Dispersion Suppressor Collimators for Heavy-Ion Operation

John Jowett, Michaela Schaumann

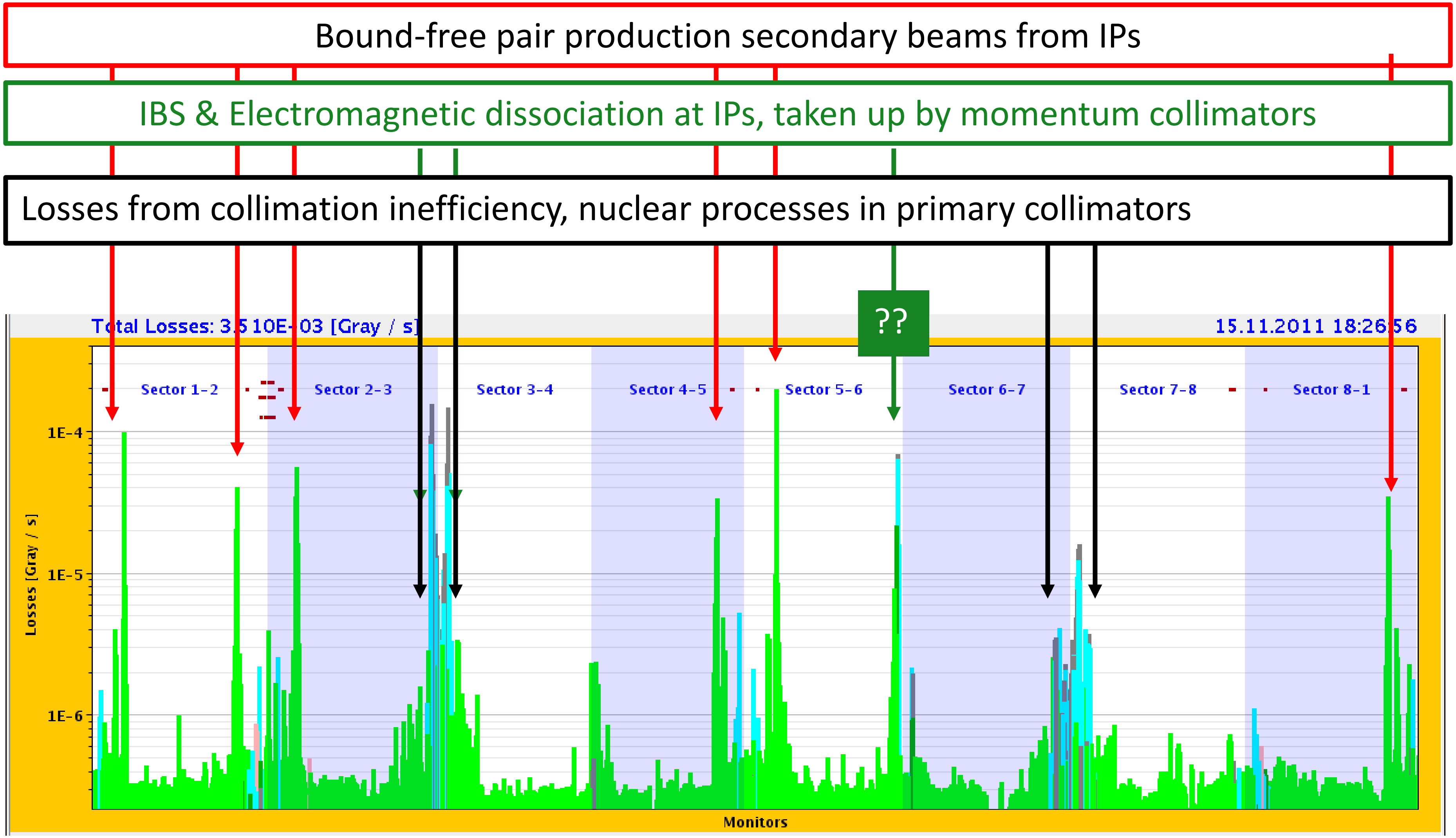
Thanks for valuable input to:

L. Bottura, R. Bruce, F. Cerutti, P. Fessia, M. Giovannozzi,
M. Karpinnen, S. Redaelli, G. E. Steele, D. Tommasini

Plan of talk

- Heavy-ion beam losses in LHC – recap
  - *Pb beams are very different from protons*
- HL-LHC heavy-ion performance goals
- Quench limits from luminosity
- Radiation damage to dipoles
- Cure by DS collimators
- Layout of DS collimators in IR2 (and IR1)
- Quench limits from cleaning efficiency
- Alternative mitigation methods

Steady-state losses during Pb-Pb Collisions in 2011



Electromagnetic processes in Pb-Pb collisions

$$\text{BFPP1:}\quad {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{81+} + e^{+},$$
$$\sigma = 281\ \text{b},\quad \delta = 0.01235$$

$$\text{BFPP2:}\quad {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{80+} + 2e^{+},$$
$$\sigma \approx 6\ \text{mb},\quad \delta = 0.02500$$

$$\text{EMD1:}\quad {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{207}\text{Pb}^{82+} + n\ ,$$
$$\sigma = 96\ \text{b},\quad \delta = -0.00485$$

$$\text{EMD2:}\quad {}^{208}\text{Pb}^{82+} + {}^{208}\text{Pb}^{82+} \longrightarrow {}^{208}\text{Pb}^{82+} + {}^{206}\text{Pb}^{82+} + 2n\ ,$$
$$\sigma = 29\ \text{b},\quad \delta = -0.00970$$

Each of these makes a secondary beam emerging from the IP with rigidity change

$$\delta = \frac{1 + \Delta m / m_{\text{Pb}}}{1 + \Delta Q / Q} - 1$$

Hadronic cross section is 8 b (so much less power in debris).

Discussed since Chamonix 2003 …

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS
12, 071002 (2009)

Beam losses from ultraperipheral nuclear collisions between $^{208}Pb^{82+}$ ions in the Large Hadron Collider and their alleviation

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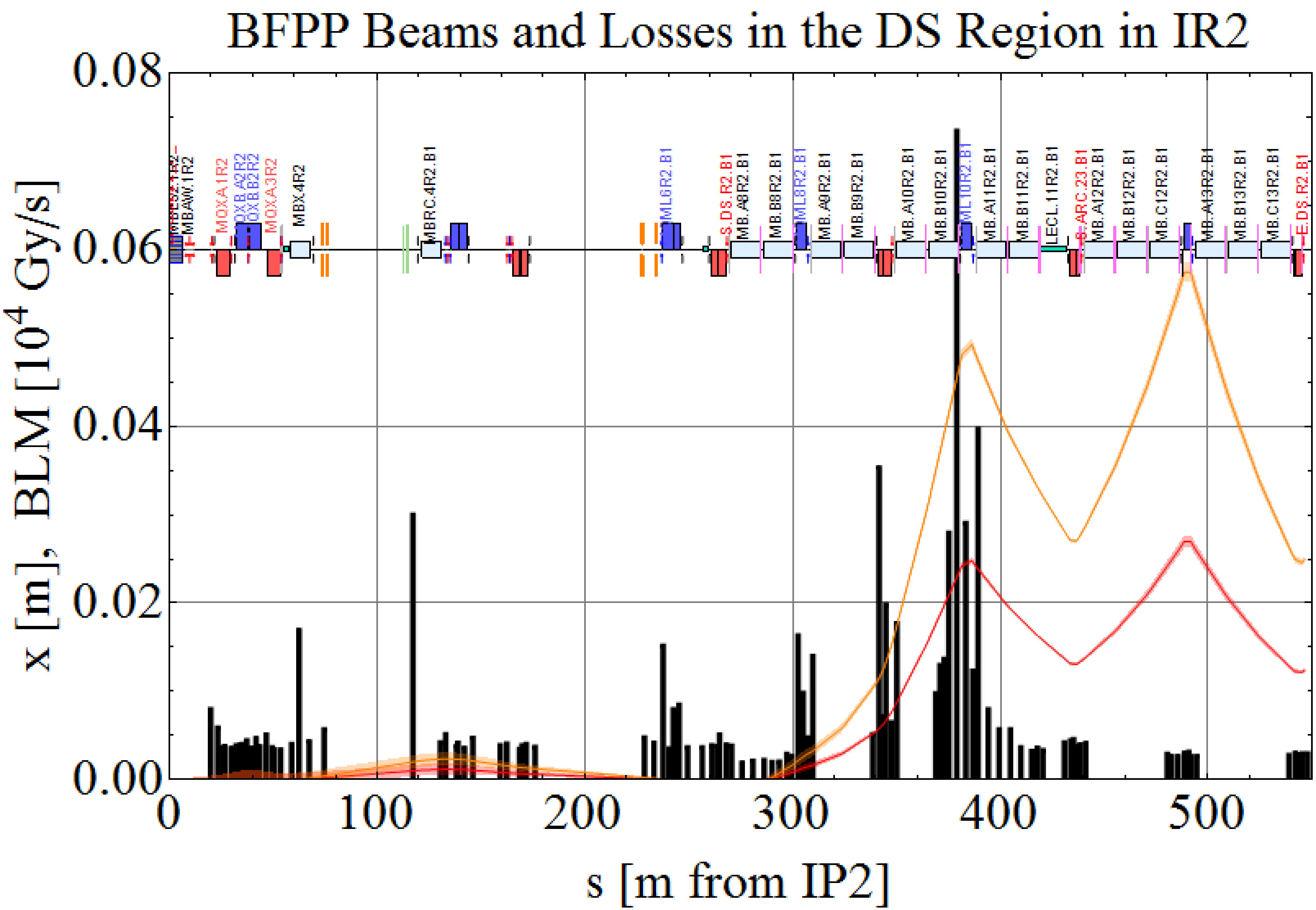
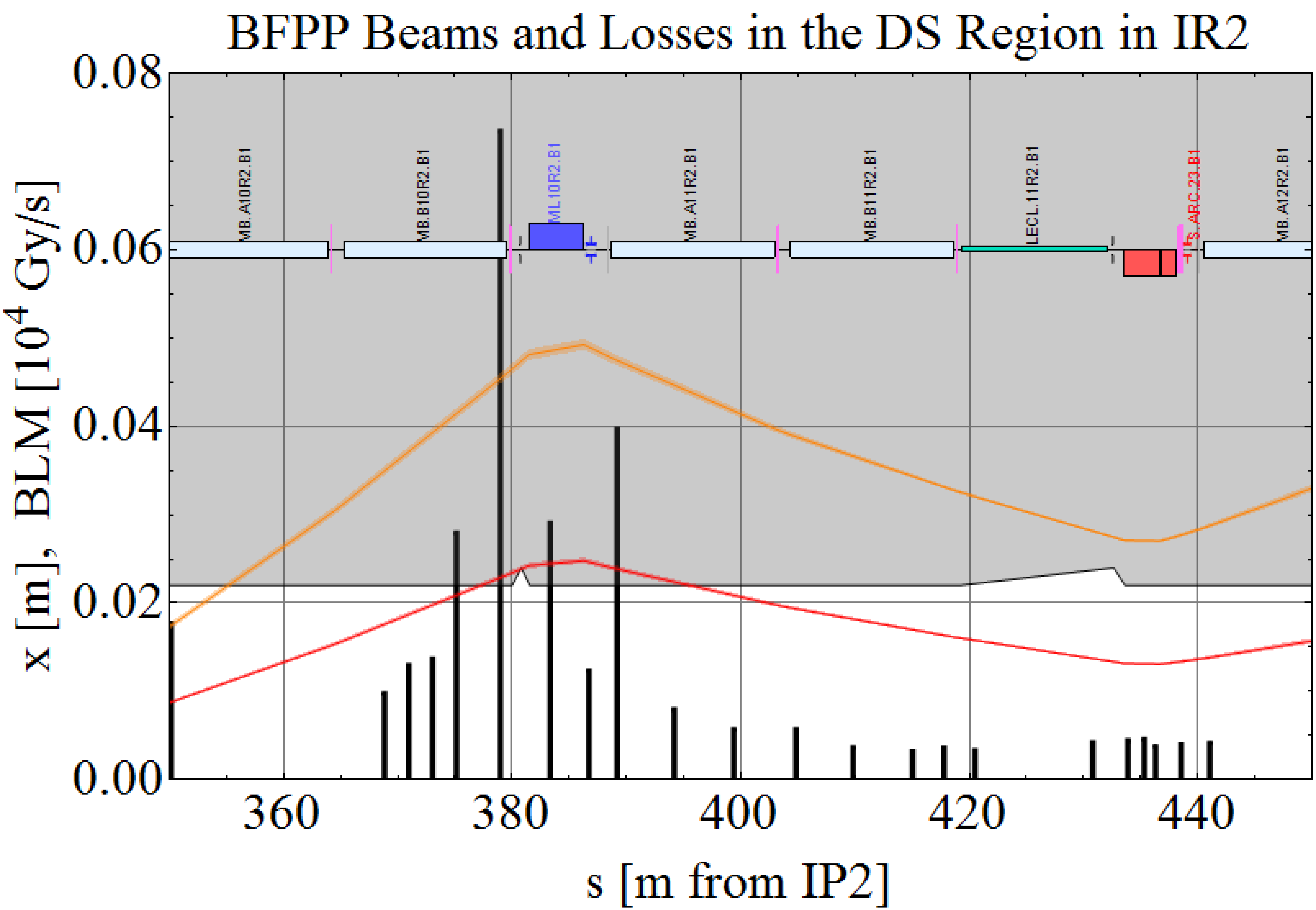
(Received 13 May 2009; published 29 July 2009)

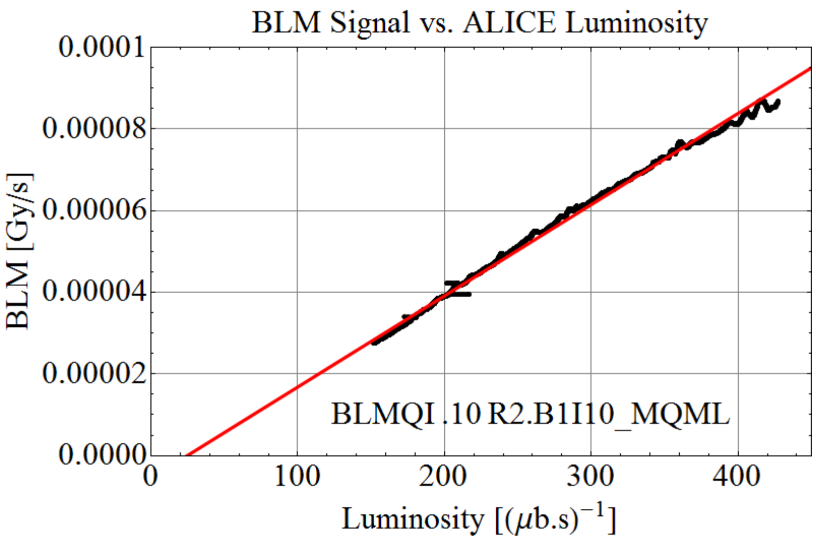
2011 Pb-Pb operation

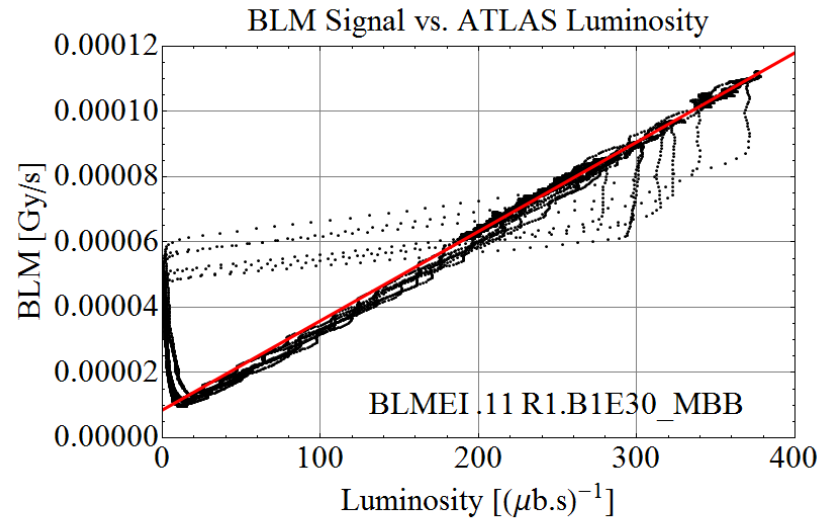


Zoom in to loss region



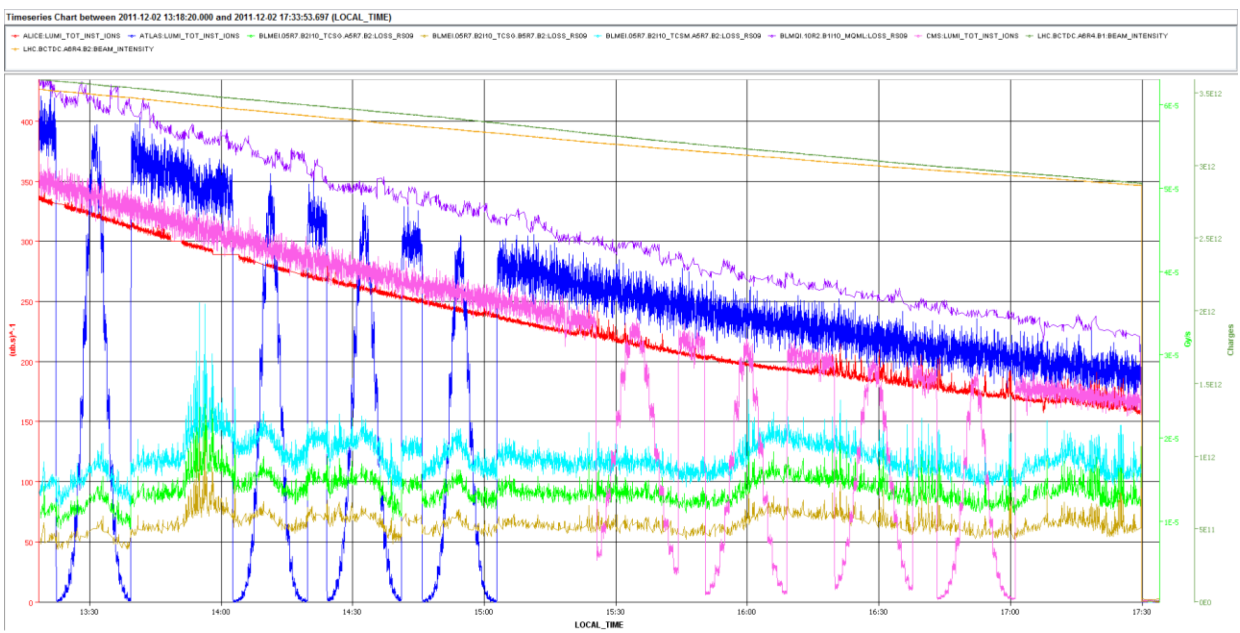
Main losses in DS are due to luminosity





Regular physics fill

From van der Meer scans



HL-LHC Performance Goals for Pb-Pb collisions

With upgrade of Pb injectors, etc, indicative parameter goals:

ALICE upgrade integrated luminosity goal for post-2018 period

$\int L\, dt = 10\ \text{nb}^{-1} = 10 \times \text{(first phase)}$

equivalent to $\int L_{NN}\, dt = 0.43\ \text{fb}^{-1}$ nucleon-nucleon luminosity.

Annual integrated luminosity (1 month run) $\approx 1.5\ \text{nb}^{-1}$

Peak luminosity $L \approx 6 \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1} = 6 \times \text{design}$

Up to $k_b = 912$ bunches with mean intensity $N_b = 2.2 \times 10^8$ Pb.

Stored energy in beam: $\text{W} \approx 18\ \text{MJ} = 4.8\ \times \text{design}$

Power in BFPP1 beam: $P_{\text{BFPP1}} = 155\ \text{W}$

Power in EMD1 beam: $P_{\text{EMD1}} = 53\ \text{W}$

ATLAS and CMS also taking luminosity (high burn-off).
Levelling strategies may reduce peak luminosity but we must aim for high intensity.
Comparison data: p-Pb runs every few years are less demanding from beam-loss point of view

Runs with lighter species (unlikely ?) are not considered here.

Power density in superconducting cable

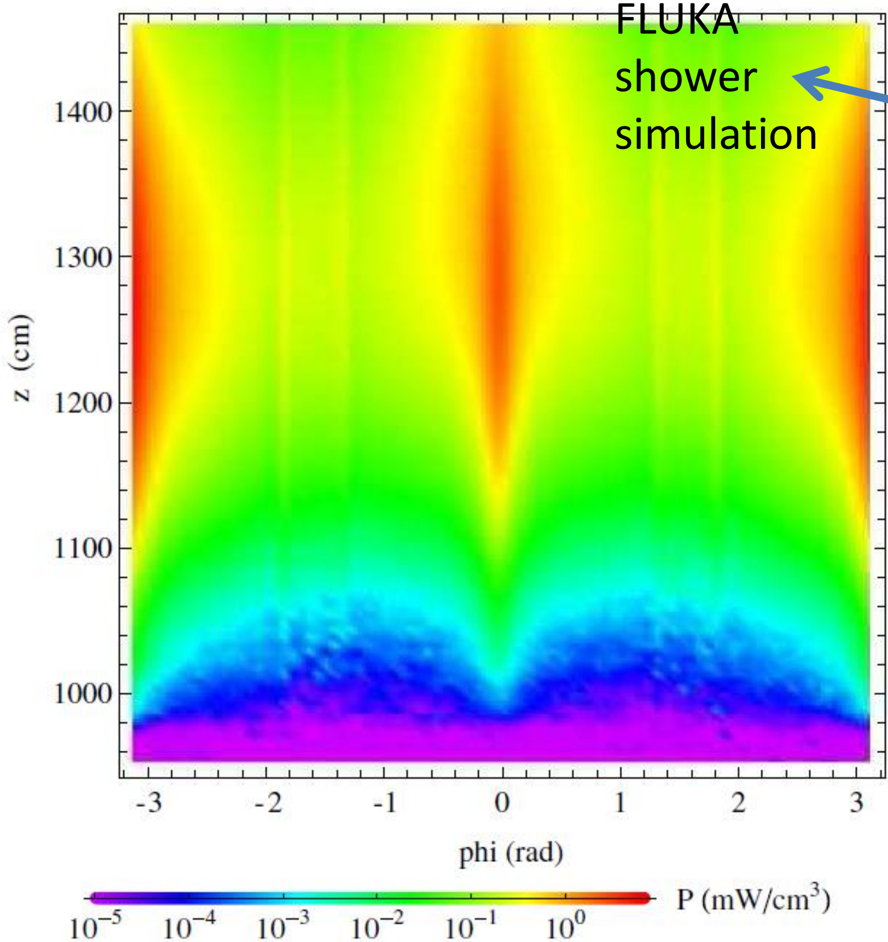


FIG. 7. (Color) The heating power from beam losses caused by BFPP in the inner layer of the coil of an LHC main dipole as simulated with FLUKA. The power density was averaged over the width of the cable and is shown as a function of azimuthal angle ϕ and longitudinal coordinate z, with $z = 0$ in the beginning of the magnet. The beam loss is centered around $z = 1206$ cm and $\phi \approx -3.11$ rad.

FLUKA shower simulation

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Maximum power density in coil at 7 Z

$P = 15.5\ \mathrm{mW/cm^3}$ at design luminosity.

For upgrade luminosity, expect

$P \approx 93\ \mathrm{mW/cm^3}$

See other talks!

c.f. quench limit (latest from A. Verwei

200 mW/cm³ at 4 Z TeV

40-50 mW/cm³ at 7 Z TeV

(higher than used previously)

Nevertheless, expect to quench MB and possibly MQ!

FLUKA studies confirmed recently (next talk).

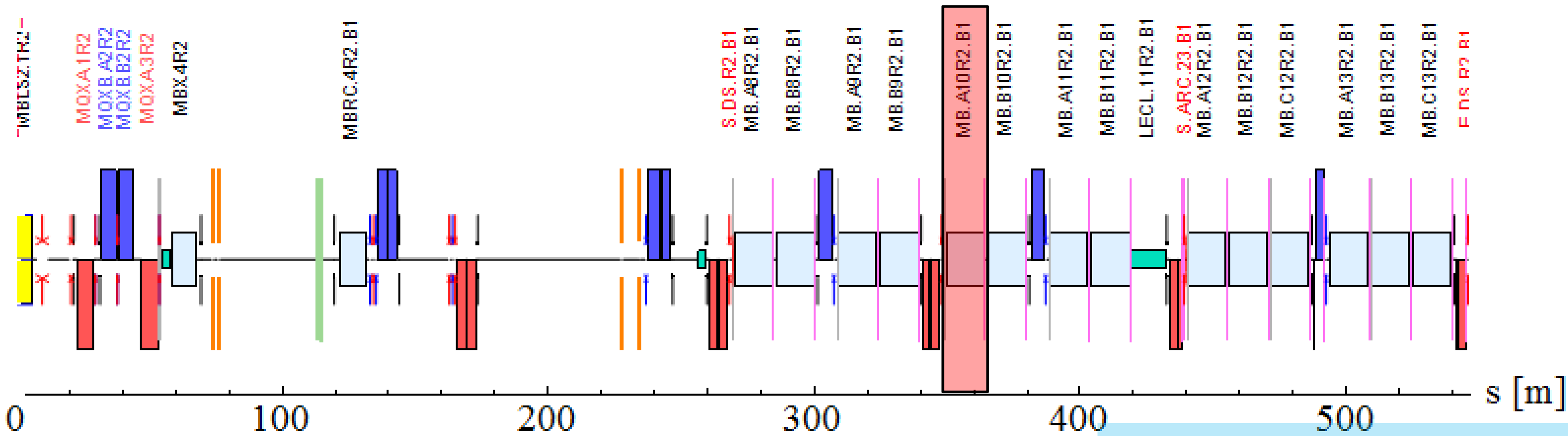
DS collimator solution

- First discussed for heavy ion operation at Chamonix workshop in 2003
  - Idea of modifying cold sections of LHC was not well-received at that time.
- *Switch to CDF file to show that:*
  - Well-placed collimator can stop the secondary beams and stay well clear of main beam.
  - By adjusting collimator gap it is possible to also select EMD1 beam and reduce losses in IR3 (possibly IR7).

DS collimator installation in IR2

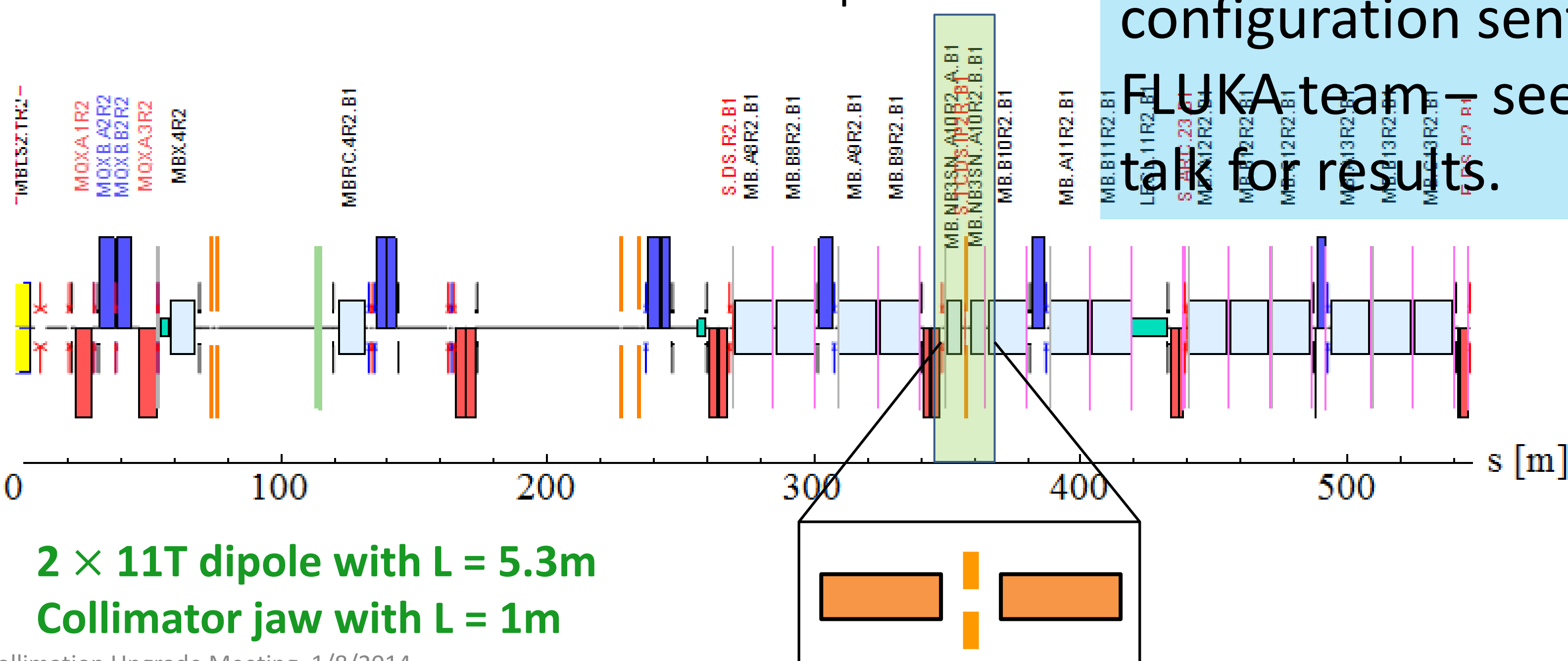
Magnet to be replaced **MB.A10R2**

Nominal Beam Line



IP2

Modified Sequence

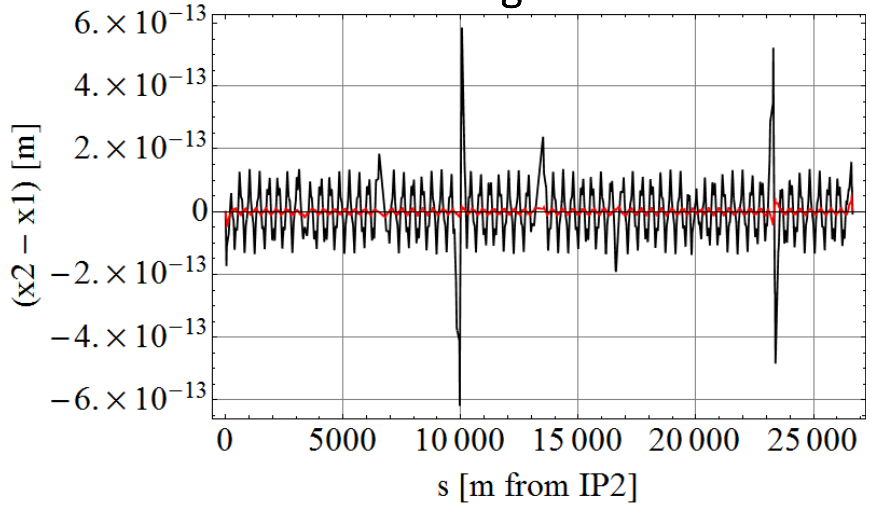


Tracking with this configuration sent to FLUKA team – see next talk for results.

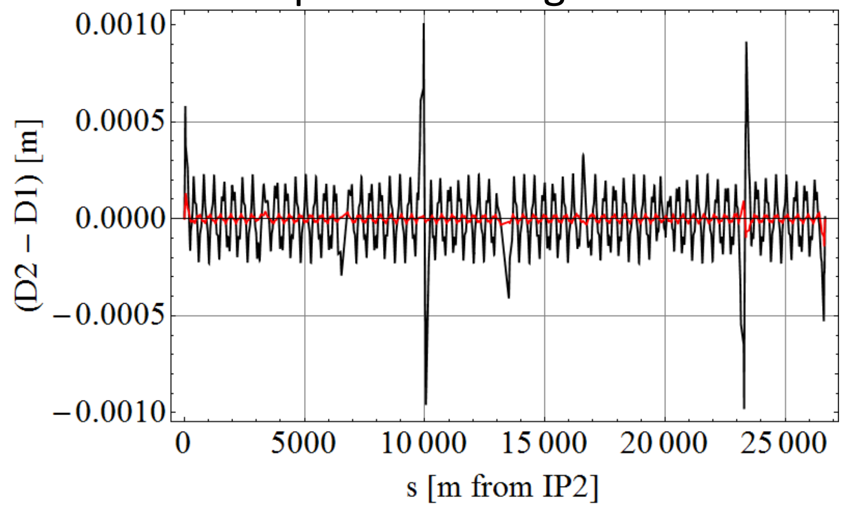
2 × 11T dipole with L = 5.3m
Collimator jaw with L = 1m

Optics and orbit perturbations

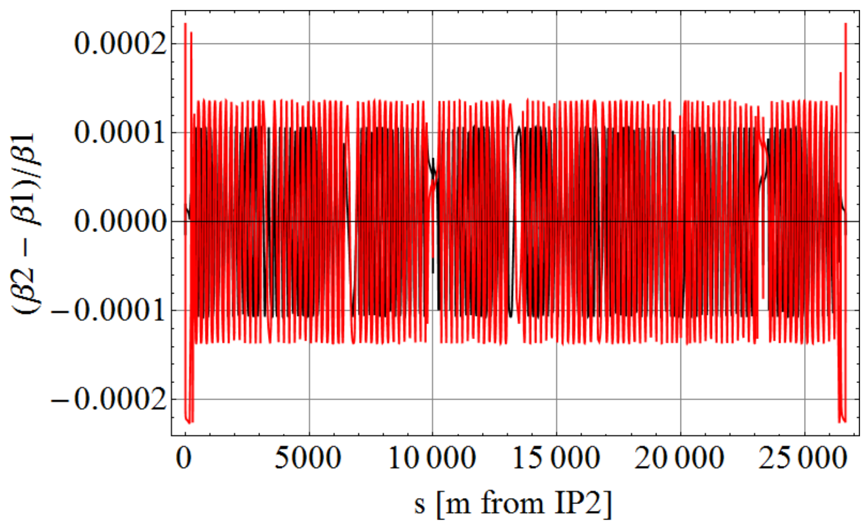
Orbit change in X and Y



Dispersion change in X and Y

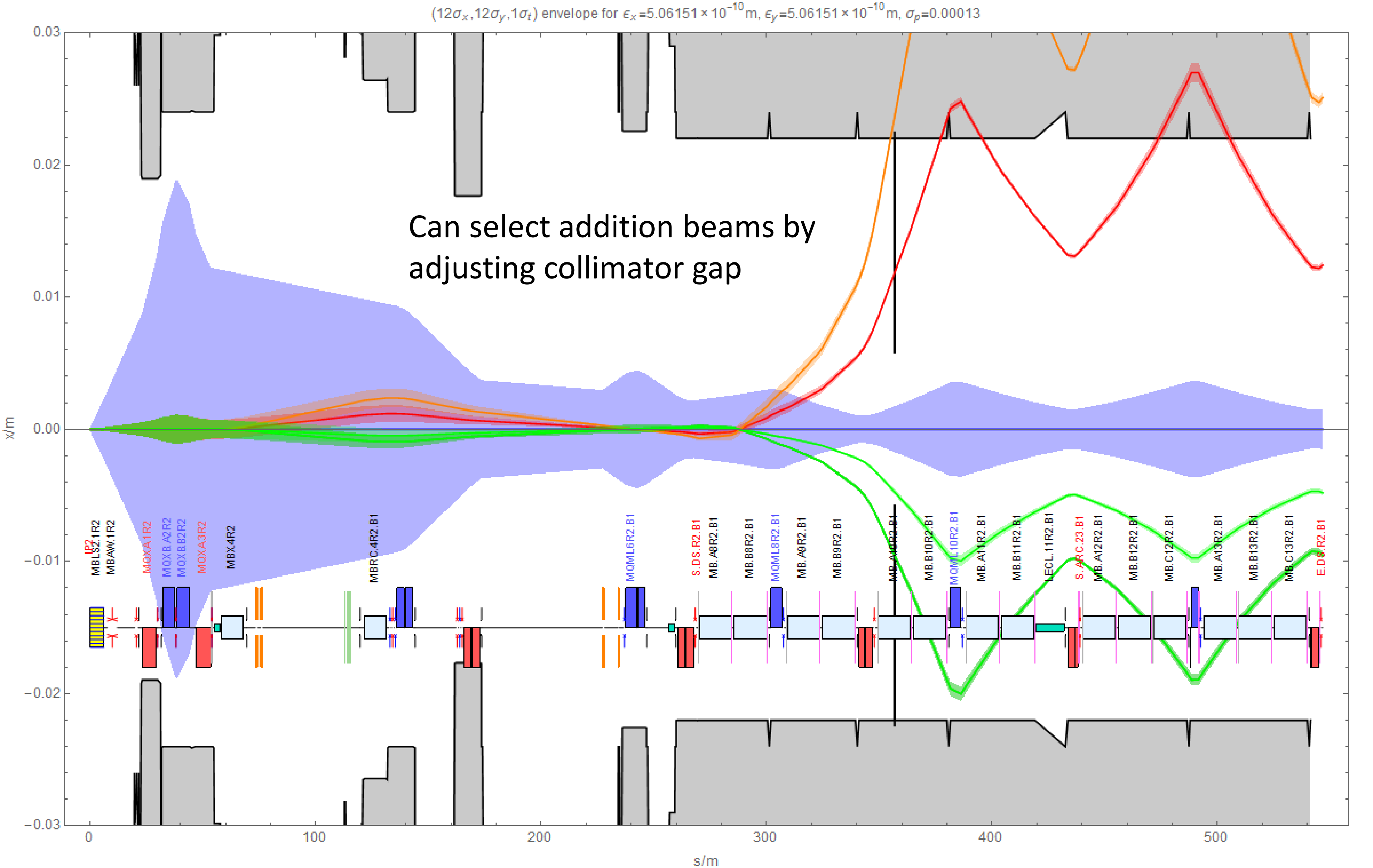


β-Beat in X and Y



Change are very small, not worth correction.

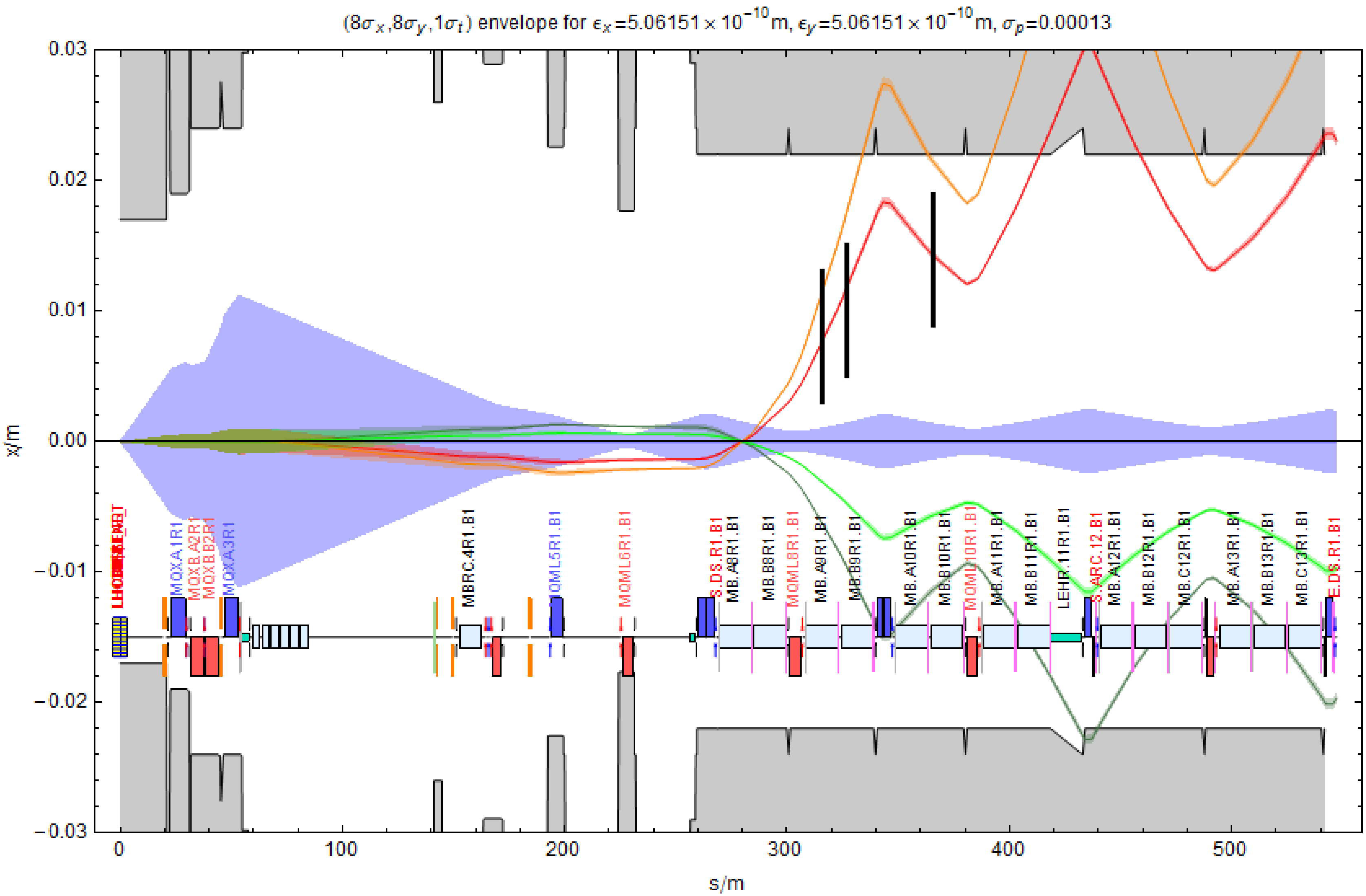
DS collimator absorbs most powerful losses



ATLAS and CMS ?

- ATLAS and CMS also take high-luminosity Pb-Pb
- The same problem of BFPP losses exists in the DSs around IP1 and IP5
  - Details of loss locations somewhat different
  - Highest BLM signals from BFPP in 2011 were right of IP5
- Previously we assumed the priority would be an installation (LS3?) designed for proton-proton luminosity debris. Now less clear …
- Motivation could now be to install DS collimators to avoid a peak luminosity limit from quenches and/or long-term radiation damage in Pb-Pb operation ?

DS Collimator locations around ATLAS



Different from IR2 but various locations seem effective

Strategy and Decision Points for HL-LHC Heavy Ions

- First Pb-Pb run at ~6.5 *Z* TeV will be in November 2015
  - Expect data on quenches for luminosity up to ~ 3×10^{27}cm^{-2}s^{-1} around ATLAS and CMS, hope for Pb quench tests but may be difficult to get the time
  - ALICE will be levelled at 10^{27}cm^{-2}s^{-1}
  - Operational experience with BFPP mitigation by bumps
  - Probably some relevant data also from proton operation and quench tests
- End 2015: assess need for DS collimator installation in LS2 along with ALICE upgrade
  - Also consider ATLAS and CMS in LS3
- DECISION

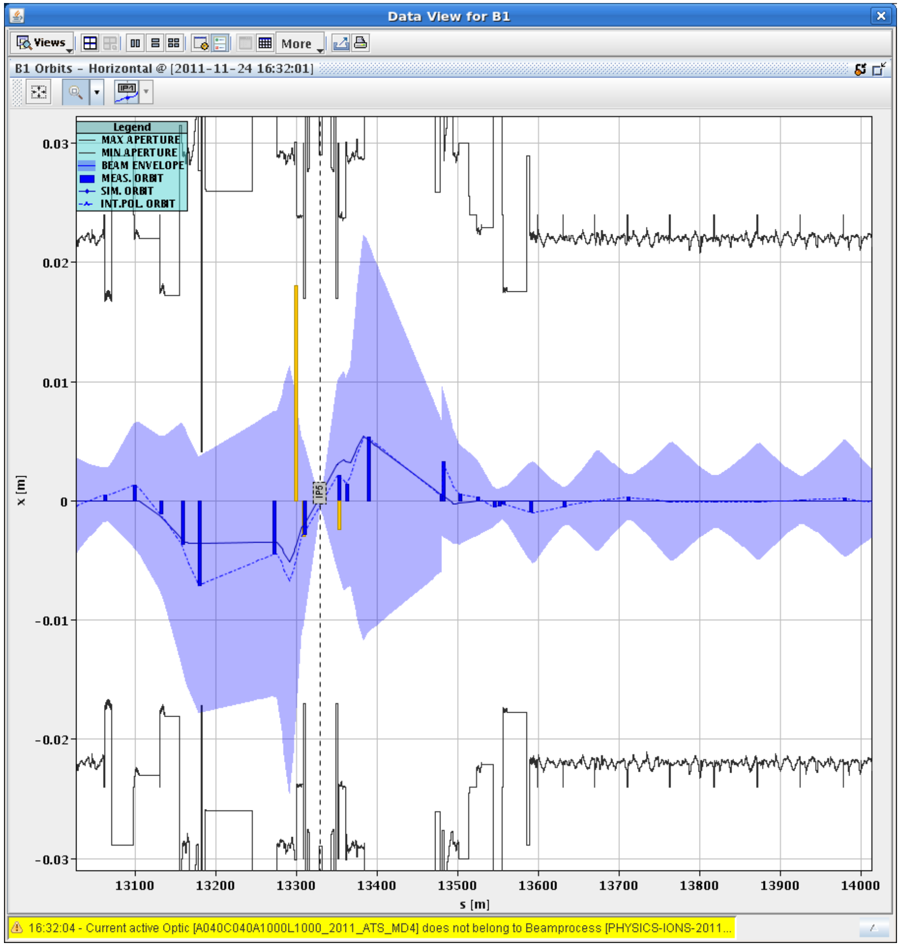
BFPP mitigation by bumps

- Proposed in R. Bruce et al, Phys Rev STAB, 12, 071002 (2009)
- Apply bump to main beam orbit in loss region, also moves BFPP beam away from impact point, reducing flux, angle of incidence, peak power density.
- Tested opportunistically in 2011 Pb-Pb run gained on BLM signals.
- If truly effective and reliable, and accepted by Machine Protection, could be an alternative to DS collimators.
- May have to rely on this in the period after LS1.

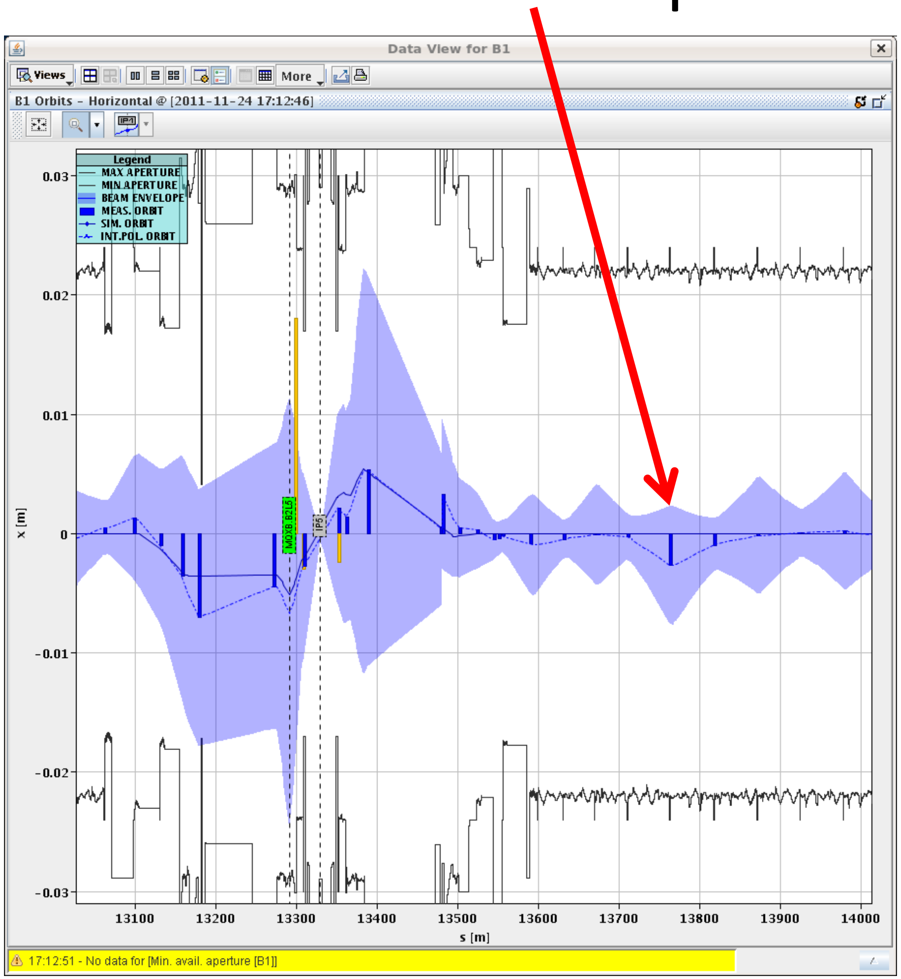
Orbit bump: -2.6 mm at Q11.R5.B1 in steps

12 sigma envelopes from online model

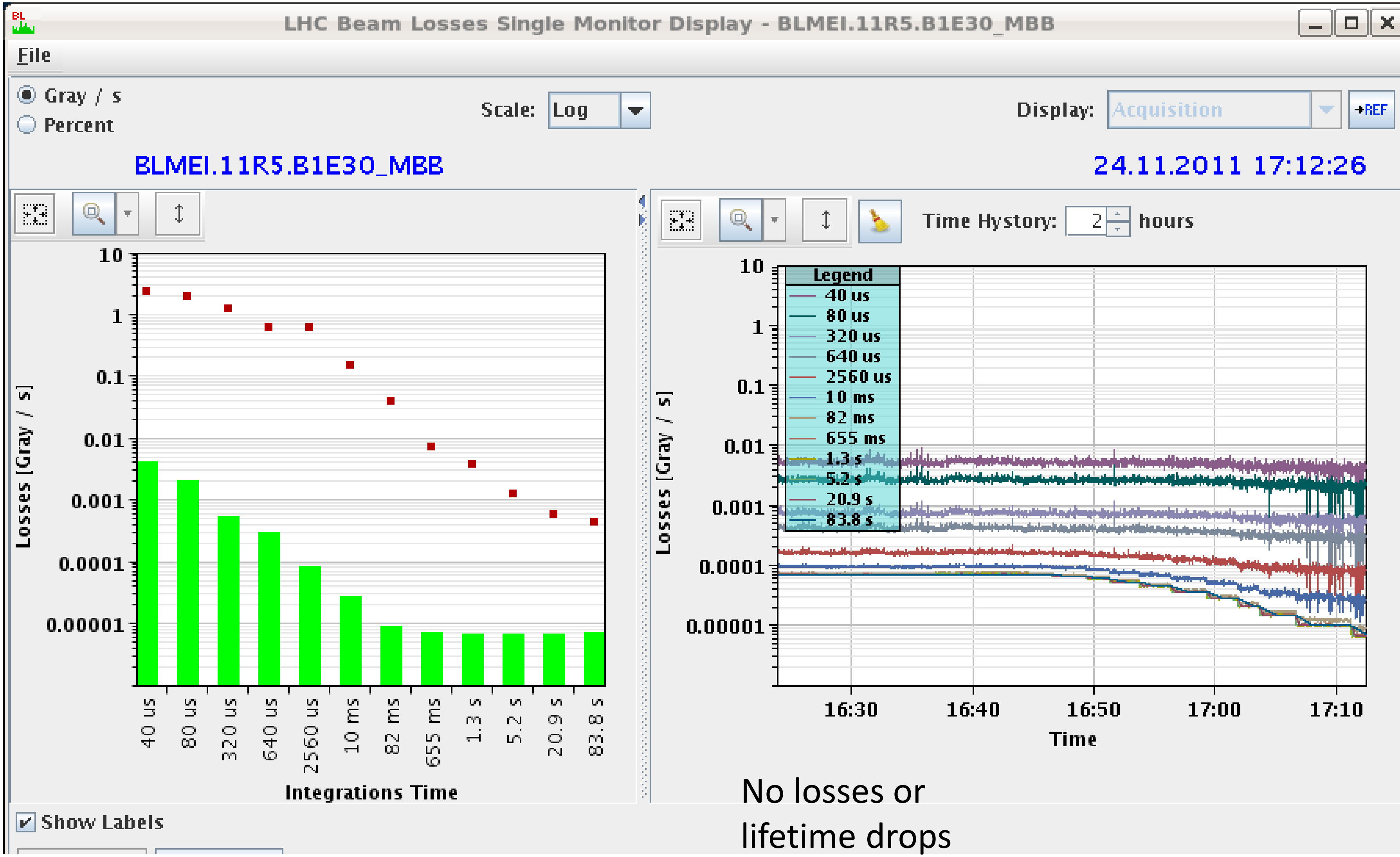
without bump



with bump

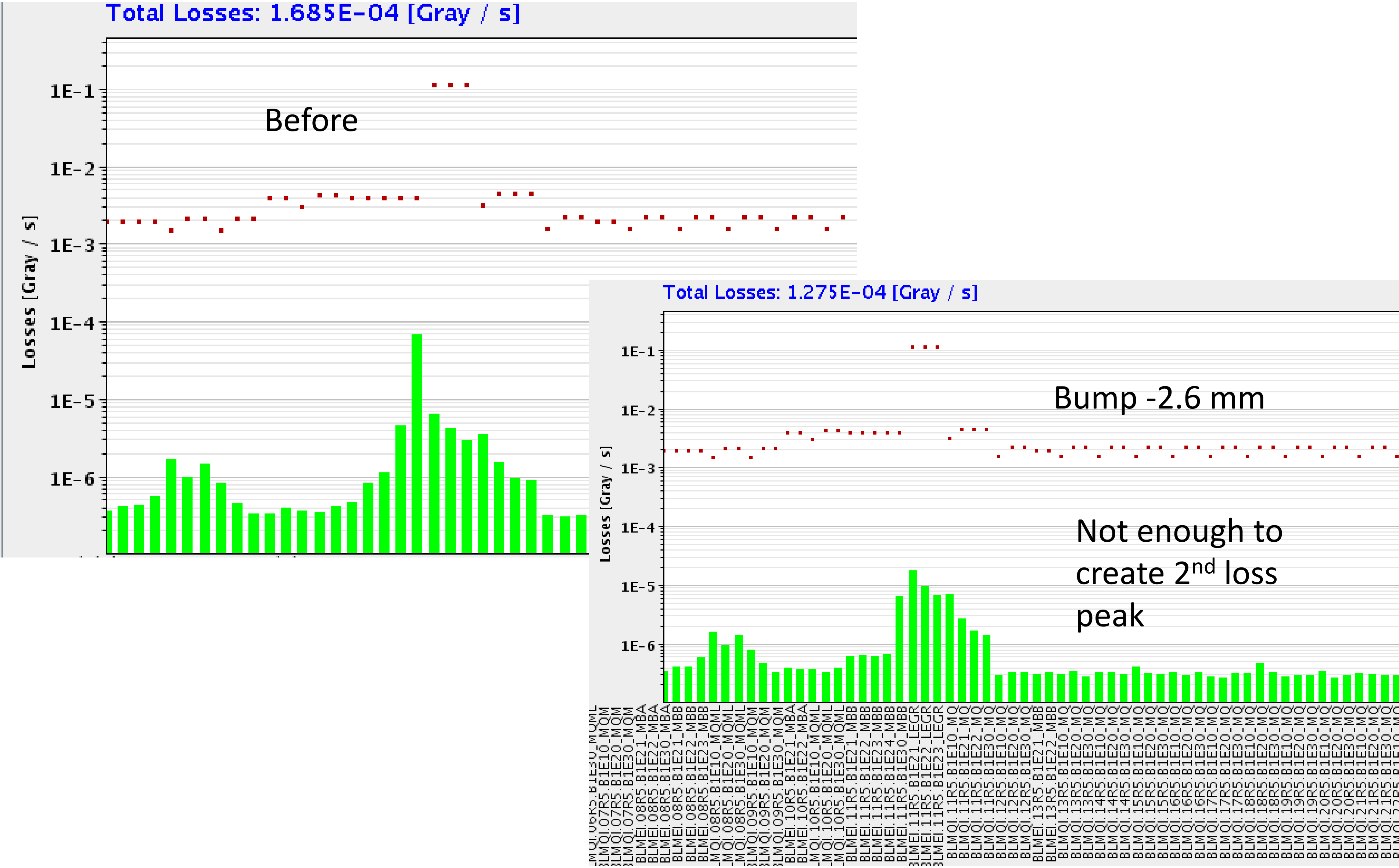


Effect on losses



No losses or lifetime drops

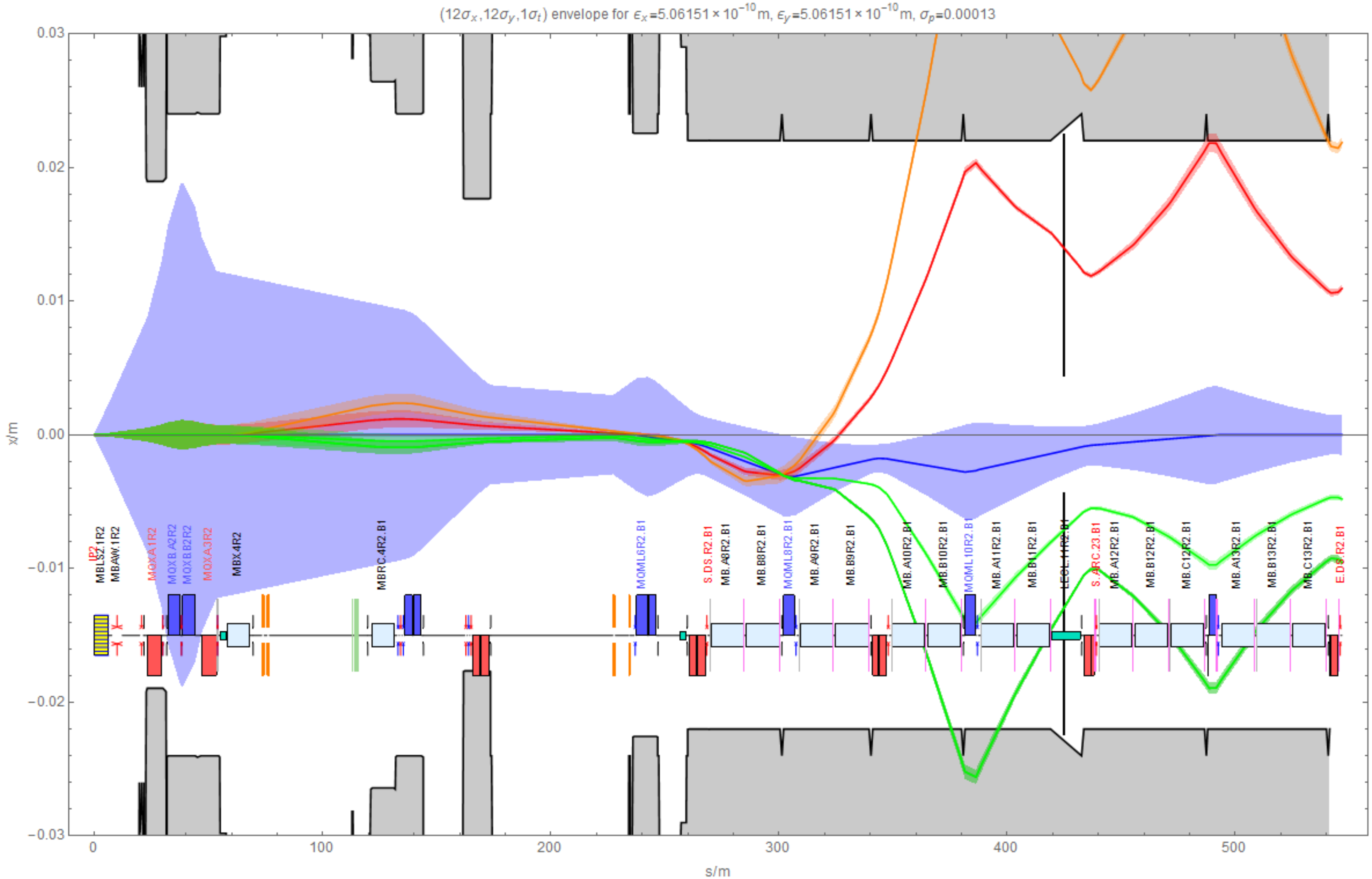
Effect on loss pattern



Alternative solution?

- There is a *possibility* that we can combine bumps and an alternative location of the TCLD
  - No 11 T magnets
  - Different but simpler integration

TCLD in connection cryostat



Remarks on alternative of TCLD in connection cryostat

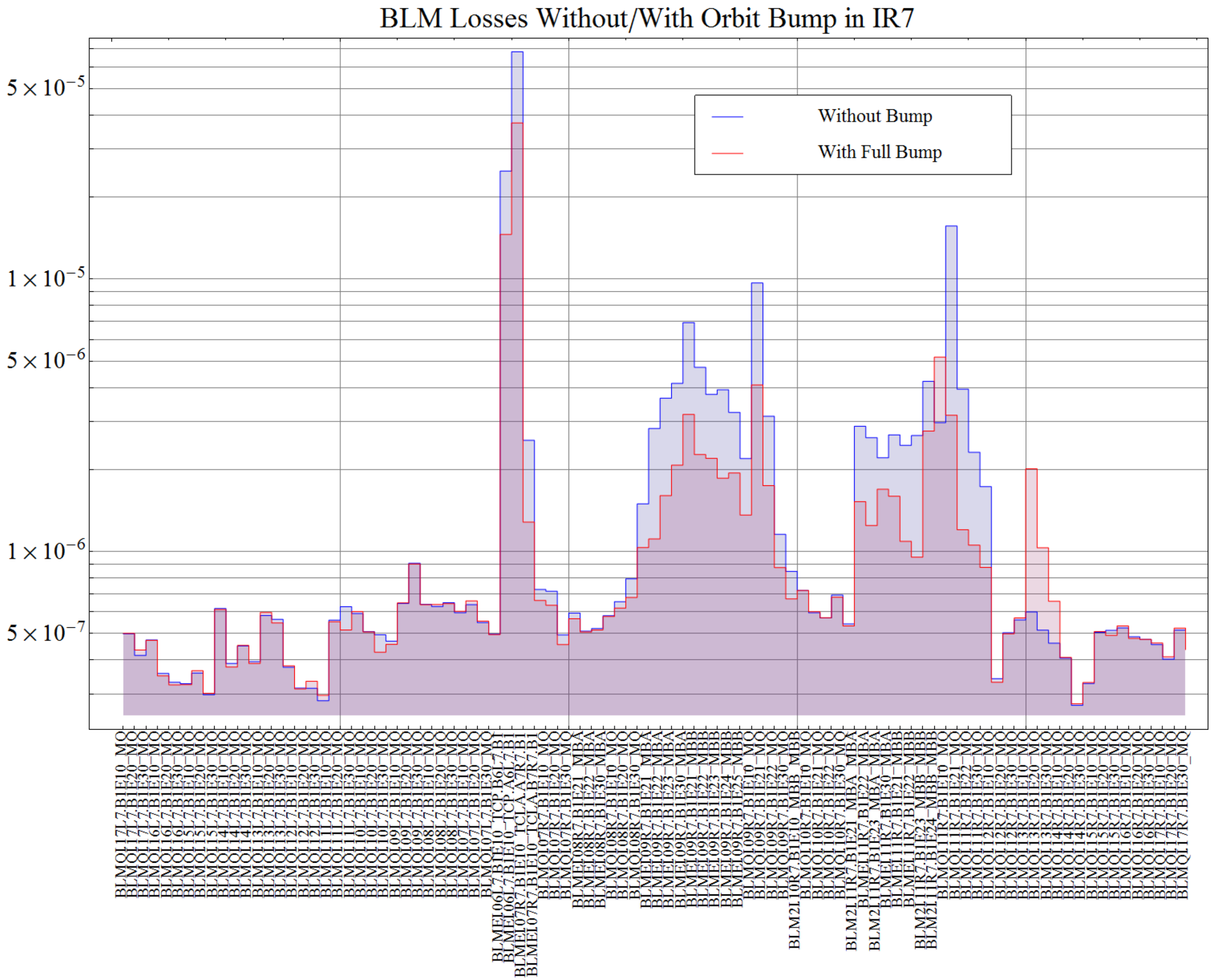
- *Might* work for ALICE in IR2
- *Cannot* work for ATLAS or CMS (or IR7 …)
  - different dispersion function
  - 11 T magnets will be needed in other IRs
- Orbit bumps of a few mm over ~200 m of dispersion suppressor
  - Requires machine protection discussion!
  - Possibility of selectively controlling losses from various mechanisms is retained
- Further study required
  - Is there sufficient remaining corrector strength for regular orbit correction purposes ?
  - Shower calculations in FLUKA, etc

Conclusions

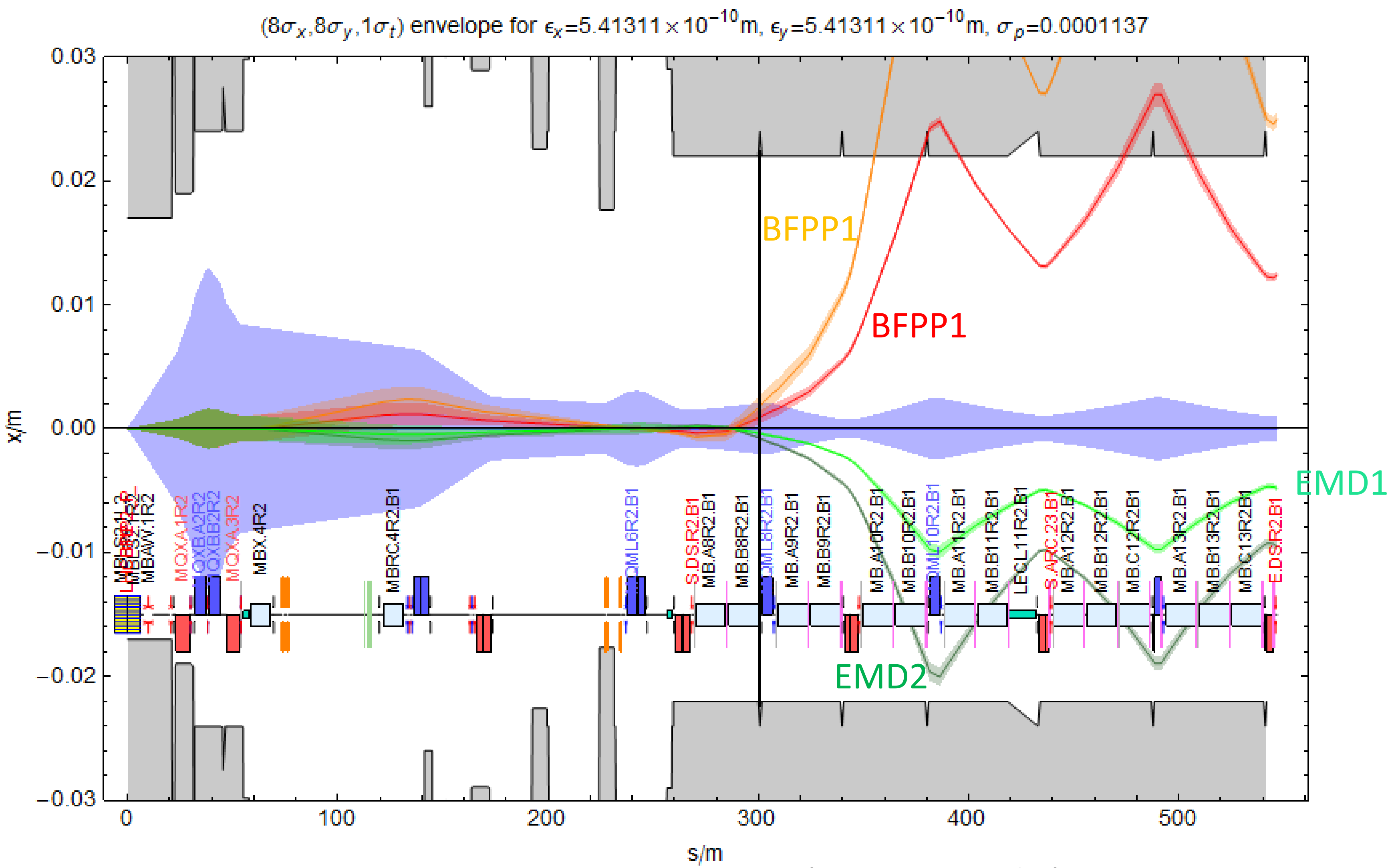
- DS collimators are very effective means to raise Pb-Pb luminosity limit
  - Four 11 T dipoles + 2 DS collimators required for ALICE in LS2
  - Some variation possible in IR1, IR5 if required for ATLAS, CMS
  - Could also be installed in IR1, IR5 dispersion suppressors to increase peak luminosity limit for ATLAS and CMS in LS3
- DS collimators in IR7 (8 dipoles, 4 collimators) may still be needed for high-intensity heavy-ion operation
- Experience from first 6.5 Z TeV Pb-Pb run (with Pb quench tests!!) at end of 2015 crucial for decision-making on DS collimator installation
- Possible alternative without 11 T dipoles for ALICE only – needs validation

BACKUP SLIDES

Unnormalized BLM losses during bump method test in IR7



Secondary beams from Beam 1 in IR2



Cannot separate BFPP and main beam in warm area (TCLs not useful)

BFPP beam is smaller than main beam (source is luminous region).

Polyimide radiation damage data

Material:	**Polyimide**	TIS No. **M 702**
Type	**Kapton H**	
Supplier:	**DuPont de Nemours**	UL 94:
Remarks:	125 micron film	LOI: n.m.

Radiation test results according to IEC Standard 544

Dose (MGy)	Mechanical test results at RT			Mechanical test results at 77 K	
	Strength (MPa)	Elongation ε (%)	Hardness (Shore D)	Strength (MPa)	Elongation ε (%)
0	165.0 ± 13.0	23.5 ± 11.0	67	274 ± 9	7.8 ± 0.1
1	177.0 ± 5.0	29.5 ± 4.1	64		
3	171.0 ± 2.0	25.5 ± 4.5	68		
10	168.0 ± 2.0	21.5 ± 3.4	68		
35				202 ± 14	7.4 ± 0.3
50	135.0 ± 6.0	9.0 ± 1.7	63		
119				172 ± 1.8	5.1 ± 0.1
RI =	> 7.7	7.3		> 8.3	[illegible]

Invoke superposition principle: radiation damage from heavy ions is similar to equivalent nucleons once they have fragmented after passing through a few cm of matter.

For the polyimide mechanical damage, that normally comes before the electrical damage see the picture here below coming from the CERN 96-05. As you can see there is no degradation surely till 10 MGy and probably till 20 .After that the degradation is very mild. The magnet is designed with margin therefore I would expect no mechanical failure probably until 30MGy (even the measured value at 50 are still ok but let's keep margin)
from P. Fessia

Radiation effect on Kapton film M 702

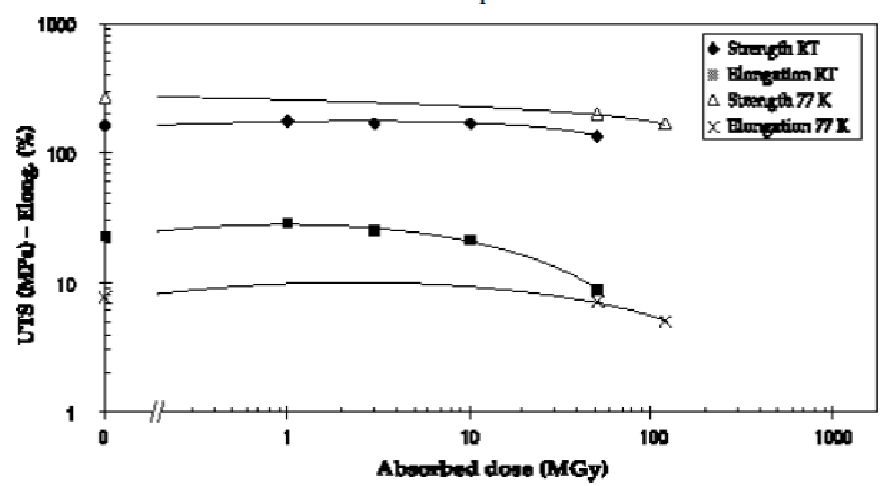


Fig. 5: Kapton H M 702

Radiation damage

Knowing the power density, P, for a given luminosity, L, and the coil material density, $\rho = 7$ g cm^{-3} (combined superconductor and polyimide insulation), we can estimate the radiation dose per unit of integrated luminosity (in the Pb-Pb runs only!)

$$\frac{P}{\rho L} = 2.2 \text{ MGy}/(\text{nb}^{-1}).$$

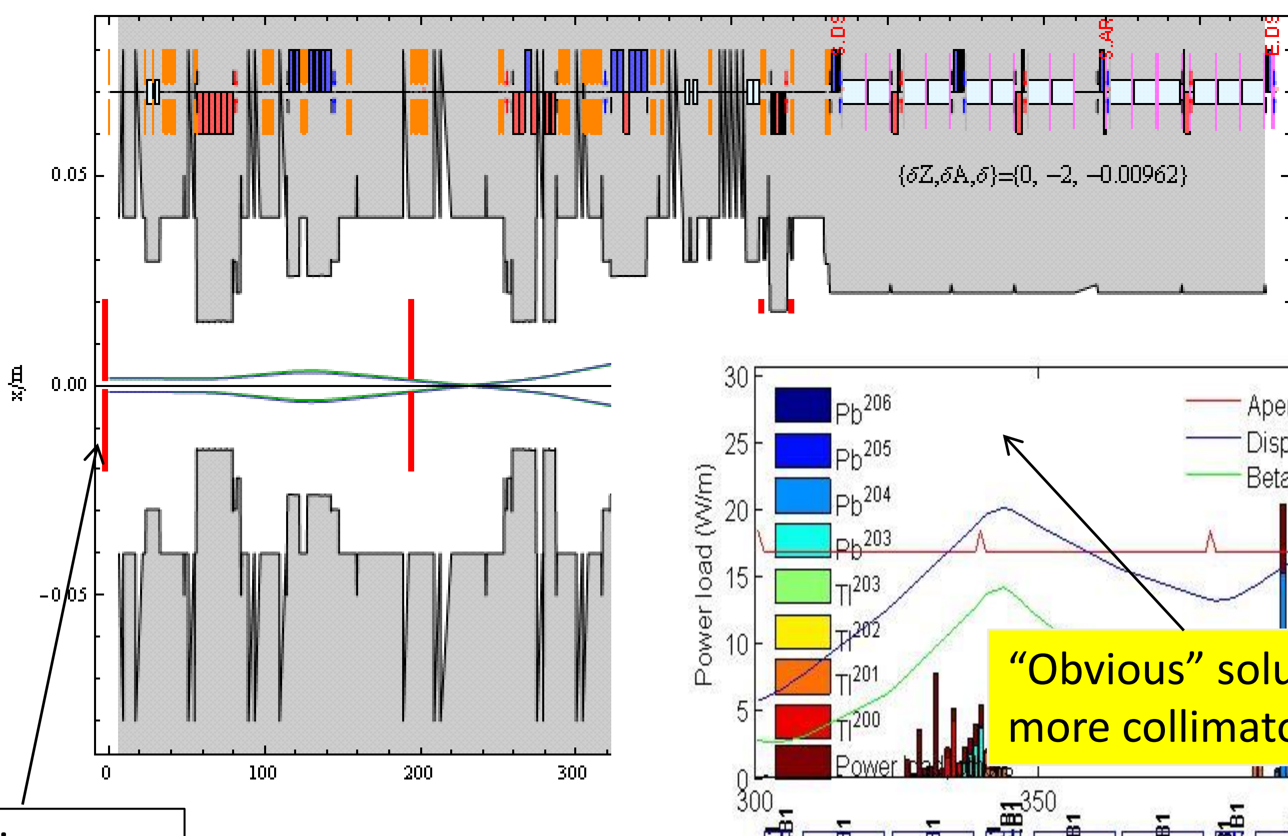
Thus, in attaining the HL-LHC luminosity goal, the coil may be exposed to a dose of some 22 MGy.

Comparable to damage limit of polyimide insulator.

Is there a risk of magnet short-circuit over lifetime of HL-LHC unless magnets are pre-emptively replaced?

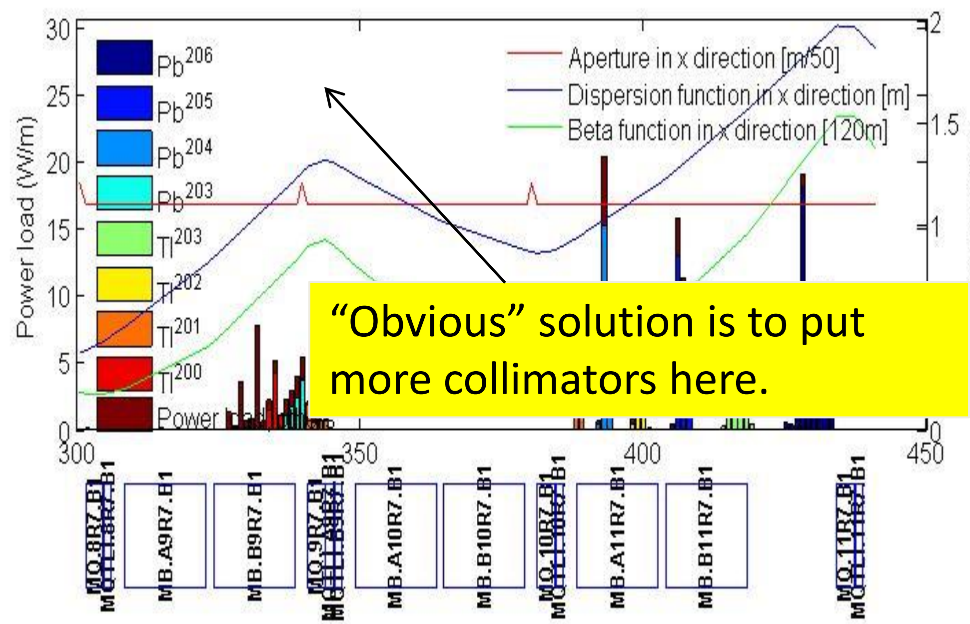
Example of ^{206}Pb created by EMD2 in primary collimator

- Green rays are ions that almost reach collimator
- Blue rays are ^{206}Pb rays with rigidity change



Beam pipe in IR7 of LHC

Primary collimator



"Obvious" solution is to put more collimators here.

DS collimators in IR7 for heavy ions

- No quench test with ion beams in 2013
- Some results from 2011 only showed that upgraded design intensity is just OK with 1 h lifetimes (questionable?).

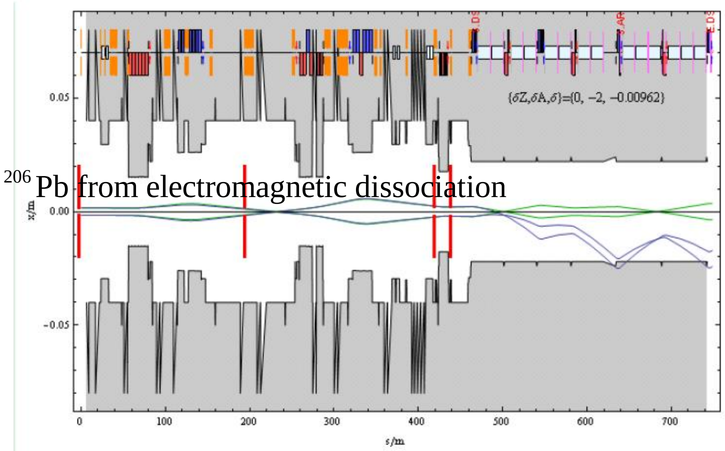
> ATS/Note/2012/081 MD
>
> 2012-10-29
>
> Giulia.Bellodi@cern.ch
>
> **Pb ions collimator losses in IR7 DS and quench test at 3.5 Z TeV**
>
> G. Bellodi, R W Assmann, R Bruce, B Dehning, E B Holzer, J M Jowett, E Nebot del Busto, L Ponce, S Redaelli, M Sapinski, M Schaumann, R Schmidt, M Solfaroli Camillocci, G Valentino, D Valuch, R Versteegen, J Wenninger, D Wollmann, M Zerlauth /

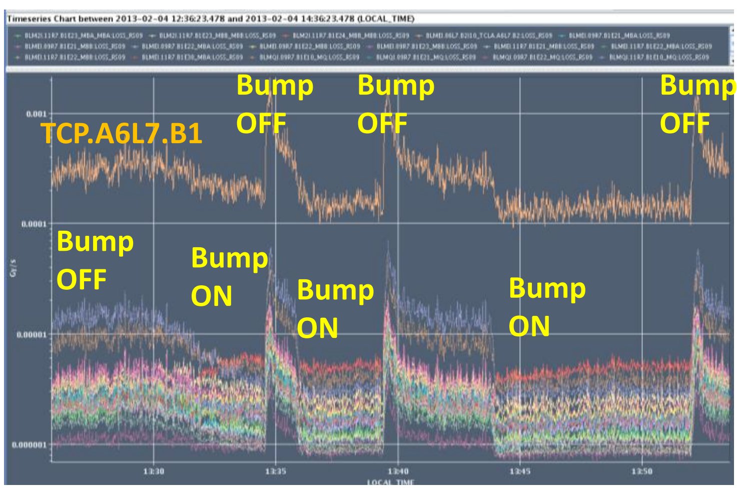
- In 2013 p-Pb run, we were forced to raise BLM thresholds to nominal quench limit in squeeze because of losses
  - Pb beams are larger than p beams
  - Partly related to movements of orbit, tight collimators
- Experience after LS1 essential to allow better evaluation of need for DS collimators in IR7. Need to watch this!
- DS collimators very effective for Pb in IR7 (see simulations by G. Bellodi in 2011 Collimation Review).

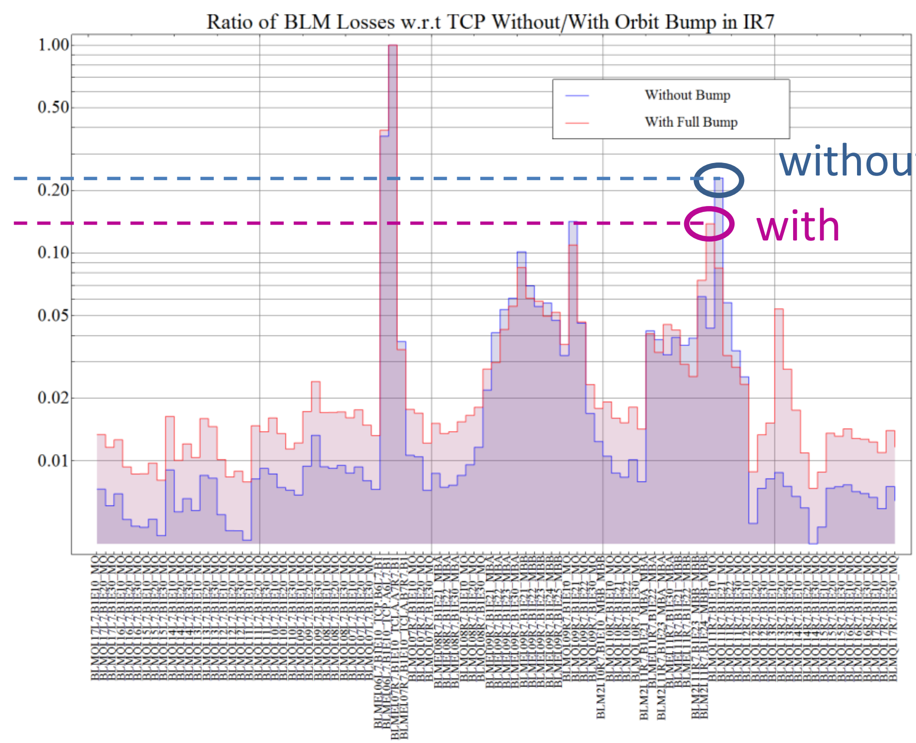
Bump method to mitigate losses in IR7 (test in 2013)

- Test of B1 horizontal orbit bump in IP7 around Q11.R7 (+2.5 mm), to spread the losses longitudinally,
- It worked, we observe a factor **1.62 ± 0.04** gain on the maximum loss peak,
- But losses were reduced at the primary collimator, which should not be influenced, → was there an orbit non closure propagating through the ring?

R. Bruce, E.B. Holzer, J. Jowett, S. Redaelli, B. Salvachua, M. Schaumann







Remark on collimator jaws

- Loss patterns for heavy-ion collimation (some isotopes go to other side of chamber) suggest that two-sided jaws are preferable
- Supported also by FLUKA simulations of shower from one jaw (see next talk) – the other jaw helps to protect the magnets