Observations of bound-free pair production and other photon-induced effects in the LHC and plans to mitigate their impact on future performance

John Jowett, Michaela Schaumann

Some contributors to this topic over the years:

A.J. Baltz, S. Klein, J.-B. Jeanneret, A. Morsch, M. Gresham, H. Braun, I. Pschenichnov, G. Smirnov, A. Ferrari, V. Vlachoudis, R. Assmann, R. Bruce, S. Gilardoni, G. Bellodi, D. Bocian, J. Wenninger, S. Redaelli, R. Alemany, G.E. Steele, …

Pair Production in Heavy Ion Collisions

Racah formula (1937) for free pair production in heavy-ion collisions

$$Z_1 + Z_2 \to Z_1 + \mathrm{e}^- + \mathrm{e}^+ + Z_2$$

$$\sigma_{\mathrm{PP}} = \frac{Z_1^{\ 2} Z_2^{\ 2} \alpha^4 \lambda_e^{\ 2}}{\pi} \frac{28}{27}\left[L^3 - 2.198L^2 + 3.821L - 1.632\right] \text{ with } L = \log\left(\gamma_1\gamma_2\right)$$

$$\approx 225 \text{ kb for Pb-Pb at LHC}$$

Cross section for Bound-Free Pair Production (BFPP) (various authors)

$$Z_1 + Z_2 \to \left(Z_1 + \mathrm{e}^-\right)_{1s_{1/2},\ldots} + \mathrm{e}^+ + Z_2$$

has very different dependence on ion charges (and energy)

$$\sigma_{\mathrm{PP}} \propto Z_1^{\ 5} Z_2^{\ 2}\left[A \log\gamma_{CM} + B\right]$$

$$\propto Z^7\left[A \log\gamma_{CM} + B\right] \text{ for } Z_1 = Z_2$$

$$\approx \begin{cases} 0.2 \text{ b for Cu-Cu RHIC} \\ 114 \text{ b for Au-Au RHIC} \\ 281 \text{ b for Pb-Pb LHC} \end{cases}$$

We use BFPP cross section values from Meier et al, Phys. Rev. A, **63**, 032713 (2001), includes detailed calculations for Pb-Pb at LHC energy.
Also papers by Serbo and others for higher order processes.

Electromagnetic processes in Pb-Pb collisions

BFPP1: $$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \longrightarrow {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + e^{+},$$

$$\sigma = 281\ \mathrm{b}, \quad \delta = 0.01235$$

BFPP2: $$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \longrightarrow {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{80+} + 2e^{+},$$

$$\sigma \approx 6\ \mathrm{mb}, \quad \delta = 0.02500$$

EMD1: $$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \longrightarrow {}^{208}\mathrm{Pb}^{82+} + {}^{207}\mathrm{Pb}^{82+} + n\ ,$$

$$\sigma = 96\ \mathrm{b}, \quad \delta = -0.00485$$

EMD2: $$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \longrightarrow {}^{208}\mathrm{Pb}^{82+} + {}^{206}\mathrm{Pb}^{82+} + 2n\ ,$$

$$\sigma = 29\ \mathrm{b}, \quad \delta = -0.00970$$

Discussed since Chamonix 2003 …

Each of these makes a secondary beam emerging from the IP with rigidity change $\delta = \dfrac{1 + \Delta m / m_{\mathrm{Pb}}}{1 + \Delta Q / Q} - 1$

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

Early History

BFPP and other processes contribute to rapid beam intensity decay, A.J. Baltz et al, Phys Reve E, **54**, 4233 (1996)

BFPP can limit luminosity by quenching superconducting magnets in heavy-ion colliders, S. Klein, NIM A **459** (2001) 51

LHC Performance Workshop, Chamonix 2003
Estimates of energy deposition with real LHC magnetic structure and magnets, using older quench limits – concerns about attaining design luminosity.

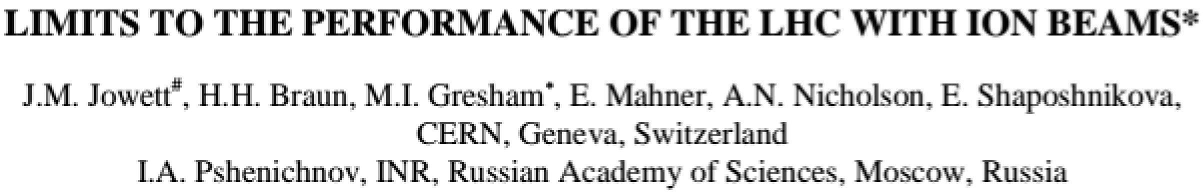
Discussion of stopping the BFPP secondary beam with collimator – ruled out by engineers as too difficult to modify cryogenic section at that stage of LHC construction (+other crazy ideas …).

HEAVY ION BEAMS IN THE LHC

J.M. Jowett, J.-B. Jeanneret, K. Schindl, CERN, Geneva, Switzerland

EPAC 2003

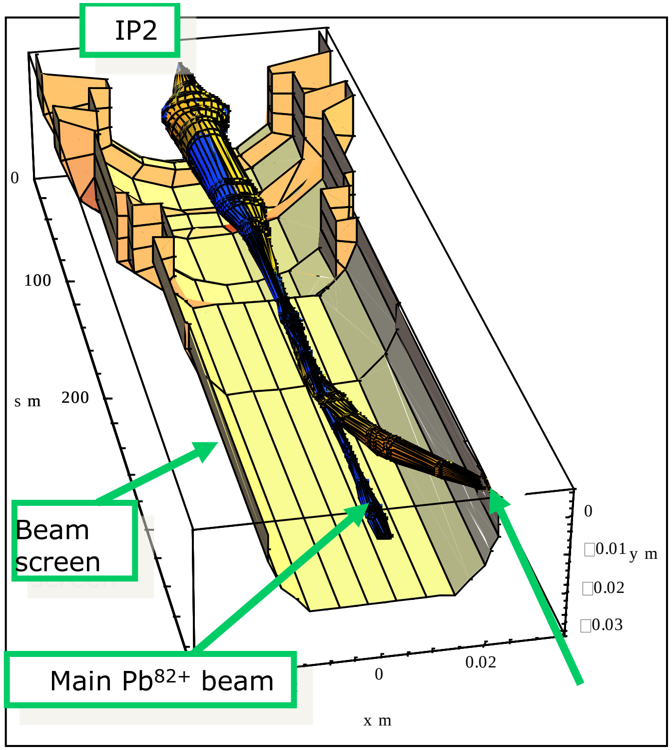
Luminosity Limit from bound-free pair production



LIMITS TO THE PERFORMANCE OF THE LHC WITH ION BEAMS*

J.M. Jowett[#], H.H. Braun, M.I. Gresham*, E. Mahner, A.N. Nicholson, E. Shaposhnikova,
CERN, Geneva, Switzerland
I.A. Pshenichnov, INR, Russian Academy of Sciences, Moscow, Russia

EPAC 2004, Chamonix 2004, LHC Design Report



Secondary Pb^{81+} beam (25 W at design luminosity) emerging from IP and impinging on beam screen. Hadronic shower into superconducting coils can quench magnet.

Also new model of luminosity evolution with IBS, radiation damping and luminosity burn-off (earlier work by A. Morsch).

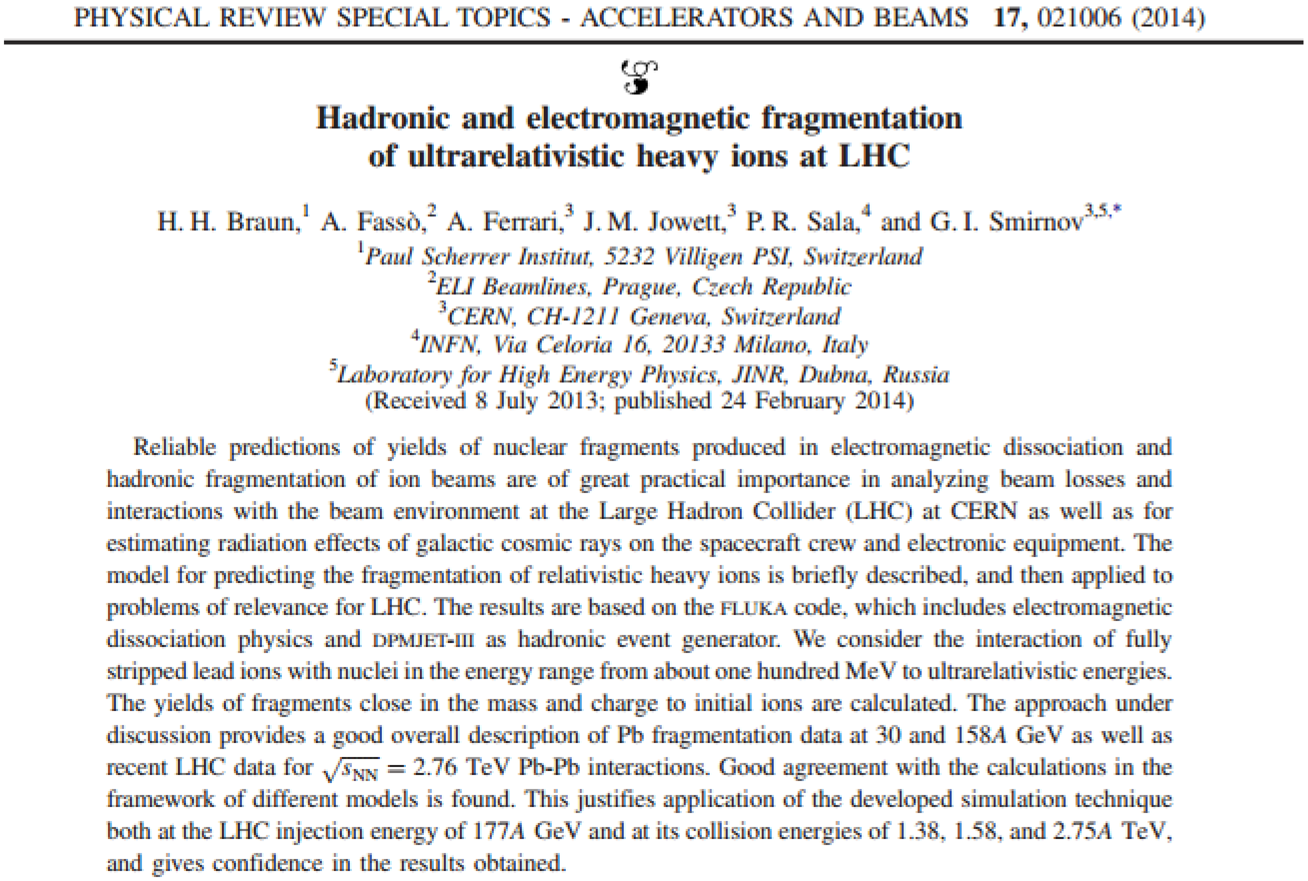
Companion paper (principal author Hans Braun) introduced simulations of heavy ion interactions with collimators.

Distinct EMD process (similar rates) does not form spot on beam pipe

$$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\mathrm{GDR}} {}^{208}\mathrm{Pb}^{82+} + {}^{207}\mathrm{Pb}^{82+} + \mathrm{n}$$

CERN Working Group 2003-2005

Working group in CERN 2003-5 to improve implementation of relevant heavy-ion physics processes in FLUKA Monte-Carlo



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **17,** 021006 (2014)

Hadronic and electromagnetic fragmentation of ultrarelativistic heavy ions at LHC

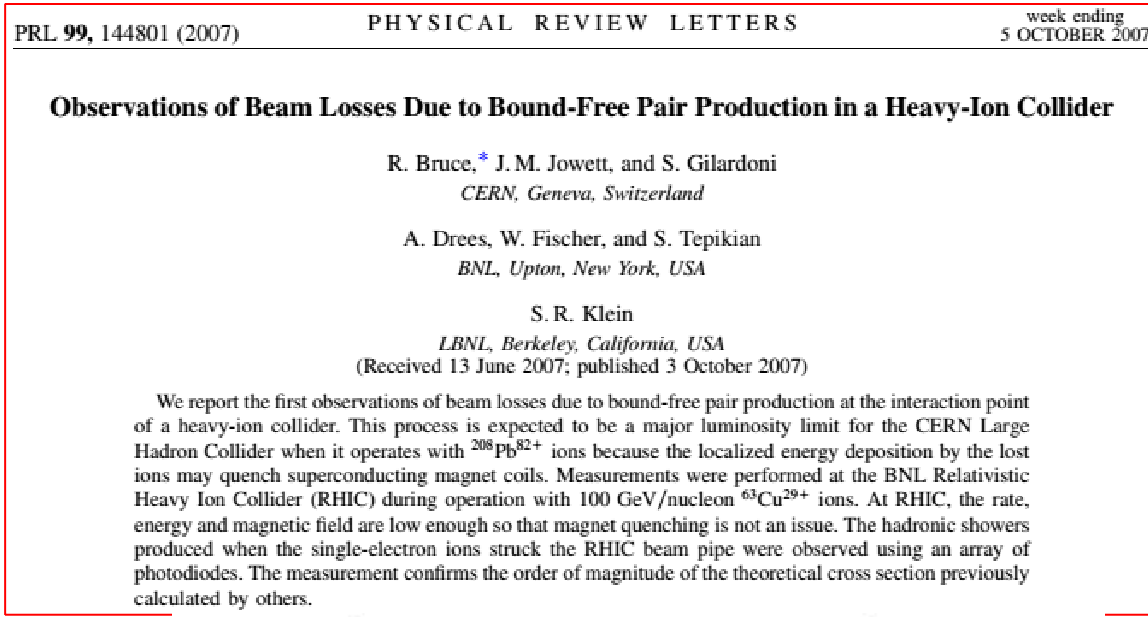
H. H. Braun,[1] A. Fassò,[2] A. Ferrari,[3] J. M. Jowett,[3] P. R. Sala,[4] and G. I. Smirnov[3,5,*]
[1] *Paul Scherrer Institut, 5232 Villigen PSI, Switzerland*
[2] *ELI Beamlines, Prague, Czech Republic*
[3] *CERN, CH-1211 Geneva, Switzerland*
[4] *INFN, Via Celoria 16, 20133 Milano, Italy*
[5] *Laboratory for High Energy Physics, JINR, Dubna, Russia*
(Received 8 July 2013; published 24 February 2014)

Reliable predictions of yields of nuclear fragments produced in electromagnetic dissociation and hadronic fragmentation of ion beams are of great practical importance in analyzing beam losses and interactions with the beam environment at the Large Hadron Collider (LHC) at CERN as well as for estimating radiation effects of galactic cosmic rays on the spacecraft crew and electronic equipment. The model for predicting the fragmentation of relativistic heavy ions is briefly described, and then applied to problems of relevance for LHC. The results are based on the FLUKA code, which includes electromagnetic dissociation physics and DPMJET-III as hadronic event generator. We consider the interaction of fully stripped lead ions with nuclei in the energy range from about one hundred MeV to ultrarelativistic energies. The yields of fragments close in the mass and charge to initial ions are calculated. The approach under discussion provides a good overall description of Pb fragmentation data at 30 and 158*A* GeV as well as recent LHC data for $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV Pb-Pb interactions. Good agreement with the calculations in the framework of different models is found. This justifies application of the developed simulation technique both at the LHC injection energy of 177*A* GeV and at its collision energies of 1.38, 1.58, and 2.75*A* TeV, and gives confidence in the results obtained.

BFPP beam detected at RHIC

RHIC collides Cu-Cu in early 2005 and we realise that BFPP should be detectable.

Rush to RHIC to set up experiment with help of Angelika Drees.



PRL **99,** 144801 (2007) PHYSICAL REVIEW LETTERS week ending 5 OCTOBER 2007

Observations of Beam Losses Due to Bound-Free Pair Production in a Heavy-Ion Collider

R. Bruce,* J. M. Jowett, and S. Gilardoni
CERN, Geneva, Switzerland

A. Drees, W. Fischer, and S. Tepikian
BNL, Upton, New York, USA

S. R. Klein
LBNL, Berkeley, California, USA
(Received 13 June 2007; published 3 October 2007)

We report the first observations of beam losses due to bound-free pair production at the interaction point of a heavy-ion collider. This process is expected to be a major luminosity limit for the CERN Large Hadron Collider when it operates with $^{208}Pb^{82+}$ ions because the localized energy deposition by the lost ions may quench superconducting magnet coils. Measurements were performed at the BNL Relativistic Heavy Ion Collider (RHIC) during operation with 100 GeV/nucleon $^{63}Cu^{29+}$ ions. At RHIC, the rate, energy and magnetic field are low enough so that magnet quenching is not an issue. The hadronic showers produced when the single-electron ions struck the RHIC beam pipe were observed using an array of photodiodes. The measurement confirms the order of magnitude of the theoretical cross section previously calculated by others.

View towards PHENIX

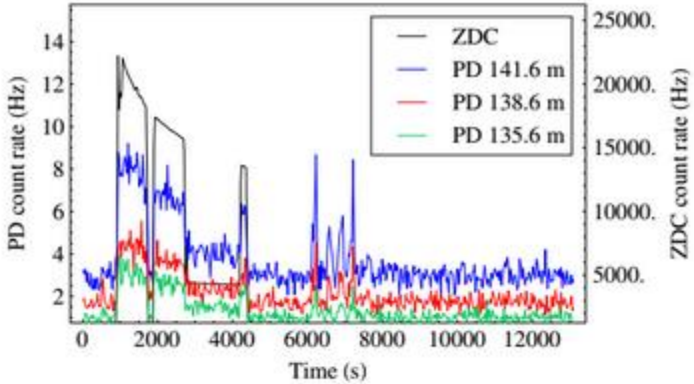
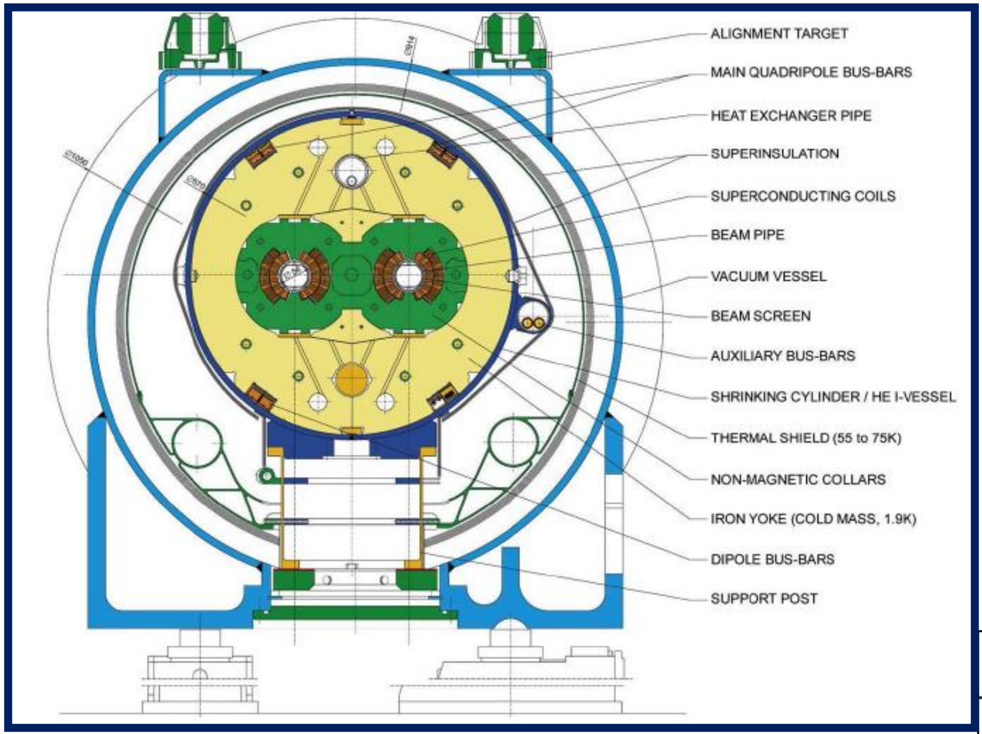
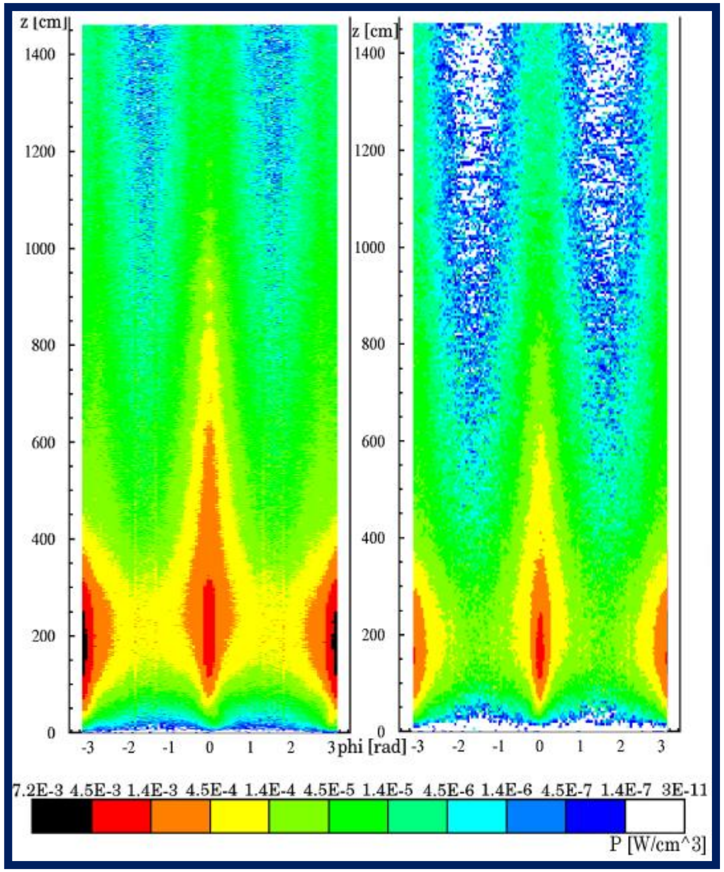


FIG. 4 (color online). Count rates measured on the ZDC luminosity monitors (black, right scale) and the three PDs with the highest signal [shades of gray, left scale (colors online)] during a store with the WPD. The data was binned in 30 sec intervals. A clear correlation between the luminosity and the PD count rates can be seen.

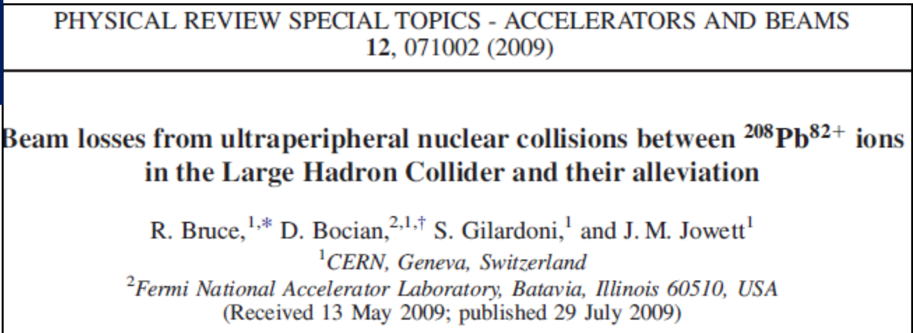
More refined studies

Three-step simulation approach, optical tracking from IP to impact point, a Monte Carlo shower simulation, and a thermal network model of the heat flow via superfluid helium inside a magnet.





FLUKA simulation, thesis of Roderik Bruce (2009)



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

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

R. Bruce,[1,*] D. Bocian,[2,1,†] S. Gilardoni,[1] and J. M. Jowett[1]

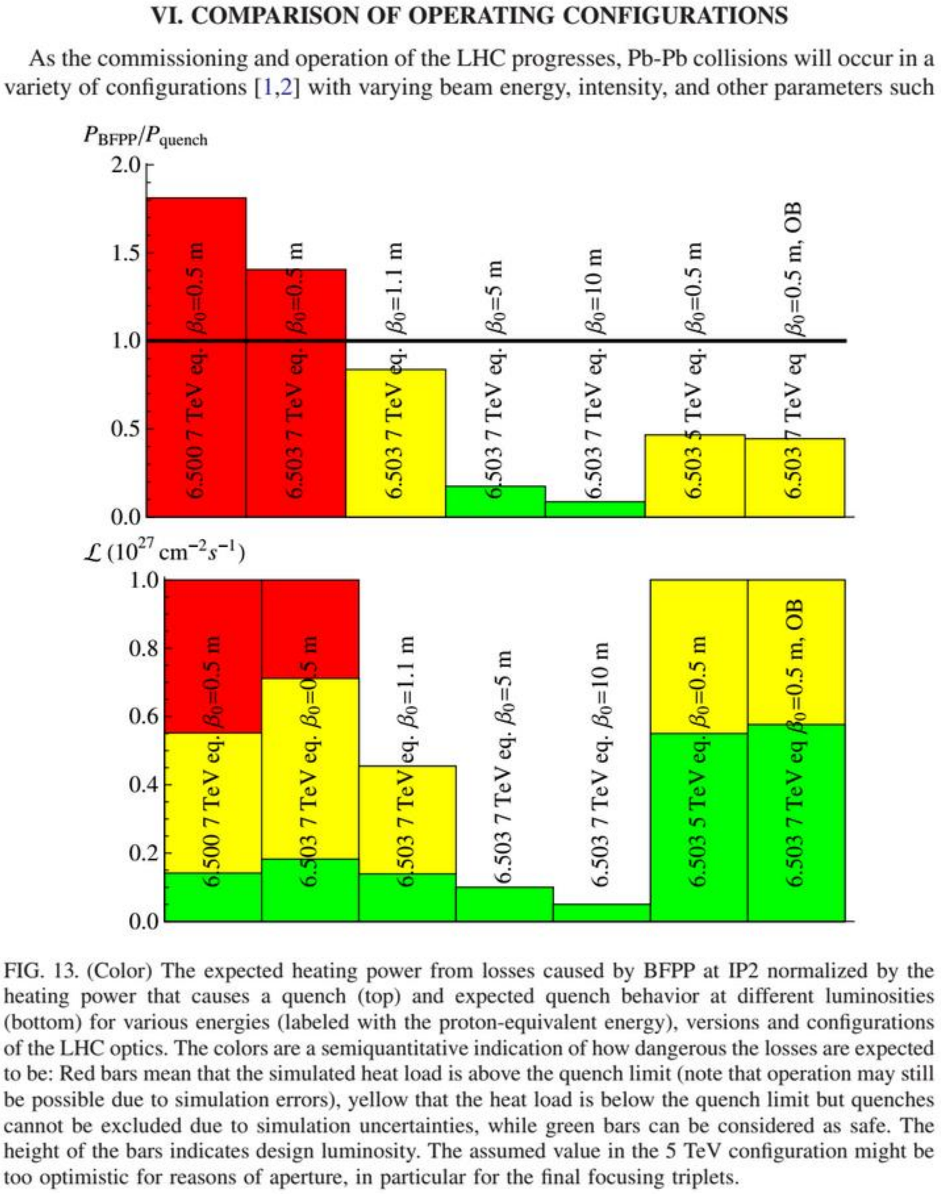
[1]*CERN, Geneva, Switzerland*

[2]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

(Received 13 May 2009; published 29 July 2009)

Expectations before LHC start-up

Prospects of attaining design Pb-Pb luminosity looked rather marginal even with the new quench level estimates in this paper (Bocian model).



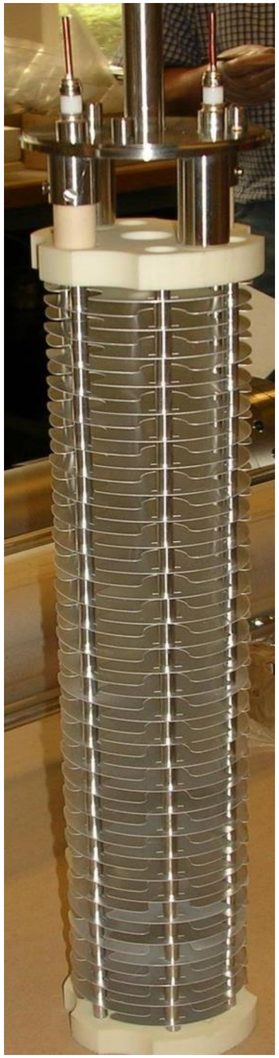
VI. COMPARISON OF OPERATING CONFIGURATIONS

As the commissioning and operation of the LHC progresses, Pb-Pb collisions will occur in a variety of configurations [1,2] with varying beam energy, intensity, and other parameters such

FIG. 13. (Color) The expected heating power from losses caused by BFPP at IP2 normalized by the heating power that causes a quench (top) and expected quench behavior at different luminosities (bottom) for various energies (labeled with the proton-equivalent energy), versions and configurations of the LHC optics. The colors are a semiquantitative indication of how dangerous the losses are expected to be: Red bars mean that the simulated heat load is above the quench limit (note that operation may still be possible due to simulation errors), yellow that the heat load is below the quench limit but quenches cannot be excluded due to simulation uncertainties, while green bars can be considered as safe. The height of the bars indicates design luminosity. The assumed value in the 5 TeV configuration might be too optimistic for reasons of aperture, in particular for the final focusing triplets.

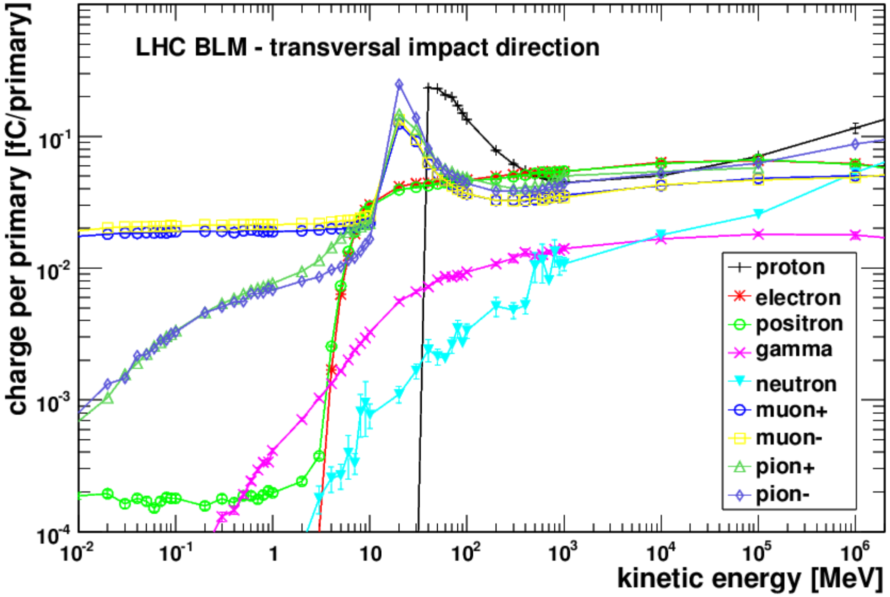
OBSERVATIONS IN FIRST HEAVY-ION OPERATION

LHC Ionisation Chamber (from B. Dehning)



- Stainless steal cylinder
- Parallel electrodes distance 0.5 cm
- Diameter 8.9 cm
- Voltage 1.5 kV
- Low pass filter at the HV input

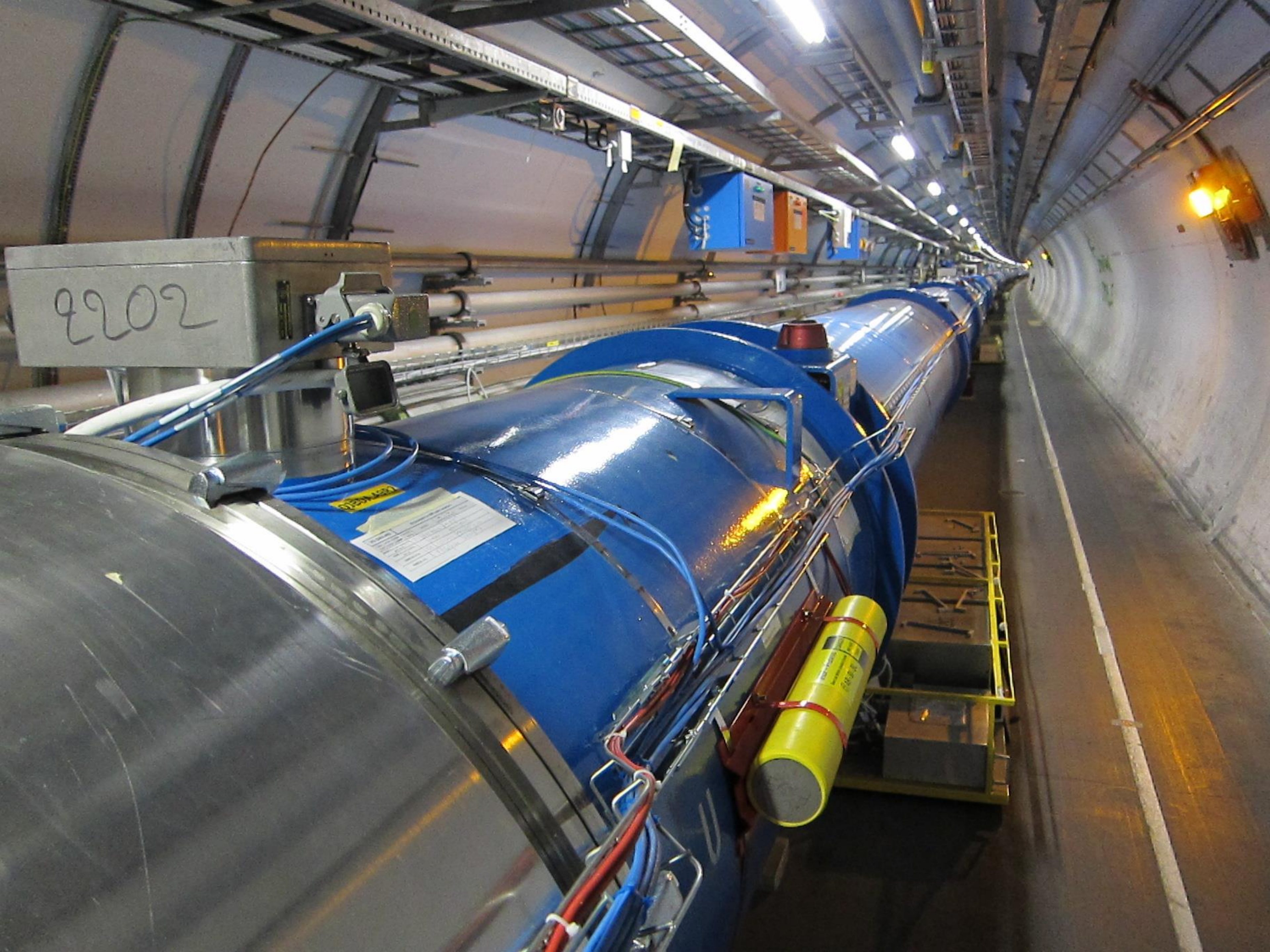
- Low pass filter at the HV input
- Al electrodes
- Length 60 cm
- Ion collection time 85 us
- N_2 gas filling at 1.1 bar
- Sensitive volume 1.5 l



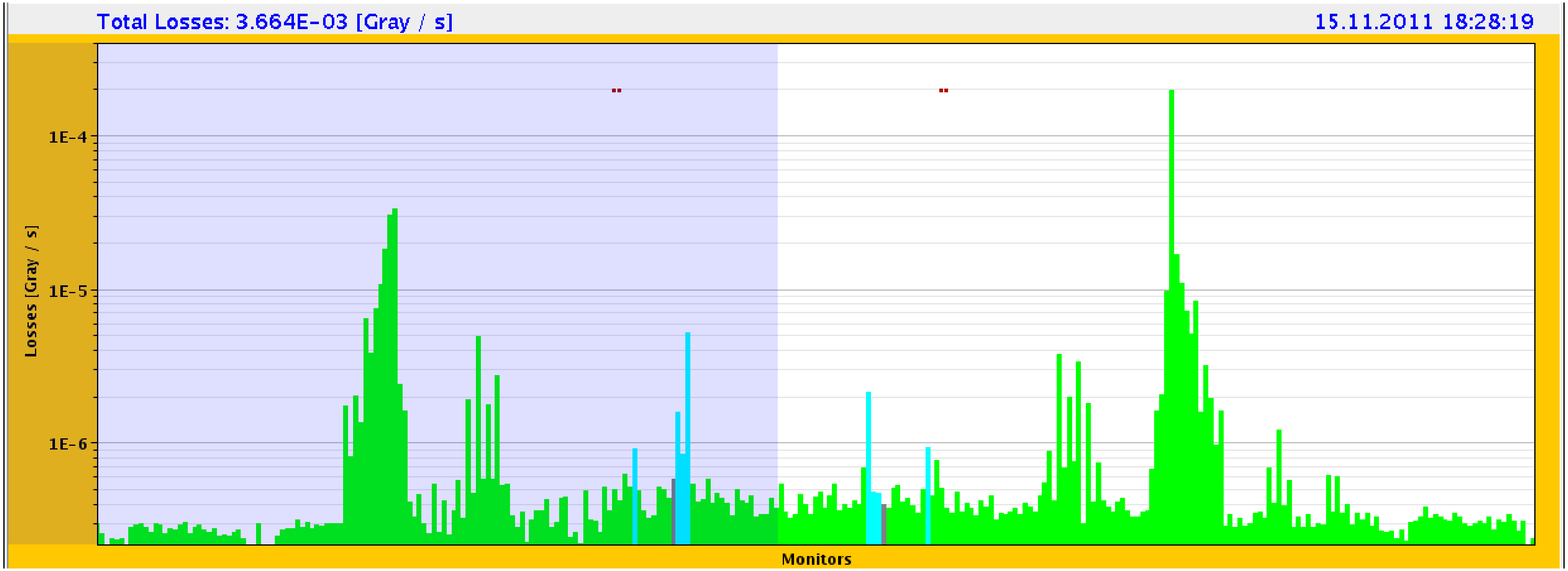
Response function as function of impacting particle energy.

LHC equipped with many of these Beam Loss Monitors (BLMs), every quadrupole, now most dipoles also.

Vital for machine protection, can dump beams.


2202

Bound-free Pair Production losses around CMS in 2011

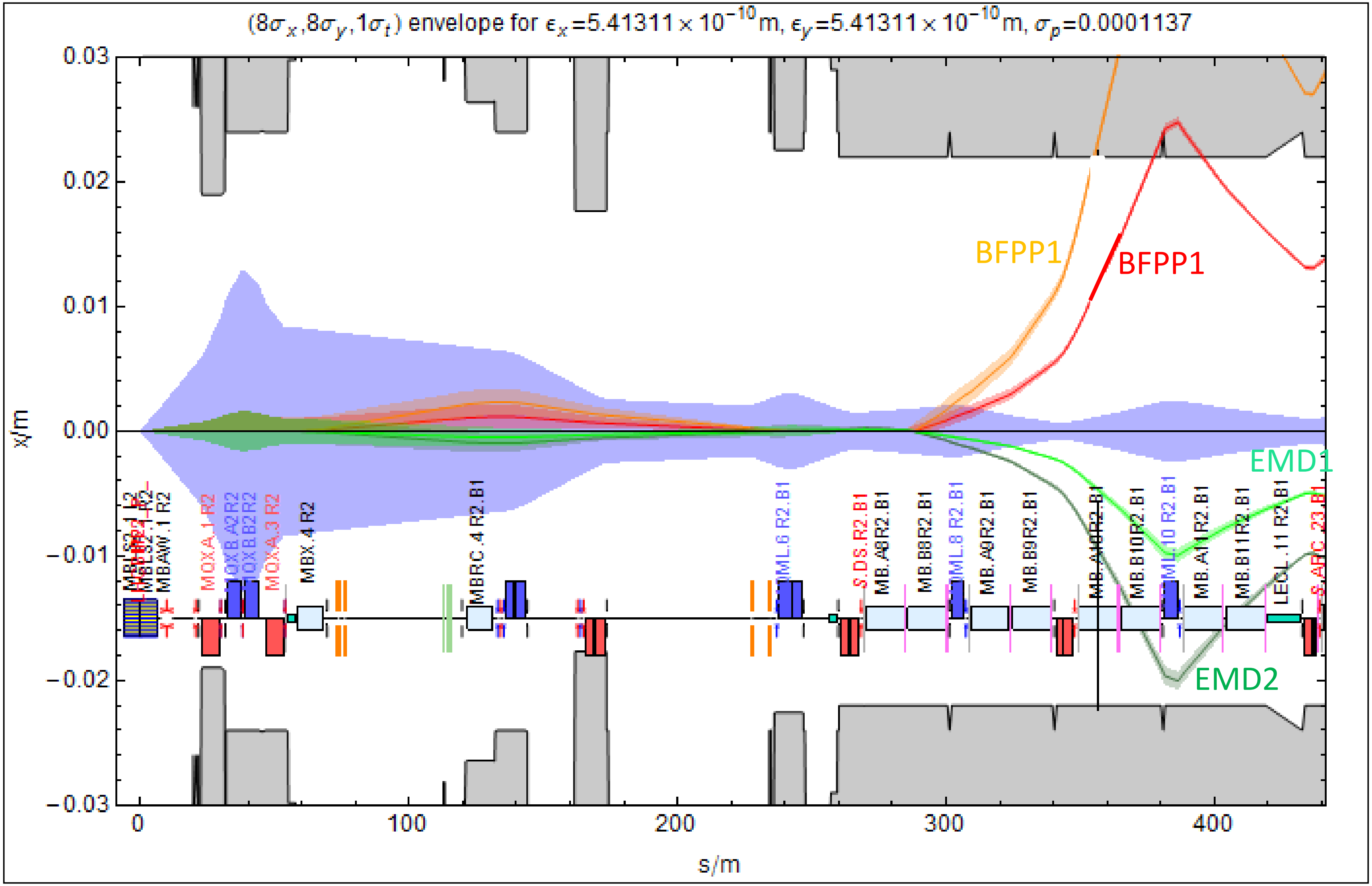


Standard display in the LHC Control Room – BFPP stares you in the face during Pb-Pb collisions !

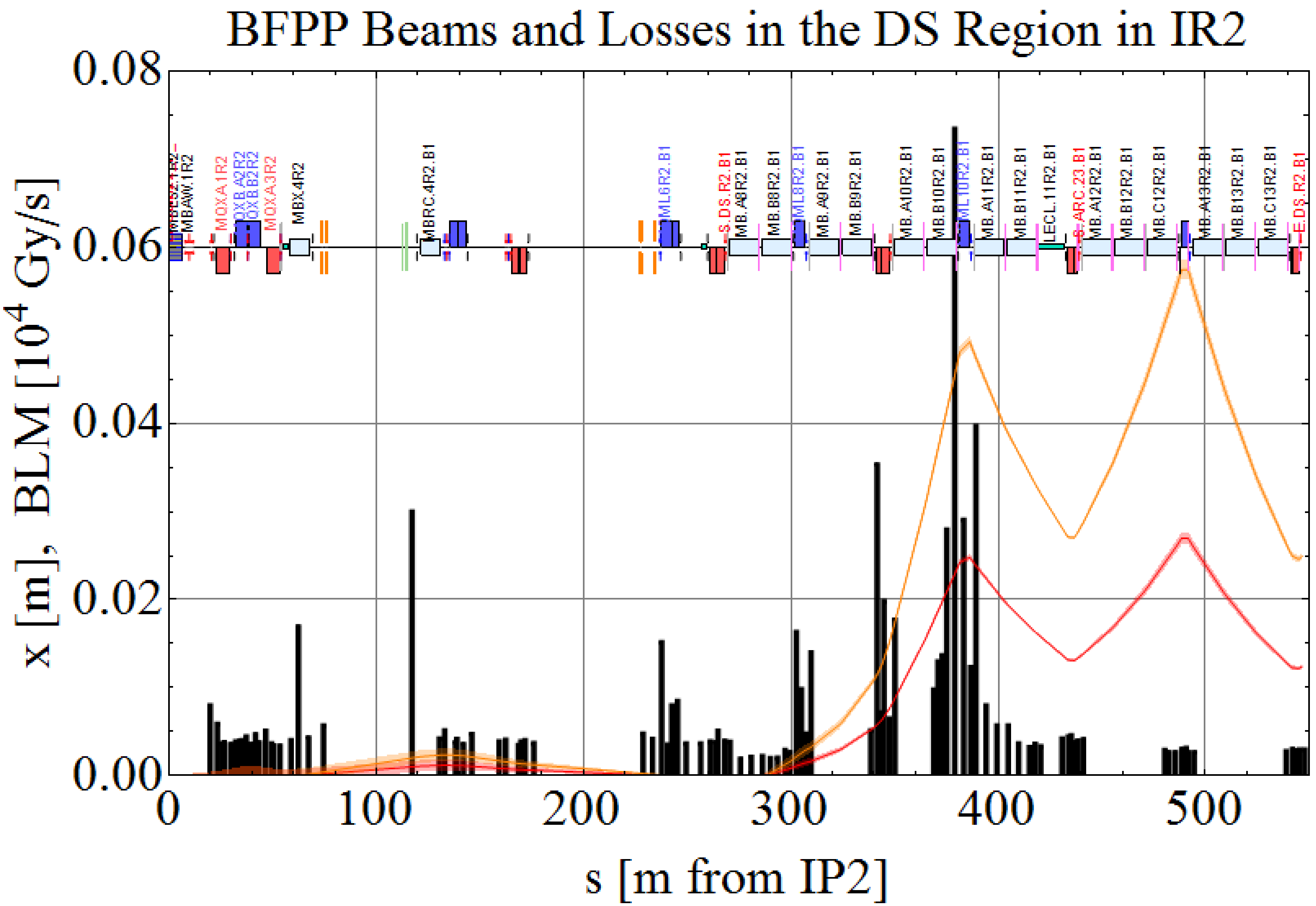
Special BLMs were installed in predicted locations, up to 36% of threshold on 170 bunch fill, we went up later to 356 bunches.

BLM dump thresholds (which were cautious …) had to be doubled.
LHC has never had a beam-induced magnet quench.

Secondary beams from Beam 1 in IR2 (horizontal plane)

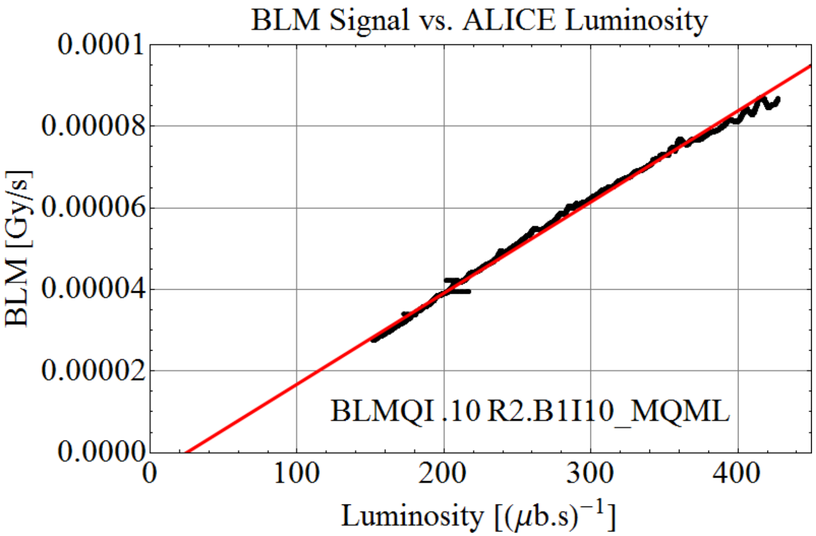


2011 Pb-Pb operation

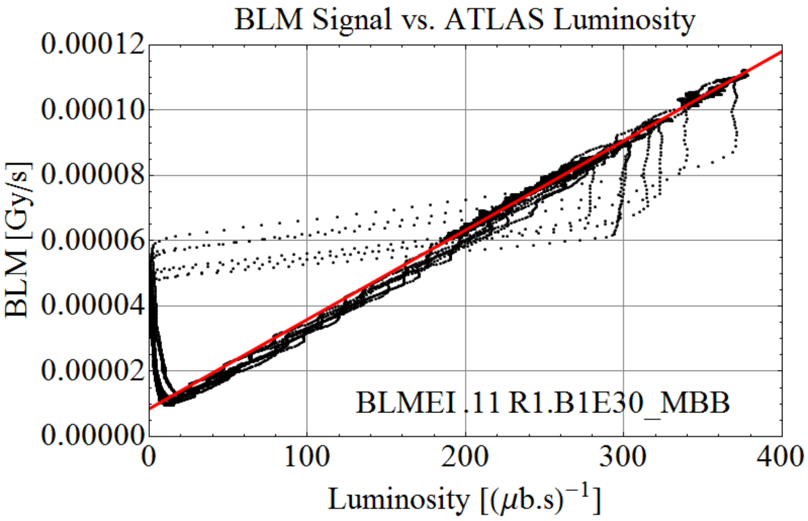


M. Schaumann

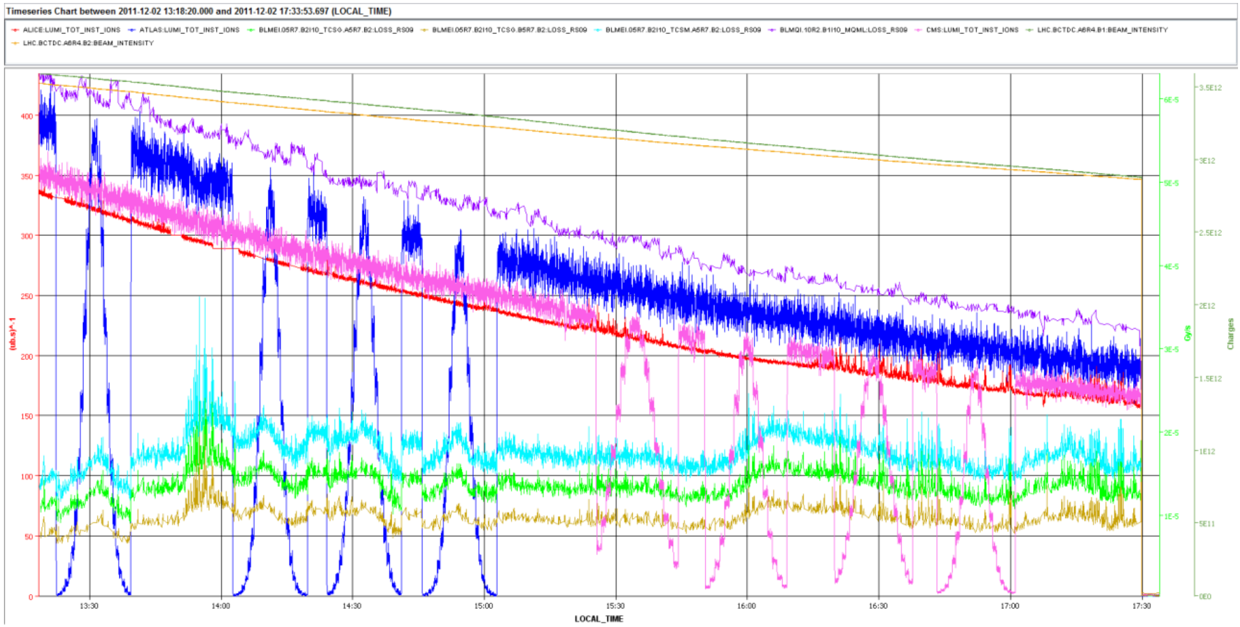
Main losses in DS are correlated with luminosity



Regular physics fill

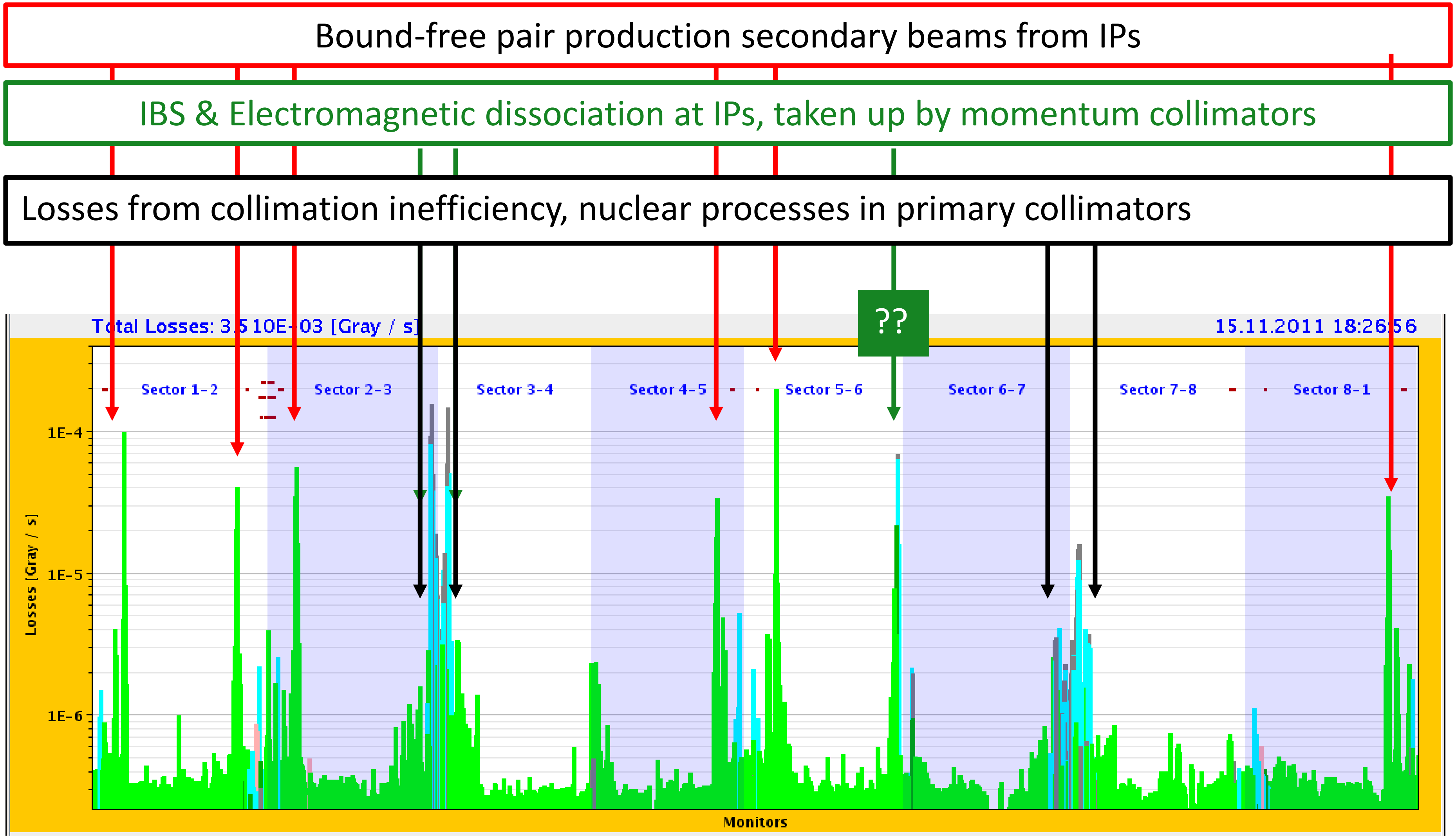


From van der Meer scans


Timeseries Chart between 2011-12-02 13:18:20.000 and 2011-12-02 17:33:53.697 (LOCAL_TIME)

M. Schaumann

Steady-state losses during Pb-Pb Collisions in 2011



Bound-free pair production secondary beams from IPs

IBS & Electromagnetic dissociation at IPs, taken up by momentum collimators

Losses from collimation inefficiency, nuclear processes in primary collimators

Beam loss monitors in the full LHC Ring

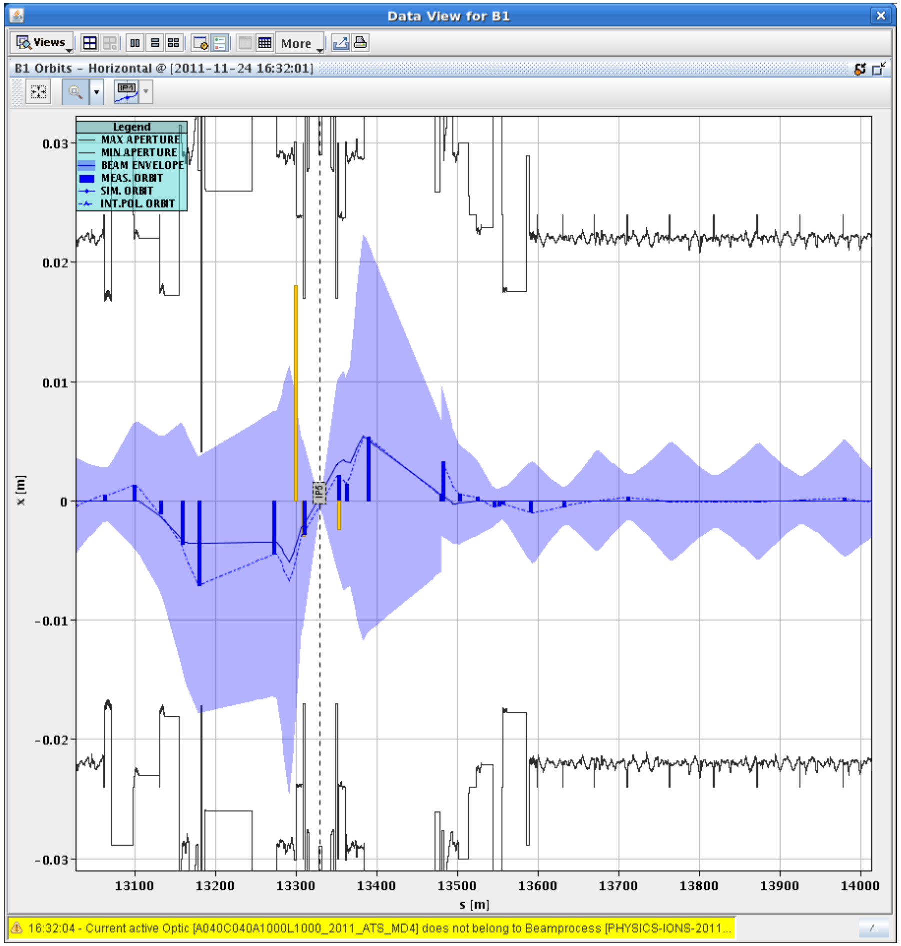
BFPP mitigation by bumps

- 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.
- We will implement this and rely on it in LHC Run 2 in 2015-2017 at energy of 6.5 Z TeV = 2.56 A TeV (or slightly less …)

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

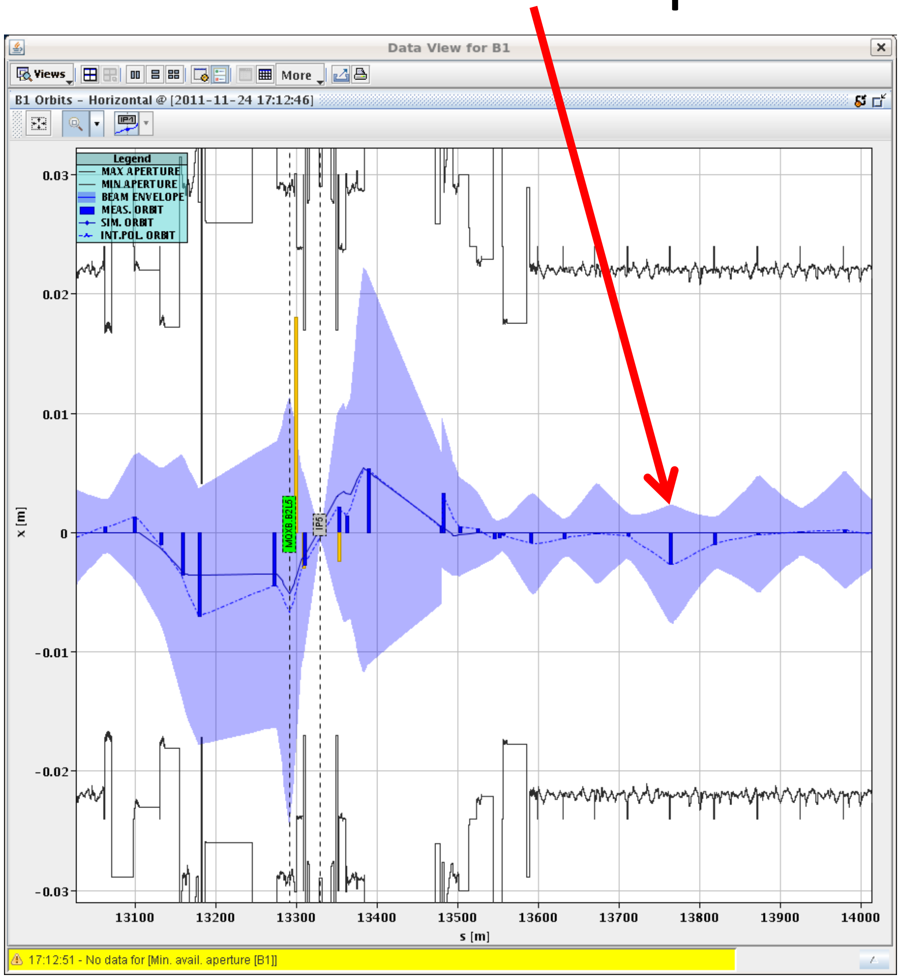
12 sigma envelopes from online model

without bump



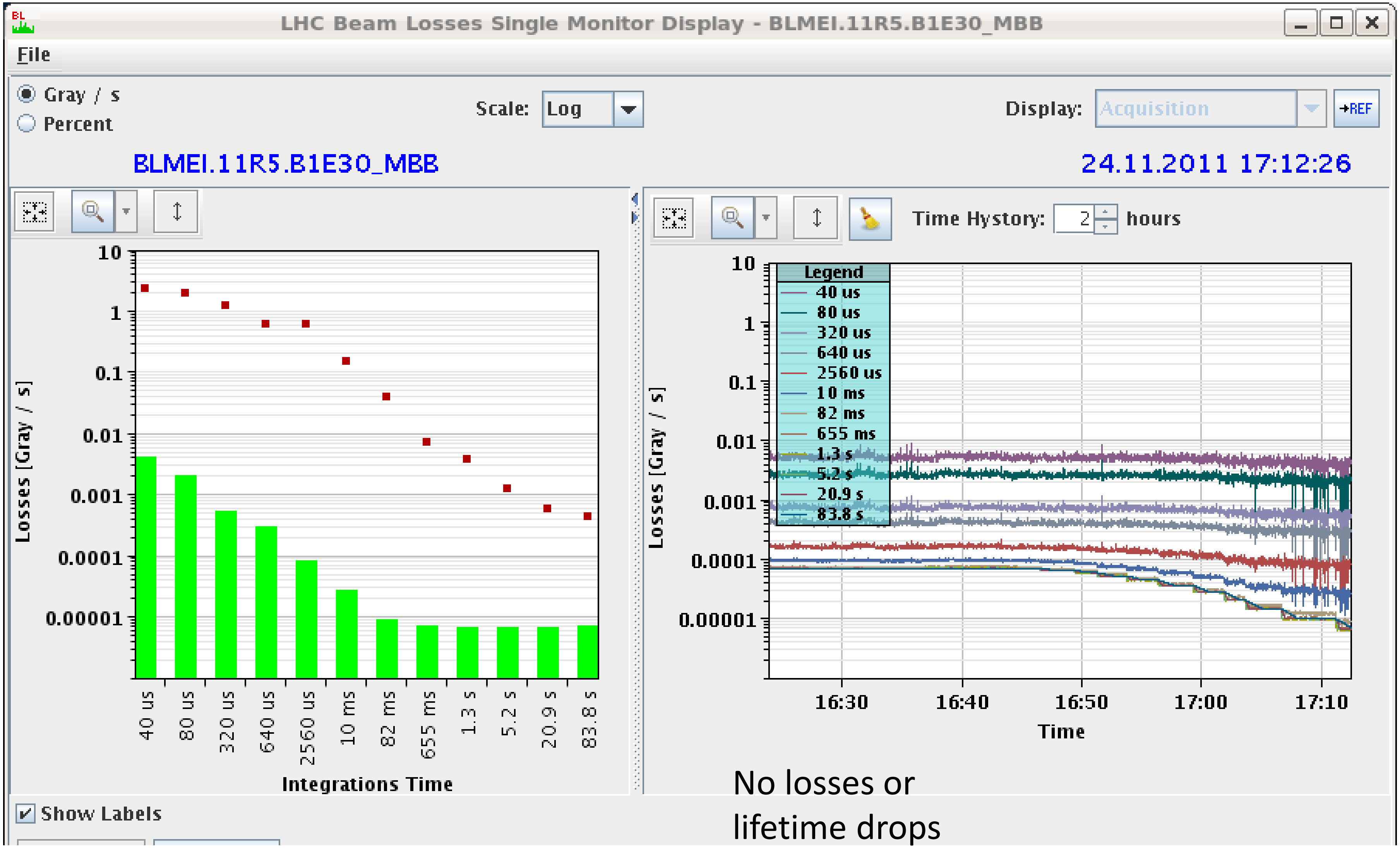
16:32:04 - Current active Optic [A040C040A1000L1000_2011_ATS_MD4] does not belong to Beamprocess [PHYSICS-IONS-2011...

with bump



17:12:51 - No data for [Min. avail. aperture [B1]]

Effect on losses



LHC Beam Losses Single Monitor Display - BLMEI.11R5.B1E30_MBB

● Gray / s
○ Percent

Scale: Log

Display: Acquisition

BLMEI.11R5.B1E30_MBB

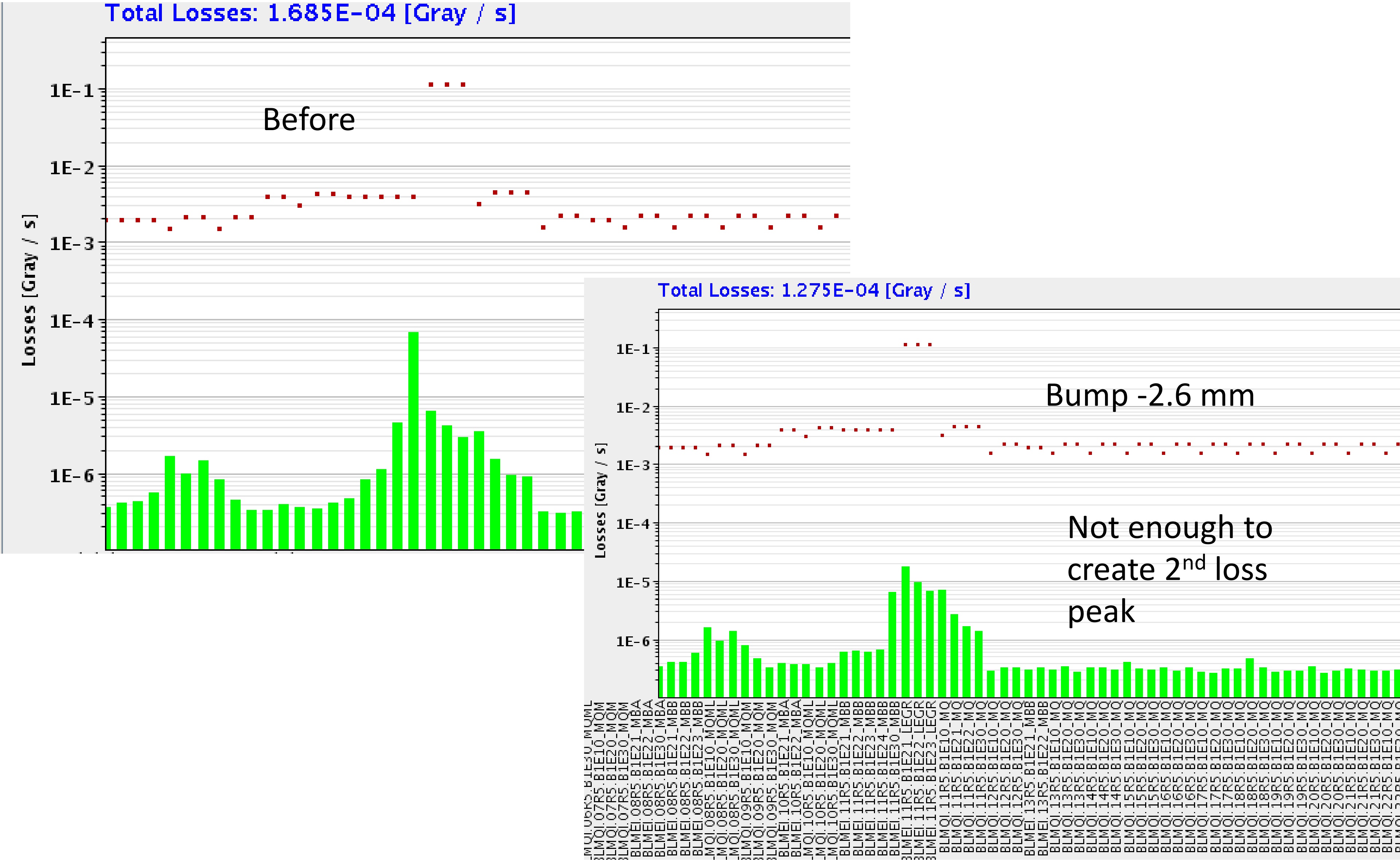
24.11.2011 17:12:26

Time Hystory: 2 hours

☑ Show Labels

No losses or
lifetime drops

Effect on loss pattern



Before

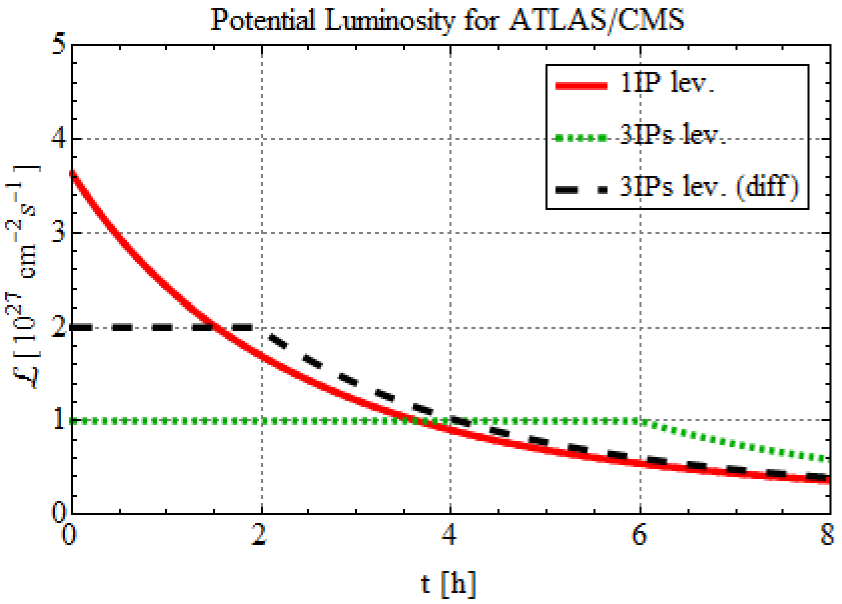
Bump -2.6 mm

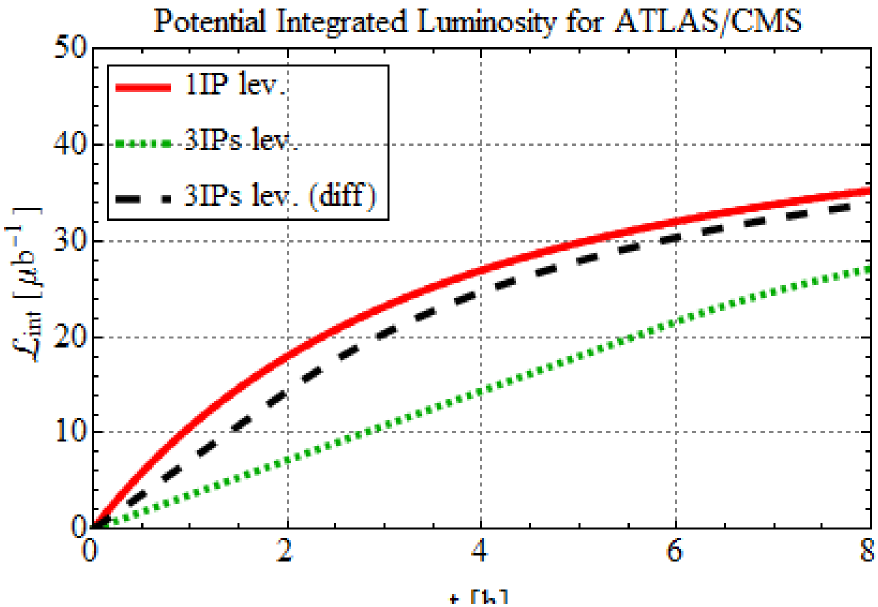
Not enough to create 2nd loss peak

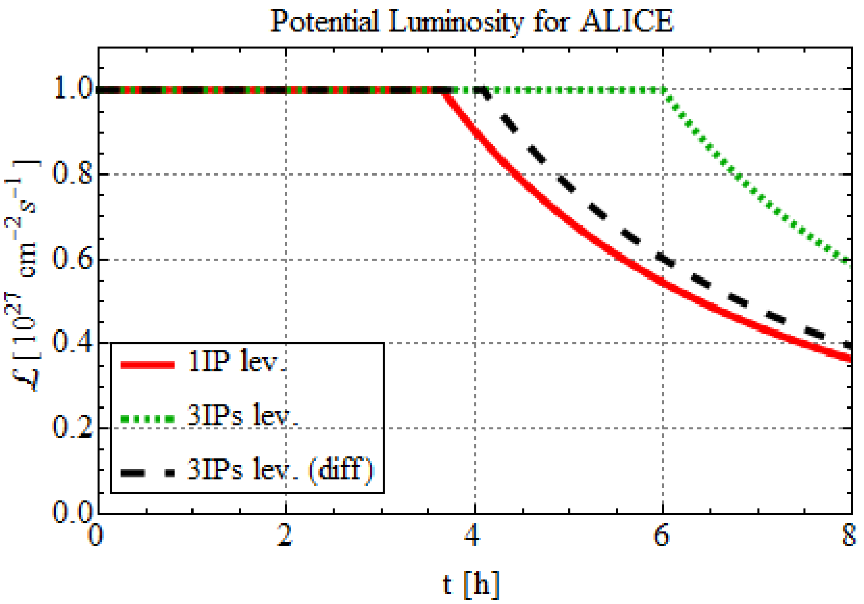
Levelling in Run 2

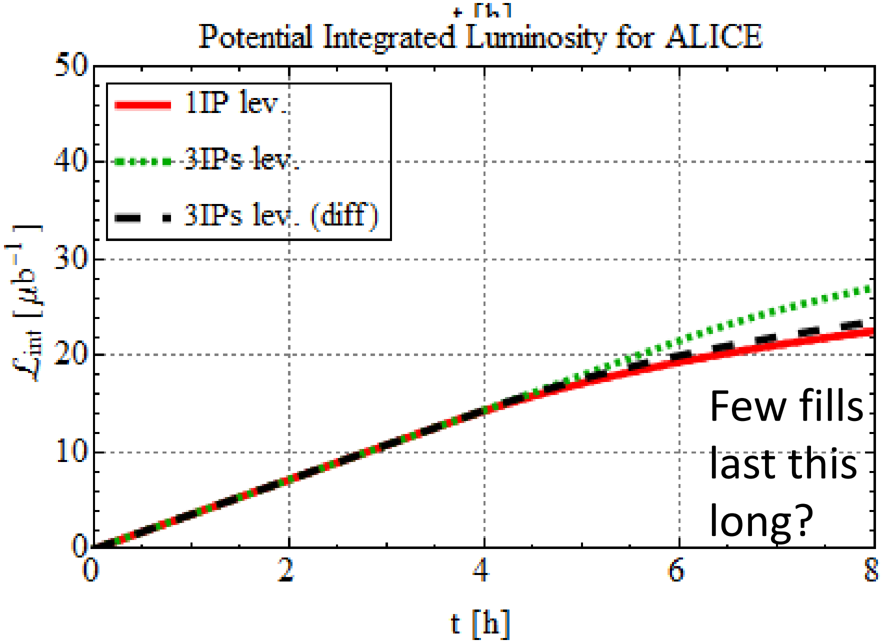
- Before the upgrade (LS2), ALICE luminosity must be levelled at $L = 1 \times 10^{27}\ \mathrm{cm^{-2}s^{-1}}$
- ATLAS and CMS are not limited in peak *L.*
- Luminosity decay dominated by burn-off: largely a conversion of stored beam particles to events.
  - Higher luminosity experiments consume beam reducing everyone’s luminosity very quickly and reducing the time that ALICE can run at levelled value.
- Should ATLAS, CMS be levelled also?
- Compare 3 possibilities
  - Levelling only in ALICE
  - Levelling all experiments to $L = 1 \times 10^{27}\ \mathrm{cm^{-2}s^{-1}}$
  - Levelling ATLAS, CMS at $L = 2 \times 10^{27}\ \mathrm{cm^{-2}s^{-1}}$

Comparison of levelling scenarios for Run 2









Few fills last this long?

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

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

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

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

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

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

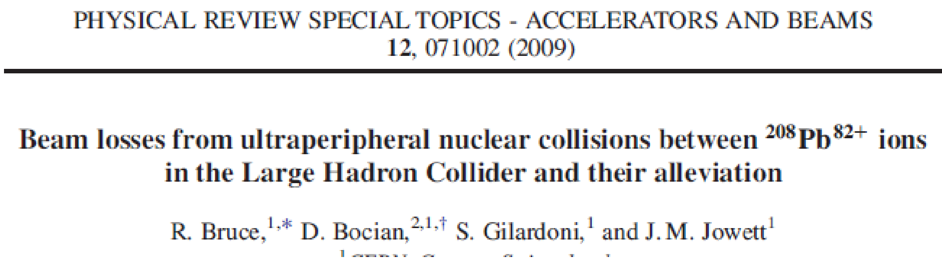
Stored energy in beam: $\mathrm{W} \approx 18\ \mathrm{MJ} = 4.8\ \times$ design

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

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

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 at high luminosity may become comparable to Pb-Pb (on one side of IP).

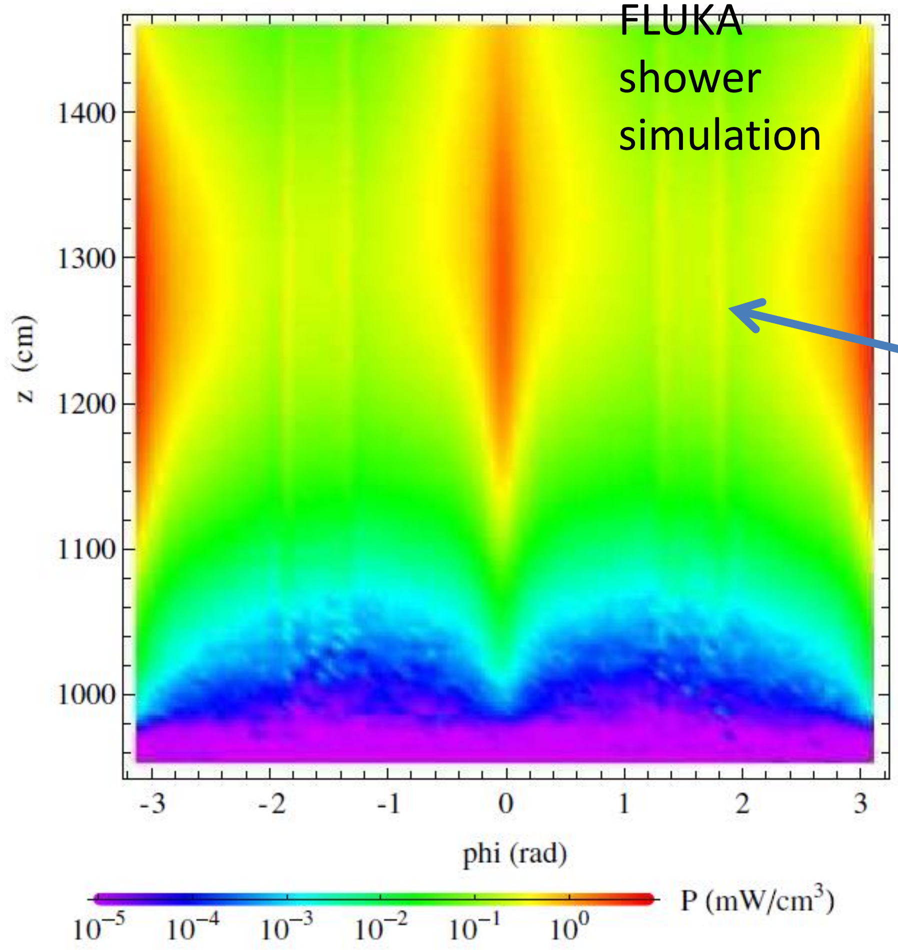
Power density in superconducting cable



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

R. Bruce,[1,*] D. Bocian,[2,1,†] S. Gilardoni,[1] and J. M. Jowett[1]



FLUKA shower simulation

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 studies confirmed recently (G.E. Steele).

Maximum power density in coil at 7 Z

$P = 15.5$ mW/cm^3 at design luminosity.

For upgrade luminosity, expect

$P \approx 93$ mW/cm^3

c.f. quench limit (recent from A. Verwe

200 mW/cm^3 at 4 Z TeV

40-50 mW/cm^3 at 7 Z TeV

(higher than used previously)

Nevertheless, expect to quench MB and possibly MQ!

Main results of quench tests

1. Removing measurement uncertainties and better **understanding** of **electro-thermal** properties of coils.
2. **Understanding** the **loss patterns** due to: beam excitations, orbit bumps, emittance blow, etc.
3. Understanding the limits of BLM to resolve loss patterns.
4. :

Beam energy	Loss duration	Experiment+FLUKA	QP3	Run1 (initial)
4 TeV	~ 5 ms	198-400 [mJ/cm^3]	58-80 [mJ/cm^3]	40 [mJ/cm^3]
4 TeV	20 s	41-69 [mW/cm^3]	74-92 [mW/cm^3]	20 [mW/cm^3]

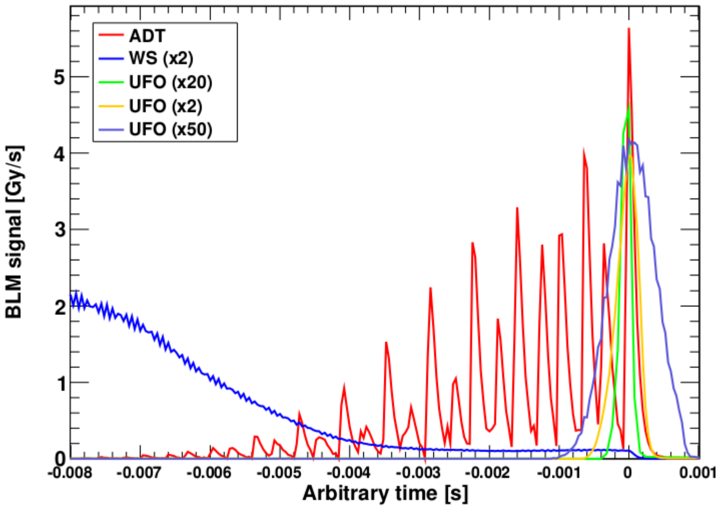
Several IPAC papers and a peer-reviewed publications are prepared,

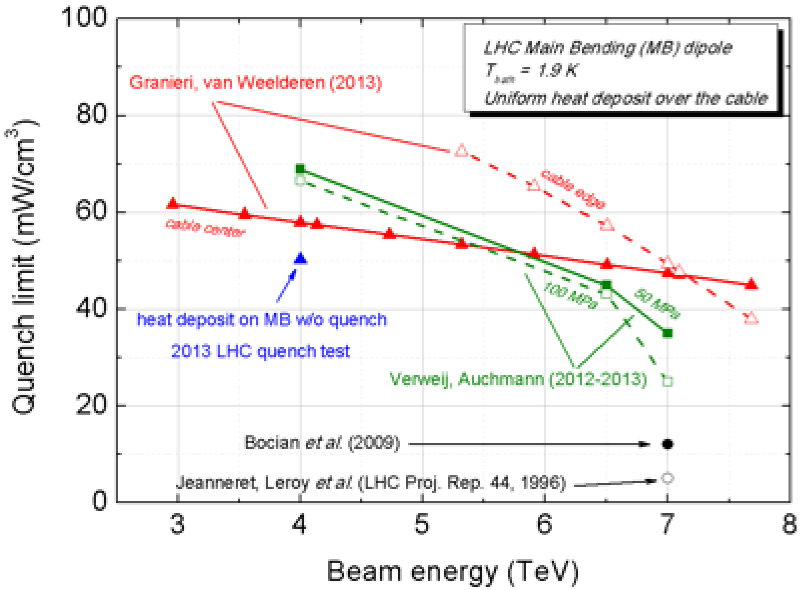
Beam Induced Quench workshop is planned for September (before Chamonix).

M. Sapinski, Evian, yesterday

Quench tests: towards BLM thresholds

1. <u>UFO-timescale quench limit:</u>
    - difficult experiment, not reached UFO loss parameters: loss duration, loss time structure, neutral peak.
    - discrepancy experiment-model, probably due to difference between spiky and continuous losses.
2. <u>Steady-state quench limit:</u>
    - Results more optimistic than previously assumed, especially at 7 TeV
3. QP3 has been validated, but empiric factors for thresholds must be used.
4. Expect quench test requests for Run2





M. Sapinski, Evian, yesterday

Radiation damage

Knowing the power density, *P*, for a given luminosity, *L*, and the coil material density, $\rho = 7\ \text{g cm}^{-3}$ (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, $10\ \text{nb}^{-1}$, the coil may be exposed to a dose of some 22 MGy.

Comparable to damage limit of polyimide insulator.

Coils are not directly exposed to ions – by the time the shower reaches them, it is totally fragmented into individual nucleons. Studies of surfaces under heavy ion irradiation not directly relevant.

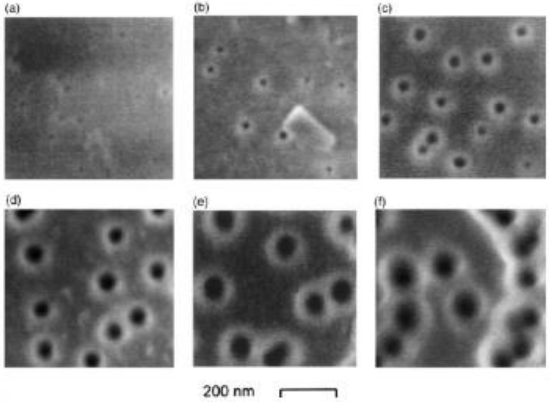
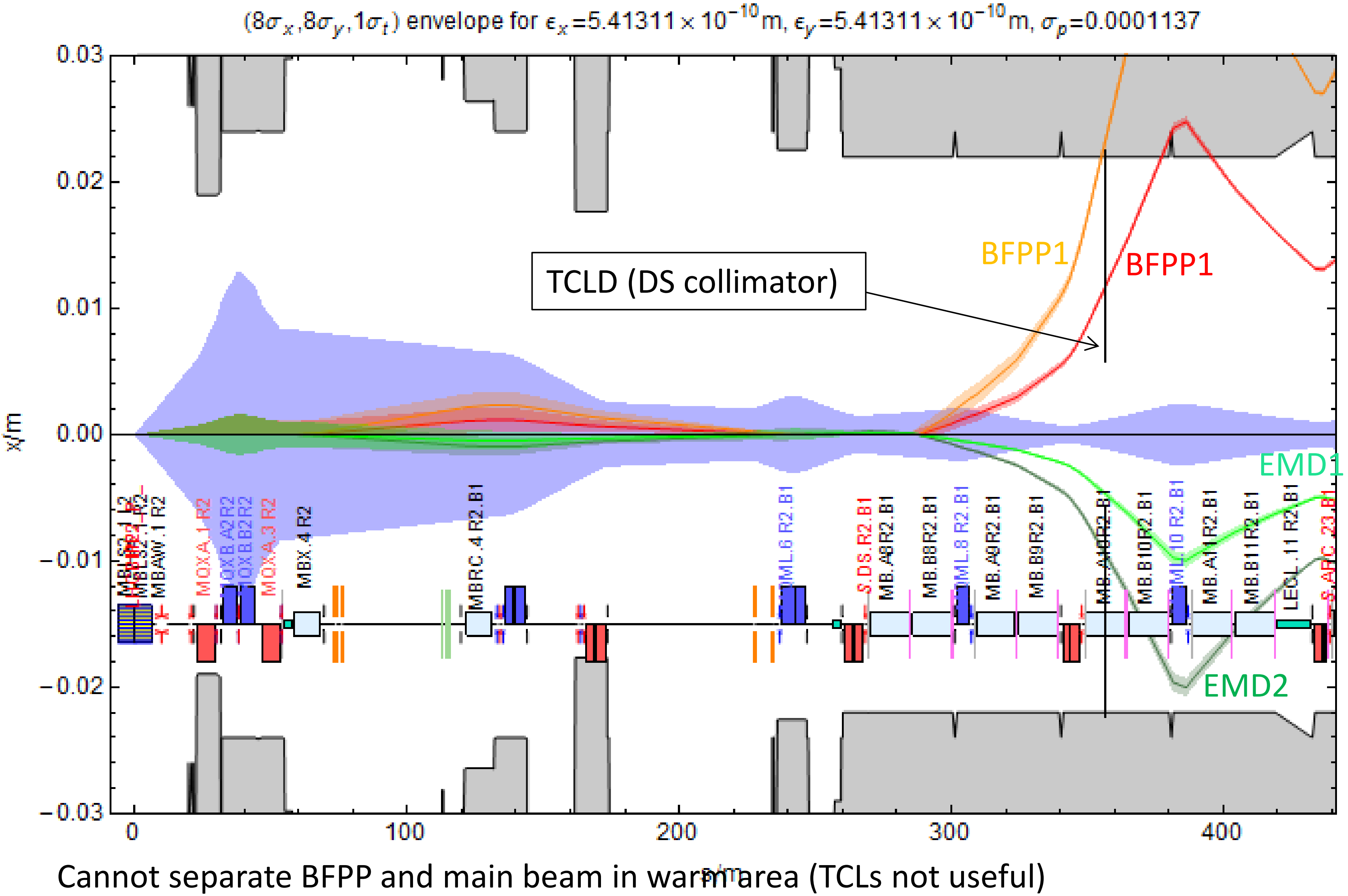


Fig. 1. HRSEM images of etched ^{238}U-ion tracks in polyimide. The etching times of the samples displayed in panels (a), (b), (c), (d), (e) and (f) were 40 s and 1, 2, 3, 4 and 5 min, respectively.

Collimators in the dispersion suppressors

- 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 but revived recently (interest also for protons in collimation insertions)
  - 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).

Secondary beams from Beam 1 in IR2 (horizontal plane)



TCLD (DS collimator)

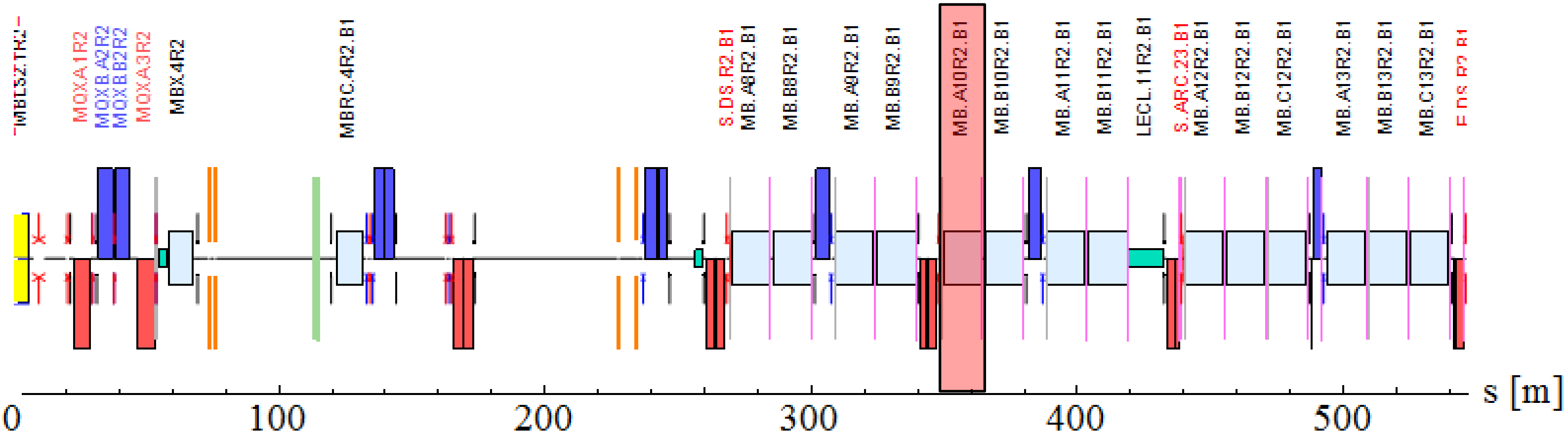
Cannot separate BFPP and main beam in warm area (TCLs not useful)

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

DS collimator installation in IR2

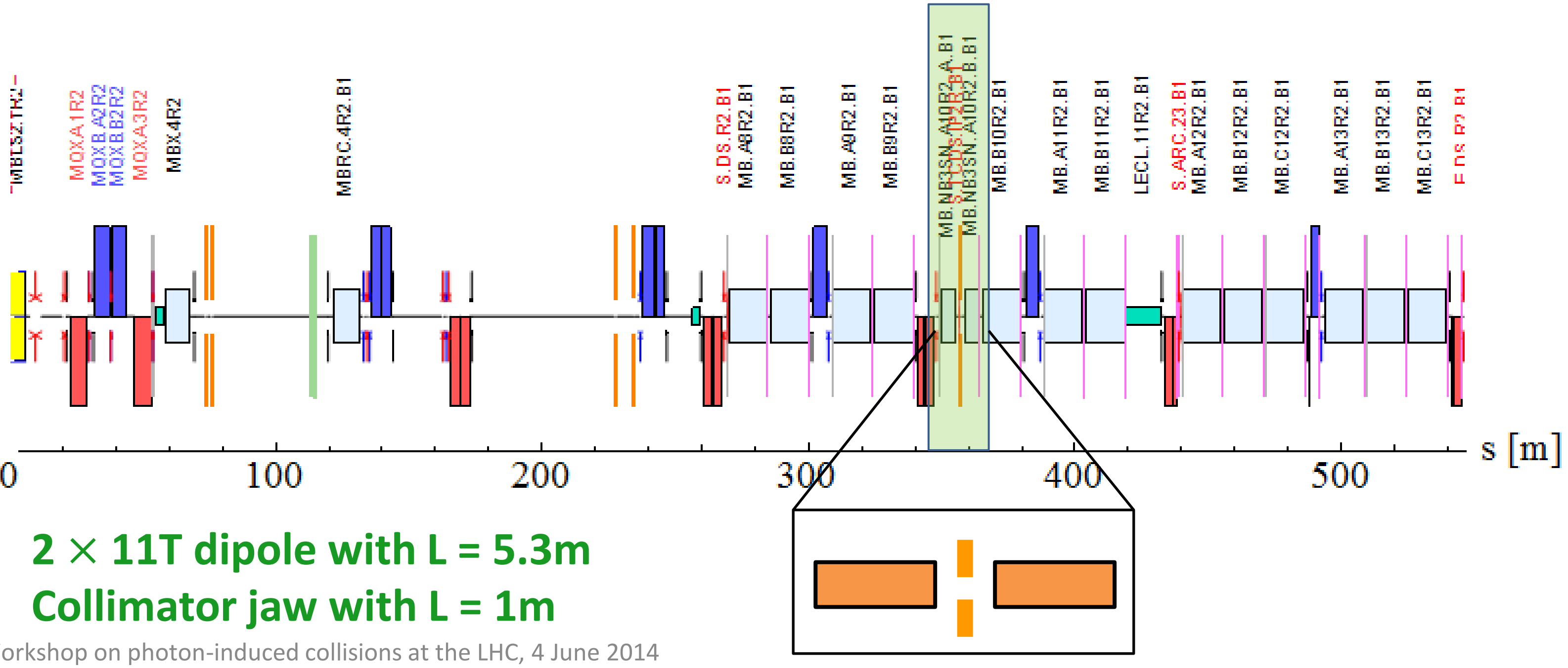
Magnet to be replaced **MB.A10R2**

Nominal Beam Line



IP2

Modified Sequence

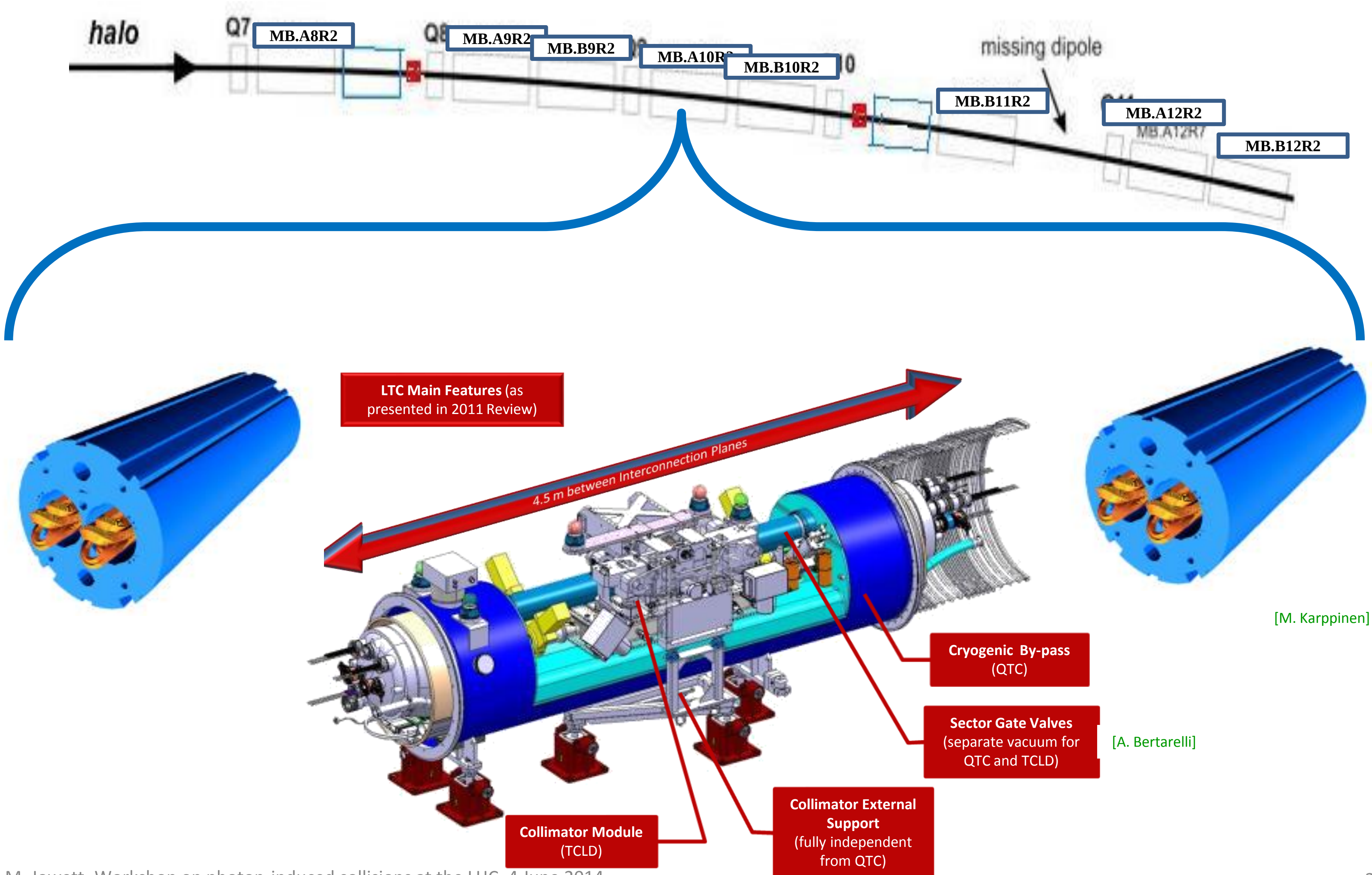


2 × 11T dipole with L = 5.3m

Collimator jaw with L = 1m

Integrated technological solution for point 2

(same solution deployable in IP 7 in case of need)



LTC Main Features (as presented in 2011 Review)

Cryogenic By-pass (QTC)

Sector Gate Valves (separate vacuum for QTC and TCLD)

Collimator External Support (fully independent from QTC)

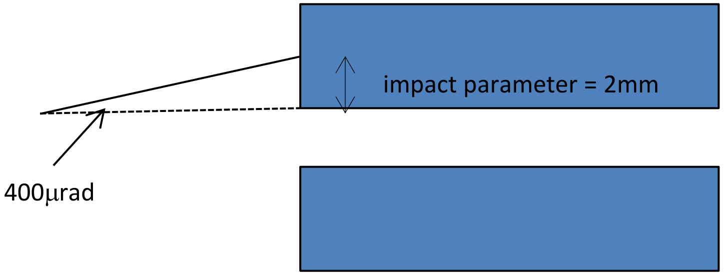
Collimator Module (TCLD)

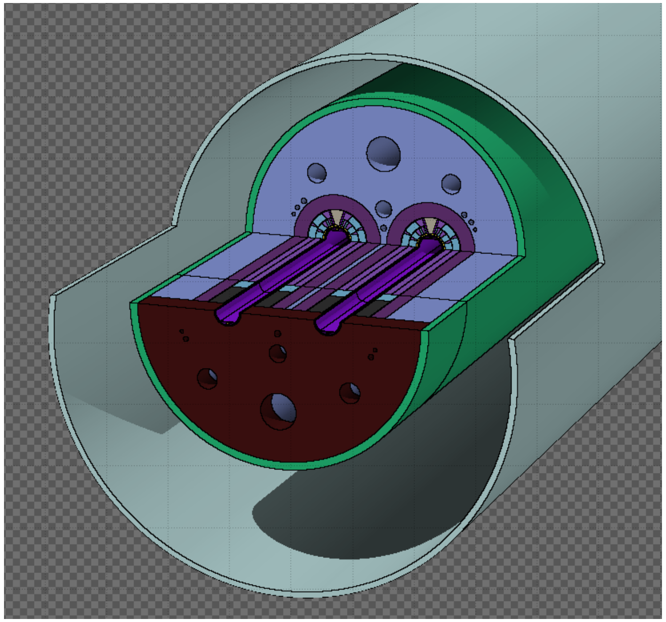
[M. Karppinen]

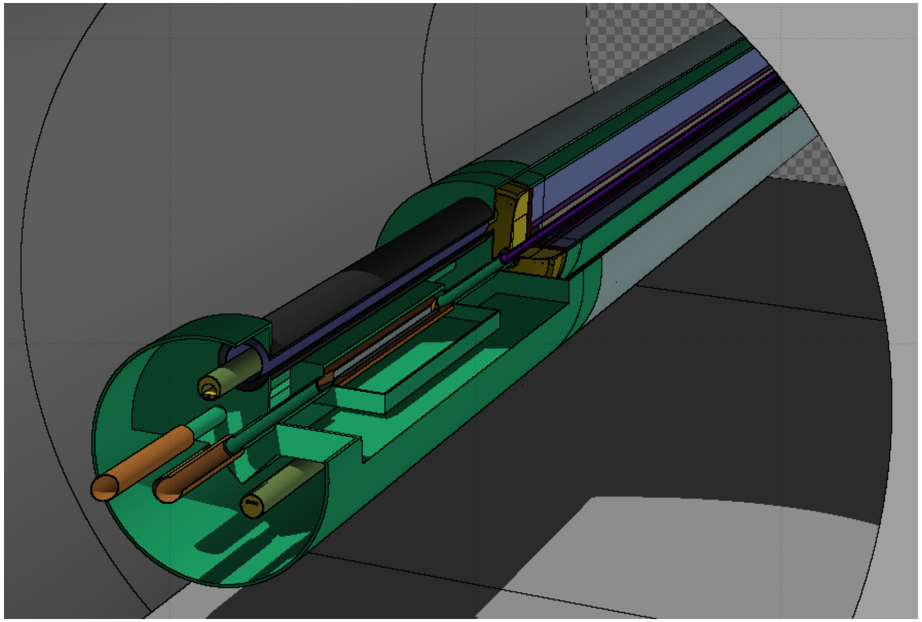
[A. Bertarelli]

TCLD and 11T dipole (MBHDP)

- Modelled in FLUKA to include all geometry essential for energy deposition studies.
- For dipole, magnetic field map included to allow particle tracking.





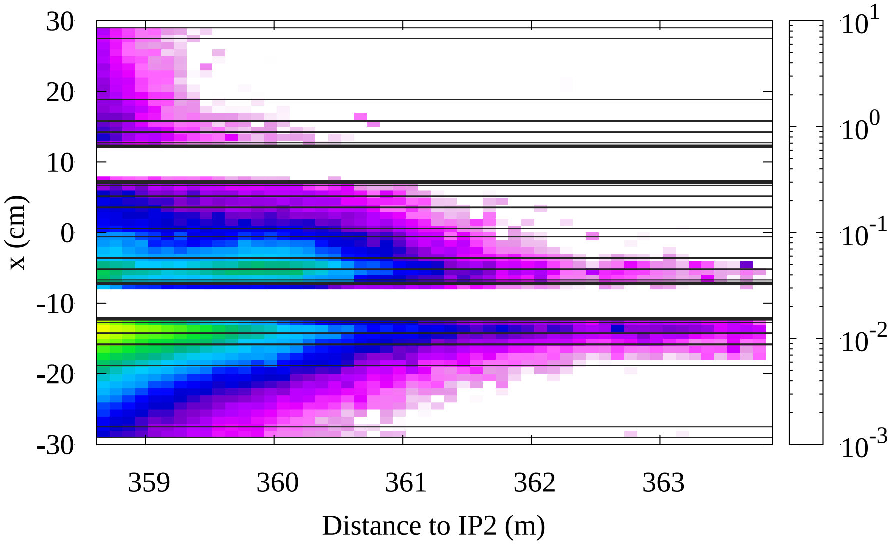


LHC Collimation Review - G. Steele

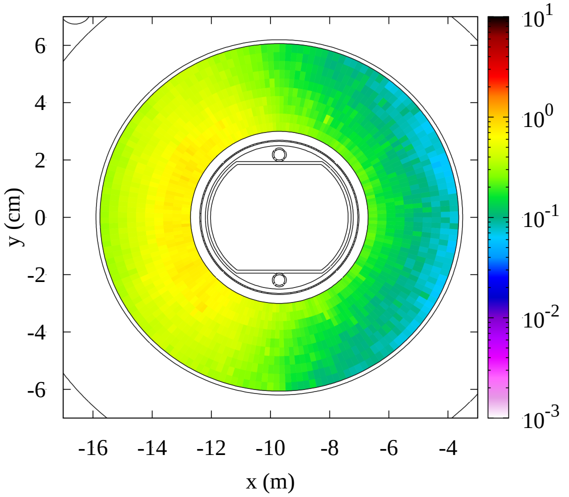
DS Coll. + MBHDP - peak power

1m W

Power density (mW/cm^3) in the MBHDP.B10R2 horizontal plane

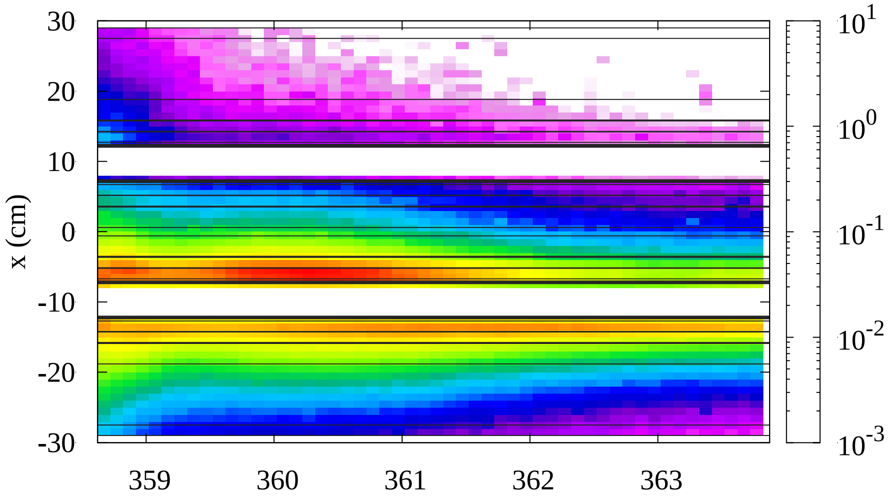


Power density (mW/cm^3) in MBHDP.B10R2 coils

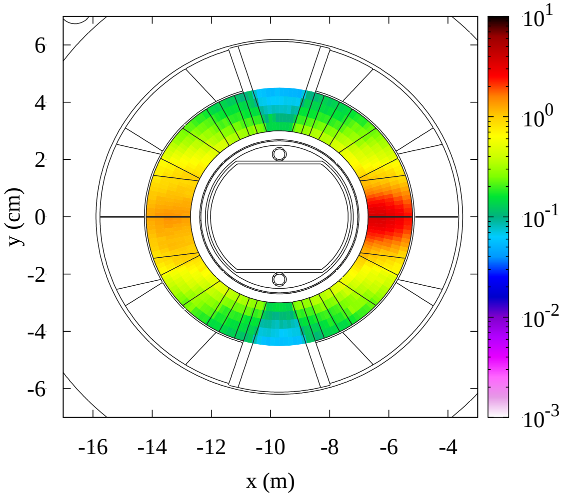


0.5m Cu

Power density (mW/cm^3) in the MBHDP.B10R2 horizontal plane

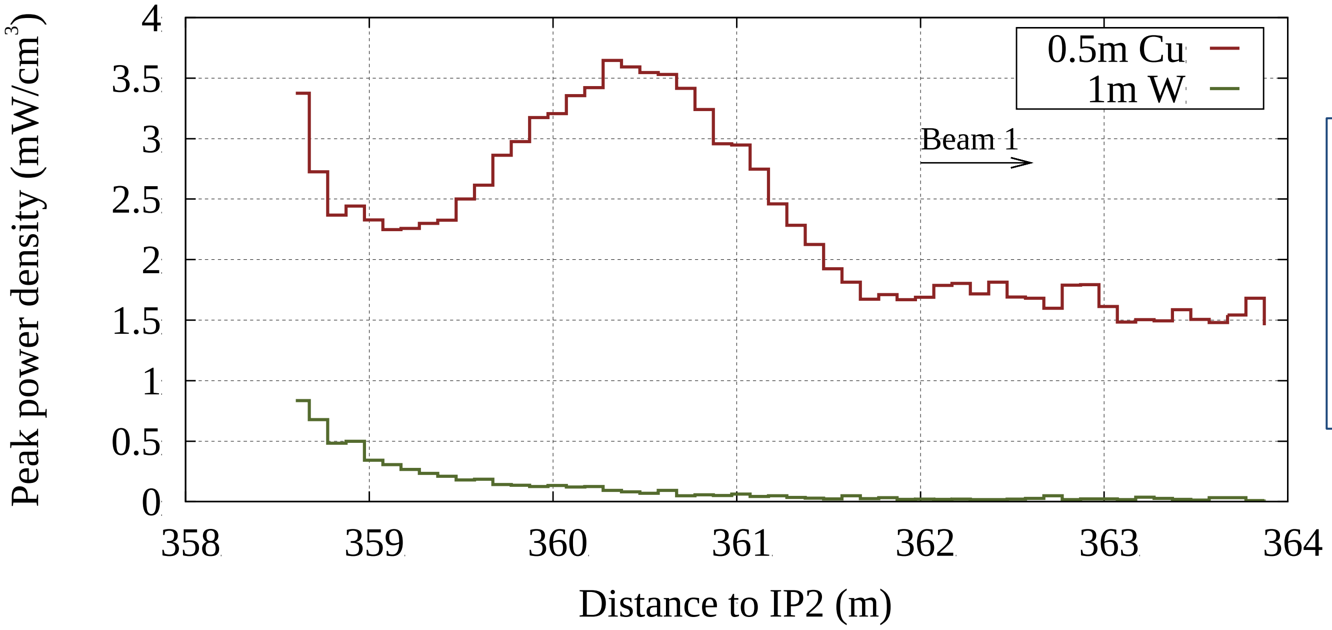


Power density (mW/cm^3) in MBHDP.B10R2 coils



Peak power deposition: MBHDP - cont.

Peak power density due to losses caused by BFPP (L σ$_{BFPP}$ = 1.69 MHz)



Reduction factor greater than 4 between the two cases.

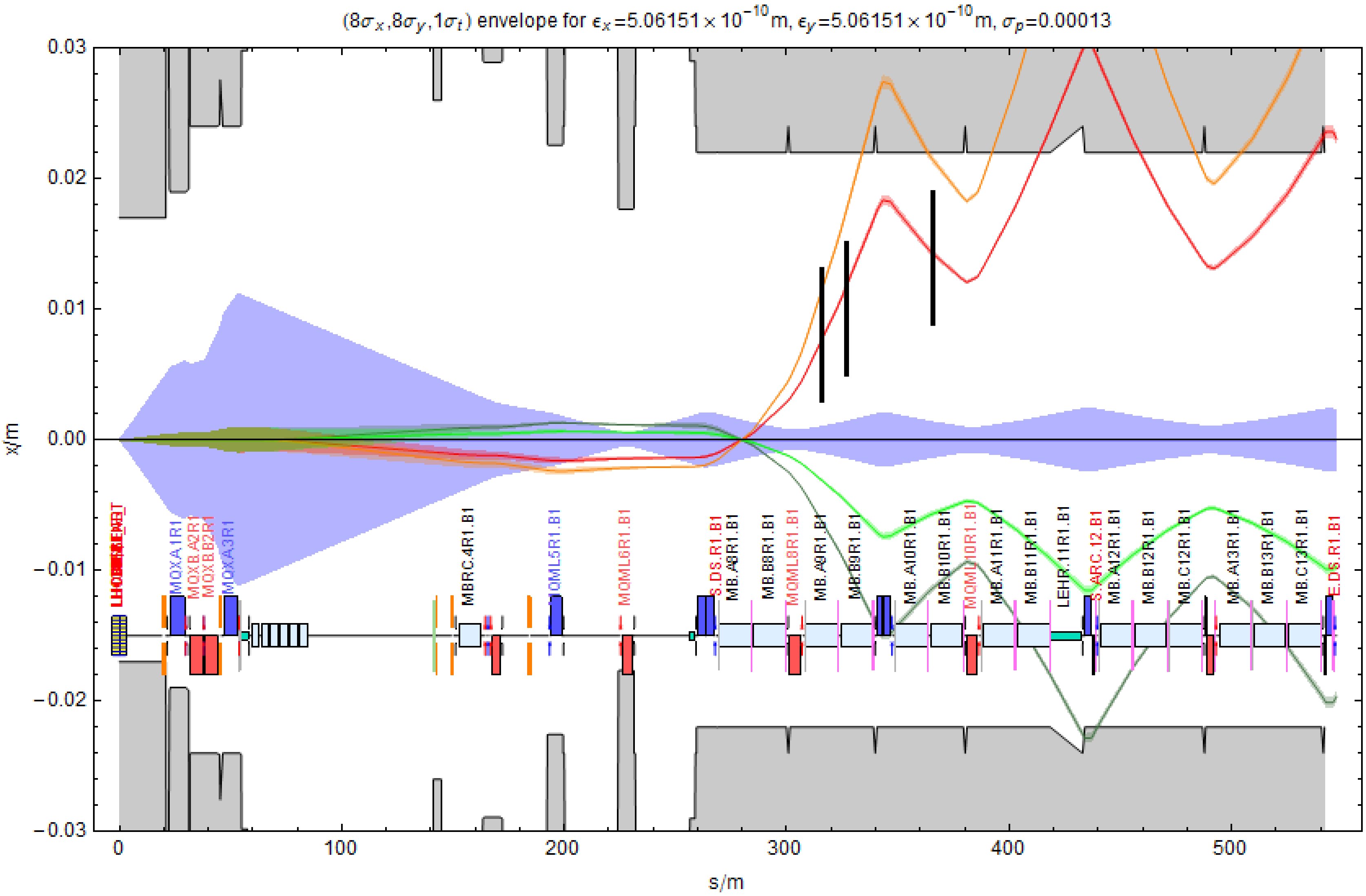
0.5m copper jaws give a peak power density of 3.7 mWcm^{-3} in the coil of the magnet.

1m tungsten jaws give a peak of 0.8 mWcm^{-3}

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
  - We have more than in ALICE scope for mitigation using the orbit bump method tested in 2011 (will be made operational for Run 2 anyway)

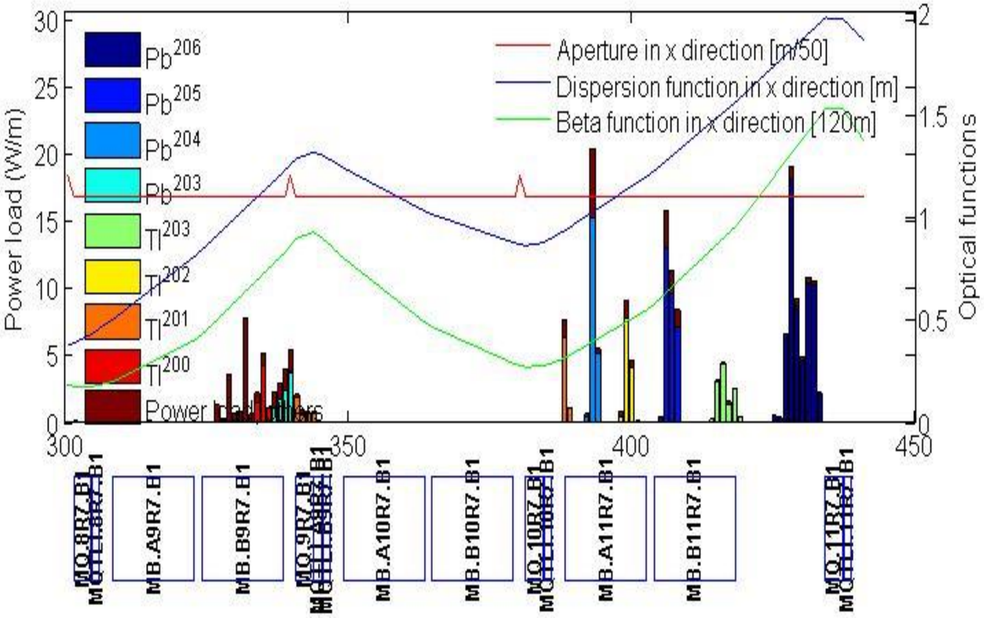
DS Collimator locations around ATLAS or CMS



Different from IR2 but various locations would be effective – not in present planning.

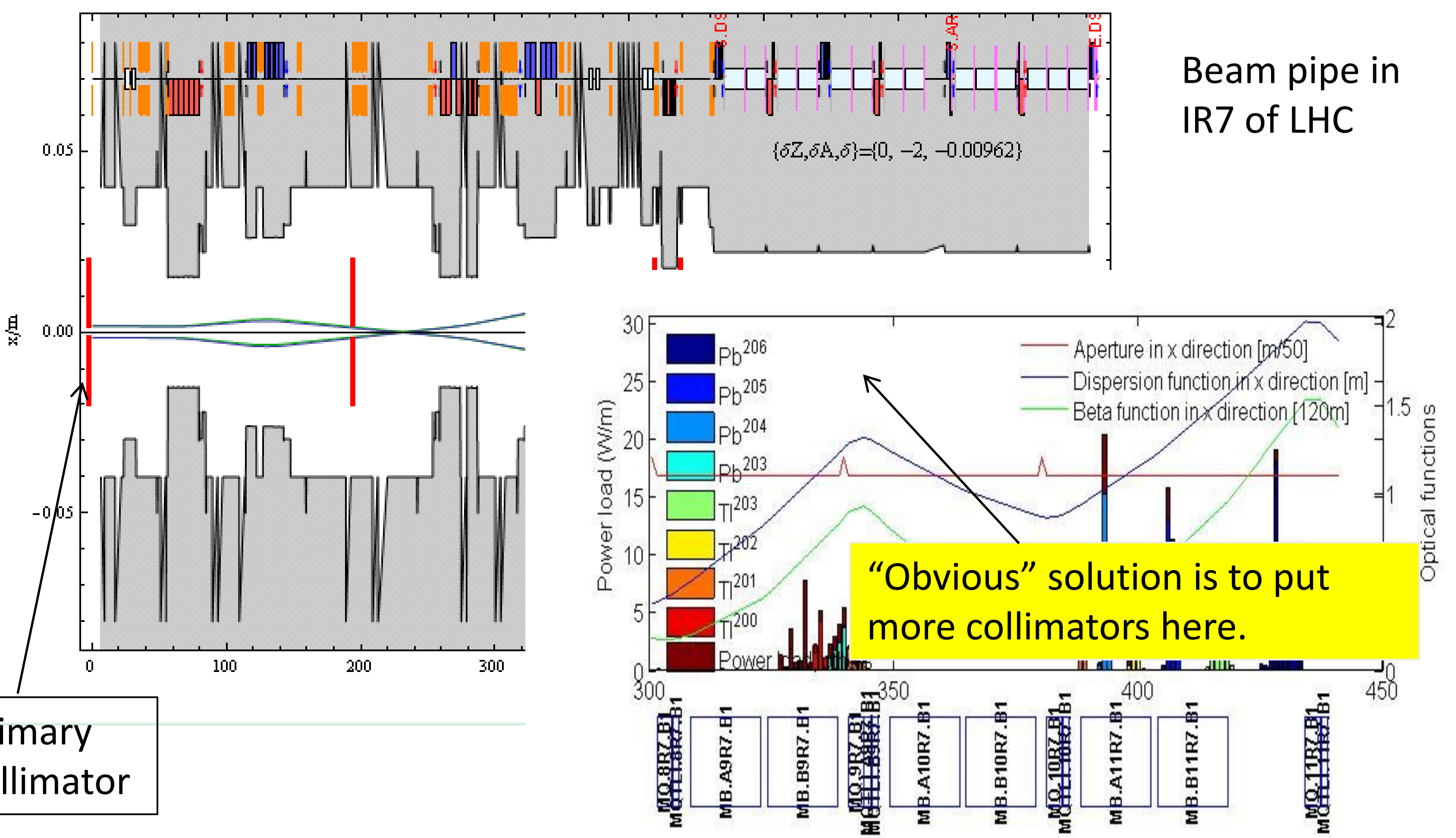
Collimation Inefficiency

- Discussed extensively in the past
  - Pb nuclei fragment (nuclear or EMD) interacting with carbon of primary collimator – unlike protons
- Mainly a limit on total intensity
  - Some situations (Pb beam sizes larger than p, putting beams into collision, off-momentum p-Pb orbits more critical)
  - Mitigation – some success with bump strategy – *backup slides*



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

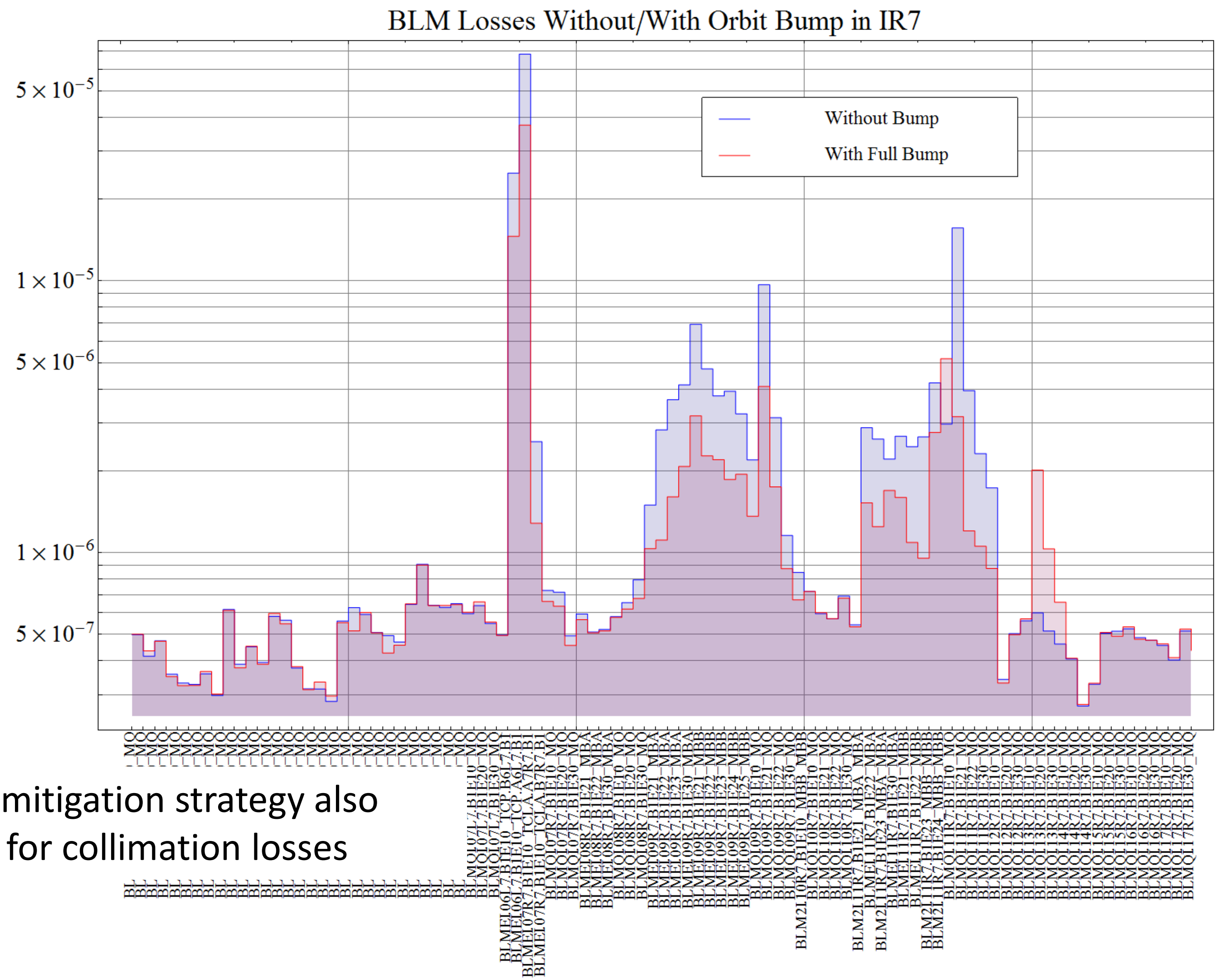


Beam pipe in IR7 of LHC

"Obvious" solution is to put more collimators here.

Primary collimator

Unnormalized BLM losses during bump method test in IR7



BFPP mitigation strategy also helps for collimation losses

New developments on heavy-ion collimation

- LHC *proton* collimation studies have long been made in the framework of the SIXTRACK tracking program
- The ICOSIM program was written by Hans Braun around 2003-4 since SIXTRACK could not accommodate changes in particle mass and charge, fragmentation, etc.
  - Nuclear and EMD cross sections originally obtained from Igor Pshenichnov’s RELDIS and ABRABLA programs and tabulated for ICOSIM
  - Experimental tests in SPS (R. Bruce et al)
  - Predictions of loss maps for Pb ions lost on collimators in LHC (shown earlier) by G. Bellodi, R. Bruce, …
  - However ICOSIM modelling of accelerator optics and particle tracking makes various compromises and is technically inconvenient to keep in sync with other collimation activities
  - Thesis project of Pascal Hermes now under way: integration of the heavy-ion fragmentation physics into the mainstream tracking software (SIXTRACK)

Conclusions

- Effects of photon-induced collisions, both at the interaction point and in beam interactions with collimators, are strikingly visible in heavy-ion operation of the LHC
  - Broadly compatible with theoretical expectations but scope for further analysis
- They may begin to limit performance as we go to higher energy (2015 data crucial!) but:
  - Magnet quench levels are higher than previously expected
  - Energy deposition from BFPP can be mitigated by the orbit-bump technique – probably important for ATLAS and CMS in Run 2 where we expect to exceed design Pb-Pb luminosity
  - Dispersion suppressor collimators should be installed in 2018 shutdown to allow higher peak luminosity for the upgraded ALICE

BACKUP SLIDES

Design Baseline and Performance Achieved

“p-Pb not part of baseline”

	Pb-Pb				p-Pb	
	Baseline	**Injection 2011**	**Collision 2011**	**Injection 2013**	**physics case paper**	**2013**
Beam Energy [Z GeV]	7000	450	3500	450	7000	4000
No. Ions per bunch $[10^8]$	0.7	1.24 ± 0.30	1.20 ± 0.25	1.67 ± 0.29	0.7	$\mathbf{1.40 \pm 0.27}$
Transv. normalised emittance $[\mu\text{m.rad}]$	1.5	---	1.7 ± 0.2	$\mathbf{1.3 \pm 0.2}$	1.5	---
RMS bunch length $[\text{cm}]$	7.94	8.1 ± 1.4	9.8 ± 0.7	8.9 ± 0.2	7.94	9.8 ± 0.1
Peak Luminosity $[10^{27}\text{cm}^{-2}\text{s}^{-1}]$	1	---	$\mathbf{0.5}$	---	115	110

$= 2 \times$ design scaled with E^2

Future runs and species

Charges Z_1, Z_2 in rings with magnetic field set for protons of momentum p_p : colliding nucleon pairs have:

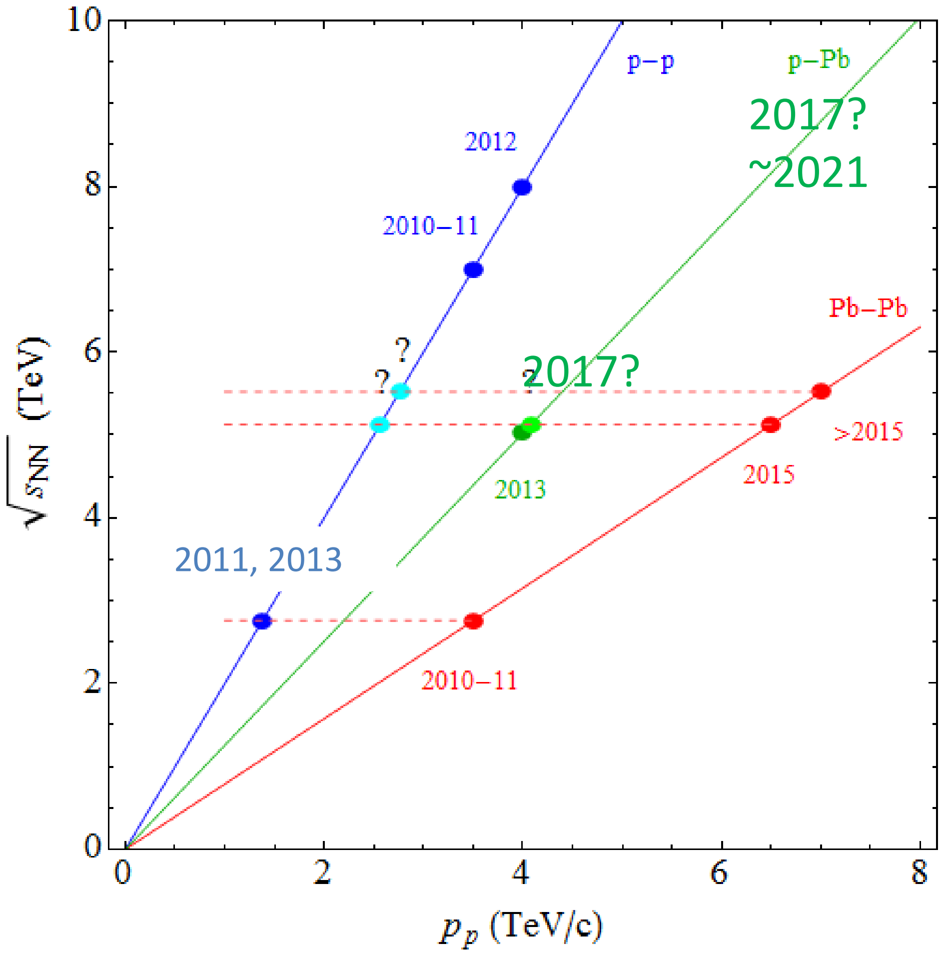
$$\sqrt{s_{NN}} \approx 2c\, p_p \sqrt{\frac{Z_1 Z_2}{A_1 A_2}}, \qquad y_{NN} = \frac{1}{2}\log\frac{Z_1 A_2}{A_1 Z_2}$$

Mainly Pb-Pb operation with p-Pb roughly every 3rd year.

More efficient to do p-Pb at same p_p energy as preceding p-p but may need to lower it to an equivalent CM energy.

Reference data in p-p also required at equivalent CM energies, should ideally track integrated Pb-Pb luminosity.

Lighter species not considered for now.



Luminosity projection summary

- Does not include any improvements beyond injection schemes and natural change of β*=0.5 m and beam size at 7 Z TeV. Some will be mentioned on next slide.
- Model will be re-fitted to real injector chain performance in the run-up to a given Pb-Pb run to re-optimise the length of the SPS trains. Improvements on SPS flat bottom can have a big impact.

Scenario	L_{peak} [Hz/mb]	L_{int} after 3h [μb^{-1}]	L_{int} after 5h [μb^{-1}]	L_{int} in run with 30×5h	$L_{int,run}$ naïve "Hubner Factor"	
200/200ns	2	15	21	$0.64\ nb^{-1}$	$0.64 nb^{-1}$	2011 @ 7Z TeV
100/225ns	3.7	19	25	$0.8\ nb^{-1}$	$1.2\ nb^{-1}$	Run 2
100/100ns	5.0	25	32	$1.0\ nb^{-1}$	$1.6\ nb^{-1}$	**Baseline**
50/50ns	4.6	29	39	$1.2\ nb^{-1}$	$1.5\ nb^{-1}$	Slip Stacking
50/100ns	4.1	26	35	$1.1\ nb^{-1}$	$1.3\ nb^{-1}$	Batch Compression

Performance for p-Pb in Run 2

E (Z GeV/c)	4	7
γ_p	4264	7463
N_p (10^{10} protons/bunch)	1.8–5?	1.8–5?
N_{Pb} (10^8 ions/bunch)	1.6	1.6
n_b	430	430
β^* (m)	0.5	0.5
$\varepsilon_{n,p}$ (µm.rad)	3.5	3.5
$\varepsilon_{n,Pb}$ (µm.rad)	1.5	1.5
f (kHz)	11.245	11.245
L_{peak} (10^{29} cm^{-2}.s^{-1})	**2.5–7?**	**4.3–12**
L_{int} (nb^{-1})	**60 (up to 180?)**	**110 (up to 300?)**

- Increasing the proton intensity is constrained by Pb stability (moving long range encounters), and arc BPMs capabilities (still uncertain),
- 5 10^{10} p/bunch is the maximum reachable in any case,
- Number of bunches per beam is taken from “baseline scenario” for Pb-Pb run in 2015-2016,
- Integrated luminosity assumes same integrated over peak luminosity ratio as in 2013.
- ALICE will level at ~10^{28} and 10^{29} cm^{-2}s^{-1} in Run 2