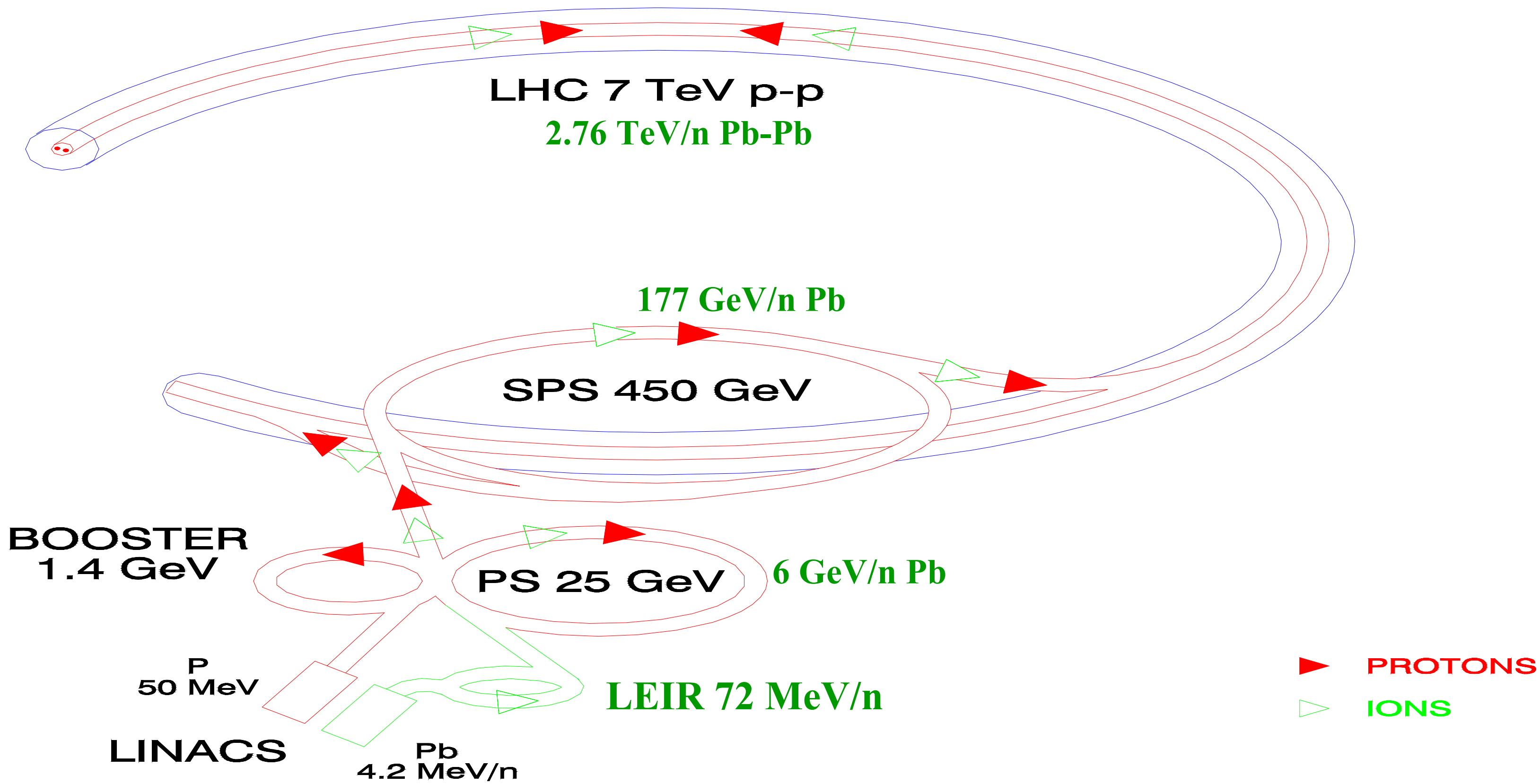
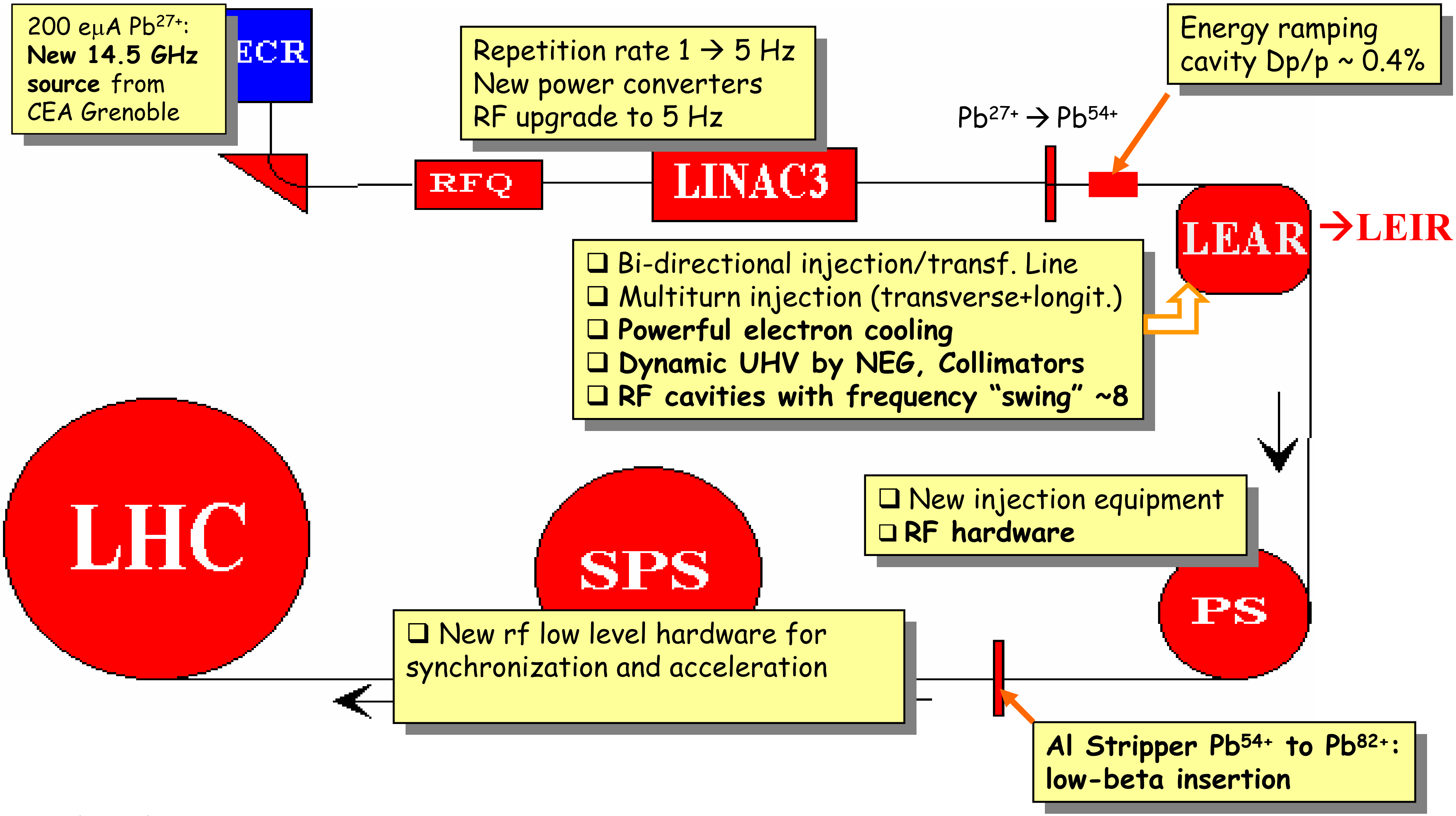
Heavy Ion Collimation for LHC

- I-LHC overview
- LHC collimation
- Specific issues for ion collimation
- ICOSIM program and results
- Heavy Ion – Matter Interactions at high γ
- Summary

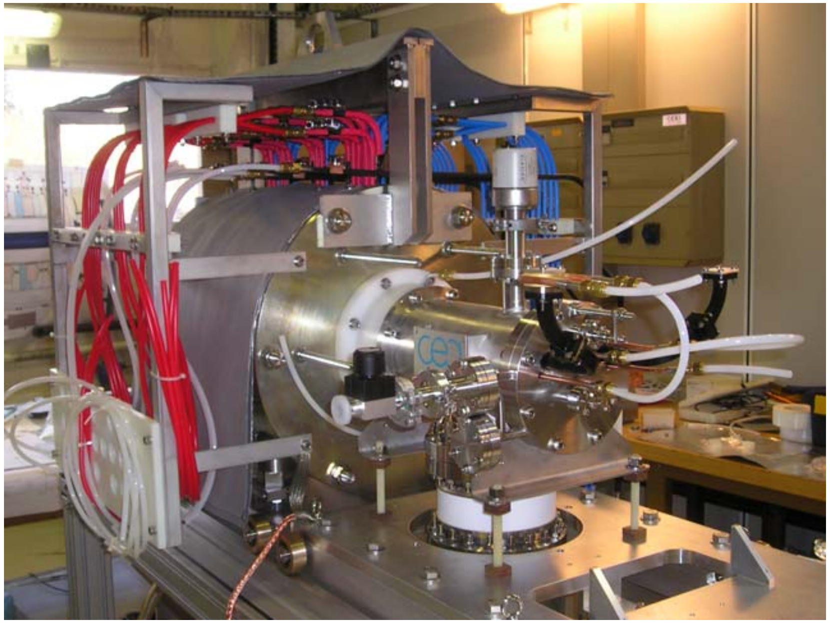
The LHC Ion Injector Chain - Overview



Pb Ions for LHC: Hardware Upgrades



The Heavy Ion (Lead) Linac3 Source



GTS (Grenoble Test Source) from CEA

Present ECR (Electron Cyclotron Resonance Source) delivers ~ 120 eμA x 200 μs Pb^{27+}.

ECR source with higher performance: >200 eμA with 14.5 GHz expected

LEIR Running-in + Early Scheme feasible with present source, without margin by injecting 2-3 pulses (test in 1997)

BINP/Novosibirsk E-cooler at CERN (for Xmas)

$T_{electron}$ T_{ions}	**2-40 keV** 4.2-72 MeV/u
$I_{electrons}$	**4.2-500 mA**
L_{active}	**3 m**
$\tau_{injection}$	**200 ms**

Tentative Ion Schedule (Early Beam)

	hardware test	Start with beam	Problems
Source and Linac3	Feb. 2005	March 2005	New source
LEIR injection line	March 2005	June 2005	
LEIR ring	Apr. 2005	Aug. 2005(?)	LEIR conversion completed ? Running-in through winter to March 2006
PS/TT2	Feb. 2006	Sept. 2006(?)	April-August 2006: No LEIR operators (AD)
SPS		late 2006 spring 2007	SPS experts busy commissioning LHC ring in 2007
LHC		from April 2008(?)	Physics with the early beam in LHC

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	- ($P_{IONS} \sim P_{PROTON}/100$)
6. beam induced desorption / vacuum degradation	probably not

What makes LHC's collimation different to other colliders and 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	instanteneous 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

Allowed intensity

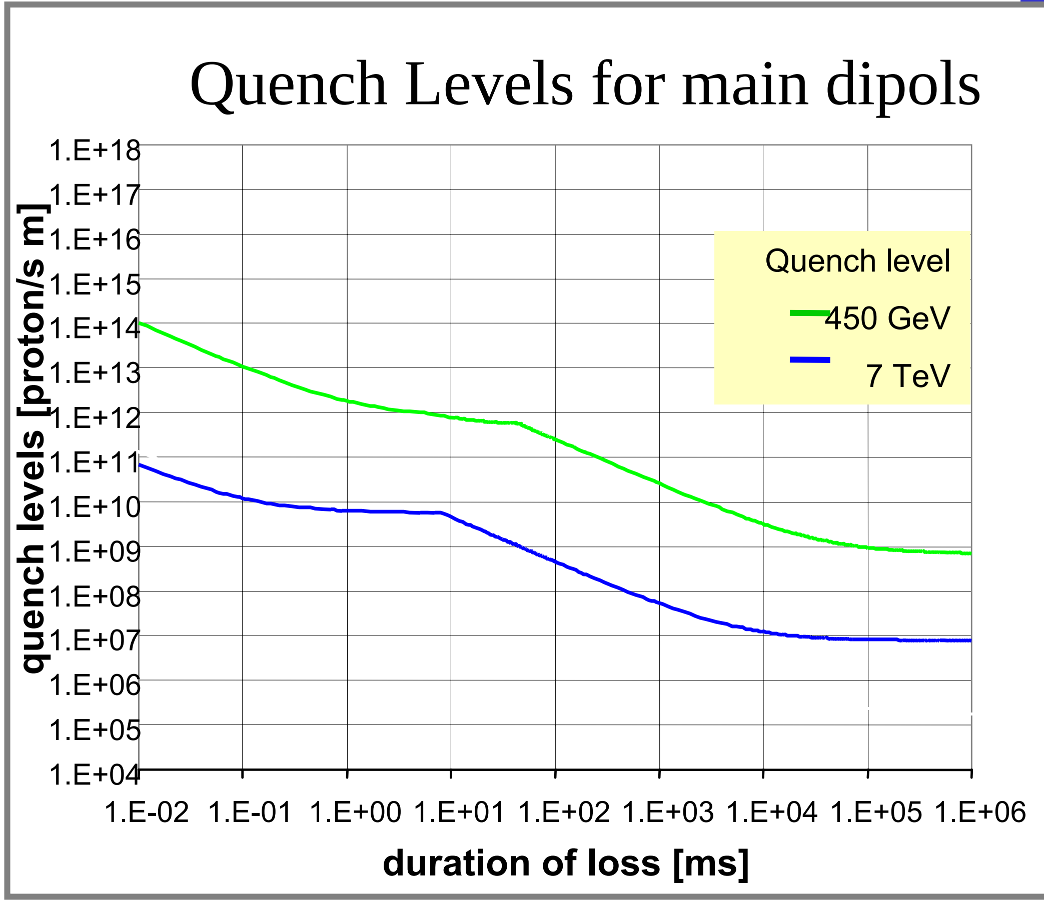
Quench threshold (7.6×10^6 p/m/s @ 7 TeV)

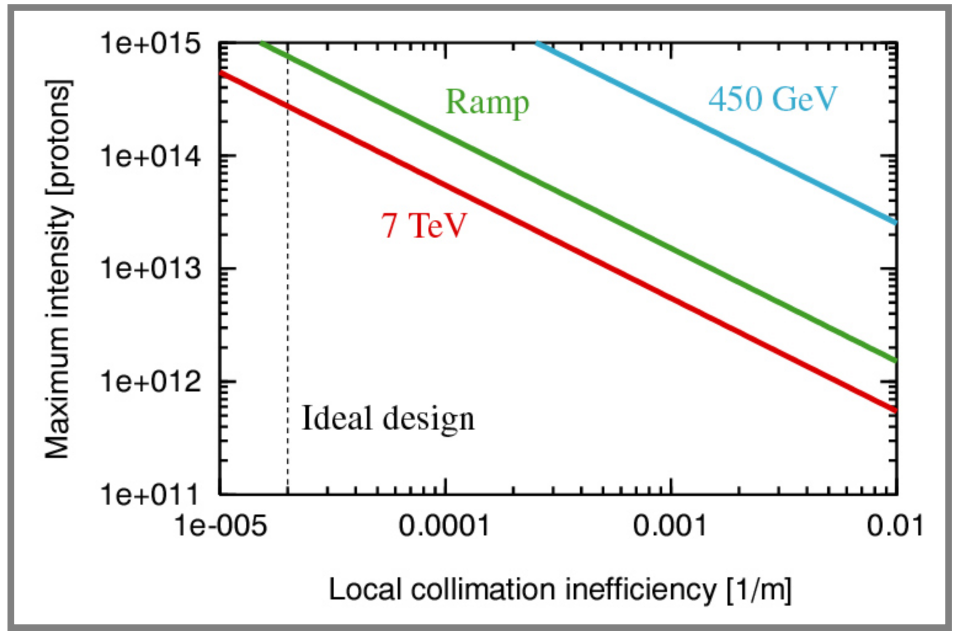
Dilution Length (50 m)

$$N_p^{max} \approx \tau \cdot R_q \cdot L_{dil} / \eta_c$$

Beam lifetime (e.g. 0.2 h minimum)

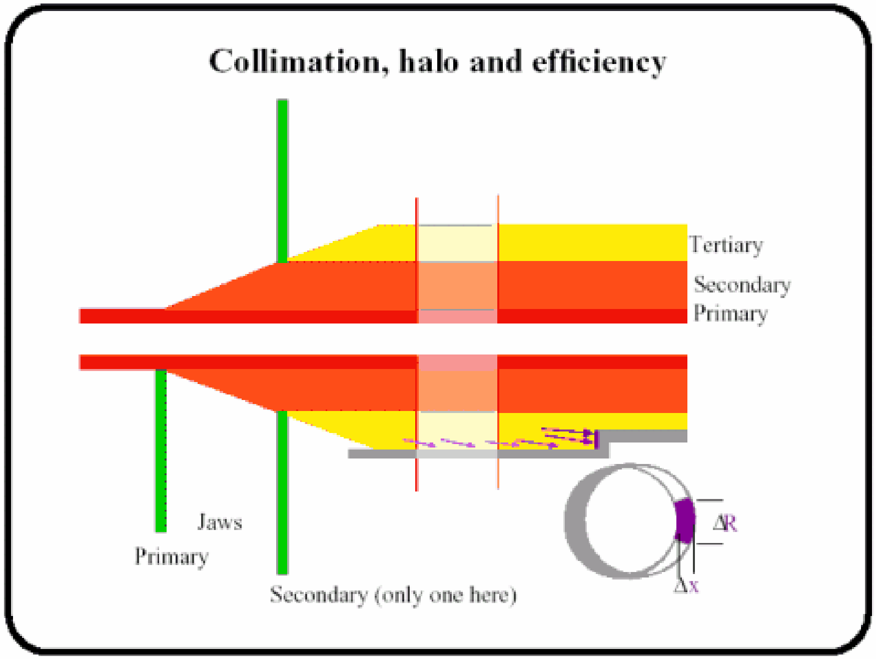
Cleaning inefficiency = $\frac{\text{Number of escaping p}}{\text{Number of impacting p}}$

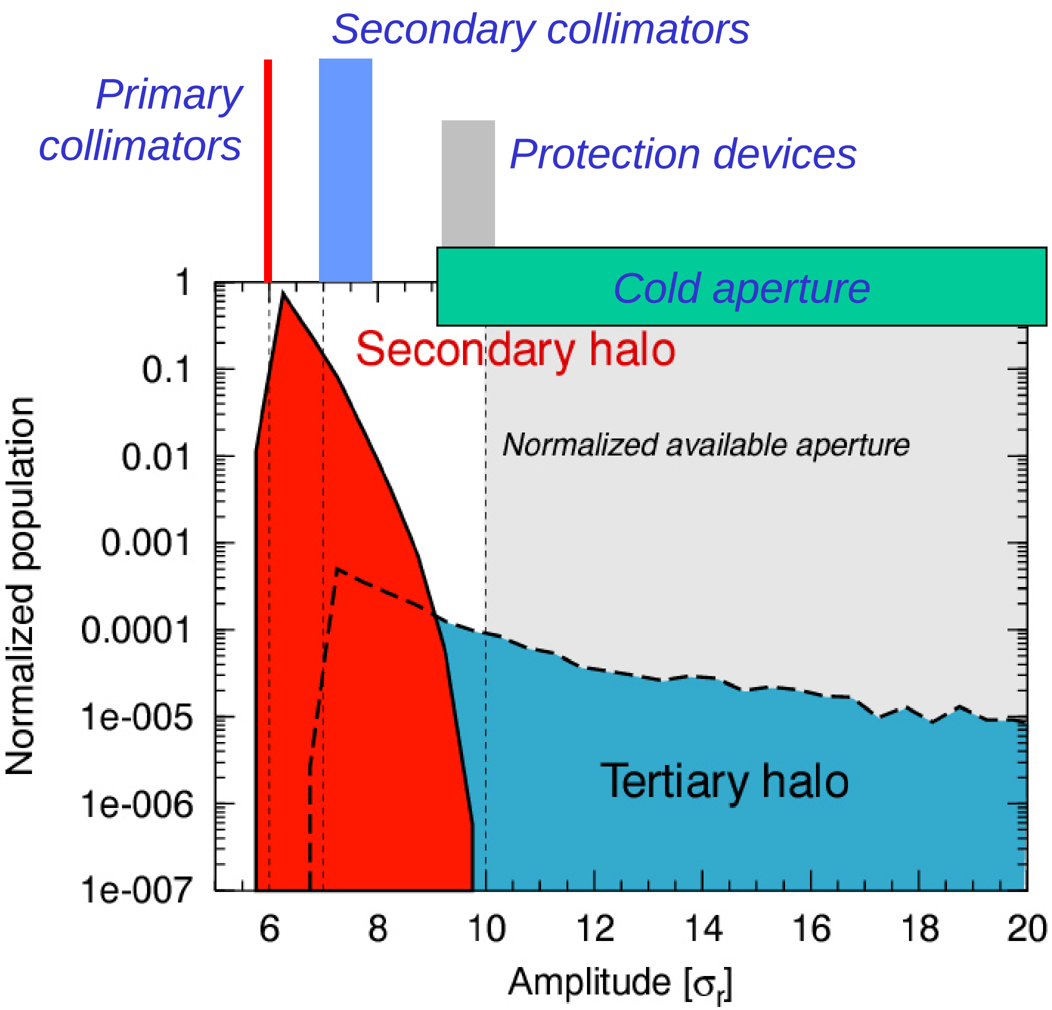




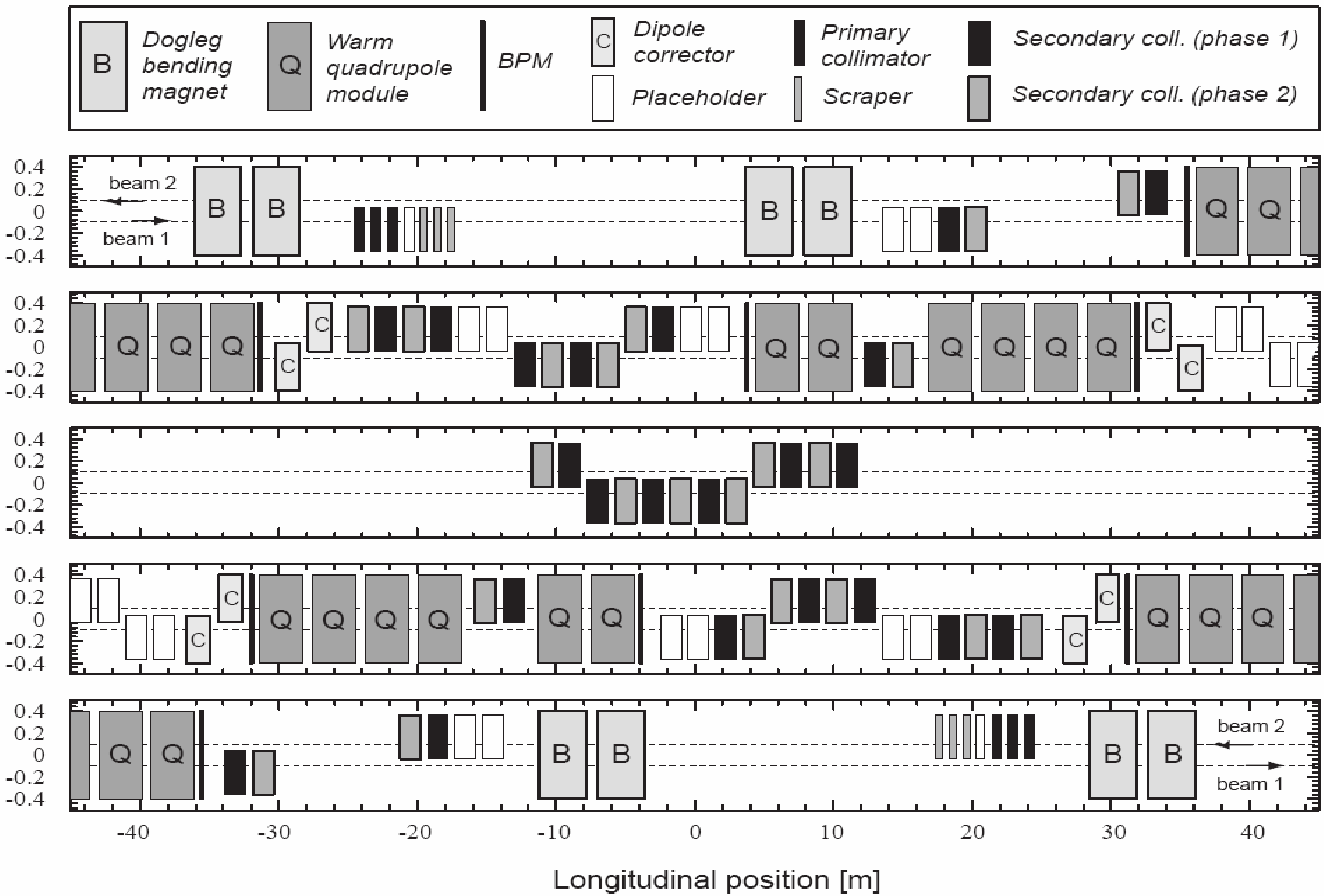
$$\dot{N} = N / \tau = 4.5 \cdot 10^{11} s^{-1} \quad \text{for} \quad \tau = 12\text{min}$$

Two stage collimation to achieve required efficiencies



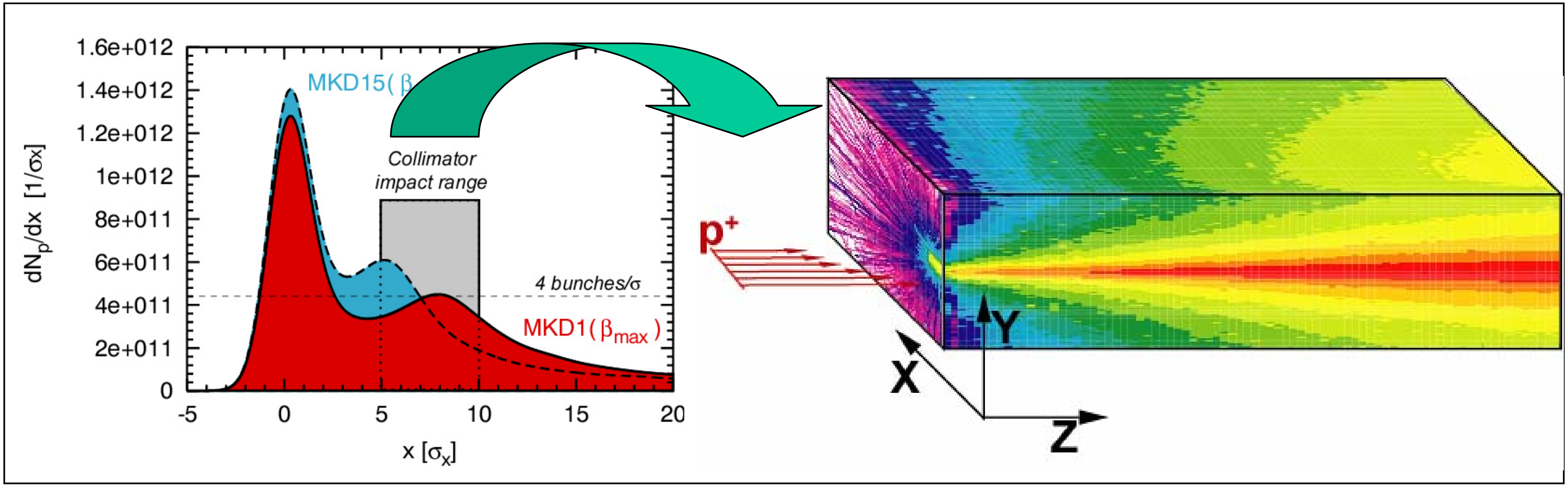


Schematics of Collimation Insertion in LHC IR7

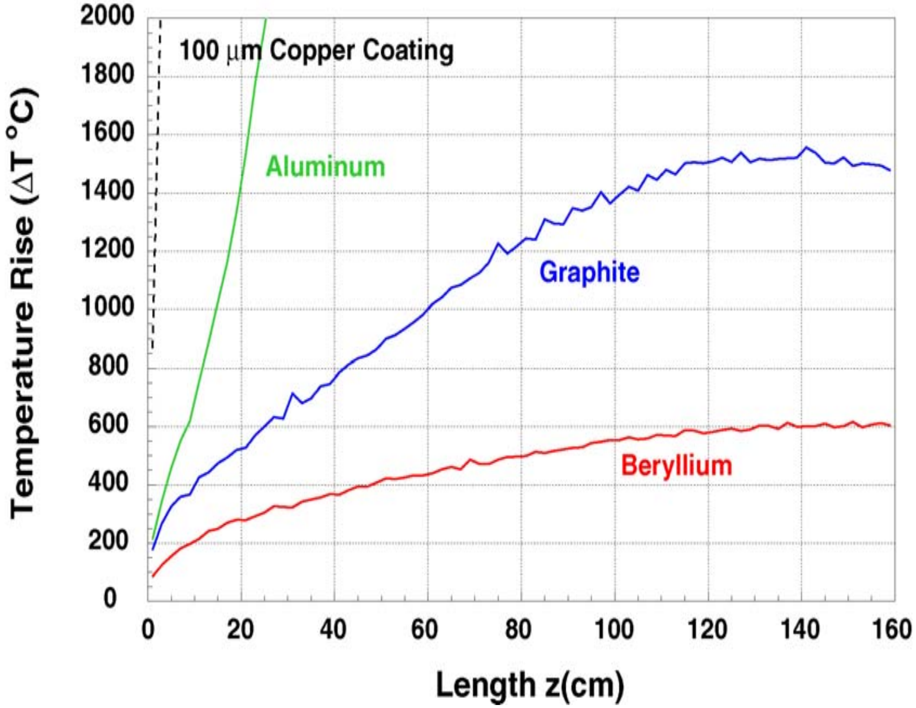


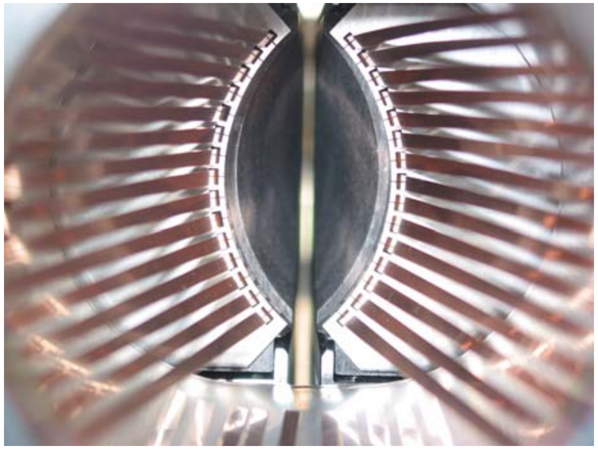
Protection against mishaps

Irregular dump → Proton impact on jaw → Proton-matter interaction



Temperature Increase in Materials





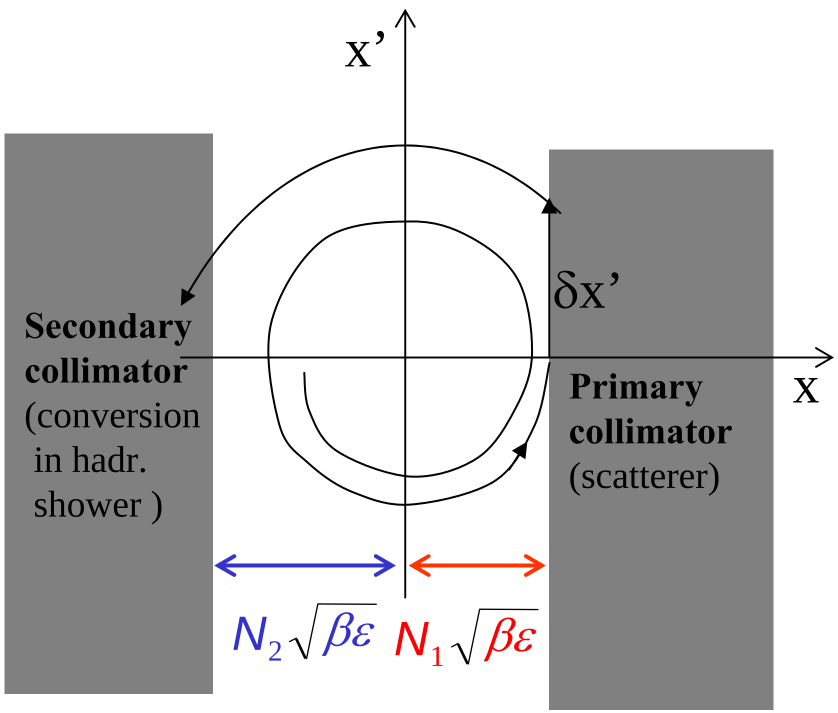
⇒ Graphite chosen as collimator material

LHC Proton collimation difficult, but proposed scheme fulfills requirements in simulations and SPS prototype tests.

But I-LHC beam has only 1/100 of the proton beam power, so only collimation $\eta \sim 10^{-3}$ required .

So what's the problem ?

Criteria for two stage betatron collimation



Necessary condition :

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

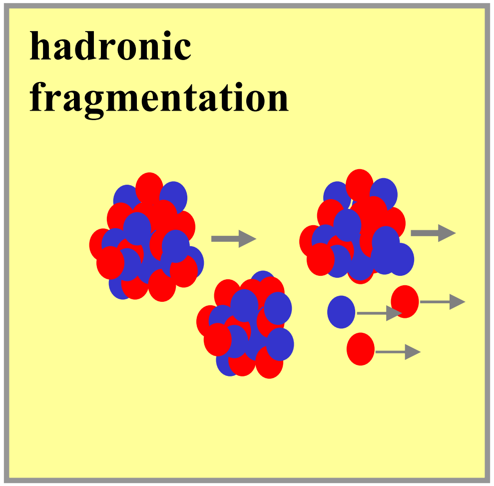
scattering at primary collimator $\delta x'$ is mainly due to multiple Coulomb scattering with

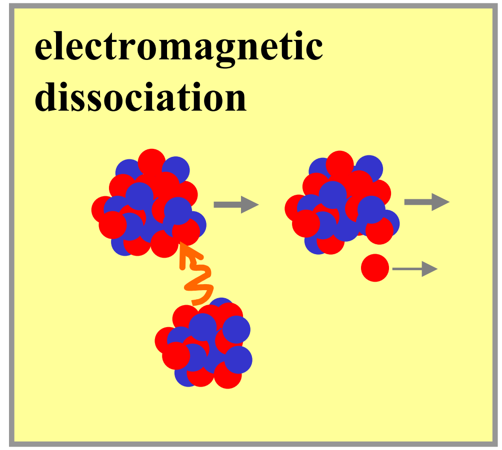
$<\delta x'^2> \sim L$

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

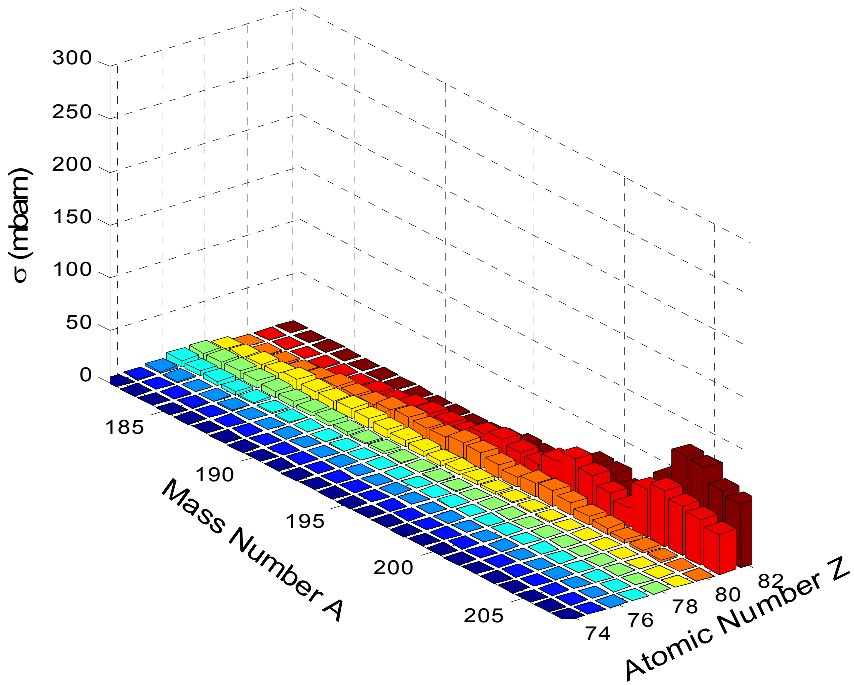
^{208}Pb-ion/matter interactions in comparison with proton/matter interactions.
(values are for particle impact on graphite)

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



Electromagnetic Dissociation
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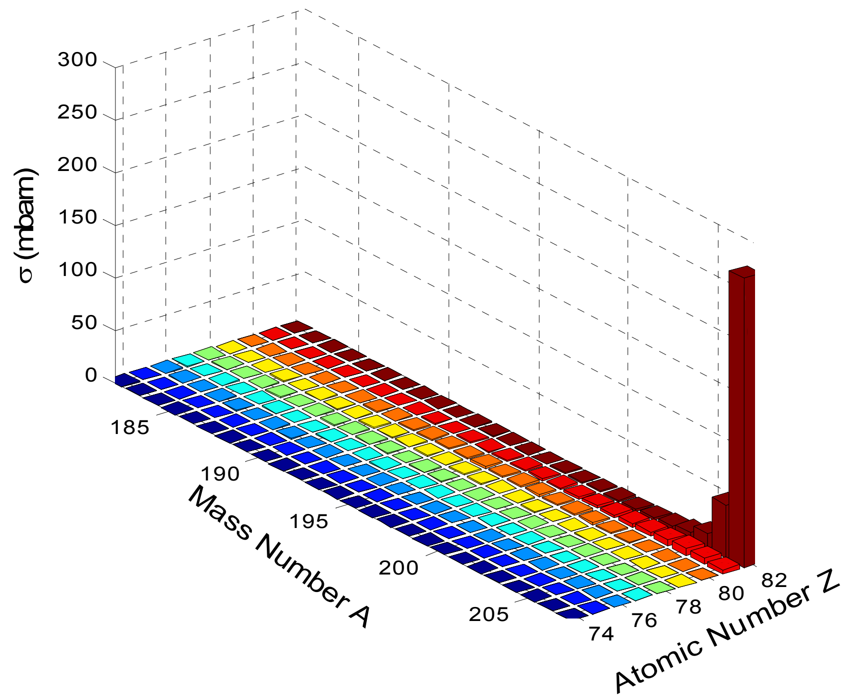
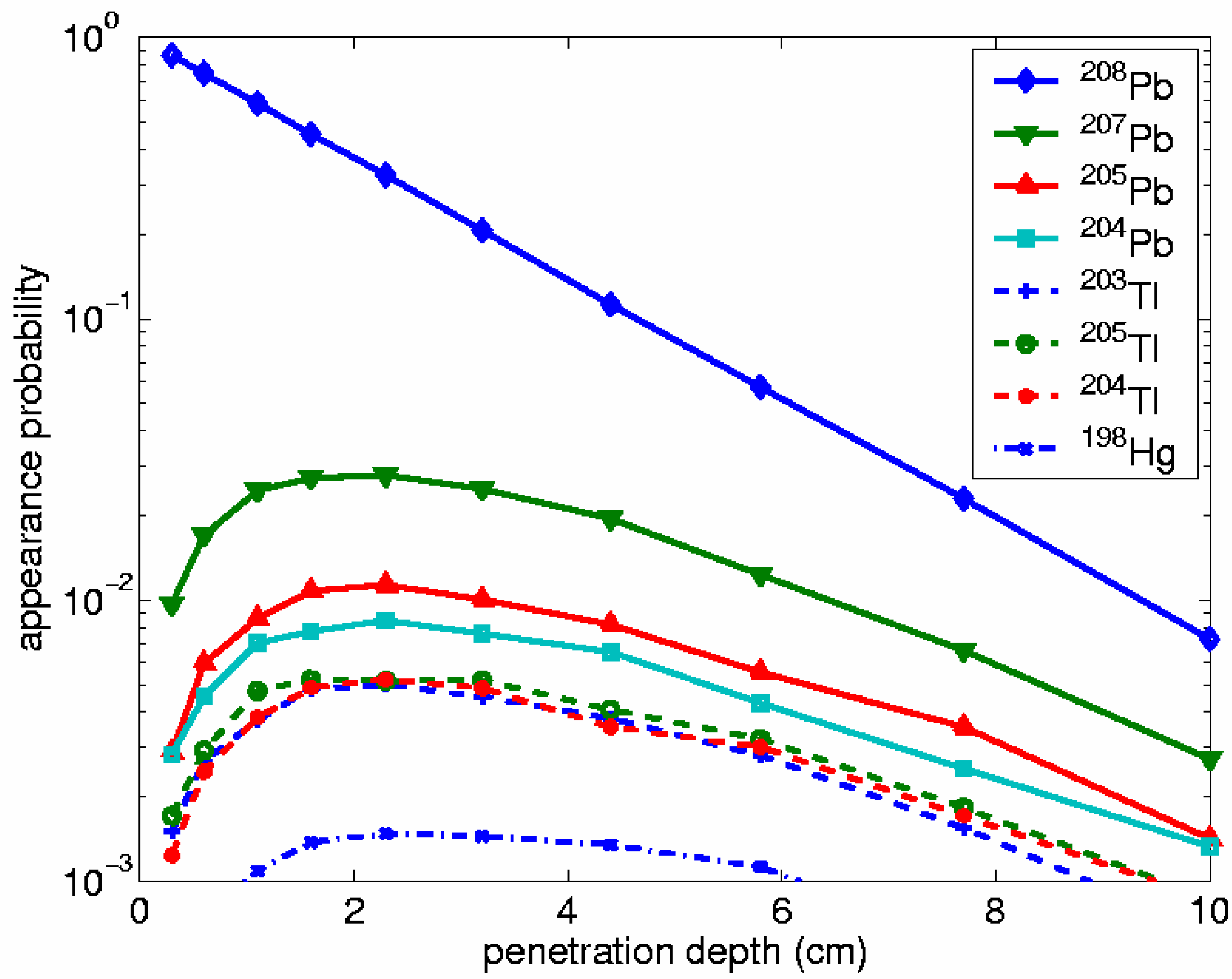




The probability to convert a ^{208}Pb nucleus into a neighboring nucleus.
The calculation is performed for ion impact on graphite at LHC collision energy

Optimising the material primary collimator material

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

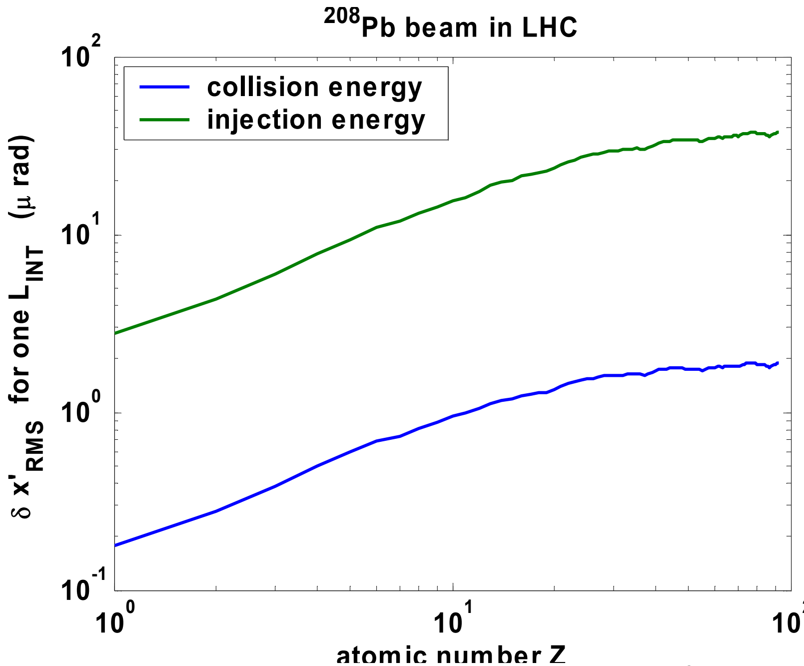
- **hadronic fragmentation** $\sigma_{HAD} \sim (A_{PROJ}^{1/3} + A_{COLL}^{1/3})^2$
- **electromagnetic dissociation** $\sigma_{EMD} \sim Z_{COLL}^2$
- **Multiple scattering** $\langle \delta x'^2 \rangle^{1/2} \sim Z_{COLL}$
- **Ionisation energy loss** $dE/dx \sim Z_{COLL}$

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

figure of merit for collimator material

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

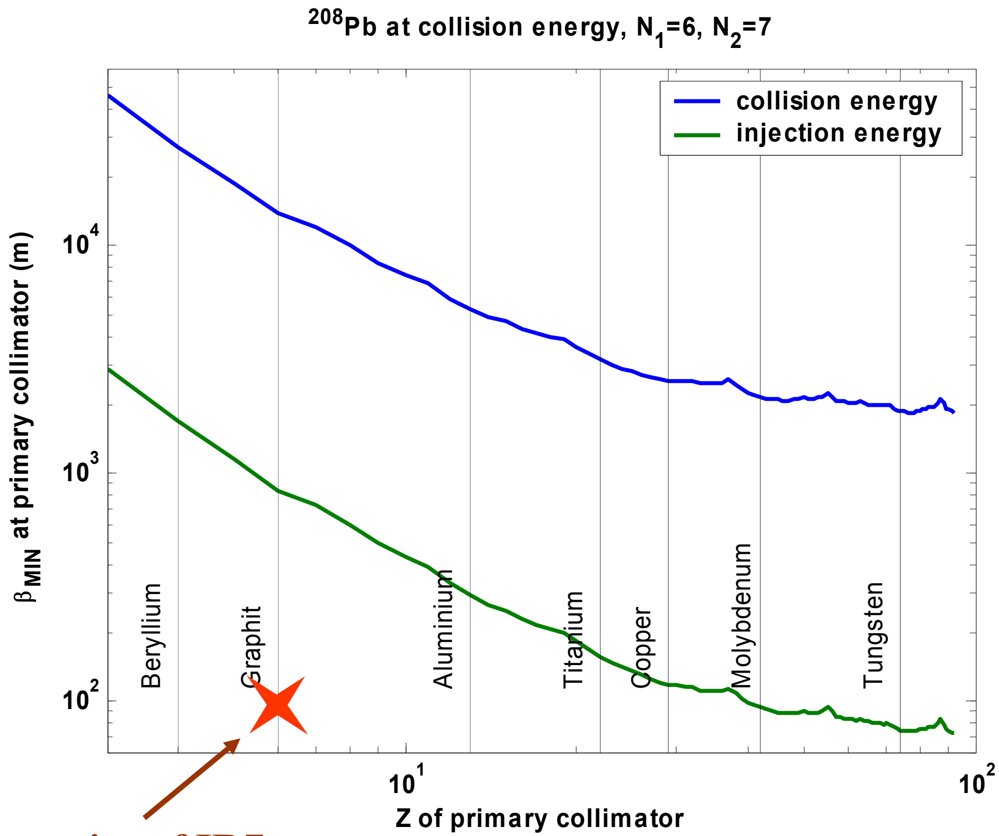
$$\text{with} \quad L_{INT} = \frac{A_{COLL}}{N_A \, \rho \, (\sigma_{HAD} + \sigma_{EMD})}$$



Condition

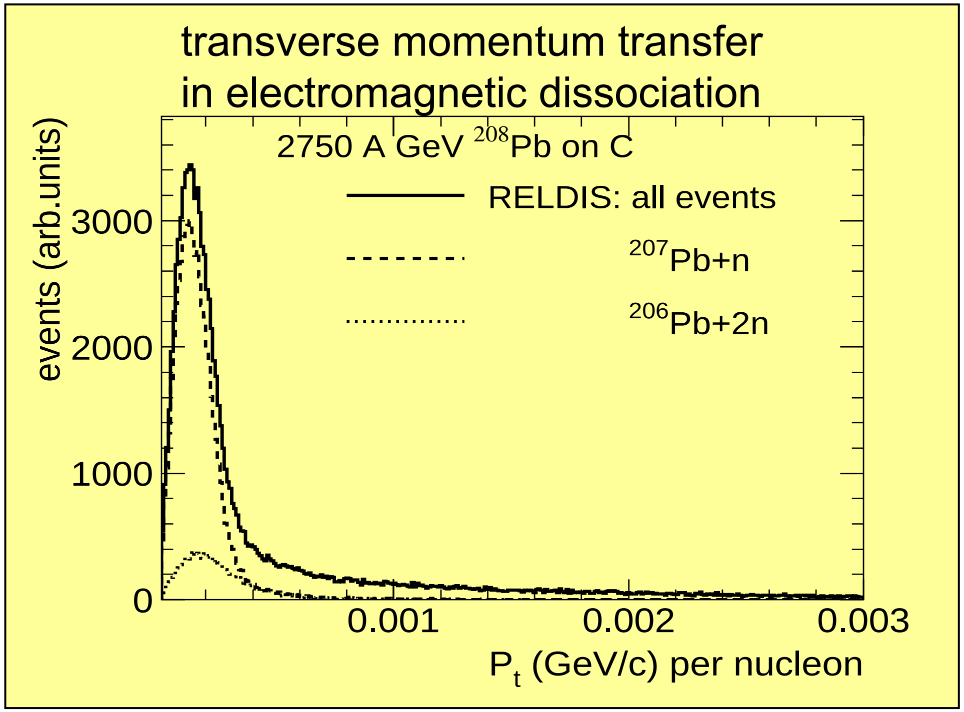
$$\delta x' >> \sqrt{\frac{\left(N_2^{\;2} - N_1^{\;2}\right)\varepsilon_N}{\gamma_{REL.}\,\beta_{TWISS}}}$$

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



Nuclear fragmentation leads to a large variety of residual nuclei. Typical transverse momentum transferred order of 1 MeV/c/u, small compared to transverse momentum due to the beam emittance (~ 10 MeV/c/u)

Electromagnetic dissociation leads predominantly to the loss of one neutron or two neutrons. The transverse momentum transfer in electromagnetic dissociation is even smaller than in nucl. Fragmentation



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**

Computing tools for ILHC collimation

RELDIS &
ABRATION/ABLATION
(programs of Igor Pshenichnov)
generates cross section tables for fragmentation processes

LHC optics files

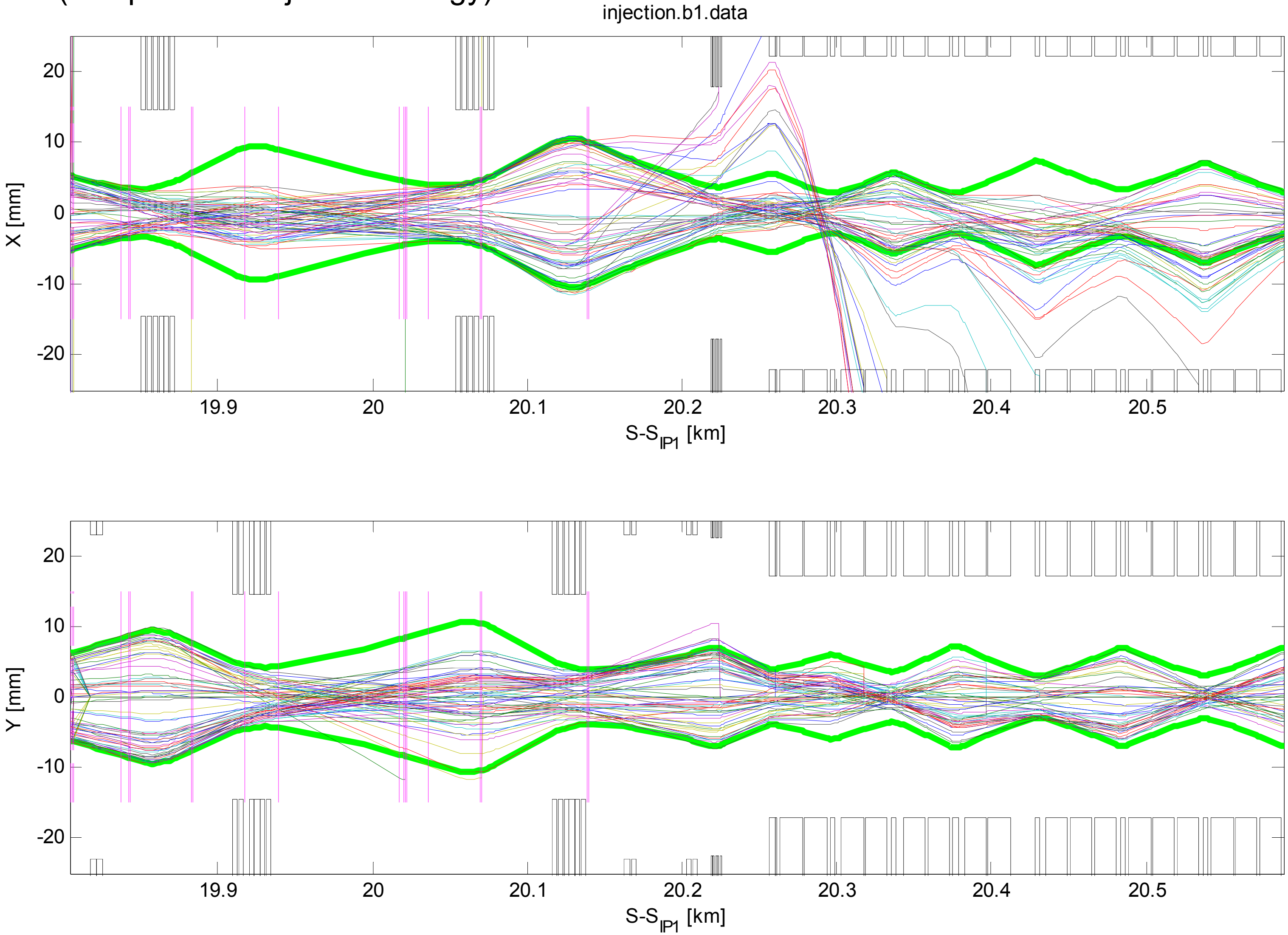
MAD-X
generates twiss function and aperture tables

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**

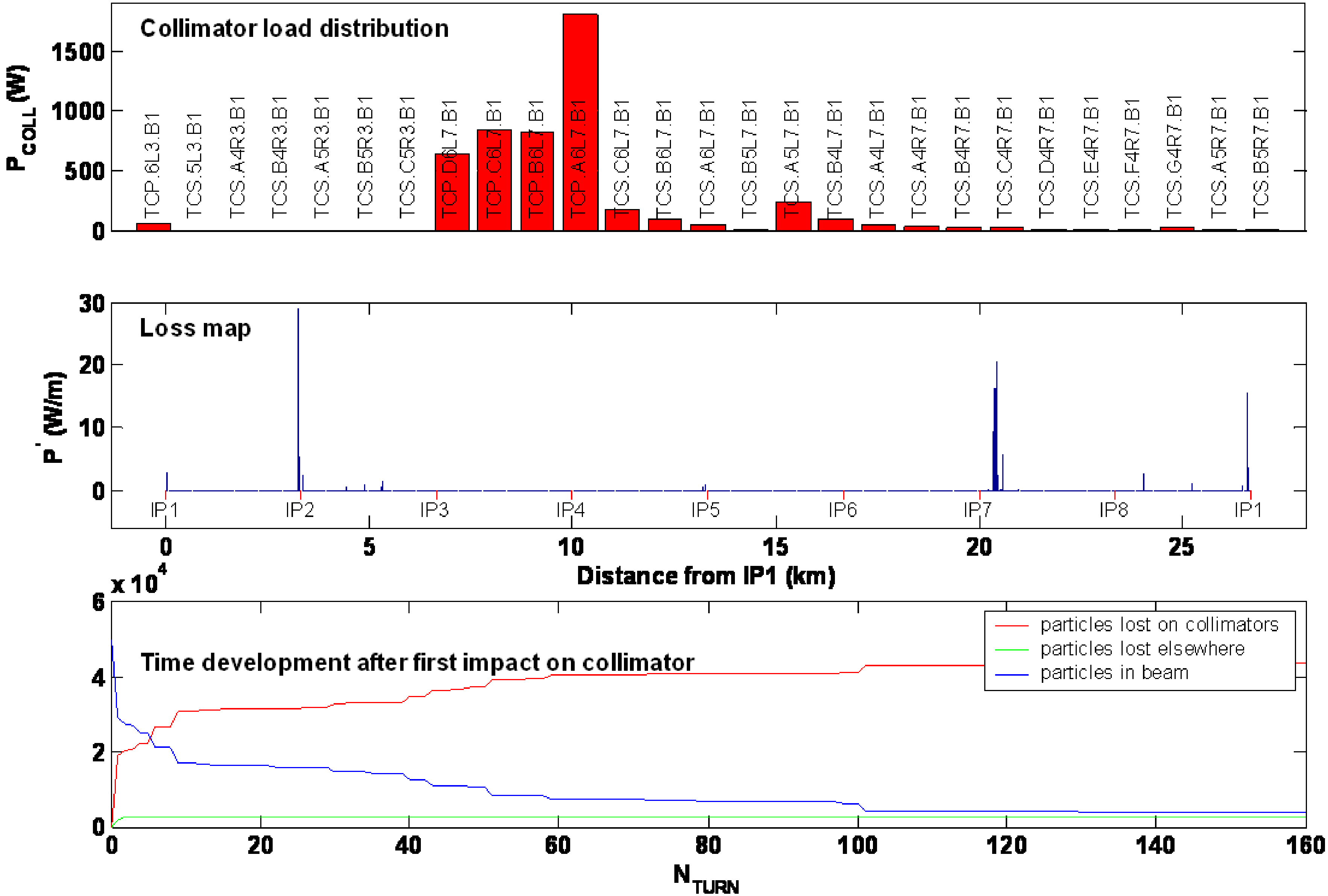
ICOSIM output
- **Loss patterns**
- **Collimation efficiencies**

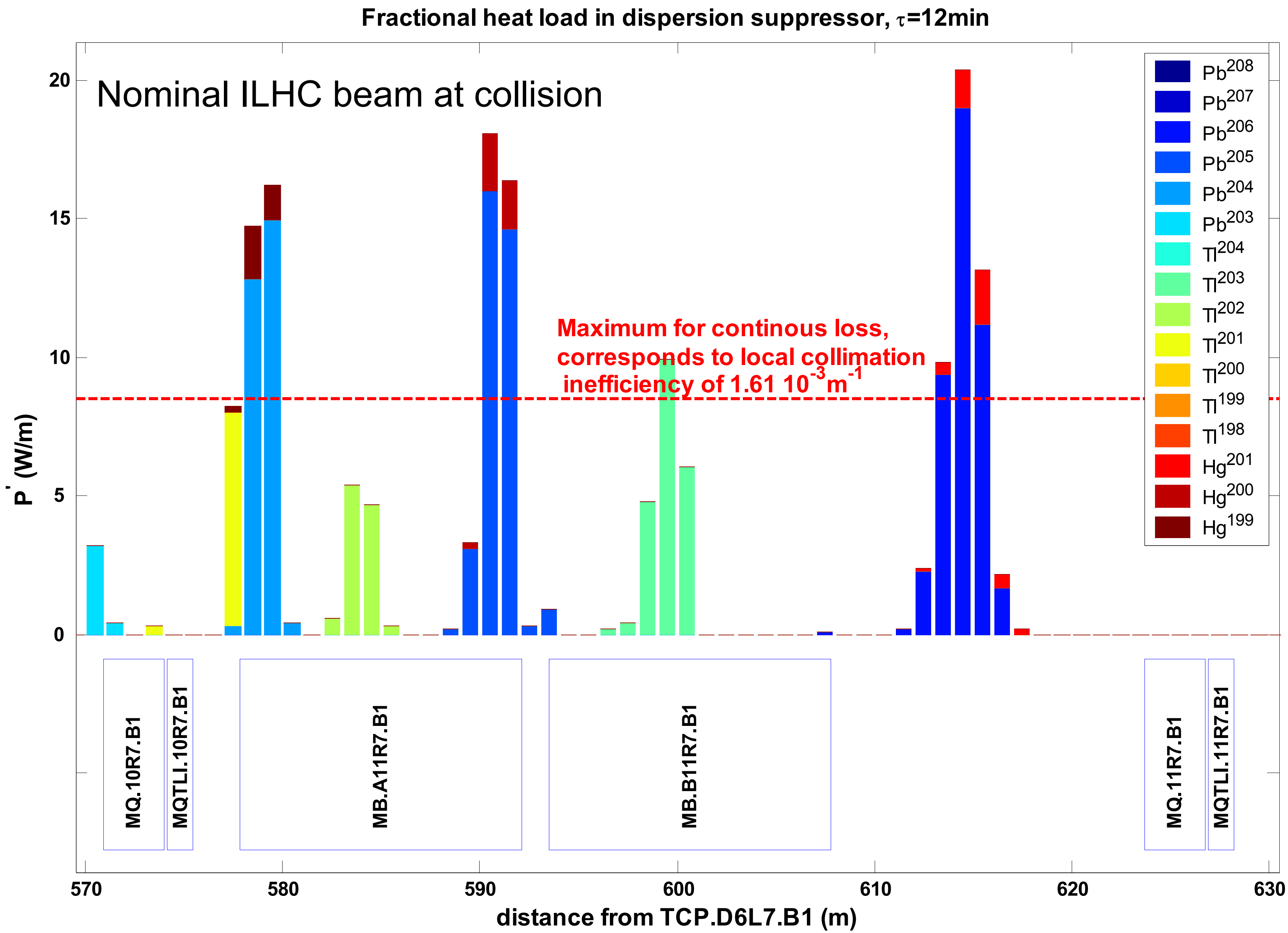
Trajectories around collimation in IR7 as computed by ICOSIM

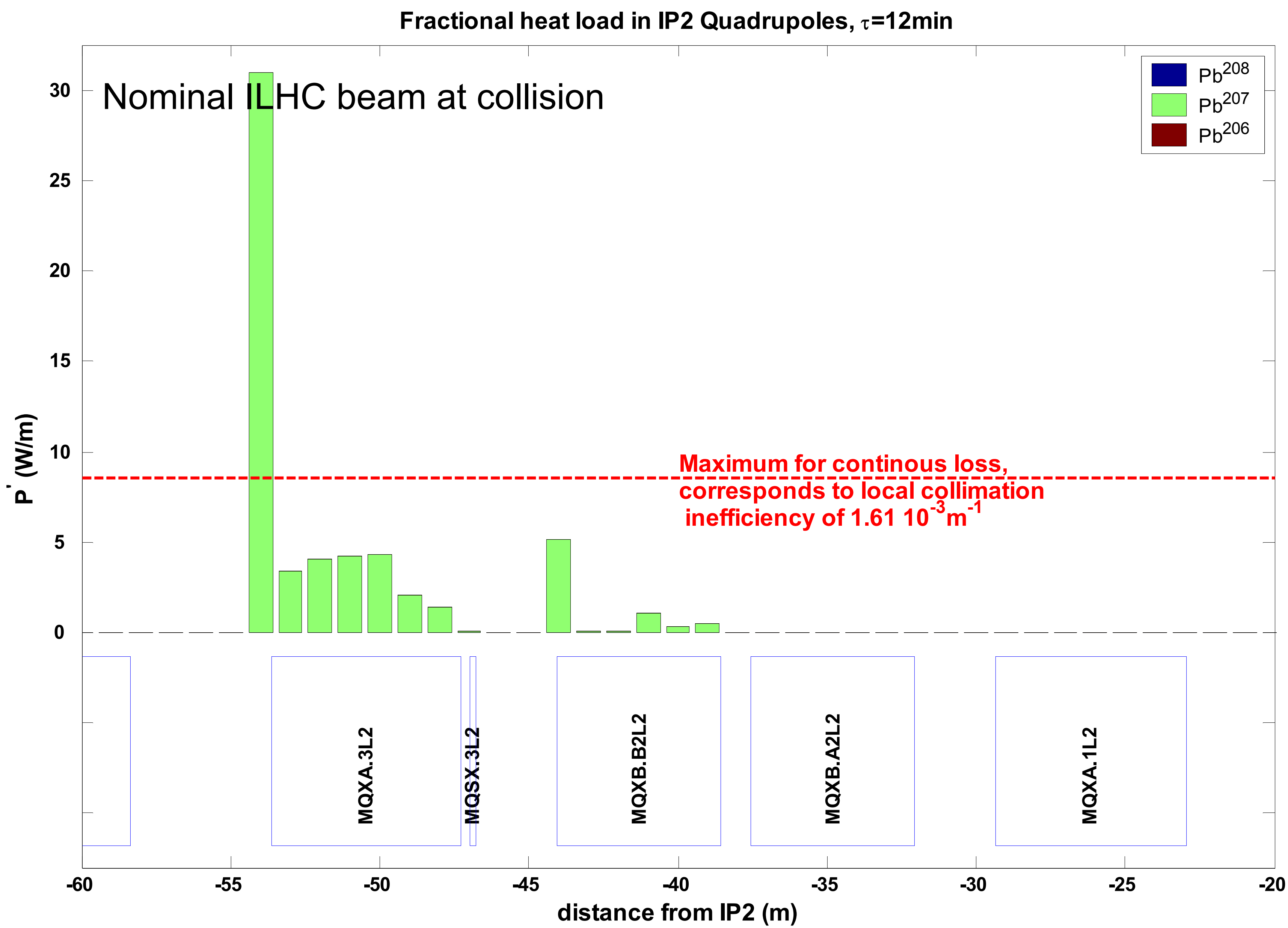
(computed for injection energy)

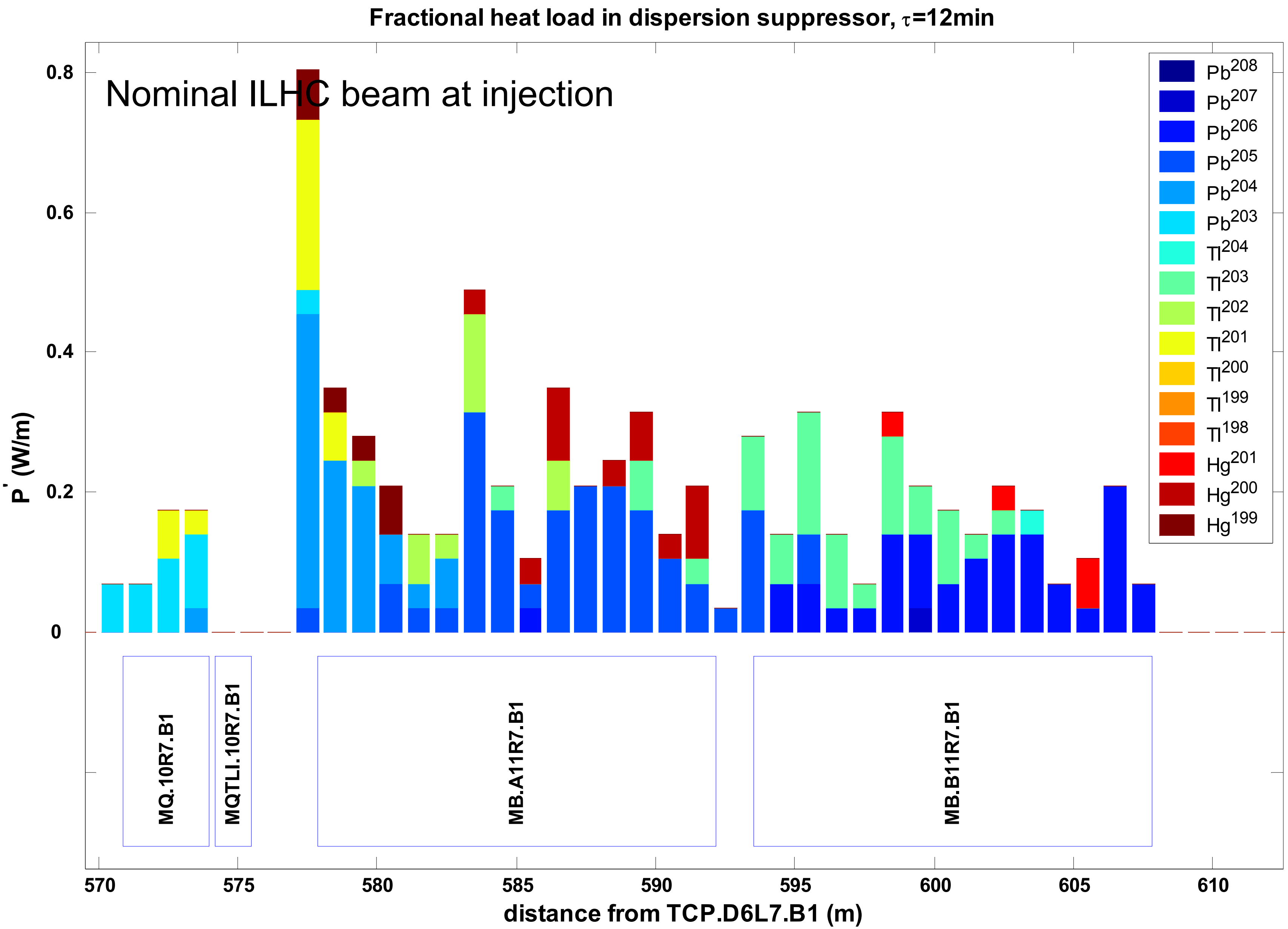


Nominal ILHC beam at collision



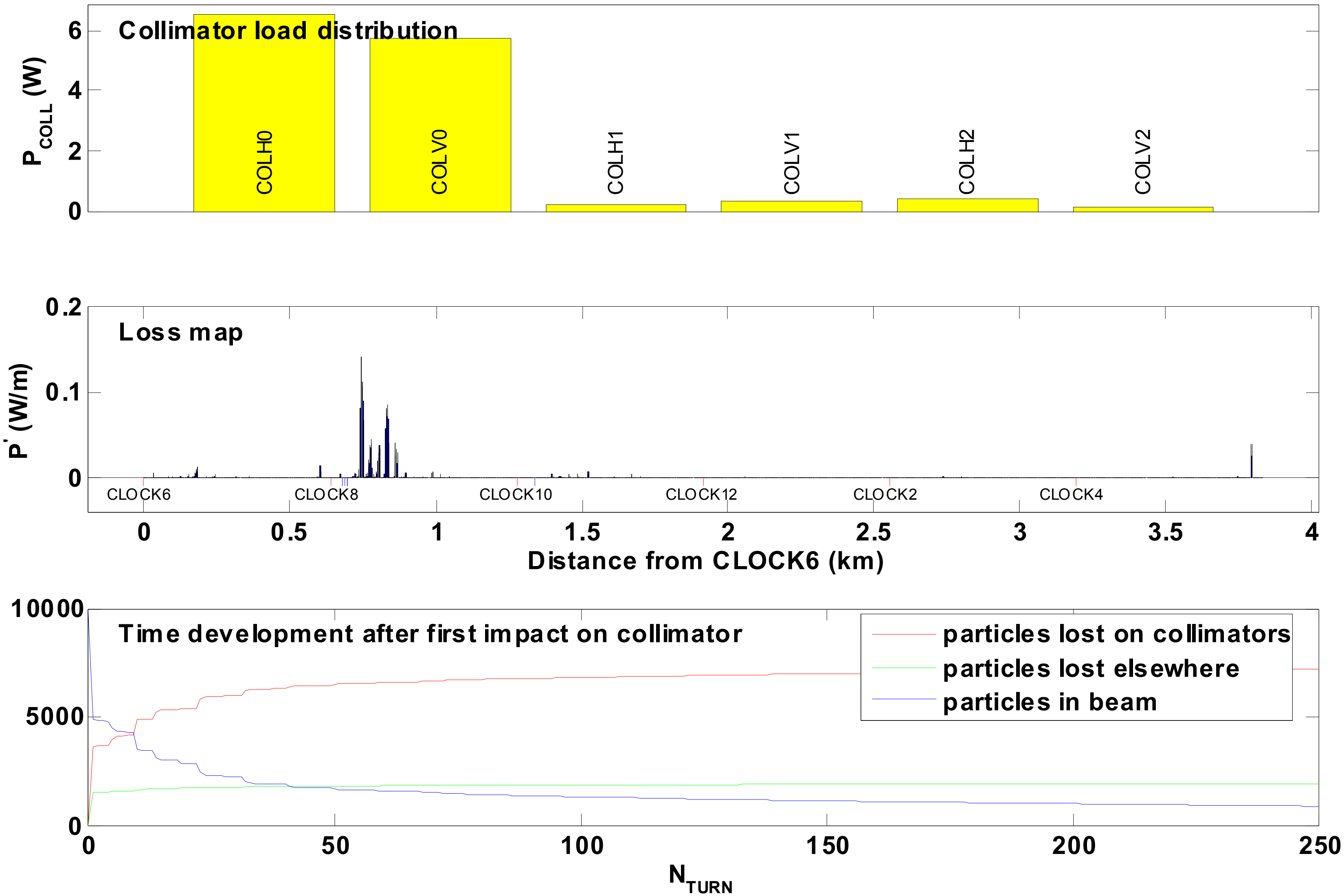

Fractional heat load in dispersion suppressor, τ=12min
Nominal ILHC beam at collision
Maximum for continous loss, corresponds to local collimation inefficiency of 1.61 10-3 m-1
P' (W/m)
distance from TCP.D6L7.B1 (m)
MQ.10R7.B1
MQTLI.10R7.B1
MB.A11R7.B1
MB.B11R7.B1
MQ.11R7.B1
MQTLI.11R7.B1
Pb208
Pb207
Pb206
Pb205
Pb204
Pb203
Tl204
Tl203
Tl202
Tl201
Tl200
Tl199
Tl198
Hg201
Hg200
Hg199
0
5
10
15
20
570
580
590
600
610
620
630


Fractional heat load in IP2 Quadrupoles, τ=12min
Nominal ILHC beam at collision
Pb208
Pb207
Pb206
Maximum for continous loss,
corresponds to local collimation
inefficiency of 1.61 10-3m-1
P' (W/m)
30
25
20
15
10
5
0
MQXA.3L2
MQSX.3L2
MQXB.B2L2
MQXB.A2L2
MQXA.1L2
-60
-55
-50
-45
-40
-35
-30
-25
-20
distance from IP2 (m)

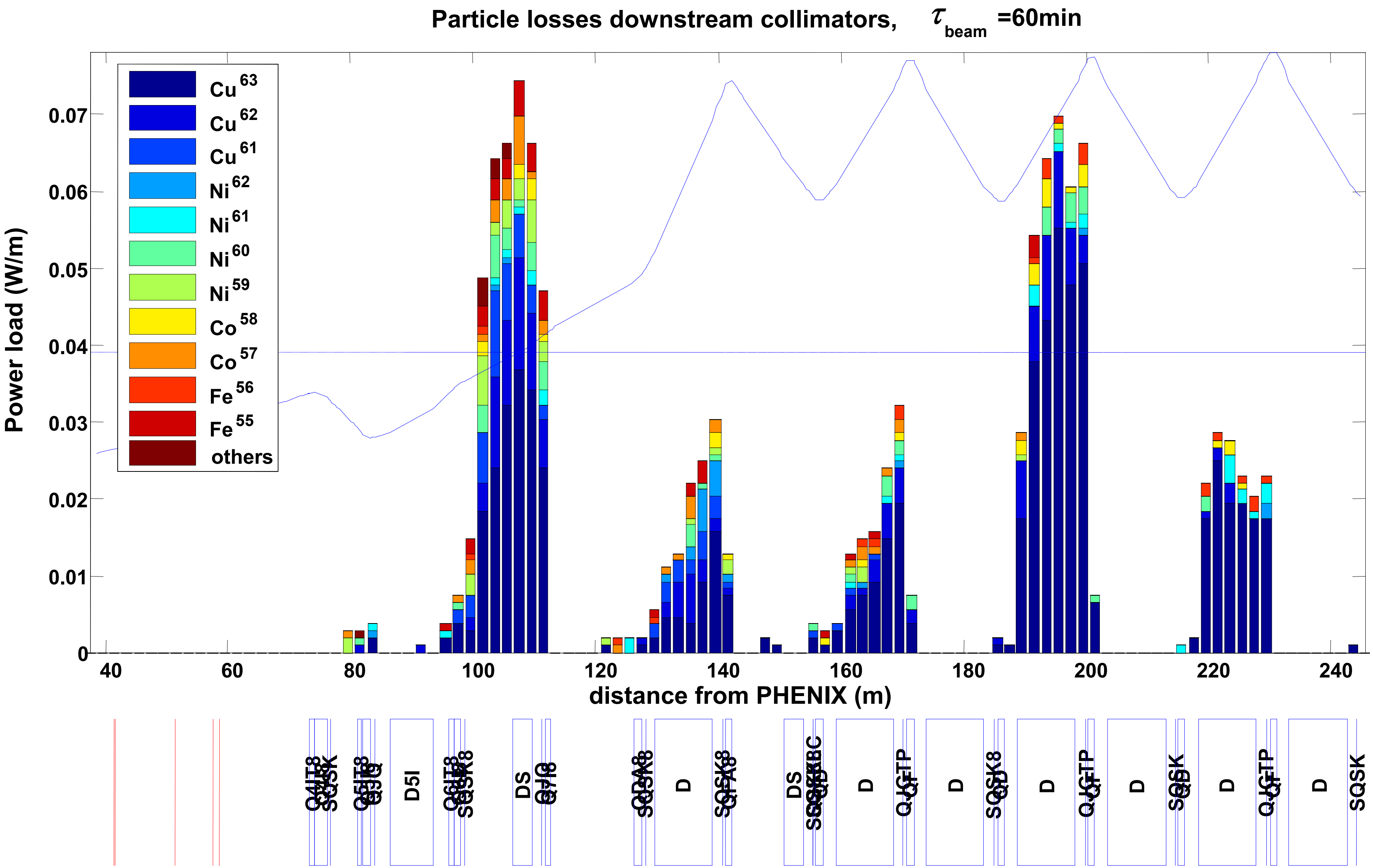


Fractional heat load in dispersion suppressor, τ=12min
Nominal ILHC beam at injection
P' (W/m)
0.8
0.6
0.4
0.2
0
Pb208
Pb207
Pb206
Pb205
Pb204
Pb203
Tl204
Tl203
Tl202
Tl201
Tl200
Tl199
Tl198
Hg201
Hg200
Hg199
MQ.10R7.B1
MQTLI.10R7.B1
MB.A11R7.B1
MB.B11R7.B1
570
575
580
585
590
595
600
605
610
distance from TCP.D6L7.B1 (m)

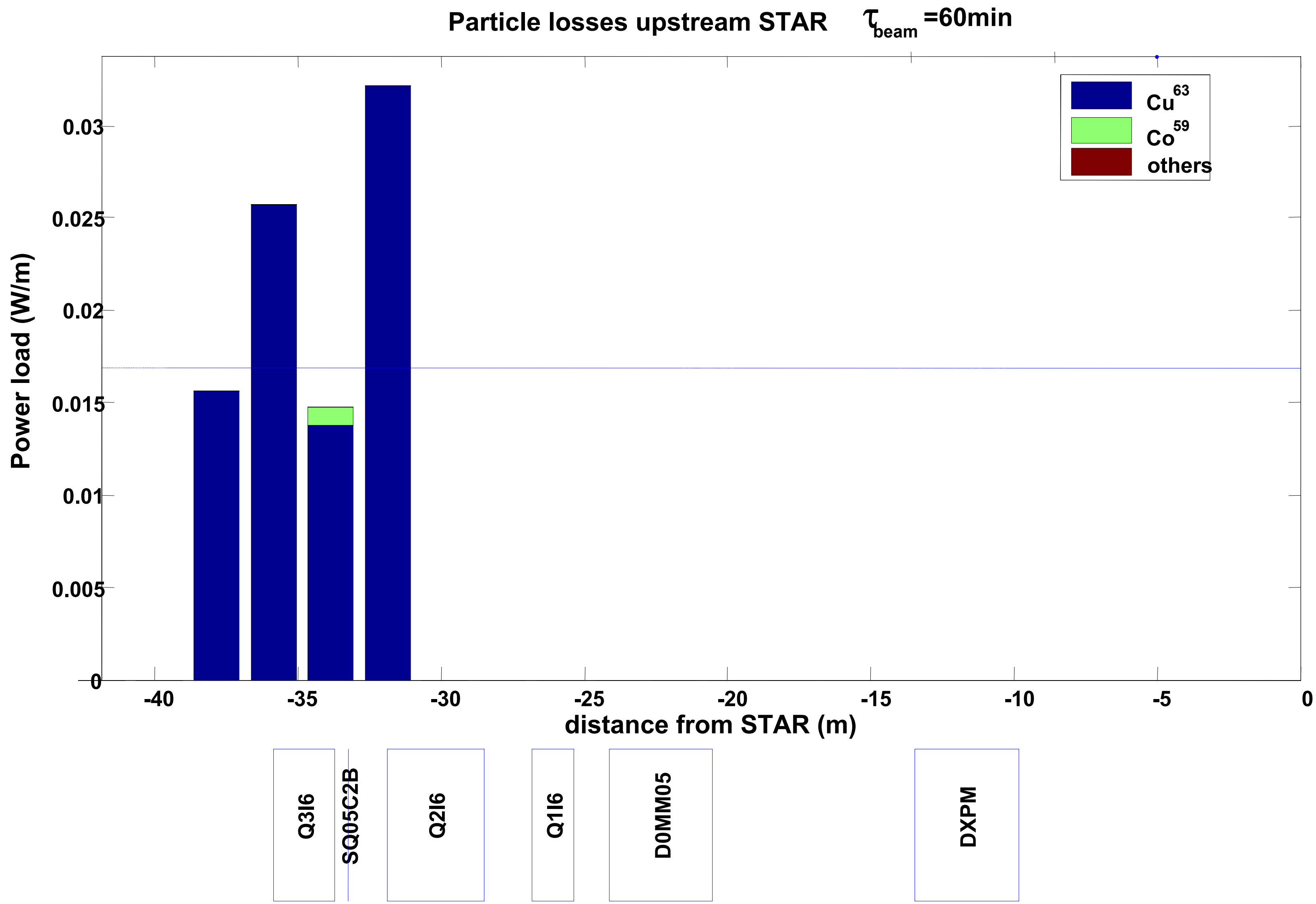
RHIC BLUE simulation with ICOSIM



RHIC BLUE downstream of collimators

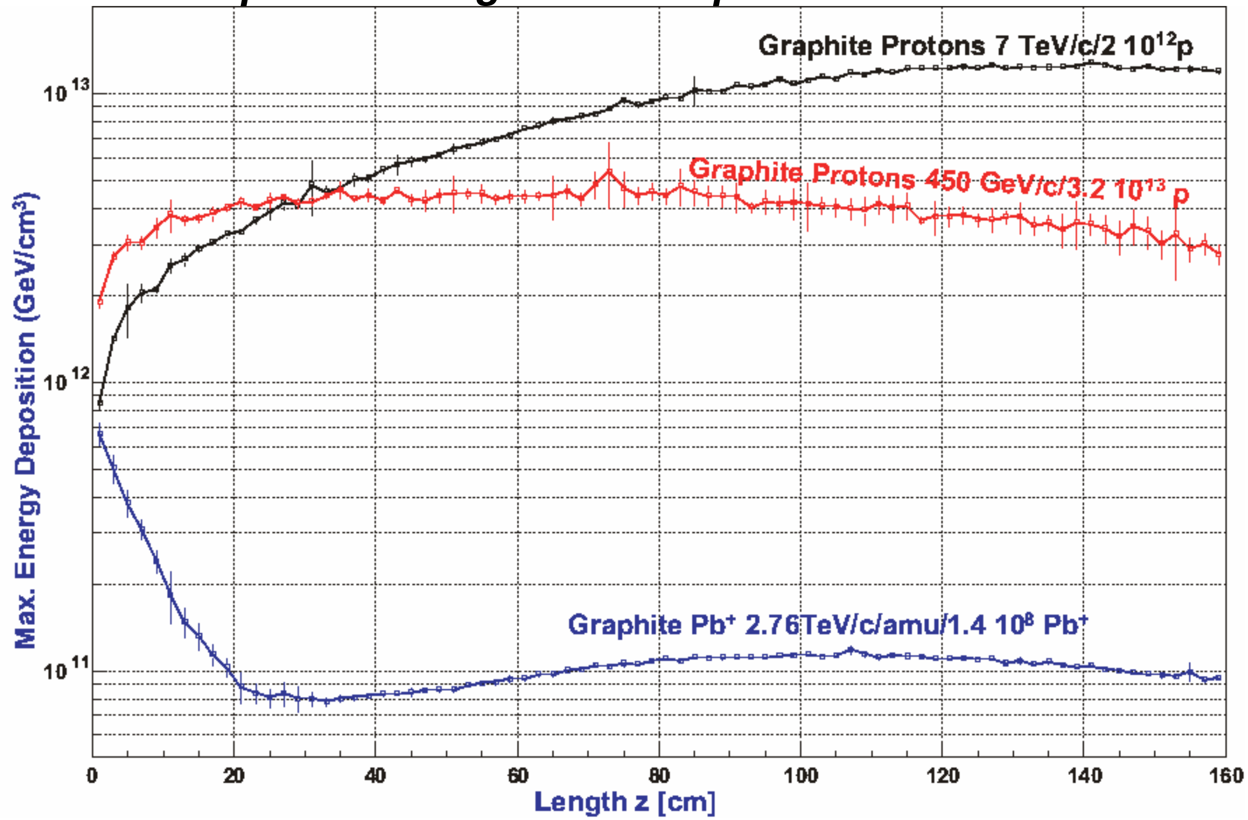


RHIC BLUE upstream STAR



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

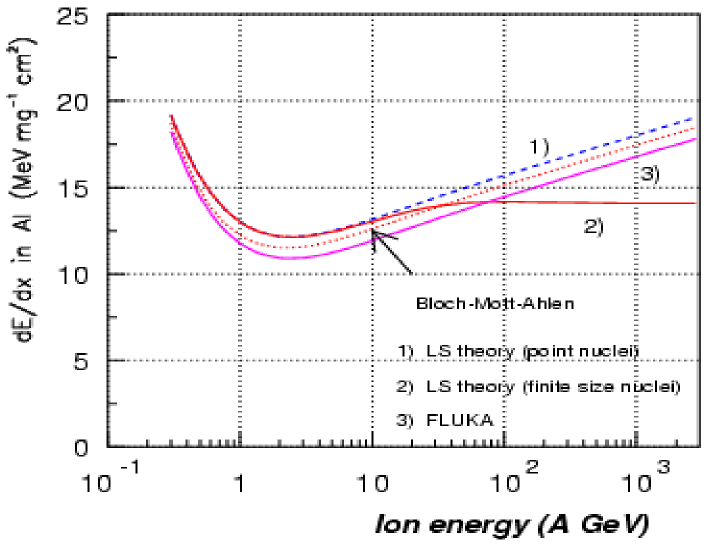
dE/dx of heavy ions deviates from Bethe-Bloch at high energies

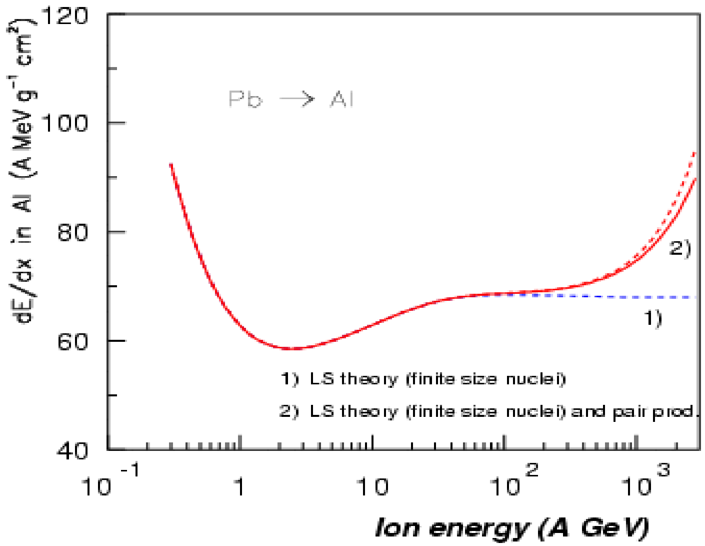
- Higher order corrections
- Finite nuclear size effects
- Pair production

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

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

Implementation of all relevant effects in FLUKA code underway.





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

- Early Ion scheme and injection seems to be ok

- Although $P_{Ions} \approx 1/100\ P_{Protons}$ the damage potential on the impact face of the collimator is comparable for both beams, because relative energy loss due to ionisation is ≈100 times larger for ions.

- Use of high Z spoilers is under study as potential improvement path.

- RHIC two stage collimation works much better due to lower energy and higher Z collimators. Tertiary halo losses in magnets not an issue for RHIC.

- Would be nice to have some sensitive BLM's on a few dipole downstream PHENIX to benchmark ICOSIM program

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