ICFA mini-workshop on
"Beam-Beam Effects in Hadron Colliders"
March 18th to 22nd, 2013

High Luminosity LHC

Summary of the 2013 workshop on beam-beam effects in hadron colliders

T. Pieloni
BE/ABP/ICE

A&T Sector Seminar
15th April 2013

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

From 1961 to 2013

A. Chao

"It all started with ***Amman & Ritson 1961***

Only one jargon in 1961:

- ***"space charge effect"*** *(beam-beam parameter by today's language)*

Good old days at ISR – van der Meer scan 1974, overlap knockout, Steve Myers 1977…"

ICFA mini-workshop on
"Beam-Beam Effects in Hadron Colliders"
CERN

52 talks

58 registrants

18 institutes/laboratories

Scientific Program

- Beam-beam **experience** in **hadron colliders** (O. Bruning)
- Beam-beam experience in **lepton colliders** (J. Seeman)
- Beam-beam **models**, analytical and simulation models, single particle and multiparticle simulations (T. Pieloni)
- Incoherent beam-beam **effects from head-on** collisions with and without crossing angle (K. Oide)
- Incoherent beam-beam **effects from parasitic** interactions (V. Schiltsev)
- **Compensation** of head-on and long range beam-beam effects, coherent and incoherent (W. Fischer)
- **Strong-strong beam-beam** interactions, self-consistent models and coherent effects (L. Rivkin)
- **Operational considerations** for colliders with strong beam-beam effects (G. Papotti)
- Studies required for **future projects** (HL-LHC, LHeC, ..) (A. Valishev)
- Summary and Discussions (A. Chao)

Very dense and interesting program: thank speakers and chairs!

2013 Jargons

A. Chao

"...the fun continues today except that it is now way more sophisticated..."

- pp, ep, pN, NN, eN
- Head on – Long range
- Beam-beam limit – tune shift – tune footprint
- dynamic beta – 1⁄2 integer tune – flip-flop
- Crossing – Piwinski angle – crab cavity – crab waist
- Weak-strong – strong-strong
- Landau damping, impedance-beam-beam interplay, damper
- e-cloud – beam-beam-beam interplay
- Simulations – Poisson solver
- Luminosity leveling – pile up
- Noise – halo – emittance diffusion – Tevatron modeling
- PACMAN – alternating crossing
- Dynamic aperture – smear – FMA
- Resonances – synchrobetatron – round/flat beam integrability
- Compensation – wire – e-lens
- beta squeeze, cogging, van der Meer scan
- Schottky – turn-by-turn – bunch-by-bunch – BTF

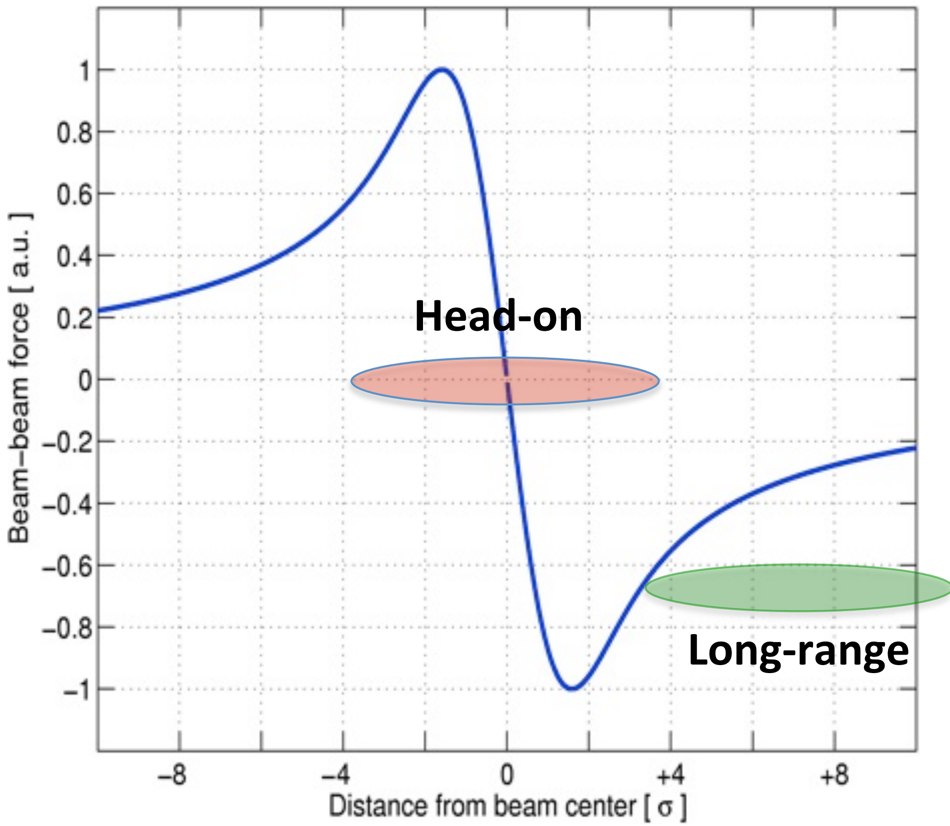
Beam-Beam effects and luminosity

Pushing for luminosity means stronger beam-beam effects

$$\mathcal{L} \propto \frac{N_p^2}{\sigma_x \sigma_y} \cdot n_b$$

$$F \propto \frac{N_p}{\sigma} \cdot \frac{1}{r} \cdot \left[1 - e^{-\frac{r^2}{2\sigma^2}}\right]$$

Beam-beam force



Typically:

- **0.001% (or less) of particles collide**
- **99.999% (or more) of particles are distorted**

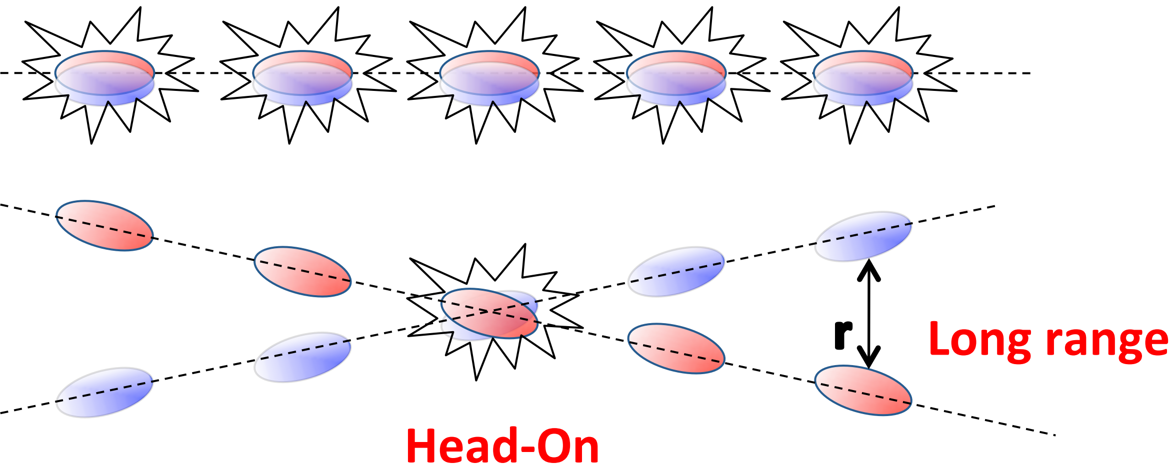
What happens to a single particle?
What happens to the whole beam?

$$\mathcal{L} \propto \frac{N_p^2}{\sigma_x \sigma_y} \cdot n_b$$

Beam-beam geometry

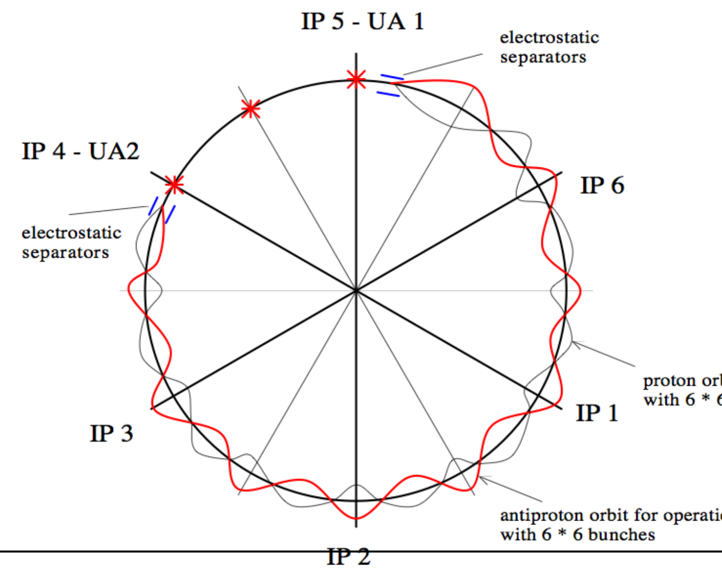
Num. of bunches : $n_b = 2808$

Crossing Angle Operation

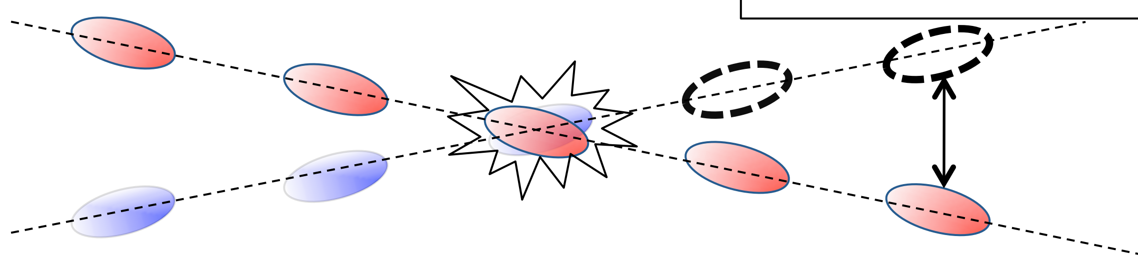


LHC:For 50ns case 64 BBIs per turn: 4 HO and 120 LR
For 25ns case 124 BBIs per turn: 4 HO and 120 LR

Pretzel operation

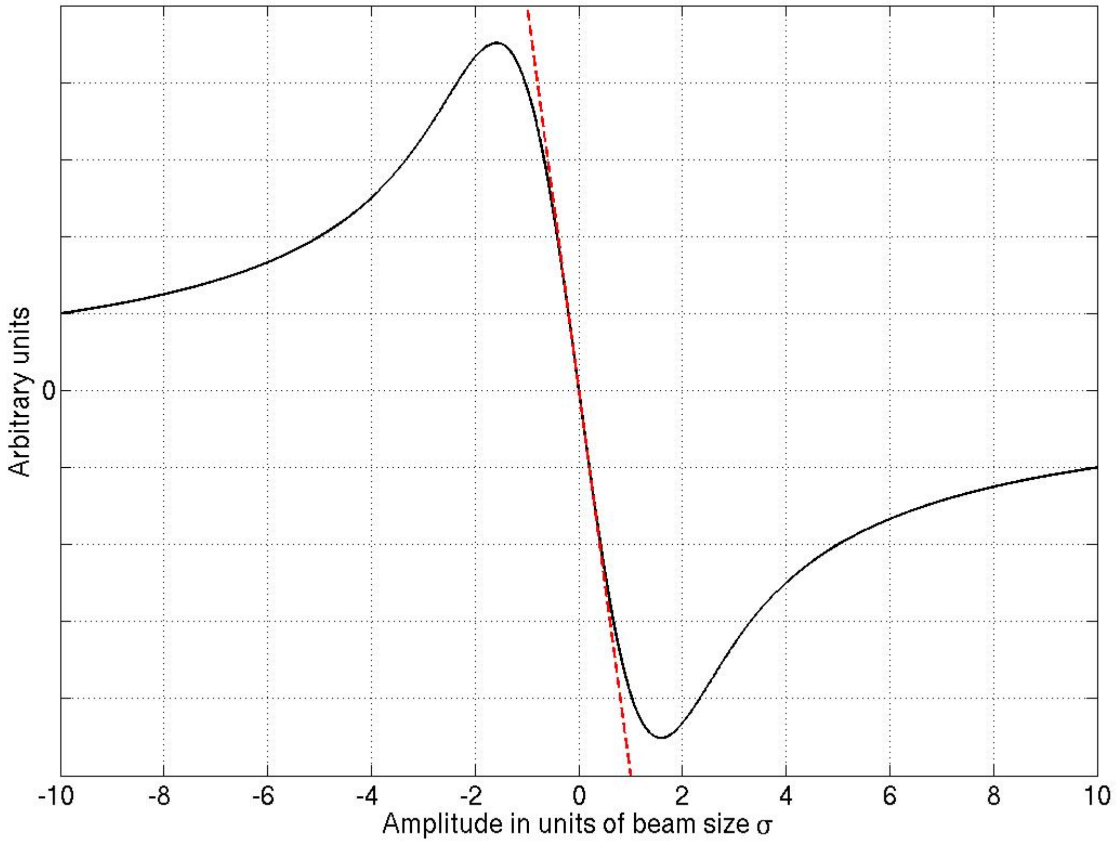


SPS collider 6 bunches 3 HO and 9 LR



PACMAN bunches less number LR
For 25ns bunches have 40-120 LR → different properties

Linear beam-beam parameter ξ



A test particle will receive a radial kick:

$$\Delta r' = \frac{2Nr_0}{\gamma}\frac{1}{r}[1-(1-(\frac{r^2}{2\sigma^2})+\ldots)]$$

$$\lim_{r\to 0}\Delta r' = \frac{Nr_0}{\gamma\sigma^2}\cdot r = +f\cdot r$$

Linear beam-beam parameter

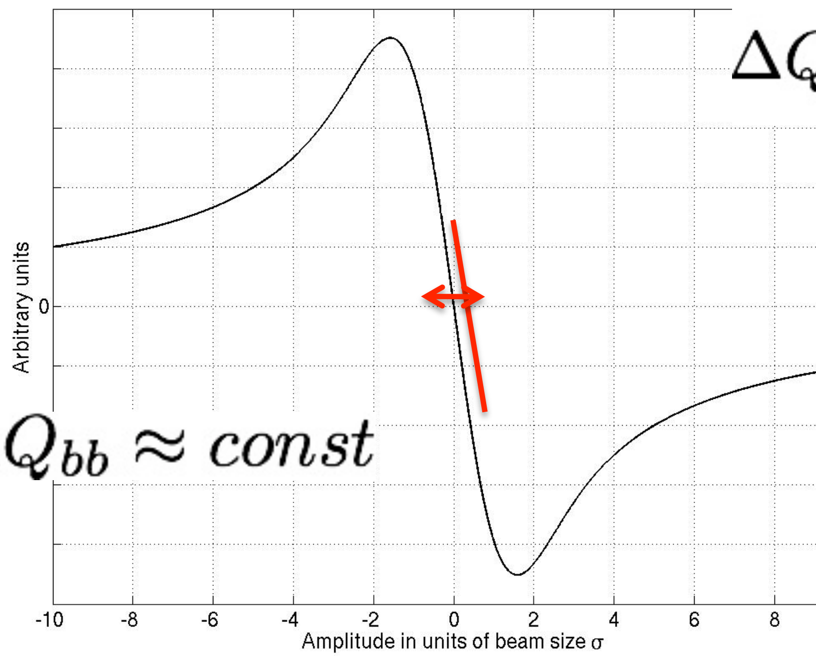
$$\xi = \frac{Nr_0\beta^*}{4\pi\gamma\sigma^2}$$

Quantifies the strength of the force but does NOT reflect the nonlinear nature of the force

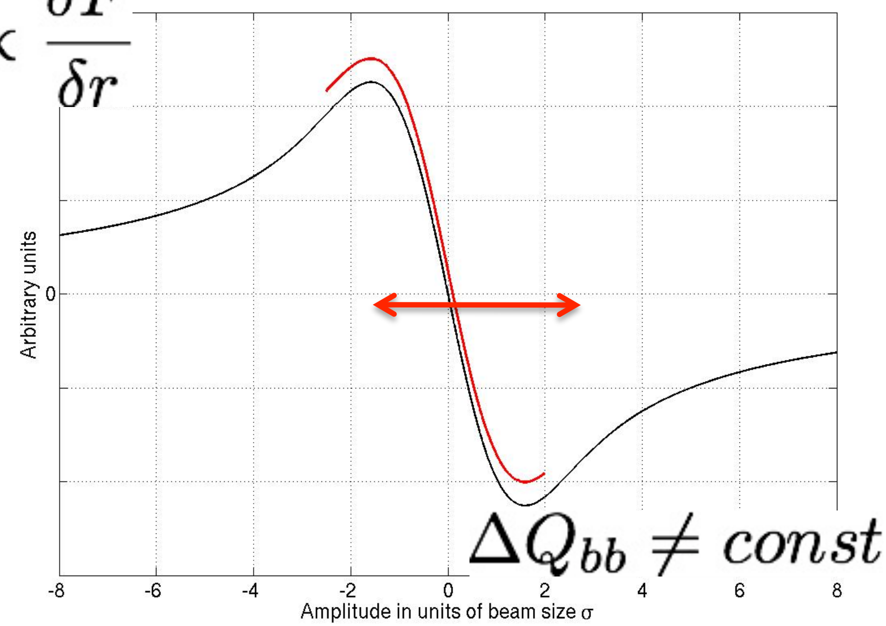
Detuning with Amplitude for HO collision

Instantaneous tune shift of test particle when it crosses the other beam is related to the derivative of the force with respect to the amplitude

$$\Delta Q \propto \frac{\delta F}{\delta r}$$



$$\Delta Q_{bb} \approx const$$



$$\Delta Q_{bb} \neq const$$

For small amplitude test particle

$$\lim_{r\to 0} \Delta Q(r) = -\frac{N r_0 \beta^*}{4\pi\gamma\sigma^2} = \xi$$

Linear beam-beam parameter

For larger amplitude test particle

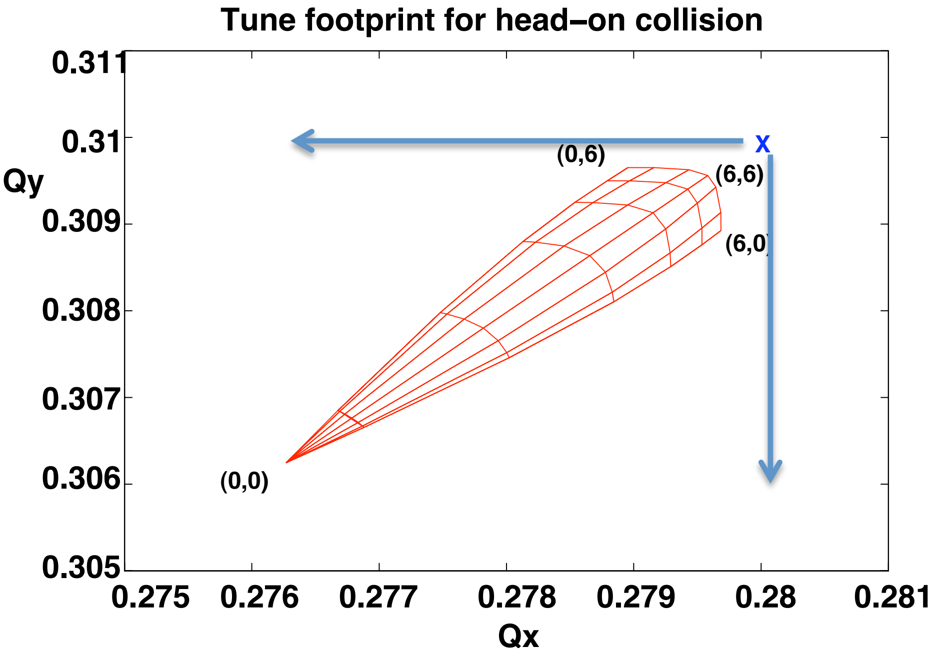
$$\Delta Q(x) = \frac{N r_0 \beta}{4\pi\gamma\sigma^2} \cdot \frac{1}{(\frac{x}{2})^2} \cdot (\exp -(\frac{x}{2})^2 I_0(\frac{x}{2})^2 - 1)$$

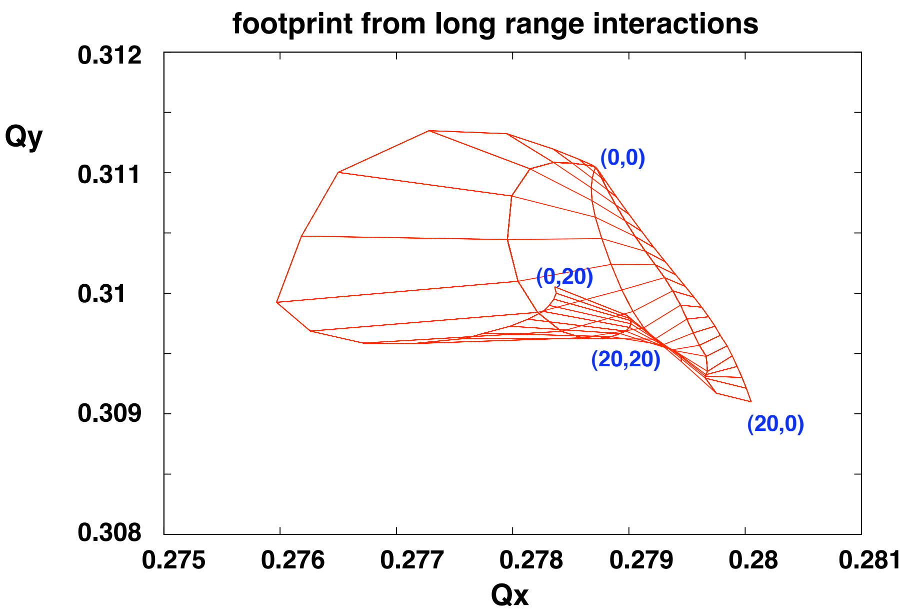
Non linear….footprints…

Detuning with amplitude and footprints

FOOTPRINT

2-D mapping of the detuning with amplitude of particles





Head-on collision **Long-range interaction**

In reality we have a mixture of the two (LHC 2head-on+1 separated+ 40-120 long-range….)

PROBLEMS: particle loss, bad lifetimes, coherent effects…

→ deteriorates collider performances!

Relevant for LHC and HL-LHC

Head-on effects

- LHC achievements over 2011-2012 tests
- noise on head-on collision and emittance growth
- Head-on effects for HL-LHC: Crab cavities from KEKB
- Diffusion in stable beam dominated by collision Tevatron versus LHC

Long-range effects

- Strategy and observations in the LHC: Do we understand them?
- Tevatron experience with Long-range: where we could improve?
- LHC achievements over 2011-2012 tests

LHC specifics: Instabilities, leveling and VdM scans

- 2012 Instabilities
- New models: interplay of effects (BB+impedance+…)
- Operational aspects
- Leveling luminosity
- VdM scans

Compensation ideas

- E-lens compensation
- Wires

…and much more not covered here!

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- Wires
- Future projects

LHC achievements:

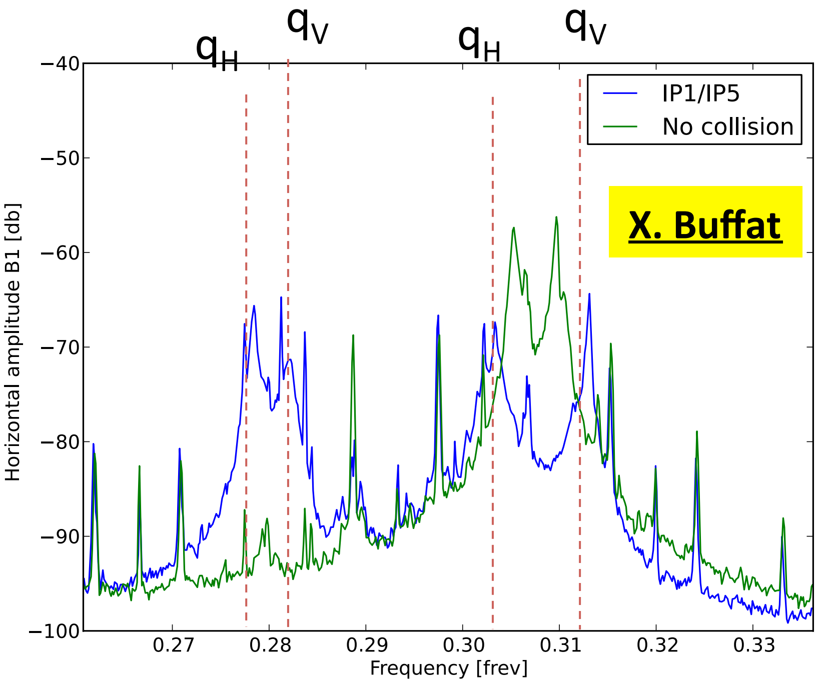
G. Trad

Several tests
Fill 1765-1766 (May 2011)

LHC nominal ξ_{bb}=0.0034/IP

GOALS:

- check the feasibilty of colliding high intensity bunches (HO) with a beam beam linear parameter greater than nominal



1.85*10^11 emitt 1.3 microns at injection
ξ : **0.017/IP** , total tune shift 0.030 (HO IP1,5)
Small tune scan, no lifetime effect
Had to Q_V=Q_H= 0.31 to avoid 10th order resonance

Under the present conditions we do not consider the HO bb interaction as a limit for the LHC performance

Systematic studies (parallel separation, leveling and noise excitation) to be done for μ=100!

What can deteriorate maximum ξ? → Noise, modulation…
How does LR change reachable ξ?

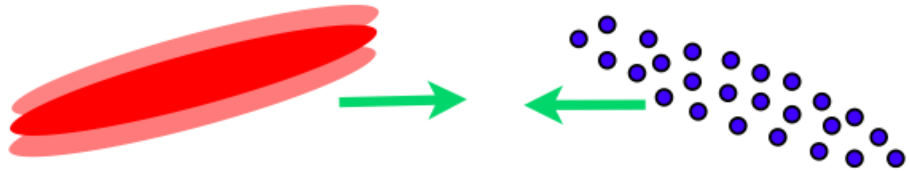
Noise of Collision offset

Noise on colliding beams

K. Ohmi

Weak-strong picture

G. Stupakov, SSC-560 (1991).
T. Sen and J. Ellison, PRL 77, 1051 (1996)



$$U = \delta_P(s)\frac{Nr_p}{\gamma}\sum_{k=0}^{\infty}U_k(a)\cos 2k\psi$$

Requirement for the theory: near integrable system, far from resonances.

$$U_k = \int_0^a \left[\delta_{0k} - (2-\delta_{0k}(-1)^k e^{-w}I_k(w)\right]\frac{dw}{w},$$

$$a = \beta^* J/2\sigma_r^2, \quad \Theta = -\ln(1-1/\tau_c),$$

$$\Delta J = -\frac{\partial U}{\partial \psi} = \frac{Nr_p}{\gamma}\sum 2kU_k \sin 2k\psi$$

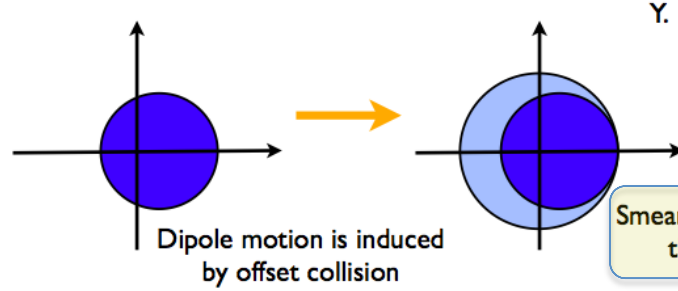
ΔJ /turn

2 models can be applied:

- **Weak-strong fast calculation** but requires near integrable system (far from resonances)

Strong-strong model

Y. Alexahin, NIM A391,73 (1996)



Smear out of the dipole motion, then emittance growth

- **Strong-strong very slow** but allows any configuration. Emittance growth comes from filamentation out of dipole motion

$$\frac{\delta\varepsilon}{\varepsilon} \approx \frac{K}{\left(1+\frac{G}{2\pi|\xi|}\right)^2}\frac{\delta x^2}{\sigma_x^2}$$

$$G = 1/\tau$$

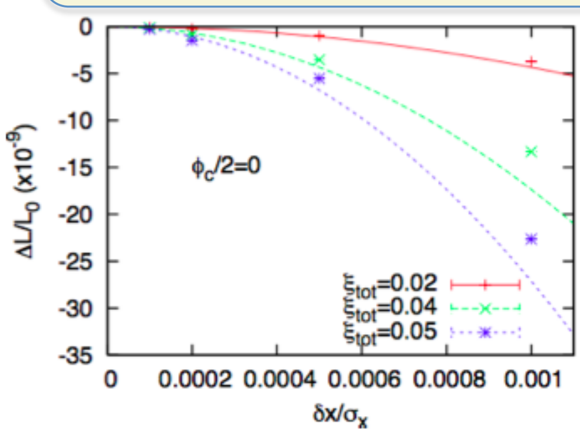
$$\Delta x^2 = \frac{\delta x^2}{2G}$$

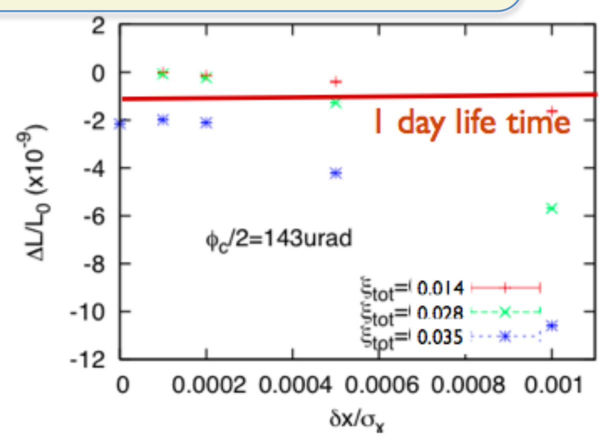
- For G=0, dipole motion is transferred into emittance.
- For G=1, phase mixing of the dipole motion is 2πξ thus $K(2\pi\xi)^2$ contributes emittance growth.

Noise on colliding beams

Simulation w/wo crossing angle

- Weak-strong simulation
- Quadratic dependence on $\delta x/\sigma_x$ and ξ. T=1
- Critical noise amplitude, 0.02% for ξ=0.04-0.05.
- Degradation due to noise depends on ξ, and little depends on the crossing angle.



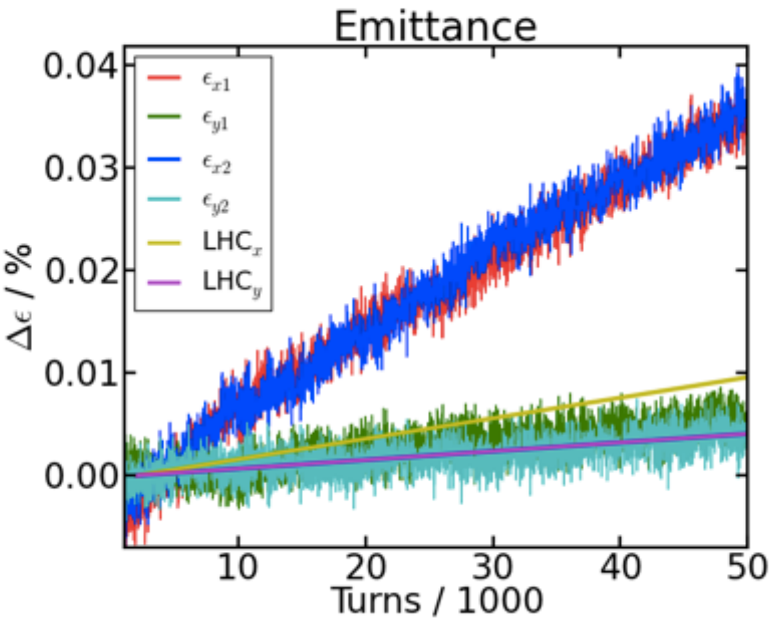


- **2 models have to be used (SS and WS)**
- LHC after LS1 and up-grades should keep in mind: **beams with higher ξ are MORE SENSITIVE to noise**
- For HL-LHC keep studying **Crab cavities noise effects**

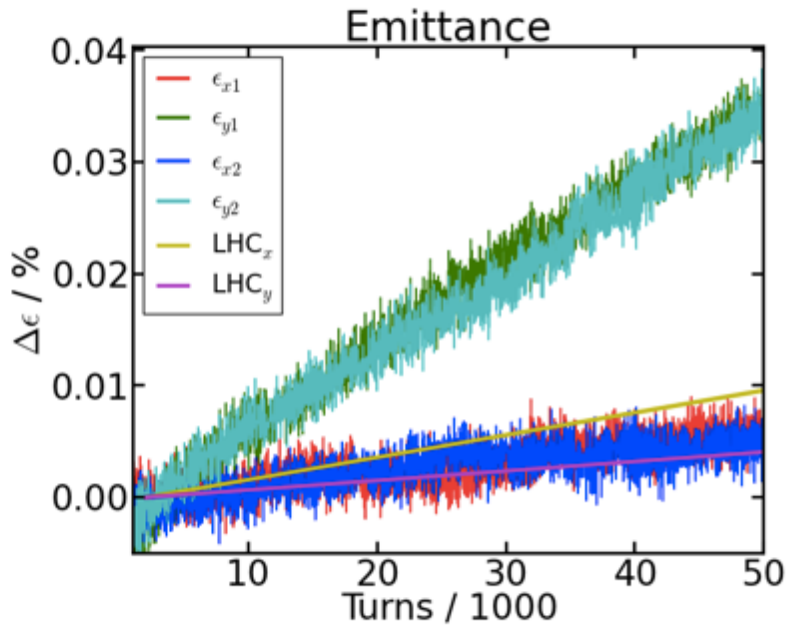
K. Ohmi

HL-LHC studies started:

θ = 0.59 mrad, with CC



θ = 0.59 mrad, with CC
Qx and Qy exchanged



Study the impact of noise on LHC colliding beams:

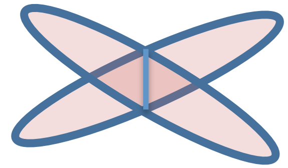
- Effect of transverse feedback
- Crab-cavities noise of different type, spectra of HL-LHC cavities
- Explore parameter space HL-LHC (tunes,int,…)

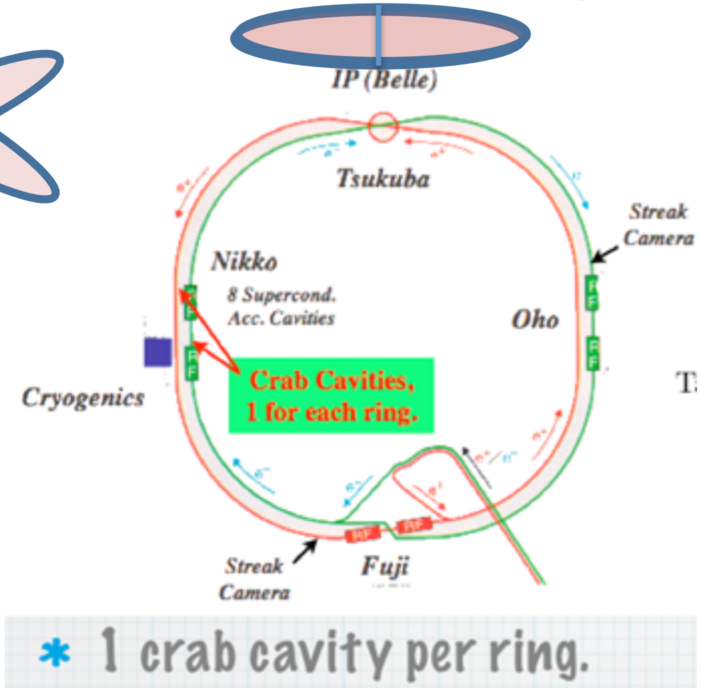
Need experimental data from LHC to benchmark

S. Paret

Crab Cavities: in KEKB at 2 x 11 mrad crossing

$$L = L_0 \frac{1}{\sqrt{1 + \frac{\sigma_{s1}^2 + \sigma_{s2}^2}{\sigma_{u1}^2 + \sigma_{u2}^2} (tan \frac{\phi_u}{2})^2}}$$



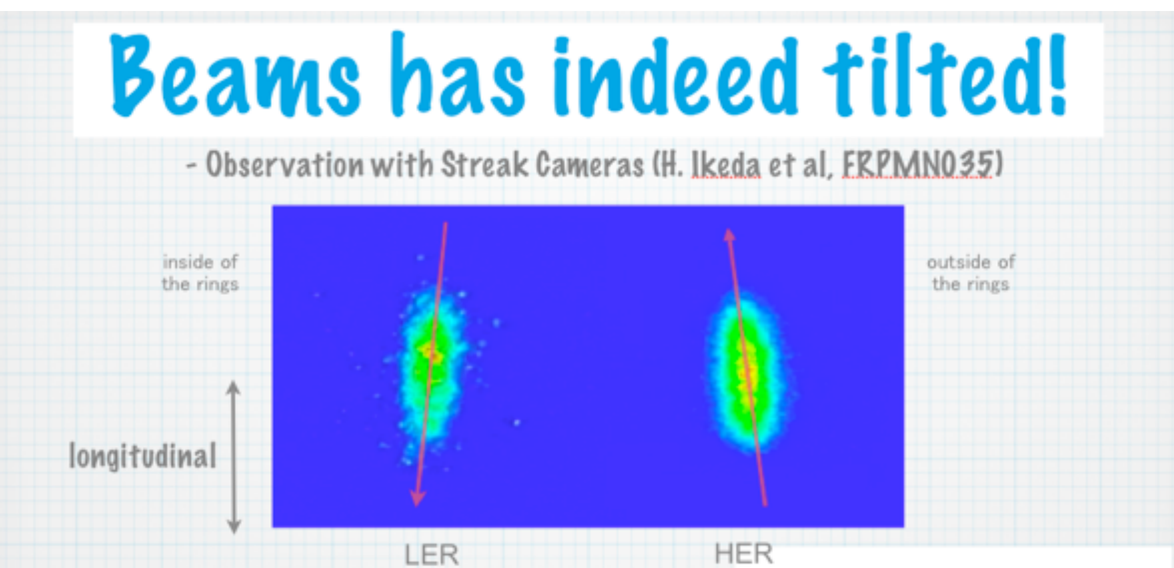


To compensate for the geometrical reduction factor at IP to give a higher luminosity:

KEKB 11%

LHC 15-20%

HL-LHC 70%



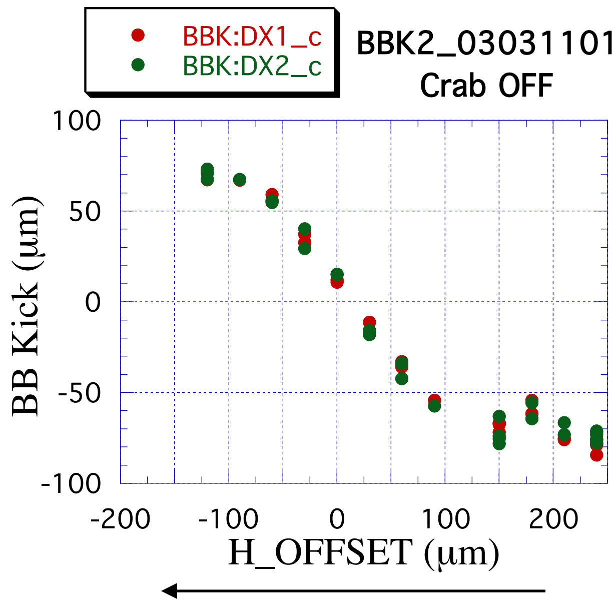
Crab Cavity tilting proved at KEKB experiment recovered 11% reduction factor.

Y. Funakoshi

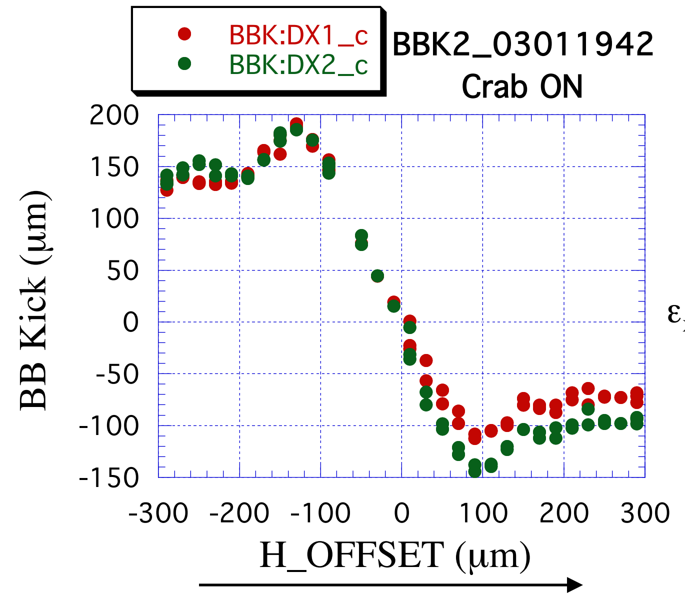
KEKB: Evidence of crabbing (2): Beam-beam deflection

Y. Funakoshi

Crab OFF



Crab ON (Vc = 1.31/0.92 MV)



ε_x L/H=18/24 nm

T. Ieiri

Bunch Current: 0.73/0.42 mA

Bunch Current: 0.64/0.47 mA

$\Sigma_{x\_x'=11}$=230 +/- 3 μm (OFF) ➡ $\Sigma_{x\_x'=00}$=167 +/- 3 μm (ON)

- **Luminosity increase from simulation 100% total obtained in KEKB 23% with CC, many ingredients…**
- **CC operational in KEKB, trip rate still needs some study**

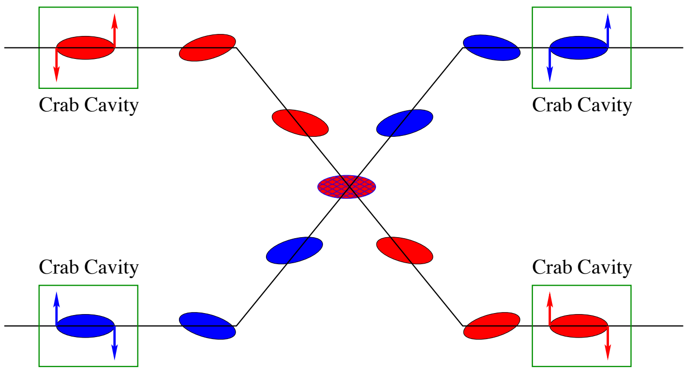
J. Seeman

How will be for HL-LHC? Different Crab Cavities…

Tolerance for the crab cavity noise

- $\Delta x/\sigma_x=0.002$ for the design parameter $N_p=2.2\times10^{11}$ and $\tau=1$. $\Delta\varphi_{RF}=4\times10^{-4}$ rad.
- $\Delta\varphi_{RF}=4\times10^{-4}\,\tau$ rad, because of the scaling of τ, $\Delta x\sim\tau$.

$$\Delta\varphi = \frac{\omega_{RF}\Delta x}{c\theta_c/2}$$

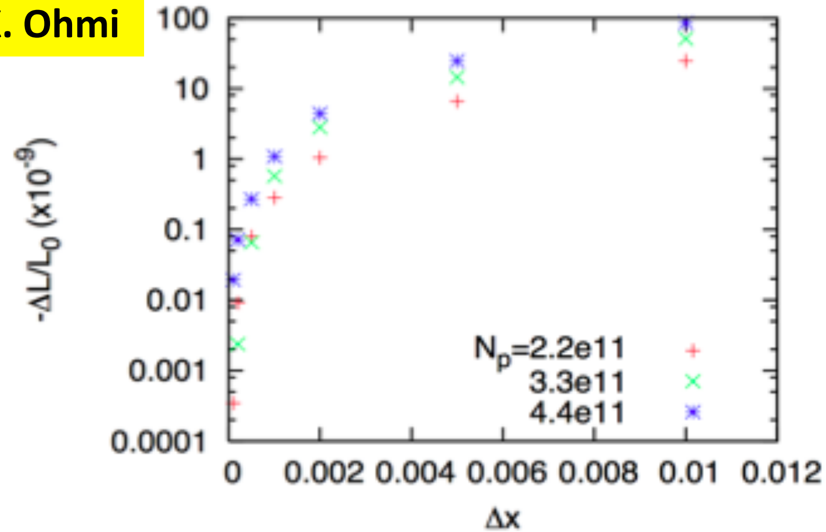


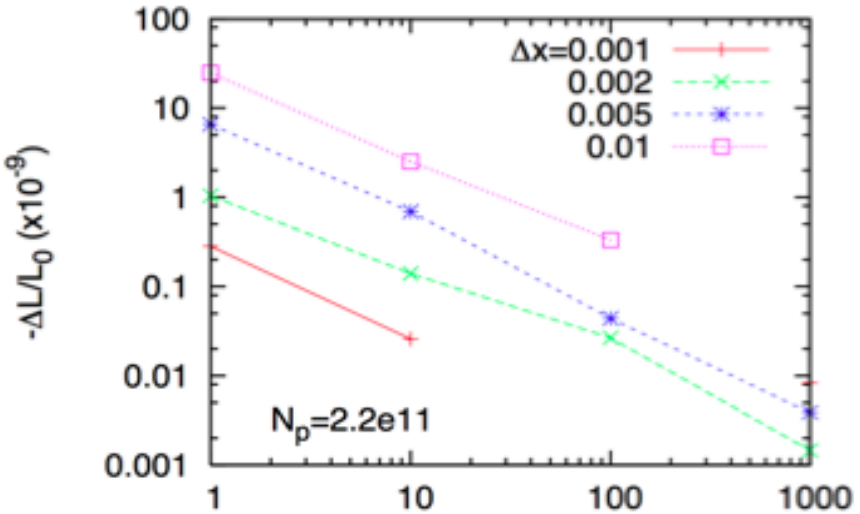
R. Calaga

- Measurement in KEKB, 1.7×10^{-4} rad at 1kHz ($\tau=11$). One order of the tolerance.

For HL-LHC CC noise should not be a problem, tolerances on cavities jitter is in reach

K. Ohmi





How will be for HL-LHC? Different CC scheme ...and hadrons....

Relevant for LHC and HL-LHC

Head-on effects

- LHC achievements over 2011-2012 tests
- noise on head-on collision and emittance growth
- Head-on effects for HL-LHC: Crab cavities from KEKB

Long-range effects

- **Strategy and observations in the LHC: Do we understand them?**
- **Tevatron experience with Long-range: where we could improve?**
- **LHC achievements over 2011-2012 tests**

LHC specifics: Instabilities, leveling and VdM scans

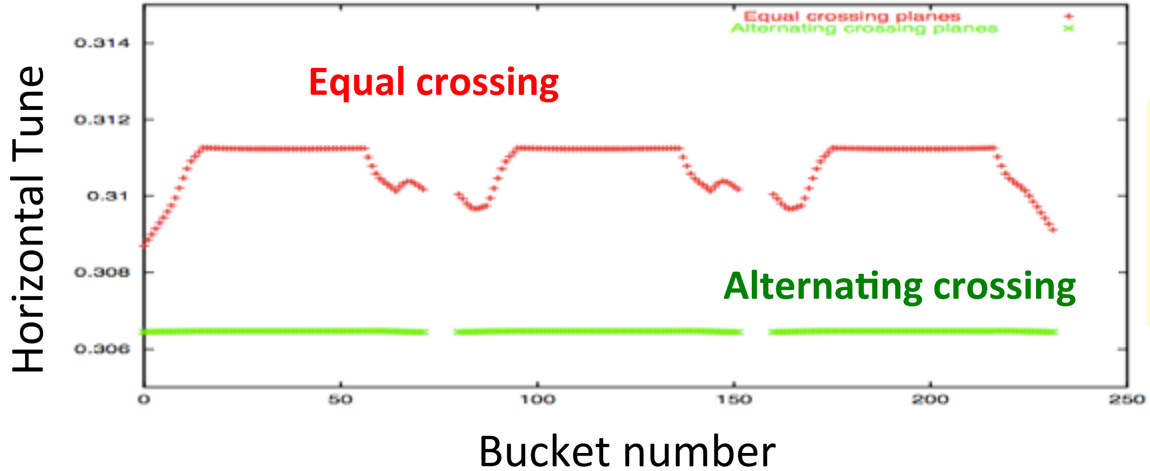
- 2012 Instabilities
- New models: interplay of effects (BB+impedance+…)
- Operational aspects
- Leveling luminosity
- VdM scans

Compensation ideas

- E-lens compensation
- Wires
- Future projects

PACMAN effects and passive compensation from HV crossing:

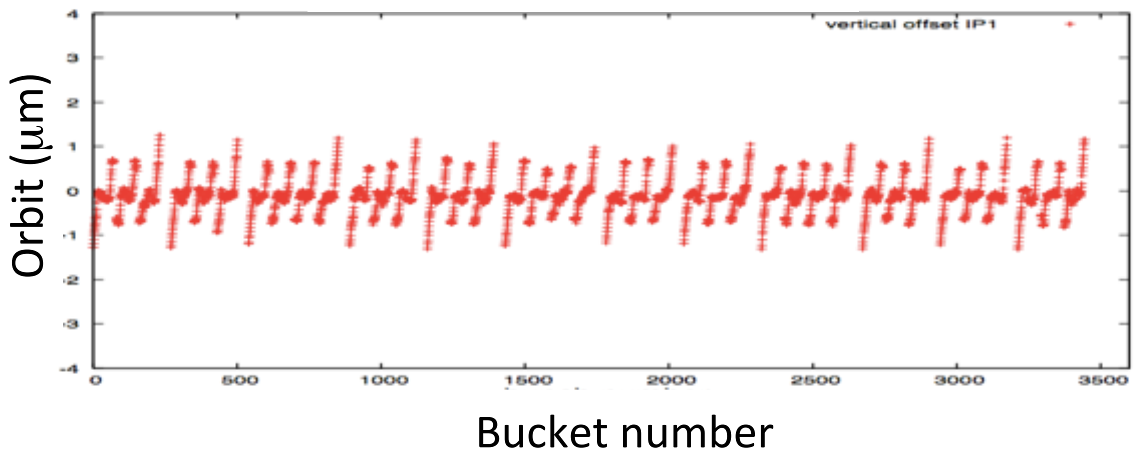
Simulation Nom LHC



Q compensation

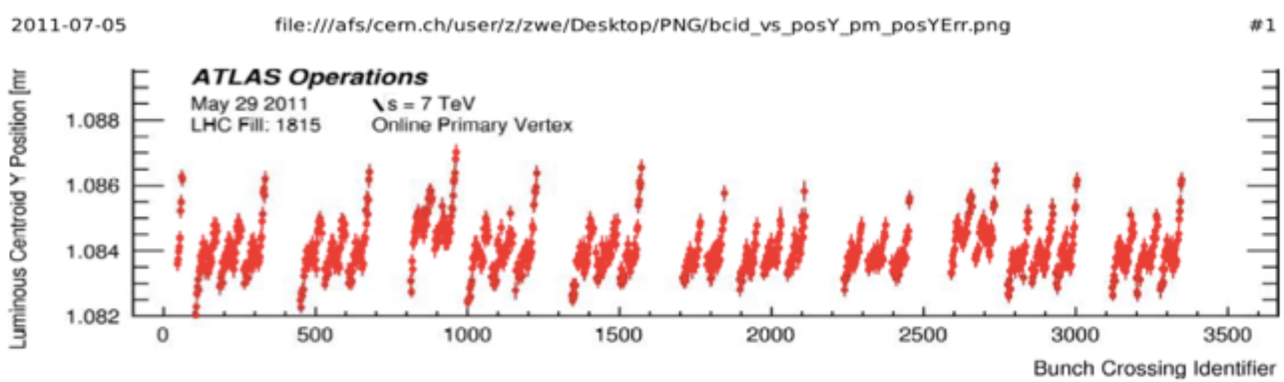
Q' compensation

Simulation Nom LHC



Orbit effects not compensated by HV but global correction doesn't affect 2 beams in opposite direction

ATLAS measurements

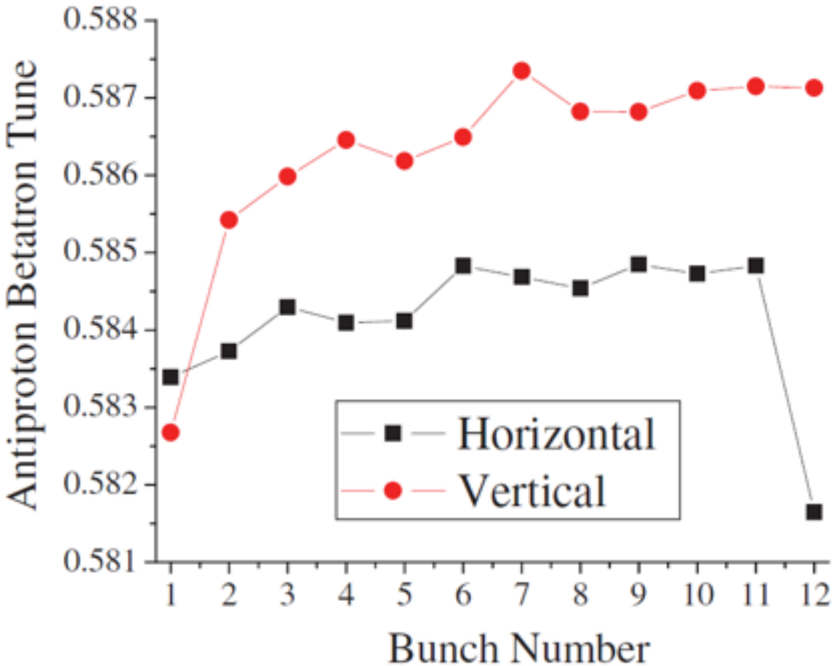


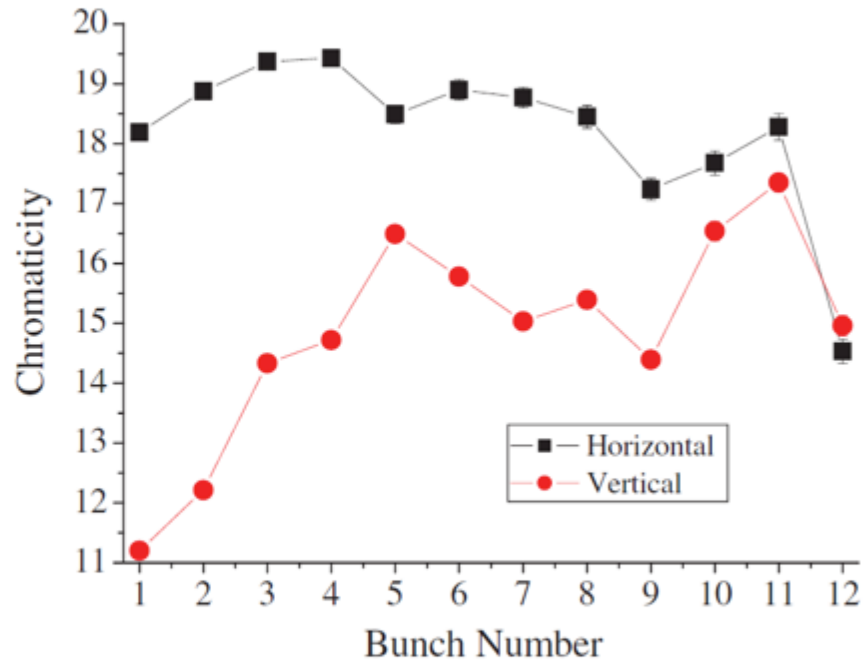
Qualitative agreement with predictions

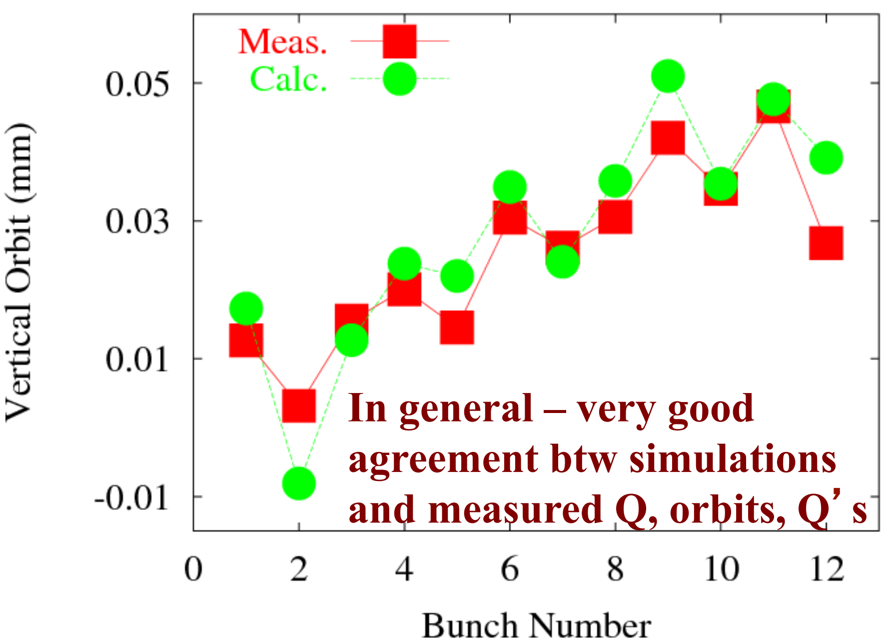
W. Herr

Long-range effects at Tevatron

V. Schiltsev



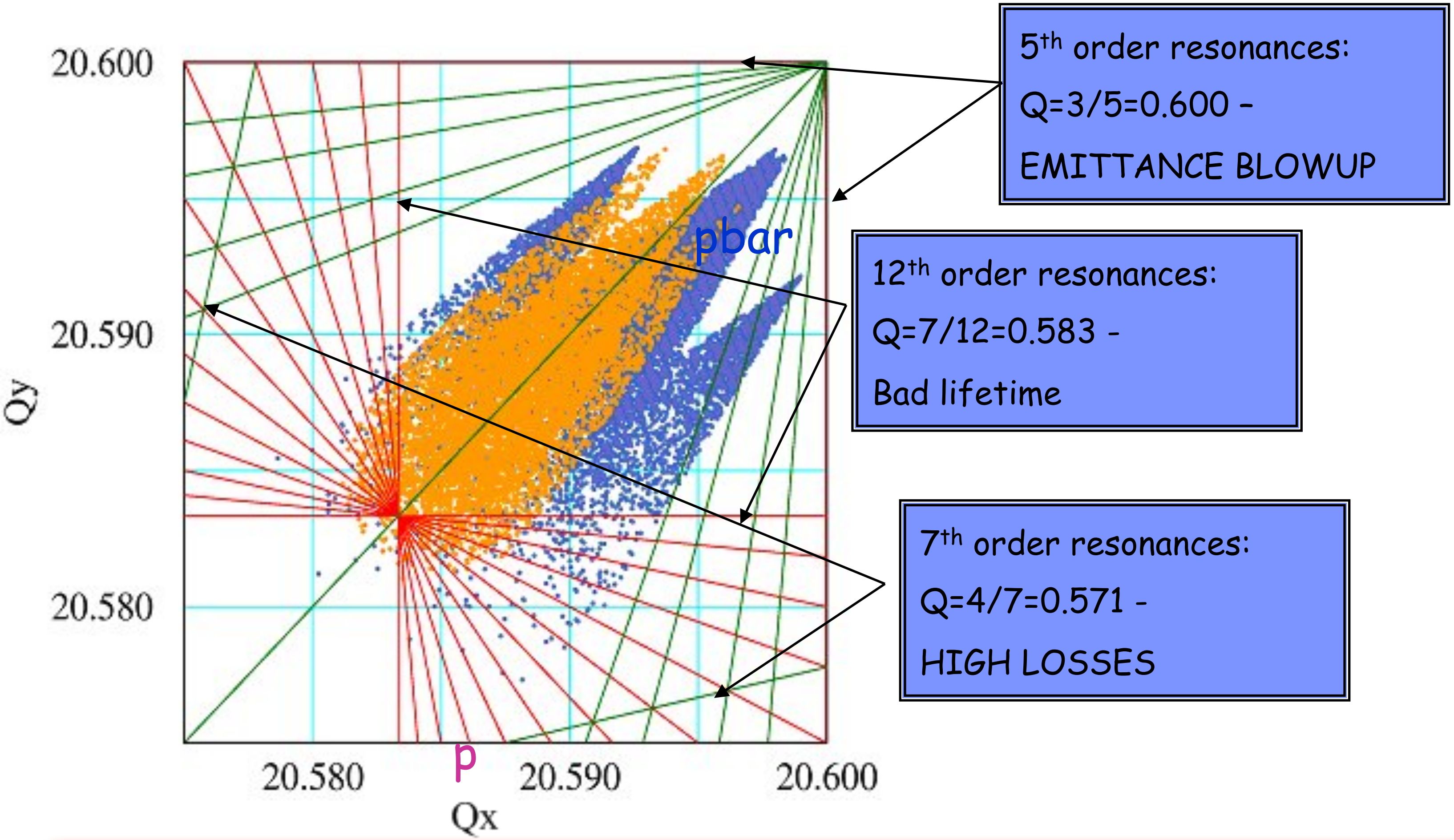




- **Long-range beam-beam effects occurred in the Tevatron at all stages** (injection, ramp, squeeze, collisions) and in both beams
- They resulted in **beam losses, bad lifetimes and emittance blow-ups**
- **Bunch-to-bunch dependent patterns**

Long-range and performances

V. Schiltsev

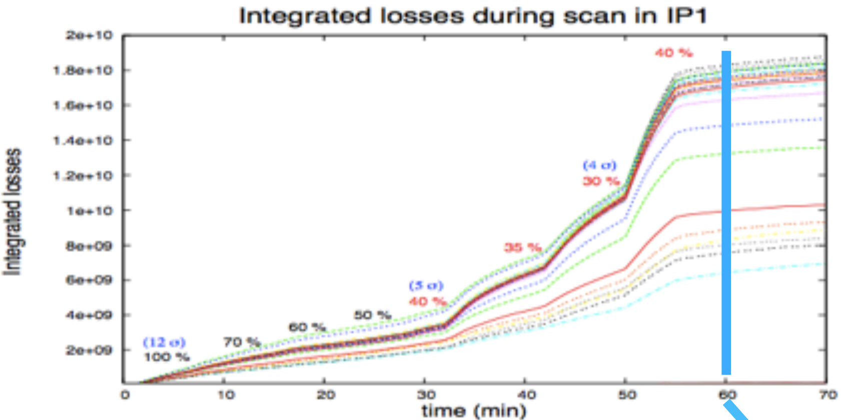


What helped us to improve *BB-situation?*

"Outstanding development of beam diagnostics
Tunes (3 instruments), emm (3), Intensity (3), lumi (2), BPM"

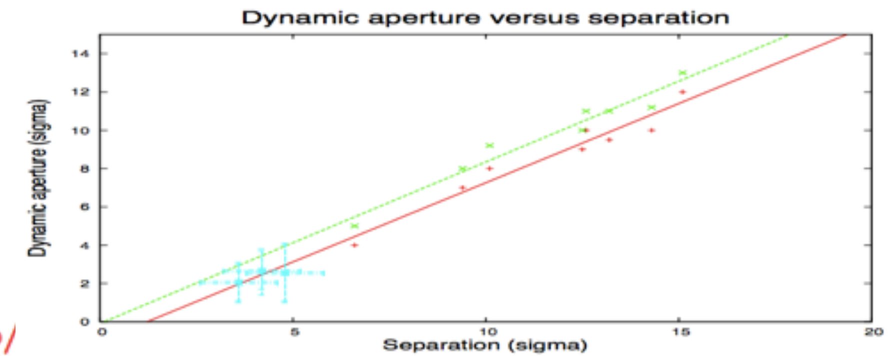
Long-range and Dynamic Aperture

W. Herr



- First test (2011) with $\beta^* = 1.50$ m, intensity: $1.2\ 10^{11}$ p/ emittance: 2.0 - 2.5 μm
- Bunch by bunch loss as function of crossing angle in IP1

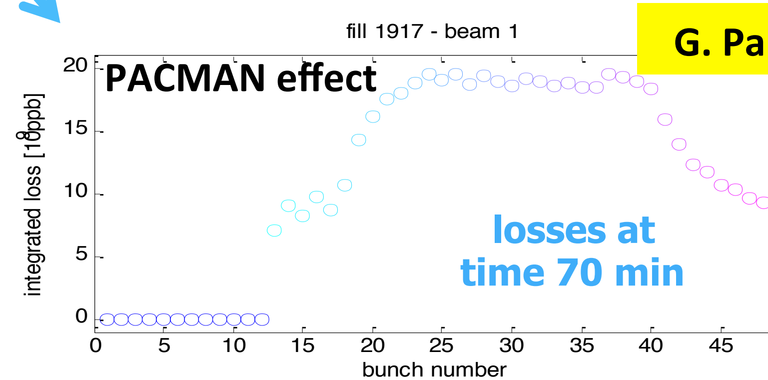
- **Losses relates to # LR encounters**
- **Onset relates to DA**



- Data estimated from separation scan (50 ns, 3.5 TeV, $1.25\ 10^{11}$p)
- Dynamic aperture as function of normalized separation (W.Herr, D.Kaltchev, LPN 416, (2008))

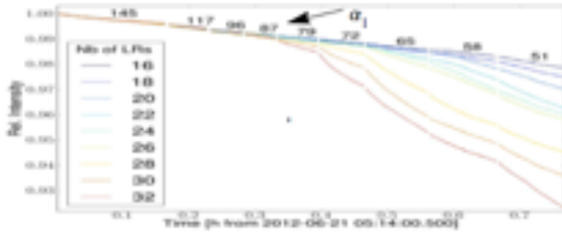
experiment	emittance	β^*	Intensity
2011 (50 ns)	2.0 - 2.5 μm	1.5 m	$1.2\ 10^{11}$
2012 (50 ns)	2.0 - 2.5 μm	0.6 m	$1.2\ 10^{11}$
2012 (50 ns)	2.0 - 2.5 μm	0.6 m	$1.6\ 10^{11}$
2012 (25 ns)	3.5 - 4.0 μm	1.0 m	$1.2\ 10^{11}$

- Combination of parameters allows parametric studies
- Normalized separation adjusted with β^* and crossing angle: $\sqrt{\beta^*} \cdot \alpha = $ const.

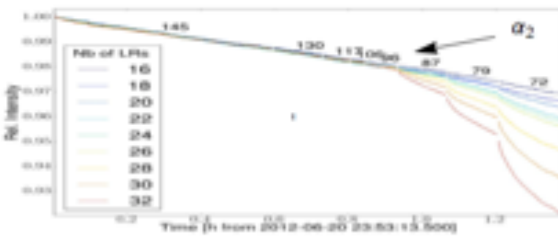


G. Papotti

Scaling law to predict intensity, separation and #LR effects



Second experiment: $N_b = 1.2\,10^{11}$, losses start at $\alpha = \alpha_1 \approx 87$? μrad



First experiment: $N_b = 1.6\,10^{11}$, losses start at $\alpha = \alpha_1 \approx 96$ μrad

(brown curves: 32 l.r.)

Smear X % at n_σ^X sigma

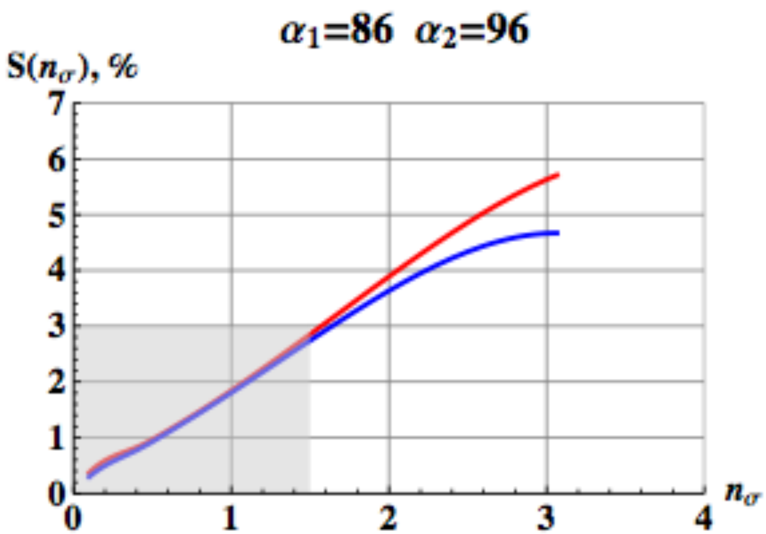
means looking for angles that are the solution of

$$S(n_\sigma^X; 1.2\,10^{11}, \alpha_1) = S(n_\sigma^X; 1.6\,10^{11}, \alpha_2) = X$$

There are two constraints for the 2 unknowns.
The graphical way used above seems better.

For LR: we have reliable predictions!

- **Scaling laws for intensity, # LR encounters and normalized separation**
- **Fast estimates, no DA tracking studies**



For these α_1 and α_2 the effects compensate: increasing intensity from $N_b = 1.2\,10^{11}$ to $N_b = 1.6\,10^{11}$ and reducing angle from α_2 to α_1 preserves the graph – the two curves overlap

$$S(n_\sigma; 1.2\,10^{11}, 86) = S(n_\sigma; 1.6\,10^{11}, 96)$$

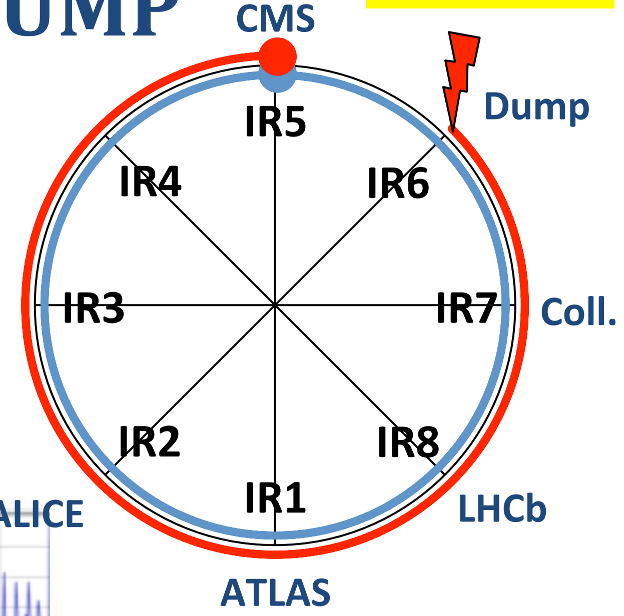
over some amplitude range

$$0 < n_\sigma < 1.5.$$

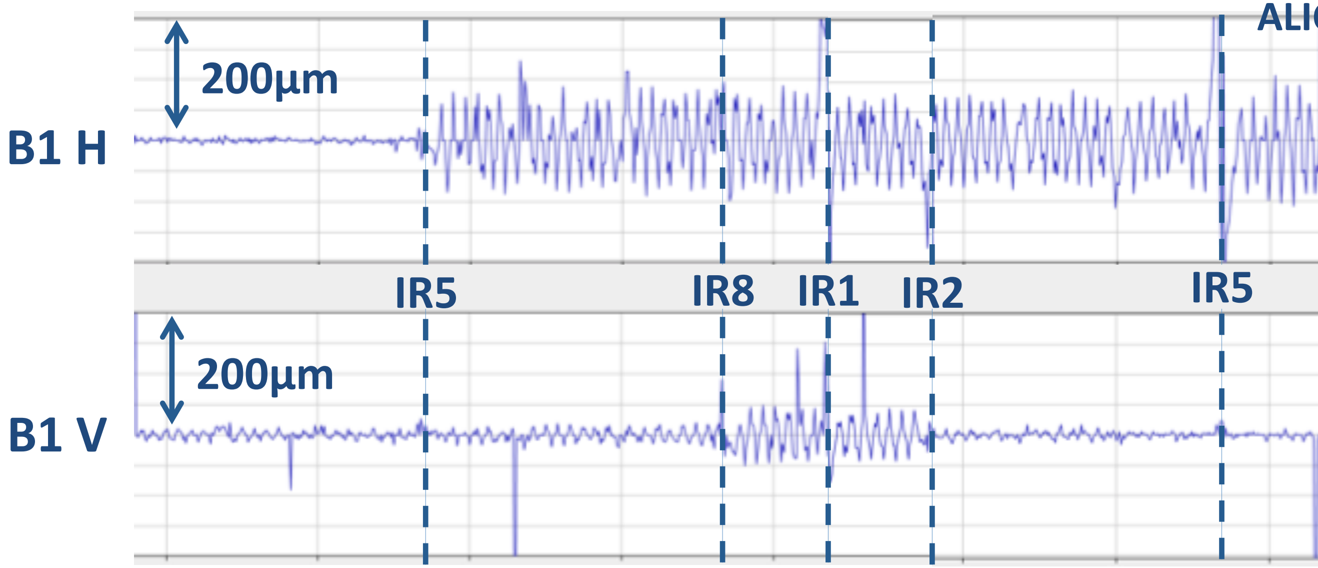
D. Kaltchev

Event Sequence: beam DUMP

T. Baer



- ***Dump trigger for B2 first.***
- ***Perturbation of B1 trajectory*** *downstream of IR5 due to* ***missing (horizontal) long-range beam-beam deflections*** *in IP5.*



Measurement is a convolution of all bunches!

- Dedicated MadX simulation have **well agreement for phase of oscillation**, but simulated oscillation amplitudes are **25% - 40% smaller** than measured. **Need further studies!**
- Scaling of the effect to **HL-LHC** era shows **that effect may increase up to ≈0.8σ** (preliminary).

Relevant for LHC and HL-LHC

Head-on effects

- noise on head-on collision and emittance growth
- Head-on effects for HL-LHC: Crab cavities from KEKB
- Diffusion in stable beam dominated by collision Tevatron versus LHC
- LHC achievements over 2011-2012 tests

Long-range effects

- Strategy and observations in the LHC: Do we understand them?
- Tevatron experience with Long-range: where we could improve?
- LHC achievements over 2011-2012 tests

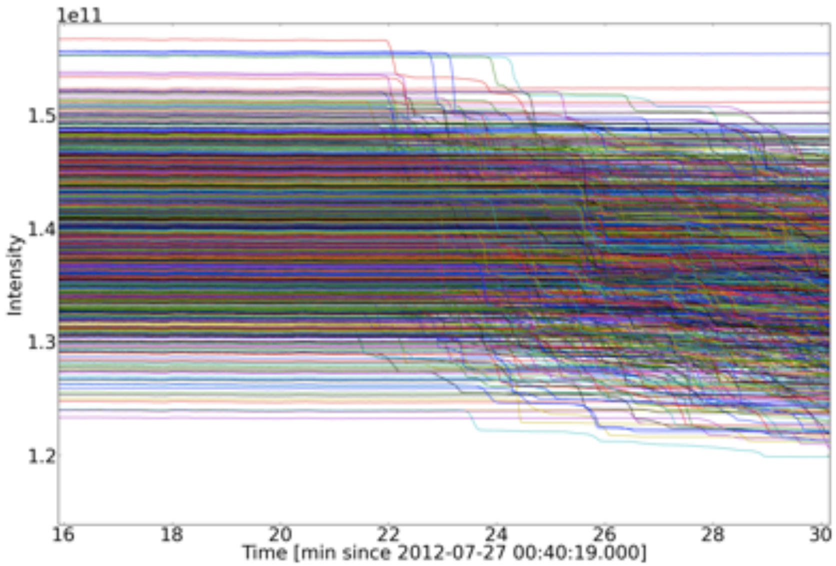
LHC specifics: Instabilities, leveling and VdM scans

- **2012 Instabilities**
- **New models: interplay of effects (BB+impedance+…)**
- **Operational aspects**
- **Leveling luminosity**
- **VdM scans**

Compensation ideas

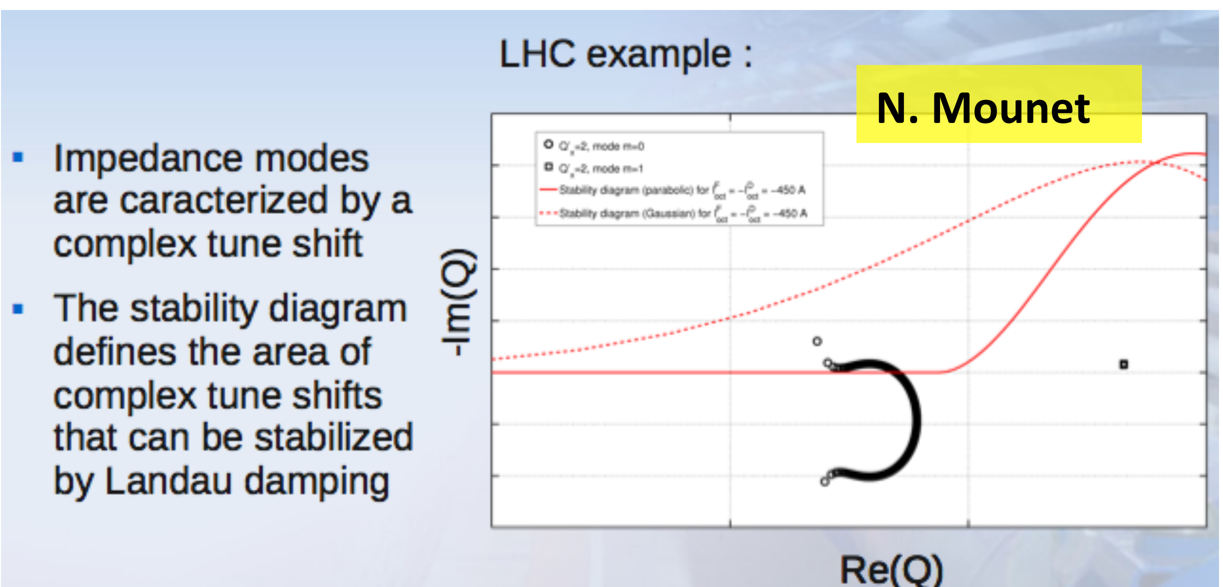
- Head-on compensation: electron lens
- Long-range compensation: wires

LHC specifics: Instabilities during 2012 run



2012 Instabilities have perturbed collider performances, they are not yet understood!

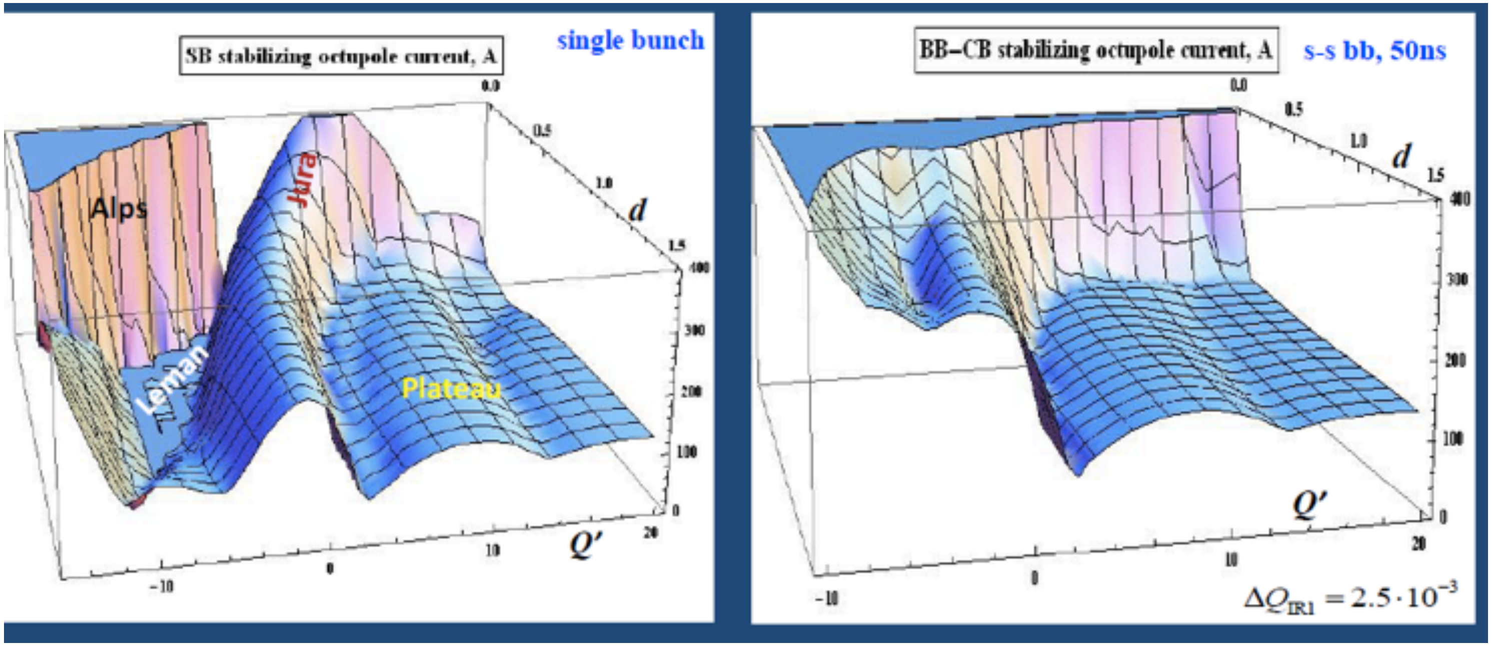
- How does the **transverse damper** acts in the picture?
- What is the role of **chromaticity**?
- Can we explain the instabilities as a modification of stability diagrams due to **beam-beam**?
- What is the effect of **noise** on stability?
- **Beam-beam and impedance interplay**?



Stability diagrams
and
Multi-particle tracking

Beam-beam, impedance, damper

A. Burov



→ NHT model predicts very little differences for the cases with and without beam-beam In the presence of high damper gain and chromaticity

- A model of three-beam instability was suggested: 2 LHC beams plus e-cloud in the high-beta area of IR1 and IR5.

Interplay of effects changes stability (Impedance, ADT, BB coherent, …).

By increasing complexity in models we get new picture.

Models have developed very fast in 2012!

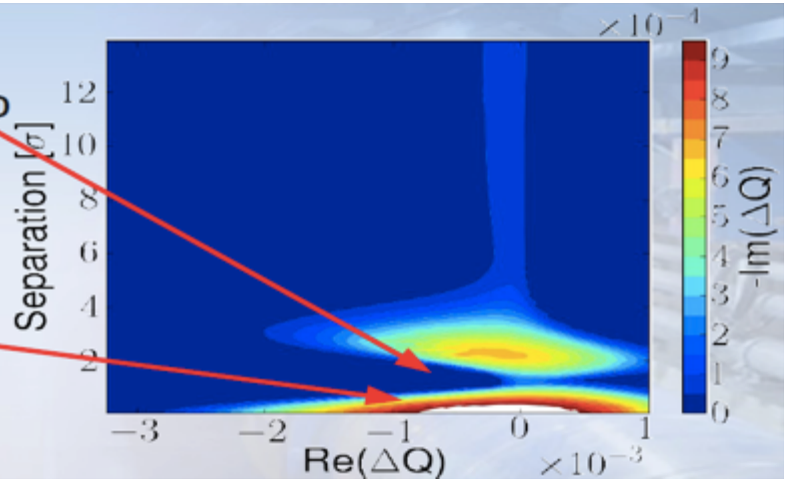
Bench-mark to data should be a priority!

We need dedicated time also in commissioning stage to verify!

Stability diagrams of colliding beams

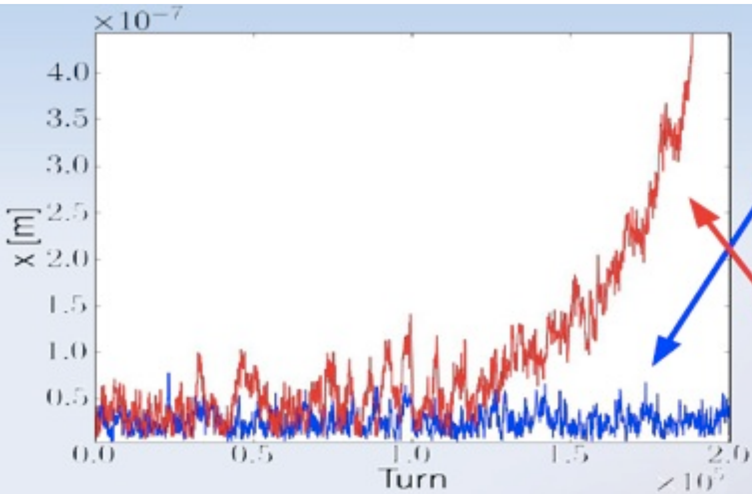
X. Buffat

- Reduction of the stability diagram, possibly leading to loss of Landau damping for impedance driven mode
- Very large stability diagram once colliding head-on



Stability has to be ensured at any moment during a fill.

Modeling as to go on-line with the machine to avoid unforeseen moments



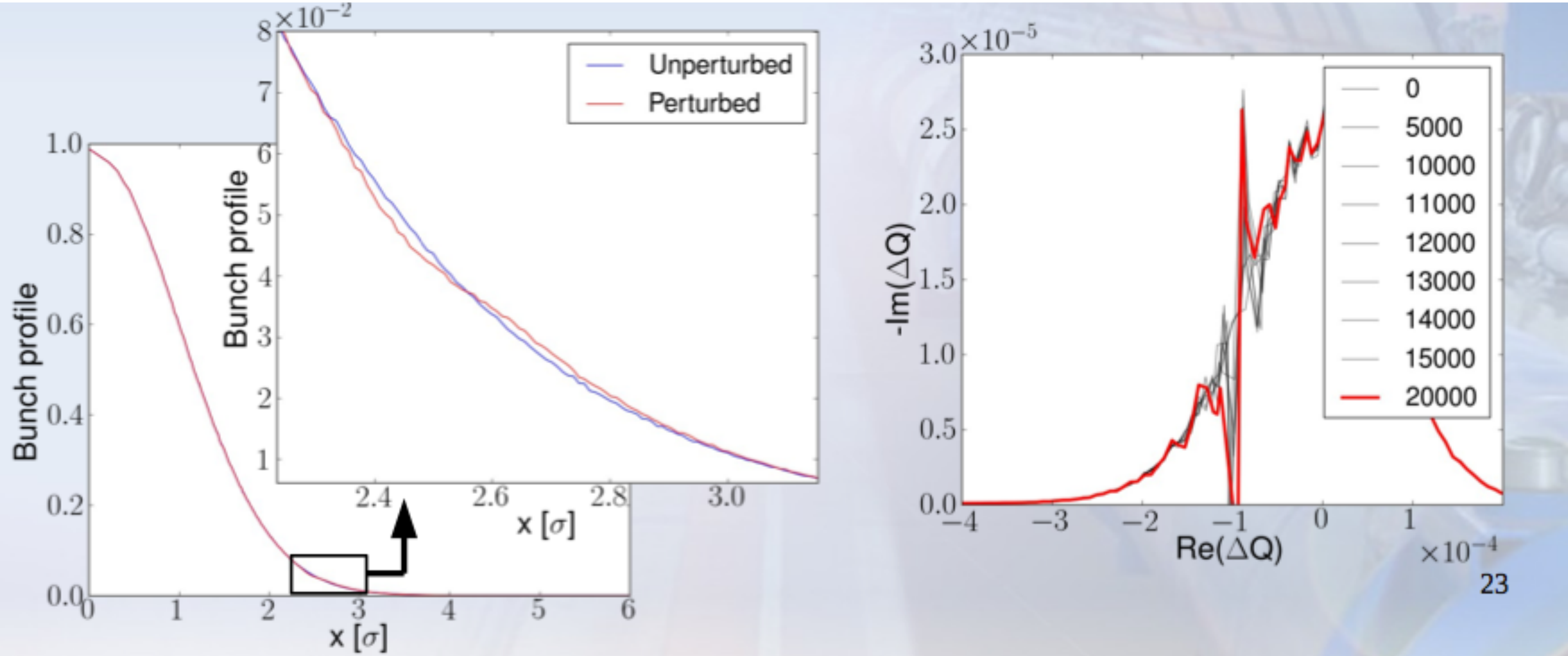
Stable with transverse damper and octupole

Rendered unstable by wide band noise of amplitude $10^{-4}\sigma_{px}$

Noise can make unstable a stable configuration….more studies needed!

Modeling and simulations should follow operation. Stability changes during fill…
How can we make BB tools flexible, fast and reliable?

Stability diagrams of colliding beams with noise



Stability rely on tail particles (octupoles, LR, ….) not the case for Head-on (core..)

Can tails be deteriorated? How can deterioration in tails affects stability?

Detailed studies needed !

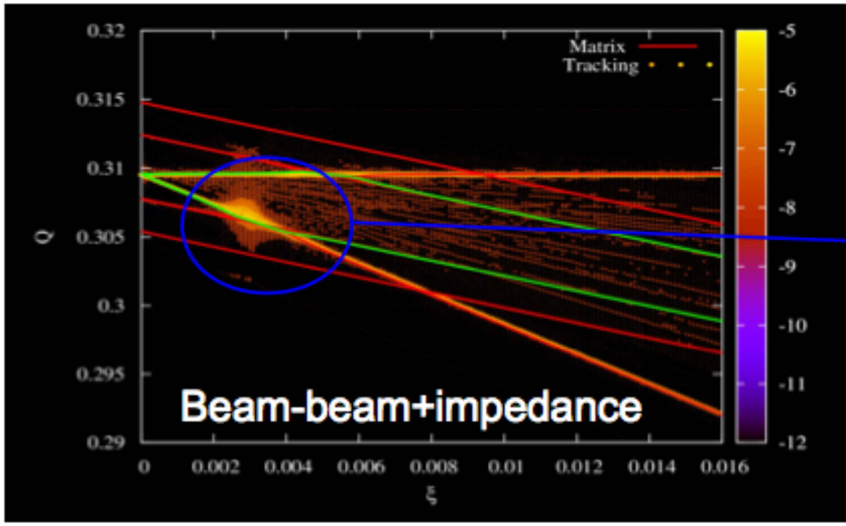
How can we make sure we have the stability we calculate? Halo monitor!

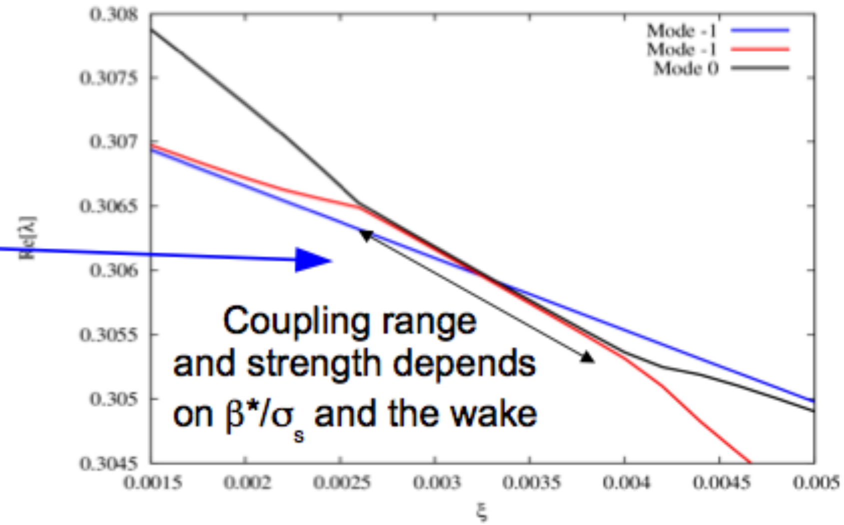
X. Buffat

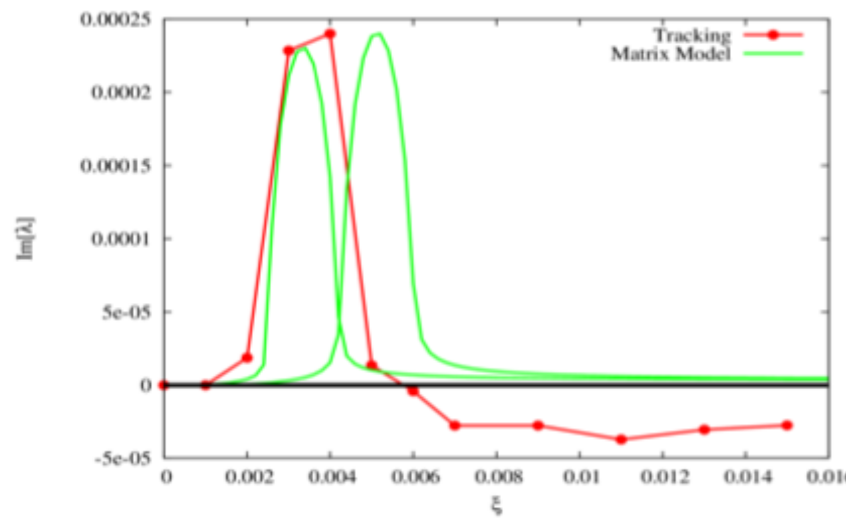
BROOKHAVEN NATIONAL LABORATORY

Impedance and beam-beam

LARP







→ Scan the head-on beam-beam parameters at Q'=0.0 and constant wake

→ The beam-beam interaction shifts the π-mode down faster: coupling between modes 0 and -1 could occur at lower intensity

→ Although the analytical model predicts also coupling between σ-mode and mode +1 it is not observed in tracking simulations

S. White

Needs studies and benchmark to data!

I wish....I wish....single Bunch diagnostics

- **Diamond detector (BLM)** nanosecond time-resolution and can very well distinguish different bunches.
- **Emittance measurement bunch by bunch at high energy (BSRT calibrated)**
- **ADT >> 72 turns Bunch by bunch measure**
- **Trigger on demand to analyse the instability**
- **Automatic measurement to be adapted to new instabilities situation**
- **Schottky measurement**
- **Beam Transfer Function**
- **Crystal detector measurement of "tails" at larger amplitude (non destructive)**
- **Head tail monitor : not yet operational, need to acquire both plane both beam at the same time, efficient triggering and adequate gain needed.**

R. Giachino

Leveling luminosity:

R. Jacobsson,T. Pieloni, B. Muratori

Possible LHC machine parameters after LS1

	Number of bunches	Nb	Emit LHC (SPS) [um]
25 ns	2760	1.15e11	3.75 (2.8)
25 ns low emit (48 bunches/PS batch)	2320	1.15e11	1.9 (1.4)
50 ns	1380	1.6e11	2.3 (1.7)
50 ns low emit (24 bunches/PS batch)	1260	1.6e11	1.6 (1.2)

Experiments desiderata:
Need to level to reduce pile-up

L= 1e34 cm-2s-1@14TeV
μ = 27 @ 25 ns
μ = 54 @ 50 ns

In all scenarios but NOMINAL we need leveling of luminosity for all experiments ALICE, ATLAS, CMS, LHCb …

Leveling Luminosity: Exp desiderata

R.Jacobsson

Conclusions 1

All:

- 25ns is a must
  - No optimization at 50ns in 2015, take the time to make 25ns work instead
  - We'll all be commissioning the new trigger in 2015 for 25ns operation
- Longitudinal luminous region should be long and stable

Atlas + CMS +TOTEM:

- A priori, levelling is not expected to be needed for Run2 (Run3)
  - Assumes 25ns operation
  - → Vital for physics

→ Preparations for levelling should be made for Run2 already
  - Problems with 25ns
  - Trigger preparation insufficient (alternative is reoptimization with unavoidable efficiency loss in some channel(s))
  - LHC going beyond 2E34 (e.g. improved emittance control, miracles in bunch inte
  - The unexpected!
  - Levelling is also needed for HL-LHC – operational experience
- Wish for a handful of non-colliding bunches

LHCb:

- Luminosity control required in all cases
  - → Physics optimization
- Tilting and polarity swaps as now

Alice:

- Take pp data during good fraction of the year with levelling (separation OK)

A Beam-Beam Workshop, 18 – 22 March 2013 R. Ja

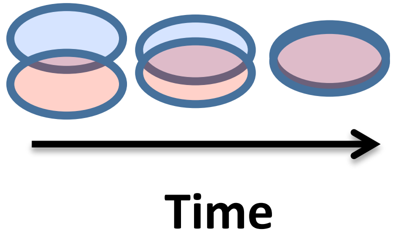
Luminous region long and stable

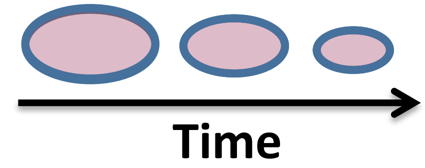
25 ns beams default option RUN2 ok
but if e-cloud problems persist …

	# bunches	N_{bunch} $[10^{11}]$	ε_{coll}[μm]
25 ns BCMS (48 bunches/PS batch)	2520	1.15	1.9
50 ns BCMS (24 bunches/PS batch)	1260	1.6	1.6

Need to level already for LHC RUN2
Preparation has to start now!
Non-colliding bunches?!
Need special considerations

Leveling Techniques



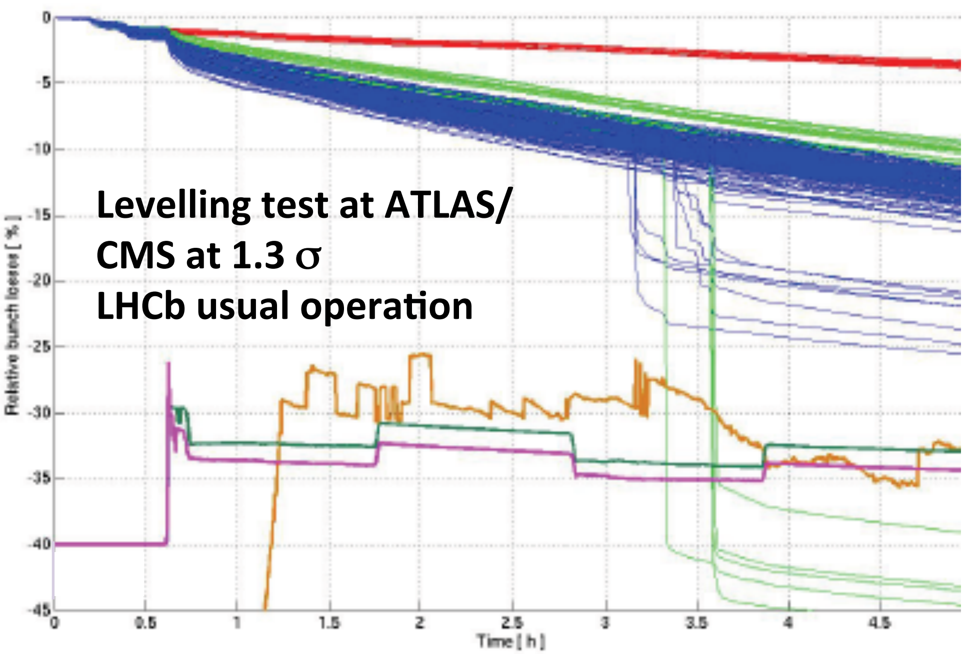


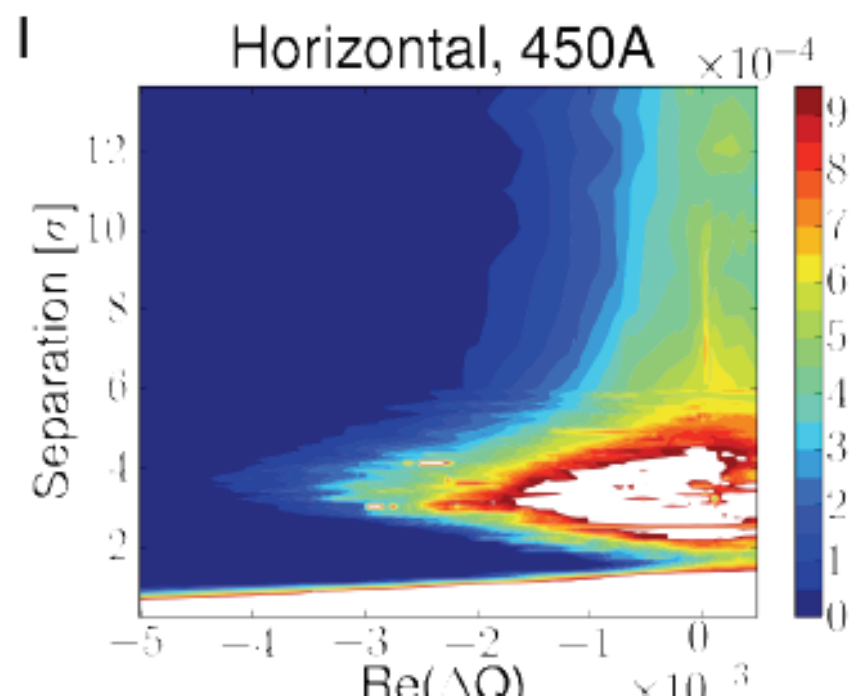
Leveling with transverse offset:

Good if another collision is ensured (25 ns symmetric filling scheme!)

Leveling with β^* : collide&squeeze

Pushed for stability issues 2012





Leveling with crab-cavities or Piwinski angle: changes luminous region, not good!

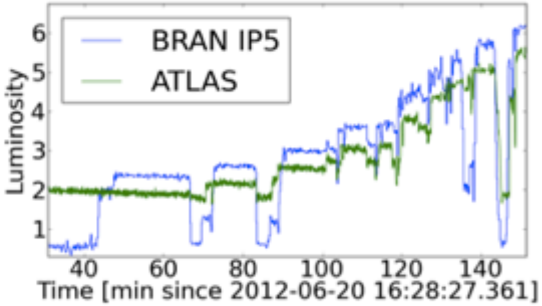
Leveling by longitudinal cogging: all experiments dependent, not good!

T. Pieloni, B. Muratori

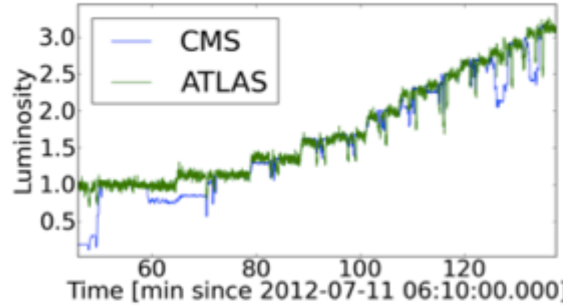
β* leveling MDs: collide&squeeze ok, leveling ….

CERN-ATS-Note-2012-071 MD and CERN-ATS-Note-2013-002

X. Buffat, W. Herr, M. Lamont, T. Pieloni, S. Redaelli J. Wenninger, L. Ponce



(a) Fill 2748

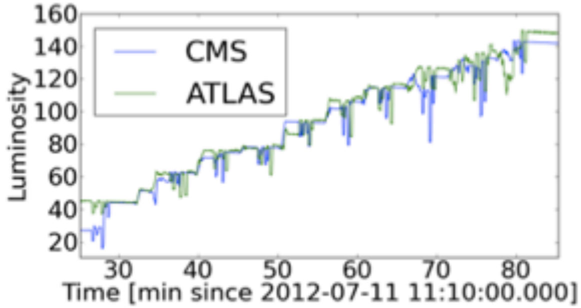


(b) Fill 2828

T. Pieloni, B. Muratori

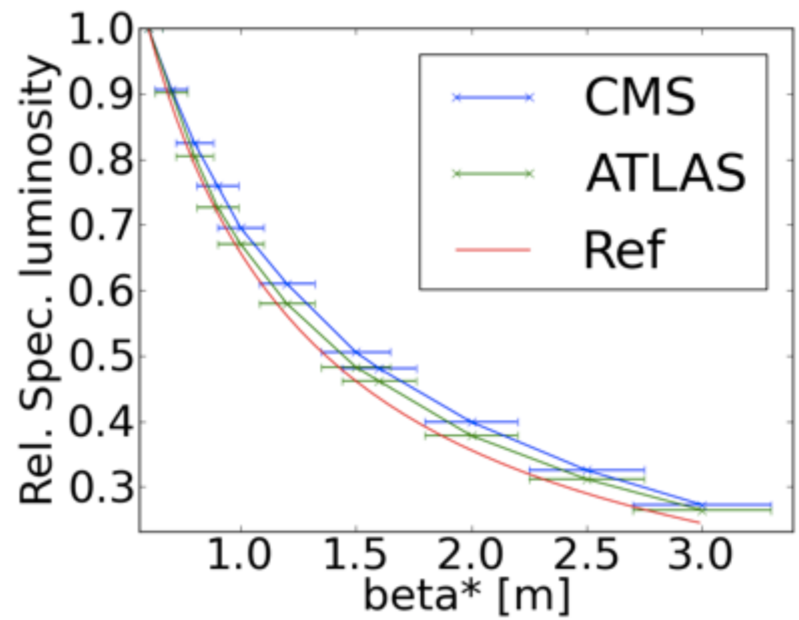
β* 3 m → 0.6 m

β* 9 m → 0.6 m



(c) Fill 2829

Prove of principle during MD experiments at the LHC to use it for leveling

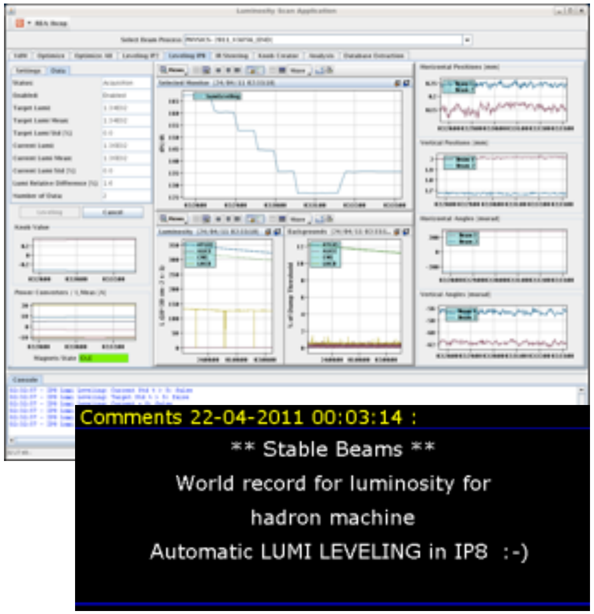


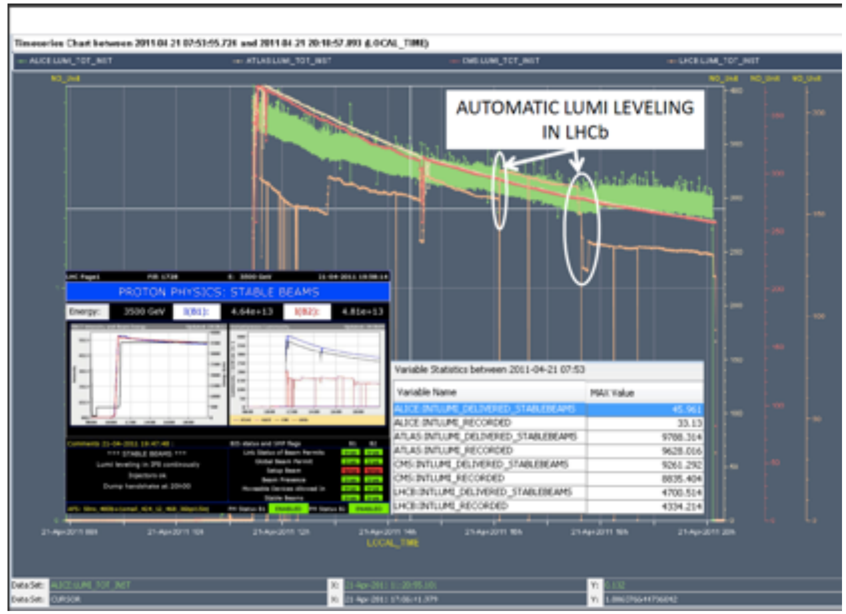
A working group will be settled to define possible leveling scenarios

OP experience

D. Jacquet

21-04-2011: First automatic luminosity leveling in LHCb



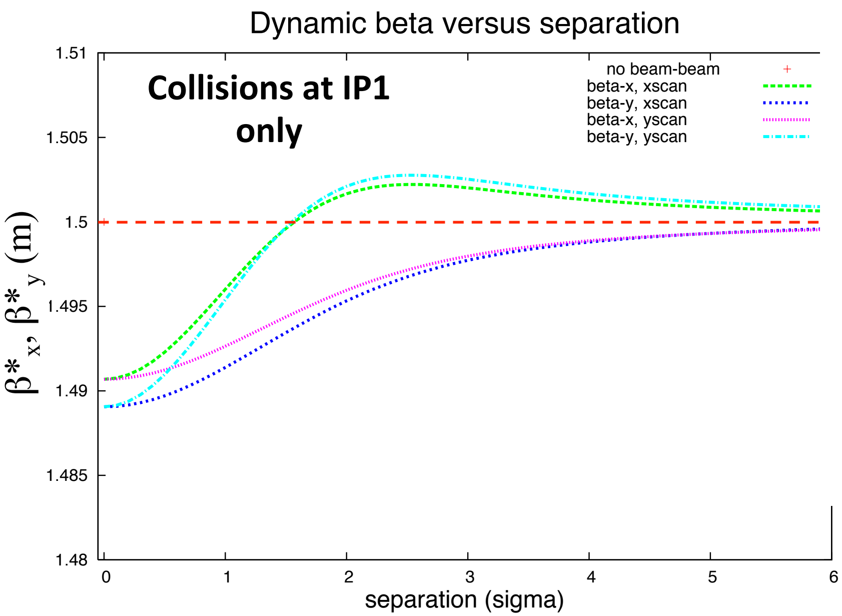


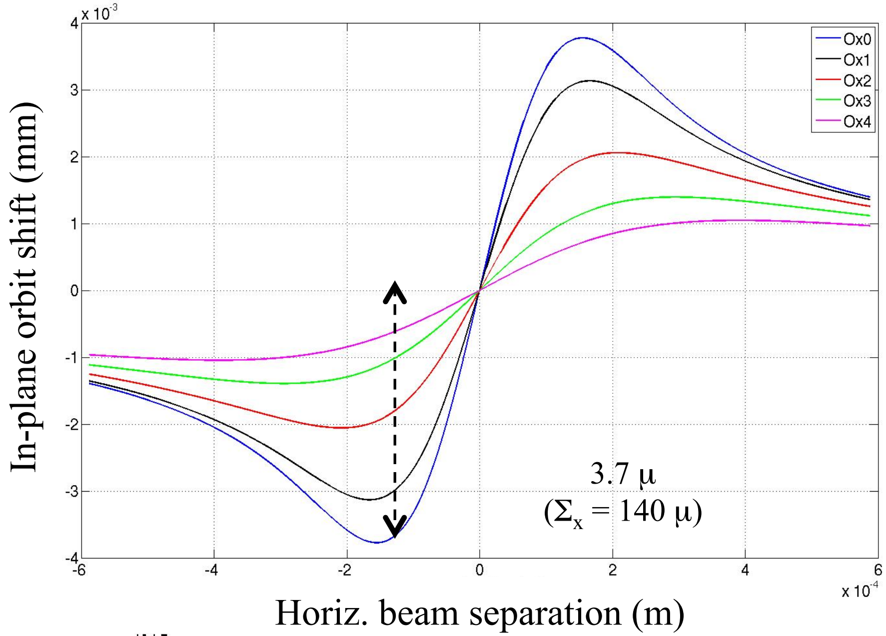
- Luminosity levelling part of the routine LHC operation for LHCb and Alice
- Luminosity levelling allows to maximize the integrated luminosity while keeping low luminosity peak and low pile-up
- After LS1 : levelling may be needed in all experiments: β* levelling and beam offset levelling will probably be used in some combination.

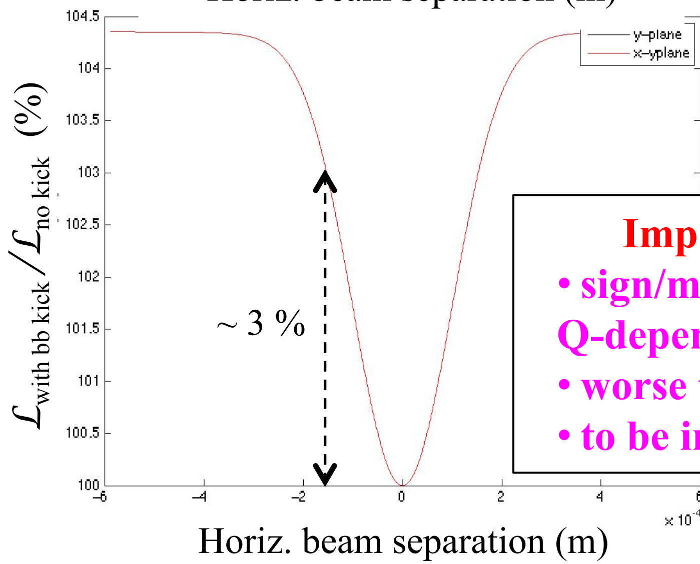
➡ VERY CHALLENGING FOR OPERATION

Van der Meer scans for Lumi calibration

Dynamic beta







Impact on Σ ?
- **sign/magnitude Q-dependent**
- **worse than dyn. β ?**
- **to be investigated!**

- For a given plane (β^* x or y) and scan direction (x or y)
  - Dependence on separation always the same
  - Starting value different, depends on ξ and on collision pattern

W. Kozanecki

Orbit Deflection

Relevant for LHC and HL-LHC

Head-on effects

- noise on head-on collision and emittance growth
- Head-on effects for HL-LHC: Crab cavities from KEKB
- Diffusion in stable beam dominated by collision Tevatron versus LHC
- LHC achievements over 2011-2012 tests

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- Tevatron experience with Long-range: where we could improve?
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LHC specifics: Instabilities, leveling and VdM scans

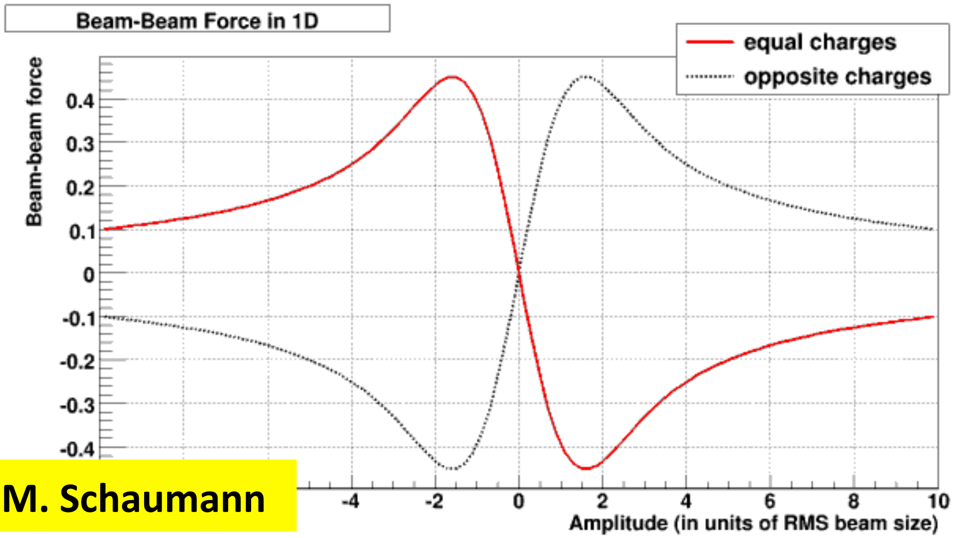
- 2012 Instabilities
- New models: interplay of effects (BB+impedance+…)
- Operational aspects
- Leveling luminosity
- VdM scans

Compensation ideas

- **Head-on compensation: electron lens**
- **Long-range compensation: wires**

RHIC electron lenses: motivation

W. Fischer

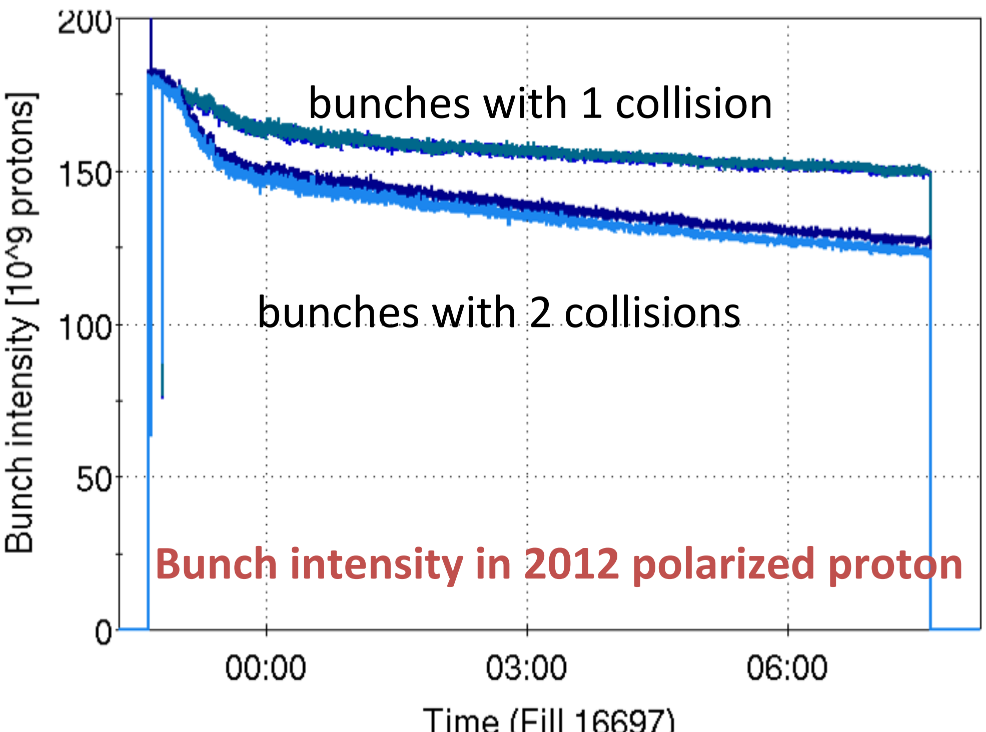


M. Schaumann

Principle:

electron force

proton force



Bunch intensity in 2012 polarized proton

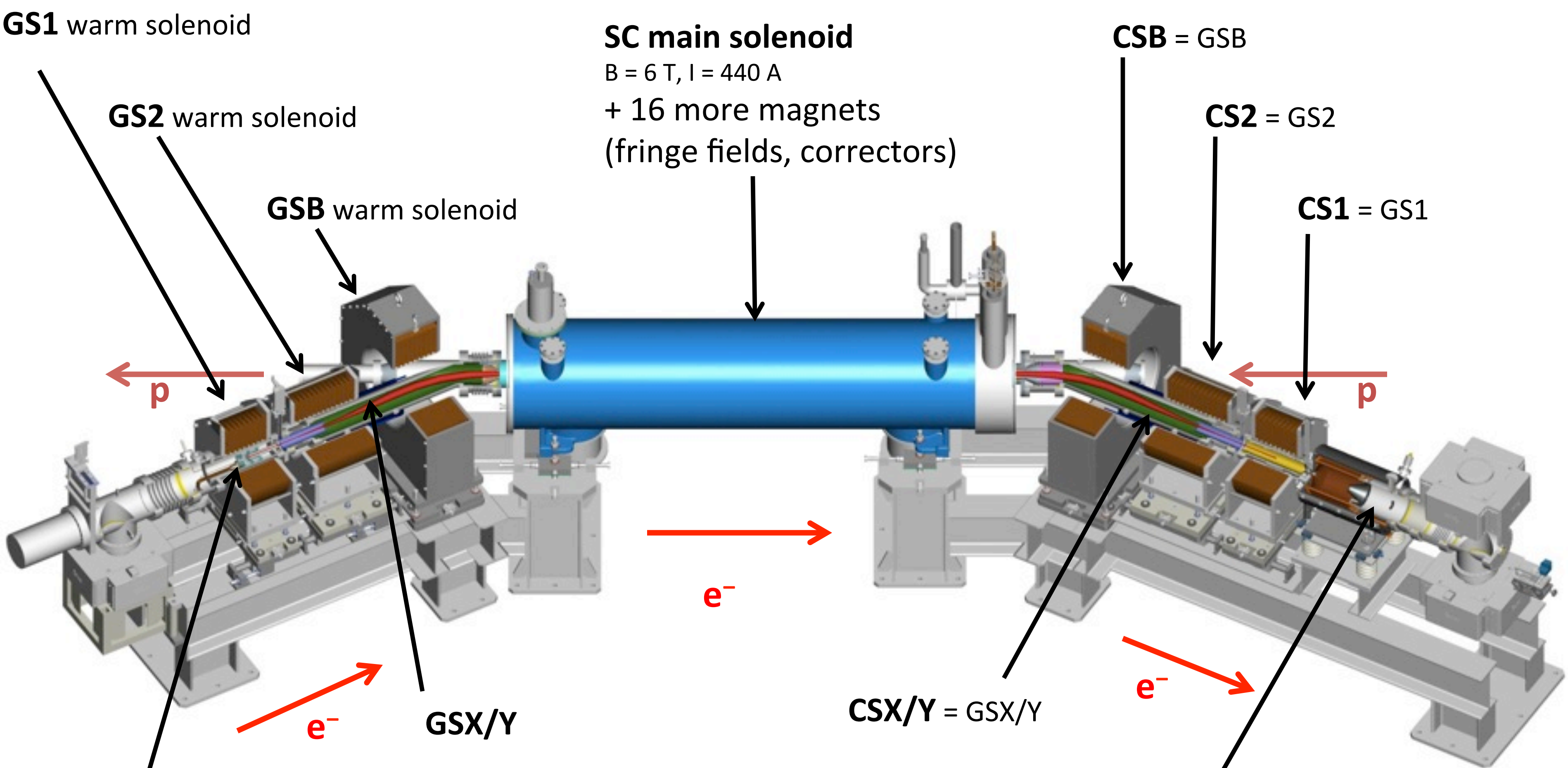
RHIC Goal:

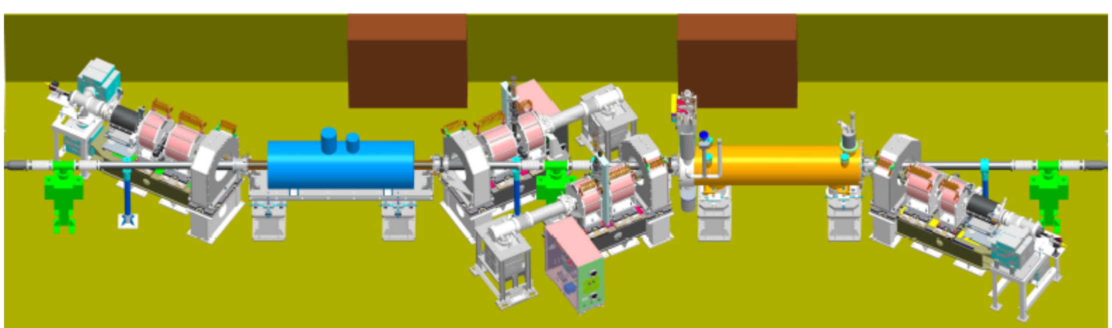
Compensate for 1 of 2 beam-beam interactions with electron lenses

Then increase bunch intensity
⇒ up to 2× luminosity

$$L \propto N_b^2$$

RHIC electron lenses: Compensation overview





W. Fischer

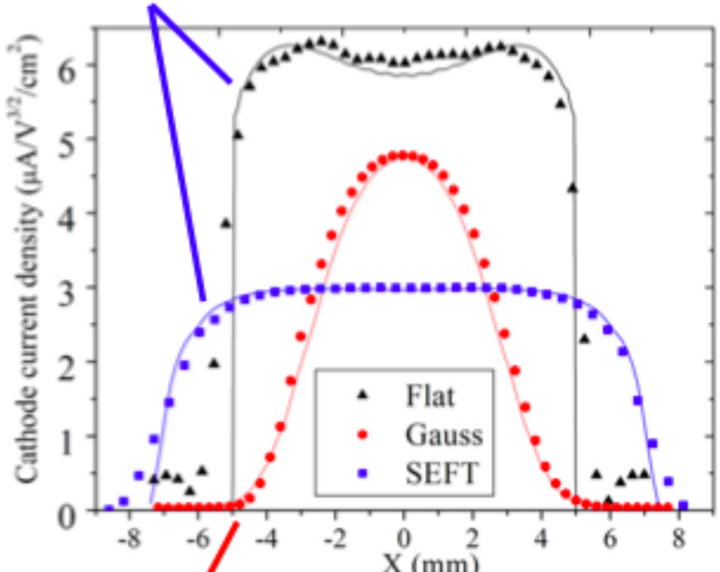
E-lens technology (Tevatron): available!

Profile control of the electron beam

- Current density profile shaped by electrode geometry/potentials
- Maintained during transport by strong solenoidal fields
- Different electron guns for different purposes

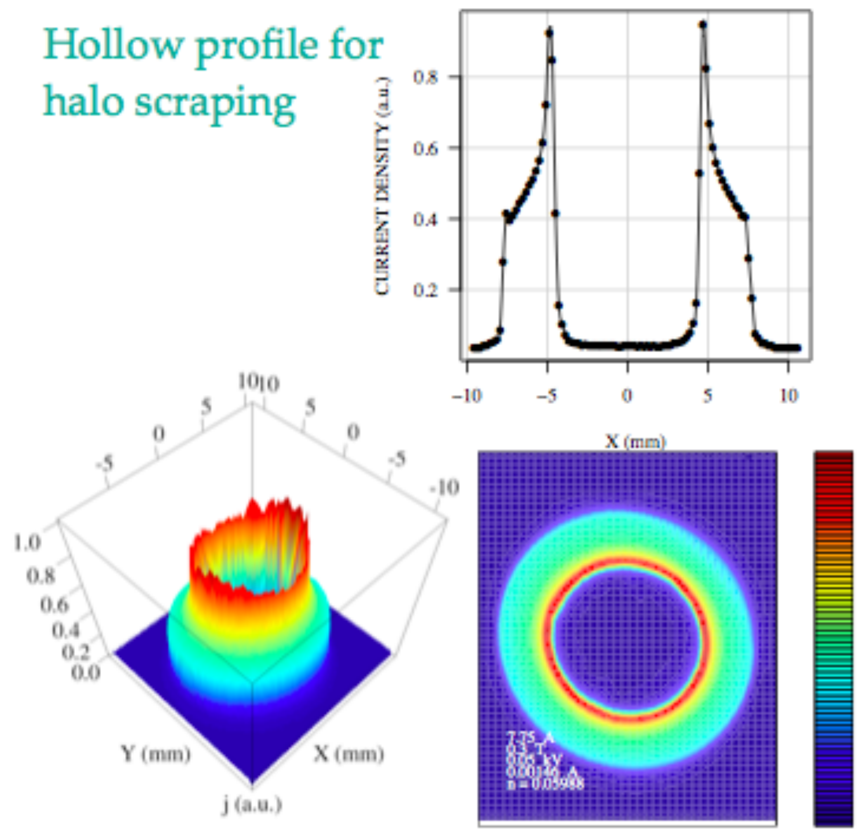
G. Stancari

Flat profiles for bunch-by-bunch betatron tune correction



Gaussian profile for compensation of nonlinear beam-beam forces

Hollow profile for halo scraping



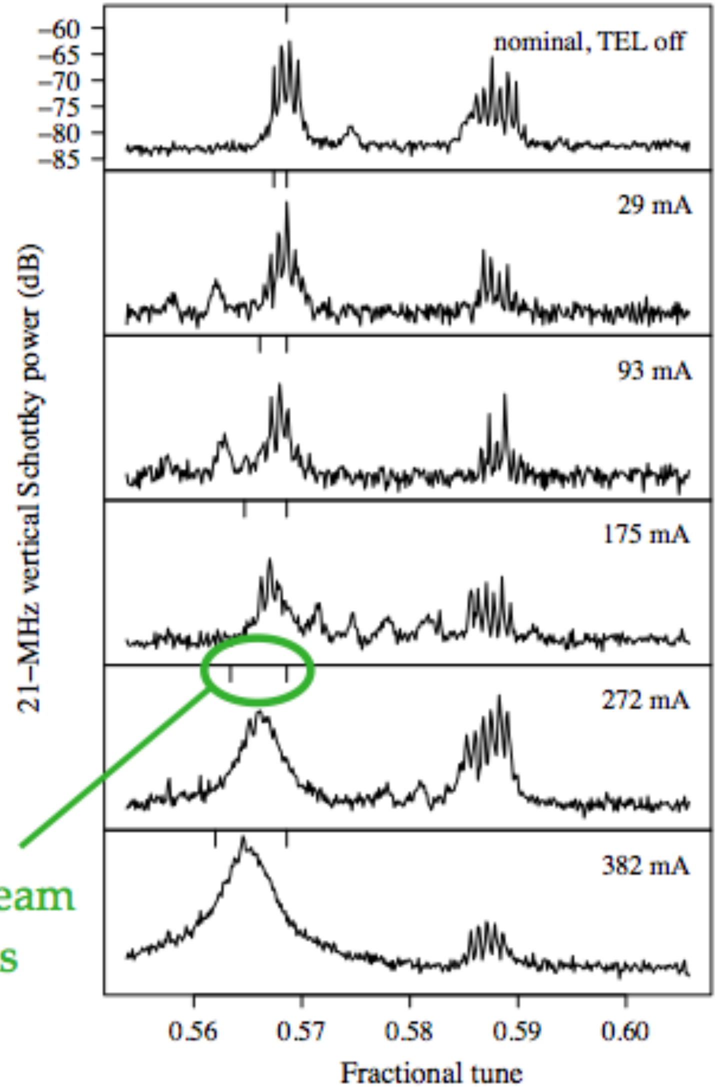
E-lens spread: proved!

G. Stancari

Incoherent tune spectrum vs. electron beam current

Schottky spectra measured during dedicated ***antiproton-only store***

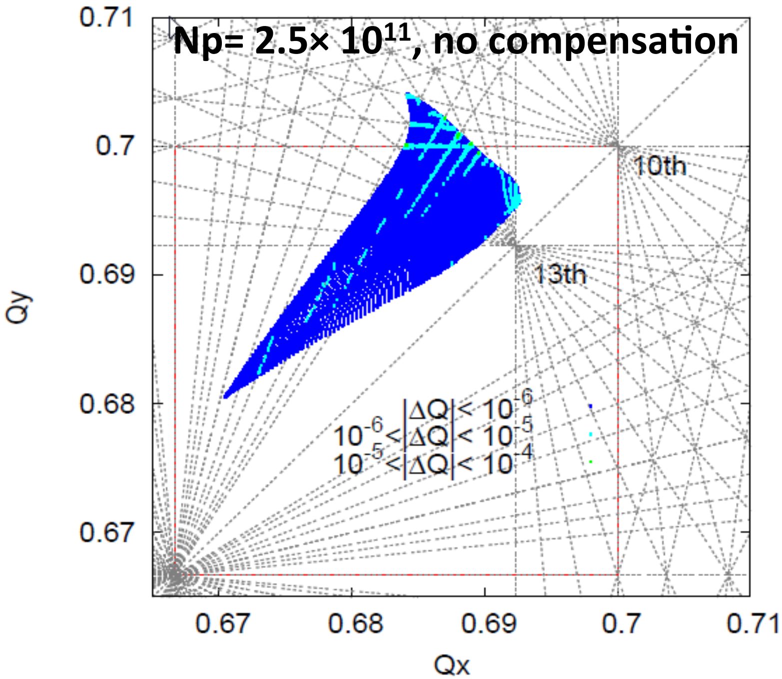
Observed effect of electron beam on antiproton tune spectrum

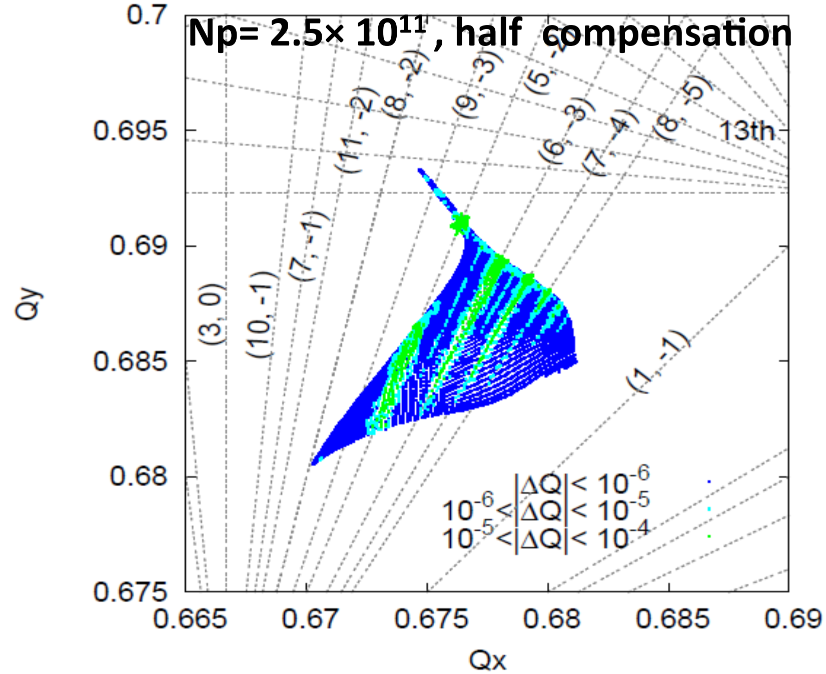


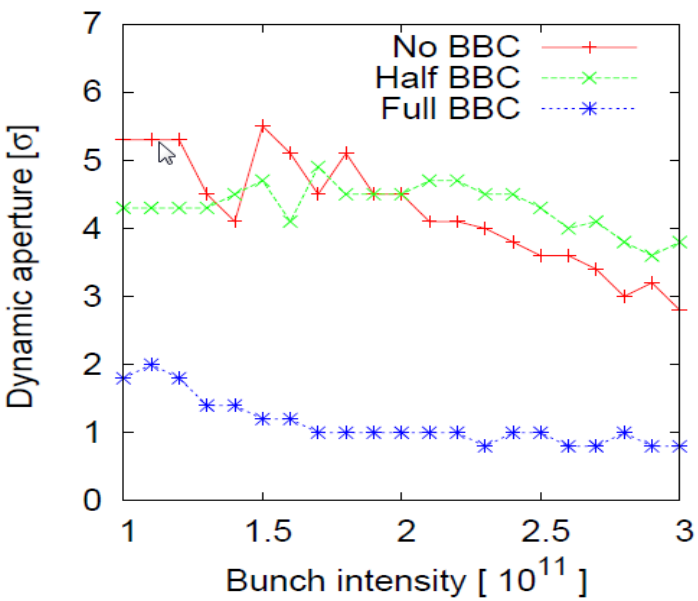
Calculated linear beam-beam **tune shift** due to electrons

Y. Luo

RHIC HO compensation strategy







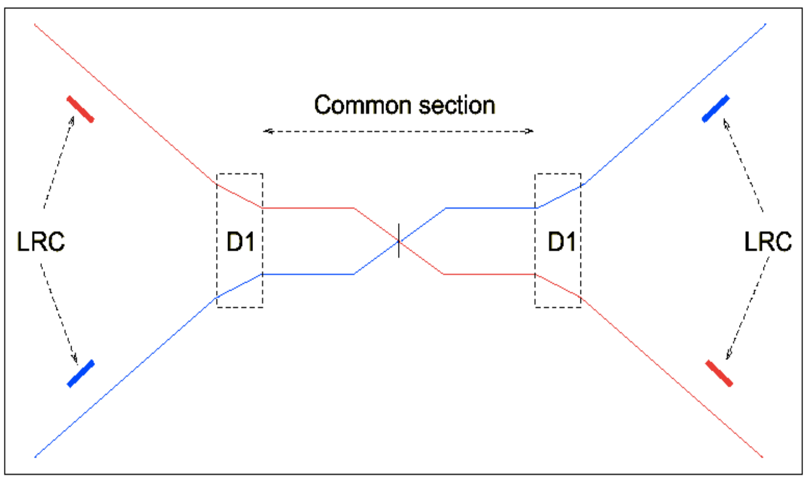
Calculated dynamic aperture and particle loss rate show that **half beam-beam compensation** improves proton beam's beam lifetime.

Phase advance adjustment between IP8 and e-lens, and second order chromaticity correction further increase the proton beam lifetime.

Proposed long-range beam-beam compensation for the LHC (2000)

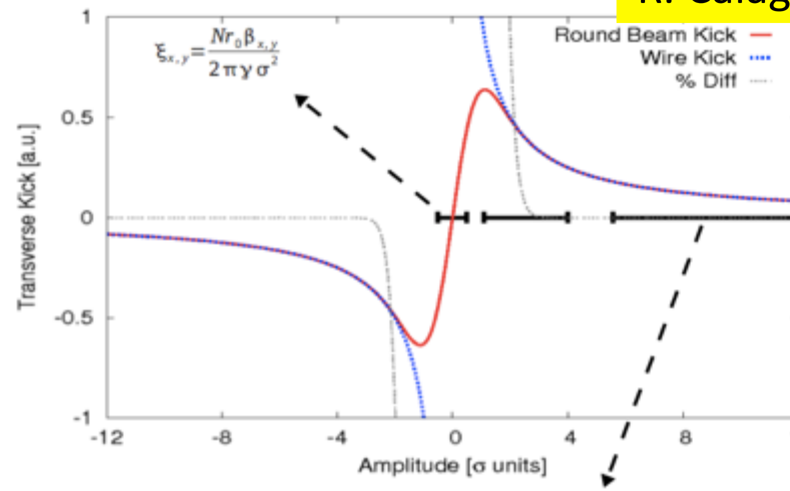
F. Zimmermann

- To correct **all** non-linear effects correction must be **<u>local</u>**.
- Layout: 41 m upstream of D2, both sides of IP1/IP5



(Jean-Pierre Koutchouk)

R. Calaga

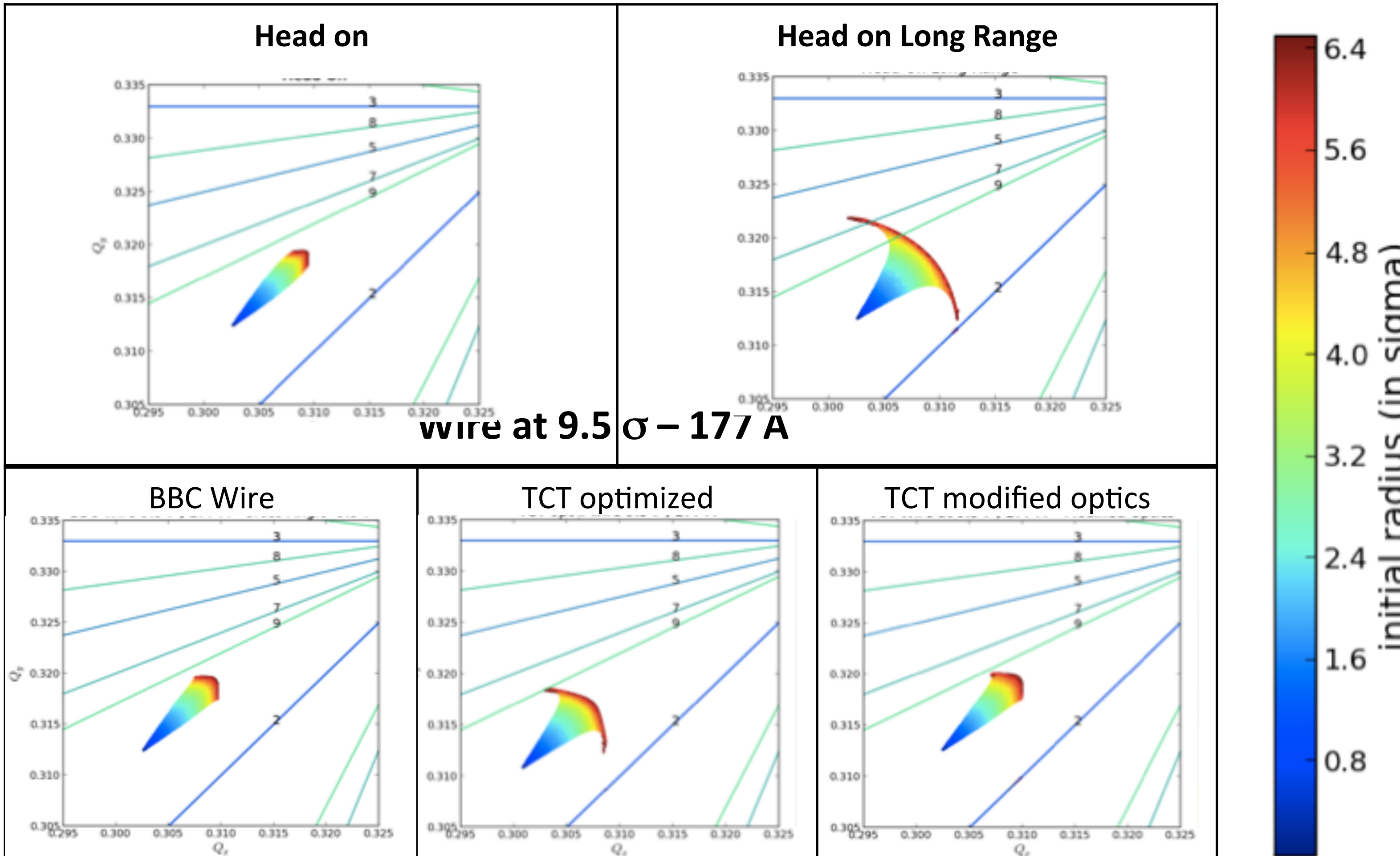


$\sigma << d$: $\Delta x'(x,d) = -\frac{K}{d}.(1+\frac{x}{d}+\frac{x^2}{d^2}+...)$

Planned for HL-LHC to reduce crossing angle!

T. Rijoff, U of Manchester/CERN

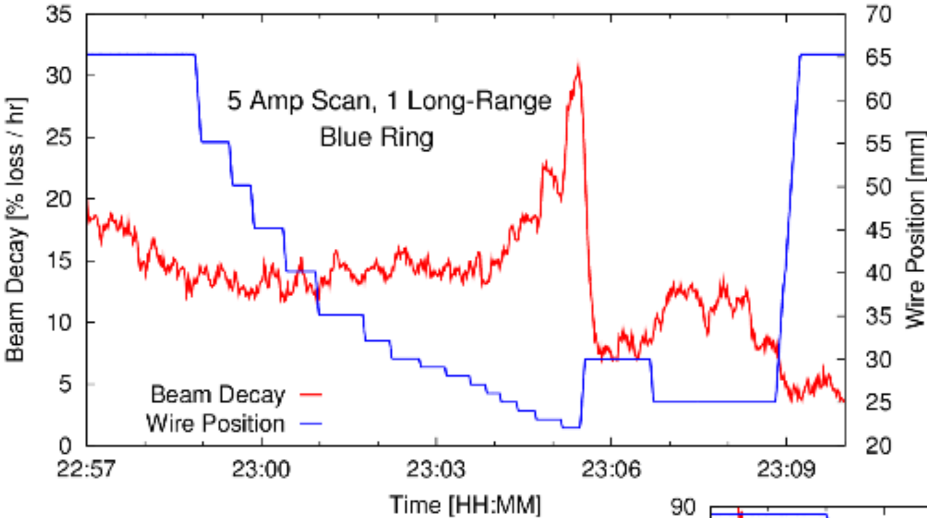
Best Tune results



✓ **Varying the crossing angle we see that wire compensator allows to reduce crossing angle of 1-2 σ maintaining the same stable region**

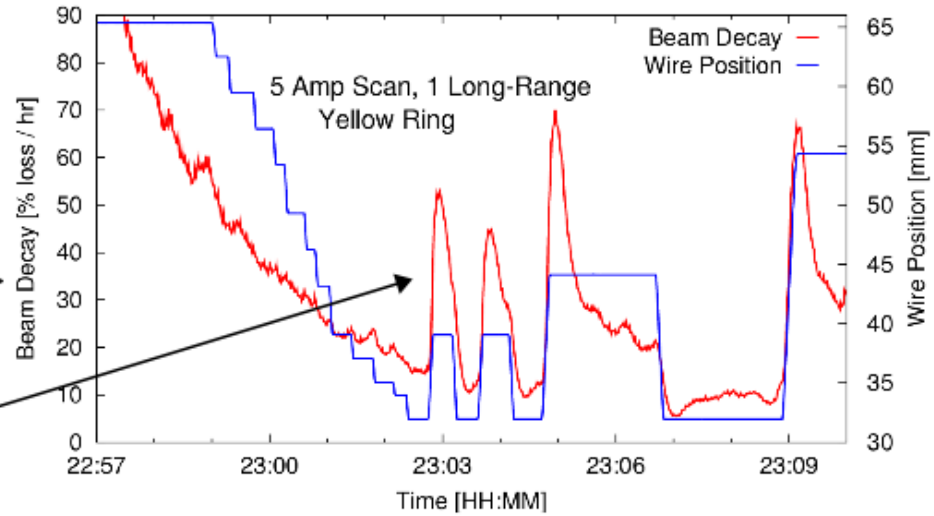
III: LR Compensation Exp, 5A

R. Calaga



Blue Ring

No visible effect



Yellow Ring

Losses increase when compensation is removed !!!

Several tests at RHIC good undertanding/studies:

- **difficult case 1 LR encounter (not so important effect)**
- **not conclusive results (two beams different behaviors)!**

2013 Jargons

A. Chao

"…the fun continues today except that it is now way more sophisticated…"

- pp, ep, pN, NN, eN
- Head on – Long range
- Beam-beam limit – tune shift – tune footprint
- dynamic beta – 1⁄2 integer tune – flip-flop
- Crossing – Piwinski angle – crab cavity – crab waist
- Weak-strong – strong-strong
- Landau damping, impedance-beam-beam interplay, damper
- e-cloud – beam-beam-beam interplay
- Simulations – Poisson solver
- Luminosity leveling – pile up
- Noise – halo – emittance diffusion – Tevatron modeling
- PACMAN – alternating crossing
- Dynamic aperture – smear – FMA
- Resonances – synchrobetatron – round/flat beam integrability
- Compensation – wire – e-lens
- beta squeeze, cogging, van der Meer scan
- Schottky – turn-by-turn – bunch-by-bunch – BTF

A. Chao comments

Each jargon invoked a new concept or new idea. All are relevant at LHC. All are under study!
Workshop was well-organized: fun, focused, and functional. Talks were informative.

A few broad brush impressions (personal):

- Compared with 1961, 1979, the progress has been amazing. Beam-beam studies are order of magnitude more sophisticated and yet the tools (analysis, simulation) can be trusted to a corresponding degree!

Experimental benchmark is required with proper diagnostics…

- As studies progress, much attention now drawn to various interplay effects: Impedance, beam- beam, damper, octupole, chromaticity.

Many ingredients….gain of experience should be part of the commissioning!

- Conceptually, beam-beam HO = beam-beam LR = e-lens = e cloud. Should all be treated using the same tool. **Development of proper tools is needed…**
- Landau damping raises its dominating head once again.” HO bunches are never unstable” (except ~ 1 sigma separation). **In case of instabilities Head On is the best cure!**
- Luminosity leveling is new challenge (somewhat unexpected). **Needs strategy!**
- e-lens highly promising, but has two patches of clouds over its head:

(i) It is a 4D device but HO beam-beam (for small beta*) is 6D. Compensation is incomplete.

Test in RHIC will help understanding

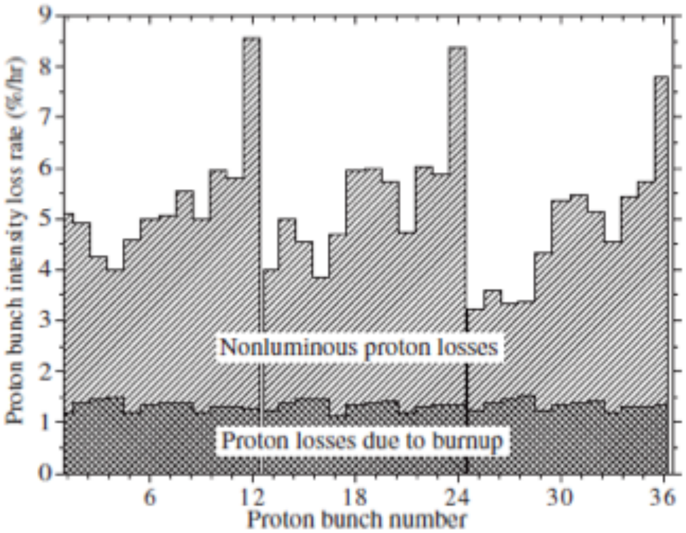
(ii) Loss of Landau damping when 100% implemented.

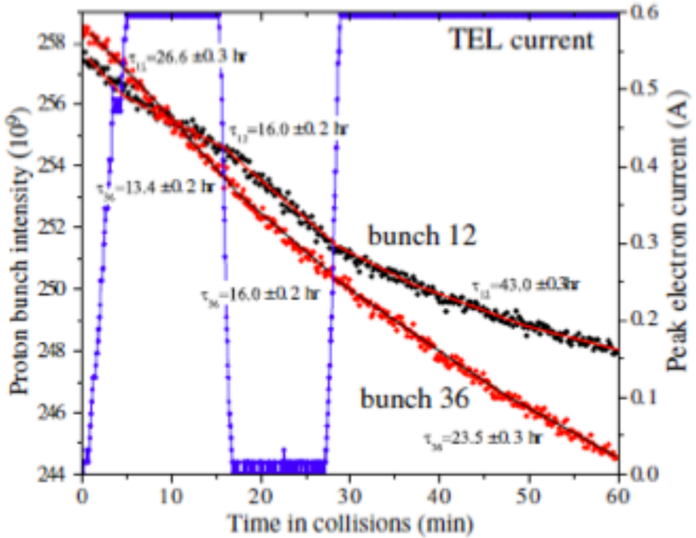
Thank you for your attention!

Tevatron electron lenses for long-range beam-beam compensation

G. Stancari

- 36 (3x12) proton bunches collide with 36 (3x12) antiproton bunches
- Because of collision pattern, beam-beam tune shift and losses depend on position in bunch train





Electron lens with flat profile improves lifetime of chosen bunch

Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)

V. Schiltsev

- Optimization of helical orbit separation and many operational tune-ups and upgrades have led to put the effects on luminosity under control by the mid/end of Run II
- Trustable LIFETRAC simulations helped us a lot, beam-beam compensation by TELs demonstrated

Diffusion model of loss rate evolution in collimator scans

Distribution function of tails evolves under diffusion with boundary condition at collimator

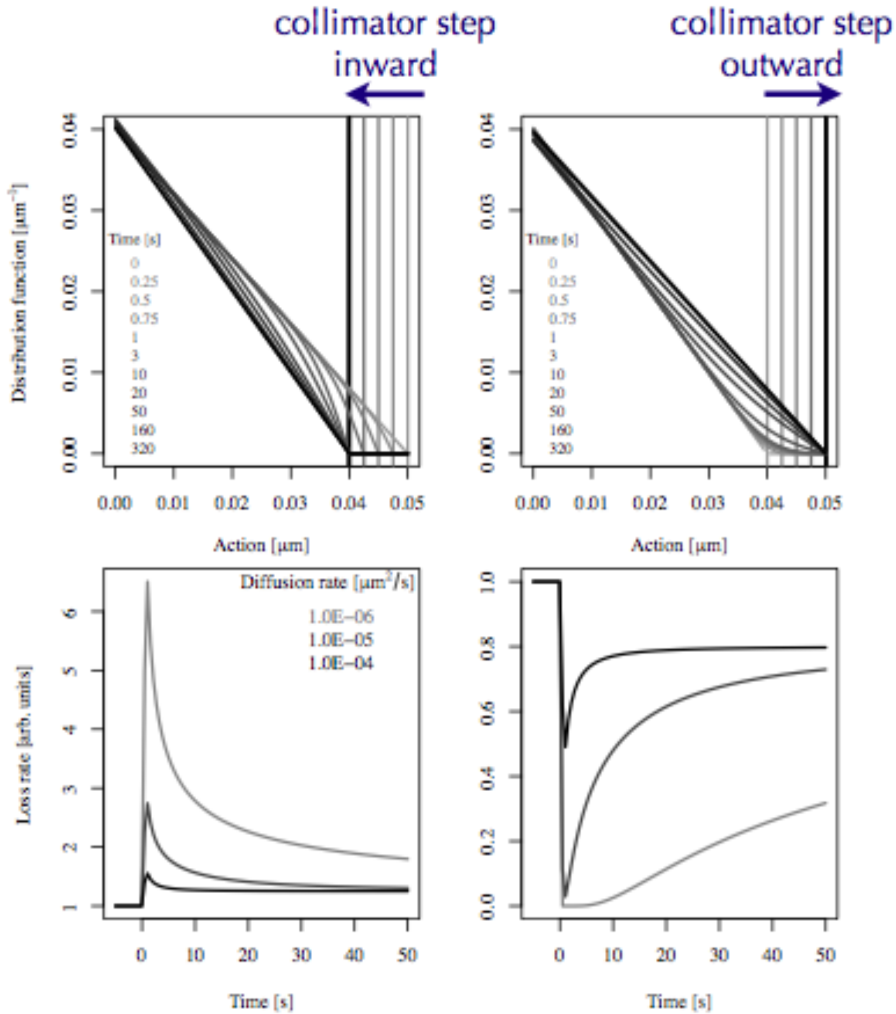
$$\partial_t f = \partial_J \left(D \cdot \partial_J f \right)$$

Instantaneous loss rate is proportional to slope of distribution function

$$R = -k \cdot D \cdot \left[\partial_J f \right]_{J=J_c} + B$$

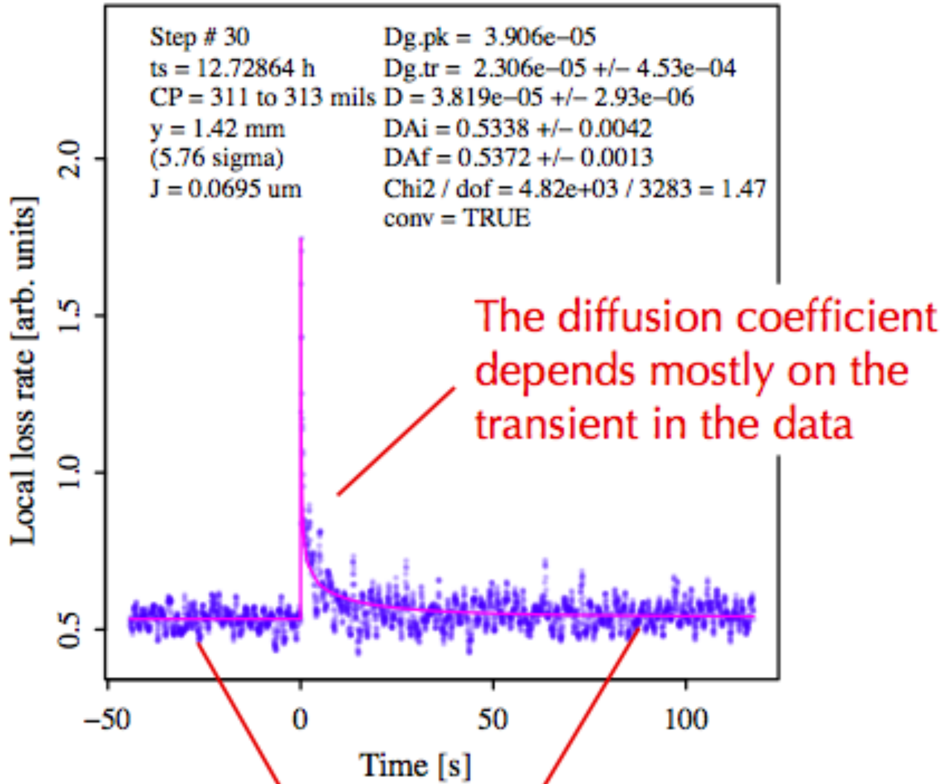
loss monitor calibration

background rate



G. Stancari

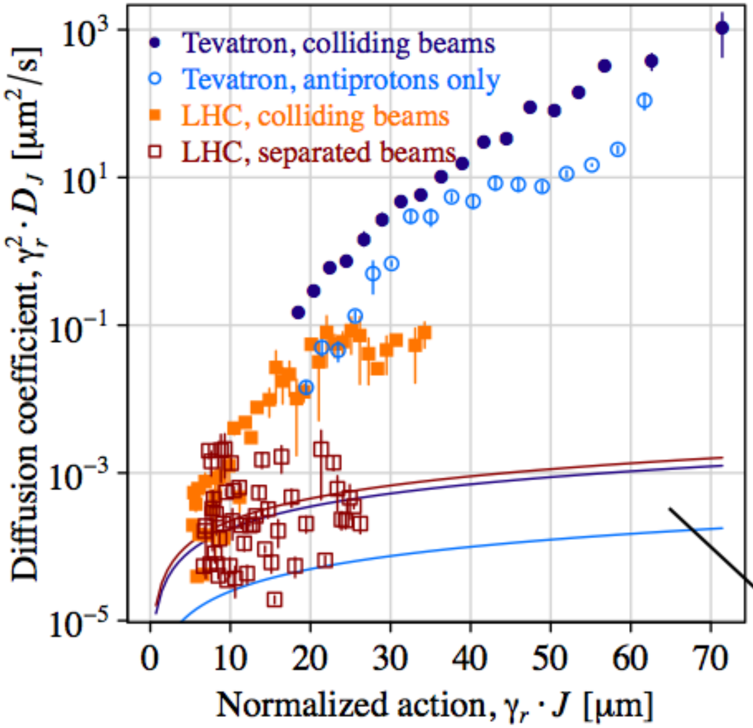
Diffusion model fit to loss rate data



Particle fluxes before and after the step are determined by the steady-state loss levels

G. Stancari

Beam halo diffusion rates in the Tevatron and in the LHC



Effect of beam-beam is 1-2 orders of magnitude

Halo diffusion in Tevatron dominated by effects other than beam-beam

Very low noise and nonlinearities in LHC

curves from measured core emittance growth

$$D_J = \dot{\varepsilon} \cdot J$$

- **First measurements of diffusion vs. amplitude** in Tevatron and LHC
- **Tevatron**
  - halo dynamics dominated by effects other than beam-beam
  - collisions enhance diffusion rate by 1 to 2 orders of magnitude
- **LHC**
  - with separated beams, halo diffusion very similar to core: nonlinearities and noise are small
  - in collision (only 1 bunch/beam), diffusion enhancement depends on amplitude, reaching 2 orders of magnitude

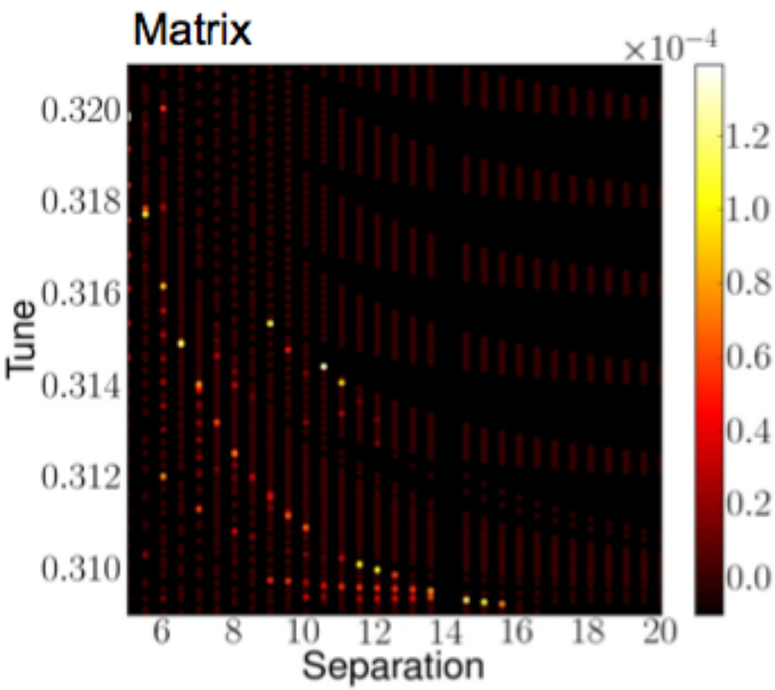
Thank you!

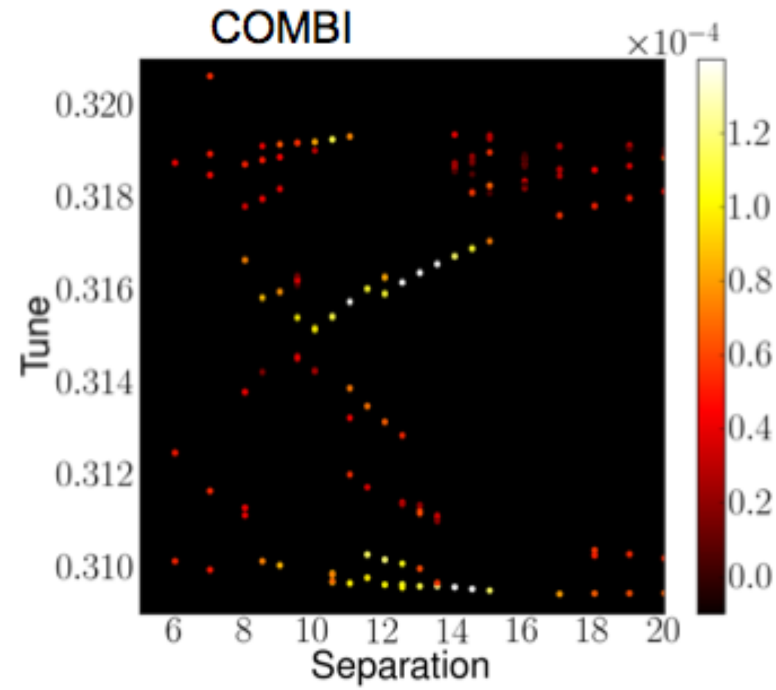
G. Stancari

BROOKHAVEN NATIONAL LABORATORY

Benchmarking

LARP





→ Comparison with the COMBI code for 36x36 bunches colliding in one IP:

→ Good agreement – instabilities in COMBI around 0.32 due to the other plane. Some discrepancies may be explained by the Yokoya factor (1 for linear model)

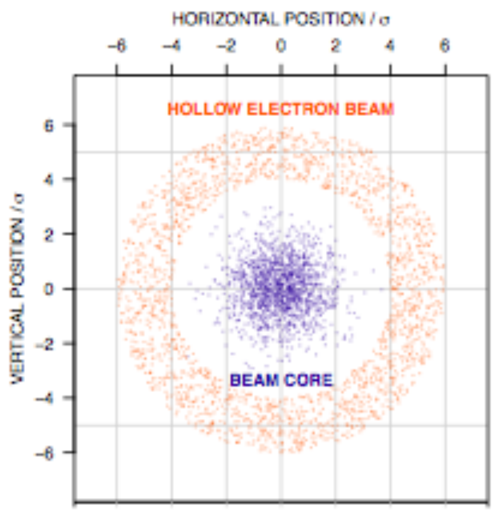
→ Done for Q_s~0.002 – using the nominal 0.002342 could move the instabilities towards lower separation – to be checked

S. White & X. Buffat

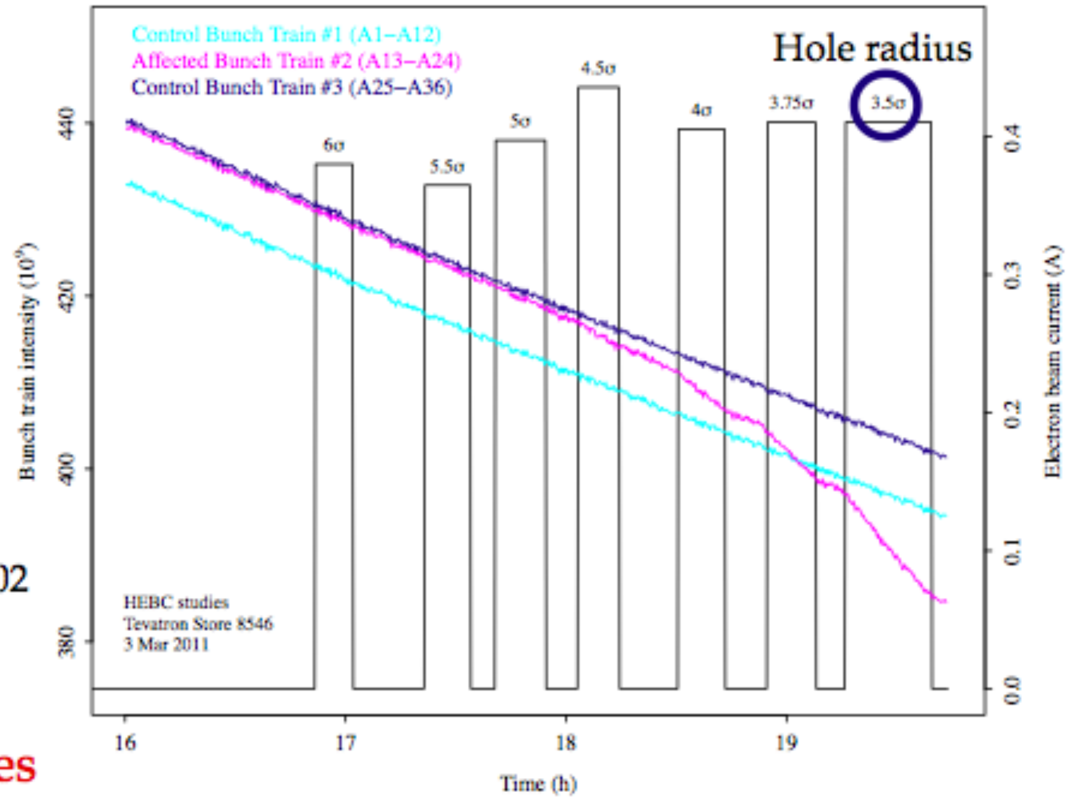
G. Stancari

Hollow E-lenses as a scraper.

Can we use a hollow electron beam to scrape the halo when beam power or impedance limit the use of conventional collimators?



Shiltsev, BEAM06, CERN-2007-002
Shiltsev et al., EPAC08

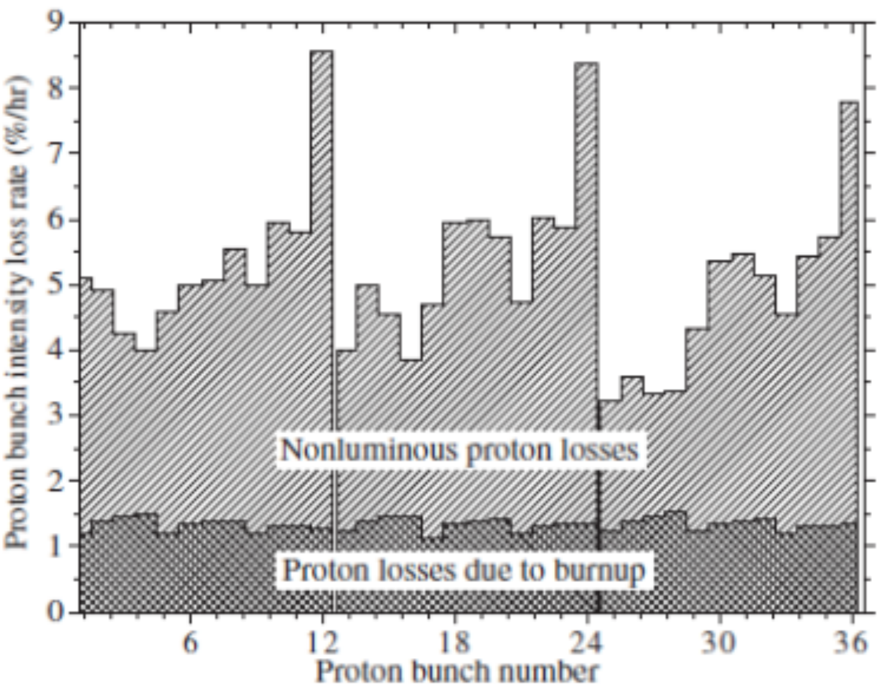


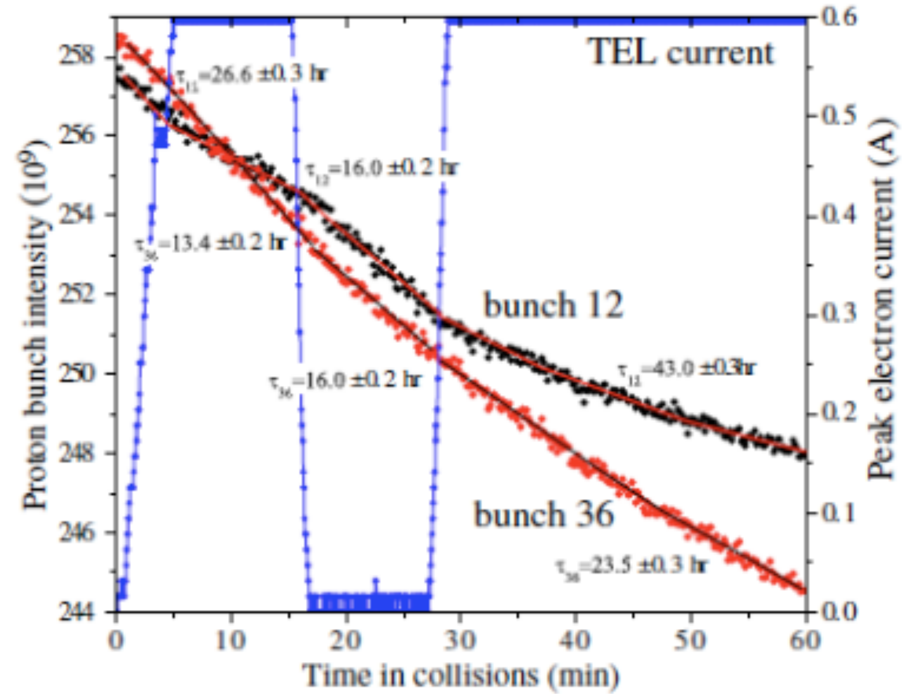
Yes! Extensive studies at the Tevatron:

Stancari, Valishev, et al., Phys. Rev. Lett. **107**, 084802 (2011)
Stancari et al., IPAC11 (2011)
Stancari, APS/DPF Proceedings, arXiv:1110.0144 [physics.acc-ph]

Tevatron electron lenses for long-range beam-beam compensation

- 36 (3x12) proton bunches collide with 36 (3x12) antiproton bunches
- Because of collision pattern, beam-beam tune shift and losses depend on position in bunch train





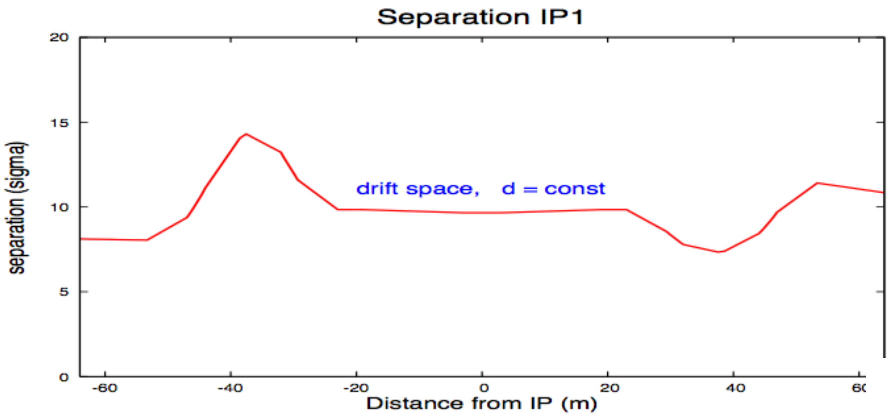
Electron lens with flat profile improves lifetime of chosen bunch

G. Stancari, CERN

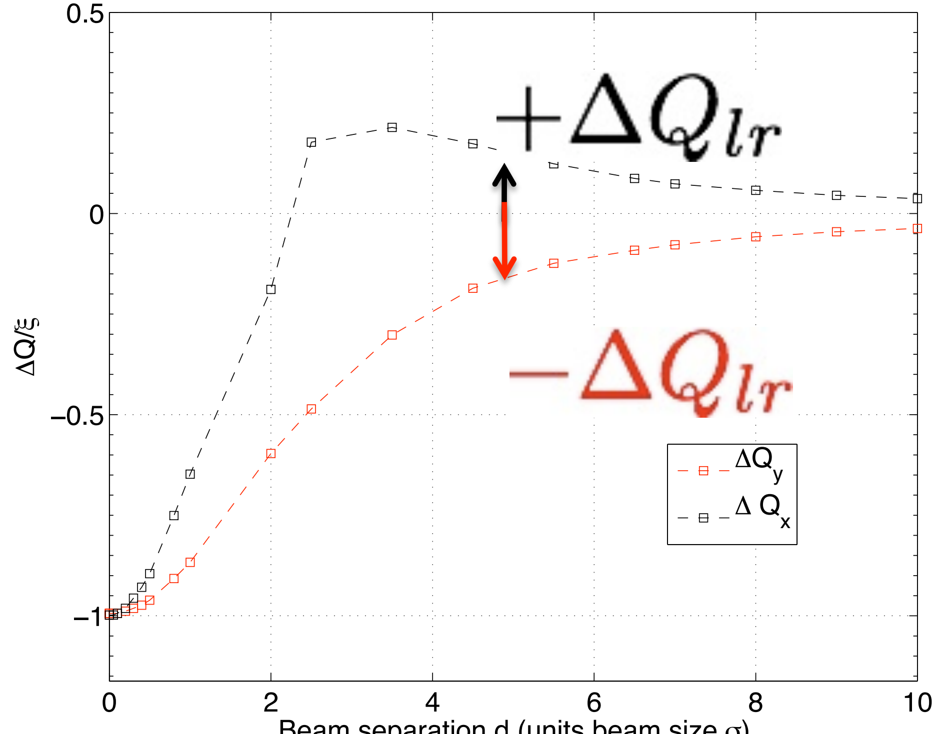
Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)

Long-Range Interactions

W. Herr

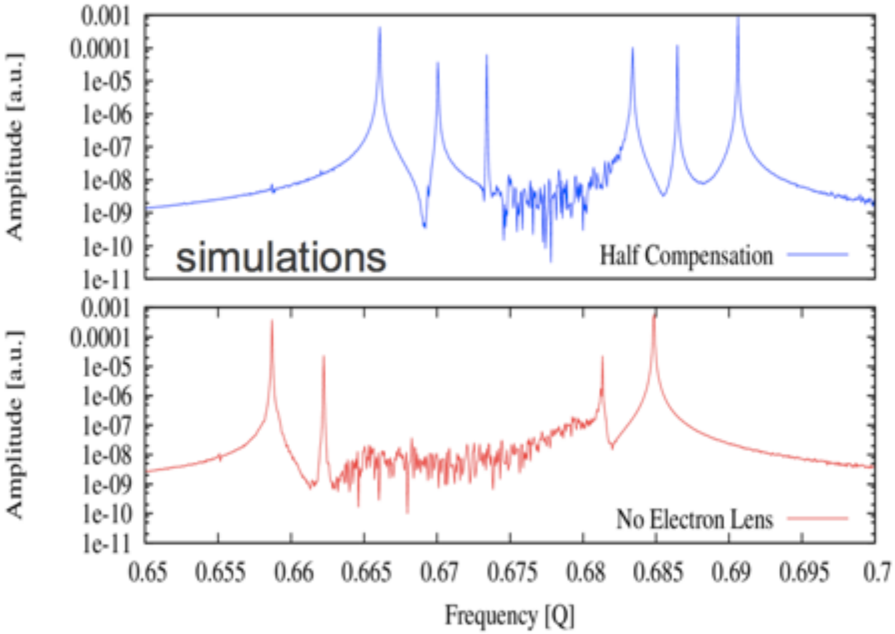


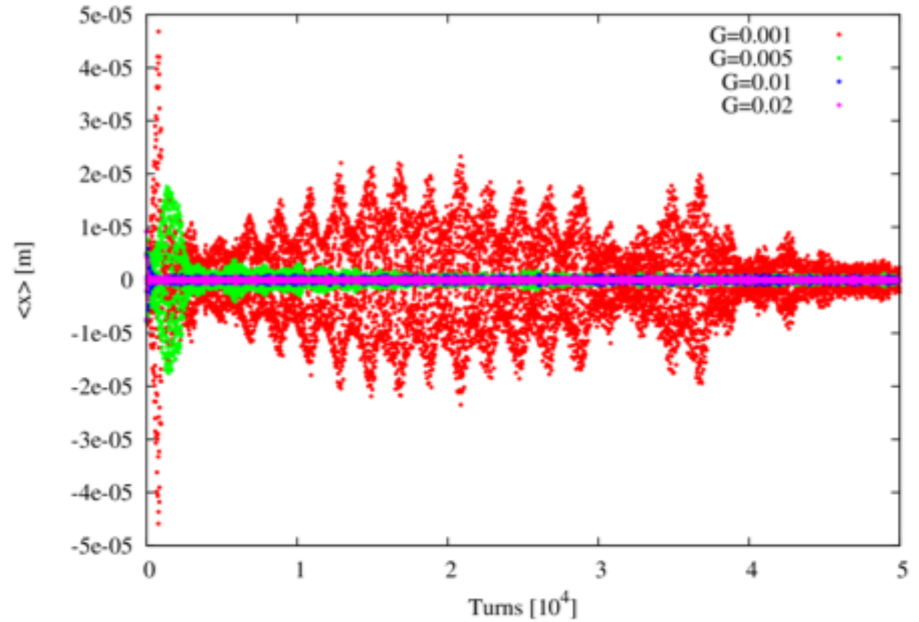
- In LHC: alternating crossing scheme (horizontal and vertical crossing planes) removes tune difference by compensation for collisions in IP1 and IP5



E-lense dynamics in RHIC

S. White





E-lense reduces Landau damping region
Coherent BB modes not damped

- BB modes seem stable (several experiments)
- Only cure now in RHIC: tune split
- Beams more sensitive to noise with tune split
- Transverse damper needed in case of problems

Electron lens driven TMCI

- E-lens and impedance only no problem
- In presence of coherent beam-beam modes much worse
- Need for transverse damper
- Need for high chroma

Studies on-going

Beam-beam, impedance, damper

A. Burov

Nested Head-Tail Vlasov Solver (AP Forum 4/12/12)

- NHT is my Mathematica-based program for LHC-type beam stability analysis. It accepts the following external data:
  - Inter- and intra-bunch wakes (arbitrary functions);
  - Damper with provided gain frequency profile;
  - Beam-beam collision scheme;
  - Octupoles and beam-beam nonlinearity;
  - Bunch distribution function.
- The code computes:
  - Azimuthal, radial, coupled-bunch and beam-beam modes;
  - Beam stability thresholds.
- NHT was cross-checked with BeamBeam3D tracking simulations (S. White), showing a full agreement.

Defines stability of beams by use of octupole detuning, chromaticity and transverse damper

Also includes BB coherent

- **INTERPLAY of effects is the key to understand the complex picture of beam-beam in an operating machine.**
- **Complexity needs step by step understanding and going to the FULL picture.**
- **Different models should agree within their approximations**