(Lead) Ions in the LHC

Large Hadrons

in the Large Hadron Collider

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Plan of talk

- Simplified survey of parameter space
  - Energy, luminosity, … for Pb-Pb collisions
- Readiness of main LHC systems
  - RF, beam instrumentation, collimation, …
- Commissioning plan for the first run
  - Pre-conditions, strategy and time estimates
- Conclusions

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  - K. Brown, M. Minty (BNL)

Parameter space for initial Pb-Pb collisions

A first step towards the goal of
1 nb^{-1} integrated luminosity
(~ 2-4 years operation)

Reminder: Ion beam energies in LHC

For our fully-stripped ${}_{208}\mathrm{Pb}^{82+}$ nuclei ("ions")
in the same magnetic field as 7 TeV protons:

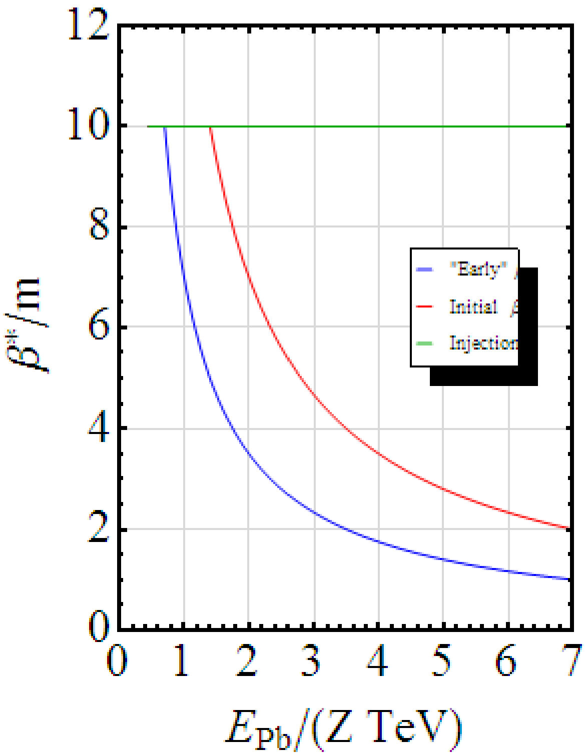
$$
\begin{aligned}
E_{\mathrm{Pb}} &= Z\,E_{\mathrm{p}} = 82\times 7\ \mathrm{TeV} = 7Z\ \mathrm{TeV} = 574\ \mathrm{TeV} \\
&= A E_n = 208\times 2.76\ \mathrm{TeV} = 2.76A\ \mathrm{TeV} = 574\ \mathrm{TeV} \\
&= 82\times(\text{kinetic energy of mosquito at 1m/s}) \\
&= (\text{kinetic energy of 1 mm diameter grain of sand at 40 km/h})
\end{aligned}
$$

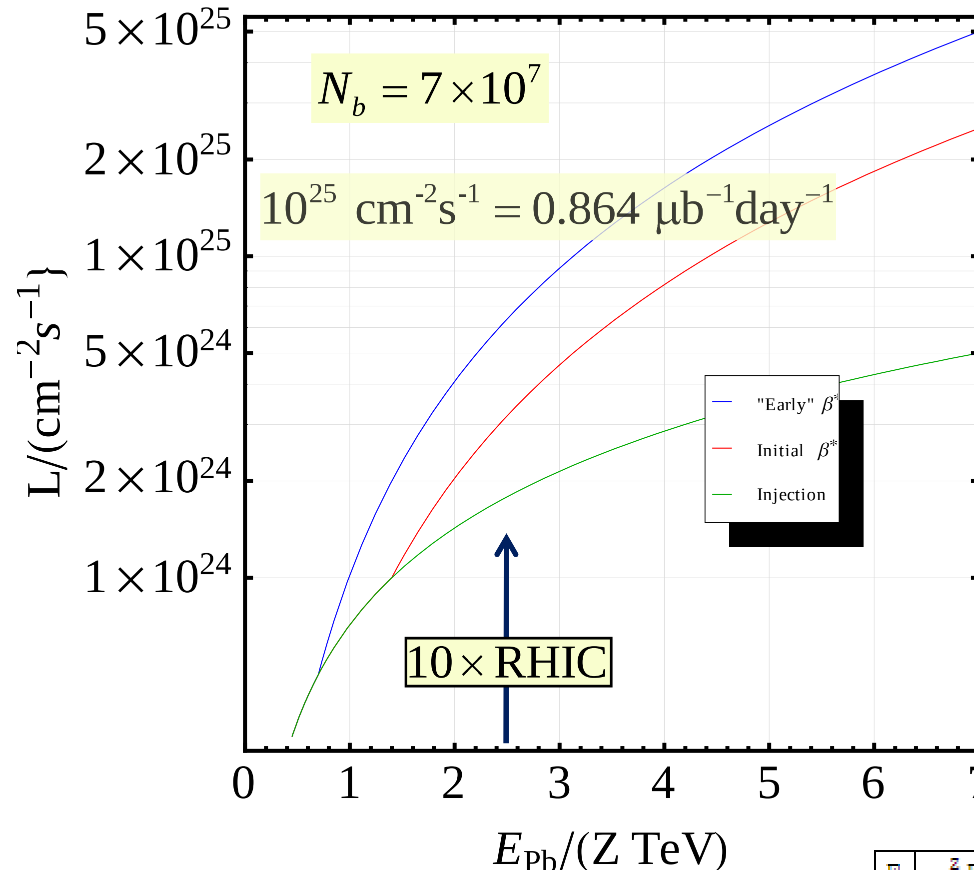
Key Parameters of "Early" Pb Ion Beam (from LHC Design Report)

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
		Only possibility for 2009 or early 2010	Goal for 2-3 years (?) beyond

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

Potential peak ion luminosity





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

$$\beta^*(E_p) = \begin{cases} \min(1.7/E_p, 10.)\ \mathrm{m} & \text{"Early"} \\ \min(3.5/E_p, 10.)\ \mathrm{m} & \text{Initial} \\ 10.\ \mathrm{m} & \text{Injection} \end{cases} \Rightarrow L = \frac{k_b N_b^2 f_0}{4\pi\sigma^{*2}} \sim \frac{E_p}{\beta^*}$$

Initial corresponds to parameters prepared for 5 TeV proton run.

E	$\frac{Z}{A}$E
1	0.394
2	0.788
3	1.18
4	1.58
5	1.97
6	2.37
7	2.76

Luminosity decay

Initial luminosity decay time from "collisions":

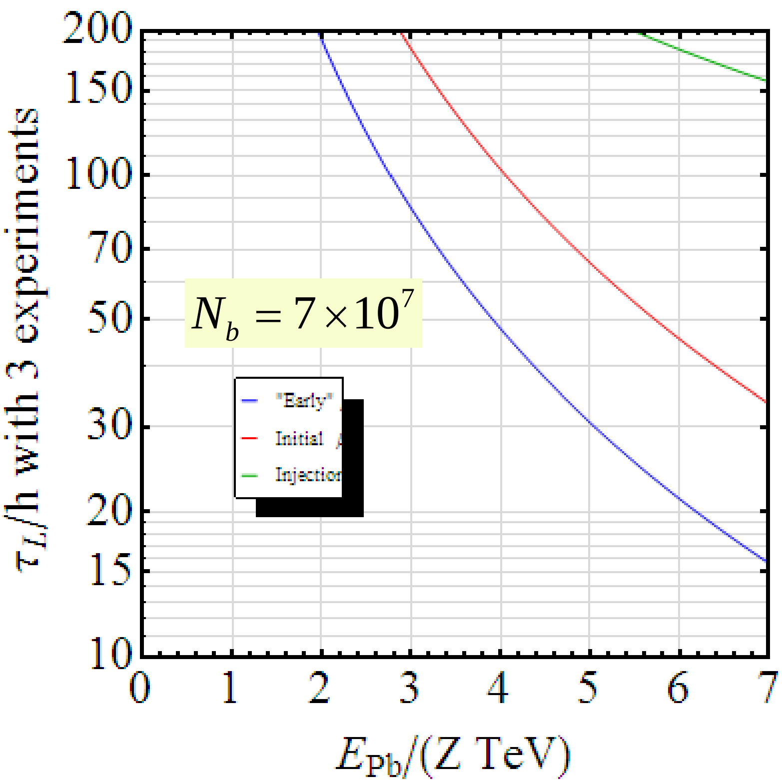
$$\tau_L = \left(\frac{\dot{L}}{L}\right)^{-1} = \frac{k_b N_b}{n_{\text{expt}} L \sigma_{\text{total}}}$$

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

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

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.)



With initial squeeze, we can hope to attain initial physics goal of 1 μb^{-1} in a few days for E > 4 Z TeV.

Time scales for emittance evolution

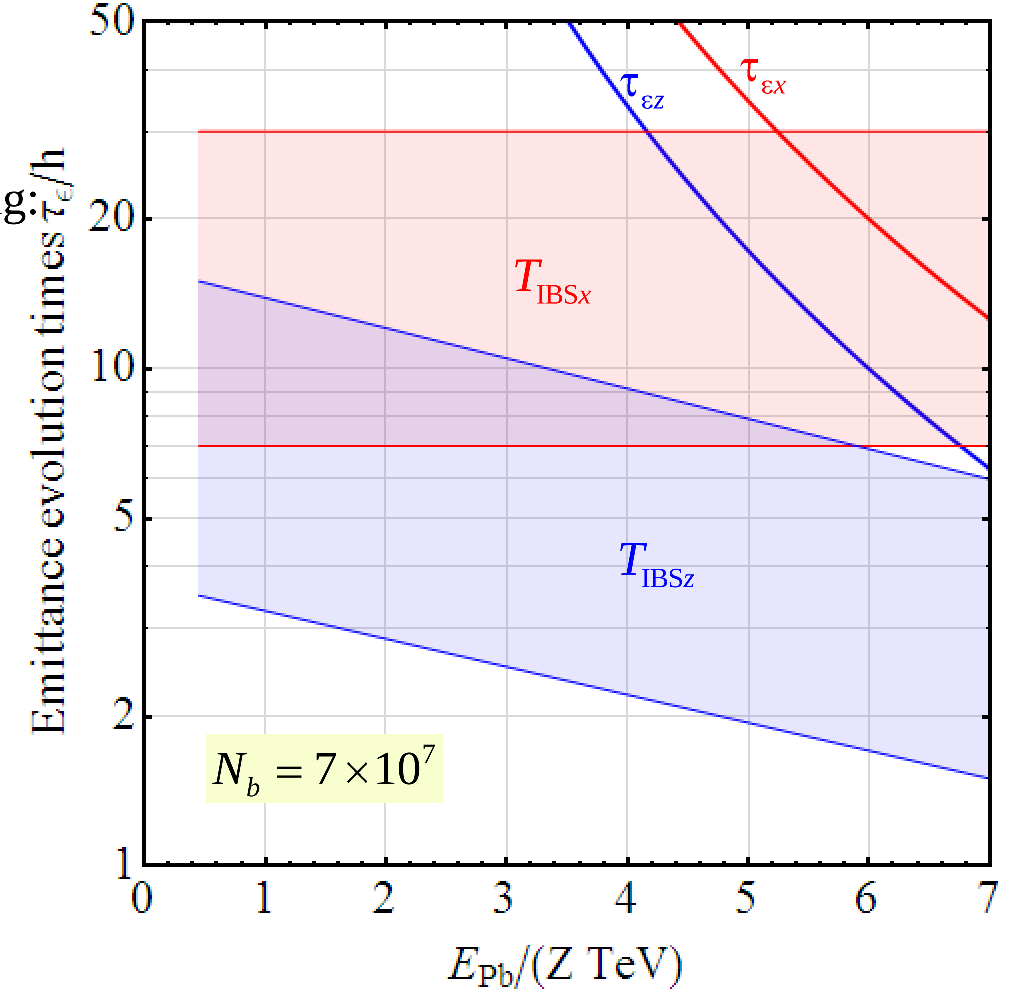
Emittances shrink by radiation damping:

$\tau_{\varepsilon x} \propto E^{-3}, \quad \tau_{\varepsilon z} = \tau_{\varepsilon x} / 2$

Emittances grow due to intra-beam scattering:

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

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

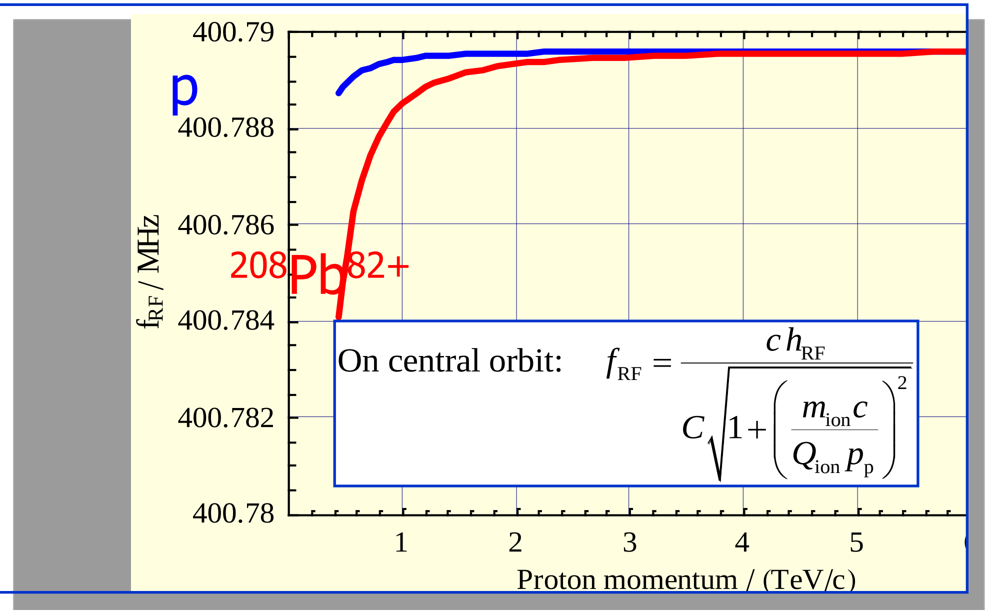


We can put all effects together to predict luminosity evolution scenarios through a fill (except for difficulty of estimating losses from longitudinal debunching).

Controlled blow-up of longitudinal emittance will be useful but not essential for first runs.

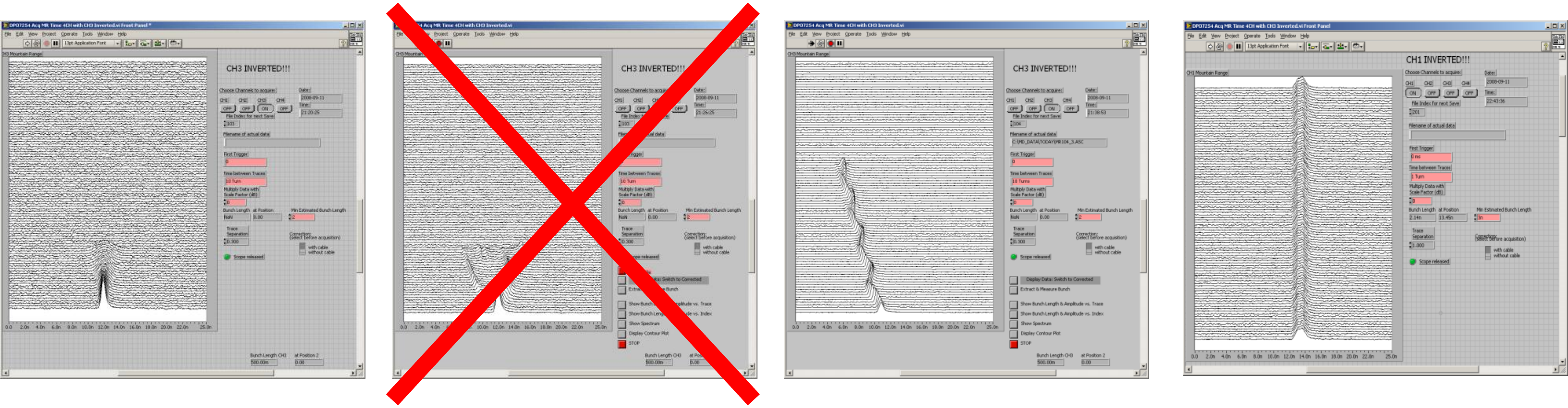
Readiness of LHC systems for Pb-Pb operation

RF capture for Pb ions



Larger frequency swing in ramp (5 kHz) than with protons (~1 kHz).

Adjust injection f_{RF} by -4.7 kHz and repeat as on 11 September 2008:



Then ramp with **adapted RF frequency programme** in LSA.

RF

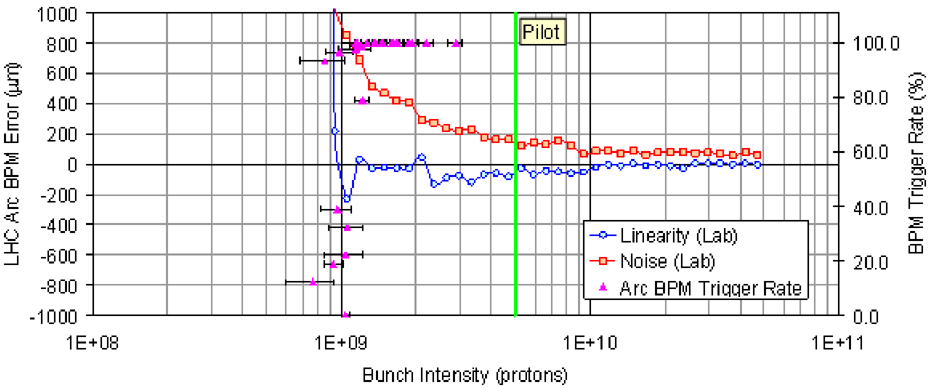
- Synchronization and capture at injection
- Different bunch filling scheme
  - Should be OK
- Phase loop pickup may be upgraded for ions
  - But present one works down to

$$N_b = 2.44 \times 10^7 \text{ ions/bunch} = 2. \times 10^9 \text{ charges/bunch}$$

  - Acceptable minimum bunch intensity for commissioning
- Controlled RF noise to blow-up longitudinal emittance (to reduce transverse IBS) desirable
  - Longitudinal damper only available next year
  - Not essential for first run
- Uncontrolled RF noise should be same as for protons – seems OK from 11/9/2008
  - Debunching losses always a concern
- Don’t forget possibility that we might need 200 MHz capture cavities one day

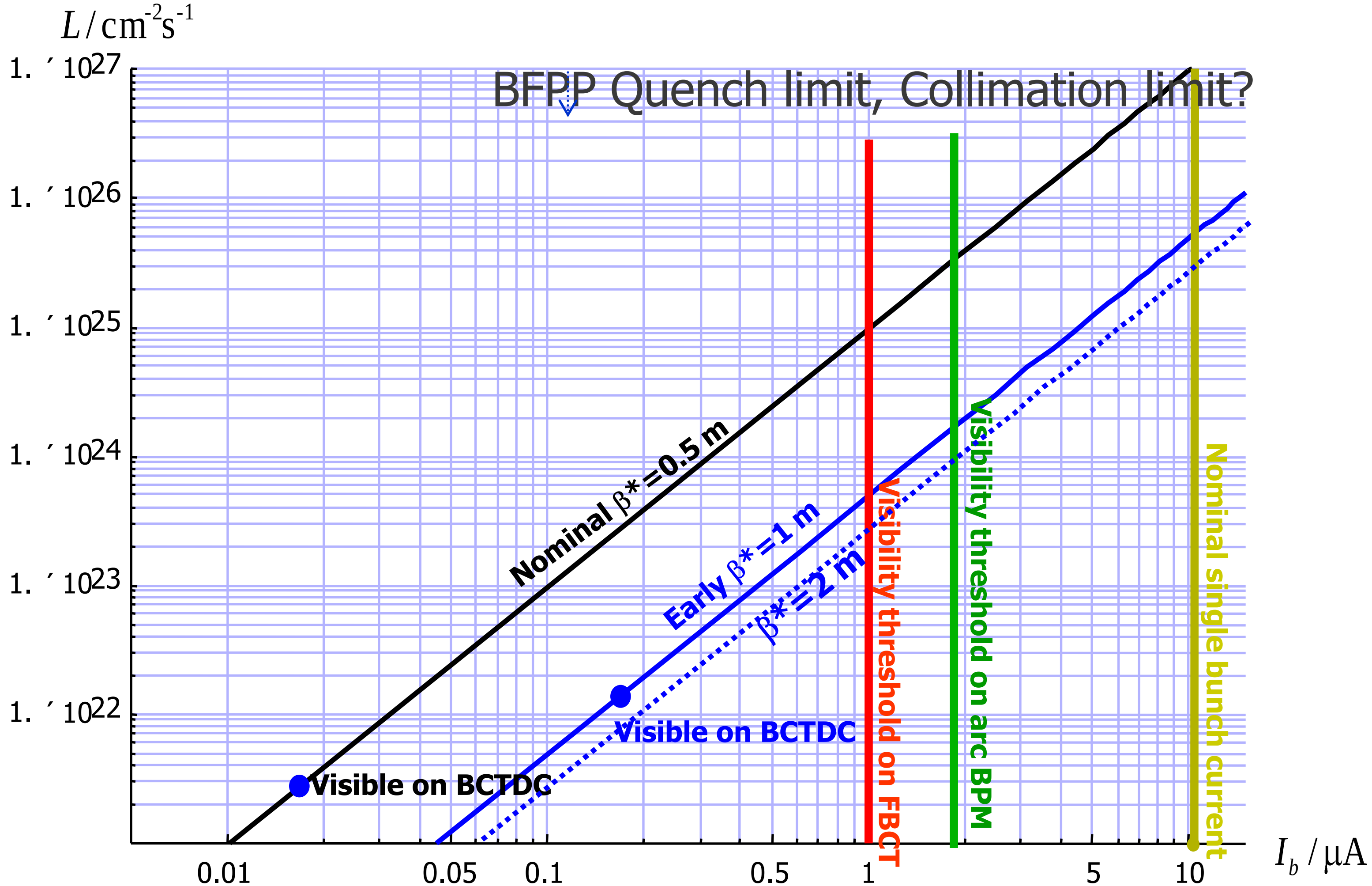
Beam Instrumentation

- BPMs
  - Good news on visibility thresholds from initial experience at LHC
  - See talk by R. Jones



- Tune, chromaticity, BBQ, etc
  - OK

Luminosity vs. single bunch current with Pb ions at 2.76 A TeV



Thresholds for visibility on BPMs have improved (Sep 2008 data) giving greater flexibility for commissioning, possibility of longer fills.

Beam Instrumentation - Emittance

- Ionization profile monitor (BGI)
  - Rely mainly on this, gas injection this shutdown
  - Performance with ion beams to be clarified
- Wire scanners
  - Intensity limit from damage to wire and/or quenches
    - at injection : 56-82 nominal ion bunches
    - at 7 Z TeV : 16-23 nominal ion bunches
- Synchrotron light monitors
  - Do not work for spectrum of radiation from ions
    - Perhaps something at top energy ?
  - For future, considering IR detector or building a new undulator for heavy ions

Schottky monitor

Special interest because, unlike most other instruments, it is not simply sensitive to the macroscopic bunch charge

$$S \propto N_b Z^2$$

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS
12, 012801 (2009)

Measuring transverse beam emittance using a 2.07 GHz movable Schottky cavity at the Relativistic Heavy Ion Collider

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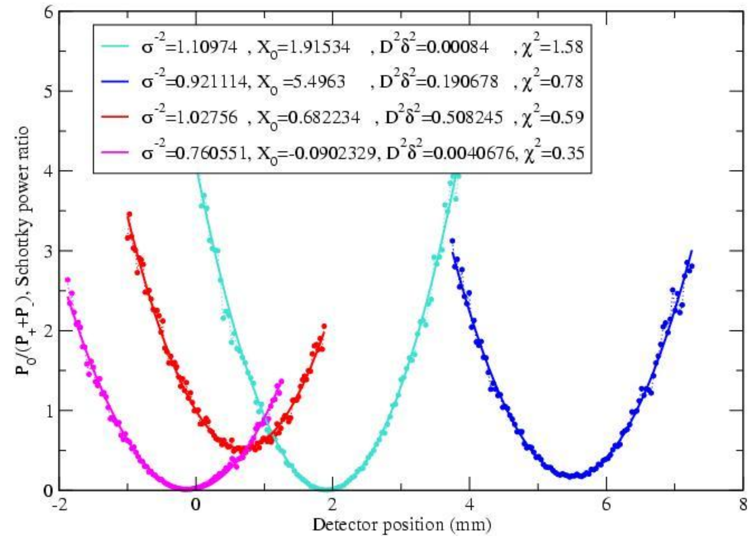
(Received 16 May 2008; published 13 January 2009)

Using a movable Schottky cavity resonant at 2.07 GHz, we have developed a simple method of deriving the beam sizes at the detector. In this report we will explain the theory behind the method, describe the system and the signal processing, and then present the results from experiments using this method. We will also present our plans for using this new technique for obtaining beam emittances during normal operation of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL).



- Hoped to implement accurate new RHIC method to measure emittance
  - Unlikely to work for LHC at 4.8 GHz (F. Caspers)
  - Can still try classical method requiring absolute calibration of spectrum

Abort-gap monitor

- Synchrotron light monitor designed to detect protons in abort gap will not work for ions
  - Try to account for intensity differences between Fast and DC beam current transformers (?)
  - Fall-back strategy is to clean the abort gap continuously

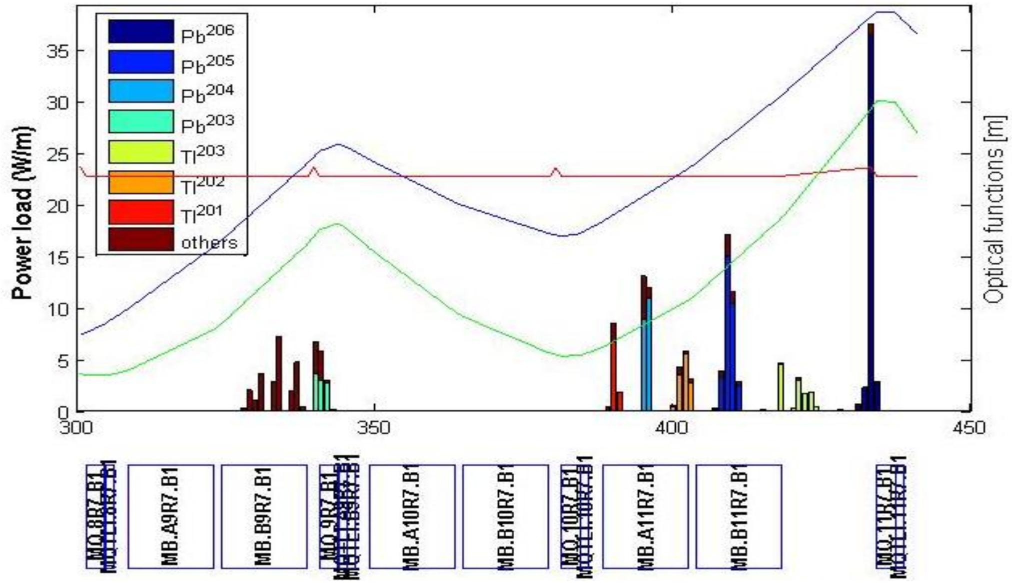
Optics

- *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, …
- Difference is that ALICE requires squeeze
  - Prepare squeeze with injection optics in other IPs
  - Establish crossing angle (~zero)
  - Then add back the others
  - At times it may be necessary to run with different β^* between experiments – need guidance on priorities

Collimation

- Collimation setup for initial runs should be straightforward
- However we need to test our predictions of loss maps and collimation inefficiency
  - Major performance limit at higher intensity
- Extra BLMs have been installed to monitor these losses
- Interference of TCTVs in IR2 with neutron flux to ZDC – discuss for collimation review

Isotope loss map downstream of IR7



Collimation of heavy ions is quite different from protons due to nuclear interactions (hadronic fragmentation, EM dissociation) in primary collimator material.

Staged collimation principle does not work.

Machine Protection

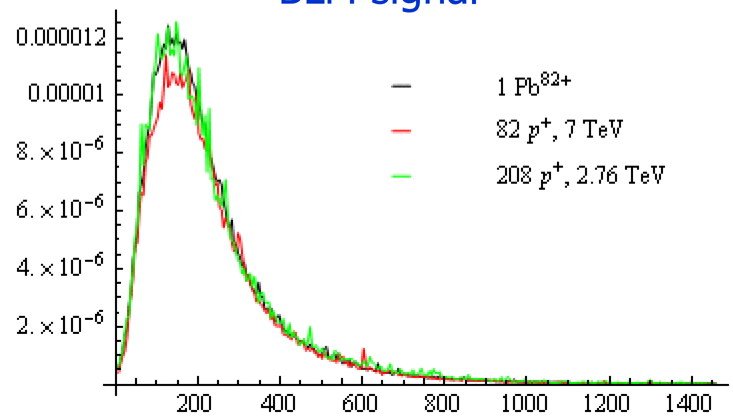
- BLM thresholds to avoid quenches
  - Most ion performance limitations are related to quenching magnets (discussed extensively elsewhere, not within scope of initial run) – see next slide
- Beam dump
  - Possible damage to window etc. checked
  - Revolution frequency lock OK
  - Need to re-validate the XPOC checks of the dump quality for the BI, also define the new references etc.
- "Safe beam" intensity can be defined as same beam charge as protons

Beam loss monitor thresholds

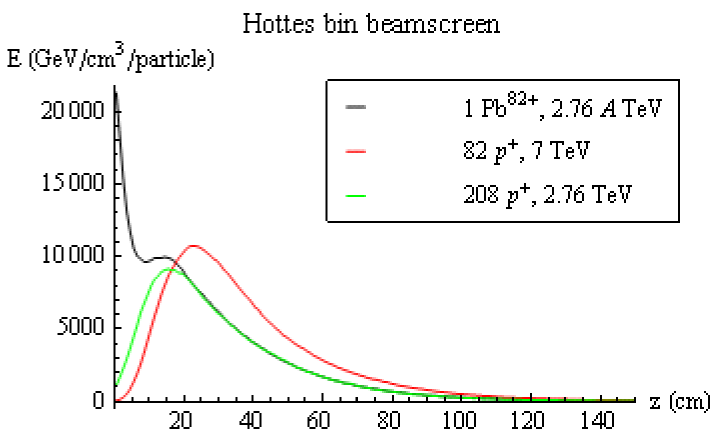
FLUKA simulations of BLM signals for LHC MB, Pb nuclei and protons impinging on beam screen (R. Bruce).

Implies that BLM thresholds to avoid quenching can be identical for Pb and p.

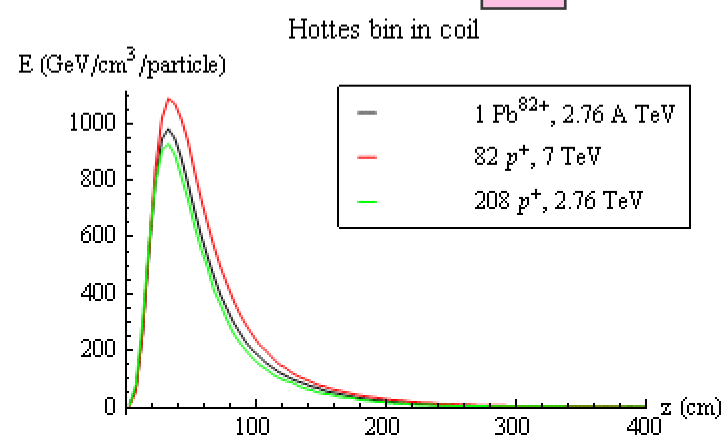
BLM signal



Nucleons shower



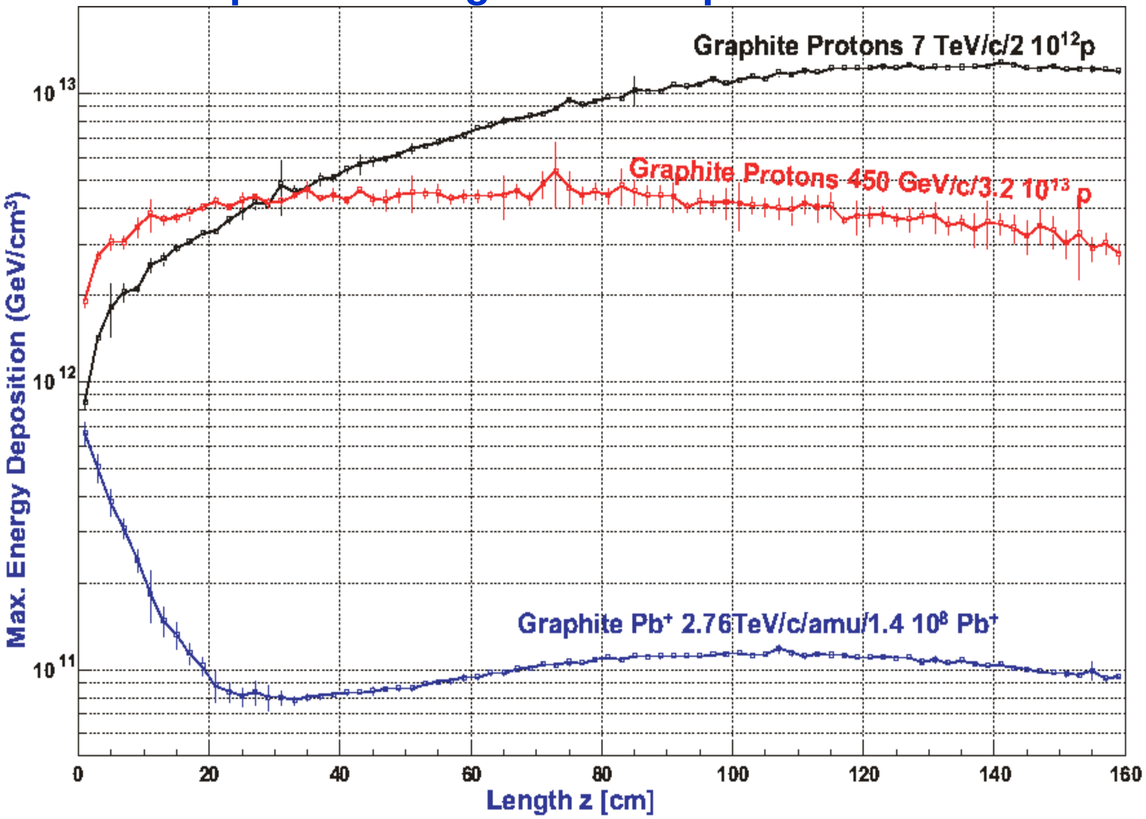
Fragmentation of nucleus



Initial high (Bethe-Bloch) ionization from nuclear charge ~ Z^2

Robustness of collimator against mishaps

FLUKA calculations from Vasilis Vlachoudis for dump kicker single module prefire



Compares full nominal proton bunch train and nominal ion train.

The higher ionisation loss makes the energy deposition at the impact side comparable to proton case, despite 100 times less beam power.

Energy deposition nowhere exceeds p case.

Vacuum

- Discussed in some detail at Chamonix 2004
  - https://ab-div.web.cern.ch/ab-div/Conferences/Chamonix/chamx2004/PAPERS/1_05_JMJ.pdf

Lead ions with lifetime 100h from each gas

Gas	σ_{in}	n/m^{-3}	P(300K)/nTorr	P(5K)/Pa
H2	3.75	2.47×10^{13}	0.768	1.71×10^{-9}
He	2.48	3.73×10^{13}	1.16	2.58×10^{-9}
CH4	10.9	8.47×10^{12}	0.263	5.85×10^{-10}
H2O	7.52	1.23×10^{13}	0.383	8.5×10^{-10}
CO	7.22	1.28×10^{13}	0.399	8.86×10^{-10}

- More stringent than for protons but expected to be OK
- To check:
  - Local pressure bumps around collimators ?
  - Any consequences of Sector 3-4 incident ?

Afterthought syndrome

- Ion beams tend to be an afterthought:
  - E.g., well known accelerator physics programs have hard-coded assumptions about charge and mass of particles … here and there.
  - Two levels:
    - Just not treated.
    - Patched in inconsistently or inaccurately (implicit use of "energy per nucleon", Am_p instead of mass, …)
  - I've done it myself
  - Conceivable also in controls software. Check!
    - We are ready to help clarify.

    - P.S. the mass of our nucleus is 207.932 GeV/c^2

Commissioning Plan for initial Pb-Pb collisions

A first step towards the goal of
1 nb^{-1} integrated luminosity
(~ 2-4 years operation)

How long will it take?

- This will be a *hot-switch*, done when the LHC is already operational with protons
  - *Not* a start-up from shutdown
- Previous experience of species-switch:
  - RHIC several times, typically from ions to p-p, with 1 week setup + 1 week performance "ramp-up"
    - More complicated optics changes than LHC (injection is below transition with ions, above with protons)
    - Protons are polarized
  - Done a few times with ISR, late 1970s
    - Went very quickly (< 1 day), because magnetically identical
    - LHC closer to ISR than RHIC from this point of view
- Refine estimate with pp experience

Principles of the transition from p-p

- Keep as many things the same as possible
  - (Almost) everything to do with the effects of magnetic fields – same magnetic rigidity
  - Many things to do with the transverse size of the beams (geometric emittances should be the same)
- Concentrate on the differences
  - Can avoid (but still learn about) the toughest performance limits in initial “Early Beam” runs
- Minimise commissioning time
  - Also helps us study and prepare ion operation

Strategy

- Pre-conditions for first ion run
  - Ion Injectors commissioned and read
  - LHC colliding protons, not necessarily squeezed, with reasonably stable and reproducible magnetic cycle to E>2.5 TeV (?)
- Keep plan under constant review
  - Much will become clearer as we get experience operating p-p
- Commissioning plan
  - Web page

Stage I	Initial commissioning Early Ion Beam (DRAFT)	Ring factor	Total Time [days]	Comments
I1	Injection and first turn	2	0.25	Magnetically identical to protons; 1 bunch/beam.
I2	Circulating beam	2	0.25	Magnetically identical to protons. Synchronisation of transfer lines and RF capture at -4.7 kHz frequency shift. Check lifetime in particular (IBS?).
I3	450 Z GeV initial commissioning	2	0.25	Beam instrumentation slightly different. Optics OK.
I4	450 Z GeV optics measurements	2	.5	Magnetically identical to protons but do minimal check.
I6	450 Z GeV - two beams	1	.5	>0.4 nominal bunch intensity, otherwise magnetically identical to protons.
I7	Collisions at 450 Z GeV	1	0	Not interesting.
I8	Snapback and ramp	2	0.5	Single and then two beams, Magnetically identical to protons. Check beam dump at various energies.
I9	7 Z TeV flat top checks	2	0.5	Single beam initially, performed following successful ramp
I12	Commission experimental magnets			Included already since done for protons.
I10	Setup for collisions - 7 Z TeV	1	0.5	
	Physics un-squeezed	1	?	Zero crossing angle in ALICE, leave as-is in CMS & ATLAS. LHCb separated.
	TOTAL to first collisions		6	
I11	Commission squeeze	2	2	Commission squeeze of ALICE to same as presently achieved with CMS and ATLAS (with ATLAS and CMS unsqueezed). May have been started with protons. Check separation. Include CMS & ATLAS squeeze depending on time.
I5	Increase intensity	2	1	Increase bunch number to 62 (Early Scheme).
	Set-up physics - partially squeezed.	1	2	
	Pilot physics run			Parasitic measurements during physics (BLMs, ...) of great interest.

LHC Pb-Pb is a new accelerator regime

- Effects limiting future performance of LHC with Pb-Pb collisions are new and uncertain:
  - See other reports on bound-free pair production, collimation, etc.
  - Loss patterns, quench limits, …
  - Data from RHIC and SPS has been exploited and published.
  - Experience of first low intensity runs will help test and calibrate simulations and assess needs for future improvements
  - (May also be able to learn about performance limits in phases beyond Pb-Pb.)

Conclusions (1)

- Given the pre-conditions (injectors ready, LHC in decent shape), commissioning first Pb-Pb collisions should be rapid
- Beam instrumentation mostly OK (concerns about emittance measurements)
  - Flexibility and safety for commissioning
- Initial Pb-Pb physics goal (1 μb^{-1}) attainable in a few days after ~1 week commissioning
- Experience important for future LHC ion programme
  - Much parasitic information, …
- Need policy guidance concerning luminosity priorities among experiments

Conclusions (2)

- The above discussion was mostly oriented towards an initial run occurring relatively early, perhaps with relatively little time available
- *If* the HI commissioning is delayed (say to end 2010) then plan may be more optimistic:
  - Development on ion injectors in 2010 could allow injection of more than 62 bunches, up to the 592 of the Nominal Ion Beam (or similar)
  - Optics etc. should be in better shape, lower β^*
  - Potential to accelerate approach to higher luminosity
    - But we will have to think on our feet with less time to digest experience at lower intensity and luminosity