



Heavy Ions in the LHC

Prospects for the first run and beyond

John Jowett, CERN



- Mainly p-p running for elementary particle physics
- 1 month/year for heavy-ion programme, initially $208\text{Pb}^{82+} - 208\text{Pb}^{82+}$
 - 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,
 - We are about to make the biggest energy step that will ever be made by any collider in history, past or future, over its predecessor
- The first Pb-Pb run will start on 6 November

Plan of talk

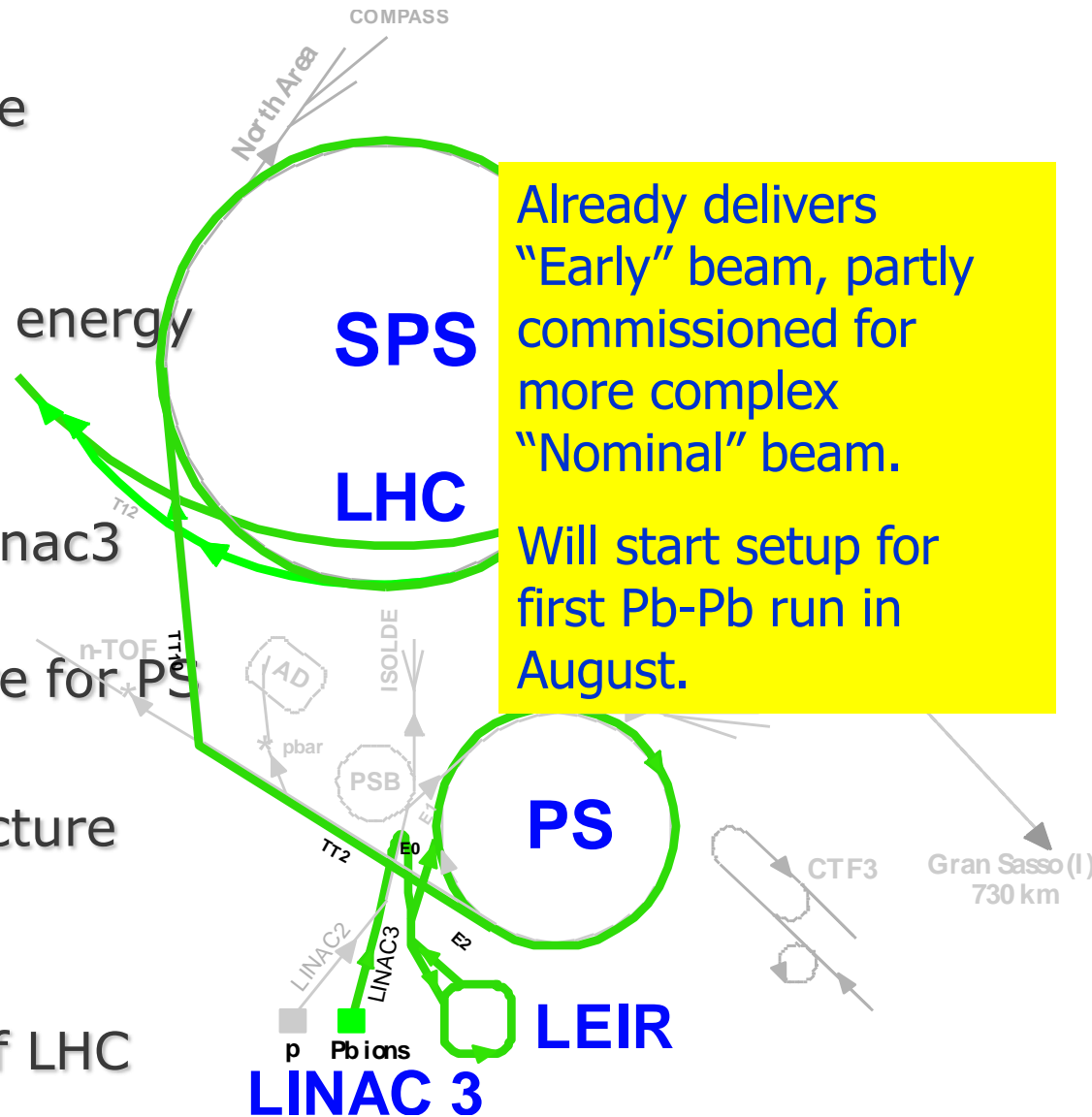
- LHC as a heavy ion collider reminder
- LHC parameters
- Strategy and rationale for 2010 run
- Commissioning plan
- Injectors, recent progress
- Path to higher luminosity
- Beyond Pb-Pb



LHC Ion Injector Chain

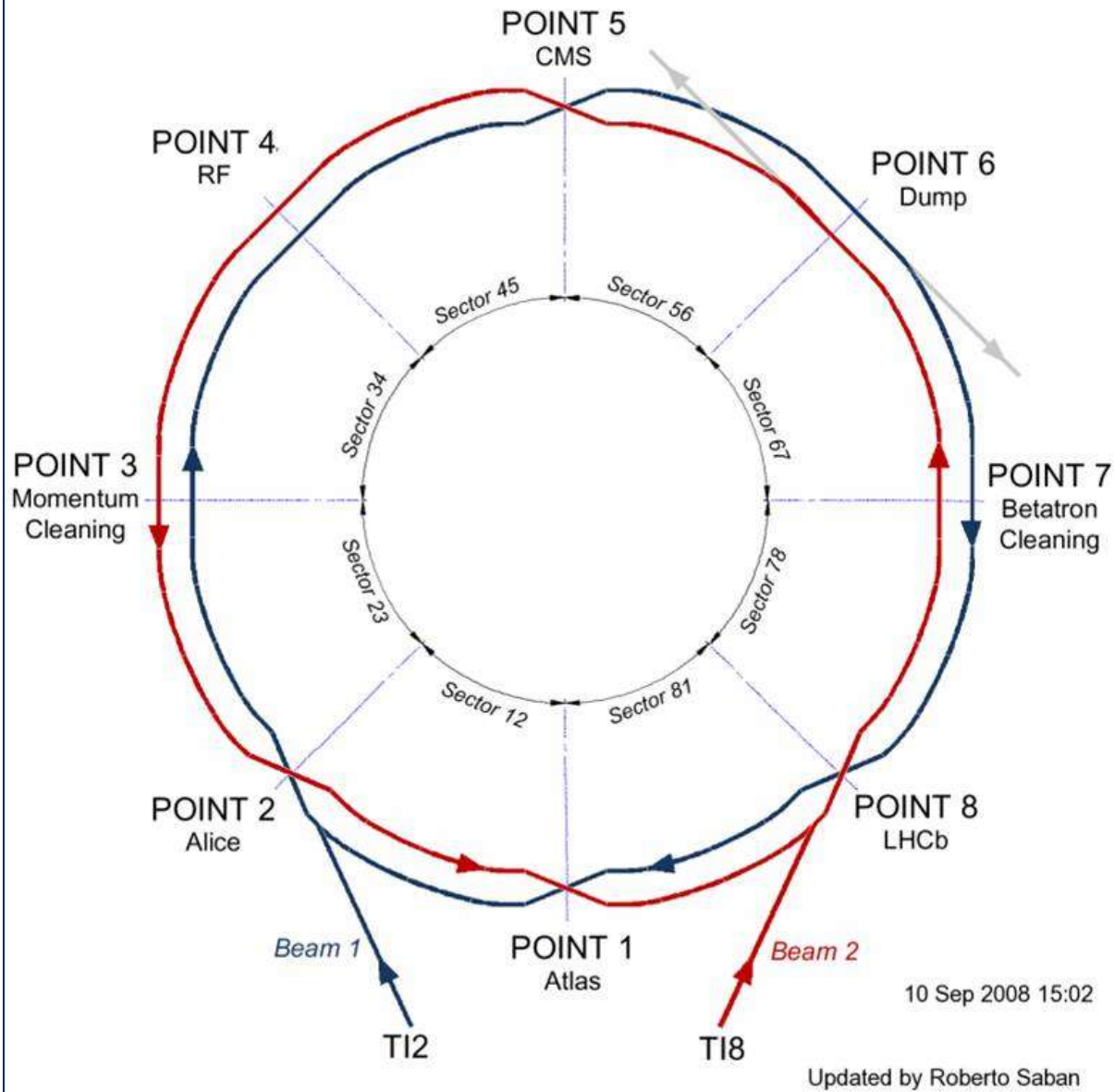


- ECR ion source (2005)
 - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
 - Adapt to LEIR injection energy
 - strip to Pb^{54+}
- LEIR (2005)
 - Accumulate and cool Linac3 beam
 - Prepare bunch structure for PS
- PS (2006)
 - Define LHC bunch structure
 - Strip to Pb^{82+}
- SPS (2007)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





LHC schematic for orientation

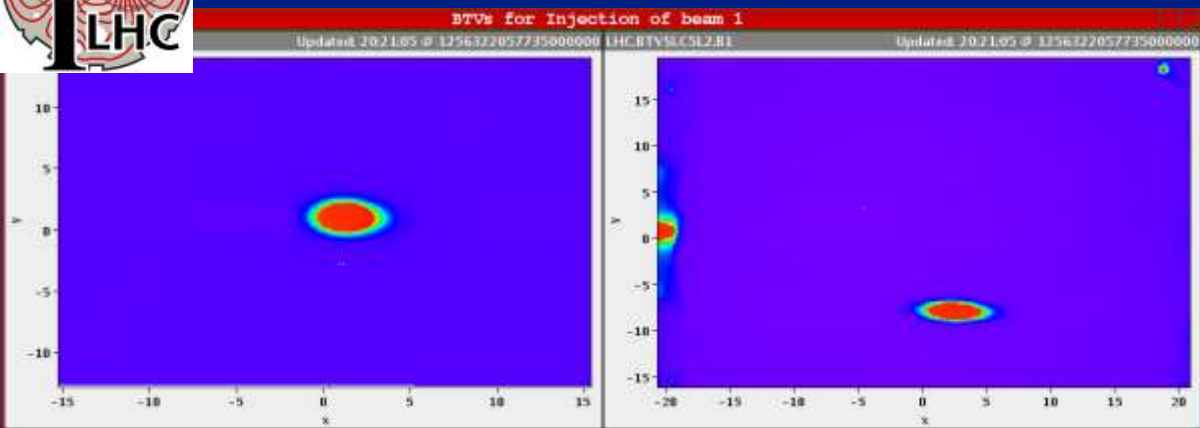




First Pb nuclei were in LHC in 2009

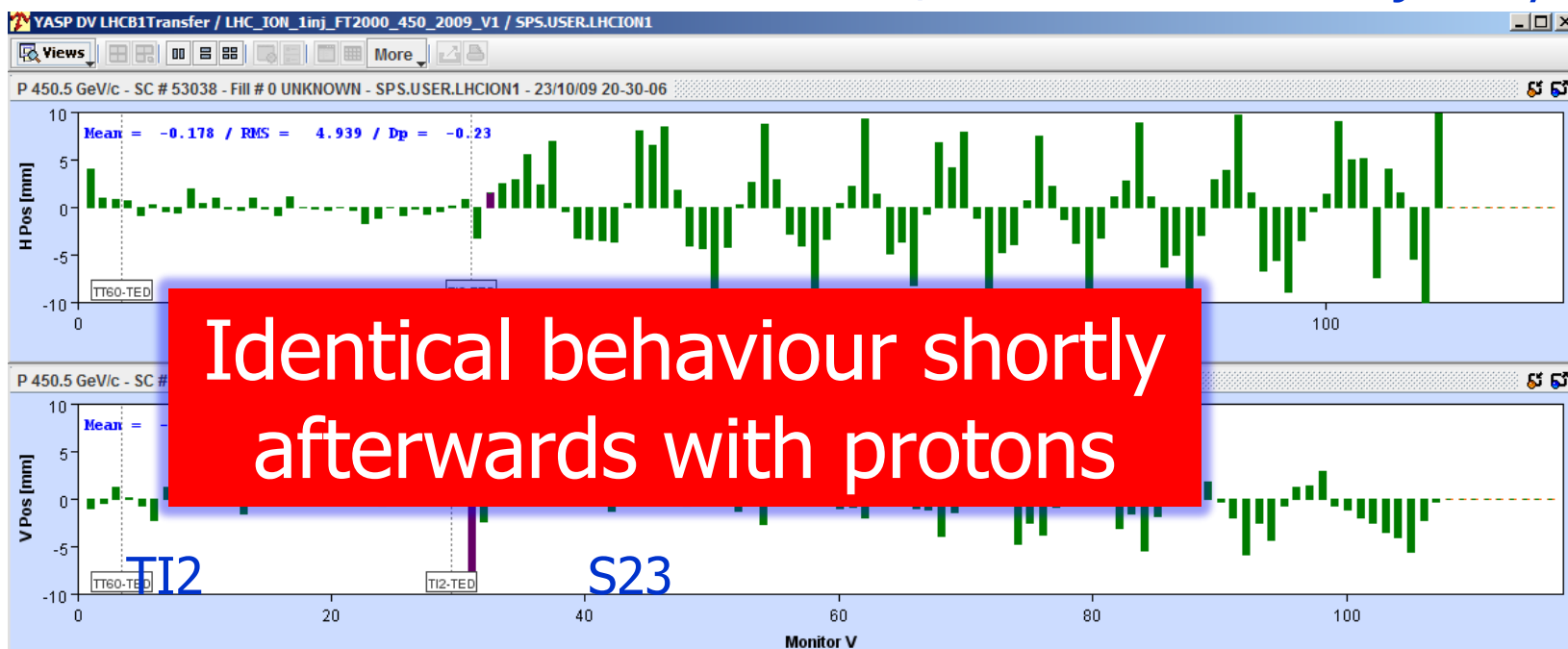


First beam to re-awaken LHC after the September 2008 incident



Injection region screens

TI2/Sector 2-3 – first trajectory



LHC working with p-p at 7 TeV in CM

Magnetically and optically well understood:

Excellent agreement with model

Magnetically reproducible:

Optics and set-up remain valid from fill to fill

Aperture clear and as expected

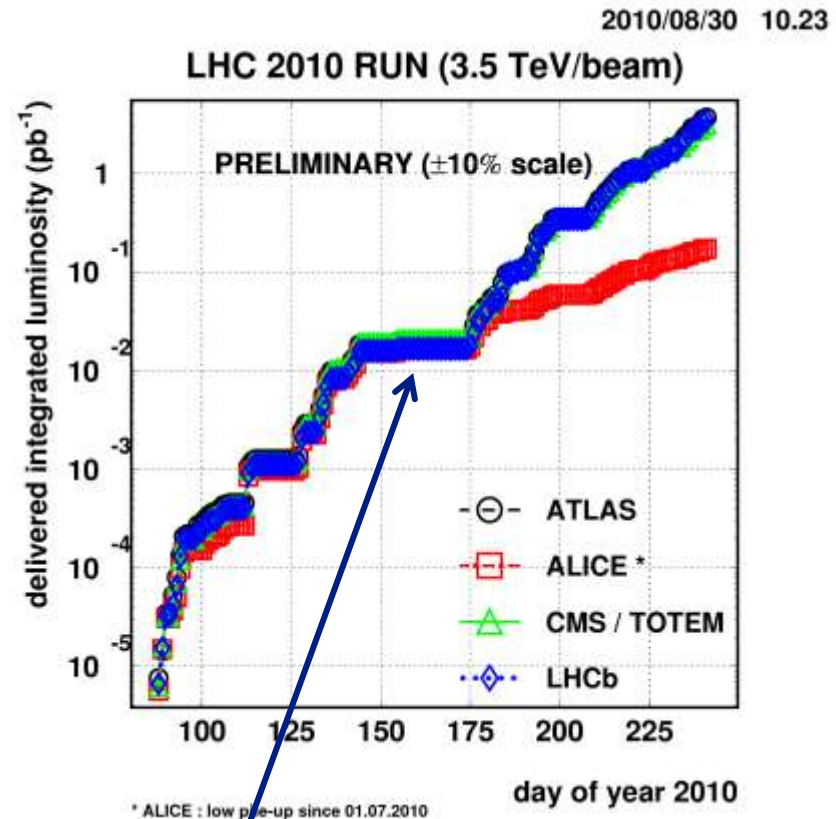
Excellent performance from instrumentation and controls

Key systems performing well:

Injection, beam dump, collimation, machine protection

Fills up to 30 h

Nominal single-bunch intensity



Time largely devoted to setup of collimation and machine protection for higher intensity

Parameters of LHC Pb (Design Report 2003)

Parameter	Units	Early Beam	Nominal
Energy per nucleon	TeV	2.76	2.76
Initial ion-ion Luminosity L_0	$\text{cm}^{-2} \text{s}^{-1}$	$\sim 5 \times 10^{25}$	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		7×10^7	7×10^7
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

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

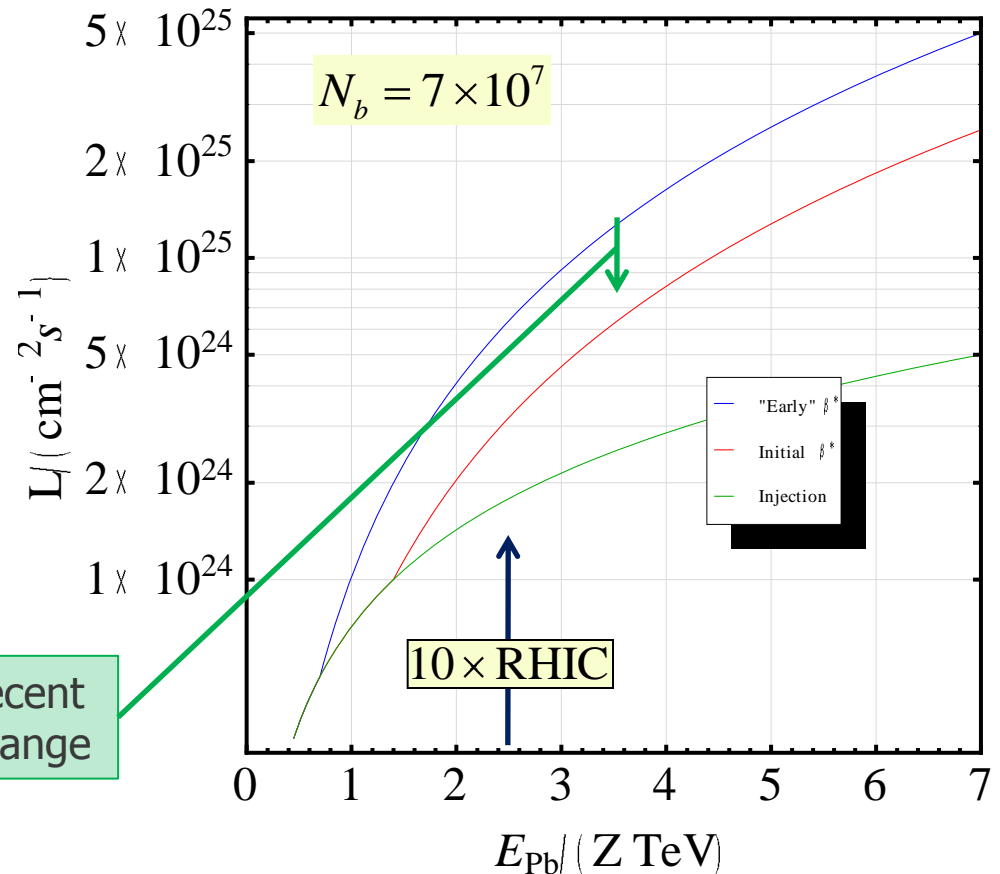
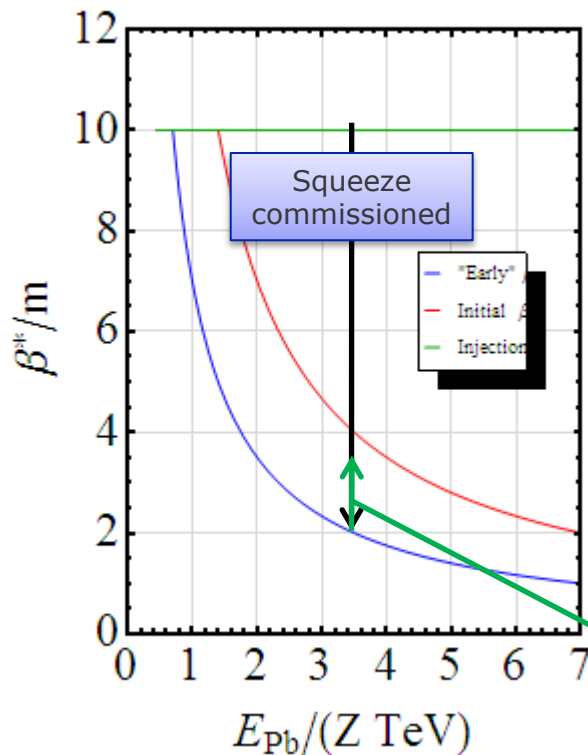
Do something like this but at reduced energy in 2010

Probably unattainable without "cryo-collimators" at least

Update expectations for Pb-Pb in 2010

- Experience with p-p has taught us many things about the LHC
- Commissioning plan for Pb-Pb has been revised in the light of experience, presented and approved at the LHC Machine Committee, 1 September 2010

Potential peak Pb-Pb luminosity



Recent change

Triplet aperture limit scaling: $\beta^* \sim \frac{1}{E_p}$

$$\beta^*(E_p) = \begin{cases} \min(1.7/E_p, 10.) & \text{m "Early"} \\ \min(3.5/E_p, 10.) & \text{m Initial} \\ 10. & \text{m Injection} \end{cases}$$

$$\Rightarrow L = \frac{k_b N_b^2 f_0}{4\pi \sigma^{*2}} \sim \frac{E_p}{\beta^*}$$

$$10^{25} \text{ cm}^{-2} \text{s}^{-1} = 0.864 \mu\text{b}^{-1} \text{day}^{-1}$$

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)	$\text{cm}^{-2}\text{s}^{-1}$	(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	$\tau_{\text{IBS}}=7-30$	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/ 10^6 s (~ 1 month)

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



Luminosity decay



Initial luminosity decay time from "collisions":

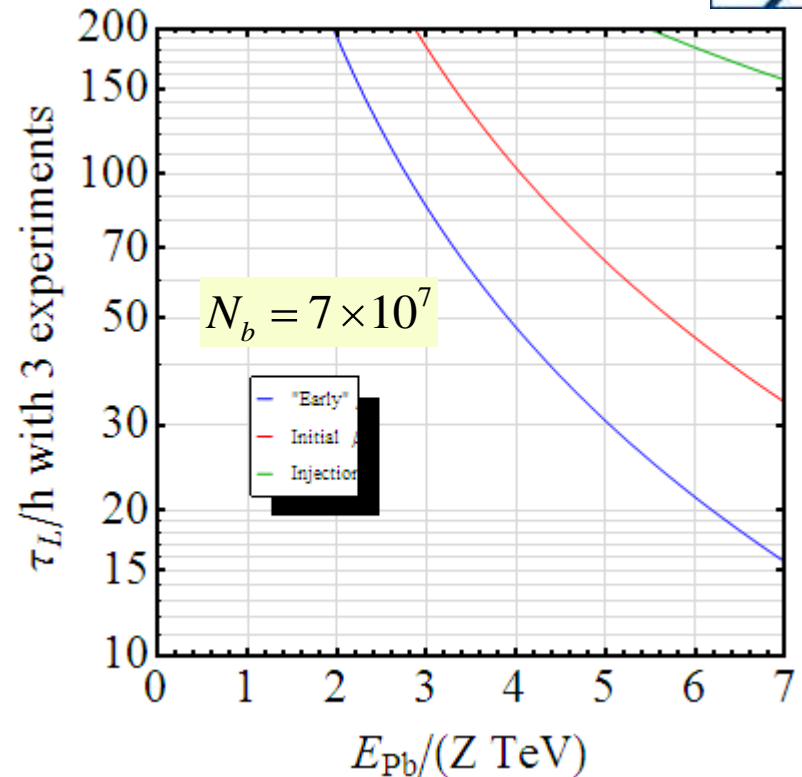
$$\tau_L = \left(\frac{\dot{L}}{L} \right)^{-1} = \frac{k_b N_b}{n_{\text{expt}} L \sigma_{\text{total}}}$$

$$\sigma_{\text{total}} = \sigma_{\text{hadronic}} + \sigma_{\text{BFPP}} + \sigma_{\text{EMD}} \\ \approx (8 + 281 + 226) \text{ barn}$$

$$\left[\text{N.B. Half-life } \tau_{L/2} \approx \sqrt{2} - 1 \tau_L \right]$$

Important consequence: fills in the initial runs can be long (provided emittance does not degrade and we don't lose beam for another reason), so we shouldn't lose time with frequent refilling.

(This will change dramatically at lower β^* later.)





Time scales for emittance evolution



Emittances shrink by radiation damping:

$$\tau_{ex} \propto E^{-3}, \quad \tau_{ez} = \tau_{ex} / 2$$

Emittances grow due to intra-beam scattering:

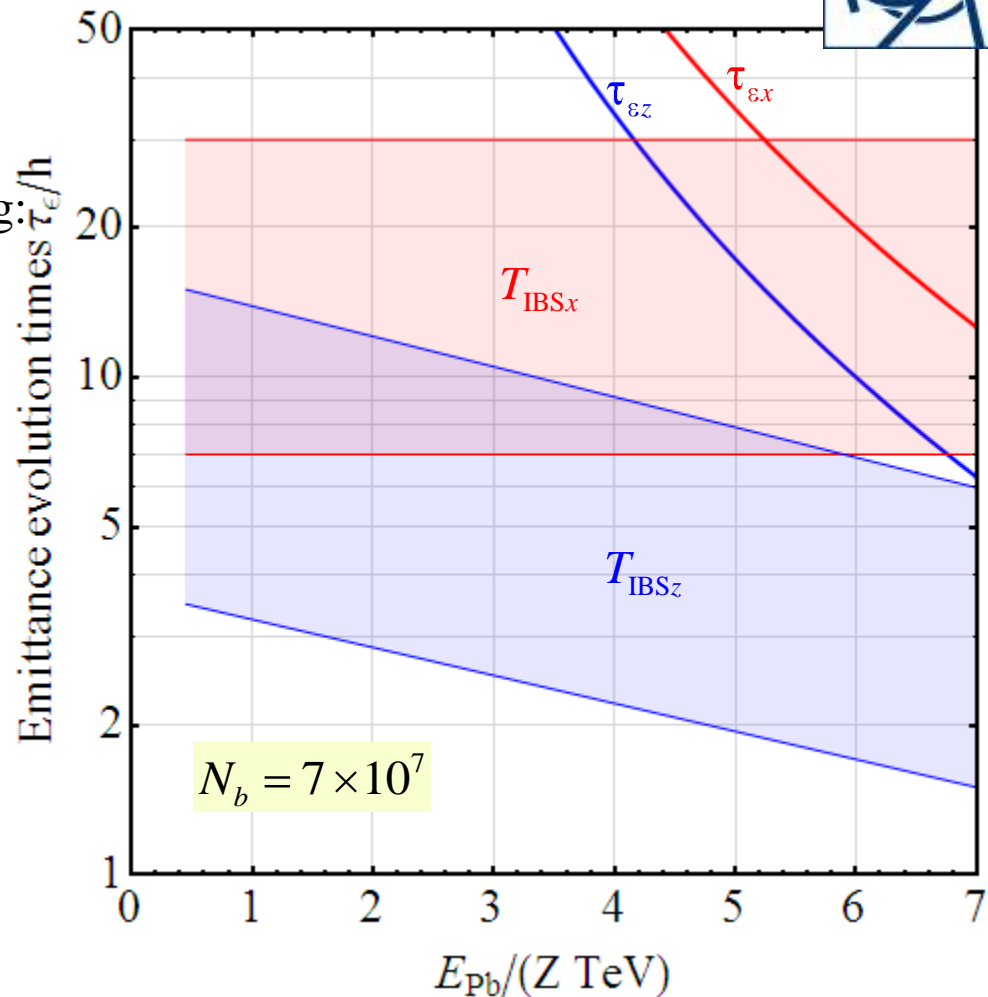
$$T_{IBSxz} \propto N_b^{-1} \times F(E, \text{emittances})$$

Indicate range at full bunch intensity only,
depending mainly on longitudinal
emittance (blown-up or not from injection).

We can put all effects together to predict
luminosity evolution scenarios through a fill,
benchmarked on RHIC (paper coming out
now in Phys Rev ST-AB).

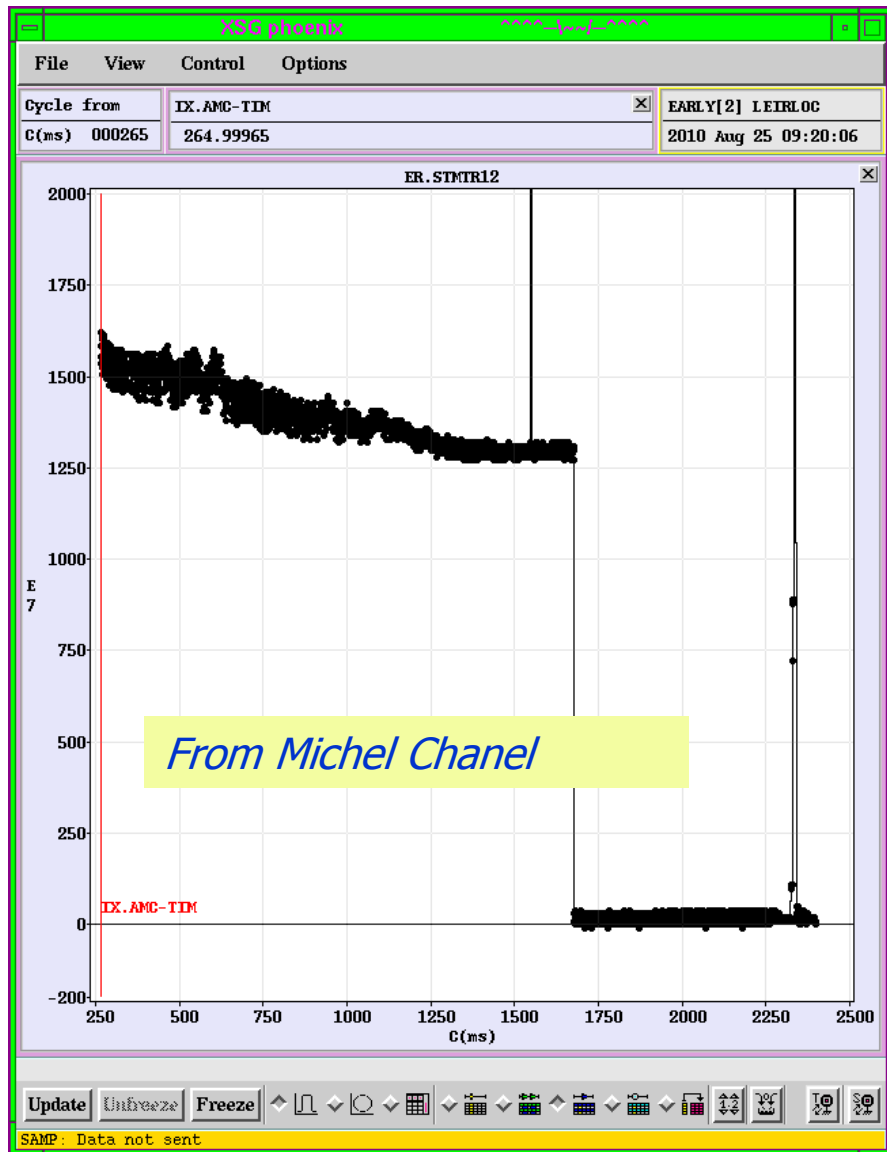
But, at present we have unwanted vertical
blowup from the "hump" which will also
affect ion luminosity.

Controlled blow-up of longitudinal emittance
(being commissioned now) will be useful but
not essential for first runs.



Fills will be terminated by emittance
growth or bunch intensity falling below
BPM threshold ($\sim 30\%$ nominal).

Early Beam in injectors

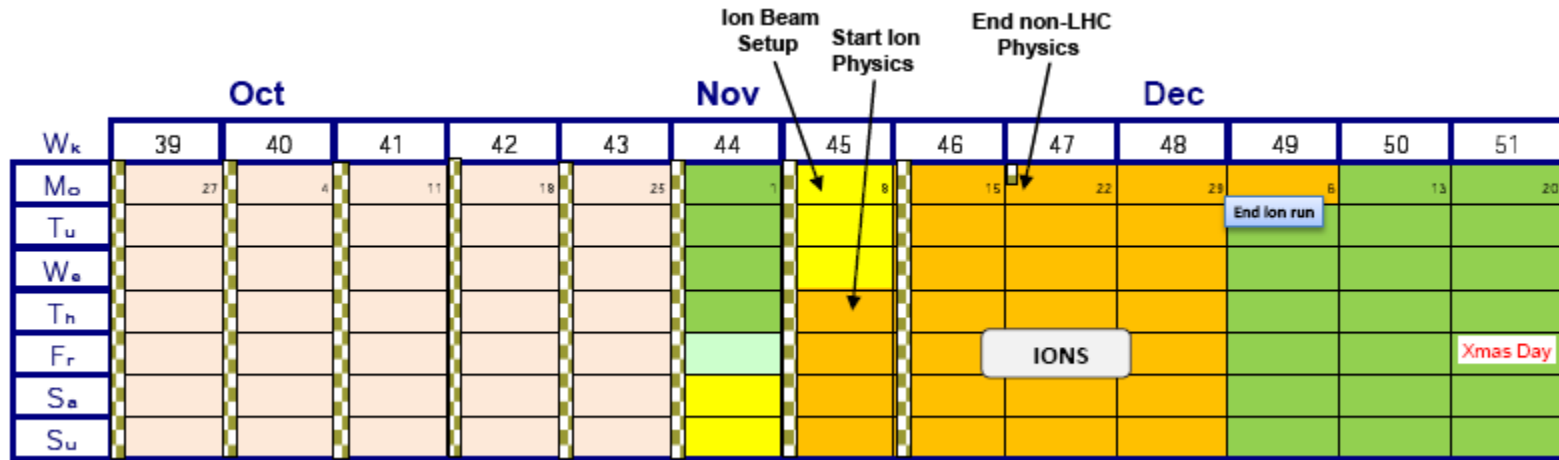


Source, Linac3 performing well.

LEIR: EARLY beam is ready and regularly sent to PS-SPS. 1200 10^7 charges are accelerated, within the specs.

Main remaining item is re-commissioning of definitive RF system in SPS.

Schedule (as of 15/8/2010)



Lead-up to lead in LHC involves a lot of work in the ion injectors.

Possibility of a short pilot run in mid-October is under discussion.

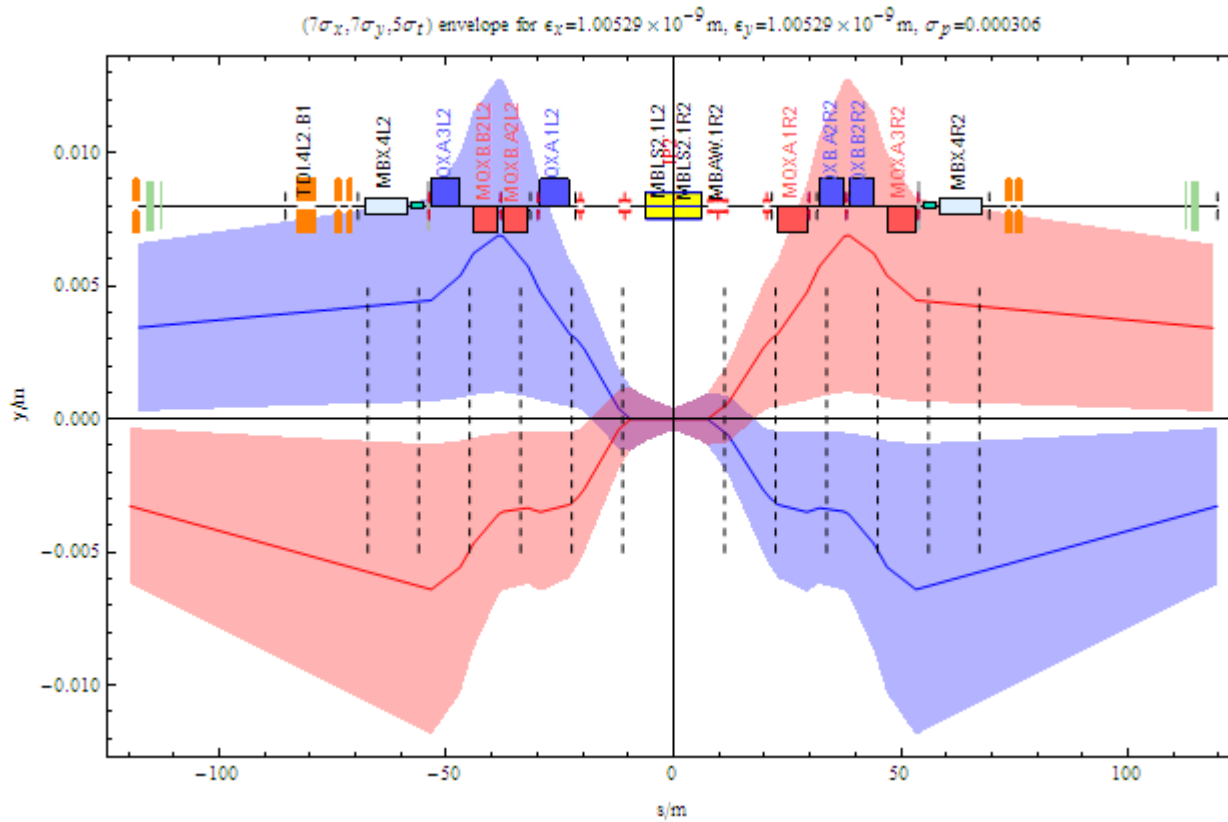
At present, we can only anticipate that the "Early Beam" can be delivered to LHC with the design parameters.



Setup choices

- *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
 - *Probably the biggest item now*
 - Set crossing angle for protons in CMS and ATLAS **to zero**
 - LHCb left squeezed, separated
 - Previously we said that ALICE would require squeeze commissioning but this is now done.

Zero-crossing angle in ALICE



External bump compensates ALICE spectrometer bump (no parasitic crossings).

Essential to minimise shadowing of spectator neutrons on ZDC by TCTVs (vital physics signal).

Hope to cure by move of γ -chamber + new TCTVs in 2012.

Beam Instrumentation

■ BPMs

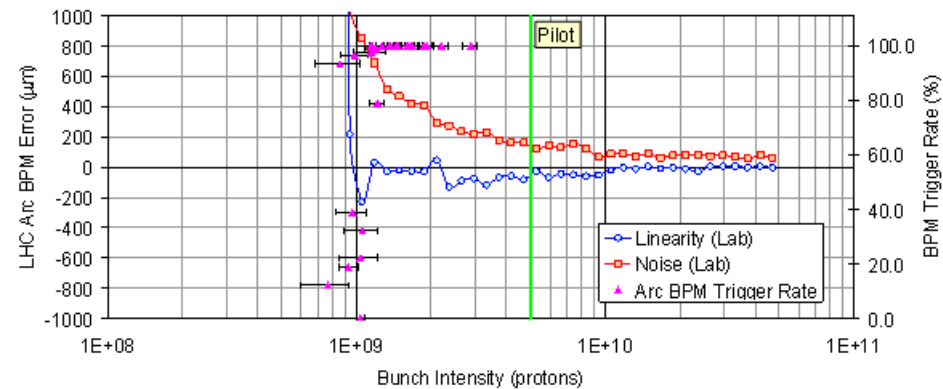
- Visibility thresholds from initial experience at LHC
- May have to dump at ~30% of nominal bunch charge

■ Emittance

- Rely on wire-scanner (frequent manual scans required to log ...), BGI

■ BCTs

- Known limits, errors to be clarified for experiments



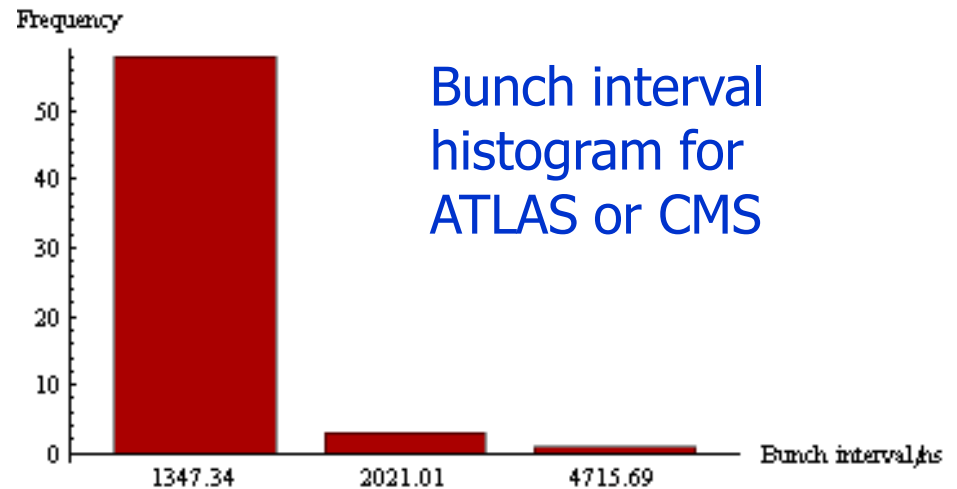
Filling scheme

Start with single bunches, move quickly to “Early” 62 bunch scheme, through few(2?)-bunch schemes like early p-p.

16 4 or 3 bunch transfers from SPS.

Number of collisions per revolution period may be 60 or 62 (to be agreed among experiments at LPC).

We assume that experiments continue to be flexible about collision schemes with HI.



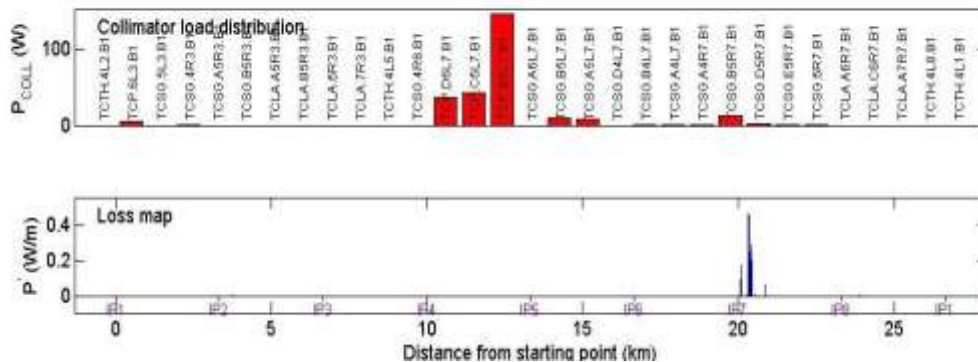
	{ 0 , 0 }	{ 0 , 1 }	{ 1 , 0 }	{ 1 , 1 }
IP1	3502	0	0	62
IP2	3500	2	2	60
IP5	3502	0	0	62
IP8	3440	62	62	0

Collimation setup

- Collimation of heavy ions very different from protons
 - Nuclear interactions (hadronic fragmentation, EM dissociation) in primary collimator material.
 - Staged collimation principle does not work.
- Set-up a single stage collimation system
 - Only primary collimators are effective
 - Retract secondaries (a little or completely)
 - Setup of TCPs, TCTs adjusted for orbit etc at
 - Injection
 - Pre-collision
 - Collision
 - Shorter time than for p-p

Beam1, betatron collimation
 $E=3.5 \text{ Z TeV}$, $\beta^* = 3.5\text{m}$,
 12min lifetime

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

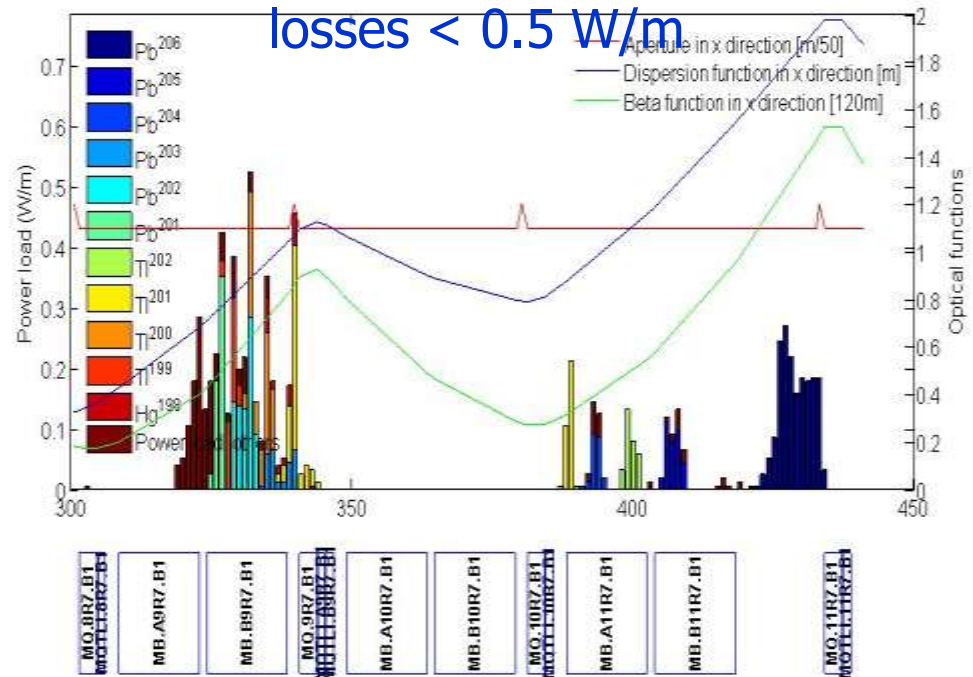
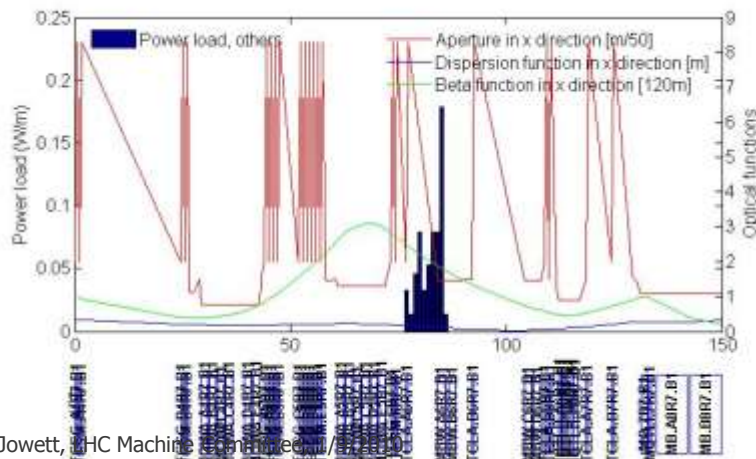


Σ aperture hits/ Σ collimator hits=
 $\eta = 0.033$

Isotopic loss map, DS.R7

losses $< 0.5 \text{ W/m}$

Max load on
 TCP.B6L7.B1=122W
 Some losses before DS



[Link to commissioning plan](#)

<http://lhc-commissioning.web.cern.ch/lhc-commissioning/Ions/IonCommissioningPlan2010.htm>

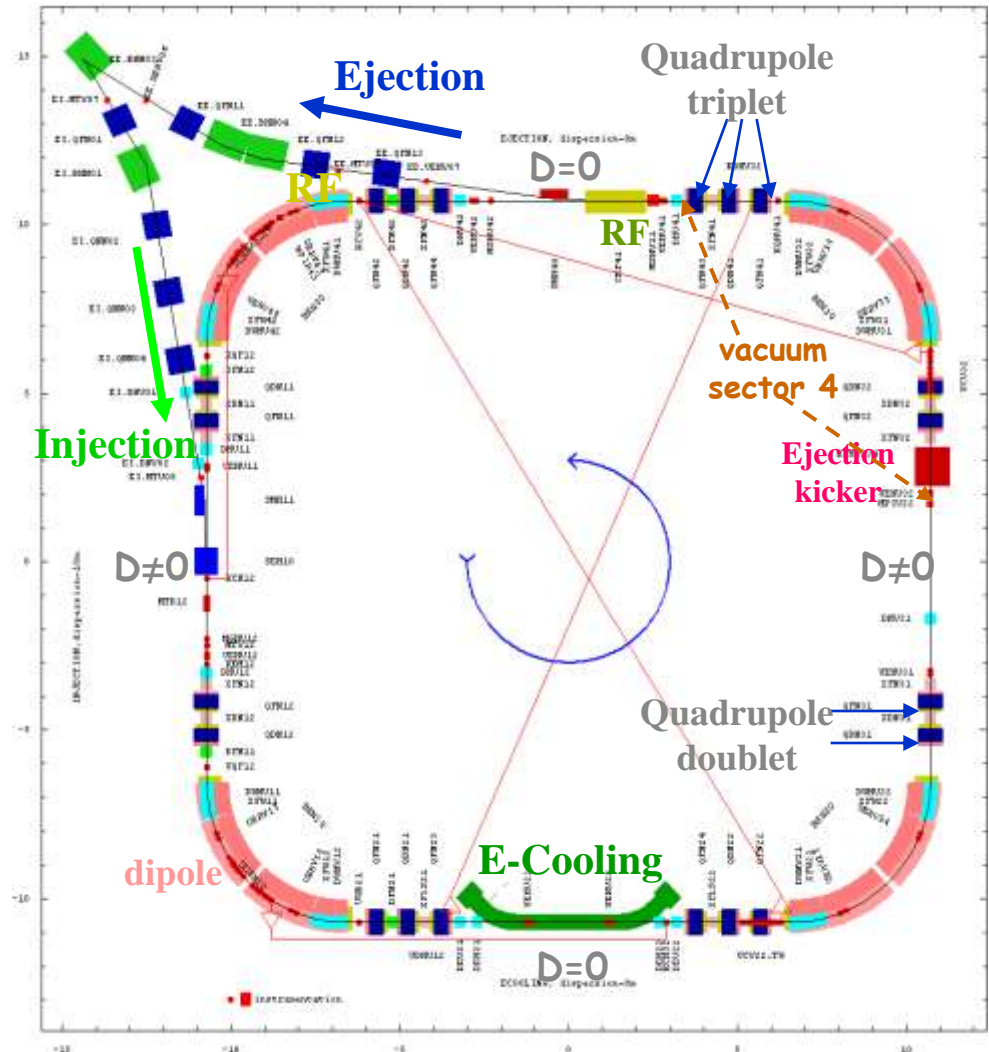
Conclusions for the 2010 run

- Given the pre-conditions (injectors ready, LHC in decent shape), commissioning first Pb-Pb collisions should be done in a little over 1 week
- Integrated luminosity in the very short physics run is extremely vulnerable to any delays, down-time, ...
- The idea of an attempt to make a short “debugging” run earlier in October looks difficult (SPS RF ready only at end Oct, ...).

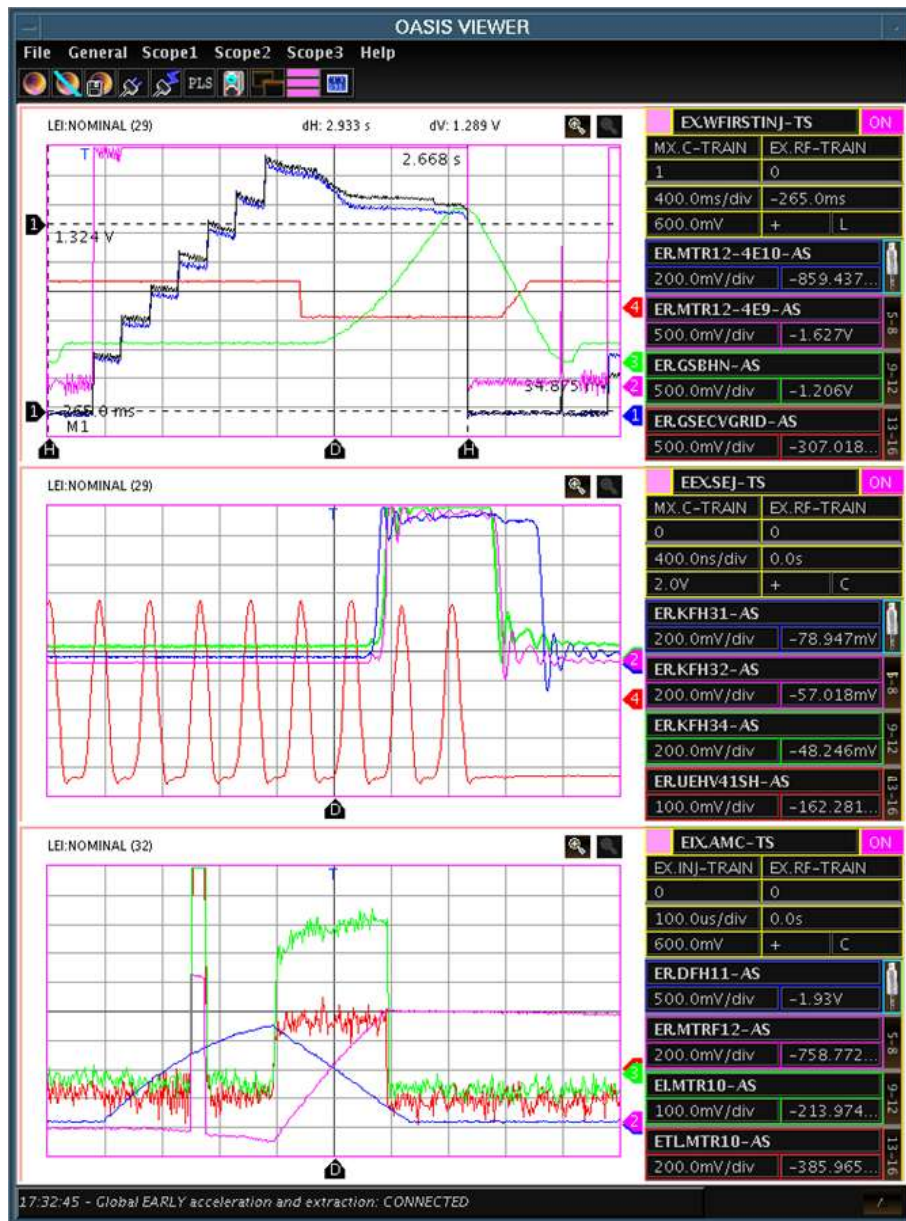
BEYOND THE FIRST RUN, PERFORMANCE LIMITS

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)



Latest news: Nominal Beam in LEIR(1)



Blue trace: number of lead ion charges, dashed line represents nominal value requested. Note 7 injection-cooling-stacking cycles every 200ms to reach the needed ion current.

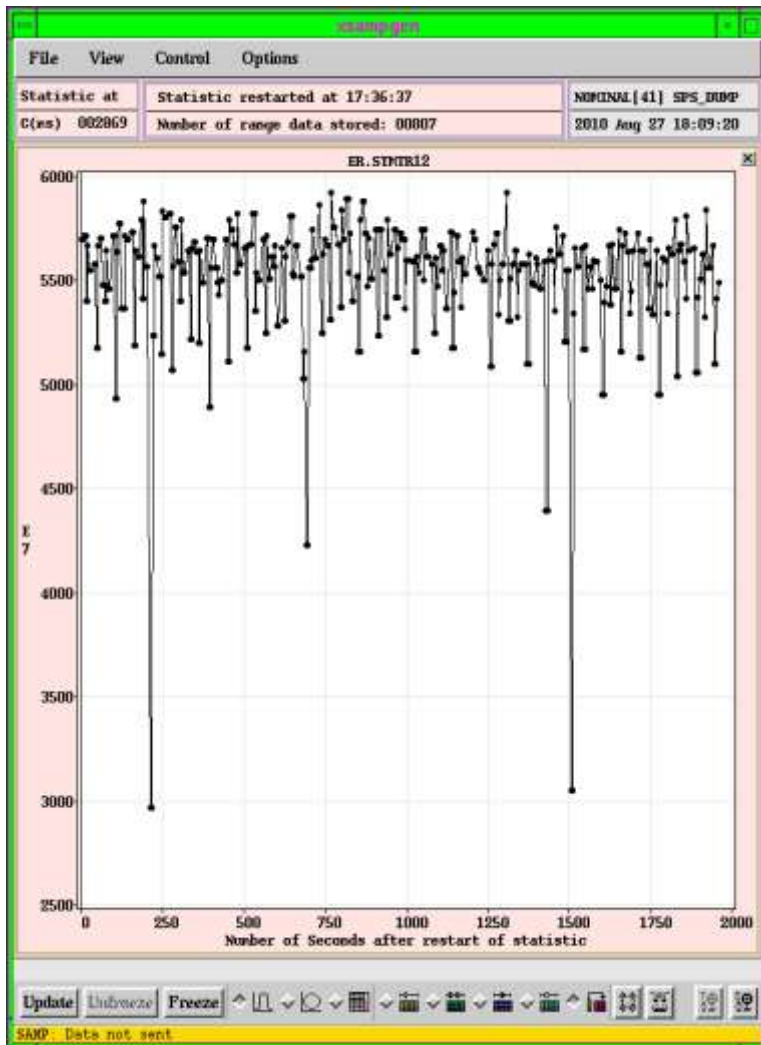
Green: bend magnet current (energy)

Extraction: 2 bunches(red) under the kickers pulses

Injection: beam from linac(red,green), injection bumper(blue), injected current(red)

From Michel Chanel

Nominal Beam in LEIR(2)



Beam intensity stability over time:
nominal values for NOMINAL are 5
 10^{10} charges per shot

Note that emittances are in the
specs, the cycle is 3.6 s as
expected, the Linac3 source with
a stainless steel chamber is very
stable around 23-26 μA .

From Michel Chanel



Collimation system cleans beam halo

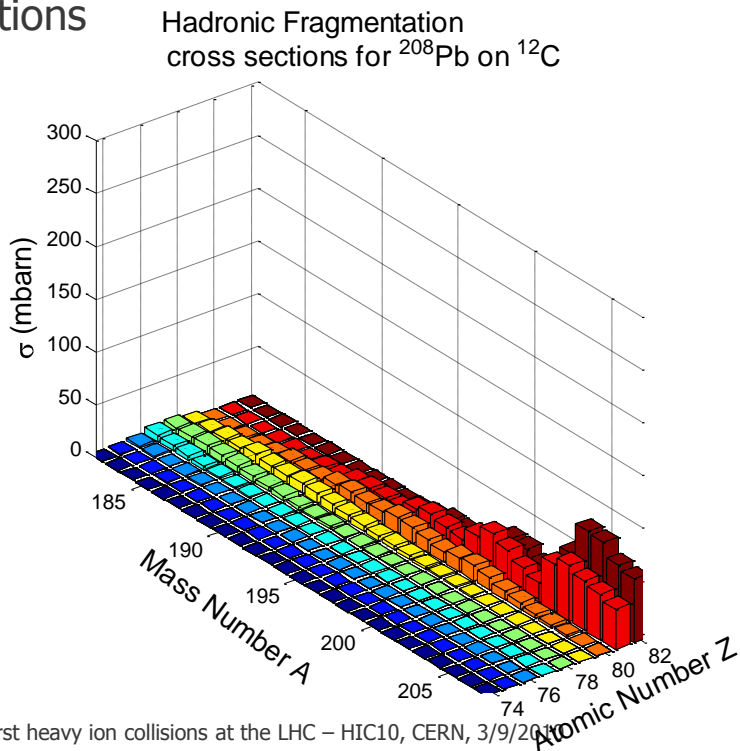


LHC design (primarily for p beam) principle: diffractive scattering of errant particles on primary collimator towards absorption in secondary collimators

Nuclear physics different for heavy ions!

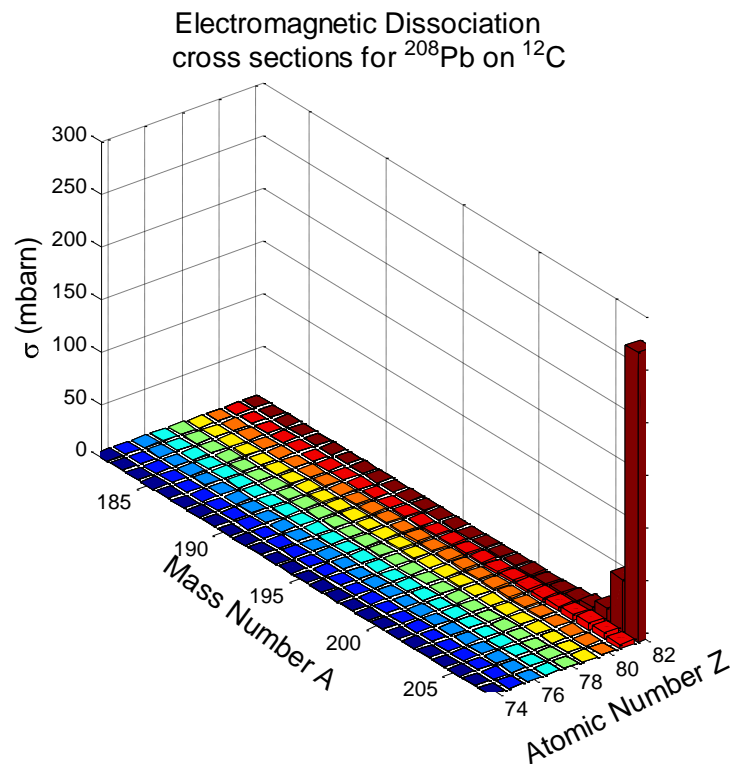
Hadronic fragmentation:

Large variety of daughter nuclei, specific cross sections



Electromagnetic dissociation:

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

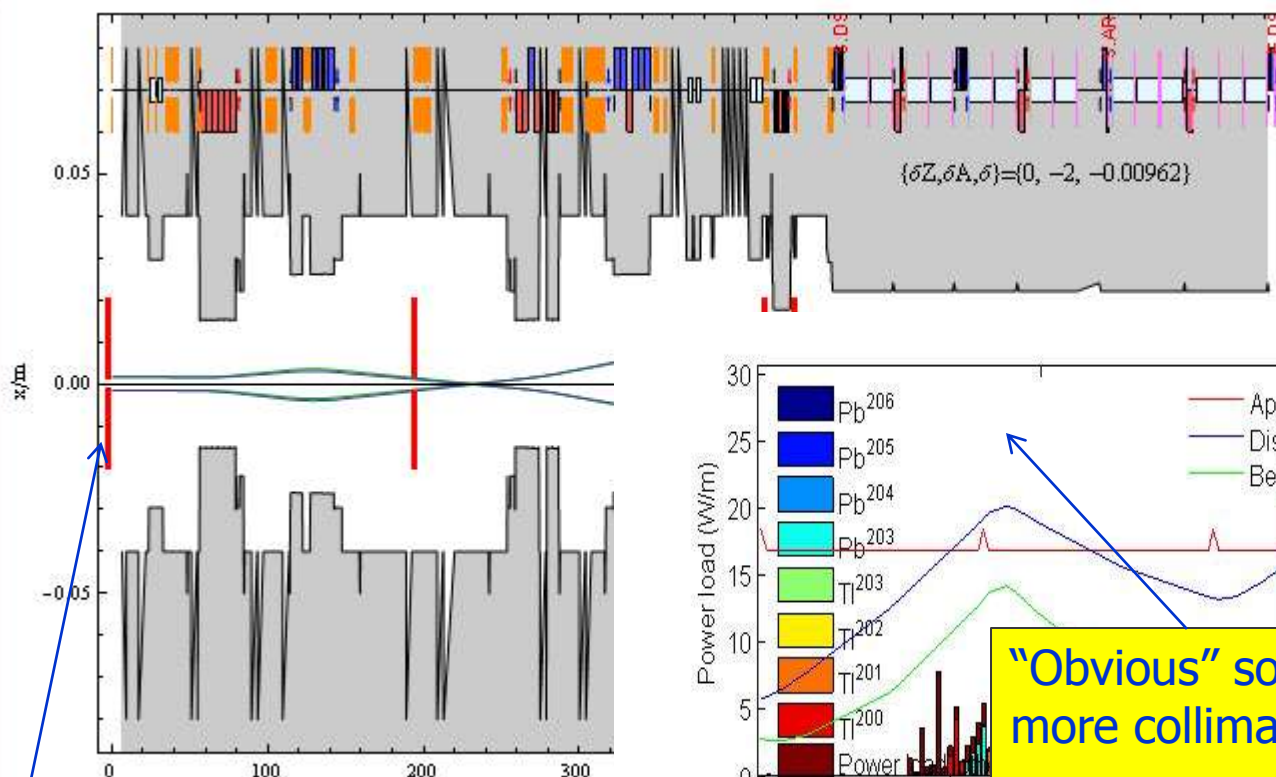




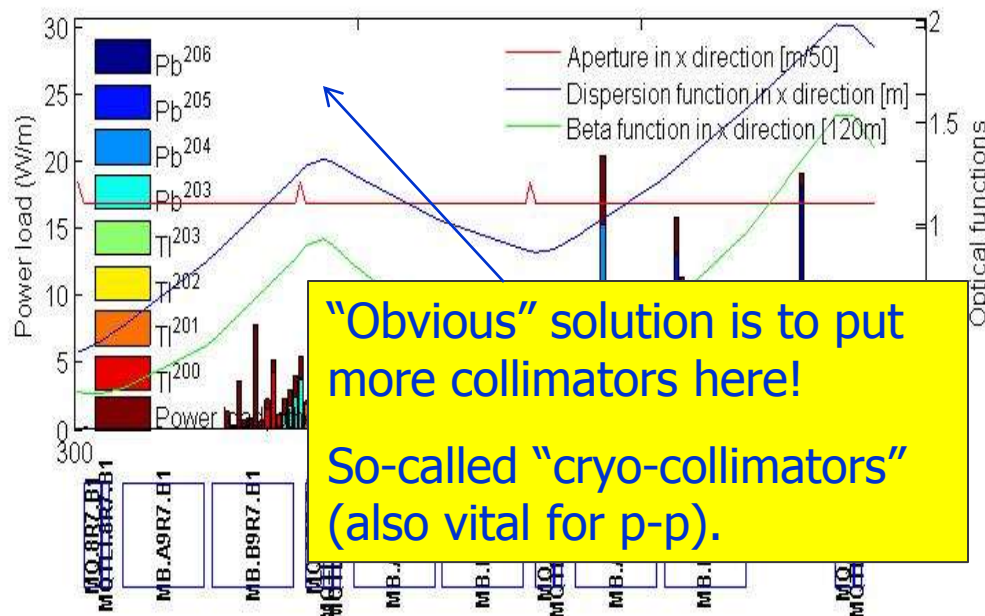
Example of ^{206}Pb created by 2-neutron EMD

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

Beam pipe in IR7 of LHC



Primary collimator

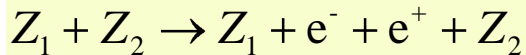


“Obvious” solution is to put more collimators here!

So-called “cryo-collimators” (also vital for p-p).

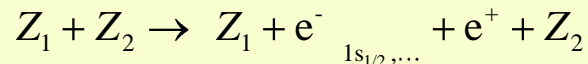
Pair Production in Heavy Ion Collisions

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



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

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



has very different dependence on ion charges (and energy)

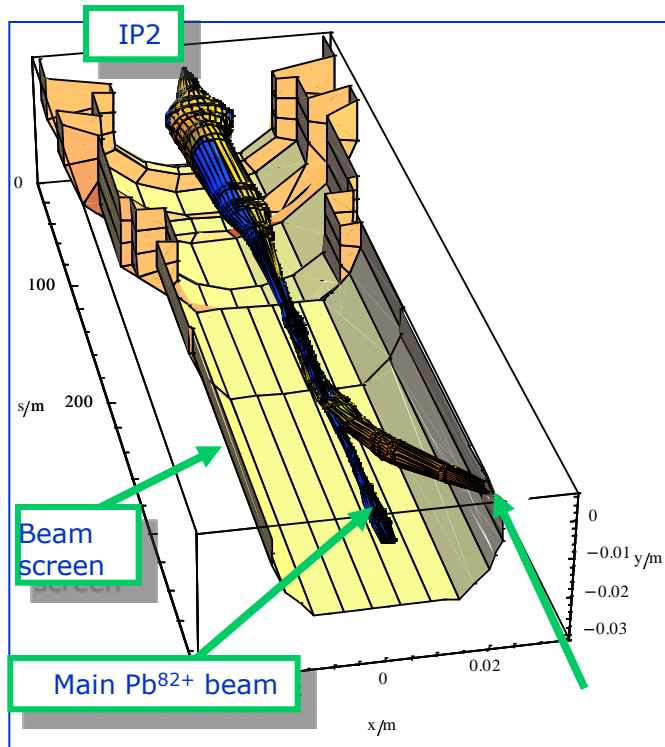
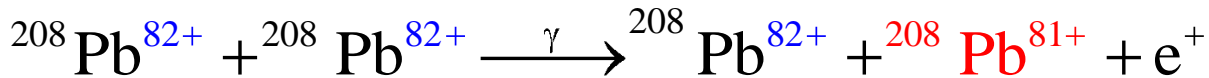
$$\begin{aligned} \sigma_{PP} &\propto Z_1^5 Z_2^2 A \log \gamma_{CM} + B \\ &\propto Z^7 [A \log \gamma_{CM} + B] \text{ for } Z_1 = Z_2 \\ &\approx \begin{cases} 0.2 \text{ b for Cu-Cu RHIC} \\ 114 \text{ b for Au-Au RHIC} \\ 281 \text{ b for Pb-Pb LHC} \end{cases} \end{aligned}$$

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

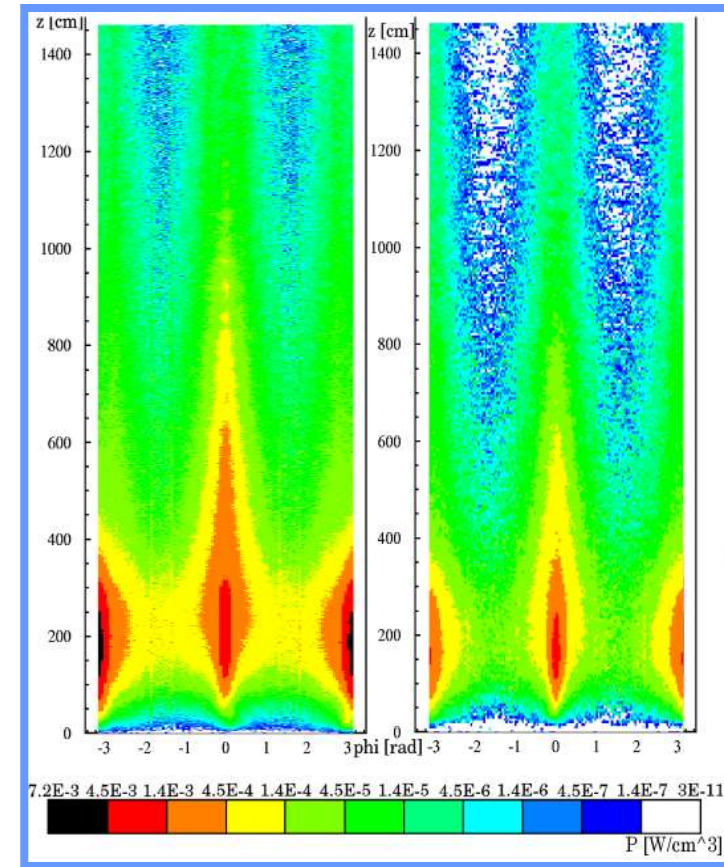


Luminosity Limit from bound-free pair production

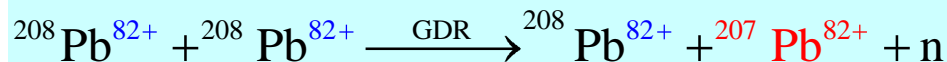


Secondary Pb⁸¹⁺ beam (25 W at design luminosity) emerging from IP and impinging on beam screen.

Hadronic shower into superconducting coils can quench magnet.

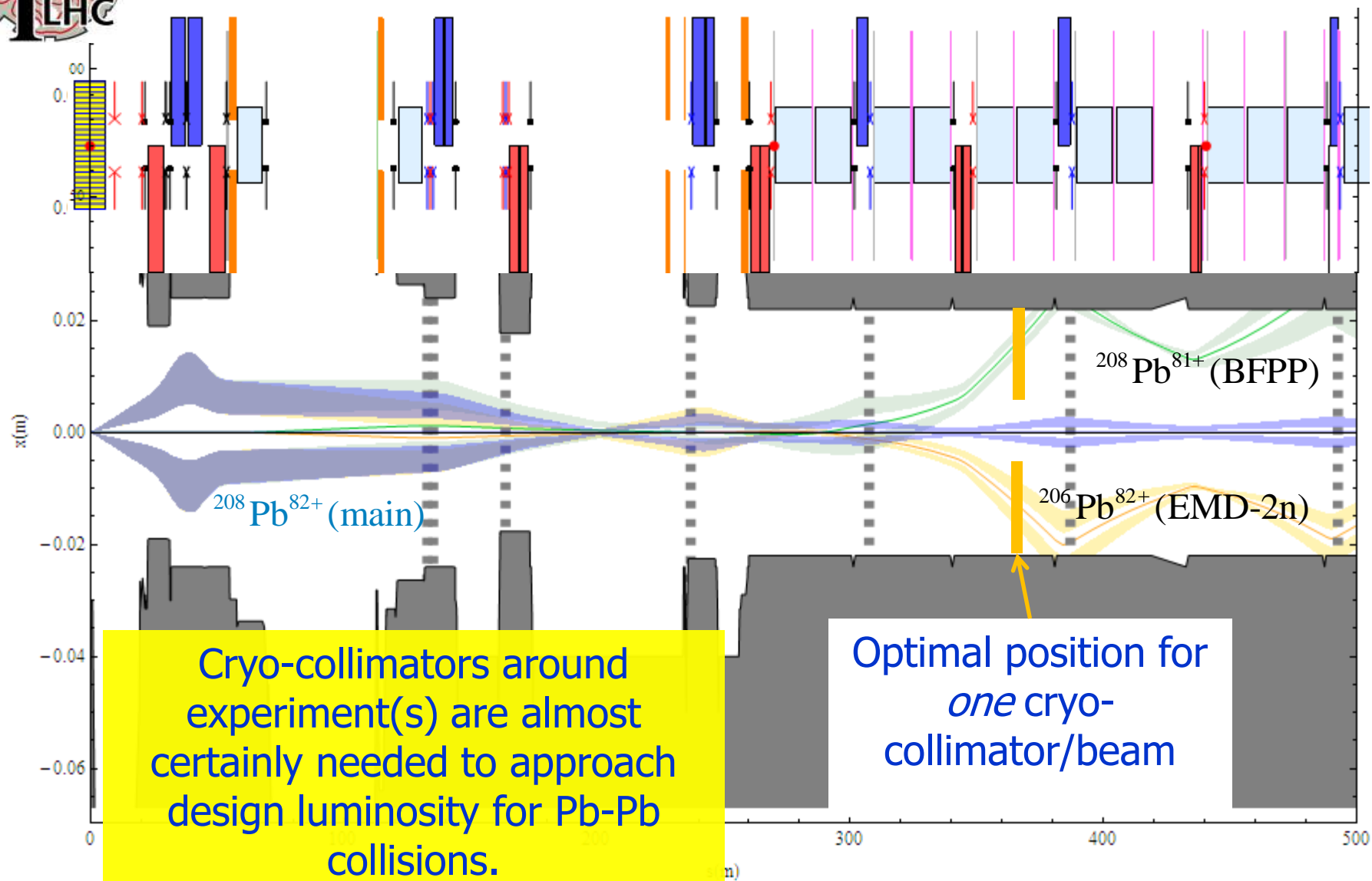


Distinct EMD process (similar rates) does not form spot on beam pipe





Main and secondary Pb beams from ALICE IP





Steps to higher Pb-Pb energy and luminosity

- 2011: continue at beam energy 1.38 A TeV
 - increase number of bunches (injector operation for “Nominal”)
 - Reduce β^*
- LHC shutdown in 2012
 - 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
 - Solve ALICE ZDC shadowing by moving y-chamber and install new tertiary collimators
- Later shutdowns
 - Equip IR2 with “cryo”-collimators to raise Pb-Pb luminosity limit for ALICE

BEYOND LEAD-LEAD



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



Accessible energies and CM rapidities



Possible range of collision energies
Minimum p-Pb energy for equal revolution frequency.

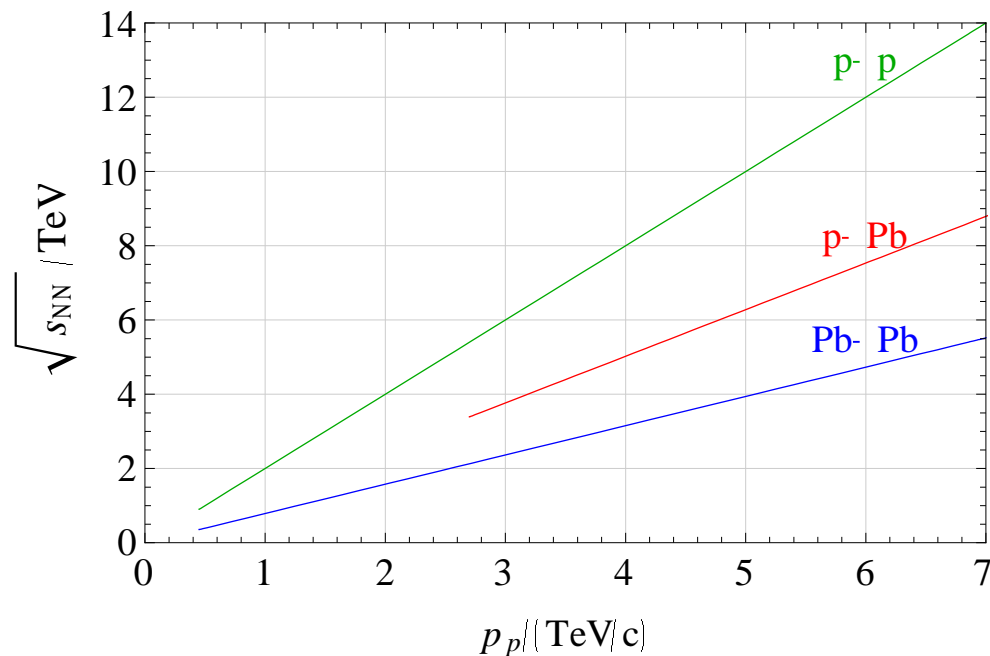
Relations between these numbers are a simple consequence of the two-in-one magnet design

	p-p	Pb-Pb	p-Pb
E / TeV	0.45-7	287-574	(2.7-7, 287-574)
E_N / TeV	0.45-7	1.38-2.76	(2.7-7, 1.38-2.76)
\sqrt{s} / TeV	7-14	73.8-1148	48.9-126.8
$\sqrt{s_{NN}} / \text{TeV}$	7-14	0.355-5.52	3.39-8.79
y_{CM}	0	0	-2.20
y_{NN}	0	0	+0.46

Charges Z_1, Z_2 in rings with magnetic field set for protons of momentum p_p

$$\sqrt{s_{NN}} \approx 2c p_p \sqrt{\frac{Z_1 Z_2}{A_1 A_2}},$$

$$y_{NN} = \frac{1}{2} \log \frac{Z_1 A_2}{A_1 Z_2}$$





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

With Pb ion nominal bunch structure in both beams, this would give luminosity
 $L = 1.5 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$, 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 $^{11}\text{B}^{5+}$, various energies, generated from primary $^{208}\text{Pb}^{82+}$

Acknowledgements

- This talk sketched some aspects of the work of many people, over many years.
- Particular thanks for material to:
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