Heavy Ions in the LHC
Baseline Programme and Upgrade Possibilities

John Jowett AB-ABP
for everyone in I-LHC Project

Particular thanks to C. Carli, M. Chanel, S. Maury, …

10. REPORT FROM THE LHCC WORKSHOP ON ION PHYSICS AT THE LHC

LARGE HADRON COLLIDER COMMITTEE

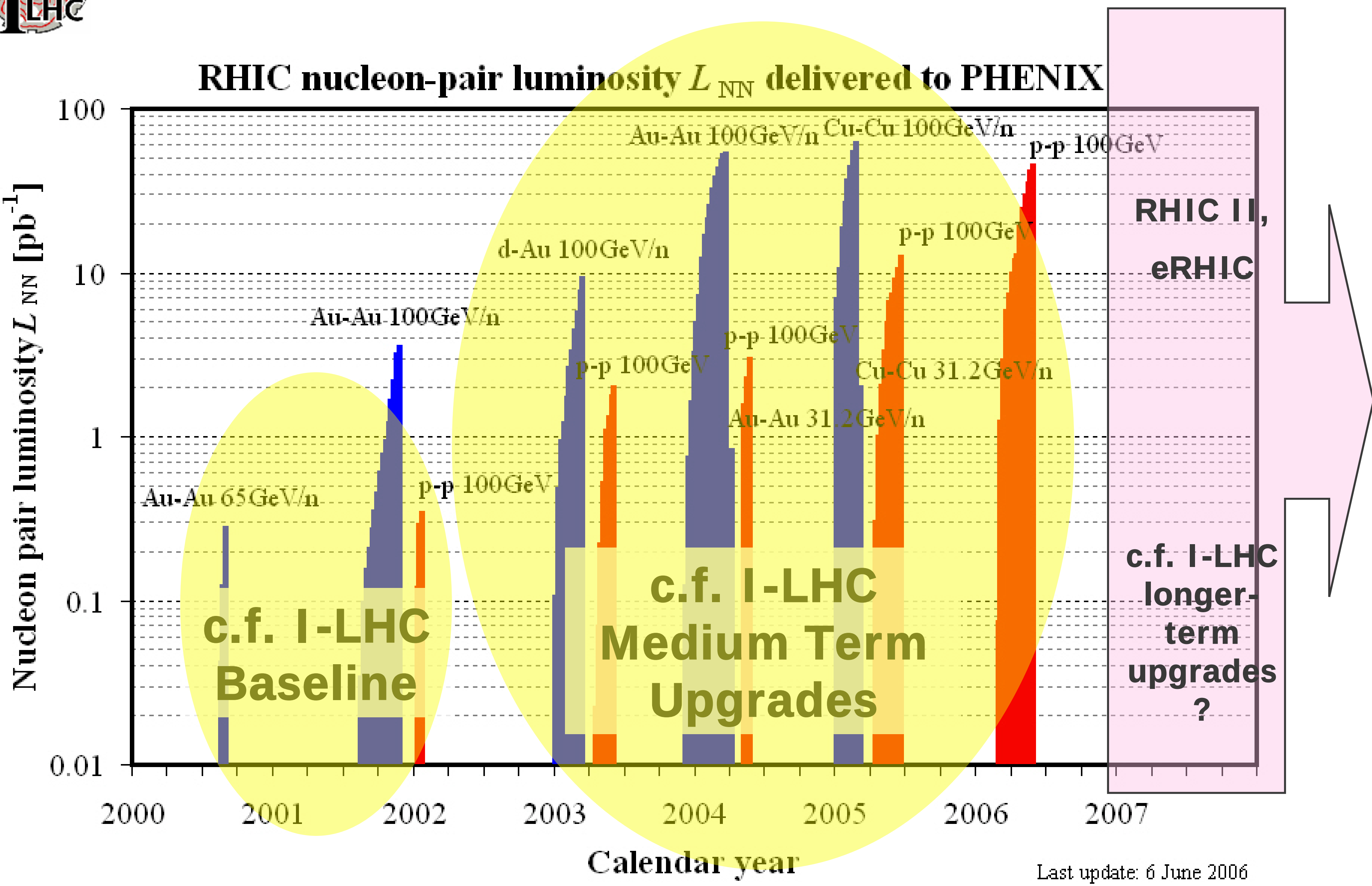
Minutes of the fifty-ninth meeting held on Wednesday, Thursday and Friday, 3-5 July 2002

P. Seyboth reported on the recent LHCC workshop on ion physics at the LHC. He reminded the Committee that a technical review of heavy-ions at the LHC and its injectors will be held later in 2002 and that in view of this the LHCC held a one-day workshop on 28 June, 2002 to collect and consolidate the requirements from the ALICE, ATLAS and CMS experiments concerning their desired running conditions – luminosities, energies, type of collisions, e.g. ion-ion (both Pb-Pb and lighter species), p-p, and p-N.

The conclusions and recommendations from the workshop are given below:

- Due to the complementary detectors and nature of the respective physics searches, participation of ALICE, ATLAS and CMS would be of great benefit and value to the LHC's ion physics programme.
- As experience at RHIC shows, an early exploratory Pb run of a few days duration in 2007 is considered to be very desirable. This would already allow many measurements to be made including the particle multiplicity, energy density, and thermodynamic properties of the Pb-Pb collisions.
- An extended Pb-Pb run should follow in 2008 and in subsequent years with the aim of collecting about 1 nb^{-1} of integrated luminosity to study the hard probes in the heavy-ion collisions.
- A p-Pb run of about one-month duration is considered crucial in benchmarking the standard nuclear effects and disentangling effects of the hot/dense medium. Running with p-p is also needed, and it was noted that participation of ALICE in p-p runs requires relatively low luminosity.
- Running with lighter ions and lower energies has also been requested by the experiments, but are of lower priority.
- There are no compelling physics reasons for a deuteron programme.
- In order to provide the requested beam intensities and luminosity, upgrades to the accelerator complex in both the PS Complex and the SPS are required. The LHCC noted and acknowledged the design efforts already made in the accelerator sector.

RHIC programme as a model for LHC

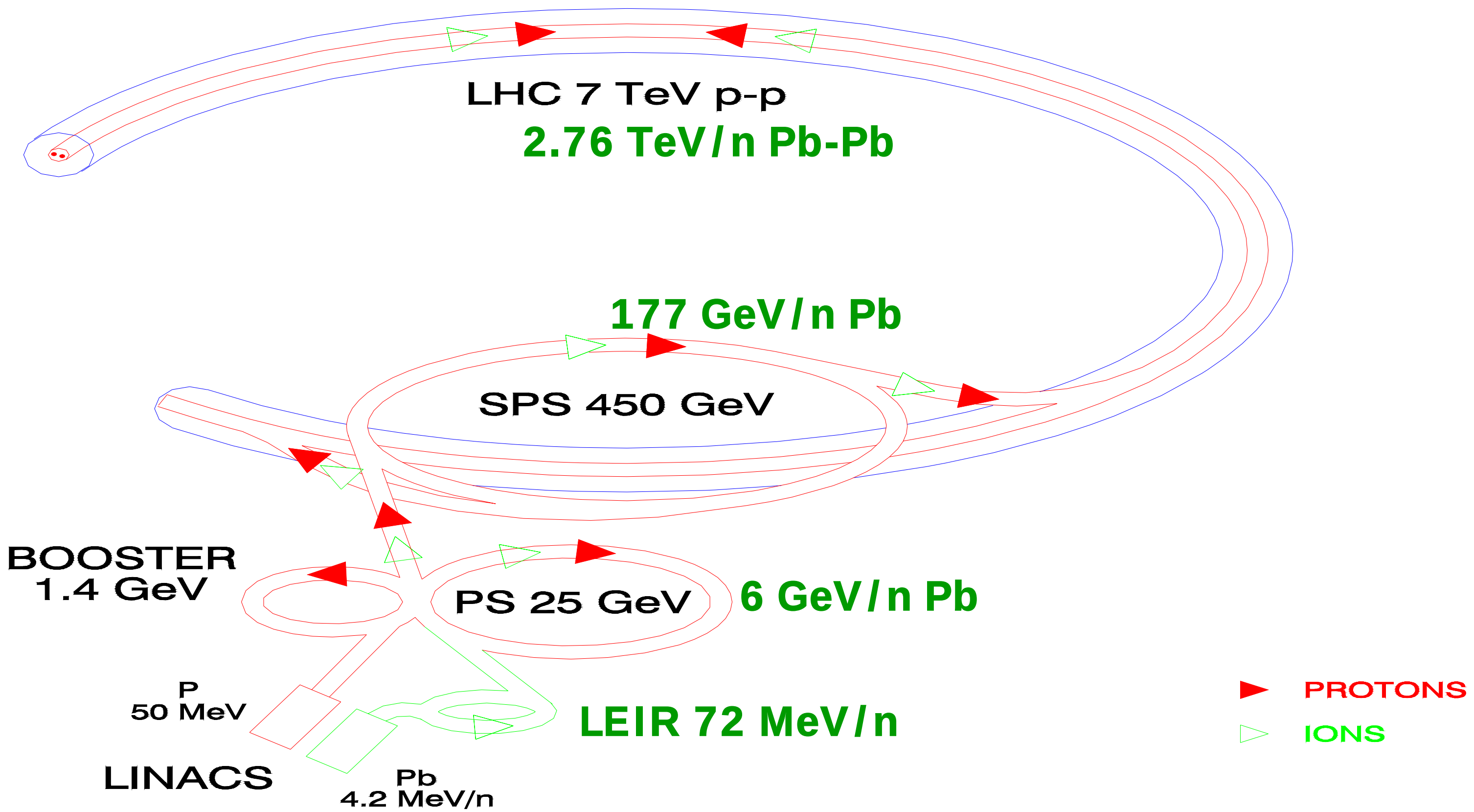


“Baseline” programme for heavy ion physics in the LHC: Pb-Pb collisions only

As defined around 2003
for the latest LHC Design Report
(not same as “ALICE Baseline”!)

The LHC Injector Chain - Schematic

Not to scale



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

	ECR Source →	Linac 3 →(4)→	LEIR →	PS →(13,12,8)→	SPS →(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

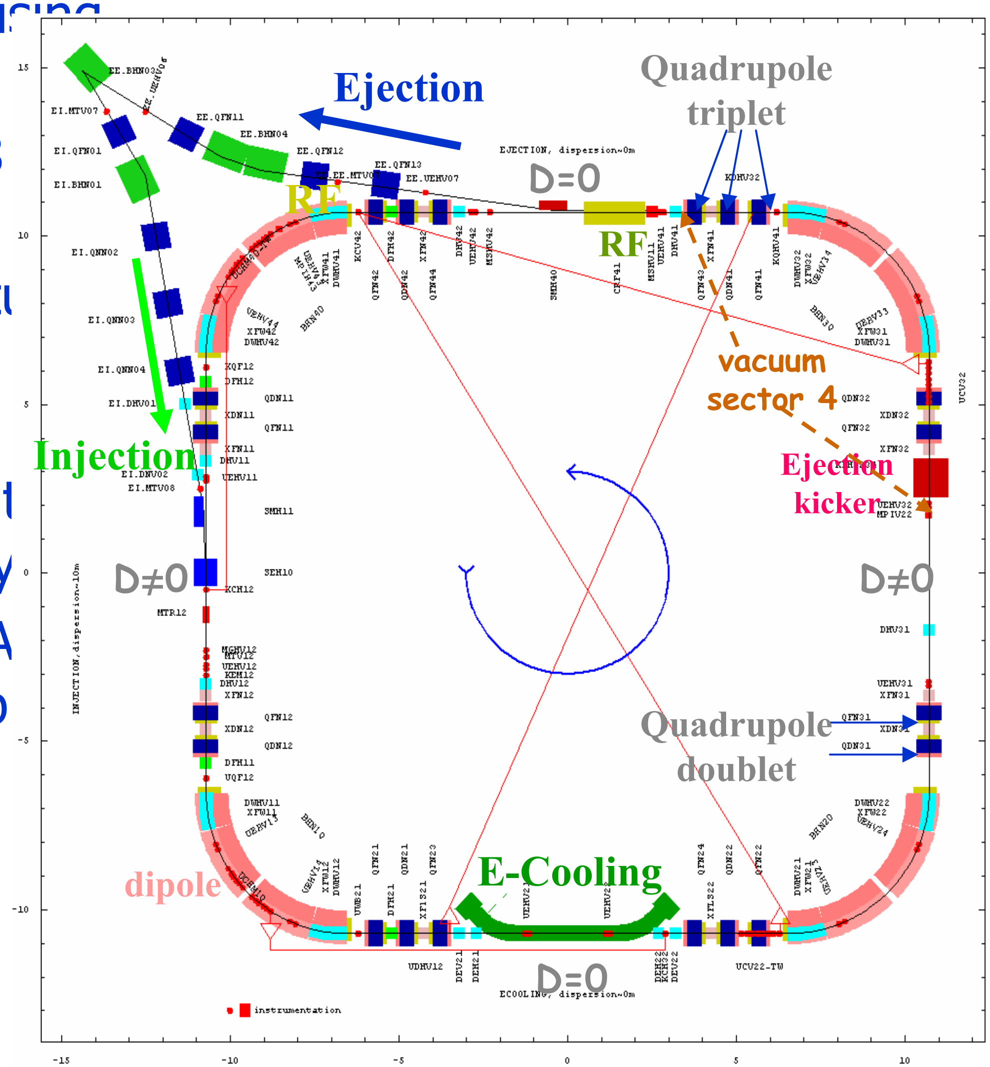
[1] 50 eμA_e x 200 μs Linac3 output after stripping

[2] Same physical emittance as protons,

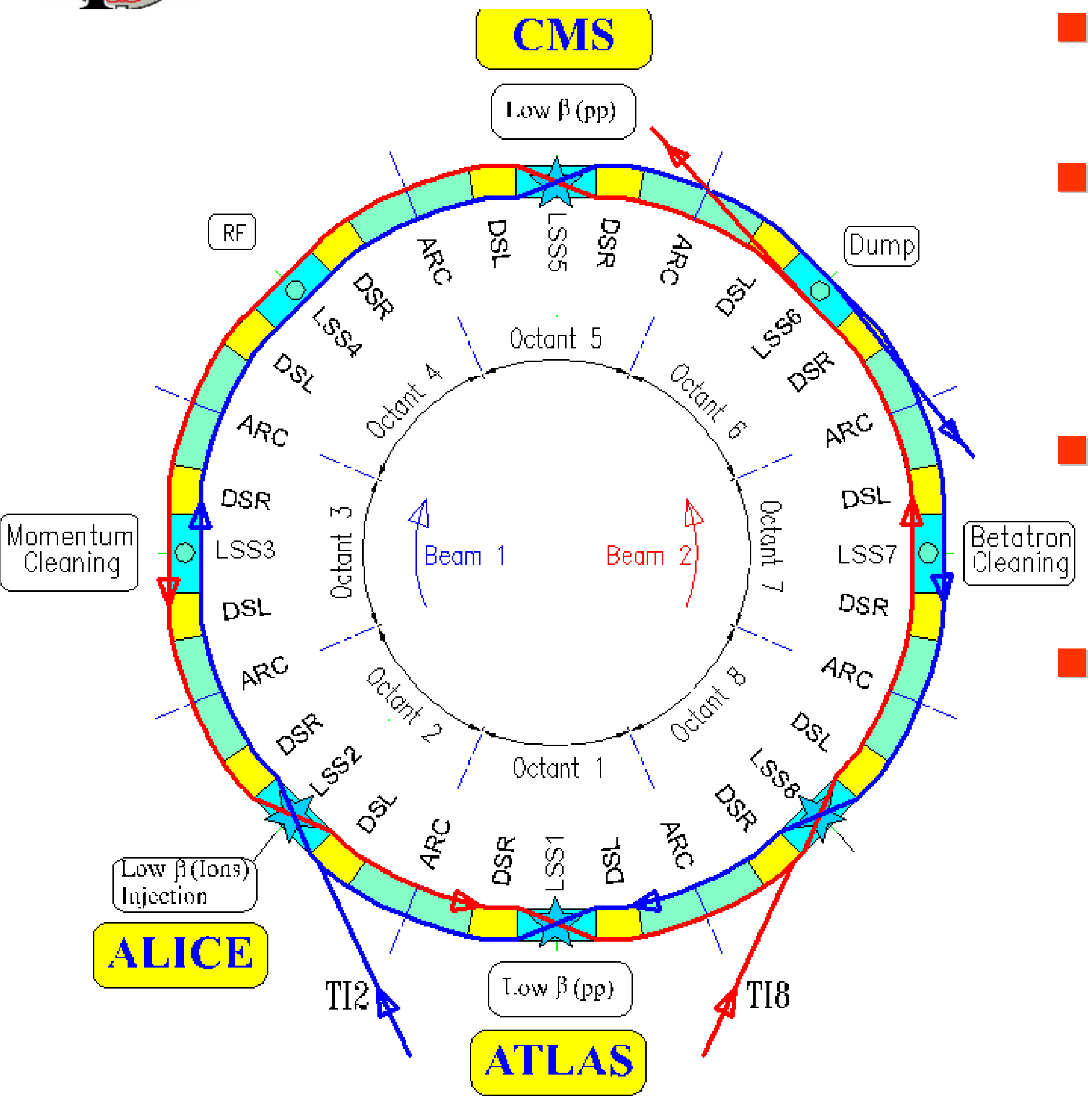
$$\varepsilon^* \equiv \varepsilon_n = \sqrt{\gamma^2 - 1}\,\varepsilon_{x,y} \text{ is } \sim \text{invariant in ramp.}$$

LEIR (Low-Energy Ion Ring)

- Prepares beams for LHC u
  electron cooling
- circumference 25p m (1/8
- Multiturn injection into
  horizontal+vertical+longitu
  l phase planes
- Fast Electron Cooling :
  Electron current from 0.5 t
  0.6 A with variable density
- Dynamic vacuum (NEG, A
  coated collimators, scrubb



LHC Collisions with Lead Ions



- $^{208}Pb^{82+}$-$^{208}Pb^{82+}$ collisions
- CM energy 1.15 PeV with nominal dipole field.
  - Beam energy 2.76 A TeV
- ALICE detector specialises in heavy ion physics
- CMS and ATLAS are also interested in heavy ion physics

Commissioning Pb-Pb in the LHC Main Rings

- Refer to detailed plan presented in Chamonix 2005
- Basic principle: *Make the absolute minimum of changes to the working p-p configuration*
  - Magnetically identical transfer, injection, ramp, squeeze of IP1, IP5
  - Same beam sizes
  - Different RF frequency swing, add squeeze of IP2
- Requirements
  - LHC works reasonably well with protons
  - Ion injector chain ready with Early Beam
  - Minimum instrumentation for ions set up
    - Need ionization profile monitors

How long will it take to commission Pb ions in LHC?

- This will be a *hot-switch*, done when the LHC is already operational with protons
  - *Not* a start-up from shutdown
- There *is* previous experience of switching a hadron collider from one species to another.
  - RHIC changed a few 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 the first ion collider at CERN (the ISR, late 1970s)
    - Went very quickly (< 1 day), because magnetically identical
    - LHC closer to ISR than RHIC from this point of view

Pilot Ion Run for 1-2 days within Proton Pilot Run

CERN
CH-1211 Geneva 23
Switzerland

the Large Hadron Collider project

LHC Project Document No.
LHC-OP-BCP-0001 rev 1.0

CERN Div./Group or Supplier/Contractor Document No.
AB-OP

EDMS Document No.
497792

Date: 2004-12-17

Beam Commissioning Procedure

OVERALL STRATEGY FOR EARLY LUMINOSITY OPERATION WITH PROTONS

Initial Pilot Run conditions with Early Ion beam would give Pb-Pb luminosity of:

$$L = (\text{few}) \times 10^{24} \ \text{cm}^{-2}\text{s}^{-1}$$

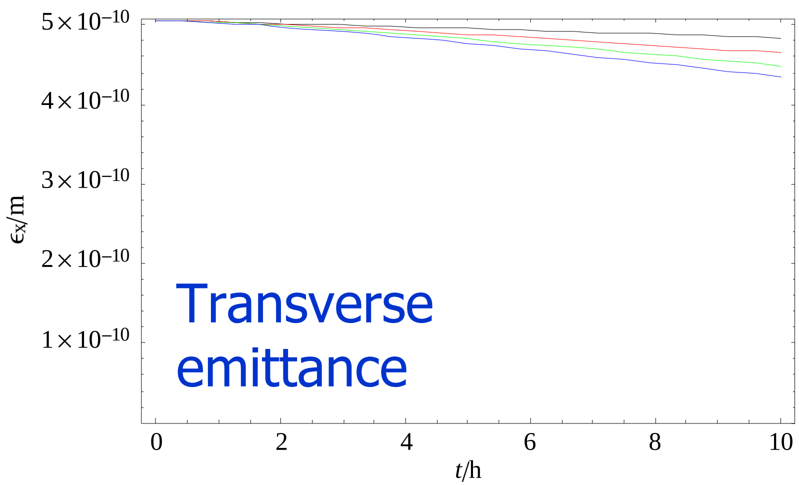
ALICE will be taking head-on collisions.

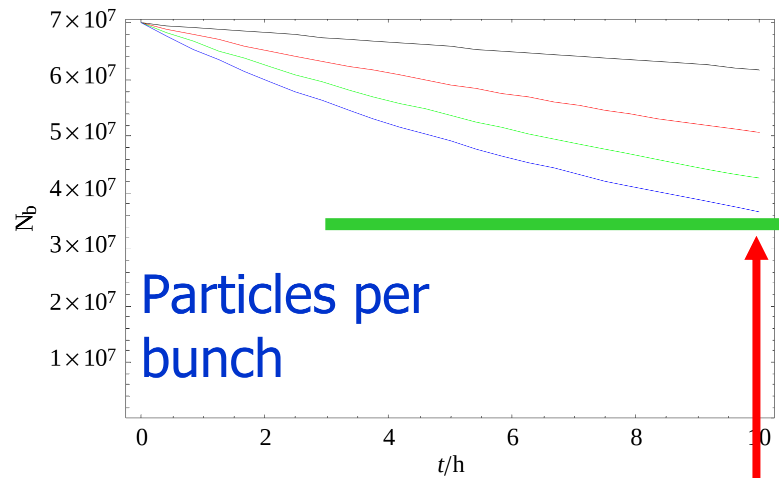
No change to magnetic configuration.

Beam energy (TeV)	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0
Number of bunches (per beam)	43	43	156
β^* in IP 1, 2, 5, 8 (m)	18,10,18,10	2,10,2,10	2,10,2,10
Crossing Angle (μR)	0	0	0
Transverse emittance (μm)	3.75	3.75	3.75
Bunch spacing (μs)	2.025	2.025	0.525
Bunch Intensity	$1\ 10^{10}$	$4\ 10^{10}$	$4\ 10^{10}$
Luminosity in IP 1 & 5 (cm^{-2} s^{-1})	~ $3\ 10^{28}$	~ $5\ 10^{30}$	~ $2\ 10^{31}$
Luminosity in IP 2 (cm^{-2} s^{-1})	~ $6\ 10^{28}$	~ $1\ 10^{30}$	~ $4\ 10^{30}$

1 μb^{-1} gives first heavy-ion physics results (c.f. RHIC)!

Luminosity evolution during a fill: Early scheme



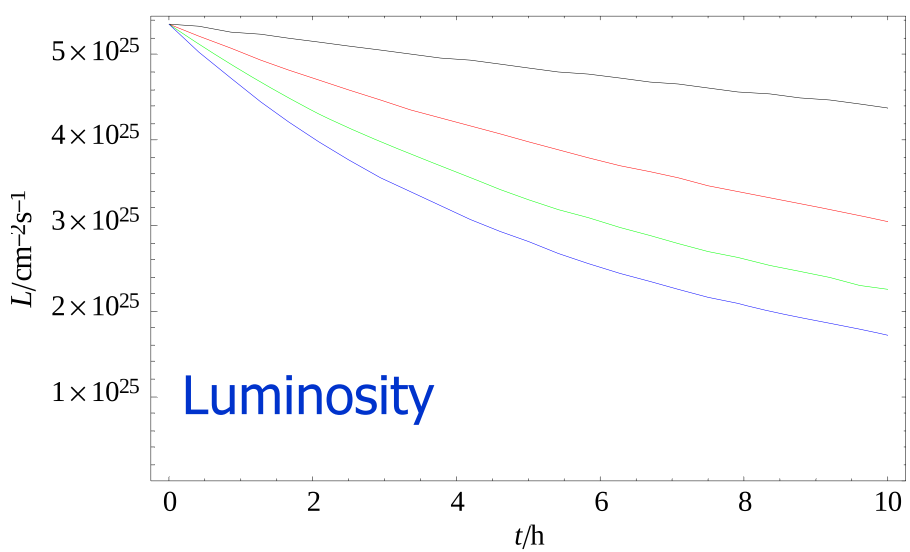


Arc BPM visibility threshold

Assuming good vacuum conditions, but including all effects.

$\beta^* = 1\,\mathrm{m}$

No. of experiments: $n = 0, 1, 2, 3$



Increasing number of experiments reduces beam and luminosity lifetime *but* we can still keep fills for a long time (useful if turn-round time is long).

I-LHC Planning

- Baseline: Lead-Lead collisions
  - "Early Pb Scheme" – much easier to achieve – for 2008 (and 2009?)
    - Allows study of performance limitations.
  - "Nominal Pb Scheme" by 2009 (or 2010?)
    - Pb-Pb is perceived as posing the most difficult accelerator physics problems
- Future "upgrades" not in Baseline:
  - p-Pb collisions under study
    - Effects of revolution frequency difference at injection expected to be *much weaker* than at RHIC
  - lighter ion-ion collisions (e.g. Ca, Ar, O, …) appear possible without major upgrades, to be studied.

Summary of Baseline

- Operation of LHC with lead ions limited by new effects, qualitatively different from protons
  - Several effects important around level of design luminosity (uncertainties in their estimation but some recent grounds for optimism)
- Restricted to a narrow operational range of parameters below the nominal luminosity
- "Early scheme" will allow relatively safe commissioning, access good initial physics
- Study of p-Pb mode has begun, looks promising
- LEIR commissioning has started with some success and some setbacks …

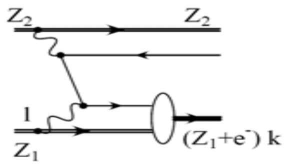
Performance limits in baseline Pb-Pb

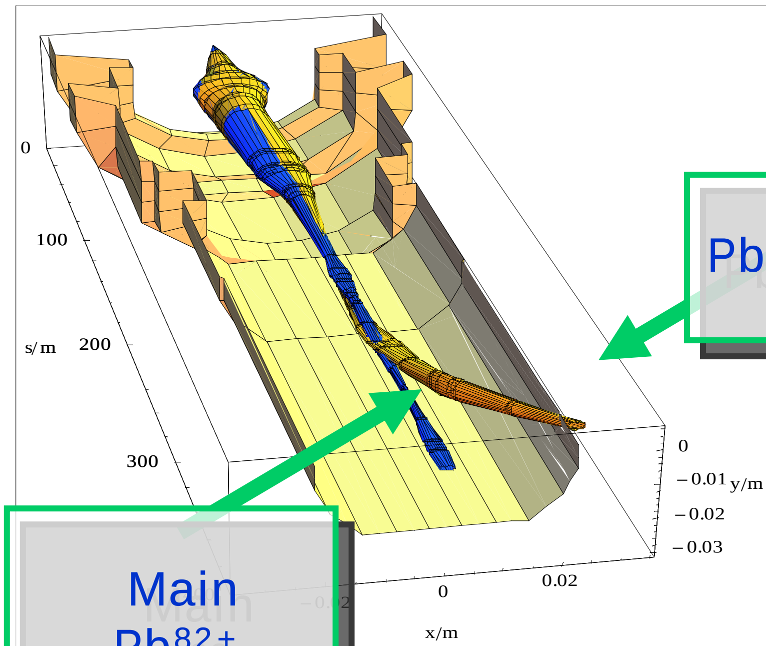
- BFPP
  - Essentially a limit on luminosity
  - Improved understanding of interaction, energy deposition of very high energy ions with matter, being implemented in FLUKA Monte Carlo
  - Our estimates of quench limit
  - BLM installation to allow this limit to be handled operationally
- Collimation
  - Essentially a limit on total beam current
  - Currently major concern, see next talk
- Instrumentation
  - Operational limitation

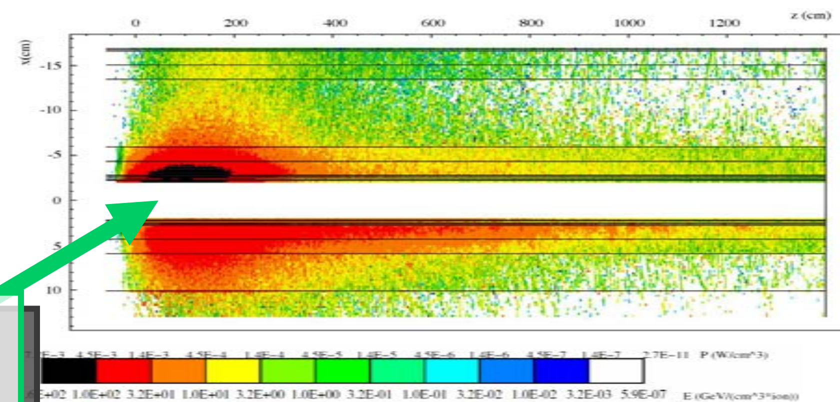
Luminosity limit from Bound-Free Pair Production

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

Improvements to models of HI interactions with matter

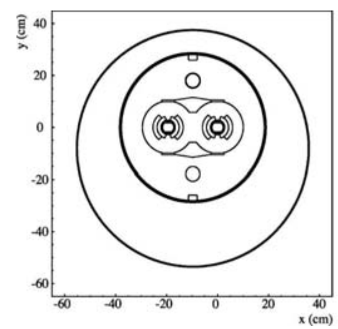


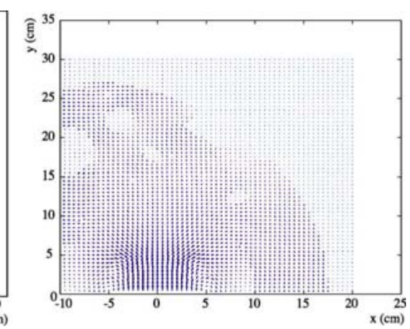




Pb^{81+}

Main Pb^{82+} beam





FLUKA dipole model & Field map

Quench Analysis

LHC Project Note XXX

25 November 2005

Roderik.Bruce@cern.ch

BFPP losses and quench limit for LHC magnets

R. Bruce, S. Gilardoni, J.M. Jowett

Keywords: Quench, heavy-ion, magnet, luminosity, beam-loss

5 Conclusions

Beam losses due to Bound-Free Pair Production in lead-ion collisions may quench certain dipole magnets in the dispersion suppressors of the LHC. By means of tracking in the LHC optics and Monte-Carlo simulation of the shower in the superconducting magnet,e have evaluated the heat deposition that can be expected with the nominal peak luminosity $L = 1.0 \times 10^{27} \mathrm{cm}^{-2}\mathrm{s}^{-}1$ for colliding beams of $^{208}\mathrm{Pb}^{82+}$ of energy 0.574 PeV. The maximum of the radially-averaged power deposited in the coil was found to be approximately $7\,\mathrm{mW/cm}^3$.

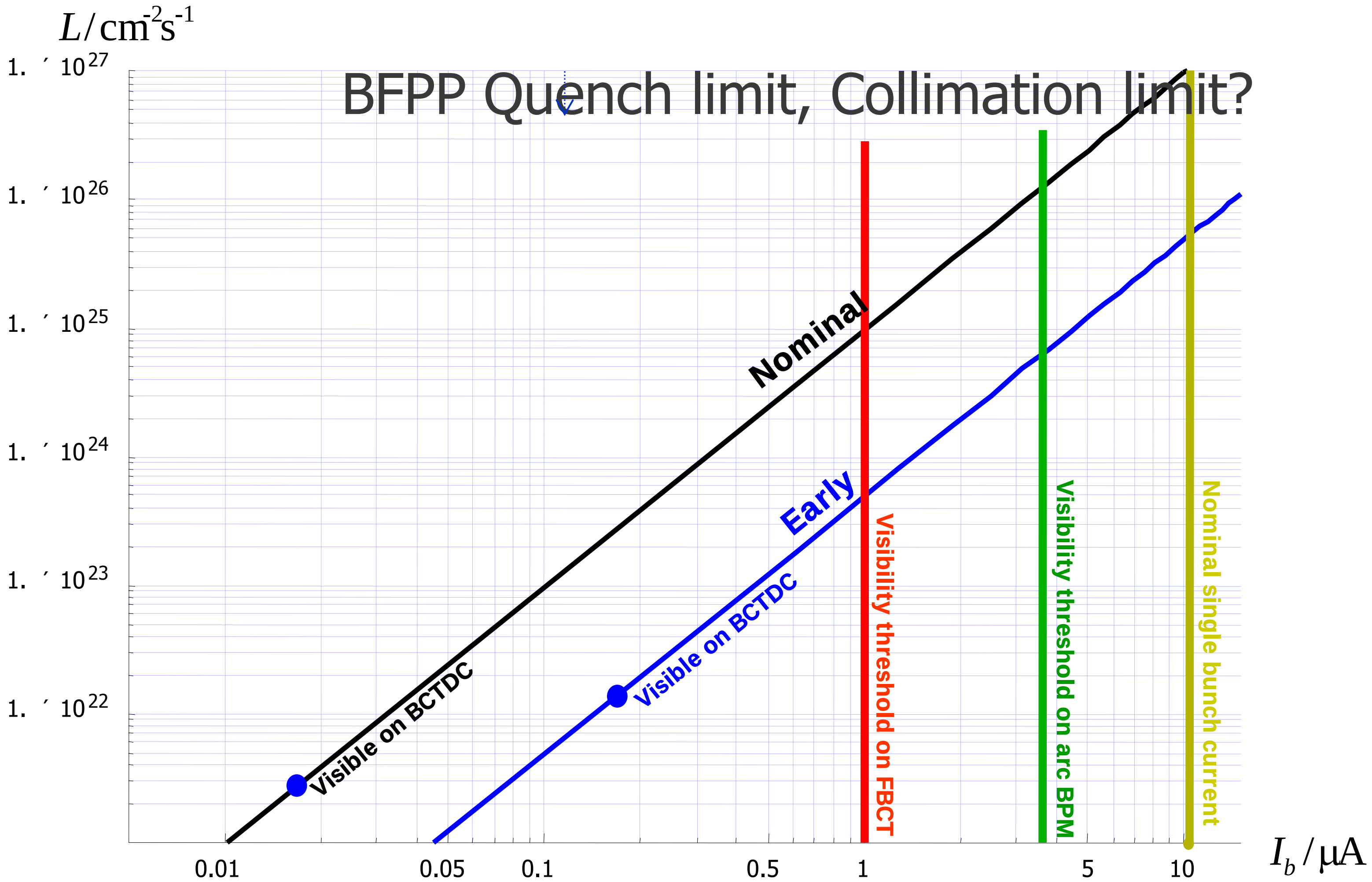
In addition, we have made a revised evaluation of the levels of energy deposition, whether steady state or transient, that can lead to quenches of LHC dipole magnets. The acceptable level of steady-state losses appears to be substantially higher than previously supposed: the magnets should withstand a heating power of at least $10\,\mathrm{mW/cm}^3$ in steady state without quenching. Thus the secondary beam of ions emerging from each collision point is not likely to quench a dipole magnet. Although we must acknowledge that several uncertainties exist, this is an encouraging indication that the Bound-Free Pair Production in lead ion collisions will not be a practical limit to the luminosity of the LHC.

We have also evaluated the response of the LHC beam loss monitors to both proton and lead ion beam losses with the preliminary conclusion that similar quench thresholds can be used for both types of beam.

Special BLMs added to LHC magnets around BFPP loss locations around 3 experiments, FLUKA simulations of response for operation.

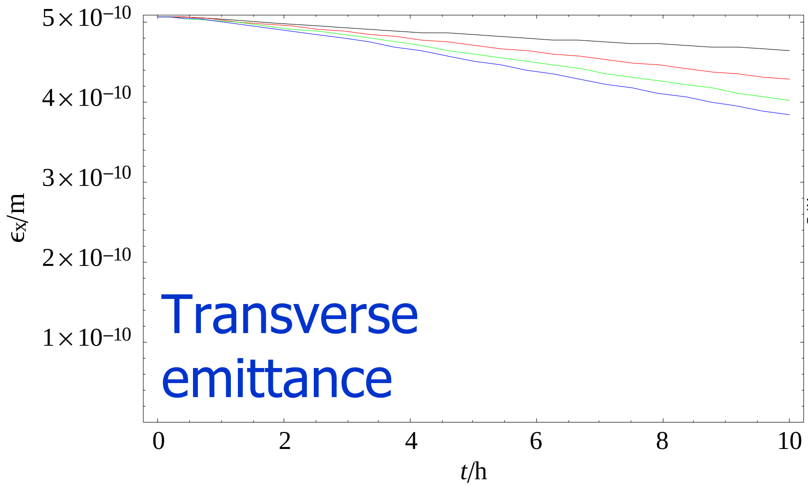
Higher luminosity will require new solutions – special shielding ?

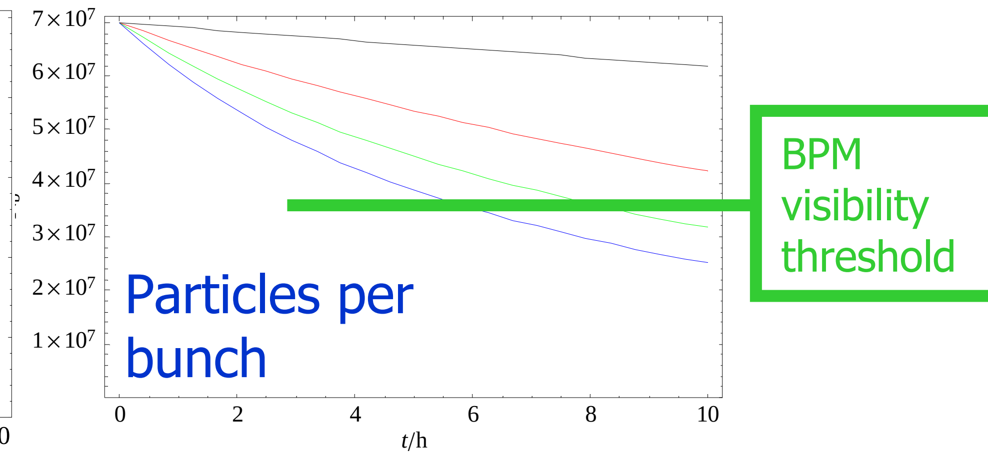
Operational parameter space with lead ions



Thresholds for visibility on BPMs and BCTs.

Luminosity evolution: Nominal scheme

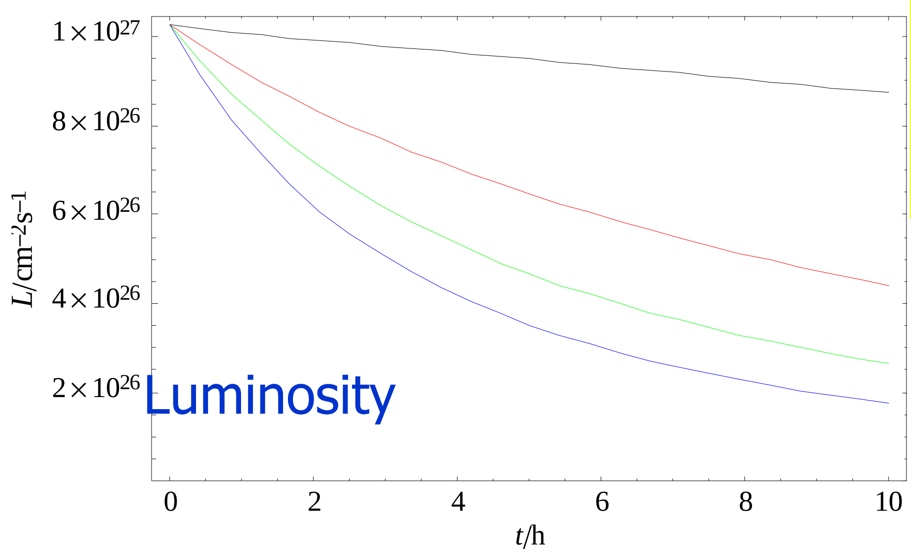




An "ideal" fill, starting from design parameters.

Luminosity burn-off,
IBS (pessimistic),
radiation damping,
RF noise,
beam-gas,
multiple scattering,
etc.

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



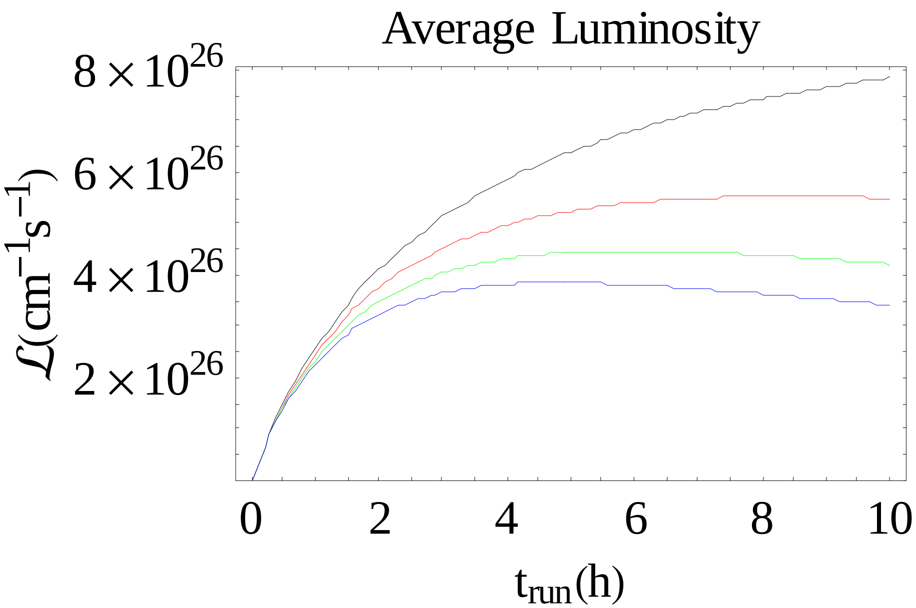
Increasing number of experiments reduces beam and luminosity lifetime.

Example: average luminosity

Average luminosity depends strongly on time taken to dump, recycle, refill, ramp and re-tune machine for collisions.

Average luminosity with 3h turn-around time, in ideal fills starting from nominal initial luminosity.

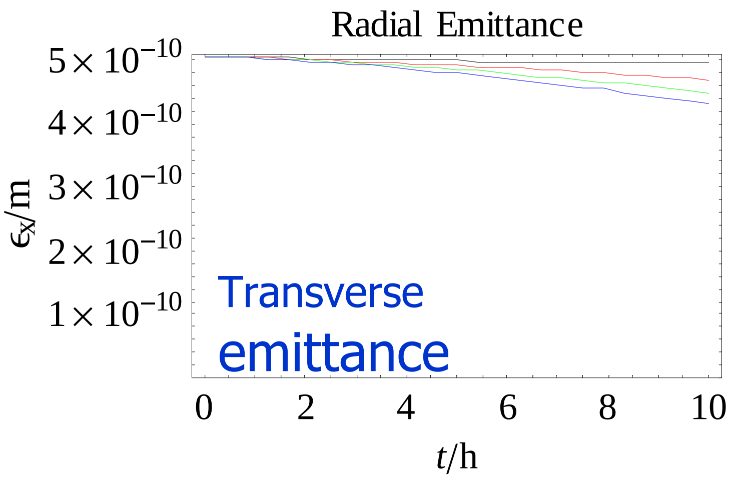
Maximum of curve gives optimum fill length.

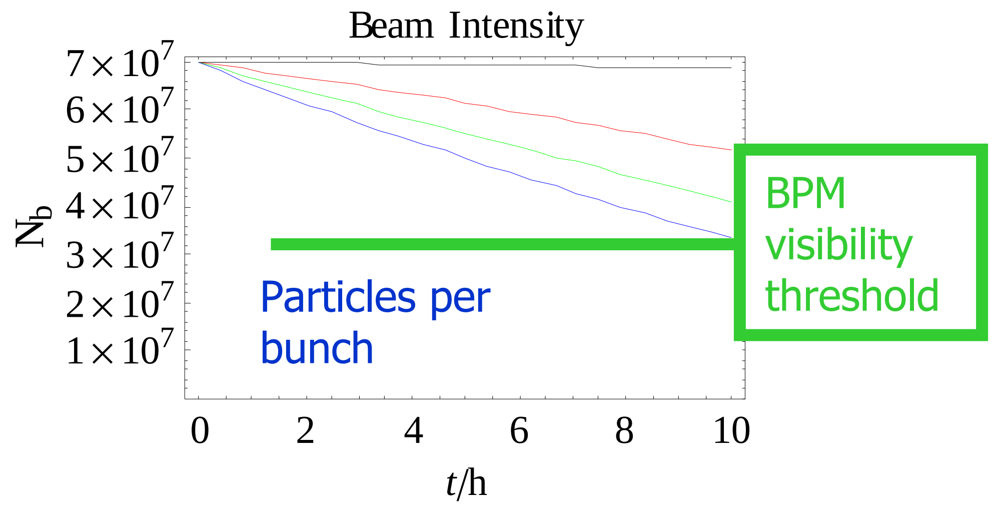


No. of experiments: $n_{exp} = 0, 1, 2, 3$

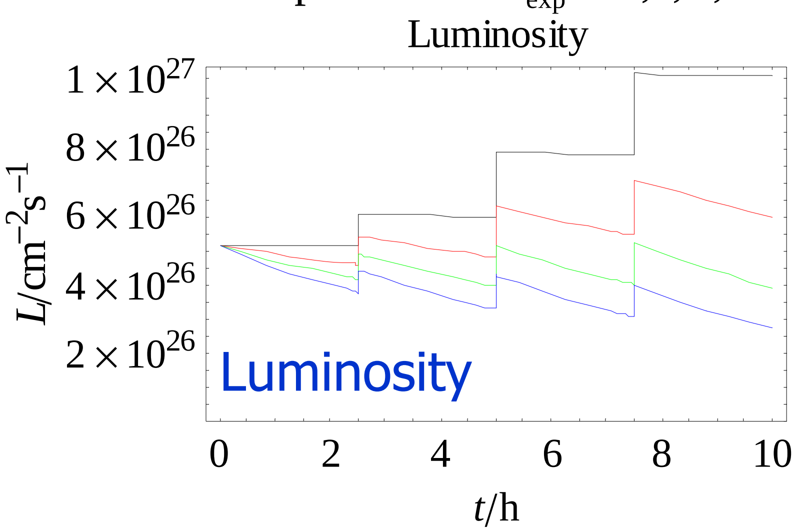
If turn-around time is short enough, beams may be dumped to maximise average L **before** BPM visibility threshold is reached.

Luminosity evolution: β*-tuning





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



A. Morsch proposed adjusting β* as intensity decays to maximise integrated luminosity.

Beams can be kept longer.

Operational feasibility in LHC to be demonstrated (to some extent in studies at RHIC).

Summary for Baseline Pb-Pb

- Early Ion Scheme to be scheduled
  - Switchover from p-p should be < 1 week.
- Opportunity for *additional* **Pilot Ion Run** for very early physics results
  - *If* ion injection available at the right time, etc
  - Very short, little loss of pp time
- Performance limits for Nominal Scheme to be clarified with Early Scheme, in particular:
  - Test understanding of BFPP and quenches
  - Test understanding of losses from collimation (see next talk!)
  - Intensity limits in PS, SPS
- After Early Scheme Run, adapt strategy (filling pattern, bunch-splitting in PS, …), increase number of bunches towards Nominal
- Complete first phase of LHC ion programme (~1 nb^{-1} Pb-Pb, several weeks total operational beam time for physics)

Medium-term Upgrade possibilities for Heavy Ion physics in the LHC

Expected for many years,

Physics case already presented.

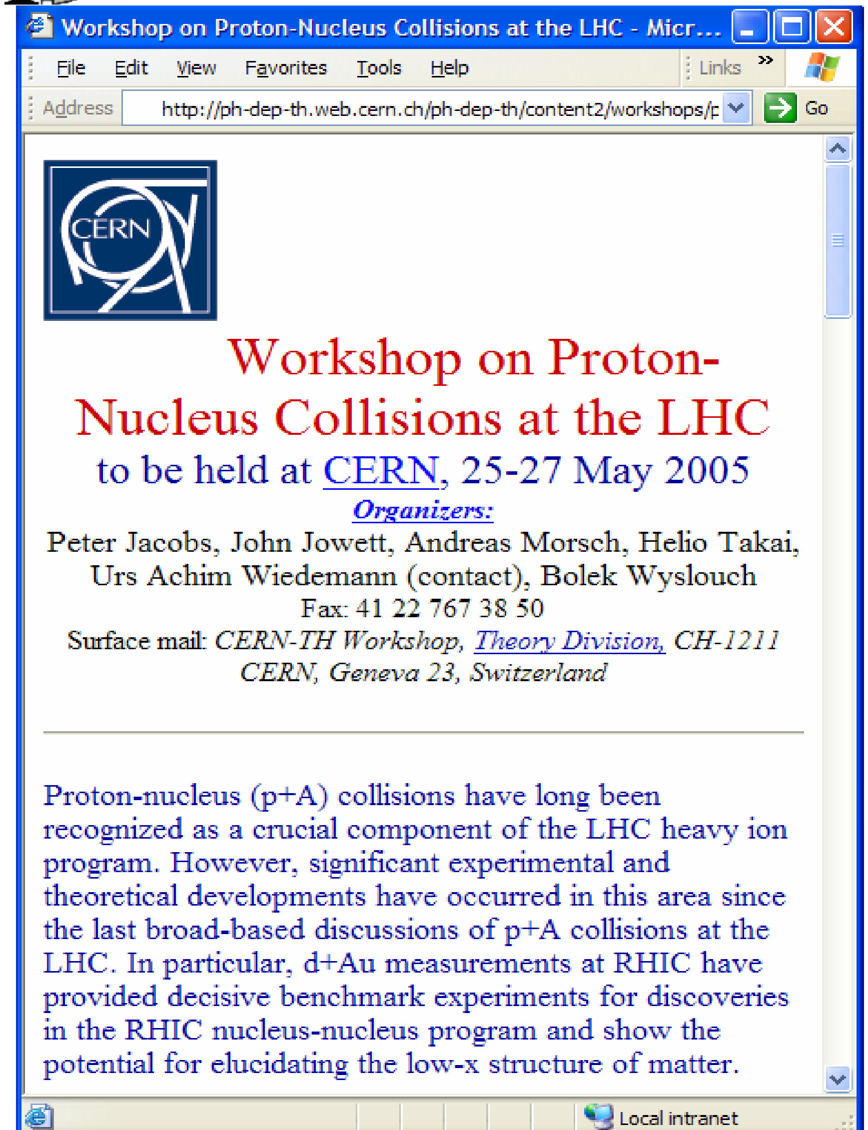
Approach for this presentation

- In the context of PAF, I will try to adopt a level of optimism comparable to that applied to other future upgrades of the LHC
  - Yes, there are certainly problems to be solved.
  - R&D may lead us to solutions
  - Many things (physics requirements, performance limits, feasibility of upgrades, …) will become clearer after some HI operation of the LHC.
- Anticipate possible future requirements of the experiments
  - LHC Experiments Committee statements
  - J. Schukraft's presentation at POFPA, 11 Nov 2005
  - NSAC Review of Heavy Ion Physics in USA (2004)
  - Guidance from evolution of RHIC programme
  - Informal communications

Status of work on the LHC Ion Upgrades

- Discussions in early 1990s
  - Luminosity, lifetime considerations for various ions
- In recent years, (almost) no CERN resources have been devoted to study of the LHC Ion upgrades beyond Baseline Pb-Pb
  - This is quite different from the situation for protons where there are busy CARE-HHH working groups, workshops, etc.
  - Nevertheless the *medium-term* Ion Upgrades are generally expected to occur *before* the pp upgrades (although there is now more risk of overlap …)
- Long-term upgrades
  - More speculative, brief mention later in this presentation

Proton-Nucleus (p-A) Collisions


Workshop on Proton-Nucleus Collisions at the LHC - Micr...
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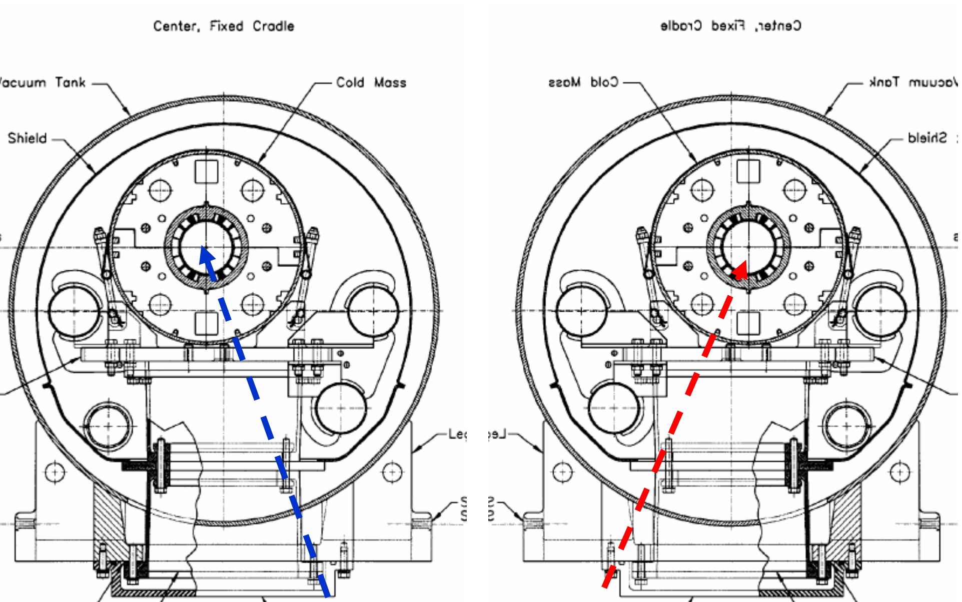
Workshop on Proton-Nucleus Collisions at the LHC
to be held at CERN, 25-27 May 2005
Organizers:
Peter Jacobs, John Jowett, Andreas Morsch, Helio Takai, Urs Achim Wiedemann (contact), Bolek Wyslouch
Fax: 41 22 767 38 50
Surface mail: *CERN-TH Workshop, Theory Division, CH-1211 CERN, Geneva 23, Switzerland*

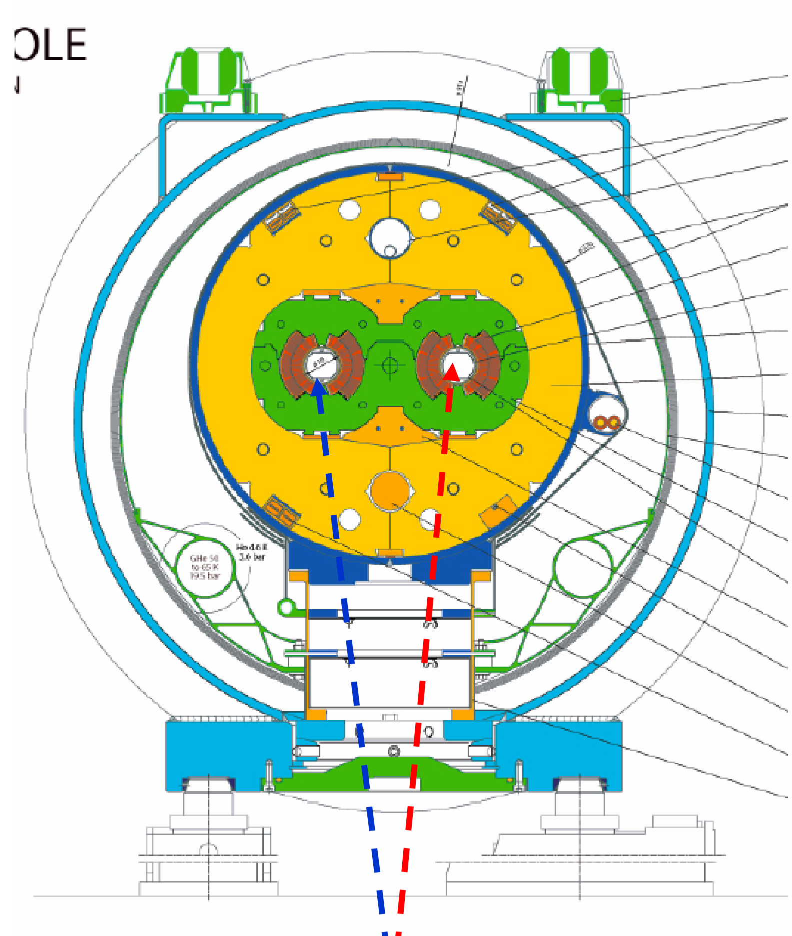
Proton-nucleus (p+A) collisions have long been recognized as a crucial component of the LHC heavy ion program. However, significant experimental and theoretical developments have occurred in this area since the last broad-based discussions of p+A collisions at the LHC. In particular, d+Au measurements at RHIC have provided decisive benchmark experiments for discoveries in the RHIC nucleus-nucleus program and show the potential for elucidating the low-x structure of matter.

Local intranet

- Workshop at CERN last year
  - Mainly on physics
- Machine session:
  - Review of RHIC experience with d-Au collisions
  - Demonstration (C. Carli) that LHC injector chains can function efficiently in tandem to produce matching filling patterns of p and Pb in LHC
  - First analysis of p-A operation of LHC, counter arguments given (JMJ) to doubts concerning feasibility (RHIC's bad experience with unequal revolution frequencies)
- See also recent EPAC06 paper

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

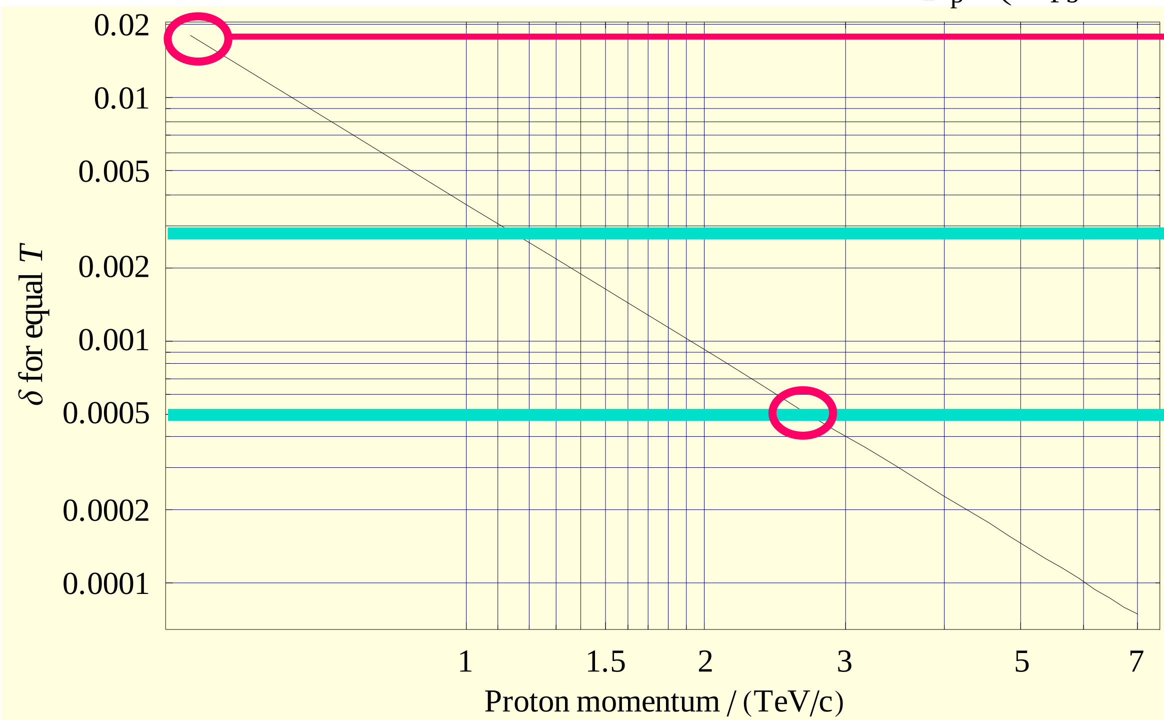
Kinematics of colliding nucleon pairs

	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)
$\sqrt{s}$ / TeV	14	1148	126.8	126.8
$\sqrt{s_{\mathrm{NN}}}$ / 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 among these numbers are a simple, direct consequence of the two-in-one magnet design.

Momentum offset for equal frequencies in ramp

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



Would move beam by 35 mm in QF!!

Limit with pilot beams

Limit in normal operation

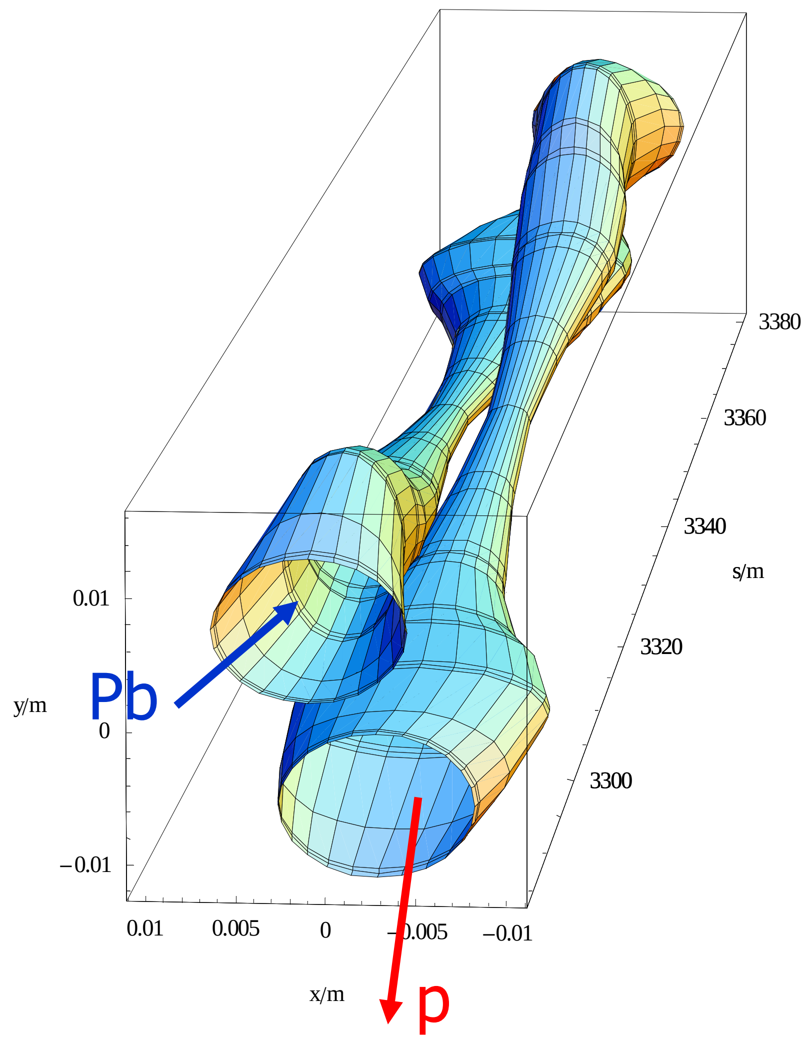
Revolution frequencies must be equal for collisions.

⇒ Lower limit on p-Pb collision energy where RF frequencies can become equal $E_{\mathrm{p}} >\sim 2.7\ \mathrm{TeV} \Rightarrow \sqrt{s_{\mathrm{NN}}} >\sim 3.3\ \mathrm{TeV}$

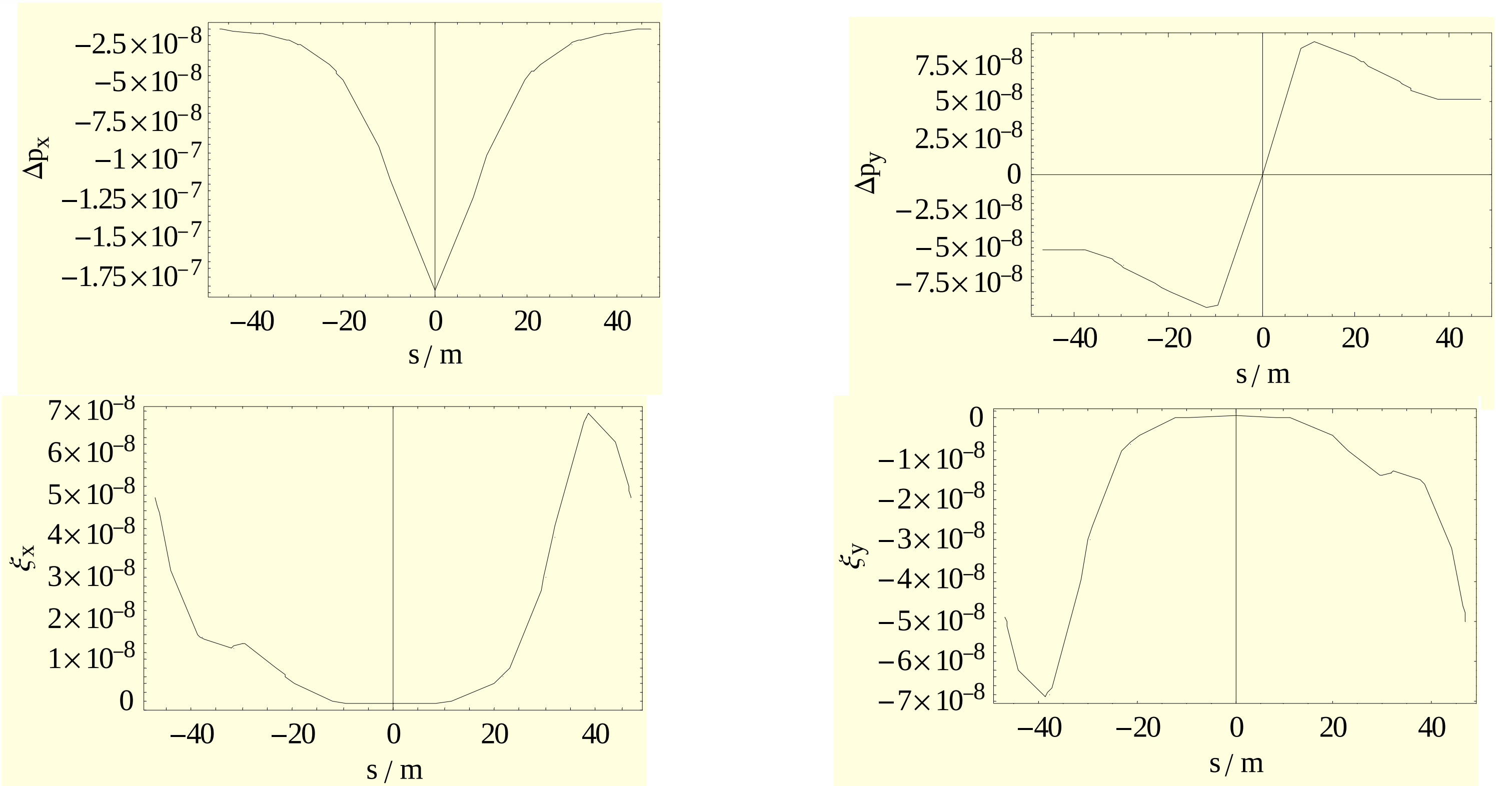
$(\text{OK for } \sqrt{s_{\mathrm{NN}}} = 5.5\ \mathrm{TeV} \Rightarrow E_{\mathrm{p}} = 4.38\ \mathrm{TeV})$

Beam Separation in IR2 (around ALICE) at injection

- 5σ envelopes of beams 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.
- Other IRs similar



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.

Typical Performance

As in above example, 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).

With Pb ion nominal bunch structure in both beams, this would give luminosity $L = 1.5\times10^{29}\ \mathrm{cm^{-2}s^{-1}}$, in p+Pb collisions at the LHC.

This luminosity is already adequate for physics but there is reasonable hope to go beyond.

Luminosity lifetime in range of a few hours, can be optimised.

Calculations need updating to include radiation damping, IBS, luminosity burn-off, added RF noise, etc.

Further work required on p-A

- General checking of all systems
- More study of common BPMs, RF systems
  - Prepare hardware modifications
- Coupling via electromagnetic cross-talk between two RF systems or other systems ?
  - c.f. PS Booster (K. Schindl)
- Machine studies at RHIC during next d-Au run ?
- Once LHC is working with p-p or Pb-Pb
  - Machine development studies on different revolution frequencies, effects of transverse feedback, acceptable δ, etc. would be valuable.
  - Fold experience into proper planning of p-A upgrade
- How much integrated luminosity is needed for physics?
  - Update lifetime and luminosity calculations

Summary and Outlook for p-A

- p-Pb upgrade of the LHC appears feasible.
  - Some, but not all, of the Pb-Pb problems
  - Some, but not all, of the p-p problems
  - Some specifically p-Pb beam dynamics problems deserve further study.
  - Modest investment in LHC Main Rings hardware
- d-Pb only slightly easier (from Main Ring beam dynamics point of view) but would require investment
  - See p-A Workshop talk on injector chain by C. Carli
- We might be asked to do this around 2011
  - Preparation should be thorough (HI runs are short so must be prosecuted efficiently!) and must start in time.
- p-(lighter A) seems not to be more difficult than p-Pb.

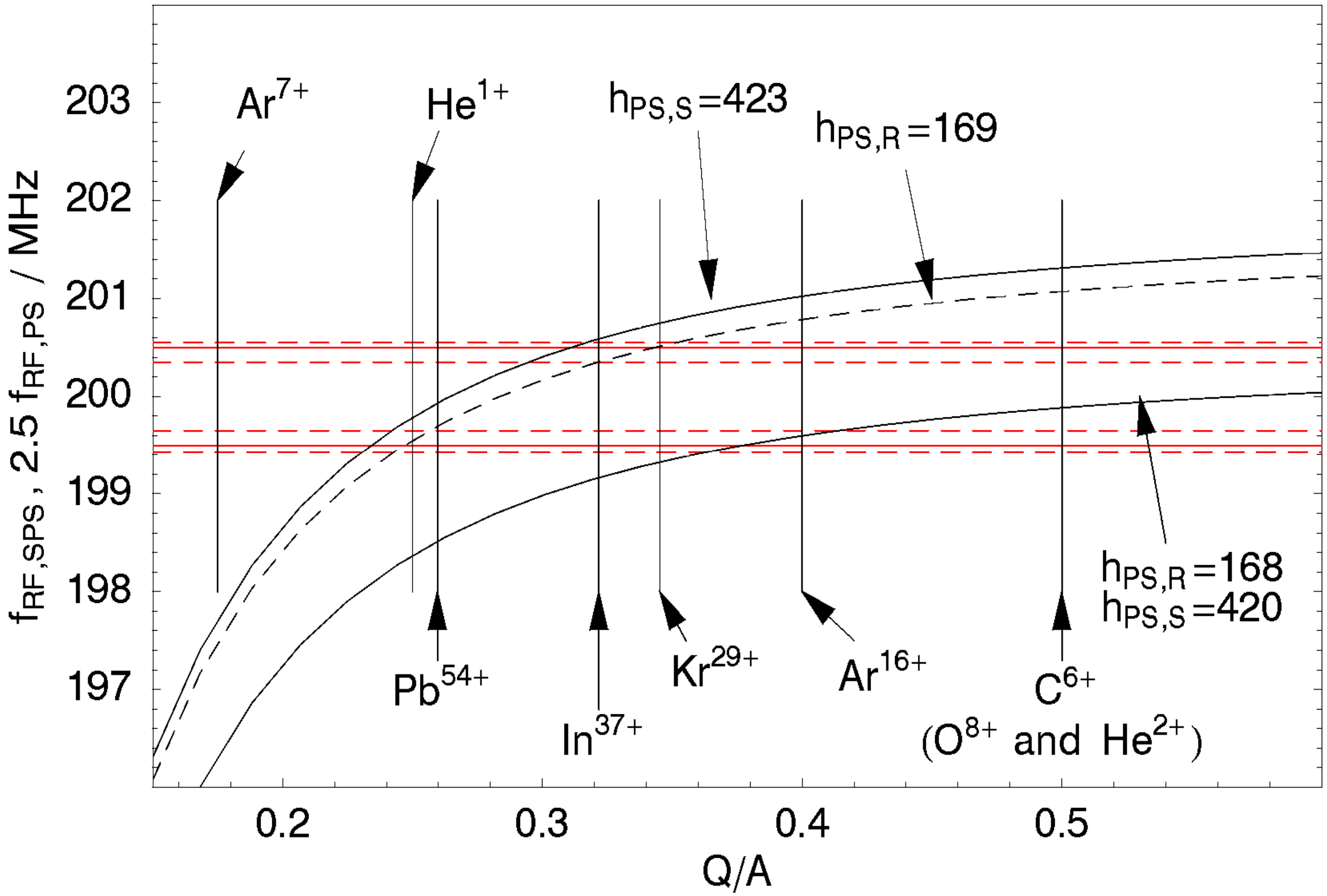
Lighter ions

- ECR source can deliver a wide range of ions
  - Some preference for lighter gaseous elements (He, Ar, O, …)
  - Needs setup time for each change
- LEIR foreseen to accelerate and cool
- Intensity limits
  - Space charge in LEIR, PS, SPS
  - IBS in SPS?
  - Vacuum in LEIR ?
  - Etc.
  - Need to be thoroughly revised to make new performance estimates
  - Many details to check, e.g., following slides …

Transfer PS->SPS for light ions

- From: C. Carli, M.Chanel, S. Hancock, J.-L. Vallet …….

- Transfer for Pb^{54+}:
  - real $h_{PS,R}$ = 169 (80 MHz cavity),
  - for synchro $h_{PS,S}$ = 423 = h_{SPS}/11 (integer harmonic in SPS),
  - distance between bunches (8/169)xC_{PS} = (20/422.5)xC_{PS}
  - distance between SPS buckets (20/423)xC_{PS},
  - bunches slightly off-centered after transfer,
  - ➢ negligible blow-up due to filamentation.
- For lighter ions assumed:
  - maximum field in the PS -> Bρ = 26 GV/c (direct space charge tune shift, IBS?),
  - use of 80 MHz cavity -> $h_{PS,R}$ = 169 or 168,
  - for synchro $h_{PS,S}$ = h_{SPS}/11 = 423 or 420 (other harmonics ruled out due to technical difficulties of low level RF).
  - (almost) identical RF gymnastics in the PS, in particular every LEIR/PS cycle provides 4 LHC bunches.



RF frequencies (solid for PS and dashed for SPS) for PS->SPS transfer versus Q/A

- maximum magnetic field in the PS,
- 200 MHz system in the SPS,
- 80 MHz system in the PS.

Summary on transfer PS->SPS for light ions

- Transfer PS->SPS
  - for light ions (say Q/A ~ 0.5), $h_{PS,R}$ = 168 is suitable for transfer PS->SPS,
  - no extrapolated solution for "intermediate Q/A" !!!!,
  - synchronization with $h_{PS,S}$ = 422 would help, but a problem for low level RF,
  - only frequencies checked, not (yet) voltages in PS ….
    - Probably o.k. : SPS injection well below γ_{tr} (i.e. large η)
- Transfer LEIR -> PS:
  - for lighter ions higher revolution frequ's for $B\rho$ = 4.8
  - kicker gap may become an issue ("eats" up a larger fraction of the LEIR circumference)
  - ➢ transfer at lower $B\rho$?
  - ➢ LEIR with harmonic 3 and two bunches & an empty gap ?
- Gymnastics in PS:
  - frequencies increase for a given beam rigidities,
  - no problems expected, but should be checked.

Lower energy ion operation

- Reduced CM energy has been a significant feature of RHIC programme
  - Usually short runs at end of longer high-energy runs
- Requirements not yet clear for LHC but:
  - May happen before any reduced energy pp runs (??), with implications for operational strategy
  - We need to check the performance limits (particularly collimation) with larger beams …
  - We need to check performance of instrumentation and other systems in case any upgrades are needed

Summary medium term upgrades

- P-Pb operation likely to come first
  - looks promising but needs more study
- Lighter ions
  - Studies needed to revise performance estimates, ensure that all systems are adequate, launch any necessary preparation

Longer-term Upgrade possibilities for Heavy Ion physics in the LHC

So far, no resources applied to studying these.

Added value for CERN complex upgrades?

Very preliminary thoughts only !

Injector system upgrades

- Upgrades PS->PS2/PS+, SPS->SPS2, etc under consideration
- PS2 doubles SPS injection energy
  - Increase Pb single bunch intensity limit (IBS, space-charge in SPS)
  - Check limits earlier in chain (measurements in 2006-8), ensure that PS2 can accelerate ions from LEIR
  - Potential boost for luminosity per bunch
- SPS2 not obviously useful for ions
  - Reduces effect of IBS at LHC injection plateau.
- New ion source: improved ECRIS or EBIS?
  - EBIS now successful and being implemented at RHIC (~20M$)
  - Easy switching over wide choice of ions (up to U…), good emittance
  - Could replace ECR source, LINAC3 and (probably) LEIR with EBIS+RFQ
    - Might relax constraints on design of PS2 ?
    - Incorporate into new pre-injector schemes (LINAC4 etc.)?
  - Worth some consideration in PAF context ?

Latest POFPA report

CERN-PH-TH/2006-175
September 2006

Physics Opportunities with Future Proton Accelerators at CERN

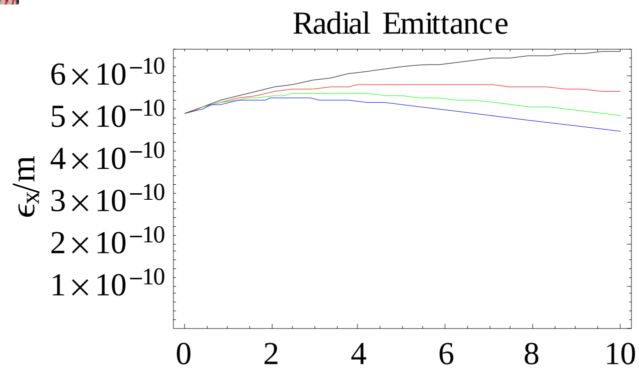
A. Blondel [a], *L. Camilleri* [b], *A. Ceccucci* [b],
J. Ellis [b], *M. Lindroos* [b], *M. Mangano* [b], *G. Rolandi* [b]

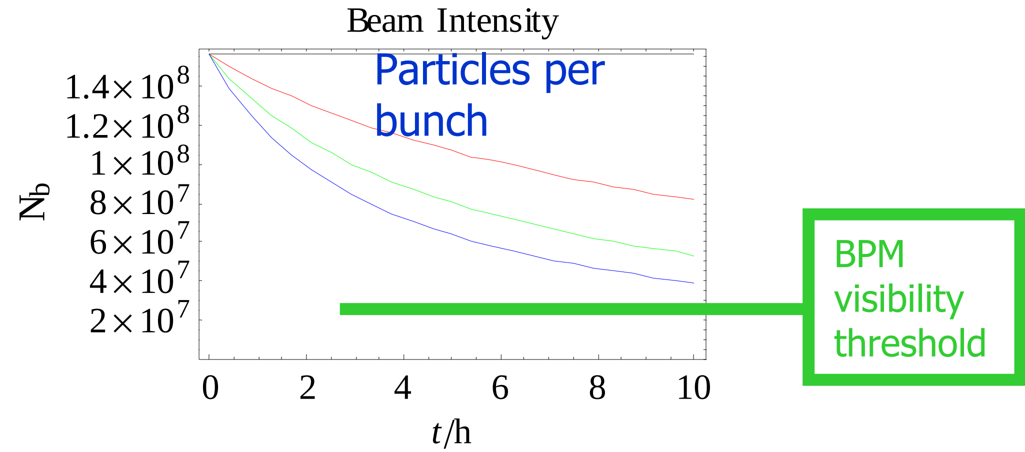
[a] *University of Geneva*
CH-1211 Geneva 4, SWITZERLAND

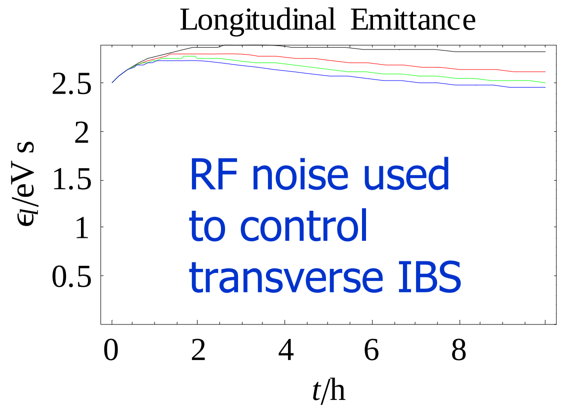
[b] *CERN,*
CH-1211 Geneva 23, SWITZERLAND

ALICE also requests an accelerator R&D programme to increase the Pb–Pb luminosity by a significant factor, aiming at 5×10^{27} $cm^{-2}s^{-1}$. This would be required to make good measurements of Υ, Υ′ and Υ″ production as well as γ–jet correlations, probes at the highest possible transverse momentum, and beauty production. In order to gather sufficient statistics, the ALICE Collaboration would like to run for three or four years at this enhanced luminosity. Obtaining this would require fighting pair production and electron capture, and rapid turnarounds and refills would also be desirable. In view of the lower multiplicity now expected in the TPC, its readout could be

Luminosity evolution in *extreme* Pb luminosity upgrade



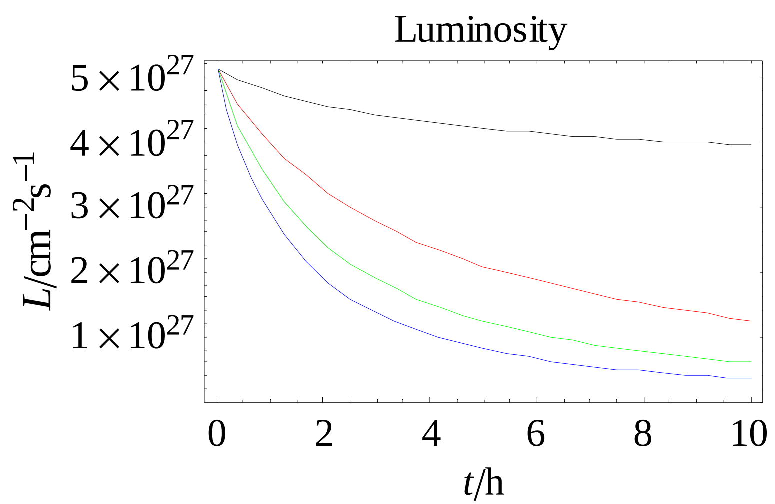




No. of experiments: $n_{exp} = 0, 1, 2, 3$

Emittance control is key, RF noise goes some way towards transverse cooling.

More bunches is another route.



An "ideal" fill, starting from parameters giving 5×nominal luminosity.

Conceivable Ion-specific Upgrade Projects

- New collimation schemes
  - Conventional, nonlinear, crystal, … see HB's talk
- Microwave stochastic cooling of ion beam halo in LHC
  - Progress with bunched-beam stochastic cooling at RHIC
  - Could help beam losses, reduce requirements on collimation system
  - Examine feasibility, R&D towards possible project ?
- Optical stochastic cooling
  - Probably not feasible in LHC (A. Zholents, JMJ) but recent "enhanced" variants are claimed to be.
  - Requires demonstration of feasibility on smaller machine first
- Electron cooling at high energy in LHC
  - Copy RHIC electron cooler at even higher energy and power ???
  - Energy Recovery Linac: 1.5 GeV, ~ GW beam power … seems unlikely

Heavy-Ion Physics after LHC IR upgrade (SLHC)

- LHC interaction regions IR1 (ATLAS) and IR5 (CMS) may be upgraded for higher luminosity
  - Assume that IR2 (ALICE) will not be substantially changed
  - During high luminosity pp runs, beams will simply be separated at ALICE – no interference
- It seems clear that, if required:
  - HI physics runs could continue at ALICE
  - HI physics runs could continue at ATLAS and/or CMS, presumably with IR optics detuned to equalise luminosity with ALICE
- LHC upgrades should keep these possibilities in mind
  - Avoid doing anything that would jeopardise them
  - Consider any adaptations that would also help ions

Heavy Ion Physics after LHC Energy Upgrade (D/TLHC)

- An increase in LHC energy by a factor 2-3 is not especially useful for HI physics (JS at POFPA) but …
  - Dramatic increase in synchrotron radiation damping of ion beams, IBS weaker also ~ free cooling system $\frac{1}{\tau} \propto E^3$
  - BFPP quenches ~ twice as bad / Luminosity
  - Collimation quenches ~ twice as bad /(Total beam current)
- If, as is hoped, the new high-field magnets are less susceptible to quenching (or we have found other solutions to these problems by that time …) then DLHC or TLHC might be a useful *luminosity* upgrade (c.f. RHIC II) for ion physics.
  - Needs study!

Other physics with ion beams

- I did not consider (c.f. September 2006 POFPA report):
  - Possible future fixed target physics with ion beams
  - Any kind of electron-ion collider
- If these are of interest, then there may be implications for the future evolution of the ion sources and injector complex at CERN.

Conclusions

- LHC Ion programme has potential for long future
  - As for protons, there are serious performance limitations (BFPP, collimation,…) to work on, even to attain the "nominal" baseline luminosity.
  - Ion collider performance has additional dimension (*E*,*L*,species)
- Long-foreseen medium-term upgrades (p-Pb, lighter A-A collisions) expected *before* major upgrades of LHC and injectors
  - Require planning and work to start in good time:
    - Ion source
    - Performance limits in injector chain and in LHC main rings
    - Verification of all systems
- LHC ion programme could benefit from LHC injector upgrades (PS2)
  - New ECRIS/EBIS source may be worth incorporation into injector upgrades
- Candidates for longer term upgrades need R&D
  - May learn from RHIC upgrades
- The number of experiments taking data is important at many stages of the programme and needs to be clarified.