Lead Ions in the LHC

Contributors to this talk
(re-run of Chamonix plus some extras):
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Thanks to: many other CERN colleagues,
I. Baishev, S. Striganov (FNAL)

Ions for LHC (I-LHC) Project

- New I-LHC Project Web pages:
  - http://carli.home.cern.ch/carli/ILHC_website/
- Members of the I-LHC Steering Group:
  - **Karlheinz Schindl :** Chairman
  - **Hans Braun :** Ion collimation in LHC
  - **Christian Carli :** Scientific Secretary
  - **Michel Chanel :** Deputy Chairman, LEIR
  - **Steven Hancock :** RF aspects in LEIR and PS
  - **Charles Hill :** Linac 3, ECR ion source
  - **John Jowett :** LHC, linkman to experiments
  - **Django Manglunki :** SPS, operational aspects
    Michel Martini : PS, line to SPS
  - **Stephan Maury :** Linkman to AC
  - **Flemming Pedersen :** Low level RF all machines
  - **Elena Shaposhnikova:** RF aspects SPS and LHC

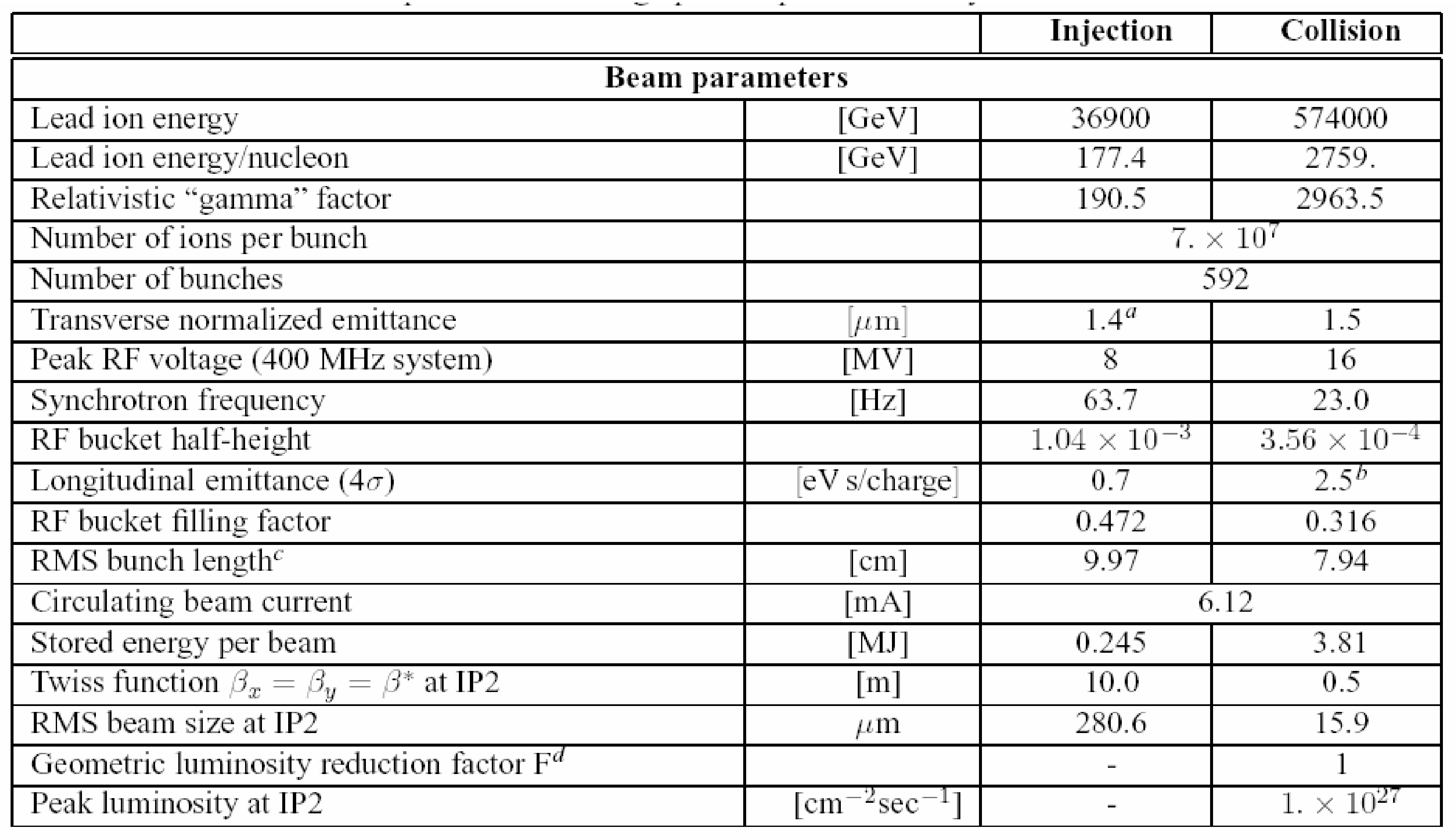
Plan of talk

- The I-LHC Project
- Review new ion parameters
- Small-angle separation scheme
- Quench limit and ECPP
- Collimation
- Vacuum Aspects
- Luminosity and beam lifetime
- Conclusions, implications

Parameters for Lead Ions in LHC

- Revision/verification of all parameters
  - Started at Chamonix Workshop 2003
  - Summarised in LHC Design Report Vol I, Chapter 21
- Recent changes:
  - Introduction of “Early Ion Scheme”
  - Optics update, small-angle crossing scheme for ALICE
  - Revised lifetimes, IBS, etc.
  - No 200 MHz RF system for capture at injection now

Nominal scheme parameters

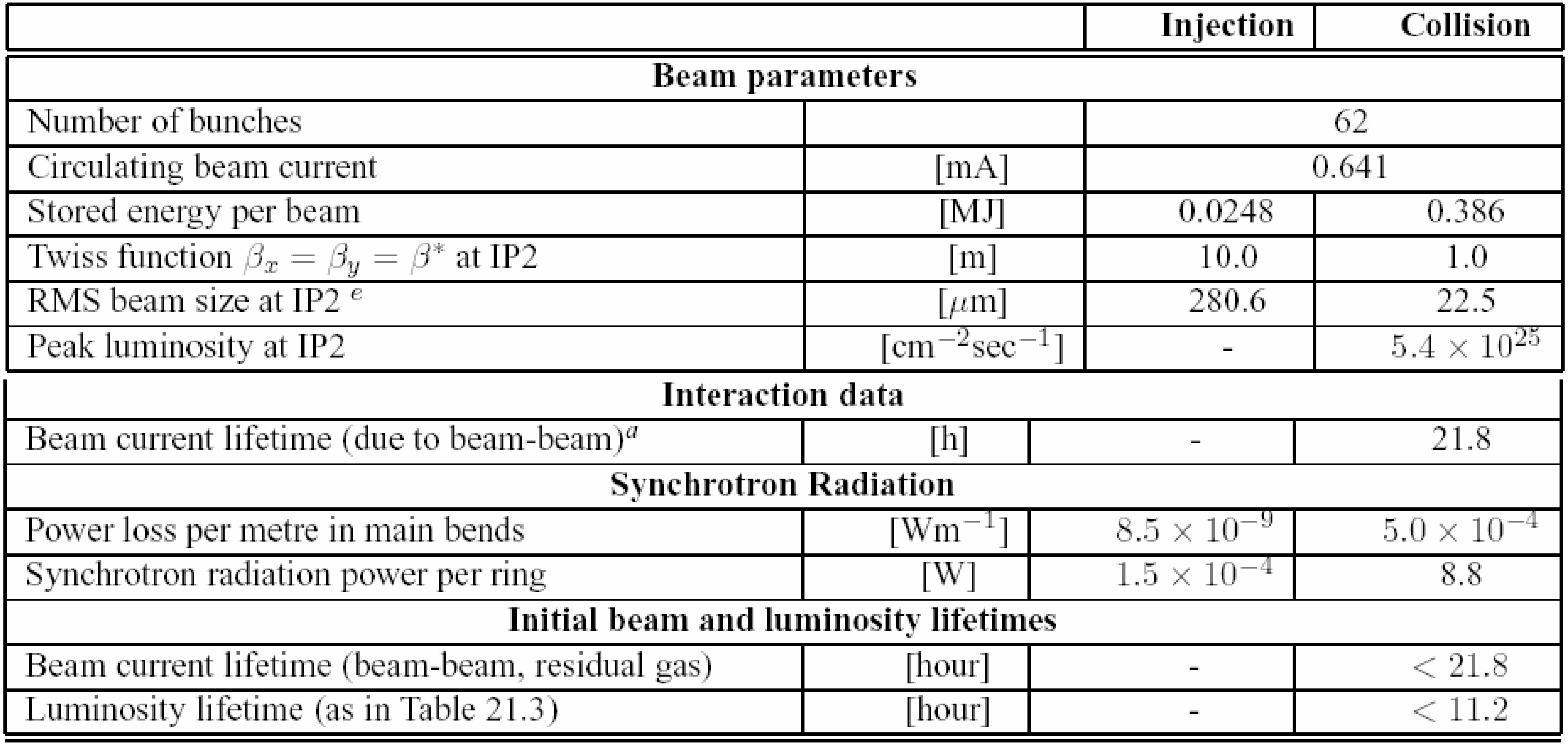


		Injection	**Collision**
Beam parameters			
Lead ion energy	[GeV]	36900	574000
Lead ion energy/nucleon	[GeV]	177.4	2759.
Relativistic “gamma” factor		190.5	2963.5
Number of ions per bunch		$7. \times 10^7$	
Number of bunches		592	
Transverse normalized emittance	[μm]	1.4[a]	1.5
Peak RF voltage (400 MHz system)	[MV]	8	16
Synchrotron frequency	[Hz]	63.7	23.0
RF bucket half-height		1.04×10^{-3}	3.56×10^{-4}
Longitudinal emittance (4σ)	[eV s/charge]	0.7	2.5[b]
RF bucket filling factor		0.472	0.316
RMS bunch length[c]	[cm]	9.97	7.94
Circulating beam current	[mA]	6.12	
Stored energy per beam	[MJ]	0.245	3.81
Twiss function $\beta_x = \beta_y = \beta^*$ at IP2	[m]	10.0	0.5
RMS beam size at IP2	μm	280.6	15.9
Geometric luminosity reduction factor F[d]		-	1
Peak luminosity at IP2	[cm^{-2}sec^{-1}]	-	$1. \times 10^{27}$

Nominal scheme, lifetime parameters

		Injection	Collision
Interaction data			
Total cross section	[mb]	-	514000
Beam current lifetime (due to beam-beam)[a]	[h]	-	11.2
Intra Beam Scattering			
RMS beam size in arc	[mm]	1.19	0.3
RMS energy spread $\delta E/E_0$	$[10^{-4}]$	3.9	1.10
RMS bunch length	[cm]	9.97	7.94
Longitudinal emittance growth time	[hour]	3	7.7
Horizontal emittance growth time[b]	[hour]	6.5	13
Synchrotron Radiation			
Power loss per ion	[W]	3.5×10^{-14}	2.0×10^{-9}
Power loss per metre in main bends	$[\mathrm{Wm}^{-1}]$	8×10^{-8}	0.005
Synchrotron radiation power per ring	[W]	1.4×10^{-3}	83.9
Energy loss per ion per turn	[eV]	19.2	1.12×10^{6}
Critical photon energy	[eV]	7.3×10^{-4}	2.77
Longitudinal emittance damping time	[hour]	23749	6.3
Transverse emittance damping time	[hour]	47498	12.6
Variation of longitudinal damping partition number[c]		230	230
Initial beam and luminosity lifetimes			
Beam current lifetime (due to residual gas scattering)[d]	[hour]	?	?
Beam current lifetime (beam-beam, residual gas)	[hour]	-	< 11.2
Luminosity lifetime[e]	[hour]	-	< 5.6

Early scheme Parameters



		Injection	Collision
Beam parameters			
Number of bunches		62	
Circulating beam current	[mA]	0.641	
Stored energy per beam	[MJ]	0.0248	0.386
Twiss function $\beta_x = \beta_y = \beta^*$ at IP2	[m]	10.0	1.0
RMS beam size at IP2 ^{e}	[μm]	280.6	22.5
Peak luminosity at IP2	[$\text{cm}^{-2}\text{sec}^{-1}$]	-	5.4×10^{25}
Interaction data			
Beam current lifetime (due to beam-beam)^a	[h]	-	21.8
Synchrotron Radiation			
Power loss per metre in main bends	[Wm^{-1}]	8.5×10^{-9}	5.0×10^{-4}
Synchrotron radiation power per ring	[W]	1.5×10^{-4}	8.8
Initial beam and luminosity lifetimes			
Beam current lifetime (beam-beam, residual gas)	[hour]	-	< 21.8
Luminosity lifetime (as in Table 21.3)	[hour]	-	< 11.2

Only show parameters that are different from nominal scheme

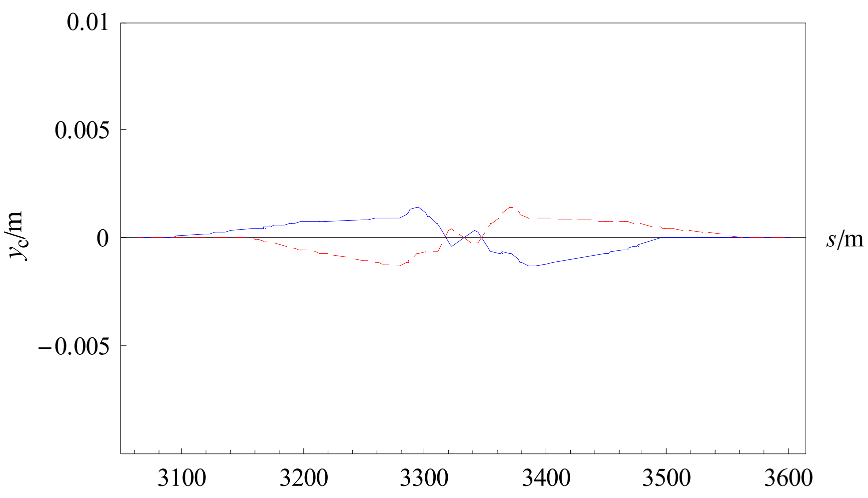
Some things are straightforward

- Beam current and stored energy 100 times lower
  - Many limits to performance of proton beams are not a problem for lead ion beams
    - impedance-driven collective effects
    - beam-beam
    - electron cloud (?)
    - activation and maintenance of collimators
- Same *geometrical* transverse beam size and emittance $\Rightarrow$ some aspects are similar
  - Optics, dynamic aperture, mechanical acceptance, etc. more or less carry over from protons.

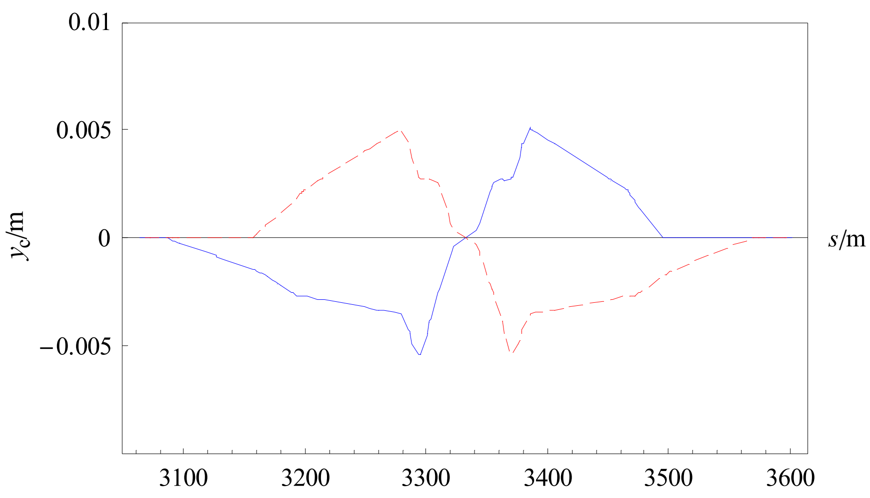
Optics

- Ion optics at injection/ramp
  - assumed to be essentially same as protons
- Lead ion optics in collision
  - Update for move of Q3 magnets (part of V6.5)
  - Focus on IR2 (ALICE, specialised ion experiment)
    - Maintain $\beta^*=0.5$ m (unlike protons which have $\beta^*=0.55$ m for reasons of aperture)
  - Ion collisions for ATLAS/CMS may use proton optics
    - Or also squeeze further
  - Main issue is separation

Separation in IR2: three illustrative cases

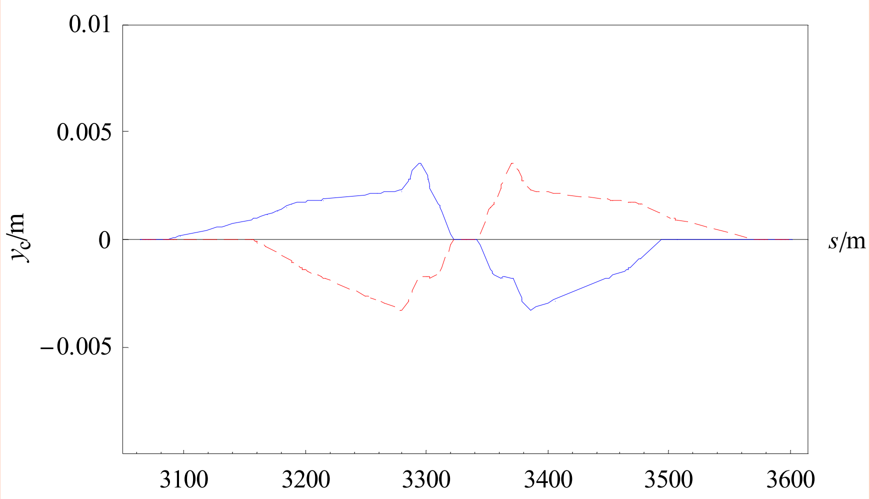


$f_{\mathrm{IP2bump}}=$ 17%, $f_{\mathrm{ALICE}}=$ 100%, $\theta_c=$ 82.2 μrad



$f_{\mathrm{IP2bump}}=$ −65%, $f_{\mathrm{ALICE}}=$ −100%, $\theta_c=$ 81. μrad

Two ways of getting a crossing angle of 80 μrad; one way to get zero crossing angle.



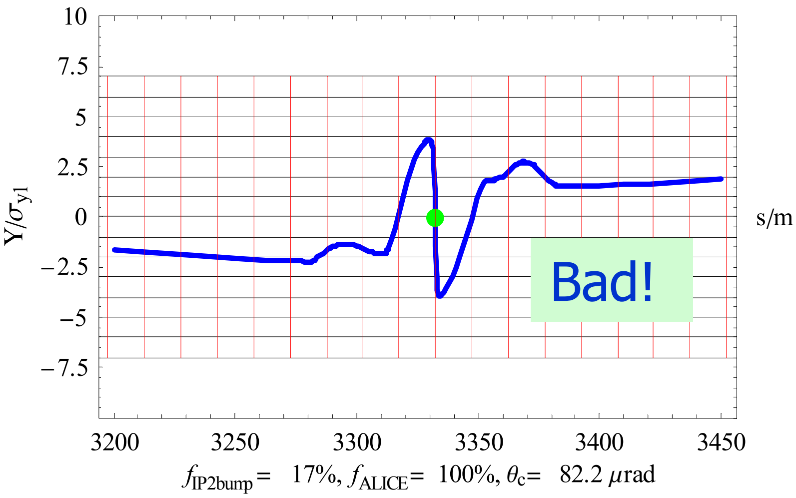
$f_{\mathrm{IP2bump}}=$ 42%, $f_{\mathrm{ALICE}}=$ 100%, $\theta_c=$ −2.8 μrad

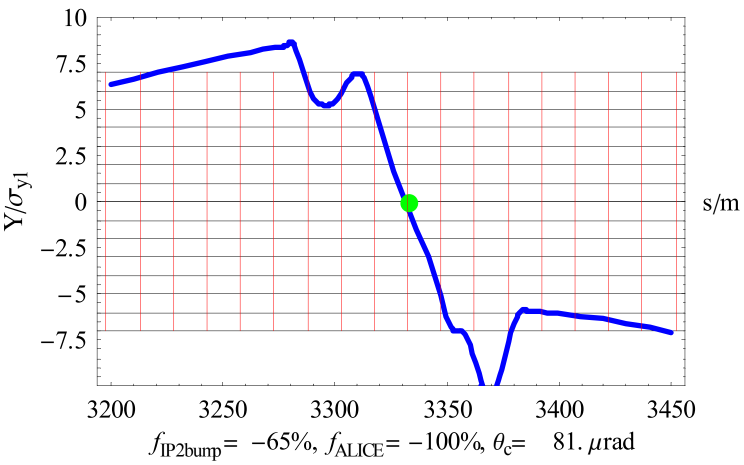
Total separation is superposition of ALICE spectrometer bump and “external” vertical separation

Beam 1 / Beam 2

Animation!

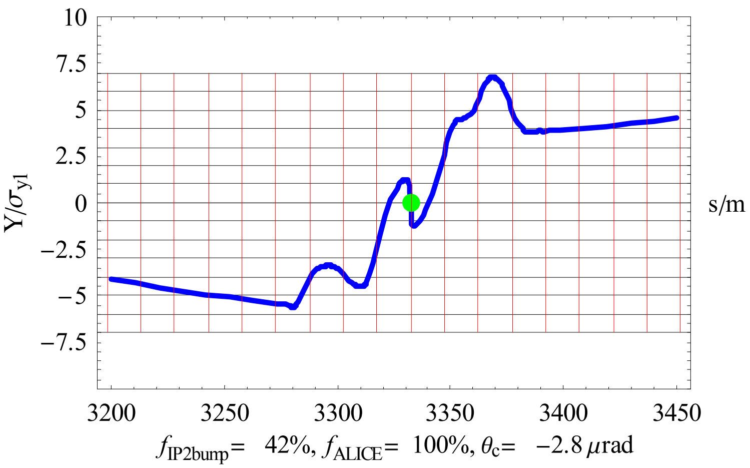
Parasitic beam-beam encounters





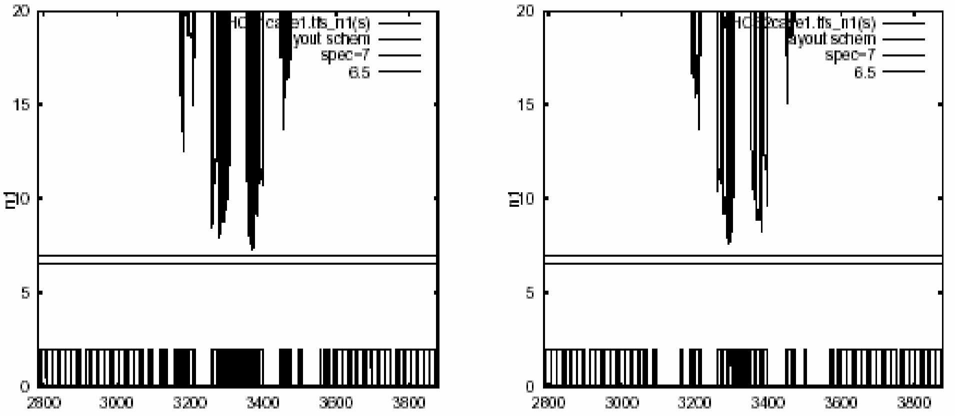
Show only vertical separation in units of vertical RMS beam size of Beam 1.

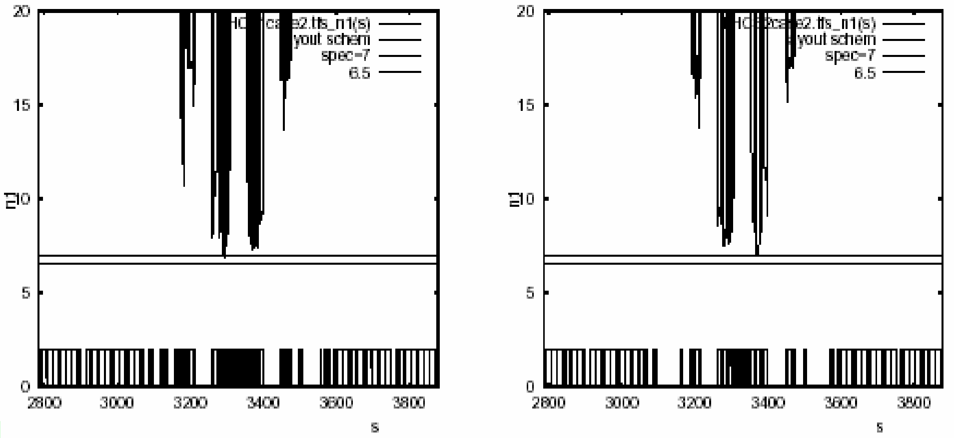
Red lines are possible (ion) encounters ($S_b/2$)

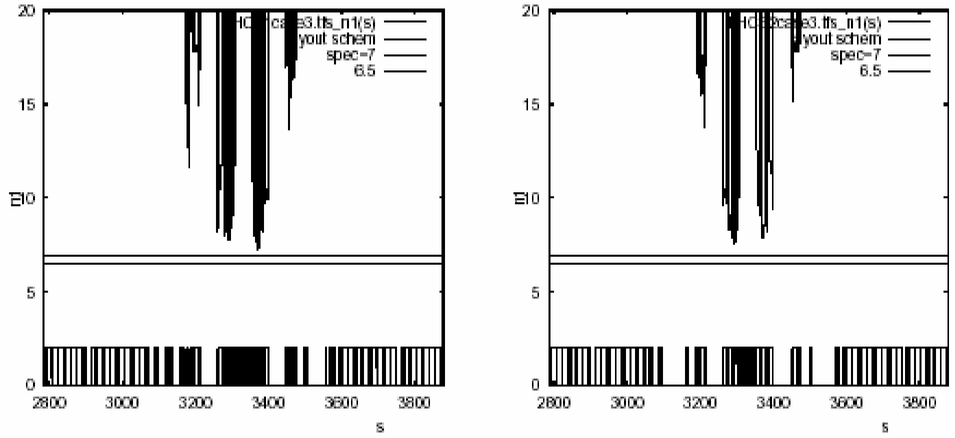


Zero crossing angle is just about achievable with minimum 3σ separation (strictly need 20 μrad).

Aperture (APL program)







All meet the canonical aperture requirements with β^*=0.5m

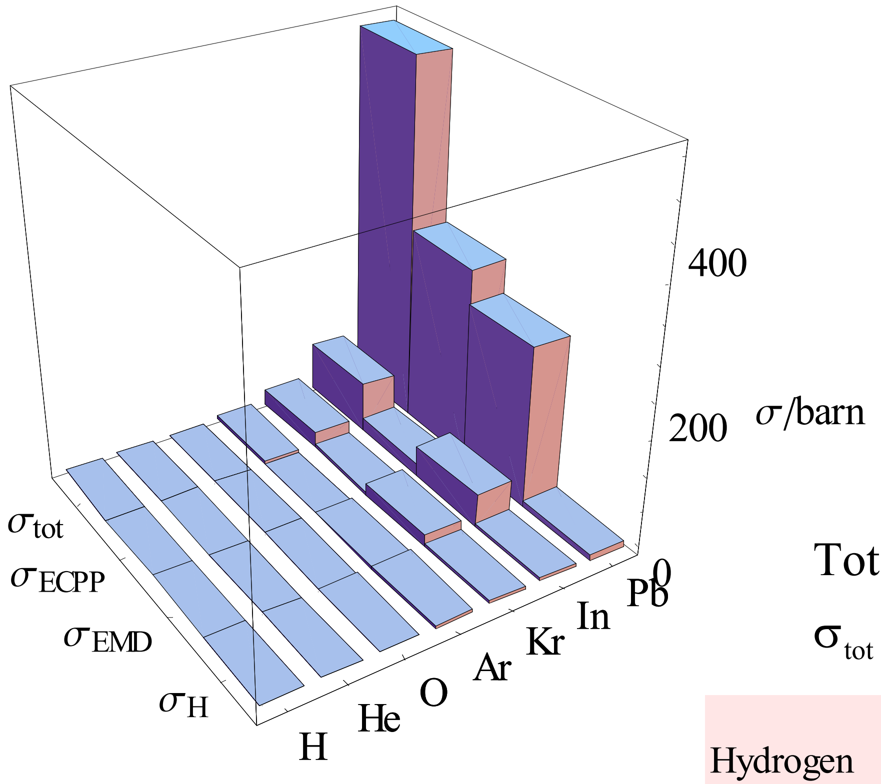
Electromagnetic Interactions of Lead ions

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: $\delta_p = -\frac{1}{A-1} = -4.8\times 10^{-3} \text{ for Pb}$

(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 ?

Total cross - section for ion removal from beam

$$\sigma_{tot} = \sigma_H + \sigma_{EMD} + \sigma_{ECPP}$$

	σ_H	σ_{EMD}	σ_{ECPP}	σ_{tot}
Hydrogen	0.105	0	4.25×10^{-11}	0.105
Helium	0.35	0.002	$1. \times 10^{-8}$	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

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

Cross-section for ECPP

Involved topic, numerous references …

Extrapolation from SPS measurements at lower energy in Grafström et al, PAC99

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

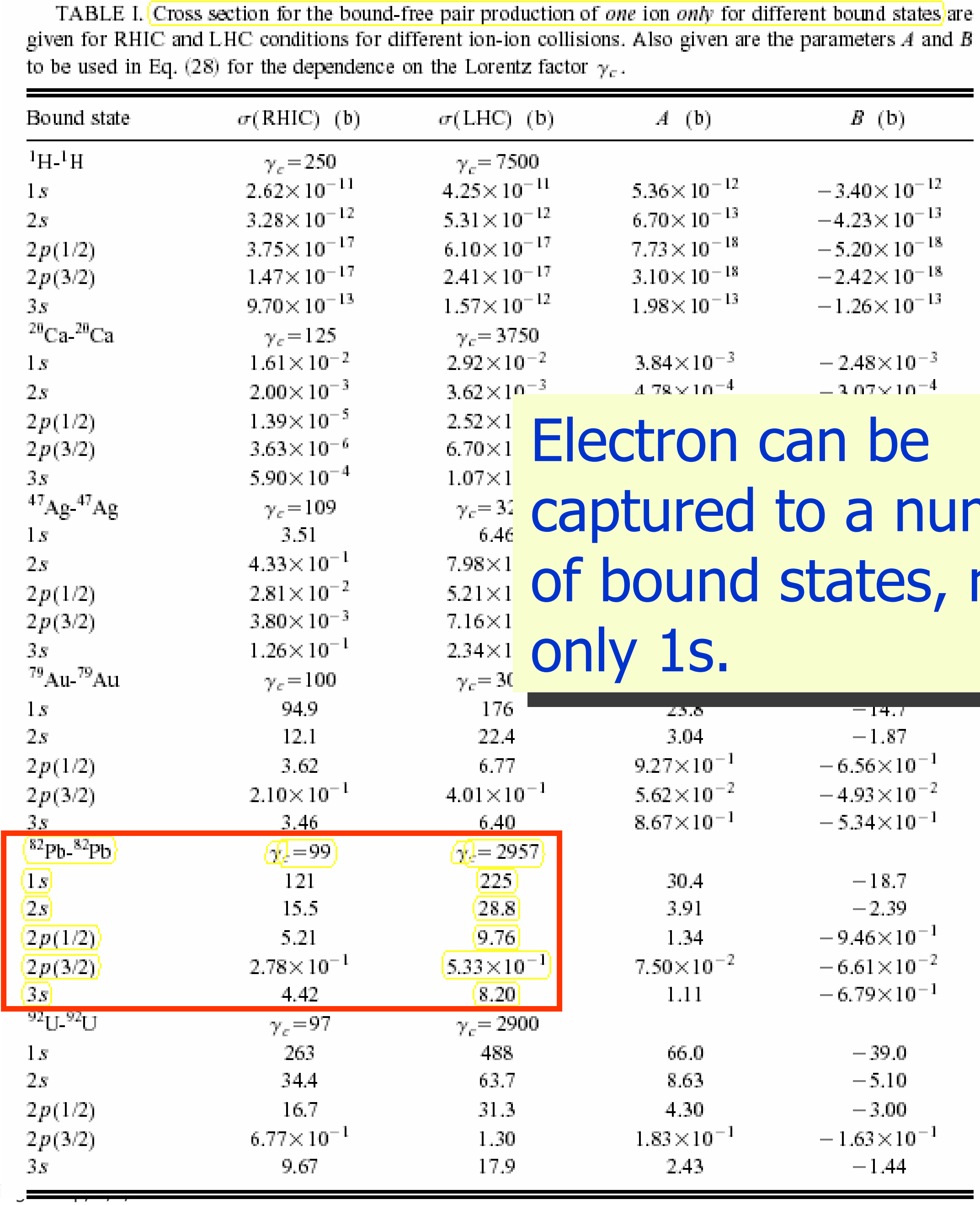


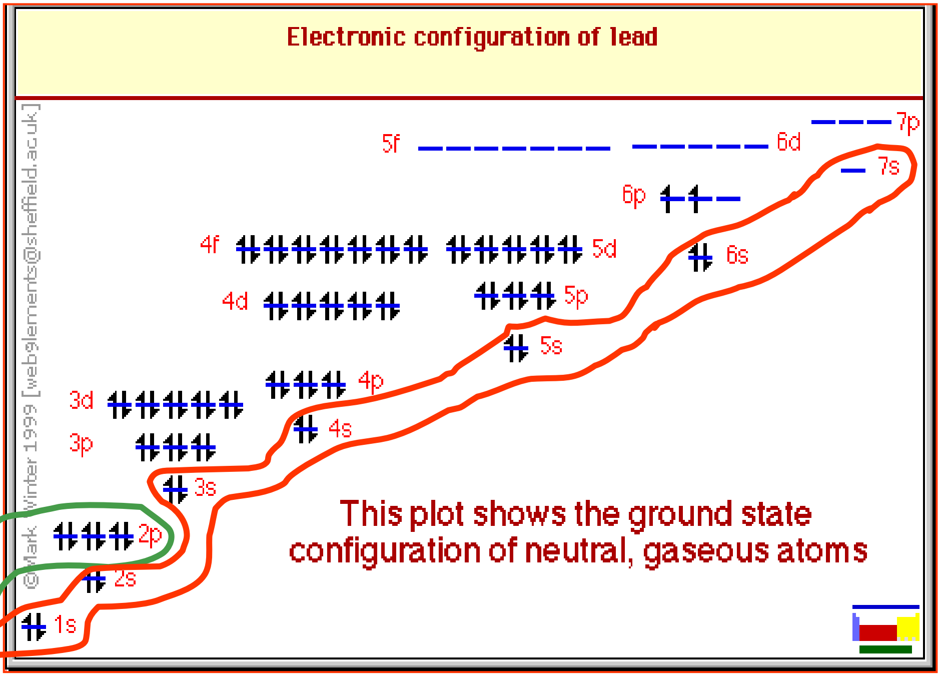
TABLE I. Cross section for the bound-free pair production of *one* ion *only* for different bound states are given for RHIC and LHC conditions for different ion-ion collisions. Also given are the parameters A and B to be used in Eq. (28) for the dependence on the Lorentz factor γ_c.

Bound state	σ(RHIC) (b)	σ(LHC) (b)	A (b)	B (b)
^{1}H-^{1}H	$\gamma_c=250$	$\gamma_c=7500$		
$1s$	2.62×10^{-11}	4.25×10^{-11}	5.36×10^{-12}	-3.40×10^{-12}
$2s$	3.28×10^{-12}	5.31×10^{-12}	6.70×10^{-13}	-4.23×10^{-13}
$2p(1/2)$	3.75×10^{-17}	6.10×10^{-17}	7.73×10^{-18}	-5.20×10^{-18}
$2p(3/2)$	1.47×10^{-17}	2.41×10^{-17}	3.10×10^{-18}	-2.42×10^{-18}
$3s$	9.70×10^{-13}	1.57×10^{-12}	1.98×10^{-13}	-1.26×10^{-13}
^{20}Ca-^{20}Ca	$\gamma_c=125$	$\gamma_c=3750$		
$1s$	1.61×10^{-2}	2.92×10^{-2}	3.84×10^{-3}	-2.48×10^{-3}
$2s$	2.00×10^{-3}	3.62×10^{-3}	4.78×10^{-4}	-3.07×10^{-4}
$2p(1/2)$	1.39×10^{-5}	2.52×1		
$2p(3/2)$	3.63×10^{-6}	6.70×1		
$3s$	5.90×10^{-4}	1.07×1		
^{47}Ag-^{47}Ag	$\gamma_c=109$	$\gamma_c=32$		
$1s$	3.51	6.46		
$2s$	4.33×10^{-1}	7.98×1		
$2p(1/2)$	2.81×10^{-2}	5.21×1		
$2p(3/2)$	3.80×10^{-3}	7.16×1		
$3s$	1.26×10^{-1}	2.34×1		
^{79}Au-^{79}Au	$\gamma_c=100$	$\gamma_c=30$		
$1s$	94.9	176	23.8	-14.7
$2s$	12.1	22.4	3.04	-1.87
$2p(1/2)$	3.62	6.77	9.27×10^{-1}	-6.56×10^{-1}
$2p(3/2)$	2.10×10^{-1}	4.01×10^{-1}	5.62×10^{-2}	-4.93×10^{-2}
$3s$	3.46	6.40	8.67×10^{-1}	-5.34×10^{-1}
^{82}Pb-^{82}Pb	$\gamma_c=99$	$\gamma_c=2957$		
$1s$	121	225	30.4	-18.7
$2s$	15.5	28.8	3.91	-2.39
$2p(1/2)$	5.21	9.76	1.34	-9.46×10^{-1}
$2p(3/2)$	2.78×10^{-1}	5.33×10^{-1}	7.50×10^{-2}	-6.61×10^{-2}
$3s$	4.42	8.20	1.11	-6.79×10^{-1}
^{92}U-^{92}U	$\gamma_c=97$	$\gamma_c=2900$		
$1s$	263	488	66.0	-39.0
$2s$	34.4	63.7	8.63	-5.10
$2p(1/2)$	16.7	31.3	4.30	-3.00
$2p(3/2)$	6.77×10^{-1}	1.30	1.83×10^{-1}	-1.63×10^{-1}
$3s$	9.67	17.9	2.43	-1.44

Electron can be captured to a number of bound states, not only 1s.

Cross-section for ECPP

Use Meier et al’s result for Pb-Pb at LHC energy:



Electronic configuration of lead

This plot shows the ground state configuration of neutral, gaseous atoms

$$\sigma_{\mathrm{ECPP}} = [\sigma_{\mathrm{ECPP}}(1s) + \sigma_{\mathrm{ECPP}}(2s) + \sigma_{\mathrm{ECPP}}(3s) + \cdots]$$
$$+ \sigma_{\mathrm{ECPP}}(2p_{1/2}) + \sigma_{\mathrm{ECPP}}(2p_{3/2}) + \cdots$$

$$\sigma_{\mathrm{ECPP}}(ns) \approx \frac{\sigma_{\mathrm{ECPP}}(1s)}{n^3}$$

$$\approx [225. + 28.8 + 8.2 + \cdots]$$
$$+ 9.76 + 0.533 + \cdots \qquad \text{barn}$$

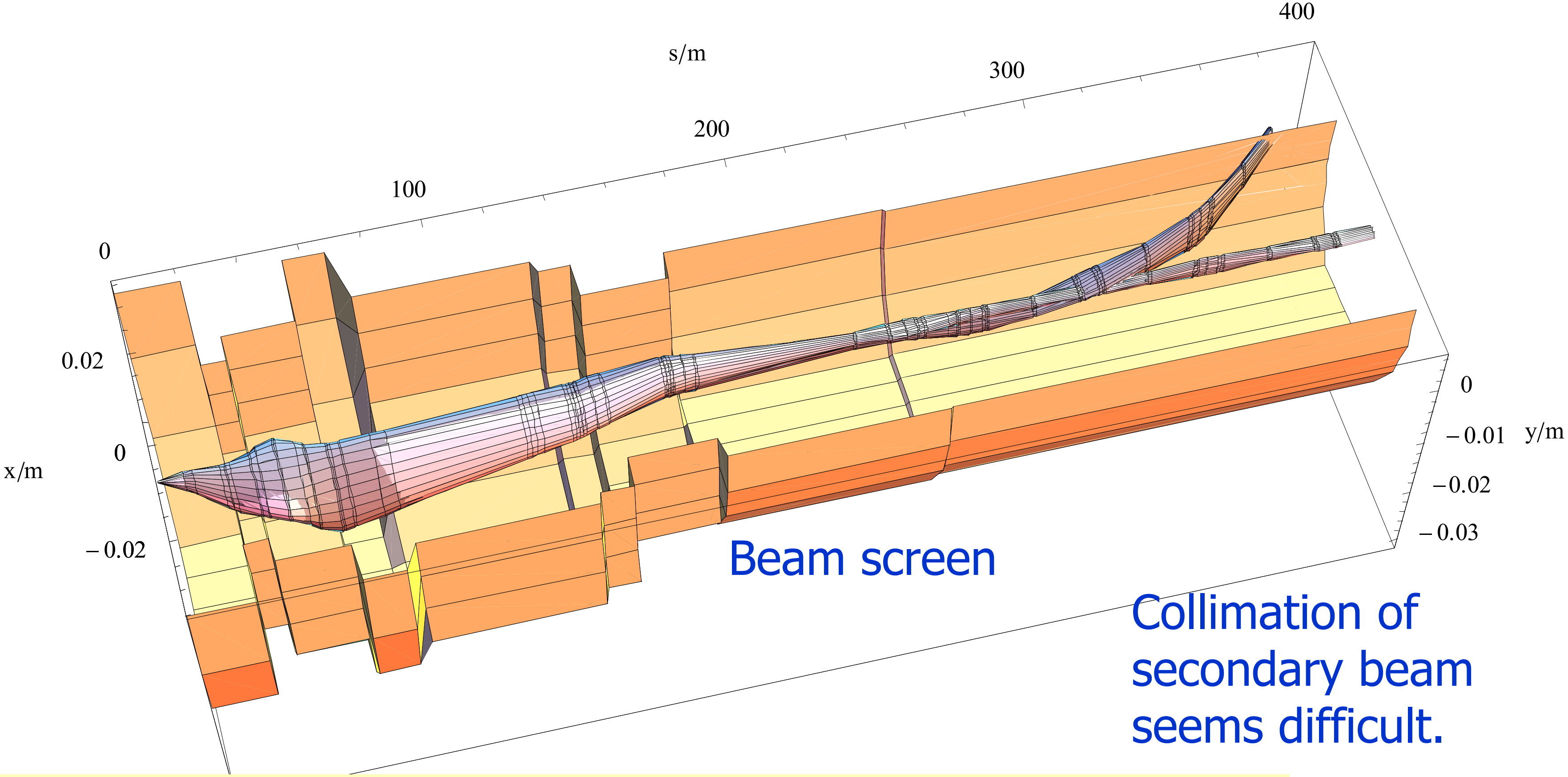
$$\approx [\zeta(3)\sigma_{\mathrm{ECPP}}(1s)] + 9.76 + 0.533 + \cdots \quad \text{barn}$$

$$\approx 281\,\text{barn}$$

C.f. 204 barn used in previous discussions

Main and ECPP secondary beams

5σ beam envelopes, emerging to right of IP2



Beam screen

Collimation of secondary beam seems difficult.

Uncorrected strong chromatic effects of low-b insertion
⇒ cannot use linear beam sizes for Pb^{71+} beam

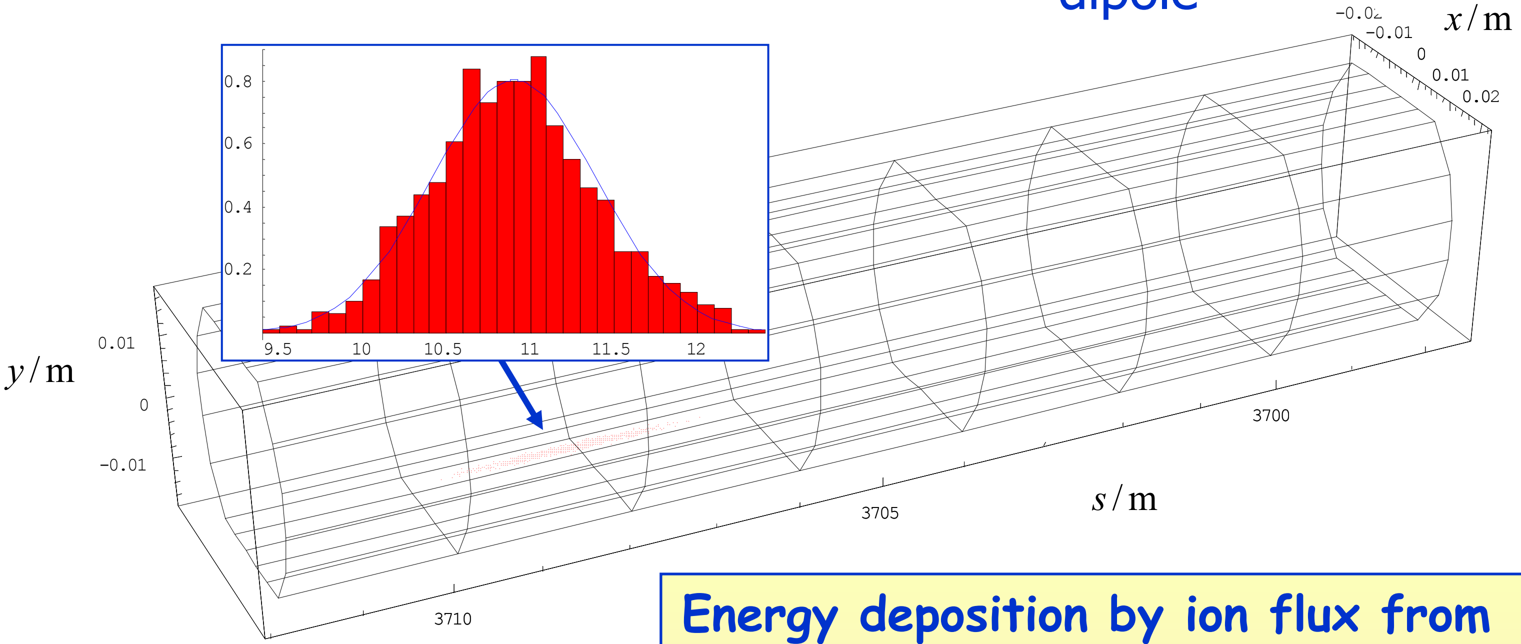
Secondary beam spot

Quench limit (conservative) is 8×10^{4} Pb/m/s

Dilution over $l_d \approx 1$ m,

In quadrature with shower length $1\text{ m} \approx 1.4\text{ m}$

Beam screen in a dispersion suppressor dipole

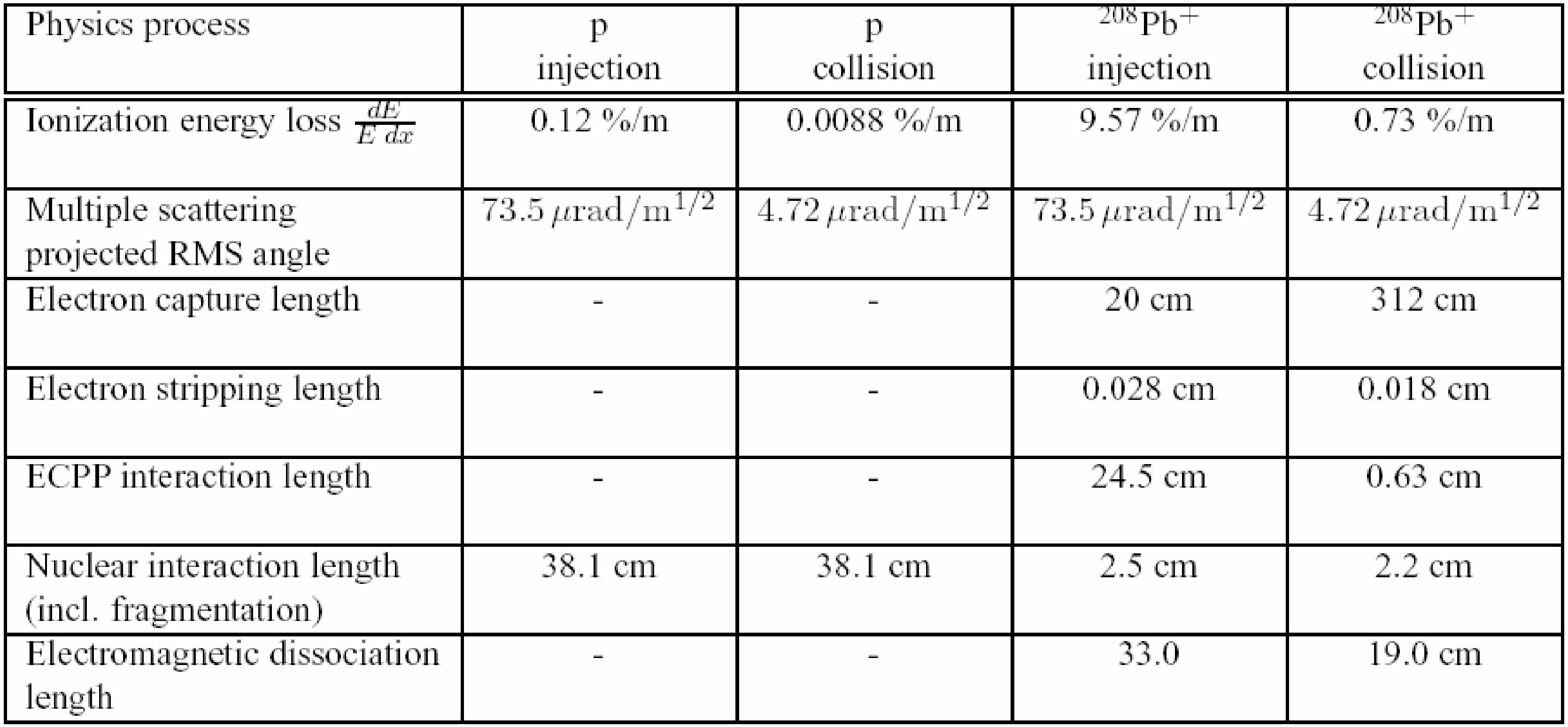


Plan to improve heat deposition estimate with FLUKA calculations.

Energy deposition by ion flux from ECPP exceeds *nominal* quench limit of superconducting magnets by factor 2 at nominal luminosity.
DIRECT LIMIT ON LUMINOSITY.

Collimation for Pb ions

- $^{208}Pb^{82+}$ ion-graphite interactions compared with p-graphite interactions.

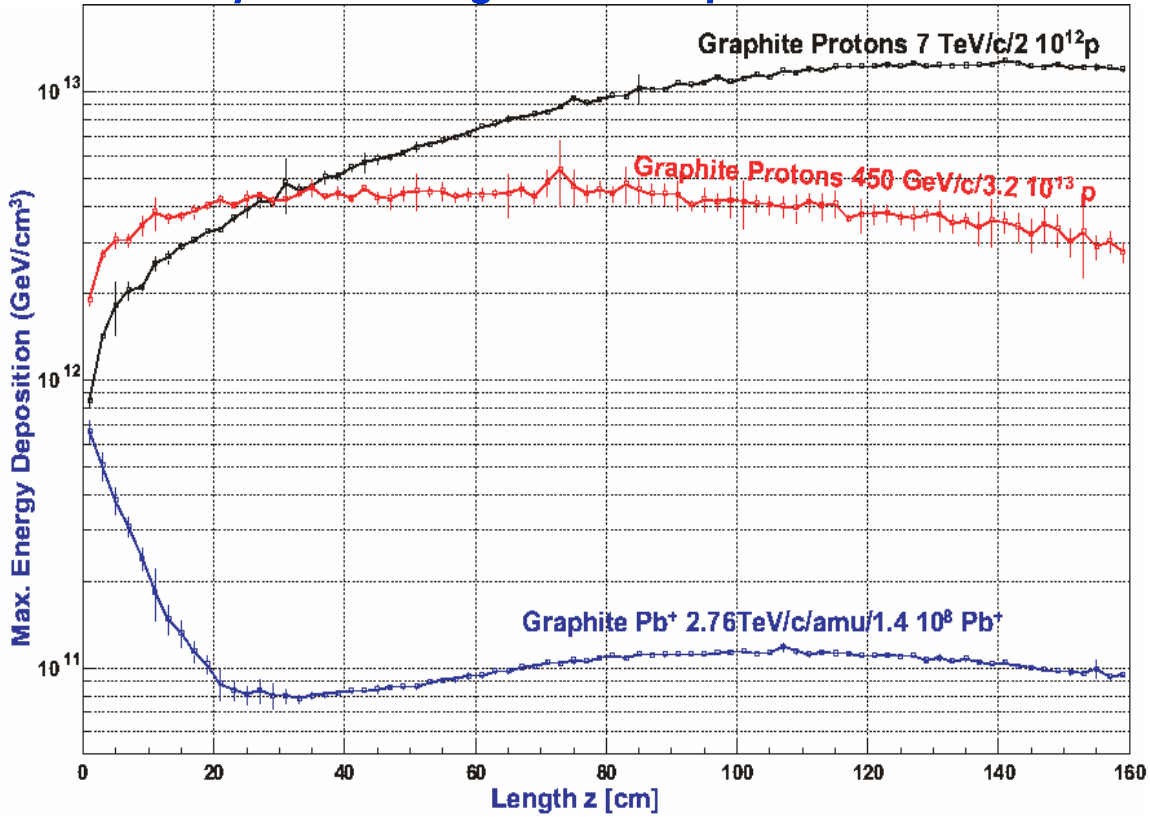


Physics process	p injection	p collision	$^{208}\mathrm{Pb}^{+}$ injection	$^{208}\mathrm{Pb}^{+}$ collision
Ionization energy loss $\frac{dE}{E\,dx}$	0.12 %/m	0.0088 %/m	9.57 %/m	0.73 %/m
Multiple scattering projected RMS angle	$73.5\,\mu\mathrm{rad}/\mathrm{m}^{1/2}$	$4.72\,\mu\mathrm{rad}/\mathrm{m}^{1/2}$	$73.5\,\mu\mathrm{rad}/\mathrm{m}^{1/2}$	$4.72\,\mu\mathrm{rad}/\mathrm{m}^{1/2}$
Electron capture length	-	-	20 cm	312 cm
Electron stripping length	-	-	0.028 cm	0.018 cm
ECPP interaction length	-	-	24.5 cm	0.63 cm
Nuclear interaction length (incl. fragmentation)	38.1 cm	38.1 cm	2.5 cm	2.2 cm
Electromagnetic dissociation length	-	-	33.0	19.0 cm

From Hans Braun

Robustness of collimator against mishaps

FLUKA calculations from Vasilis Vlachoudis for dump kicker single module prefire

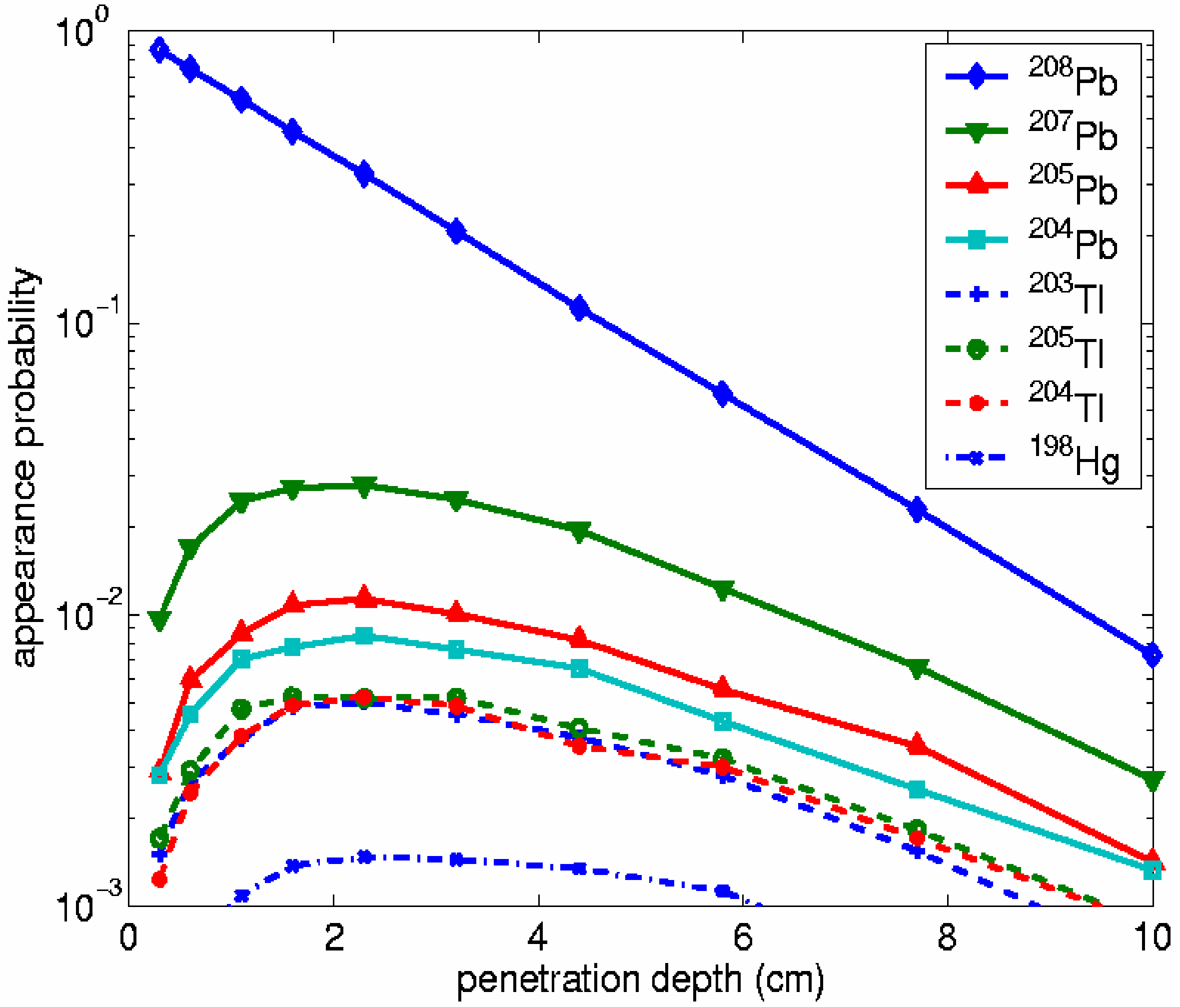


- The higher Ionisation loss makes the energy deposition at the impact side almost equal to proton case, despite 100 times less beam power.

- Similar damage potential.

From Hans Braun

Cleaning efficiency



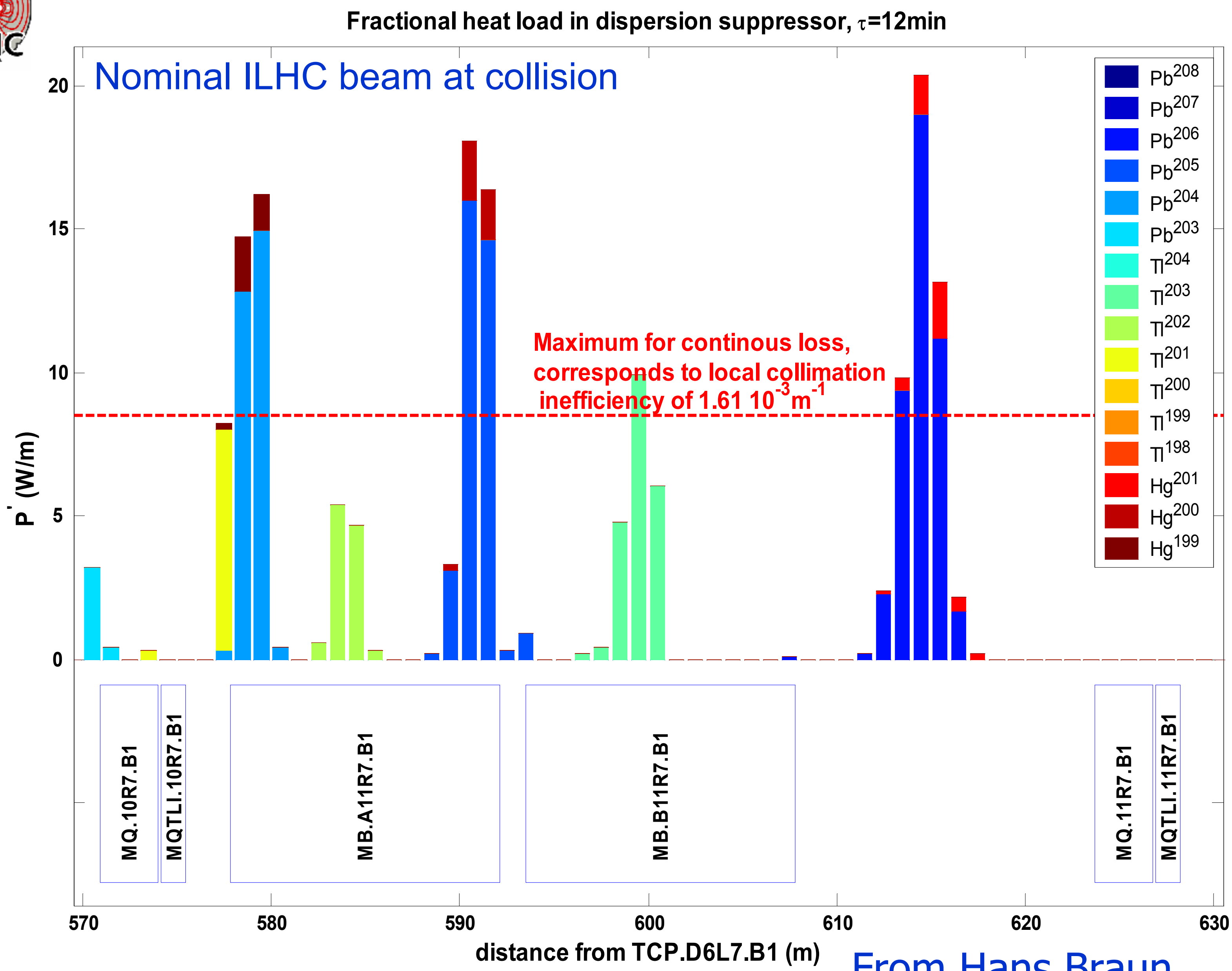
The probability to convert a ^{208}Pb nucleus into a neighboring nucleus.
Impact on graphite at LHC collision energy.

From Hans Braun

Simulation of collimation (Hans Braun)

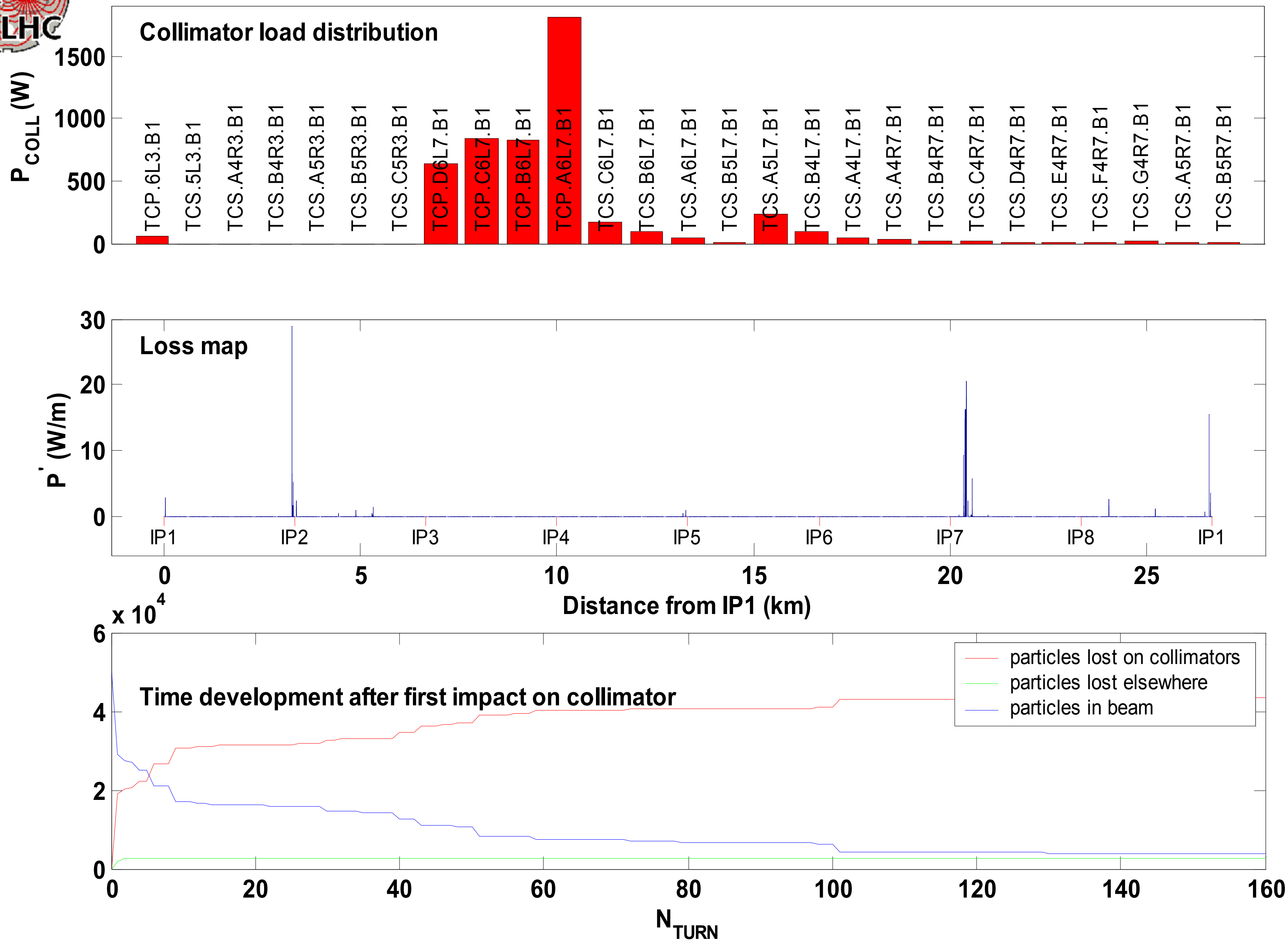
- Model of ion fragmentation, linear optics, collimators and beam aperture
- Suppose beam lifetime is down to 12 min
  - due to non-luminosity processes, e.g., IBS, beam-gas, resonances, …
- Collimators tend to put ion fragments on trajectories with large momentum errors and small betatron amplitude –
  - but the secondary collimators are designed to cut betatron amplitudes
- Acts like one-stage system
- Worrying results at collision energy (following slides)
  - Various hot-spots around ring
- Seems OK at injection energy

Nominal ILHC beam at collision



From Hans Braun

Nominal ILHC beam at collision



Interaction of Pb ions with residual gas

- Losses due to nuclear scattering on residual gases
  - Atoms in residual gases (6 usual suspects in Design Report for protons) have Z≤8.
  - For simplicity, discuss only the dominant inelastic nuclear scattering (leave out elastic and electromagnetic contributions, EMD, ECPP which are smaller). Somewhat optimistic!
  - Dominant beam-gas lifetime: is independent of intensity

$$\frac{1}{\tau_{\mathrm{bg}}} = c \sum_{i \in \mathrm{gases}} \sigma_i n_i$$

  - Multiple Coulomb scattering on residual gas also causes emittance growth (similar to protons, not treated here).
  - Lost ions are a heat load:

$$P_{bg} = \frac{k_b I_b E}{Z e c \, \tau_{\mathrm{bg}}}$$

Inelastic nuclear cross sections

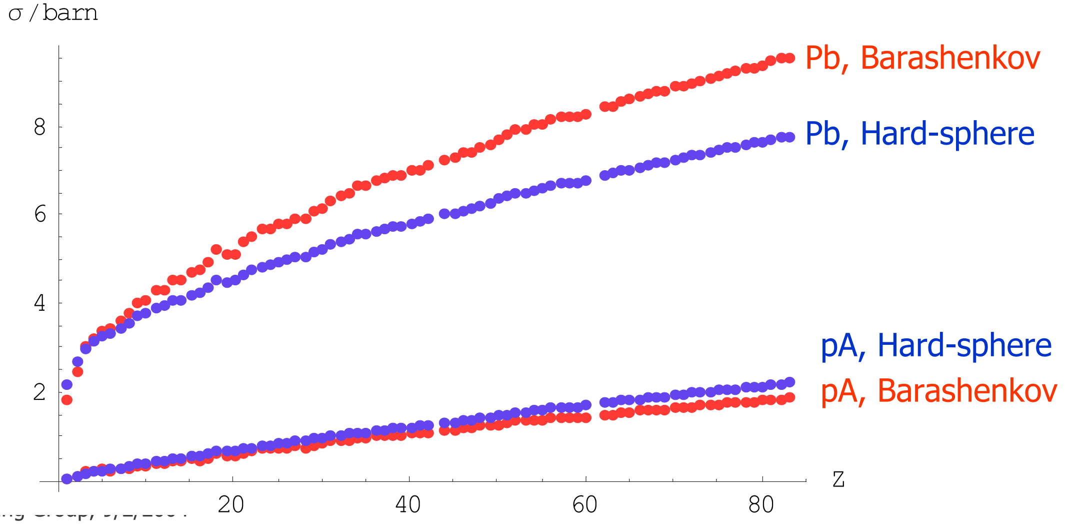
- Cross-sections of proton-nucleus and nucleus-nucleus inelastic interactions at ~10 GeV/n, assumed similar at 2.75 TeV/n (as is the case for protons)
  - Simple formula, V.S. Barashenkov, 1993

$$\mathrm{pA:}\quad \sigma_{\mathrm{in}}(Z,A)=\sigma_0\left[A^{1/3}+1.85\frac{A^{1/3}}{1+A^{1/3}}+2.5\left(1-\frac{2Z}{A}\right)-1\right]^2$$

$$\mathrm{A_1A_2:}\quad \sigma_{\mathrm{in}}(Z_1,A_1,Z_2,A_2)=\sigma_0\left[A_1^{1/3}+A_2^{1/3}+1.85\frac{(A_1A_2)^{1/3}}{A_1^{1/3}+A_2^{1/3}}+2.5\left(1-\frac{Z_1}{A_1}-\frac{Z_2}{A_2}\right)-2\right]^2$$

where $\sigma_0 = 0.038$ barn.

Comparison with earlier Hard-sphere overlap model (Bradt & Peters 1950)



Required gas pressures

Protons with lifetime 100h

Gas	σ_{in}	n/m^{-3}	P(300K)/nTorr	P(5K)/Pa	$P_{bg}/(W/m)$
H2	0.09	1.03×10^{15}	32.	7.11×10^{-8}	0.0377
He	0.113	8.2×10^{14}	25.5	5.66×10^{-8}	0.0377
CH4	0.433	2.14×10^{14}	6.65	1.48×10^{-8}	0.0377
H2O	0.397	2.33×10^{14}	7.24	1.61×10^{-8}	0.0377
CO	0.56	1.65×10^{14}	5.14	1.14×10^{-8}	0.0377
CO2	0.86	1.07×10^{14}	3.32	7.37×10^{-9}	0.0377

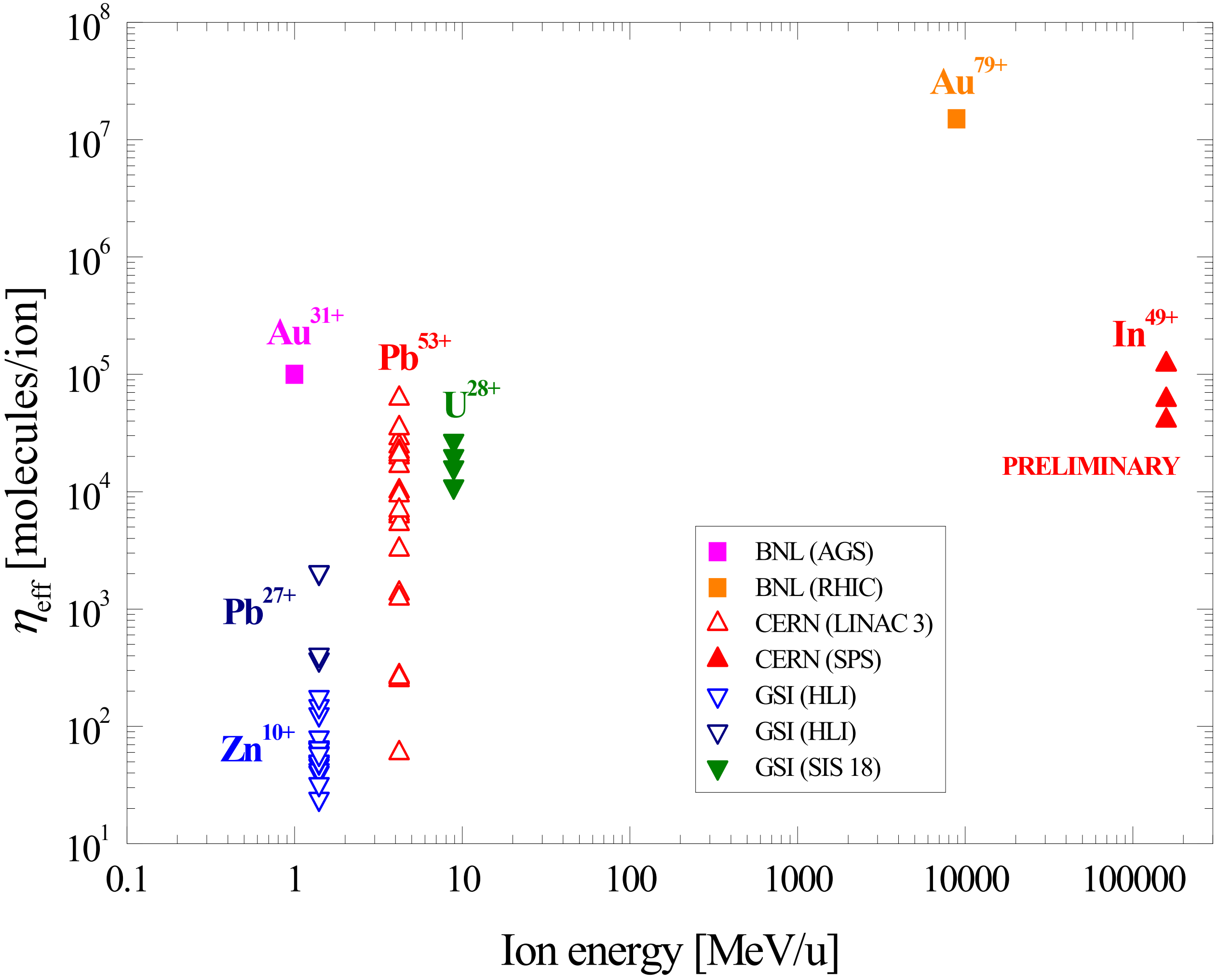
Lead ions with pressure that gave proton lifetime 100h

Gas	σ_{in}	n/m^{-3}	τ_{bg}/h	$P_{bg}/(W/m)$
H2	3.75	1.03×10^{15}	2.4	0.0165
He	2.48	8.2×10^{14}	4.55	0.00872
CH4	10.9	2.14×10^{14}	3.96	0.01
H2O	7.52	2.33×10^{14}	5.28	0.00752
CO	7.22	1.65×10^{14}	7.76	0.00512
CO2	11.	1.07×10^{14}	7.89	0.00503

Lead ions with lifetime 100h

Gas	σ_{in}	n/m^{-3}	P(300K)/nTorr	P(5K)/Pa	$P_{bg}/(W/m)$
H2	3.75	2.47×10^{13}	0.768	1.71×10^{-9}	0.000397
He	2.48	3.73×10^{13}	1.16	2.58×10^{-9}	0.000397
CH4	10.9	8.47×10^{12}	0.263	5.85×10^{-10}	0.000397
H2O	7.52	1.23×10^{13}	0.383	8.5×10^{-10}	0.000397
CO	7.22	1.28×10^{13}	0.399	8.86×10^{-10}	0.000397
CO2	11.	8.43×10^{12}	0.262	5.82×10^{-10}	0.000397

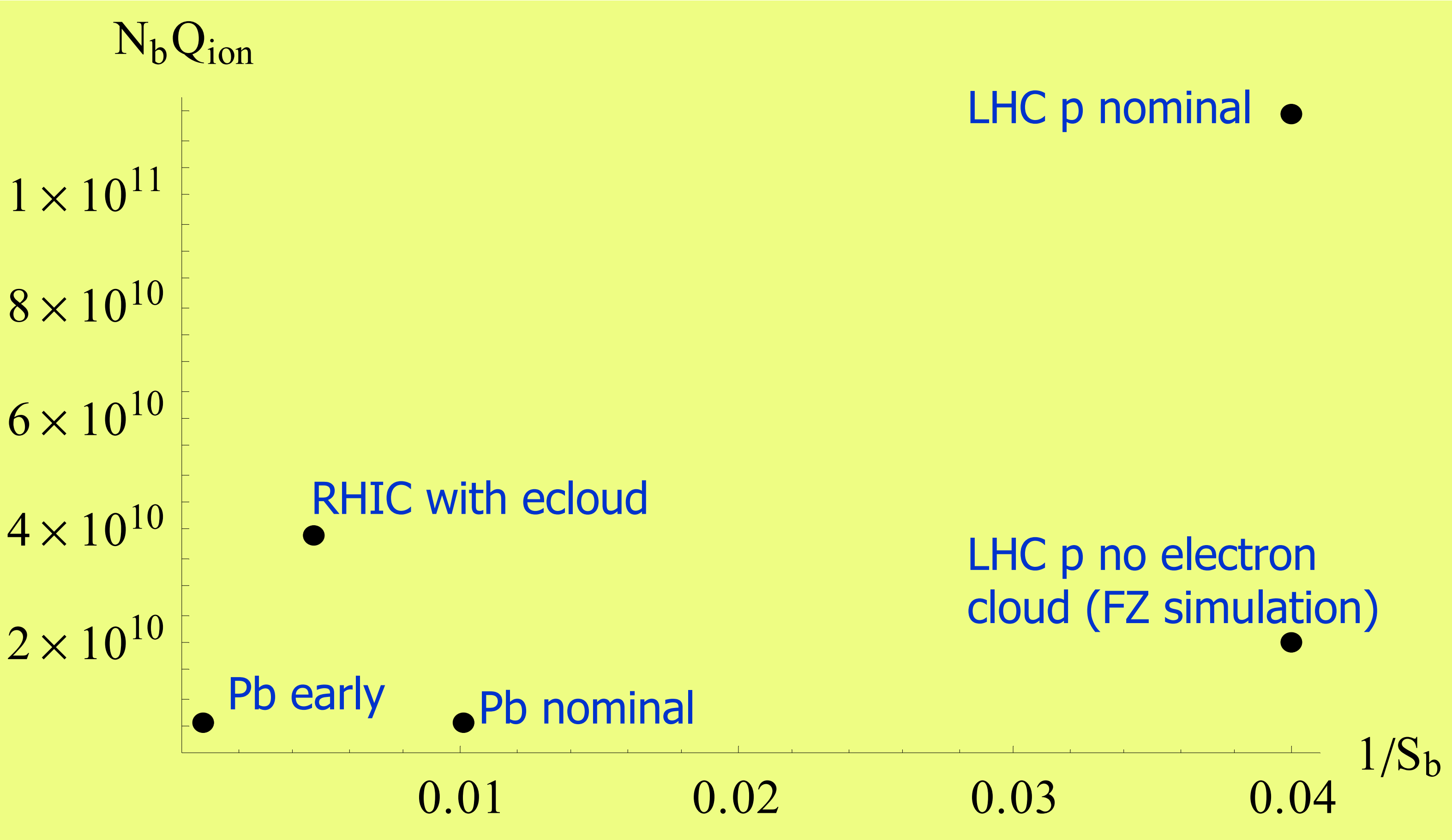
Heavy-ion induced desorption data: New Overview



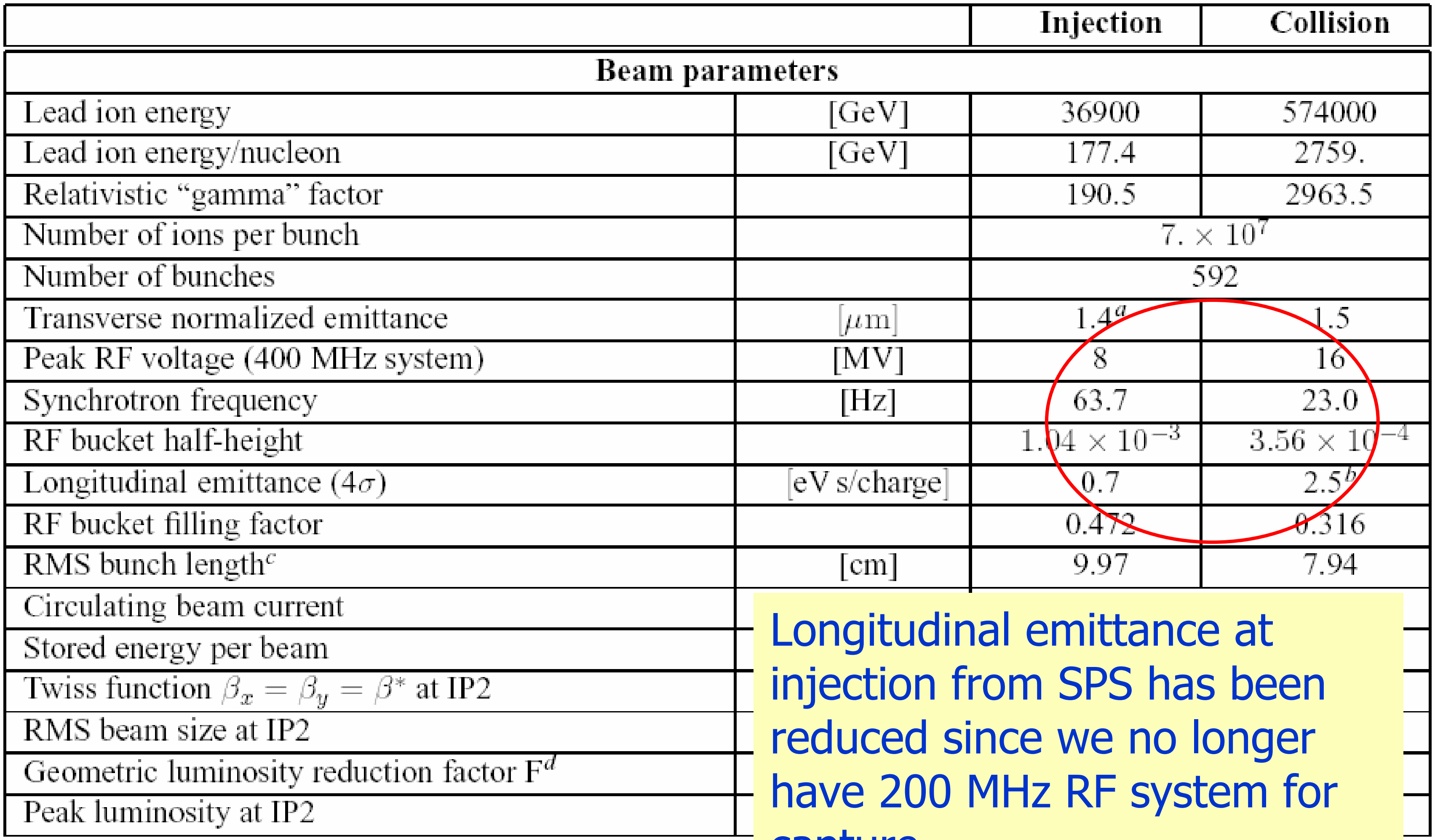
From Edgar Mahner

Electron Cloud effect with ions ?

- Key parameters are charge/bunch and bunch spacing
  - We do not expect electron cloud effects with Pb ions.



Longitudinal parameters



		Injection	Collision
Beam parameters			
Lead ion energy	[GeV]	36900	574000
Lead ion energy/nucleon	[GeV]	177.4	2759.
Relativistic “gamma” factor		190.5	2963.5
Number of ions per bunch		$7. \times 10^7$	
Number of bunches		592	
Transverse normalized emittance	[μm]	1.4[a]	1.5
Peak RF voltage (400 MHz system)	[MV]	8	16
Synchrotron frequency	[Hz]	63.7	23.0
RF bucket half-height		1.04×10^{-3}	3.56×10^{-4}
Longitudinal emittance (4σ)	[eV s/charge]	0.7	2.5[b]
RF bucket filling factor		0.472	0.316
RMS bunch length[c]	[cm]	9.97	7.94
Circulating beam current			
Stored energy per beam			
Twiss function $\beta_x = \beta_y = \beta^*$ at IP2			
RMS beam size at IP2			
Geometric luminosity reduction factor F[d]			
Peak luminosity at IP2			

Longitudinal emittance at injection from SPS has been reduced since we no longer have 200 MHz RF system for capture.

Intra-beam scattering

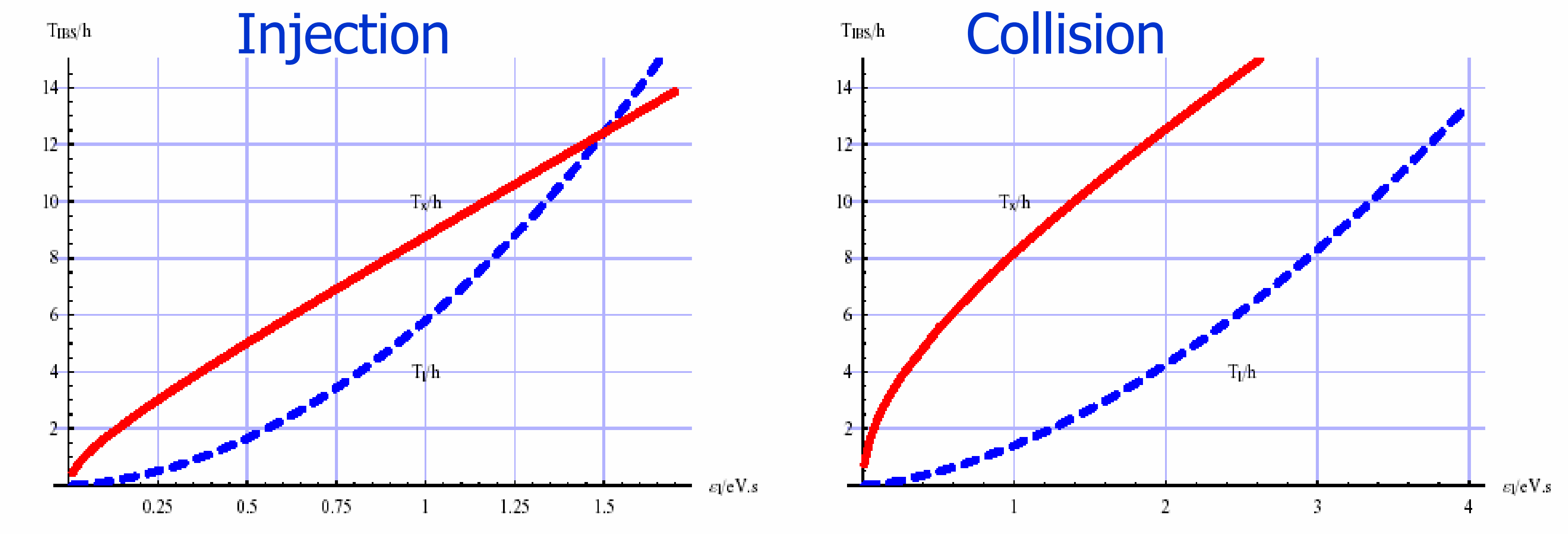


Figure 21.6: Emittance growth times from intra-beam scattering as a function of longitudinal emittance for $^{208}\mathrm{Pb}^{82+}$ at injection (left plot) and collision (right plot) energies. The transverse emittances and beam intensities are taken to have their nominal values and the total circumferential voltage from the 400 MHz RF system are $V_{\mathrm{RF}} = 8\,\mathrm{MV}$ and $V_{\mathrm{RF}} = 16\,\mathrm{MV}$ respectively. Solid and dashed lines correspond to the growth times for horizontal and longitudinal emittances.

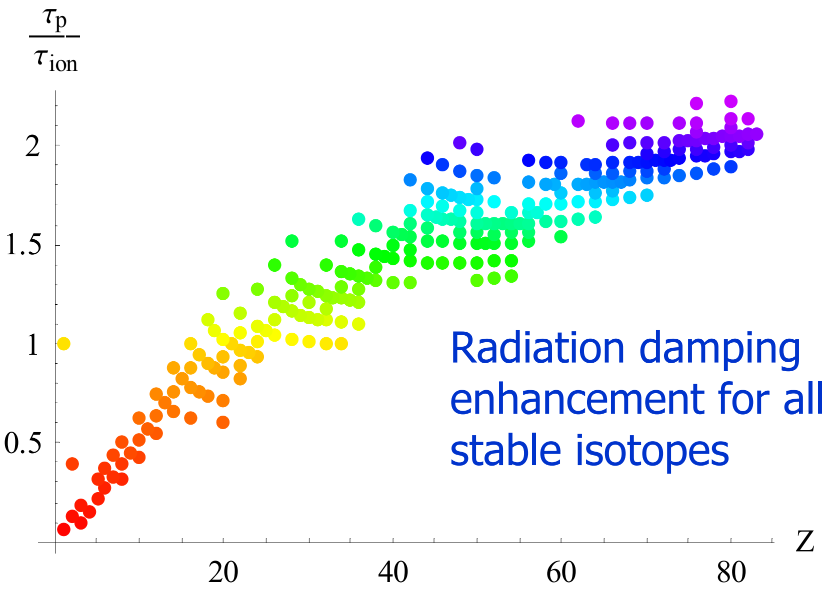
Synchrotron Radiation

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

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

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

  - 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.

Damping partition number variation

Variation of longitudinal damping partition number with momentum deviation of closed orbit:

$$J_\varepsilon(\delta_s) = \frac{d\log U(\delta_s)}{d\delta_s} \approx 2 + \frac{I_4}{I_2} + 2\frac{I_8}{I_2}\delta_s, \qquad \delta_s = -\frac{1}{\eta}\frac{\Delta f_{\mathrm{RF}}}{f_{\mathrm{RF}}}$$

$$I_2 \approx \frac{2\pi}{\rho}, \quad I_4 \approx 10^{-3} I_2,$$

$$I_8 = \oint \left(K_1(s) D_x(s)\right)^2 ds$$

Damping rate for horizontal betatron motion

$$\alpha_x(\delta_s) = J_x(\delta_s)\alpha_x(0) = \left(3 - J_\varepsilon(\delta_s)\right)\alpha_x(0)$$

- Allows us to switch some radiation damping from longitudinal into horizontal motion
  - Heavily used at LEP, PETRA, TRISTAN, …
  - Overcome IBS, shrinking horizontal emittance to maximise integrated luminosity
  - Price of a few mm negative closed orbit in arc QFs – needs further study

Luminosity and beam lifetime

- *Initial* beam (intensity) lifetime due to beam-beam interactions (non-exponential decay)

$$\tau_{NL} = \frac{k_b N_b}{n_{\exp} L \, \sigma_{\mathrm{tot}}} = \frac{22.4 \text{ hour}}{n_{\exp}} \quad \text{for nominal } L = 10^{27} \text{ cm}^{-2}\text{s}^{-1} \text{with Pb - Pb}$$

  - where $n_{\exp}$ is the number of experiments illuminated
- But luminosity may be limited by experiment or quench limit

$$L = \frac{k_b N_b{}^2 f_0}{4\pi \sigma^{*2}} = \frac{k_b N_b{}^2 f_0}{4\pi \beta^* \varepsilon_n} \gamma$$

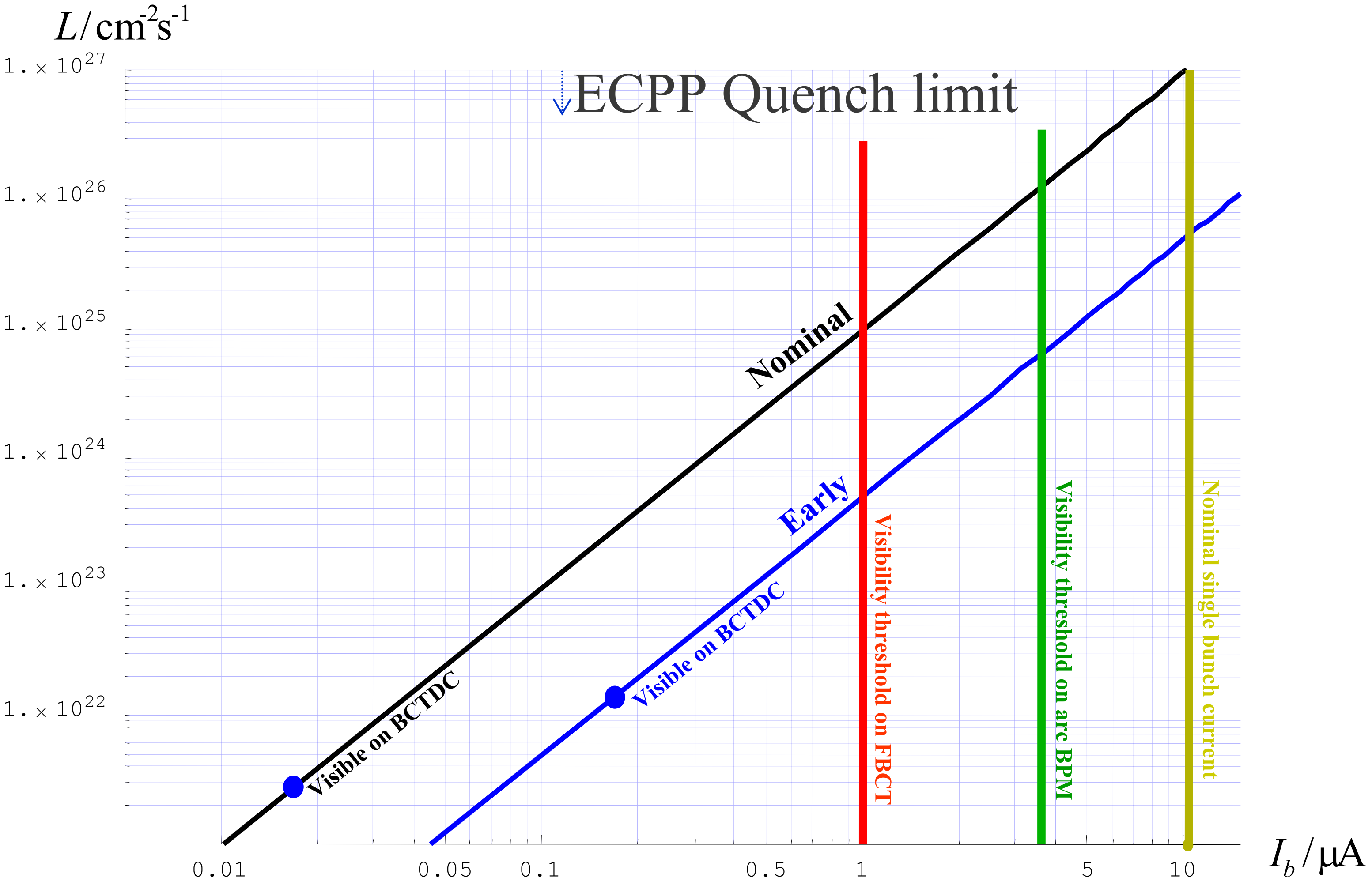
$$\Rightarrow \text{ can have same luminosity by varying } \beta^* \propto N_b{}^2$$

  - β*-tuning during collision to maximise integrated luminosity – especially if N_b can be increased.

Nominal scheme, lifetime parameters (again)

		Injection	**Collision**
Interaction data			
Total cross section	[mb]	-	514000
Beam current lifetime (due to beam-beam)[a]	[h]	-	11.2
Intra Beam Scattering			
RMS beam size in arc	[mm]	1.19	0.3
RMS energy spread $\delta E/E_0$	$[10^{-4}]$	3.9	1.10
RMS bunch length	[cm]	9.97	7.94
Longitudinal emittance growth time	[hour]	3	7.7
Horizontal emittance growth time[b]	[hour]	6.5	13
Synchrotron Radiation			
Power loss per ion	[W]	3.5×10^{-14}	2.0×10^{-9}
Power loss per metre in main bends	$[\mathrm{Wm}^{-1}]$	8×10^{-8}	0.005
Synchrotron radiation power per ring	[W]	1.4×10^{-3}	83.9
Energy loss per ion per turn	[eV]	19.2	1.12×10^{6}
Critical photon energy	[eV]	7.3×10^{-4}	2.77
Longitudinal emittance damping time	[hour]	23749	6.3
Transverse emittance damping time	[hour]	47498	12.6
Variation of longitudinal damping partition number[c]		230	230
Initial beam and luminosity lifetimes			
Beam current lifetime (due to residual gas scattering)[d]	[hour]	?	?
Beam current lifetime (beam-beam, residual gas)	[hour]	-	< 11.2
Luminosity lifetime[e]	[hour]	-	< 5.6

Operational parameter space with lead ions



Thresholds for visibility on BPMs and BCTs.

Conclusions

- Operation of LHC with lead ions limited by diverse effects, often qualitatively different from protons
- ECPP leading to magnet quench limits luminosity
- Poor collimation efficiency, large particle losses in dispersion compressor, limit on total current
  - Either keep > 40 min lifetime for nominal Ion parameters in collision (!) or reduce beam current
- "Early scheme" will allow relatively safe commissioning, access good initial physics
  - Reduced risk of magnet quenches from ECPP
  - Reduced heat deposition related to collimation
- But Pb ions require much lower vacuum pressure than protons
  - Independent of beam intensity!
- Restricted to a small range of operational parameters below the nominal luminosity
  - Do everything possible to expand it!

Implications

- Some effects (collimation,…) limit *total beam current* but there are no hard limits on single bunch current
  - More luminosity by distributing current in fewer bunches
  - Optimum filling scheme may be somewhere between Early (kb=62) and Nominal (kb=592)
  - Possibility of running with, e.g, 100-300 bunches should be kept in mind by injectors, all LHC systems and the experiments.
- Do everything possible to increase single-bunch current
  - Push all limits in injector chain
- Many uncertainties to be resolved with further work
  - ECPP heating, EMD losses, vacuum, collimation, RF noise, …