Outcome of 2011 DS Collimation Review

R. Assmann, CERN

for the collimation team

22/8/2011

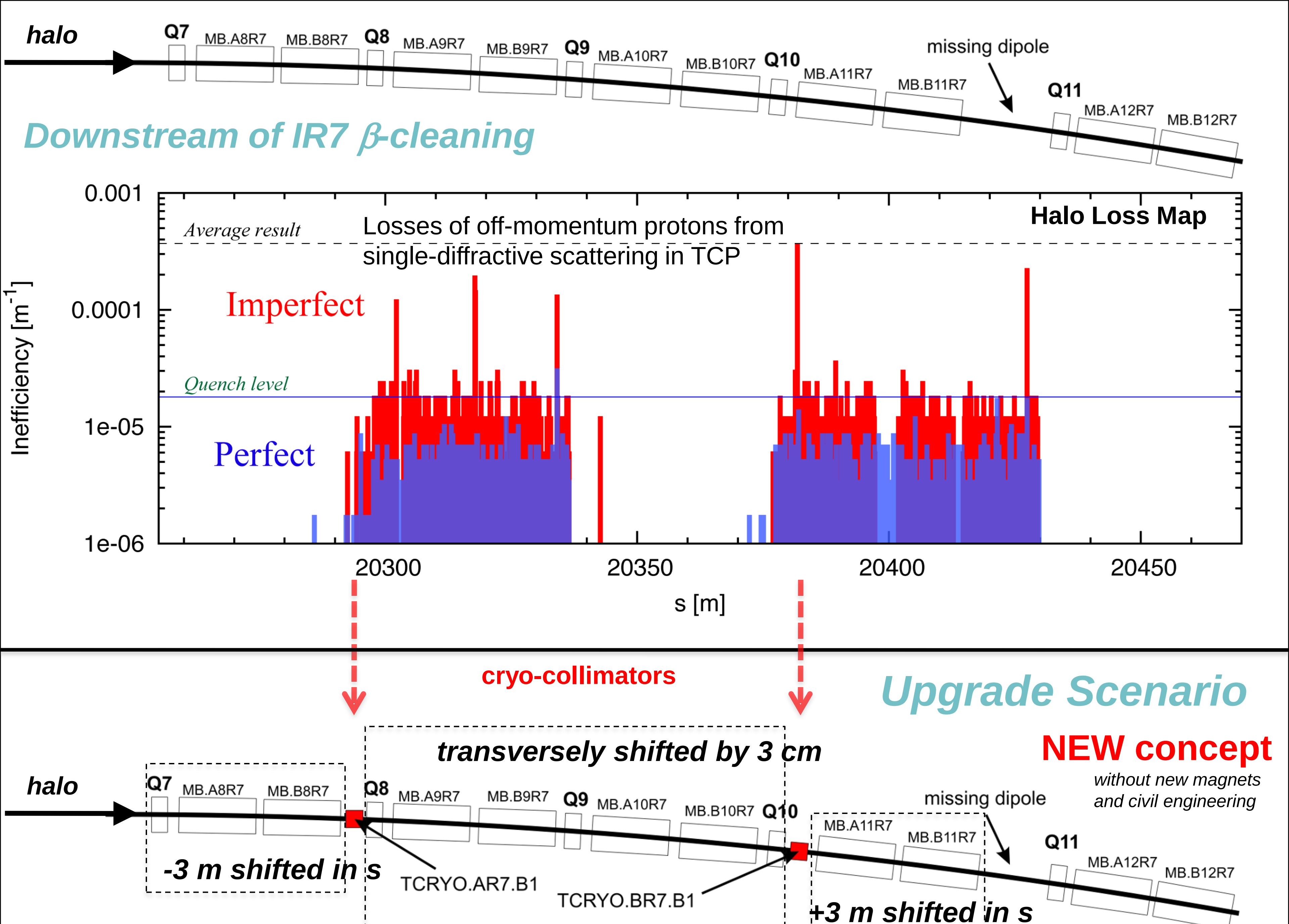
CERN Machine Advisory Committee

Committee and Mandate

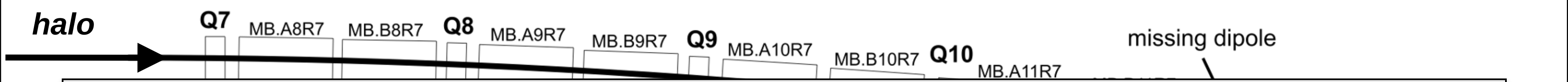
- Committee:
  - **Mike Seidel (PSI, chair), Tiziano Camporesi (CERN), Wolfram Fischer (BNL), Brennan Goddard (CERN), Mike Lamont (CERN), Thomas Markiewicz (SLAC), Nikolai Mokhov (FNAL), Andrzej Siemko (CERN), Johannes Wessel (U. Muenster)**
- Review collimation status and upgrade plans. Advise on the following questions:
  - Are collimation performance and limitations properly analyzed and adequately addressed by upgrade plans?
  - **Can the collimation upgrade in the IR3 dispersion suppressors, presently foreseen for the 2013/4 shutdown, be delayed by three years without limiting LHC performance at 7 TeV?**
  - Have any issues or risks been overlooked that should be addressed in the collimation upgrade plan?
- Produce a report, summarizing the recommendations and findings.

Reminder: Upgrade of Dispersion Suppressors with Collimators

- LHC collimation has two collimation systems per beam in IR3 and IR7, handling betatron and off-momentum losses.
- These systems have **3 stages of cleaning with a 4^{th} stage in the experimental IR's**. In total more 112 collimators and absorbers.
- Optimized for best possible performance. Fundamental limitation:
  - **Primary collimators create off-momentum particles.**
  - These pass straight through next two stages.
  - First dipoles deflect off-energy particles into subsequent dipole.
  - Problem for ions and protons.
  - Can be cured by installing collimators into the dispersion suppressors. Not possible in 2004 when we realized this!
- Upgrade plan: **Upgrade IR3 dispersion suppressor in LS1 (2013/4).**
- Strong effort as reshuffling of whole DS's required.


halo
Q7
MB.A8R7
MB.B8R7
Q8
MB.A9R7
MB.B9R7
Q9
MB.A10R7
MB.B10R7
Q10
MB.A11R7
MB.B11R7
missing dipole
Q11
MB.A12R7
MB.B12R7
Downstream of IR7 β-cleaning
Halo Loss Map
Average result
Losses of off-momentum protons from single-diffractive scattering in TCP
Imperfect
Perfect
Quench level
Inefficiency [m^-1]
0.001
0.0001
1e-05
1e-06
20300
20350
20400
20450
s [m]
cryo-collimators
Upgrade Scenario
NEW concept
without new magnets and civil engineering
transversely shifted by 3 cm
halo
Q7
MB.A8R7
MB.B8R7
Q8
MB.A9R7
MB.B9R7
Q9
MB.A10R7
MB.B10R7
Q10
missing dipole
MB.A11R7
MB.B11R7
Q11
MB.A12R7
MB.B12R7
-3 m shifted in s
TCRYO.AR7.B1
TCRYO.BR7.B1
+3 m shifted in s

8/22/2011



Solution catches off-momentum beam around any IR (any collisions generate off-momentum beam)! We had this solution for LEP2, FAIR will have it, …

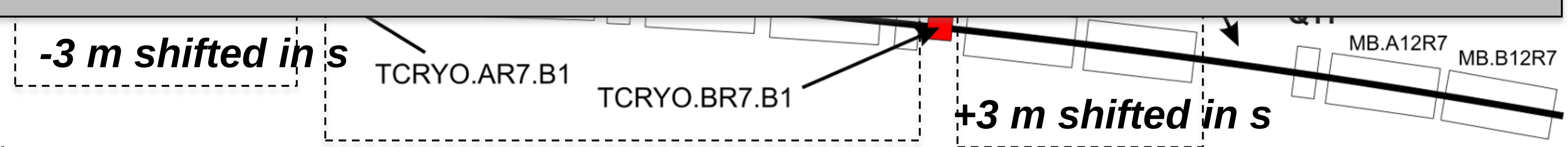
LHC implementation involves shifting 24 magnets per side of each IR. Also affects the connection cryostat obviously and possibly the DFBA.

We propose this solution for the cleaning insertions IR3 and IR7. We are lucky: Easiest to modify these 2 insertions.

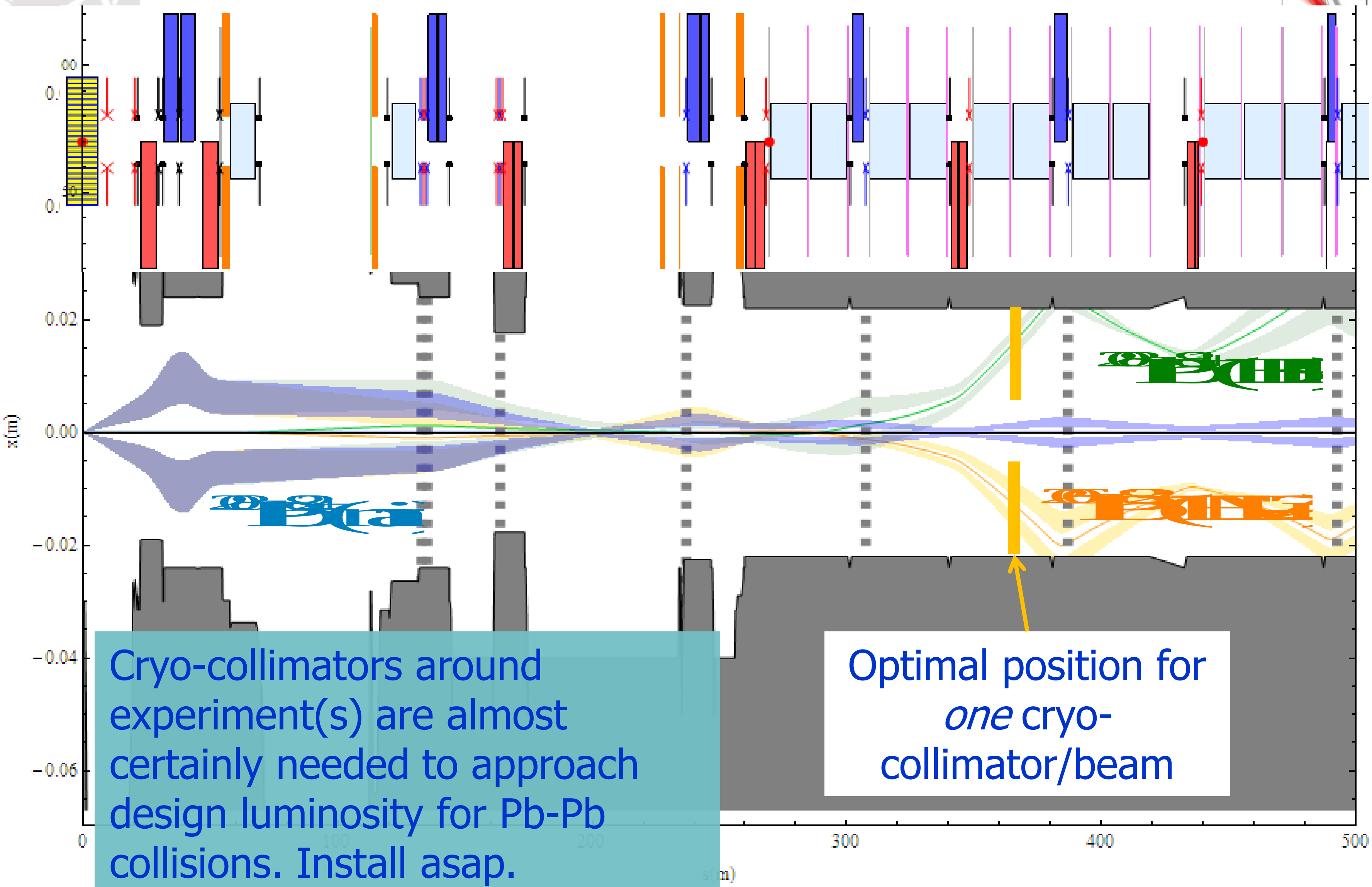
However, solution also solves IR2 ion luminosity limitation. Should be put there as well. *The installation of cryogenics collimator at P2 will be more complicated than for P3&7 because of the presence of individually powered quadrupoles at 6 kA instead of 600 A at 3&7 so the N line at 2 is not standard (same for all other points except 3&7 which are the easiest).*

No plans for IR1 and IR5, as existing collimation should be good for nominal and ultimate luminosities. However, might become needed at some point…

Collimation efficiency: **99.997% (phase 1) ➔ 99.99992% (phase 2)**



Main and secondary Pb beams from IP2



Cryo-collimators around experiment(s) are almost certainly needed to approach design luminosity for Pb-Pb collisions. Install asap.

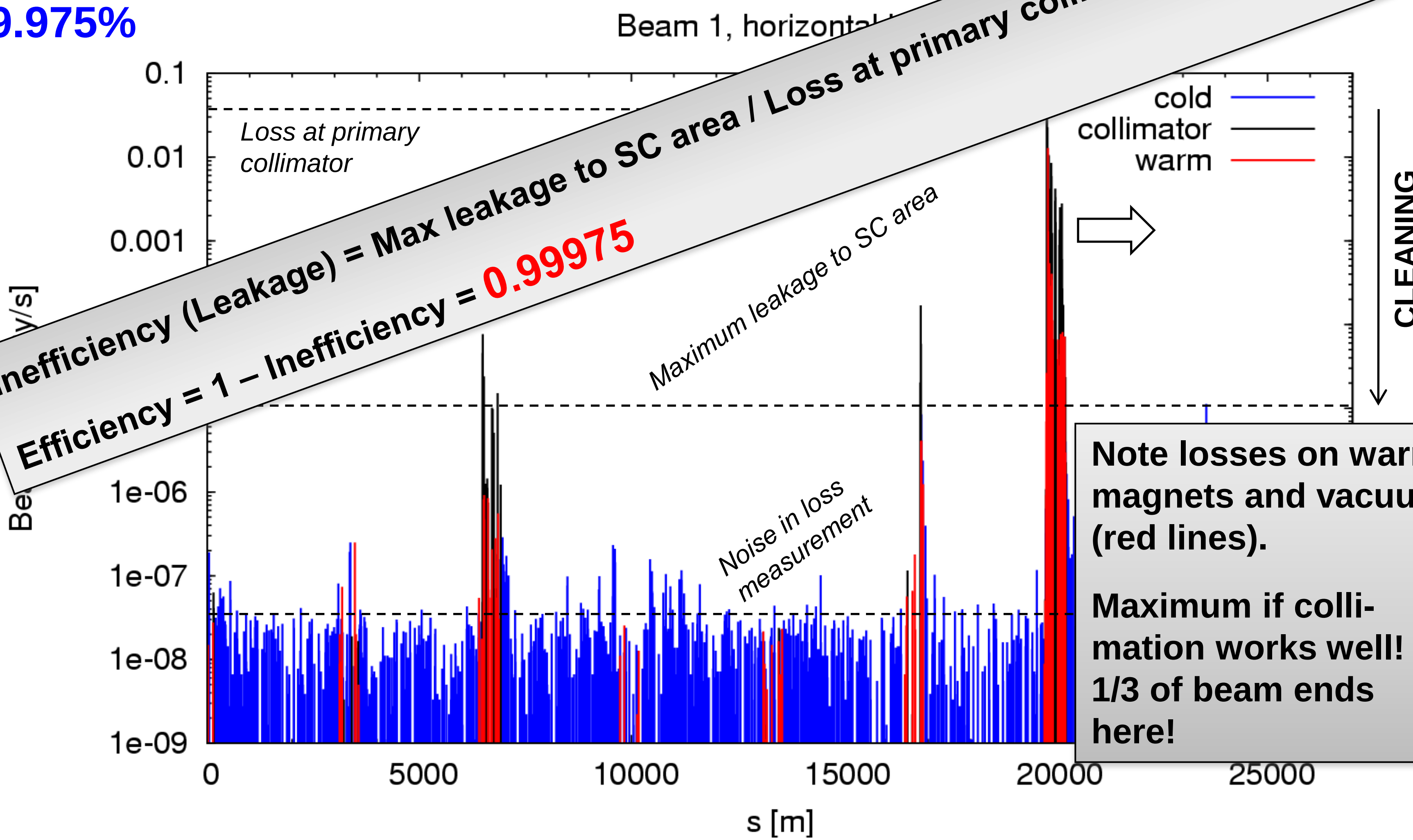
Optimal position for *one* cryo-collimator/beam

John Jowett

Phase 1 Cleaning Measurement

Beam 1 – Horizontal (Q_x crossing of 1/3 resonance)

99.975%



Inefficiency (Leakage) = Max leakage to SC area / Loss at primary collimator = 2.5e-4

Efficiency = 1 – Inefficiency = 0.99975

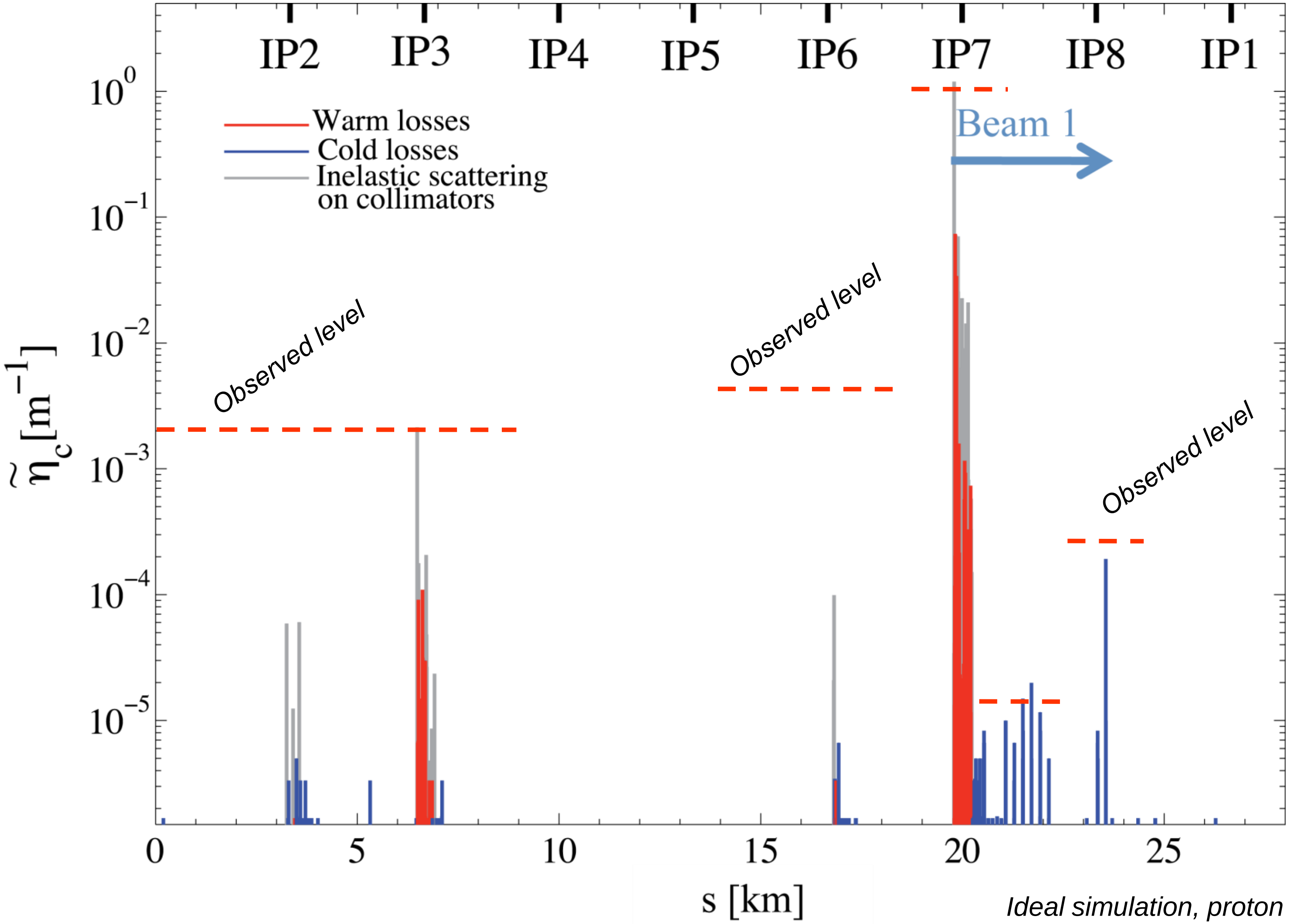
Note losses on warm magnets and vacuum (red lines).

Maximum if colli-mation works well! ~ 1/3 of beam ends here!

Measured 6 days after beam-based setup of collimators – no retuning…

Simulation

(PhD C. Bracco 2008, p. 74)



Ideal simulation, proton tracking, no showers

Program and Speakers

Tuesday 14 June 2011

09:00 - 09:30 **Executive session (closed)**
Location: 40-S2-A01 - Salle Andersson

09:30 - 12:30 **Presentations: Overview on collimation system and present results**
Convener: Dr. Ralph Assmann (CERN)
Location: 40-S2-A01 - Salle Andersson

09:30 **Welcome** *05'*
Speaker: Dr. Ralph Wolfgang Assmann (CERN)

09:35 **Introduction to LHC collimation** *20'*
Collimation system description: multi-stage cleaning, different planes, betatron and momentum. Definition of cleaning efficiency. Introduction quench limit. Hierarchy. Limiting physics processes: single-diffractive p scattering, ion fragmentation, ... Comments on hollow e-beam scrapers.
Speaker: Dr. Stefano Redaelli (CERN)
Material: Slides

09:55 **Discussion** *05'*

10:00 **Collimation setup and performance** *20'*
How is it adjusted? How does it perform in LHC (loss maps: measurement and simulation). MD results at 3.5TeV and performance reach at 7TeV. Losses in luminosity production (dispersion suppressors). Measurement protons vs ions. Minimum beam lifetime. First SPS results BPM's in jaws.
Speaker: Daniel Wollmann (CERN)
Material: Slides

10:20 **Discussion** *05'*

10:25 **Coffee Break** *25'*

10:50 **Radiation to electronics** *15'*
Issues with radiation to electronics in LHC, with focus on collimation insertions. IR7 versus IR3 sensitivity. Benefit of moving losses from IR7 to IR3.
Speaker: Markus Brugger (CERN)
Material: Slides

11:05 **Discussion** *05'*

11:10 **Collimation margins and beta*** *15'*
Stability of LHC machine (orbit, beta). Required margins for collimation setup. Connection collimation to beta. What beta* can be achieved? Origins of limitations: protection condition, infrequent collimation setups, machine drifts.*
Speaker: Roderik Bruce (CERN)
Material: Slides

11:25 **Discussion** *05'*

11:30 **Beam-machine interaction: simulation benchmarking vs first LHC experience** *15'*
FLUKA models and predictions. Comparison between measurements and simulations. Safety margins.
Speaker: Mr. Anton Lechner (Atomic Institute of the Austrian Universities, TU Vienna)
Material: Slides

11:50 **Collimator design: phase 1 and beyond** *20'*
Short description phase 1 design. Second generation collimators. Improved jaw materials. Collimators for cryogenic regions (warm/cold solution).
Speaker: Alessandro Dallocchio (CERN)
Material: Slides

12:10 **Discussion** *05'*

12:15 **Collimation remote handling** *10'*
Highlights from work for collimation remote handling and remote survey. Plans.
Speaker: Keith Kershaw (CERN)
Material: Slides

12:25 **Discussion** *05'*

14:00 - 17:40 **Presentations: Motivation and plans for collimation upgrade (with ATS management)**
Convener: Steve Myers (CERN)
Location: 13-2-005

14:00 **Expectations from Review** *05'*
Speaker: Steve Myers (CERN)

14:05 **Collimation project upgrade plan and questions** *25'*
Outline of collimation upgrade plan. What is planned when and why? What are the questions arising for this upgrade plan?
Speaker: Dr. Ralph Assmann (CERN)
Material: Slides

14:30 **Discussion** *05'*

14:35 **Dispersion-suppressor upgrade IR3** *15'*
Foreseen work in IR3 for first long shutdown? Short description. Planning aspects.
Speaker: Vittorio Parma (CERN)
Material: Slides

14:50 **Discussion** *05'*

14:55 **Proton beam performance with and without IR3 upgrade** *15'*
What is lost when not doing the IR3 upgrade? Gain from DS collimators. Performance reach without (see also morning presentation) and with dispersion suppressor collimators for protons.
Speaker: Adriana Rossi (CERN)
Material: Slides

15:10 **Discussion** *05'*

15:15 **Ion beam performance with and without IR3 upgrade** *15'*
Ion performance reach without and with dispersion-suppressor collimators in IR3. Other ion limitations (IR2, ...). Possible impact from delay of IR3 work on IR2 upgrade of dispersion suppressors.

15:30 **Coffee Break** *20'*

15:50 **Energy deposition with and without IR3 upgrade** *15'*
Predicted energy deposition with and without IR3 dispersion suppressor collimators. Gain from collimators. Performance reach from comparing peak heat deposition with quench limit. Comparison with MD results.
Speaker: Dr. Vittorio Boccone (CERN)
Material: Slides

16:05 **Discussion** *05'*

16:10 **Impedance without IR3 upgrade** *15'*
Impedance from tight collimation settings as achieved in MD. Will the beams be stable with impedance, taking into account stabilization from transverse damper and octupoles?
Speaker: Nicolas Mounet (Ecole Polytechnique Federale de Lausanne (EPFL)-Unknown-Unknown)
Material: Slides

16:25 **Discussion** *05'*

16:30 **Outcome Risk Review for IR3 Work** *20'*
Conclusions from May review in EN/TE departments. Technical feasibility? Major risks? Any show-stoppers identified?
Speaker: Philippe Lebrun (CERN)
Material: Slides

16:50 **Discussion** *05'*

16:55 **Activation issues in dispersion suppressors** *15'*
Expected activation levels. Are additional limits expected on work in dispersion suppressors during later shutdowns?
Speaker: Stefan Roesler (CERN)
Material: Slides

17:10 **Discussion** *05'*

17:15 **Radiation damage in dispersion-suppressor magnets** *15'*
Can the radiation dose on unprotected magnets in the dispersion suppressors be accepted? What is the radiation hardness and can unacceptable damage to magnets be excluded, for protons and ions?
Speaker: Dr. Davide Tommasini (CERN)
Material: Slides

Why a Review?

- Collimation behaves as expected and indeed expected leakage to the DS's is observed.
- Operational lessons:
  - **Peak losses are a factor 5 lower than specified.**
  - **High losses around IR1 and IR5 → more important than IR3?**
- MD tests gave us important input:
  - **Imperfections in LHC much weaker than expected → better efficiency achieved in MD (less efficiency than expected lost due to imperfections).**
  - **With standard settings we could manage a 500 kW beam loss at a primary collimator without quench in MD.**
- Experimental data must be taken into account: Can the upgrade of the DS's be delayed by three years while not preventing nominal beam intensity? → Review of our assessment!

Our Main Input

- The presentations showed several key points:
  - Simple extrapolation takes the **p intensity prediction to ~ nominal intensity**.
  - Combining both MD's takes p intensity to **~4 times nominal (less certain)**.
  - Calculations show **impedance ~OK for small gaps** used in MD.
  - However: **Less good for ions: ~ ½ of nominal intensity**, but not terrible (in shadow of L limitation in IR2?).
  - SC magnets should **survive the DS losses for more than 5 years**.
  - Additional **activation does not prevent later upgrade** of dispersion suppressors.
  - The **IR3 upgrade is not required for mitigation of R2E** in LSS7.
  - Additional **mitigation measures**: hollow e-beam lens, … available.
  - Strong **benefits in equipping all collimators with BPM buttons**: Can gain even when we do not upgrade the dispersion suppressors.

https://indico.cern.ch/conferenceDisplay.py?confId=139719

Required Cleaning Efficiency

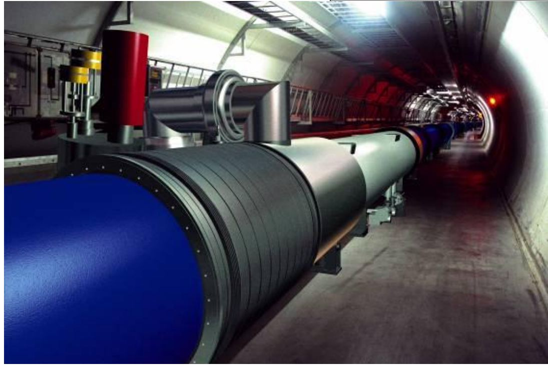


Illustration of LHC dipole in tunnel

Allowed intensity

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

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

Very well predicted and measured

Cleaning inefficiency

=

$$\frac{\text{Number of escaping p } (>10\sigma)}{\text{Number of impacting p } (6\sigma)}$$

Beam lifetime
(e.g. 0.2 h minimum)

BLM threshold
(e.g. 30%)

Loss length

Many variables: quench limit for various magnets and various time scales, dilution of losses in length and transverse area, achievable cleaning efficiency, minimum beam lifetime, …

Proton Performance Reach from MD: 3.5 TeV

$$N_p^{max} \; 3 \; t \times R_q \times F_{BLM} \times L_{dil} \, / \, h_c$$

Loss rate at quench / BLM limit

$$\text{»} \; t \times R_{loss}^{DS} / h_c = t \times R_{loss}^{prim} \times h_c / h_c = t \times R_{loss}^{prim}$$

Measured MD1:

$$N_p^{max} \; 3 \; t \times R_{loss}^{prim} = 3.2 \, ´ \, 10^{15} p$$

3600 s **9e11 p/s**

Extrapolated with MD2: Factor 3.3 better inefficiency from second MD

$$N_p^{max} \; 3 \; 3.3 \times t \times R_{loss}^{prim} = 1.1 \, ´ \, 10^{16} p$$

Proton Performance Reach from MD: 3.5 TeV

$N_p^{max} \geq \tau \times R \times F$ … at quench / BLM limit

$\approx \tau \times R$ … $_{loss}$

Estimate independent of dilution length, quench limit and BLM response functions!

Measured MD1:

$$N_p^{max} \geq \tau \times R_{loss}^{prim} = 3.2 \times 10^{15} p$$

3600 s (τ) — **9e11 p/s** (R_{loss}^{prim})

Extrapolated with MD2: Factor 3.3 better inefficiency from second MD

$$N_p^{max} \geq 3.3 \times \tau \times R_{loss}^{prim} = 1.1 \times 10^{16} p$$

CERN-ATS-Note-2011-042 MD (LHC)

May 24, 2011
Stefano.Redaelli@cern.ch

Collimator losses in the DS of IR7 and quench test at 3.5 TeV

R.W. Assmann, R. Bruce, F. Burkart, M. Cauchi, D. Deboy, B. Dehning, E.B. Holzer, E. Nebot del Busto, A. Priebe, S. Redaelli, A. Rossi, R. Schmidt, M. Sapinski, G. Valentino, J. Wenninger, D. Wollmann, M. Zerlauth,
CERN, Geneva, Switzerland

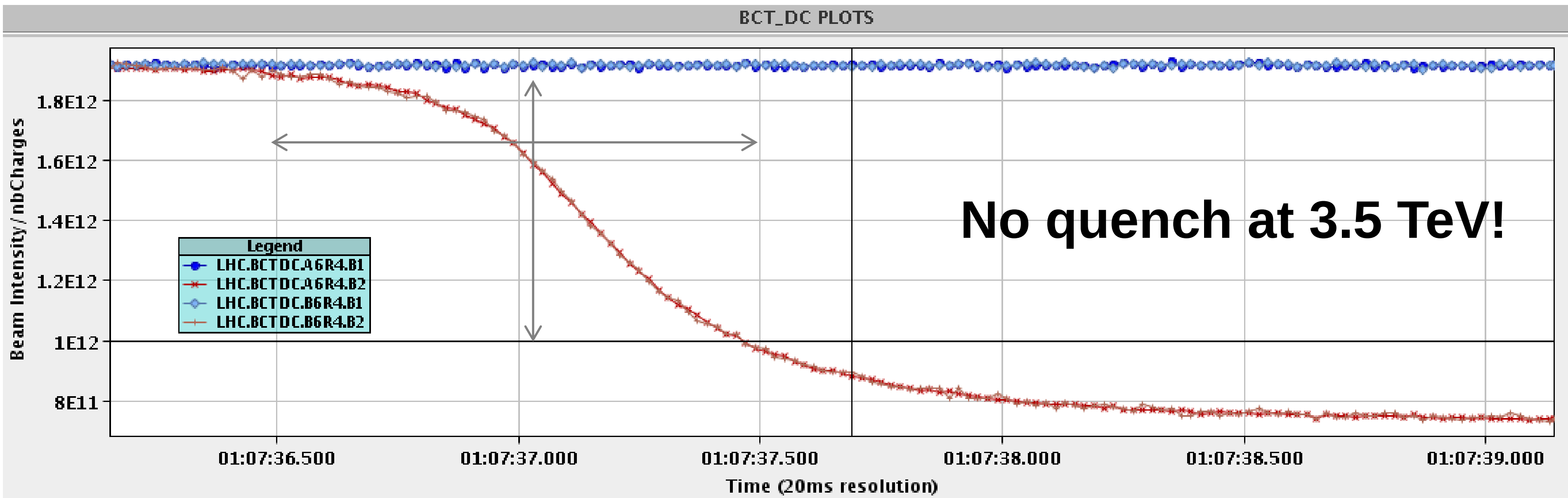
Keywords: Collimation, beam losses, quench, dispersion suppressor

LHC Collimation Project

16 bunches, 3.5 TeV

Provoked beam loss: beam blow up on 1/3 resonance

MD1



No quench at 3.5 TeV!

Loss rate:

9e11 p/s @ 3.5 TeV → 505 kW

(In) Efficiency Reached *(Coll → SC Magnet)*

MD2

99.960 %

worse

99.995 %

better

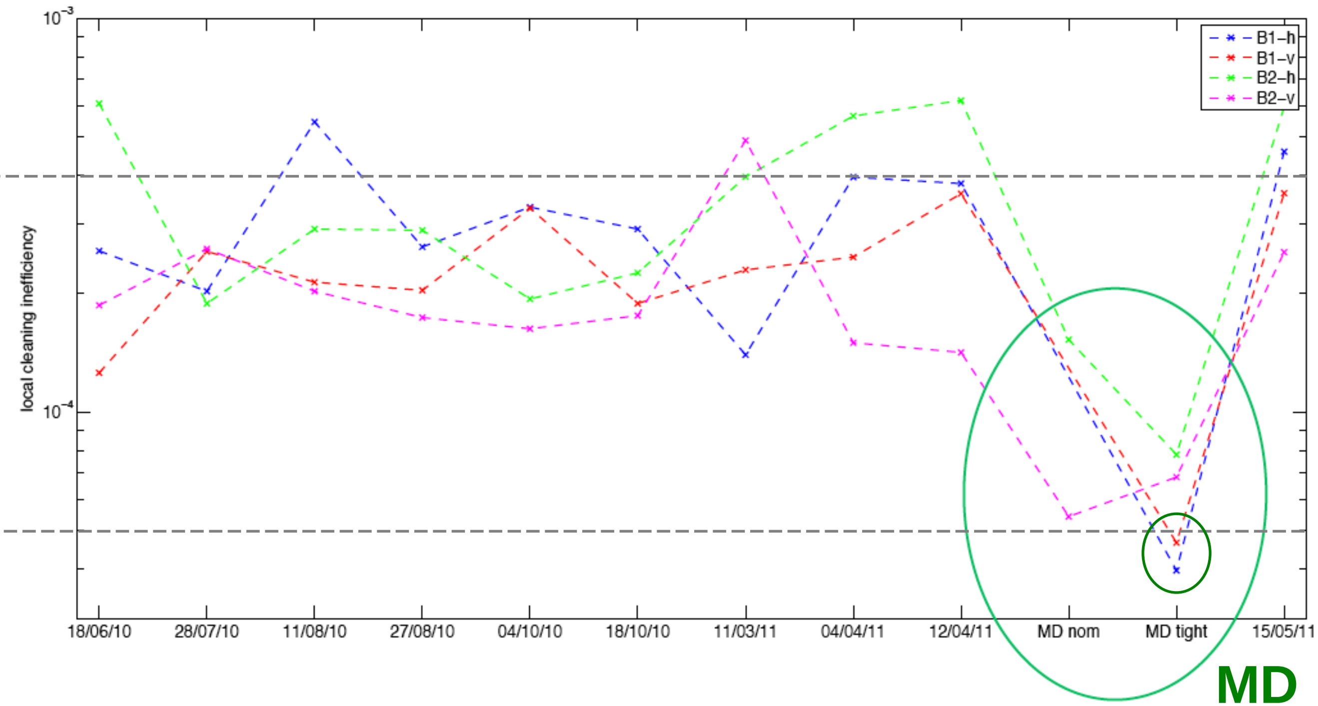


Figure 5: Beam 1 and Beam 2 maximum local cleaning inefficiency in the cold parts of the LHC at 3.5TeV over about one year operation. The results from this MD are contained in the second and third sets of points from the right, where a clear decrease can be observed.

Proton Performance Reach from MD: 7 TeV

Measured MD1 put to 7 TeV:

$$N_p^{\max} \geq \frac{\eta_c^{3.5TeV}}{\eta_c^{7TeV}} \times \frac{R_q^{7TeV}}{R_q^{3.5TeV}} \times \tau \times R_{loss}^{prim}$$

0.4 **0.29**

$$N_p^{\max} \geq 0.12 \times \tau \times R_{loss}^{prim} = 3.9 \times 10^{14}\, p$$

Tolerances ~shown, impedance ~OK for small emittance operation
Beta* lower than 1m not feasible with these settings (these are somewhat relaxed collimation settings).

Proton Performance Reach from MD: 7 TeV

Extrapolated with MD2:

$$N_p^{\max} \;3\; 3.3 \times \frac{h_c^{3.5TeV}}{h_c^{7TeV}} \times \frac{R_q^{7TeV}}{R_q^{3.5TeV}} \times t \times R_{loss}^{prim}$$

$\frac{h_c^{3.5TeV}}{h_c^{7TeV}}$ ↑ **0.4**

$\frac{R_q^{7TeV}}{R_q^{3.5TeV}}$ ↑ **0.29**

$$N_p^{\max} \;3\; 0.4 \times t \times R_{loss}^{prim} = 1.3 ´\; 10^{15}\, p$$

Requires collimation at 4 sig_nom with tighter tolerances than nominal. OK for nominal beta*.
Tolerances not achieved (we tried in MD1), impedance only OK for large emittance operation.

FLUKA for p Performance Reach

- Can give detailed power deposition.
- Simulation for perfect machine. No imperfections (orbit, beta beat, misalignments, …).
- Predicted 3.5 TeV energy deposition:
  - Deposit **11 mW/cm^3** (relaxed collimation settings, MD1 loss: 9e11p/s)
  - Quench limit: **5.5 – 41 mW/cm^3** (latest estimate islargest)
- Predicted 7 TeV energy deposition:
  - Deposit **4 mW/cm^3** (tight collimation settings, **0.2h** lifetime: 4e11p/s)
  - Quench limit: **2 – 15 mW/cm^3** (latest estimate is largest)
- Results consistent with no quench.
- Results consistent with p performance reach estimate.
- Detailed reach depends on quench limit, collimation settings, lifetime (better), imperfections (worse), …

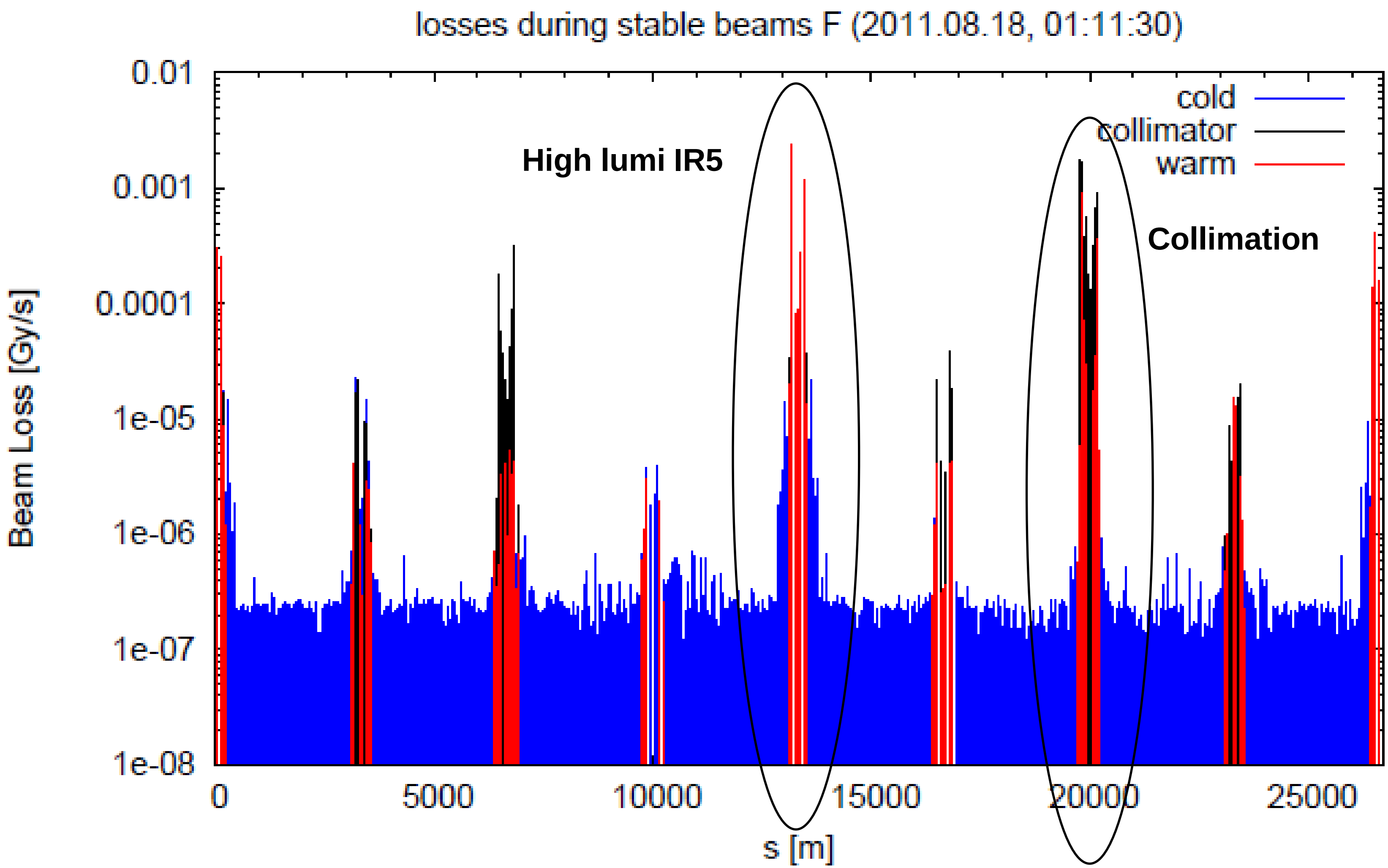
Ion Performance Reach

- Analyzed with ion lifetimes and taking into account MD results.
- Prediction for 7 TeV equivalent:
  - **50% of nominal ion intensity**

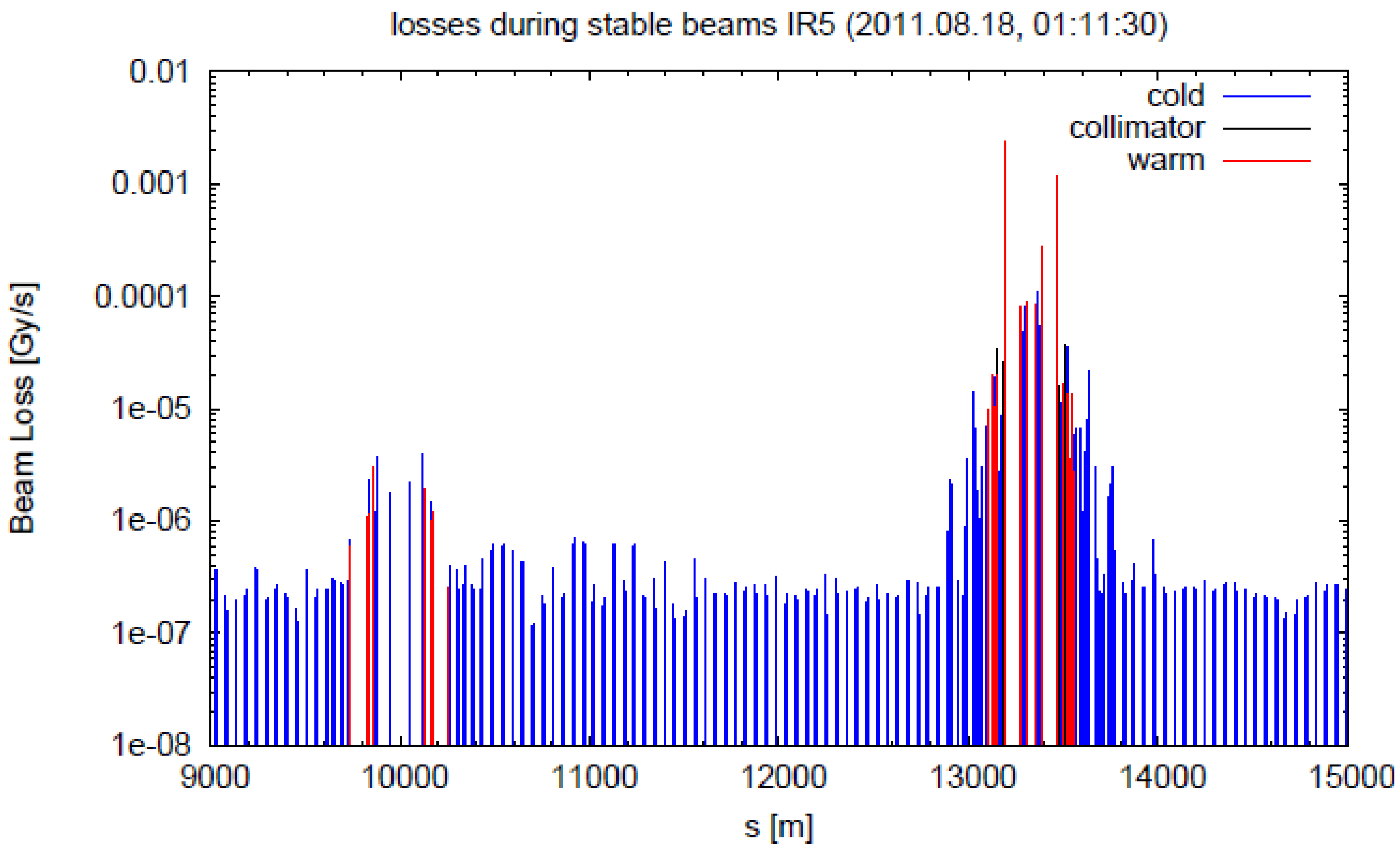
Disclaimer

- Many assumptions have been removed with the MD tests. Much more certain!
- However, there are still some strong assumptions, explained in detail during the review:
  - Same minimum beam lifetime at 3.5 TeV and 7 TeV.
  - Minimum lifetime independent of intensity (e.g. strength of beam-beam interaction, number of LR interactions, …).
  - Same distribution of losses.
  - …
- If we push intensity to the limit: What is the limit?
  - So far the limit is still given by allowable losses in collimators without damage and without quench (push beam closer to stability limit).
  - Other hard limits might or might not manifest before (final UFO limit, HOM heating, …)

Does not Mean that Losses are No Worry!



Zoom into IR5



Outcome of Review

- Written report has been produced and is available.
- Will go through some main points.

From Report…

- "The general progress of LHC, and particularly the performance of the collimation system, is outstanding."
- "It is worth noting that the collimation system performs two critical roles: in its cleaning role it prevents protons from impacting the LHC’s cold mass; its secondary role is as passive protection in certain beam loss scenarios. In both roles it has performed impeccably."
- "collimation performance and limitations are properly analyzed and adequately addressed by the upgrade plans“

… thanks …

From Report…

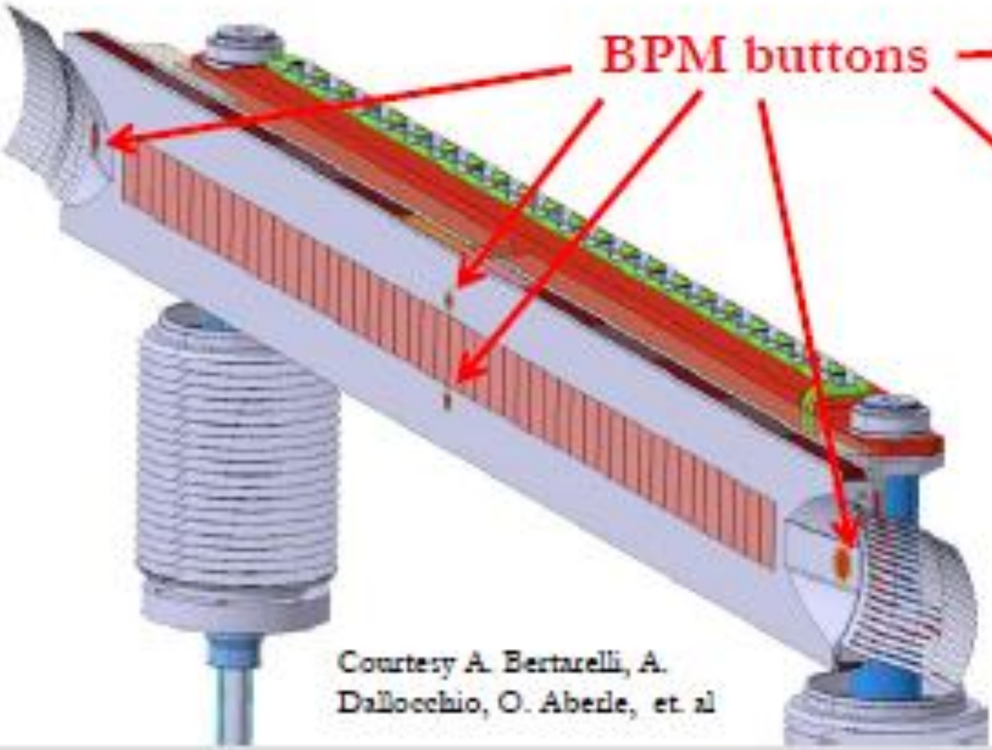
- "On the basis of the evidence presented, the committee concludes that the nominal proton beam intensity of LHC at 7 TeV can be achieved without the installation of additional collimators in the IR3 dispersion suppression region during the LS1 shutdown."
- "For heavy ion beams less experimental evidence exists and thus the extrapolation to full energy entails more uncertainty.“
- With this input we took some decisions in LMC:
  - No upgrade of IR3 DS’s in 2013/4.
  - Complete prototype for cryo-bypass. Complete drawings for DS collimator, if needed later.

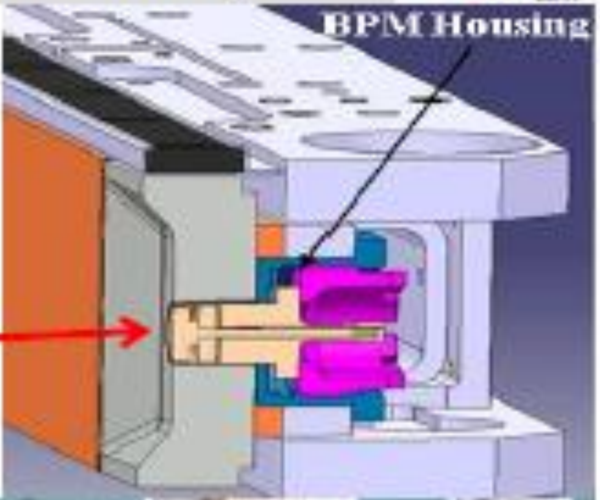
From Report…

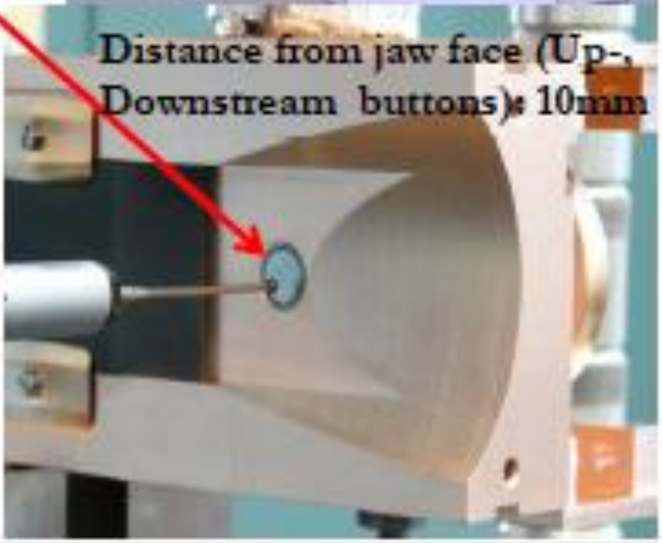
- "the committee feels that the proposed installation of BPMs embedded collimators should take high priority"
- "The committee feels nevertheless that the upgrade of collimation in the IR3 and IR7 DS should be carried out in the long term (LS2) as it will allow for increased machine performance."
- "If the proposed mitigation measures go ahead as planned, they should be sufficient to reduce R2E effects at IR7 to an acceptable area. In this case, the shift of betatron cleaning to IR3 will not be required. It is felt, however, that preparation for the move should be undertaken.“

First CERN mock-up collimator with integrated BPM buttons (Jan 2010)

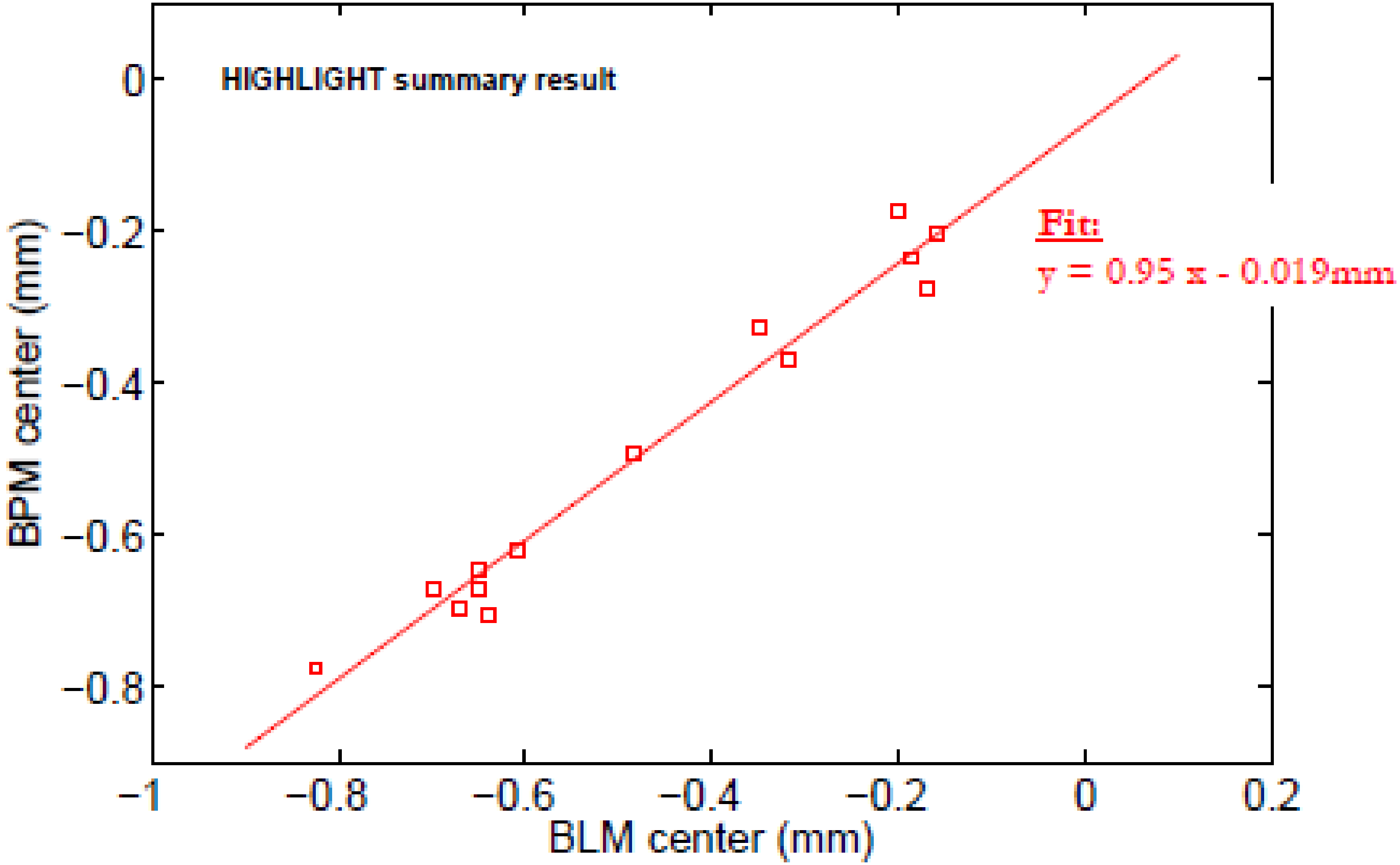
- BPM mock-up produced at CERN (EN-MMI, BE-BI, Collimation Team)
- Installed into SPS in 2010



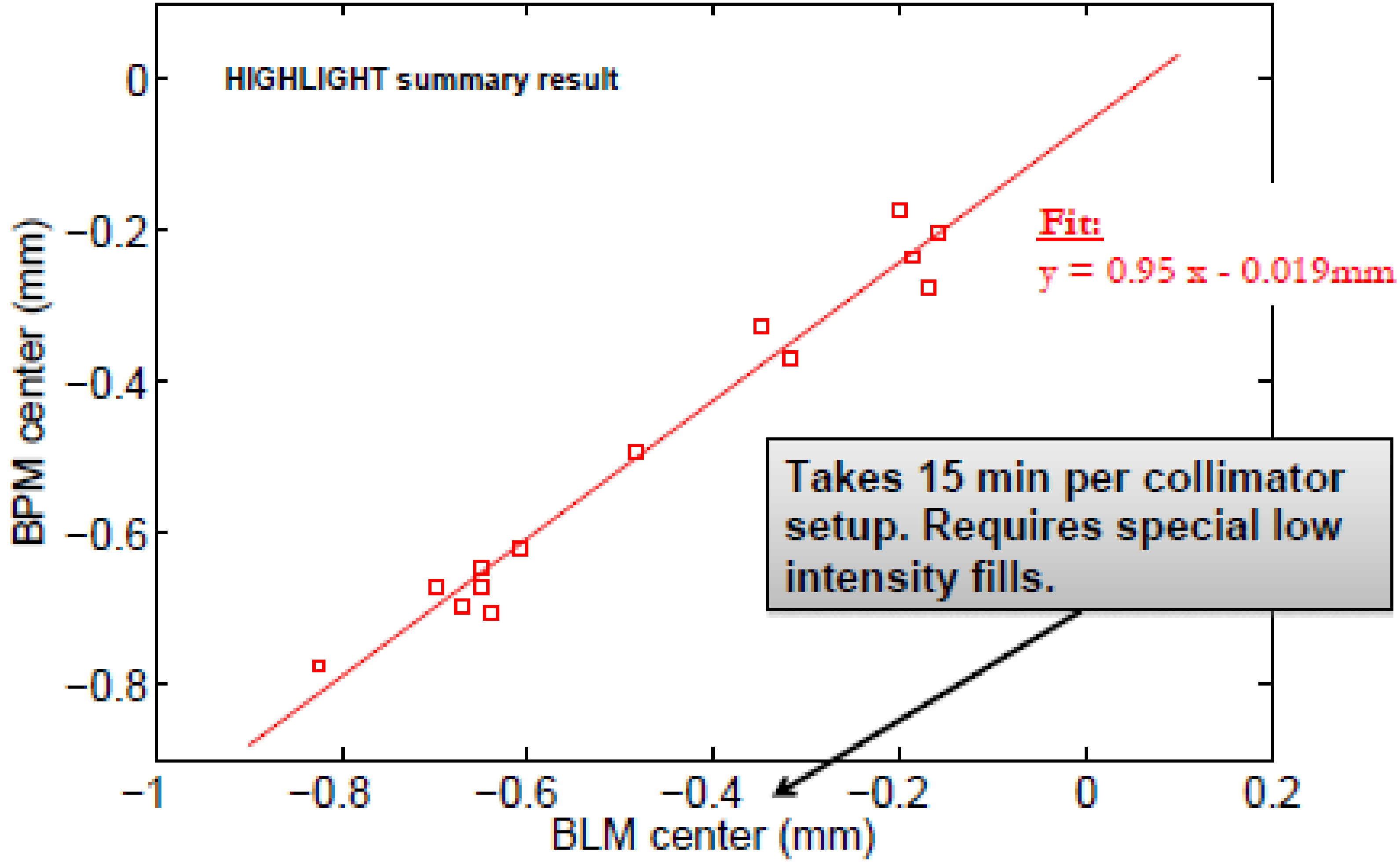




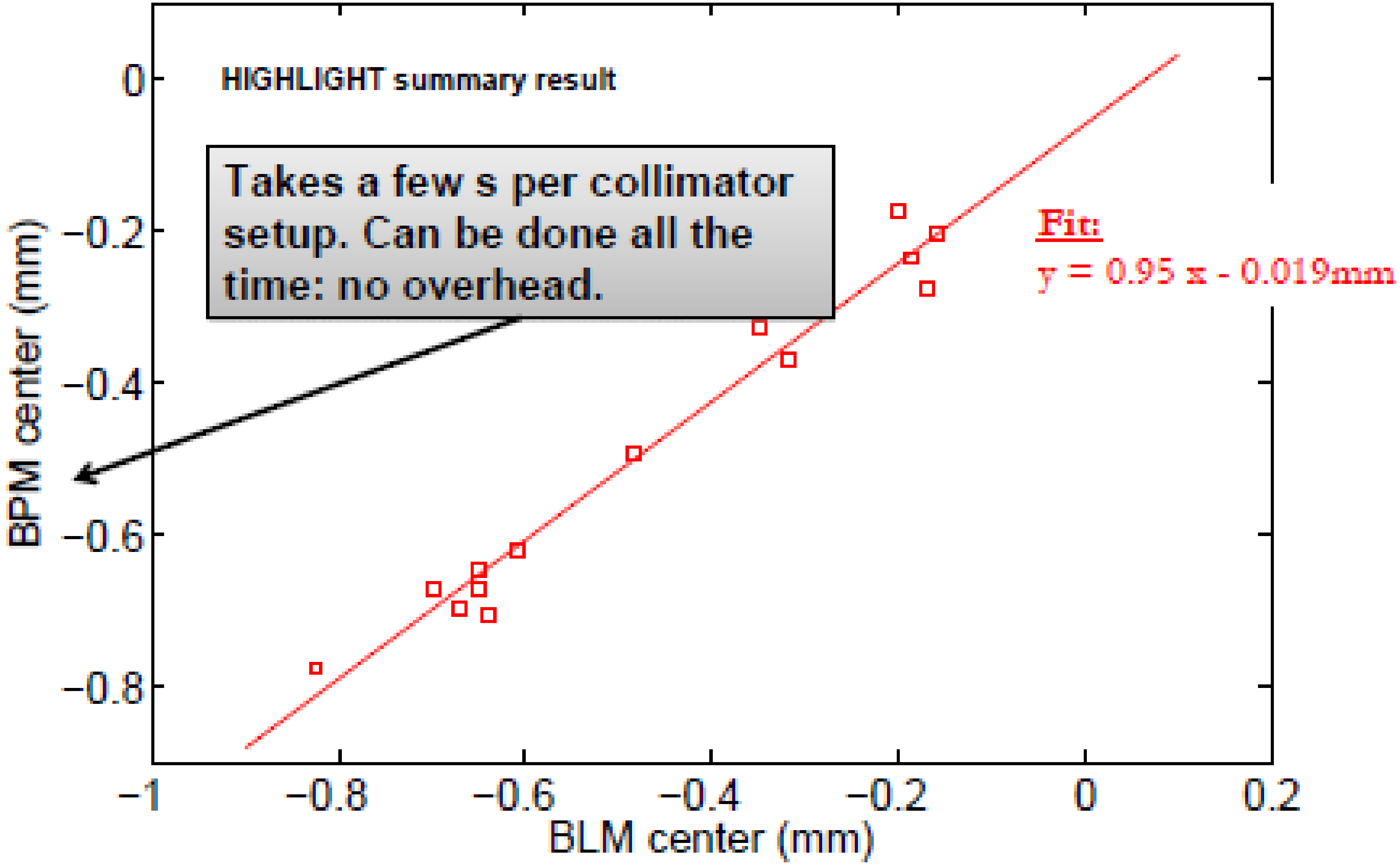
Correlation:
BPM-method versus BLM-method



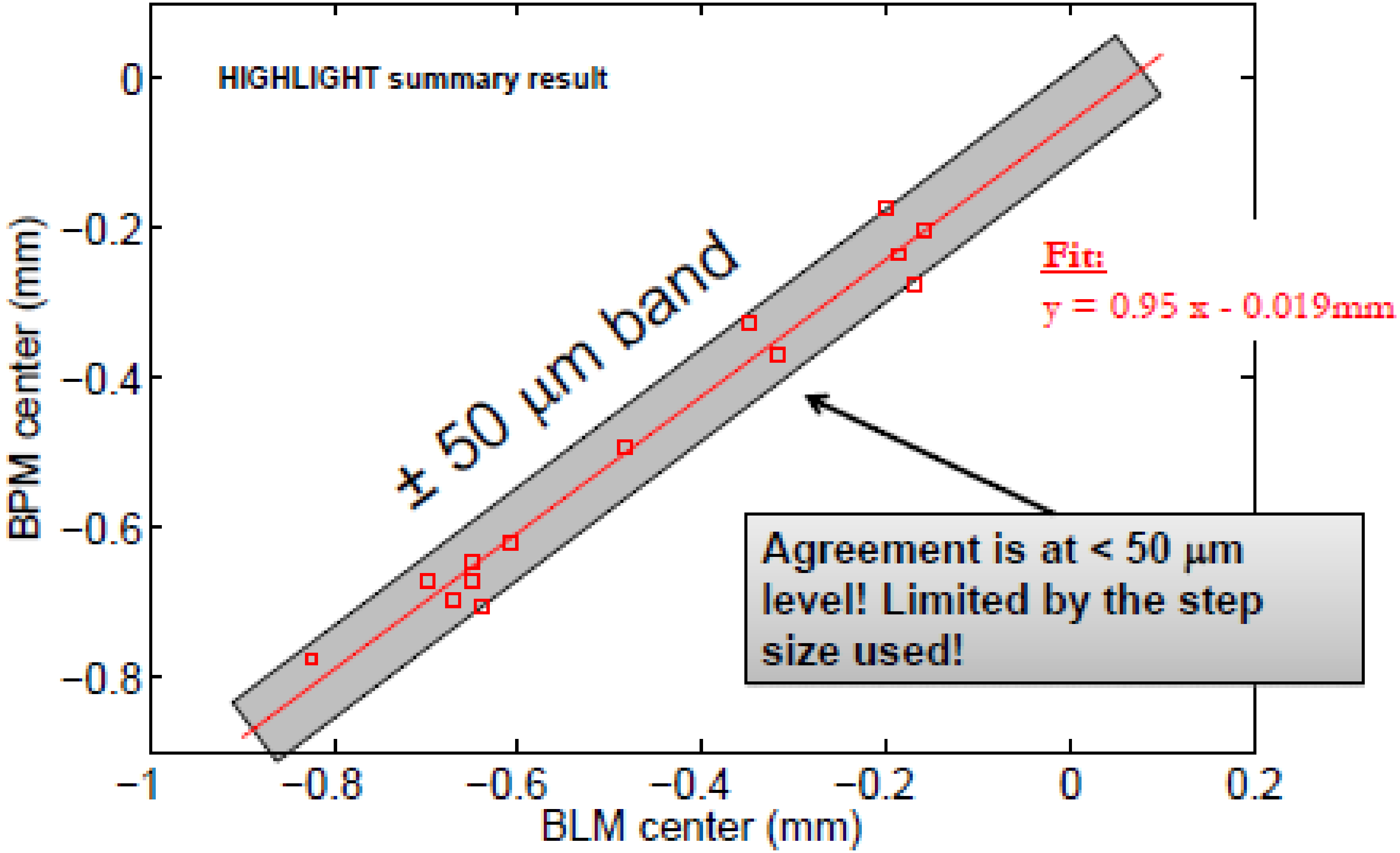
Correlation: BPM-method versus BLM-method



Correlation: BPM-method versus BLM-method



Correlation: BPM-method versus BLM-method



Summary from Committee

recommendations 1

- mechanism for lifetime dips at 3.5 TeV should be better understood and how this scales with energy; perform studies to evaluate effects of varying operational parameters on lifetime dips
- consider mitigation measures against lifetime dips, e.g. collide before squeeze
- estimate radiation damage to stabilizing material of superconducting cable at cryogenic temperatures

Summary from Committee

recommendations 2

- quench limit studies, including provoking quenches, should be continued to
  - benchmark simulation predictions
  - gain data for heavy ion operation
  - establish a link to 1D beam loss model used throughout the collimation project, particularly in IR3
  - increase confidence concerning 7TeV predictions

Summary from Committee

recommendations 3

- investigate other upgrade options (postponing work on DS collimators until LS2)
  - fixed masks inside large aperture dipole magnets
  - possibility of 11 T magnet to replace main dipole, to make space
  - thin Tungsten primary collimators
  - hollow e-beam
- evaluate risk level with present tolerances and 0.55 m β^*
- impedance: 7 TeV settings on the edge for stability for headtail modes and TMC; Investigate feedback?
- addition of combined cleaning will maybe double the total impedance coming from the collimators due to smaller gaps...this should be properly evaluated.

Conclusions

- The delay of the IR3 DS upgrade is a fully logical conclusion, given the results we found in the MD and reported to the committee (no quench with 500 kW).
- A delay of the IR3 collimation upgrade is not a zero risk decision but risk is acceptable and decision is defendable, given the resources saved in LS1.
- Excellent news for the collimation project and LHC:
  - Collimation works even better than expected and is likely sufficient for nominal intensity, given the better-than-design LHC accelerator quality.
  - Will then have made a factor 1,000 beyond state-of-the-art in one go!
- Will not be easy though:
  - Full gaps to 1.4 mm (smaller than design). Pay in tolerances/impedance.
  - Need experts to run system at its limits until LS2. Pay in expert manpower.

Illustration of Assumed Tight Settings

23.25 mm

Present operation
@ 3.5 TeV

We like the challenge!

Ahead for Collimation I

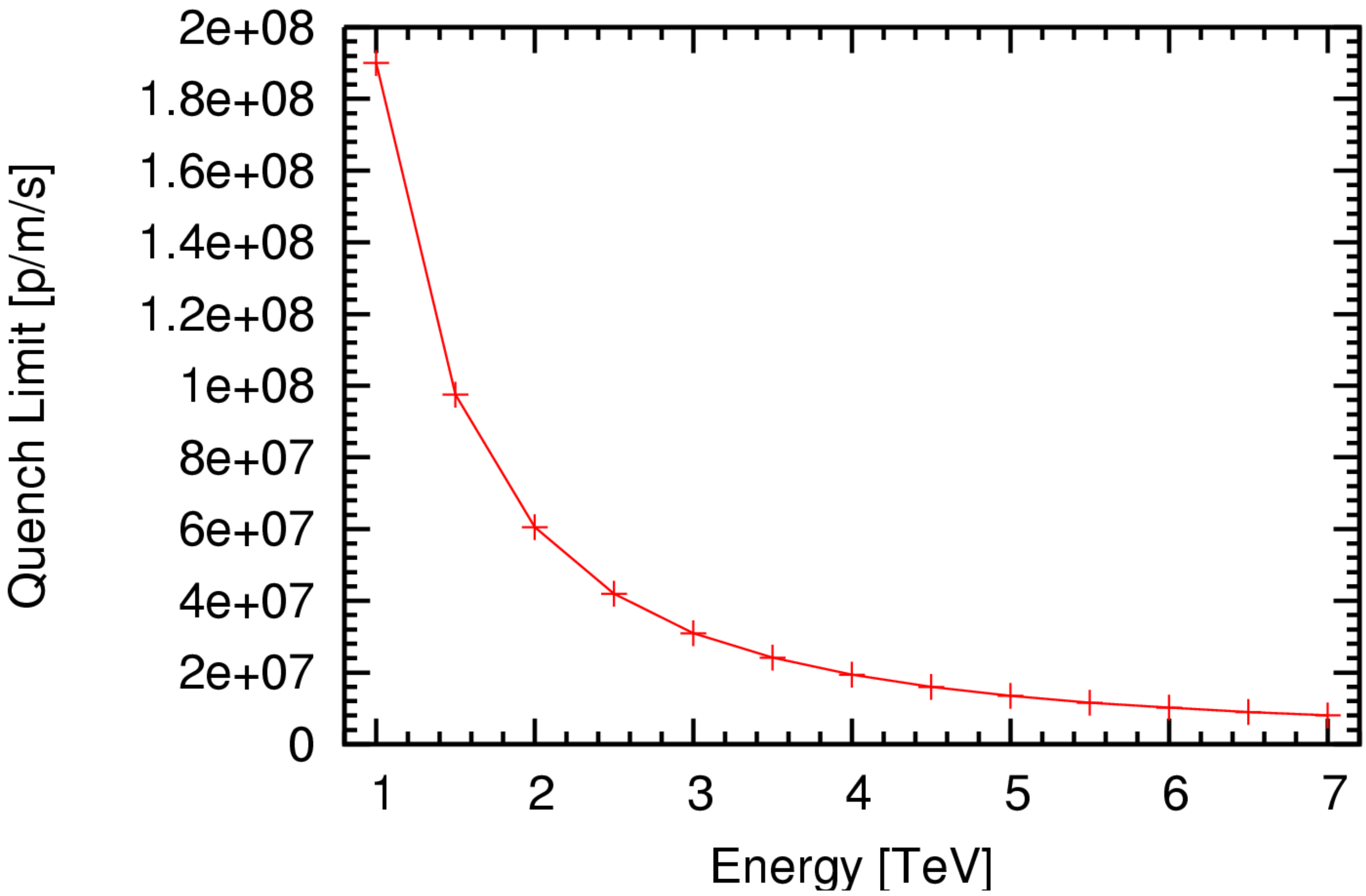
- Decisions taken at LMC 22.6.2011:
  - Delay the IR3 DS upgrade by three years to LS2.
  - Complete the ongoing prototyping and testing for the cryo-bypass.
  - Complete the TCLD design to 100% and document solution. No prototype.
  - No decision on vertical collimation in IR3, being aware that this will prevent readiness for LS1 in present schedule.
  - Focus work on installing collimators with BPM buttons as soon as possible (always best efficiency, minimal margins, lowest beta*, …).
- Upgrades of DS's:
  - Start studies for collimation upgrade of the DS's in 5 IR's for LS2.
  - Start design of cold collimators for 11 T magnet solution (new shorter, high field magnets instead of moving magnets).
  - Will need to set up working group for specifications and design study.

Ahead for Collimation II

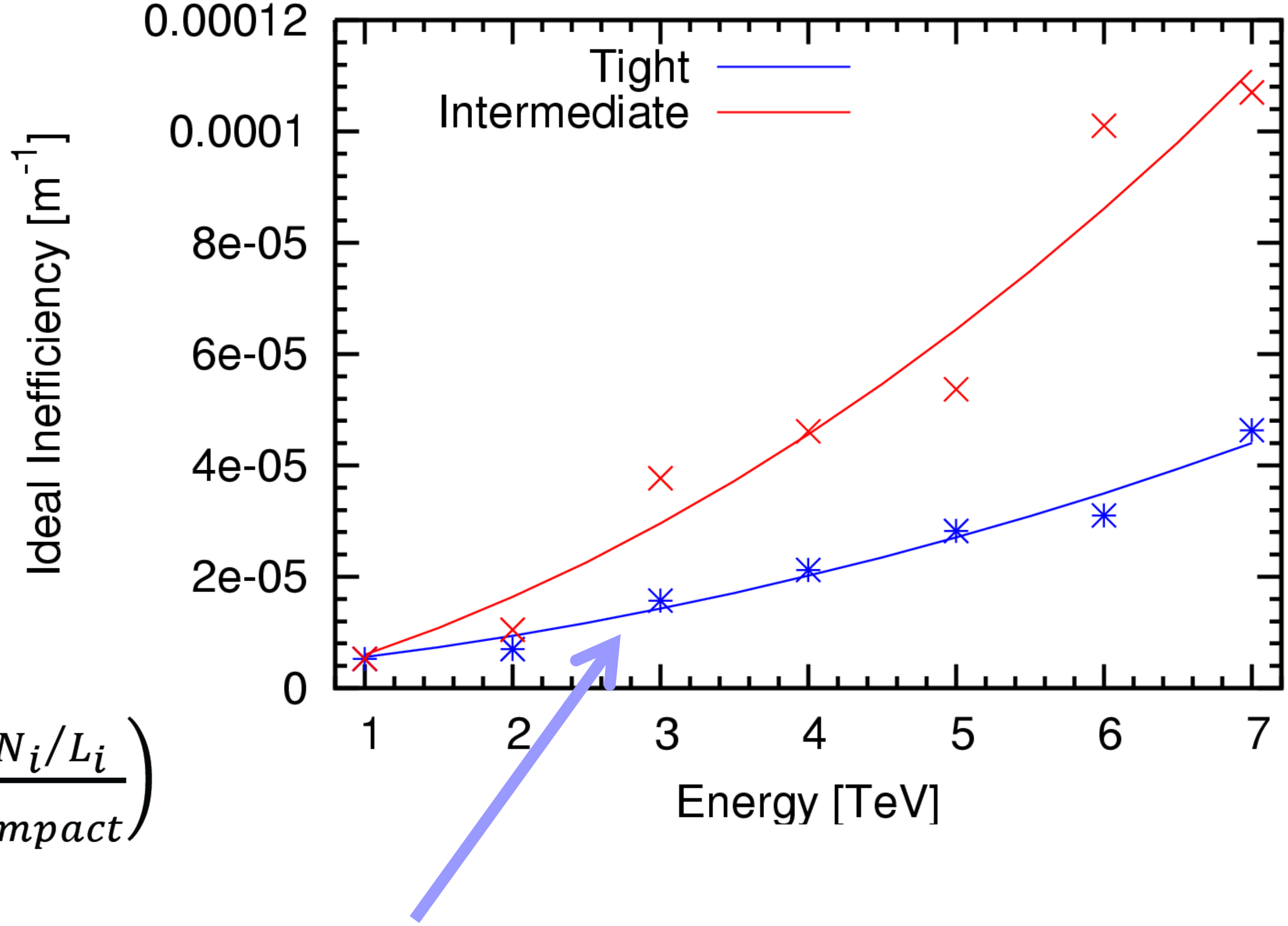
- The R&D for hollow e-beam lenses (done at FNAL) is supported by the review and gives us a backup solution to reduce peak losses when going into collisions.
- Other collimation activities ongoing and not affected: new TCT's in IR2, remote handling, material R&D for high brightness beams, R&D for LHC scrapers, HL-LHC upgrade issues, …

Thank You

Quench Limit vs Energy



Inefficiency versus Energy



$$\tilde{\eta}_{ineff} = \max_i \left(\frac{\Delta N_i / L_i}{N_{impact}} \right)$$

$$\frac{\tilde{\eta}_{ineff}}{10^{-4}} = 0.0276 \frac{1}{m} + 0.0231 \frac{1}{m} \cdot E + 0.0051 \frac{1}{m} \cdot E^2$$