Collimation for Heavy Ions

- Specific issues for ion collimation
- ICOSIM program and results
- BLM sensitivity ions vs. protons
- Mishaps
- Remedies ?
- Heavy Ion – Matter Interactions at high γ
- Conclusions

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} ~I_{PROTON}/100)
5. activation and maintainability	- (P_{IONS} ~P_{PROTON}/100)

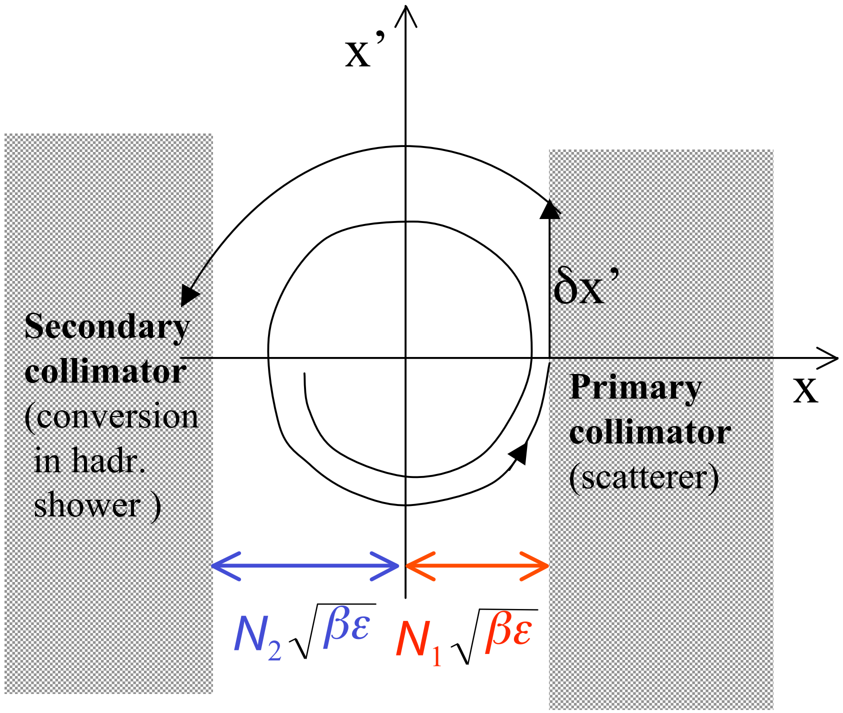
Why is heavy ion collimation for LHC a specific issue?

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 $\delta x'$ is mainly due to multiple Coulomb scattering with

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

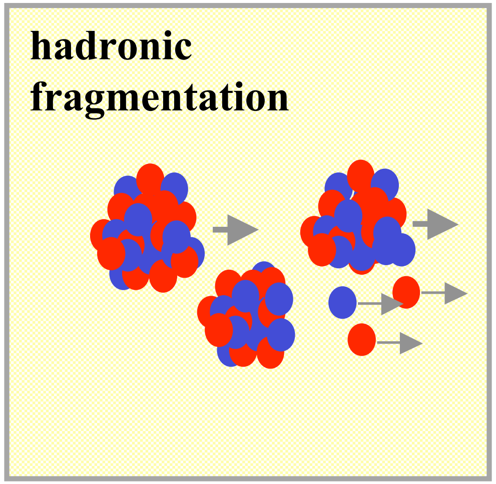
But:

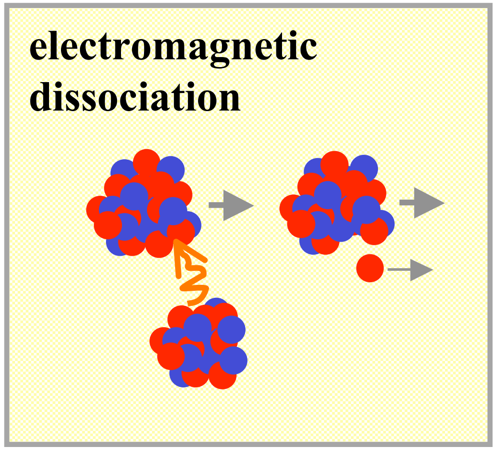
if required $L > L_{INT}$ particle undergoes nuclear reaction before secondary collimator is reached !

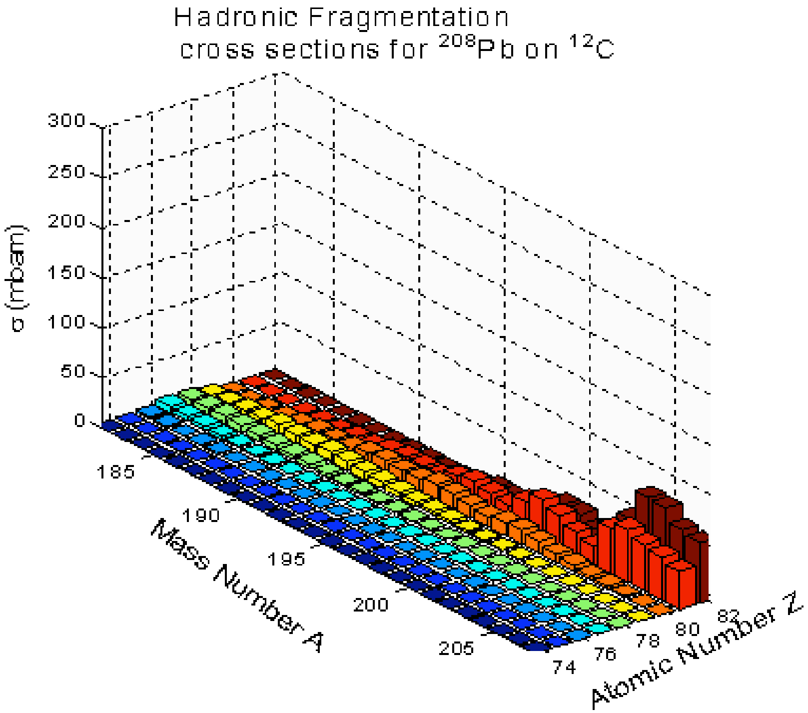
^{208}Pb-ion/matter interactions in comparison with proton/matter interactions.

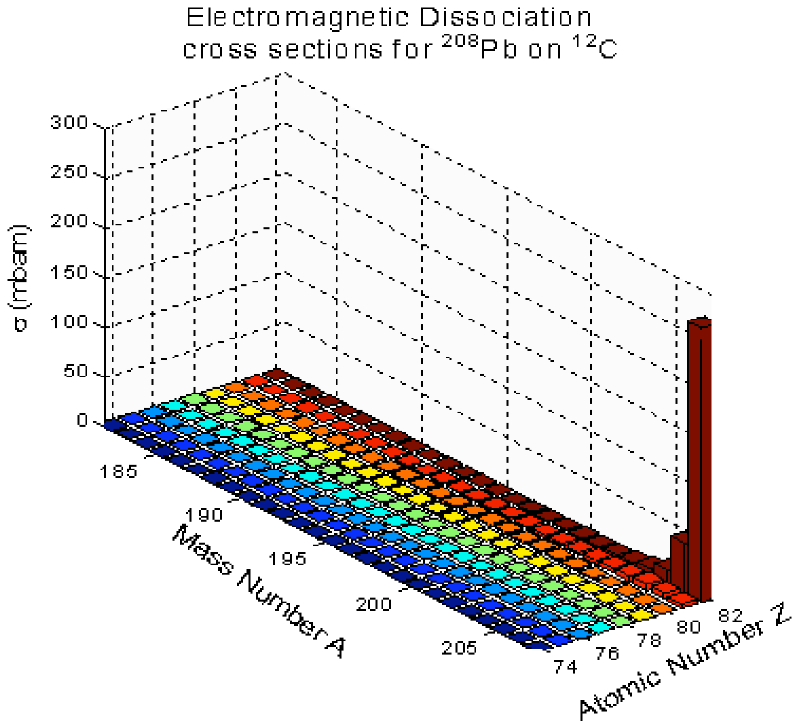
(values are for particle impact on graphite)

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





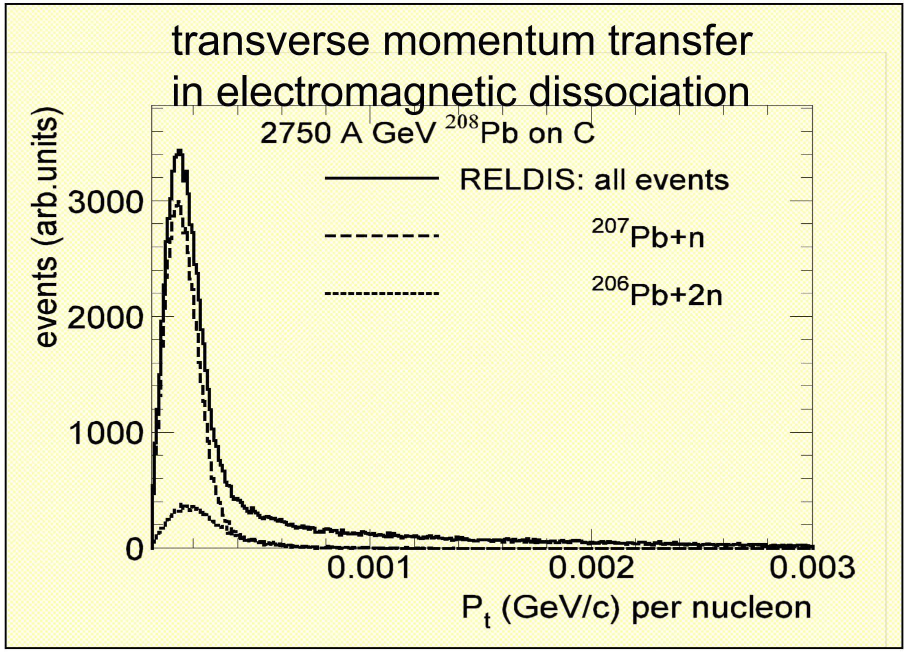




Computation of cross-sections by Igor Pshenichnov (INR, Moscow)

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



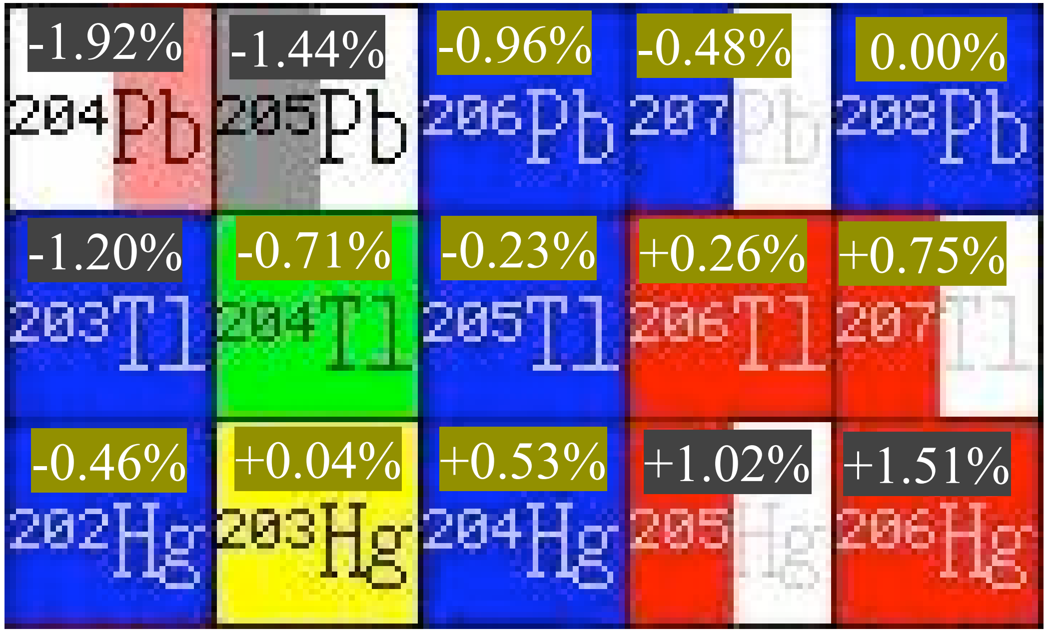
First impacts of halo ions on primary collimators is usually grazing, small effective length of collimator.

— 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

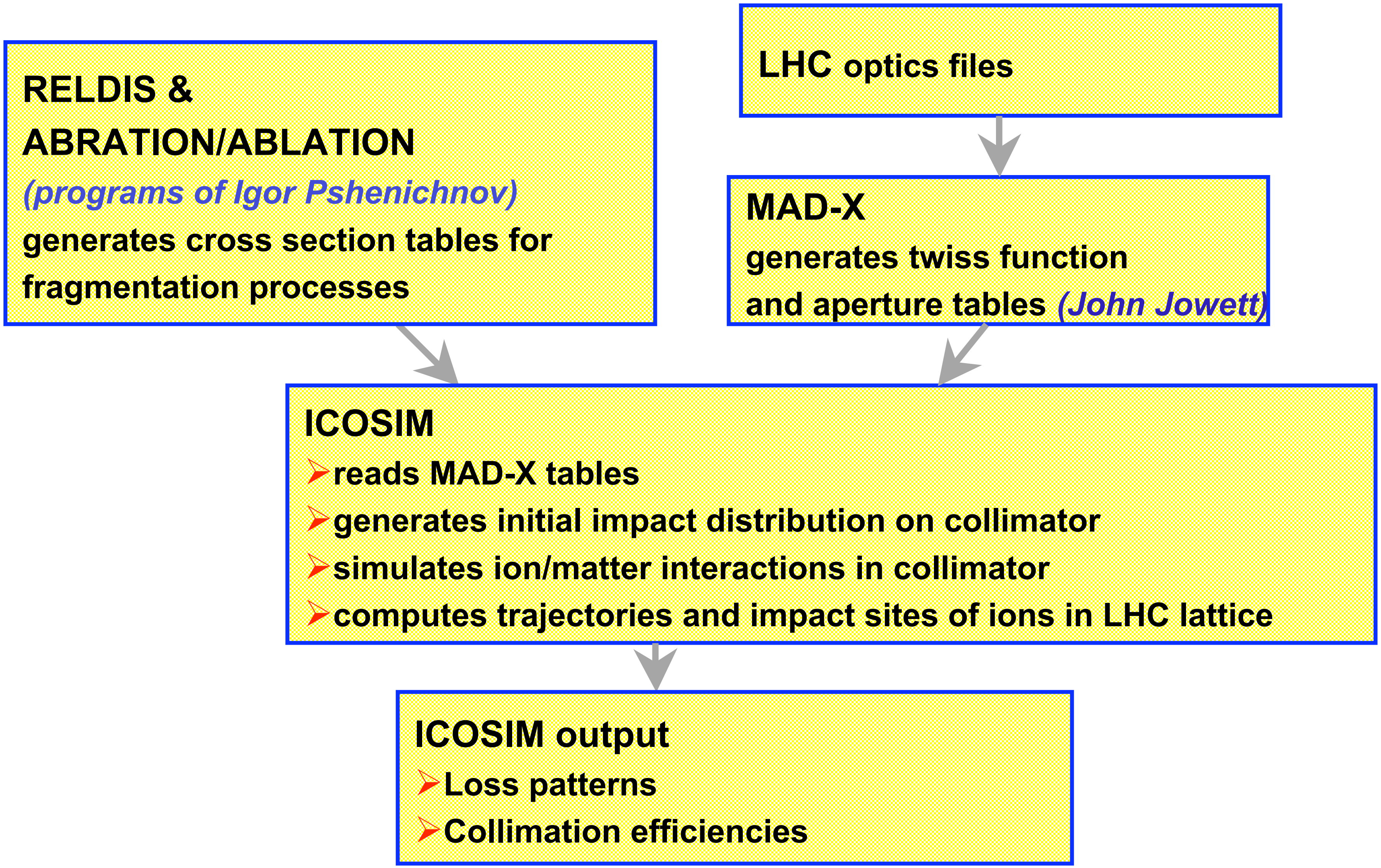
$$\left.\frac{\Delta P}{P}\right|_{EFF.} = \frac{Z_1}{A_1}\frac{A_2}{Z_2} - 1$$



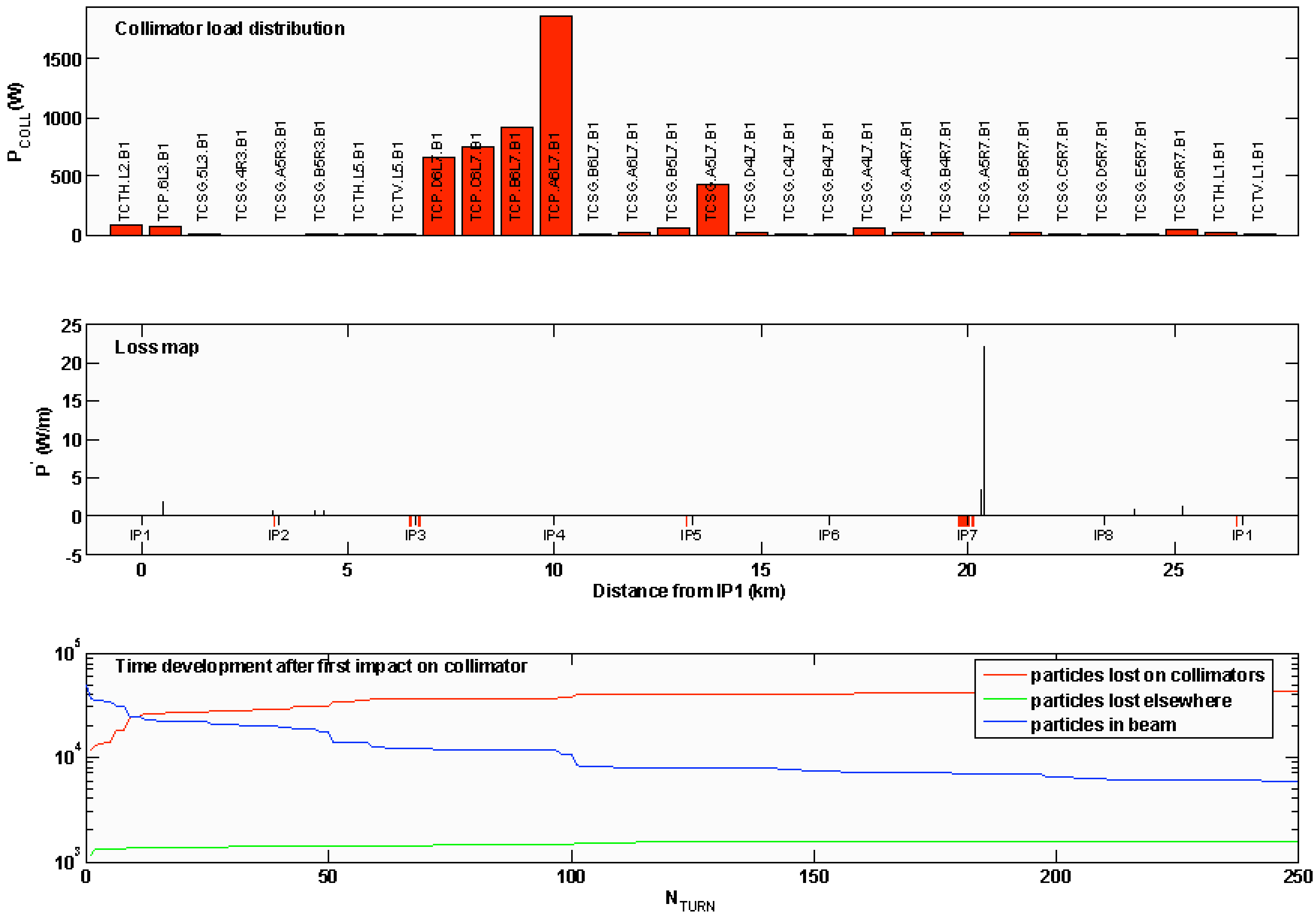
Energy acceptance LHC arcs ≈ ±1%

Energy acceptance energy cleaning IR3 ≈ ±0.2%

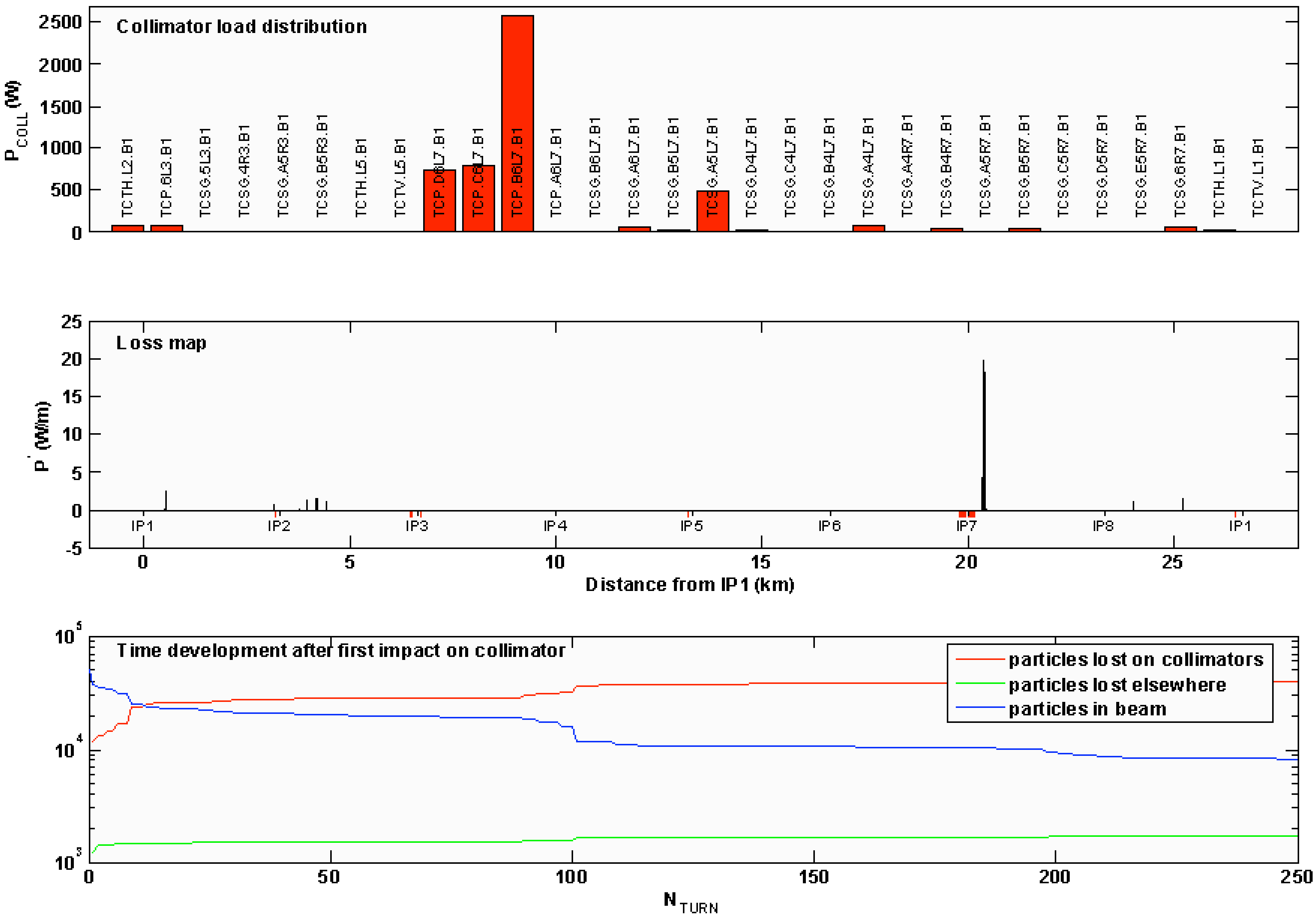
Computing tools for ILHC collimation

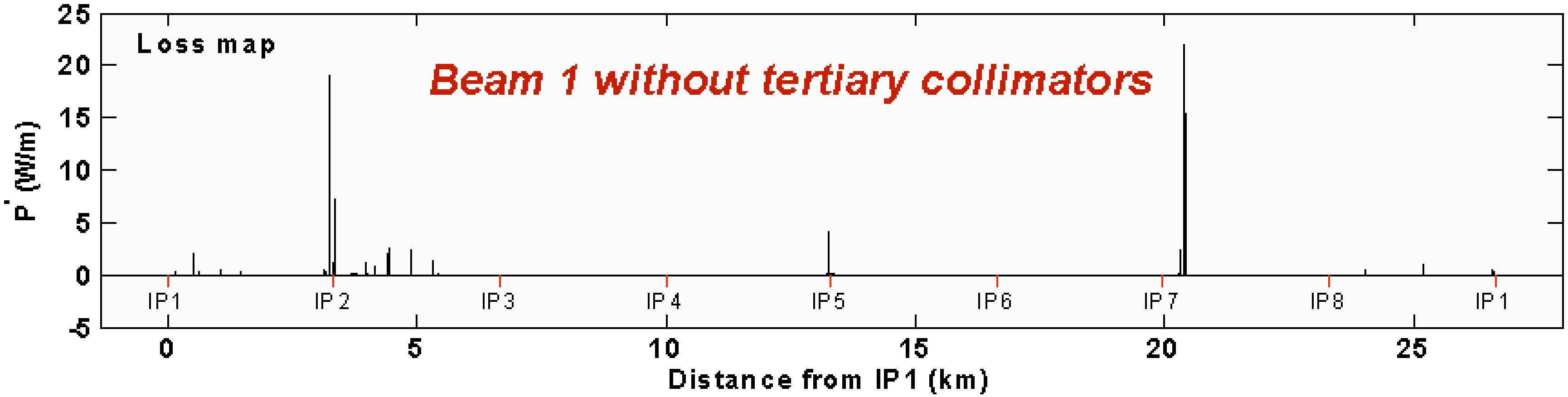


Beam 1 with tertiary collimators, τ_{beam} =12min

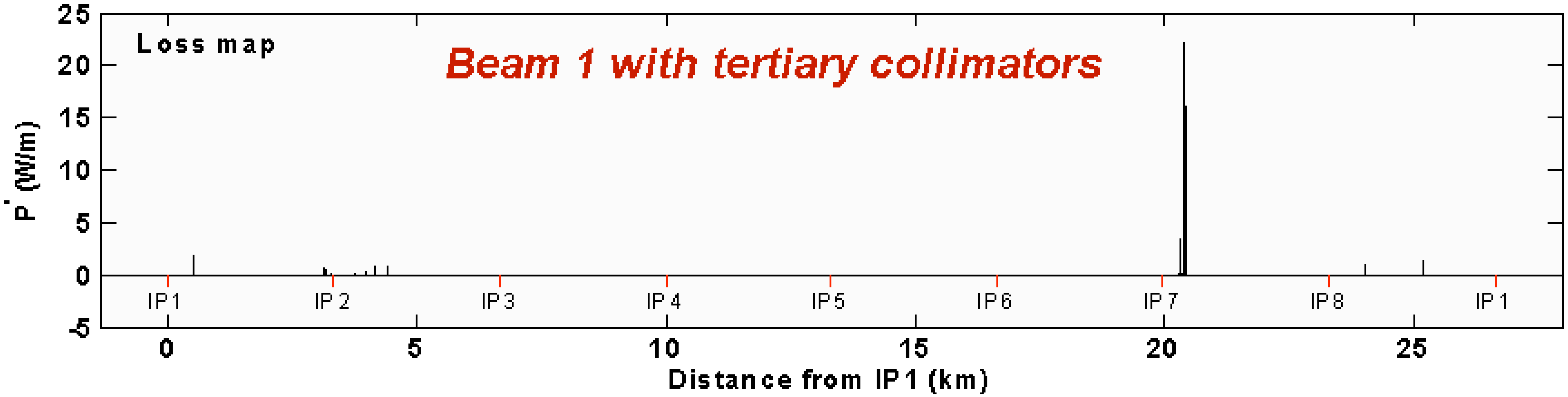


Beam 1 with tertiary collimators, τ_{BEAM}=12min, without TCP.A6L7.B1



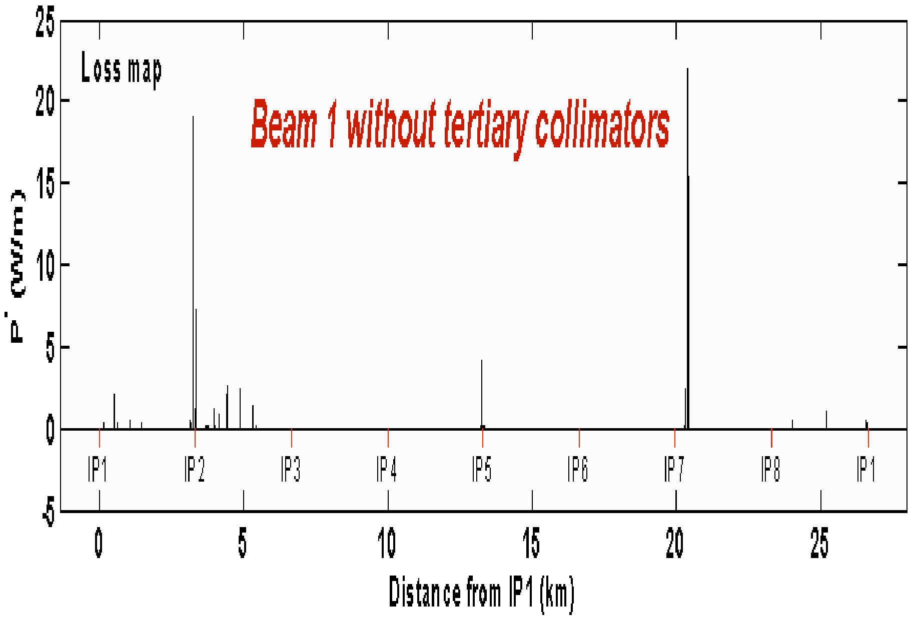


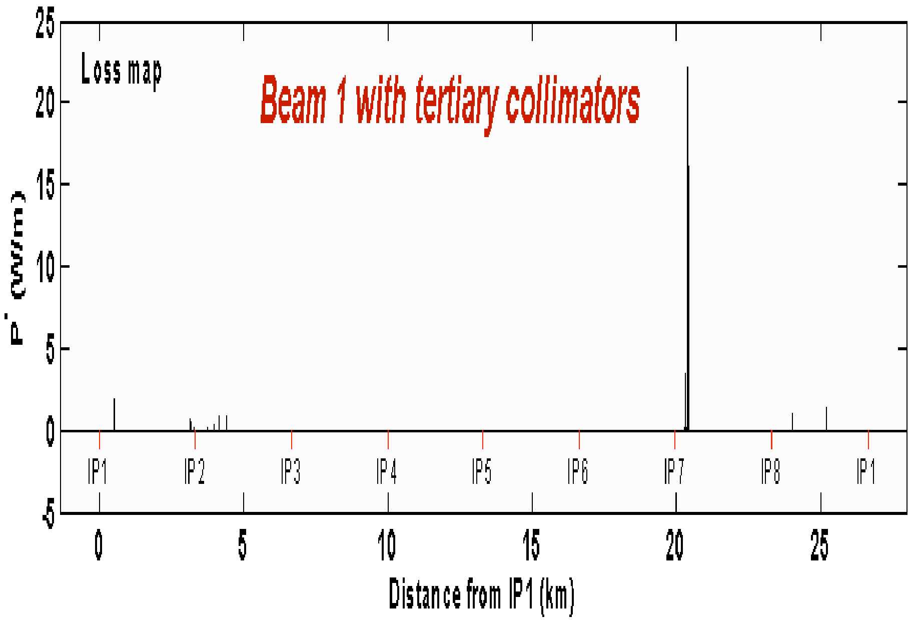
Loss map
Beam 1 without tertiary collimators
P' (W/m)
25
20
15
10
5
0
-5
IP1
IP2
IP3
IP4
IP5
IP6
IP7
IP8
IP1
0
5
10
15
20
25
Distance from IP1 (km)



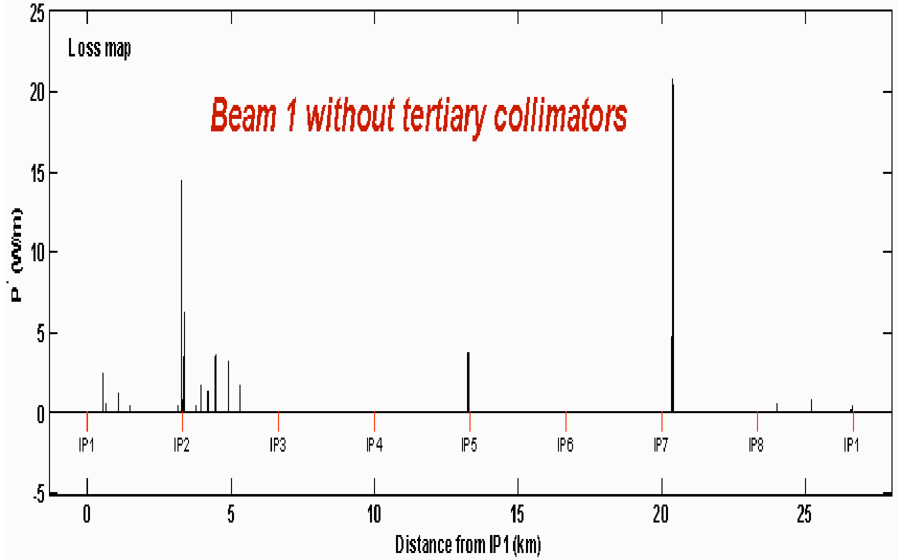
Loss map
Beam 1 with tertiary collimators
P' (W/m)
25
20
15
10
5
0
-5
IP1
IP2
IP3
IP4
IP5
IP6
IP7
IP8
IP1
0
5
10
15
20
25
Distance from IP1 (km)

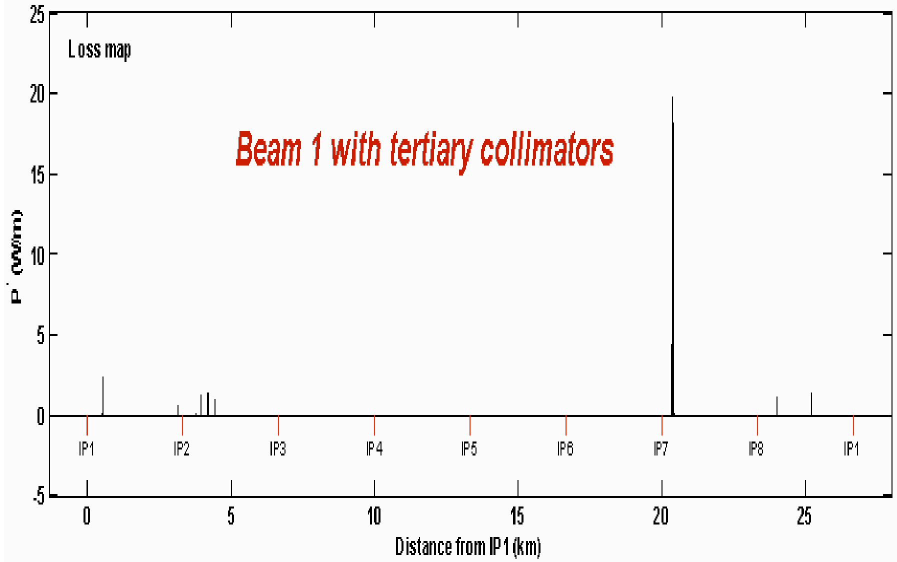
with TCP.A6L7.B1

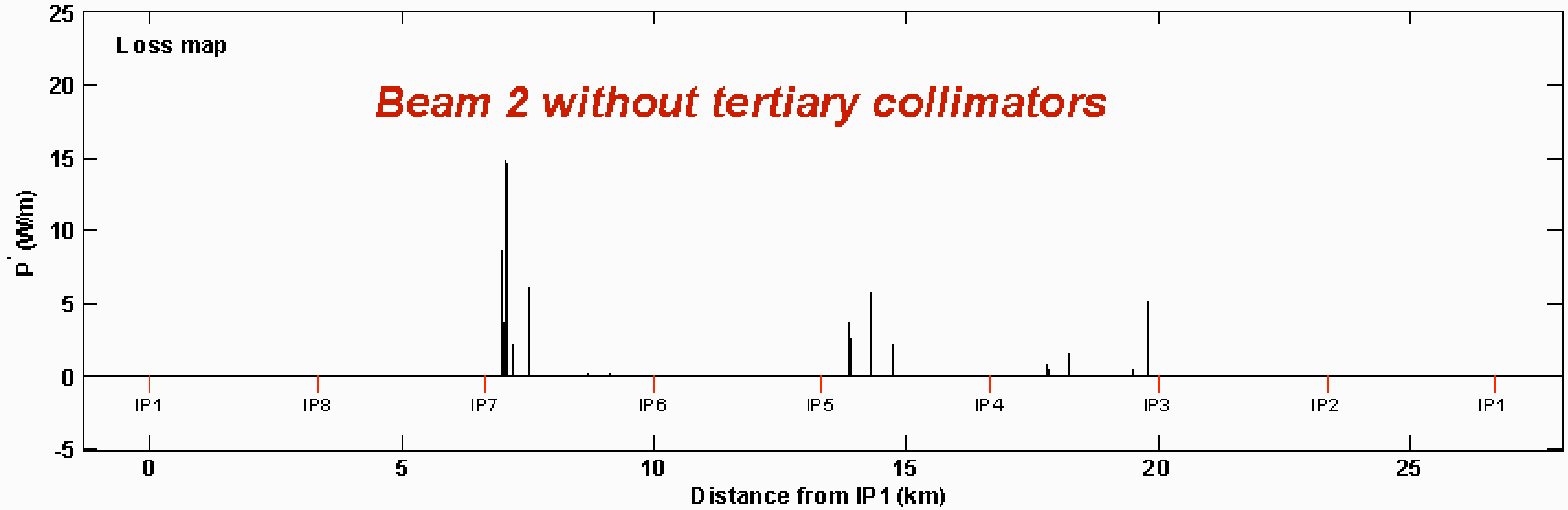


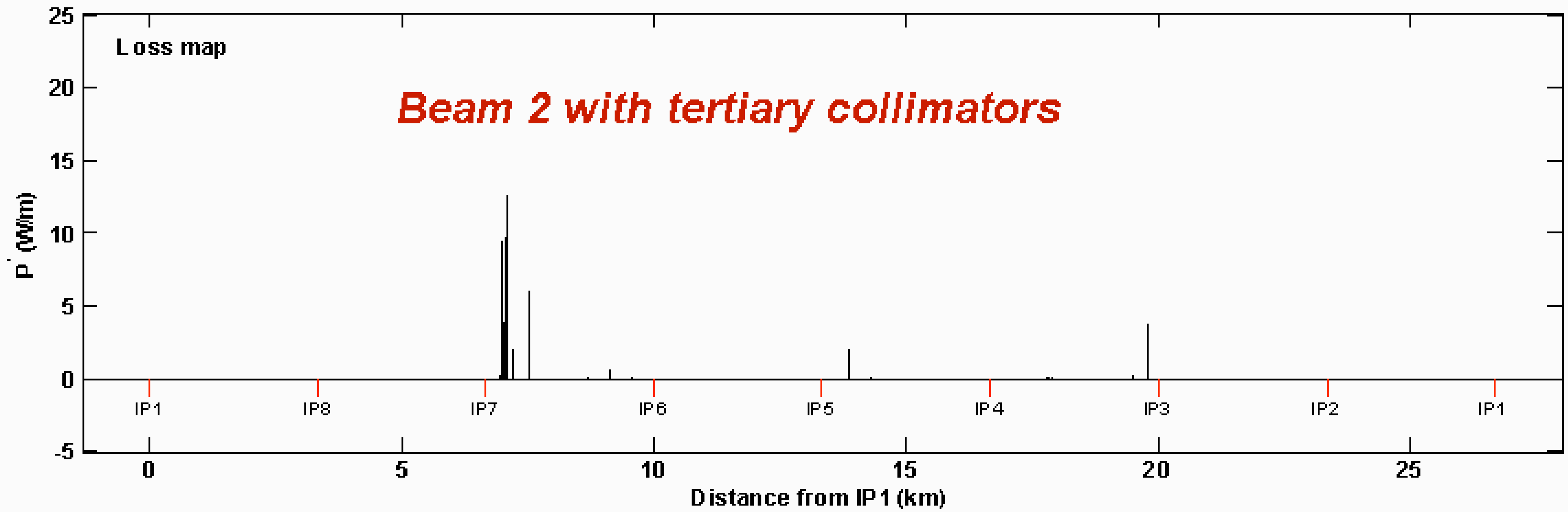


without TCP.A6L7.B1

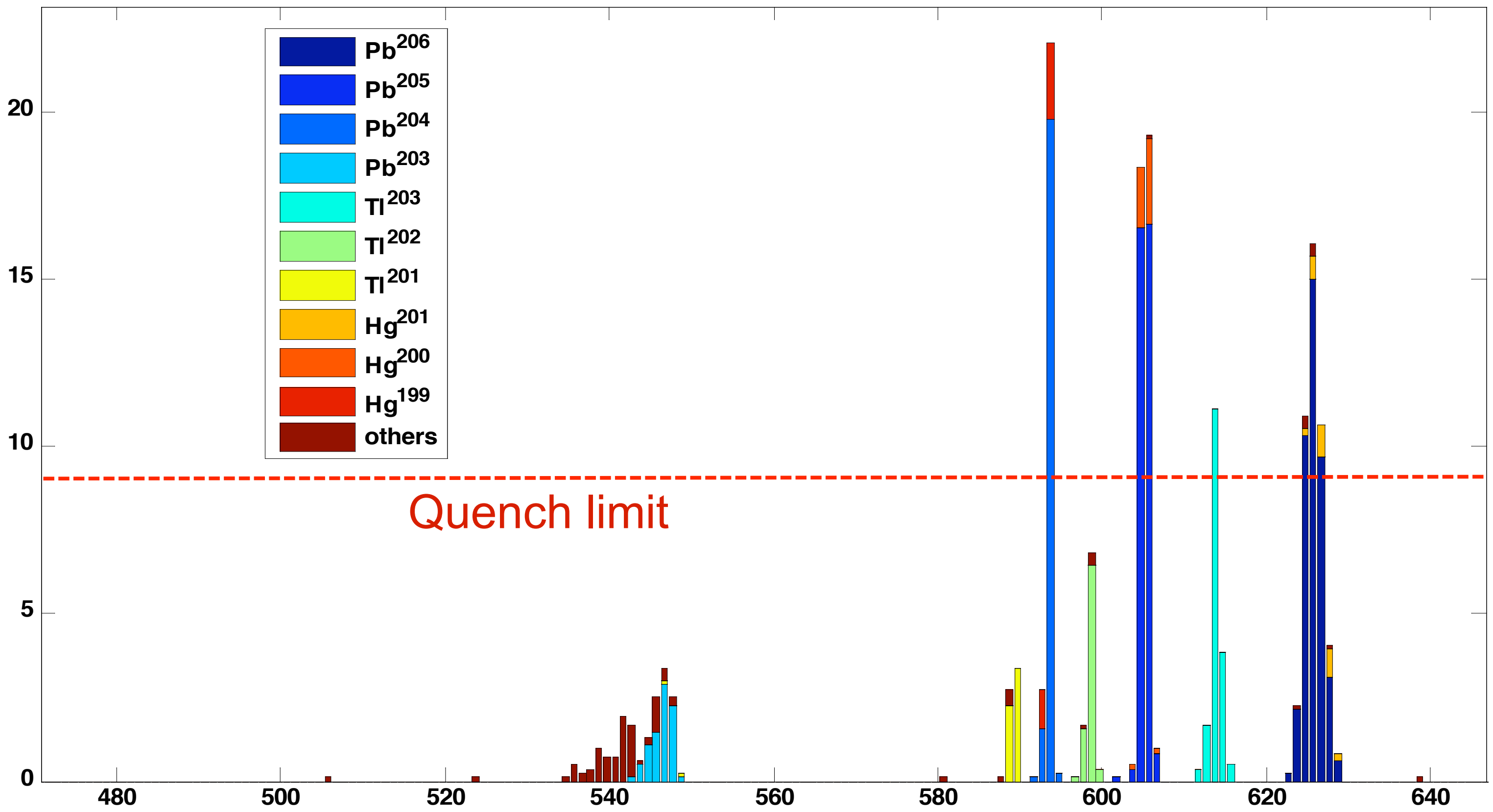





Loss map
Beam 2 without tertiary collimators
25
20
15
10
5
0
-5
P' (W/m)
IP1
IP8
IP7
IP6
IP5
IP4
IP3
IP2
IP1
0
5
10
15
20
25
Distance from IP1 (km)


Loss map
Beam 2 with tertiary collimators
25
20
15
10
5
0
-5
P' (W/m)
IP1
IP8
IP7
IP6
IP5
IP4
IP3
IP2
IP1
0
5
10
15
20
25
Distance from IP1 (km)

Nominal Ion beam 1 with collision optics and collimator settings



According to a discussion of John J. with Daniel Leroy permissible losses in LHC MB's can be increased by factor 2

_ Ion collimation problems almost solved

Somewhat more official agreement on acceptable loss rates desirable.

ELSEVIER

Cryogenics 39 (1999) 921–931

Cryogenics

Heat transfer in electrical insulation of LHC cables cooled with superfluid helium

C. Meuris [a,*], B. Baudouy [a], D. Leroy [b], B. Szeless [c]

[a] Service des Techniques de Cryogénie et de Magnétisme, Direction des Sciences de la Matière, CEA/Saclay, 91191 Gif sur Yvette, France
[b] LHC Division, CERN, 1211 Geneva 23, Switzerland
[c] EP Division, CERN, 1211 Geneva 23, Switzerland

Received 23 August 1999; accepted 22 September 1999

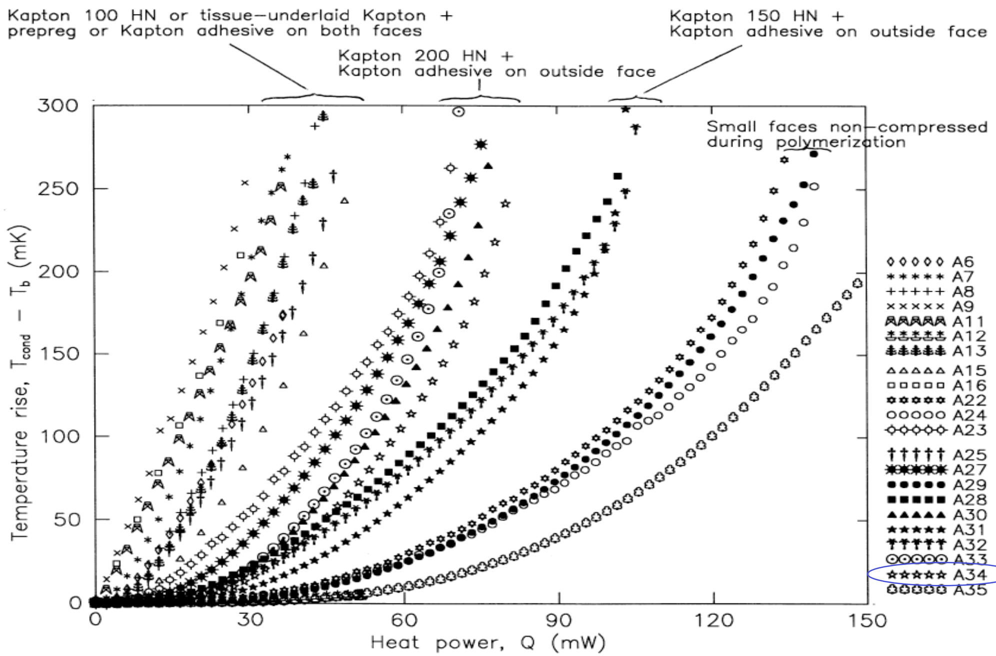
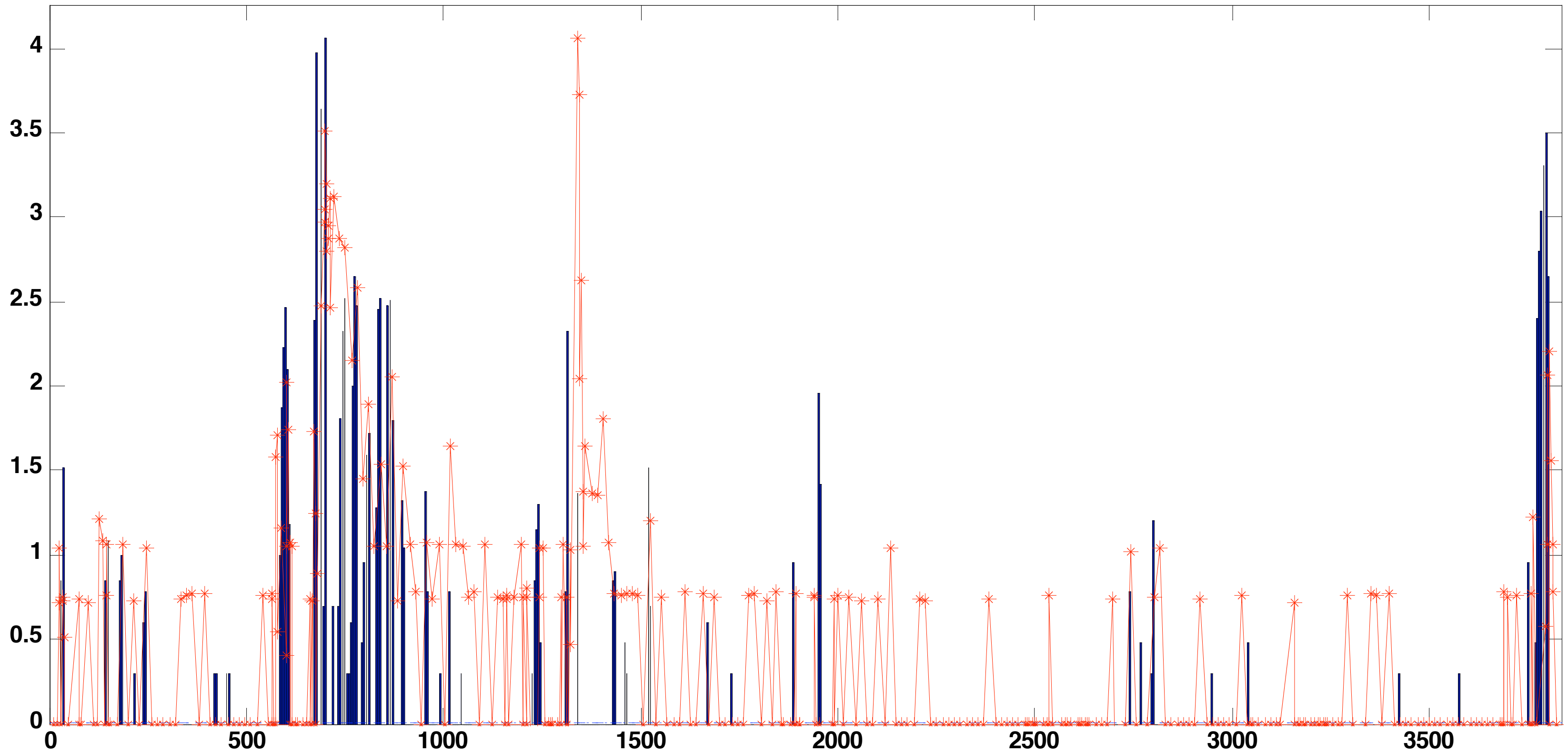


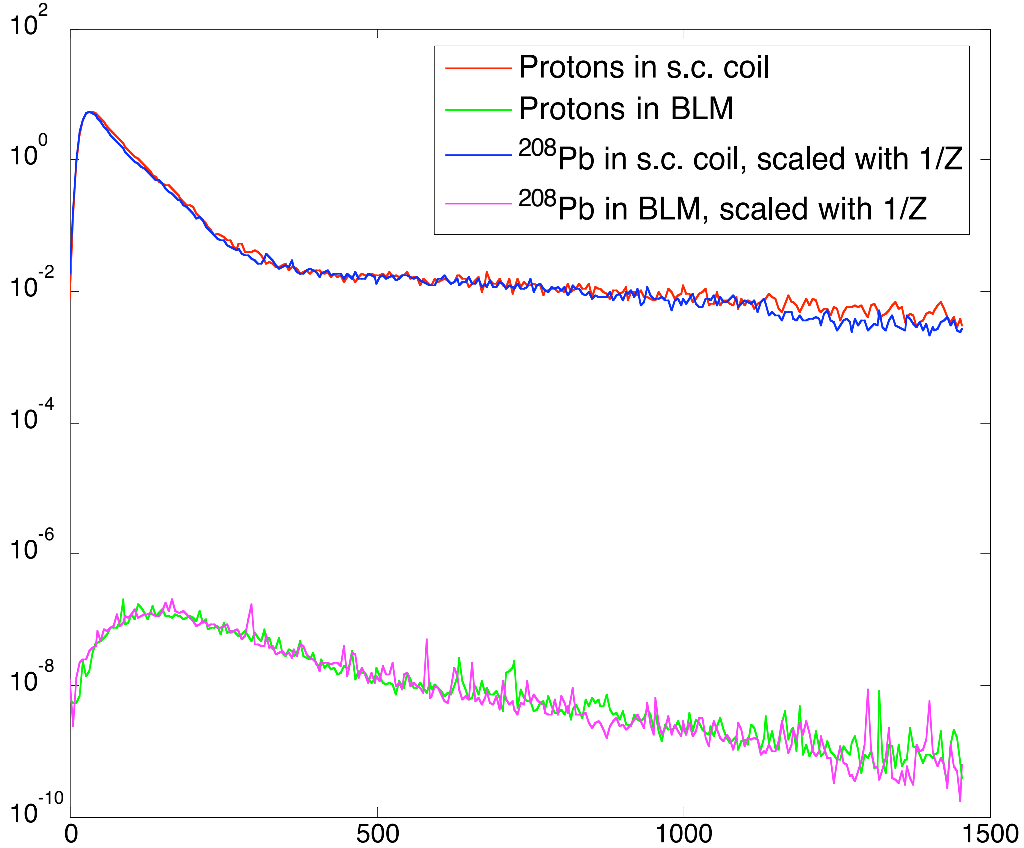
Fig. 5. Temperature rise of central conductor when the three central conductors are heated. Secondary wrapping with spacing (family 1). $T_b = 1.9$ K.

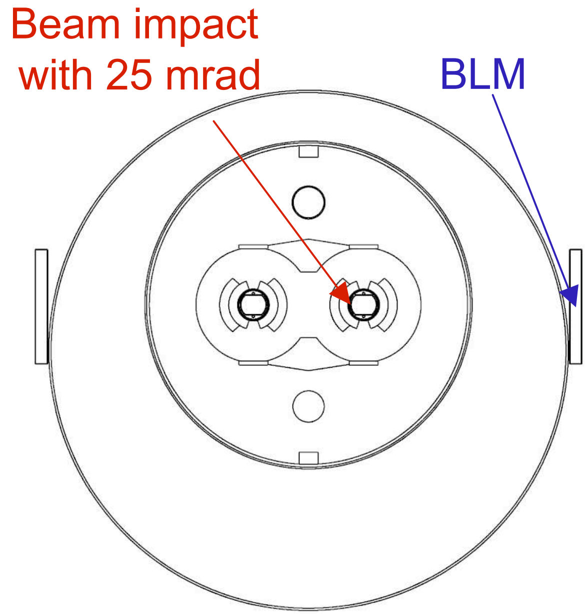
Benchmarking of ICOSIM with RHIC data

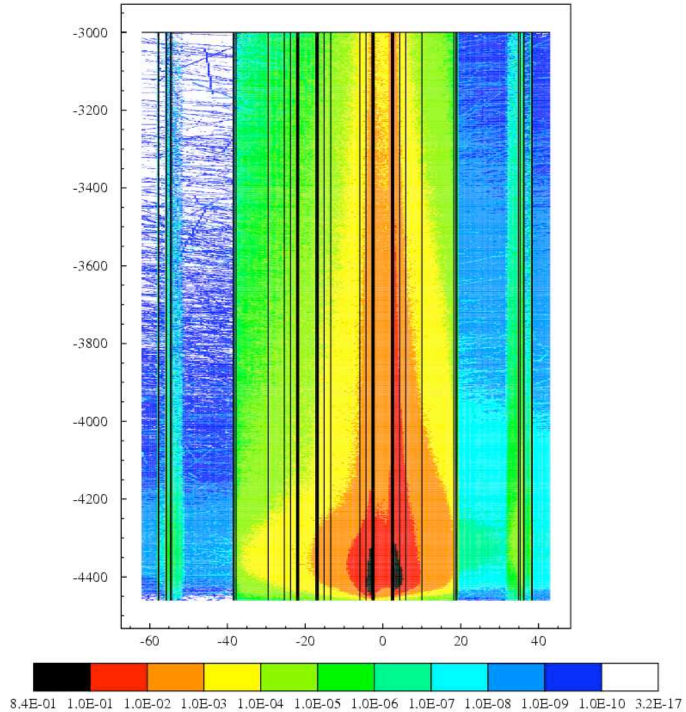


Is the ratio of heat deposition in SC coils to BLM signals the same for Protons and Ions ?

FLUKA calculations by Roderik Bruce

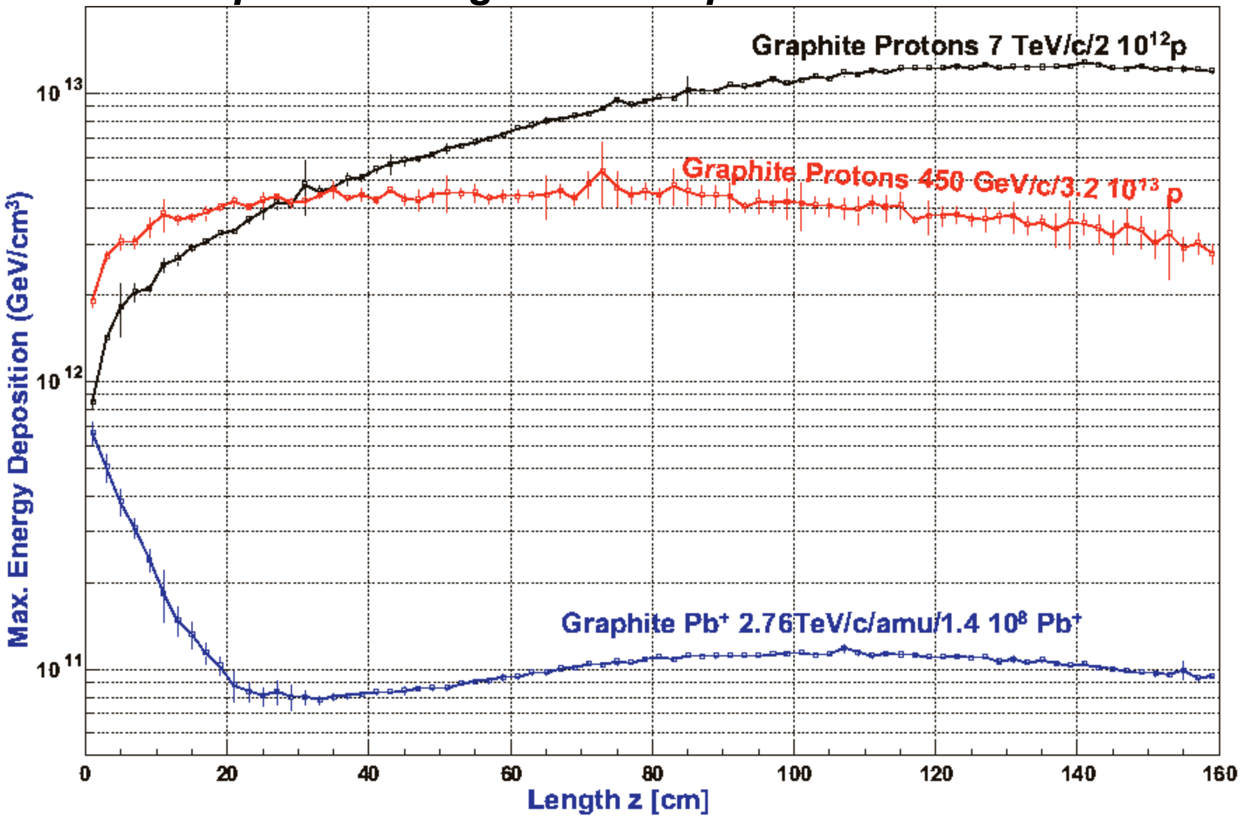






Robustness of collimator against mishaps

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 of 100 times less beam power

Energy Loss by High Energy Ions in Matter

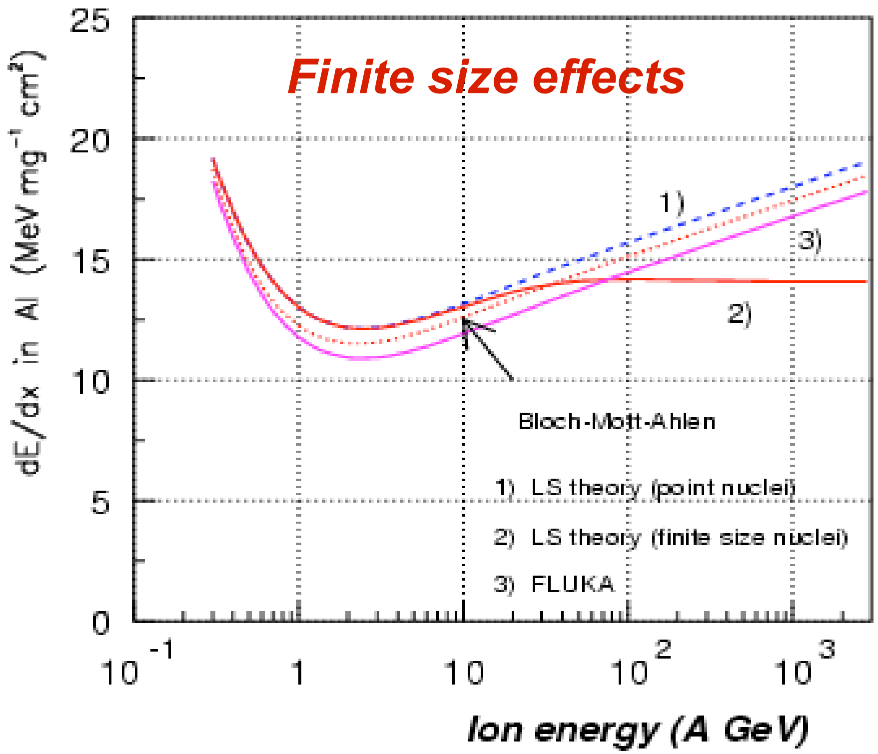
Alfredo Ferrari and George Smirnov (JINR, Dubna) and

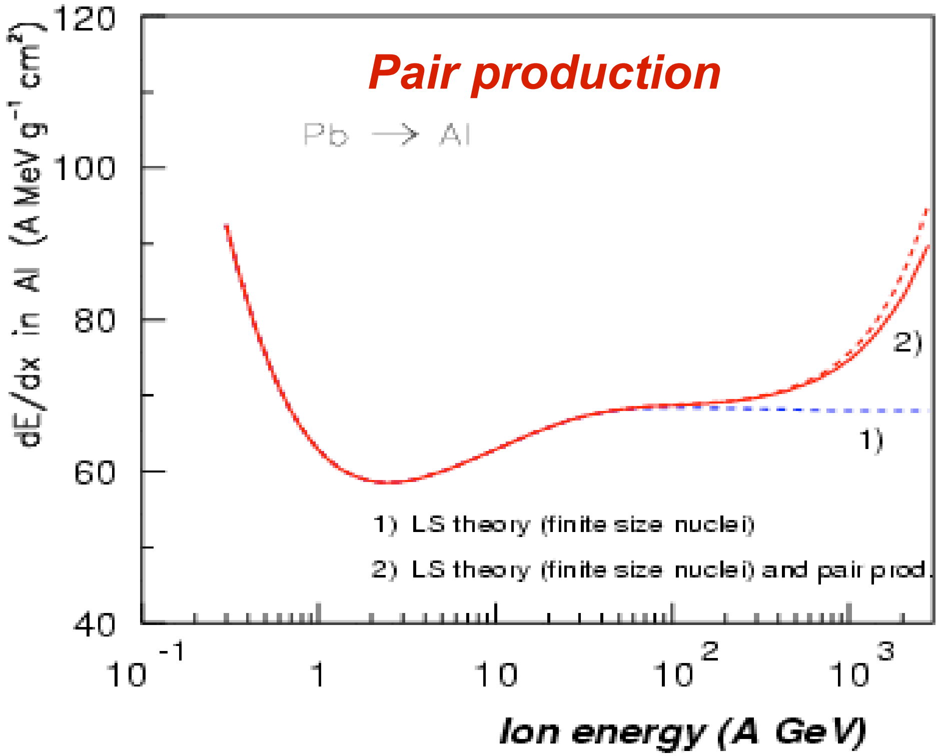
dE/dx of heavy ions deviates from Bethe-Bloch formula at high energies

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

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.





Remedies ?

Optimising the material primary collimator material

The important ion/matter interactions for ions in this context are

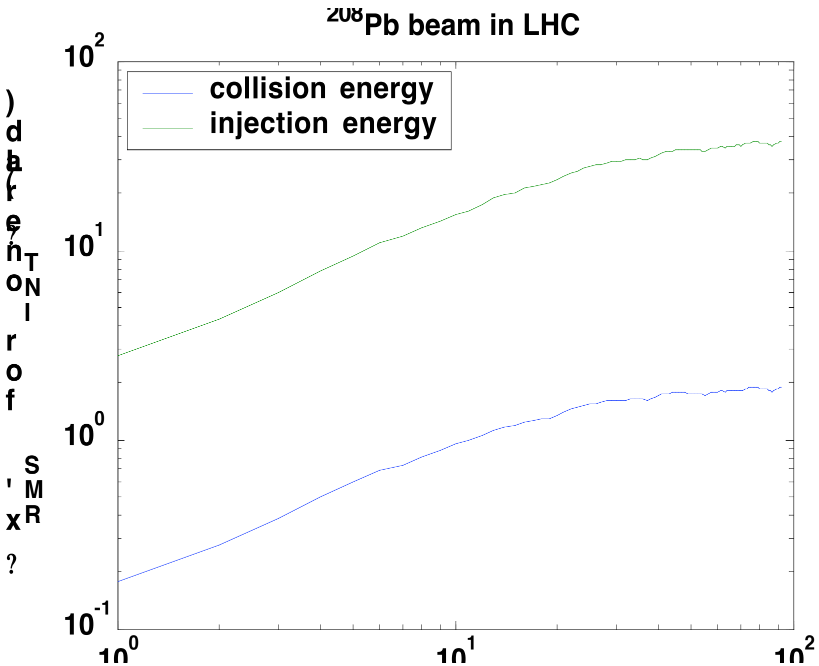
- **hadronic fragmentation** $\sigma_{HAD} \sim (A_{PROJ}^{1/3} + A_{COLL}^{1/3})^2$
- **electromagnetic dissociation** $\sigma_{EMD} \sim Z_{COLL}^2$
- **Multiple scattering** $\langle \delta x'^2 \rangle^{1/2} \sim Z_{COLL}$
- **Ionisation energy loss** $dE/dx \sim Z_{COLL}$

remark:
angle deflection for hadronic fragmentation and electromagnetic dissociation are negligibly small for LHC conditions

figure of merit for collimator material

$$\sqrt{\langle \delta x'^2 \rangle}\Big|_{L=L_{INT}}$$

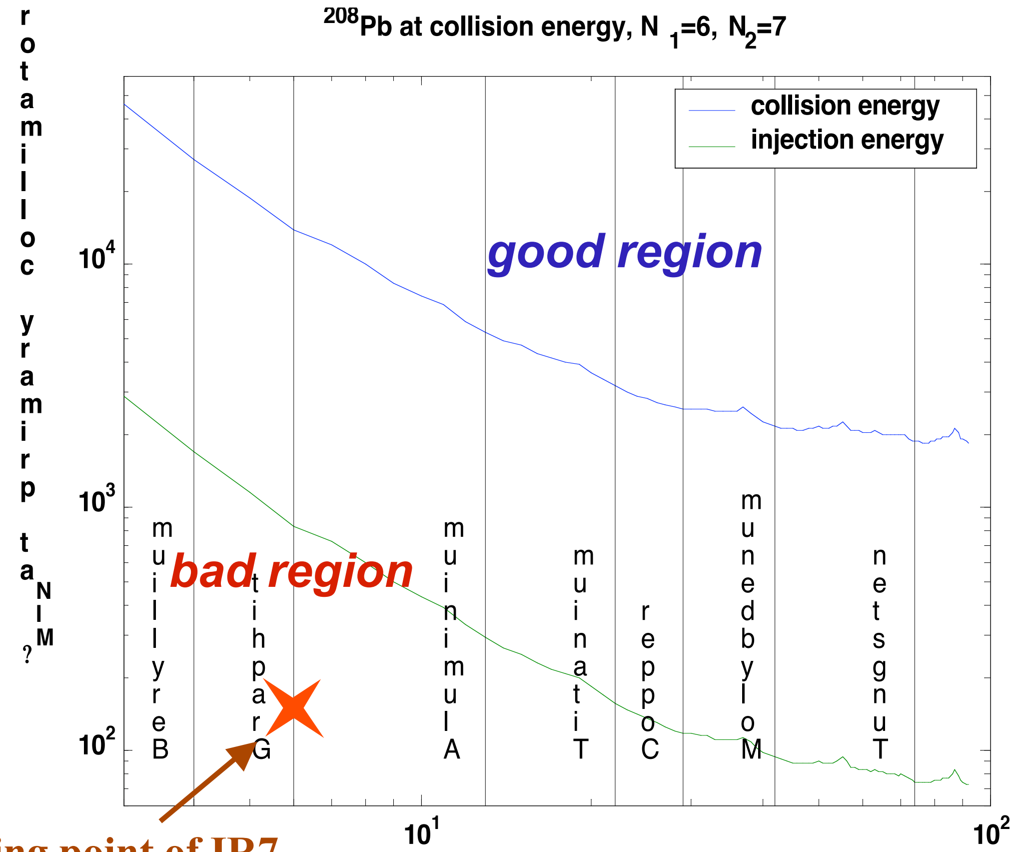
with $$L_{INT} = \frac{A_{COLL}}{N_A\ \rho\ (\sigma_{HAD} + \sigma_{EMD})}$$



Condition

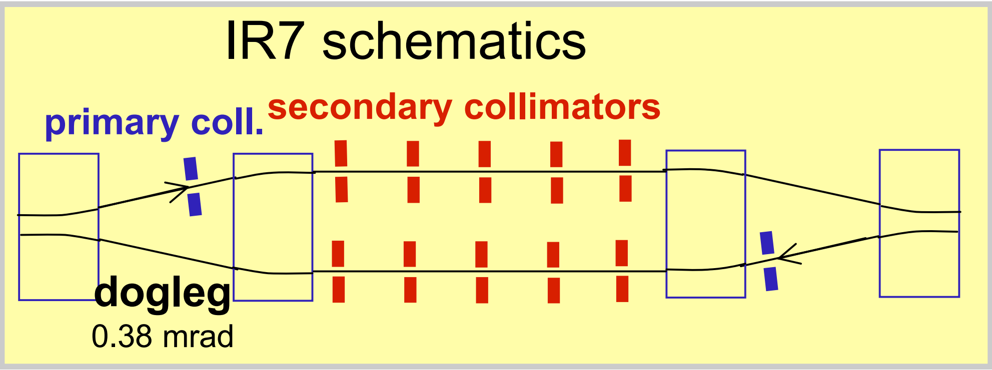
$$\delta x' >> \sqrt{\frac{\left(N_2^{\ 2} - N_1^{\ 2}\right)\varepsilon_N}{\gamma_{REL.}\ \beta_{TWISS}}}$$

can be used to define boundaries in $Z - \beta_{TWISS}$ plane



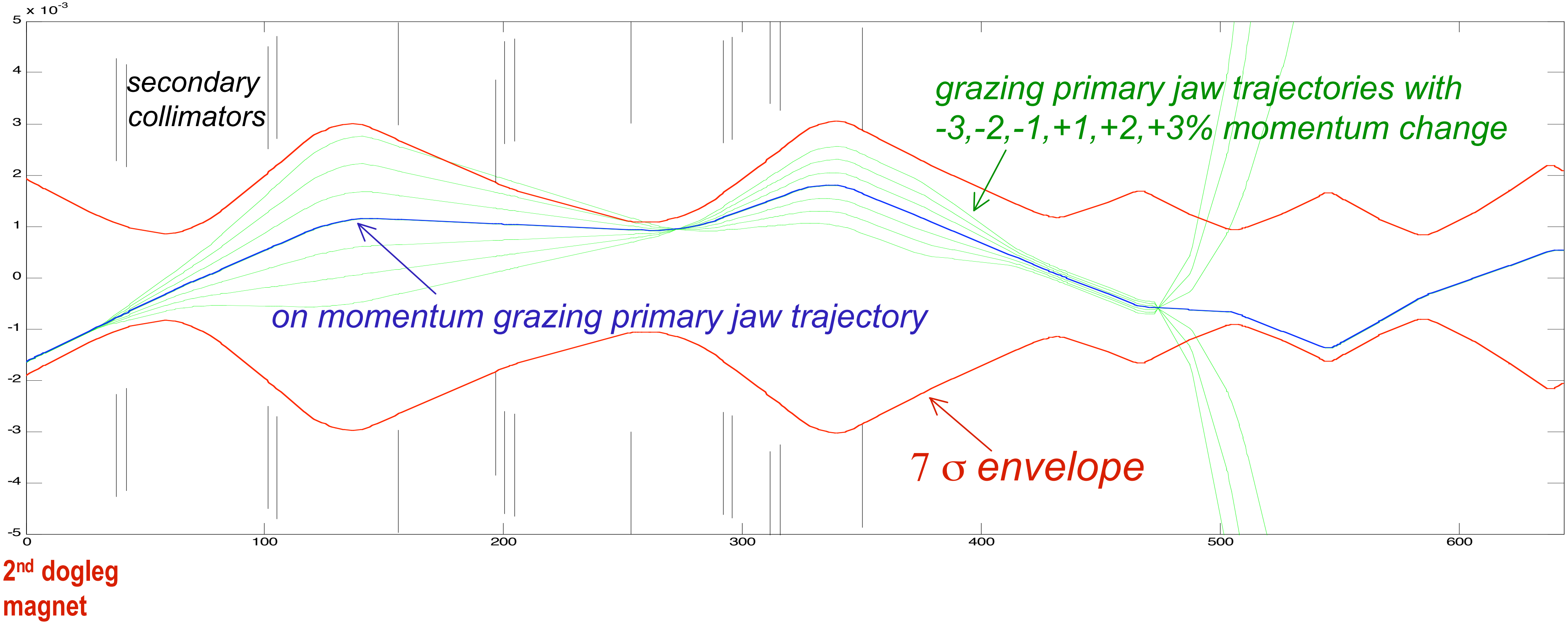
working point of IR7 primary collimators

High Z scrapers (already foreseen behind primary collimator) may give some improvement. Needs further study.



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

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



Conclusions

- **Present 2 stage collimation of LHC gives insufficient protection of s.c. magnets against heavy ion fragments.**
  Collimation system acts almost like a single stage system.
  ⇒ ***particle losses in SC magnets exceeds permissible values by a factor ~2 for nominal ion beams at collision energy.***
  Calculations have considerable accumulated errors !

- **This is a soft limitation depending on 12min lifetime requirement.**

- **Early Ion scheme and losses at injection seem to be ok**

- **Collimator robustness sufficient for kicker accidents with ion beams**

- **FLUKA simulations indicate that BLM thresholds for beam abort are comparable for protons and ions.**

- **Inventory of nuclear physics relevant for collimation efficiency and energy deposition has been established. Presently partially implemented in FLUKA code. Complete implementation progress.**

- **No solution for nominal beam found yet**