Hans-H. Braun, PAF meeting, 9.10.2006

I-LHC collimation issues

- Recall of heavy ion specific collimation problems
- Simulation tools and related physics issues
- Expected performance limitations
- Protection of LHC during Ion runs
- Improvement scenarios

LHC collimation

Issues for p-LHC collimation	**Issues for I-LHC as well ?**
1. cleaning efficiency	✓
2. protection of magnets against quenches	✓
3. robustness of collimator against mishaps	**?**
4. impedance	**-** $(I_{IONS} \sim I_{PROTON}/100)$
5. activation and maintainability	**-** $(P_{IONS} \sim P_{PROTON}/100)$

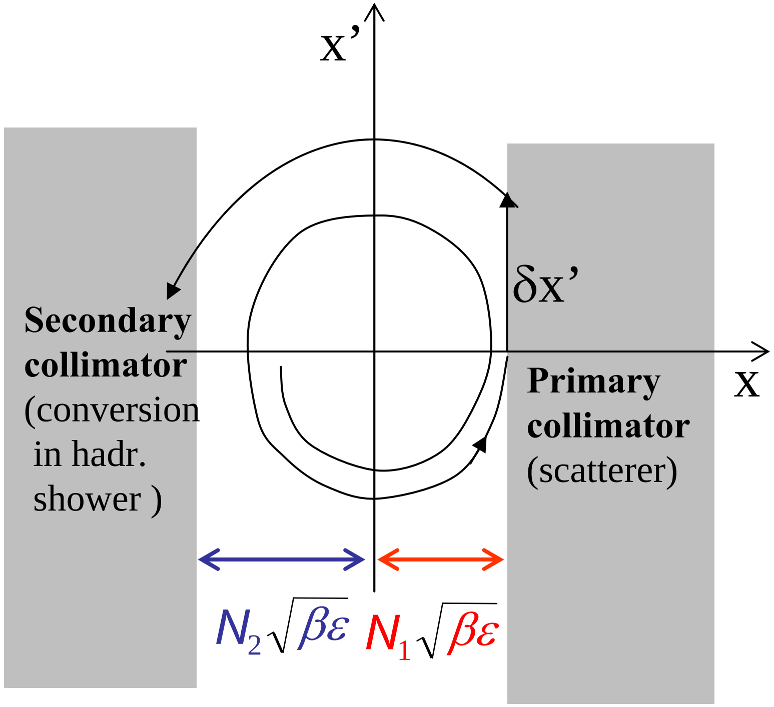
Why is heavy ion collimation for LHC a specific issue?

Collider	Atomic number	Mass number	Energy / nucleon GeV/u	Circumference m	Number of Bunches	Number part. / Bunch 10^7	stored energy / beam MJ	instantaneous beam power GW
p-LHC	1	1	7000	26659	2808	11500	362.1	4075
I-LHC	82	208	2760	26659	592	7	3.8	43
I-LHC early scheme	82	208	2760	26659	62	7	0.4	4
p-HERA	1	1	920	6336	180	7000	1.9	88
TEVATRON	1	1	980	6280	36	24000	1.4	65
I-RHIC	79	183	99	3834	60	110	0.2	14
p-RHIC	1	1	230	3834	28	17000	0.2	14

LHC Proton collimation difficult because collimation efficiency $\eta \approx 10^{-5}$ required, but proposed scheme fulfills requirements in simulations and SPS prototype tests.

I-LHC beam has only 1/100 of the proton beam power, so only collimation efficiency $\eta \approx 10^{-3}$ required . Where is the problem ?

Criteria for two stage betatron collimation



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

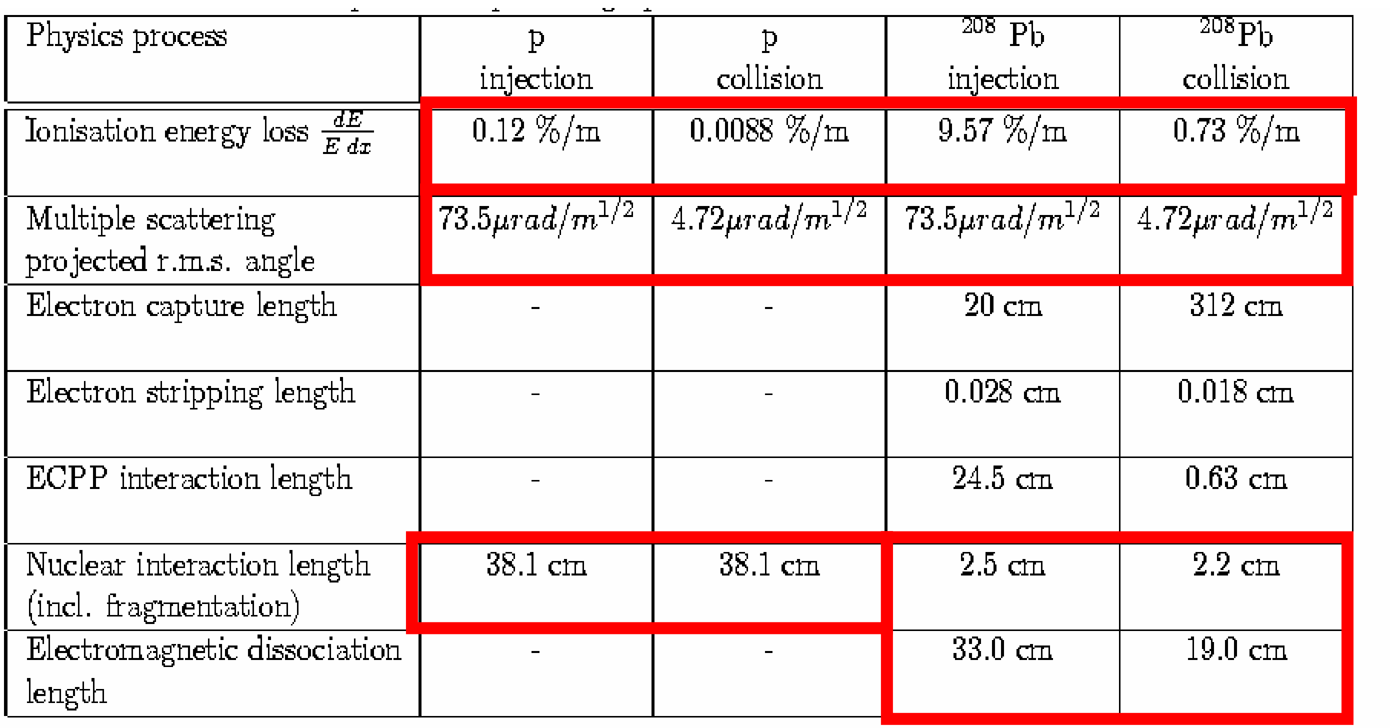
$<\delta x'^2> \sim L$

But:

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

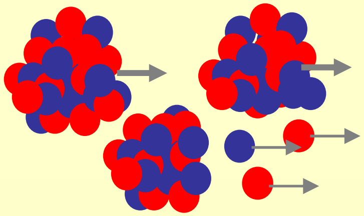
^{208}Pb-ion/matter interactions in comparison with proton/matter interactions.

(values are for particle impact on graphite)

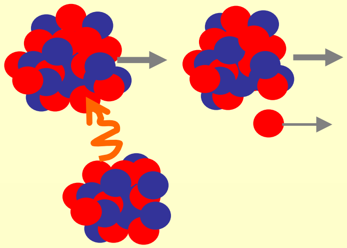


Physics process	p injection	p collision	^{208} Pb injection	^{208}Pb collision
Ionisation energy loss $\frac{dE}{E\,dx}$	0.12 %/m	0.0088 %/m	9.57 %/m	0.73 %/m
Multiple scattering projected r.m.s. angle	$73.5\mu rad/m^{1/2}$	$4.72\mu rad/m^{1/2}$	$73.5\mu rad/m^{1/2}$	$4.72\mu rad/m^{1/2}$
Electron capture 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 cm	19.0 cm

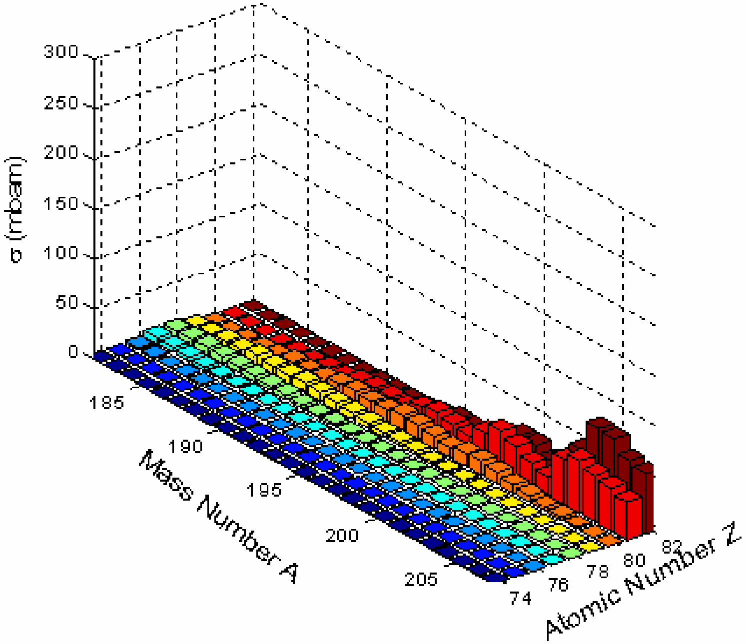
hadronic fragmentation



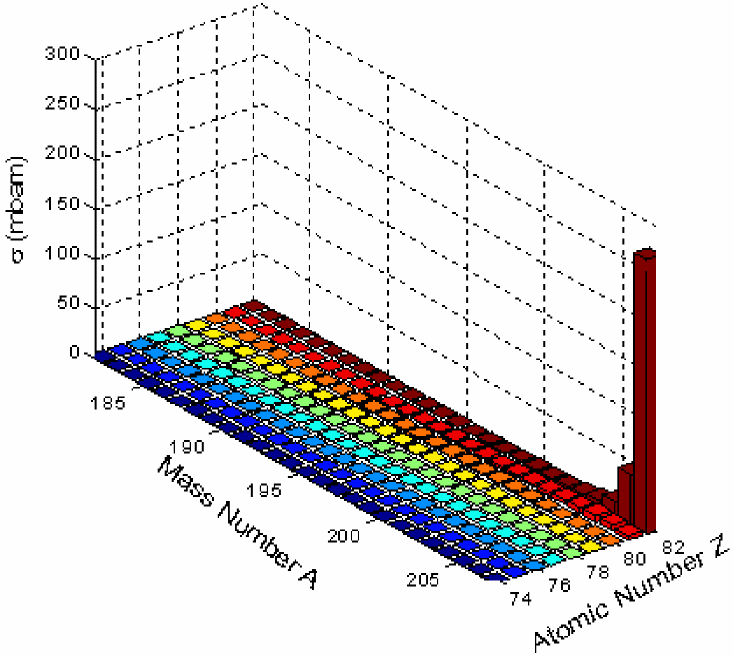
electromagnetic dissociation



Hadronic Fragmentation cross sections for ^{208}Pb on ^{12}C



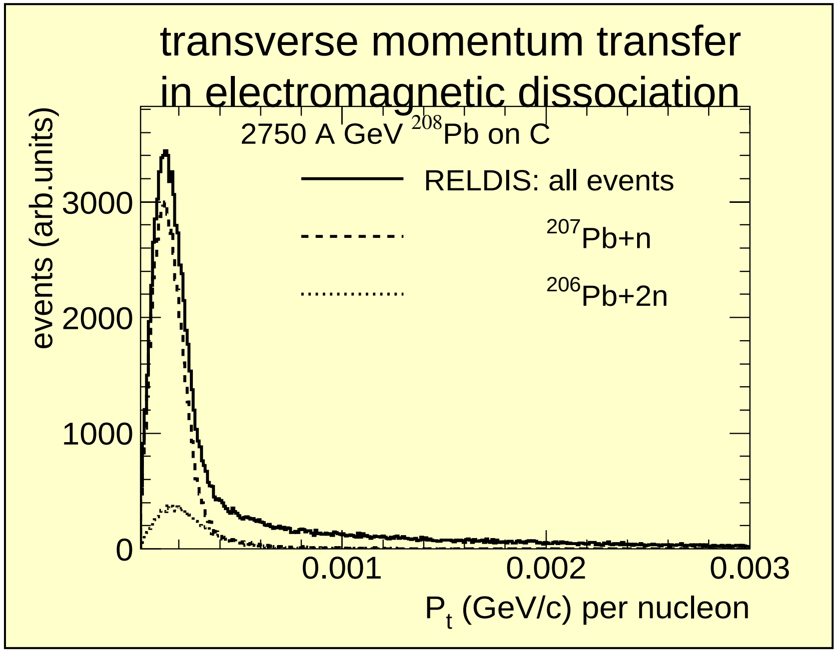
Electromagnetic Dissociation cross sections for ^{208}Pb on ^{12}C



Computation of cross-sections by Igor Pshenichnov (INR, Moscow)

Nuclear fragmentation and dissociation
lead to a variety of daughter nuclei.

Typical transverse momentum ≤ 1 MeV/c/u,
transverse momentum due to emittance ≈ 10 MeV/c/u

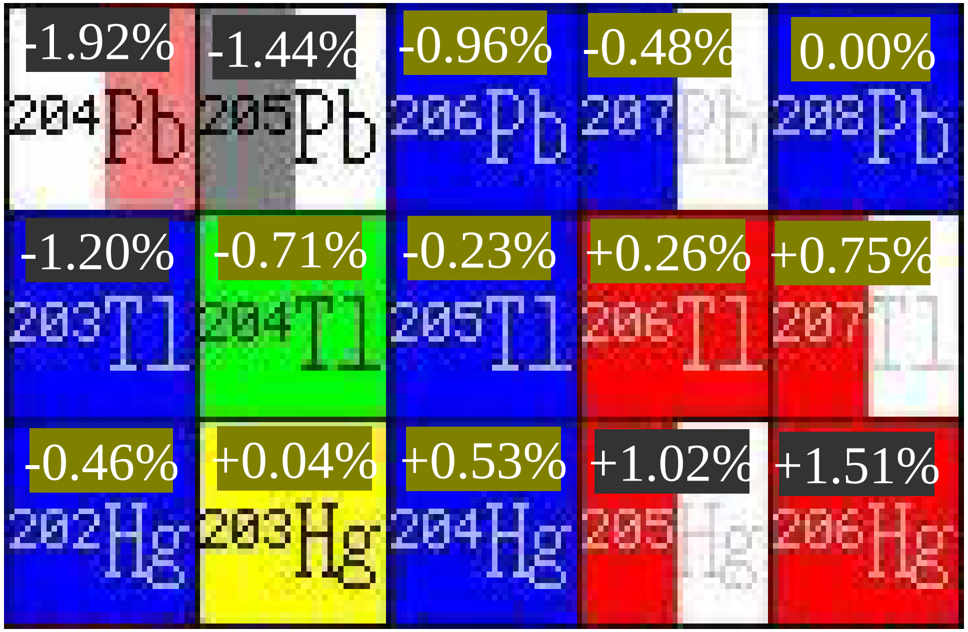


First impacts of halo ions on primary collimators is usually grazing, small effective length of collimator.

→ high probability of conversion in neighbouring isotopes without change of momentum vector

→ **isotopes miss secondary collimator and are lost in downstream SC magnets because of wrong $B\rho$ value**

Effective momentum error of daughter nuclei $\left(\frac{\Delta P}{P}\right)_{EFF.} = \frac{Z_1}{A_1}\frac{A_2}{Z_2} - 1$



-1.92% ^{204}Pb	-1.44% ^{205}Pb	-0.96% ^{206}Pb	-0.48% ^{207}Pb	0.00% ^{208}Pb
-1.20% ^{203}Tl	-0.71% ^{204}Tl	-0.23% ^{205}Tl	+0.26% ^{206}Tl	+0.75% ^{207}Tl
-0.46% ^{202}Hg	+0.04% ^{203}Hg	+0.53% ^{204}Hg	+1.02% ^{205}Hg	+1.51% ^{206}Hg

Energy acceptance LHC arcs ≈ +/-1%

Energy acceptance energy cleaning IR3 ≈ +/-0.2%

Simulations Tools for Ion Collimation Issues

- ICOSIM, tracking program custom made for I-LHC applications
  main purpose: predict loss patterns around ring

- FLUKA, general purpose transport code used already for LHC proton collimation
  Prediction of: heat deposition, ratio between local losses and BLM signals, component activation …

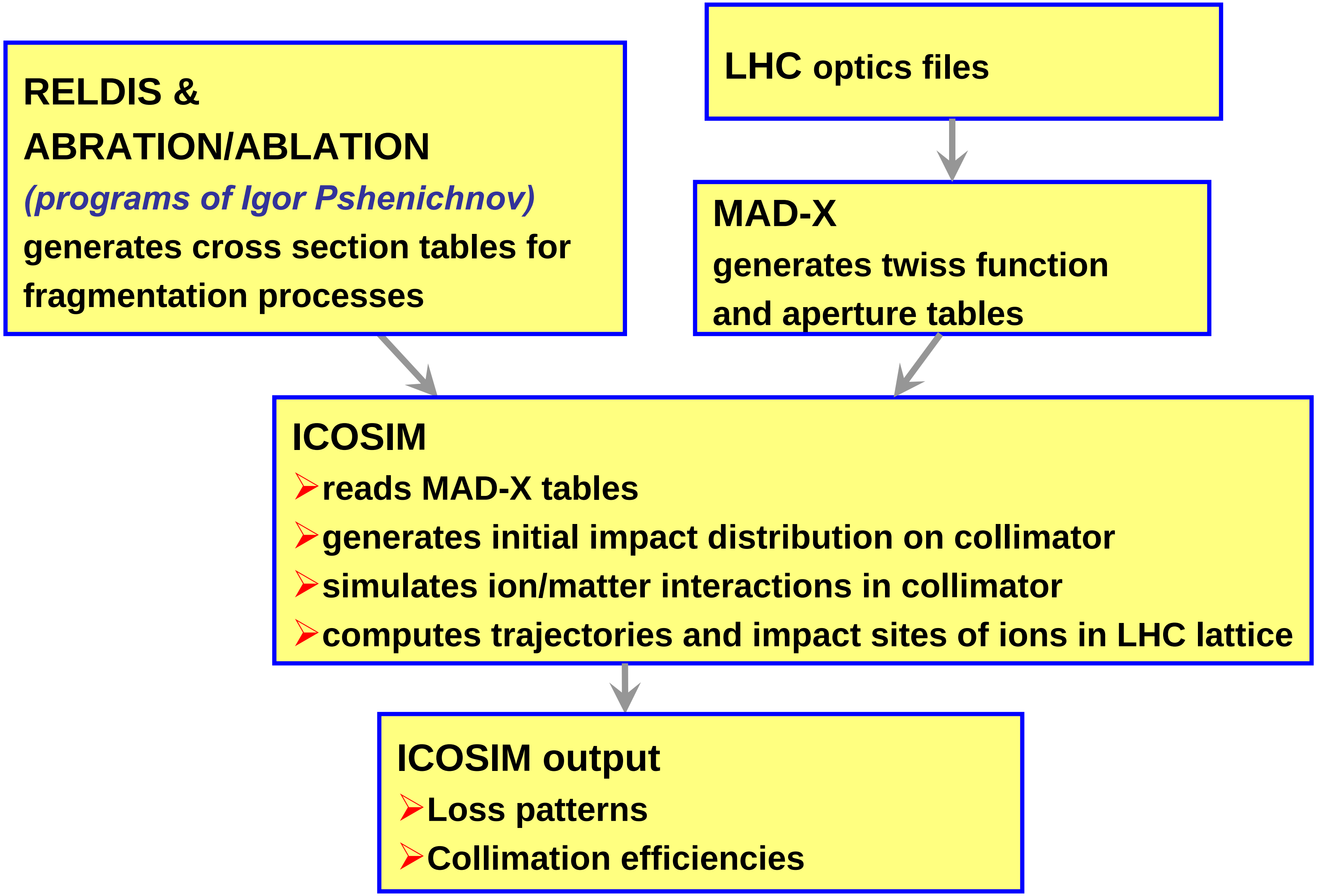
  WG group to implement all effects relevant for Ions at LHC.
  George Smirnov, Vasilis Vlachoudis, Alfredo Ferrari, Roderik Bruce, Hans Braun, John Jowett and Giulia Bellodi

  Already implemented
  - Fragmentation and e.m. dissociation:

  Implementation in progress:
  - Improved energy-loss model with pair production, DPA calculations.

  Theory description waiting for implementation:
  - Improved multiple scattering routine

ICOSIM computing tools to predict ILHC collimation loss patterns



RELDIS & ABRATION/ABLATION

(programs of Igor Pshenichnov)

generates cross section tables for fragmentation processes

LHC optics files

MAD-X

generates twiss function and aperture tables

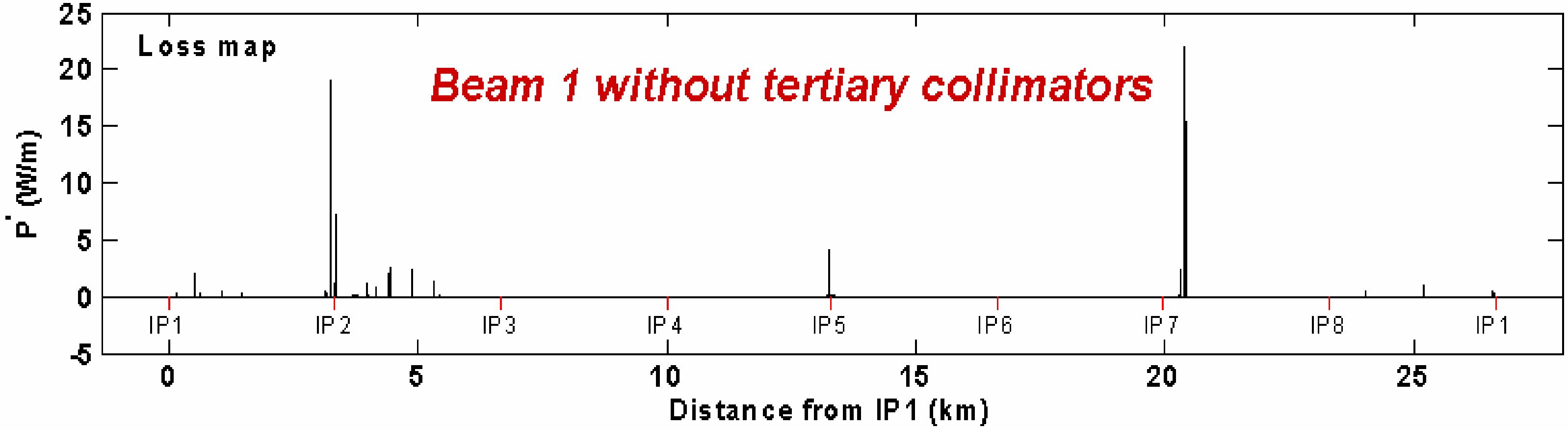
ICOSIM

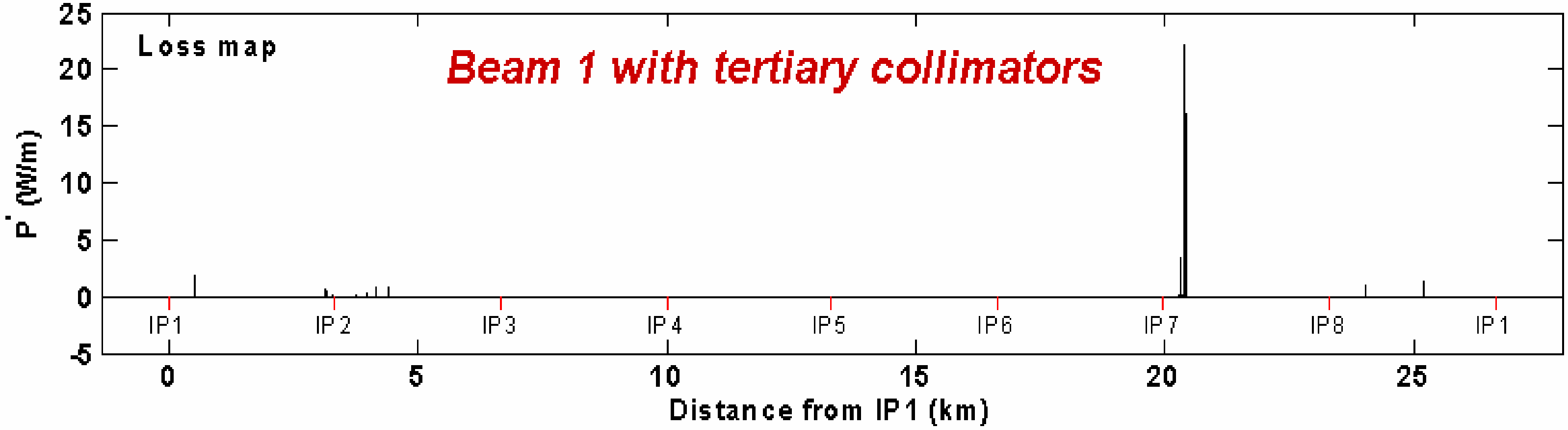
- **reads MAD-X tables**
- **generates initial impact distribution on collimator**
- **simulates ion/matter interactions in collimator**
- **computes trajectories and impact sites of ions in LHC lattice**

ICOSIM output

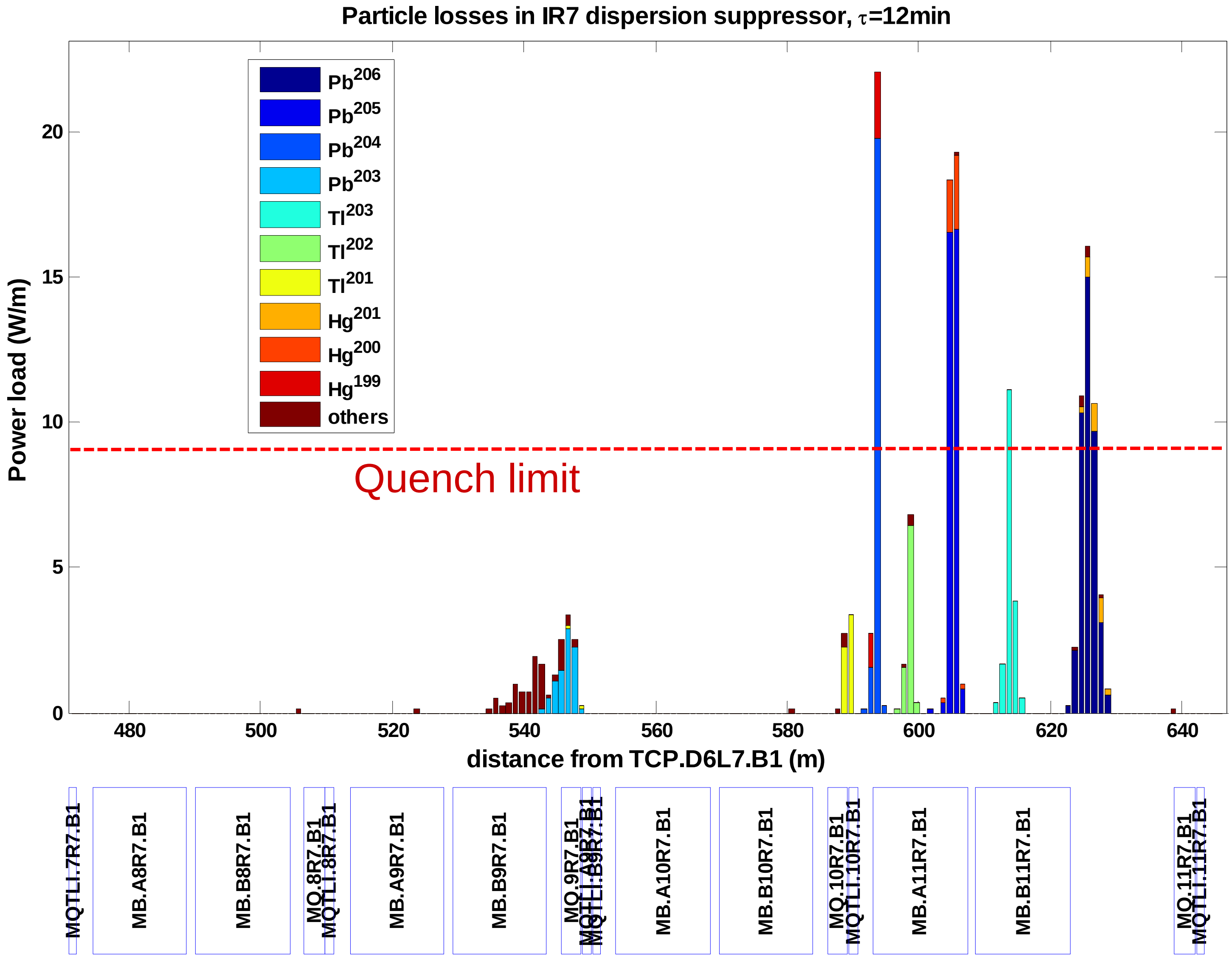
- **Loss patterns**
- **Collimation efficiencies**

Loss maps from ICOSIM for beam losses with first impact on IR7 betaron amplitude collimators


Beam 1 without tertiary collimators


Beam 1 with tertiary collimators

Nominal Ion beam 1 with collision optics and collimator settings


Particle losses in IR7 dispersion suppressor, τ=12min

ICOSIM indicates beam current limitation ≈50% nominal ^{208}Pb due to η_{coll}

This is a "soft limit" !

- Input specification of collimation system 12 min lifetime is an arbitrary number
- Cross section for fragmentations into specific channels are have estimated errors of ≈ +/- 50%.
- The 8 W/m permissible heat load in SC magnets is from an early LHC note. The real number is subject of discussion. Moreover, depends on magnet type and specimen
- η_{coll} has a strong dependends on impact distribution on collimator. Difficult to predict and depends on specific loss mechanisms

⇒ ***Could be better, could be worse !***

Fact is that the second stage of two stage collimation system as devised for protons doesn't work for heavy ions ⇒ halo from primary collimators hits SC magnets

Essential to assure detection of ion halo losses with BLM’s

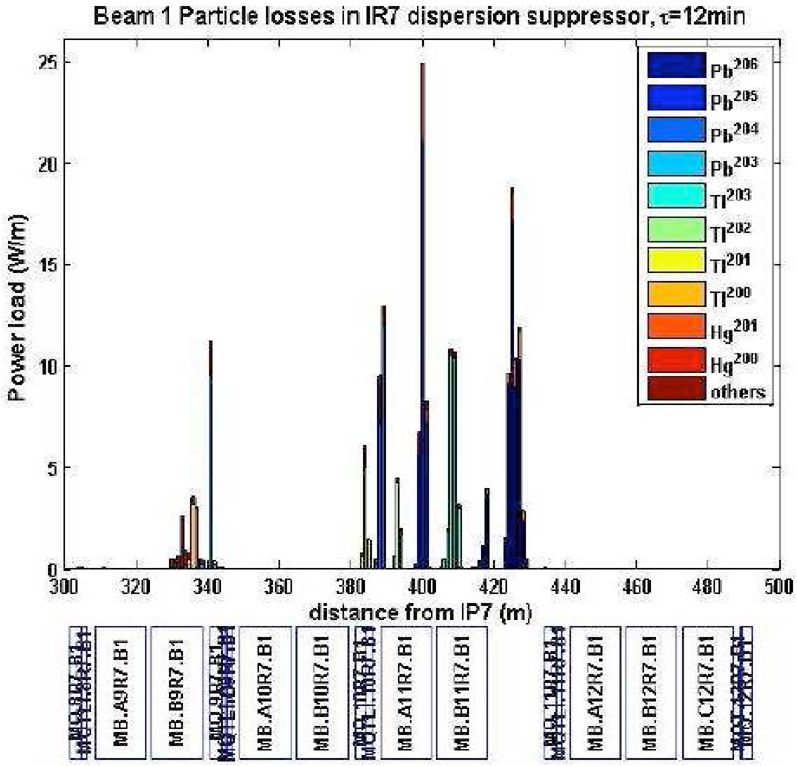
Most baseline BLM’s are mounted on quadrupoles,
because losses due to betatron amplitude occur preferably there.

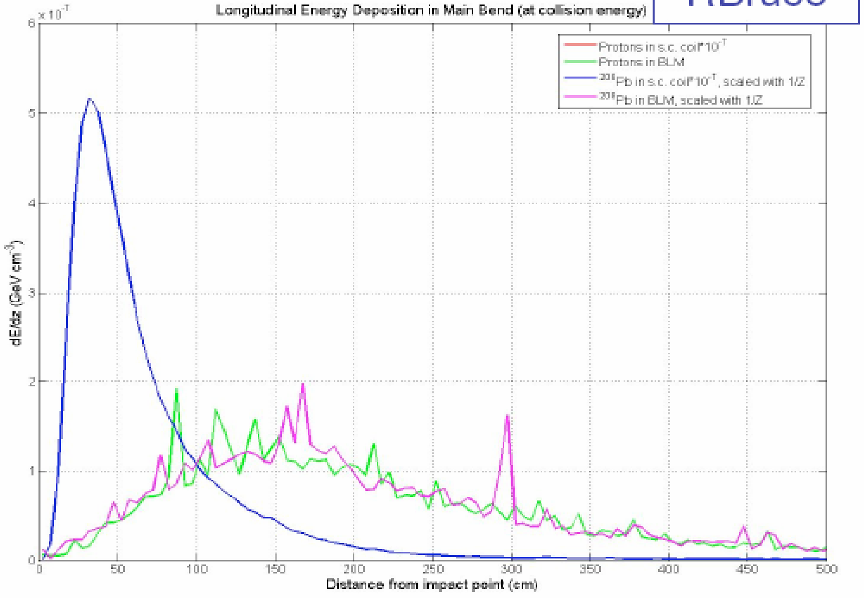
Ion losses appear preferably in SC dipoles

⇒ ***Extra BLM’s at heavy ion specific locations required !***

BLMs coverage:

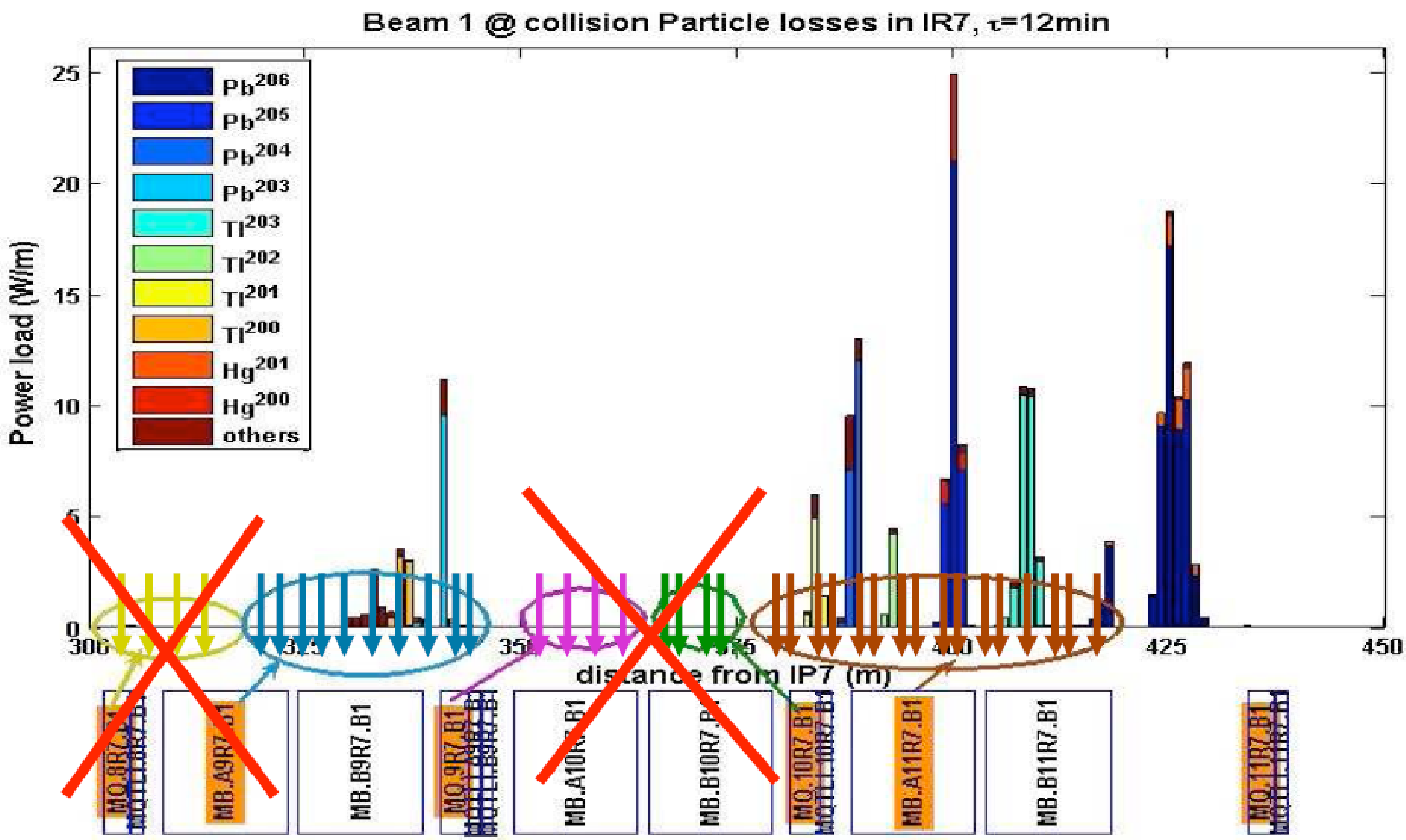
RBruce





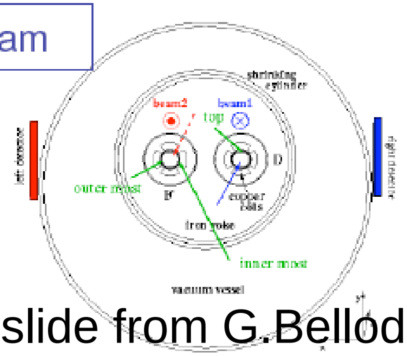
At collision energy loss pattern with sharp peaks like mass spectrometer
Hadronic shower smears out signal for BLM's over 2.5 m.

⇒ Closely spaced (2.5m) BLM's required on dipole magnets in dispersion suppressors of IR3 and IR7



B. Dehning's team

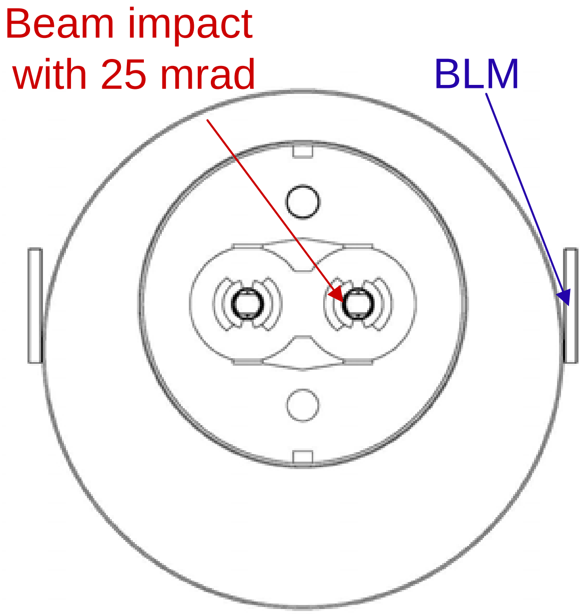
- **New**: 2.5 m spacing in cells 9 (downstream dipole) & 11, no coverage in cell 10
- Transverse position: inside (left) for beam2, outside (right) for beam1

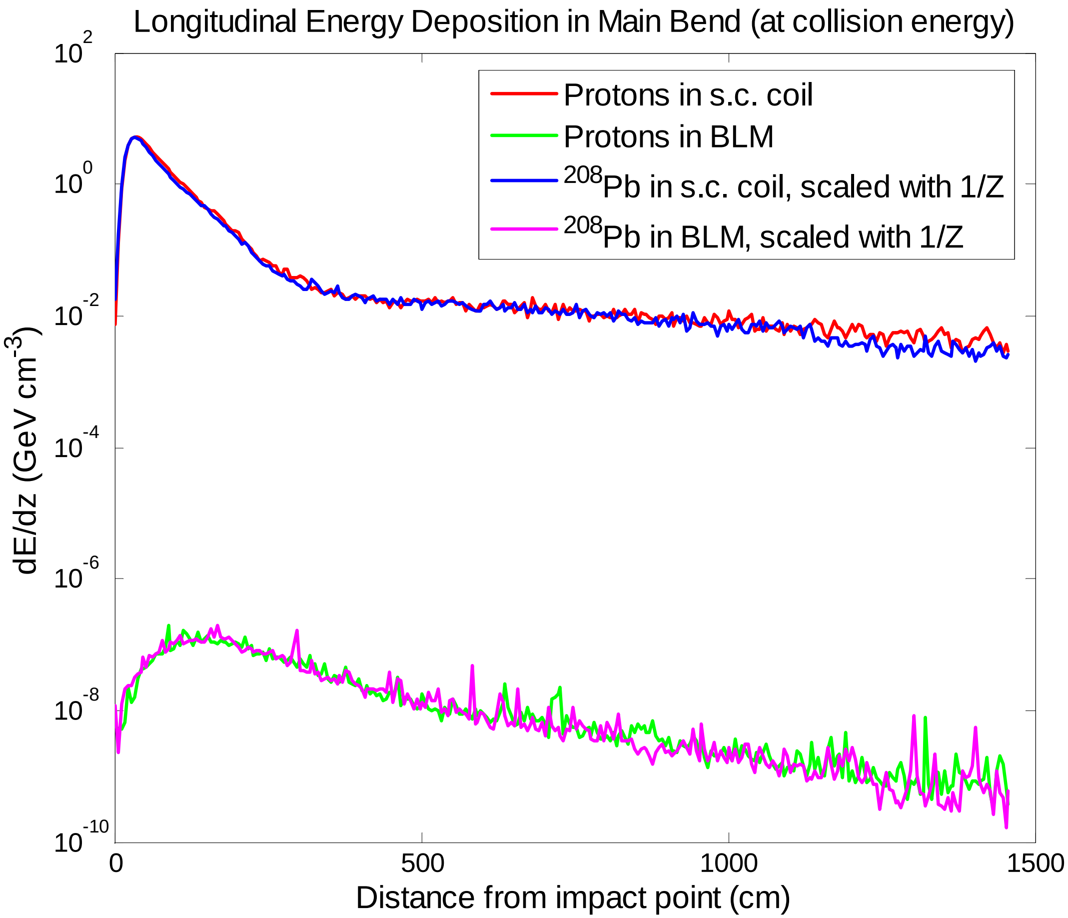


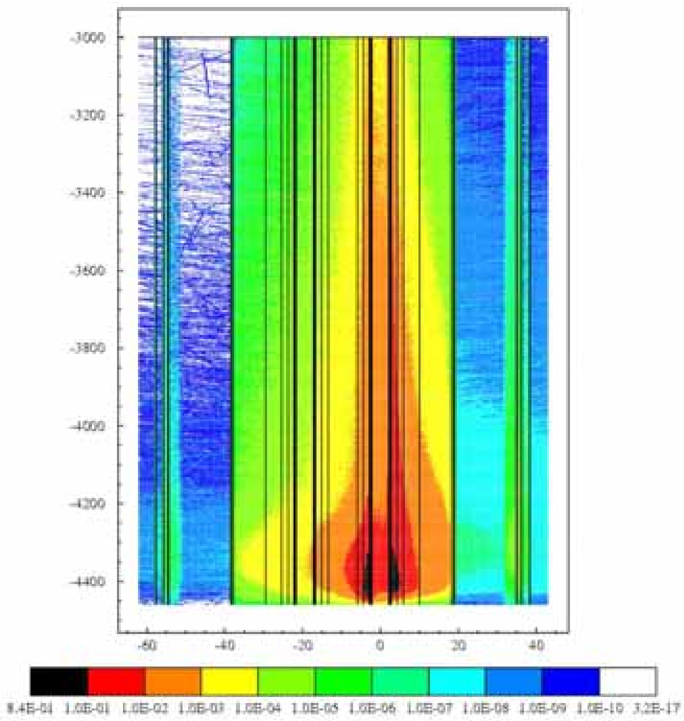
slide from G.Bellodi

Is the ratio of heat deposition in SC coils to BLM signals the same for Protons and Ions ?

FLUKA calculations by Roderik Bruce





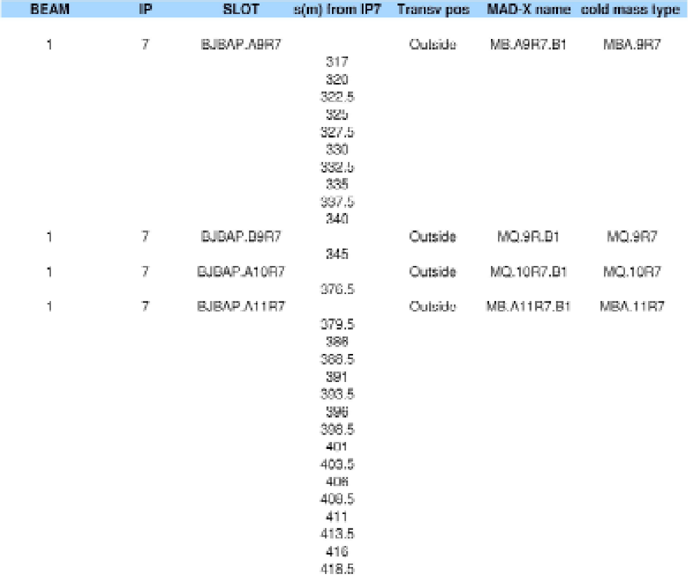


Additional 78 BLM’s required* for IR3 (momentum collimation) dispersion suppressors and downstream arc

Additional 57 BLM’s required* for IR7 (betatron cleaning)

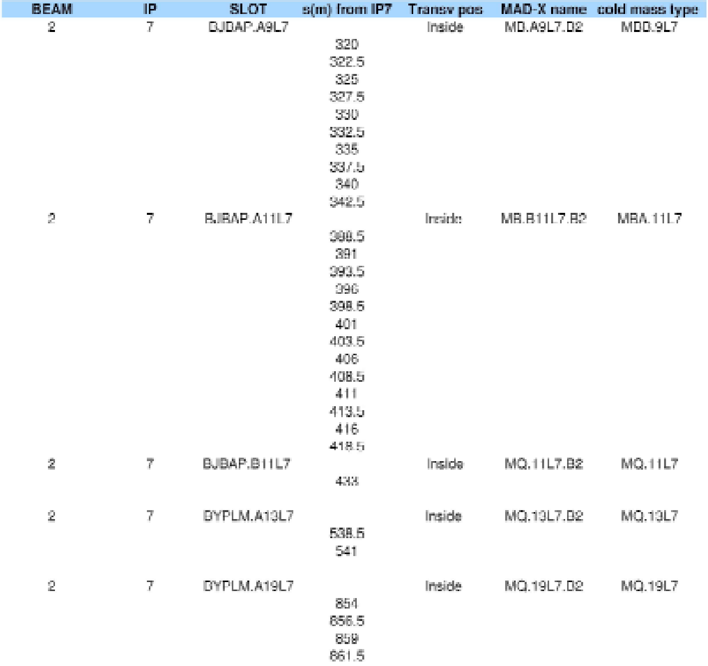
* for both beams

Beam 1



BEAM	IP	SLOT	s(m) from IP7	Transv pos	MAD-X name	cold mass type
1	7	BJBAP.A9R7		Outside	MB.A9R7.B1	MBA.9R7
			317			
			320			
			322.5			
			325			
			327.5			
			330			
			332.5			
			335			
			337.5			
			340			
1	7	BJBAP.B9R7		Outside	MQ.9R.B1	MQ.9R7
			345			
1	7	BJBAP.A10R7		Outside	MQ.10R7.B1	MQ.10R7
			376.5			
1	7	BJBAP.A11R7		Outside	MB.A11R7.B1	MBA.11R7
			379.5			
			386			
			388.5			
			391			
			393.5			
			396			
			398.5			
			401			
			403.5			
			406			
			408.5			
			411			
			413.5			
			416			
			418.5			

Beam 2



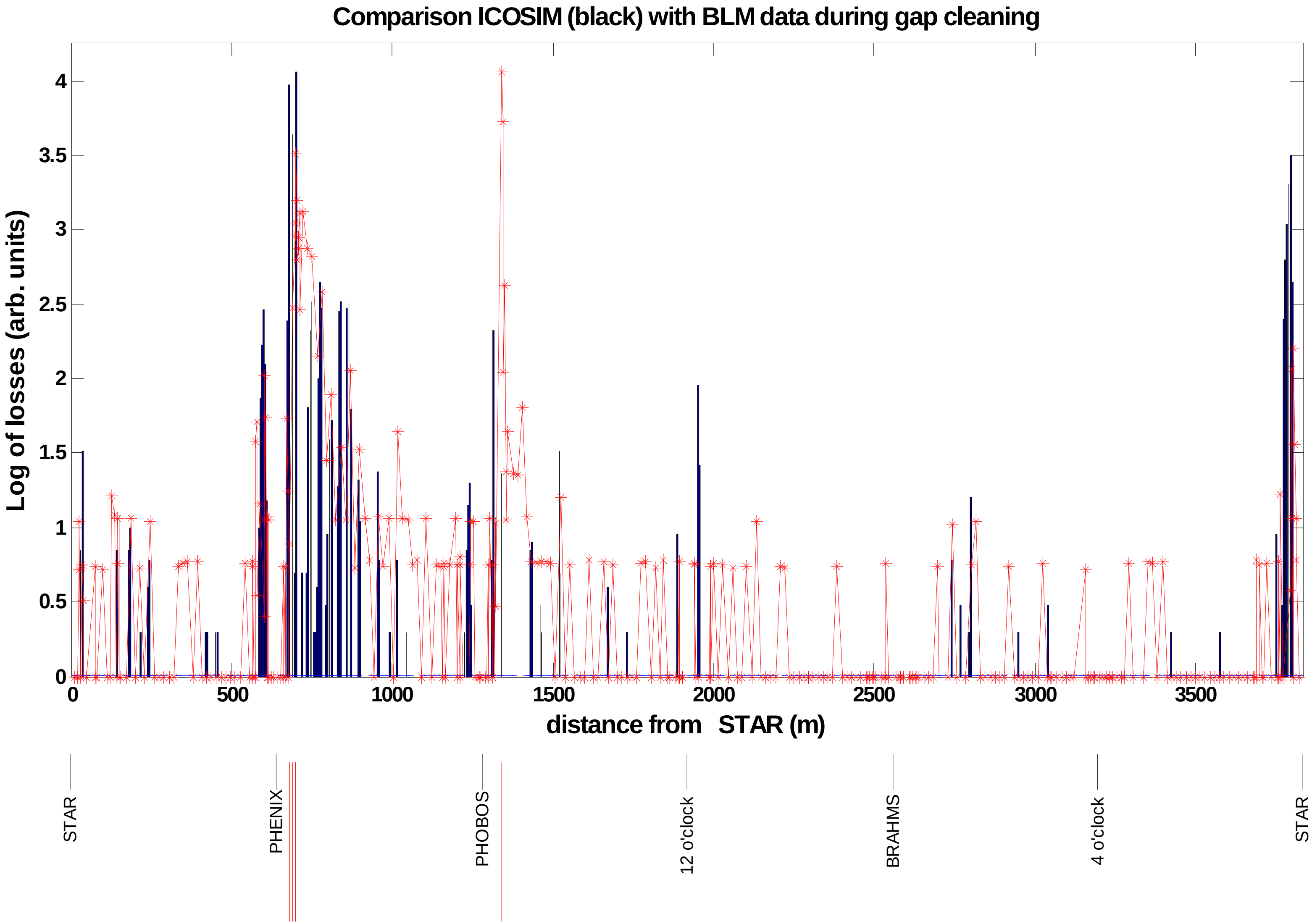
BEAM	IP	SLOT	s(m) from IP7	Transv pos	MAD-X name	cold mass type
2	7	BJBAP.A9L7		Inside	MB.A9L7.B2	MBB.9L7
			320			
			322.5			
			325			
			327.5			
			330			
			332.5			
			335			
			337.5			
			340			
			342.5			
2	7	BJBAP.A11L7		Inside	MB.B11L7.B2	MBA.11L7
			388.5			
			391			
			393.5			
			396			
			398.5			
			401			
			403.5			
			406			
			408.5			
			411			
			413.5			
			416			
			418.5			
2	7	BJBAP.B11L7		Inside	MQ.11L7.B2	MQ.11L7
			433			
2	7	BYPLM.A13L7		Inside	MQ.13L7.B2	MQ.13L7
			538.5			
			541			
2	7	BYPLM.A19L7		Inside	MQ.19L7.B2	MQ.19L7
			854			
			856.5			
			859			
			861.5			

4 patches, 27 BLMs

5 patches, 30 BLMs

slide
from G.Bellodi

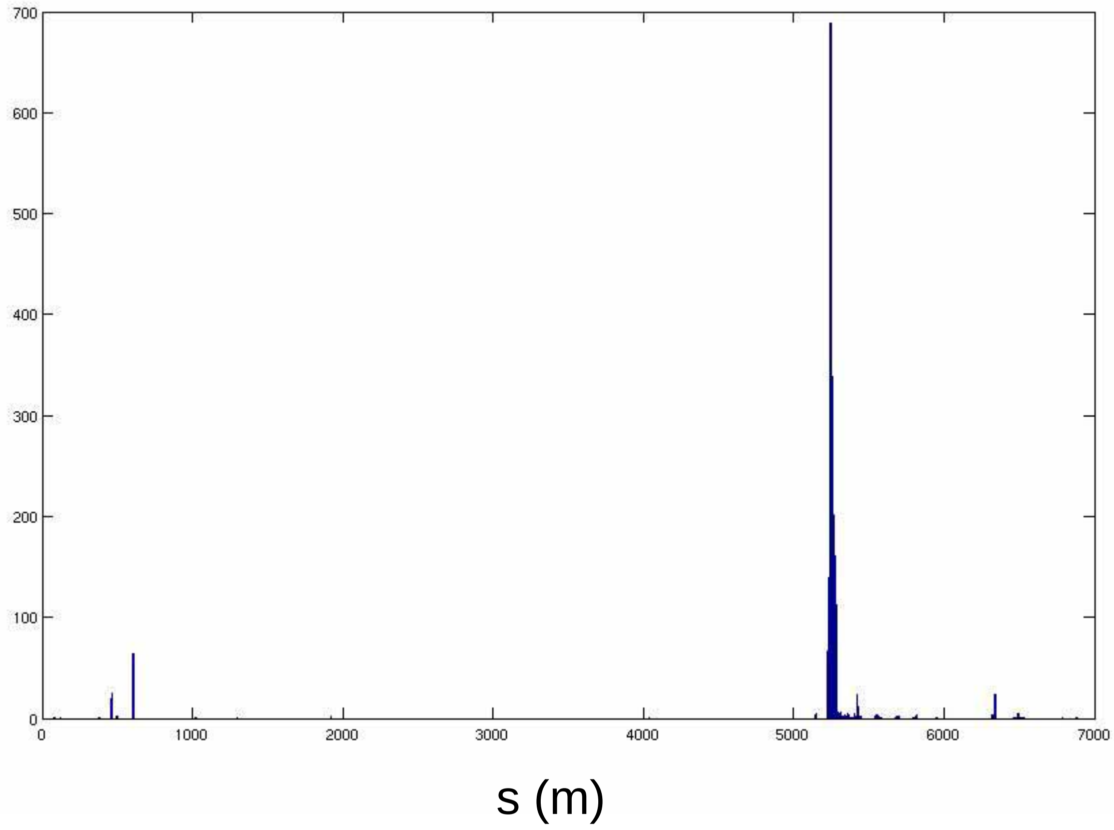
Benchmarking of ICOSIM with RHIC data


Comparison ICOSIM (black) with BLM data during gap cleaning

ICOSIM for protons, benchmarking with SPS collimator tests and SIXTRACK

Roderick Bruce

Loss map for collimator test with protons in SPS



Energy Loss by High Energy Ions in Matter

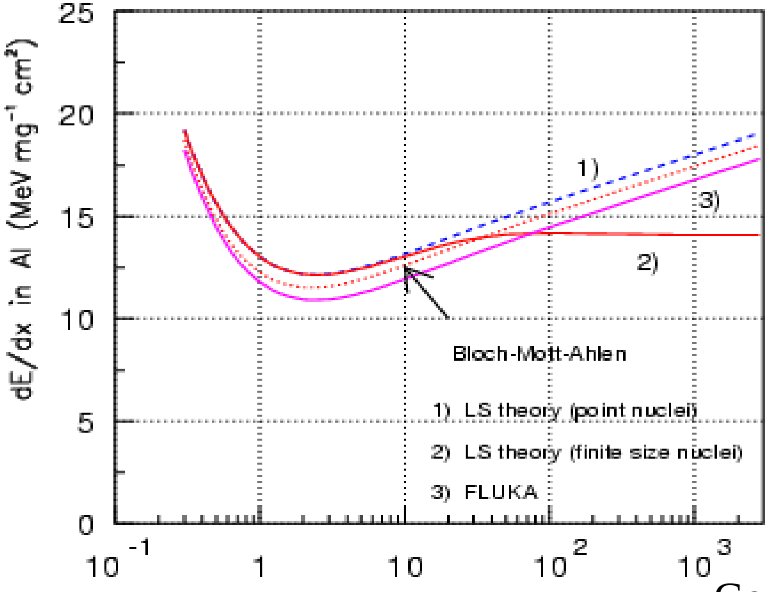
dE/dx of heavy ions deviates from Bethe-Bloch at high energies

- Higher order corrections
- Finite nuclear size effects
- Pair production

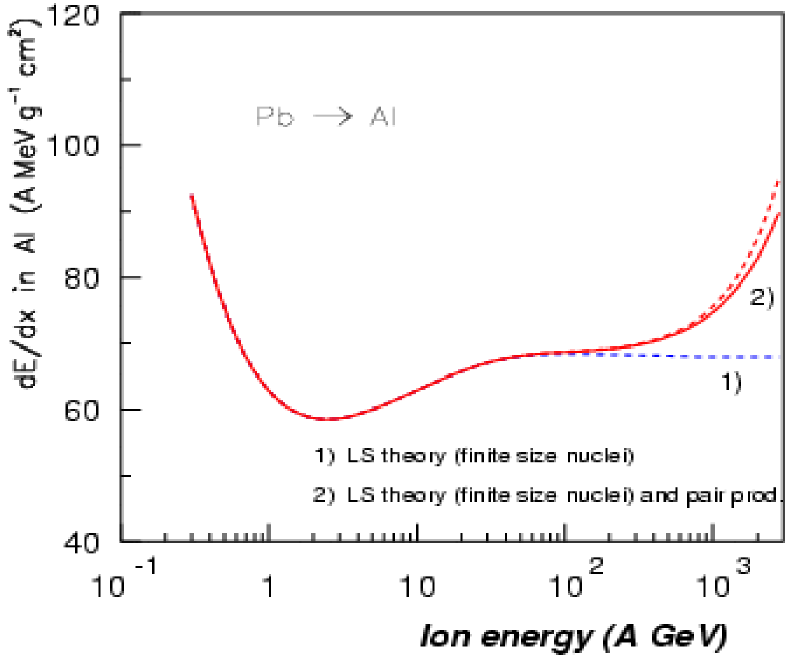
Mult. scattering rms angles are reduced and Moliere tails are suppressed due to finite nucl.size.

Consequences for local energy deposition of impacting beams and for collimation efficiency needs to be understood.

Implementation of all relevant effects in FLUKA code underway.



plots from George Smirnov



Remedies ?

Trivial and for practical reasons impossible solution: Increase strength of collimation doglegs by factor 4.

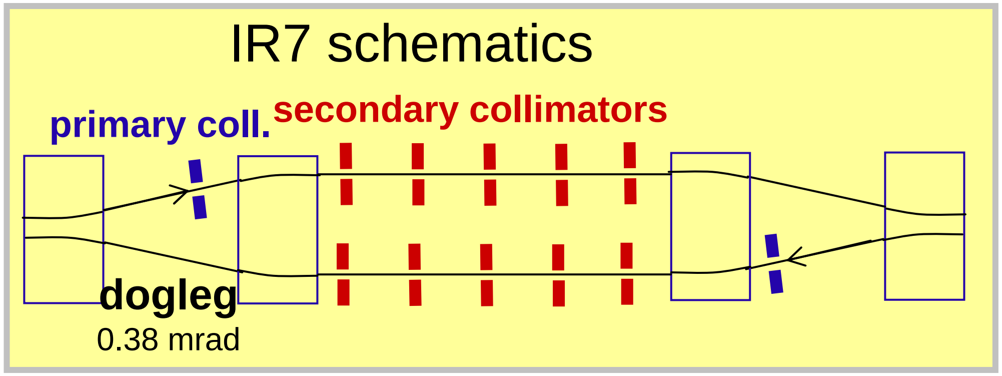
Explore optics with large dispersion, small phase advance in IR3 and IR7. Probably difficult to achieve without major rebuild of IR3 and IR7

~~High Z scrapers in high β region downstream IP1 (ATLAS), IP2 (ALICE), IP5 (CMS)~~

Bend crystal collimators. Conceptually appealing,
But:
– Test at RHIC not very promising
– Difficult to predict & test behavior of ion grazing on surface
– How to simulate ?

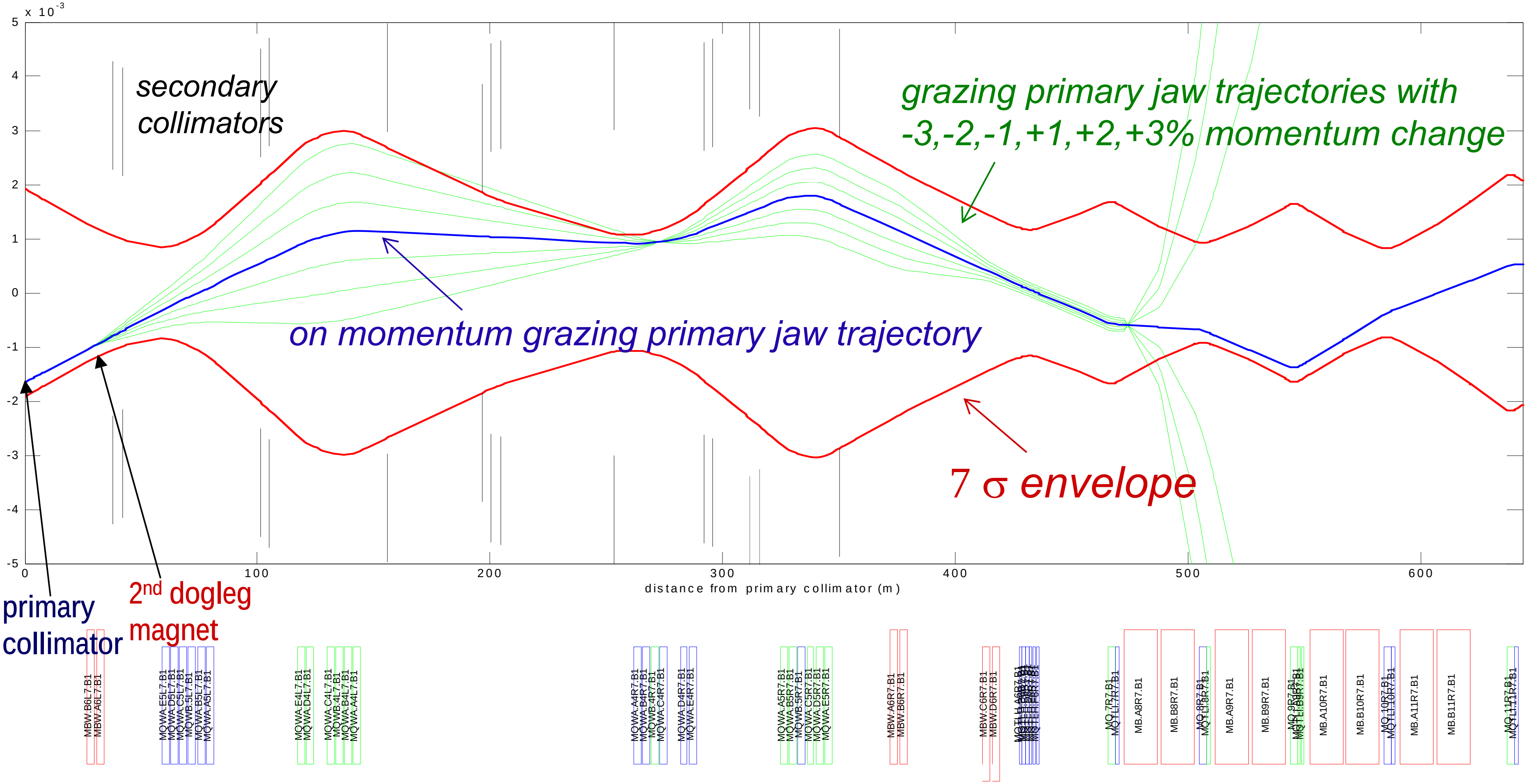
Develop secondary collimators for use inside cold SC (would also solve BFPP problems)

Special heavy ion collimators with magnetized jaws ?



Only particles with effective ΔP/P>3% can be intercepted with secondary collimators.
Trivial (and impossible) solution:
Increase dogleg magnets strength by factor 4

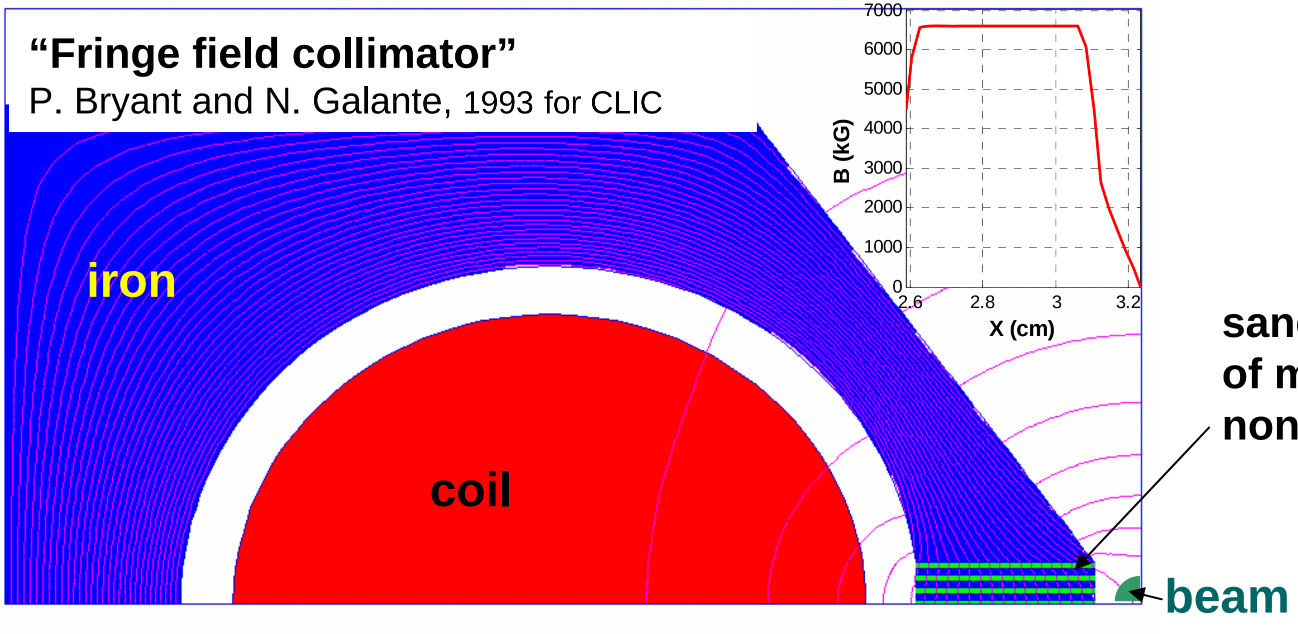
Perhaps a different IR7 optics could give some improvement. Needs further study.



Magnitized Jaw for primary collimator

Condition to bend particle enough to hit secondary collimator :

$$\delta x' > \sqrt{\frac{\left(N_2^{\,2} - N_1^{\,2}\right)\varepsilon_N}{\gamma_{REL.}\,\beta_{TWISS}}} \quad \Rightarrow \quad BL > \sqrt{\frac{\left(N_2^{\,2} - N_1^{\,2}\right)\varepsilon_N}{\gamma_{REL.}\,\beta_{TWISS}}}\,\frac{P}{Z\,e} \quad \approx \quad 0.2\ \mathrm{Tm}$$


“Fringe field collimator”

P. Bryant and N. Galante, 1993 for CLIC

sandwich structure of magnetic and non-magnetic metal

All halo particles getting close enough to jaw for nuclear reactions are bend to 2nd collimator

Impact on dynamics of beam core, magnetic design in 3D and technical feasibility needs study

Conclusions

- Tools to predict collimation efficiency for ion beams are available, further improvements under progress
- Present LHC baseline two stage collimation doesn't work for ions.
  System acts as single stage collimation,
  primary halo from collimators lost in SC magnets.
  This will lead to a soft beam current limitation at ≈ 50% of nominal I_{beam}.
- BLM system has been extended to assure safe operation of LHC with ion beams.
- Remedies for current limitation are under study.
  Problem is to find a satisfactory solution feasible with limited efforts.
- Beams of other ion species have not been studied yet.
  For ions A>20 problem will probably be comparable.