# AC-Dipole

**S. Fartoukh and R. Tomas, LHCCWG 10/04/2007**

- Basic Principles
- Aperture measurement
- Linear optics measurement (e.g. β-beating and coupling).
- Measurement of non-linear driving terms
- Emittance preservation and ramping-up/down adiabaticity conditions
- Summary

# Basic Principles (1/2)

- **AC-dipole**: a dipole magnet with an oscillating field at a (more or less) tunable frequency $Q_D$, close (but not too close!) to the beam eigen-frequency $Q_y$ or $1\text{-}Q_y$:

→ AC –dipole excitation at abscissa $s=0$: $\Delta y'(n)[\sigma_{beam}] \equiv A_D \times \sin(2\pi Q_D n + \varphi_D)$ (1)

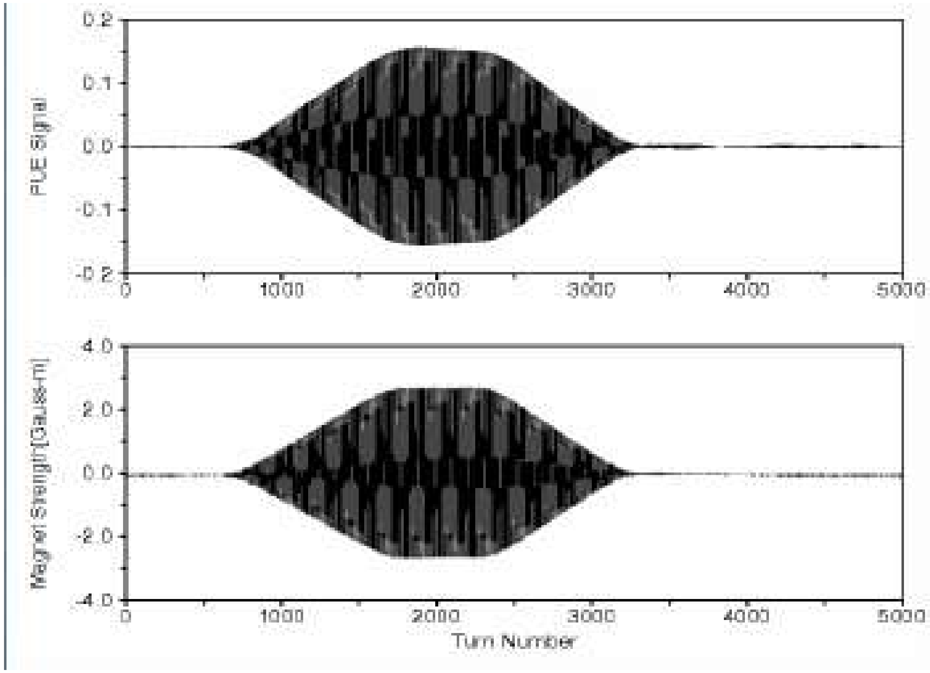
→ Beam response at abscissa $s$: $\frac{y(n;s)}{\sqrt{\varepsilon\beta_y(s)}} \approx \frac{A_D}{4\pi(Q_D - Q_y)} \times \sin(Q_D n + \phi_D + \mu_y(s))$ (2)

(assuming perfectly linear machine w/o coupling)

→ Allows to achieve **long-lasting coherent oscillations** with amplitude proportional to the AC-dipole amplitude $A_D\,[\sigma_{beam}]$ and inversely proportional to the distance $\delta Q = Q_D - Q_y$ in the frequency domain.

# Basic Principles (2/2)

- Technique first developed in the Brookhaven AGS (**M. Bai et al.**) and tested in the CERN SPS using the transverse damper:




**AC-dipole driven oscillation in RHIC**

- **Advantages w.r.t. the kick method:**
  1. **Long-lasting oscillations of sizeable and tunable amplitude in spite of tune spread** (but provided strong enough AC excitation amplitude)
  2. To some extent (see later), **non-destructive technique in terms of emittance preservation** provided the ac excitation can be ramp up and down adiabatically.

# Aperture measurement

- The fast method by **kicking the beam** was already discussed by Stefano (at the 11th LHCCWG)

→ Main drawbacks (playing the evil advocate!):

2. Apply "blindly" large kicks up to some signal in BLM ….or magnet quenches!
3. **Need to refill after each kick** (due to the induced emittance growth) to re-measure (e.g. off-momentum at $\delta = \pm 1.5\ 10^{-3}$) and eventually re-optimized the orbit.

- With **the AC-dipole**,

1. One can in principle **excite safely the beam**, e.g.

   - by increasing slowly the ac excitation amplitude at constant tune**,**

   - or changing the tune (to put it closer to the ac frequency) at constant excitation amplitude (see Eq. 2).

2. a priori **no need to refill** after each aperture measurement, e.g. using the same beam for off-momentum scan and/or optimizing the closed orbit at critical locations.
3. one can even **measure in parallel and possibly correct the beta-functions** (see hereafter).

# Linear Optics measurement (1/4)

## β-function and phase advances

Assuming a **perfectly linear machine but with linear coupling**, the AC-dipole theory can be extended in 4 D (S. Fartoukh  SL-Report 2002-059 and LPR 644):

→ Exciting in one transverse plane, say vertically:

$$\Delta y'(n)[rad] \equiv y'_D \times \sin(2\pi Q_D n + \varphi_D)$$

→ Looking at the beam signal FFT at the excitation frequency $Q_D$:

$$\begin{cases} \hat{x}(Q_D;s) \equiv \frac{1}{N}\sum_{n=0}^{N-1} x(n;s)\exp(-2i\pi Q_D n) \\ \hat{y}(Q_D;s) \equiv \frac{1}{N}\sum_{n=0}^{N-1} x(n;s)\exp(-2i\pi Q_D n) \end{cases}$$

→The betatron phase advance between BMP $i$ and BPM $j$ is given by

$$\mu_y(s_j) - \mu_y(s_i) \equiv \mathrm{Arg}\left[\frac{\hat{y}(Q_D;s_j)}{\hat{y}(Q_D;s_i)}\right]$$

→The beta-function at BPM number $i$ is known within a multiplicative constant

$$\beta_y(s_i) \equiv \frac{\left|\hat{y}(Q_D;s_i)\right|^2}{\mathbf{K}^2}$$

→With K given by

$$\mathbf{K} \equiv \frac{y'_D\sqrt{\beta(s=0)}}{8\left|\sin(\pi(Q_D - Q_y))\right|} \approx \sqrt{\frac{1}{N_{BPM}}\sum_{j=1}^{N_{BPM}}\frac{\left|\hat{y}(Q_D;s_j)\right|^2}{\beta_y^{(0)}(s_j)}}$$

(the approximation for **K** is only valid when there is no **systematic** β-beating w.r.t. the nominal β-function, namely $\beta^{(0)}$ ).

→ This technique has an intrinsic measurement error of the order of

$$\varepsilon = \frac{\Delta\beta_y}{\beta_y} \approx \frac{\sin(\pi(Q_D - Q_y))}{\sin(\pi(Q_D + Q_y))} \approx 3-6\% \text{ for the LHC when exiting at 0.01 or 0.02 from the tune}$$

( can be cured by a multi-carrier excitation on both sides of the betatron tune).

# Linear Optics measurement (2/4)

## Linear coupling

→The beam signal FFT in the other plane contains the full information on linear coupling:

$$\hat{x}(Q_D; s) \approx \frac{\pi \mathrm{K} \sqrt{\beta_x(s)}\; e^{i\varphi_D + i\mu_x(s) + i\pi(Q_x - Q_y)}}{2\sin(\pi(Q_D - Q_x))} \times C_-(Q_x - Q_D; s)$$

$$\text{with } C_-(q;s) \equiv \underbrace{c_-}_{\substack{\text{usual coupling coefficient} \\ \text{(closest tune approach)}}} - \frac{i}{\pi} e^{-i\pi q} \sin(\pi q) \underbrace{\int_0^s ds' K_{skew}(s') \sqrt{\beta_x \beta_y}\, e^{i(\mu_x - \mu_y)}}_{\substack{\text{contribution of the coupling sources} \\ \text{from the AC-dipole to the observation point}}} \underset{q \ll 1}{\approx} c_-$$

→Note that determining the phase of $c_-$, implies the knowledge of the phase $\varphi_D$ of the AC-excitation with respect to the beam at turn n=0 (starting point for the FFT, see Eq. (1)).

→ This technique has an intrinsic measurement error of the order of

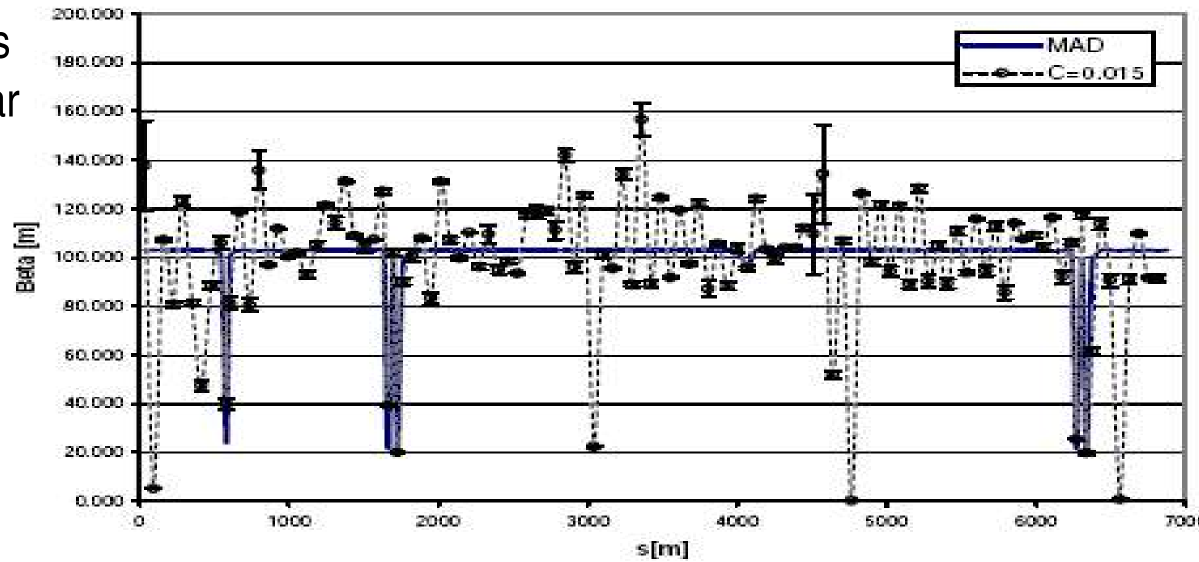
$$\varepsilon = \frac{\Delta|C_-|}{|C_-|} \approx \frac{\sin(\pi(Q_D - Q_x))}{\sin(\pi(Q_D + Q_x))} \approx 5\% \text{ for the LHC when exciting exactly in between } Q_x \text{ and } Q_y.$$

(can be cured by a multi-carrier excitation, say above $Q_y$ and below $Q_x$ with, as a side product the combined measurement of the sum coupling coefficient, see SL-Report 2002-059)

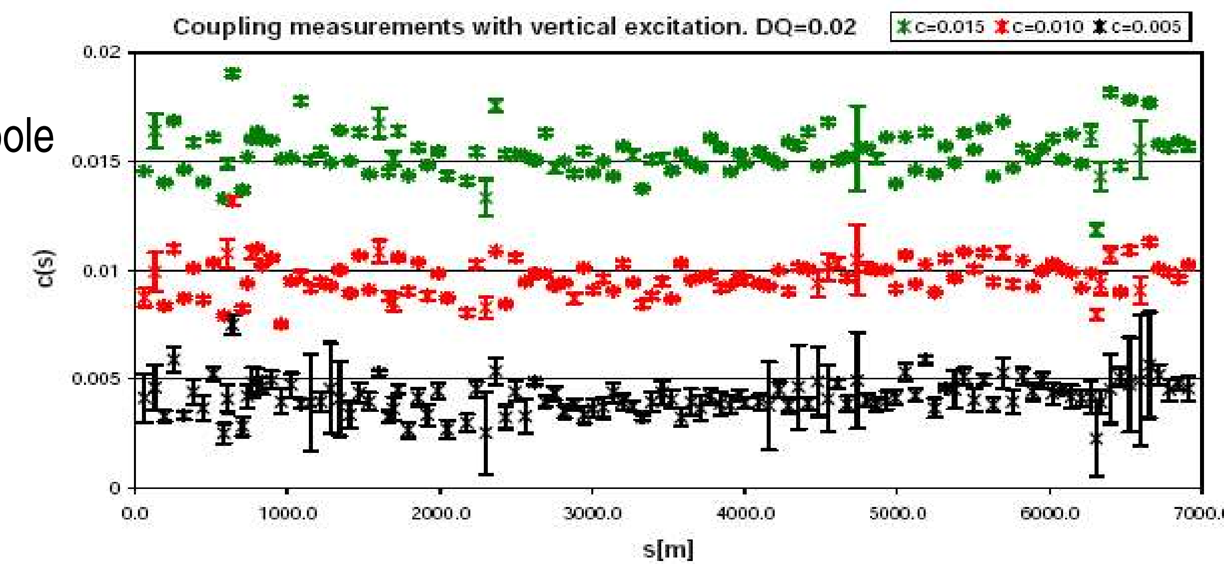
Correction is guaranteed

# Linear Optics measurement (3/4)
# SPS MD

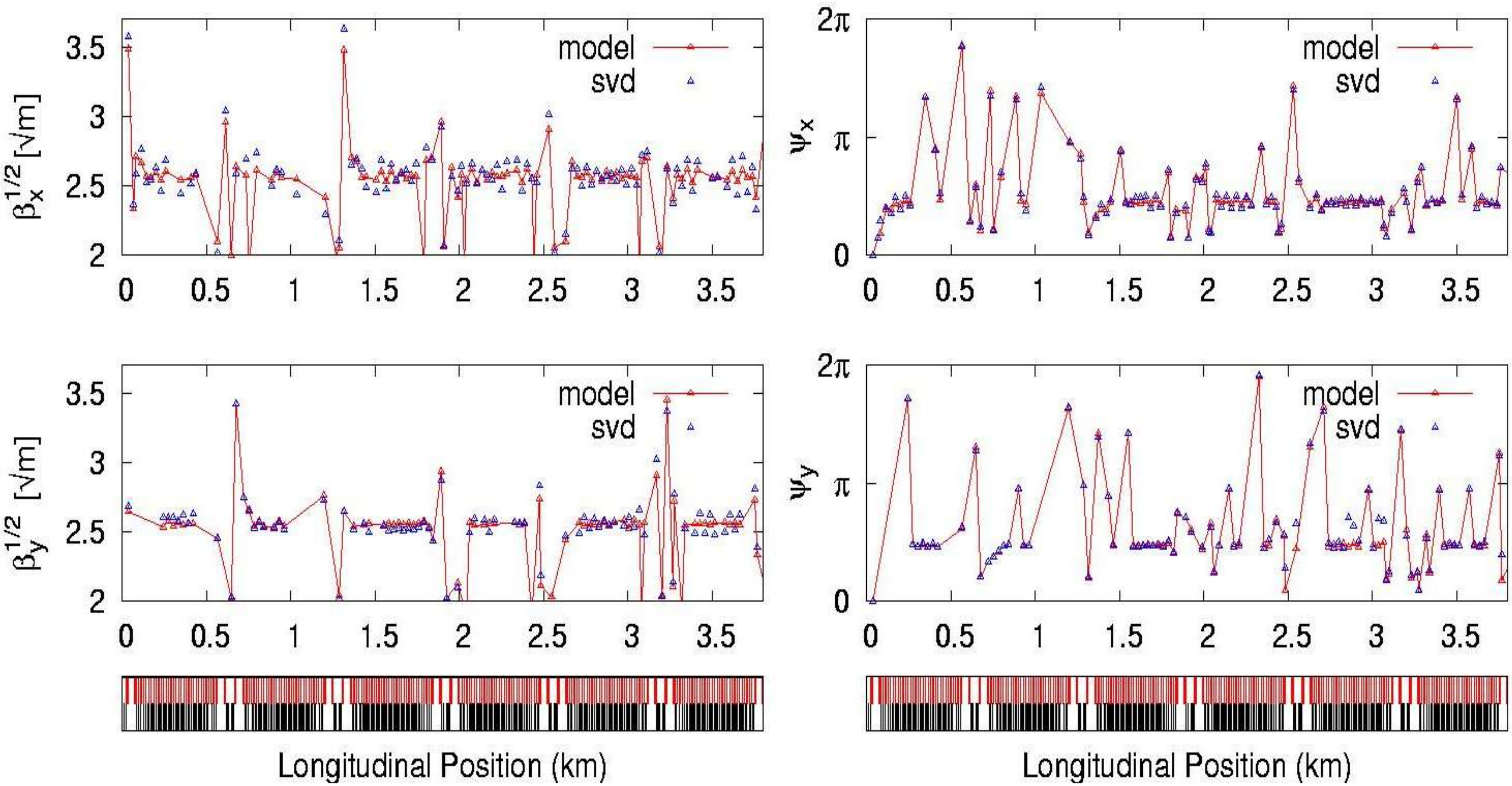
Measurement of the beta-functions in the SPS in the presence of linear coupling ($|c_-|$=0.015).




Measurement of the modulus of $C_-(q;s)$ for different skew quadrupole settings.

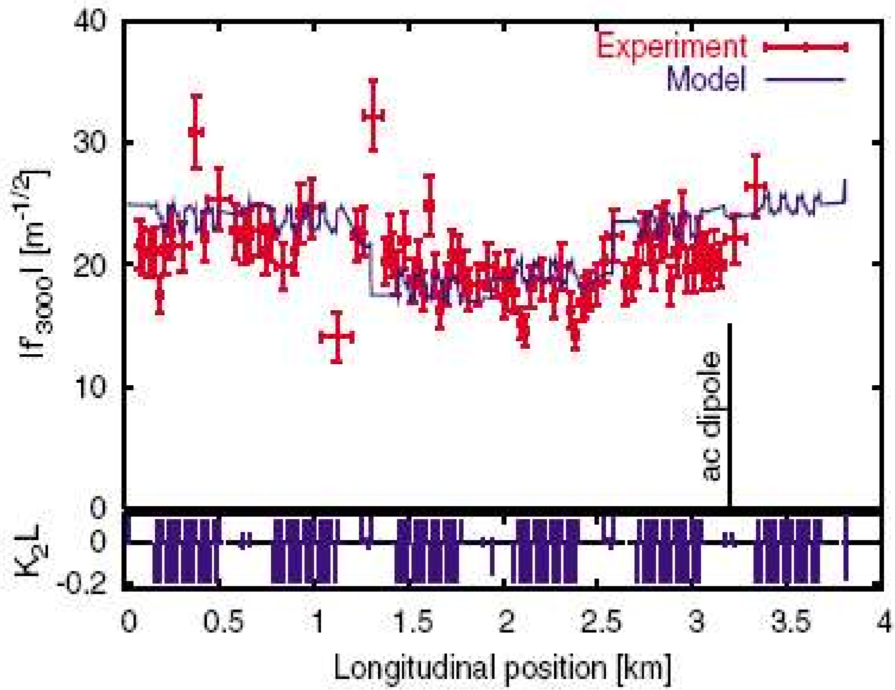


# Linear Optics measurement (4/4) RHIC

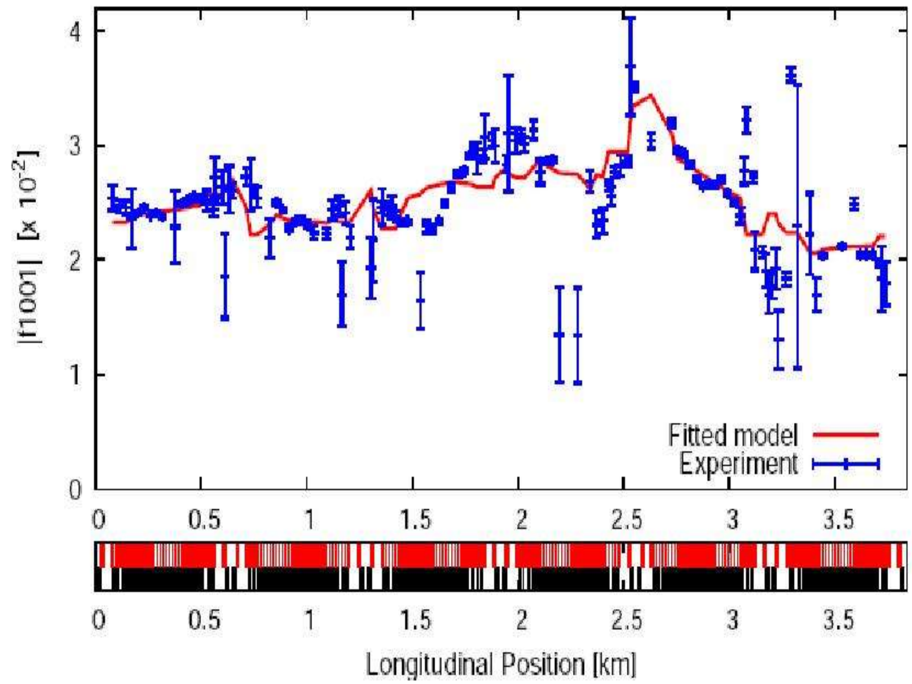



R. Calaga et al

# Resonance driving terms in RHIC




R. Tomas et al**, PRSTAB 8**, 024001, 2005




R. Calaga et al, EPAC 2006

Sextupolar and coupling resonance terms measured in RHIC with AC dipoles

# Emittance preservation

In presence of chromaticity, emittance blow up is given by:

$$\Delta\epsilon_x = \frac{k^{(n)2}}{2n^2}\sum_{q=-\infty}^{\infty} e^{-s^2} \mathrm{I}_q(s^2)\frac{\sin^2(\pi Q_{q-} n)}{16\sin^4(\pi Q_{q-})}$$

R. Tomas, **PRSTAB 8**, 024401 (2005)

Ramp turn number

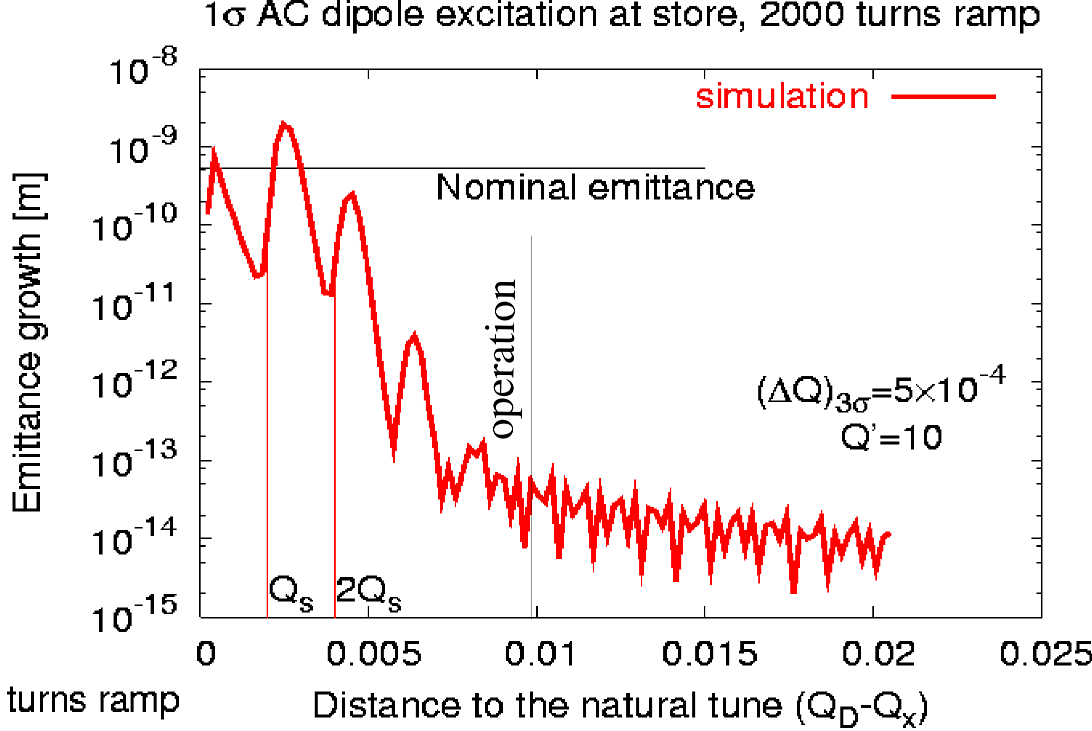
Distance to sideband q

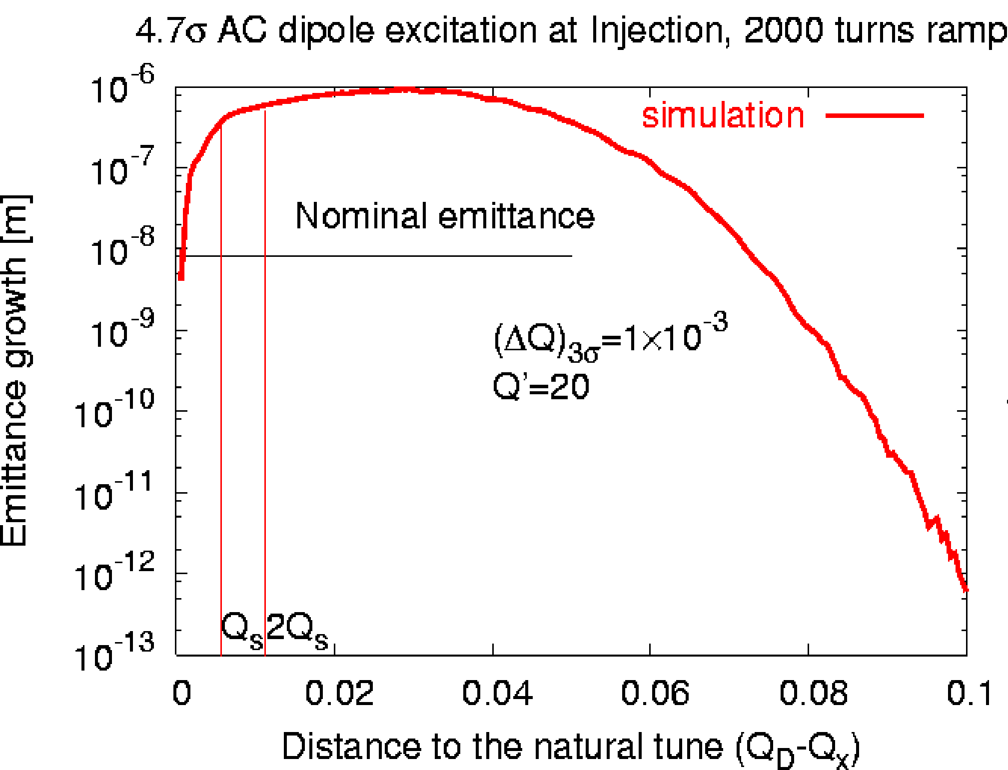
In presence of amplitude detuning excitation within the bunch frequency spectrum is forbidden (including resonances)

Rule of thumb: Excite after Q'/2 sidebands (dist > Q'/2*Qs)

# LHC pessimistic simulations

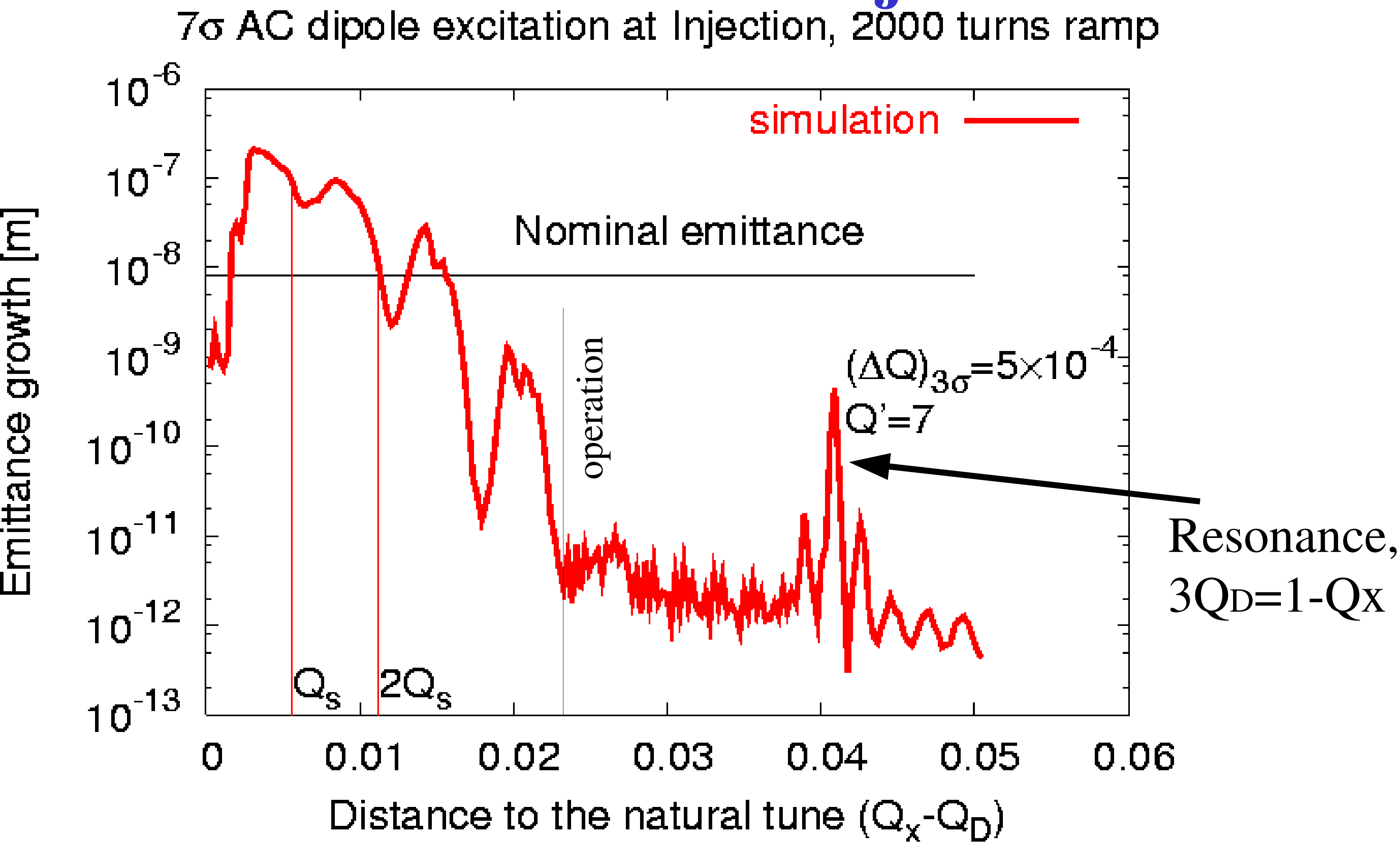
Store
within specs!




Injection,
unavoidable blow up with
pessimistic assumptions

# LHC injection simulations




7sigma oscillations at injection require Q'<7 and avoiding amplitude detuning and resonances

# Summary

- AC-dipole has been demonstrated to induce **long-lasting coherent oscillations** without emittance growth.
- Powerful instrument for commissioning the LHC. Measure and optimize **the mechanical aperture** (or golden orbit).
- Very useful for **optics**: **beta-functions, phase advance, linear coupling and non-linear resonance driving terms.** At injection control of chromaticity is required.
- Other applications can be envisaged **for Q' and dQ/dJ measurement** but still to be benchmarked by MDs and requesting a sizeable improvement of the measurement system : measurement of head-tail phase shift inside the bunch with tiny ac-excitation at the betatron tune (see S. Fartoukh, LPR986)