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

Luminosity Levelling Techniques: Implications for beam-beam

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(STFC, Daresbury Lab) and (CERN)
On behalf of LHC and HL-LHC BB teams

Special thanks: G. Arduini, X. Buffat, W. Herr, M. Lamont , S. Redaelli, R. Tomas, J. Wenninger, LHC OP crews and Collimation Team

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Outline:

- Motivations
- Leveling with transverse offset
- Crossing angle CC
- Level β^*
  - Experimental results
- Leveling by longitudinal cogging
- Combinations/alternatives
- Summary

Why leveling: LHC

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

R. Jacobsson talk has all the requirements from the 4 experiments

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

Why leveling: HL-LHC

‘Stretched’ Baseline Parameters following 2nd HL-LHC-LIU:

Parameter	nominal	25ns	50ns
N	1.15E+11	**2.2E+11**	**3.5E+11**
n_b	2808	2808	1404
beam current [A]	0.58	**1.12**	**0.89**
x-ing angle [μrad]	300	590	590
beam separation [σ]	9.9	12.5	11.4
β^* [m]	0.55	**0.15**	**0.15**
ε_n [μm]	3.75	2.5	3.0
ε_L [eVs]	2.51	2.51	2.51
energy spread	1.20E-04	1.20E-04	1.20E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	**18.5**	**17.2**
IBS longitudinal [h]	61 -> 60	**20.4**	**16.1**
Piwinski parameter	0.68	**3.12**	**2.85**
geom. reduction*	0.83	**0.305**	**0.331**
beam-beam / IP	3.10E-03	**3.3E-03**	**4.7E-03**
Peak Luminosity	1 10^{34}	**7.4 10^{34}**	**8.5 10^{34}**
Virtual Luminosity	1.2 10^{34}	**24 10^{34}**	**26 10^{34}**
Events/crossing	19 /28	**207/140**	**476/140**

Large ξ_{bb}

DA studies with Working Point optimization & Orbit effects

Large crossing angle requires compensation of geometrical factor by CRAB-CAVITIES

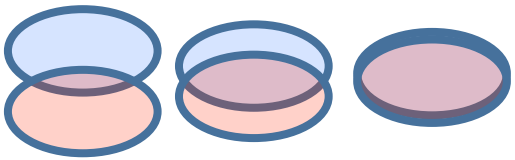
High pile-up needs robust strategy for leveling

HL-LHC rubust leveling and possible techniques have to be tested operationally in the LHC to define the best strategy

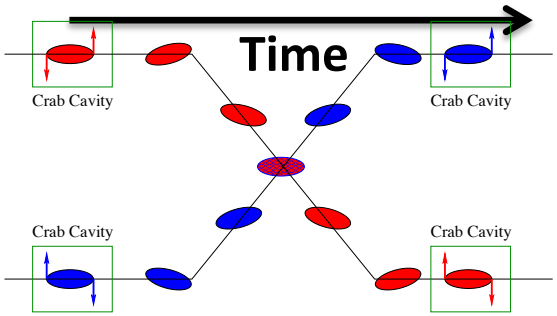
O. Bruning

Luminosity Leveling options:

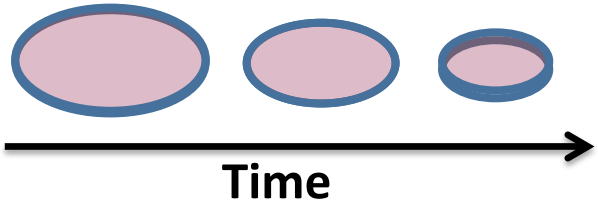
Leveling with transverse offset



Leveling with Crab Cavities



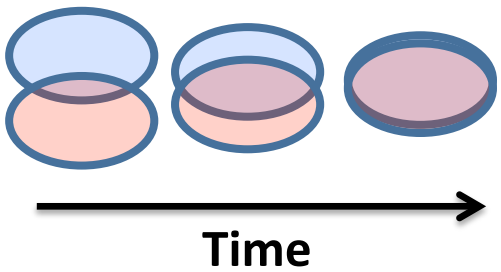
Leveling with β^*



Combinations and/or alternatives: combining different methods, longitudinal cogging

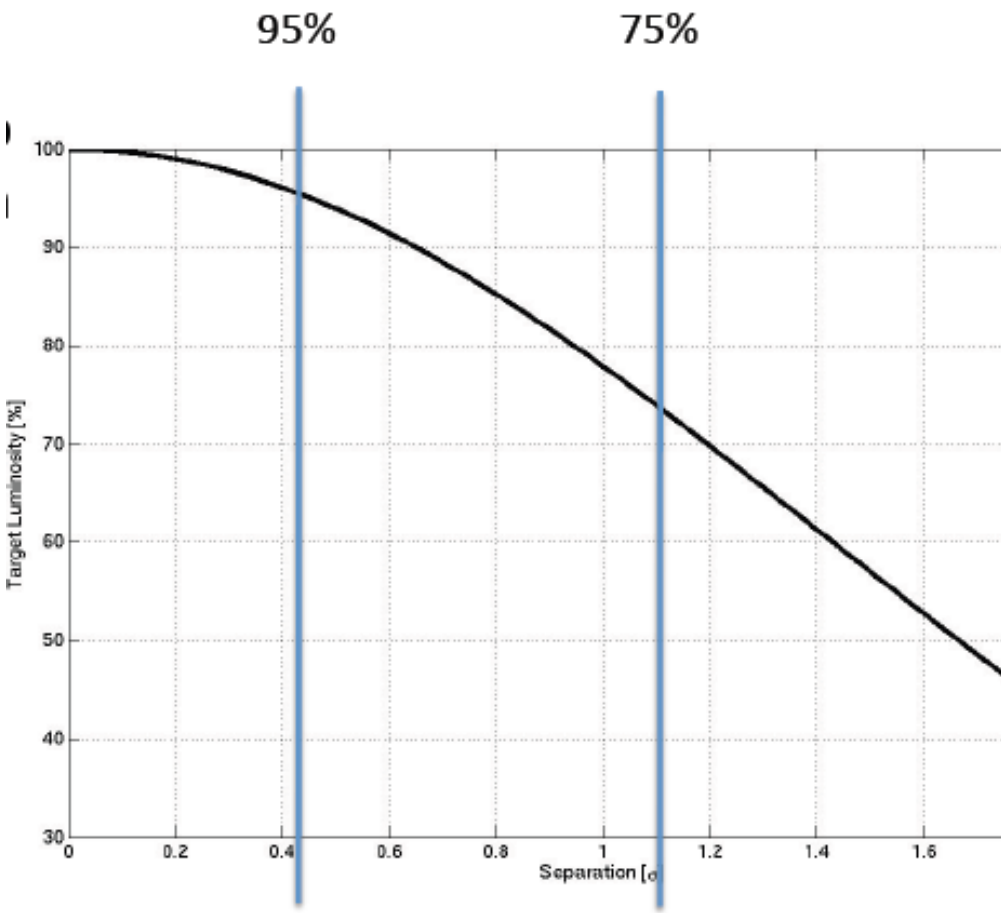
Levelling with offset – **pros**

$$L = L_0 \exp\left(-\frac{dx^2}{2(\sigma_{x1}^2 + \sigma_{x2}^2)}\right)$$



Operational scenario for LHCb since 2010 and leveling test in 2012 for ATLAS and CMS

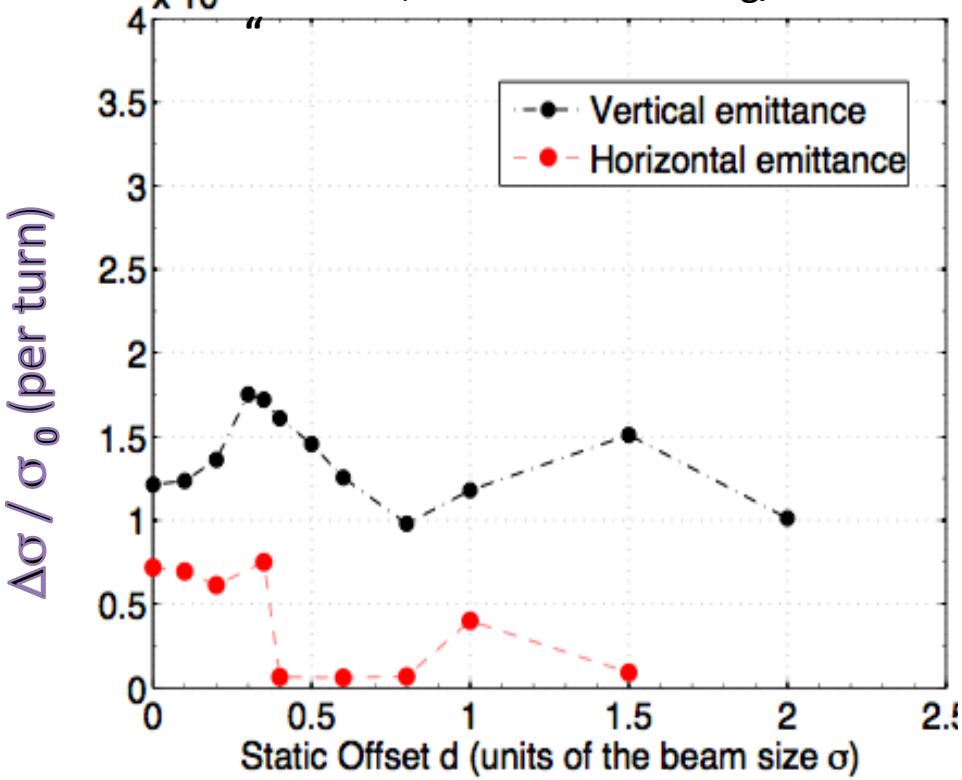
- **Simple** & easy from operations point of view
- Can go back and forth
- **Smaller tune spread** → reduced losses wrt HO
- **Constant longitudinal vertex density**
- All **IPs independent** (local bump)
- **Large range** of leveling
- HL-LHC 25 ns parameters (2.3e11 ppb and 2.5mm normalized emittances) tested 2011
- Operational **experience ok**



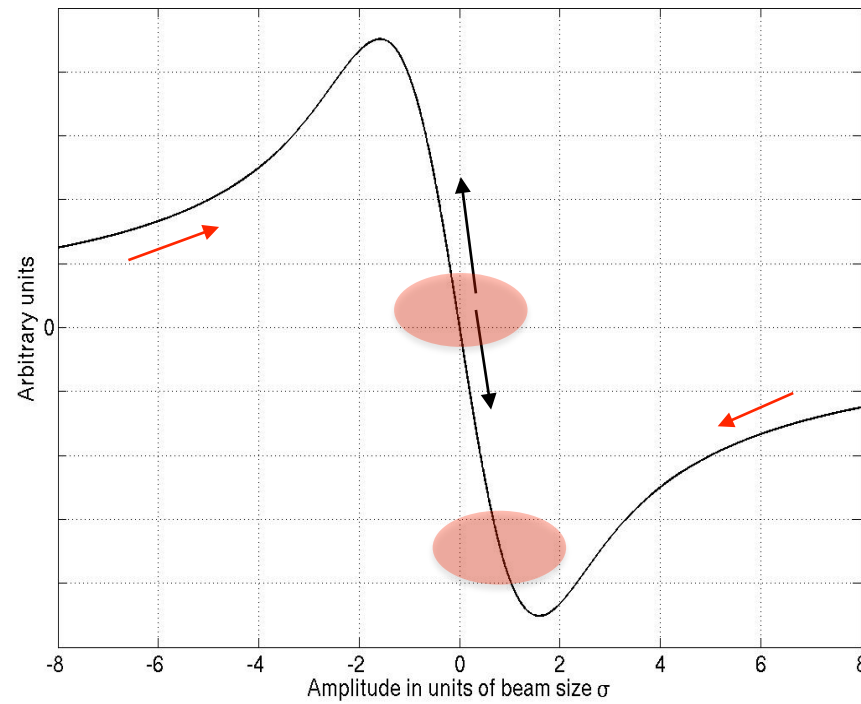
Levelling with offset – **cons (1)**

- Different separation → **different BB force/dynamics**
- **Emittance growth** from small offsets at collision

T. Pieloni, W.Herr and J.Qiang, **PAC 09**



Beam-beam force

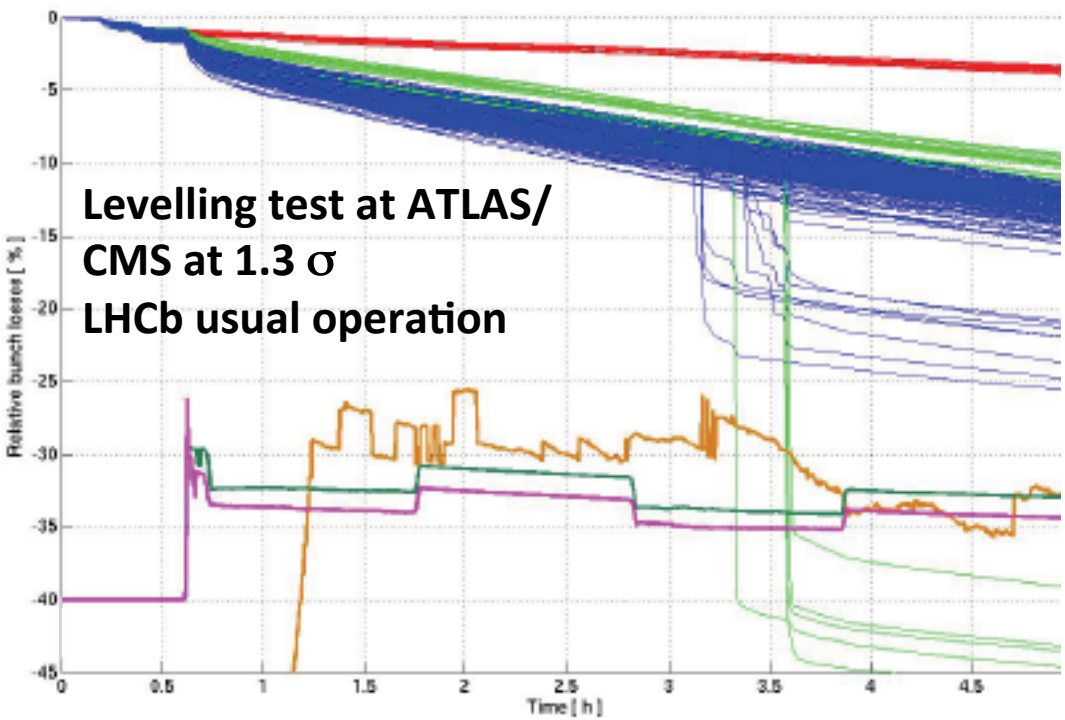


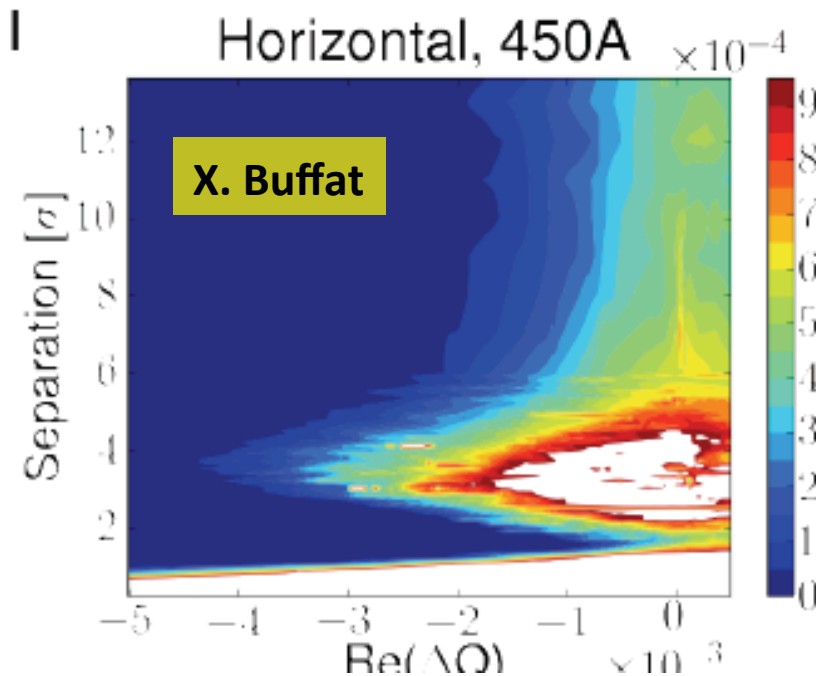
Needs test for higher brightness bunches for long term effects

Levelling with offset – cons (2)

- No head-on collisions → **small stability area**
- Bunches generally **more sensitive to instabilities** with respect to head-on (2012 experience)
- No check of **long term emittance effects** of beams with high brightness (High pile-up MD 2012 not conclusive)

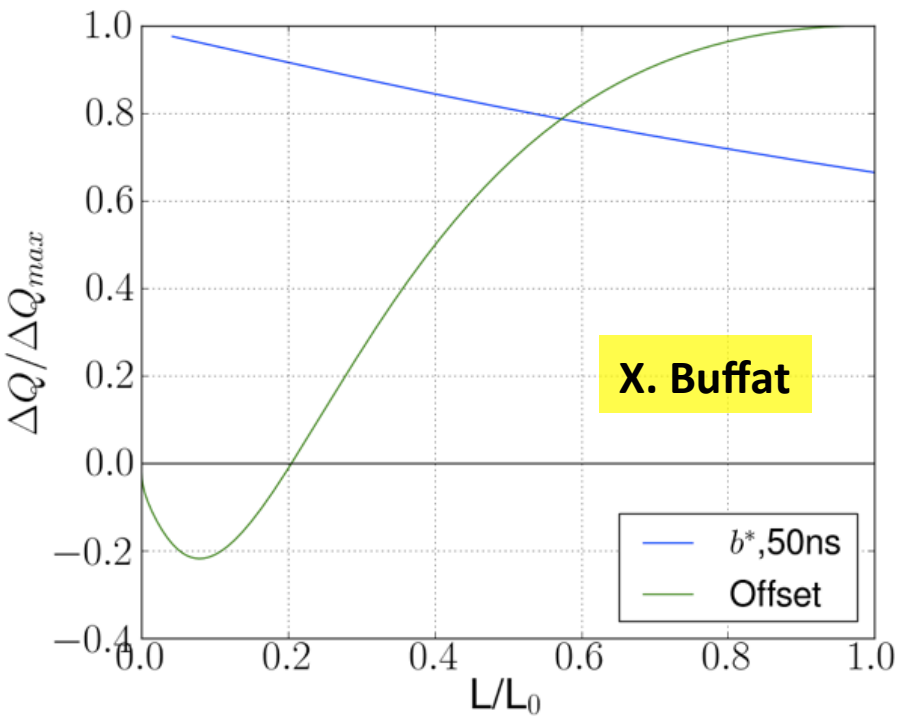
If bunches stability guaranteed by other means this is still a valid option to keep ΔQ_{bb} smaller, one can avoid 1 HO

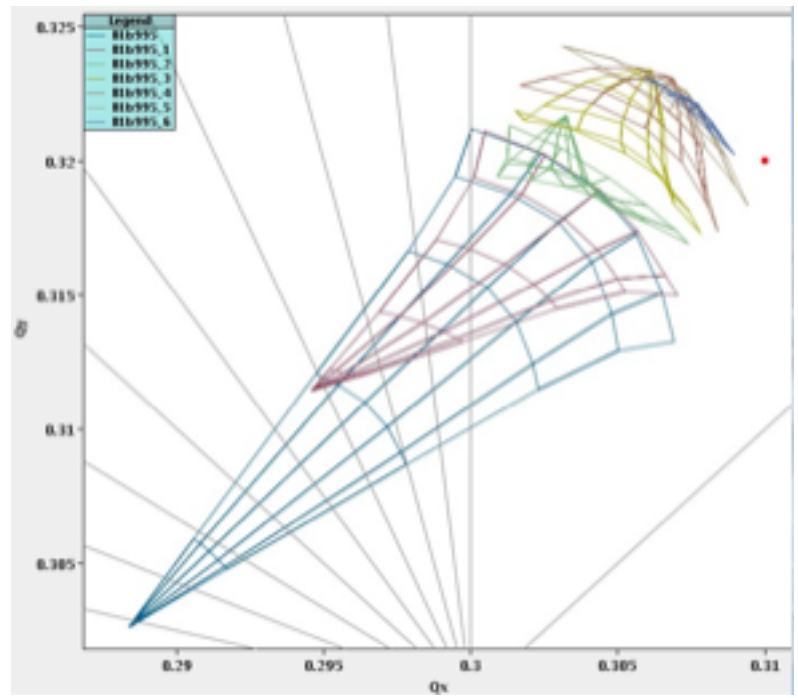




Levelling with offset – cons (2)

- **Variable tune** shift

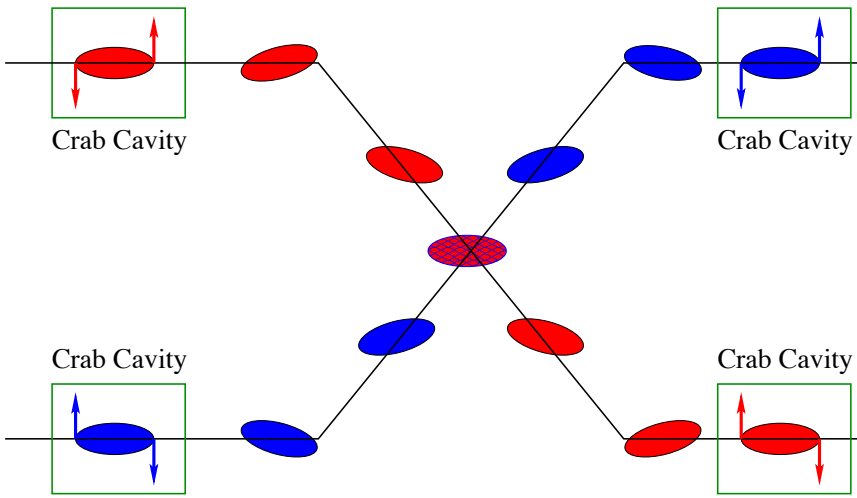




If bunches stability guaranteed by other means this is still a valid option to keep ΔQ_{bb} smaller in combination with other techniques

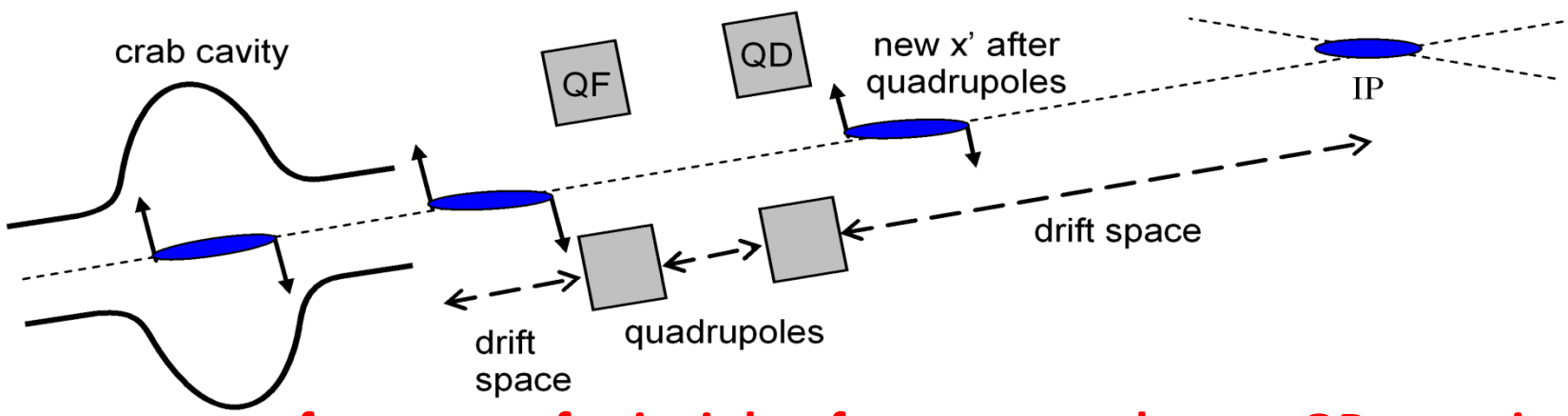
Crossing angle/Crab cavity levelling – **pros**

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



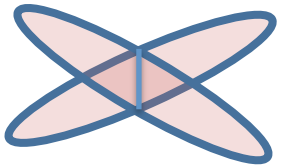
R. Calaga

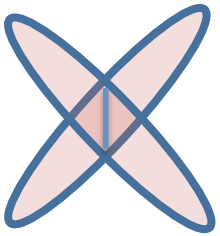
- **Reduces the geometrical reduction factor** to give a higher luminosity (LHC little range R 15-20%, HL-LHC 70%)
- All **IPs independent**
- Can go **back and forth** (increase & decrease luminosity)



Needs some tests for prove of principle of system…and some OP experience!

Crossing angle/Crab cavities



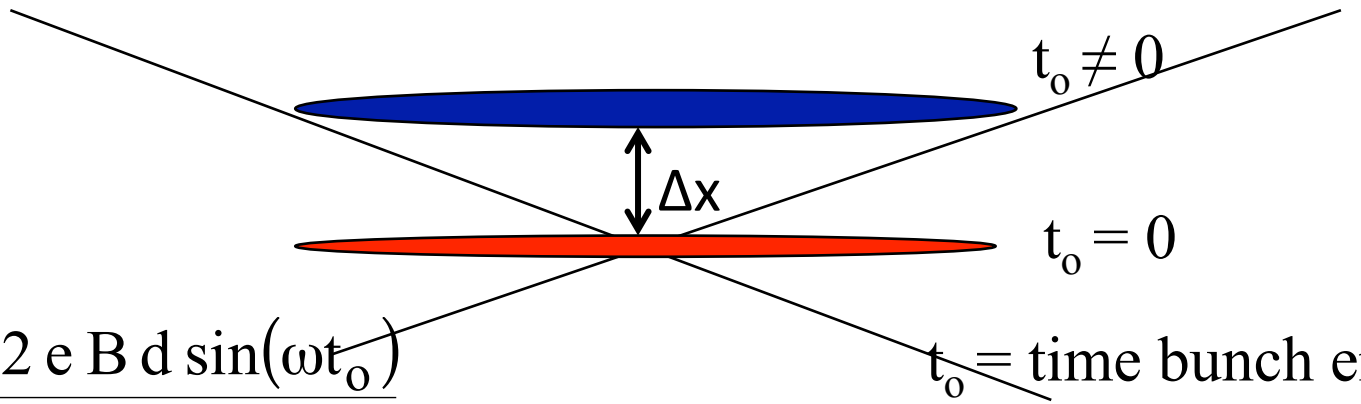


Cons:

- **Longitudinal vertex density changes** with the leveled angle
- **Tunes keep changing** with crossing angle
- Could introduce **noise on colliding beams**
- **No operational experience** with **p**, and have increase OP complexity
- Can **reduce the reachable** ξ_{bb}, (50 ns option should be studied carefully)
- **Phase jitter** in cavities → reduced luminosity
- **Phase jitter** in cavities → emittance blow-up
- Not obvious they can be accepted by Machine Protection

Talks:

- **S. Paret (Thur)**
- **Y. Funakoshi (Thus)**
- **Studies by Ohmi**



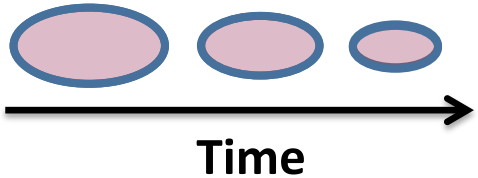
$$\Delta x = \frac{-2\, e\, B\, d \sin(\omega t_o)}{m\, \omega}$$

t_o = time bunch enters cavity

d = distance to IP

Needs still simulations studies for different HL-LHC scenarios, possibly tests for prove of principle of system in the LHC…and OP experience!

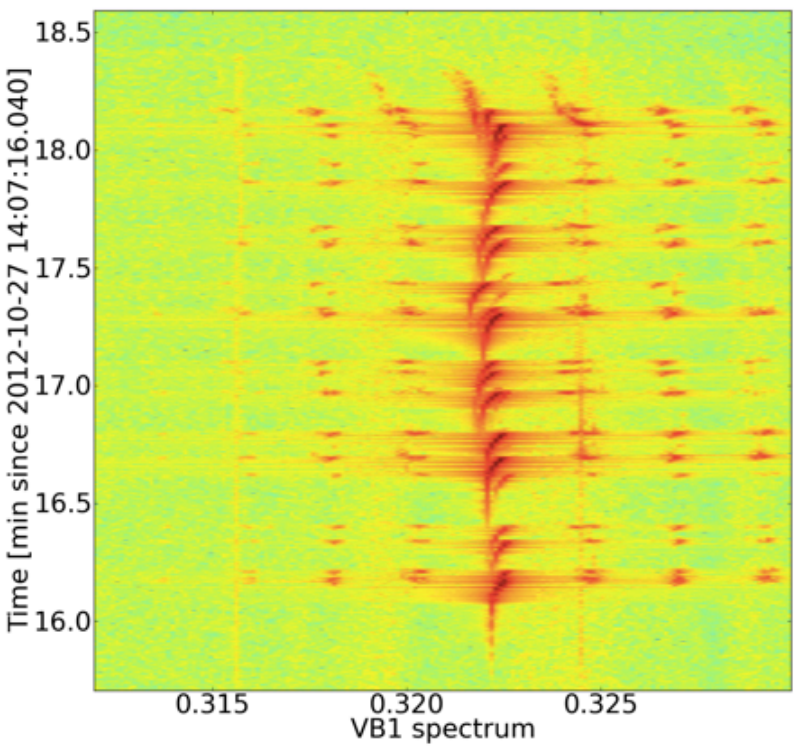
β* leveling

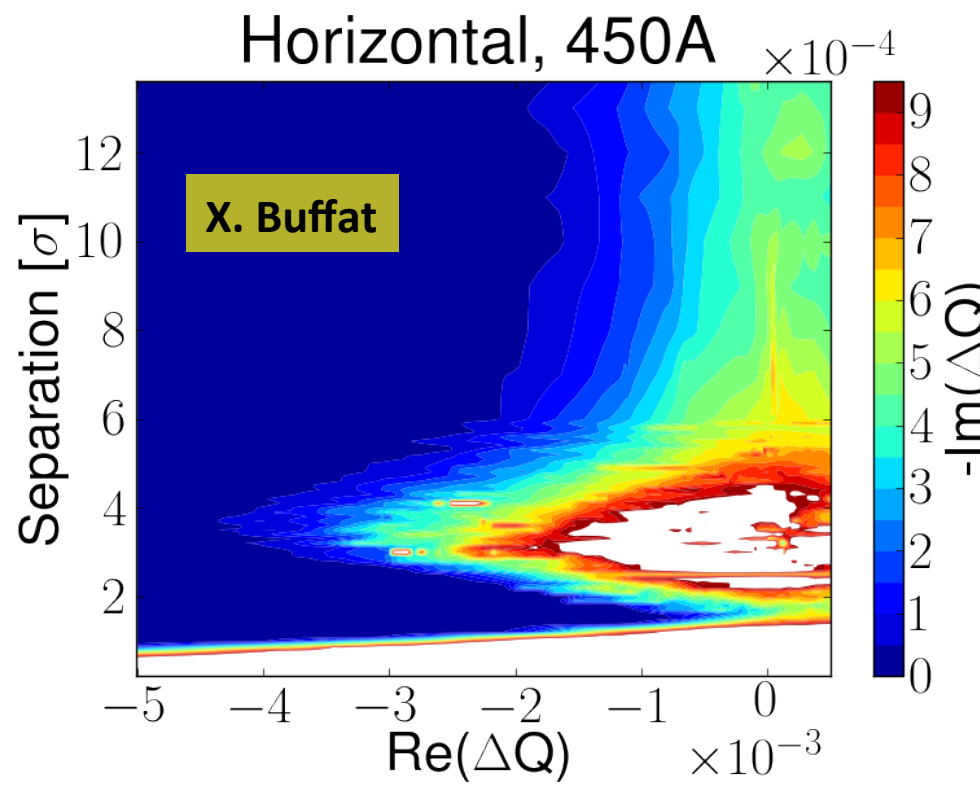


Pros:

- Can be **used also for stability**, gives largest area for Landau damping
- Doesn't change HO tune shifts **constant over the fill**
- Ensures **constant longitudinal vertex density** to Experiments

Collide&Squeeze&level motivated by instability issues of 2012 (LMC 11 April 2012): talk X. Buffat



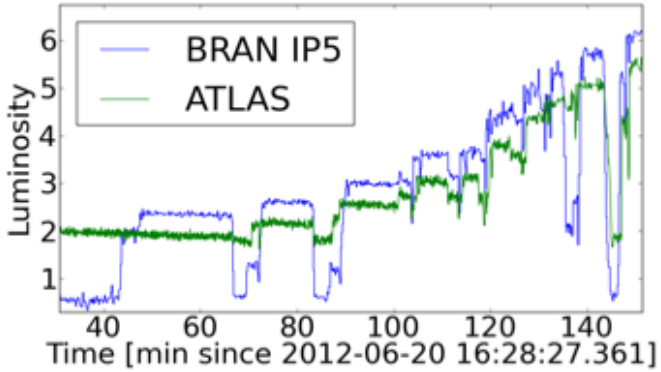


Prove of principle during MD experiments at the LHC to use it for leveling

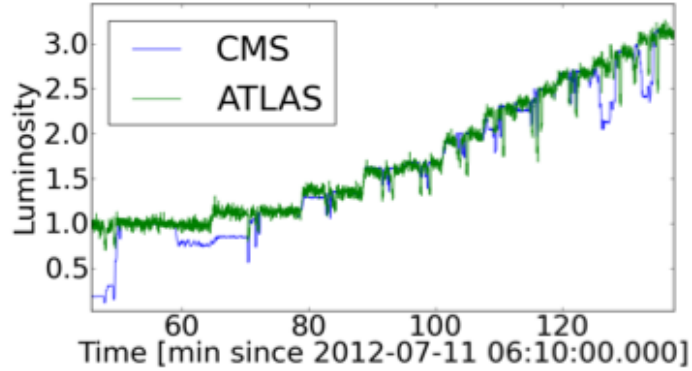
β* leveling MDs: collide&squeeze for stability!

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

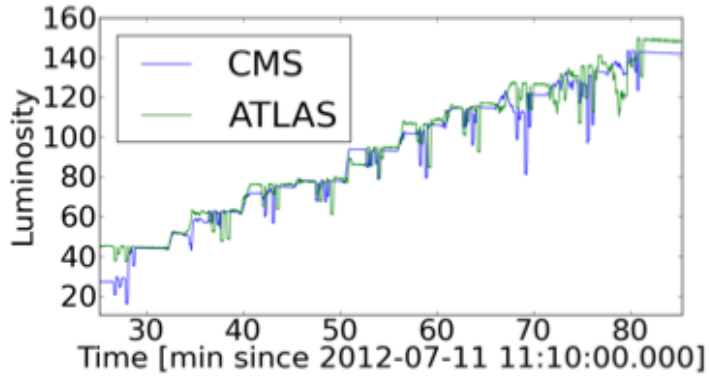
X. Buffat, W. Herr, M. Lamont, T. Pieloni, S. Redaelli J. Wenninger, L. Ponce



(a) Fill 2748



(b) Fill 2828



(c) Fill 2829

β* 3 m → 0.6 m
β* 9 m → 0.6 m

a) **Single bunchs test**: single bunches IP1 and IP5 lumi optimization at each squeeze step. Orbit corrections implemented

b) **Orbit reproducibility**:20 days later: single bunches and test of orbit stability

c) **β* and long-range:** repeat above with 1 train 48 bunches

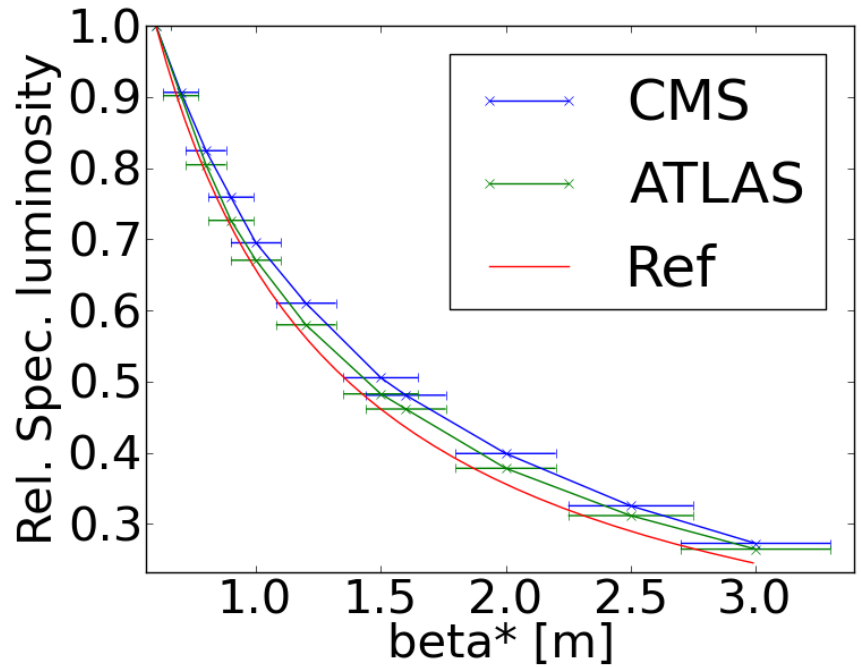
d) **β* 9 m →0.6 m**

β* leveling:

$$d_{sep} = \frac{\sqrt{\beta^*} \cdot \sqrt{\gamma}}{\sqrt{\epsilon_n}} \cdot \alpha$$

Cons:

- **Reduces LR separations** (for constant α)
- Needs good control on orbit, **separations should be below 1σ**
- **Feedback solution** is required to make it OP robust?
- Control system and Instrumentation of LHC need changes (during LS1) and thoughts on best way to implement



- **LHC after LS1: depends on 25-50 ns beams maybe can optimize crossing angle versus beta (little gain)**

- **HL-LHC might be only solution for stability and level, needs operational experience in LHC**

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

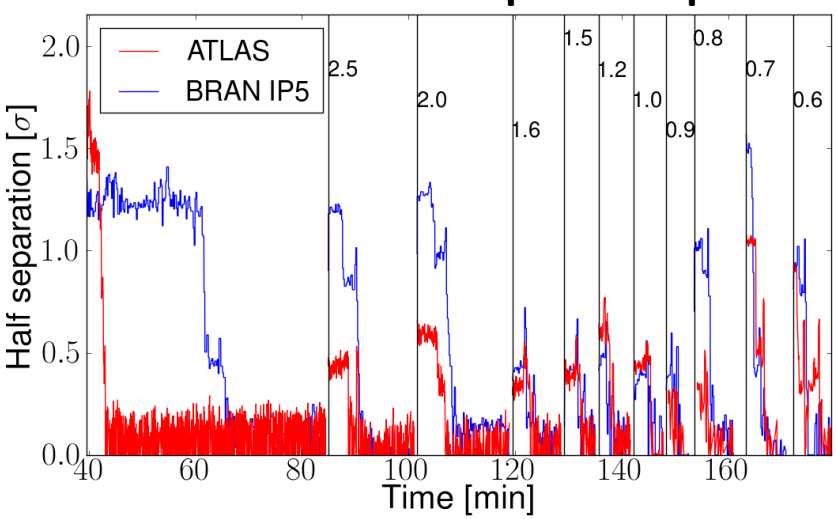
X. Buffat, W. Herr, M. Lamont, T. Pieloni, S. Redaelli J. Wenninger, L. Ponce

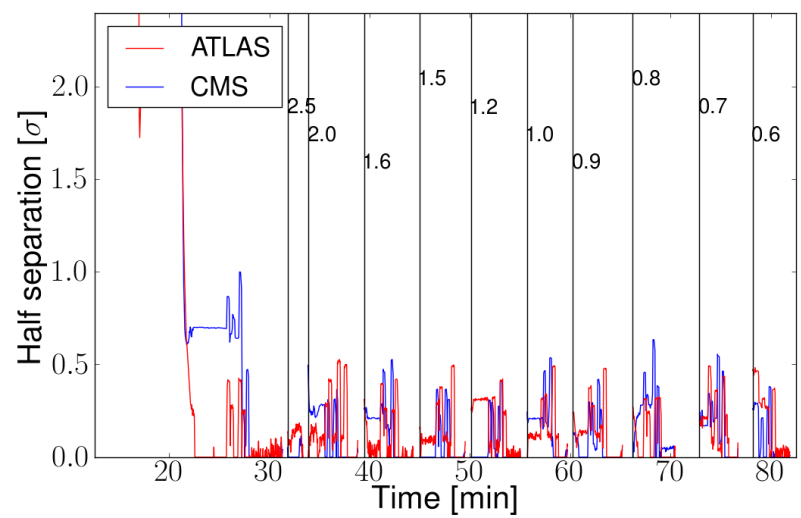
Leveling β*:

Considerations/open questions:

- For LHC depends on 25-50 ns beams
- For HL-LHC only solution for stability and level fundamental operational experience in LHC
- If orbit not controlled < 1 σ then like transverse offset leveling.
- Can the IPs be all independent?
- Does special optics (ATS) needs special considerations? Yes, but doesn't seem out of reach!

Half separation per beta squeeze steps from lumi data





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

β* leveling:

Considerations/open questions:

- Pseudo Flat beams ($\beta x \neq \beta y$): keep crossing plane constant (LR effects constant) and level in separation plane and small gain in lumi
- Can be combined with offset leveling to keep ΔQ_{bb} smaller

	β* cross	β* sep	β* sep collide&squeeze	α/2 urad	BB sep σ
50 ns, 2.5 um	35	33	30	150	9.3
50 ns, 1.6 um	31	33	30	127	9.3
25 ns, 3.75 um	46	33	30	205	12
25 ns, 1.9 um	37	33	30	163	12

R. Bruce

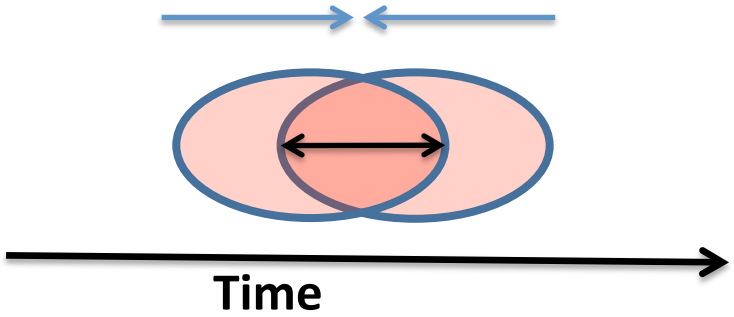
Needs changes in control system, instrumentation and some experience from LHC!

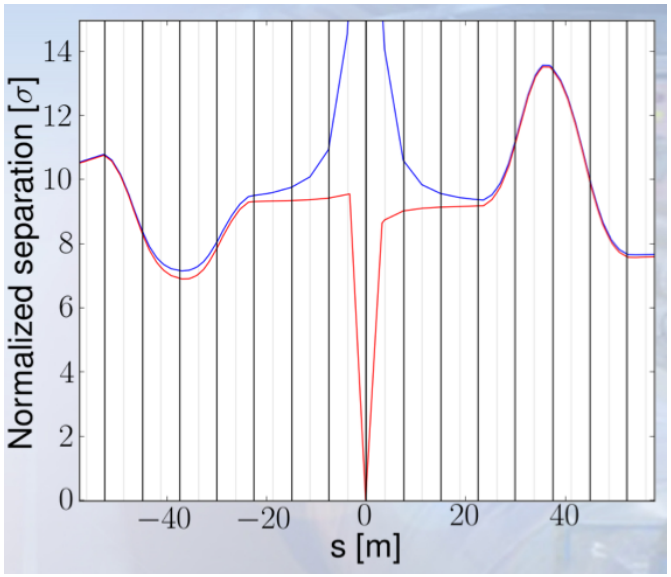
Planned for LHC as a possible leveling option and cure instability for after LS1

Other possibilities for levelling

Longitudinal cogging

- **All Ips will be affected**
- 2012 experiments only for full jump of 1 RF period or 5 RF periods, moving LR fast seems not to be a problem
- **Leveling (slow LR moving)** needs BB studies of stability





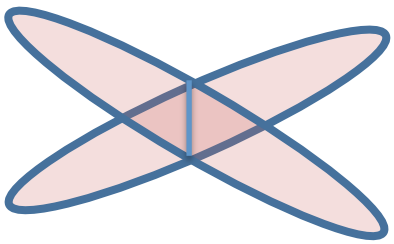
10/26/2012 LSWG meeting 8

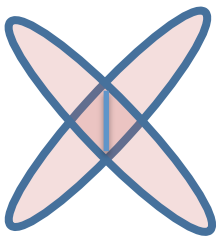
Conclusion

- As requested by MP, the rephasing has been validated with high intensity beams at both 450 GeV and 4 TeV
- In the future we will use 1 Hz/s rate and -12 Hz frequency offset (1E-4 Δp/p)
- With these settings we move one beam by ¼ turn in 13 minutes
- For large rephasing angles, the time scales linearly with the azimuthal rotation
- **We are ready for the next TBI MD…**
- For very small shifts (below 144 RF buckets), the rephasing is completed before the maximum momentum offset is reached. Rephasing time then scales as the square root of the desired displacement. For example
  - 2 seconds to move 1 beam by 1 RF period
  - 4.5 seconds to move 1 beam by 5 RF periods (2.5E-5 max Δp/p)

Rephasing tests during 2 beam Impedance MD
P. Baudrenghien, J. Noirjean, T. Mastoridis

Combinations and alternatives:





- **Piwinski angle** leveling option
  similar considerations as for CC

$$R_\phi = \frac{1}{\sqrt{1+\phi^2}}; \quad \phi \equiv \frac{\theta_c \sigma_z}{2\sigma_x} \quad \text{“Piwinski angle”}$$

Combinations of the different techniques should be also considered with symmetric beams (all bunches 3 IPs) :

- Allow full flexibility to different experiments
- **Guarantee 1 HO collision for stability**
- Optimize machine on ΔQ_{bb}
- Stability studies needed for un-known effects

example:

- **Scenario1: IP1 and IP5 offset leveling and IP8 β^***
- **Scenario 2: IP8 offset leveling IP1 and IP5 β^***
- **…several possibilities!**

Summary

- List of various scenarios for levelling

- Leveling by crossing angle not interesting for experiments and for MP considerations (Crab Cavities leveling or Piwinski angle NOT an option)
- Leveling by Cogging links all experiments (NOT an OPTION for Experiments)

- Options: β^* leveling and transverse offset seem most promising
  - Collide&Squeeze is needed to cure instabilities (2012)
  - HO collision worse than LR
  - Keep ΔQ_{bb} small when possible (offset leveling)
  - β^* leveling: fixed crossing angle and pseudo-flat beams to keep LR effects "constant" over the fill, squeeze in separation plane
  - …many possibilities! Need to decide for possible scenarios and start BB studies in complex configurations!

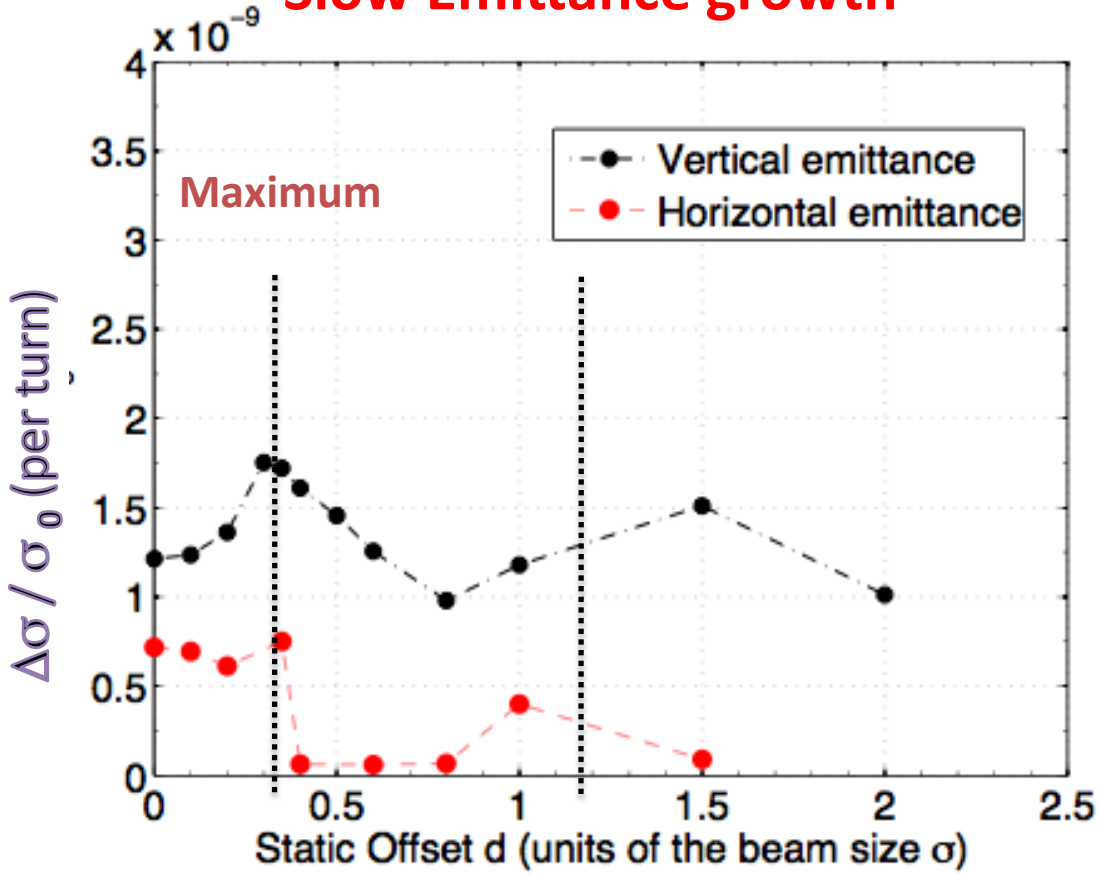
- Compromise between
  - Experiment requirements and constraints
  - Operational implementation, simpler is better!
  - Different techniques have different BB issues (Landau damping, Orbit changes, emittance effects, moving long-range etc) and should guide operational scenarios choices.

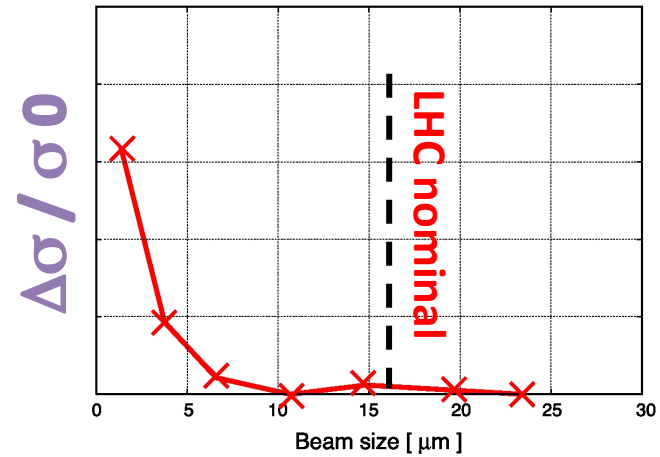
- **A working group will be settled to define possible leveling scenarios for after LS1 and for HL-LHC parameters: first meeting after Easter**

Thank you ☺

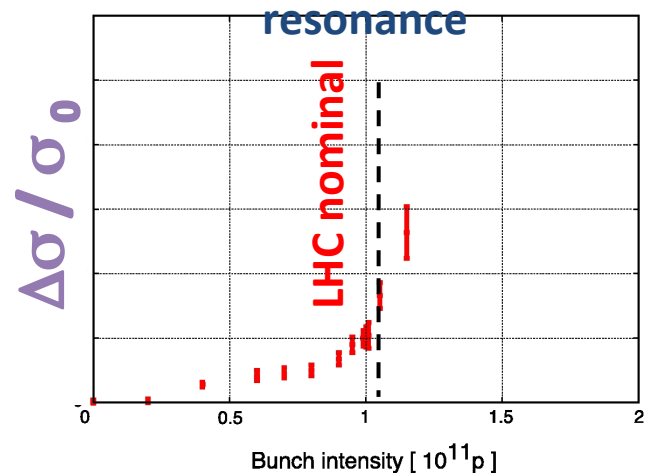
Small offset effects on emittances

Slow Emittance growth





And strong tune dependency stay away from 3rd order resonance



T. Pieloni, W.Herr and J.Qiang, **Emittance growth due to beam-beam effects with a static offset in collision in the LHC (PAC 09)**

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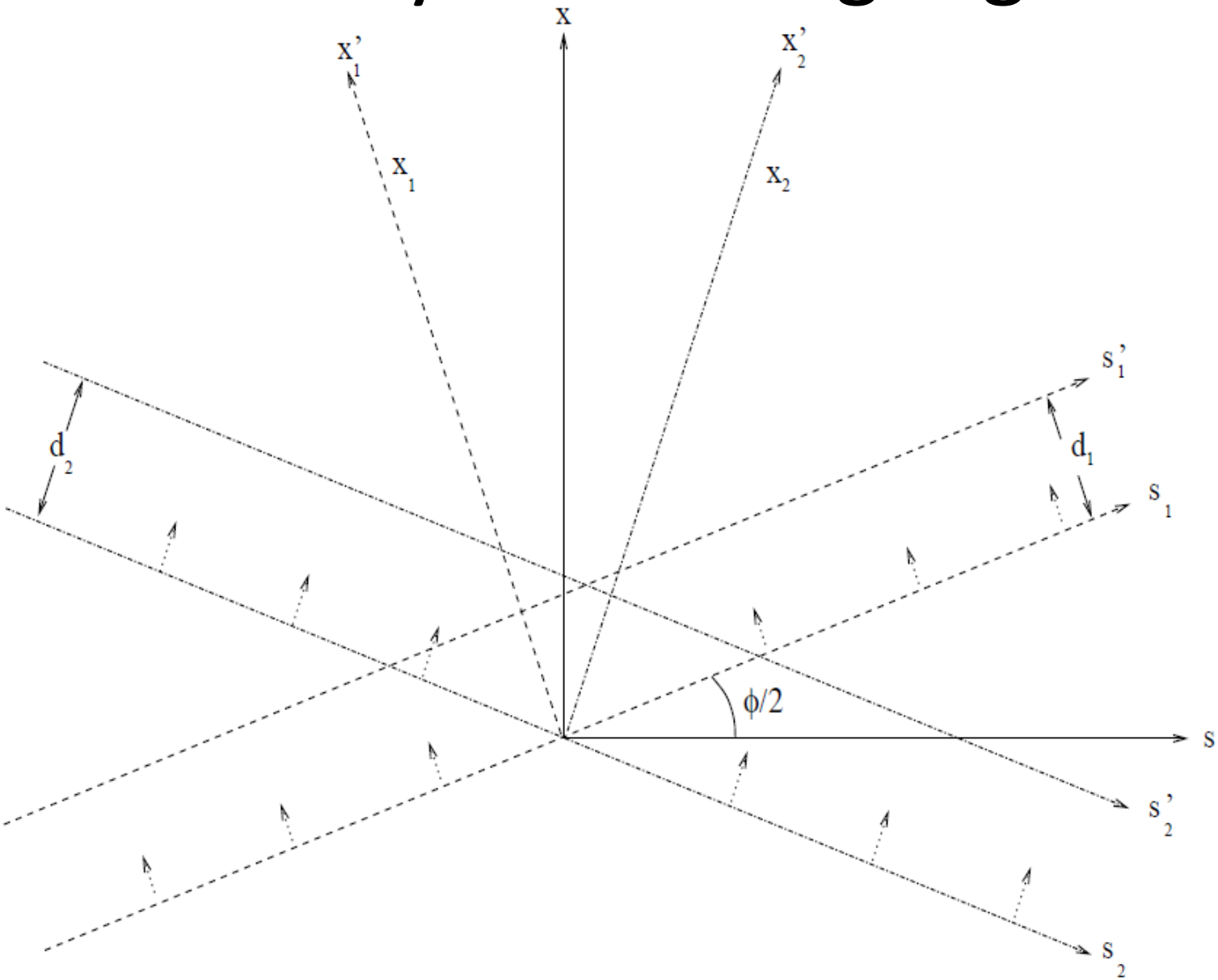
Geometry of crossing region



Luminosity expression

- Luminosity may be calculated for a Gaussian bunch to give:

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} W e^{\frac{B^2}{A}} \frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2})^2}}.$$

- With

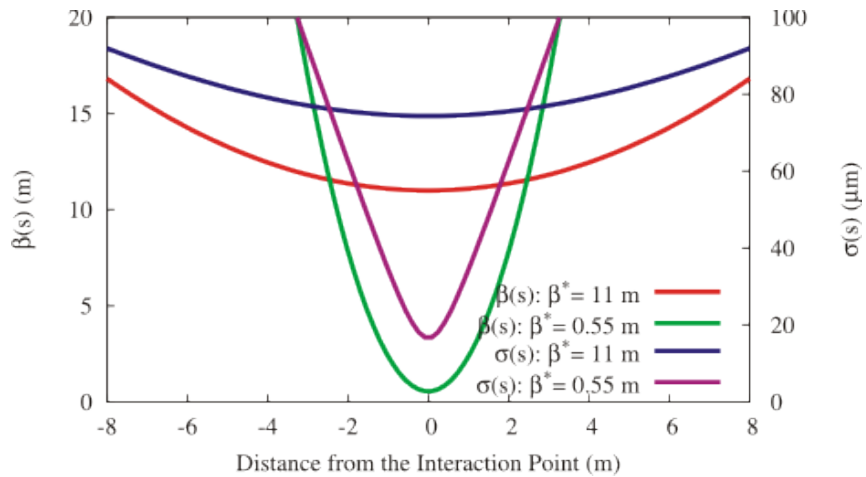
$$A = \frac{\sin^2\frac{\phi}{2}}{\sigma_x^2} + \frac{\cos^2\frac{\phi}{2}}{\sigma_s^2}, \quad B = \frac{(d_2 - d_1)\sin(\phi/2)}{2\sigma_x^2},$$

$$W = e^{-\frac{1}{4\sigma_x^2}(d_2 - d_1)^2}.$$

Hourglass Effect

$$\beta(s) = \beta^*\left(1 + \frac{s^2}{\beta^*}\right)$$

$$\sigma(s) = \sigma^*\sqrt{1 + \frac{s^2}{\beta^*}}$$



- **Effect becomes relevant when β^* equal or smaller than σ_s**
  ⇒ Include dependency in the overlap integral

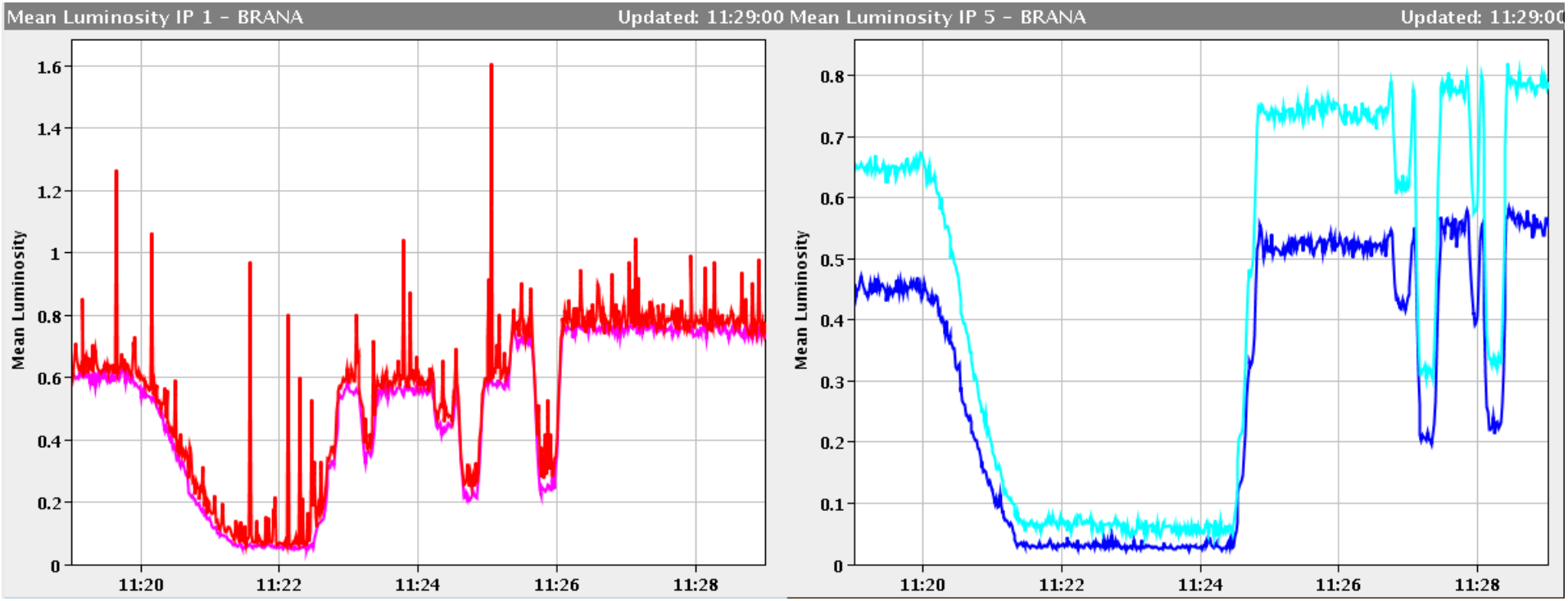
- **Round beams approximation:**

$$\frac{L}{L_0} = \sqrt{\pi}\; t_r\; e^{t_r^2}\,\mathrm{erfc}(t_r) \quad \text{where} \quad t_r^2 = \frac{2\beta^{*2}}{(\sigma_{1s}^2 + \sigma_{2s}^2)}$$

β* [m]	t_r	$H(t_r)$
10	132	0.999972
2	26.5	0.999289
1	13.2	0.9971774
0.55	7.28	0.990833

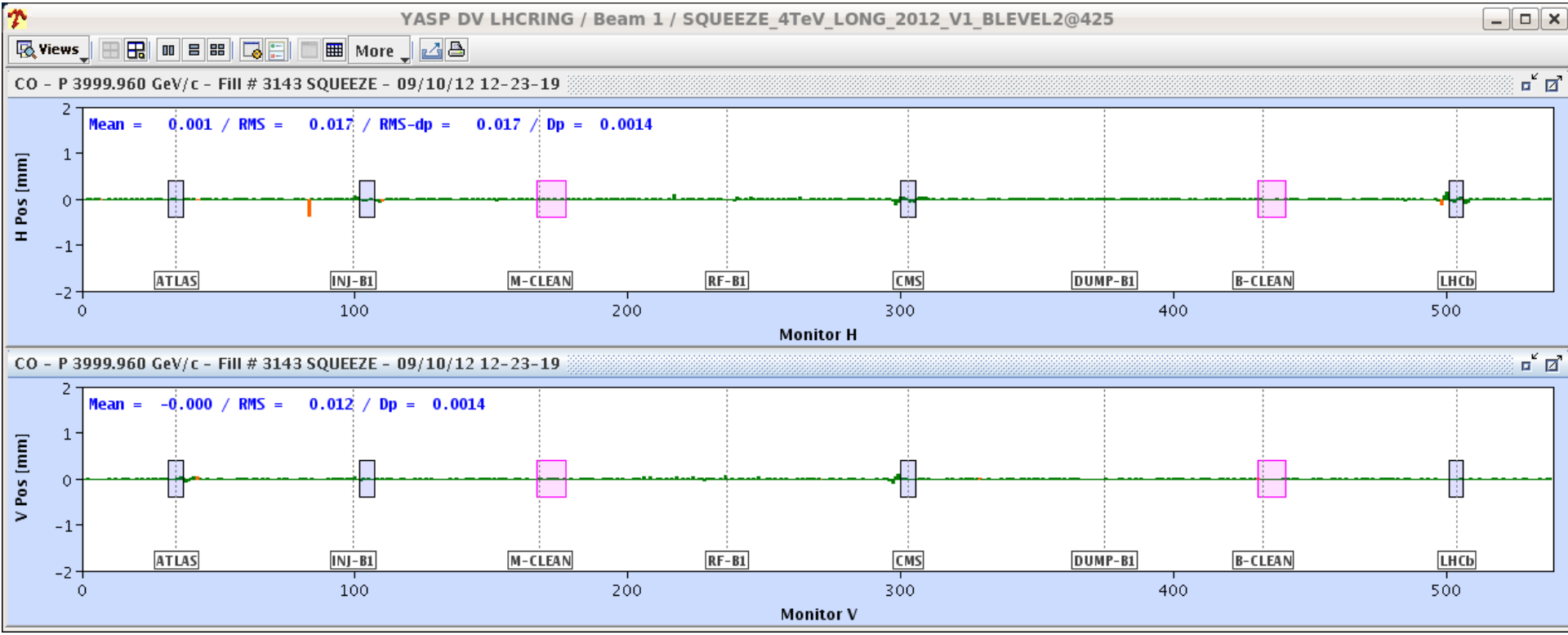
⇒ 2010 beam parameters negligible effect
⇒ 2011 beam parameters, in case we run at 1.5 m effect remains negligible
⇒ At the level of 1% for nominal LHC beam parameters: keep β* not too small

Recent (09/10/12) beta* levelling MD



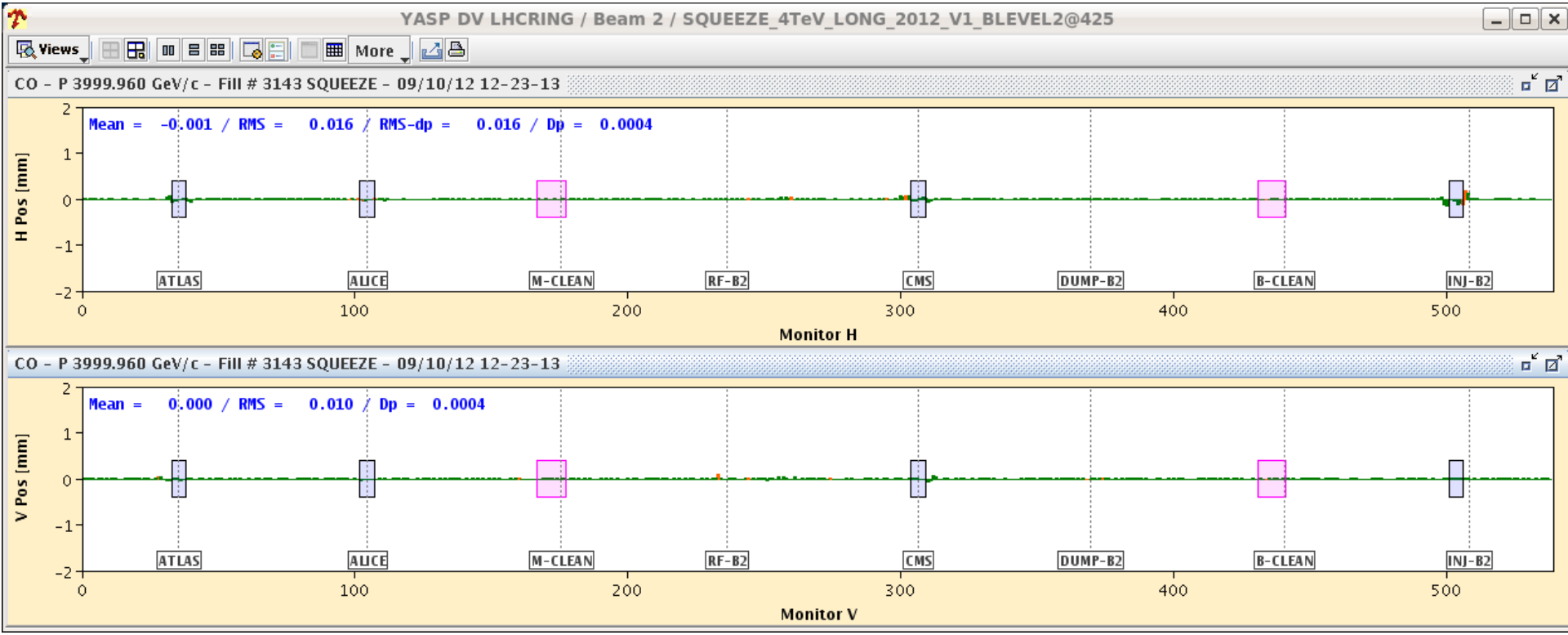
Look at behaviour of luminosity at every stage

Recent (09/10/12) beta* levelling MD



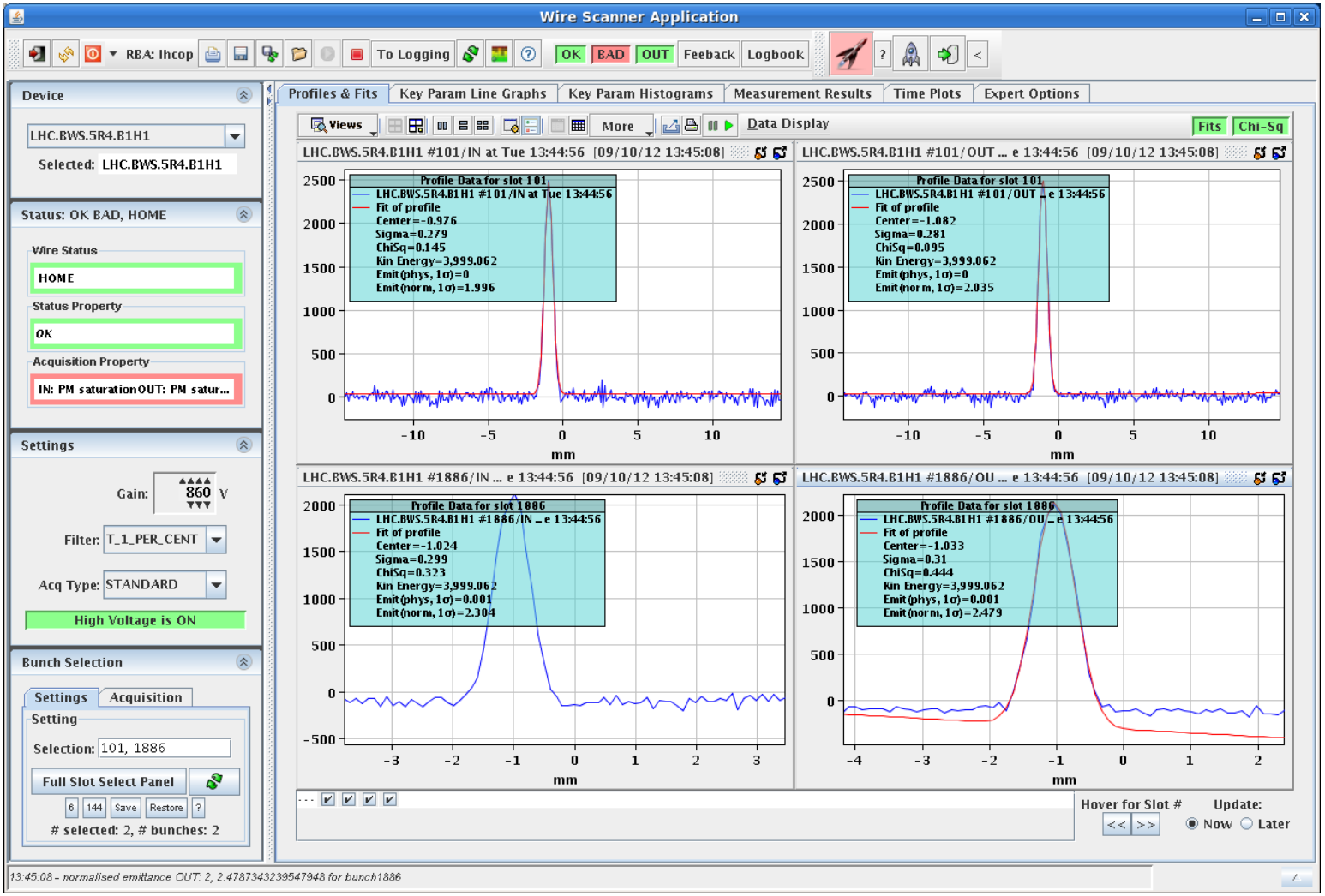
Orbit behaviour for beam 1 (looked at online)

Recent (09/10/12) beta* levelling MD



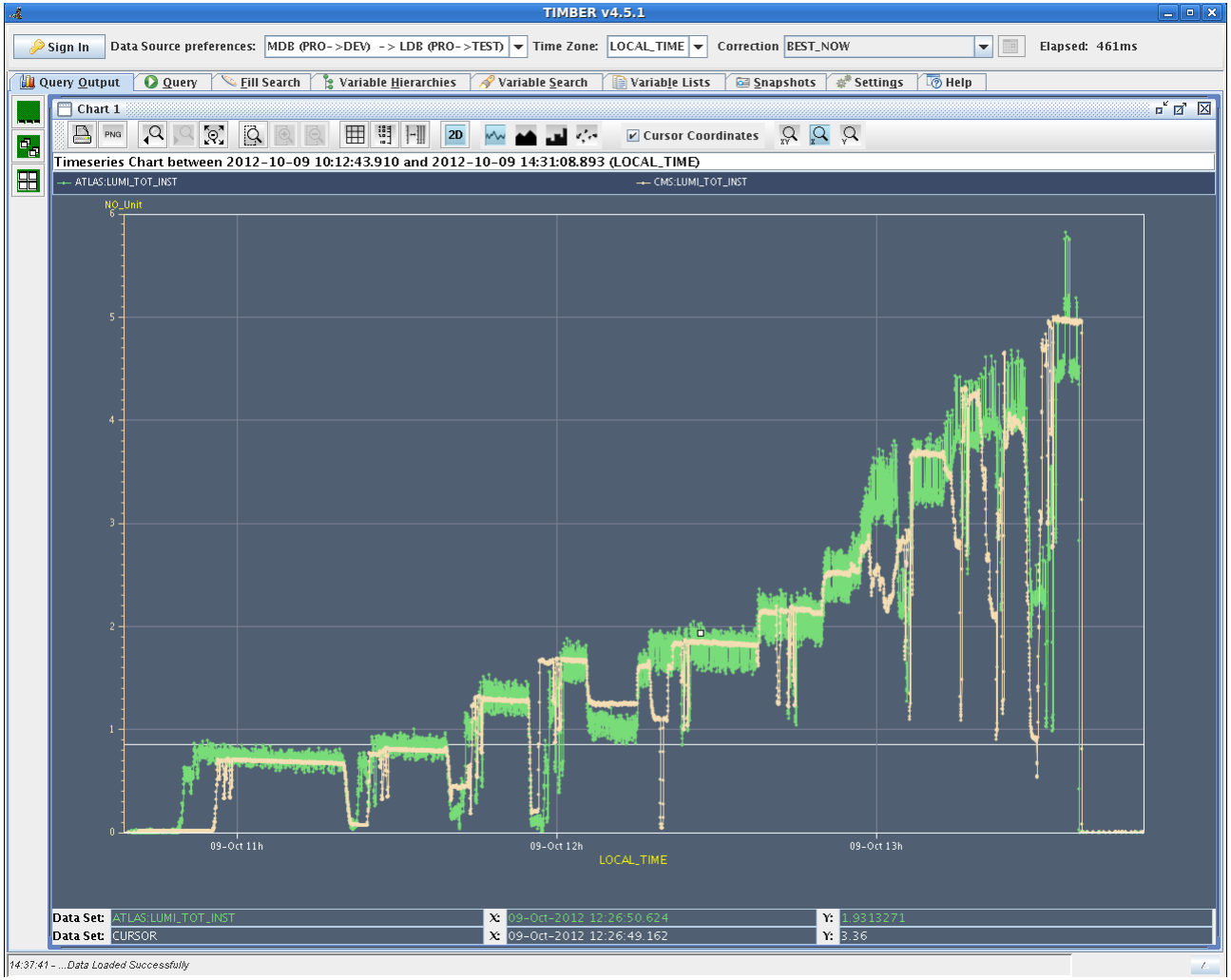
Orbit behaviour for beam 2 (looked at online)

Recent (09/10/12) beta* levelling MD

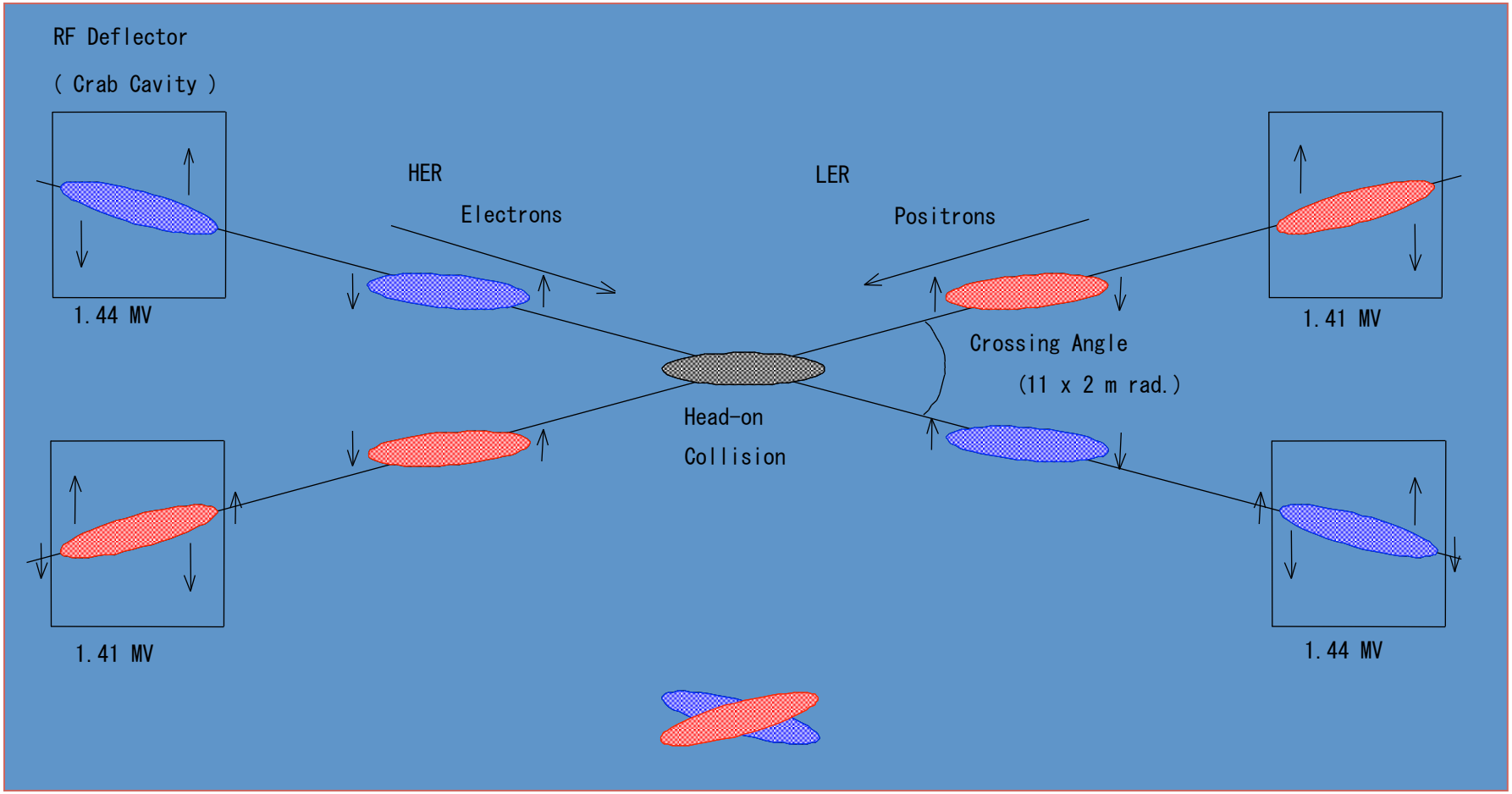


Beam properties etc. at end

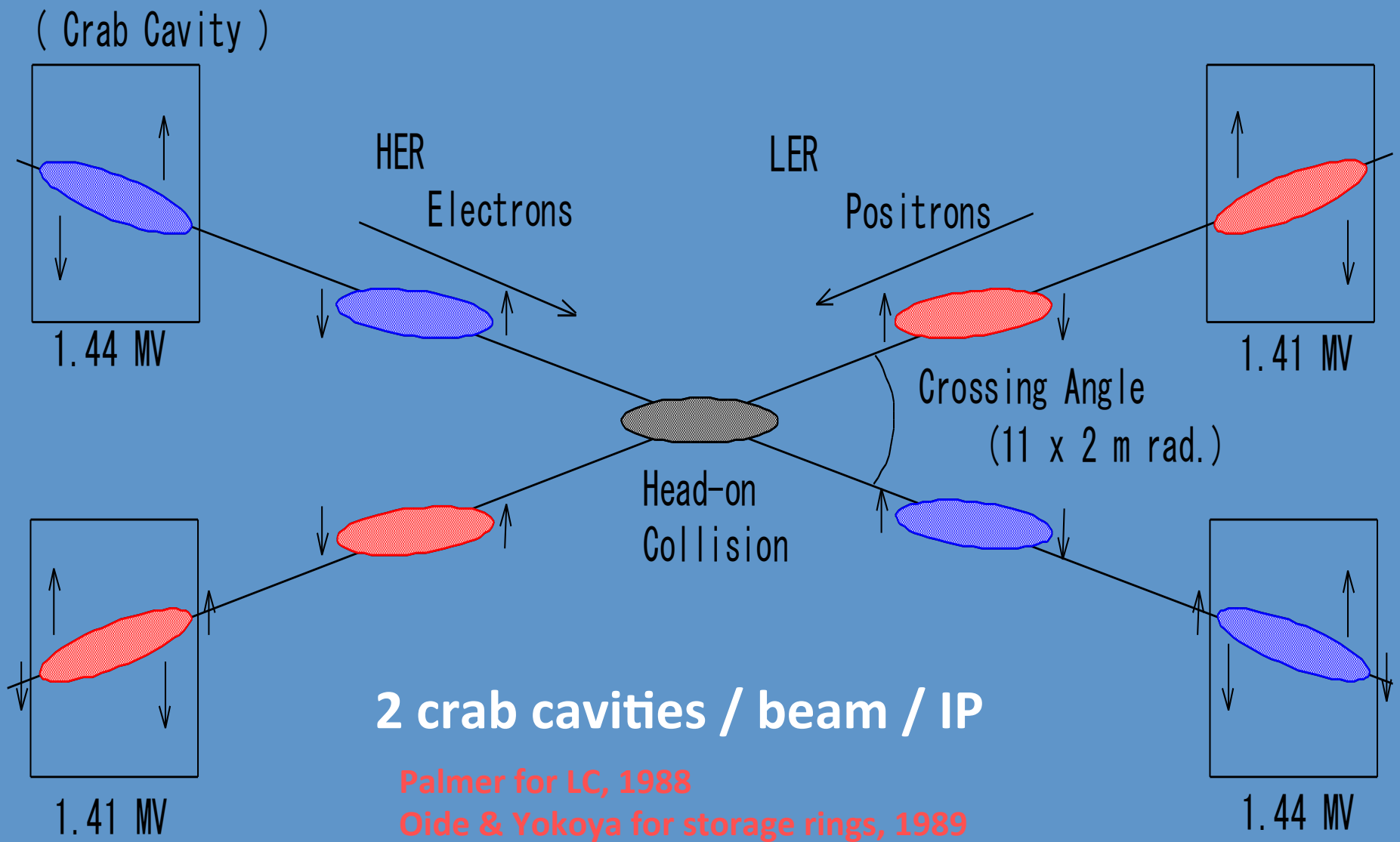
Recent (09/10/12) beta* levelling MD



Luminosity vs. Time for the entire shift (about 6 hours)

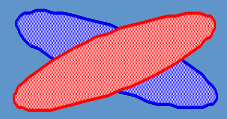

RF Deflector
(Crab Cavity)
HER
Electrons
LER
Positrons
1.44 MV
1.41 MV
Crossing Angle
(11 x 2 m rad.)
Head-on
Collision
1.41 MV
1.44 MV

Super-KEKB crab cavity scheme



2 crab cavities / beam / IP

Palmer for LC, 1988
Oide & Yokoya for storage rings, 1989



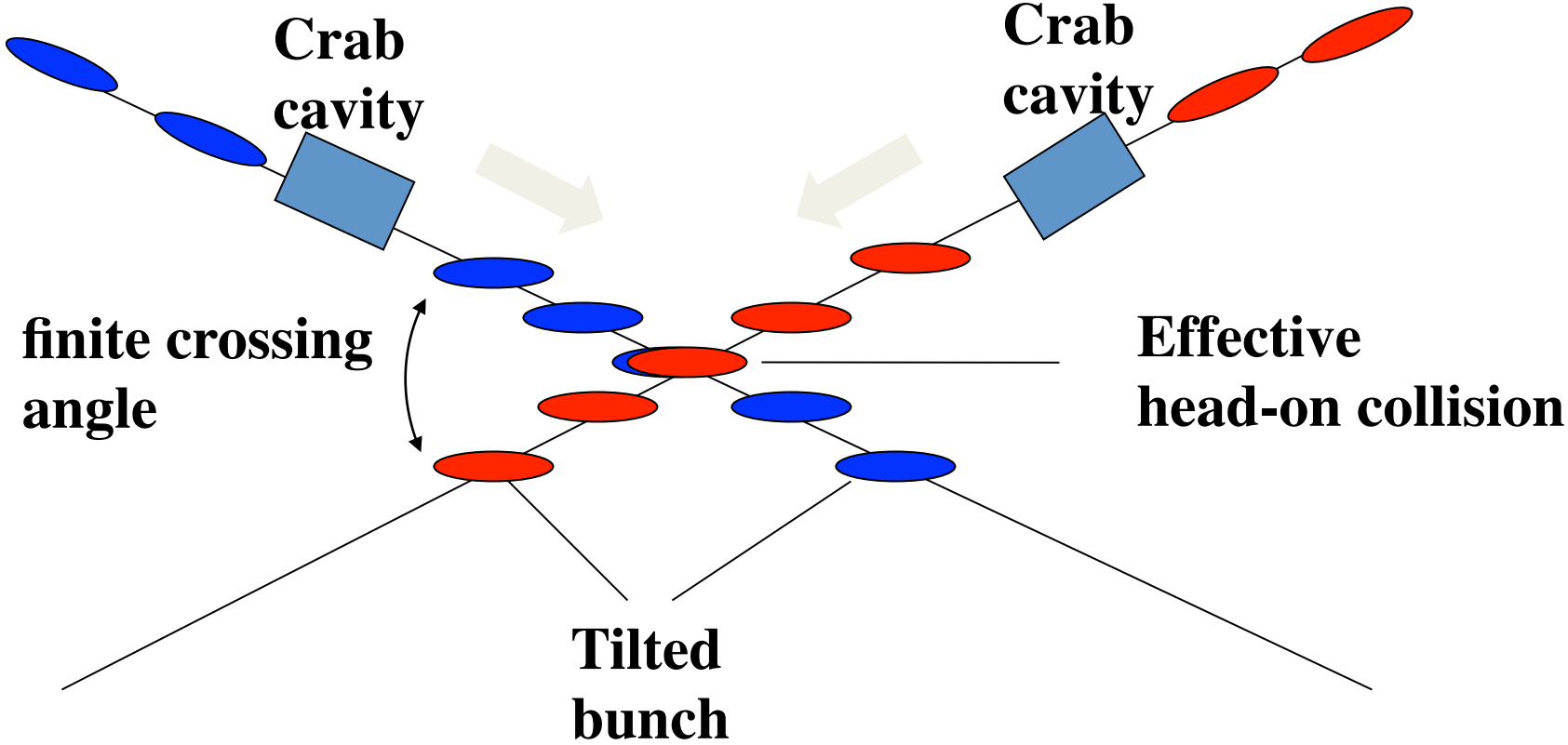
first crab cavities will be installed at KEKB in early 2006

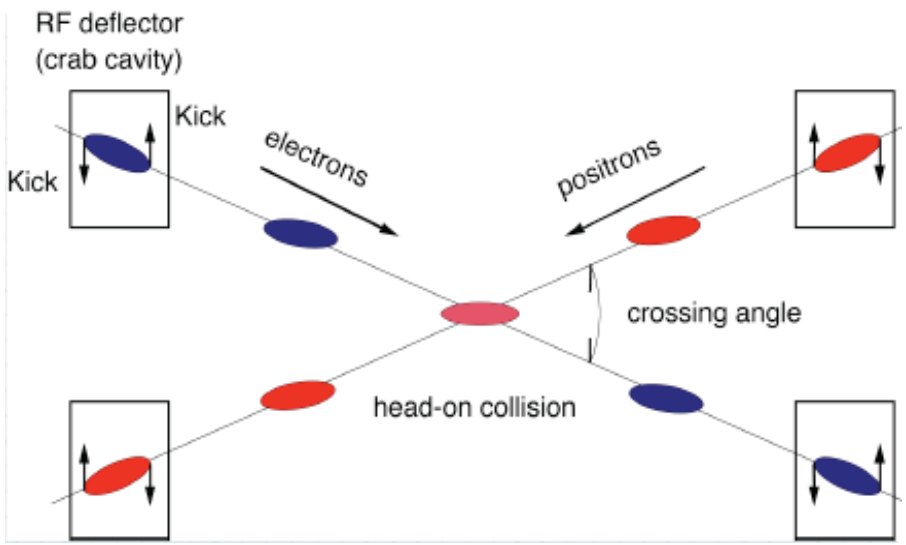
Crab Crossing Started at KEKB

- Two crab cavities were installed.
- Beam commissioning with crab crossing started in Feb. 2007.
- The effective head-on collision was confirmed by
  - streak camera
  - crab-phase scan
  - horizontal beam-beam kick, etc.

First in the world

- The highest vertical beam-beam tune-shift parameter is about 0.088 so far, which is higher than the geometrical gain due to head-on colliison by 15%.
  - 16.1/nb/s was obtained yesterday.
- There are a few speculated reasons for why the luminosity is lower than the prediction, but not yet confirmed.
- We will do more study & machine tuning.
- Crab crossing is a must for SuperKEKB.


Crab cavity
Crab cavity
finite crossing angle
Effective head-on collision
Tilted bunch


RF deflector
(crab cavity)
Kick
Kick
electrons
positrons
crossing angle
head-on collision

ELIC R&D: Beam-Beam (cont.)

Luminosity of a collider

(when $\sigma_{xe}=\sigma_{xp}$, $\sigma_{ye}=\sigma_{yp}$, and $\beta^*_{xe}=\beta^*_{xp}$, $\beta^*_{ye}=\beta^*_{yp}$)

$$L = \frac{N_e N_p f_c}{2\pi\sqrt{\sigma_{xe}^2+\sigma_{xp}^2}\sqrt{\sigma_{ye}^2+\sigma_{yp}^2}}$$

$$L = \frac{I_e \gamma_e \xi_{ye}}{r_c^e \beta_{ye}^*}\frac{1}{2}\left(1+\frac{\sigma_y}{\sigma_x}\right) \propto \xi_{ye}$$

proportional to b-b parameter

we assume both are *Gaussian* bunches, N_e and N_p are number of electrons and protons in bunches, f_c is collision frequency, σ_{xe}, σ_{ye}, σ_{xp} and σ_{yp} are bunch spot size

Beam-beam parameter (tune-shift)

(characterizes how strong the beam-beam force is)

$$\xi_{ye} = \frac{r_c^e N_p \beta_{ye}^*}{2\pi\gamma_e \sigma_{yp}(\sigma_{xp}+\sigma_{yp})}$$

Where r^c_e is electron classical radius of, γ_e is relativistic factor, and β^*_{ye} is vertical beta function at interaction point

Increasing beam-beam parameter

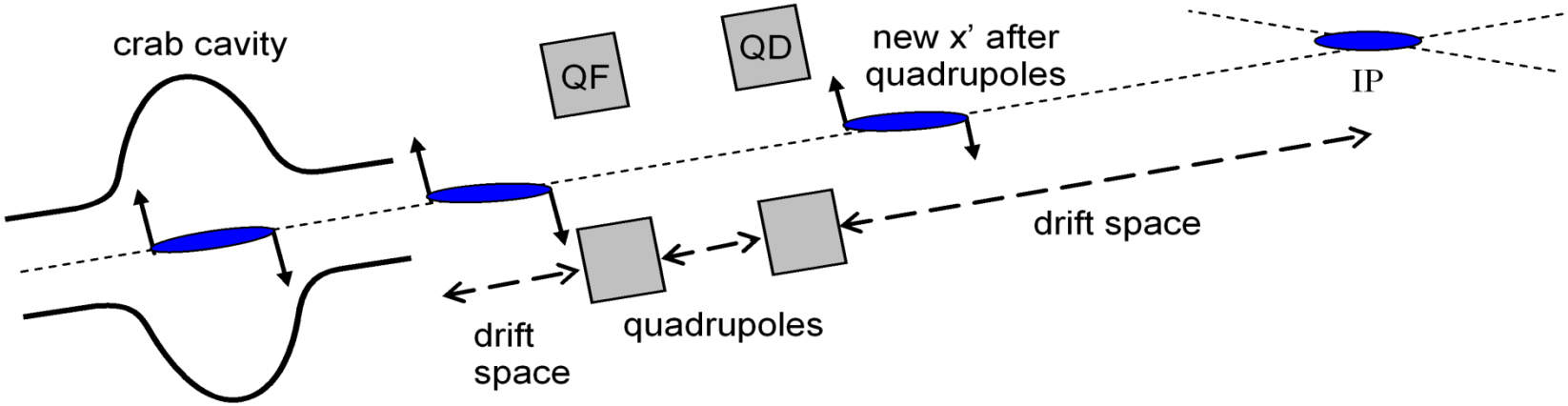
→ increasing luminosity

→ increasing beam-beam instability

Beam-beam effect

- linear part → tune shift
- nonlinear part → tune spread

Crab Cavity Function



The crab cavity is a deflection cavity operated with a 90° phase shift.

A particle at the centre of the bunch gets no transverse momentum kick and hence no deflection at the IP.

A particle at the front gets a transverse momentum that is equal and opposite to a particle at the back.

The quadrupoles change the rate of rotation of the bunch.