Ion Collimation in LHC
Status and plans

John Jowett

Thanks for slides and information to: Giulia Bellodi, Hans Braun, Roderik Bruce, Alfredo Ferrari, George Smirnov, Vasilis Vlachoudis, + Collimation Working Group

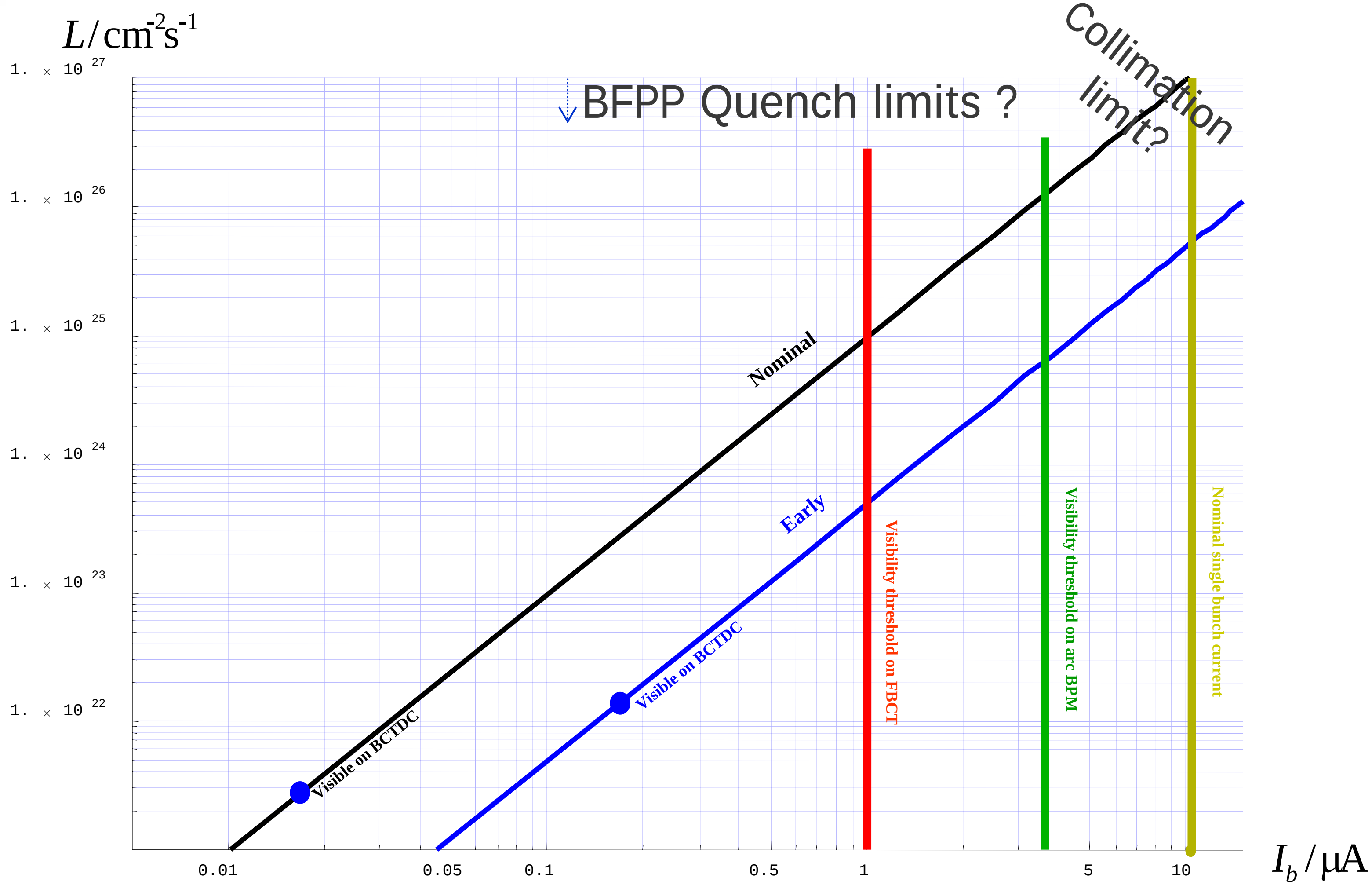
Collimation of Pb ions in LHC

- Performance of Phase I collimation system for ions
  - Physics is different because of ion fragmentation : halo from primary collimators is mostly lost in SC magnets.
- Operation in initial phases
  - BLMs added for collimation losses
  - Avoid magnet quenches
- Test understanding on SPS
  - MDs this year
- Possible solutions
  - Adapting optics of collimation insertions
  - High Z spoilers – to be studied
  - Magnetised collimators
  - Crystal collimation, to be tested in H8 beam line
  - Nonlinear collimation ?
  - Hollow electron beam (Shiltsev at LUMI06 workshop)

Nominal and Early Pb Ion Beam

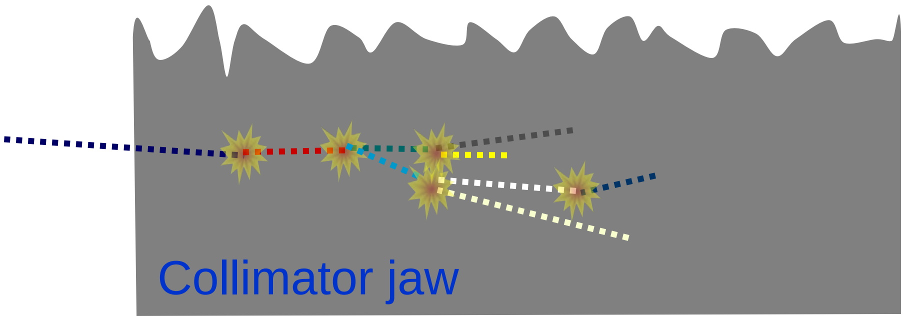
Parameter	Units	Nominal	Early Beam
Energy per nucleon	TeV/n	2.76	2.76
Initial Luminosity L_0	$cm^{-2}\ s^{-1}$	$1\ 10^{27}$	$5\ 10^{25}$
No. bunches/bunch harmonic		592/891	62/66
Bunch spacing	ns	99.8	1350
β^*	m	0.5 (same as p)	1.0
Number of Pb ions/bunch		**$7\ 10^7$**	**$7\ 10^7$**
Transv. norm. RMS 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
Stored energy /beam	MJ	3.81	0.39

Operational Parameter Space for Pb Ions

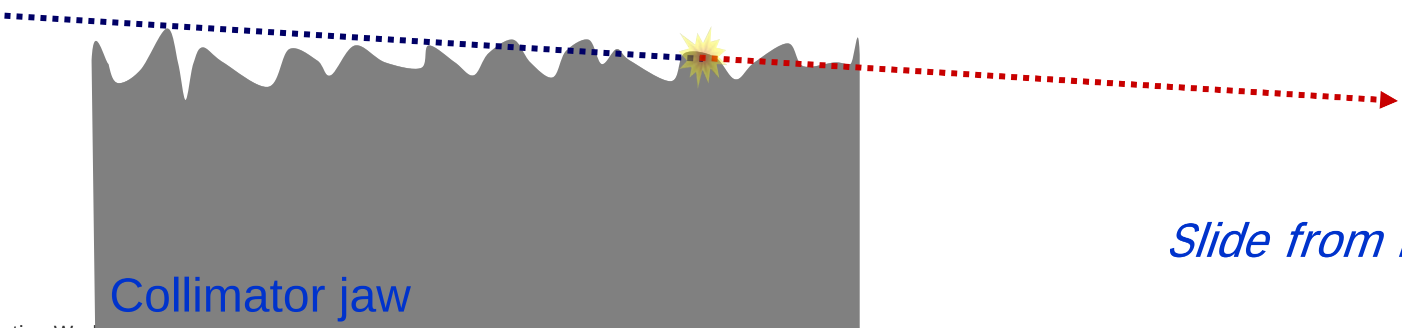


Thresholds for visibility on BPMs and BCTs.

Ions with ***betatron amplitude >> acceptance***
cause no problems
interaction length << collimator length



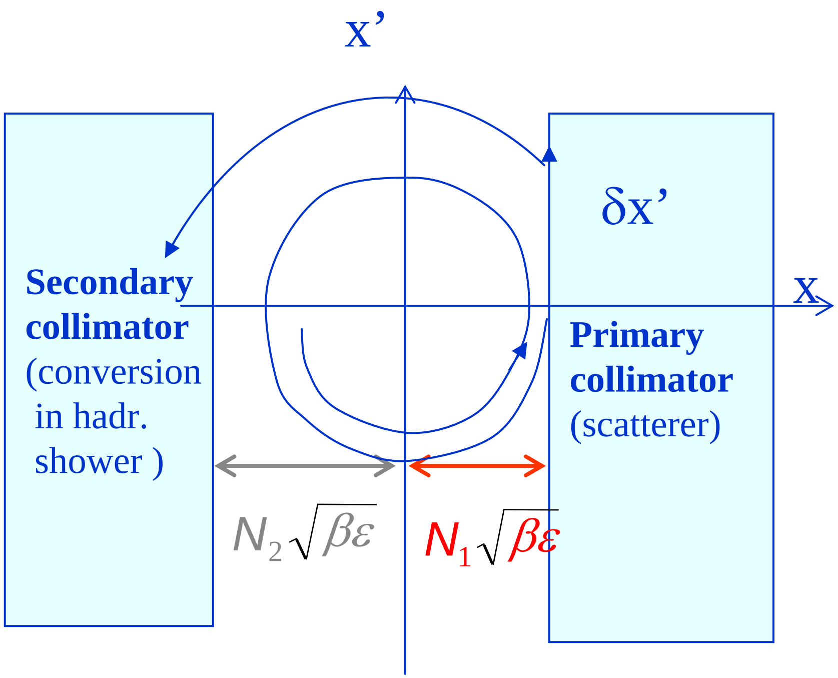
Ions with ***betatron amplitude ≈ acceptance***
can be subject to a single nuclear reaction,
thus ending in SC magnets because of resulting wrong *Z/A*
Unfortunately most halo generating processes tend to have maximum
halo density just at this amplitudes



Slide from H. Braun

The LHC collimation system

Based on a two-stage collimation concept, with short TCPs and longer TCSs downstream with larger gap aperture to capture halo particles (multi-turn effect, amplitude increase via MS).



Necessary condition:

$$\delta x' > \sqrt{\frac{\left(N_2^{\,2} - N_1^{\,2}\right)\varepsilon_N}{\gamma_{REL}\,\beta_{TWISS}}}$$

δx' mainly due to multiple Coulomb scattering, with

$\langle \delta x'^2 \rangle \sim L$

Ion collimation: why it's a problem

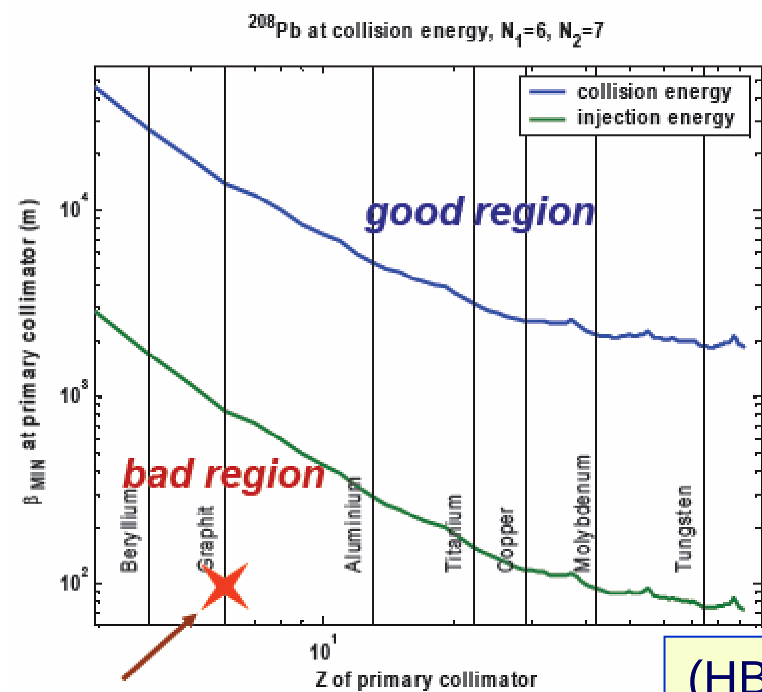
Nominal ion beam has <u>100 times less beam power</u> than proton beam, but particle-collimator physics very different:

Physics process	Proton	^{208}Pb
$\frac{dE}{Edx}$ due to ionisation	-0.12 %/m -0.0088 %/m	-9.57 %/m -0.73%/m
Mult. Scattering (projected r.m.s. angle)	$73.5\mu rad/m^{1/2}$ $4.72\mu rad/m^{1/2}$	$73.5\mu rad/m^{1/2}$ $4.72\mu rad/m^{1/2}$
Nucl. Interaction length ≈fragment. length for ions	38.1cm 38.1cm	2.5cm 2.5cm
Electromagnetic dissociation length	-	33cm 19cm

~20 times higher probability of nuclear interactions

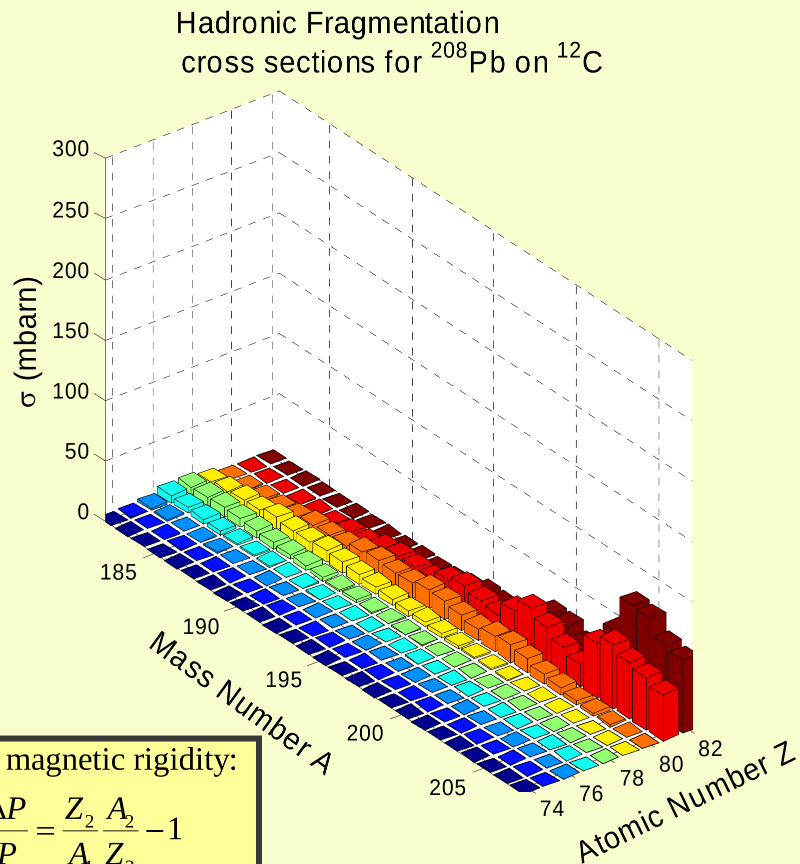
$$L \approx L_{int} = \frac{A_{coll}}{N_A \rho (\sigma_{had} + \sigma_{emd})}$$

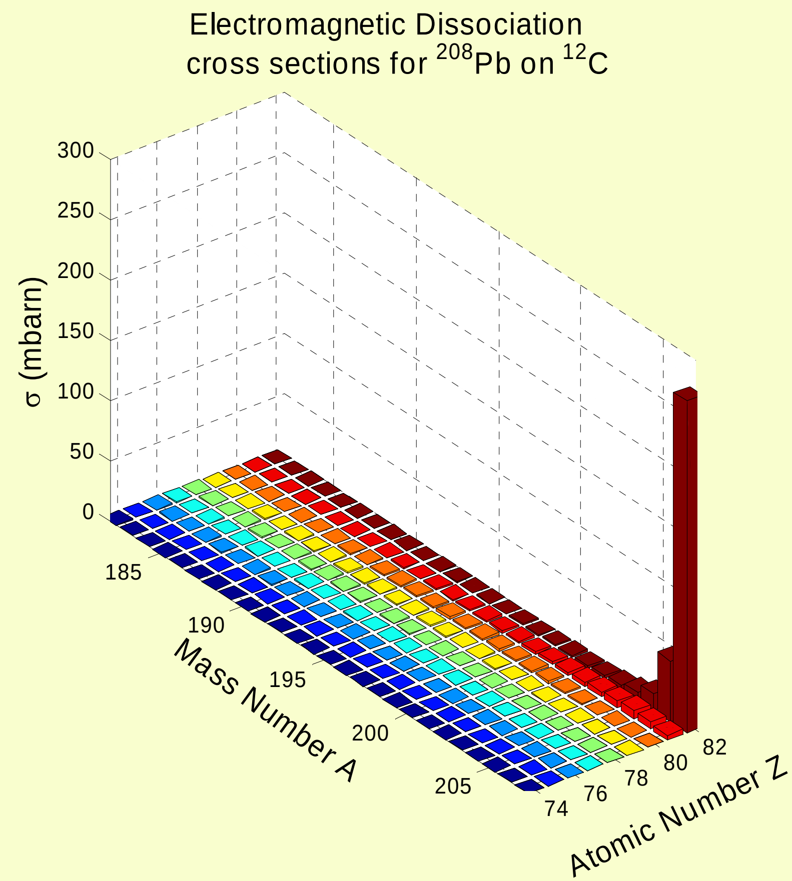
High probability to undergo nuclear interactions in the TCP before 2-stage collimation condition is satisfied



(HB)

Ion-collimator interactions





Change in magnetic rigidity:

$$\frac{\Delta P}{P} = \frac{Z_2}{A_1}\frac{A_2}{Z_2} - 1$$

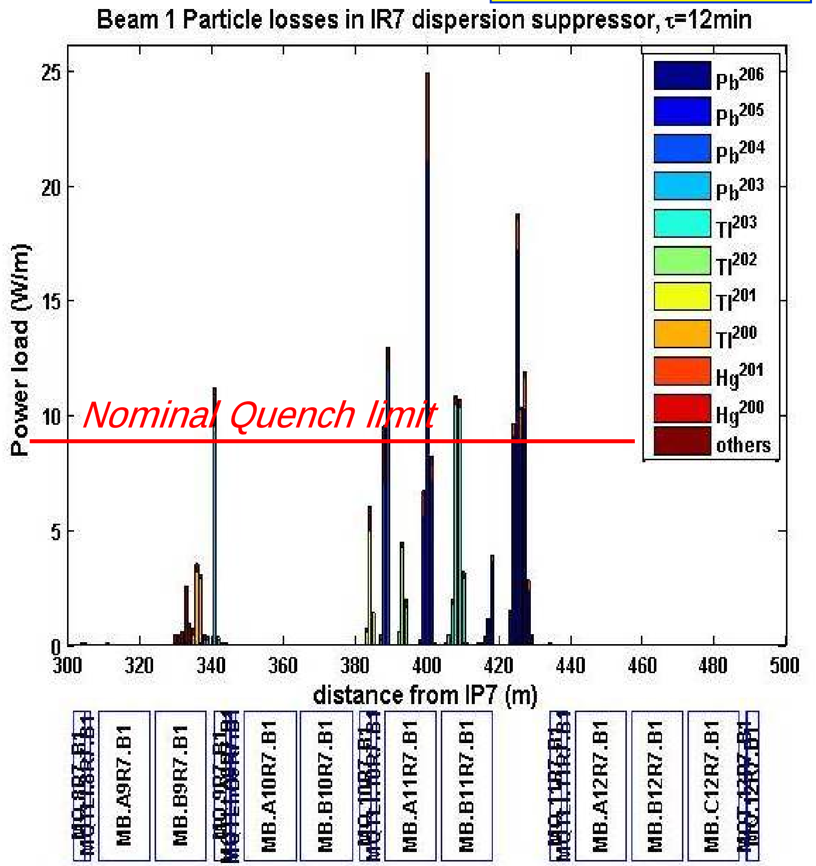
Large variety of daughter nuclei, Monte Carlo calculated specific x-sections

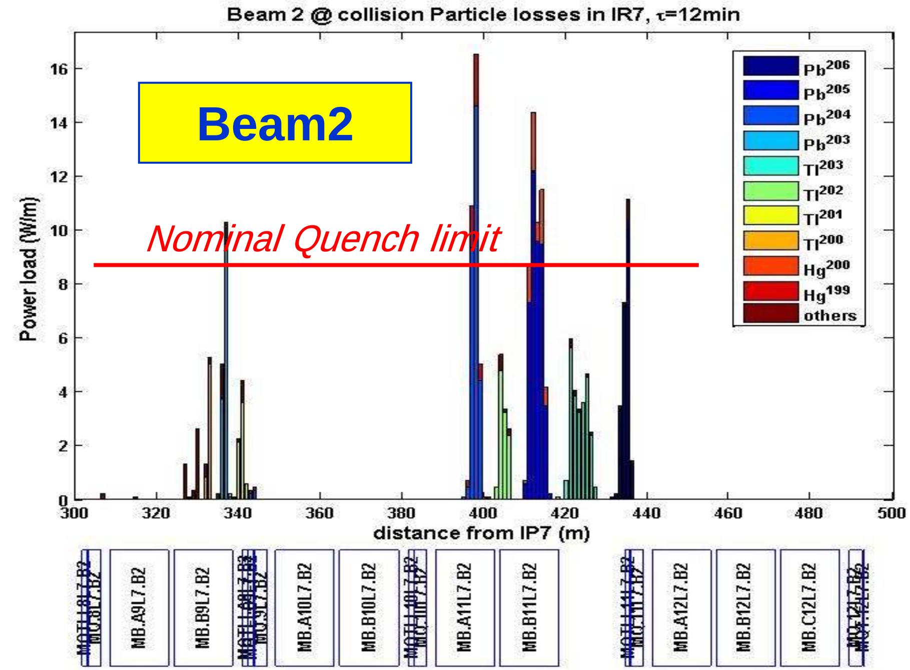
Mainly loss of 1 neutron (59%) or 2 (11%) → ^{207}Pb, ^{206}Pb

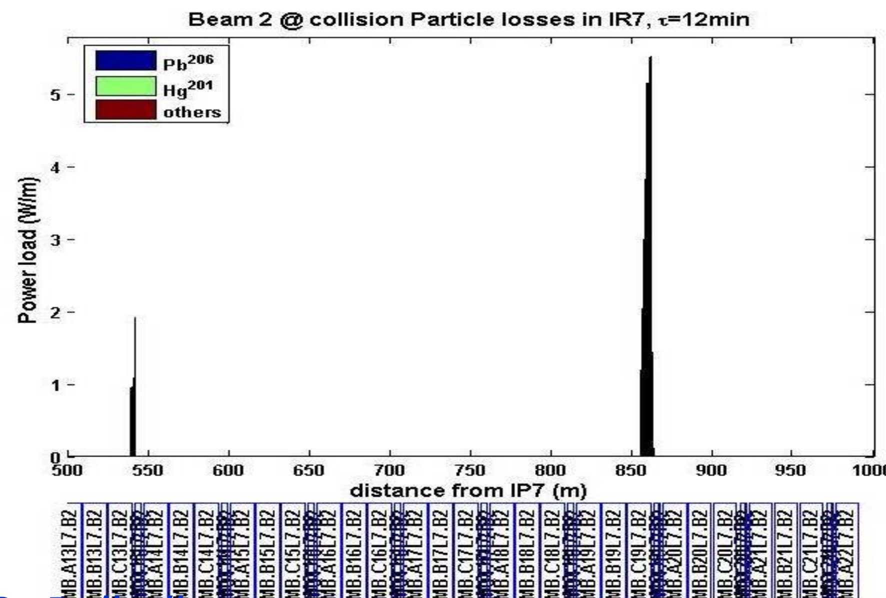
Slide from G. Bellodi/H. Braun

Collision:

Beam1







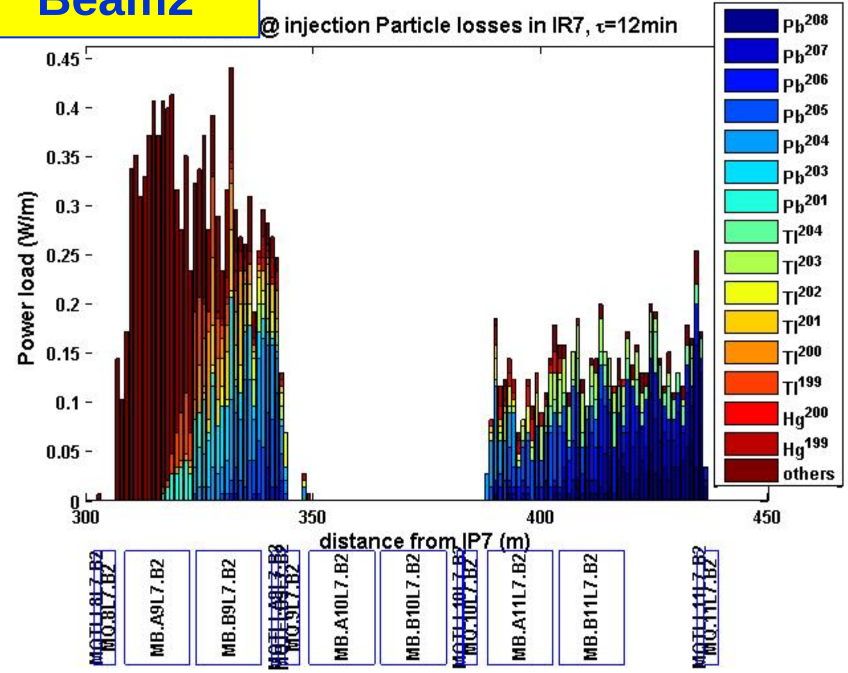
Losses confined to IR7 dispersion suppressor, cells 9 & 11

Two peaks downstream in the arc for Beam2

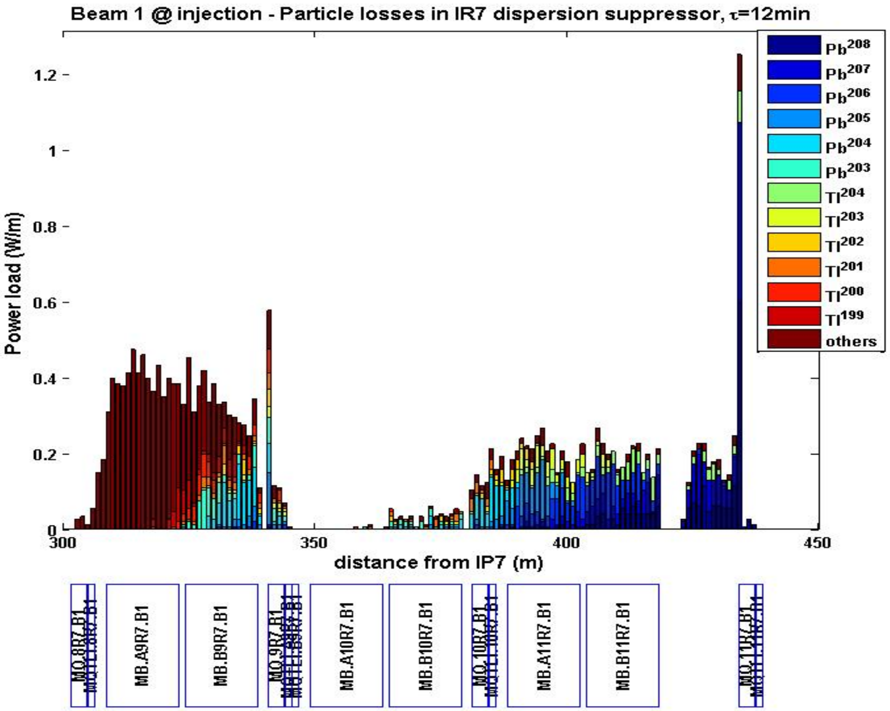
Slide from G. Bellodi

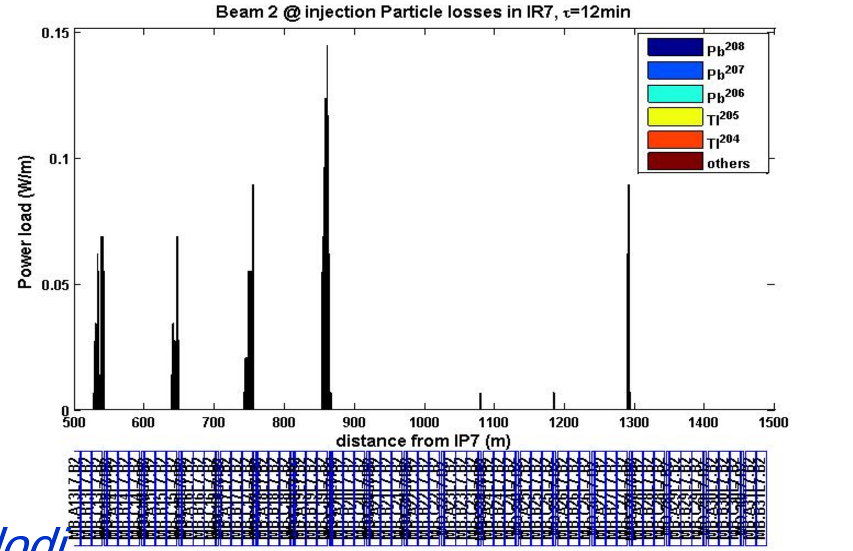
Injection:

Beam2



Beam1





Slide from G. Bellodi

BLM coverage for Pb ions

- Additional BLMs
  - Some of the extra BLMs are required because of the ion collimation inefficiency
  - Motivation and BLM configuration described in detail in LHC Project Note 399

BLMs coverage:

Philosophy :

Adding 1mm to aperture (all elements) causes a shift in the beam loss peaks by up to 2m

BLMs coverage of IR7:
3 patches available in cells 8,9,11 (dipoles) X 8 channels (max) X 2 BLMs

2 channels available on quad patches (regions 8,9,10,11,13)

Need tight coverage of cells 9-11

Numbers:

RBruce

BLM active length = 40 cm

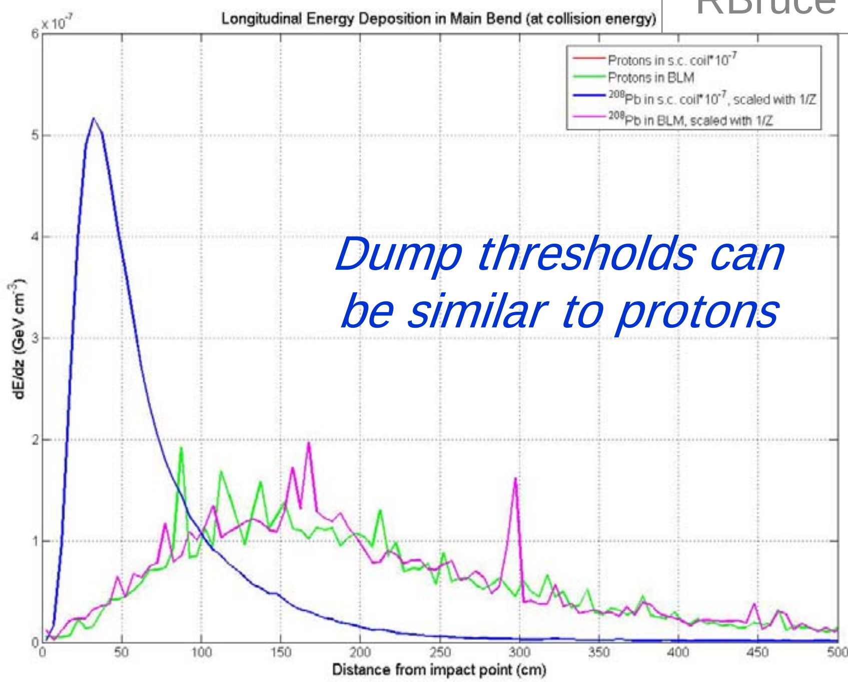
Dipole length = 14.3 m (x2)

Long. spread of energy deposition=

2.5 m FWHM

peak @ 1.5 m from impact

For coil deposition peak @ 30cm from impact point



Simulation tools

FLUKA: for prediction of heat deposition, ratio between local losses and BLM signals etc.

ICOSIM:

ICOSIM (H.Braun)

- Generates initial beam distribution
- Tracks particles through machine
- Simulates ion-matter interactions in collimators
- Computes impact sites of ions in LHC lattice

MAD-X optics files and aperture tables

Nuclear interaction cross-sections from RELDIS & ABRATION/ABLATION routines

(Igor Pshenichnov)

OUTPUT

Loss patterns

Collimation efficiencies

Plans to replace by integrating FLUKA and ICOSIM

Slide from G. Bellodi

New ICOSIM simulations to be done

- Better incorporation of orbits (IR bumps)
  - Under way (G. Bellodi)
- Inclusion of all items (TCLAs)
  - Under way (G. Bellodi)
- Energy ramping
  - Depends on integration with FLUKA
- Effects of high-Z scrapers
  - Depends on integration with FLUKA

Testing of methodology in SPS

- Compare ICOSIM predictions for protons
  - MDs/SIXTRACK simulations done in 2004 (Roderik Bruce, Simone Gilardoni)
  - Interfaced ICOSIM to MARS, results soon
- MDs with Pb beam and LHC collimator in SPS (Sep-Oct 2007)
  - Once Pb beam commissioned in SPS, compare measured losses from BLMs with predicted loss maps of fragments from ICOSIM at 106 GeV/A and at 10.3 GeV/A (injection energy).
  - Proton loss maps at same magnetic rigidities (270 GeV and 26 GeV) for comparison.
  - Need few extra BLMs installed temporarily at critical locations.
  - Need help of collimation team ...

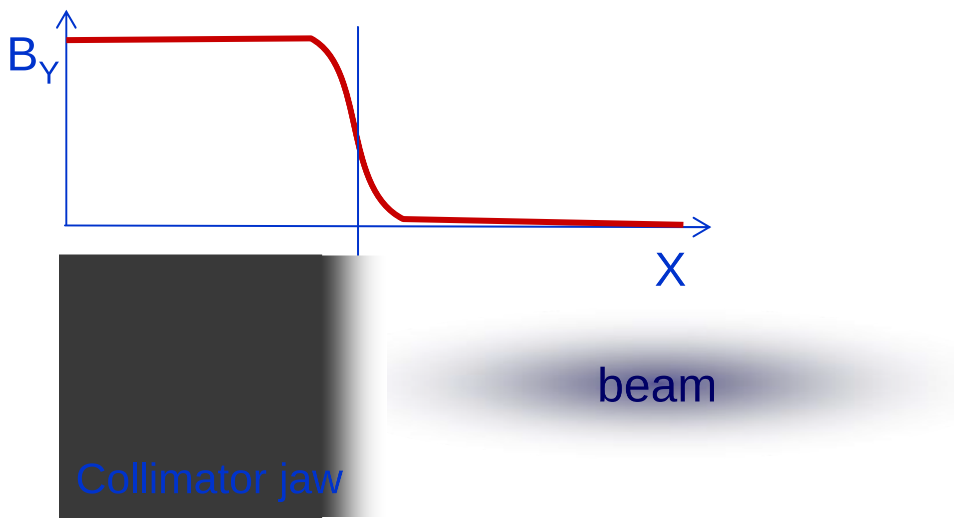
Changes of optics in IR3, IR7

- Look at possibility of improving situation by changing the optics of the collimation insertions
  - Increase bx at primary collimators
  - Maximise dispersion created after primary collimators

- I plan to look at this but a priori not very hopeful ...

- Ideal, simple solution: rebuild of the cleaning insertions
  - Increased beam separation (4 times) in the collimation doglegs
  - Expensive, long shutdown of LHC
  - Also good for protons though ...

Introducing a magnetic field which extends over the diffuse boundary region of the collimator assures that all particles getting close to surface will be deflected to secondary collimator

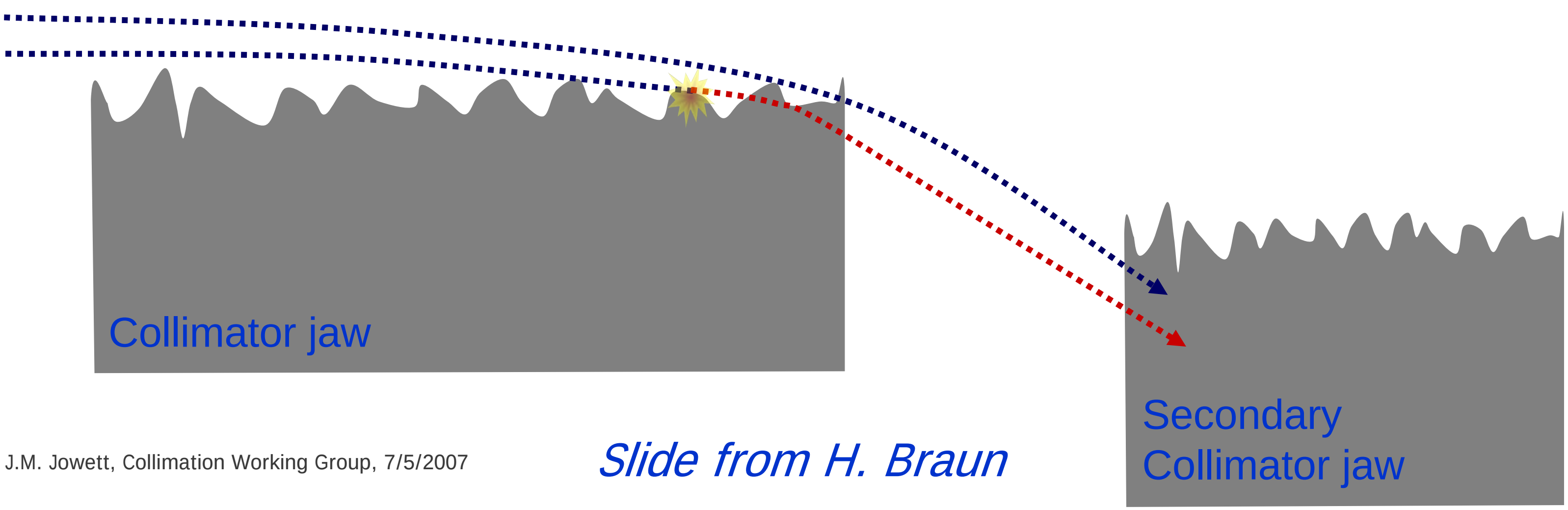


Condition to bend particle sufficiently to hit secondary collimator

$$\delta x' > \sqrt{\frac{\left(N_2^{\,2} - N_1^{\,2}\right)\varepsilon_N}{\gamma_{REL.}\,\beta_{TWISS}}}$$

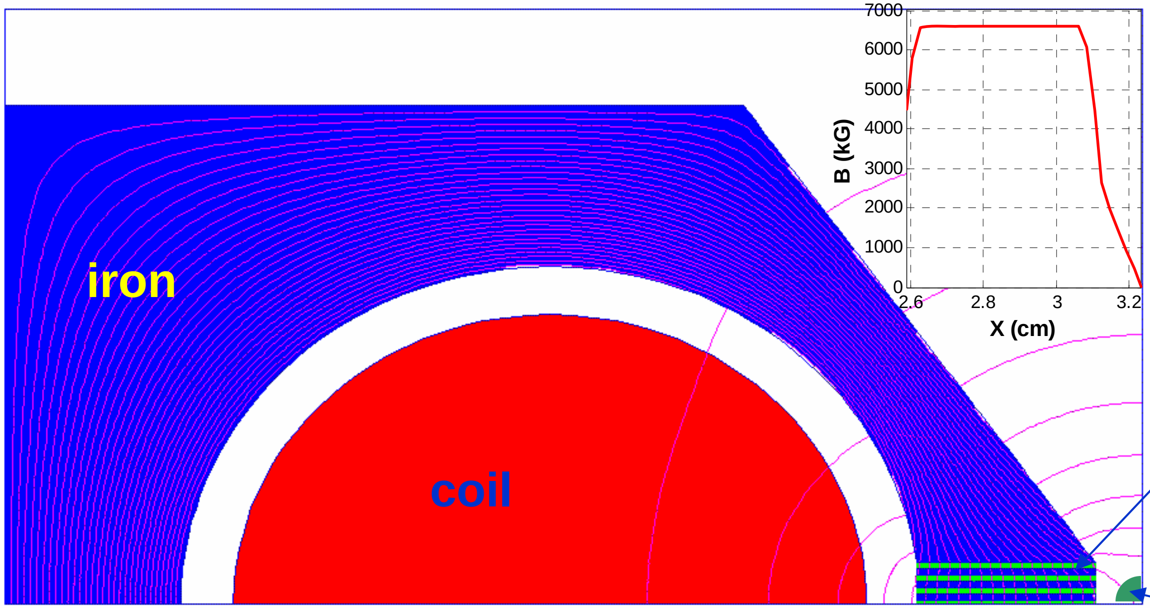
$$\Downarrow$$

$$B\,L > \sqrt{\frac{\left(N_2^{\,2} - N_1^{\,2}\right)\varepsilon_N}{\gamma_{REL.}\,\beta_{TWISS}}}\;\frac{P}{Z\,e} \approx 0.2\ \text{Tm}$$



Slide from H. Braun

Magnitized Jaw for primary collimator, first attempt with 2D magnet code

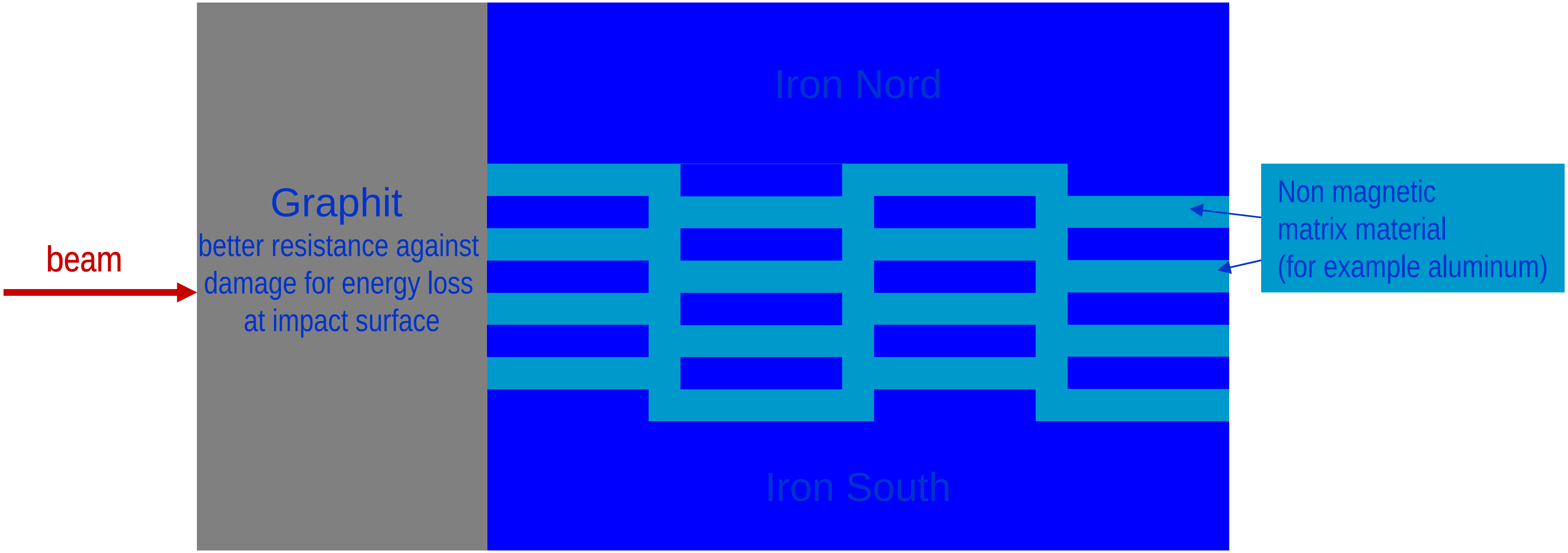


sandwich structure of magnetic and non-magnetic metal

beam

Slide from H. Braun

3D structure with iron sheets between poles

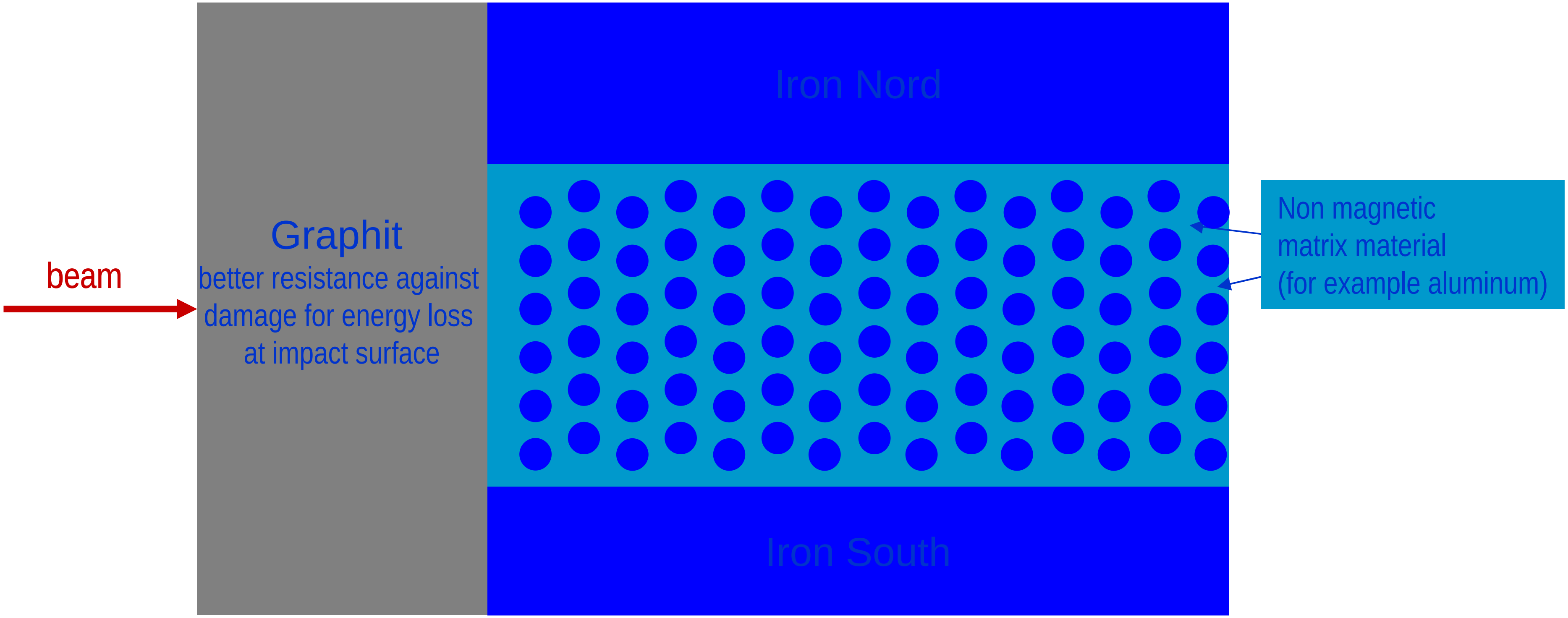


Interleaved positioning to cover all initial *y* positions

Sheet thickness allows to adjust “skin depth of magnetic field”

Slide from H. Braun

3D structure with iron rods between poles



Interleaved positioning to cover all initial *y* positions

Size and distance of iron rods allows to adjust “skin depth of magnetic field”

Rods instead of sheets probably allow faster field drop towards beam core

Slide from H. Braun

Proposed development program

1. Magnet design studies with 3D magnet code to find configuration with best properties. Problems: **2007**
   - Get right "magnet field skin depth" in the order of 100 μm
   - Minimize or linearize residual field at beam core
   - Thin sheets of ferromagnetic materials have not necessary same magnetic properties as bulk material
2. Implement magnet model in ICOSIM and predict cleaning efficiency
3. Engineering design of prototype **2008**
4. Build prototype
5. Check performance with prototype test in SPS **2009**
6. Implement dedicated ion primary collimators in LHC IR7 **2010**

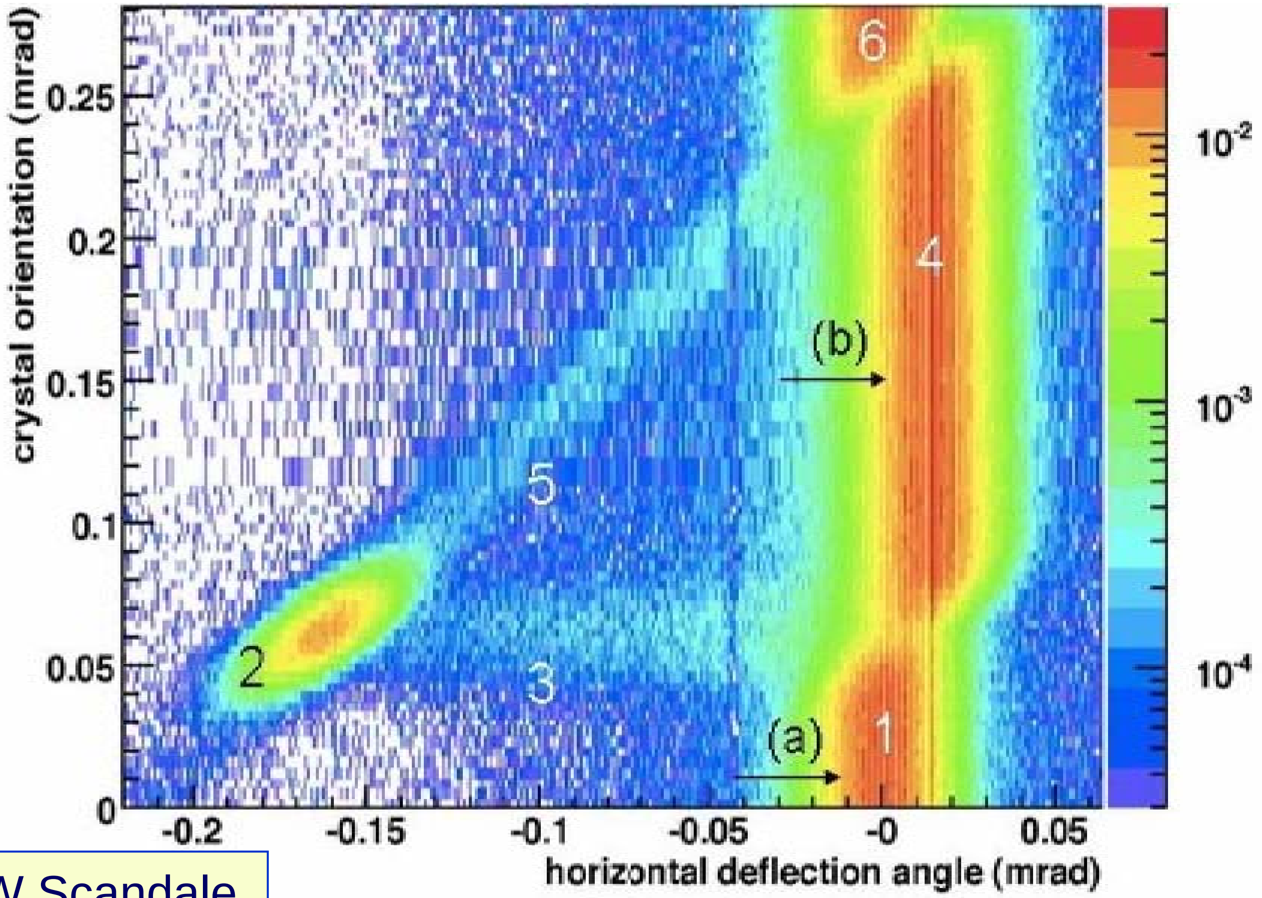
Can we shortcut the magnet calculations and make quicker simulation?

Slide from H. Braun

Crystal collimation

- Bend crystal collimator for channeling (or volume reflection)
  - See recent workshop, talk by Giulia Bellodi
  - May benefit from suppression of fragmentation and electromagnetic dissociation of ions
  - Long history already, not yet made practical

Crystal angular scan (H8 RD22)



W.Scandale

Channelling:

def. angle~160 μrad

prob. ~50%

V reflection:

Def. angle~10μrad

prob~97%

2. channelling, 4. volume reflection, 5.volume capture

Pb-Beam Transport in Continuum Potential

Trajectory is defined by the transverse energy of Pb ion:

distance ***b*** of the ion from row of atoms

$$\mathbf{r < b < d/2}$$

Distance of closest approach to the row of atoms : $r = 2.5u_1 = a$

$$a = 0.8853 a_0 (Z_1^{2/3} + Z_2^{2/3})^{-1/2}$$

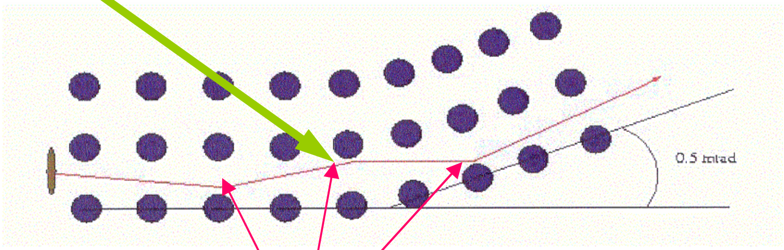
$\mathbf{r = 1\ 10^4\ f}$

$\mathbf{d/2 = 2.7\ 10^5\ f}$

u_1 is the amplitude of crystal atoms thermal oscillations

a is the screening length

a_0 = 0.529 10^5 f — Bohr radius



Largest time to stay in the channel

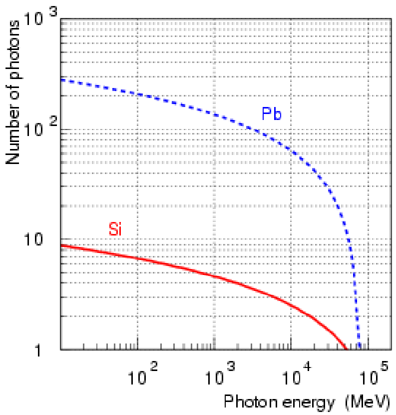
Slide from G. Smirnov

No channeling

discrete potential

Photon flux from Pb or Si at LHC after integrating over impact parameter ***b***

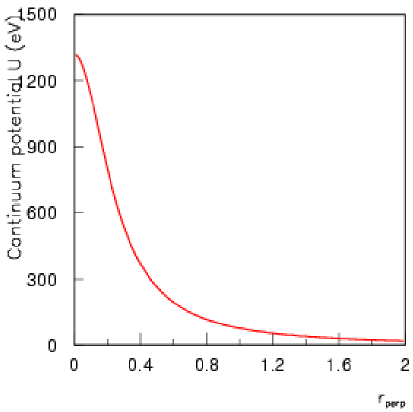
$$n(\omega) = \frac{2Z^2\alpha}{\pi} \ln(\frac{\gamma}{\omega R_A})$$



channeling

continuum potential

Potential $U_\perp$ at some arbitrary temperature of the Si crystal



Distance from the atomic row (Angstrom)

Slide from G. Smirnov

discrete potential

b_{min} = 2.9 f

1 MeV < E_{gamma} < 10^5 MeV

continuum potential

b_{min} = 9400 f

E_{gamma} < 1 MeV

$\gamma + {}^{208}\mathbf{Pb}$

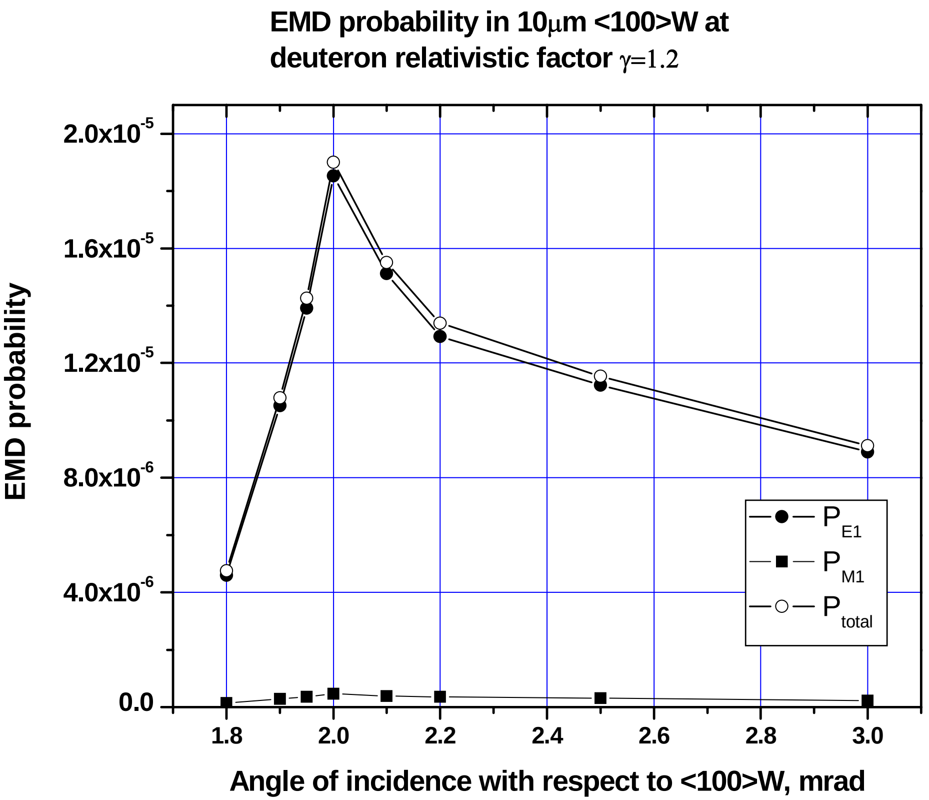
Threshold Energies (MeV)								
γ,n	γ,p	γ,t	γ,He-3	γ,α	γ,2n	γ,np	γ,2p	γ,3n
7.37	8.01	12.88	14.39	-0.52	14.11	14.85	15.38	22.19

No reaction on Pb with photon energy < 1 MeV

Slide from G. Smirnov

Simulation of EMD of deuterons in a tungsten crystal under different channeling conditions

Fig. 8 from the talk presented at "Channeling-06" (Frascati, 3-7 July 2006) by Yu. Pivovarov and V.Dolgikh



Slide from G. Smirnov

Further questions on crystals

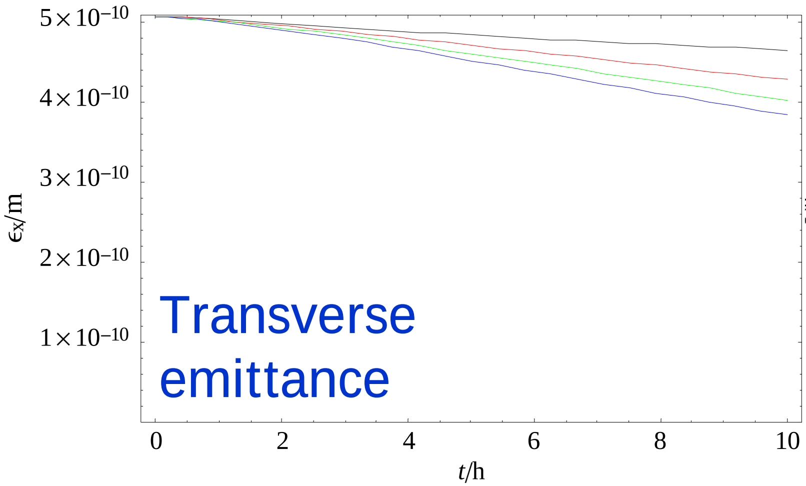
- Volume reflection effect
  - More efficient, smaller deflection
  - Does not benefit from suppression of nuclear electromagnetic interactions
  - Seems to need detailed simulation to evaluate interest compared with channelling
  - Maintain contacts with Tomsk and Dubna groups
- How much can we expect to find out from experiments in H8 beam line later this year ?

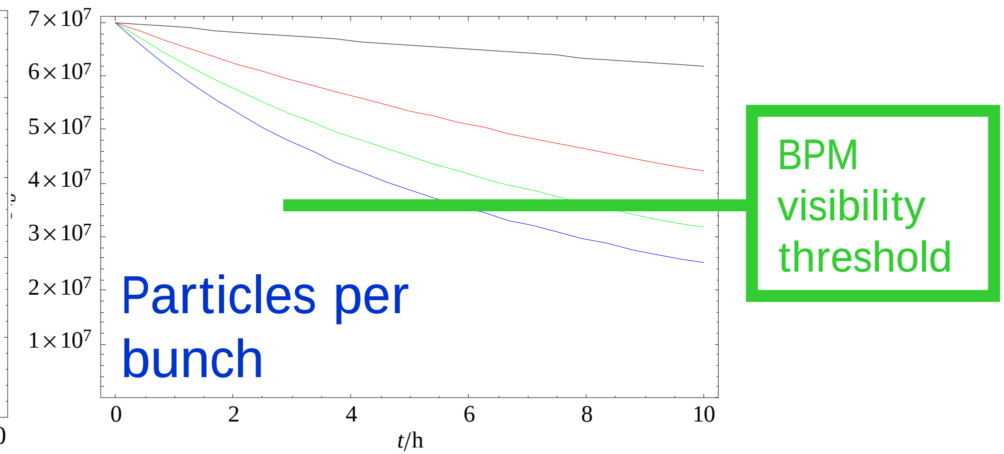
Conclusions

- Collimation may be a problem for Pb ion beams in LHC
  - Operational strategies to alleviate
- Several possible solutions, none clearly effective
  - Plan to gain information from experiments and simulations in the coming months
  - Evaluate our best bet
  - Time scales for prototyping and installation at time of Phase II collimator upgrade are tight and manpower is limited (and somewhat fragmented and scattered)
- Need help of Collimation team and others
- In future we need to evaluate collimation of lighter ions
  - Remember that Pb-Pb runs have goal of 1 nb^{-1} integrated luminosity

Backup slides

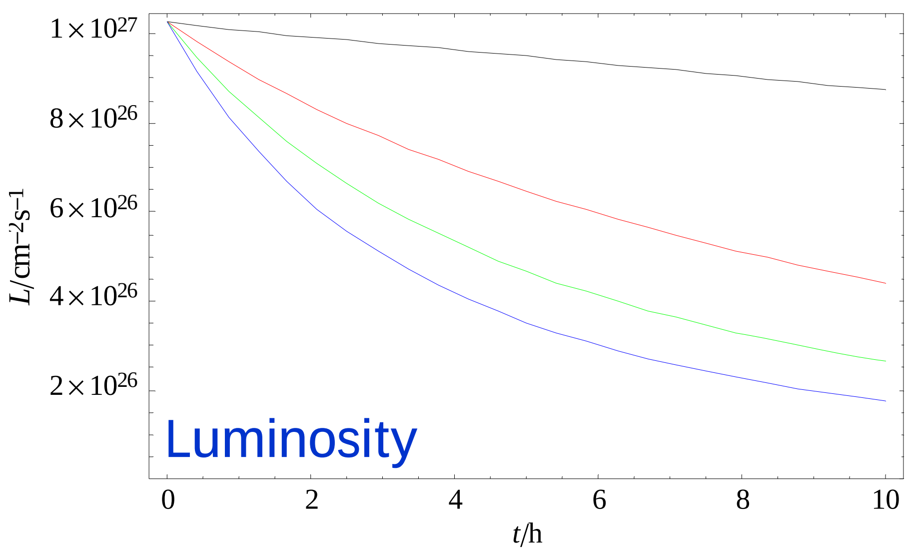
Luminosity evolution: Nominal scheme





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

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



Increasing number of experiments reduces beam and luminosity lifetime

May not want design peak luminosity! Increase β^*