Simulations of ion beam losses

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Outline

- Introduction: difference between ion and proton beam losses
- Short qualitative description of most important physical processes involved
- Simulations of ion beam losses (worst cases selected)
  - particle beam hitting generic target
  - Particle beam with grazing incidence in LHC main dipole
  - Hits on collimator caused by erroneous trigger of dump kicker (V. Vlachoudis)
- Conclusion

Introduction

- Question: what setup beam limit can be used for Pb ions?
- Resulting question: What is the ratio of peak energy deposition in a target between Pb ion and protons?

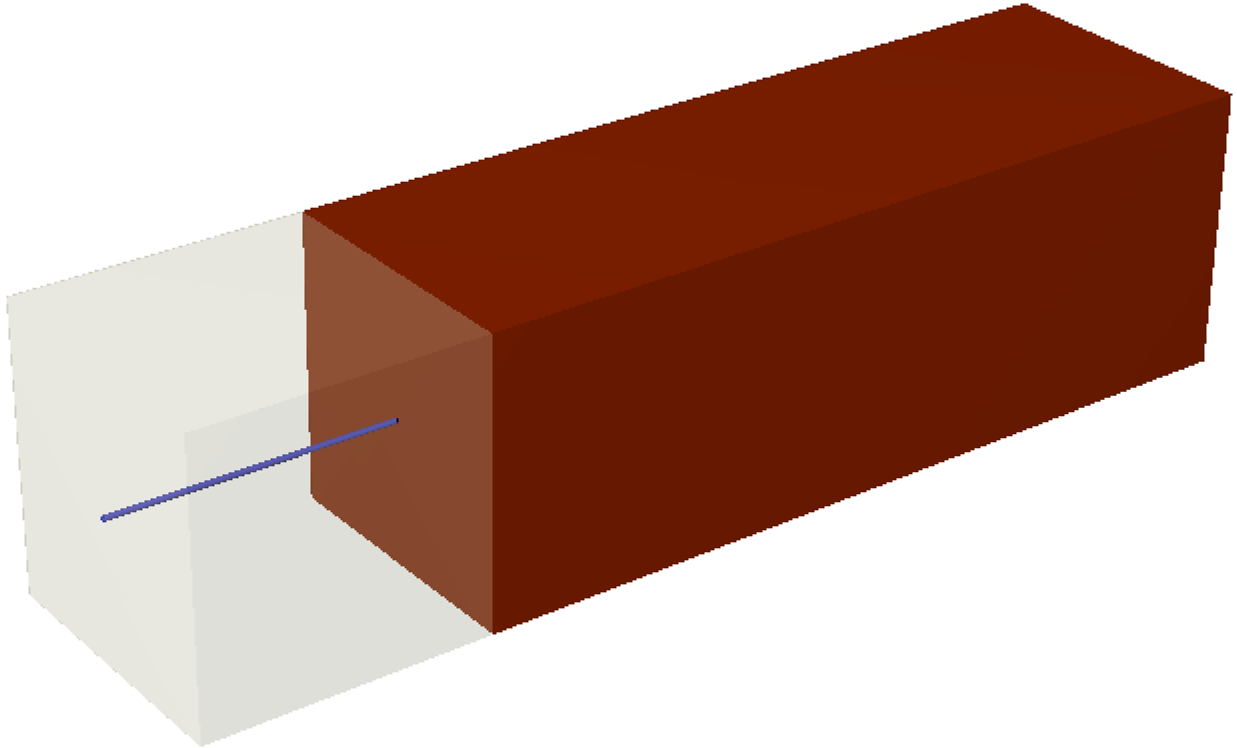
Physics process	p injection	p collision	$^{208}Pb^{+}$ injection	$^{208}Pb^{+}$ collision
Ionisation energy loss $\frac{dE}{E\,dx}$	0.12 %/m	0.0088 %/m	9.57 %/m	0.73 %/m
Multiple scattering projected RMS angle	$73.5\,\mu rad/m^{1/2}$	$4.72\,\mu rad/m^{1/2}$	$73.5\,\mu rad/m^{1/2}$	$4.72\,\mu rad/m^{1/2}$
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

We might naively fear a factor 82 higher energy deposition per beam current from Pb ions!

LHC design report, ch 21

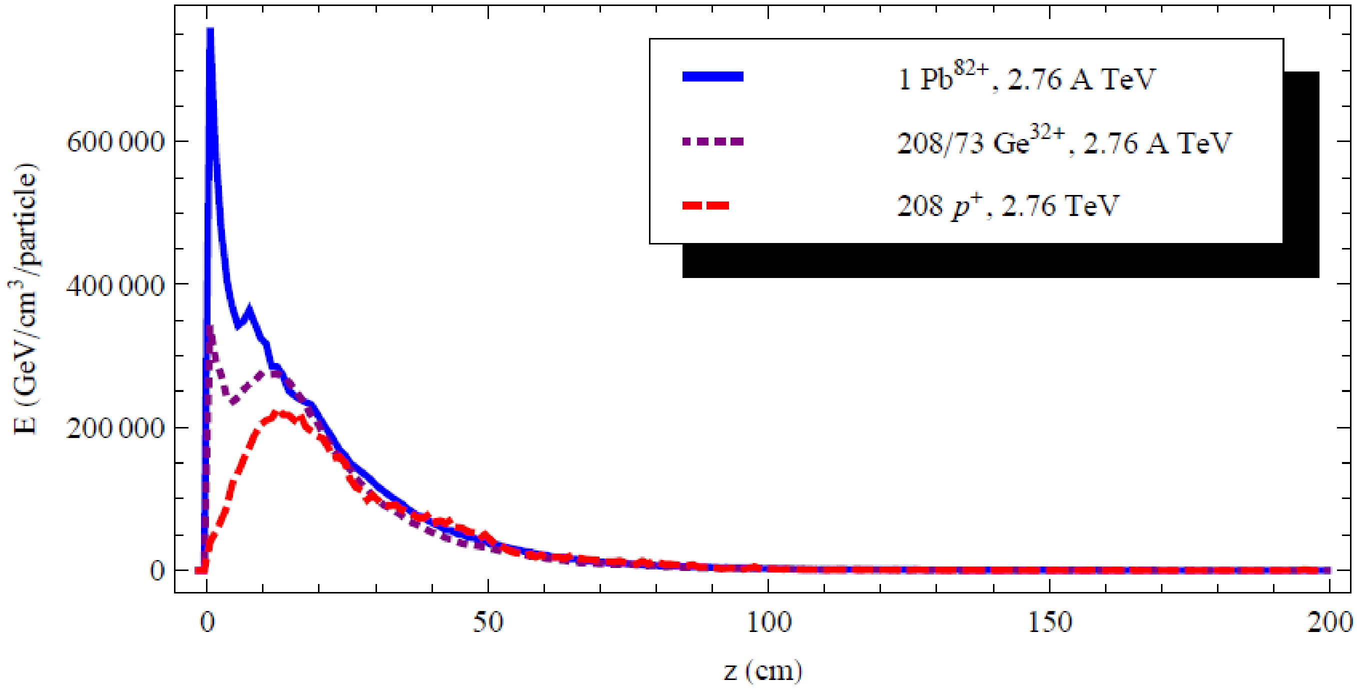
Simulations of ion and proton beam losses

- All relevant ion-matter interactions implemented in FLUKA
- Simple case: beams of Pb ions and protons hitting homogenous target at straight angle



FLUKA simulation of Cu target

- Gaussian beam with 40 micron sigma hitting Cu target at straight angle
- Three different particle species simulated: Pb^{82+}, Ge^{32+} and p^+, all at 2.76 TeV/nucleon
- Sharp peak for ions near the entry point
- Second peak after some 20 cm
- energy deposition from Pb roughly factor 4 higher than energy deposition from protons



Energy deposition in target

- Ionization energy loss
  - Scales with Z^2, approximately described by Bethe-Bloch formula:

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \log \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

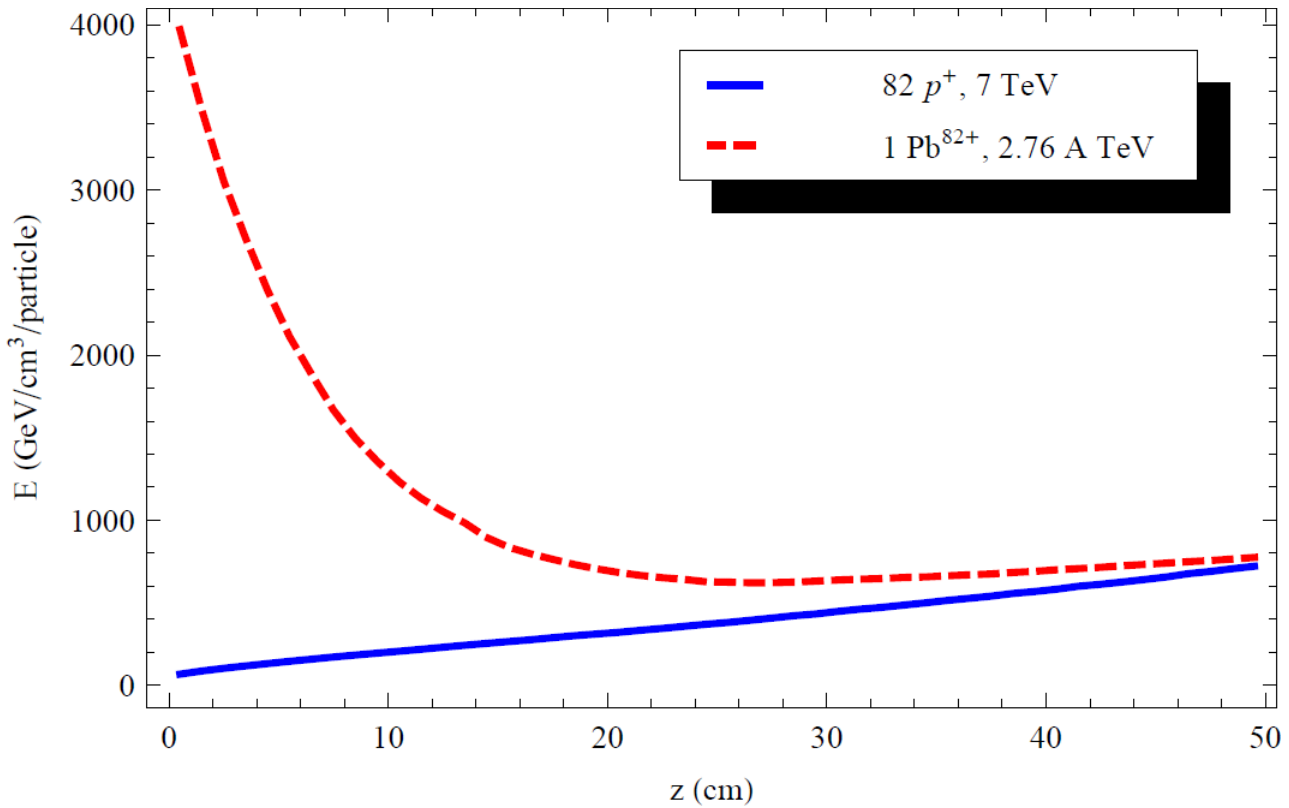
  - Corrections needed at high energy. There pair production and bremsstrahlung become important
  - creates many soft electrons, which makes the final energy deposition close to the point of creation => very localized energy deposition around the trace of incident particle
- nuclear inelastic interactions (hadronic shower)
  - Causes electromagnetic shower through decays of pi0
  - Exponential increase in number of created particles
  - Final energy deposition to large part done by large number of EM patricles
  - Scales roughly with total energy of incident particles
  - Ions can be approximated as independent nucleons

Energy deposition in target

- Electromagnetic dissociation
  - Fragmentation of ions caused by strong EM fields between incident ion and target nuclei
- As the ion breaks up into smaller fragments through nuclear inelastic interactions and electromagnetic dissociation, energy deposition from ionization becomes less important
- Hadronic shower needs some distance to develop
- Once the ion is fully fragmented, showers and energy deposition as for independent nucleons
- Narrow first peak from ionization
- Wide second peak from shower

Carbon target

- Comparison of 2.76 A TeV Pb ions and 7 TeV protons
- Gaussian beam, sigma = 286 microns (roughly size at horizontal TCP at top energy)
- Central bin of radius 30 microns (roughly 10% of one sigma)
- Roughly factor 4 higher energy deposition from Pb ions

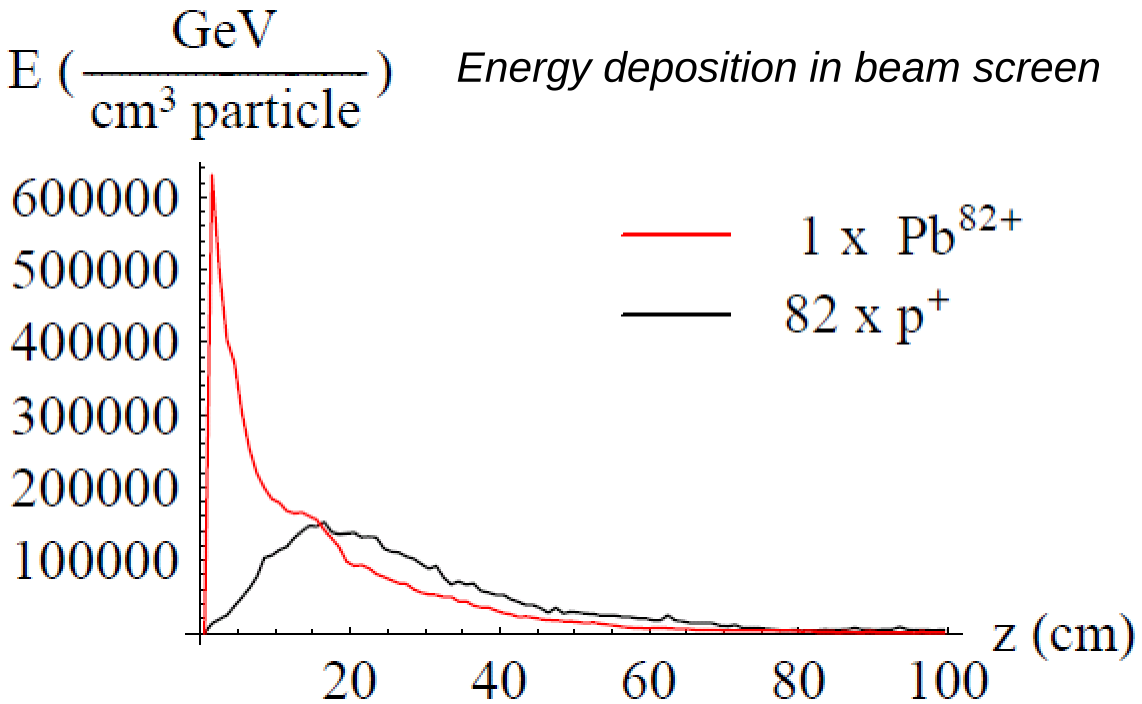


Statistical error < 1%

Generic loss in LHC dipole

- Purpose: study ratio of peak energy deposition in superconductors and expected BLM signal
- Pencil beam hitting in horizontal plane close to entrance of MB dipole, 0.5 mrad incident angle
- Energy deposition scored in beam screen, coils and BLMs
- Roughly factor 4 difference of ED per charge around incident beam

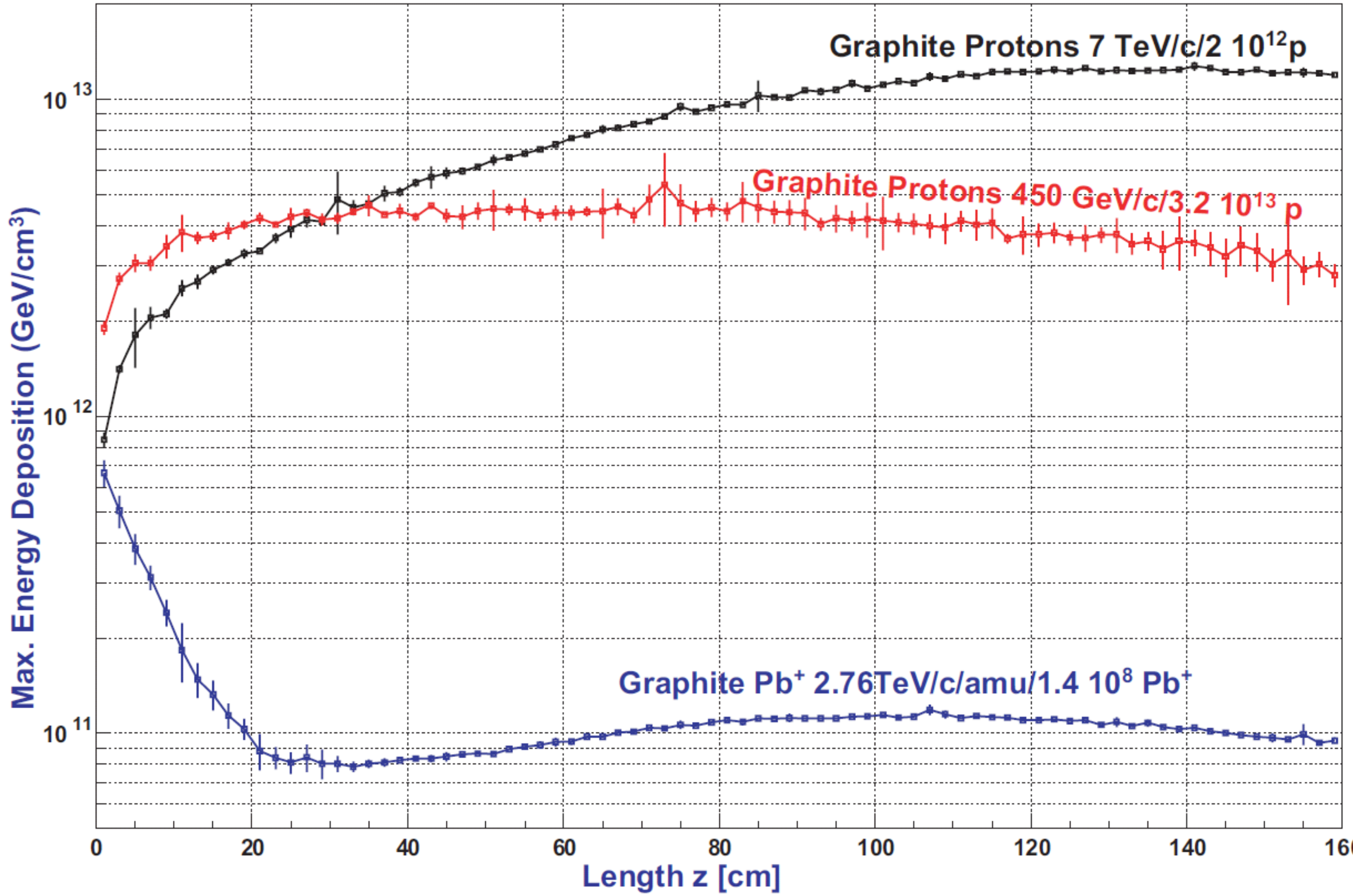
Energy deposition in beam screen



References:
LHC project note 402,
Phys. Rev. STAB 12, 071002 (2009).

Erroneous trigger of dump kicker (V. Vlachoudis)

- Superposition of 5 bunches hitting collimator
- Scaling by charge, the max of the hadronic showers are roughly equal for Pb ions and protons
- Roughly factor 6 higher energy deposition per charge from Pb ions at peak



Courtesy: V. Vlachoudis, FLUKA team.
Reference: LHC design report Ch 21

Conclusions

- Hadronic shower develops with good approximation as if ion consisted of independent nucleons => similar for ions and protons
- Ions have additional peak in energy deposition from ionization where beam hits target (Z^2 law)
- Resulting energy deposition highly dependent on target material and initial beam distribution
- Worst cases found among old simulations shown here (other simulations exist with lower ratio between Pb ion and proton peak losses)
- From results shown here, we see a factor 4-6 higher peak energy deposition per charge for 2.76 TeV/nucleon Pb ions compared 7 TeV protons
- Systematic study of losses needed to conclude that this is the really worst case