A summary on CARE-HHH activities on beam-beam effects & beam-beam compensation at the LHC

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1. Introduction
2. Phenomenology and beam-beam limit
3. Simulations and predictability
4. Wire compensation
5. Electron Lens compensation
6. Conclusions

1- Introduction

The beam-beam effect is central to the performance of existing colliders (TEV, RHIC) and of the LHC. Not surprisingly, it was on the menu of many CARE-HHH events:

2002	**LHC IR Upgrade collab. Meeting, CERN**
2004	**HHH-2004, CERN**
2005	**LUMI-05, Arcidosso**
2006	**LUMI-06, Valencia**
2007	**• Contributions to US-LARP workshop on beam-beam compensation, SLAC,** **• BEAM'07, CERN** **• IR'07, Frascati**
2008	**Meeting on beam-beam effect and compensation, CERN**

Some **60** presentations of pure beam-beam issues for hadron colliders are recorded, authored by:

N. Abreu, Y. Alexahin, K. Cornelis, U. Dorda, W. Fischer, M. Furman, W. Herr, A. Kabel, V. Kamerdzhiev, J.-P. Koutchouk, V. Lebedev, Y. Luo, C. Milardi, K. Ohmi, S. Peggs, T. Pieloni, F. Pilat, J. Qiang, P. Raimondi, F. Ruggiero, T. Sen, W. Shiltsev, G. Sterbini, E. Tsyganov, A. Valishev, F. Zimmermann.

I have attempted, in the following, to combine or confront these contributions. *If some material (taken from the slides), would be mis-interpreted please correct me.*

1. Introduction
2. **Phenomenology & beam-beam limit**
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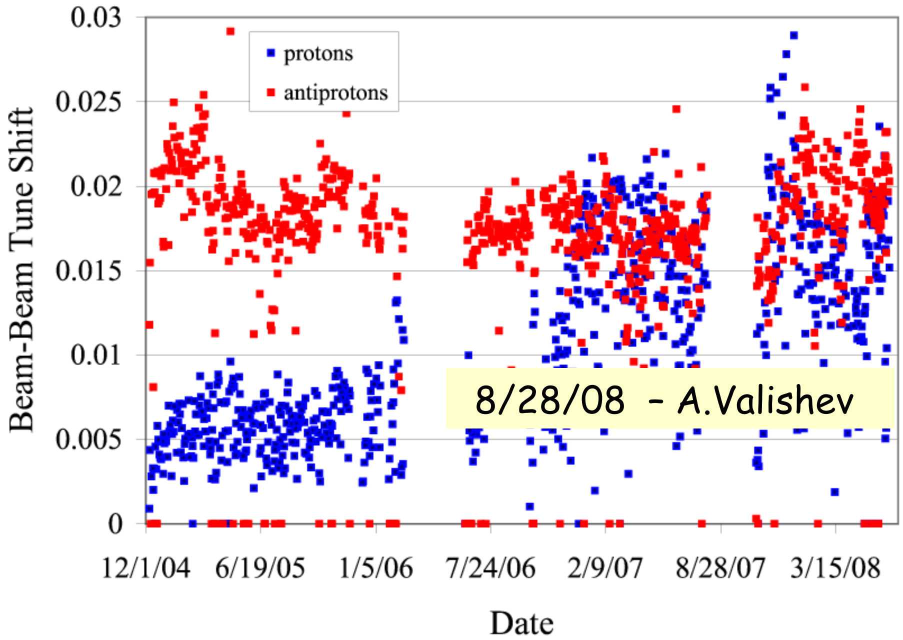
2.1 Beam-beam limit

The limit for ΔQ_{bb} (HO+LR) has been taken to be 0.01 for SLHC (LPR626, 2002).

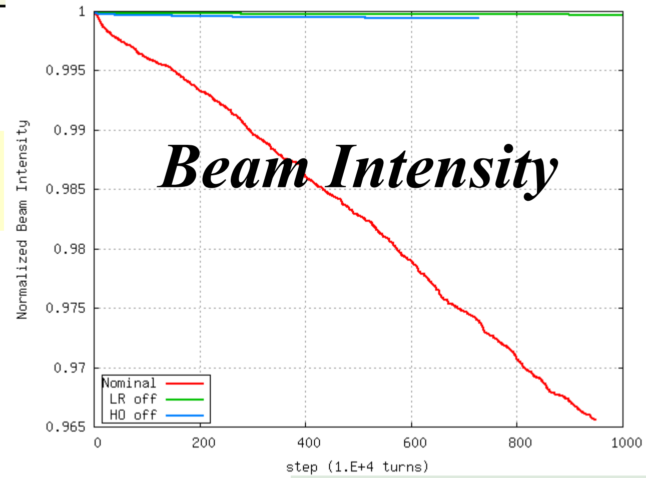
The Tevatron is now doing much better (HO):

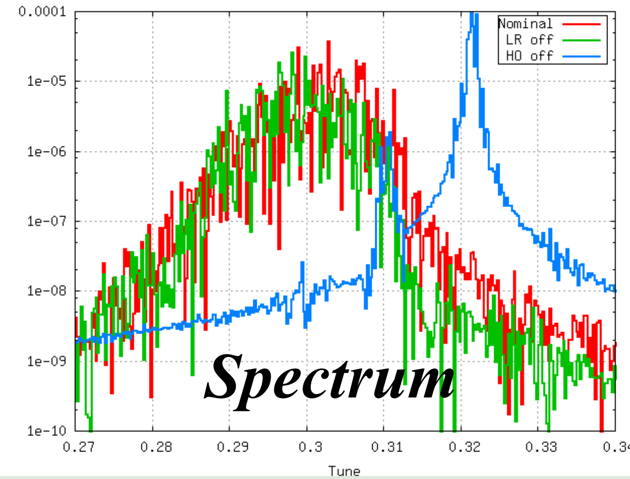


Naively, increasing the bunch current to 2.5 10^{11}, decreasing the emittance by a factor 2 and running with 2 experiments gives $L=10^{35}$ at ΔQ_{bb} =0.03 with "no further investment"

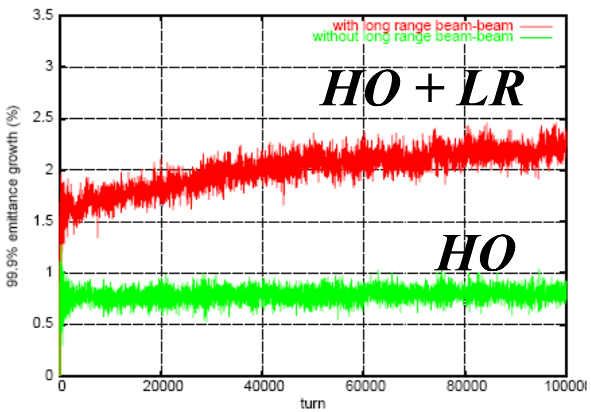
…but: "Lessons from TEV", Sen, 2007: the b-b performance cannot be characterized by the ΔQ_{bb} alone… examples:

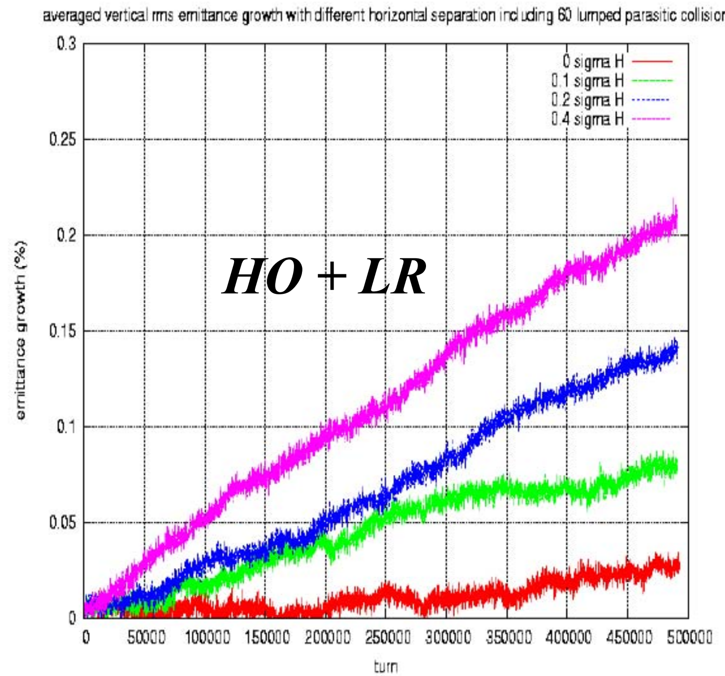
8/28/08
A.Valishev





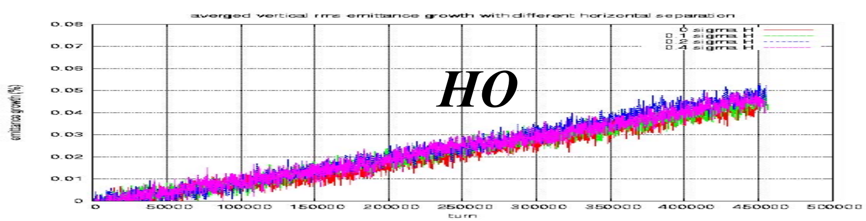
The de-stabilizing effect of the LR encounters



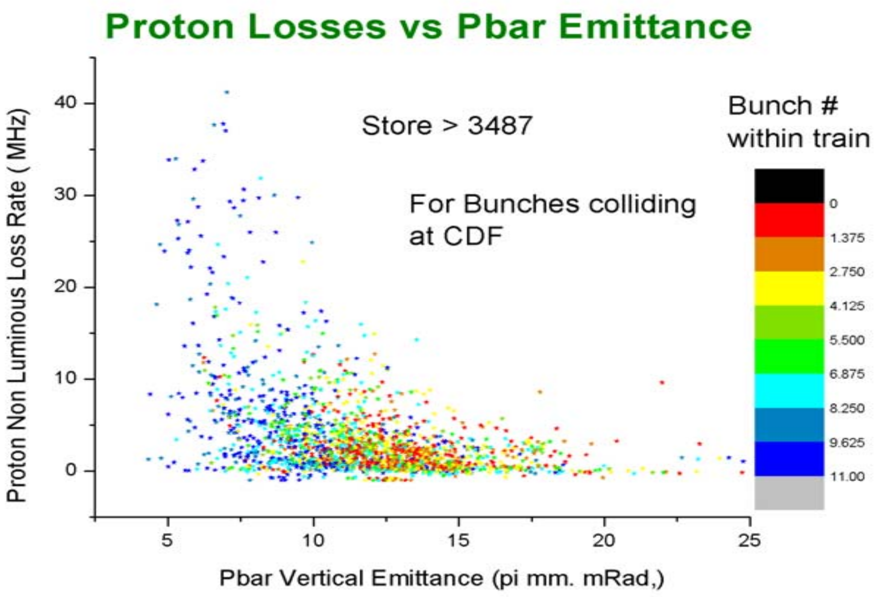


Emittance growth

J. Qiang, LBNL, BeamBeam3D

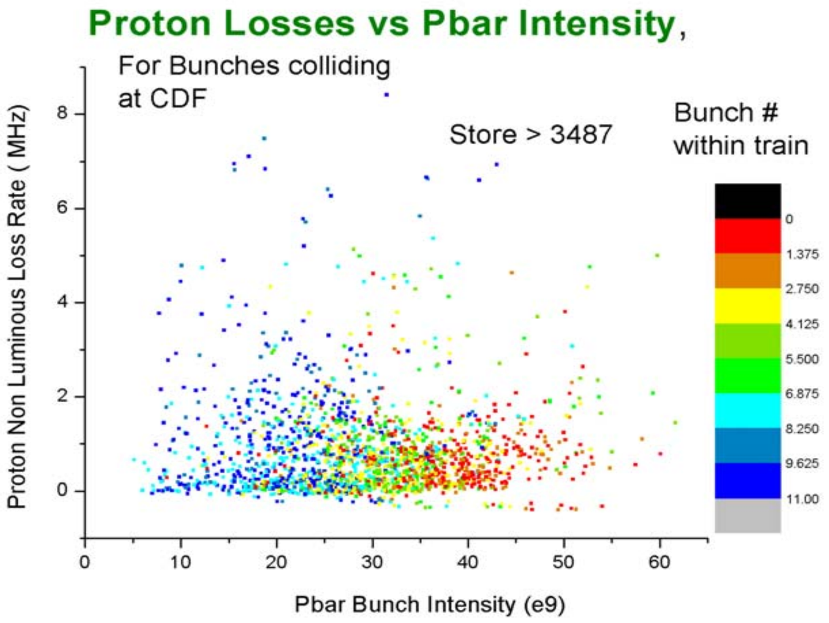


hidden parameters ?



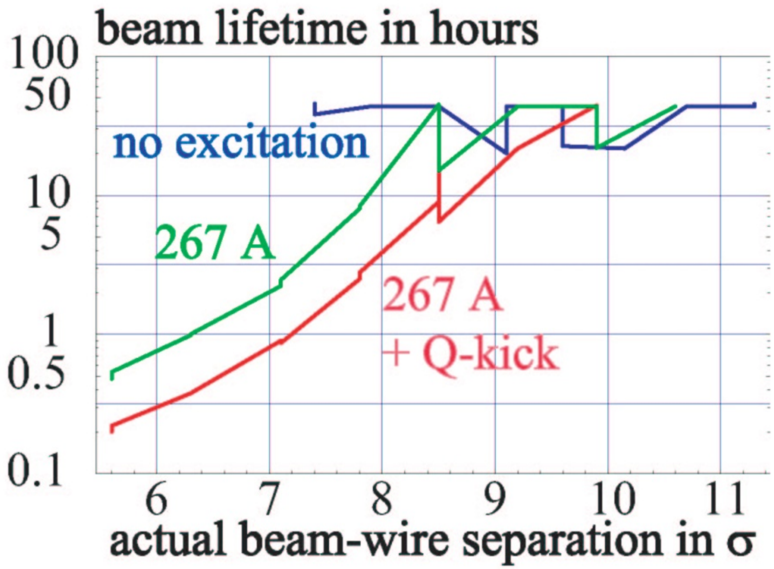
expected

Not expected

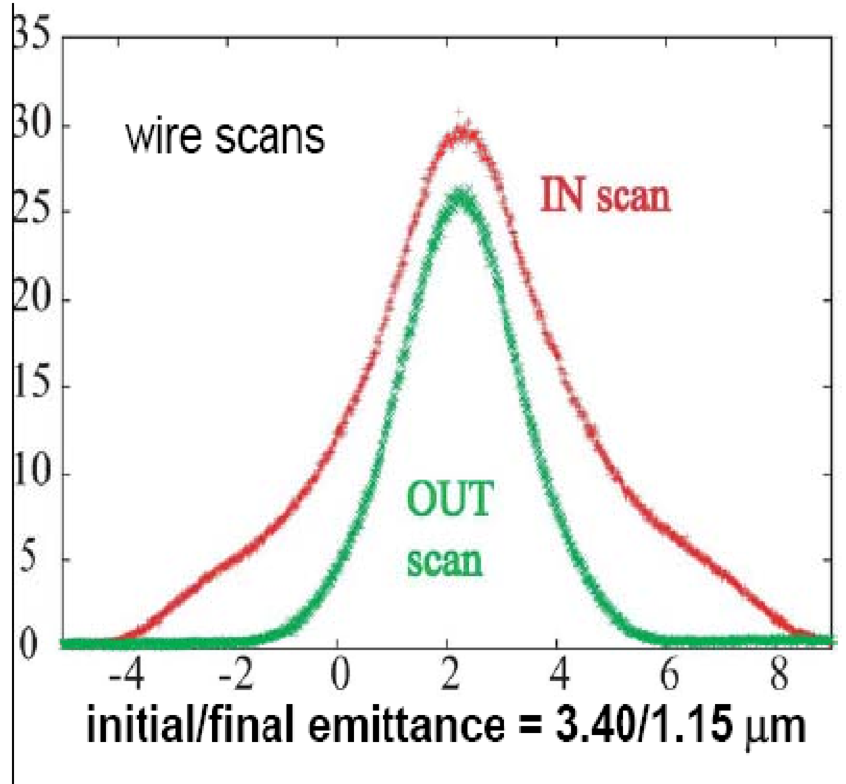


P. Lebrun

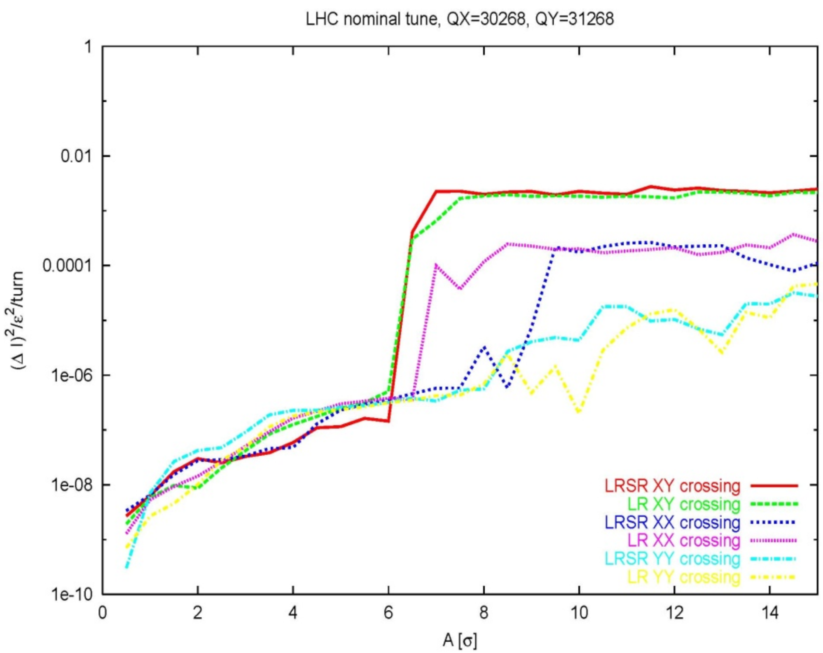
SPS experiment

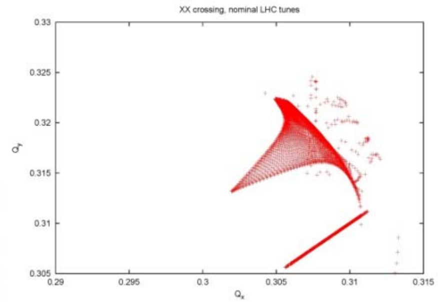


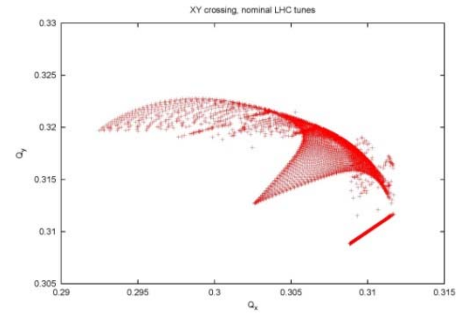
The LR can cut the beam tails like a scraper.



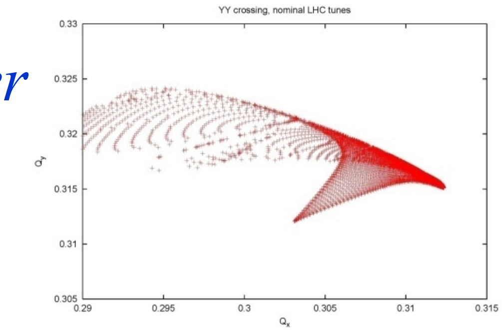
2.2 Combination of Xing planes







Zimmermann



Ohmi, 2007: H-H collision gives wide tune spread but limited resonance, while H-V collision gives narrow tune spread but more resonances.

F.Zimmermann, SPS exp with several wires: HH best, then quasi VV, then quasi HV (lifetime) for nominal bunches

2.3 Minimum beam separation

This is a key issue for the Early Separation Scheme that requires tolerance to 4, 8 or 12 LR encounters at reduced distance. The conjecture is that 5σ could be sufficient for 4 encounters, perhaps for more.

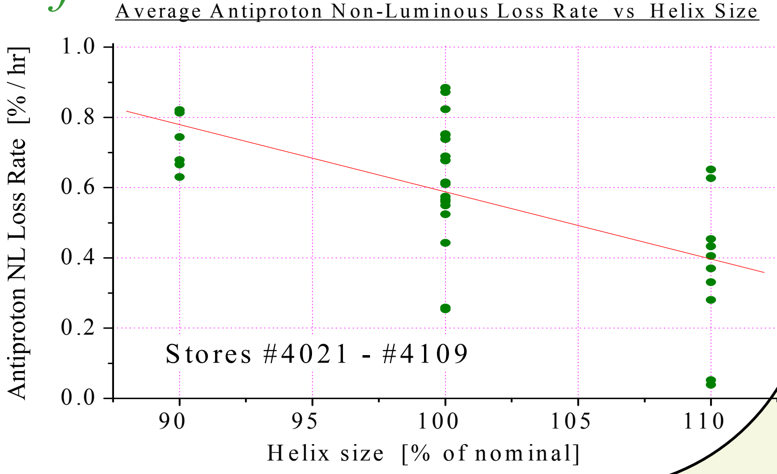
If not, either LR compensation must be used or an increased separation to 7σ with a corresponding loss of performance must be accepted for this scheme.

2.3 Minimum beam separation

- **SppbarS:** 7 LR's at **6σ** + 1 LR at **3.5σ** + 1 LR at **9σ** for ultimate bunch charge OK in operation for years.

- **TEV:** ran until 07/2006 with 4 LR's at [**5.0..5.6σ**]; gained 5% to 10% in L integrated by increasing the separation to [**5.6..6.4σ**]. *Questions: where the other LR's changed?; Simulation of wire compensation of the few LR's at reduced separation had shown no benefit ? Zhang et al., PAC 2003: 80% of helix OK?*

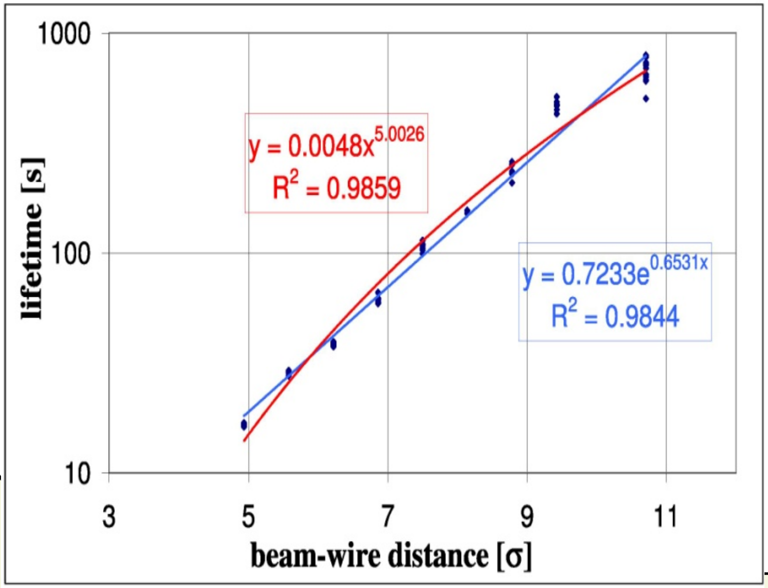
Valishev, 2007: Separation is not the sole important parameter: resonances, Q', betatron coupling



• **RHIC:** Dorda simulations:"1LR per side per IP means trouble"
Comment: this seems in contradiction with former observations. Is it related to the "preparation" of RHIC?

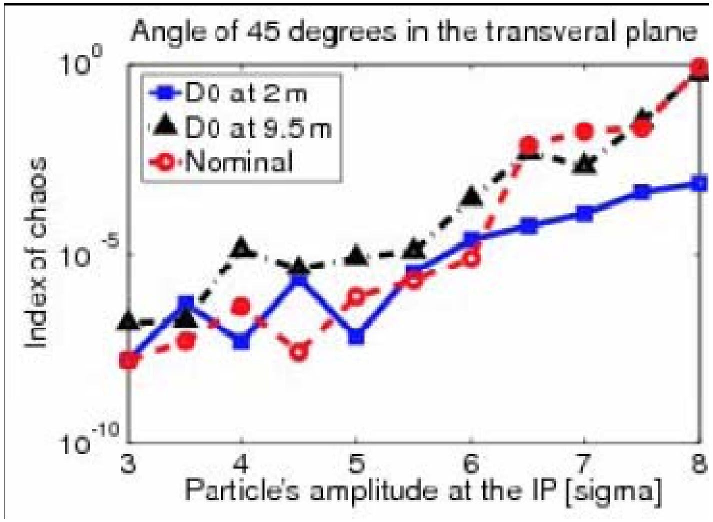
• **LHC:** nominal scheme includes 17 LR's at **7σ** + 1 LR at **5σ**

• **SPS wire experiments (26 & 37 GeV/c):** possibly 4 LR's at **5σ** can be accepted. Variation of lifetime with separation very fast:

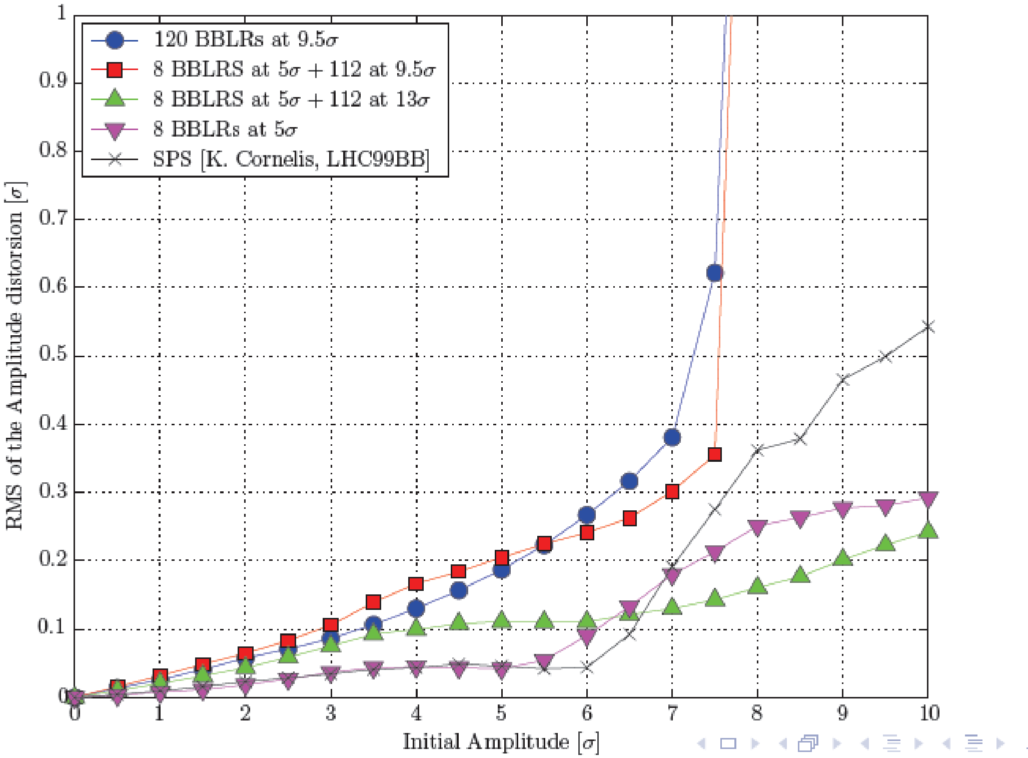


Hence the 3.5σ encounter at the SPS would be equivalent to 243 encounters at 10σ with ultimate bunch charge: contradiction? Too low lifetime in SPS experiments?

• ***ESS tracking (Sterbini)***



4D

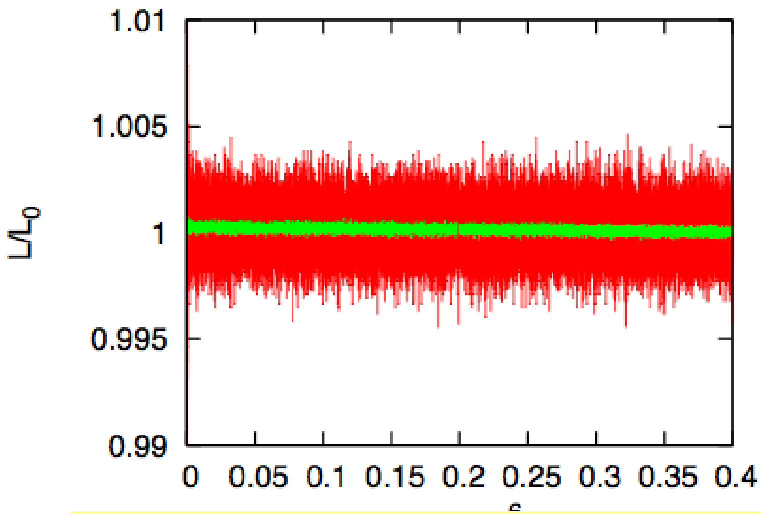


2D + noise + tune averaging

Hint: would the large number of LR's at 10 σ matter more than the few at reduced separation?

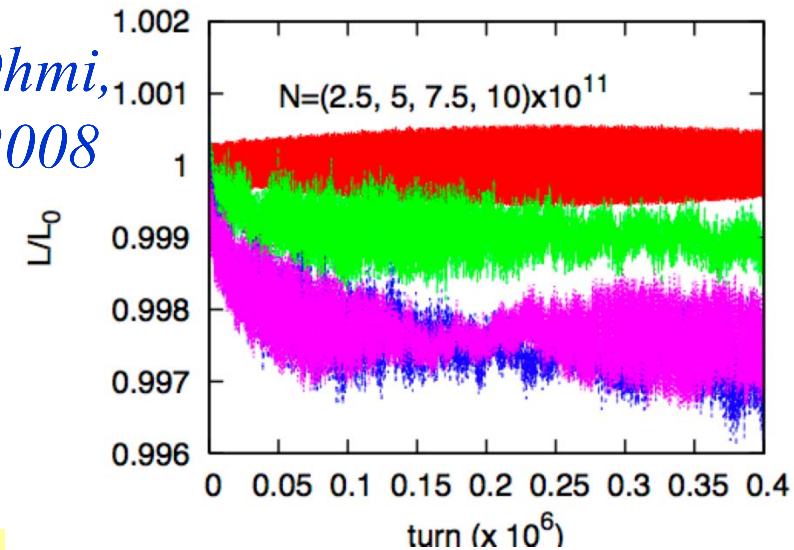
2.4 Effect of Large Piwinski angles

The LPA option and the Early Sep. with levelling both require large Piwinski angles: <u>2 to 3.5 instead of 0.4 nominal</u>.



LPA: WS & SS, OK for N_p=4.9 10^{11} but not for 6 10^{11} (with LR)

Ohmi, 2008



ES + level: WS, no LR

Ohmi, 2008: No problem found due to large LPA for HO collisions. Tolerance for noise as usual for LHC (~0.1% in Xing position).

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Quadruplet: Λ_{++}, Λ_{+-}, Λ_{-+}, Λ_{--};

$\langle\Lambda_{++}|\Lambda_{--}\rangle = \langle\Lambda_{+-}|\Lambda_{-+}\rangle^* = 1$

$$|q_1\rangle = 1/2(|\Lambda_{--}\rangle - |\Lambda_{++}\rangle + |\Lambda_{-+}\rangle - |\Lambda_{+-}\rangle)$$

$$|q_2\rangle = i/2(|\Lambda_{--}\rangle + |\Lambda_{++}\rangle - |\Lambda_{-+}\rangle - |\Lambda_{+-}\rangle)$$

$$|p_2\rangle = i/2(|\Lambda_{++}\rangle - |\Lambda_{--}\rangle - |\Lambda_{+-}\rangle + |\Lambda_{-+}\rangle)$$

$$H = \Re\Lambda \sum_i (p_i^2 - q_i^2)/2 + \Im\Lambda(q_1 p_2 - q_2 p_1)$$

By setting $\omega^2 = \Re\Lambda, \Omega = \Im\Lambda, \mathbf{p} = m^{3/2}(\mathbf{v} + \Omega\mathbf{e}_3 \times \mathbf{x})/\omega, \mathbf{q} = \omega m^{-1/2}\mathbf{x}$ this can be identified as an isotropic, repulsive oscillator rotating with frequency $-\Omega$ in the $\mathbf{x}$-plane.

3.1- Position of the problem

The three tools to study the beam-beam effect have different limitations:

- Experiments: scarce, delicate, results may depend on hidden parameters.
- Operations: parameters not disentangled.
- **Simulations**: ***three main issues: 1) relevance of the physical model, 2) accuracy and speed of the computational methods, 3) ability (or most often impossibility) to compute observables.***

3.2 Status

We now have a large number of codes with a clear progress in computational methods and speed.

The ability to produce observables (lifetime) is not far.

However, **the model has limitations**: artifacts to cope with the too limited speed, impossibility to describe a process largely influenced by unknown imperfections and by distribution tails,…

3.3 - Judgments

S. Peggs (2002): *The HO b-b effect in weak-strong approximation is quite well understood.*

M. Furman (2004): *beam-beam simulations can predict the past.*

T. Sen (2004): *Simulations are not yet the "real thing". Prepare for the unexpected.*

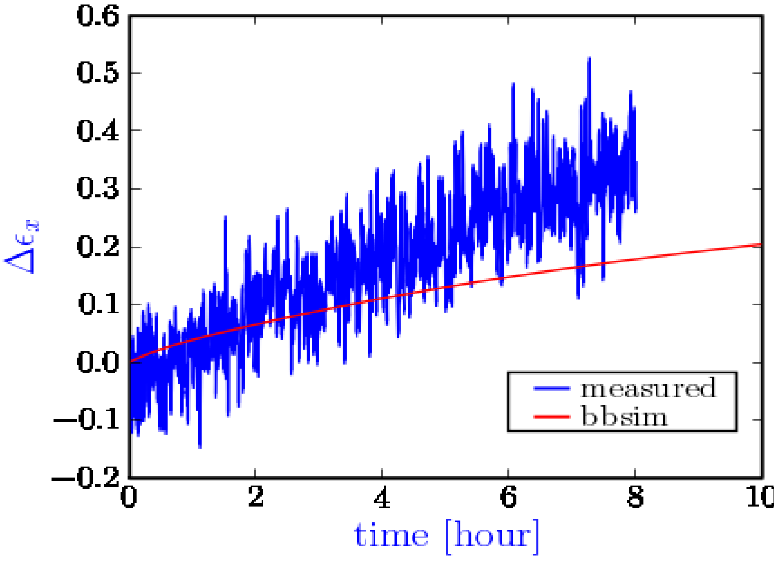
A. Kabel (2007): *Bias-free calculation of observable quantities in proton machines is within our reach*

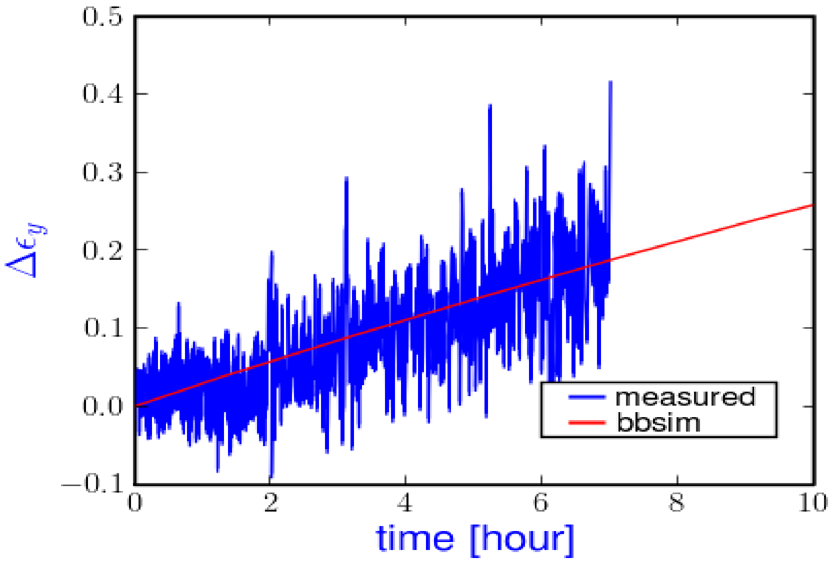
V. Lebedev (2007): *Good predictivity for the TEV.*

T. Sen (2008): *Encouraging results…*

Tracking is essential but let's remain critical.

3.4 – An example: diffusion model for emittance growth at RHIC (BBSIM)





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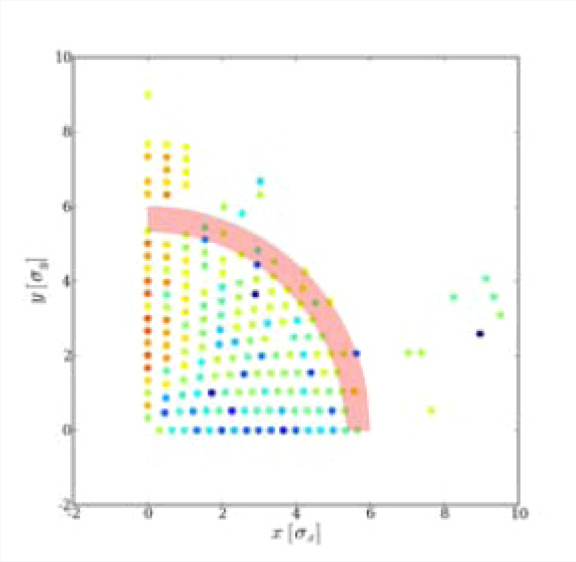
4.1 – Compensation efficiency

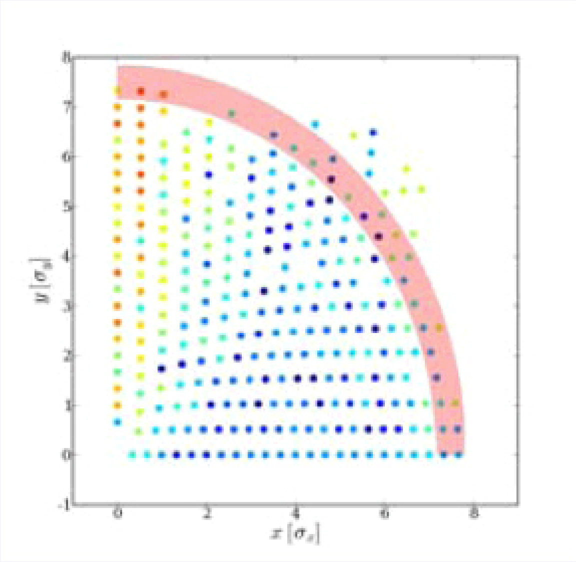
1) Simulation: here tune diffusion

Uncompensated



$DA = 5.4\sigma$

Wire-compensated



$DA = 7.2\sigma$

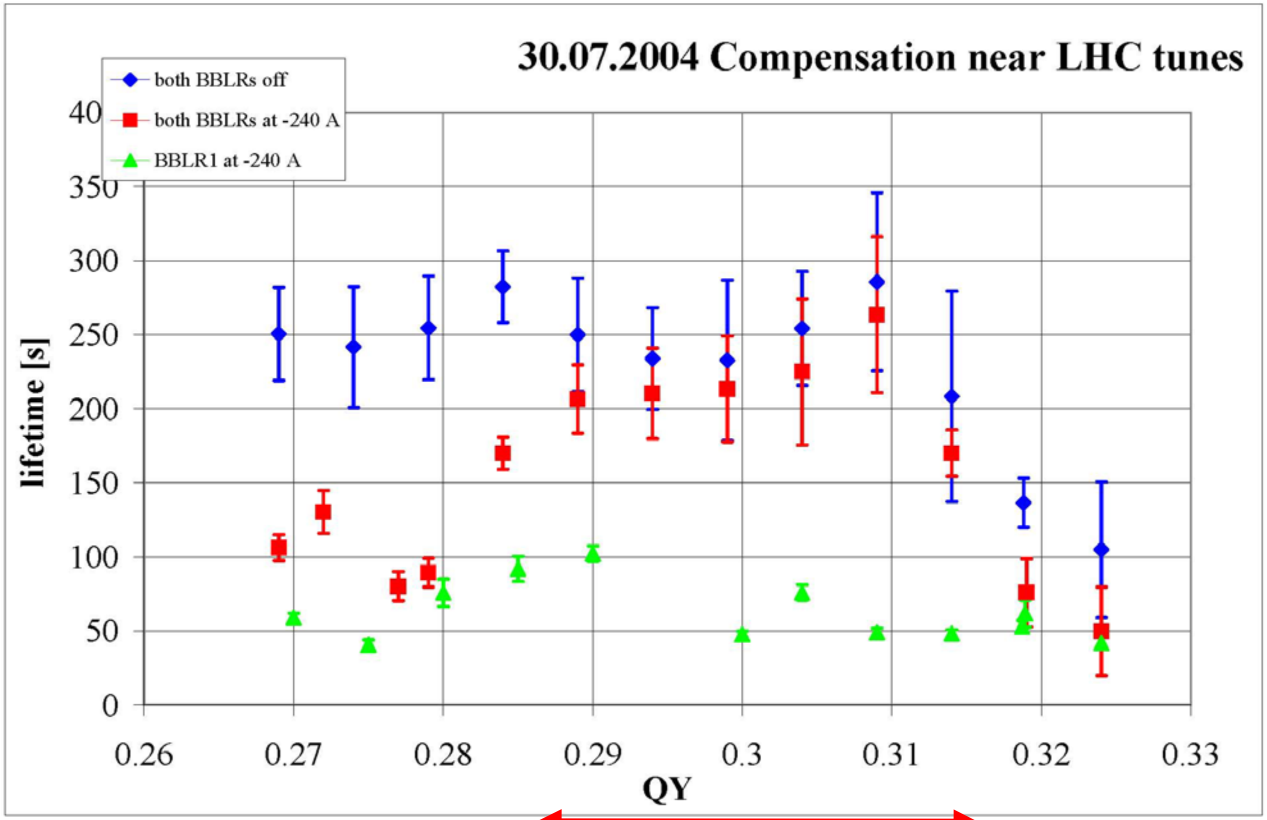
Dorda, 2007

The color indicates the tune diffusion.
Lower amplitude particles are also "stabilized".

2) "compensation": BBLR1 by BBLR2 in the SPS

CERN BBLR team, 30.07.04

Similar results in 2008: the tune dependence is likely to be associated to an imperfect compensation. Furthermore, the optimal tunes for HO are not optimal for LR *(consistent with SppbarS observations)*

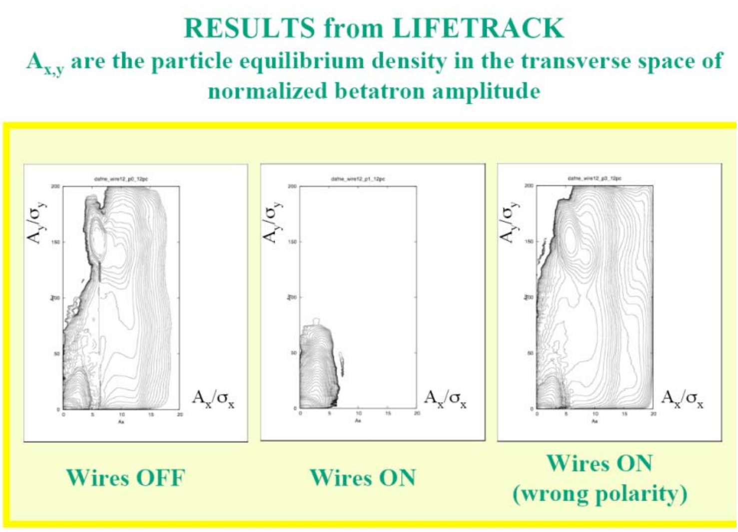


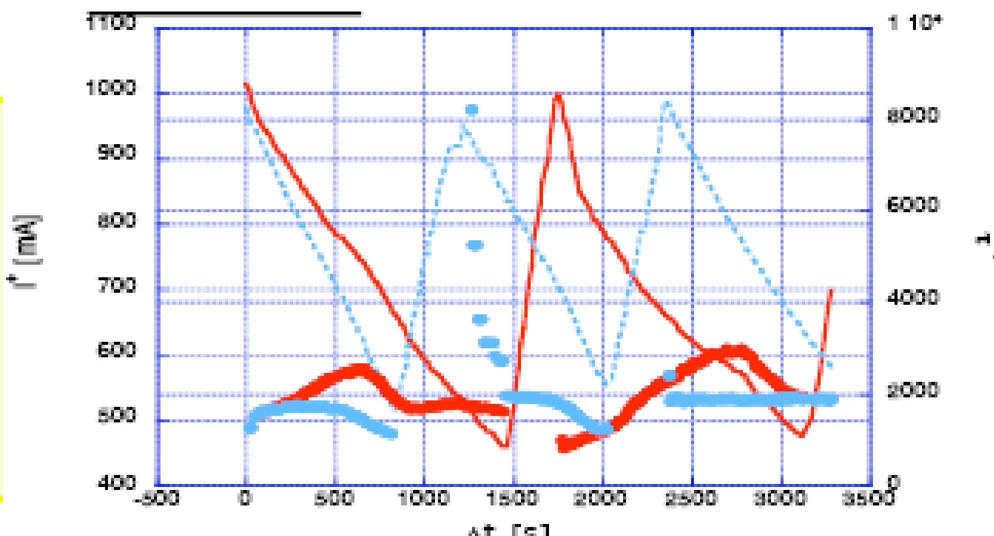
nearly perfect compensation

3) LR compensation at Dafne

Approximate compensation: *it is not possible in Dafne to locally correct as in the LHC.*

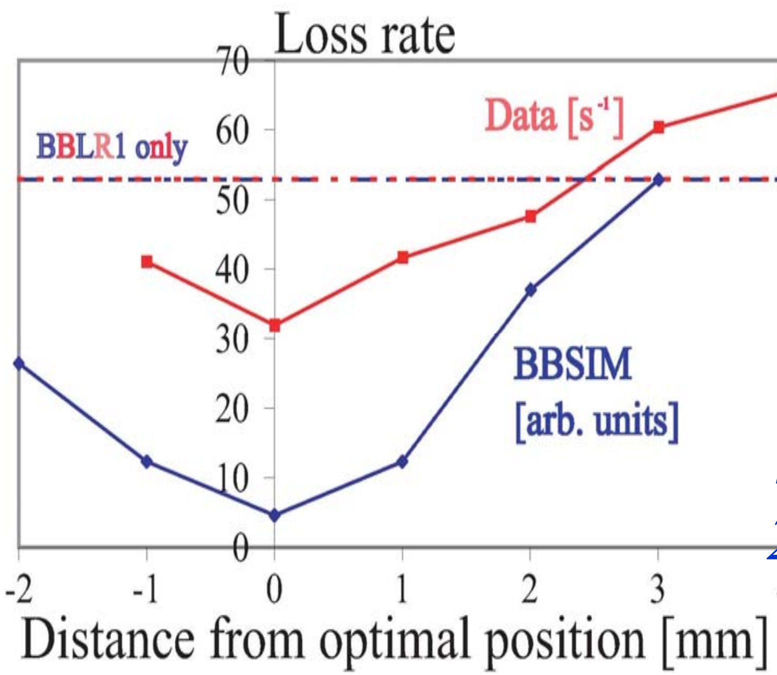
Observations: *no increase of luminosity but increase of lifetime yielding 30% increase in integrated luminosity; suppression of a sudden blow-up; reduction of background.*

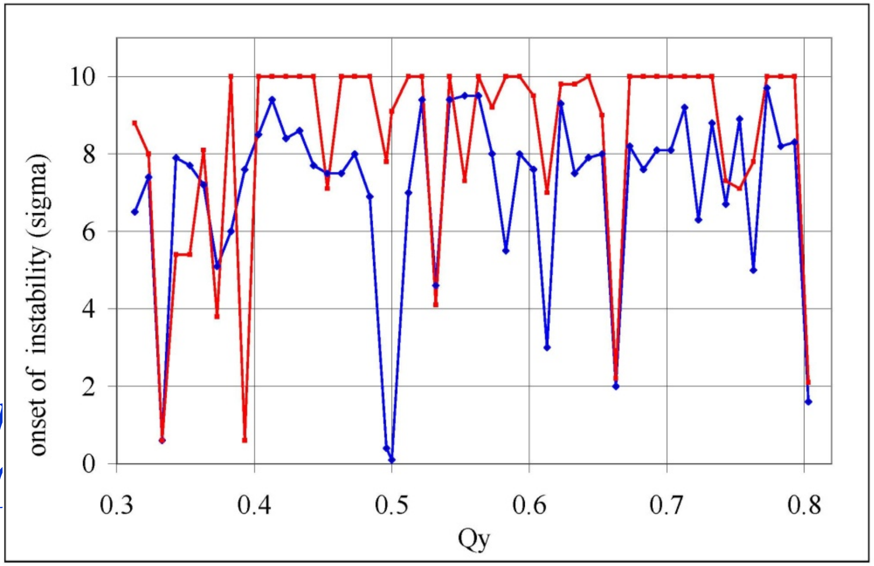




4.2 – Compensation robustness

Versus position and tunes



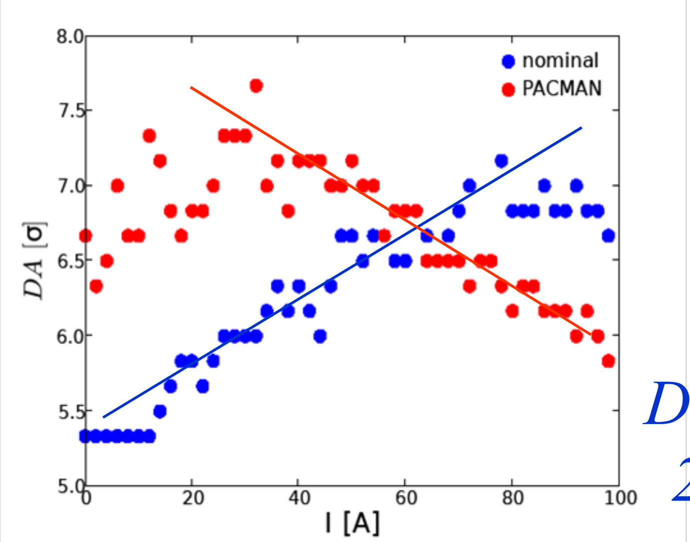


Red: with compensation for nominal bunch

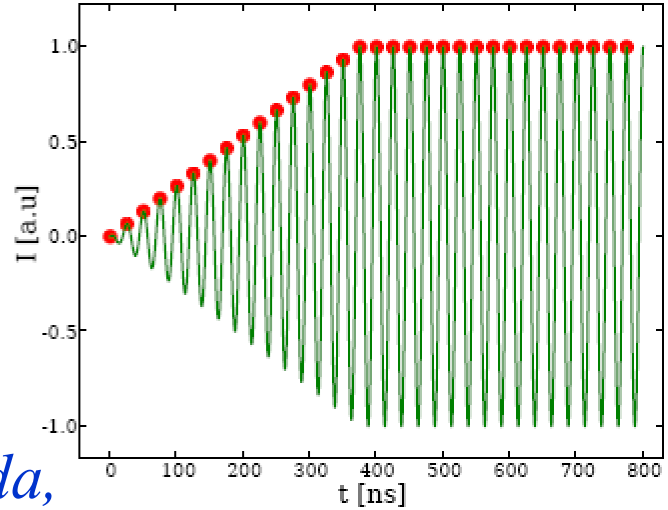
An effective compensation does not require accurate control of position neither tunes. Other data suggest the same robustness with respect to the excitation current. The noise level is very low.

4.3 Compensation of Pacman bunches

Mitigation, using dc wire

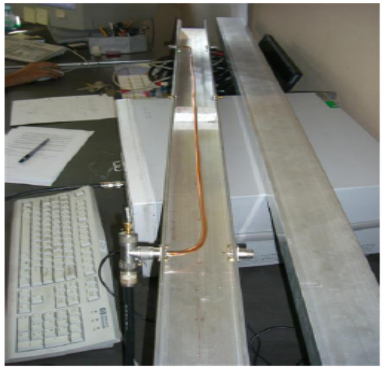


Dorda, 2007

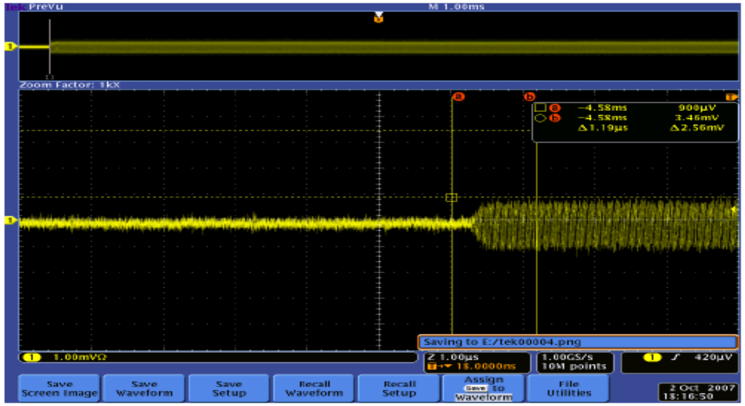


(e) RF-BBLR

RF solution: feasibility to be demonstrated



Experimental setup



first RF-BBLR

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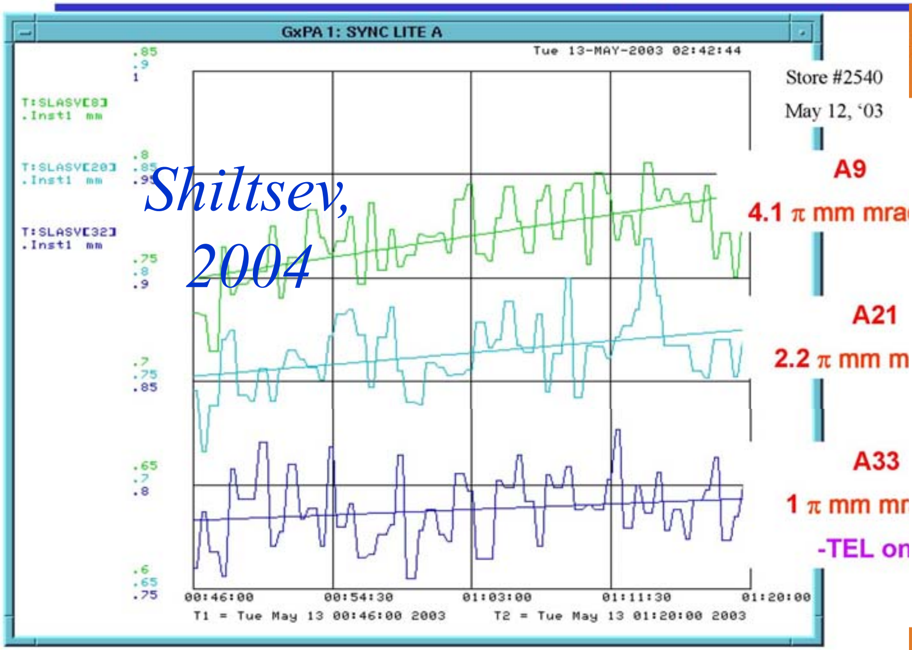
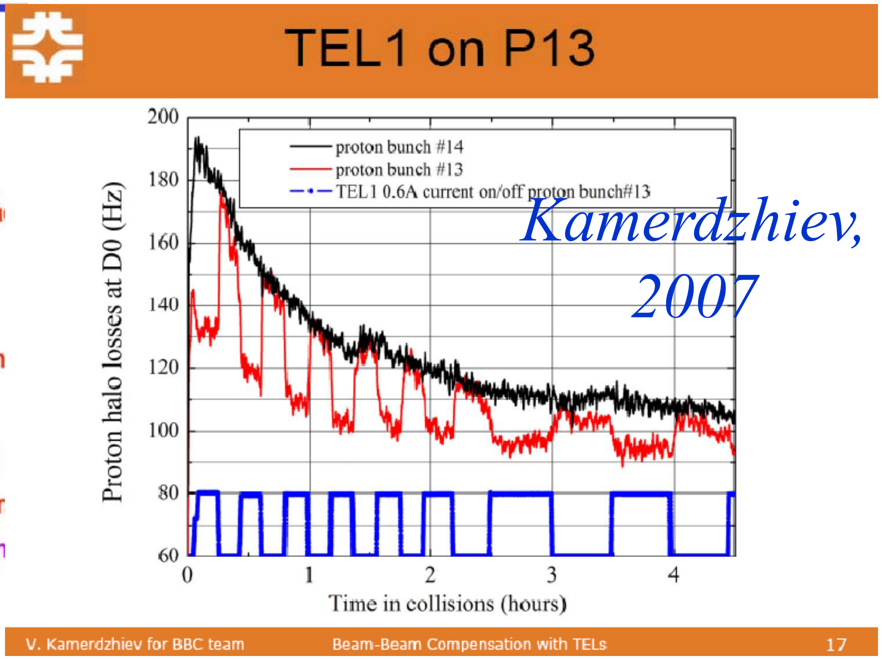
5.1- TEL Performance at the TEV

Emittance Growth of A33 Suppresed by TEL





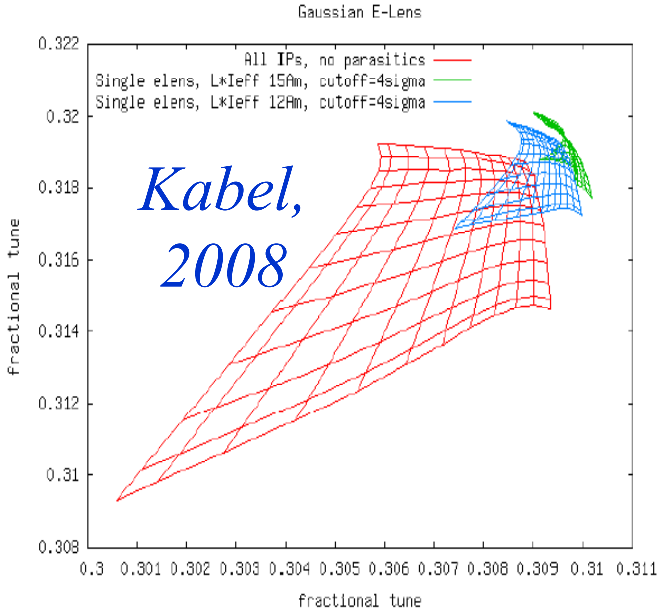
- The TEL is **reliable** (since 2002) and **does not cause blow up of p's**.
- Its success as a **bunch-to-bunch linear tune shift corrector is established,** with improved beam and luminosity lifetimes.
- Its performance as a **non-linear HO beam-beam compensator is not yet experimented.**

5.2- TEL Performance for the LHC

Tsyganov, (SSC 1993) 2007

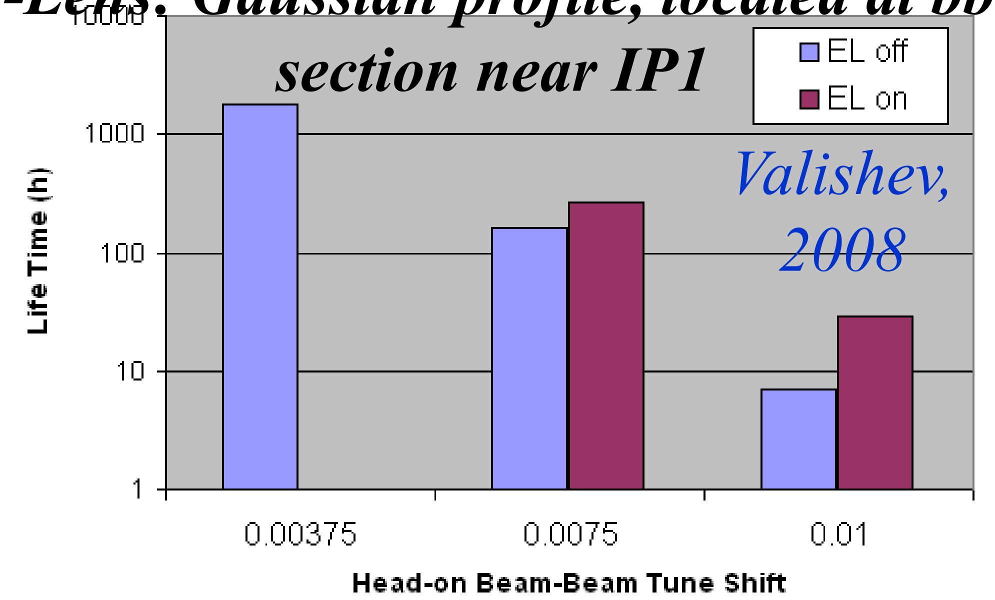
- It was shown for the LHC that for reasonable tolerances of the low energy beam parameters quite good head-on beam-beam effect compensation could be obtained and beam-beam tune spread could be reduced by a factor up to about 100.

Kabel, 2008



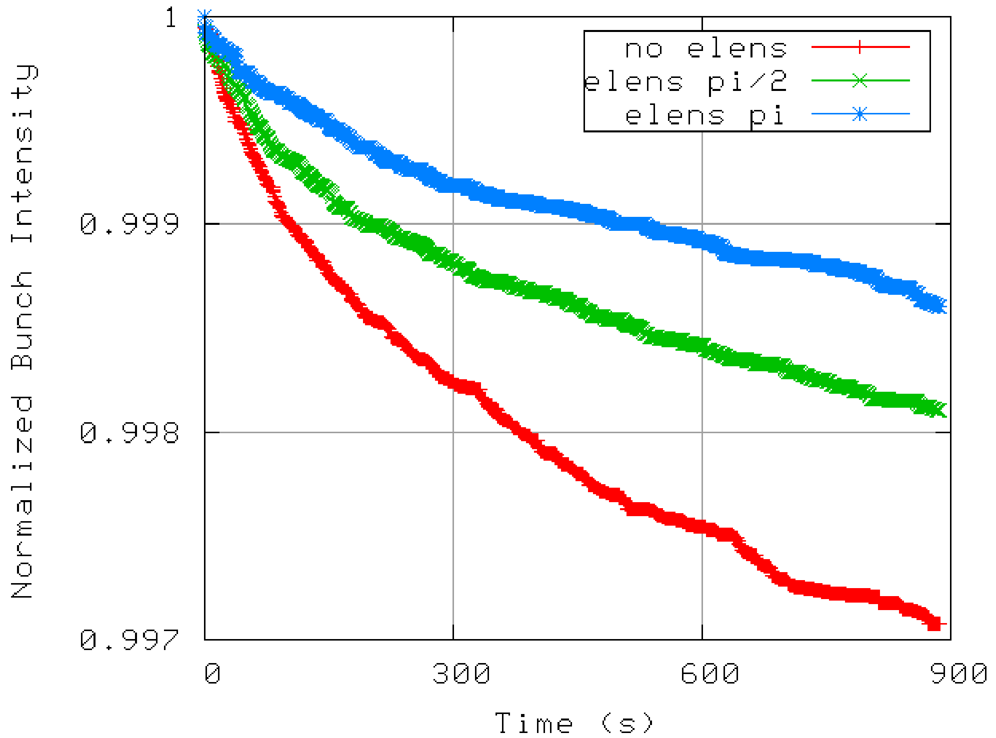
E-Lens: Gaussian profile, located at bbc section near IP1

Valishev, 2008



A clear benefit for LHC appears for intensities and beam-beam parameters above nominal, i.e. for SLHC.

5.3- Sensitivity of TEL Performance to the betatron phase



Valishev, reported by Sen, 2008

The TEL remains effective for a "wrong" betatron phase. The tune footprint compression seems to dominate over resonance excitation.

6 - Conclusions

The beam-beam effect: *The TEV has raised significantly the beam-beam limit. The complexity of the HO b-b effect is much enhanced by the long-range beam-beam encounters. There is a great incentive to be able to separate more than by 10σ.*

Crossing planes: *The best scheme does not seem to be decidable by simulation. Provisions for all schemes (HV, HH, VV) seems advisable for the SLHC.*

Minimum beam separation: *The operations, experimental and simulation results are not yet consistent. The simulation effort is on-going (Kaltchiev). RHIC experiments critically needed.*

Large Piwinski angle: *no show stopper identified. More simulation needed (effect of LR, diffusion in tails,..)*

6 - Conclusions

Simulations: *the major tool for studying b-b even though its predictability is not established except in "perturbative mode". Requires lots of care.*

Wire Compensation: *Its efficiency is established as far as possible. A positive experience already exists (Dafne). A mitigation can be made for the PACMAN bunches using a dc wire excitation. The principle of an RF solution has been put forward but its feasibility remains to be established.*

TEL Compensation: *With the TEV experience, the TEL is not anymore an exotic idea, but a reliable device. It will gain full acceptance when some gain will have been demonstrated in non-linear HO compensation mode. Significant potential for LHC.*

…and leveling, flat beams, wire technology, …