ION AND PROTON LOSS PATTERNS AT THE SPS AND LHC

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Outline

- Motivation for extra loss map studies for ions in the LHC
- Collimation losses:
  - The ICOSIM code and simulation results for the LHC
  - Benchmarks of ICOSIM in the SPS
    - With proton coasting beam
    - With injected ion or proton beam (ongoing study)
- Electromagnetic loss processes in the LHC
- Conclusion

Motivation of the study

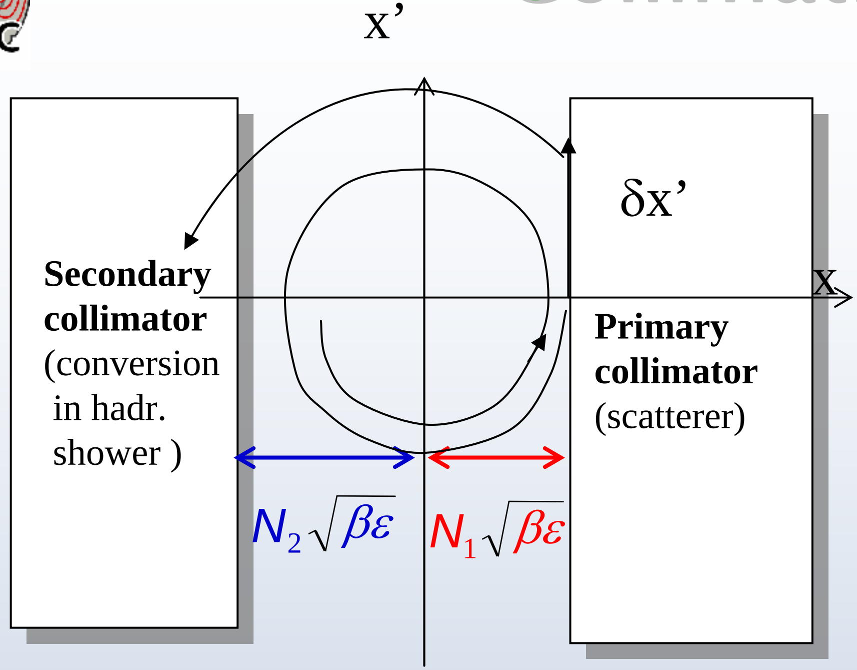
The LHC will run ~1 month/year with heavy ions.

	$^{208}Pb^{82+}$ ions	Protons
Energy per nucleon	2.76 TeV	7 TeV
Number of bunches	592	2808
Particles per bunch	7×10^7	1.15×10^{11}
Bunch spacing	100 ns	25 ns
Peak luminosity	10^{27} cm^{-2} s^{-1}	10^{34} cm^{-2} s^{-1}
Stored energy per beam	3.81 MJ	350 MJ

Why do we need to redo loss map calculations for heavy ions in the LHC ?

- Although beam power is 100 times less in the LHC Pb82+ beam, the collimation efficiency is much lower than for protons
- Losses specific for heavy ions due to electromagnetic interactions at the IP (e.g. BFPP … see later)

Collimation of ions



	2.76 A TeV Pb ions on graphite	7 TeV protons on graphite
Nucl. Interaction length	2.2 cm	38.1 cm
EM dissociation length	19 cm	
RMS multiple scattering angle	4.72 μ rad/m$^{1/2}$	4.72 μ rad/m$^{1/2}$

Necessary condition :

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

scattering at primary collimator *δx'* is mainly due to multiple Coulomb scattering with

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

But:

if required $L > L_{INT}$ particle undergoes nuclear reaction before secondary collimator is reached !

Ion collimation (continued)

- Large probability for fragmentation in primary collimator

  ⇒ Production of isotopes with different Z/A ratio (different rigidity) that are not intercepted by secondary collimator, assuming same collimation optics as for protons.

  These particles follow the local dispersion and may be lost downstream, causing heat deposition in superconducting magnets

  ⇒ Specialized tools needed for prediction of collimator interaction and tracking of ions.

The ICOSIM code

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

(Igor Pshenichnov)

ICOSIM (H. Braun)

- Generates initial beam distribution
- Tracks particles through machine (linear + leading order in chromatic effects, thin sextupoles)
- Simulates ion-matter interactions in collimators (nucl. fragm., em. dissociation, ionization, mult. scatt.)
- Tracks heaviest fragment, computes impact sites of ions in LHC lattice

MAD-X optics files and aperture tables

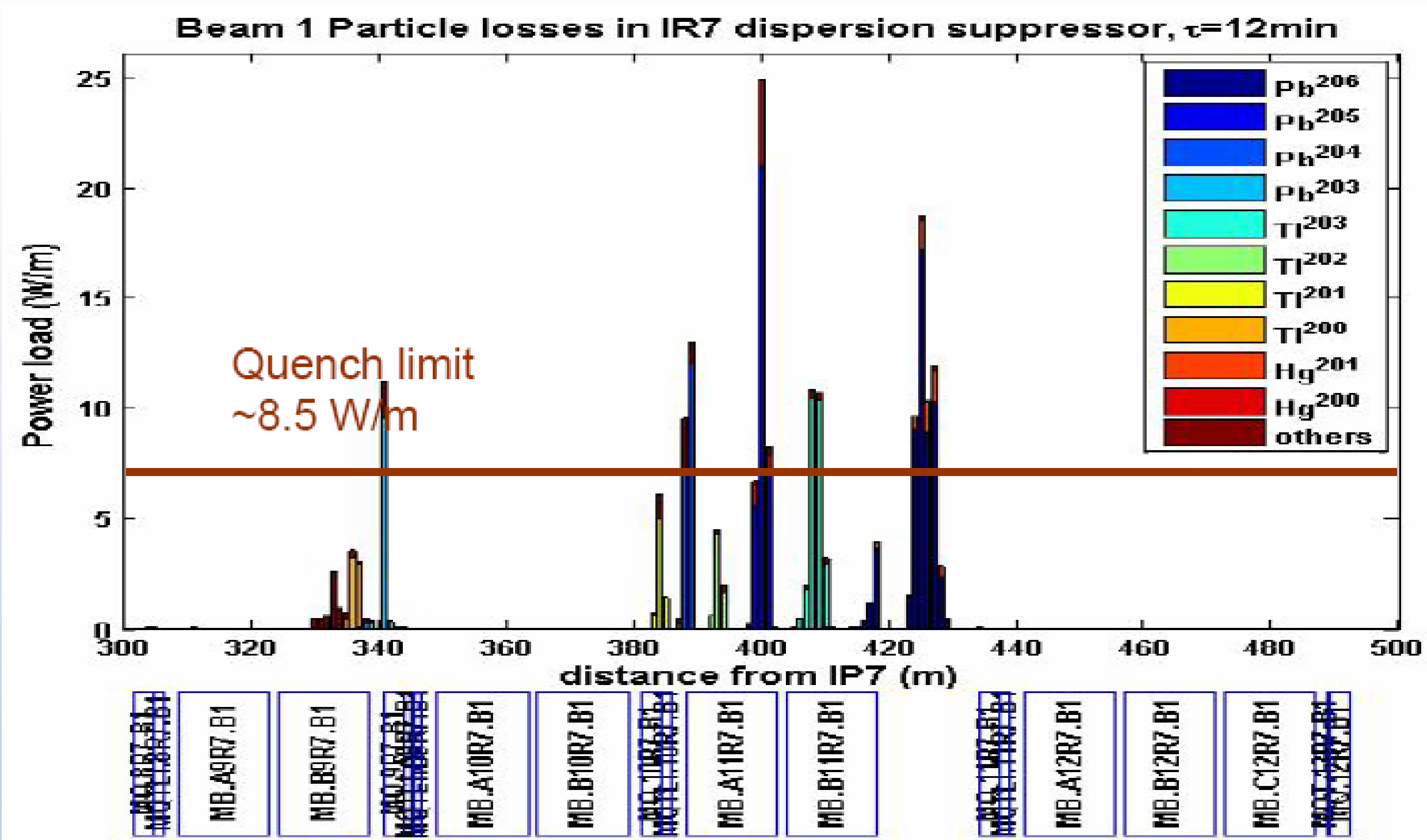
OUTPUT:

Loss patterns

Collimation efficiencies

(For more details, see H. Braun et al in EPAC04)

LHC example



Dispersion suppressor

Loss map after IR7 (betatron cleaning).
Collision optics, standard collimator settings

(G. Bellodi)

Conclusions for the LHC

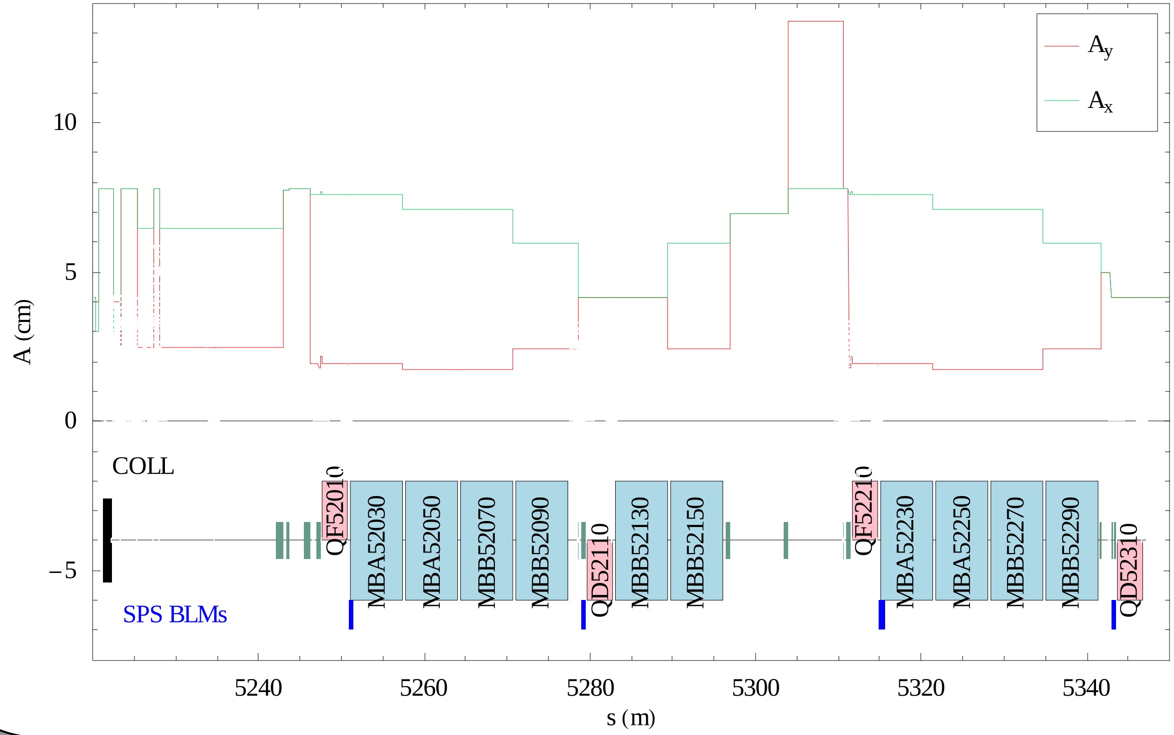
- LHC ion nominal luminosity may be limited due to heating of the superconducting magnets irradiated by fragments not intercepted by primary/secondary collimators.

- Uncertainties:
  - Quench limit (not well known and depends on magnet type)
    - Studies ongoing in AT department
  - Nuclear cross sections for ion and proton interaction might have up to 50% error bars
    - Obviously we cannot measure cross sections for primary ions at 2.76 A TeV without the LHC, but we can measure loss maps at injection energies
  - Uncertainty in the impact distribution on the collimator and beam life time

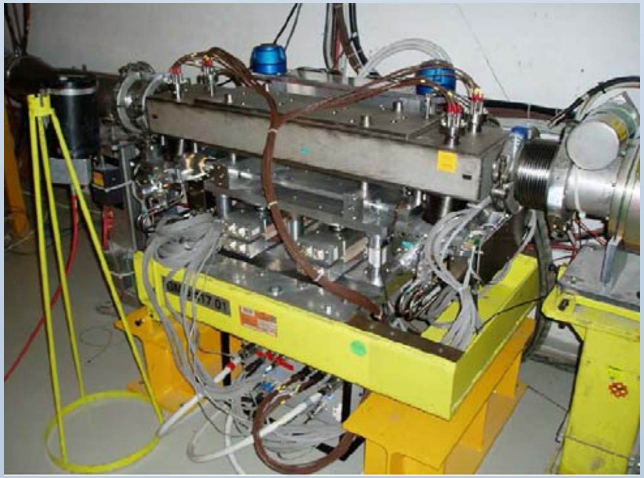
⇒ Benchmark of simulation vs data needed.

Possibilities at CERN:
- Protons in the SPS
- Pb82+ ions in the SPS

SPS with LHC collimator



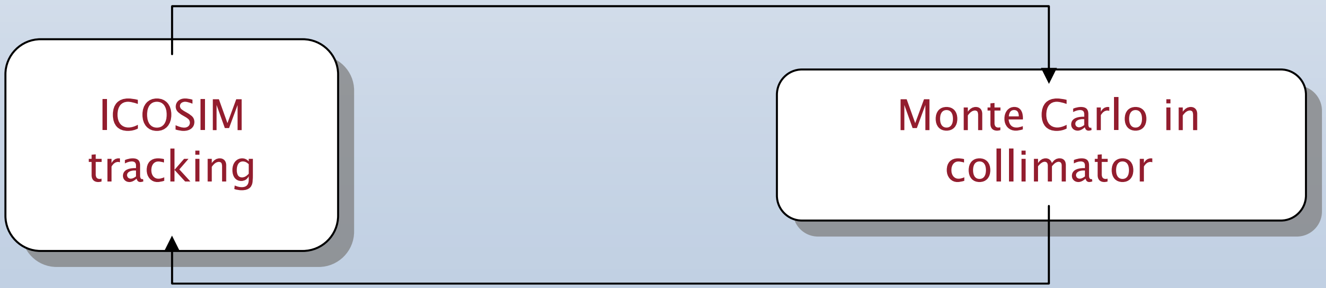
- LHC secondary collimator prototype installed in SPS (2 independent carbon jaws in hor. plane)
- Jaws moved in and out during operation
- BLM signals recorded from all 216 monitors in the ring
- September 2007: LHC BLMs installed on predicted ion-specific loss locations



(picture from S. Redaelli et al)

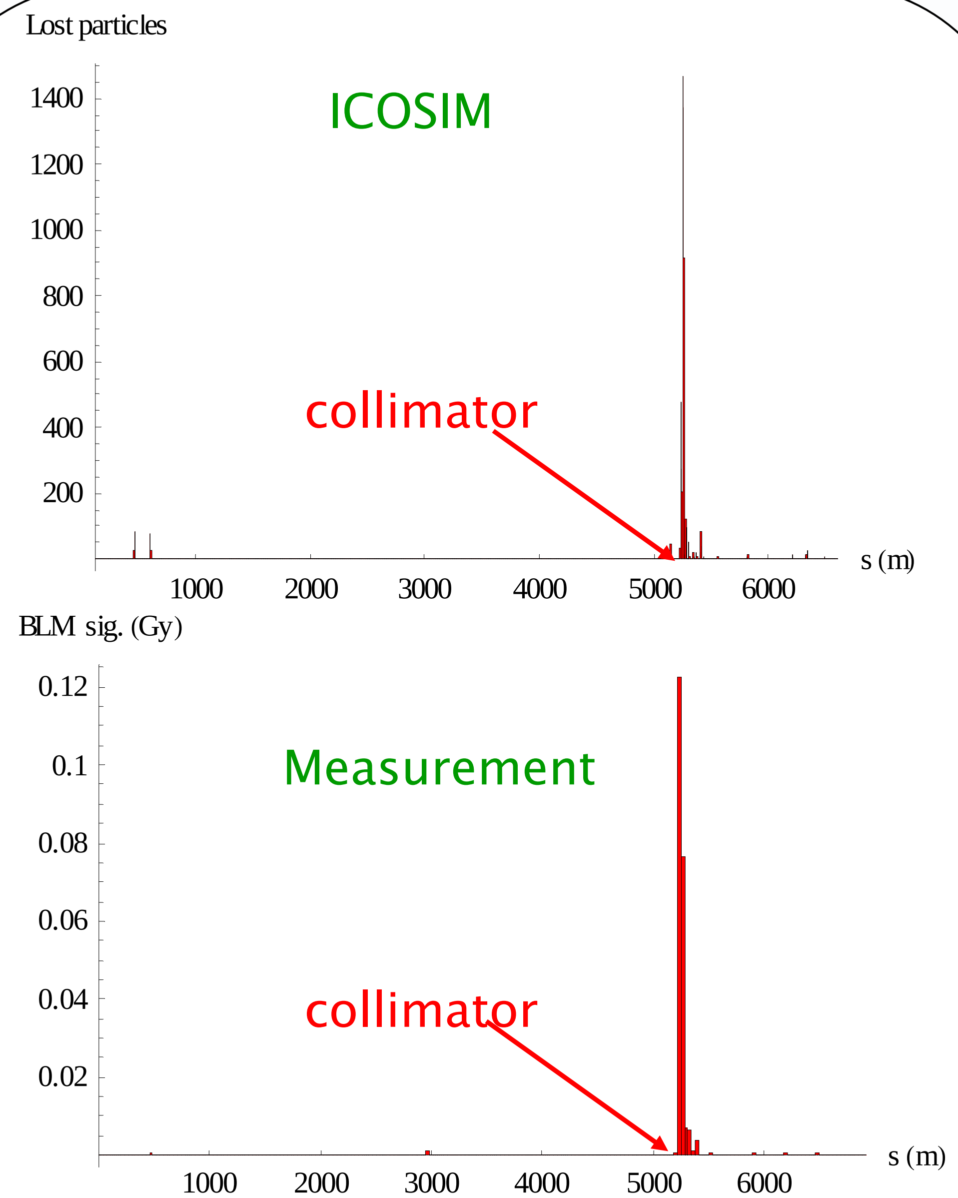
Benchmark with protons

- Data taken with 270 GeV coasting proton beam (Nov. 2006)
- Modification of ICOSIM to include proton physics in collimator interaction.
  - Simplest option: Call to external Monte Carlo code (MARS or FLUKA). This is interesting also for the LHC – more accurate (but slower) tracking (ongoing project in collaboration with FLUKA team).



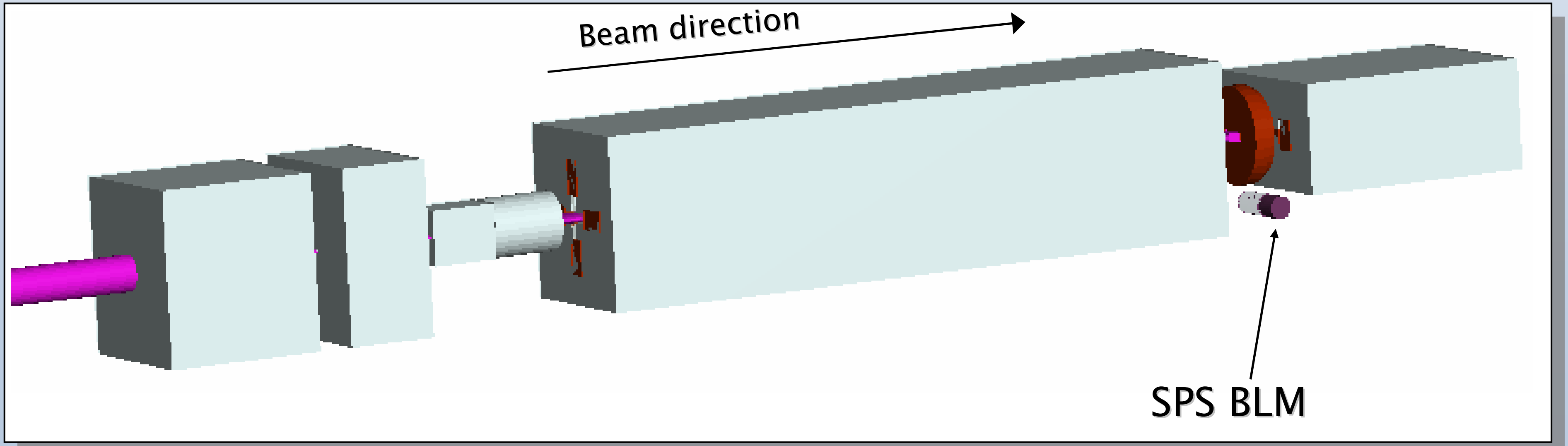
Qualitative comparison (270 GeV protons)

- Simulation results plotted with 5 m binning
- Good agreement qualitatively – main loss peak well reproduced
- “Grass” in first part of machine not measured, but no BLM close to predicted impact locations
- Fair agreement with SixTrack



Quantitative comparison

- To compare quantitatively, the signal in the BLM has to be simulated
- Impact coordinates of lost protons on the vacuum chamber are fed as starting conditions into FLUKA, where the full geometry with magnets and BLM is implemented.
- Energy deposition per proton in BLM gas scored.
- Simulating the BLM closest to the collimator with the strongest signal
- 3D geometry of the SPS beam line before the BLM as implemented in FLUKA:



Magnet geometry with BLM

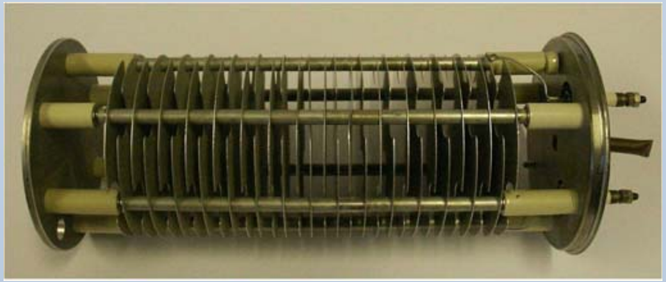
Simulation of BLM signal

- Two possibilities:
  1. Simulation of single jaw movement corresponding to data, or
  2. Simulation of "general loss pattern" averaged over data

- Using option 1), we have to simulate first loss map and then BLM signal for many collimator positions (very time consuming!)

- Second option better, provided that
  - Relative loss pattern not very dependent on jaw movement and position
  - BLM signal approximately proportional to decay in beam current (measured with BCT), regardless of jaw position

- Can be false in general (e.g. different collimation efficiency for different jaw angles), but jaws were centered during this MD.



- BLM signal in Bits or Gy. Conversion from GeV via weight of gas inside BLM

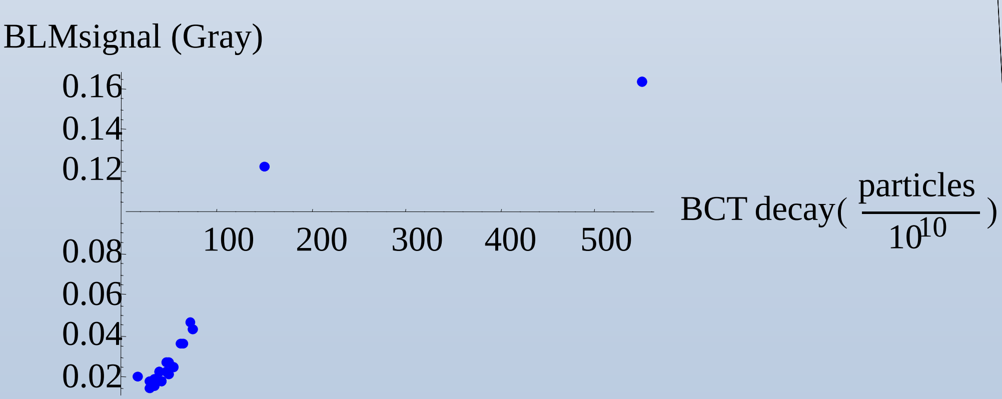
$$\text{Dose[Gy]} = \frac{Q\,W}{m\,e}$$

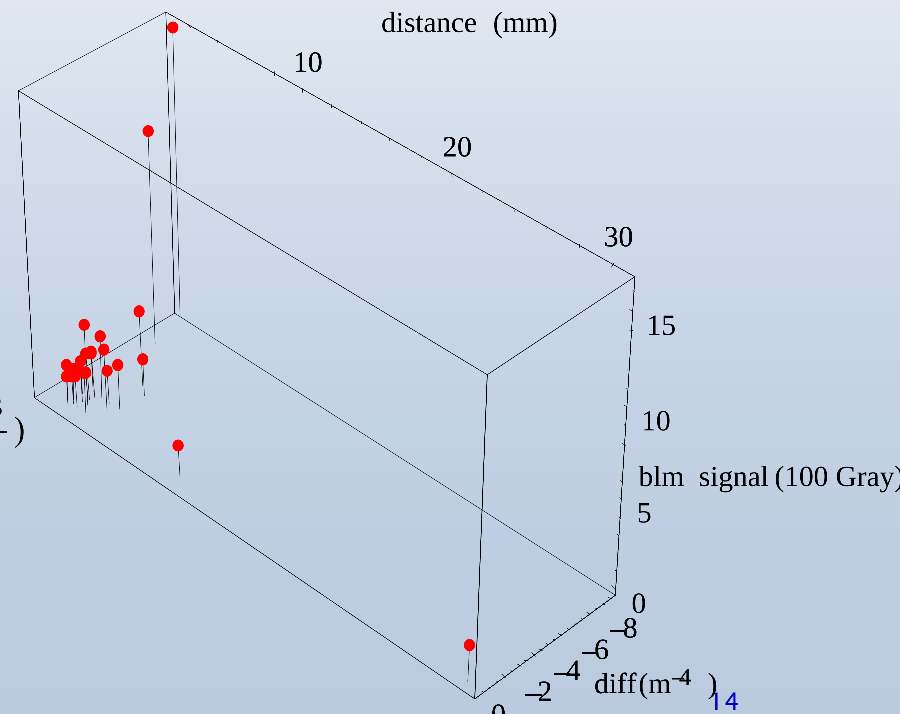
Collected charge → Q; Ionization energy → W; Mass of gas → m

BLM signal during proton run

- These assumptions can easily be checked both with data and simulations
- Before saturation, measured BLM signal shows approximate linear behavior as a function of beam current (BCT) decay (data taken parasitically during each supercycle), regardless of jaw positions and movement (see plots)

⇒ In this case, we can approximate the loss signal as a linear function of BCT decay regardless of jaw movement



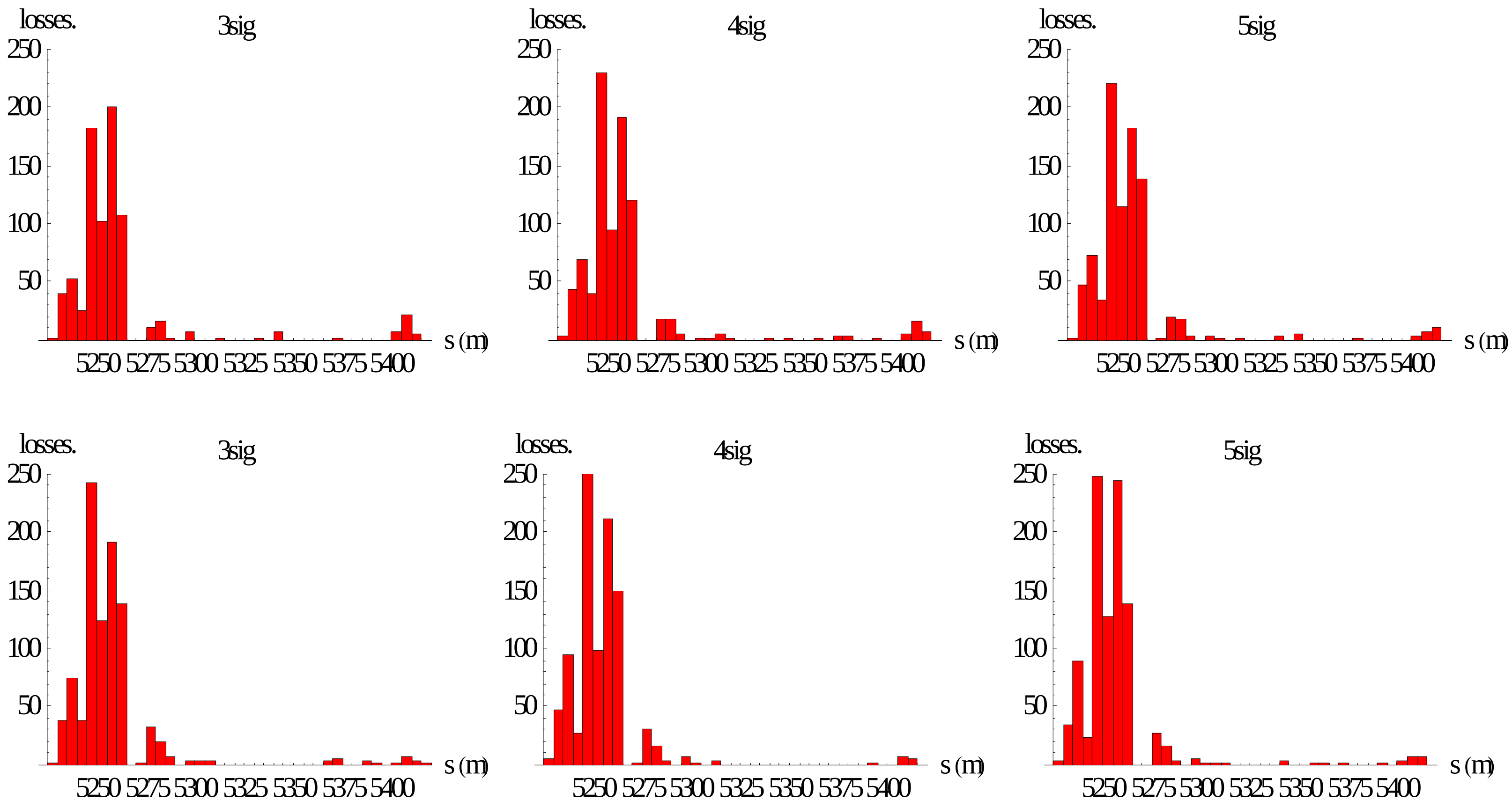


Simulation of proton loss maps

- Simulations confirm this (Scan over gap widths for protons)
- Shape of loss map is approximately unchanged with different jaw distances

Right jaw only

Left jaw only



Comparison between simulation and measurement

Normalisation of simulation:

- Selecting supercycles with a collimator movement towards the beam, and a BLM signal above 0.01 Gray (to avoid noise) the average BLM signal per 10^{10} lost proton is: 0.576 mGy, standard deviation 0.16 mGy

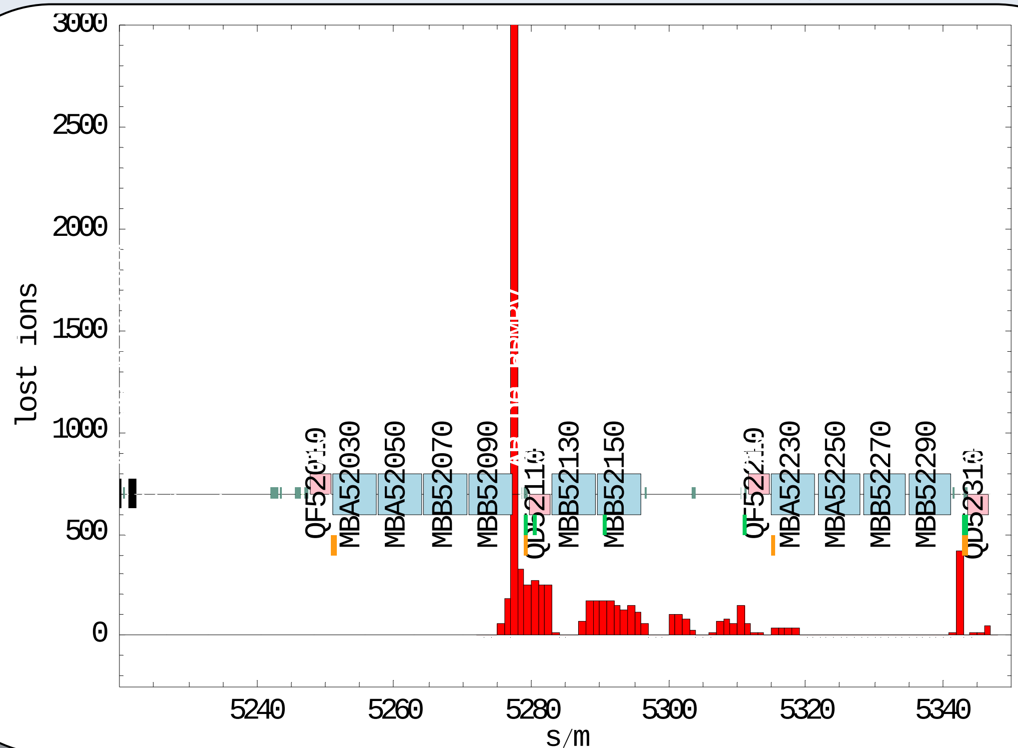
- Average simulated signal obtained by normalizing the signal per lost proton around the BLM (from FLUKA) by the ratio (from loss map):

  (protons lost around the BLM)/(protons lost in total)

- Doing this we obtain 0.15 mGy per 10^{10} lost protons – we are a factor 3.8 too low
  - Possible error sources: electronics, Monte Carlo simulations, generation of impact coordinates on collimator….
  - Stat error and systematics not yet included

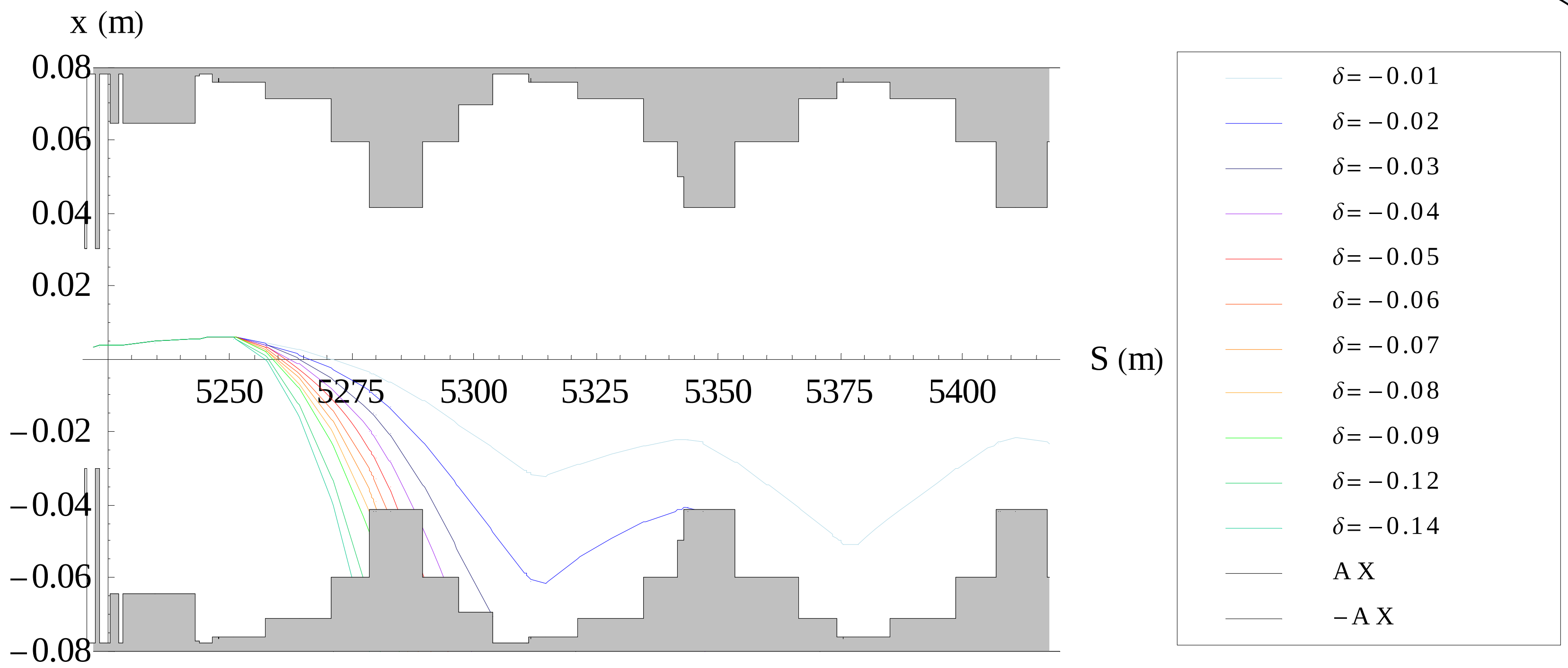
New measurements at injection

- Ongoing study – measurements performed on the 20th and 26th of September 2007
- Proton momentum 26 GeV, Pb^{82+} momentum 10.25 A GeV
- Measuring ions and protons hitting collimator at injection in the SPS
- ICOSIM used to calculate ion loss maps in the SPS
- Ions lost due to dispersion caused by fragmentation, protons lost due to angular kicks
- Expected ion loss pattern for the heaviest fragments:



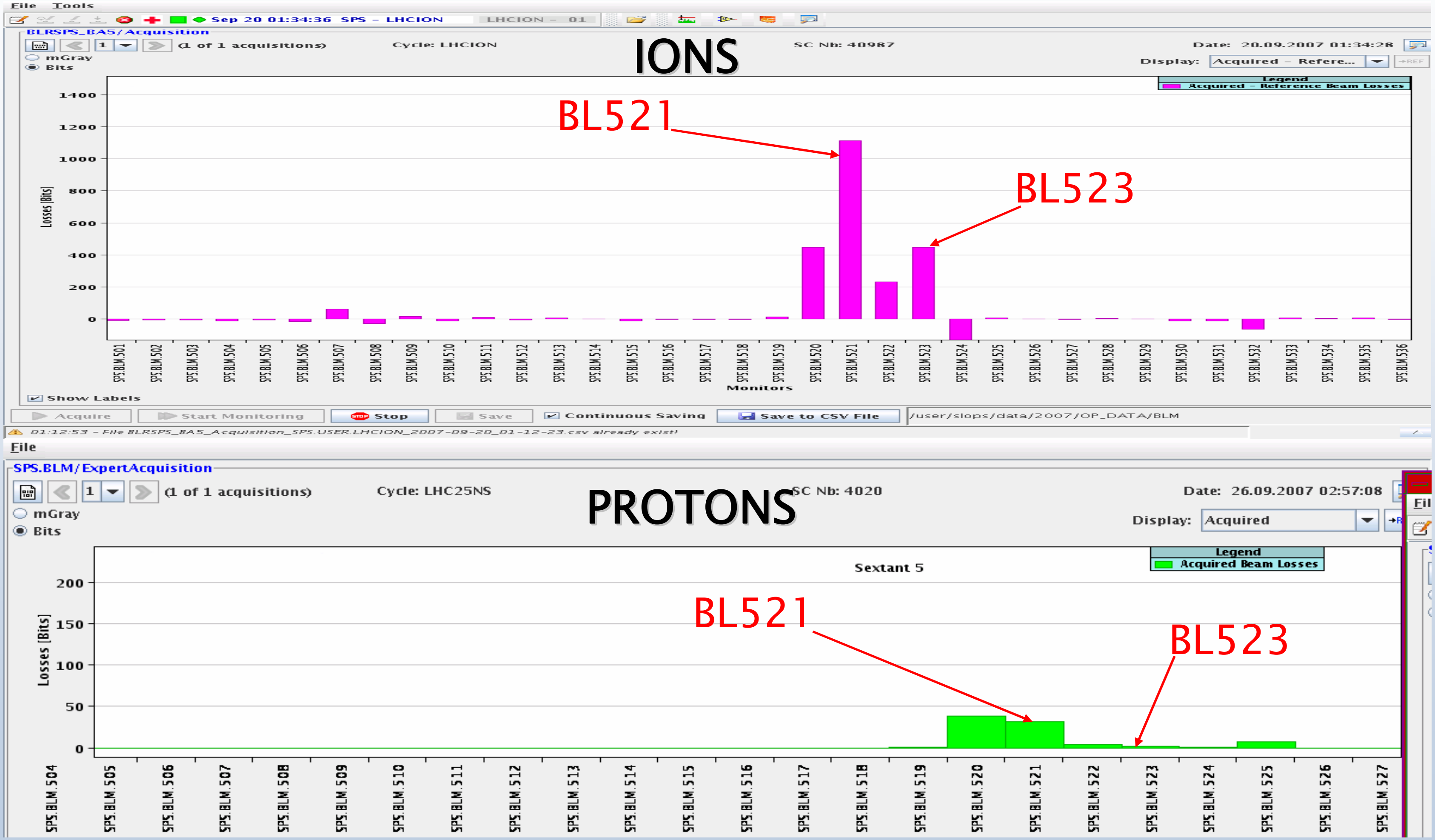
Ion loss pattern

- Ions lost mainly due to dispersion caused by fragmentation
- Effective momentum deviation $\delta = \frac{A}{A_0} \frac{Z_0}{Z} - 1$
- Scan over dispersive orbits from collimator shows main loss peak for heavy fragments:



Preliminary result

- BLM signals in Sector 5 (different gains on the BLMs for the two cases)



- Clear qualitative difference in loss pattern in agreement with predictions. Ongoing study – more to come!

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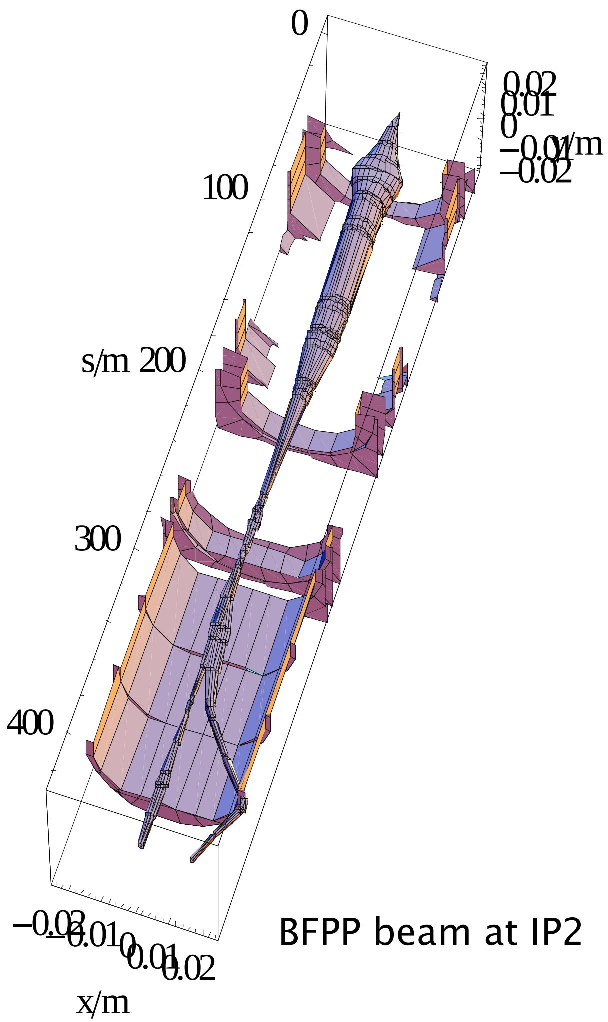
Electromagnetic loss processes in the LHC

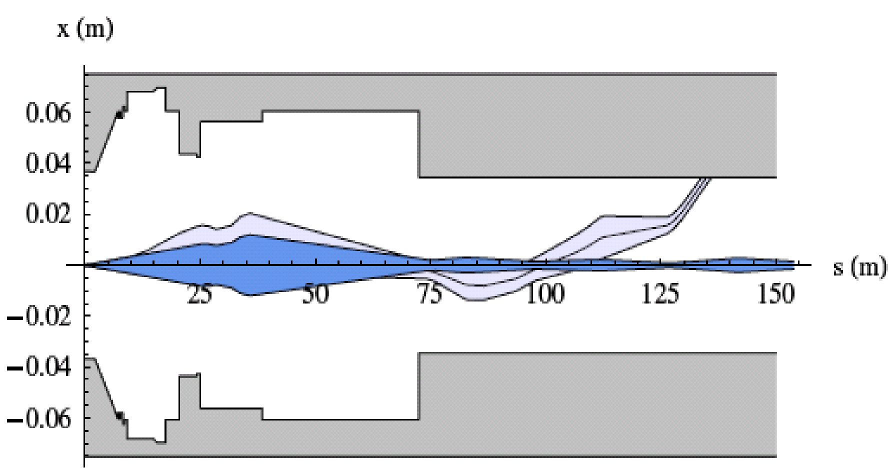


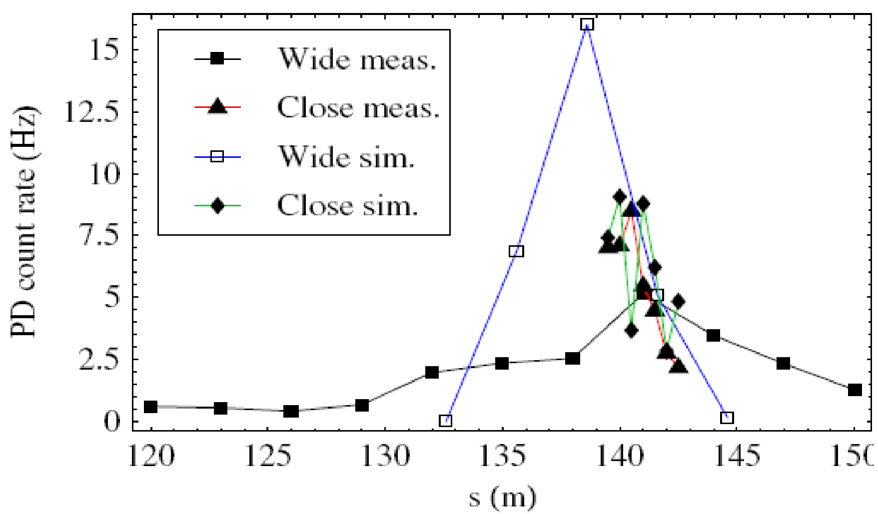
BFPP beam at IP2

- e+e- pair created at IP in ultraperipheral collision, e- caught in bound state by one of the colliding ions (Bound Free Pair Production, BFPP), or
- Ion loses one or two neutrons through interaction with field of opposing ion (Electromagnetic Dissociation)
- Secondary beam with wrong rigidity created, lost where local dispersion and aperture satisfies A=d δ. May quench magnets.
- Single turn problem without collimator interaction ⇒
  direct MAD-X tracking generates impact coordinates
- Need for additional BLMs at these locations

Measurements at RHIC

- Similar method used to calculate BLM signals at RHIC caused by secondary BFPP beam
- Losses observed ~130 m downstream of the IP by array of BLMs in form of PIN diodes
- Again, secondary beam emerging from IP tracked with MAD-X, generating starting conditions for shower simulation with FLUKA
- Magnet geometry and BLMs simulated in FLUKA. Measured signals agree with simulation within a factor 2.





(For more details, see R. Bruce et al, Upcoming issue of Phys. Rev Letters)

Conclusions

- Ion-specific processes during collimation in the LHC makes it necessary to use specialized tracking tools
- ICOSIM (tracking + Monte Carlo in collimator) is constructed to meet this need
- Old benchmark of ICOSIM with proton data shows good qualitative agreement in loss map. Simulated BLM signal off by a factor 3.8
- New data shows specific peaks for ions predicted by ICOSIM. Detailed analysis still to be done.
- BFPP losses simulated and measured at RHIC. Simulated BLM signal within factor 2.
- Future work: Repeat measurements on coasting ion beam in SPS

Thanks to:

- Collimation team: R. Assmann, C. Bracco, S. Redaelli, T. Weiler et al + M. Jonker
- BLM team: B. Dehning, B. Holzer, D. Kramer, M. Stockner, C. Zamantzas et al
- Machine operators