I-LHC Project
Overview and Status

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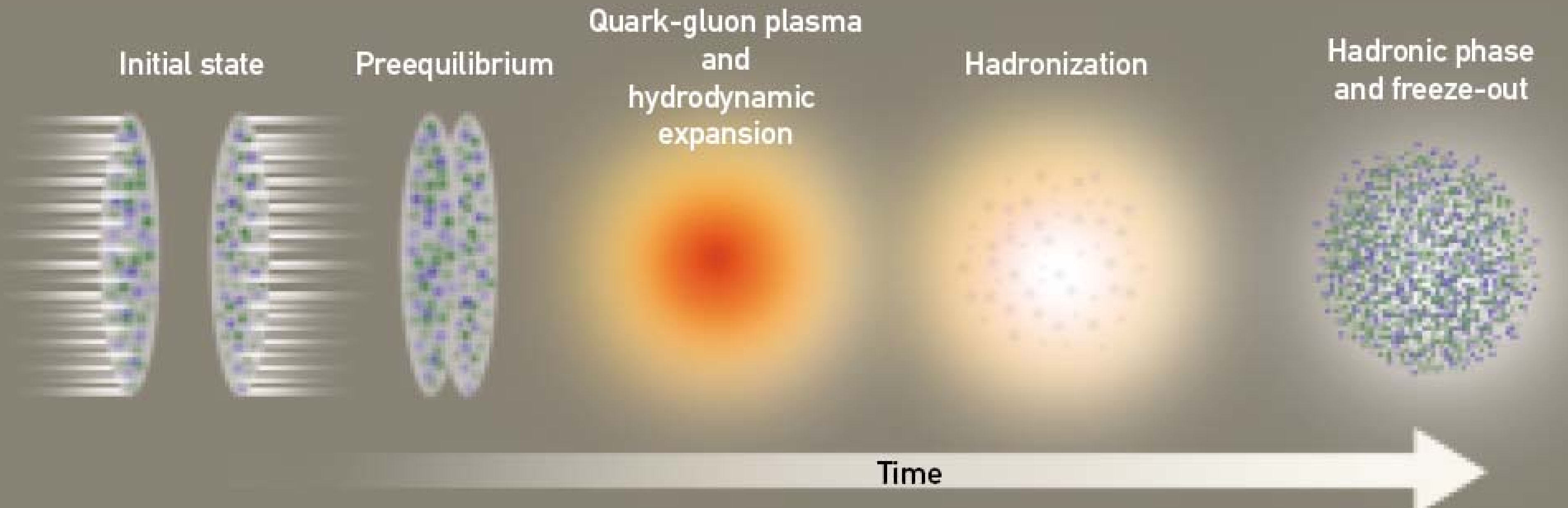


Heavy Ion Physics Parameters

		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 / 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.

I-LHC Long-Term 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
    - 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.

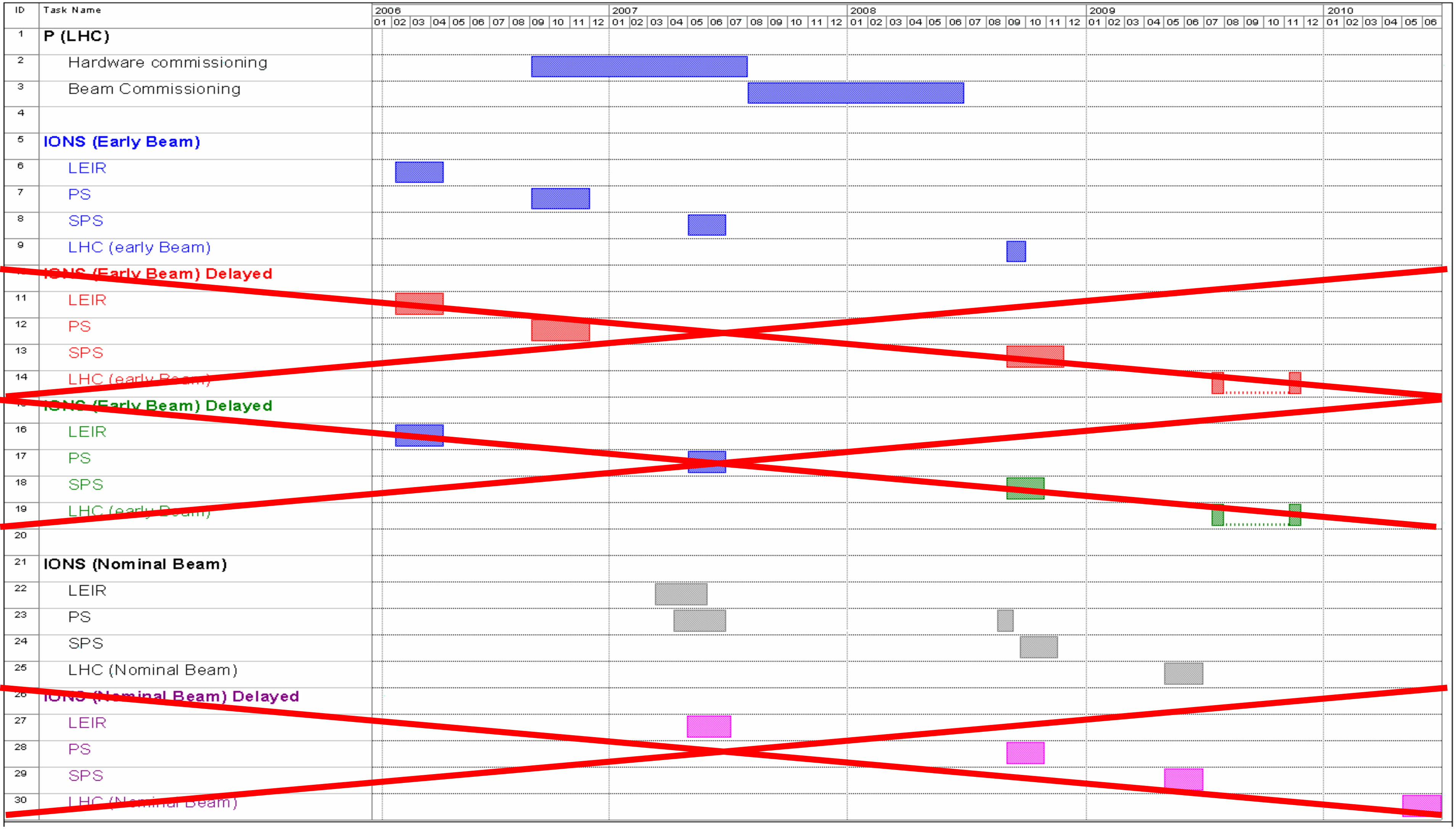
Nominal vs Early Ion Beam in LHC

- Why Early Beam?
  - Easier for injectors, shorter LHC filling time (4 min/ring)
  - Keep nominal bunch population (7 10^7 ions/bunch) to study limitations without risks
  - A Luminosity of L=5. 10^{25} cm^{-2} s^{-1} (lower by a factor 20) by fewer bunches (1/10) and β^* =1 m (factor 1/2) useful for physics (early results)
  - Improved Luminosity lifetime because of larger β^*

Nominal vs. Early Ion Beam: Key Parameters

Parameter	**Units**	**Nominal**	**Early Beam**
Energy per nucleon	TeV/n	2.76	2.76
Initial Luminosity L_0	cm^{-2} s^{-1}	1 10^{27}	5 10^{25}
No. bunches/bunch harmonic		592/891	62/66
Bunch spacing	ns	99.8	1350
β^*	m	0.5 (same as p)	1.0
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	8, 4.5, 3	14, 7.5, 5.5

Lead Ion Schedule (post-Chamonix 2006)



ID	Task Name
1	**P (LHC)**
2	Hardware commissioning
3	Beam Commissioning
4	
5	**IONS (Early Beam)**
6	LEIR
7	PS
8	SPS
9	LHC (early Beam)
~~10~~	~~**IONS (Early Beam) Delayed**~~
~~11~~	~~LEIR~~
~~12~~	~~PS~~
~~13~~	~~SPS~~
~~14~~	~~LHC (early Beam)~~
~~15~~	~~**IONS (Early Beam) Delayed**~~
~~16~~	~~LEIR~~
~~17~~	~~PS~~
~~18~~	~~SPS~~
~~19~~	~~LHC (early Beam)~~
20	
21	**IONS (Nominal Beam)**
22	LEIR
23	PS
24	SPS
25	LHC (Nominal Beam)
~~26~~	~~**IONS (Nominal Beam) Delayed**~~
~~27~~	~~LEIR~~
~~28~~	~~PS~~
~~29~~	~~SPS~~
~~30~~	~~LHC (Nominal Beam)~~

Electromagnetic Interactions of Heavy ions

QED effects in the peripheral collisions of heavy ions		
Rutherford scattering:	$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+}$	Copious but harmless
Free pair production:	$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} + e^+ + e^-$	Copious but harmless
Electron capture by pair production (ECPP)	$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + e^+$ Electron can be captured to a number of bound states, not only 1s.	Secondary beam out of IP, effectively off-momentum" $\delta_p = \frac{1}{Z-1} = 0.012 \quad \text{for Pb}$
Electromagnetic Dissociation (EMD)	$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + ({}^{208}\mathrm{Pb}^{82+})^*$ $\downarrow$ $^{207}\mathrm{Pb}^{82+} + n$	Secondary beam out of IP, effectively off-momentum: $\delta_p = -\frac{1}{A-1} = -4.8\times10^{-3} \text{ for Pb}$

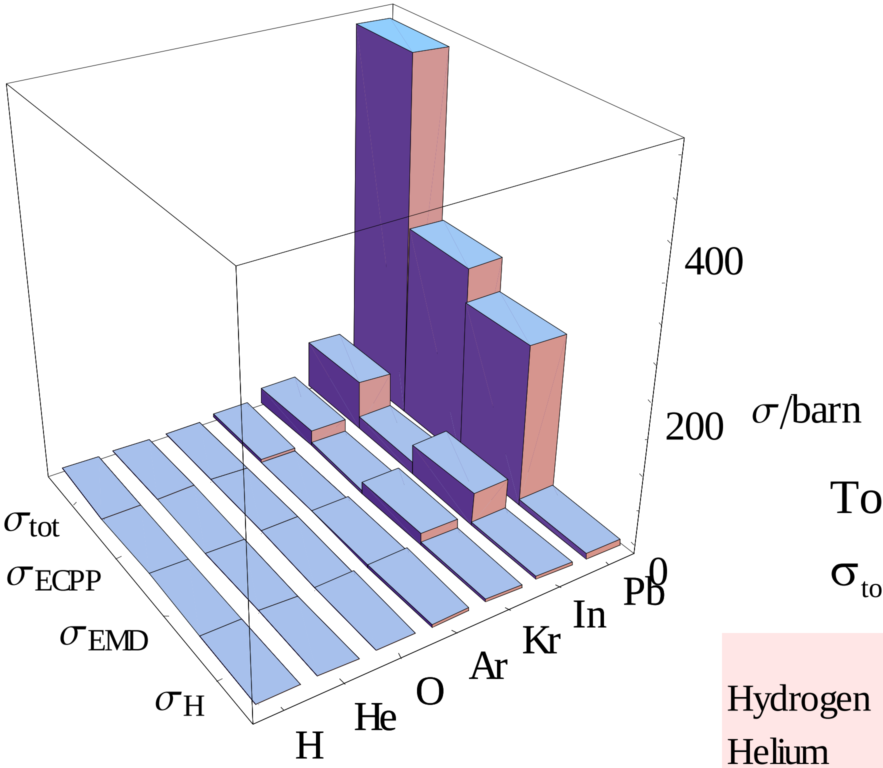
(Numerous other changes of ion charge and mass state happen at smaller rates.)

$$\delta(\Delta Q, \Delta A) \simeq \frac{1+\Delta A/A}{1+\Delta Q/Q} - 1$$

Nuclear cross sections

- Cross-section for Pb totally dominated by electromagnetic processes
- Values for non-Pb ions may need upward revision

BFPP(=ECPP) from Meier et al, Phys. Rev. A, **63**, 032713 (2001), calculation for Pb-Pb at LHC energy



Total cross-section for ion removal from beam

$$\sigma_{\text{tot}} = \sigma_{\text{H}} + \sigma_{\text{EMD}} + \sigma_{\text{ECPP}}$$

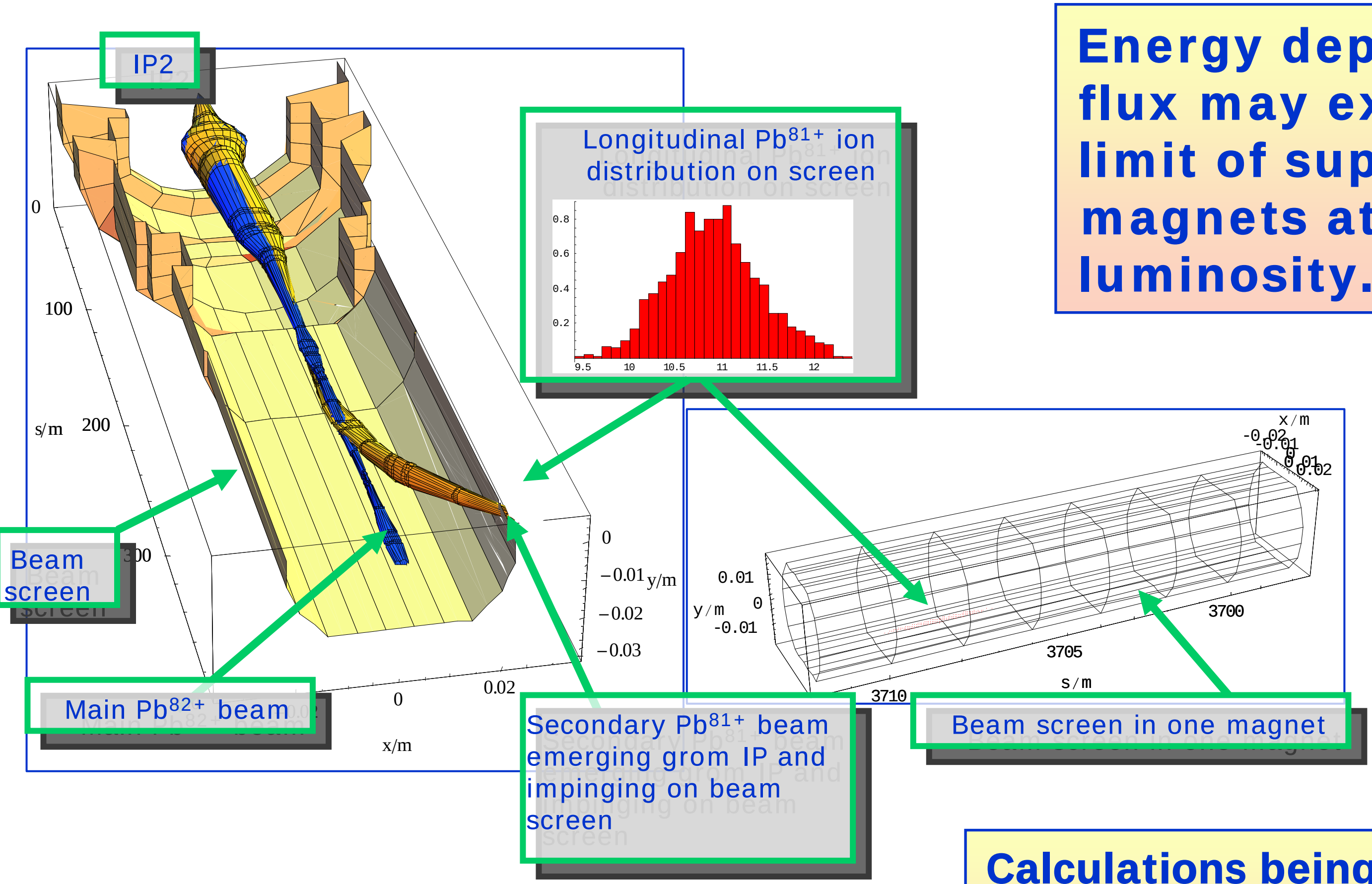
	σ_{H}	σ_{EMD}	σ_{ECPP}	σ_{tot}
Hydrogen	0.105	0	4.25×10^{-11}	0.105
Helium	0.35	0.002	$1.\times10^{-8}$	0.352
Oxygen	1.5	0.13	0.00016	1.63016
Argon	3.1	1.7	0.04	4.84
Krypton	4.5	15.5	3.	23.
Indium	5.5	44.5	18.5	68.5
Lead	8	225.	280.756	513.756

$$\delta(\Delta Q, \Delta A) \simeq \frac{1+\Delta A/A}{1+\Delta Q/Q} - 1$$

Need to update

Luminosity Limit from BFPP

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



IP2

Longitudinal Pb^{81+} ion distribution on screen

Beam screen

Main Pb^{82+} beam

Secondary Pb^{81+} beam emerging grom IP and impinging on beam screen

Beam screen in one magnet

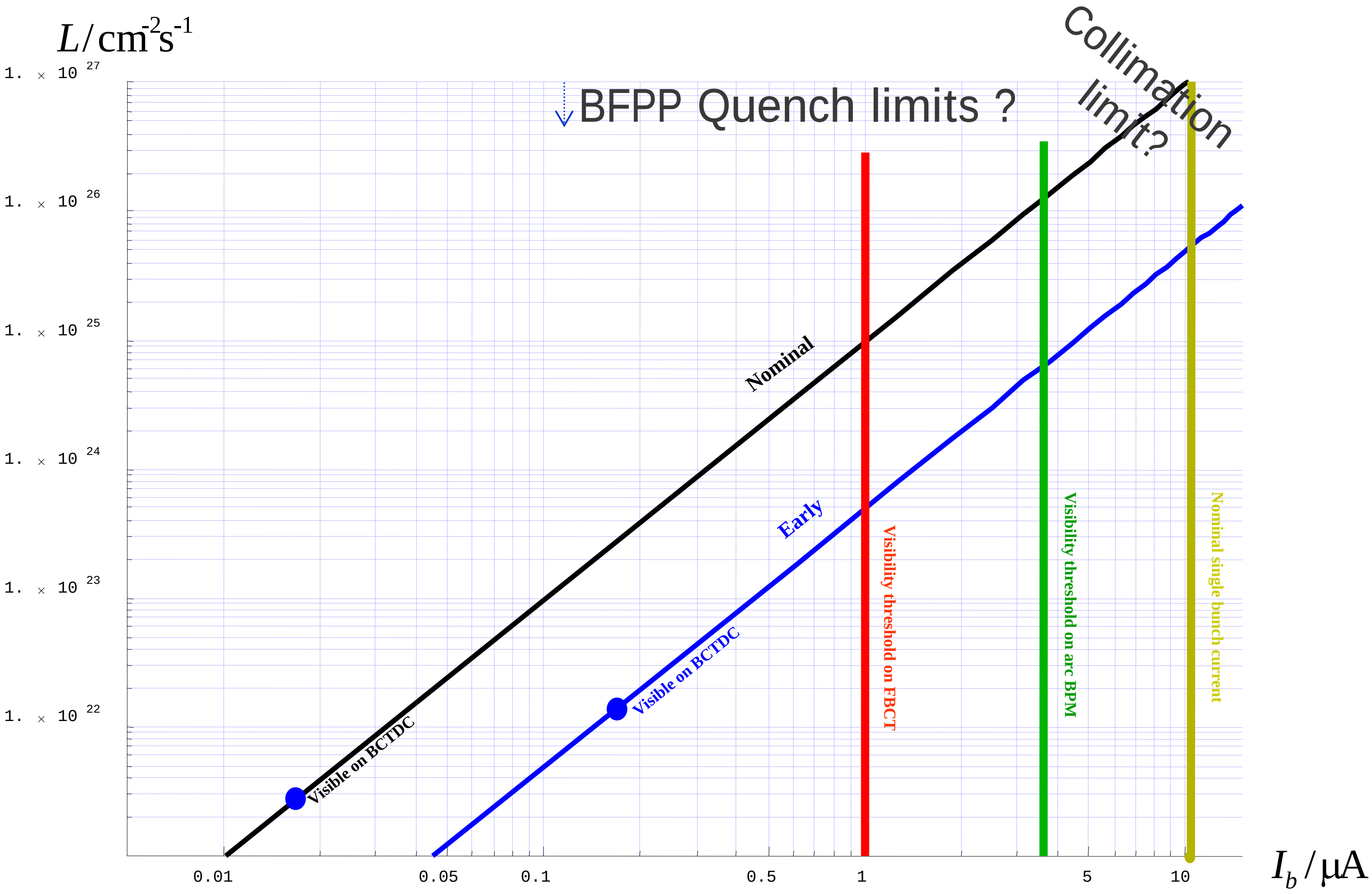
Energy deposition by ion flux may exceeds quench limit of superconducting magnets at nominal luminosity.

See LHC Project Note 379,

New estimates for dipole quench limit

Calculations being refined with new ion-matter interaction models in FLUKA

Operational Parameter Space for Pb Ions



Thresholds for visibility on BPMs and BCTs.

Optical Parameters at the IPs (Nominal)

```
IPopticsTable["CollisionIons", "LHCB1"]
```

//NumberForm=

	IP1	IP2	IP5	IP8	IP1.L1
β_x/m	0.55	0.5	0.55	10.	0.55
β_y/m	0.55	0.5	0.55	10.	0.55
x_c/mm	1.1×10^{-9}	-3.59×10^{-9}	0.5	-3.18×10^{-9}	1.1×10^{-9}
y_c/mm	-0.5	5.77×10^{-9}	2.08×10^{-9}	-0.5	-0.5
p_{xc}/μrad	-2.95×10^{-6}	2.63×10^{-6}	142.	$-210.$	-2.95×10^{-6}
p_{yc}/μrad	143.	$-10.$	-7.9×10^{-6}	-1.81×10^{-7}	143.

```
IPopticsTable["CollisionIons", "LHCB2"]
```

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	IP1	IP2	IP5	IP8	IP1.L1
β_x/m	0.55	0.5	0.55	10.	0.55
β_y/m	0.55	0.5	0.55	10.	0.55
x_c/mm	4.11×10^{-9}	3.94×10^{-9}	0.5	-2.43×10^{-8}	4.11×10^{-9}
y_c/mm	-0.5	-6.01×10^{-9}	-2.72×10^{-9}	0.5	-0.5
p_{xc}/μrad	-2.79×10^{-6}	5.5×10^{-6}	$-142.$	210.	-2.79×10^{-6}
p_{yc}/μrad	$-142.$	10.	-0.0000107	-2.69×10^{-6}	$-142.$

Optical Parameters at the IPs (Early)

```
IPopticsTable["EarlyCollisionIons", "LHCB1"]
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	IP1	IP2	IP5	IP8	IP1.L1
β_x/m	2.	1.	2.	10.	2.
β_y/m	2.	1.	2.	10.	2.
x_c/mm	-1.11×10^{-9}	2.29×10^{-9}	0.322	1.78×10^{-9}	3.08×10^{-9}
y_c/mm	-0.322	2.78×10^{-9}	3.61×10^{-10}	-2.	-0.322
p_{xc}/μrad	2.37×10^{-6}	-1.83×10^{-6}	92.	-170.	1.86×10^{-6}
p_{yc}/μrad	92.	-2.13×10^{-6}	-1.98×10^{-6}	8.67×10^{-7}	92.

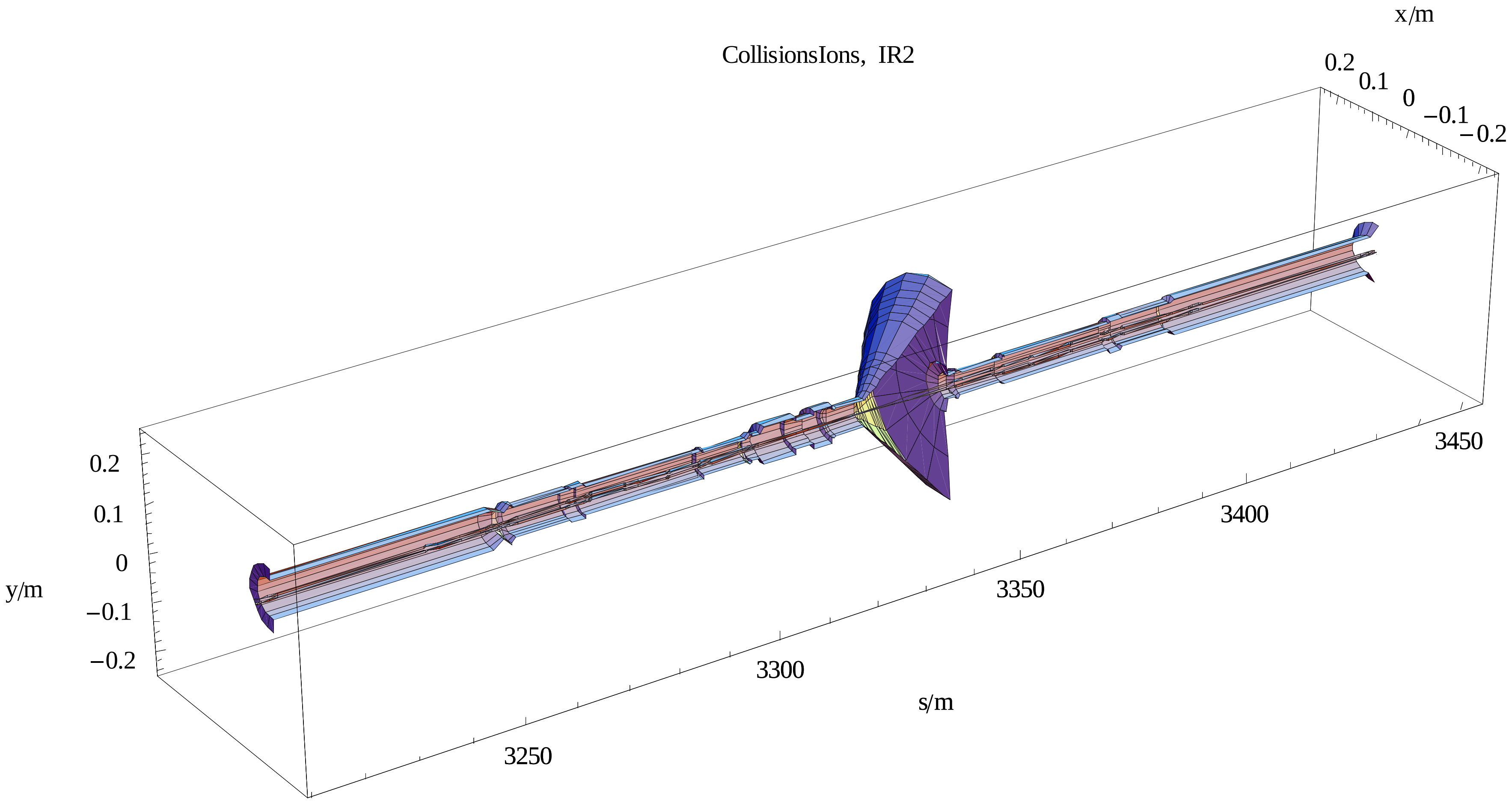
```
IPopticsTable["EarlyCollisionIons", "LHCB2"]
```

/NumberForm=

	IP1	IP2	IP5	IP8	IP1.L1
β_x/m	2.	1.	2.	10.	2.
β_y/m	2.	1.	2.	10.	2.
x_c/mm	3.94×10^{-9}	3.09×10^{-9}	0.322	-8.36×10^{-9}	3.94×10^{-9}
y_c/mm	-0.322	-4.5×10^{-9}	-5.35×10^{-9}	2.	-0.322
p_{xc}/μrad	-1.74×10^{-6}	1.11×10^{-8}	-92.	170.	-1.74×10^{-6}
p_{yc}/μrad	-92.	-3.55×10^{-7}	-1.07×10^{-6}	-1.13×10^{-6}	-92.

Beams crossing inside LHC aperture, Nominal, IR2

```
IRcrossingPlot3D["CollisionsIons", "IR2", 2, 0.25]
```



Beams crossing, Nominal+EARLY, IR2 (2σ beam)

```
IRcrossingPlot3D["CollisionIons", "IR2", 2, 0.02]
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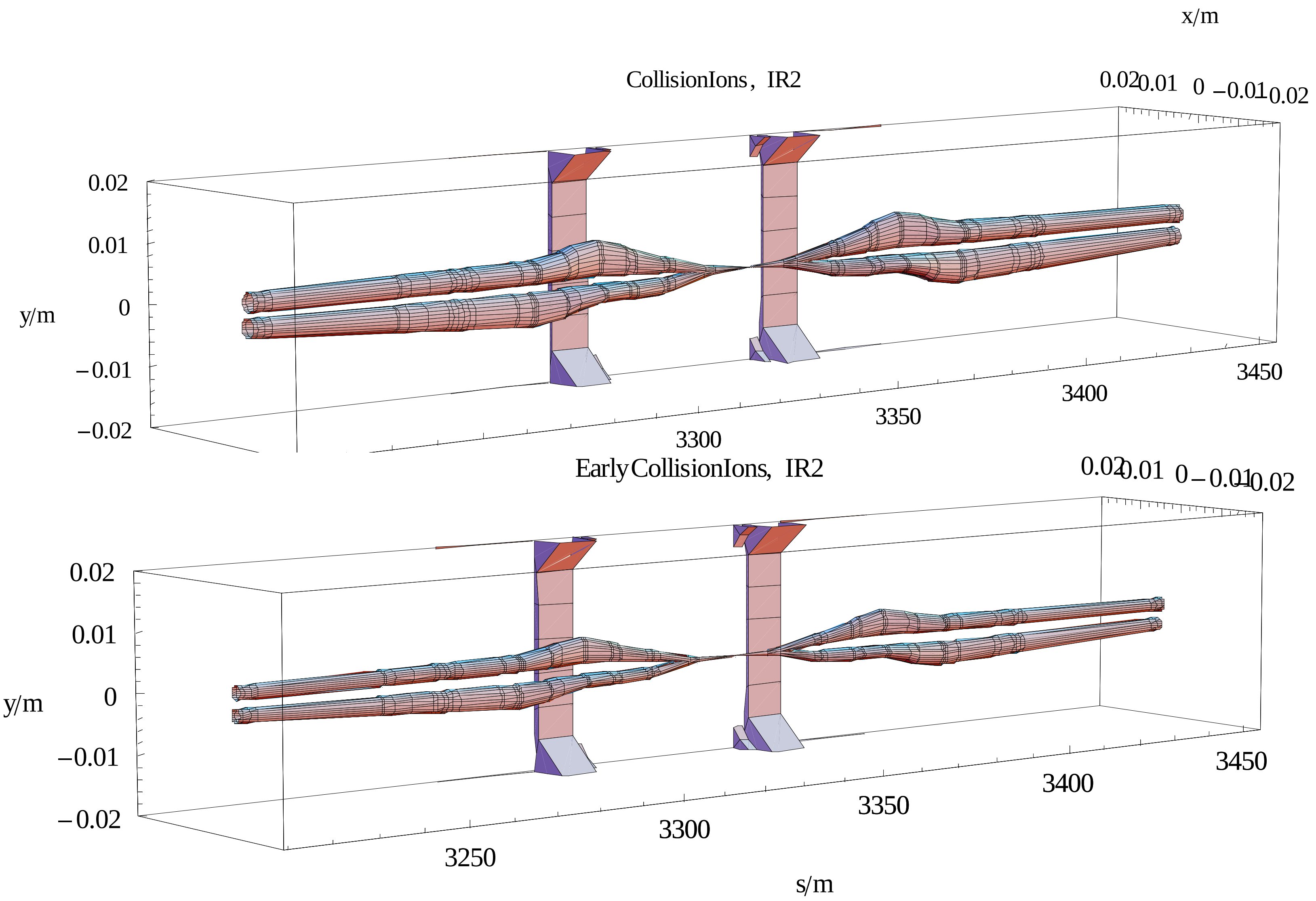
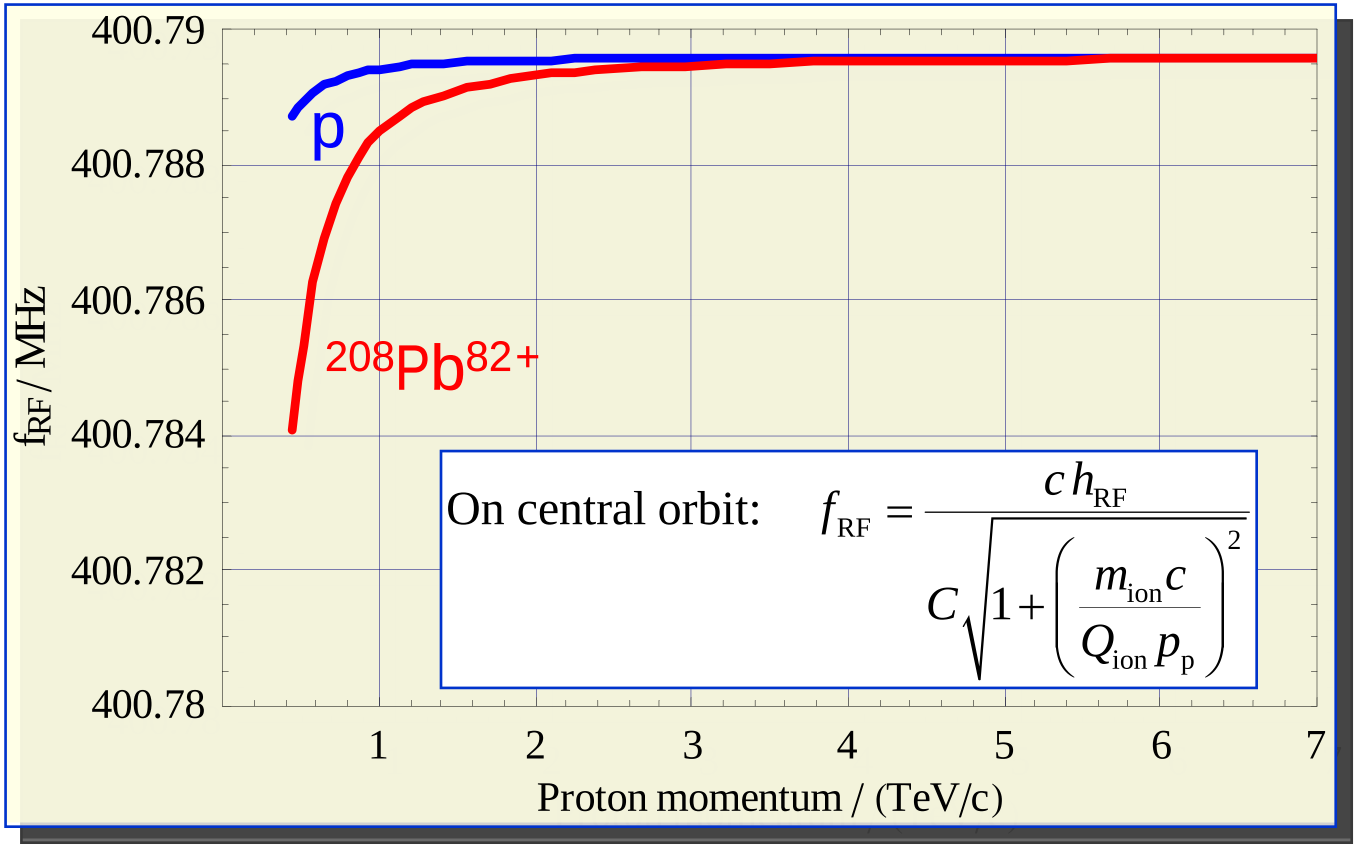


RF



On central orbit: $$f_{RF} = \frac{c\,h_{RF}}{C\sqrt{1+\left(\frac{m_{ion}c}{Q_{ion}\,p_p}\right)^2}}$$

- Larger frequency swing than with protons, no problem
- Different bunch filling schemes
- RF noise to be clarified (SPS MD to test continuous use)
- Needed to blow-up longitudinal emittance at collision energy (IBS)

Optics for the Early and Nominal Ion Schemes

- Same *geometrical* transverse beam size and emittance
  - Optics, dynamic aperture, mechanical acceptance, etc. similar to protons.
- Injection and ramp done with **exactly the same** optics, orbits, corrections, etc. as for protons
  - Should shorten ion commissioning time considerably!
- Colliding in ATLAS, CMS $\Rightarrow$ same squeeze as protons
- Leave IR8 in injection configuration
- Main difference is that IR2 is squeezed to $\beta^* = 2.,1.,0.5\ \mathrm{m}$
  - May - or may not - be operationally convenient to commission the ion optics first with low-intensity protons.
- Crossing angle at IP2 (1,5?) may be small (includes ALICE muon spectrometer, details in Design Report)
  - Aperture requirements somewhat relaxed w.r.t. protons
  - Operational time for polarity reversals

Plan for Commissioning LHC Rings with Lead Ions (1)

- Assume that protons can be collided
  - **Injection, ramp, squeeze (where applicable) are set up**
- Re-commission injection and first turns with single ion “pilot” bunch (close to nominal intensity)
  - Adjust BST
  - Energy matching to different SPS cycle, each ring
  - Should go quickly (magnetic reproducibility...)
  - Deal with any difference of geometric beam size from protons (collimator settings, etc.)
- Set up RF and capture (“few shifts”), instrumentation

Plan for Commissioning LHC Rings with Lead Ions (2)

- Re-commission ramp
  - Should also go quickly (magnetic reproducibility again)
  - Deal with any difference of geometric beam size from protons (collimator settings, etc.)
- Commission squeeze of IP2 (if applicable)
  - Including crossing angle with ALICE spectrometer bump
  - (Alignment of IR2 triplet quadrupoles?)
  - Could take a few days (see experience with IP1 and IP5)
- Collide Pb-Pb
  - Re-optimise collimation (how?), measurements, etc.

Need to review time requirements with proton experience.

Provide > 4 weeks of physics with Early Scheme for ALICE, ATLAS, CMS.

Don’t forget MD time (→ Nominal Scheme) with Pb ions

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)
- It is also 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

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

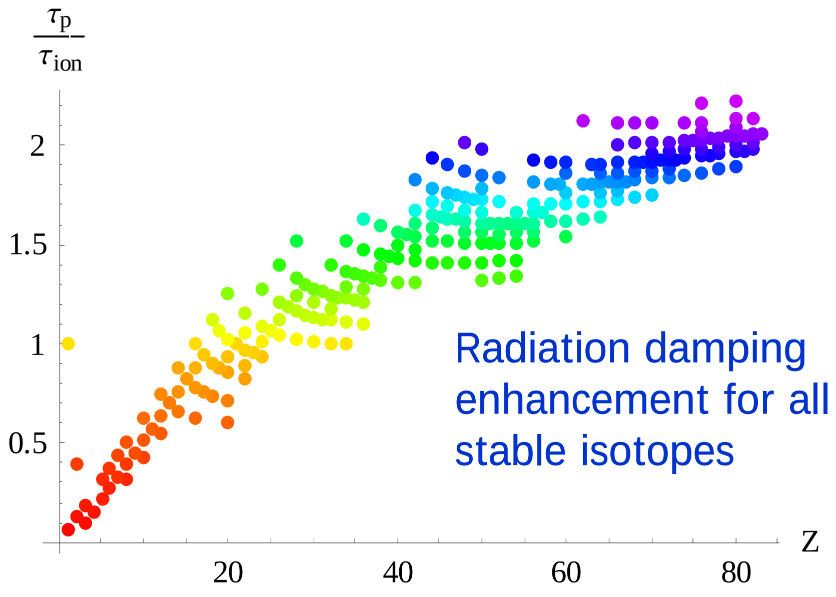
Synchrotron Radiation

- Scaling with respect to protons *in same ring, same magnetic field*

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

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

  - Radiation damping for Pb is twice as fast as for protons
    - Many very soft photons
    - Critical energy in visible spectrum



Radiation damping enhancement for all stable isotopes

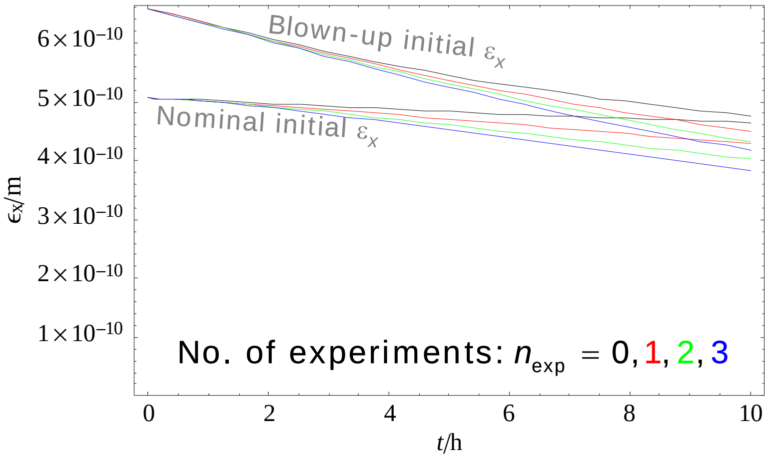
Lead is (almost) best, deuteron is worst.

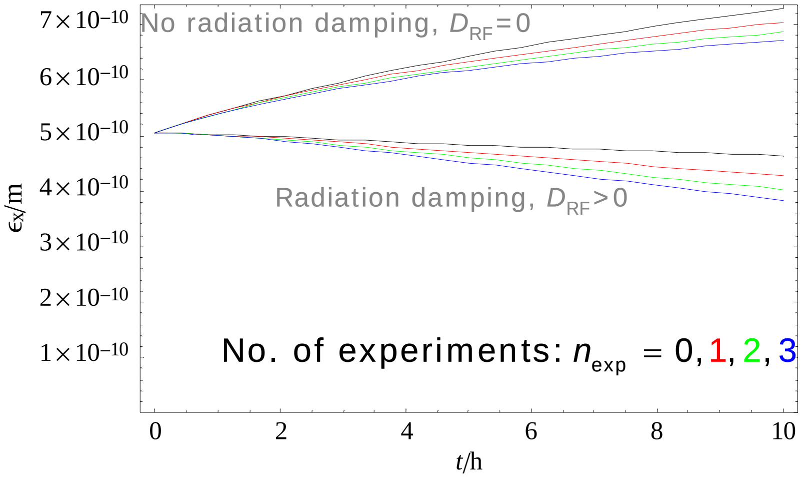
Evolution during a fill

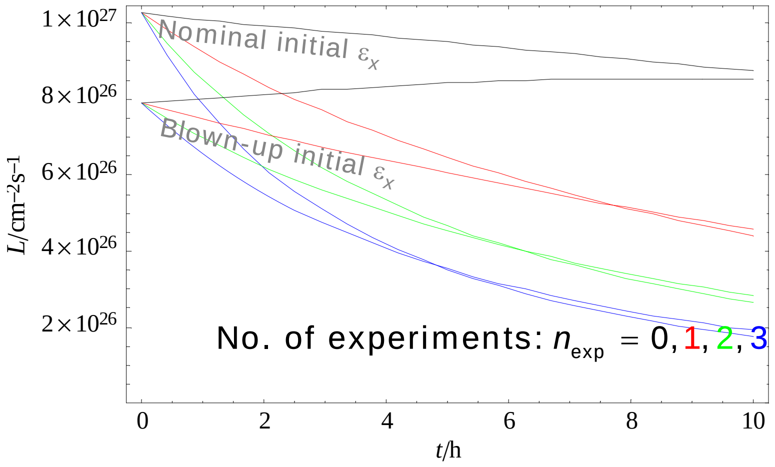
$$\dot{N}_b(t) = \underbrace{-\left(\sum_g n_g \sigma_{bg}\right) v_b N_b(t)}_{\text{beam-gas}} - \underbrace{\frac{\sigma_{\mathrm{tot}} n_{\mathrm{exp}} f_0 N_b(t)^2}{4\pi \beta^* \varepsilon_x}}_{\text{luminosity burn-off}}$$

$$\dot{\varepsilon}_x(t) = \frac{\varepsilon_x(t)}{T_{\mathrm{IBS}x}\left(N_b, \varepsilon_x(t), \varepsilon_l(t)\right)} - \frac{2\varepsilon_x(t)}{\tau_x}$$

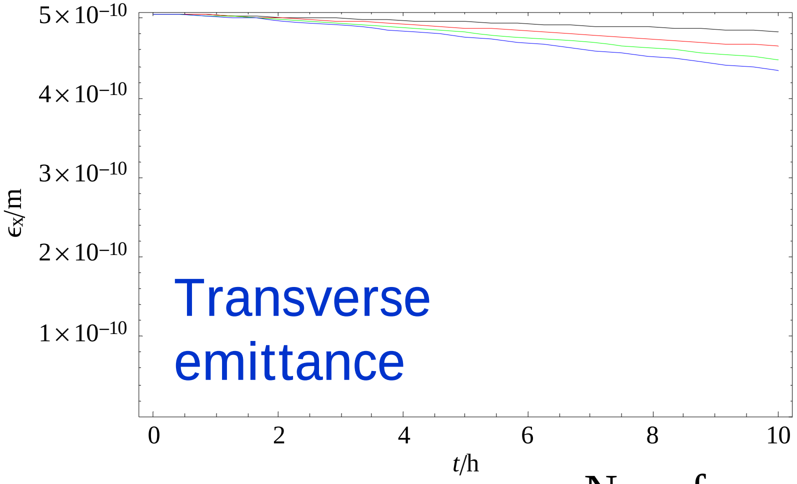
$$\dot{\varepsilon}_l(t) = \underbrace{\frac{\varepsilon_x(t)}{T_{\mathrm{IBS}l}\left(N_b(t), \varepsilon_x(t), \varepsilon_l(t)\right)}}_{\text{Bj-M in MAD, full lattice}} - \underbrace{\frac{4\varepsilon_l(t)}{\tau_x}}_{\text{radiation damping}} + \underbrace{D_{\mathrm{RF}}(t)}_{\text{Injected RF noise}}$$



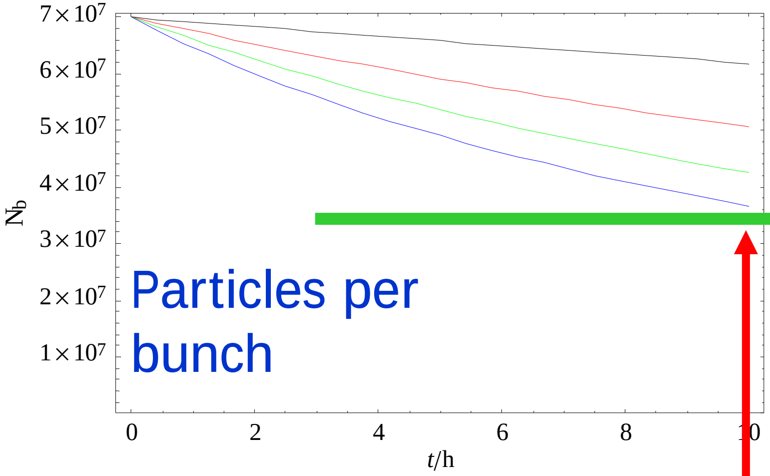




Luminosity evolution during a fill: Early scheme



Transverse emittance



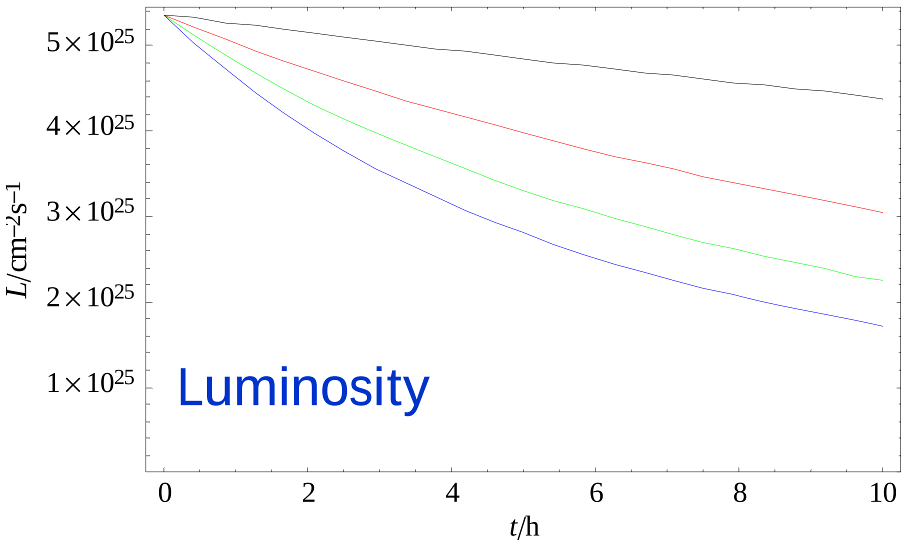
Particles per bunch

Arc BPM visibility threshold

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

Assuming good vacuum conditions, but including all effects.

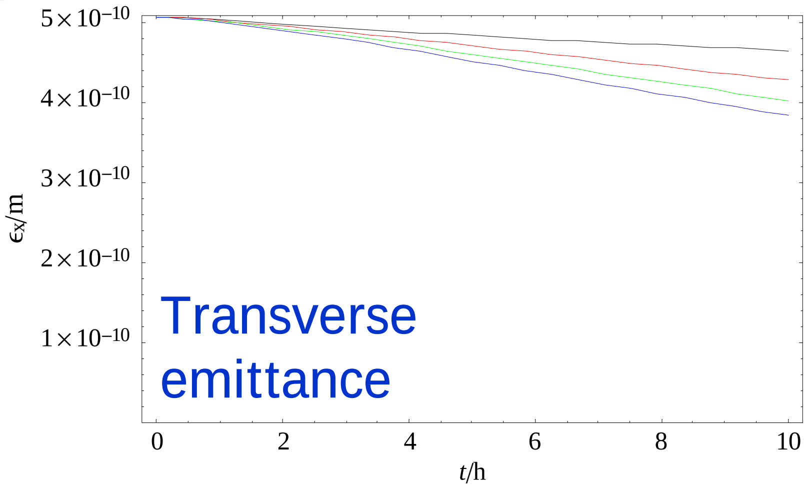
$\beta^* = 1\,\mathrm{m}$



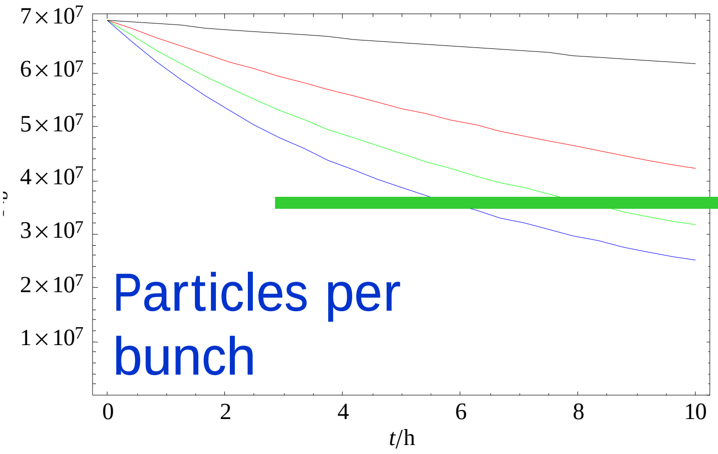
Luminosity

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).

Luminosity evolution: Nominal scheme



Transverse emittance

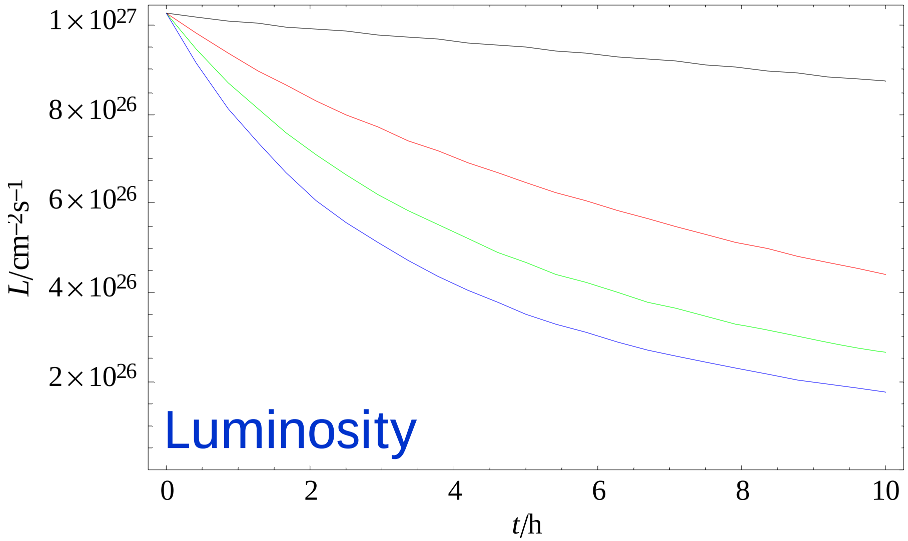


Particles per bunch

BPM visibility threshold

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

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



Luminosity

Increasing number of experiments reduces beam and luminosity lifetime.

Summary

- I-LHC Project remains on track for Pb-Pb collisions with “Early Scheme” at end 2008
  - See talk by S. Maury at Chamonix 2006
  - No serious performance limits expected
- Move towards Pb-Pb nominal parameters from 2009
  - Various performance limits, including collimation
- This is just the first step in the ion programme

Conclusions

- US DOE/NSAC Review 2004:
  - “LHC will open up a new regime of ultra-relativistic heavy-ion physics with significant opportunities for new discoveries.”
- Added-value for the world-wide investment in LHC.
- Operation of LHC with lead ions limited by new effects, qualitatively different from protons
  - Several effects important around design luminosity.
  - Challenge to achieve design luminosity.
- Extensive future programme, colliding p-Pb, Ar-Ar, O-O, p-Ar, p-O, ... with further challenges.