Luminosity optimization and leveling

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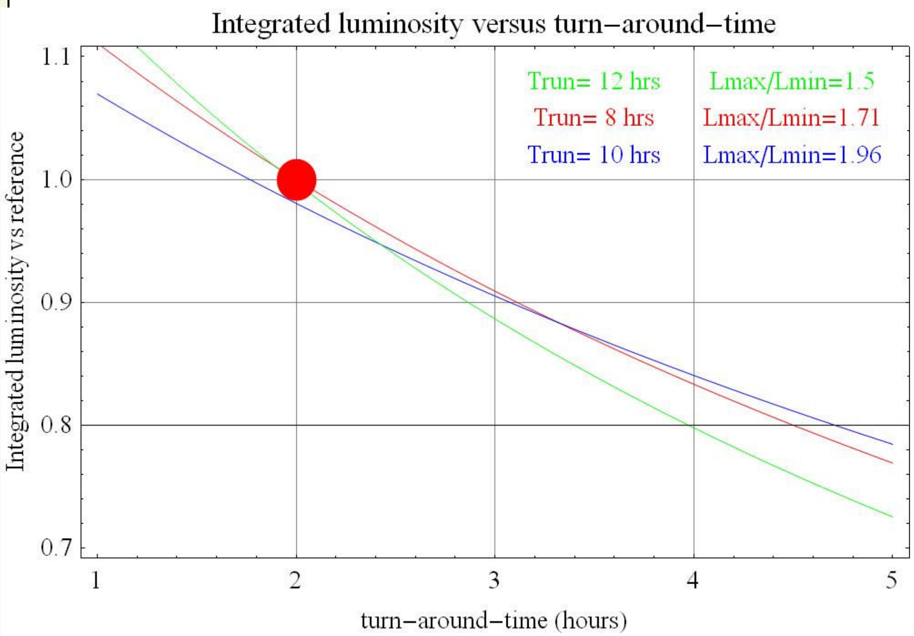
DG/PRJ

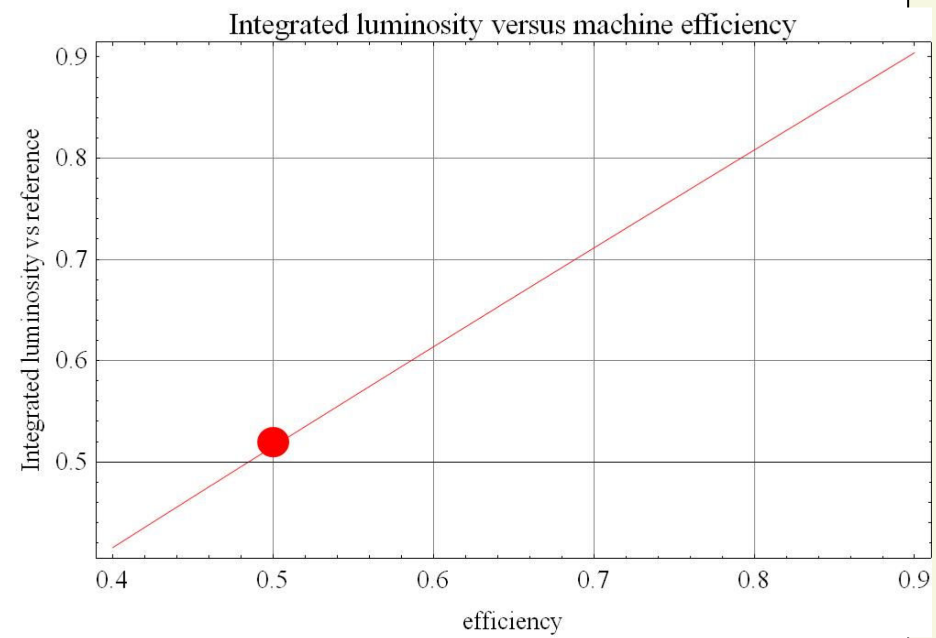
How can the effective luminosity be optimized by complementary measures, like beam-beam compensation (long-range, head-on) and luminosity leveling (various schemes)? Which are the merits and challenges of each measure? Are there lessons for the upgrade strategy?

Outline

1. **What contribution from improved turn-around-time and machine availability?**
2. Why luminosity leveling in sLHC-II?
3. Methods of luminosity leveling
4. Adverse effects of the beam-beam interactions, and compensation schemes
5. Conclusions

Turn-around-time and machine availability





$$\eta = \frac{\text{effective integrated luminosity}}{\text{integrated luminosity in scheduled collision time assuming design Lpeak and decay}}$$

The impact of turn-around time or machine efficiency remains modest in comparison with the ambitions of the upgrade

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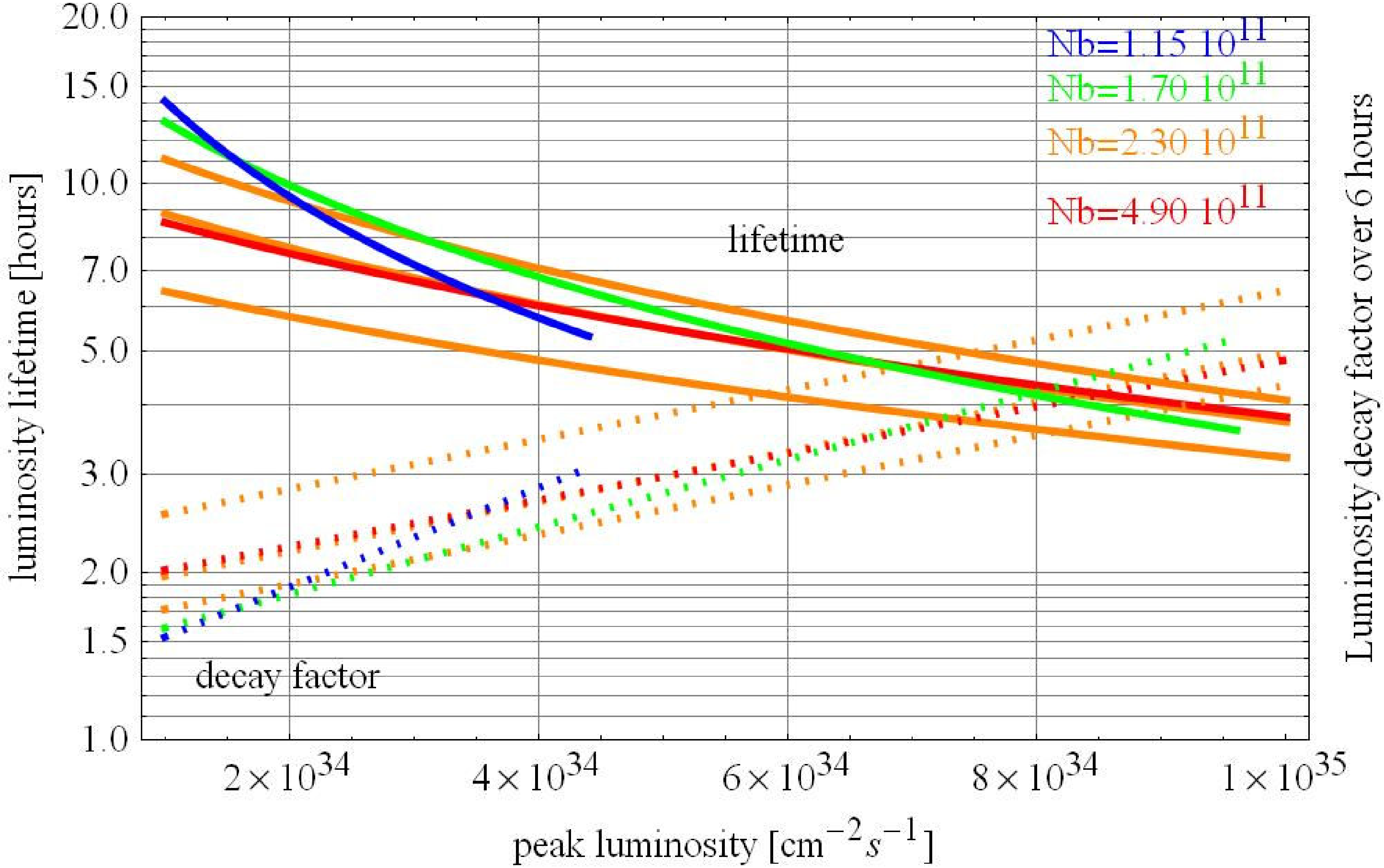
Relative importance of "nominal" decay sources

Scenario: 10^{35} cm^{-2}s^{-1}, by increasing the bunch charge to 2.3 10^{11} and reducing beta* & crossing angle at IP:

Source	Time constant [h]
Proton burning	**5.8**
IBS	**46**
Rest gas	**39**
Luminosity	**4.1**

Do we have an effective handle on the decay rate?

Let's assume that any peak luminosity between 1 and 10×10^{34} $cm^{-2}s^{-1}$can be reached and investigate the luminosity lifetime (i.e. effective luminosity) versus the peak luminosity and the parameters that can be modified: *bunch charge, bunch spacing, emittance*.



Whatever the scenario, the lifetime is short compared to typical operations "time constants": for a realistic upgrade, leveling appears as a requirement rather than a complementary measure.

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Luminosity leveling

$$L \propto \frac{1}{\beta^* \sqrt{1+\frac{\theta_c^2 \sigma_s^2}{4\beta^* \varepsilon}}} \qquad \Delta Q_{bb} \propto \frac{Nb}{\varepsilon_N} \frac{1}{\sqrt{1+\frac{\theta_c^2 \sigma_s^2}{4\beta^* \varepsilon}}}$$

3 possibilities in LHC, specific to crossing at an angle:

1. Leveling via dynamic beta* adjustments
2. Leveling via dynamic Xing angle adjustments
3. Leveling via dynamic bunch length adjustments

An important feature of LHC:

The beam-beam tune shift dependence on details

Leveling via β* (1)

1. ***Strategy 1:*** keep constant the normalized beam separation:

$$\Delta Q_{bb} \propto 1/\sqrt{1+k/\beta^{*2}}$$

For $\beta^* \in$ [50 cm→25 cm], *potential* loss of L by ×2

If ΔQ_{bbmax}=0.01, then Np ≤ 1.9 10^{11}ppp (2 IP's)

2. ***Strategy 2***: keep constant the physical beam separation:

$$\Delta Q_{bb} \propto 1/\sqrt{1+k'/\beta^{*}}$$

For $\beta^* \in$ [50 cm→25 cm], *potential* loss of L by 50%

If ΔQ_{bbmax}=0.01, then Np ≤ 2.15 10^{11}ppp (2 IP's)

Leveling via β* (2): implementation

- No specific additional HW.
- Looks simple but may not be: global machine perturbation: very accurate feedback necessary on Q, Q', coupling, orbits all around the LHC+ Xing bumps (±0.1σ at IP's).

- Taken from a talk on leveling by V. Lebedev/FNAL in the CARE-HHH BEAM'07 meeting:

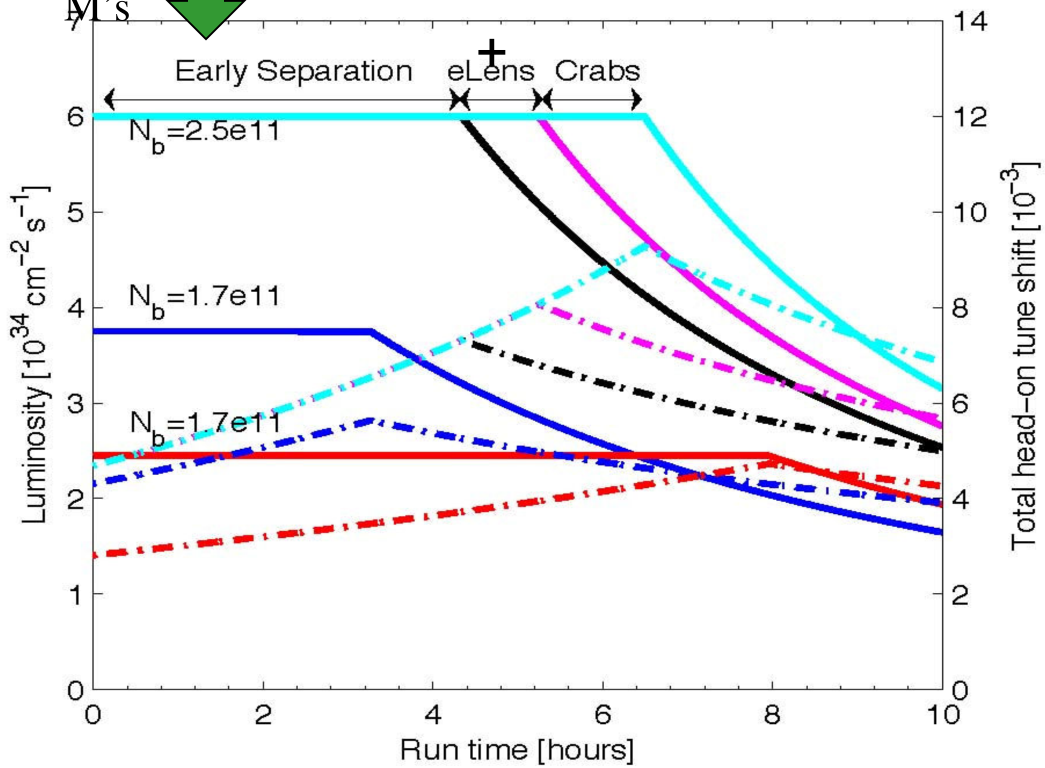
- *"When in collision TEV is extremely sensitive to any optics change;*
- *Only scheme seriously discussed is a single step β-function change [the anticipated procedure requires beam separation,…]*
- *It looks like that the luminosity leveling will never be implemented in the course of Tevatron Run II."*

Leveling via θ_c

$$\Delta Q_{bb} \propto L \quad \text{versus } \theta_c$$

Leveling may increase L_{int}!

Xing bumps + enlarged β*'s



studied in G. Sterbini's PhD

Crab Xing: minor optical side effects, challenge shifted to active HW and insertion design.

Early Separation Scheme: no optical side effects; not as efficient as crab Xing; passive and robust.

Xing bumps: probably not an option (constraints on max and min beam separation).

In all cases, initial reduction of the length of the luminous region

Leveling via σ_s

$$\Delta Q_{bb} \propto L \quad \text{versus } \sigma_s$$

$$\sigma_s \propto V^{-1/4} \Rightarrow L \propto 1/\sqrt{1+\frac{k''}{\sqrt{V}}}$$

no or minor side effect if the beam remains stable; needed:
reduction of the voltage by 16 + bunch shortening

Could be combined with another method

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The beam-beam effect

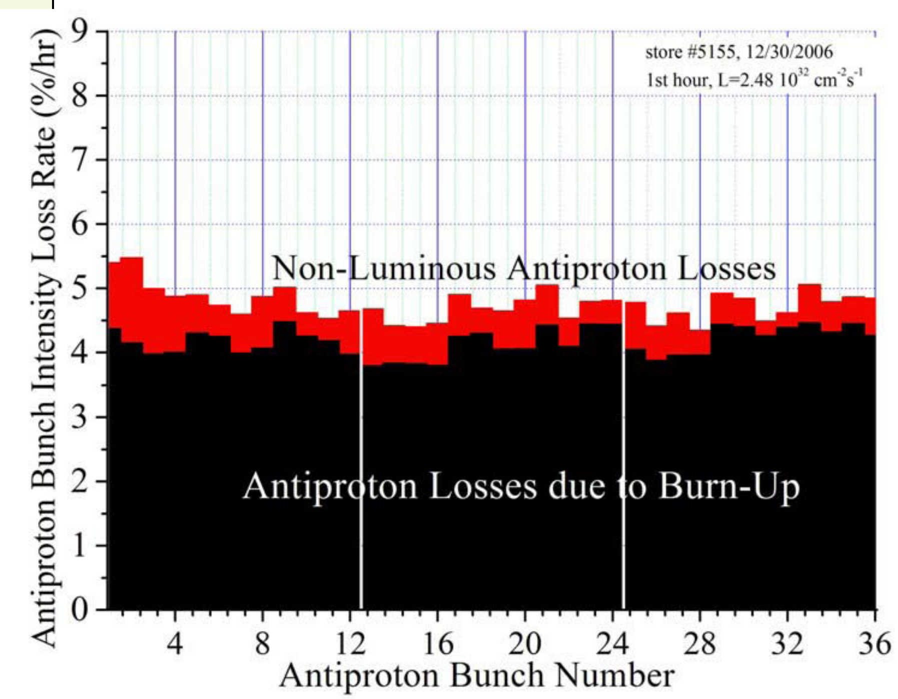
So far, we assumed a perfect beam dynamics below a well-defined beam-beam limit.

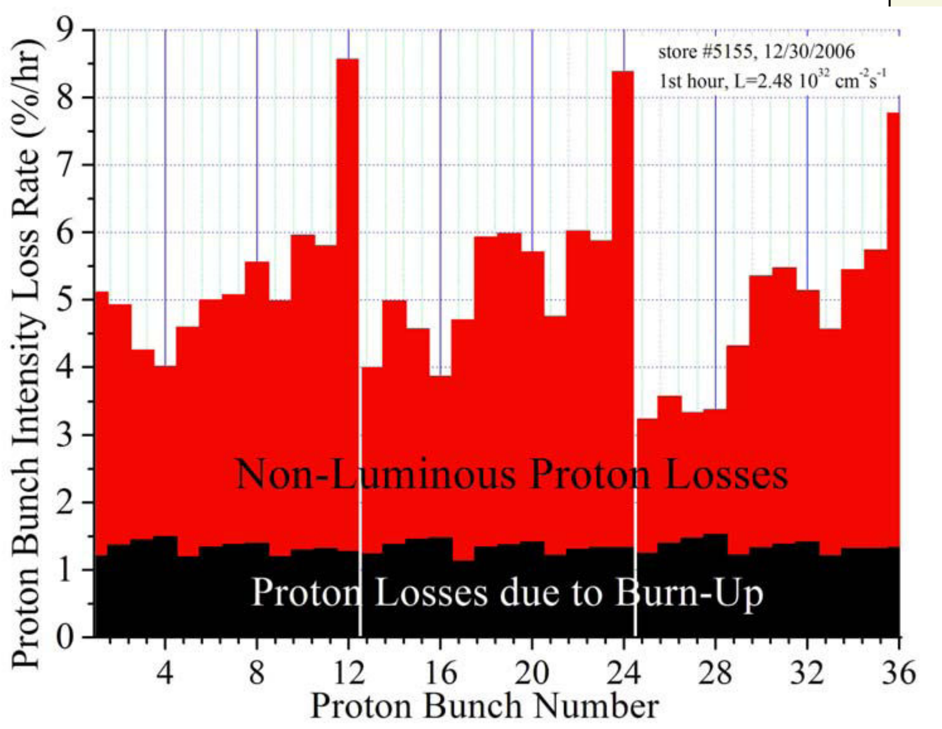
This is well known not to be the case:

- Approaching the **head-on** (phenomenological) beam-beam limit gives rise to a variety of adverse effects: lifetime, emittance blow-up, extreme sensitivity to details, coherent oscillations,…
- The **long-range** beam-beam effect of the LHC is predicted to be the performance limit.

These limits are usually rarely well defined and very time (or luminosity) consuming to investigate.

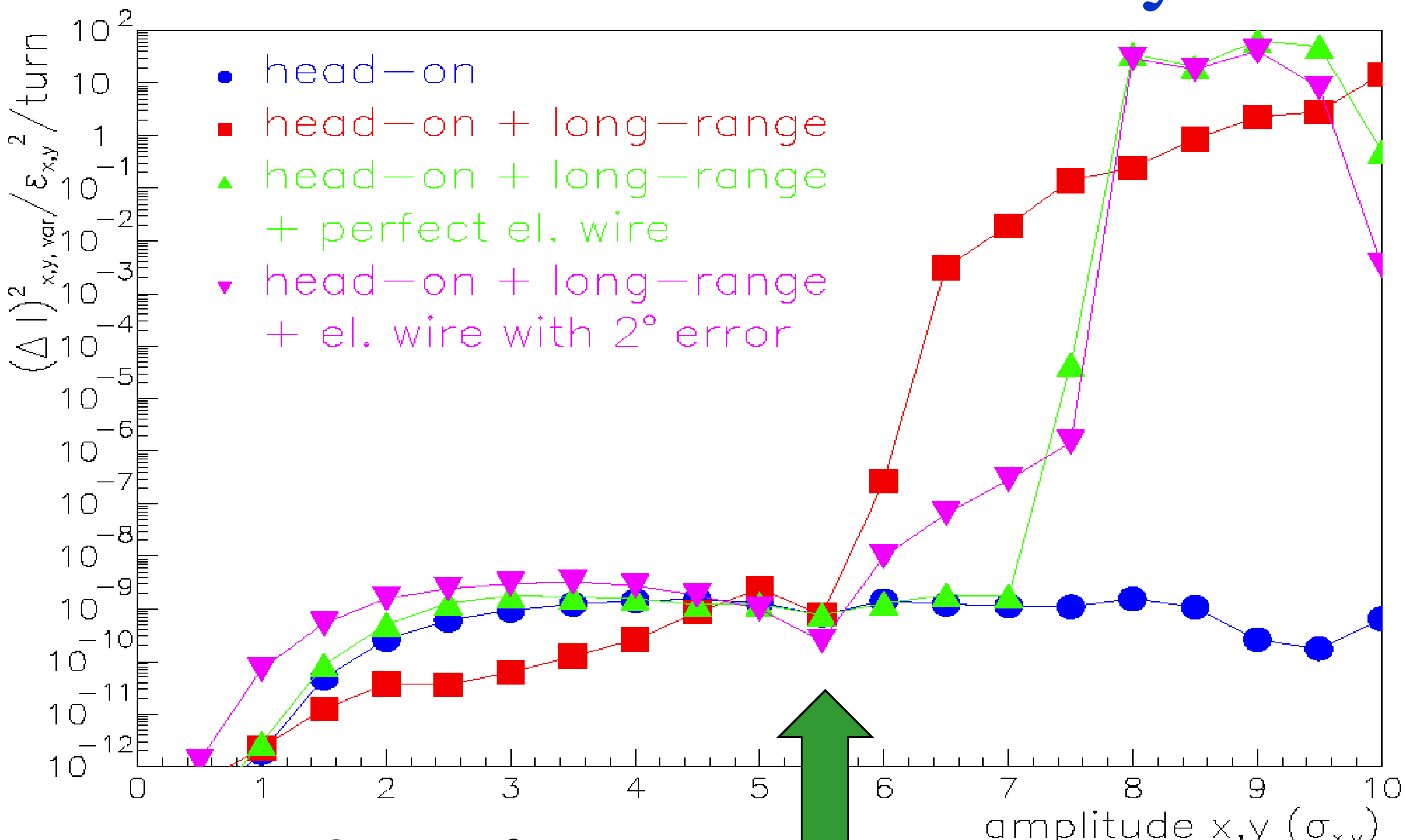
Non-luminous losses in the Tevatron (store 5155)





V. Kamerdzhiev for BBC team

Impact of the long-range beam-beam effect on beam stability

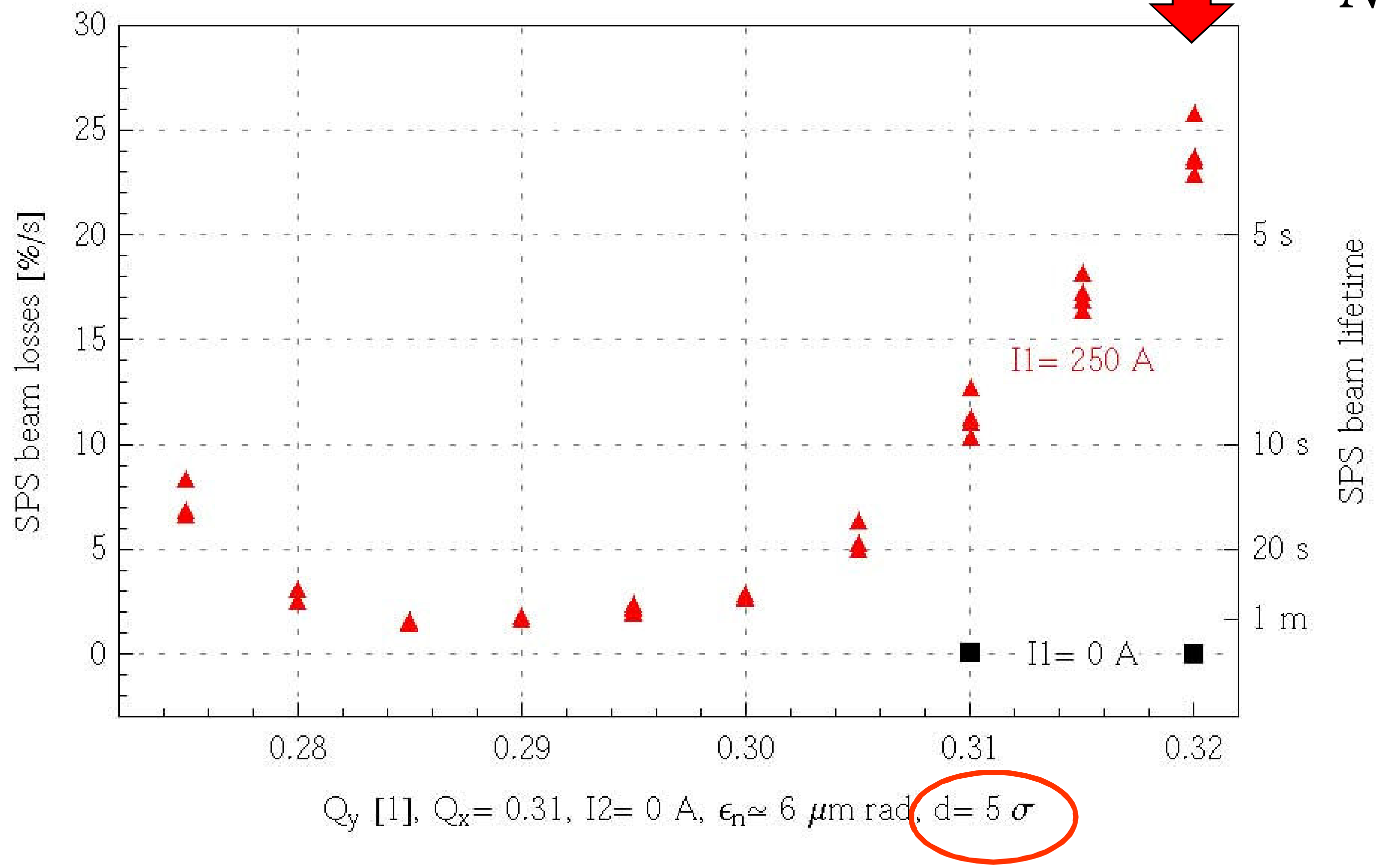


Onset of a strong diffusion

F. Zimmermann

Tune dependence of the long-range beam-beam effect

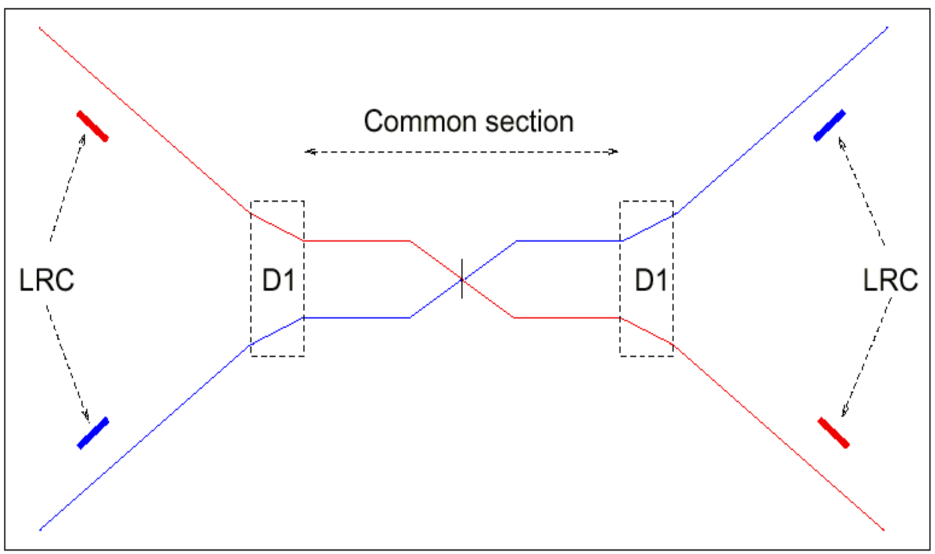
LHC Nominal



SPS 2009 MD, 37 GeV/c

Wire compensation of the long-range beam-beam effect

This scheme, proposed in 2000 has now been studied in detail by several physicists at CERN and within USLARP, by simulations and several experiments in the SPS with 2 wires reproducing the LHC case.



CERN
CH-1211 Geneva 23
Switzerland

the **Large Hadron Collider** project

LHC Project Document No. **LHC-BBC-EC-0001**
EDMS Document No. **503722**
Engineering Change requested by (Name & Div./Grp.) : **C.Fischer AB/BDI**

Date: 2004-10-27

Engineering Change Order – Class I

RESERVATIONS FOR BEAM-BEAM COMPENSATORS IN IR1 AND IR5

Brief description of the proposed change(s) :

Reservations on the vacuum chamber in IR1 and IR5 for beam-beam compensator monitors.
We propose to include these modifications in the next v.6.5 machine layout version.

Equipment concerned :	*Drawings concerned :*	*Documents concerned :*
BBC	**LHCLSX—0001** **LHCLSX—0002** **LHCLSX—0009** **LHCLSX—0010**	

PE in charge of the item :	*PE in charge of parent item in PBS :*
J.P. Koutchouk AT/MAS	**C. Rathjen AT/VAC**

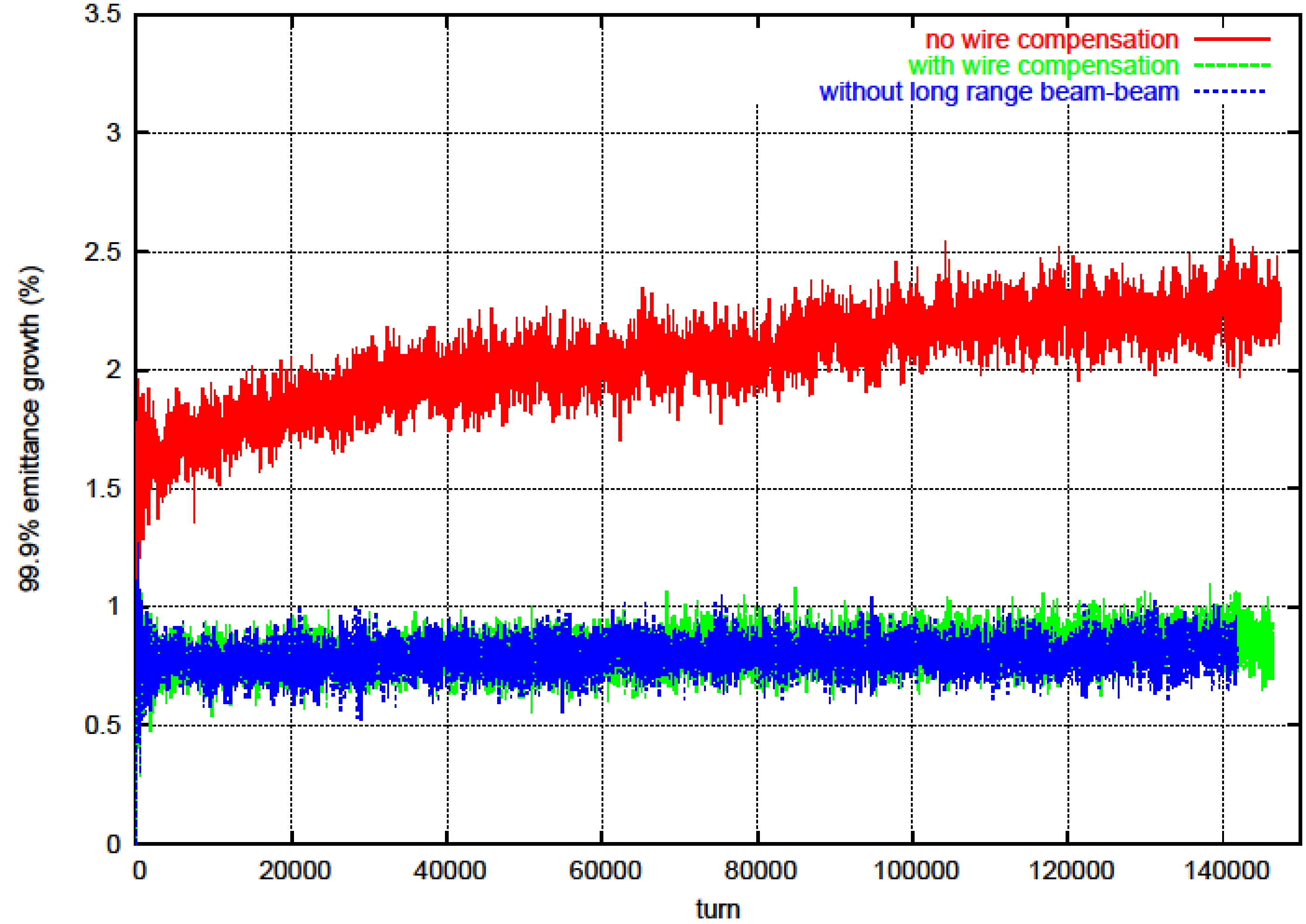
Decision of the Project Engineer :	*Decision of the PLO for Class I changes :*
☐ Rejected. ☐ Accepted by Project Engineer, no impact on other items. *Actions identified by Project Engineer* ☑ Accepted by Project Engineer, but impact on other items. *Comments from other Project Engineers required. Final decision & actions by Project Management*	☐ Not requested. ☐ Rejected. ☑ Accepted by the Project Leader Office. *Actions identified by Project Leader Office*
Date of Approval : 2004-10-27	*Date of Approval :* 2004-10-27

Actions to be undertaken :

Modify the drawings and Equipment codes concerned to reflect the changes described in this ECO.

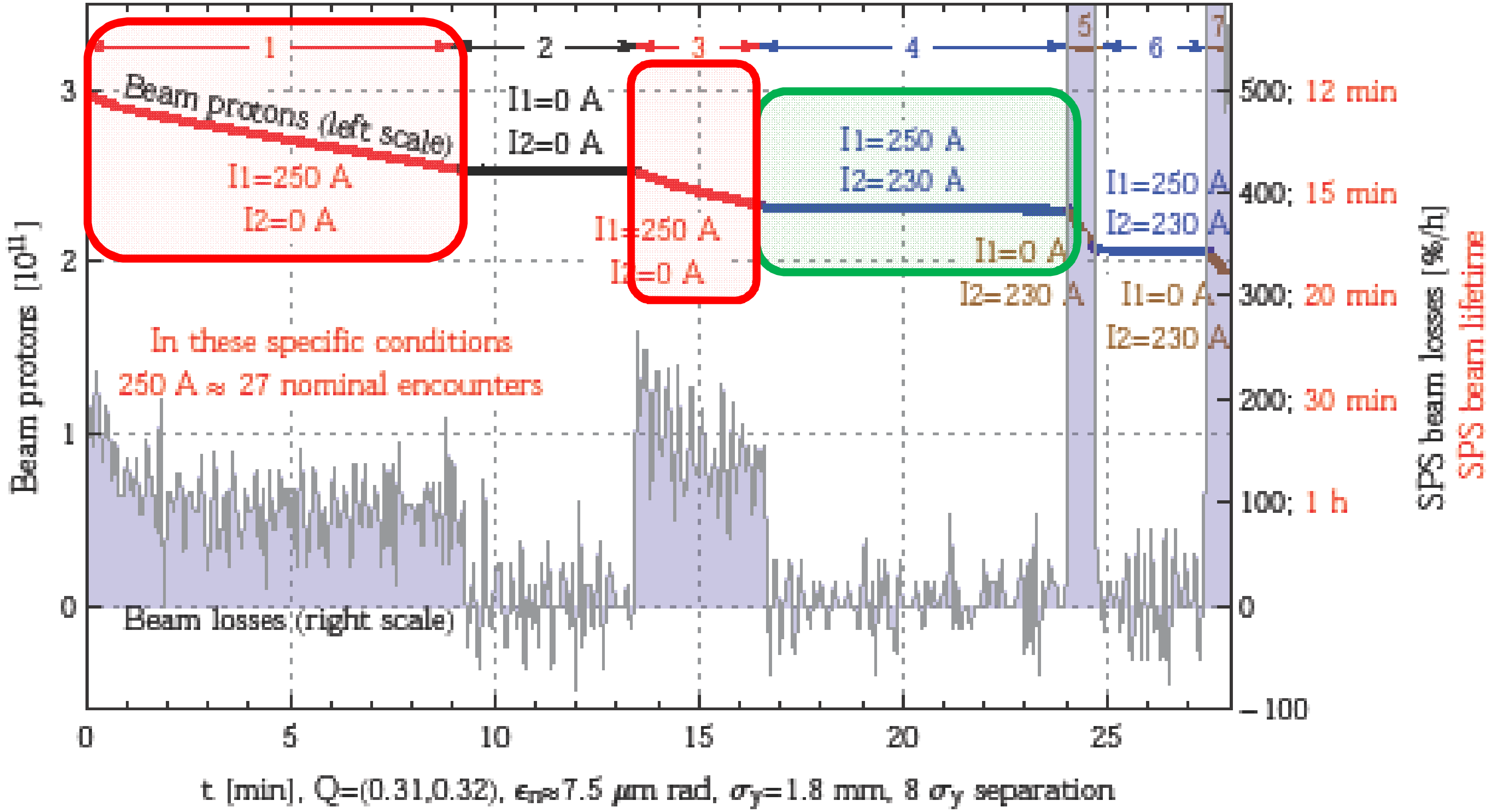
Date of Completion : 2004-10-27	*Visa of QA Officer :*

Note : when approved, an ***Engineering Change Request*** *becomes an* ***Engineering Change Order/Notification.***



Simulation by Ji Qiang, LBL, 2008

Wire compensation of the long-range beam-beam effect



SPS 2009 MD, 120 GeV/c

Other goodies to be considered for reducing the perturbations of the beam-beam effect

- **Electron lens** (W. Shiltsev/FNAL): for head-on beam-beam compensation and long-range compensation for a few reduced separation interactions;
- **Fully coupled beams at IP** (Y. Derbenev): reduce the diffusion by the b-b by reducing the dimensionality of the dynamics.
- **Crab waist scheme** (P. Raimonsi/INFN): CERN/INFN study scheduled in EuCARD.

Conclusions

At a luminosity level of $10^{35} cm^{-2}s^{-1}$, whatever the scenario, the luminosity lifetime becomes close to operations "time constants" (cycling and filling, travel time to remote buidings and repairs,…).

Hence, **luminosity leveling** could be raised as a requirement for all scenarios. Leveling is also useful for the machine: peak energy deposition, beam-beam effect, operation efficiency.

Accordingly, the performance goal of Phase II would become $L_{average} \sim 5$ to $6\ 10^{34}\ cm^{-2}s^{-1}$, almost constant over one shift (multiplicity ~ 100 for 25 ns spacing).

Conclusions

Leveling via the **Xing angle** appears to have the best potential (performance, complexity) but requires unexplored solutions (Crab Crossing) or some interference with detectors (Early Separation).

Leveling via the **bunch length** is worth a detailed study to understand its feasibility.

Leveling by β^* has an inherent performance limit, is probably complex to implement but is cheap.

More than one leveling method must be available for phase II to face the uncertainties attached to each solution.

Conclusions

The **long-range beam-beam compensation** addresses a fundamental LHC performance limit; it appears effective and robust from several simulations, experiments and one implementation in DaΦne.

It is mature for implementation at the LHC. *An early dc implementation would allow the study of the beam-beam limits well before the LHC can reach this performance level.*

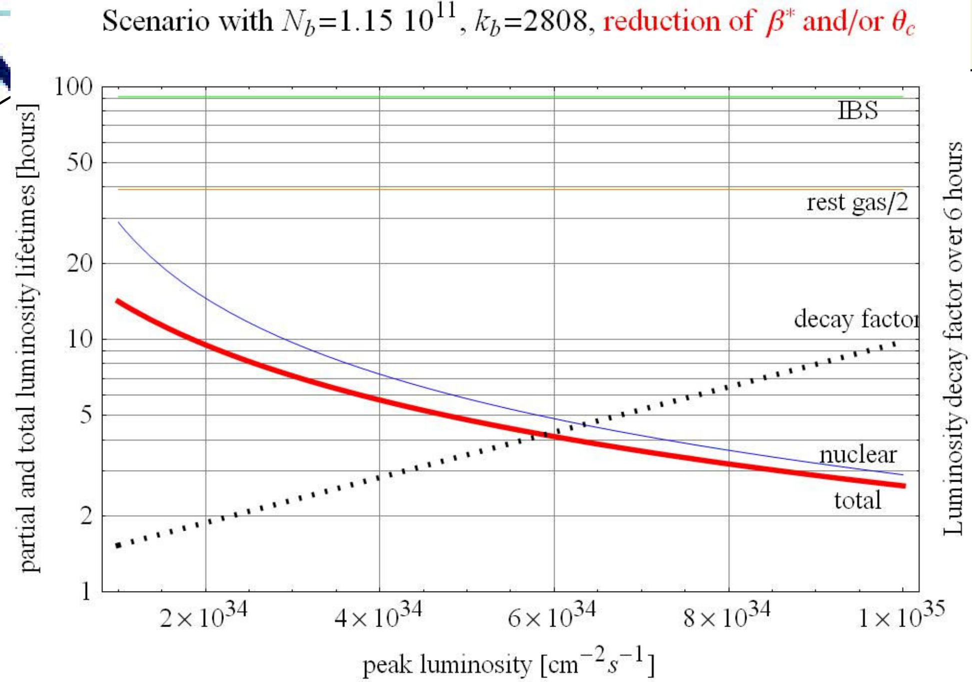
In view of the many unknowns on the beam-beam effects, detailed studies on the Phase II ingredients, often exotic such as impact of large Piwinski angle, electron lens, crab waist,… are needed.

Acknowledgments and references

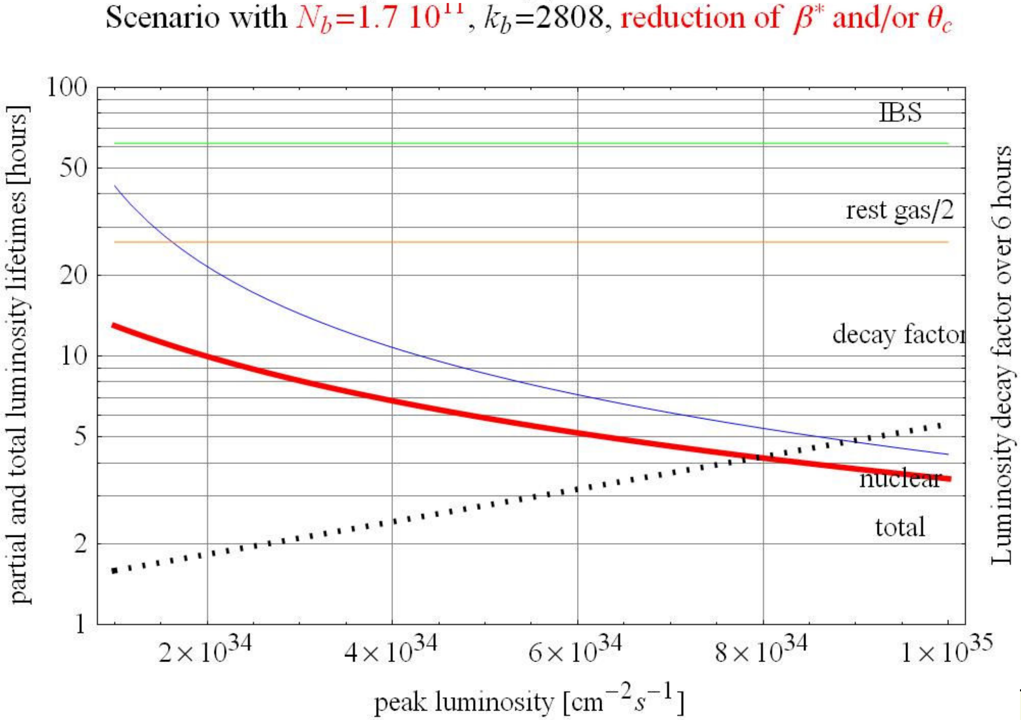
Thanks to *E. Chapochnikova, L. Rossi, G. Sterbini, F. Zimmermann, the SPS "wire MD team" with R. Calaga, R. Tomas, the USLARP colleagues ,…*

References: *many presentations in CARE-HHH and conferences + "An Early Separation Scheme for the LHC Luminosity Upgrade", PhD thesis by G. Sterbini (Nov. 2009),public presentation at EPFL on Feb. 18th at 17:15.*

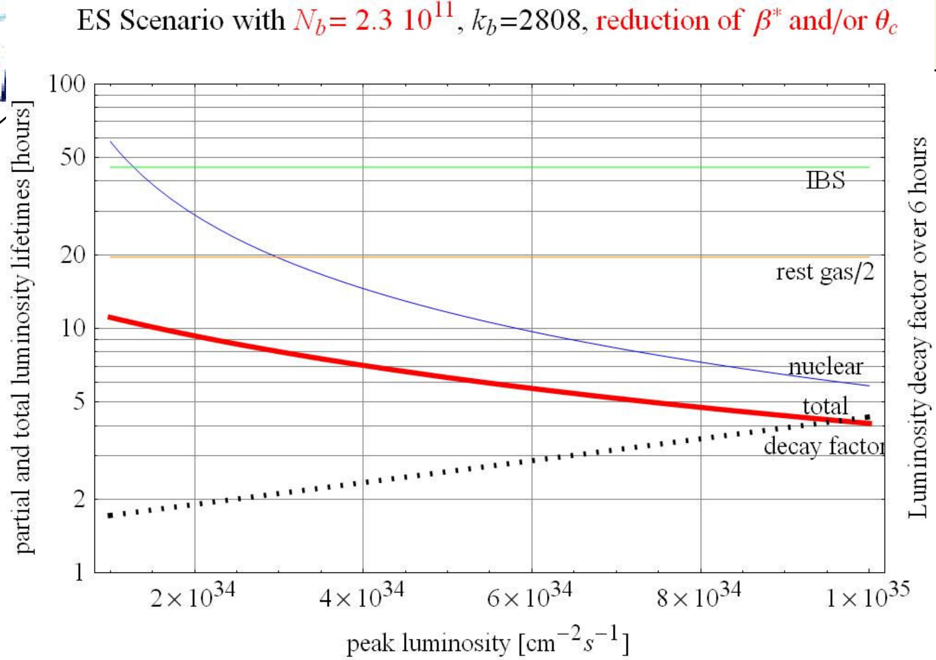
Additional material



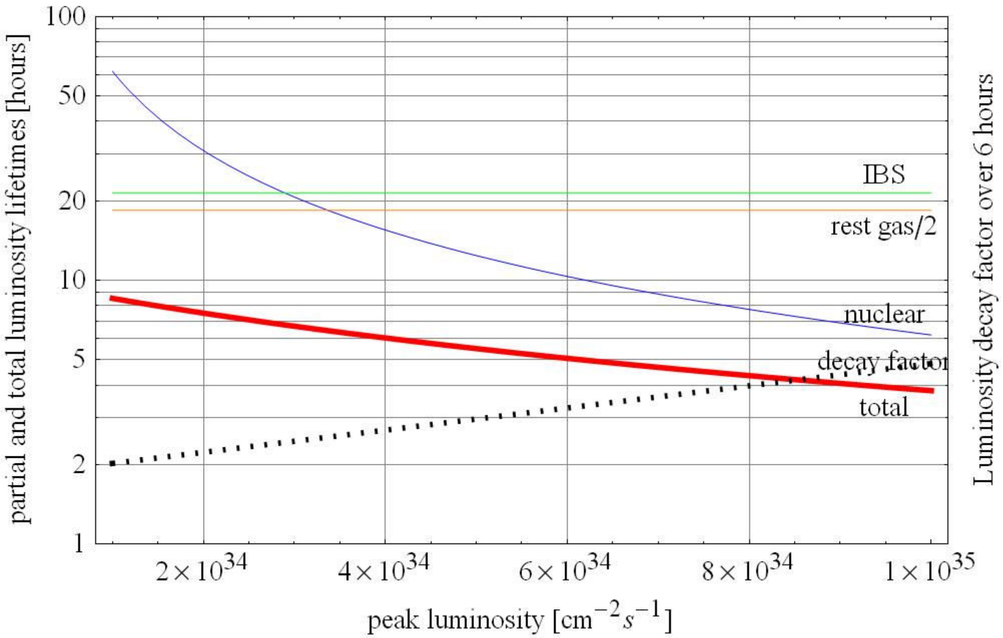
Reduction of beta alone*



Reduction of beta and ultimate bunch charge*

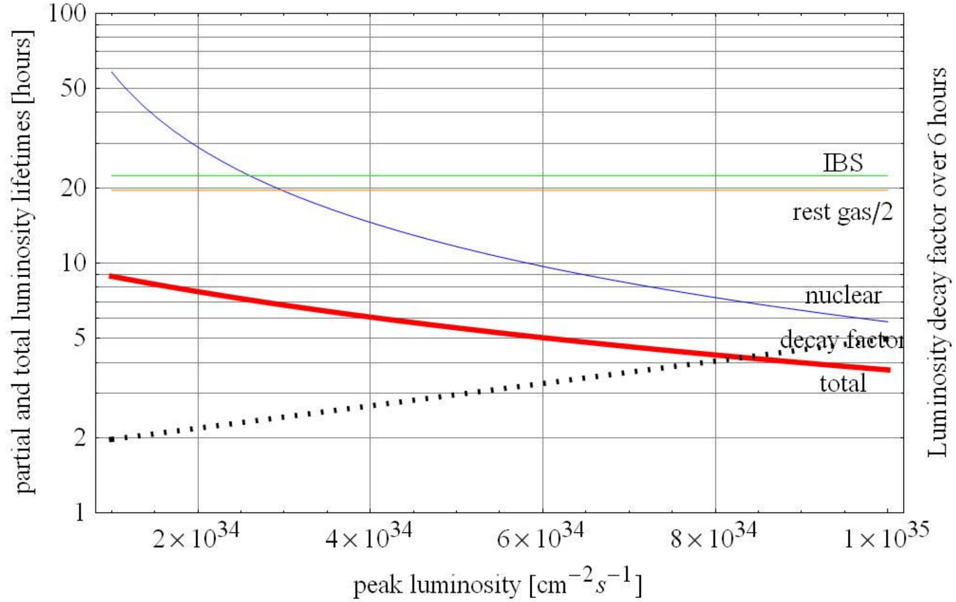


Reduction of beta* and 2× nominal bunch charge

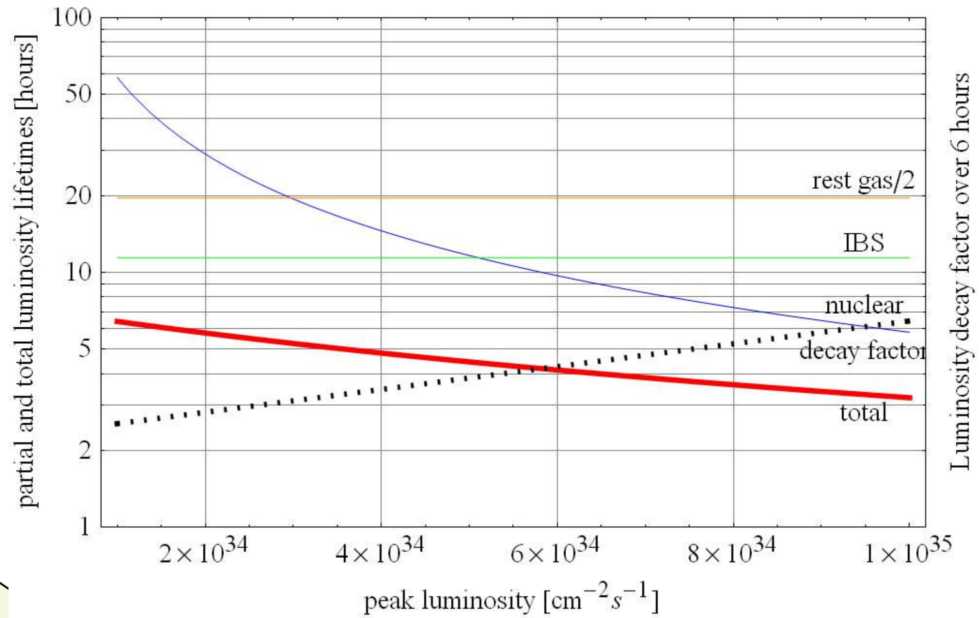


LPA scenario

LE Scenario with $N_b = 2.3\ 10^{11}$, $k_b = 2808$, $\epsilon_N = 2.6$, reduction of β^* and/or ϵ



Lower emittance by 30% with 2× nominal bunch charge on lower beta* optics



Lower emittance by 50% with 2× nominal bunch charge on nominal optics

Is Luminosity Leveling going to happen in Tevatron*?,from V. Lebedev/FNAL, CARE-HHH-APD Beam'07, oct. 2007, CERN.*

- When in collisions Tevatron is extremely sensitive to any optics change;
- Therefore the only scheme which was seriously discussed is the single step beta-function change *[not a continuous adjustment]*;
- It requires ~5 min to perform the following steps
  - ♦ Beam separation in IPs
  - ♦ Optics and helix adjustments
  - ♦ Bringing beams back to collisions
  - ♦ Scraping
- Implementation of such a scheme would require considerable study time and would result in 10-20% loss of the luminosity integral;
- It looks like that the luminosity leveling will never be implemented in the course of Tevatron Run II