 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^*

Equal amplitude functions:

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

Geometric and normalised emittance:

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

$\Rightarrow$ Round beams at IP:

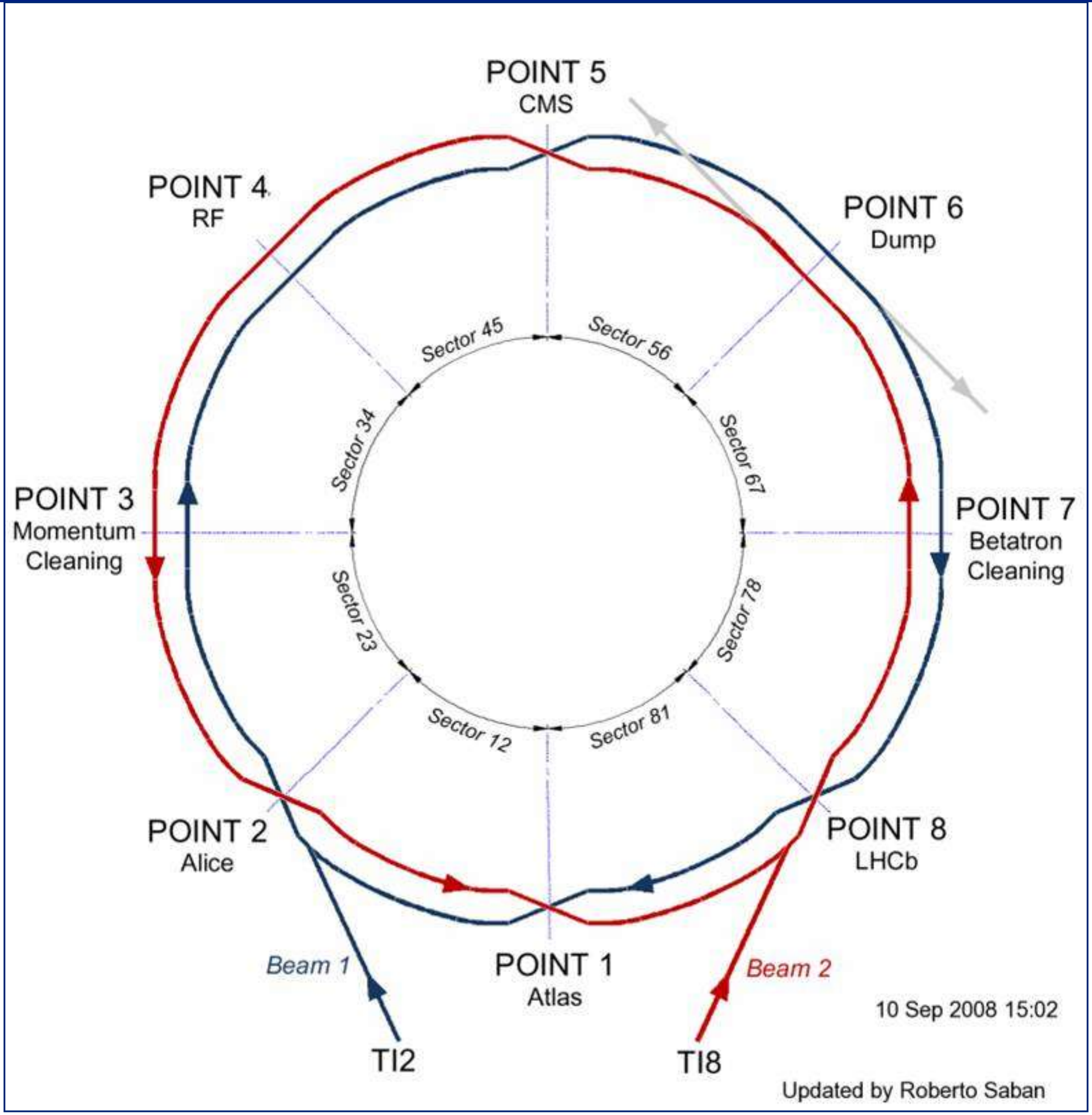
$$\sigma_x^* = \sigma_y^* = \sigma^* \approx \sqrt{\frac{\beta^* \varepsilon_n}{\gamma}}$$

(N.B. LHC uses RMS emittances.)

LHC

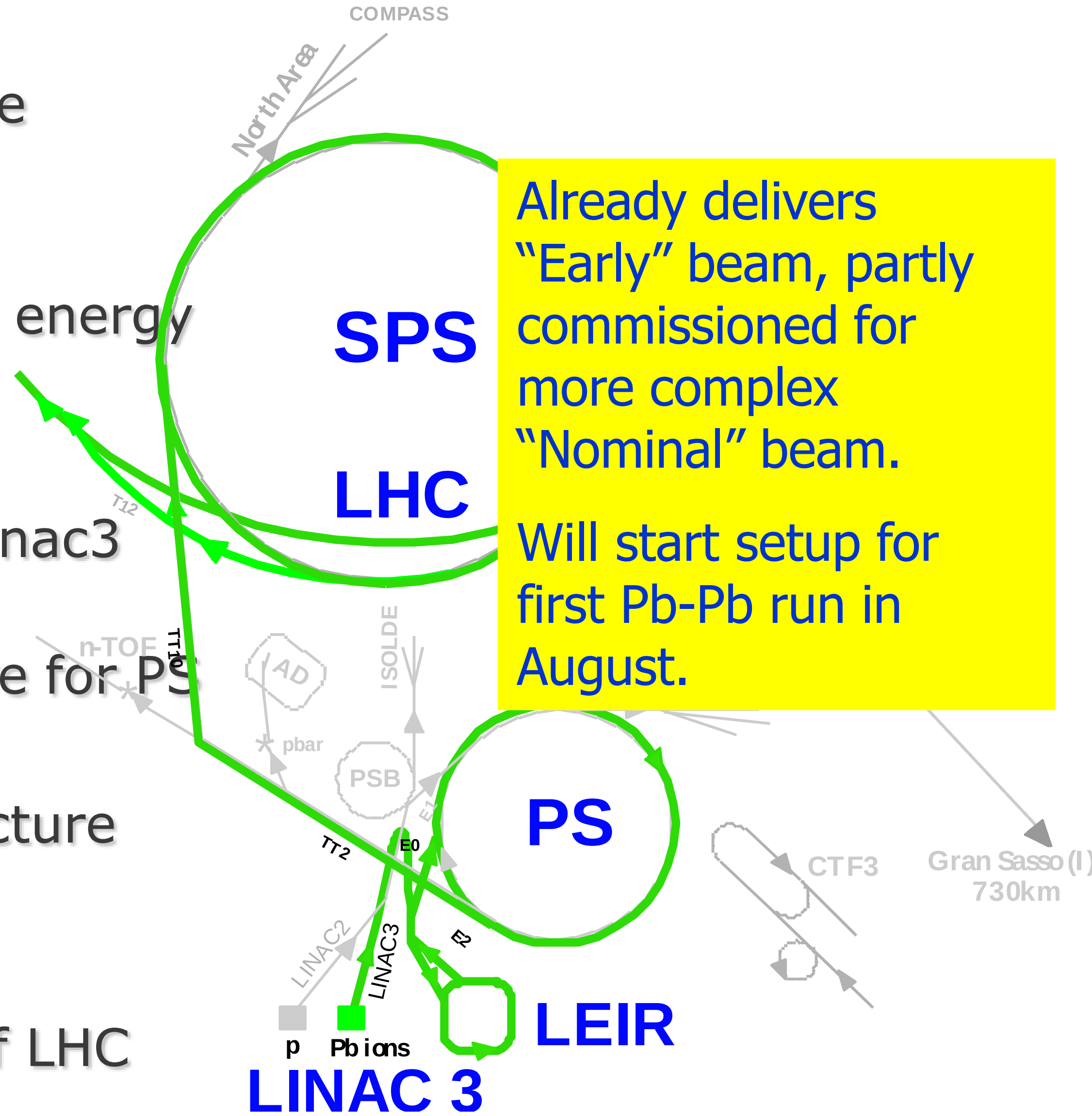
- Mainly p-p running for elementary particle physics
- 1 month/year for heavy-ion programme, initially $^{208}Pb^{82+}$- $^{208}Pb^{82+}$
  - Later p-Pb, lighter A-A, …
- Even at initial half-nominal energy, pushes the energy frontier for laboratory nuclear collisions a factor 13.7 (later up to 28) beyond RHIC,
  - Biggest energy step ever made by any collider over its predecessor ?
- The first Pb-Pb run is planned for 2 November
  - 7 days setup, then 28 days physics

LHC schematic for orientation



LHC Ion Injector Chain

- ECR ion source (2005)
  - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR injection energy
  - 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



Already delivers "Early" beam, partly commissioned for more complex "Nominal" beam.

Will start setup for first Pb-Pb run in August.

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.

Design Parameters for Pb-Pb (~2001)

Parameter	Units	Early Beam	Nominal
Energy per nucleon	TeV	2.76	2.76
Initial ion-ion Luminosity L_0	$cm^{-2}\ s^{-1}$	$\sim 5 \times 10^{25}$	1×10^{27}
No. bunches, k_b		62	592
Minimum bunch spacing	ns	1350	99.8
β^*	m	1.0	0.5 /0.55
Number of Pb ions/bunch		$\mathbf{7 \times 10^7}$	$\mathbf{7 \times 10^7}$
Transv. norm. RMS emittance	μm	1.5	1.5
Longitudinal emittance	eV s/charge	2.5	2.5
Luminosity half-life (1,2,3 expts.)	h	14, 7.5, 5.5	8, 4.5, 3

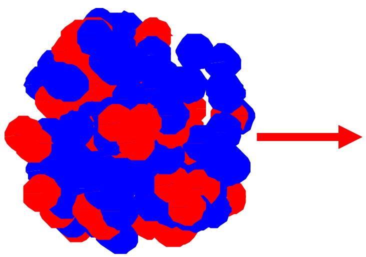
Do something like this at reduced energy in 2010

Probably unattainable without "cryo-collimators" at least

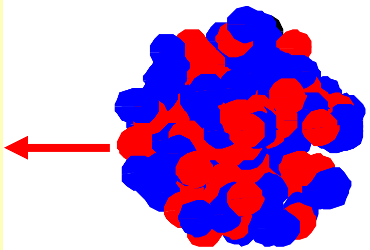
At full energy, luminosity lifetime is determined mainly by collisions ("burn-off" from ultraperipheral electromagnetic interactions) $\sigma \approx 520$ barn

On Luminosity with Lead Ions

- Luminosities quoted for lead ions may seem low compared to pp or e^+e^-
- But one can/should also quote nucleon pair luminosities



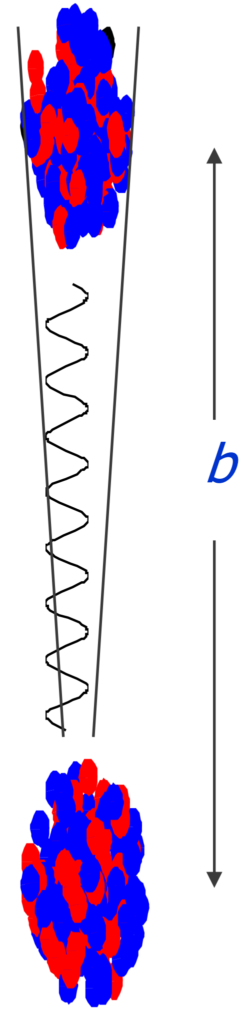
$$
\begin{aligned}
L &= 1.0\times 10^{27}\ \text{(Pb)(Pb)}\ \text{cm}^{-2}\text{s}^{-1} \\
&= 6.7\times 10^{30}\ \text{(p)(p)}\ \text{cm}^{-2}\text{s}^{-1} \\
&= 4.3\times 10^{31}\ \text{(nucleon)(nucleon)}\ \text{cm}^{-2}\text{s}^{-1}
\end{aligned}
$$



Ultra-Peripheral Collisions

- Electromagnetic interactions in encounters which are not close enough to overlap nuclear densities
  - –Extremely Lorentz-contracted Coulomb fields (equivalent quasi-real photons in Fermi-Weizsacker-Williams method)
  - –In this sense, LHC is a $\gamma\gamma$ collider.
  - –Frequency spectrum of FWW photons depends on impact parameter, *b.*

$$\gamma_{\text{target}} = 2\gamma^2 - 1 \approx 1.7\times 10^7$$



$$\text{Coupling } Z\alpha = \frac{82}{137} \approx 1$$

Pair Production in Heavy Ion Collisions

Racah formula (1937) for free pair production in heavy-ion collisions

$$Z_1 + Z_2 \to Z_1 + e^- + e^+ + Z_2$$

$$\sigma_{PP} = \frac{Z_1^{\,2} Z_2^{\,2} \alpha^2 r_e^2}{\pi}\left[\frac{224}{27}\log(2\gamma_{CM})^3 + \cdots\right] \approx \begin{cases} 1.7\times 10^4\,\text{b for Au-Au RHIC} \\ 2.\times 10^4\,\text{b for Pb-Pb LHC} \end{cases}$$

Cross section for Bound-Free Pair Production (BFPP) (several authors)

$$Z_1 + Z_2 \to \left(Z_1 + e^-\right)_{1s_{1/2},\ldots} + e^+ + Z_2$$

has very different dependence on ion charges (and energy)

$$\sigma_{PP} \propto Z_1^{\,5} Z_2^{\,2}\left[A\log\gamma_{CM} + B\right]$$

$$\propto Z^7\left[A\log\gamma_{CM} + B\right] \text{ for } Z_1 = Z_2$$

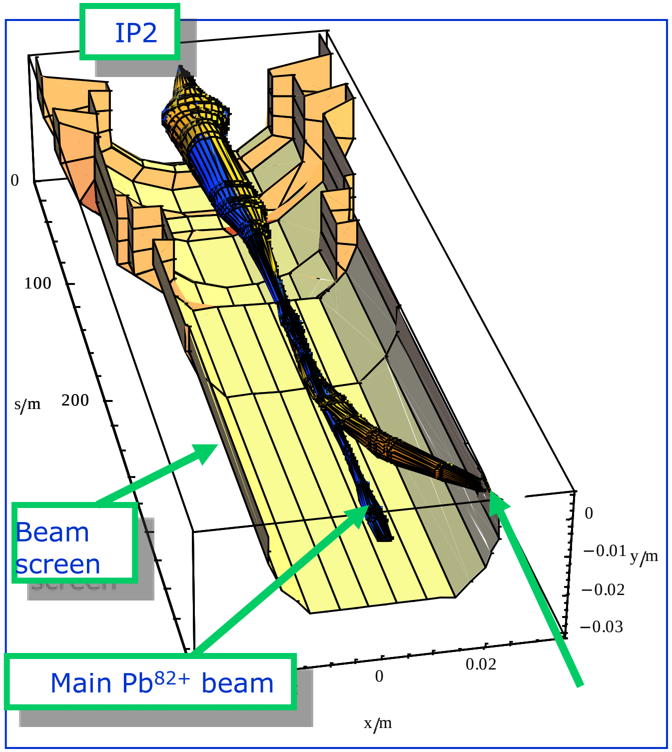
$$\approx \begin{cases} 0.2\text{ b for Cu-Cu RHIC} \\ 114\text{ b for Au-Au RHIC} \\ 281\text{ b for Pb-Pb LHC} \end{cases}$$

We use BFPP values from Meier et al, Phys. Rev. A, **63**, 032713 (2001), includes detailed calculations for Pb-Pb at LHC energy

BFPP can limit luminosity in heavy-ion colliders, S. Klein, NIM A **459** (2001) 51

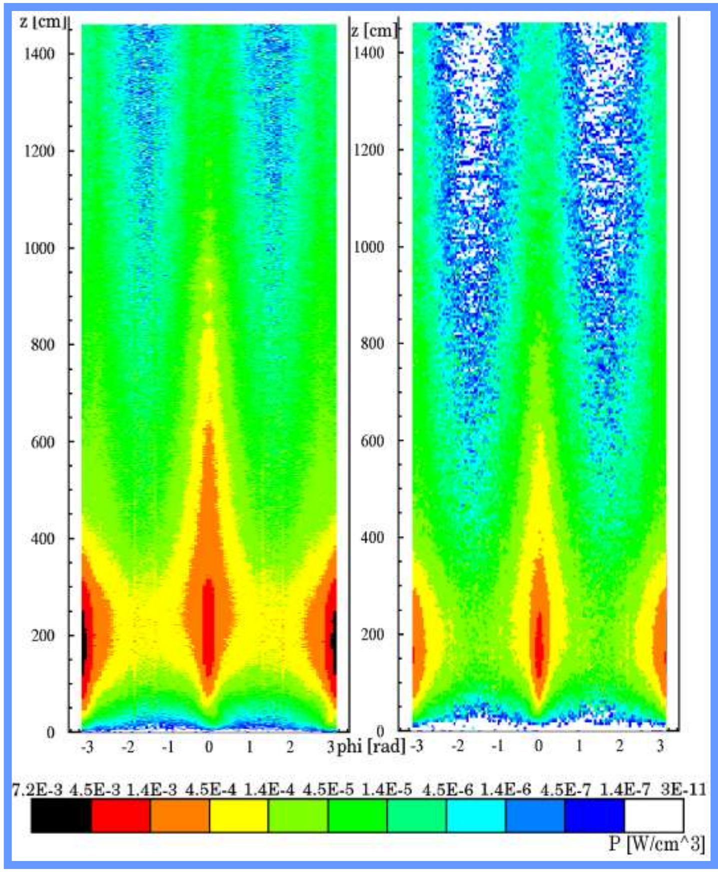
Luminosity Limit from bound-free pair production

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} ^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{81+} + e^{+}$$



Secondary Pb^{81+} beam (25 W at design luminosity) emerging from IP and impinging on beam screen.

Hadronic shower into superconducting coils can quench magnet.



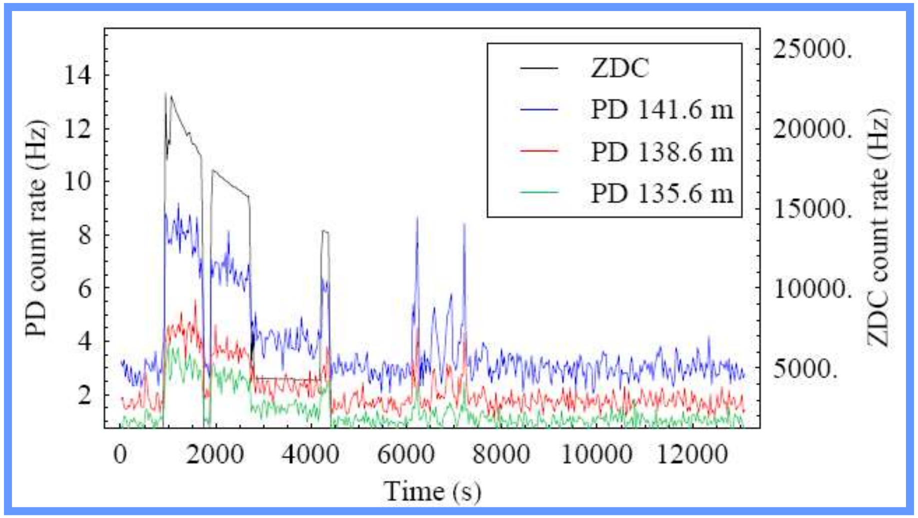
Distinct EMD process (similar rates) does not form spot on beam pipe

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \xrightarrow{\mathrm{GDR}} ^{208}\mathrm{Pb}^{82+} + ^{207}\mathrm{Pb}^{82+} + n$$

Test of LHC methodology at RHIC

- Parasitic measurement during RHIC Cu-Cu run in 2005
  - Loss monitors setup as for LHC
  - Just visible signal!
- Compared predictions and shower calculations as for LHC
  - Reasonable agreement
- *R. Bruce et al, Phys. Rev. Letters 99:144801, 2007*
- We still need to benchmark quench limit (in LHC!)

View towards PHENIX



Luminosity limit from collision products

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Phys. Rev. ST Accel. Beams 12, 071002 (2009) [17 pages]

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

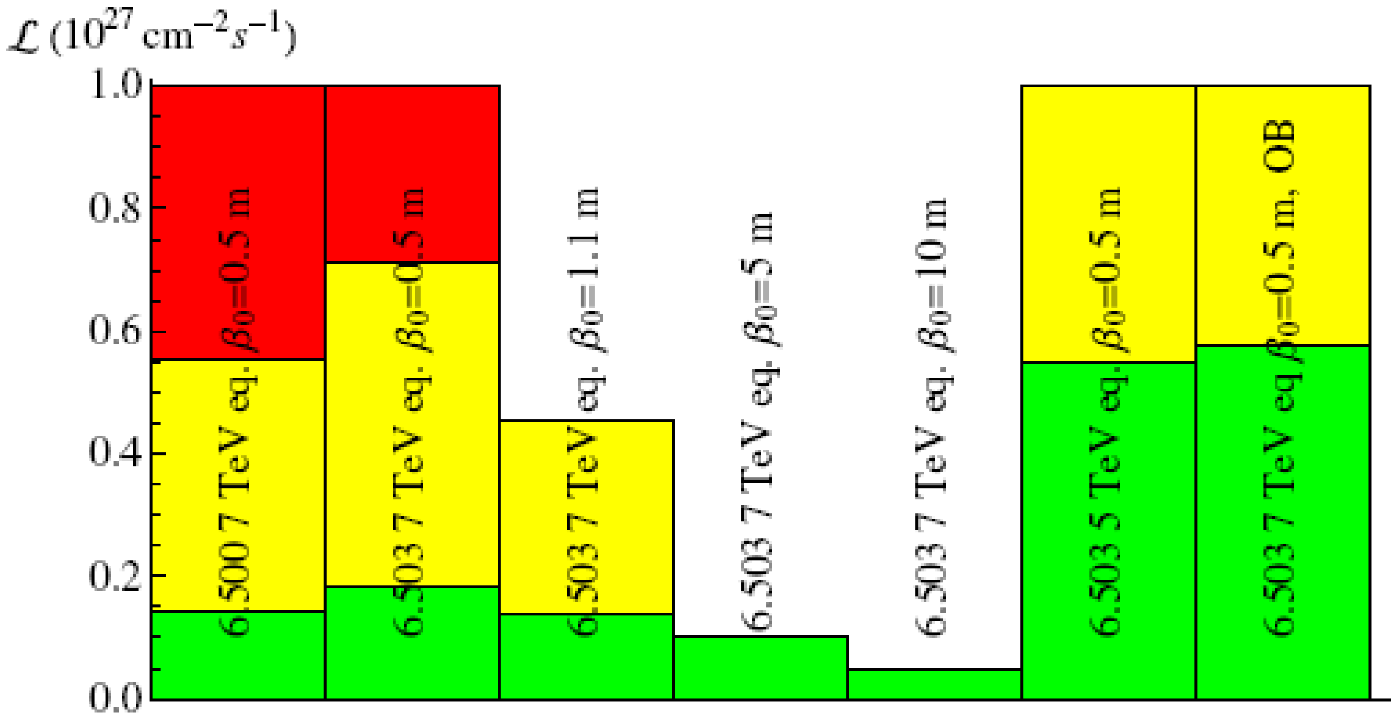
Abstract References No Citing Articles

Download: PDF (3,720 kB), One-column PDF (3,733 kB) **Export:** BibTeX or EndNote (RIS)

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*

Also thesis of R. Bruce, Univ. Lund in CDS).

Propensity to quench



Various operating conditions, see paper for details.

Elaborate chain of calculations with several uncertainties.

Some improvement might be possible with orbit bump method.

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

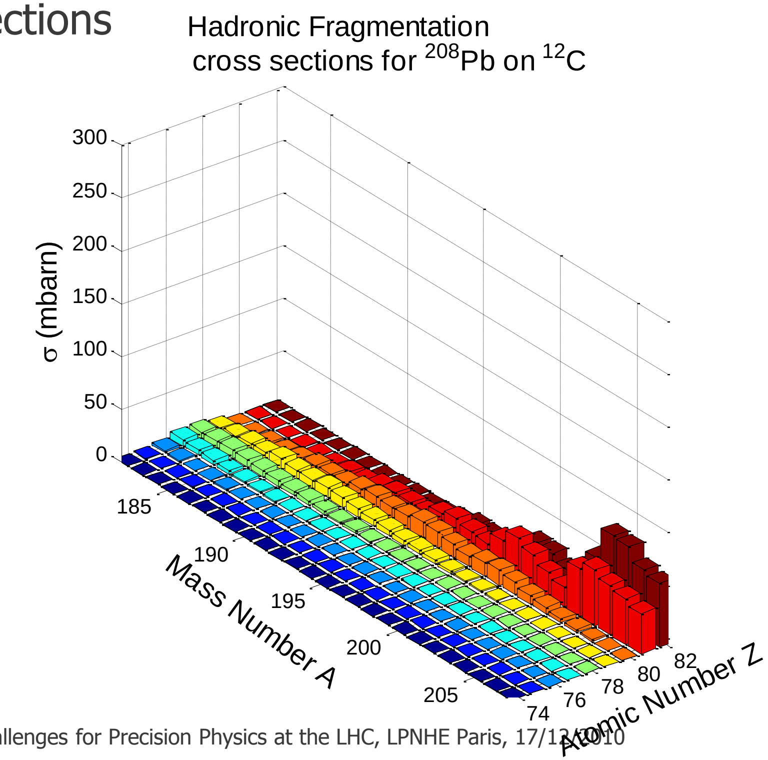
Collimation system cleans beam halo

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!

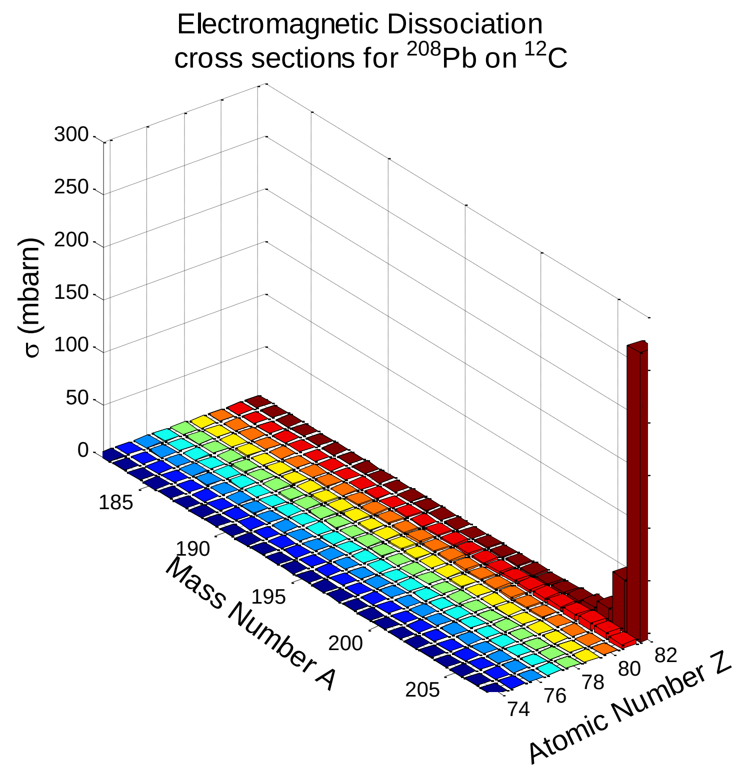
Hadronic fragmentation:

Large variety of daughter nuclei, specific cross sections

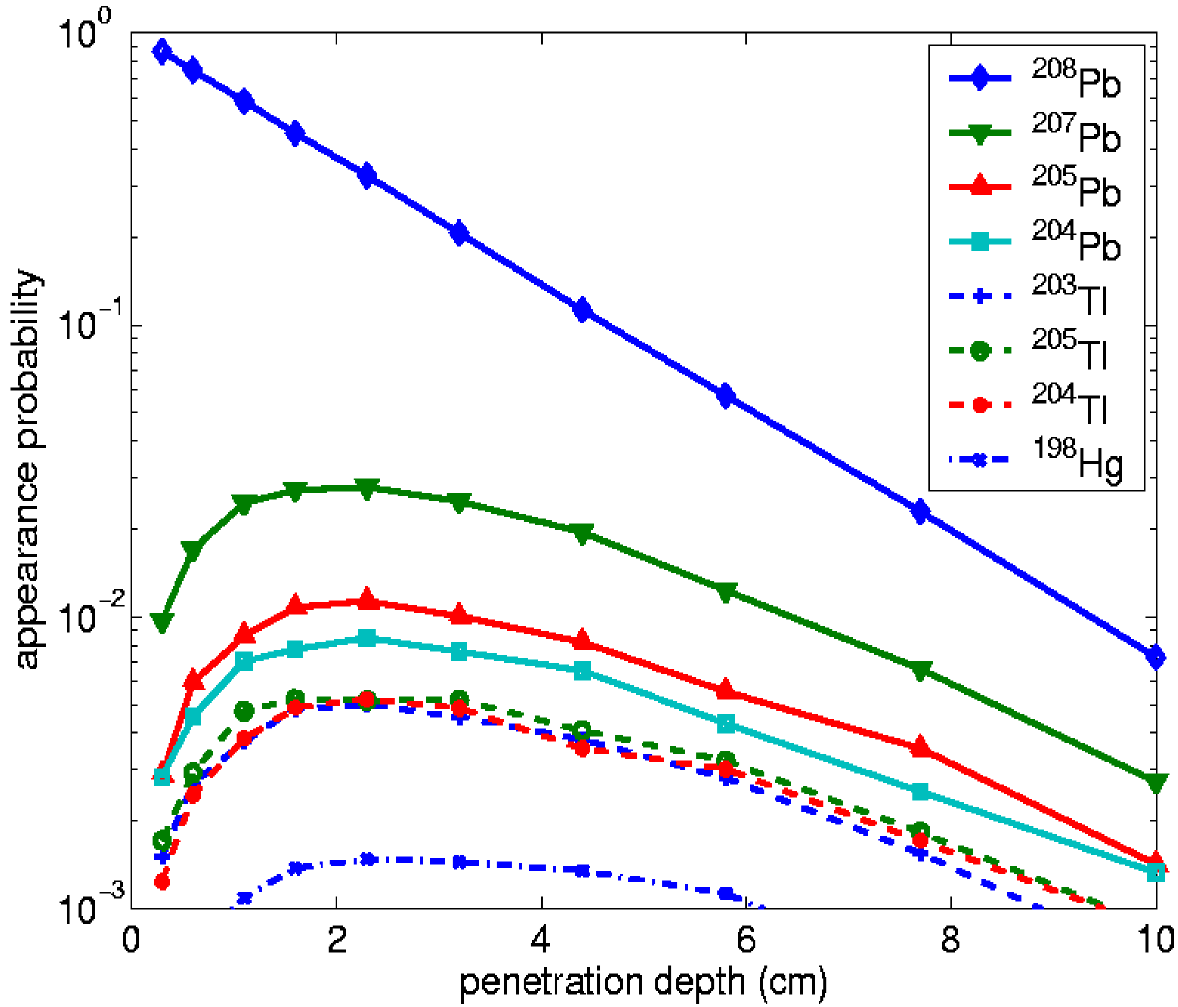


Electromagnetic dissociation:

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



Cleaning efficiency



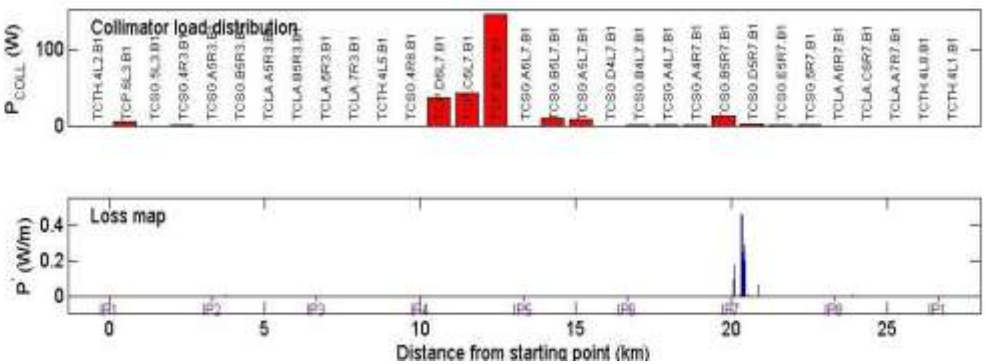
Collimators tend to put fragments on trajectories with large effective momentum errors (Z/A) and small betatron amplitude – but the secondary collimators are designed to cut *betatron* amplitudes

The probability to convert a ^{208}Pb nucleus into a neighboring nucleus. Impact on graphite at LHC collision energy.

From Hans Braun

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



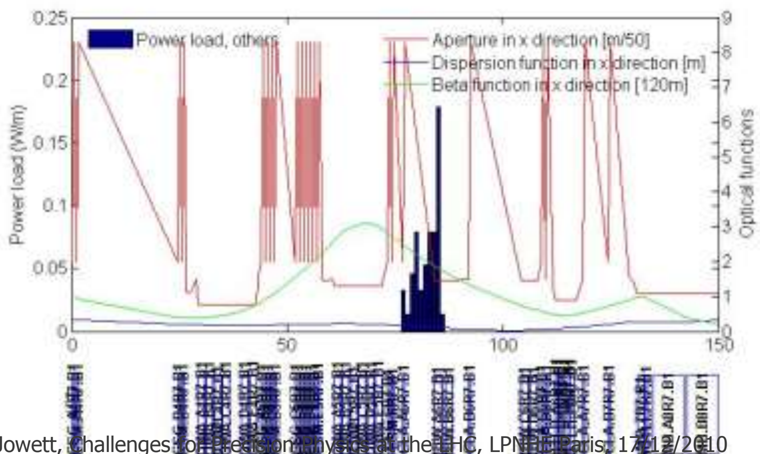
Σ aperture hits/Σ collimator hits= η= 0.033

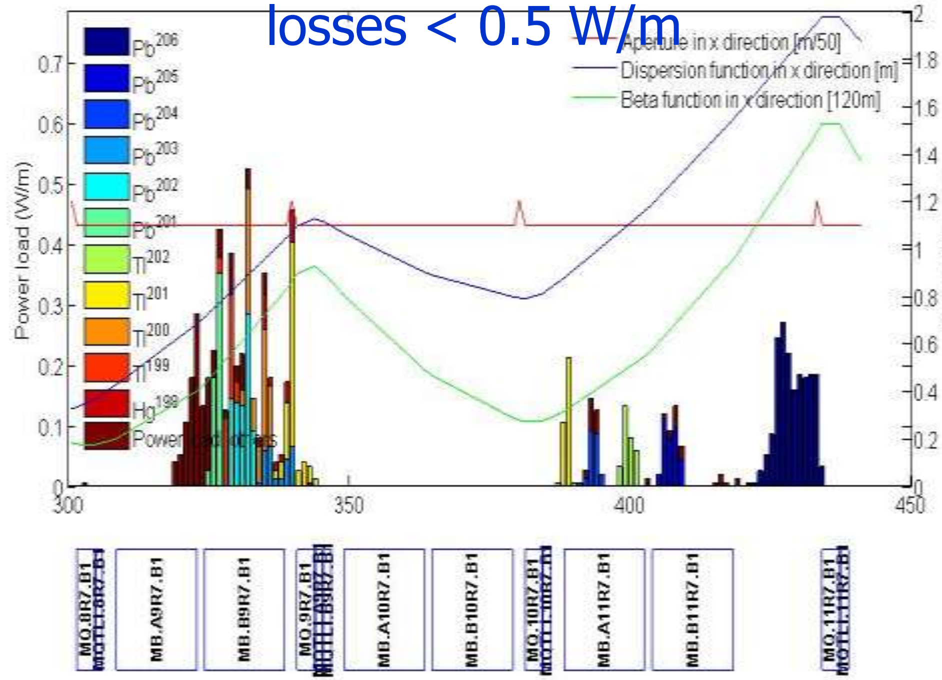
Isotopic loss map, DS.R7

losses < 0.5 W/m

Max load on TCP.B6L7.B1=122W

Some losses before DS





From G. Bellodi

Other limits on performance

- Total bunch charge is near lower limits of visibility on beam instrumentation, particularly the beam position monitors
  - Must always inject close to nominal bunch current and not lose too much!
  - Rely on ionization profile monitors more than with protons ,etc
- Intra-beam scattering (IBS)
  - Multiple Coulomb scattering within bunches is significant but less so than at RHIC where it dominates luminosity decay
- Vacuum effects (losses, emittance growth, electron cloud …) should not be significant

THE 2010 LEAD-LEAD RUN

Target luminosity in 2010 vs. "Nominal"

		Early (2010/11)	Nominal
$\sqrt{s_{NN}}$ (per colliding nucleon pair)	TeV	2.76	5.5
Number of bunches		62	592
Bunch spacing	ns	1350	99.8
β^*	m	$2 \rightarrow 3.5$	0.5
Pb ions/bunch		7×10^7	7×10^7
Transverse norm. emittance	μm	1.5	1.5
Initial Luminosity (L_0)	$cm^{-2}s^{-1}$	$(1.25 \rightarrow 0.7)$ 10^{25}	10^{27}
Stored energy (W)	MJ	0.2	3.8
Luminosity half life (1,2,3 expts.)	h	τ_{IBS}=7-30	8, 4.5, 3

Caveat: assumes design emittance

Initial interaction rate: 50-100 Hz (5-10 Hz central collisions b = 0–5 fm)

$\sim 10^8$ interaction/10^6s (~1 month)

In 2010: anticipated integrated luminosity 3-10 μb^{-1}

Strategy for switch to Pb from p

- *Make the absolute minimum of changes to the working p-p configuration*
  - Magnetically identical : Transfer, injection, ramp, orbits, optics, tunes, chromaticity…
  - Same beam sizes : aperture, collimators, …
  - Collimation and machine protection to be checked out
  - Reduce crossing angle to zero in CMS and ATLAS.
  - Real zero crossing angle in ALICE
- Differences in basic setup
  - RF frequency (Pb mass), energy matching to SPS

Heavy ion commissioning plan (1)

ACTION	No. OF BUNCHES/BEAM	TIME ESTIMATE (in shift)	COMMENT	Beam1	Beam2	GROUP	PERSON RESP	SLOT
LHCb switch off		till noon	ACCESS and recovery	OK	OK			THU M
Check with protons after access	protons	1 h	Calibrate BCTs	OK	OK	OP		THU M
			Injection of high intensity proton bunch	OK	OK			
			Injection of low intensity proton bunch	OK	OK			
			switch injector chain to ions	OK	OK			
Injection and circulating beams	1 (non colliding)	1	Injection of Ions (to establish the reference orbit)	OK	OK	OP		THU A
			Rough BI check	OK	OK	BI	JJG	
			Resteering of transfer lines (if needed)	OK	OK	ABT	BG	
			RF capture (at -5 kHz frequency shift)	OK	OK	RF	PB	
			check injection oscillation	OK	OK	OP		
			check 450 GeV dump ok	OK	OK	ABT	BG	
450 Z GeV commissioning (BI setup)	1 (non colliding)	0.5	Wire-scanner for 1 beam	OK	OK	BI	JJG	THU N
			BGI				JJG	THU N
450 Z GeV optics checks with two beams	1 (non colliding)	0.5	beta-beating. >0.4 nominal bunch intensity	OK	OK	ABP	RT	THU N
Collimation	1 (non colliding)	1	Collimation check	OK	OK	COLL	SR, RA, DW	FRI M
			Loss maps	OK	OK			
LBDS	1 (non colliding)	0.25	Asynchronous beam dump	OK	OK	ABT	BG	FRI A
Ramp	1 (non colliding)	1	Blowup off - TFB off - OFB on - QFB on - Collimators ramp if no issues at injection	OK	OK	OP, COLL	RA	FRI A
			Collimator check, NO squeeze, loss maps	OK	OK	OP, ABP	RT	
			check 3.5 TeV dump ok	OK	OK	ABT	BG	

Heavy ion commissioning plan (2)

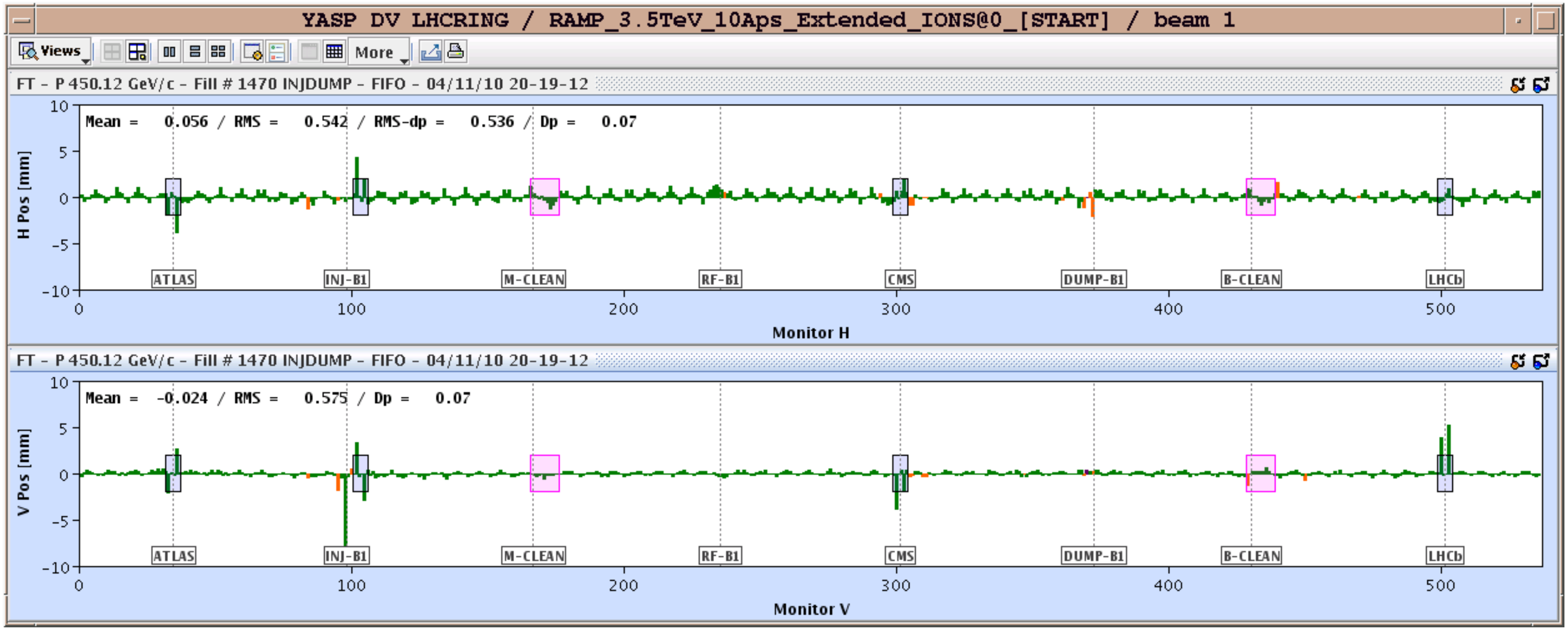
			check 3.5 TeV dump ok	OK	OK	ABT	BG	
RAMP and SQUEEZE	1 (non colliding)	0.5	Ramp THEN squeeze, optics check	OK	OK	COLL	RA, DW, GV, GB	FRI N
LBDS	1 (non colliding)	0.25	Asynchronous beam dump	OK	OK	ABT	BG	FRI N
Setup for collisions	2 (colliding)	2	Squeeze, find collision, and transition to zero real crossing angle in ALICE, CMS & ATLAS. LHCb separated, squeezed.	OK!!	OK!!	OP		SAT M,A
			Collimation setup.	OK	OK	COLL	RA, RB, DW,	
Collimation	2 (colliding)	1	Loss maps	OK	OK	OP	GB	SAT N
LBDS	2 (colliding)	0.25	Asynchronous dump	OK	OK	ABT	BG	SUN M
First collisions + PHYSICS	2 colliding	1 or 2	Ramp with two beams, squeeze, checks, Stable beams.	OK!!	OK!!			SUN M
Increase intensity (1)	17	1 or 2	Increase bunch number to 17 (16 colliding in IP1,2,5 + 1 probe)	OK	OK			
Increase intensity (1.5)	69	1	New scheme, 65 or 66 collisions/turn	OK	OK			*WED A*
Increase intensity (2)	121	1	Increase bunch number to 128	OK	OK			
Physics	121		Parasitic measurements during physics (luminosity evolution, BFPP, etc, ...) to test models and prepare future runs	OK	OK			

Last updated: 16/11/2010 11:56

Thursday evening – ions to the LHC

- Adjustment of the offsets LHC-SPS to place ions bunch on the MKI of Beam 1
- No threading or corrections
- 20:20 First 75+ trajectories in the LHC

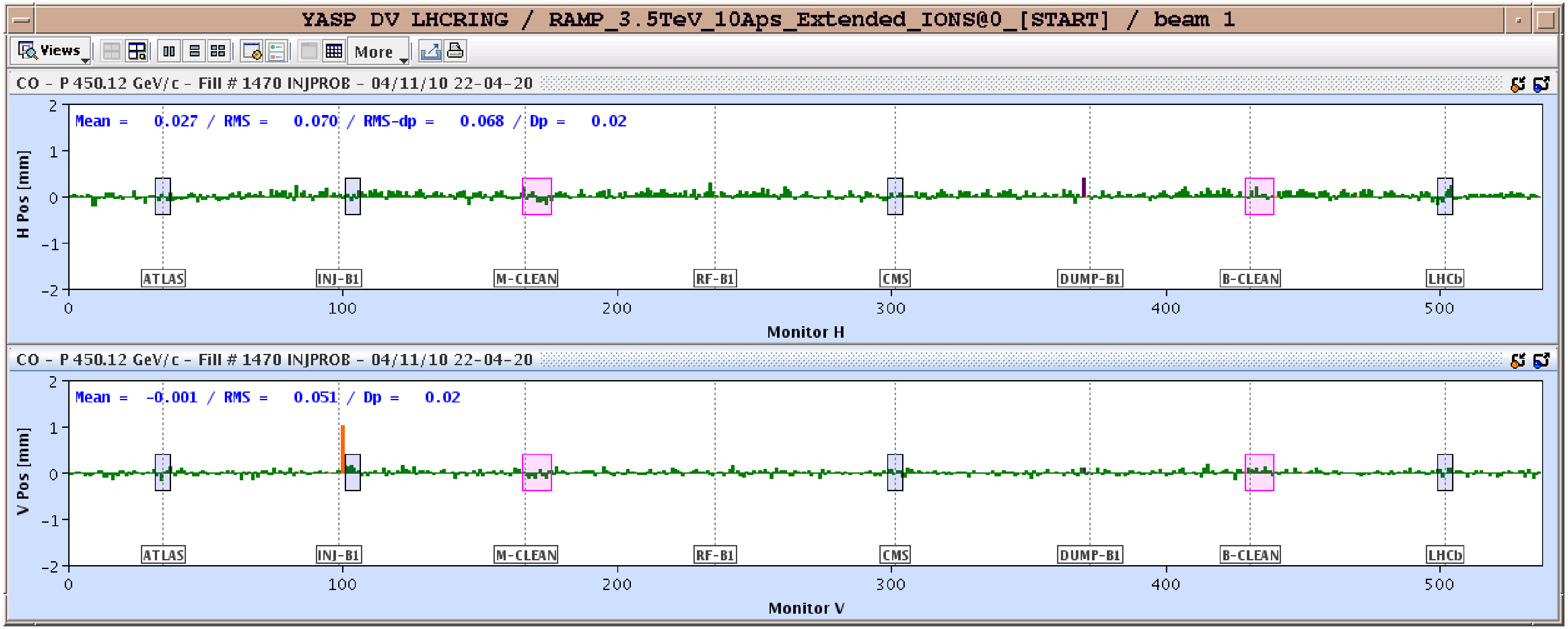
Beam 1 turn 1 compared to proton closed orbit – very close !!



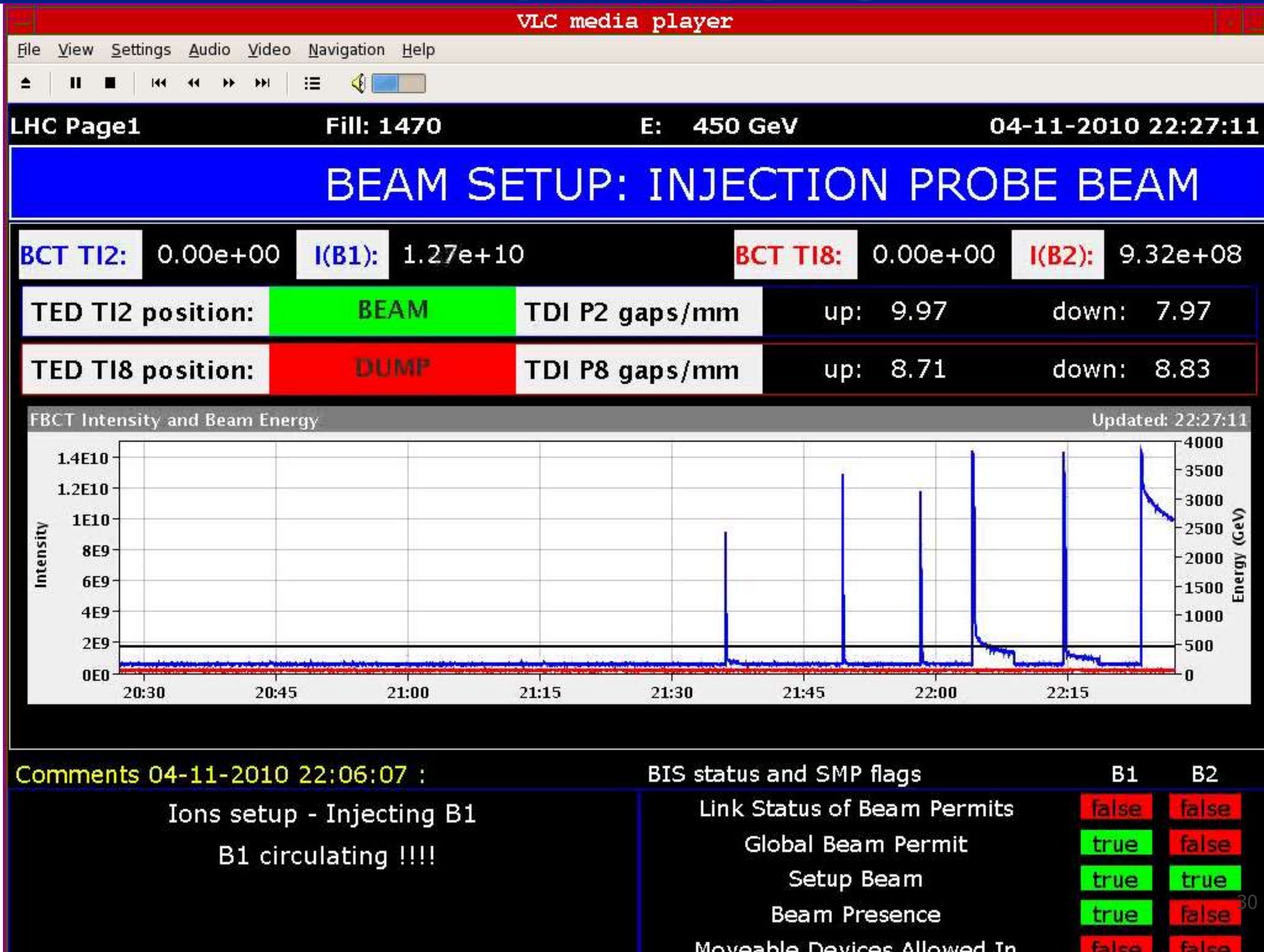
Circulating Beam 1

- 20:30-22:00 RF : placing bunch into correct bucket.
- 22:00 :Beam 1 captured and circulating for many seconds.
- 01:50 : both beams circulating.

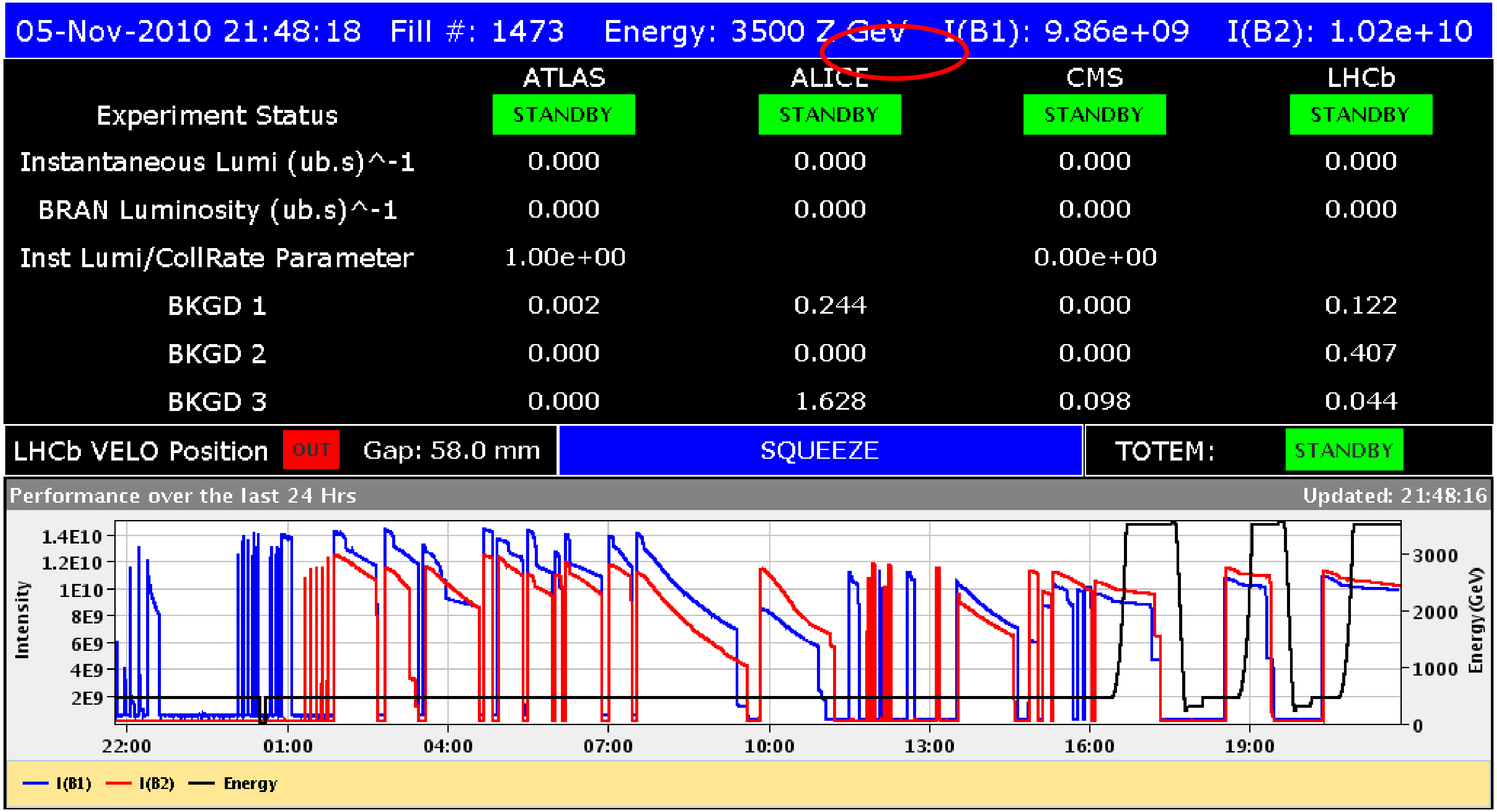
Beam 1 Pb orbit compared to proton orbit – no steering !



Beam 1 (and RF) progress



Ion Commissioning: Thursday & Friday



Beam 1
Inj., Circ.
& Capture

Beam 2
Inj., Circ.
& Capture

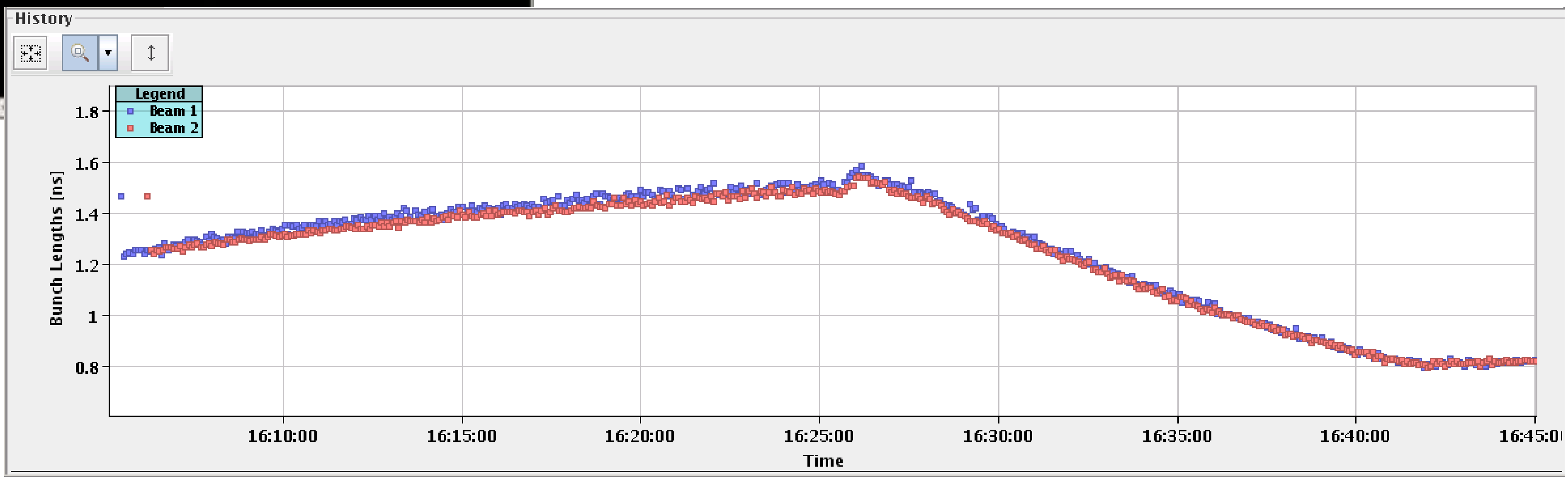
Optics Checks
BI Checks
Collimation Checks

First Ramp
Collimation Checks
Squeeze

Friday afternoon: first ramp – no losses

World first: observation of synchrotron light from nuclei

Appears around 0.55 Z TeV (later if filtered)



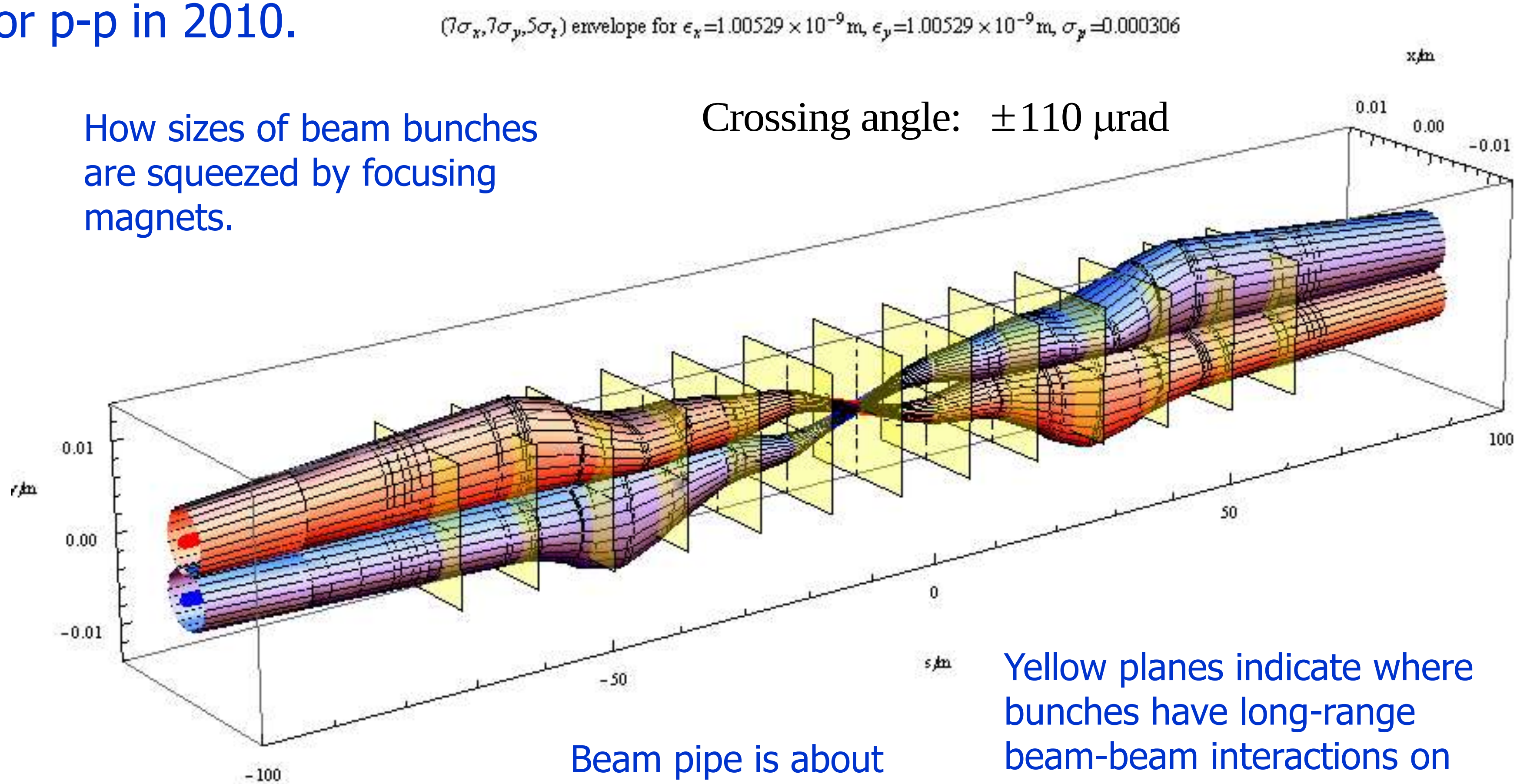
Bunch length increasing at injection (IBS), down during the ramp, increasing again at 3.5 TeV (IBS)

Beam envelopes around ALICE experiment

Collision conditions for p-p in 2010.

How sizes of beam bunches are squeezed by focusing magnets.

Crossing angle: $\pm 110\ \mu\mathrm{rad}$

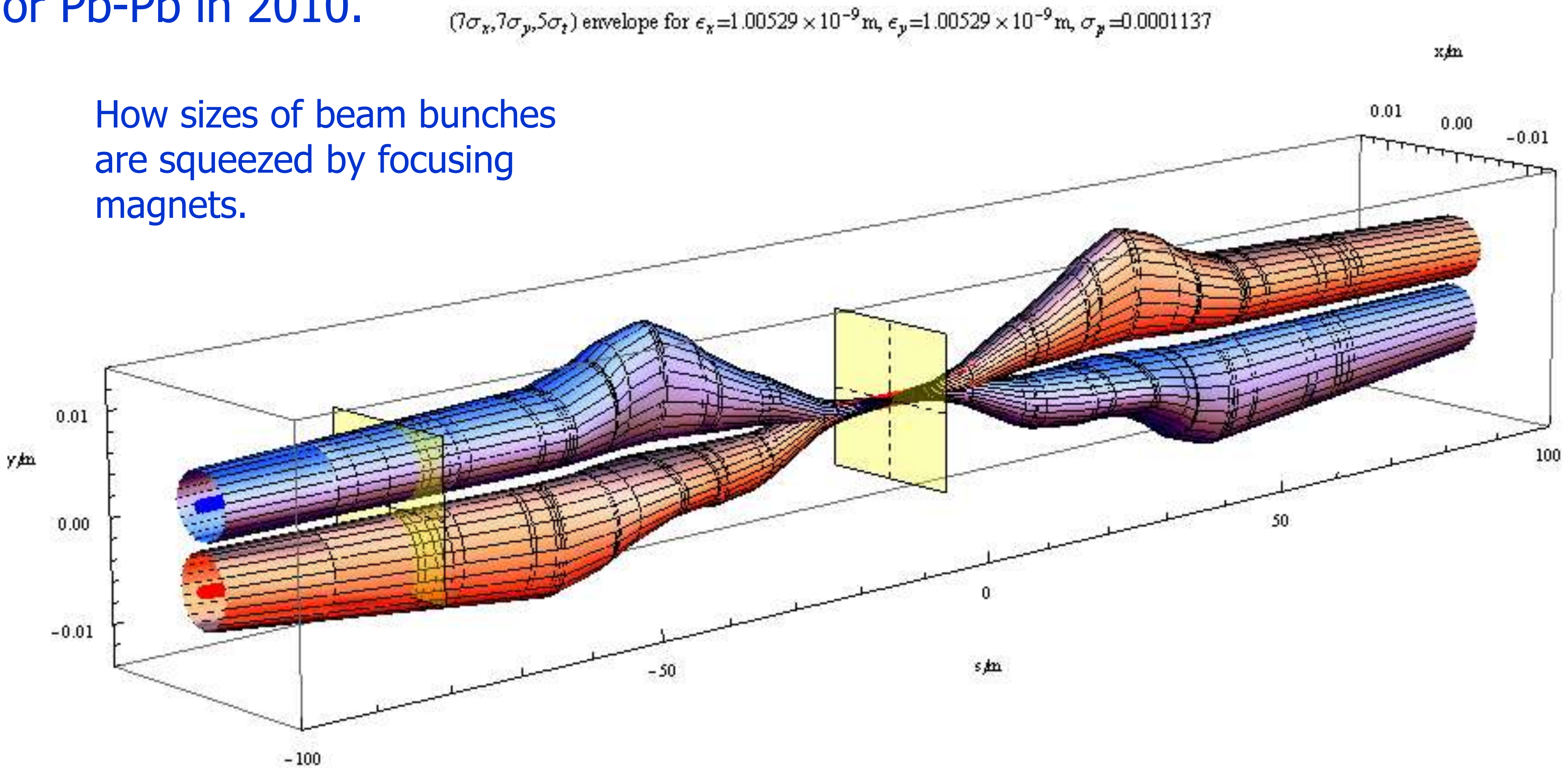


Beam pipe is about twice transverse size of box.

Yellow planes indicate where bunches have long-range beam-beam interactions on their way in and out of the collision point (75 ns bunch spacing).

Beam envelopes around ALICE experiment

Collision conditions for Pb-Pb in 2010.



How sizes of beam bunches are squeezed by focusing magnets.

Zero crossing angle at IP (external crossing angle compensates ALICE spectrometer magnet bump).

Beam pipe is about twice transverse size of box.

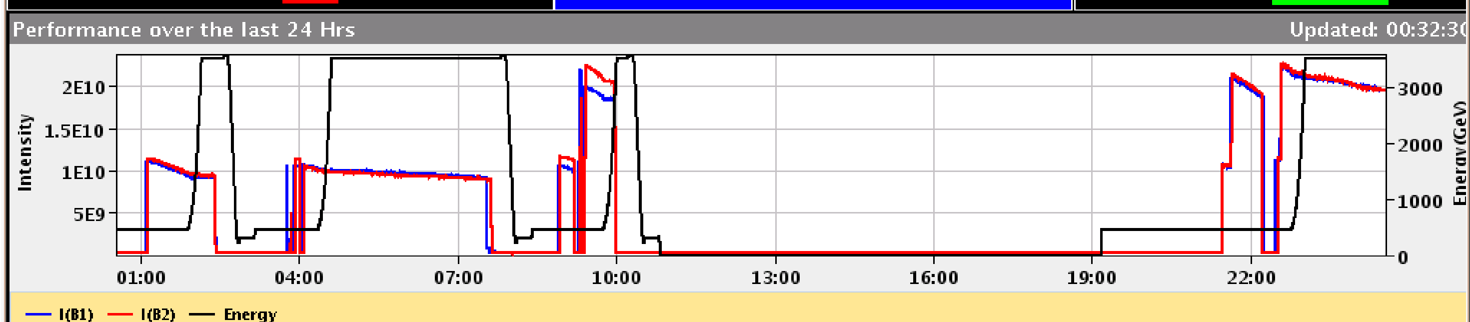
Sunday early morning – first collisions !

- 00:30: Colliding in all IPs with TCTs at 25σ.
  - With proton settings for crossing angles and luminosity scan knobs (ALICE separation to 0).
- 2 bunches / beam.
- Optimized orbit and beam overlap.
  - Luminosity ~ 2 x 10^{23} $cm^{-2}s^{-1}$ (1 colliding pair / IP)

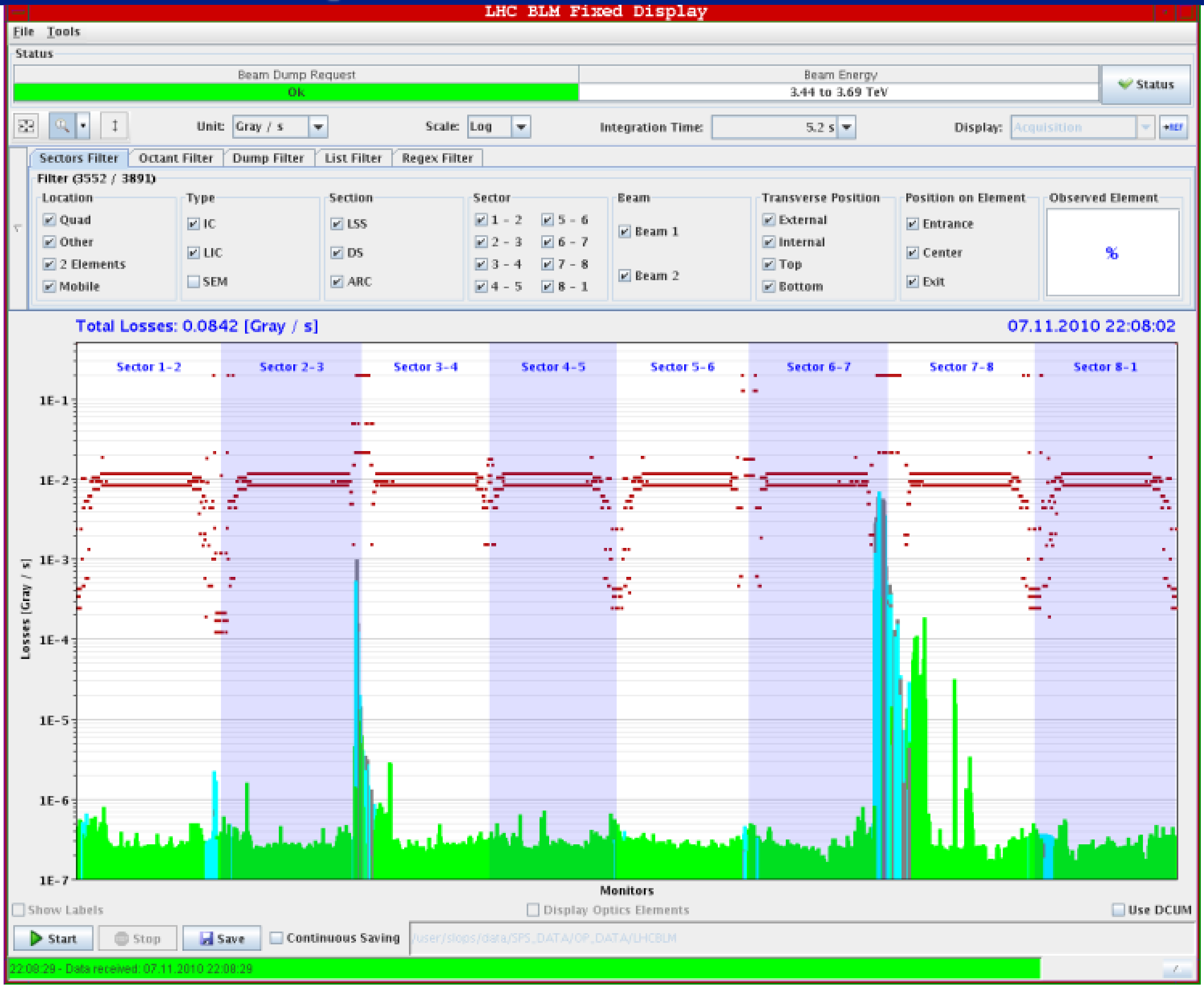
07-Nov-2010 00:32:33 Fill #: 1477 Energy: 3500 Z GeV I(B1): 1.96e+10 I(B2): 1.96e+10

	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	0.005	0.005	0.003	0.000
Inst Lumi/CollRate Parameter	2.40e+01	9.46e+00	5.75e+01	
BKGD 1	0.002	0.195	0.000	0.131
BKGD 2	0.000	0.000	0.000	2.903
BKGD 3	2.000	1.526	0.098	0.038

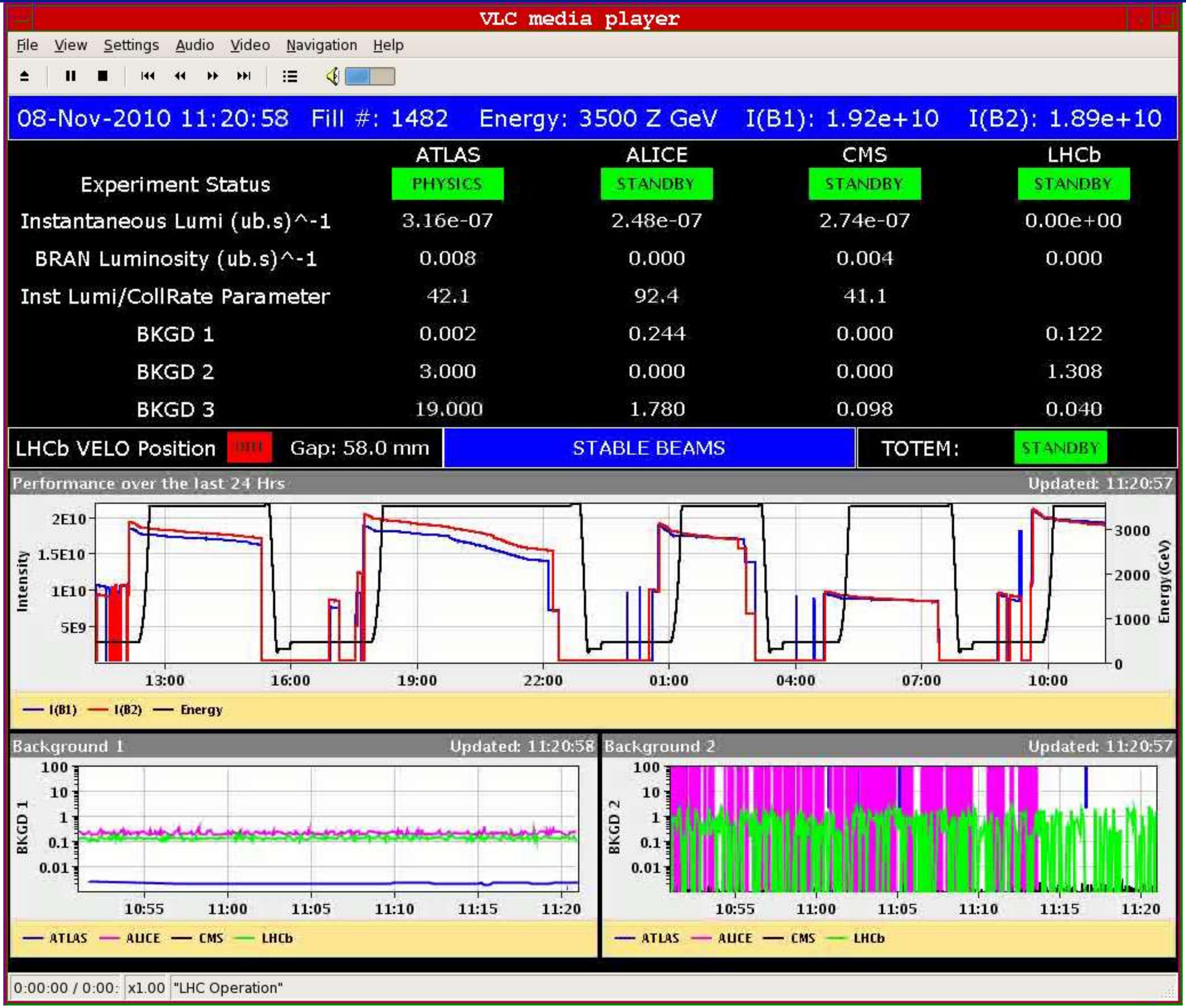
LHCb VELO Position OUT Gap: 58.0 mm ADJUST TOTEM: STANDBY



Loss maps in collisions – Beam 1 V

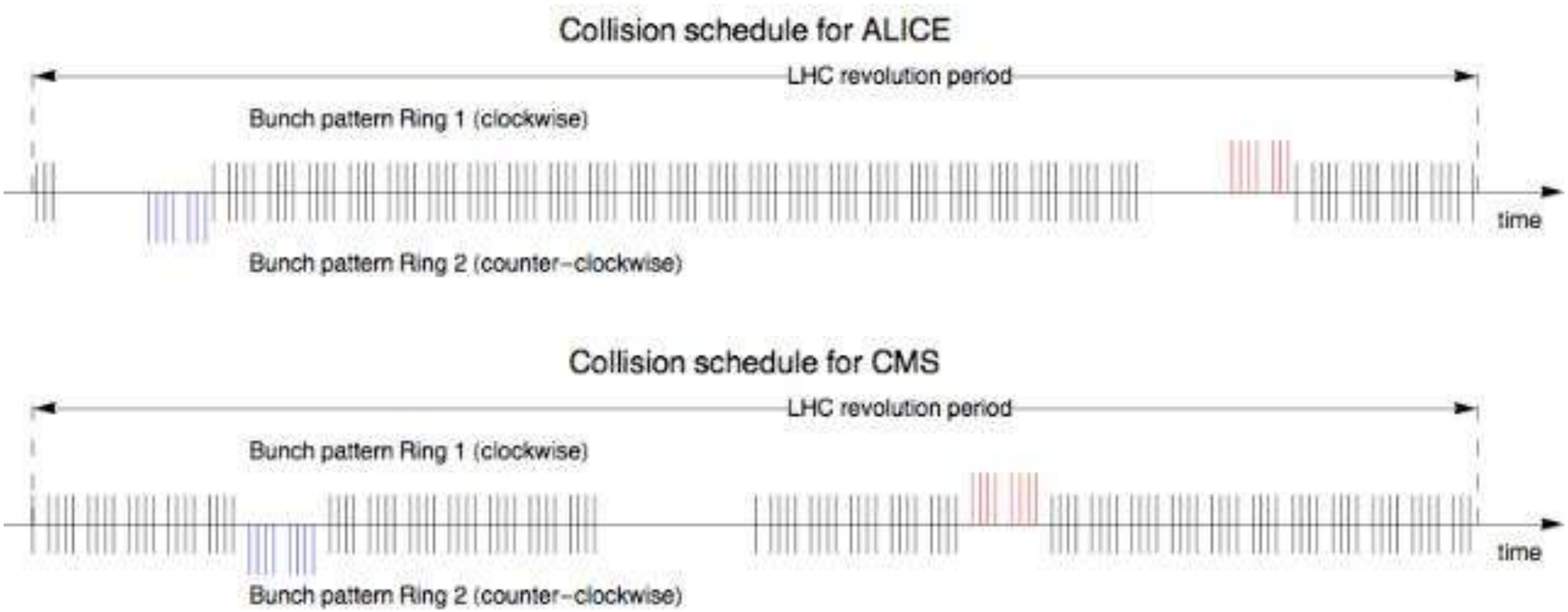


Monday morning: First Stable Beams for Pb-Pb



Filling schemes

- First week: no two fills with same number of bunches
  - 2,5,17,69, then 121 per beam (475 ns basic spacing)



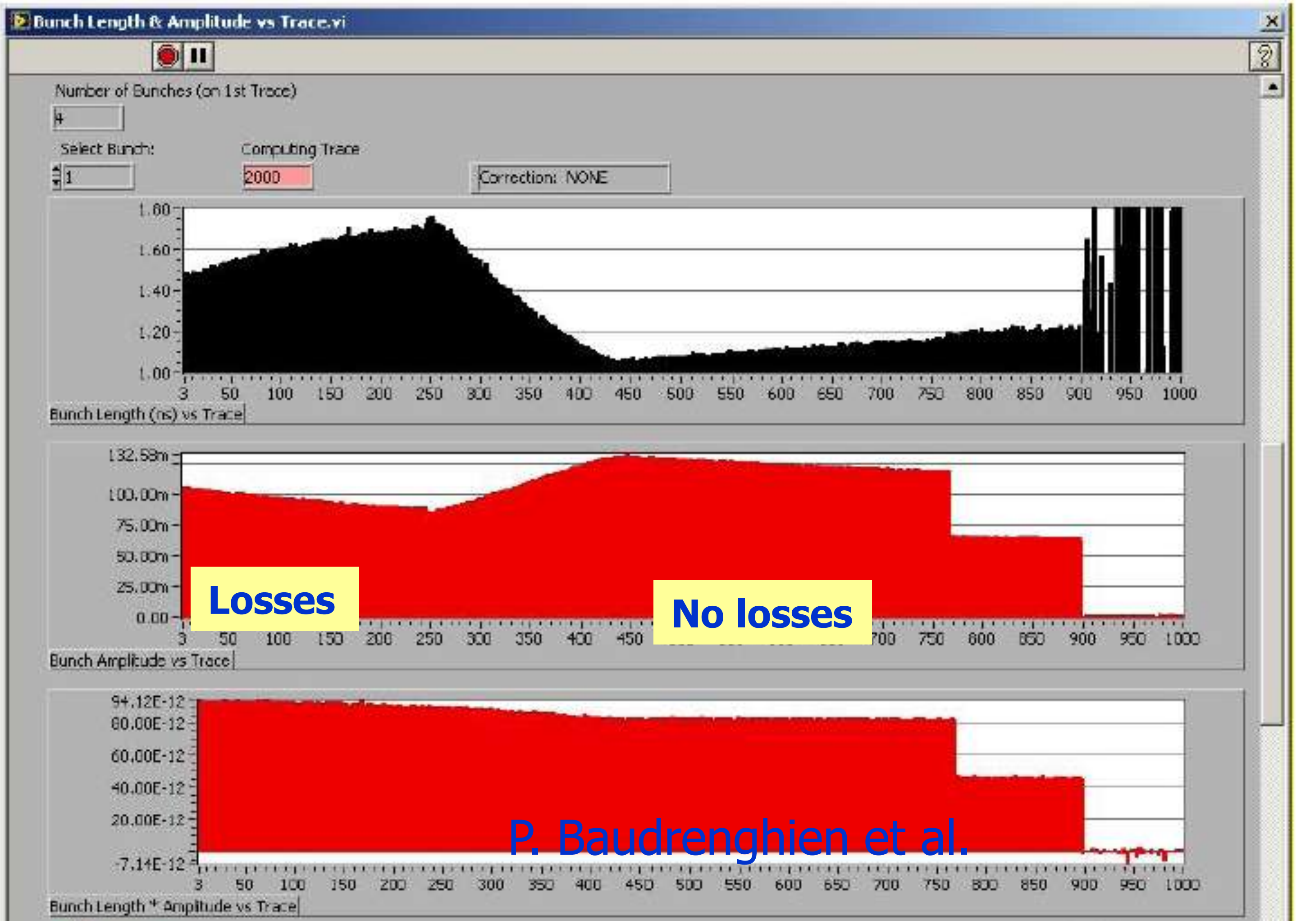
Losing ions from the RF bucket

- No losses from the bucket in the first few hours at 3.5 TeV

Bunch length

Amplitude

Length*amplitude



Predicted IBS and debunching at injection

Phys. Rev. ST Accel. Beams 13, 091001 (2010) [16 pages]

Time evolution of the luminosity of colliding heavy-ion beams in BNL Relativistic Heavy Ion Collider and CERN Large Hadron Collider

Abstract | References | No Citing Articles

Download: PDF (2,301 kB), One-column PDF (2,294 kB) Export: BibTeX or EndNote (RIS)

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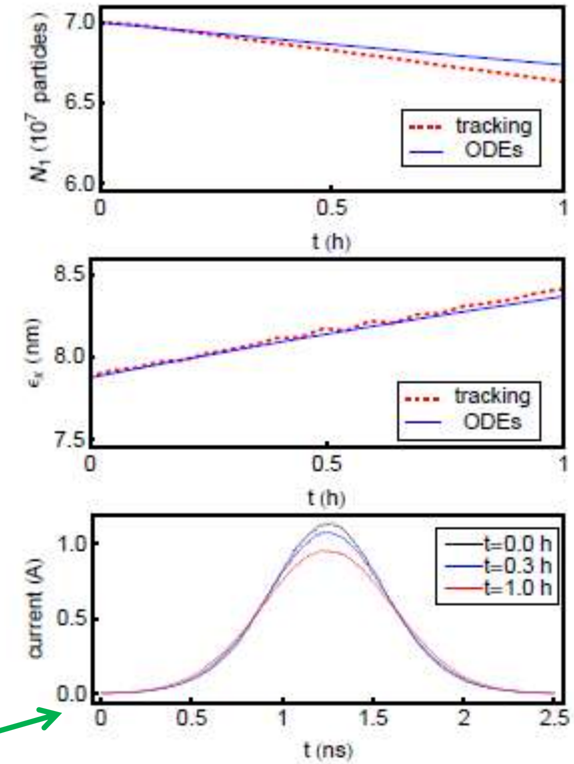
Received 30 November 2009; published 7 September 2010



Predicted non-gaussian profile from IBS

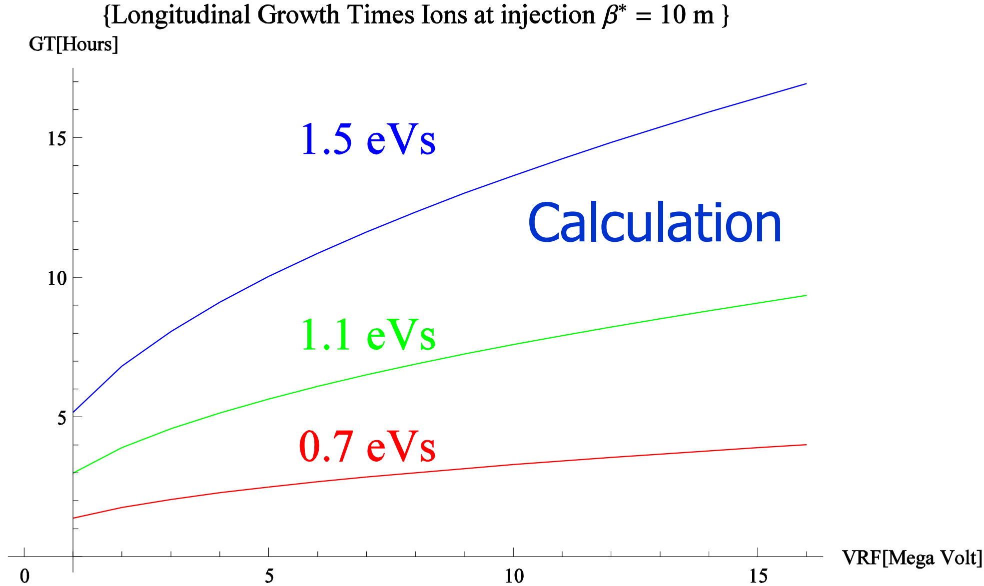
FIG. 10: The simulated time evolution in the LHC of the bunch intensity and transverse rms emittance during 1 h at the injection plateau without collisions. The bottom plot shows the longitudinal bunch profile at different times as simulated with tracking.

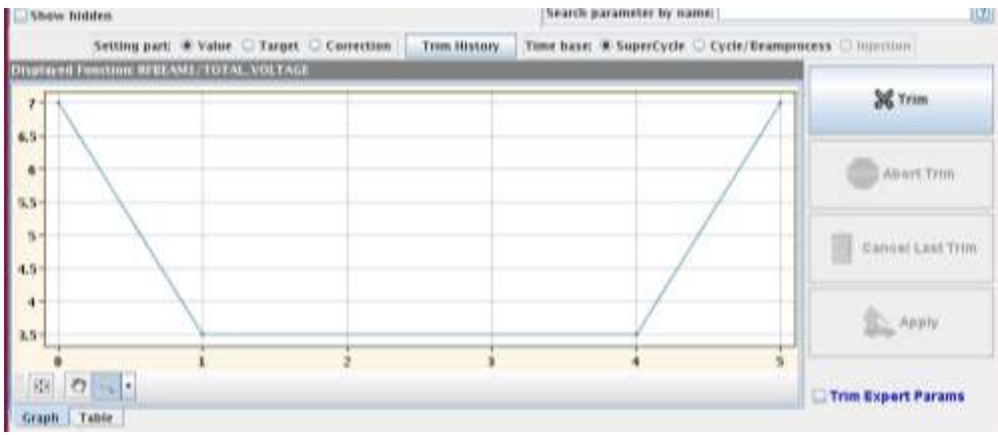
$$V_{\mathrm{RF}} = 8\ \mathrm{MV}$$

$$\varepsilon_t(4\sigma) = 0.71\ \mathrm{eV\ s}$$

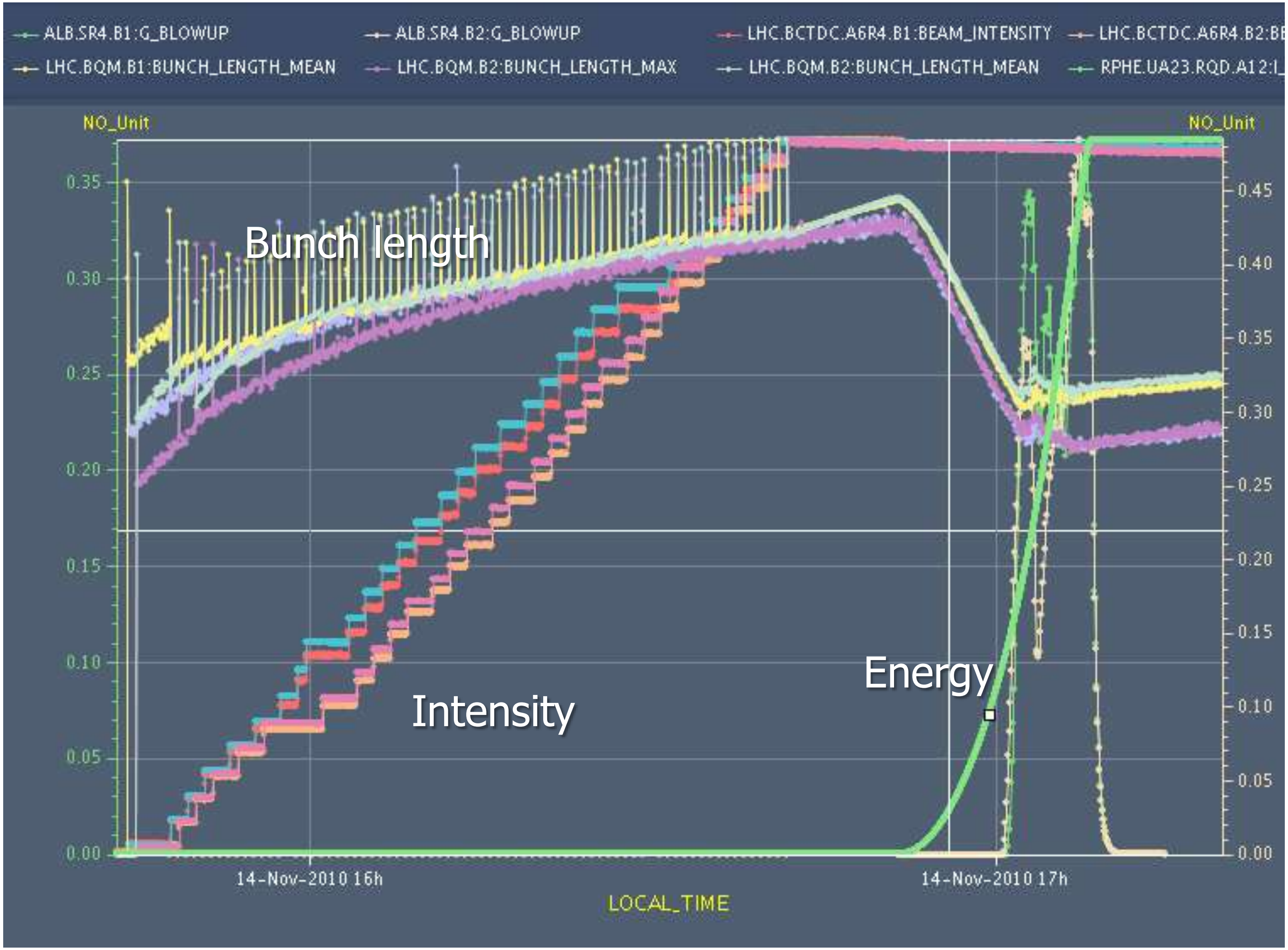
RF voltage modulation

- Required voltage for injection matching 3.5 MV
- Increased voltage would reduce IBS and debunching
- Solution: keep at 7 MV between injections with adiabatic reduction to 3.5 MV for 3 s at each injection



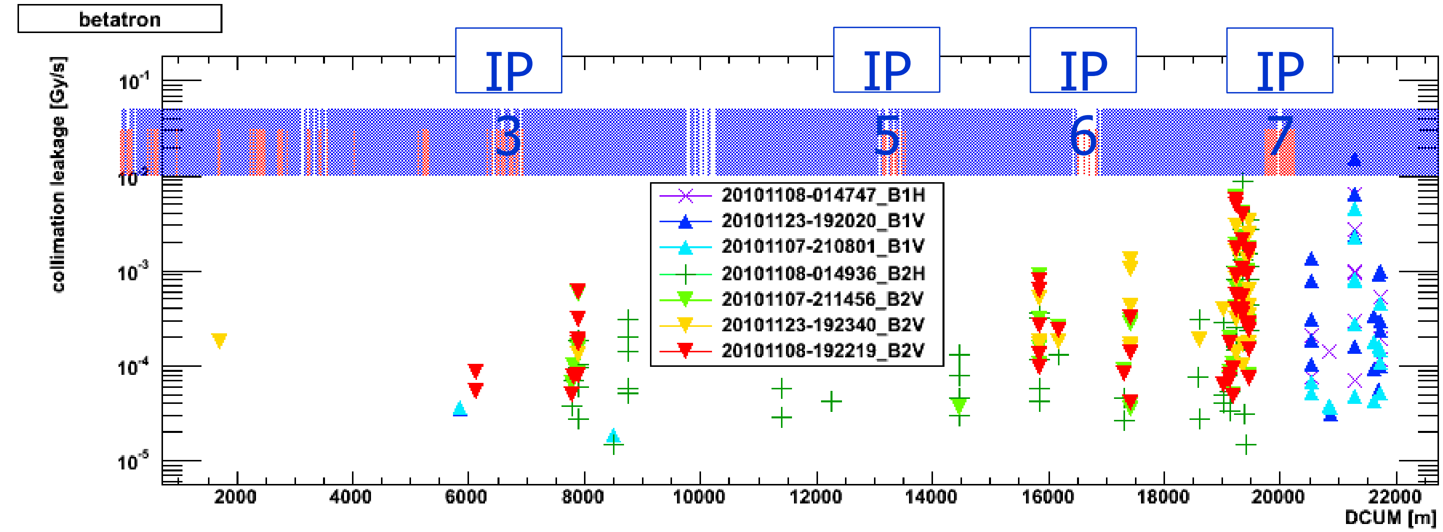


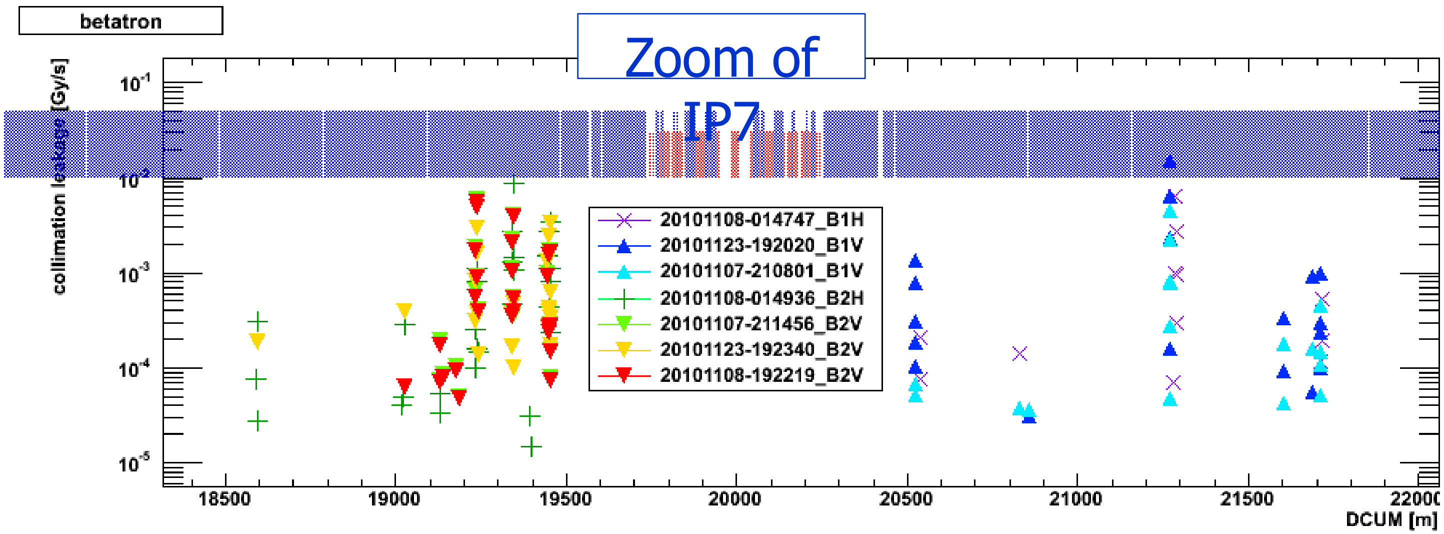
Injection with VRF modulation, ramp



Pb Betatron Collimation Leakage

Arc Loss only



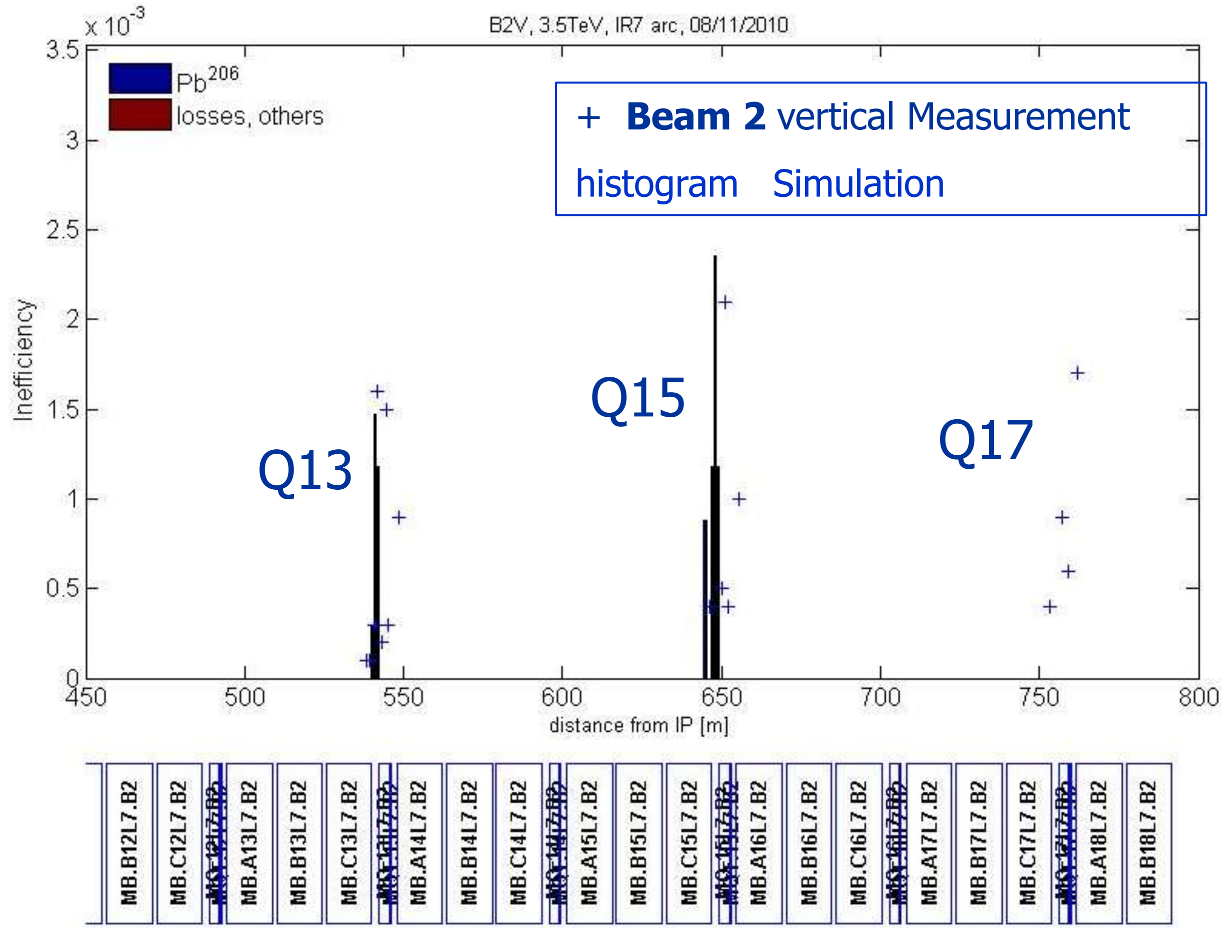


B. Holzer

Pb Collimation Losses vs Simulations

Preliminary comparison loss maps with simulations

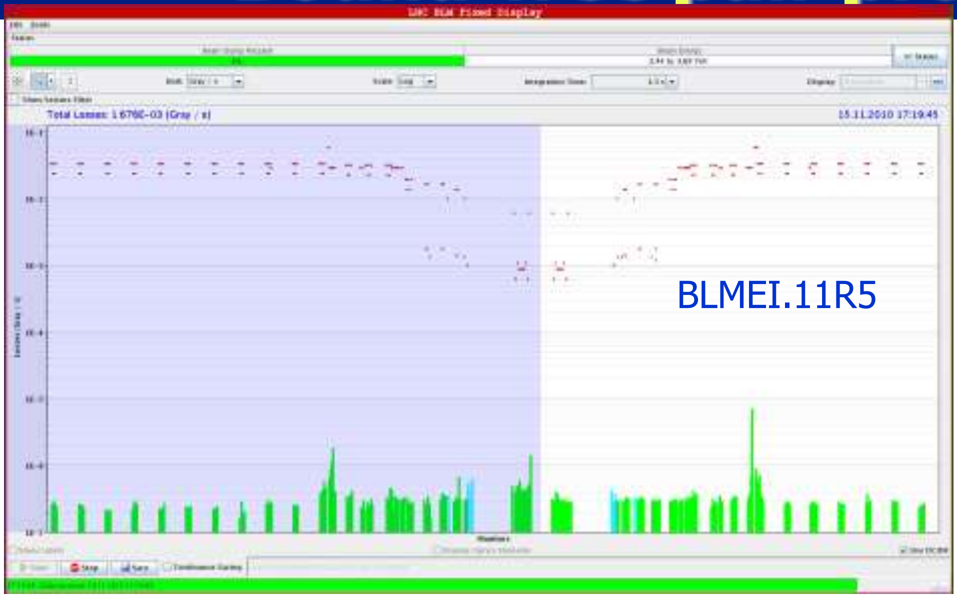
- Beam 1: hardly any losses seen in simulations
- Beam 2: magnitude and certain positions compare well

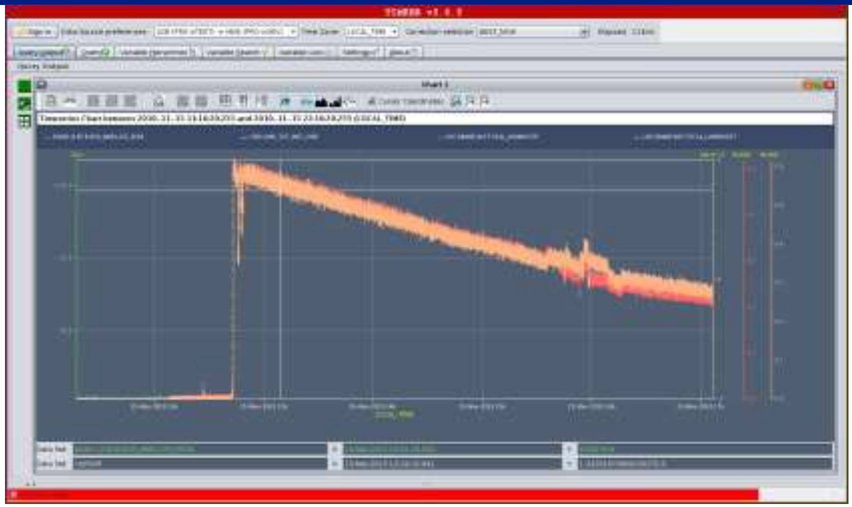


G. Bellodi,

B. Holzer

Bound-free pair production at all IPs





Perfect correlation of BLM at Q11 with luminosity

$$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + e^{+}$$

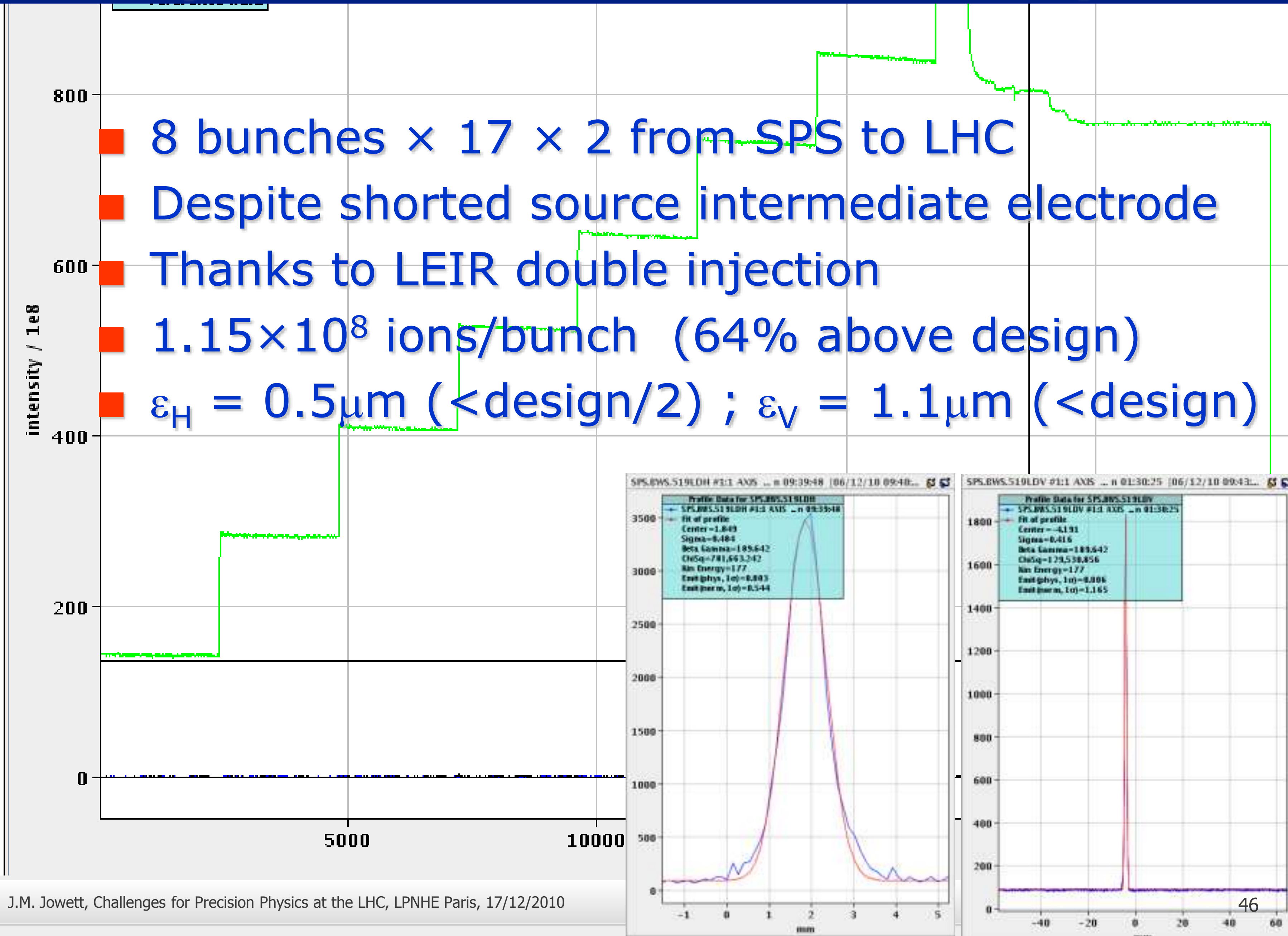
Secondary Pb^{81+} beam (25 W at design luminosity and energy) emerging from IP and impinging on beam screen.

Hadronic shower into superconducting coils can quench magnet.

Effective luminosity monitor ?

Injectors for last LHC ion fill of the year

- 8 bunches × 17 × 2 from SPS to LHC
- Despite shorted source intermediate electrode
- Thanks to LEIR double injection
- 1.15×10^{8} ions/bunch (64% above design)
- $\varepsilon_H = 0.5\mu m$ (<design/2) ; $\varepsilon_V = 1.1\mu m$ (<design)

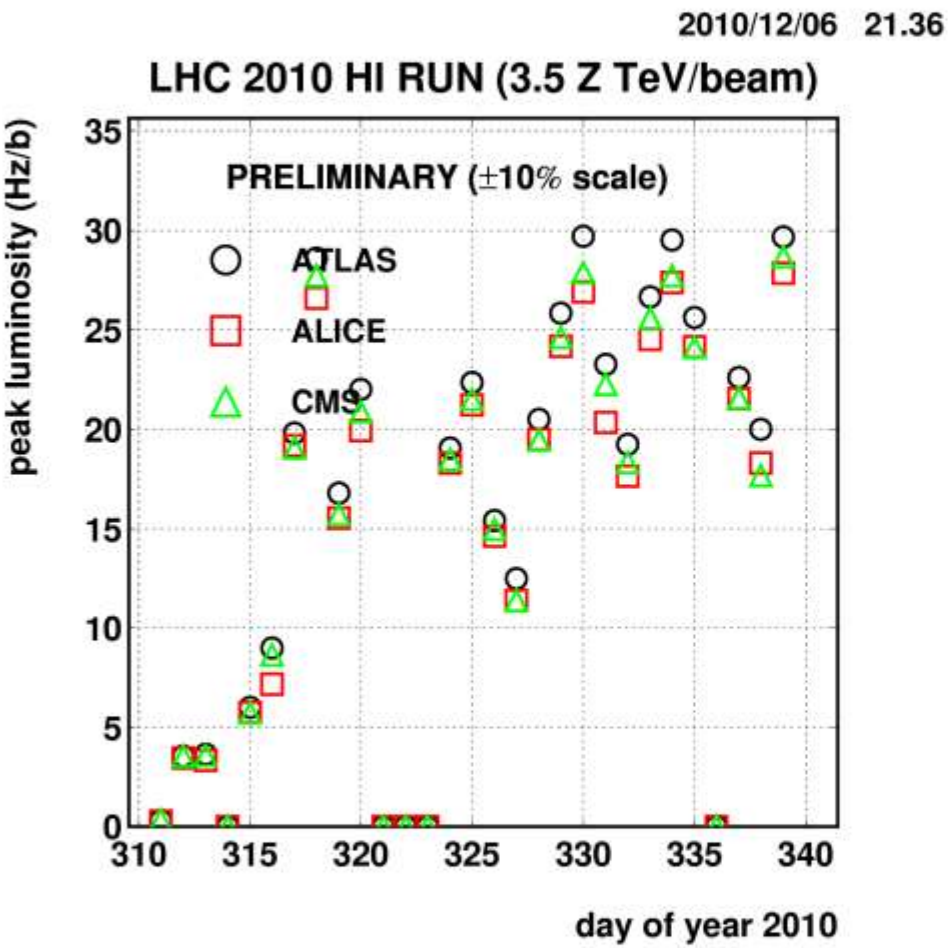


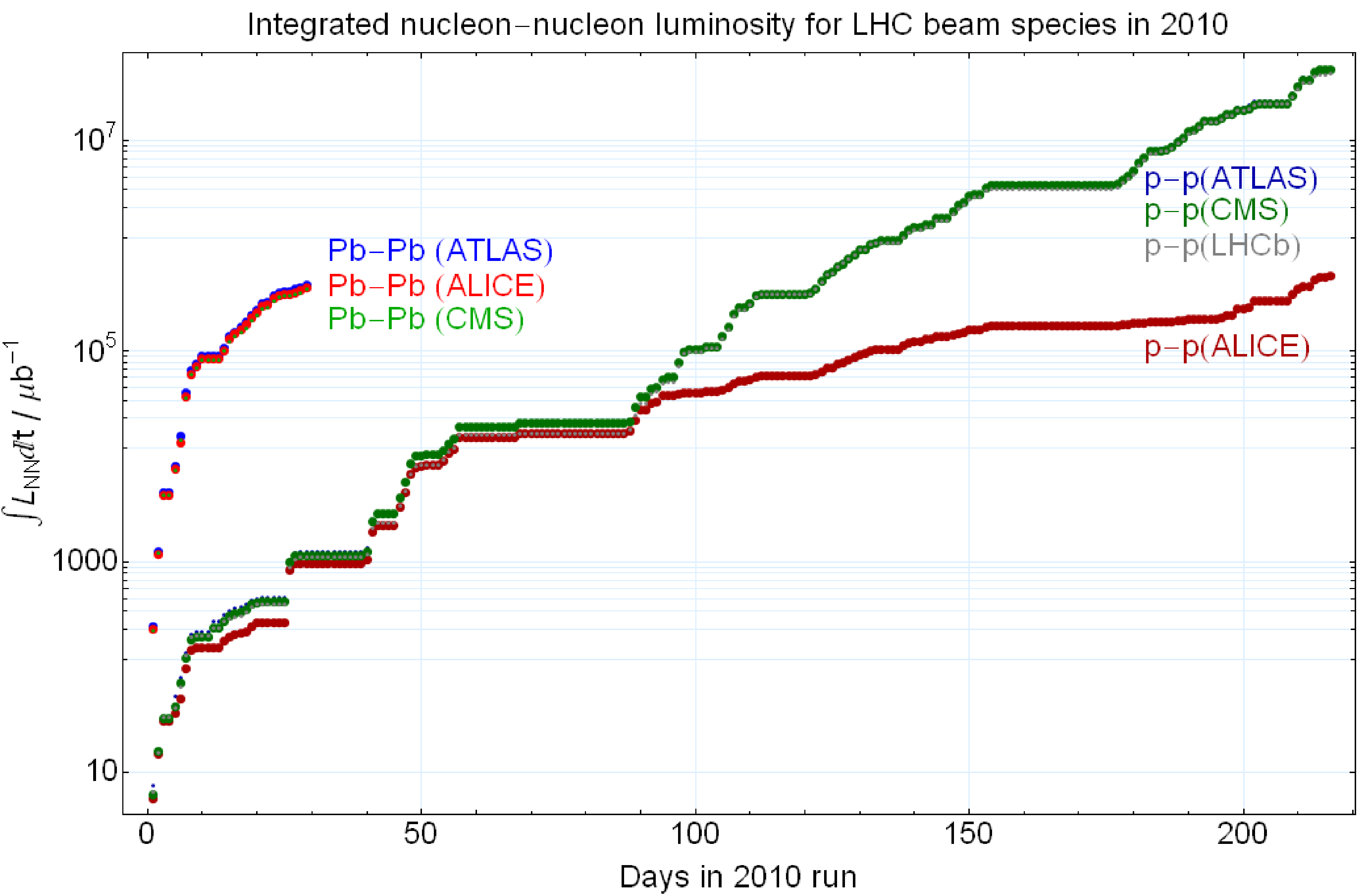
Peak luminosity in fills

Peak performance reached very quickly.

Interrupted twice by source refills (+ "parasitic" proton MD), some time to recover source performance.

Last few days, bunch number increased again to 137 with 8-bunch/batch from SPS.




Integrated nucleon−nucleon luminosity for LHC beam species in 2010
Pb−Pb (ATLAS)
Pb−Pb (ALICE)
Pb−Pb (CMS)
p−p(ATLAS)
p−p(CMS)
p−p(LHCb)
p−p(ALICE)
10^7
10^5
1000
10
0
50
100
150
200
Days in 2010 run
$\int L_{NN} dt \ / \ \mu b^{-1}$

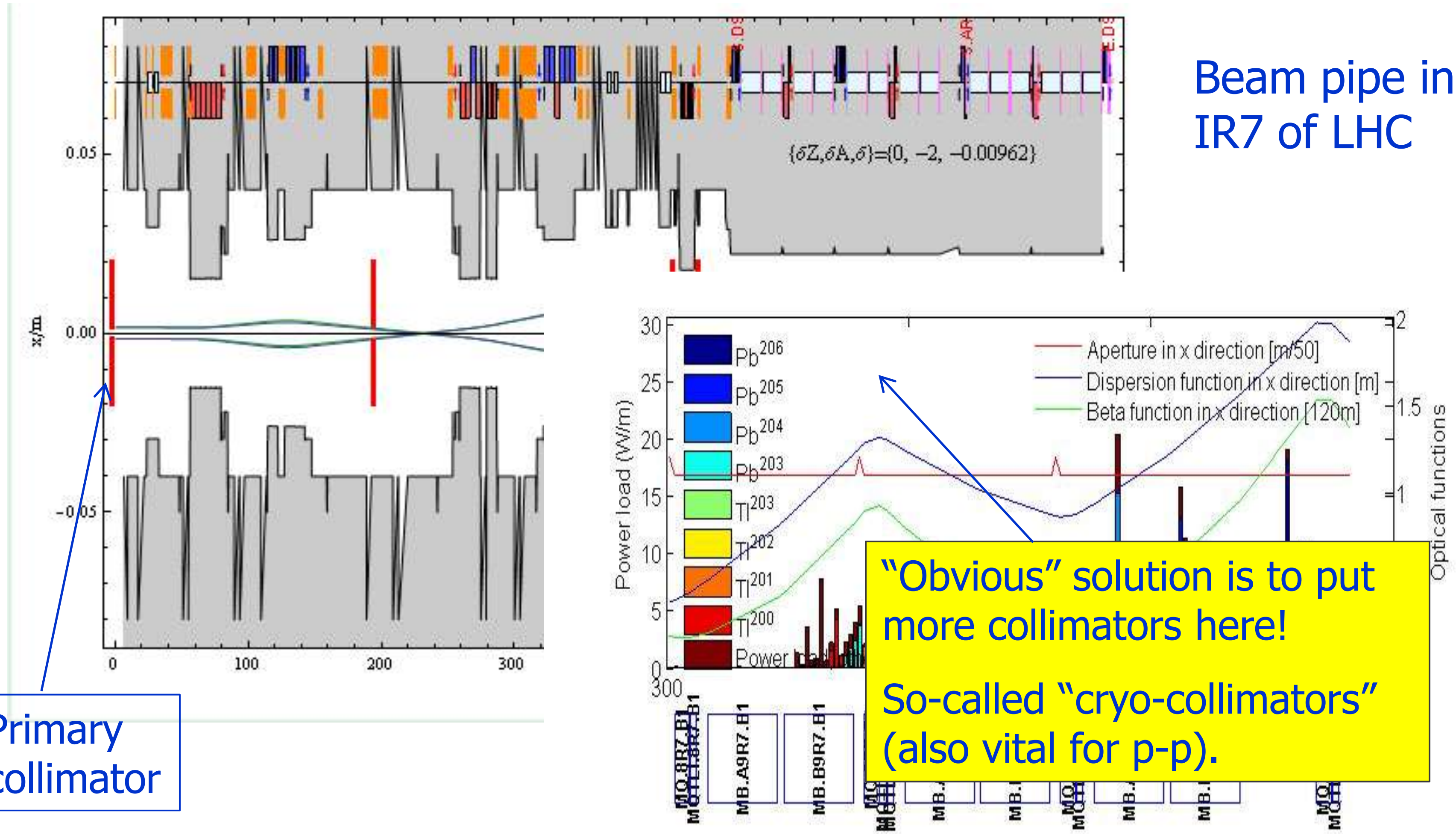
FUTURE NUCLEAR BEAMS

Steps to higher Pb-Pb energy and luminosity

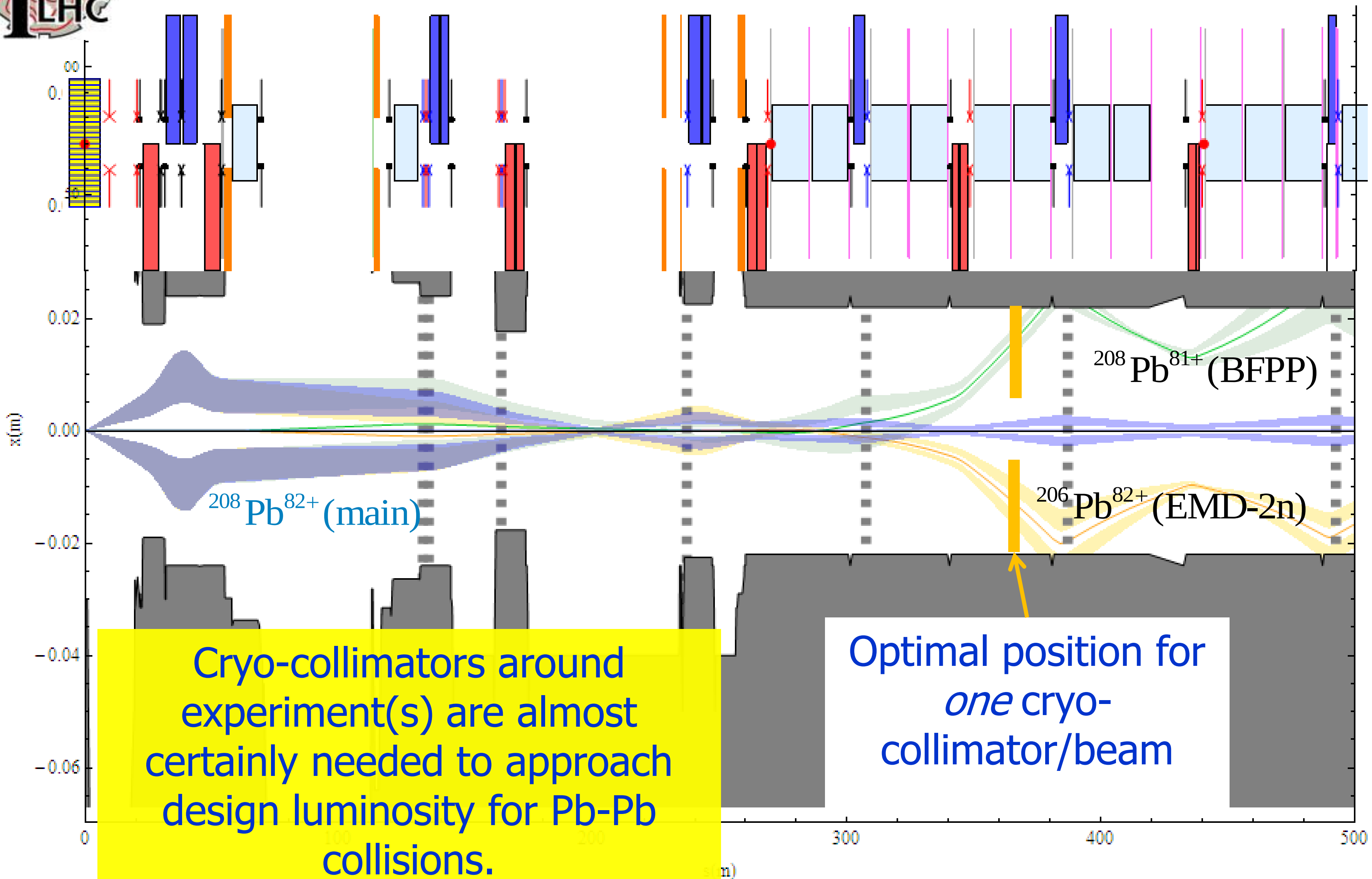
- 2011: continue at beam energy 1.38 A TeV or a bit more …
  - increase number of bunches (injector operation for "Nominal" ?)
  - Reduce β^*
- LHC shutdown in 2012/2013
  - Upgrade of quench protection system, etc, towards full beam energy 2.76 A TeV
  - Hope to equip IR3 with the first cryo-collimators – a major intervention, moving dipole magnets
- Later shutdowns
  - Equip IR2 with cryo-collimators to raise Pb-Pb luminosity limit for ALICE, IR7, …

Example of ^{206}Pb created by 2-neutron EMD

- Green rays are ions that almost reach collimator
- Blue rays are ^{206}Pb rays with rigidity change



Main and secondary Pb beams from ALICE IP



Cryo-collimators around experiment(s) are almost certainly needed to approach design luminosity for Pb-Pb collisions.

Optimal position for *one* cryo-collimator/beam

Synchrotron Radiation

- LHC is the first *proton* storage ring in which synchrotron radiation plays a noticeable role, (mainly as a heat load on the cryogenic system)
- At full energy, it will be the first *heavy ion* storage ring in which synchrotron radiation has significant effects on beam dynamics.
  - Surprisingly, perhaps, some of these effects are stronger for lead ions than for protons.
  - Nucleus radiates coherently:

Synchrotron radiation loss per turn

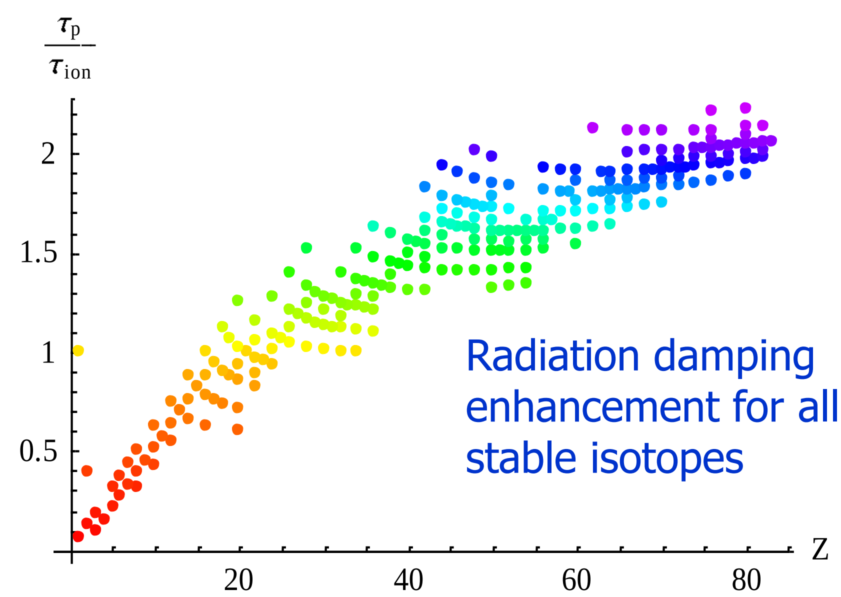
$$U = \frac{4}{3}\frac{\pi r_{\mathrm{ion}} E_{\mathrm{ion}}{}^4}{c^6 m_{\mathrm{ion}}{}^3 \rho} = \frac{4}{3}\frac{\pi Z^2 r_p E_{\mathrm{ion}}{}^4}{c^6 A^4 m_p{}^3 \rho}, \qquad E_{\mathrm{ion}} = \frac{Z}{A} E_p$$

Synchrotron Radiation

- Nuclear charge radiates *coherently* at relevant wavelengths (~ nm)
- Scaling with respect to protons *in same ring, same magnetic field*
  - Radiation damping for Pb is twice as fast as for protons
    - Many very soft photons
    - Critical energy in visible spectrum
- This is fast enough to overcome IBS at full energy and intensity

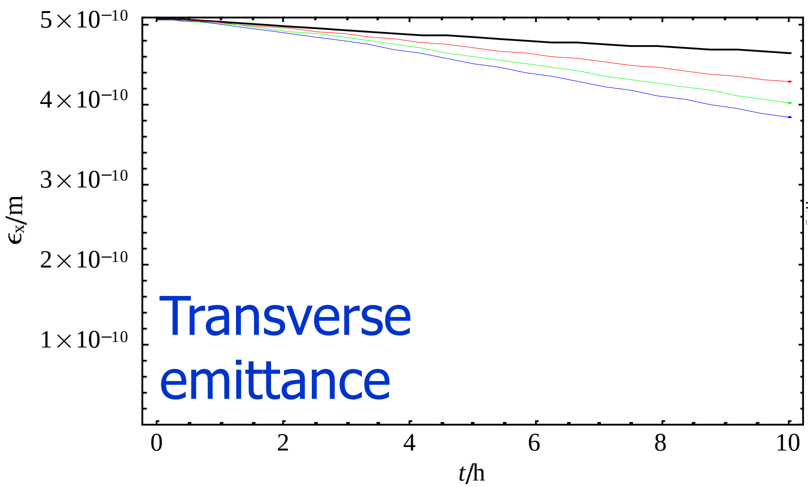
$$\frac{U_{\rm ion}}{U_{\rm p}} \simeq \frac{Z^6}{A^4} \simeq 162, \qquad \frac{u^c_{\rm ion}}{u^c_{\rm p}} \simeq \frac{Z^3}{A^3} \simeq 0.061,$$

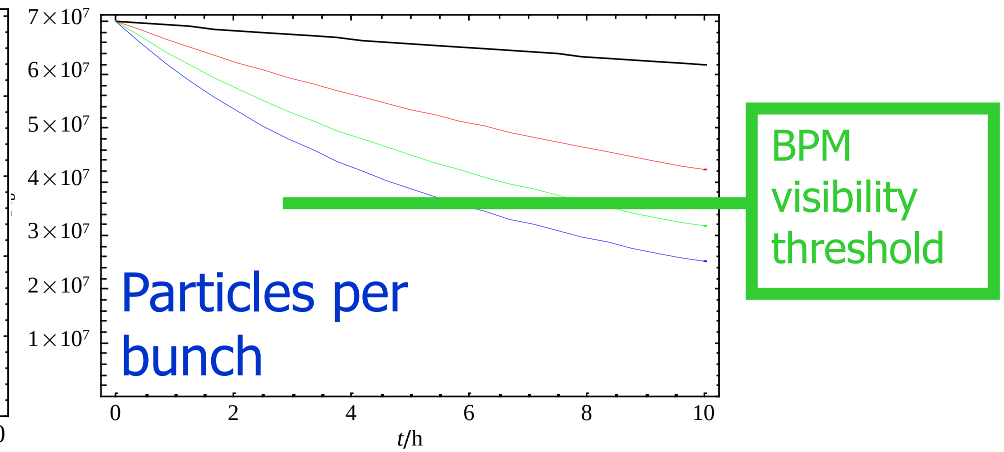
$$\frac{N_{\rm ion}}{N_{\rm p}} \simeq \frac{Z^3}{A} \simeq 2651, \qquad \frac{\tau_{\rm ion}}{\tau_{\rm p}} \simeq \frac{A^4}{Z^5} \simeq 0.5$$



Lead is (almost) best, deuteron is worst.

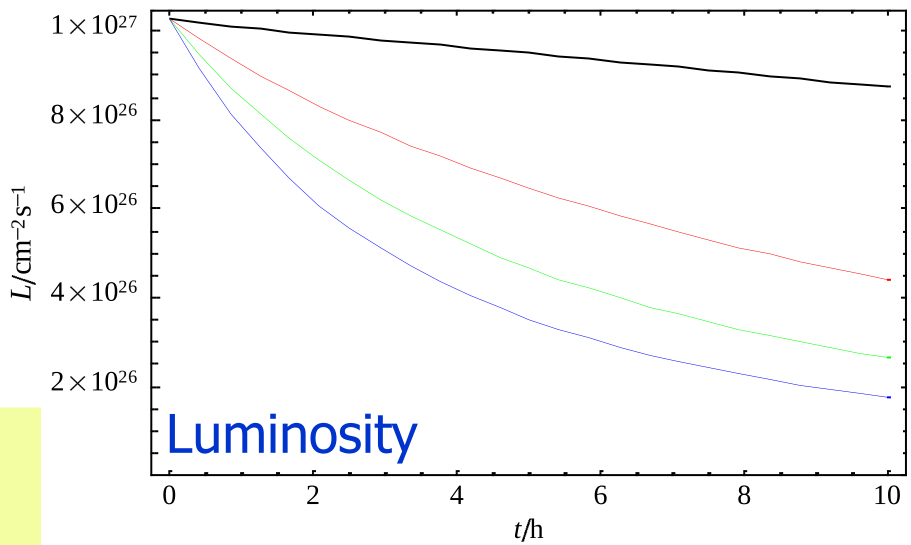
Luminosity evolution: Nominal scheme





No. of experiments: $n_{exp} = 0, 1, 2, 3$

An "ideal" fill, starting from design parameters giving nominal luminosity.



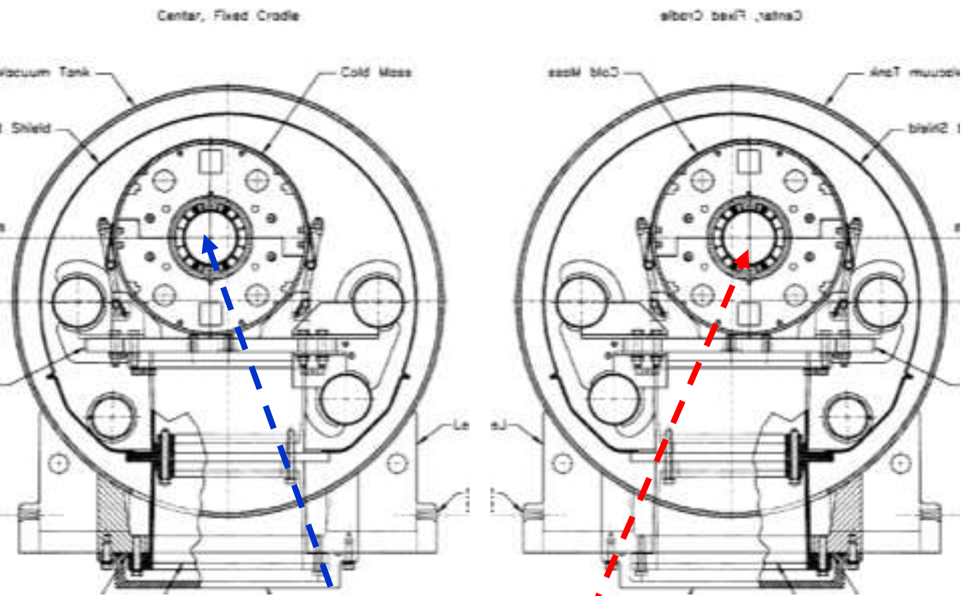
Increasing number of experiments reduces beam and luminosity lifetime.

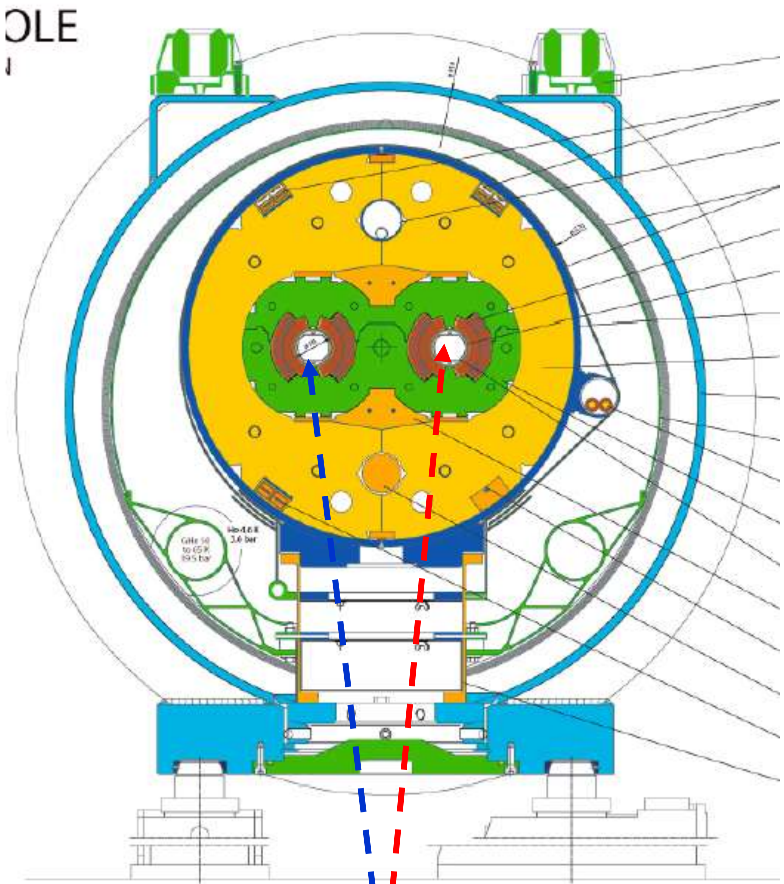
A glimpse of HE-LHC pp

Proton-Nucleus Collisions in LHC

- Dual purpose (as d-Au at RHIC and p-A at SPS):
  - baseline measurements for the nucleus-nucleus program (*J/Ψ*-suppression, jet quenching,…)
  - unique possibilities for particular QCD investigations (parton saturation, gamma-p, gamma-gamma, …)
- Special machine physics issues
  - Twin-aperture magnet: determines experimental conditions
- See forthcoming CERN report, edited by Carlos Salgado

Critical difference between RHIC and LHC





RHIC: Independent bending field for the two beams

LHC: Identical bending field in both apertures of two-in-one dipole

Relation between Beam Momenta

- LHC accelerates protons through the momentum range

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

  - Use this as reference, measure of magnetic field in main bending magnets

- The two-in-one magnet design of the LHC (unlike RHIC) fixes the relation between momenta of beams in the two rings

$$\frac{p_{\mathrm{Pb}}}{Q} = p_{\mathrm{p}}$$

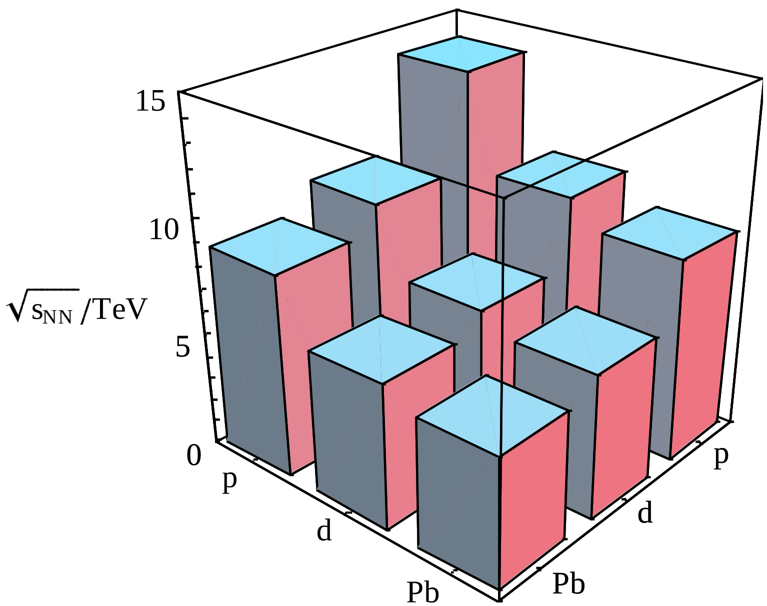
where $Q = Z = 82,\ A = 208$ for fully stripped Pb in LHC

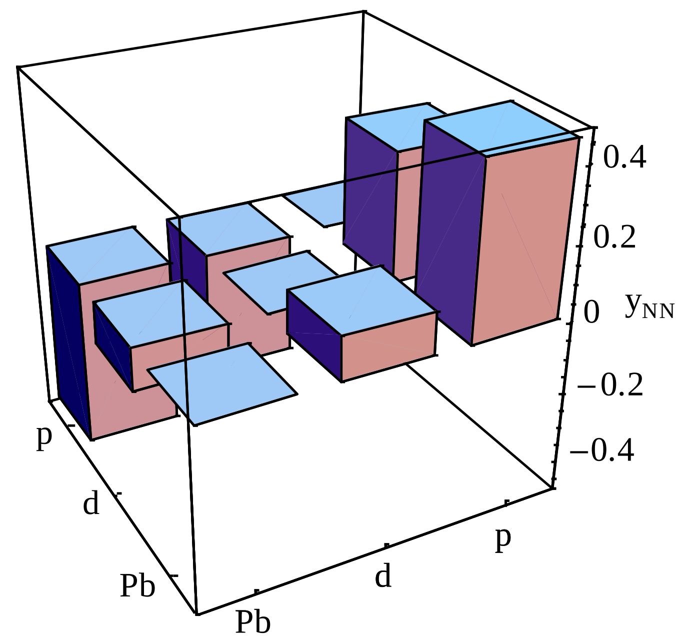
No “DX-magnet” issues.

Kinematics of colliding nucleon pairs

Centre-of-mass energy and velocity/rapidity for nucleon pairs in collisions of ions of charges Z_1, Z_2 in rings with magnetic field set for protons of momentum p_p

$$\sqrt{s_{NN}} \approx 2c\, p_p \sqrt{\frac{Z_1 Z_2}{A_1 A_2}}, \qquad \frac{v_{\mathrm{CMNN}}}{c} \approx \frac{Z_1/A_1 - Z_2/A_2}{Z_1/A_1 + Z_2/A_2}, \quad y_{NN} = \frac{1}{2}\log\frac{Z_1 A_2}{A_1 Z_2}$$





$p_p = 7\,\mathrm{TeV}/c$

Sign change w.r.t. CM of whole ion

Kinematics of colliding nucleon pairs

	p-p	Pb-Pb	p-Pb	d-Pb
E/TeV	7	574	(7,574)	(7,574)
E_N/TeV	7	2.76	(7,2.76)	(3.5,2.76)
$\sqrt{s}/\mathrm{TeV}$	14	1148	126.8	126.8
$\sqrt{s_{\mathrm{NN}}}/\mathrm{TeV}$	14	5.52	8.79	6.22
y_{CM}	0	0	2.20	2.20
y_{NN}	0	0	-0.46	-0.12

- Maximum values, corresponding to proton equivalent momentum ($\Leftarrow$ magnetic bending field) of 7 TeV/c
- Relations between these numbers are a simple, direct consequence of the two-in-one magnet design.

The Revolution Period Problem

- Synchrotrons and storage rings are based on the existence of a *closed orbit,* length *C,* that an ion of the right momentum, mass *m*, charge *Q*, will follow.
- The Hamiltonian is *periodic* if arc-length *s* along the closed orbit is used as independent "time" variable.
- The frequencies of small oscillations around the closed orbit (in units of revolution period) are called the *tunes.*
- Revolution period on the closed orbit depends on ion mass (speed):

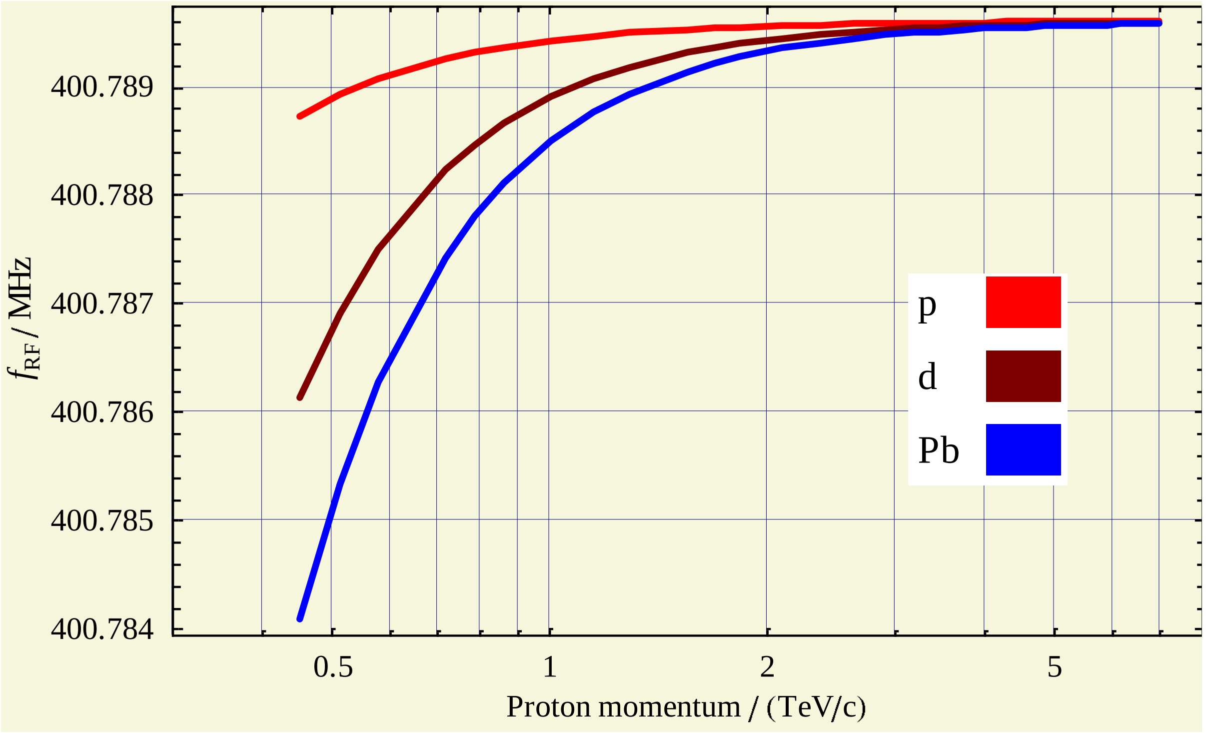
$$T\left(p_{\mathrm{p}}, m, Q\right) = \frac{C}{c}\sqrt{1+\left(\frac{mc}{Qp_{\mathrm{p}}}\right)^2}$$

RF Frequency

$$\text{RF frequency} \qquad f_{\mathrm{RF}} = \frac{h_{\mathrm{RF}}}{T\left(p_{\mathrm{p}}, m, Q\right)}$$

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

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



No problem in terms of hardware as LHC has independent RF systems in each ring (modest timing upgrade needed).

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

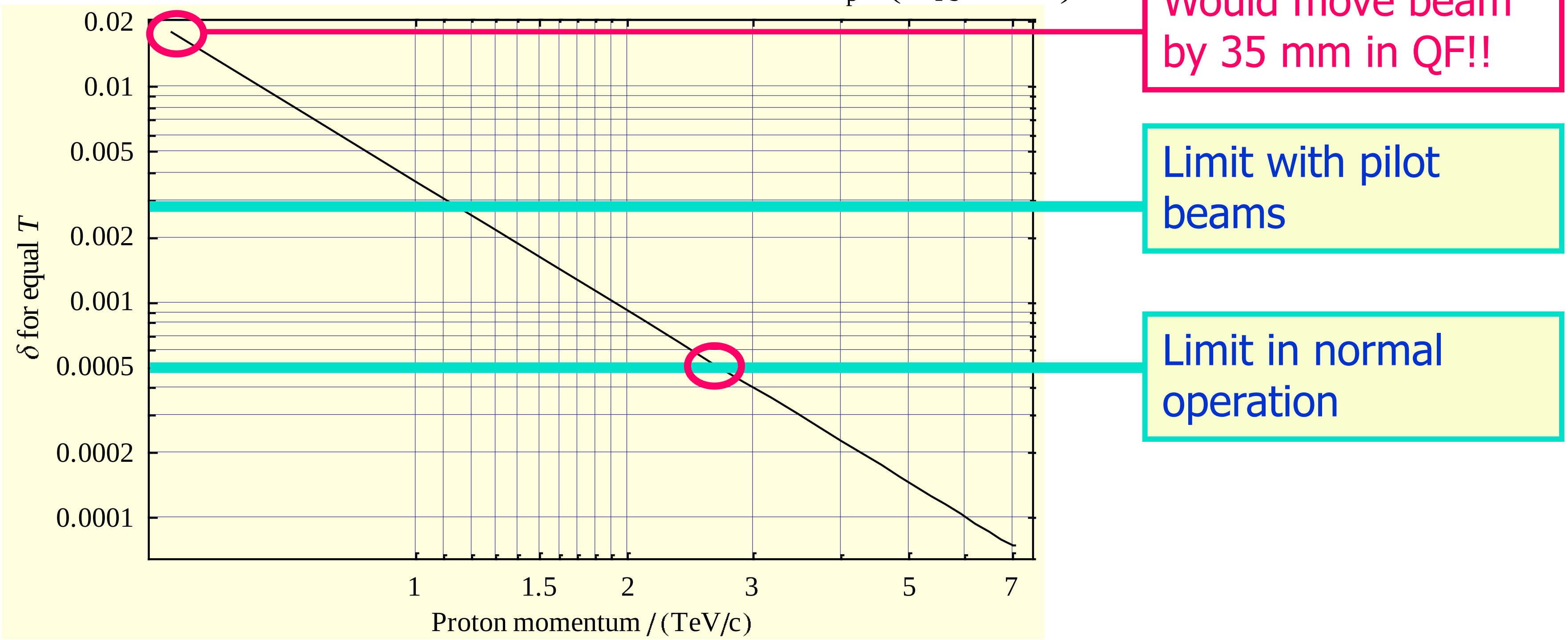
the phase-slip factor $\eta=\dfrac{1}{{\gamma_T}^2}-\dfrac{1}{\gamma^2}, \quad \gamma=\sqrt{1+\left(\dfrac{Qp_{\mathrm{p}}}{mc}\right)^2}, \quad \gamma_T=55.8$ for LHC optics.

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

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

Momentum offset required in ramp

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



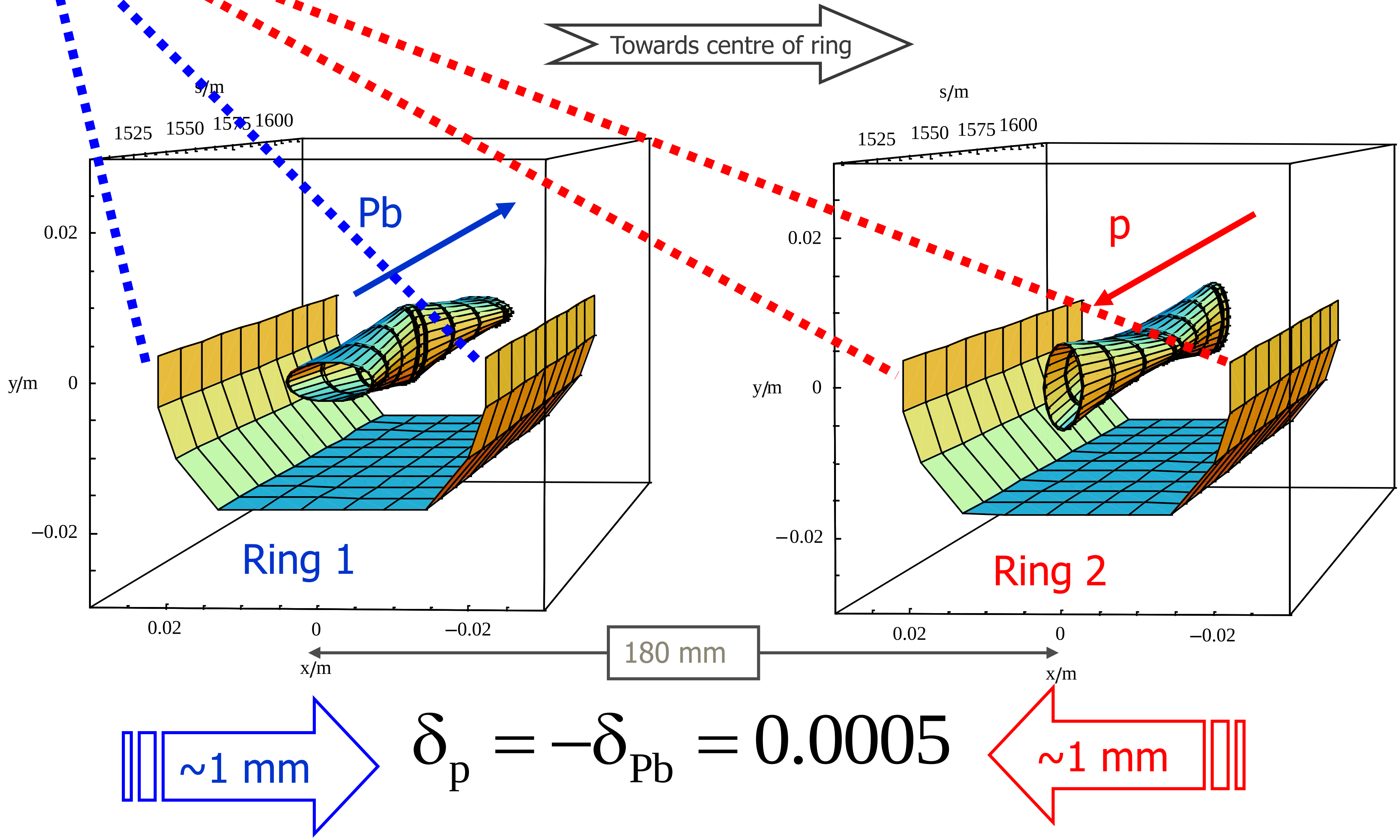
Revolution frequencies must be equal for collisions.

⇒ Hard lower limit on energy of p-Pb collisions, E_p=2.7 TeV

Energy where RF frequencies can become equal in ramp.

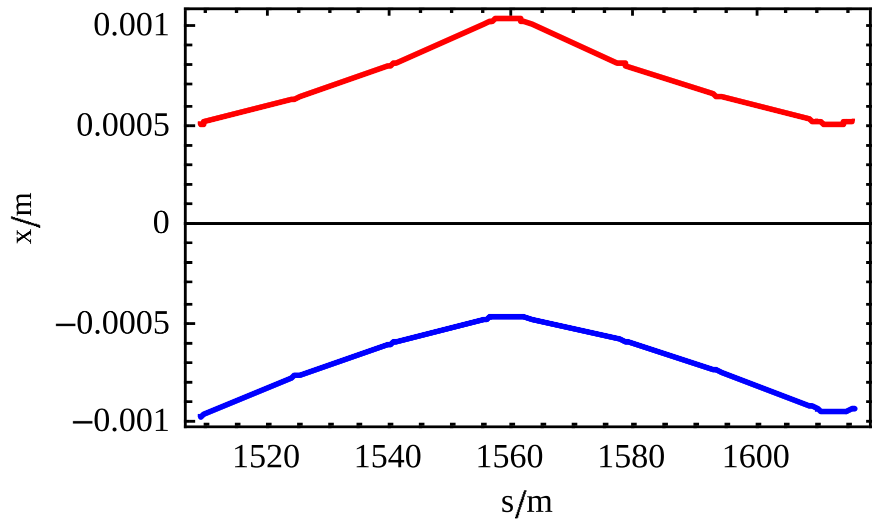
A FODO cell in the arc between ATLAS and ALICE

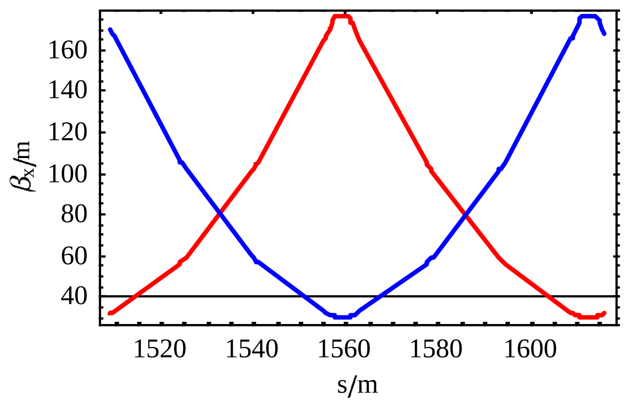
Beam screens with 5σ envelopes of nominal injection beam



$$\delta_p = -\delta_{Pb} = 0.0005$$

Orbit and optics of the two beams





So what’s the problem if we can collide beams with a small offset (<0.2 mm at QFs at 7 TeV) at high enough energy?

We have to inject and ramp to get there…

Beam-beam Encounters in IRs

- RHIC found that this led to intensity limit or emittance blos-up
  - attributed to kicks and tune-modulation from moving long-range beam-beam encounters.

Encounter points move at speed $V = \dfrac{v_{\mathrm{p}} - v_{\mathrm{Pb}}}{2} = 1734\ \mathrm{m/s} = 0.15\ \mathrm{m/turn}$

Hamiltonian is no longer periodic in *s*.

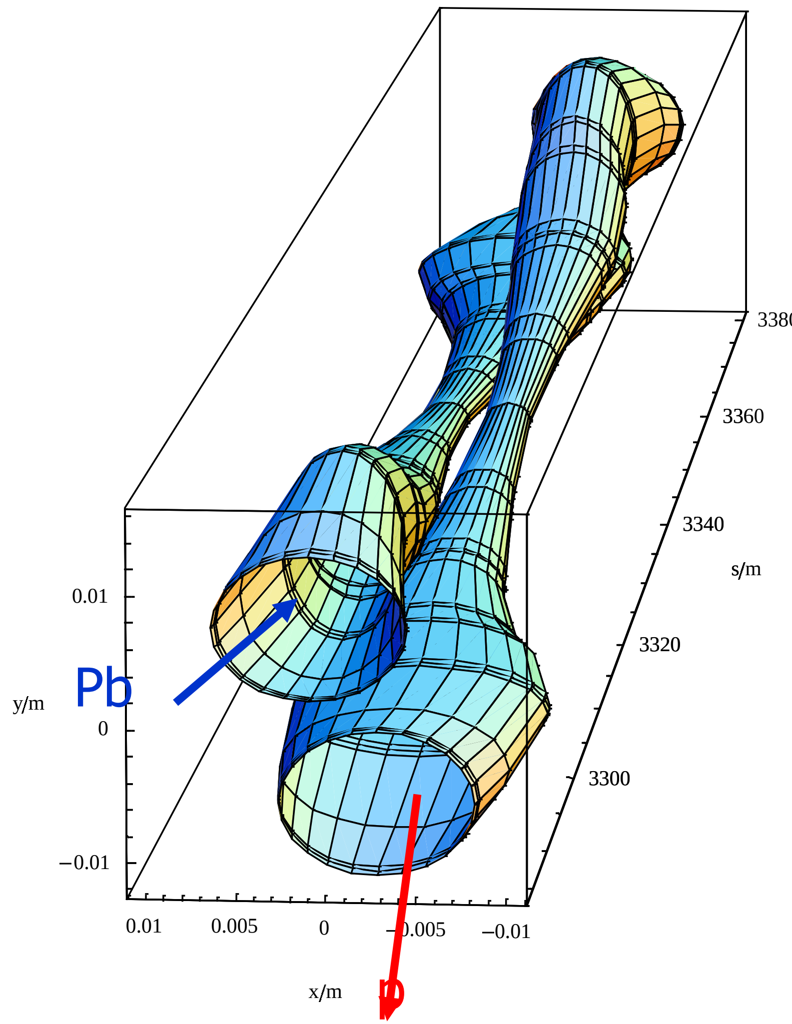
Excites modulational resonances (called "overlap knock-out" at the ISR):

$$m_x \nu_x + m_y \nu_y = p + k \underbrace{\frac{c\left(T_{\mathrm{Pb}} - T_{\mathrm{p}}\right)}{S_b}}_{0.01}; \;\; m_x, m_y, p, k \in \mathbb{Z}$$

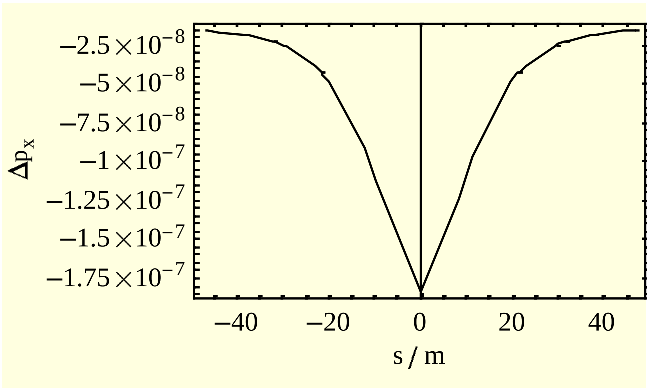
  - Solution for d-Au at RHIC was to adjust magnetic field separately in the two rings
  - No predictive model for intensity limit.

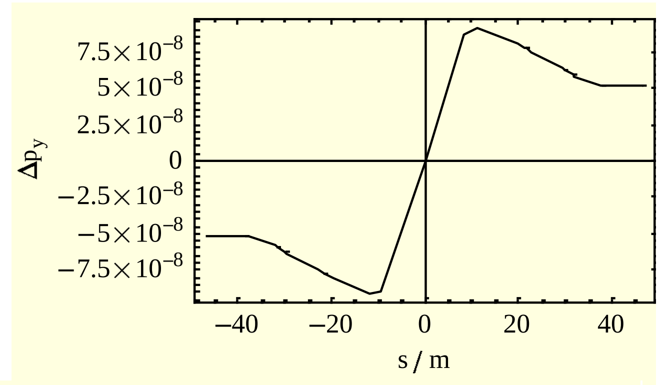
Beam Separation in IR2 (around ALICE)

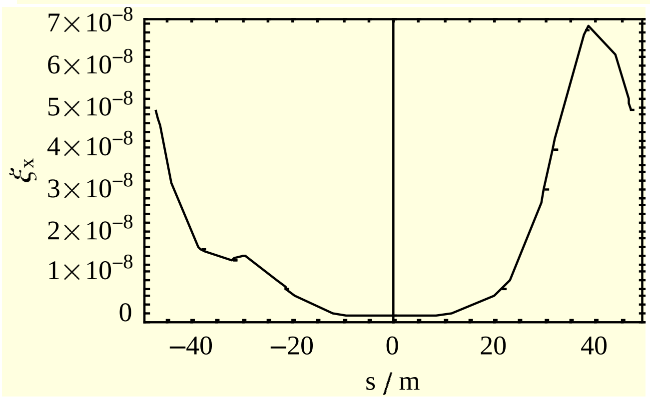
- 5σ envelopes of beams at injection out to first D1 separation magnet
  - Vertical crossing angle bump
  - Horizontal injection separation bump
  - Encounter points have basic spacing of 15 m, but there are gaps in the bunch train.
  - Comb of 5-6 encounter points moves across IR at 0.15 m per turn.

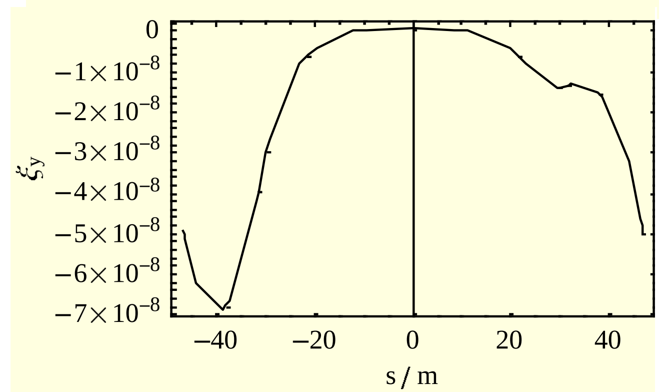


Beam-beam Kicks and Tune-shifts in IR2









Assumes Pb ion bunch with nominal intensity $N_b = 7\times10^7$,
proton bunch with 10% nominal intensity $N_b = 1.15\times10^{10}$,
nominal emittances (equal geometric beam sizes).

This level of effect very probably acceptable.

Deuteron beams in the LHC ?

- Linac 4 cannot accelerate deuterons
  - D^- in DTL (possible?) but then CCDTL (impossible)
- The PS Booster will no longer be able to accelerate ions once Linac 4 starts (2017)
  - H^- injection, incompatible with ion injection.
- So the only options for deuterons are:
  - Before 2017 through Linac2 +PSB, no protons during that period (Linac 2 should work in $2\beta\lambda$ mode, ½ velocity), new Duoplasmotron source (?) and RFQ
  - From 2017 through Linac 3+LEIR, with new source (for D-Pb), RFQ, operating with switchyard before Linac 3, longer cycle in LEIR, etc
  - ECR ion source might work for D-D (to be studied)
- Much reduced intensities wrt protons
  - (> factor 10, so > factor 100 in luminosity, probably worse).
- Much to be studied …

Potential Performance for p-Pb (tentative)

Concerns about modulational effects of moving parasitic encounters at injection and in ramp.

Separation is large but nevertheless we take VERY conservative proton bunch intensity.

Assume Pb ion bunch with nominal intensity $N_b = 7\times10^7$,

proton bunch with 10% (present) nominal intensity $N_b = 1.15\times10^{10}$,

nominal emittances (equal geometric beam sizes).

With Pb ion nominal bunch structure in both beams, this would give luminosity

$L = 1.5\times10^{29}\ \text{cm}^{-2}\text{s}^{-1}$, in 7 Z TeV p+Pb collisions at the LHC.

Luminosity lifetime much longer than Pb-Pb (BFPP etc. negligible).

Lighter nuclei in LHC and SPS fixed target

- Synergy with NA61/SHINE
  - 2010: During LHC run, will study $^{11}B^{5+}$, various energies, generated from primary $^{208}Pb^{82+}$
  - 2011: Studies of Ar & Xe primary beams in North Area
- Ar
  - studies at CERN source in 2011
  - Commissioning of LEIR, PS & SPS, followed by NA61 physics run in 2012-13 (??)
  - Later Ar-Ar collisions in LHC, likely similar N-N luminosity to Pb-Pb
- Xe
  - Collaboration with iThemba (South Africa)
    Study of Xe production in "clone" source in 2011-12

Outlook for nuclear collisions in the LHC

- The LHC works amazingly well and is *flexible*
- First Pb-Pb run in 2010 exceeded expectations
  - First experience of performance limits
- Further steps in Pb-Pb luminosity may not come so quickly
- Hybrid p-Pb collisions – uncertainties remain
- Lighter A-A collisions should come eventually but a lot of work remains to be done
- Other options (D-D, D-Pb, …) might be feasible
  - Physics case to be made ?
- The next decade will see the exploration of a vastly extended energy frontier in nuclear collisions at the LHC

Acknowledgements

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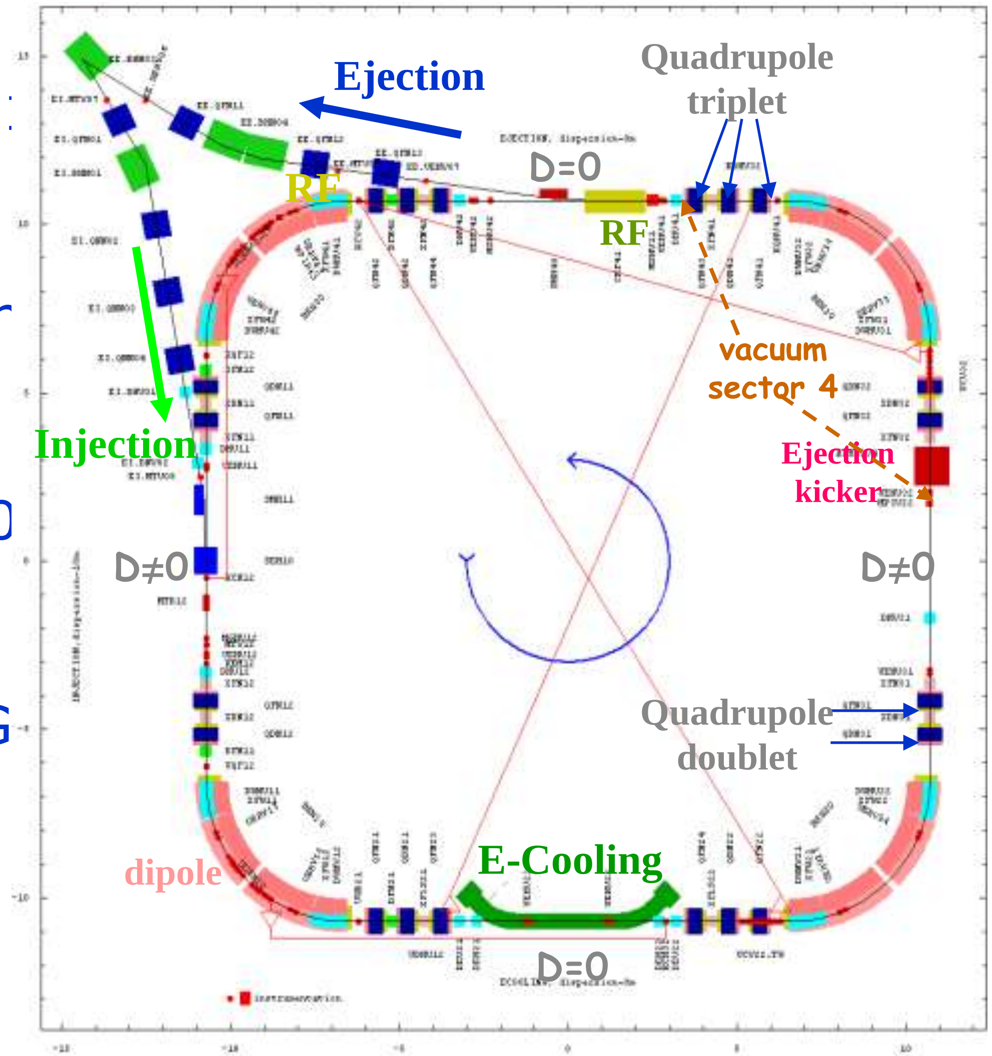
BACKUP SLIDES

LEIR (Low-Energy Ion Ring)

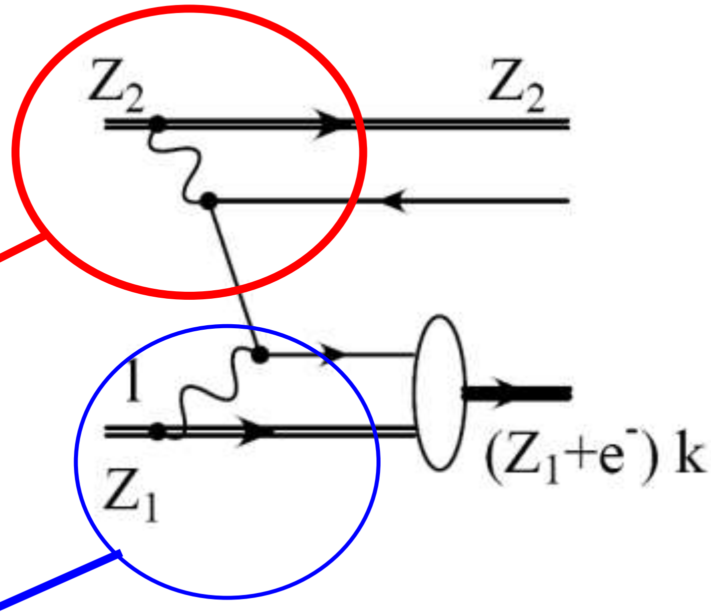
- Prepares beams for LHC using electron cooling
- circumference 25p m (: PS)
- Multiturn injection into horizontal+vertical+lor dinal phase planes
- Fast Electron Cooling : Electron current from 0 to 0.6 A with variable density
- Dynamic vacuum (NEG Au-coated collimators, scrubbing)



Dependence of BFPP cross-section on Z

Typical diagram contributing to

$$Z_1 + Z_2 \to \left(Z_1 + \mathrm{e}^-\right)_{1\mathrm{s}_{1/2},\ldots} + \mathrm{e}^+ + Z_2$$



Pair production $\propto Z_1^{\,2} Z_2^{\,2}$

Radial wave function of $1\mathrm{s}_{1/2}$ state of hydrogen-like atom in its rest frame

$$R_{10}(r) = \left(\frac{Z_1}{a_0}\right)^{3/2} 2\exp\left(-\frac{Z_1 r}{a_0}\right) \;\Rightarrow\; \Psi(0) \sim Z_1^{\,3/2} \;\Rightarrow\; \left|\Psi(0)\right|^2 \sim Z_1^{\,3}$$

Total cross-section $\sim Z_2^{\,2} Z_1^{\,5}$

Hand-waving, over-simplified argument!

G. Baur et al, Phys. Rept. 364 (2002) 359

Heavy Ion Physics Parameters

		SPS	RHIC	LHC	
CM energy / nucleon	$\sqrt{s}\,/\,u\,/\,[\mathrm{GeV}]$	17	200	5500	$\times\,28$
Charged multiplicity	$\frac{dN_{ch}}{dy}$	400	800	>3000	challenge
Energy density	$\epsilon\,/\,[\mathrm{GeV}/\mathrm{fm}^3]$	3	5	$15-60$	denser
Freeze − out volume	$V_f\,/\,\mathrm{fm}^3$	$\approx 10^3$	$\approx 10^4$	$\approx 10^5$	larger
QGP lifetime	$\tau_{\mathrm{QGP}}\,/\,[\mathrm{fm}/c]$	$\leqslant 1$	$1.5-4$	>10	longer
Thermalization time	$\tau_0\,/\,[\mathrm{fm}/c]$	$\geqslant 1$	≈ 0.2	$\leqslant 0.1$	faster
	$\tau_{\mathrm{QGP}}\,/\,\tau_0$	1	6	$\geqslant 30$	

With increasing energy, more partons are available, interact more effectively.
Thermalized high-T phase established more quickly and lasts longer.