Ion collimation outlook and Phase II improvements

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for the ion collimation team

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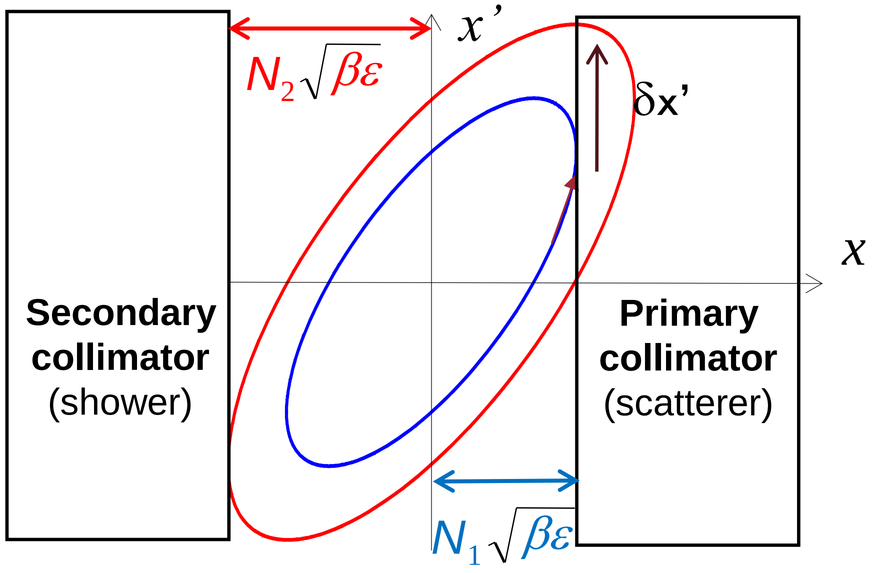
LHC ion collimation: why an issue?

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 ion beam has 1/100 of the proton beam power
(also the impedance is scaled down by factor 100).

Where is the problem?

LHC 2-stage betatron collimation system

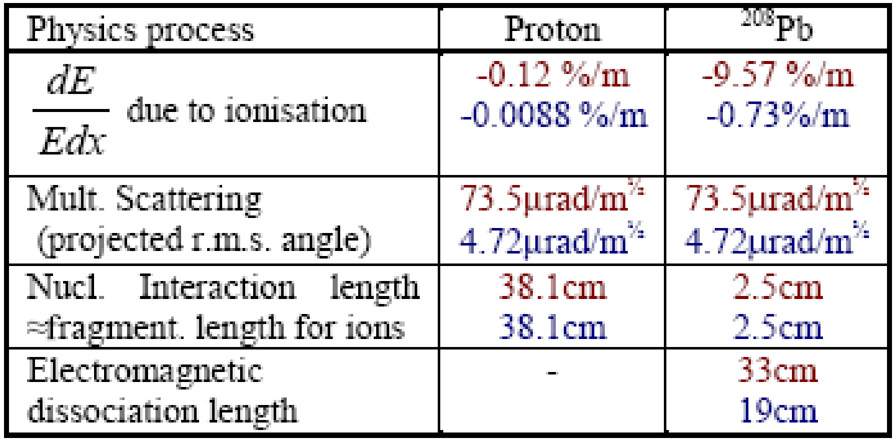


Necessary condition to reach secondary collimator:

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

with δx' due to multiple Coulomb scattering at primary collimator

For 2.76A TeV Pb ions in the LHC:
δx'>7μrad



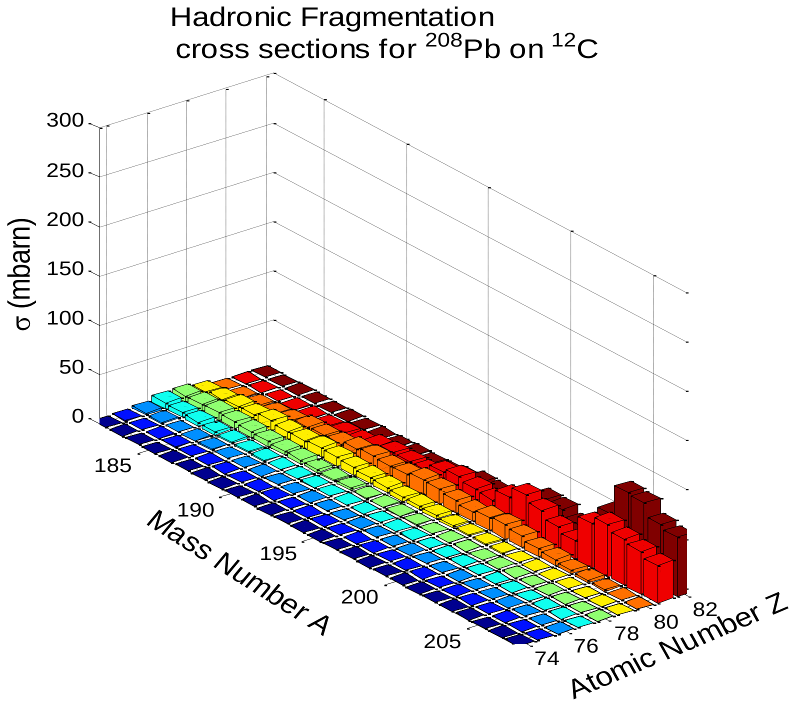
Physics process	Proton	^{208}Pb
$\frac{dE}{Edx}$ due to ionisation	-0.12 %/m -0.0088 %/m	-9.57 %/m -0.73%/m
Mult. Scattering (projected r.m.s. angle)	73.5μrad/m$^{1/2}$ 4.72μrad/m$^{1/2}$	73.5μrad/m$^{1/2}$ 4.72μrad/m$^{1/2}$
Nucl. Interaction length ≈fragment. length for ions	38.1cm 38.1cm	2.5cm 2.5cm
Electromagnetic dissociation length	-	33cm 19cm

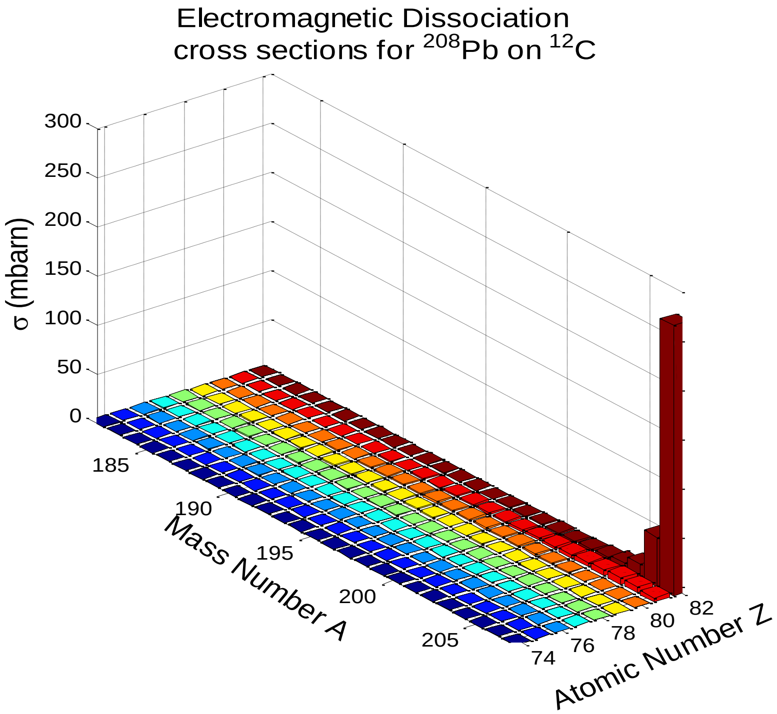
2m long collimator >> λint

Ions undergo nuclear interactions before acquiring necessary kick to reach secondary collimators

—— injection —— collision

Physics interactions in the collimator





Large variety of daughter nuclei, Monte Carlo calculated specific x-sections

Mainly loss of 1 neutron (59%) or 2 (11%) → ^{207}Pb, ^{206}Pb

..where it all fails

Typical transverse momentum transferred in nuclear/dissociation events < 1MeV/c/u (compared to ~10 MeV/c/u due to beam emittance).

After first impact/grazing with TCPs:

- high probability of nuclear interactions with TCP material
- production of isotopes with different Z/A ratio and momentum and direction almost unchanged
- fragments follow locally generated dispersion and are lost downstream in SC magnets because of different $B\rho$

^{204}Pb -1.92%	^{205}Pb -1.44%	^{206}Pb -0.96%	^{207}Pb -0.48%	^{208}Pb 0.0%
^{203}Tl -1.2%	^{204}Tl -0.71%	^{205}Tl -0.23%	^{206}Tl 0.26%	^{207}Tl 0.75%
^{202}Hg -0.46%	^{203}Hg 0.04%	^{204}Hg 0.53%	^{205}Hg 1.02%	^{206}Hg 1.51%

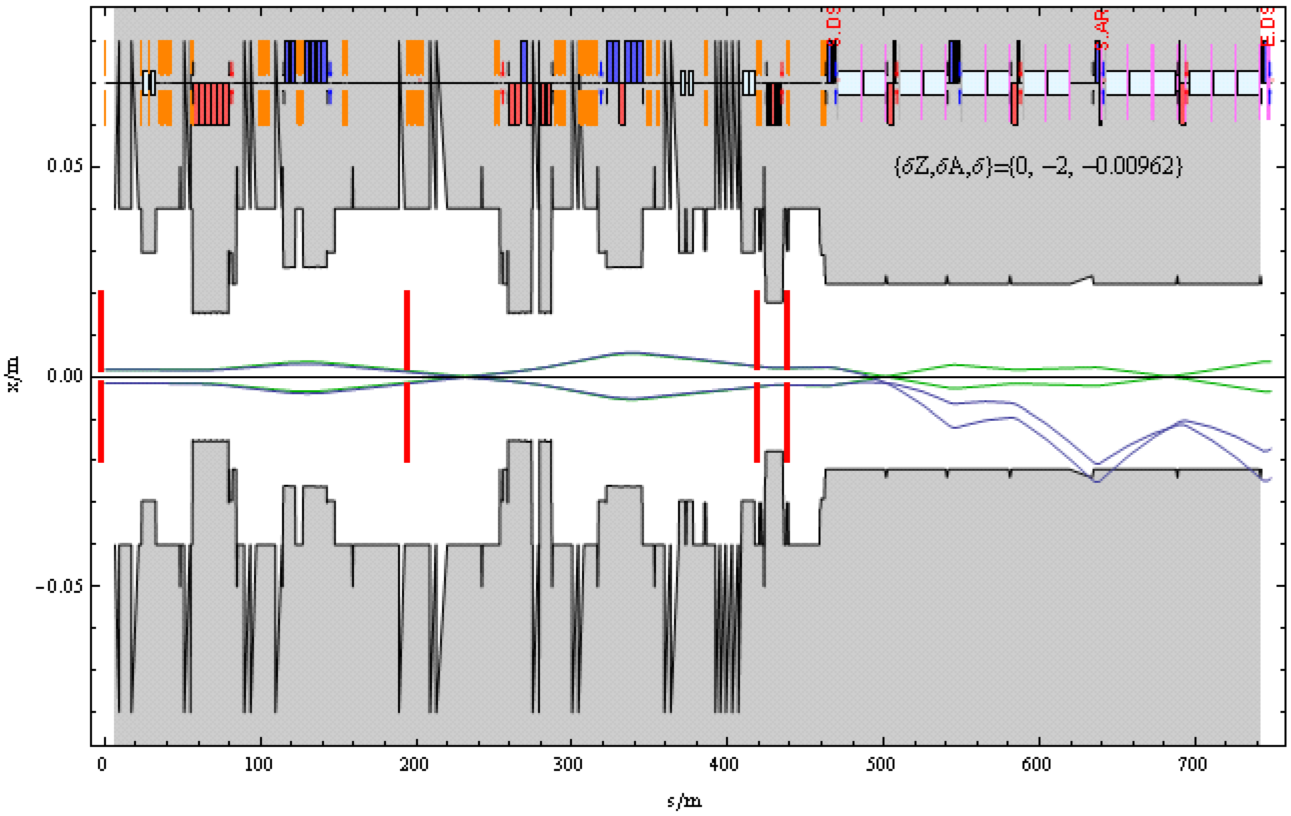
Change in rigidity:

$$\frac{\Delta P}{P} = \frac{Z_2}{A_1}\frac{A_2}{Z_2}\left(1+\delta_{kin}\right)-1$$

LHC energy acceptance:

- arcs: ~ 1%
- IR3: ~ 0.2%

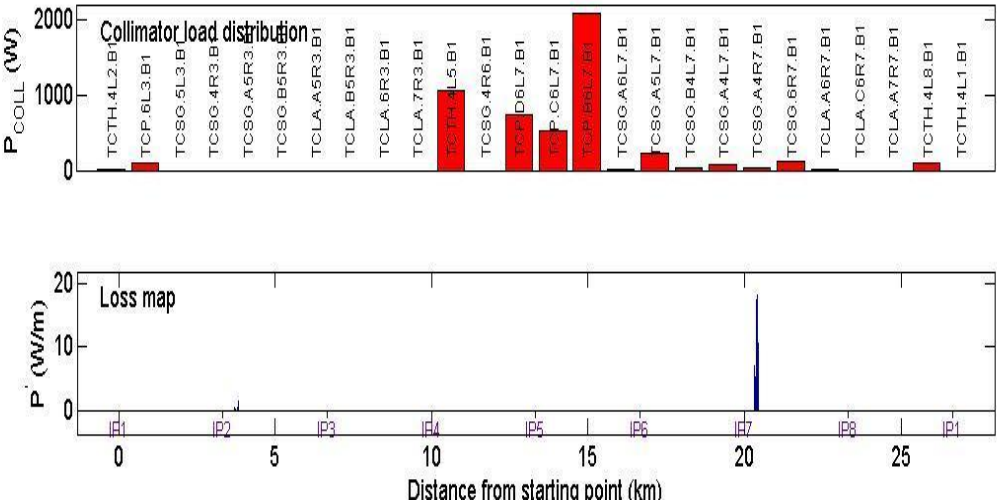
Example: losses in the aperture of Pb^{206} ions

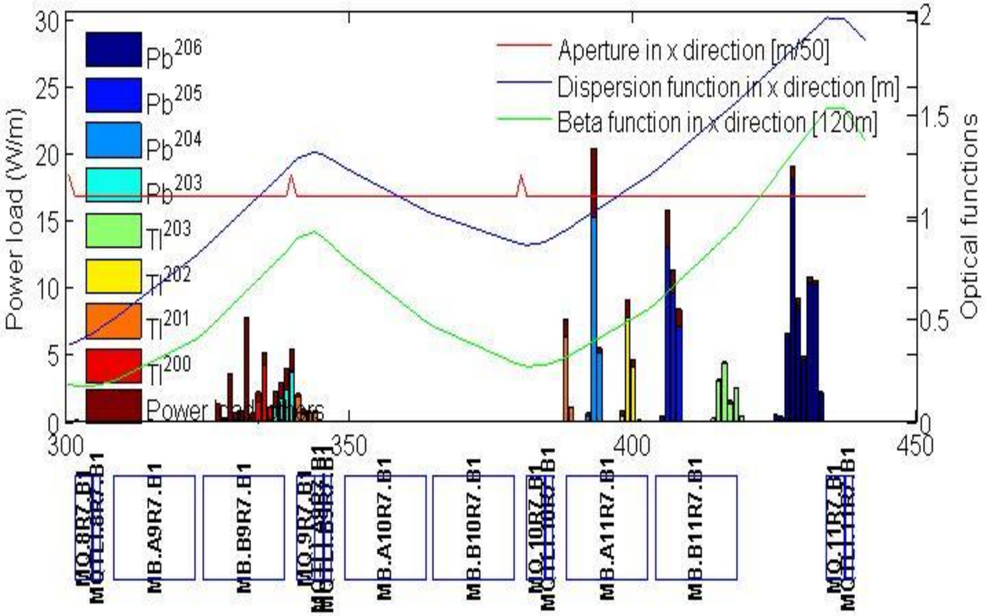


Loss map phase I

Beam1 with first impact on IR7 betatron collimators

Quench limit ~ 8.5W/m





τ=12 min lifetime

50,000 ions statistics

E= 2.76 A Tev

Nominal ion beam parameters

Collision optics

Standard collimator settings (as per LHC p setup)

$$\eta = \frac{\#\text{aperture hits}}{\#\text{collimator hits}} = 0.045$$

Model uncertainties

❑ Input specification of 12min lifetime is an arbitrary number.

❑ Nuclear and EM dissociation cross sections have an estimated error of ~50% .

❑ Simplified model of scattering and energy deposition in the collimator material

❑ Reported quench limit is from early estimates and should rather vary magnet by magnet .

❑ Efficiency depends on impact parameter distribution on collimator which is difficult to predict (beam diffusion/loss mechanism). Usually the most pessimistic case is considered.

❑ Only nominal beam and perfect machine considered. Aperture uncertainties of ±4mm were the only imperfection studied: effect was to shift the peaks position by few meters.

Outlook on first ion beam operation

Phase I beam current limitation of 30%-50% (nominal ion beam parameters), "soft limit" due to uncertainties.

Fundamental to ensure fail-safe ion losses detection for first nominal ion run.

Baseline BLMs mounted on quadrupoles, where most proton losses occur.
Ion losses are more concentrated on SC dipoles in the dispersion suppressor, additional set of BLMs requested and installed at specific locations for machine protection.

Efforts to come up with remedies for Phase II….

Some ideas looked into..

Gain in efficiency

☐ Optics modifications: increasing dispersion and reducing phase advance (IR3/IR7)

no immediate solution found without major rebuild..

☐ High Z scrapers at high β location ($Z \geq 100$, $\beta \geq 2000$) - few mm long scatterers near TCPs

high β only near interaction regions!

☐ Special collimators with magnetised jaws to provide extra kick to primary halo particles

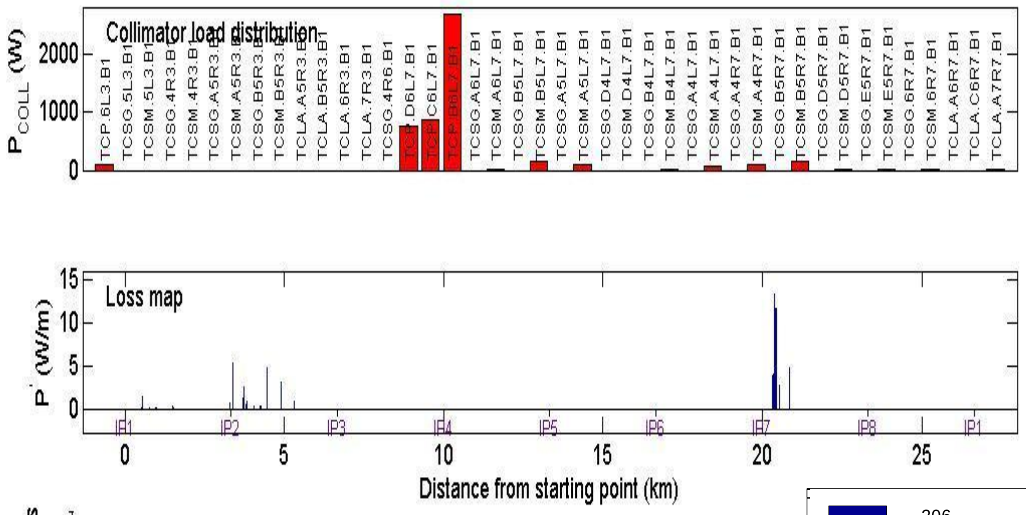
very simple model simulated, not too promising in efficiency gain
+ would require lengthy R&D to test feasibility

cleaner

☐ Crystal collimators

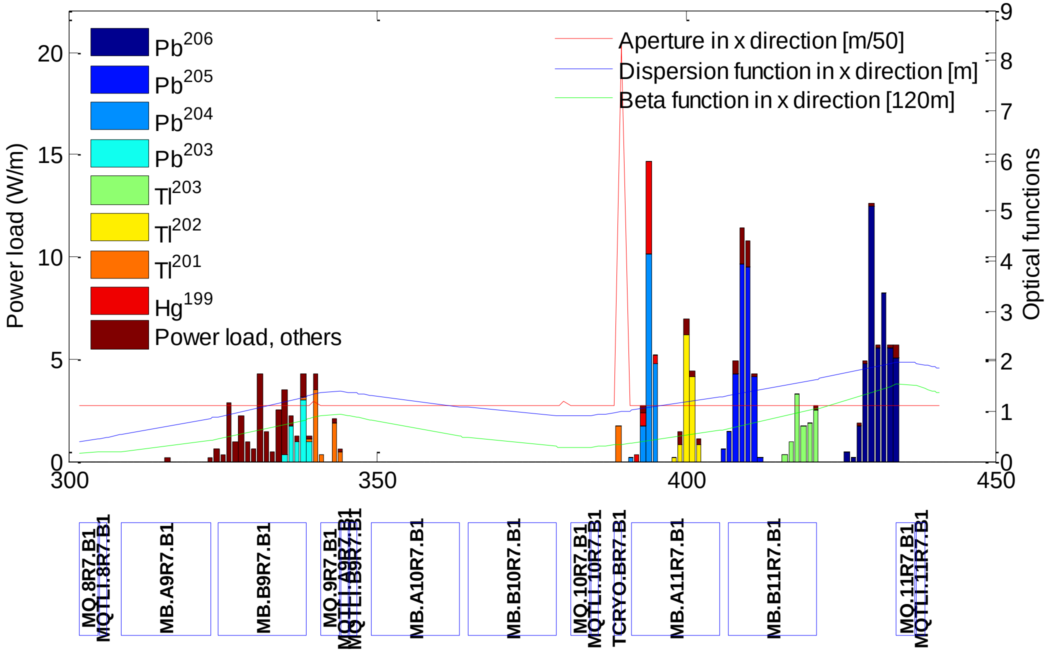
conceptually appealing, but lack of conclusive (positive!) experimental evidence (channelling should suppress fragmentation, but volume reflection not a clean mechanism) → *see talk in the afternoon*

Phase II: standard extra metallic TCSMs



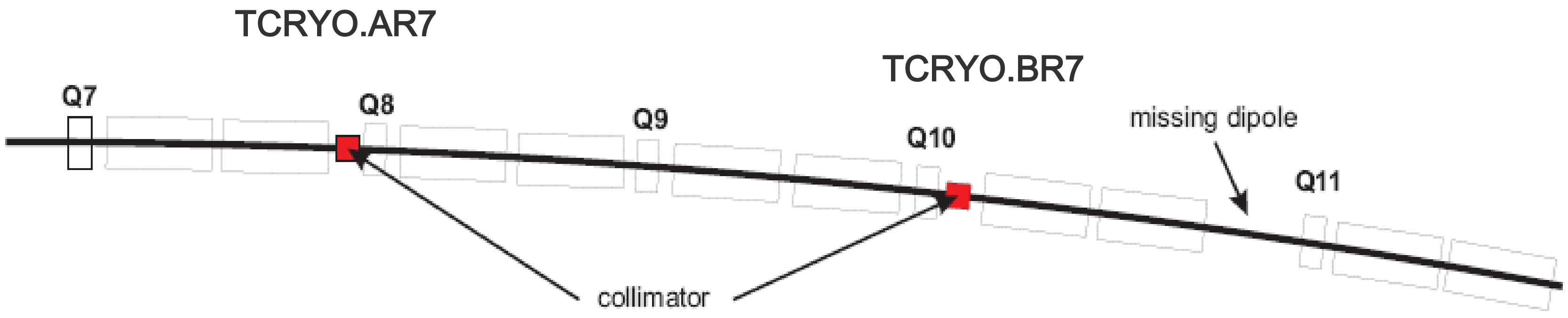
Additional Cu secondaries opened at 7σ

No improvements…



Phase II + cryogenic collimators

Proposed layout:

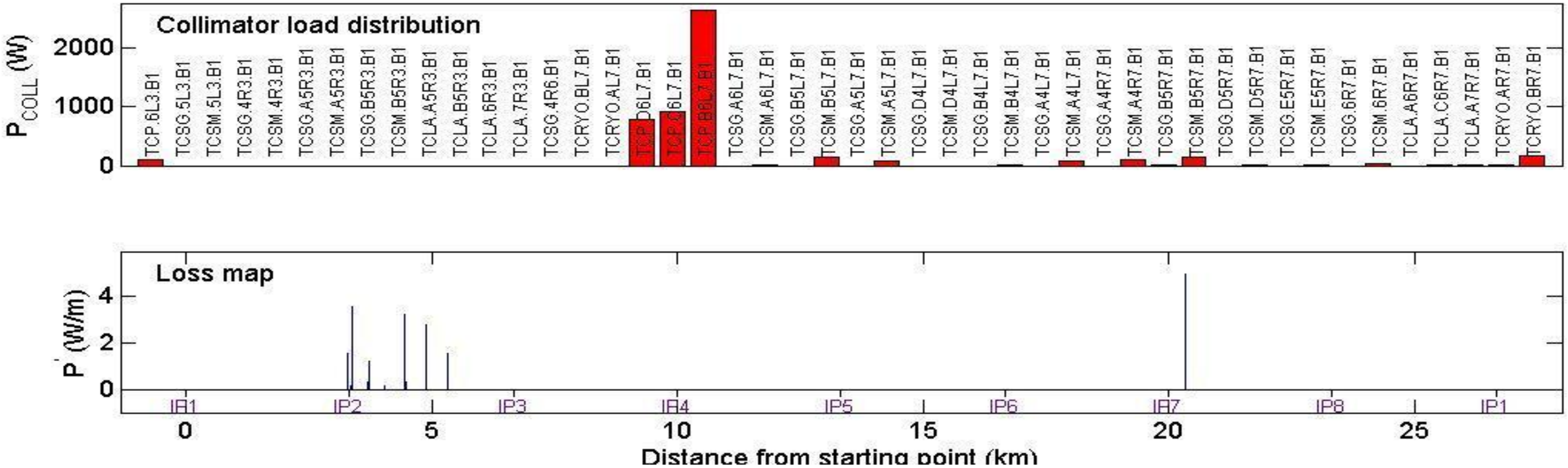


TCRYO.AR7 at 300.19m from IP7

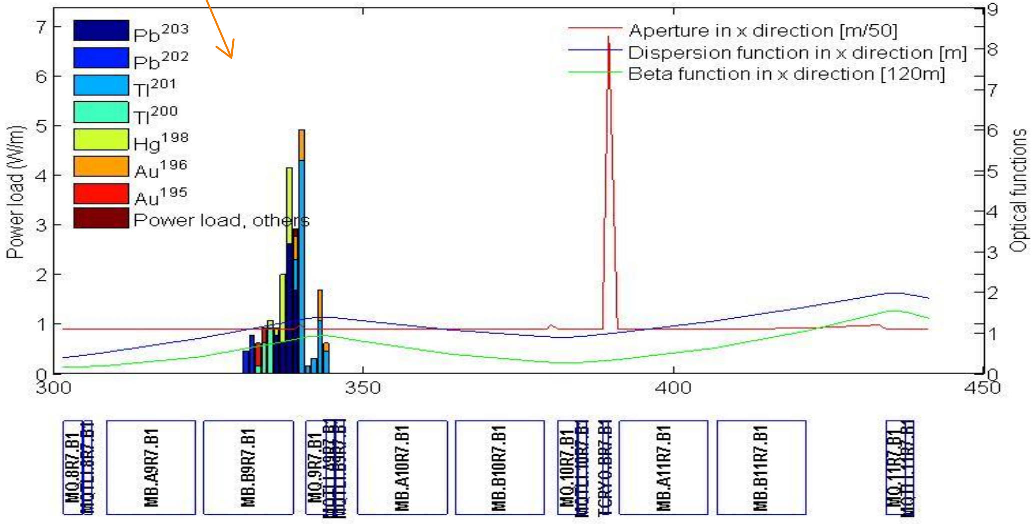
TCRYO.BR7 at 387.29 from IP7

Gap in #σ	
TCP	6.0
TCSG	26.5
TCSM	7.0
TCRYO	15.0
TCLA	10.0
TCT	retracted

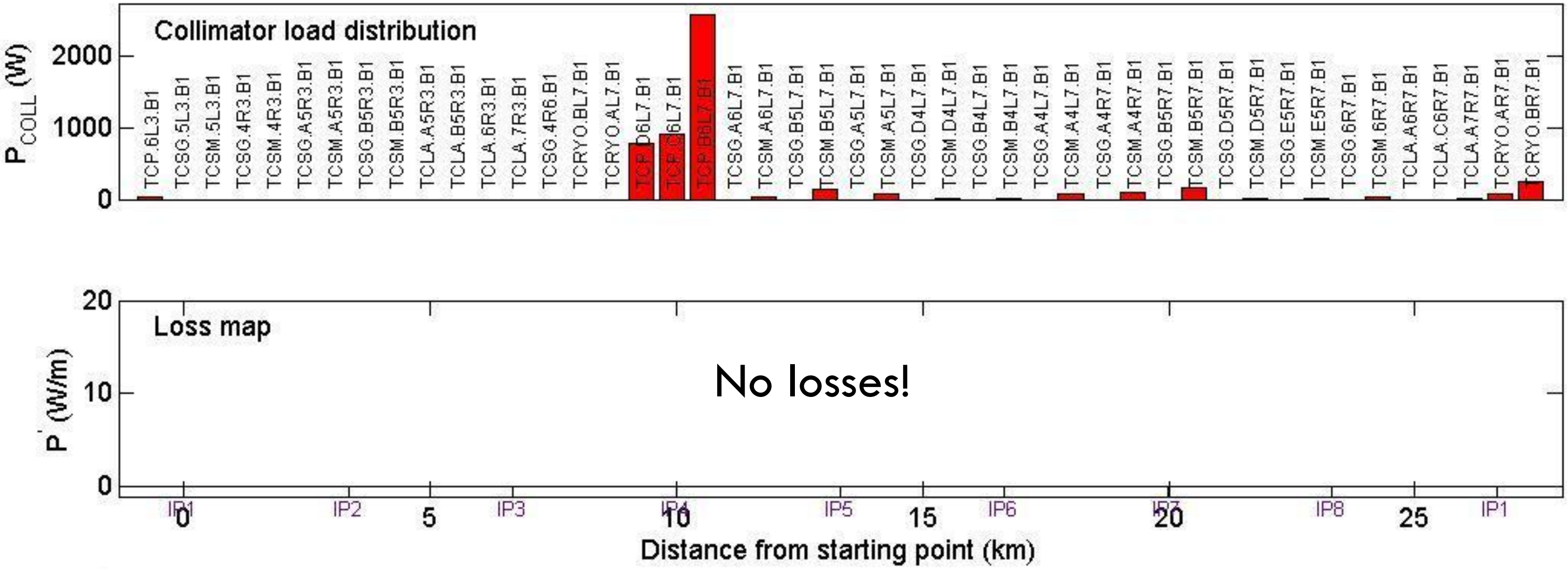
TCRYOs at 45σ



Below quench limit



TCRYOs at 30σ



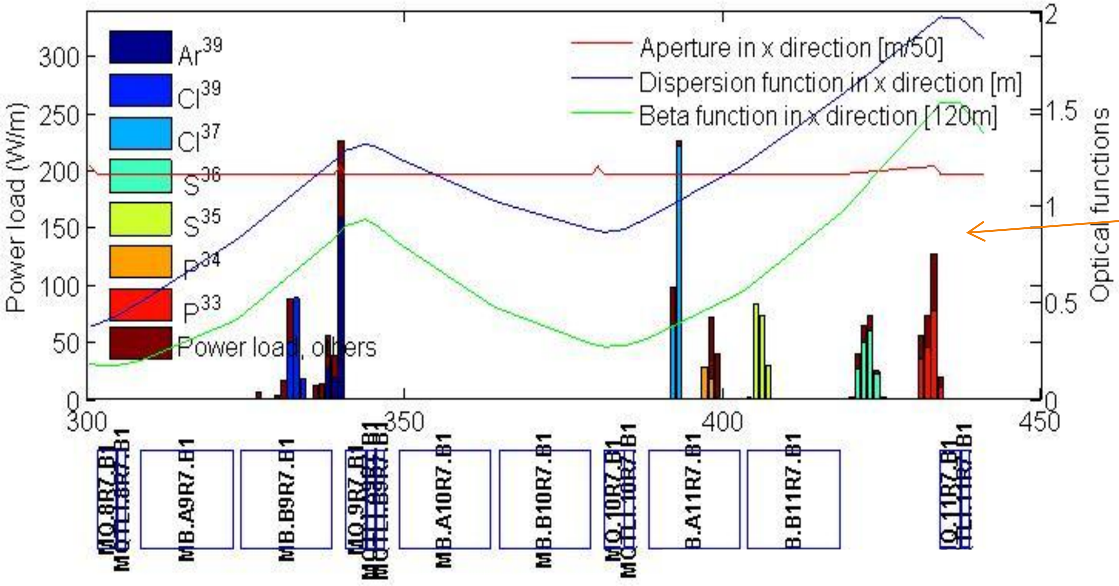
No losses!

Power load on cryogenic collimators

Gap size	TCRYO.AR7	TCRYO.BR7
15σ	186 W	180 W
30σ	83 W	260W
45σ	21 W	190 W

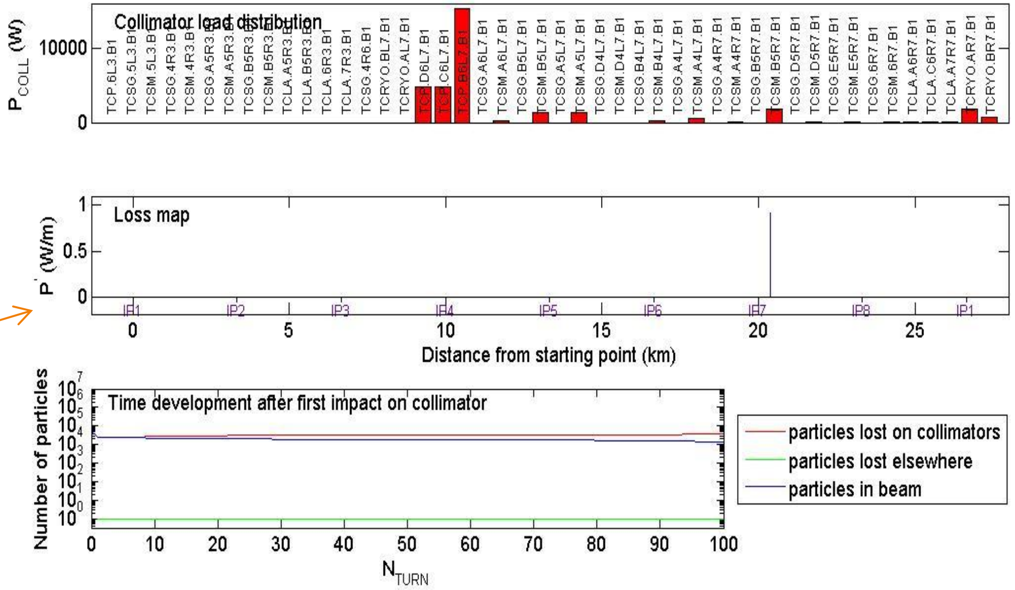
Light ions

Beam of Ar40 (Z=18)
E= 3.15 A TeV
2×10^{9} ions per bunch



Phase I-type setup,
Loss map qualitatively
similar to Pb ions

Phase II with TCRYOs at 15σ
Losses < 1W/m



Conclusions

Phase I

Baseline LHC collimation system does not work for ions (acts as single stage system, with primary halo getting lost on SC magnets)

→ 'soft' beam current limitation of 30-50% of nominal values

BLM system extended to ensure safe LHC operation with Pb beams

Phase II

Several ideas considered to improve collimation efficiency and overcome intensity limitations. The addition of cryogenic collimators has been found to be the only remedy to combine:

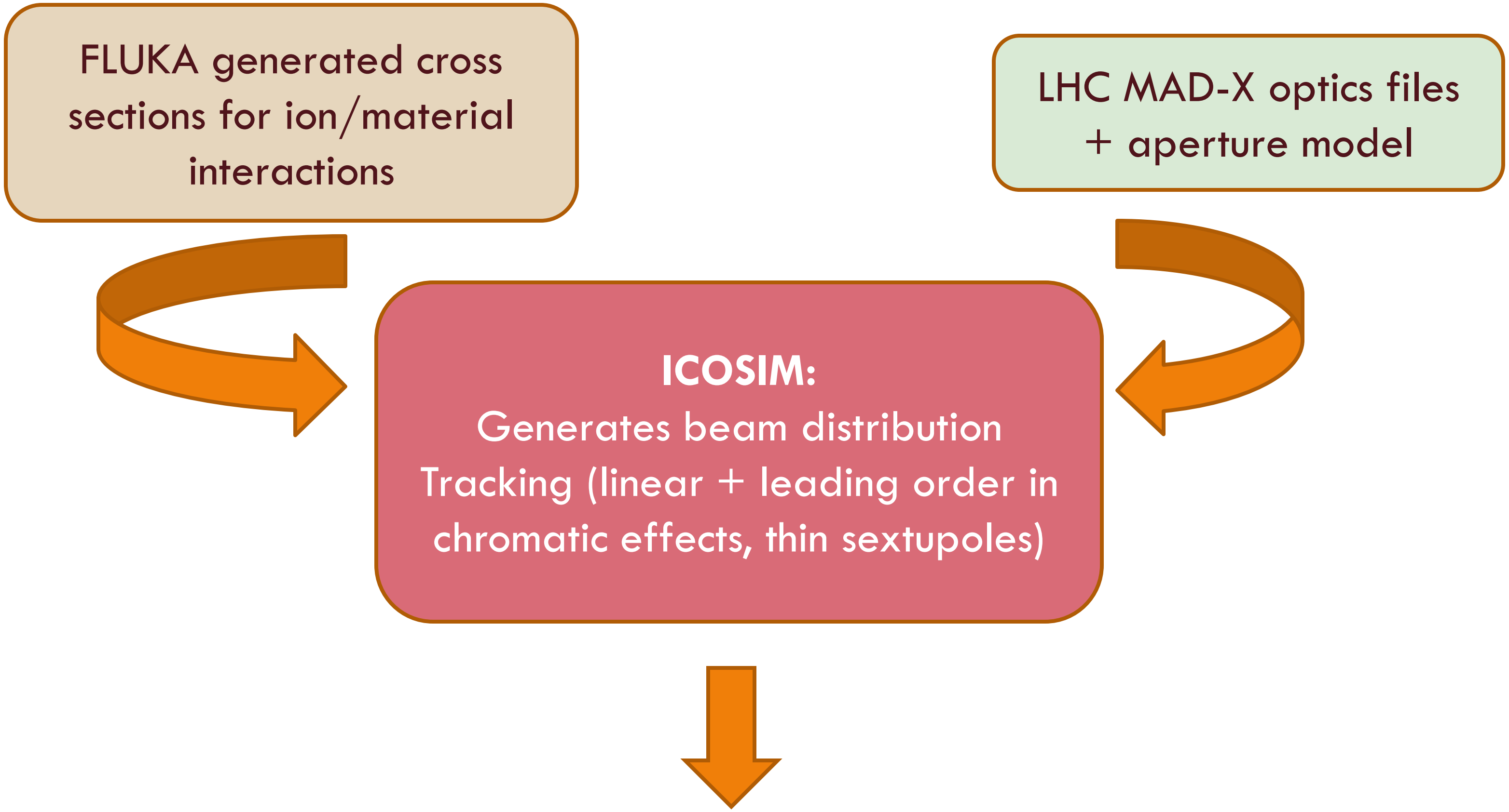
- substantial gain in efficiency

  (all losses in IR7 absorbed, similar behaviour expected in IR3)
- practicable and relatively fast implementation

  (no need of lengthy R&D for proof of principle…)
- added benefit to reduce load on TCTs (fully retracted in the simulations)

Reserve slides

Simulation tools

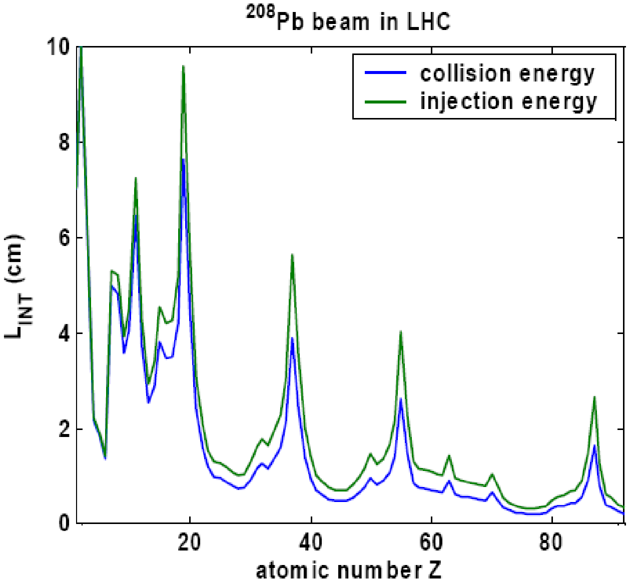


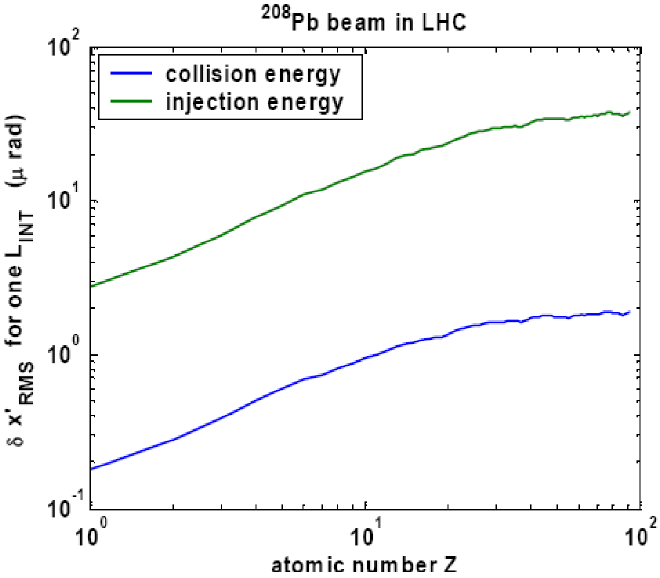
FLUKA generated cross sections for ion/material interactions

LHC MAD-X optics files + aperture model

ICOSIM:
Generates beam distribution
Tracking (linear + leading order in chromatic effects, thin sextupoles)

Loss maps, collimation efficiency





$$L \approx L_{\text{int}} = \frac{A_{coll}}{N_A \rho(\sigma_{had} + \sigma_{emd})}$$

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