Pb ion Collimation Performance with and without IR3 upgrade

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Heavy Ion collimation is very different from proton collimation

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^{½} 4.72µrad/m^{½}	73.5µrad/m^{½} 4.72µrad/m^{½}
Nucl. Interaction length ≈fragment. length for ions	38.1cm 38.1cm	2.5cm 2.5cm
Electromagnetic dissociation length	-	33cm 19cm

Ions undergo nuclear interactions in primary collimators (TCPs) before acquiring necessary kick to reach secondary collimators

→ **One stage cleaning only!**

Hadronic fragmentation → Large variety of daughter nuclei, Monte Carlo calculated specific cross-sections

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

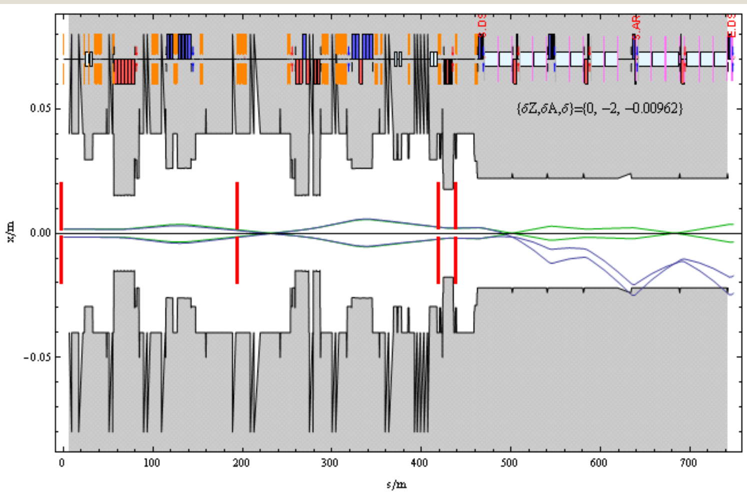
Typical transverse momentum transferred in nuclear/dissociation events < 1MeV/c/n (compared to ~10 MeV/c/n due to beam emittance).

One stage cleaning

pact/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%



Example: 206 Pb

J.M. Jowett, Collimation Review 2009

Change in rigidity:

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

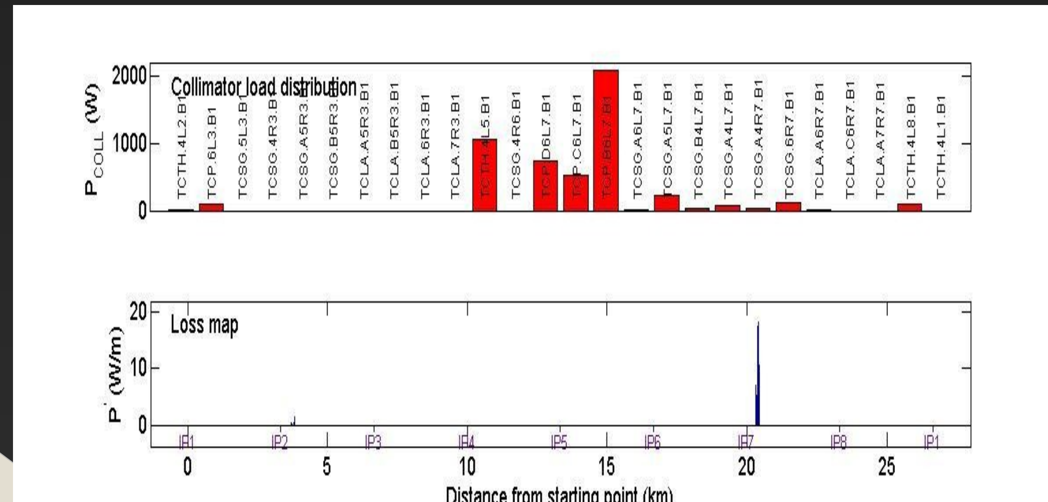
LHC energy acceptance:

- arcs: ~ ±1%
- IR3: ~ ±0.2%

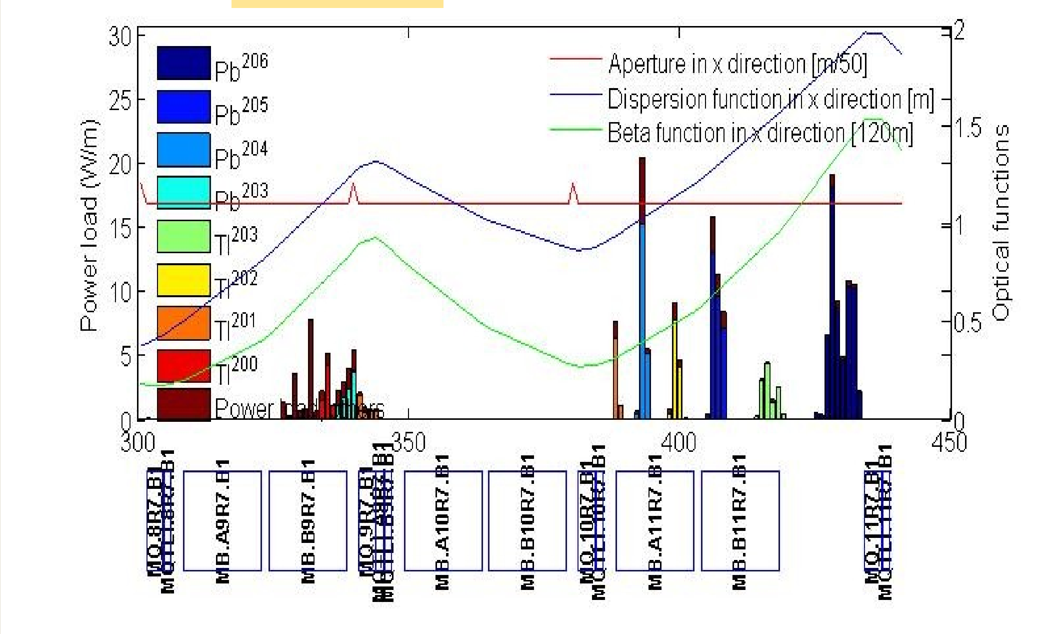
IR7 β-tron cleaning at 7 Z TeV

Simulations
(ICOSIM program by H. Braun):

τ=12 min lifetime
50,000 ions statistics
E= 7 Z TeV = 2.76 A Tev
Nominal beam parameters:
7e7 x 592= 4.14×10^{10} ions intensity (3.8MJ)
Collision optics (ideal)
Standard collimator settings (as per LHC p setup)



IR7 DS



Quench limit (theory) ~ 8.5W/m

Max TCP load ~ 2700W
Peak loss in DS3 ~ 18W/m
η (local) = 0.007

Betatron collimation:

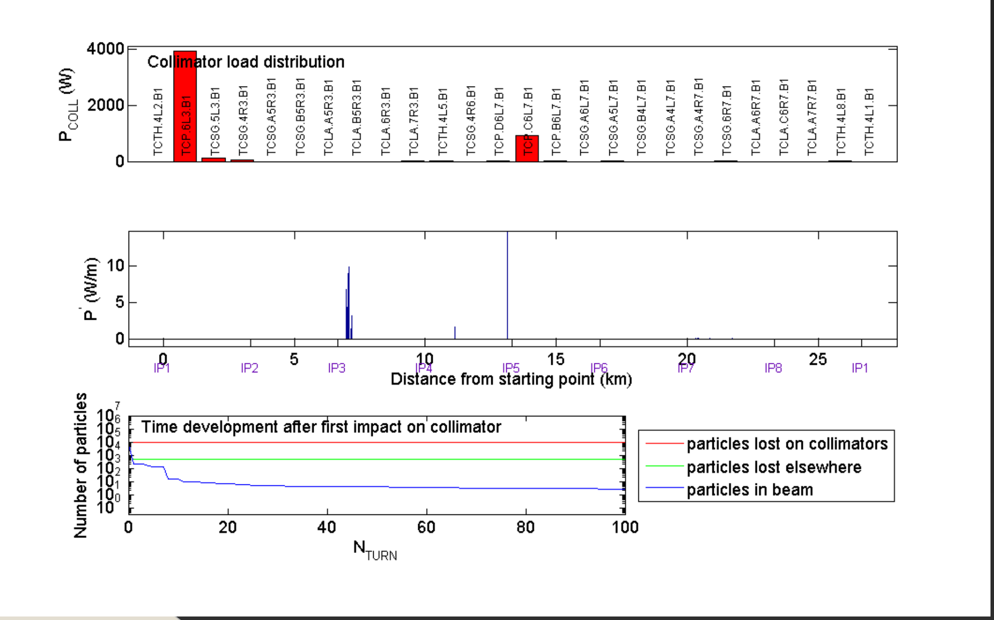
$$\eta = \frac{\sum \text{aperture hits}}{\sum \text{collimator hits}} = 0.047$$

IR3 momentum cleaning at 7 Z TeV

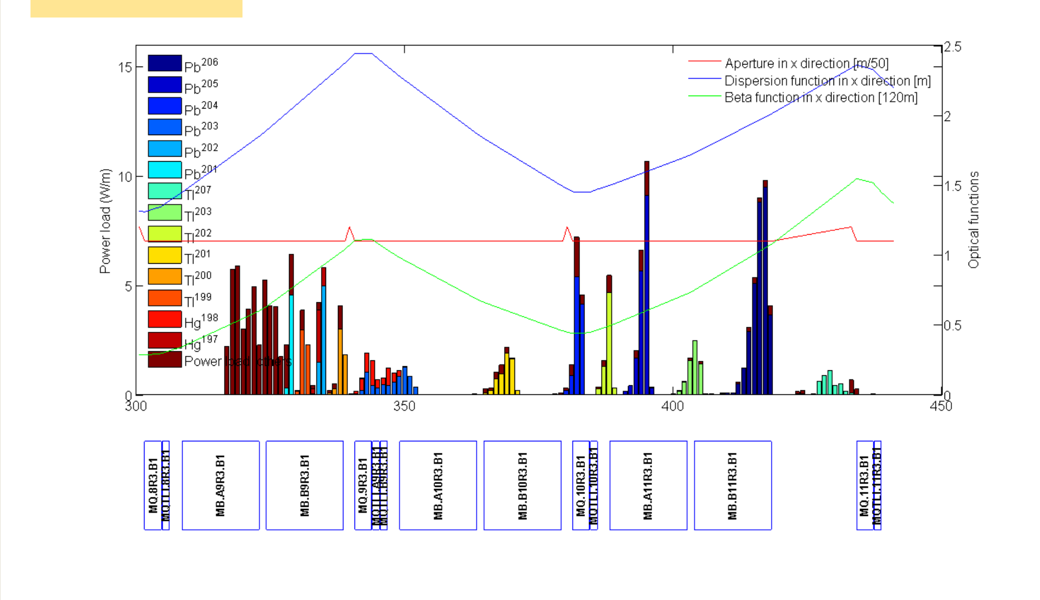
Simulations:

100k particles, 100 machine turns
τ=12 min lifetime
7e7 x 592= 4.14×10^{10} ions intensity (3.8MJ)

Max TCP load ~ 3900W
Peak loss in DS3 ~ 12W/m
η (local) = 0.003



IR3 DS

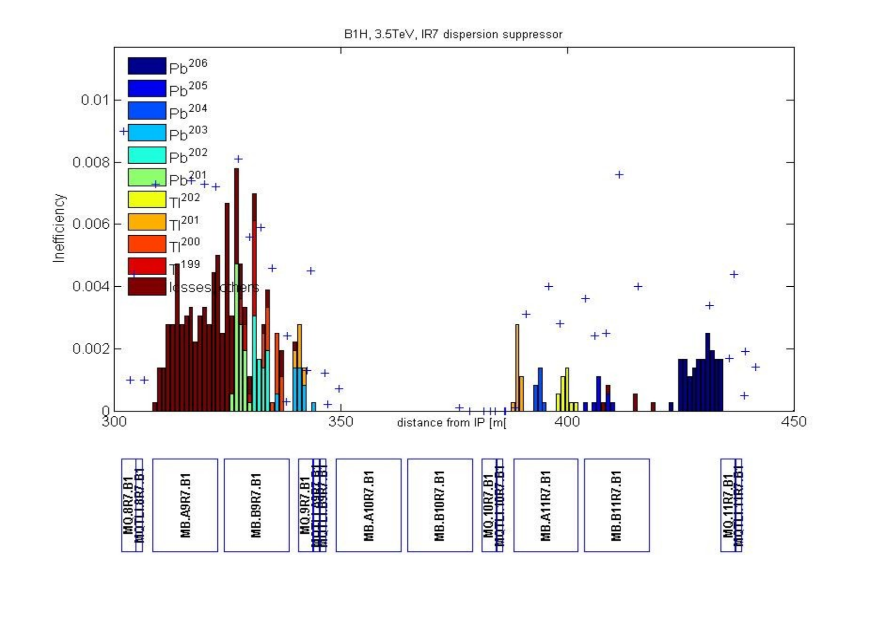


Standard momentum collimation

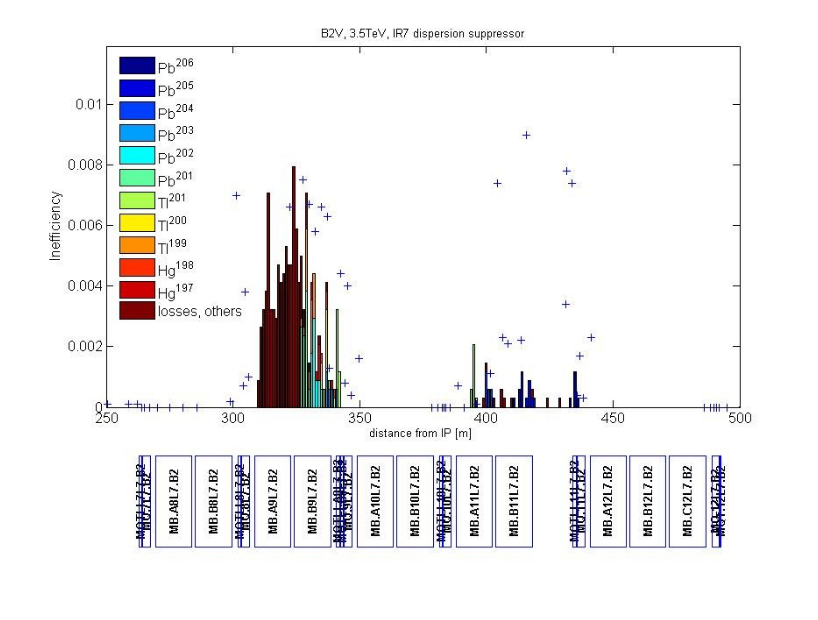
$$\eta = \frac{\sum \text{aperture} \quad \text{hits}}{\sum \text{collimator} \quad \text{hits}} = 0.05$$

Ion commissioning loss maps *vs* simulation – Nov 2010

B1H



B2V



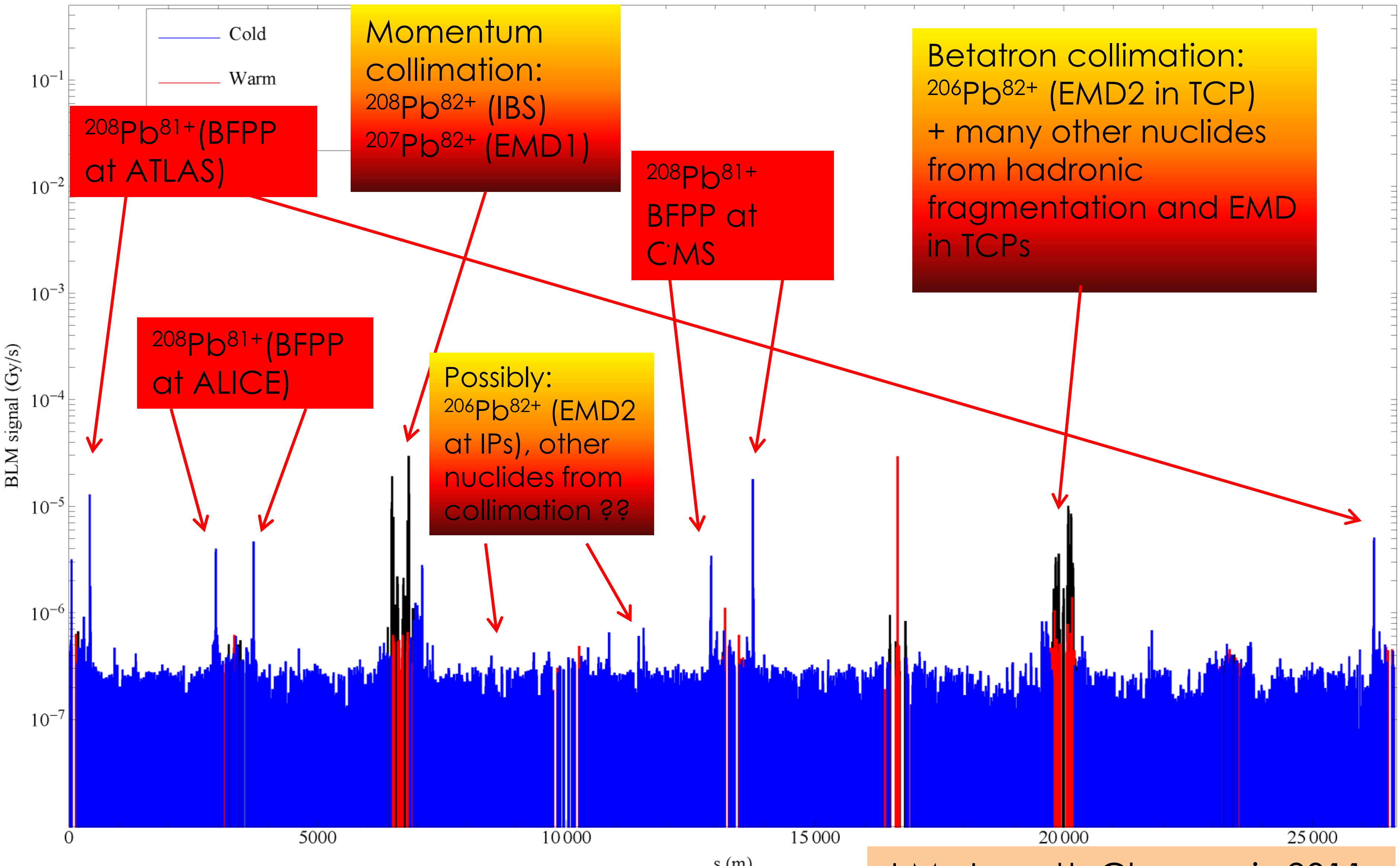
	DS	COLD	TCT
B1h	0.02	0.006	1.0×10^{-4}
B1v	0.027	0.005	0.001
B2h	0.03	0.011	8×10^{-5}
B2v	0.025	0.006	1.4×10^{-4}
B1+B2 pos. off momentum	0.045	8e-4	0.06
B1+B2 neg. off momentum	0.007	2e-4	0.005

3.5TeV eq. Physics conditions

D Wollmann, Evian Dec 2010

Global view of losses, Pb-Pb stable beams

Record luminosity, the last fill of 2010



J.M. Jowett, Chamonix 2011

Commissioning lessons

- Positions of loss peaks in the dispersion suppressor are well reproduced in simulations.
- Leakage is higher in measurements than in simulations.
- Higher losses in IR3 than expected (combination of BFPP-luminosity effects and off-momentum feed-down from IR7?)
- Simulations performed with perfect machine conditions
- Cross sections uncertainties: good news from 2011 Quark-Matter conference (talk by C. Oppedisano)

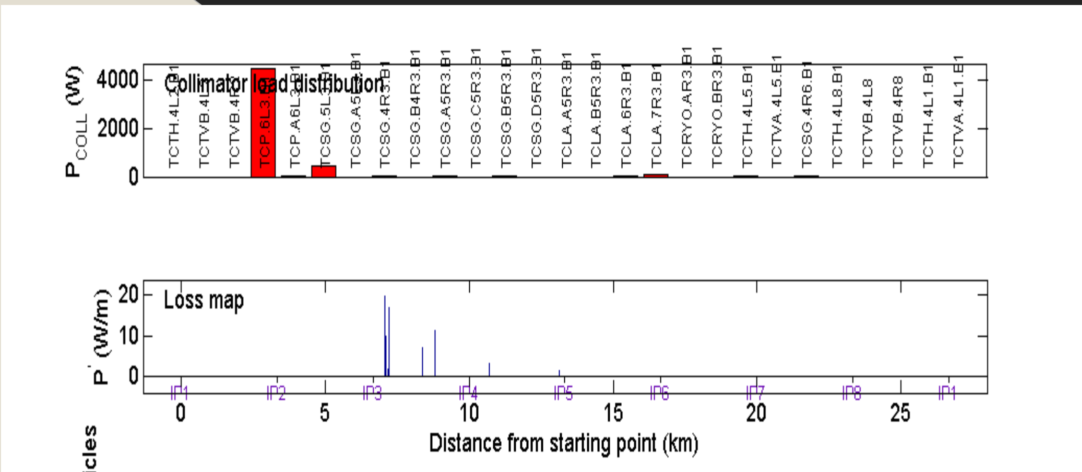
- Cross sections for EMD processes have been measured in Pb-Pb collisions at 2.76 A TeV detecting the emitted neutrons with the ZDCs and using the absolute cross section values measured in the Van der Meer scan

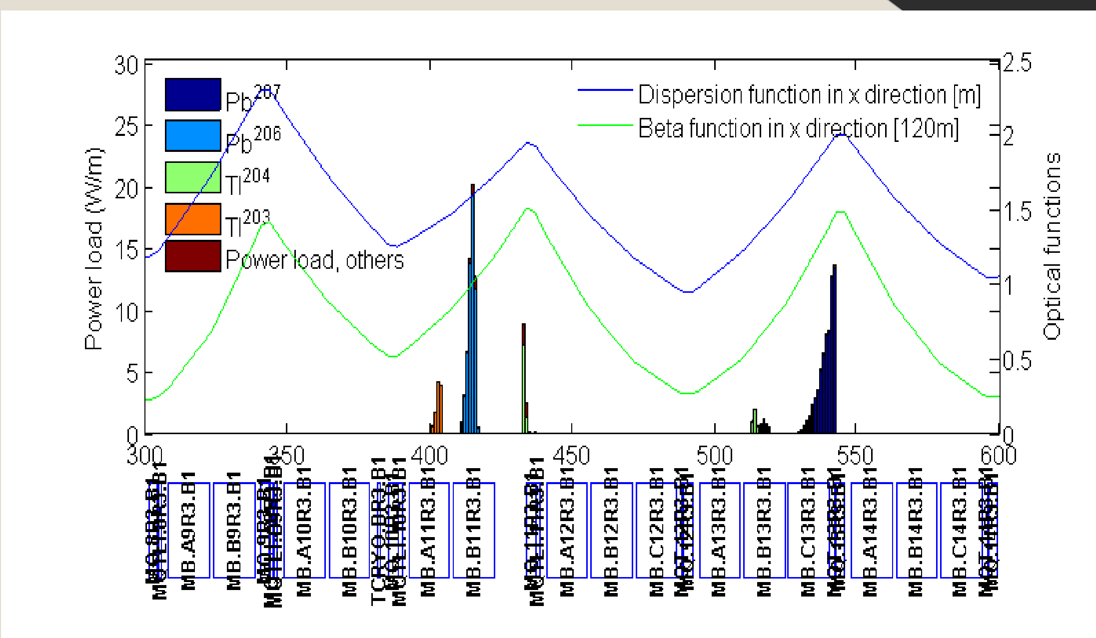
ALICE results

	DATA (PRELIMINARY)	RELDIS MODEL
$\sigma^{sEMD} + \sigma^{had}$	$(195.6 \pm 0.1\ \text{stat.}\ ^{+24.2}_{-11.7}\ \text{syst.})$ b	$(192.9 \pm 9.2\ \text{syst.})$ b
$\sigma^{sEMD} - \sigma^{mEMD}$	$(176.9 \pm 0.1\ \text{stat.}\ ^{+21.6}_{-10.6}\ \text{syst.})$ b	$(179.7 \pm 9.2\ \text{syst.})$ b
σ^{mEMD}	$(5.7 \pm 0.2\ \text{stat.}\ ^{+0.7}_{-0.3}\ \text{syst.})$ b	(5.5 ± 0.6) b
σ^{sEMD}	$(185.7 \pm 0.2\ \text{stat.}\ ^{+22.6}_{-11.1}\ \text{syst.})$ b	(185.2 ± 9.2) b

- Experimental results are in very good agreement with predictions from RELDIS

IR3 combined cleaning without TCRYOs





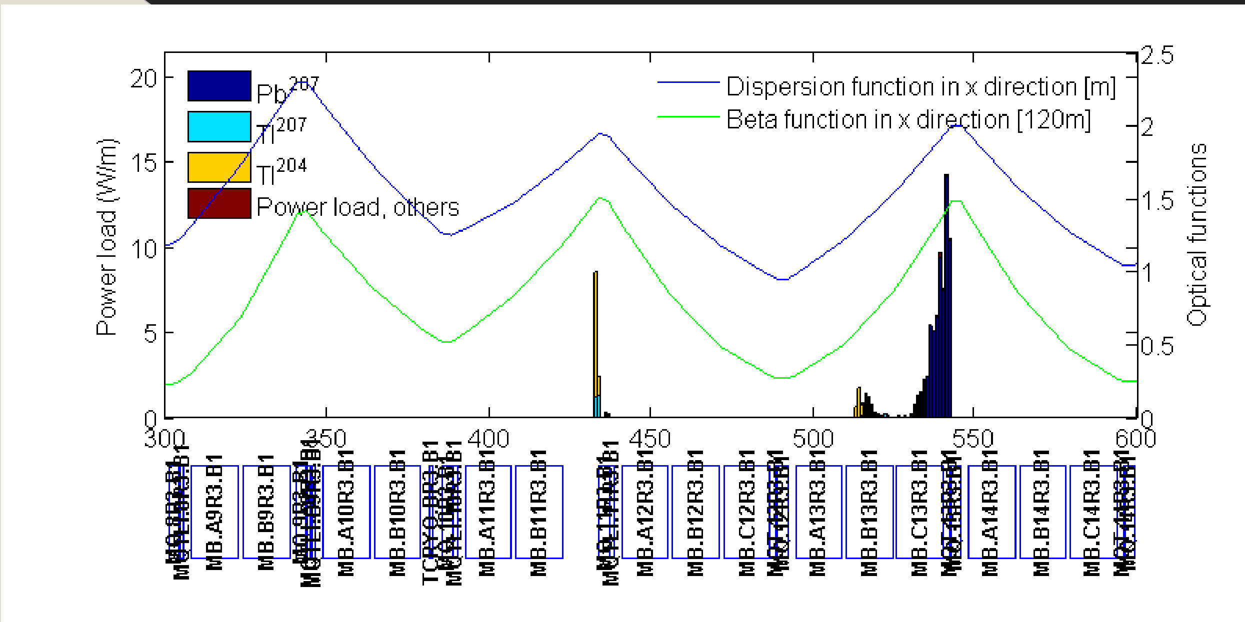
Sector	Family	Half gap
LSS7	TCP IR7	Open
	TCSG IR7	Open
	TCLA IR7	open
LSS3	TCP IR3	6
	TCSG IR3	7
	TCLA IR3	10
LSS1/2/5/8	TCTH	8.3
	TCTV	8.3

τ=12 min lifetime
$7\times10^7 \times 592 = 4.14\times10^{10}$ ions
E=7 Z TeV eq.

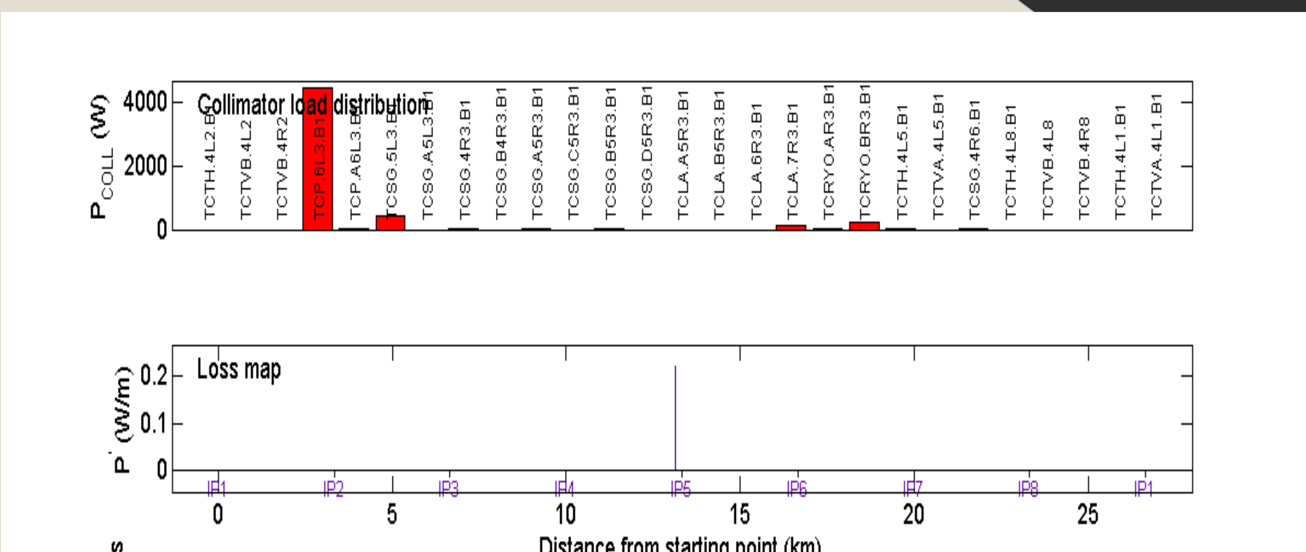
Max TCP load ~ 4500W
Peak loss in DS3 ~ 20W/m
η (local) = 0.0044

$$\eta = \frac{\sum \text{aperture hits}}{\sum \text{collimator hits}} = 0.04$$

and with TCRYOs in



50 sigma half gap – DS already significantly cleaner



20 sigma half gap, No losses visible!

Performance reach without TCRYOs: extrapolation from proton MD

DATA

1) Minimum lifetime for steady-state losses derived from data (end Nov ion runs)
   τ= ~1-1.5 hrs (vs 12 min used in simulations) **at 3.5 TeV eq.** (DW, FB)

2) Protons quench test (16 bunches at 3.5 TeV in 1s):
   336W deposited on DS Q8 w/o quench – lower limit

3) Same BLM response as for protons (**factor of 2** between primary and DS)

$$\eta N_{max} = \tau \cdot R_q d_L \cdot c_{BLM} \cdot c_{fluka}$$

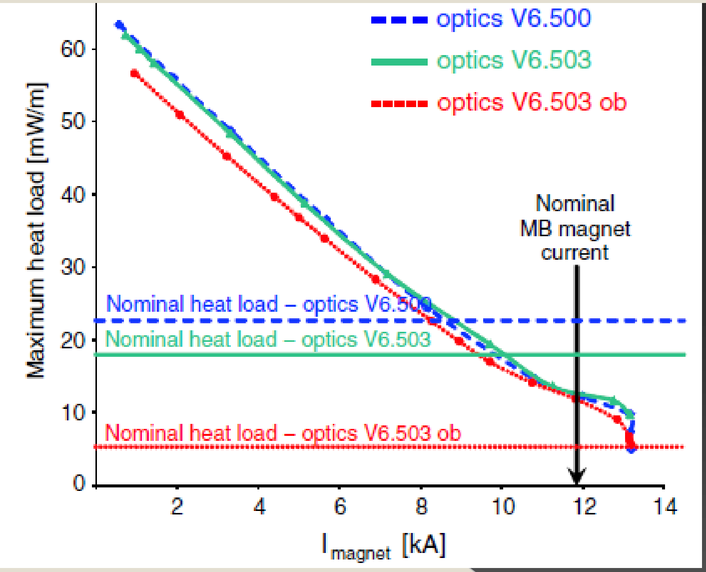
- ηN_{max}: Highest measured local cleaning inefficiency
- τ: Minimum lifetime (measured)
- $R_q d_L$: Quench limit x dilution length
- $c_{BLM} \cdot c_{fluka}$: Correction factors

At 3.5 Z TeV:

336 W on Q8 → ~**60W on MB** or 2.6E6 ions/s (with BLM factor 2)
Assume η=0.045, τ=3600s and x2 dilution length safety factor

N_max (ions) = 1×10^{11} Pb = 2.4 × Pb nominal intensity

R. Bruce et al. Phys. Rev. ST AB, **12,** 071002 (2009)



At 7 Z TeV:

60 W → ~24W
(Heat flow simulations for BFPP give quench limit scaling with magnet current)
= 0.52E6 ions/s

Assume η=0.045, τ=3600s and x2 dilution length (for Pb) safety factor

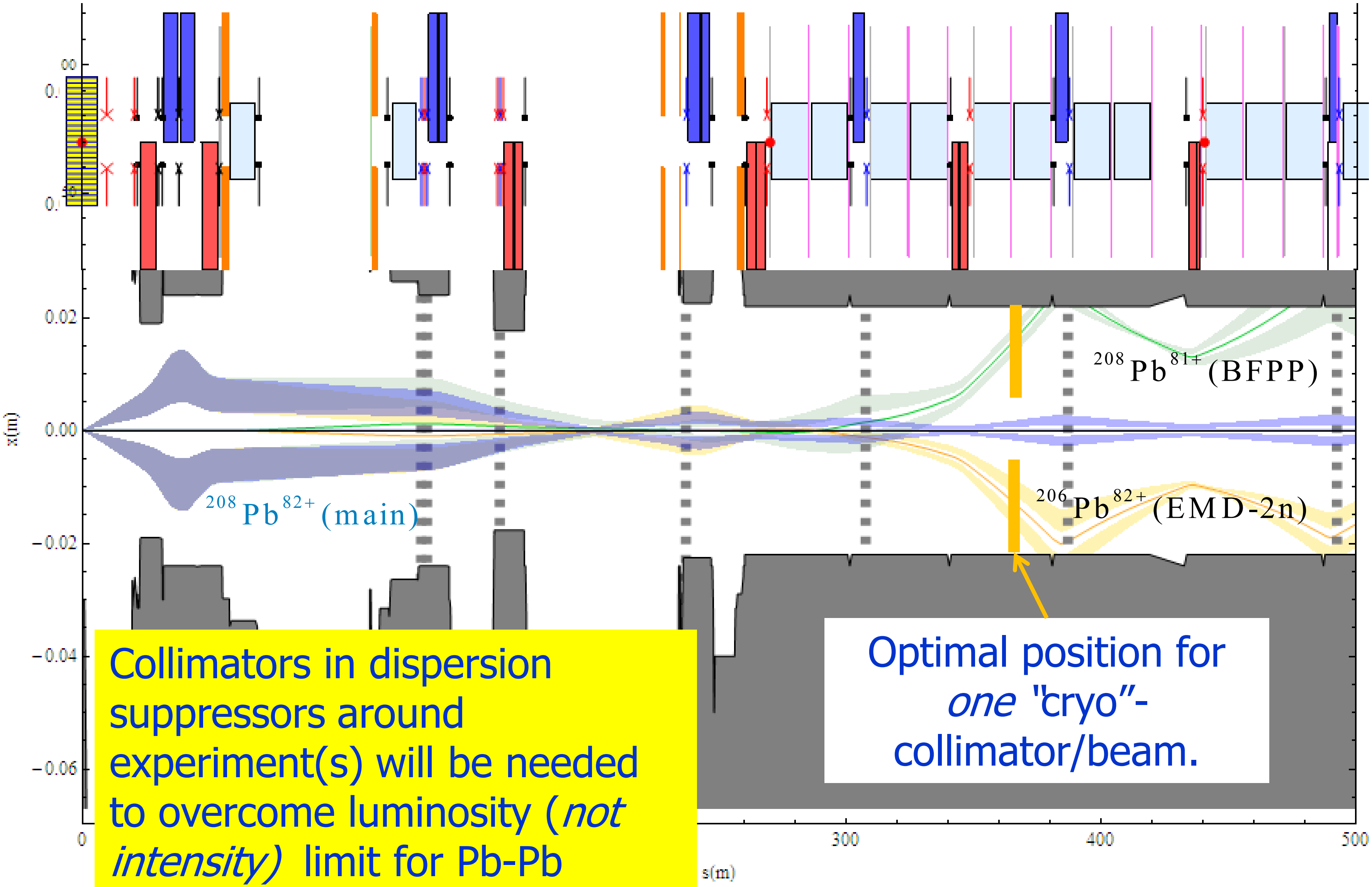
N_max (ions) ~ 2×10^{10} Pb = 0.5 × nominal Pb intensity

Assumptions/caveats/disclaimers

- Same minimum beam lifetime at 3.5 TeV and 7 TeV.
- Minimum beam lifetime independent from intensity.
- Safety factor x2 in dilution lengths to account for different ion loss patterns (more concentrated and localised, less diffractive scattering effects..)

  R. Bruce et al, Phys. Rev. ST Accel. Beams 12, 071002 (2009)
- Same spatial distribution of losses in SC magnets at 3.5 TeV and 7 TeV
- No change in cleaning inefficiency between 3.5 TeV and 7 TeV
- BLM response as for protons
- Losses are mainly collimation/intensity driven ... possible luminosity effects are not considered
- .....

Main and secondary Pb beams from ALICE IP



Collimators in dispersion suppressors around experiment(s) will be needed to overcome luminosity (*not intensity)* limit for Pb-Pb collisions.

Optimal position for *one* "cryo"-collimator/beam.

IR2 DS collimators

- BFPP is direct limit on Pb-Pb luminosity in each IP
  - *Continuous, localised* loss during luminosity
  - Expect very effective mitigation from DS collimators around IPs
  - Installation is different from IR3/IR7
  - No resources for detailed layout study so far
- ALICE has requested IR2 be equipped
  - Next step after IR3, 2017 shutdown
  - If IR3 installation is delayed, can both IR3 & IR2 be done in 2018? Otherwise risk that IR2 installation will be so late as to compromise integrated Pb-Pb luminosity up to ~2020 (see next slide …)
- Similar installations for IR1, IR5
  - May be needed for p-p luminosity debris in future HL-LHC beyond 2021 ??
  - Would also help their Pb-Pb luminosity

LHC medium-term heavy-ion programme

Year	HI beams	TCRYO in 2013-14	Delayed TCRYO
2011	Pb-Pb, 3.5 Z TeV	I_{tot} limited	I_{tot} limited
2012	p-Pb/Pb-Pb	I_{tot} limited	I_{tot} limited
2013-14	LS1	**TCRYOs in IR3**	No TCRYOs
2015-16	Pb-Pb, 7 Z TeV	*L* limited	I_{tot} limited
2017	p-Pb/Pb-Pb	*L* not limited/limited	I_{tot} limited
2018	LS2	**TCRYOs in IR2**	TCRYOs in IR3
2019	Pb-Pb, 7 Z TeV	*L* not limited	*L* limited
2020	p-Pb (D-Pb??)	*L* not limited	??
2021	Ar-Ar	??	??
2022	LS3	TCRYOs in IR1, IR5 ?	TCRYOs in IR2 ?

Highly simplified scheme:
"I_{tot} limited" means close to limit, as determined in previous slides
"*L* limited" means probably factor ~2-4 below design of 10^{27}cm^{-2}s^{-1}
see R. Bruce et al. Phys. Rev. ST AB, **12,** 071002 (2009)

Conclusions

I. 2010 measurements successfully validated predictions on DS loss locations and patterns and EMD/had Pb ion cross sections

II. Observed leakage to IR7 (IR3) DS is more important than predicted: especially high losses seen with stable beams in IR3 (combined effect?)

III. Solution for combined betatron and momentum cleaning in IR3 (one extra vertical TCP) is expected to have similar collimation efficiency to IR3 momentum only/IR7 betatron only schemes.

Hardly sufficient to meet the needs for Pb ion operation performance at 7 Z TeV and nominal intensity.

Without IR3 upgrade

Performance reach estimate on the basis of recent MD results:

At 3.5 Z TeV:

N_{max} ~ 1×10^{11} **Pb**

=(2.4×nominal Pb intensity)

At 7 Z TeV:

N_{max} ~ 2×10^{10} **Pb**

=(0.5×nominal Pb intensity)

Important assumptions (are they all justified??) → large error bars / far reaching extrapolation....

No margin for higher beam intensities / operation with different ion species (Ar40 more demanding!)

IR2 probably delayed

With IR3 upgrade

IR3 DS upgrade with cryogenic collimators is an effective solution to the ion collimation problem.

all leakage in the DS is absorbed even at > 20 σ jaw opening.

Scheme has been shown (in simulations) to work for:

- higher beam intensities
- light ions operation

(^{40}Ar study in 04/2009 review)

Single bunch intensity 70% > nominal already demonstrated (Early scheme only, so far)

Opens the way for timely IR2 upgrade to remove BFPP limit on luminosity for main part of Pb-Pb programme.