LHC optimization

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July 9, 2014

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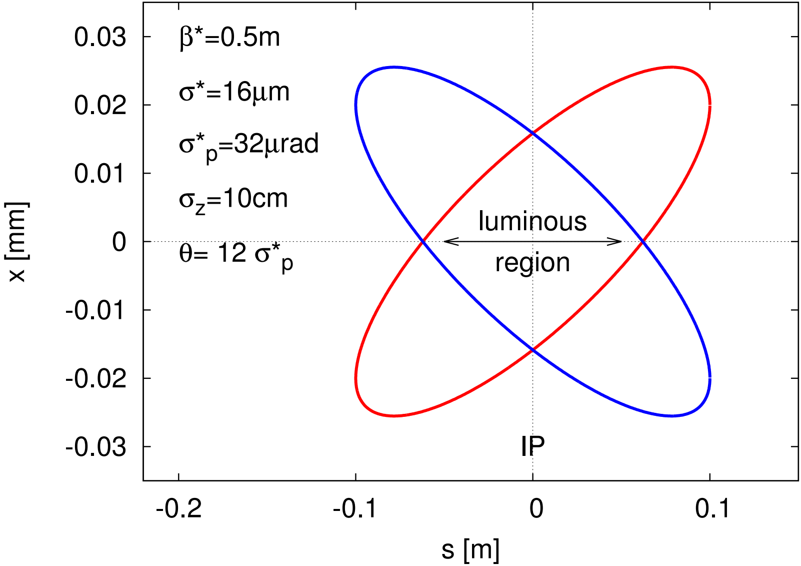
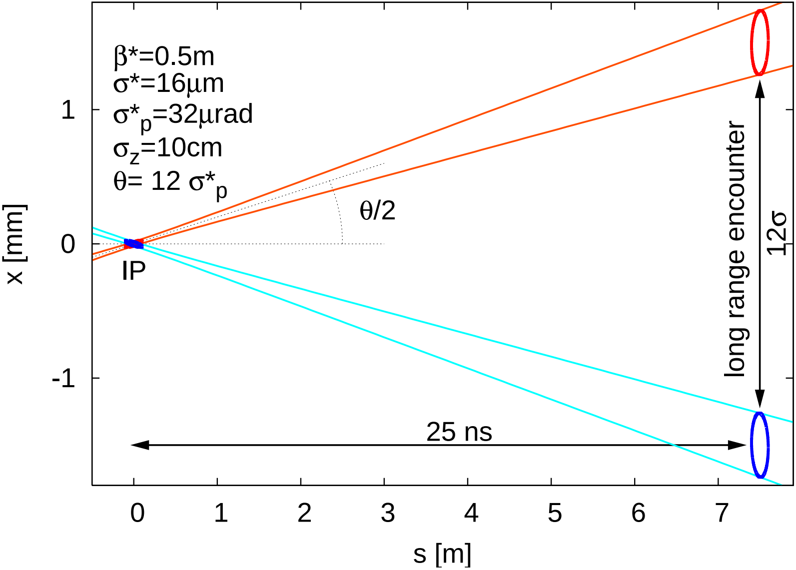
Collision



β*=0.5m
σ*=16μm
σ*p=32μrad
σz=10cm
θ= 12 σ*p
luminous
region
IP
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
x [mm]
-0.2
-0.1
0
0.1
s [m]

Crossing scheme



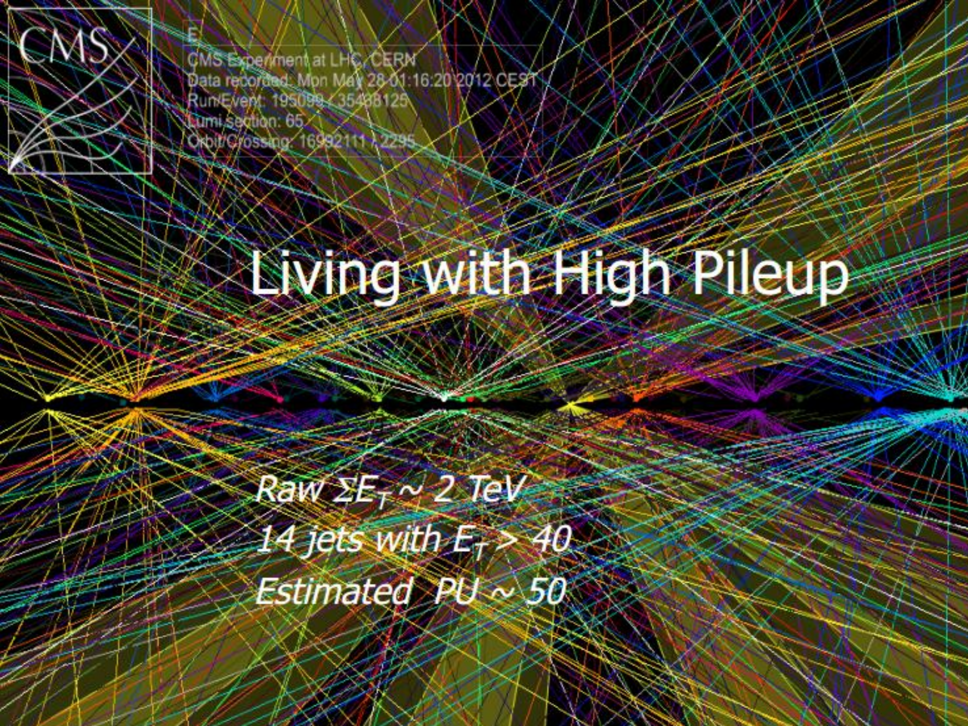
Luminosity, pile-up & luminous region

$$L = \frac{N_p^2 f_{rev} N_b}{4\pi\sigma^2} \frac{1}{\sqrt{1+\phi^2}}$$

with $\sigma = \sqrt{\beta^* \epsilon}$, Piwinski angle $\phi = \frac{\sigma_z}{\sigma}\frac{\theta}{2}$.
The event rate per second is $R = L\sigma_p$.
The pile-up is the number of events per crossing:

$$PU = \frac{L\sigma_p}{f_{rev} N_b}$$

The luminous region: $\dfrac{\sigma_z}{\sqrt{2(1+\phi^2)}}$



Living with High Pileup

Raw $\Sigma E_T \sim 2$ TeV

14 jets with $E_T > 40$

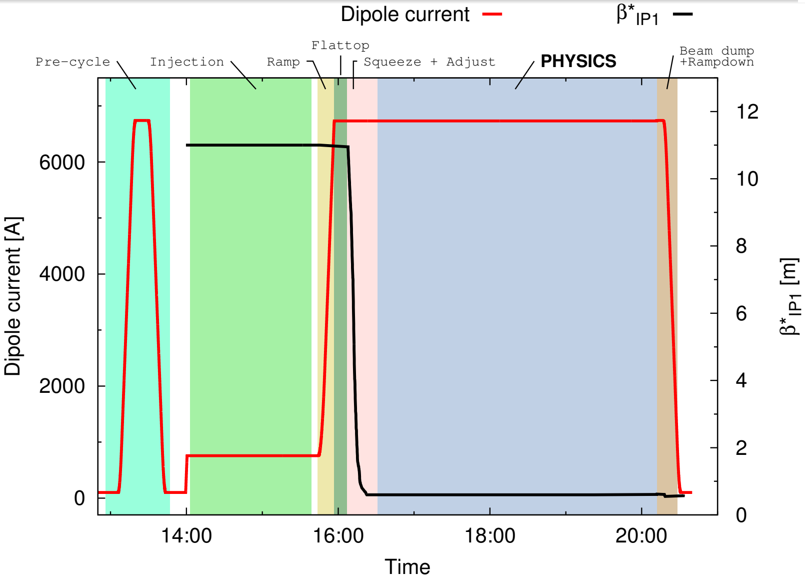
Estimated PU ~ 50

What happens in physics

- Intensity decays due to *burn-off*, $R = L\sigma_p$, events correspond to lost protons.
- Emittances blow-up due to non-linear diffusion and to intra-beam scattering
- Emittances shrink due to synchrotron radiation damping
- Integrated luminosity:

$$L_{int} = \int L(t)dt$$

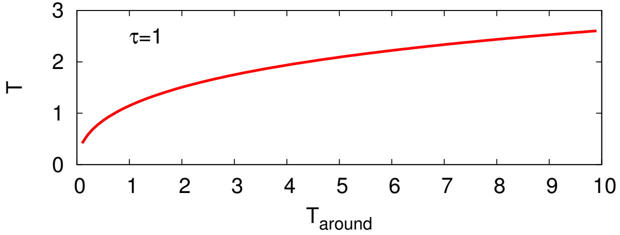
The LHC magnetic cycle



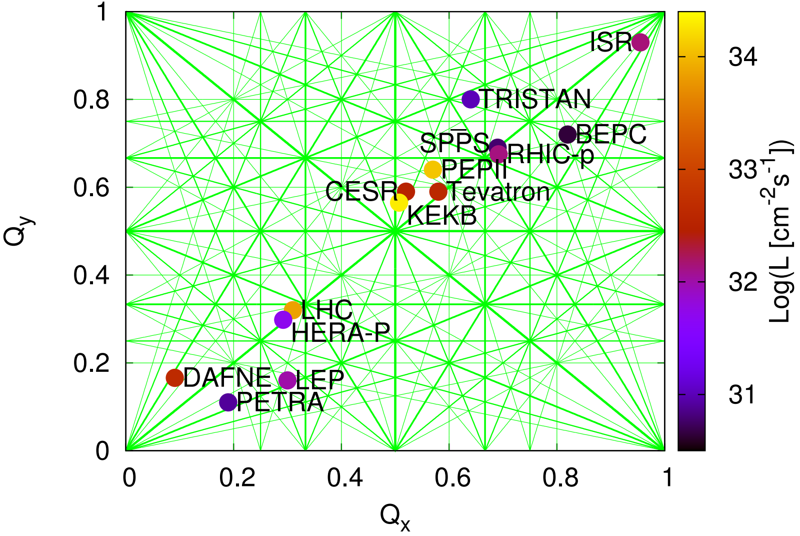
Not always in physics...

Optimal fill length T

- During the *turn-around*, T_{around}, $L(t) = 0$
- During the physics fill $L(t) \approx L_0 e^{-t/\tau}$
- Integrated lumi over a run T_{run}:
  $L_{int} = L_0\tau(1 - e^{T/\tau})\frac{T_{run}}{T+T_{taround}}$
- Maximum L_{int} for
  $T = -\tau W_{-1}(-e^{-T_{around}/\tau-1}) - (T_{around} + \tau)$
  W_{-1} is the Lambert W function in branch -1.

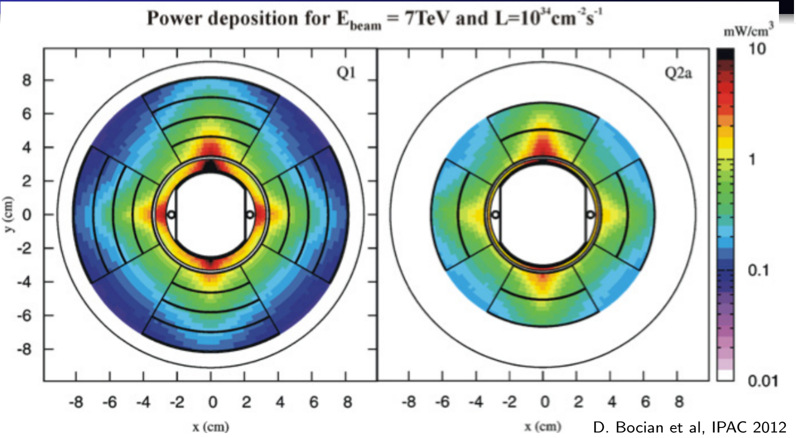


Colliders in the tune space



The winner so far, KEKB, sits near $Q_x \approx Q_y \approx 0.5$

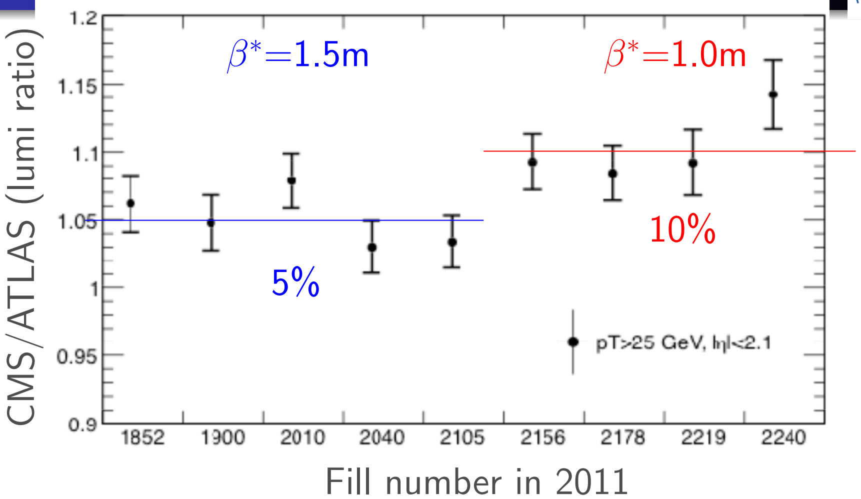
Can LHC beat KEKB?



D. Bocian et al, IPAC 2012

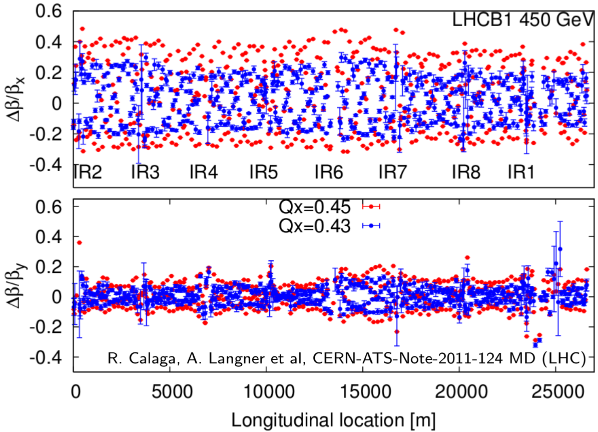
- ★ Collision debris can quench IR triplets
- ★ Luminosity limited to $\approx 1.7 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (LHC cannot beat KEKB on paper)
- ★ HL-LHC with large quadrupoles $\rightarrow 5 \times 10^{34}$

Luminosity imbalance CMS/ATLAS



ATLAS was not happy to get lower luminosity. This was due to optics errors, different β^*, called β-beating $= (\beta_{meas} - \beta_{model})/\beta_{model}$

Can LHC operate at $Q_x \approx Q_y \approx 0.5$?



- ★ Half integer resonance represents a challenge for optics control
- ★ First exploration at injection in 2011 → Need further demonstrations

Optics measurements

Betatron oscillations after a single kick

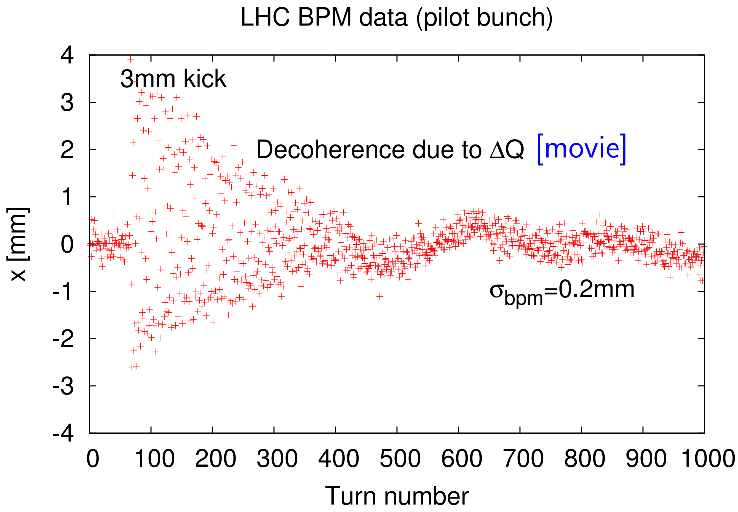
$$x(N,s) = \sqrt{2\,\beta_x(s)\,J_x}\,\cos(2\pi\,Q_x\,N + \phi_x(s))$$

Beta function , tune , phase

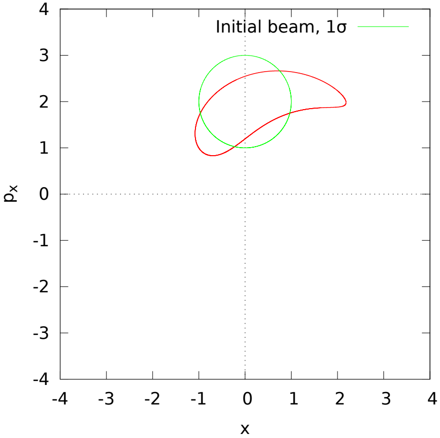
β and ϕ are related by:

$$\phi_{0\to 1} = \phi(s_1) - \phi(s_0) = \int_{s_0}^{s_1} \frac{\mathrm{d}s}{\beta(s)}$$

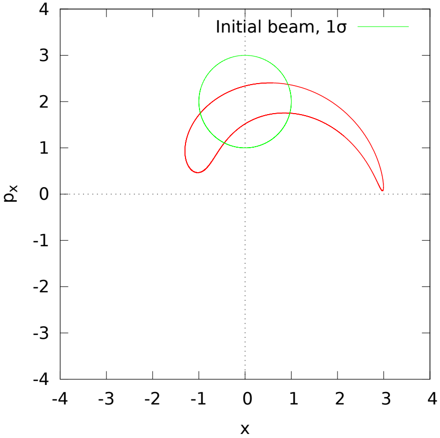
Turn-by-turn BPM data



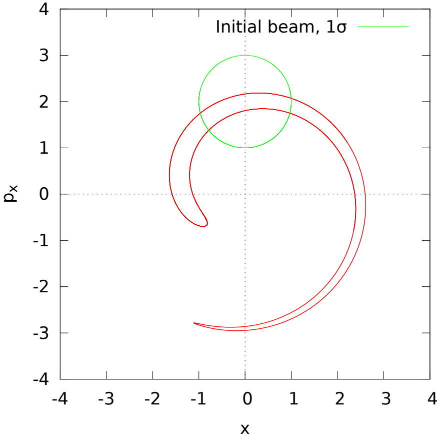
Decoherence from amplitude detuning



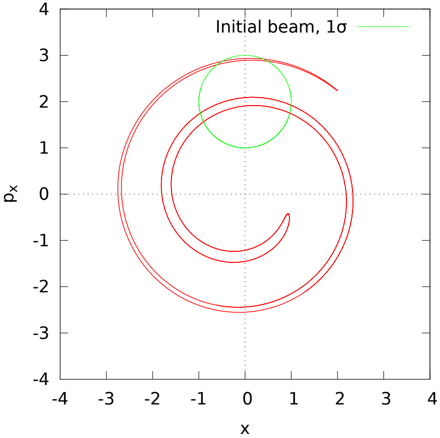
Decoherence from amplitude detuning



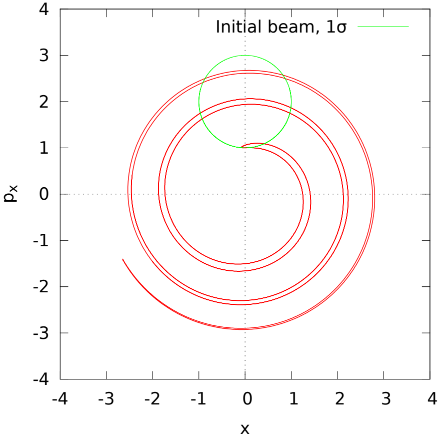
Decoherence from amplitude detuning



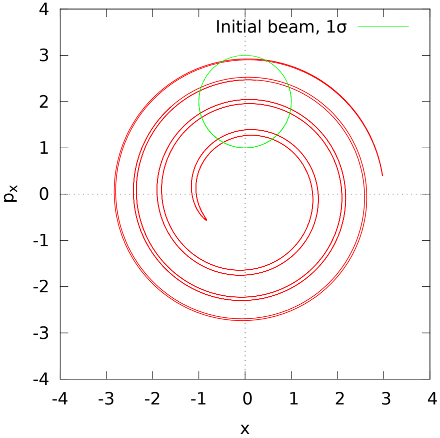
Decoherence from amplitude detuning



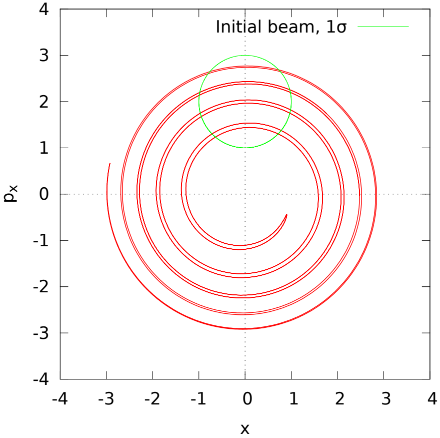
Decoherence from amplitude detuning



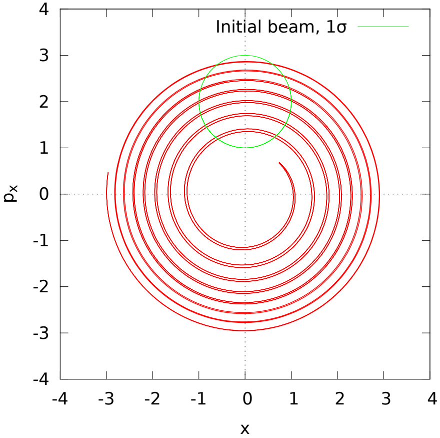
Decoherence from amplitude detuning



Decoherence from amplitude detuning

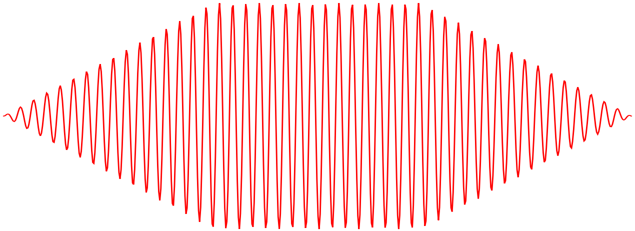


Decoherence from amplitude detuning

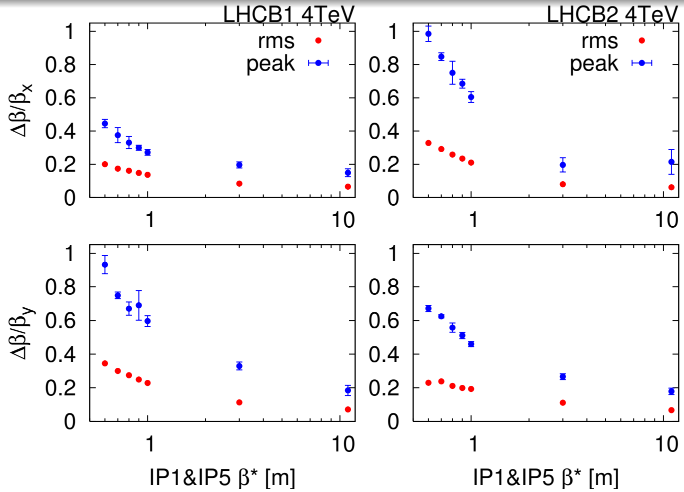


Forced oscillations with AC dipole

- An AC dipole forces betatron oscillations
- If addiabatically ramped up & down causes no emittance blow up
- Can be used as many times as needed with the same beam

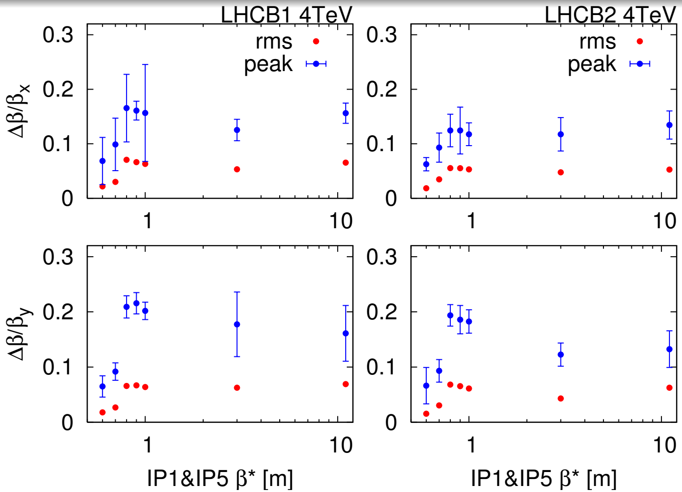


Measuring β-beating versus β^*



Measuring virgin machine (100% β-beating!) to compute best local corrections (also for coupling)

After correcting β-beating



Local and global corrections yield about 5% β-beating at 0.6 m!

LHC optics makes history

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 091001 (2012)

Record low β beating in the LHC

R. Tomás,* T. Bach, R. Calaga, A. Langner, Y. I. Levinsen, E. H. Maclean, T. H. B. Persson,
P. K. Skowronski, M. Strzelczyk, and G. Vanbavinckhove
CERN, CH 1211 Geneva 23, Switzerland

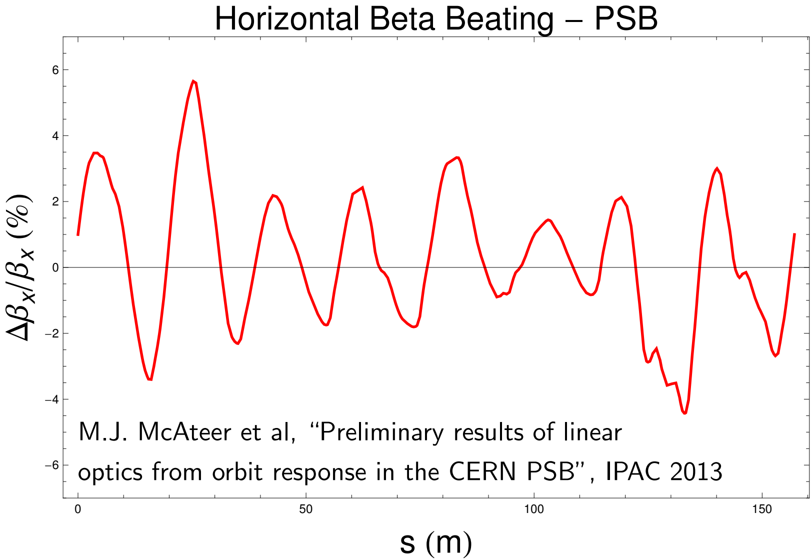
R. Miyamoto
ESS AB, SE-221 00 Lund, Sweden
(Received 12 July 2012; published 28 September 2012)

Lepton Collider	Circumference [km]	Peak $\Delta\beta/\beta$ [%]	Hadron Collider	Circumference [km]	Peak $\Delta\beta/\beta$ [%]
PEP II	2.2	30	HERA-p	6.3	20
LEP	27	20	Tevatron	6.3	20
KEKB	3	20	RHIC	3.8	20
CESR	0.8	7	**LHC**	27	7

CMS and ATLAS luminosities in 2012 got equal!

Phys. Rev. ST Accel. Beams **15**, 091001, 2012

Comparison to PSB β-beating



Peak β-beating of $\approx$5% without corrections.

AC dipole for non-linear diagnostics

- ★ **Adiabaticy with non-linearities**

  "Adiabaticity of the ramping process of an AC dipole" PRSTAB **8** 024401

- ★ **Resonace Driving Terms**

  "Measurement of global and local resonance terms" PRSTAB **8** 024001

- ★ **Coupling & Chromatic coupling**

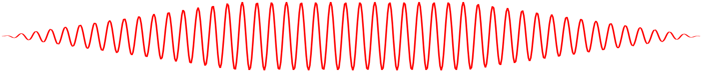
  "Measurement of Coupling Resonance Driving Terms in the LHC with AC Dipoles" IPAC 2011

  "Chromatic coupling correction in the LHC" PRSTAB **16**, 081003

- ★ **Amplitude detuning**

  "Direct amplitude detuning measurement with AC dipole" PRSTAB **16** 071002

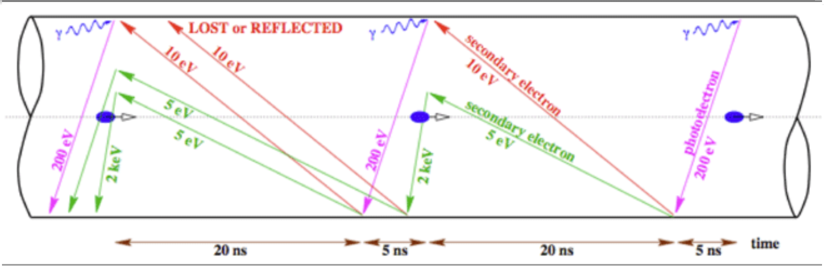
- ★ **Impedance measurements** N. Biancacci CERN-THESIS-2014-043



Limits and solutions for LHC

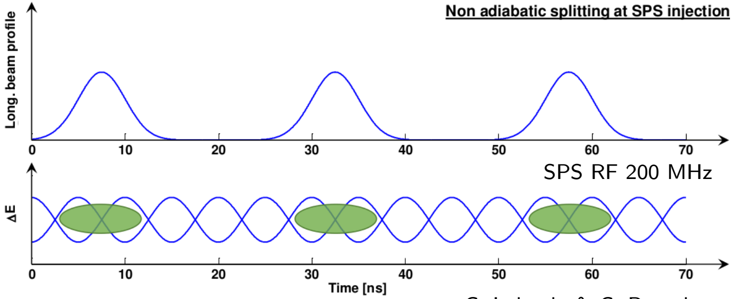
- ★ Quench limit
- ★ e-cloud and scrubbing with doublets
- ★ 200 MHz main RF system in LHC
- ★ Crab cavity for enlarged luminous region
- ★ Wire for beam-beam long-range compensation

Electron cloud in the LHC



- ★ Cascade process filling the vacuum chamber with e-
- ★ Causes too large heat-load and instabilities
- ★ Luckily it self-conditions (*scrubbing*)
- ★ However e-cloud made 25 ns operation impossible so far

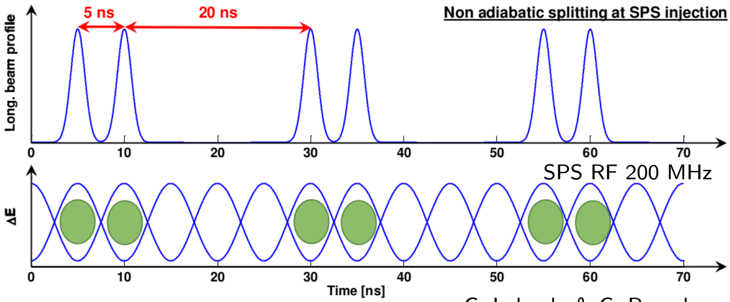
e-cloud mitigation: doublet scrubbing



G. Iadarola & G. Rumolo

- ★ The 5-20 ns bunch structure generates more e-cloud and more scrubbing
- ★ The only promissing mitigation so far...
- ★ Generation of doublets to be demonstrated

e-cloud mitigation: doublet scrubbing



G. Iadarola & G. Rumolo

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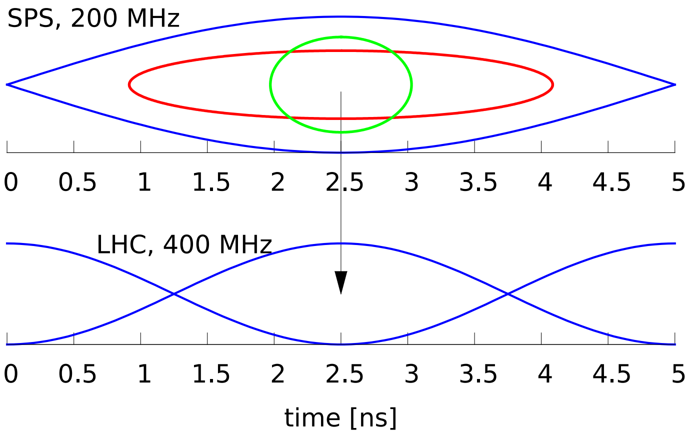
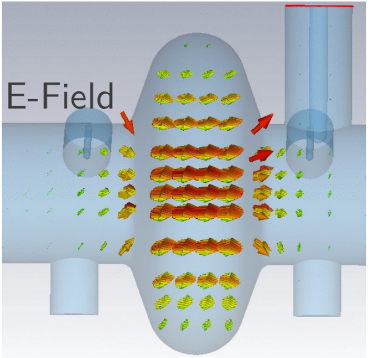
Why 400 MHz RF in the LHC?



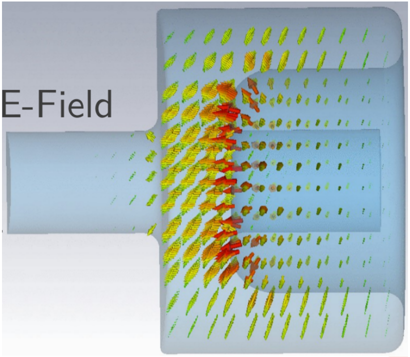
Wouldn't 200 MHz RF in LHC be more natural?
20 years ago SC RF cavities of 200 MHz were not an option.

200 MHz SC cavities design, LHC

400 MHz (current)



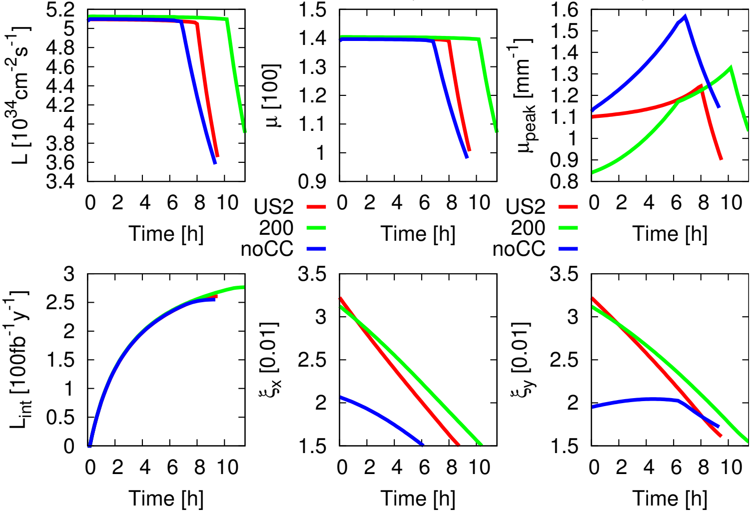
200 MHz



- ★ New design concept, quarter-wave cavity, allows for SC 200 MHz for LHC (R. Calaga).
- ★ This would allow longer bunches with more intensity!

Physics fill in HL-LHC I

R. Tomas et al, “HL-LHC alternatives”, RLIUP 2013

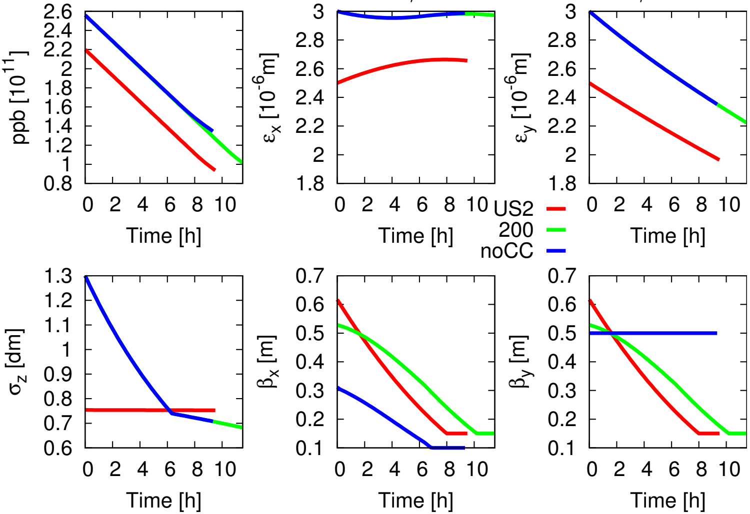


Luminosity leveling with β^* for 3 scenarios:

Nominal, 200 MHz and 200 MHz & no crab cavities

Physics fill in HL-LHC II

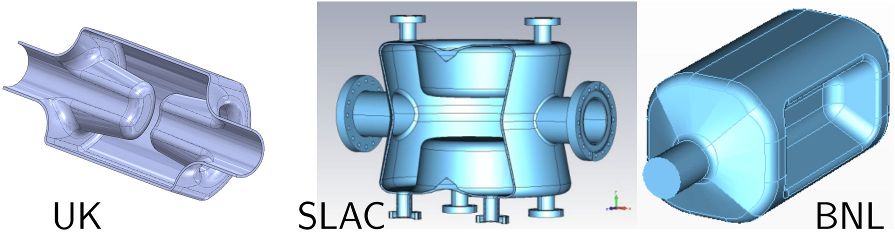
R. Tomas et al, "HL-LHC alternatives", RLIUP 2013

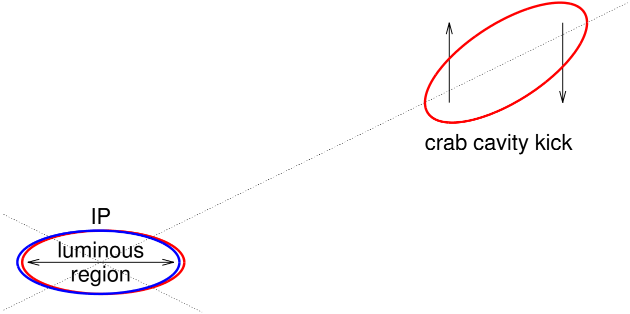


Luminosity leveling with β^* for 3 scenarios:

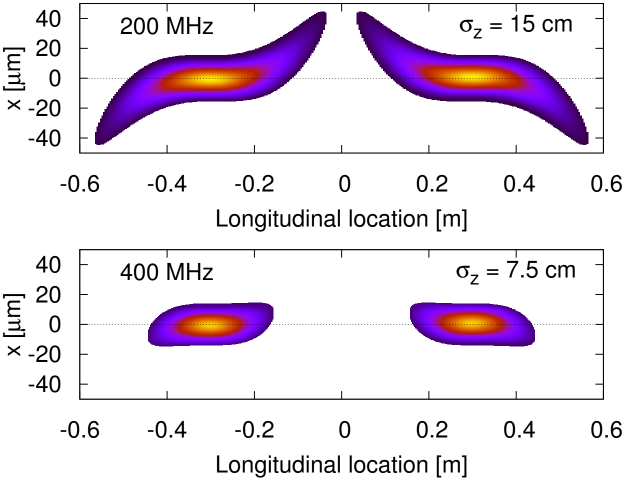
Nominal, 200 MHz and 200 MHz & no crab cavities

Crab cavity





Overlap with real crab cavities

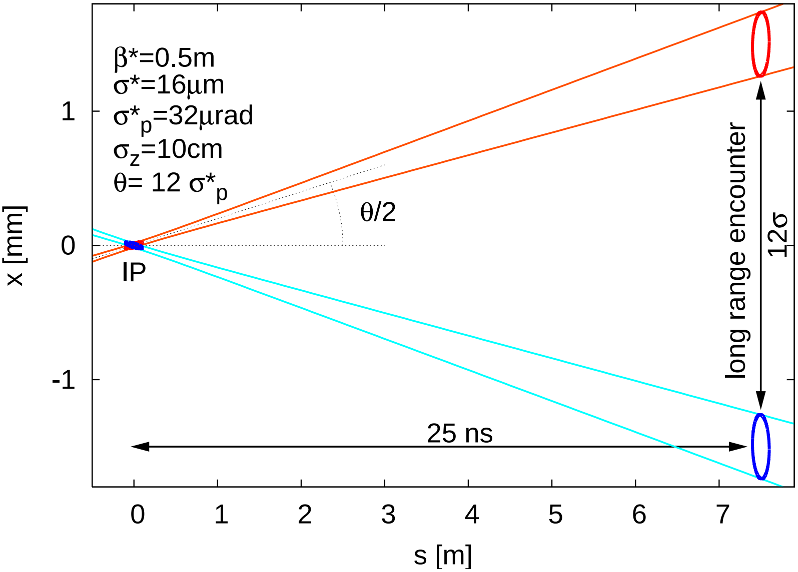


Luminosity integral

$$2N^2 c f_r n_b \cos^2\frac{\theta}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\rho_x(x_1)\rho_x(x_2)\times$$
$$\rho_y(y_1)\rho_y(y_2)\rho_s(s_1-ct)\rho_s(s_2+ct)dxdydsdt=$$

$$\frac{N^2 f_r n_b}{4\pi\sigma_x\sigma_y}\frac{c\cos\frac{\theta}{2}}{\pi\sigma_s^2}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}dtds\exp\Bigg[-\frac{c^2t^2}{\sigma_s^2}-\frac{s^2\cos^2\frac{\theta}{2}}{\sigma_s^2}$$
$$-\frac{\sin^2\frac{\theta}{2}}{4k_{cc}^2\sigma_x^2}\Big[-4\cos^2[k_{cc}s]\sin^2[k_{cc}ct]$$
$$-8sk_{cc}\sin[k_{cc}s]\cos[k_{cc}ct]$$
$$+2-\cos[2k_{cc}(s-ct)]-\cos[2k_{cc}(s+ct)]+4k_{cc}^2s^2\Big]\Bigg]$$

Compensating long-range with wires

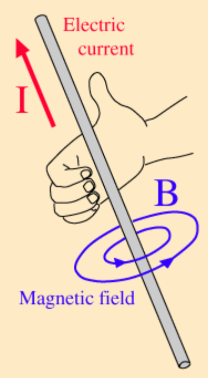


Compensating long-range with wires

★ Beam-beam kick:

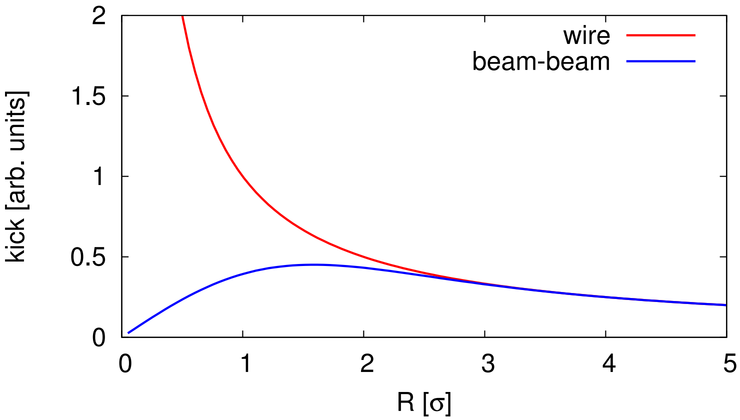
$$\Delta p_R = 8\pi\epsilon\xi \frac{1 - e^{-R^2/(2\sigma^2)}}{R}$$

★ Magnetic field of a wire with current I:



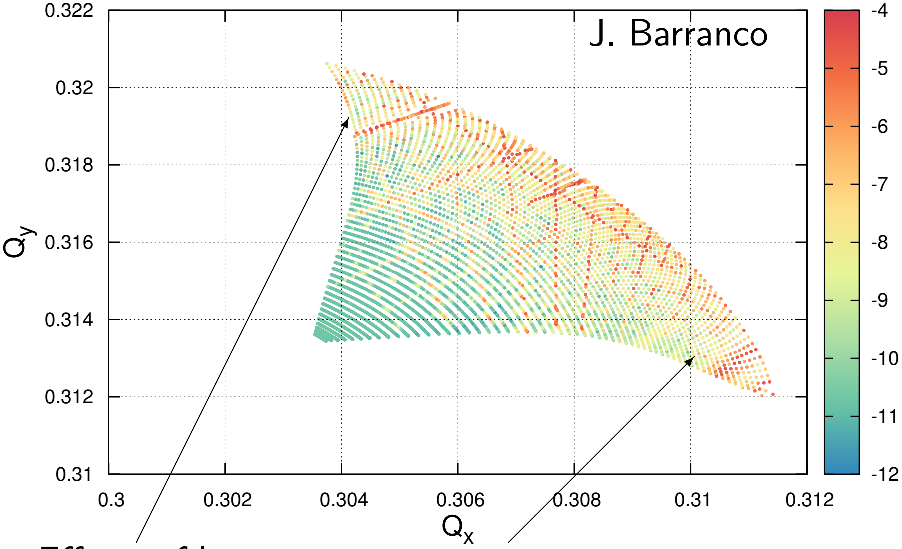
$$B = \frac{\mu_0 I}{2\pi R}$$

Compensating long-range with wires



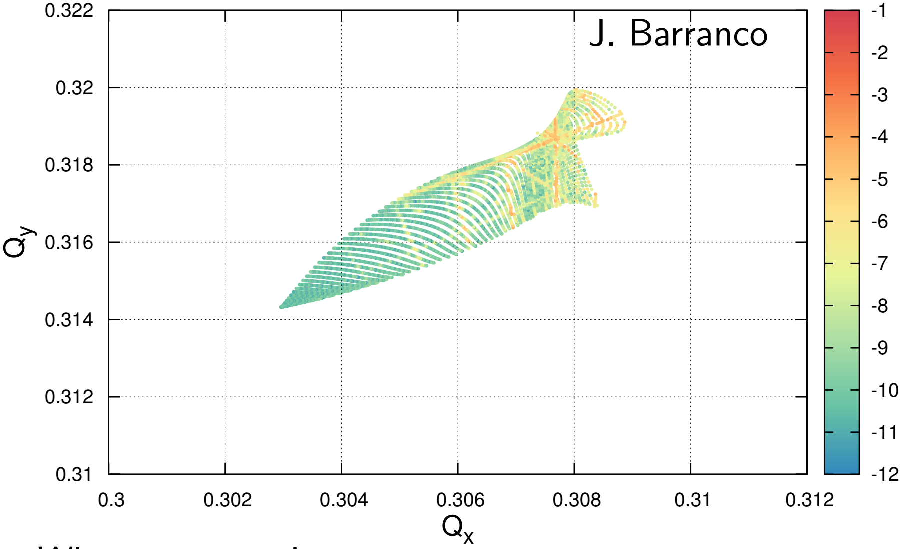
At large R the beam-beam kick gets approximately equal to the wire kick.

HL-LHC nominal frequency map



Effects of long range encounters

HL-LHC frequency map with wire



Wire compensation

Summary

- LHC challenges appear on all fronts:
    - optics control
    - detectors (ATLAS/CMS luminosity imbalance, pile-up, peak pile-up density, luminous region)
    - e-cloud
    - quench limit
    - beam dynamics
    - technology choice
- Continuous R&D in beam dynamics and new technologies is fundamental to boost LHC's performance