Betatron Resonance Compensation at the CERN PS Booster Synchrotron

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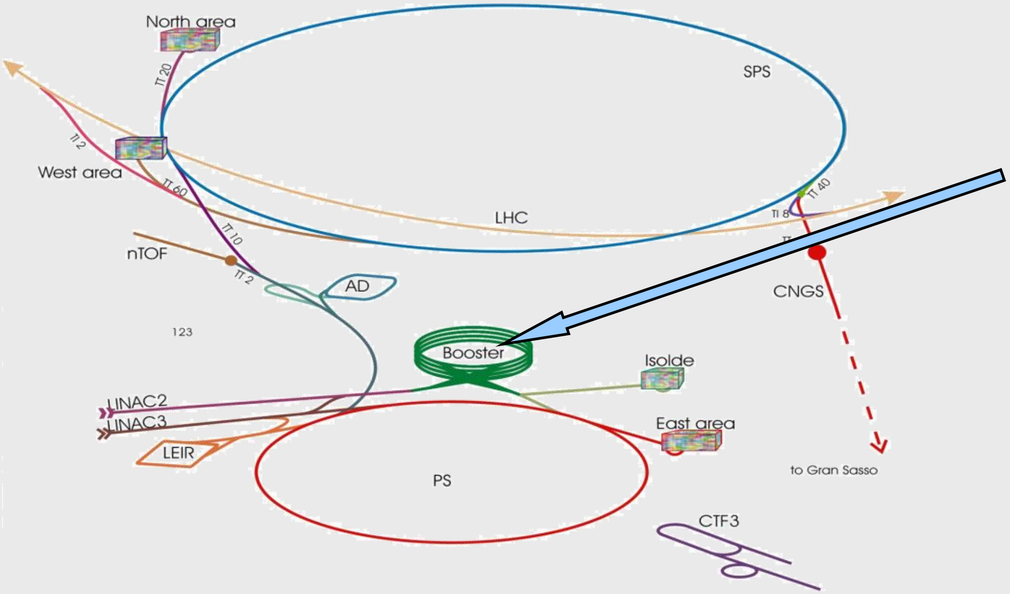
Outline

- **Brief information on the PS Booster Synchrotron**
- **Motivation for the betatron resonance compensation**
- **Measurement set-up, constraints and strategy**
- **Some measurement results**
  - **3rd order resonance**
  - **Alternative working point for the PS Booster**
- **Conclusions**

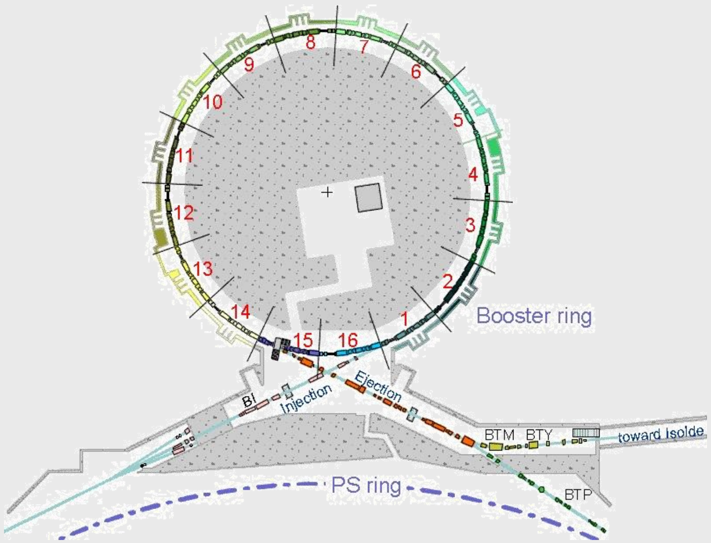
The PS Booster in the CERN accelerator chain



The PS Booster (PSB) consists of 4 superimposed rings.

- 40 years old machine
- The PSB links the Linac 2 and the Proton Synchrotron (PS).
- Direct beam supplier for the On-line Isotope Mass Separator facility (ISOLDE).

PS Booster



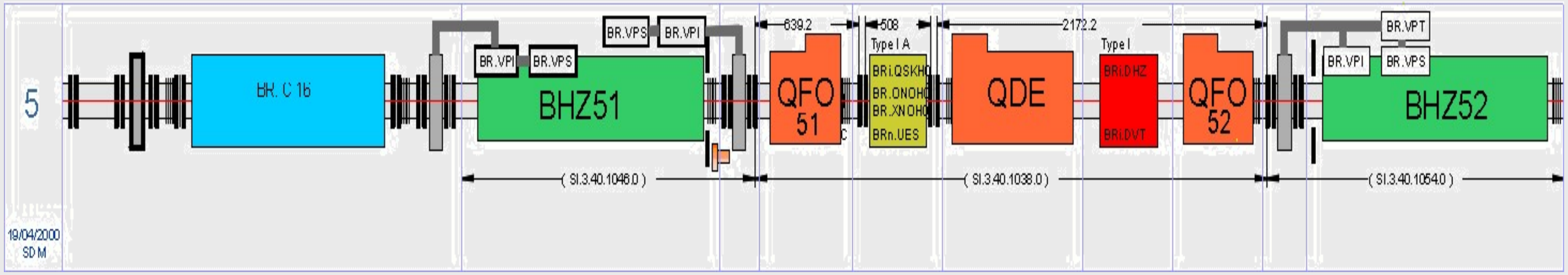
The PS Booster ring

Key data:

- Radius: 25 m (1/4 of PS)
- 16 identical periods
- Lattice type: regular triplet (QF – QD – QF)
- Cycle time: 1.2 s
- Multi-turn injection (up to 13 turns)

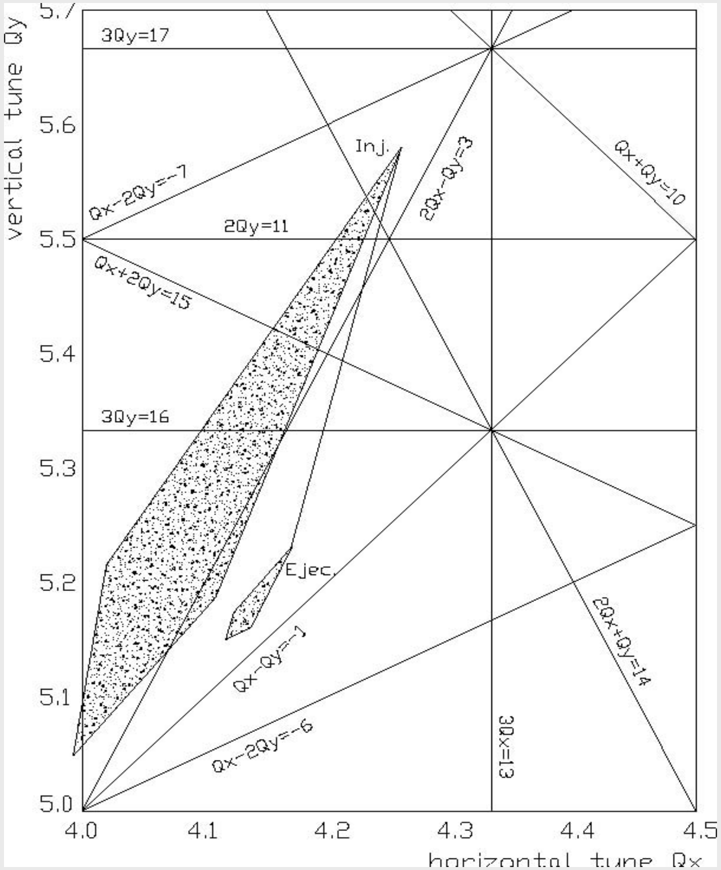
Protons:

- Energy: at injection: 50 MeV
  at extraction: 1.4 GeV
- Intensities: up to 10^{13} (in all 4 rings)



Assembly of one period

Motivation for resonance compensation

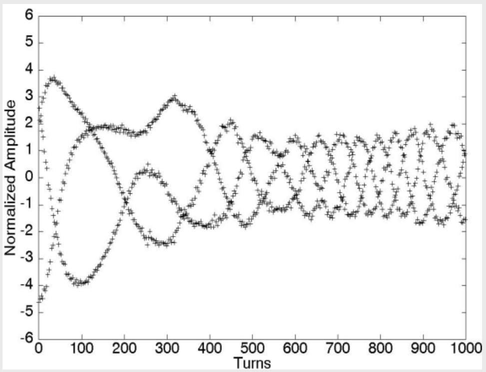


PSB tune diagram for high intensity beams.

- Large incoherent space charge tune spread (for high intensity beams) – "Necktie" shaped area
- Nominal tunes: Q_x=4.17, Q_y=5.23
- At injection: Tunes moved to: Q_x=4.26, Q_y=5.58
- Resonances to be considered: 2nd and 3rd order (e.g. $3Q_y = 16$)
- PSB offers a variety of multipoles (only up to sextupoles used for resonance compensation).
- Resonance compensation already done 35 years ago (orthogonal search for proper multipole currents)

Betatron resonance compensation is mandatory for a satisfactory performance of the PSB!

How to measure and compensate resonances ?

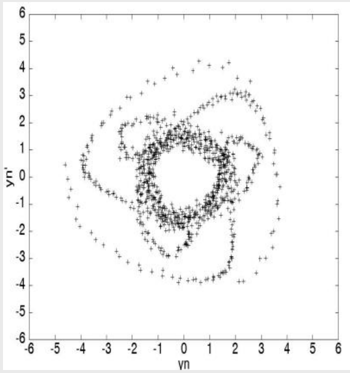


Beam position

$$\begin{pmatrix} X_2 \\ X'_2 \end{pmatrix} = \begin{pmatrix} \cos(\Delta_\mu) & \sin(\Delta_\mu) \\ -\sin(\Delta_\mu) & \cos(\Delta_\mu) \end{pmatrix} \bullet \begin{pmatrix} X_1 \\ X'_1 \end{pmatrix}$$

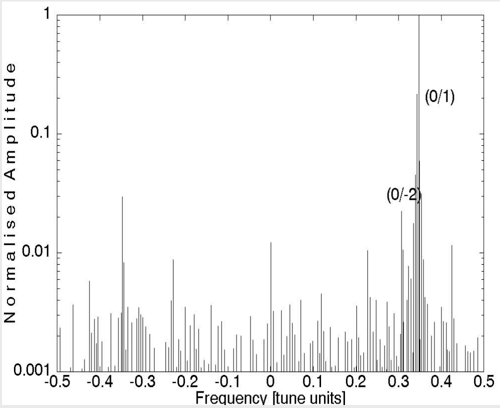
X_1, X_2 from BPMs

(normalized amplitudes)



Normalised phase space

FFT



Fourier spectrum

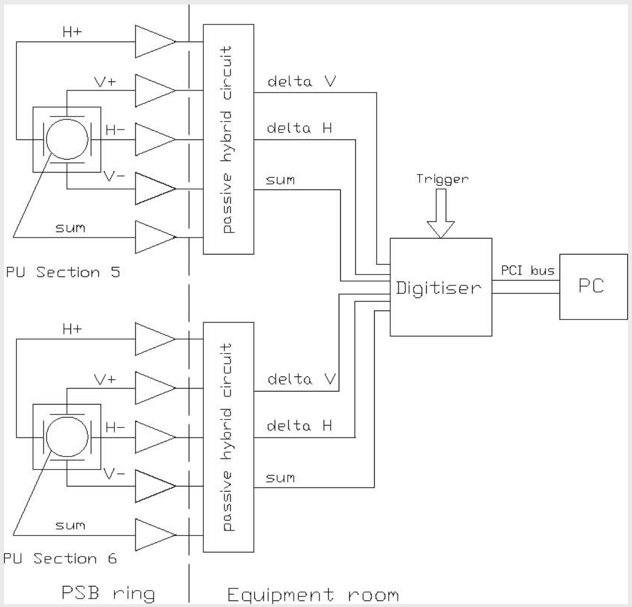
	Driving Term	Horizontal Spectral Line
Line		$(1-j+k, m-l)$
Amplitude	$\lvert h_{jklm}\rvert$	$(2I_x)^{\frac{j+k-1}{2}}(2I_y)^{\frac{l+m}{2}}\frac{j\cdot\lvert h_{jklm}\rvert}{\sin(\lvert\hat{\phi}\rvert)}$
Phase	ψ_{jklm}	$\psi_{jklm}+(1-j+k)\psi_{x_0}-(l-m)\psi_{y_0}-\frac{\pi}{2}+sgn(\hat{\phi})(\frac{\pi}{2}-\lvert\hat{\phi}\rvert)$
		where $\hat{\phi}=\pi[(j-k)\nu_x+(l-m)\nu_y]$

Table 3.1: *Relation between the horizontal spectral lines and the amplitude and phase of the resonant Hamiltonian term [16].*

Relation between spectral decomposition of particle motion and Hamiltonian perturbation theory (Normal Form)

Driving terms: h_{jklm}
(strength and phase of the resonance) – prop. to multipole coefficients

Measurement system



- 2 BPMs were used in the PSB.
- 5 electrode signals were converted into sum and difference signals.
- Digitiser (Acqiris modules):
  - 2 modules with each 4 channels
  - f_{sampl}=500 MS/s (~800 samples/turn)
  - memory: 2MS/channel
    record ~**2500 turns**
- Control and Processing Program
  - Controls the digitiser
  - Graphical user interface
  - Digital data conversion into beam position

Constraints in the PSB

1) Limitation to injection energy (50 MeV)

PSB does not offer a dedicated kicker ⟹ Injection mis-steering had to be used to obtain sufficiently large oscillation amplitudes. Resonance studies were limited to injection energy.

2) Decoherence of the BPM signals due to chromaticity

- Only one sextupole family for chromaticity correction available. Decoherence of one signal in the transverse planes is unavoidable (natural chromaticities: $Q'_x \sim -3.5$, $Q'_y \sim -9.3$)
- For purely horizontal or vertical resonances: no problem, chromaticity corrected in one plane.
- Limitation if coupling resonances are considered, because both (horizontal and vertical) beam position signals are needed.

Measurement set-up

What do we need to determine resonance driving terms?

- A bunched beam performing coherent oscillations with a reasonably large oscillation amplitude (some mm) over a sufficiently large number of turns (some 100). A decoherence of the signal (chromaticity, amplitude detuning) should be avoided.

Measurement set-up:

- One third of the ring was filled to obtain a quasi-bunched beam (containing 1 to 2 * 10^{11} protons).
- RF was already switched on at injection to avoid longitudinal debunching.
- Use of injection mis-steering.
- For each measurement only a single resonance was considered.
  - Tunes close to resonance condition,
  - Chromaticity adjusted either to zero in one plane or to reasonably low values in both planes (coupling resonances).

Procedure for determination of resonance driving terms

- Measurements for the bare (uncorrected) machine; result: resonance vector
- Reference measurements with a defined multipole excitation (for calibration purposes).
- Simulation of the resonance phases for the compensation elements.
- Calculation of compensation currents for multipoles
- New measurements with compensation currents (if necessary second iteration was done).

Reference measurements and simulation:

(e.g.: Skew Sextupole(XSK2L4) = -45 A)

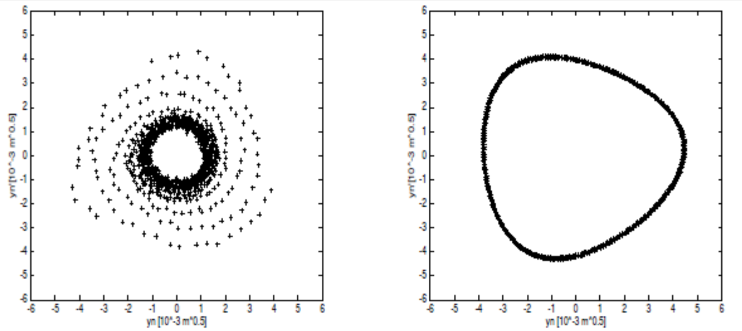


Figure 6.9: *Normalised phase spaces obtained from measurement (left) and simulation (right).*

	measurement	simulation
$\|h_{0030}\|$ [$mm^{-1/2}$]	$15 \pm 1 * 10^{-3}$	$14 * 10^{-3}$
Ψ_{0030}	$157^o \pm 7^o$	347^o

- Opposite polarity of the skew sextupole magnet was indeed verified during the shut down period!

- Measurement includes contribution from bare machine.

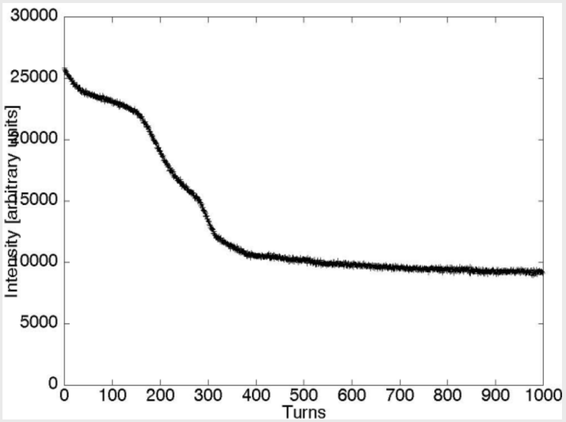
Measurement results:

$3Q_y$=16 resonance (skew sextupole resonance)

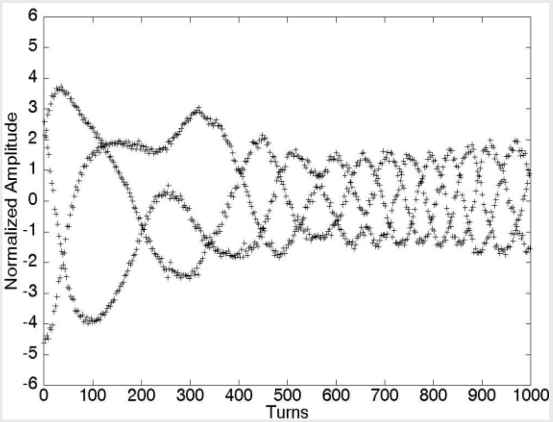
- It's a **systematic** resonance (16 periods in PSB)!
- It has to be compensated in standard operation (with skew sextupoles).
- Corresponding resonance driving term: h_{0030}
- Resonance spectral line (in vertical spectrum): (0,-2)

- Tunes: Q_y ~ 5.35 (close to resonance condition: Q_y =5.333)
- Interest only in vertical particle motion.
- Vertical chromaticity was corrected to zero.

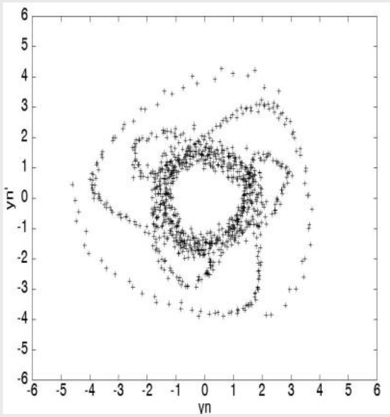
$3Q_y$=16 – uncorrected



Beam intensity



Vertical beam position



Normalised phase space

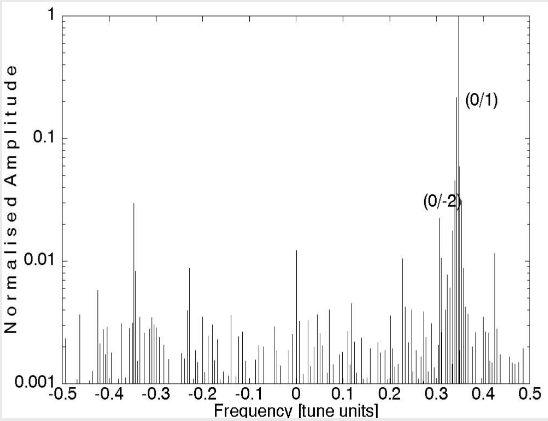
resonance strength and phase:

$$|h_{0030}| = \frac{1}{3}\frac{a_{y1}}{a_{y0}^2}\sin(|\hat{\phi}|)$$

$$\psi_{0030} = \phi_{y1} + 2\psi_{y0} + \frac{\pi}{2} - \mathrm{sgn}(\hat{\phi})(\frac{\pi}{2} - |\hat{\phi}|)$$

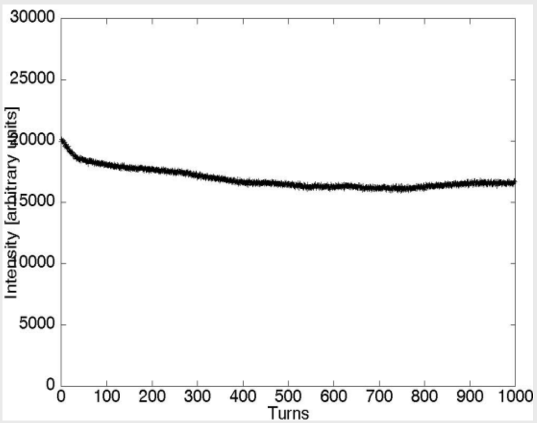
Phase and amplitude data obtained from

Fourier spectra

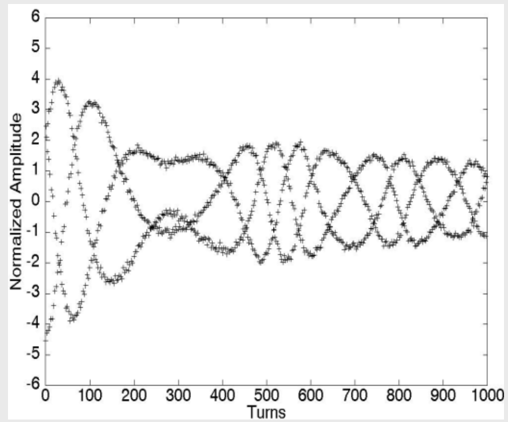


Fourier spectrum

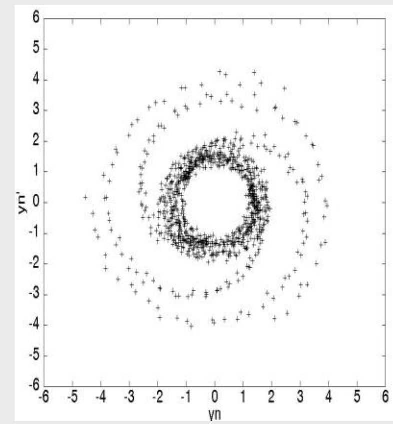
$3Q_y=16$ – compensated



Beam intensity



Vertical beam position



Normalised phase space

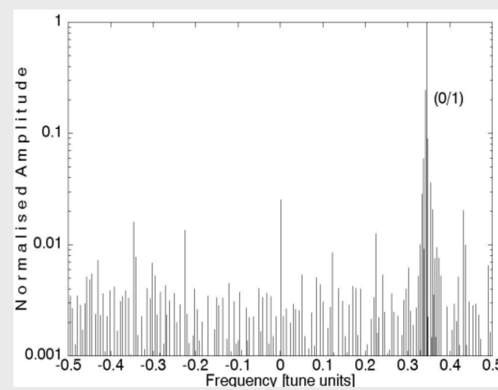
Results from the measurements:

$|h_{0030}| = 9.0\pm0.6*10^{-3}\ mm^{-1/2}$

$\psi_{0030} = -21^o\pm14^o$

Calculated compensation currents (for two independent skew sextupoles):

$I_{XSK2L4} = -29.3$ A, $I_{XSK9L1} = +15.3$ A

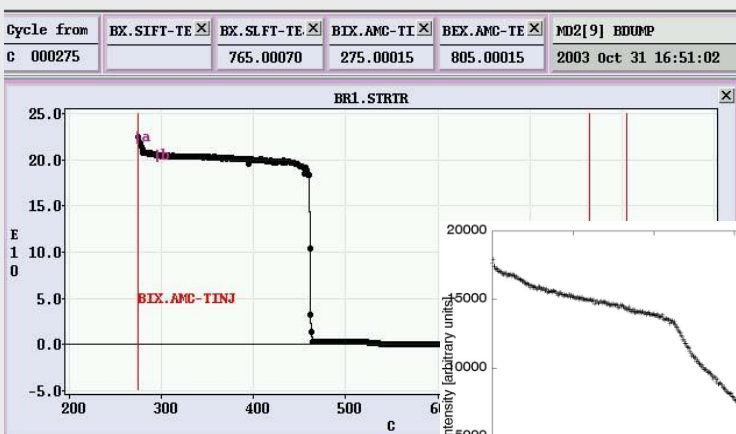


Fourier spectrum

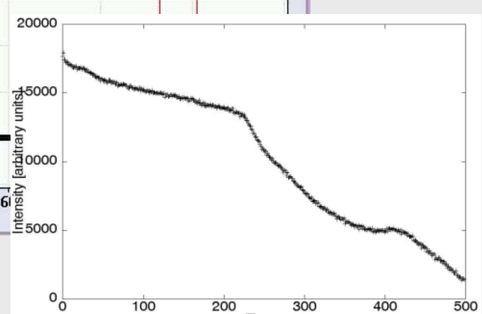
Further results…

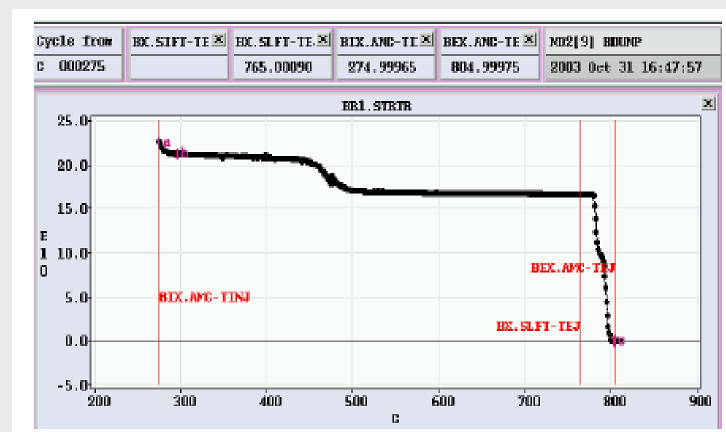
- Further resonances studied and compensated:
  - Quadrupole resonance: $2Q_y = 11$
  - Linear coupling resonance: $Q_x - Q_y = -1$
  - Other third order coupling resonances: $2Q_x - Q_y = 3$, $2Q_x + Q_y = 14$, $Q_x + 2Q_y = 15$

e.g.: $2Q_y=11$ – quadrupole resonance



uncorrected

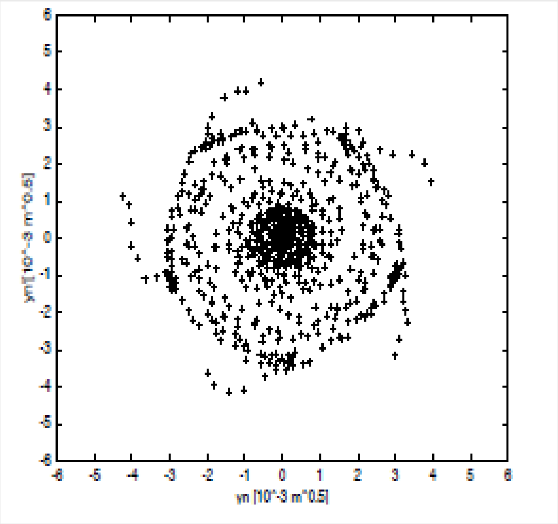




corrected

Further studies…

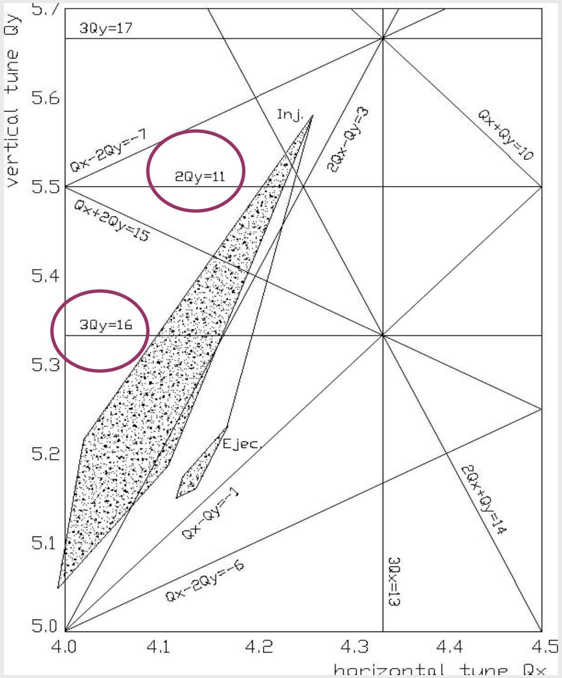
- Studies with different injection mis-steering (oscillation amplitudes)
- Studies with different chromaticities
- By chance we got clear signs of a decapole resonance:
  - $5Q_y = 27$



Fivefold symmetrie due to decapole resonance 5Qy = 27

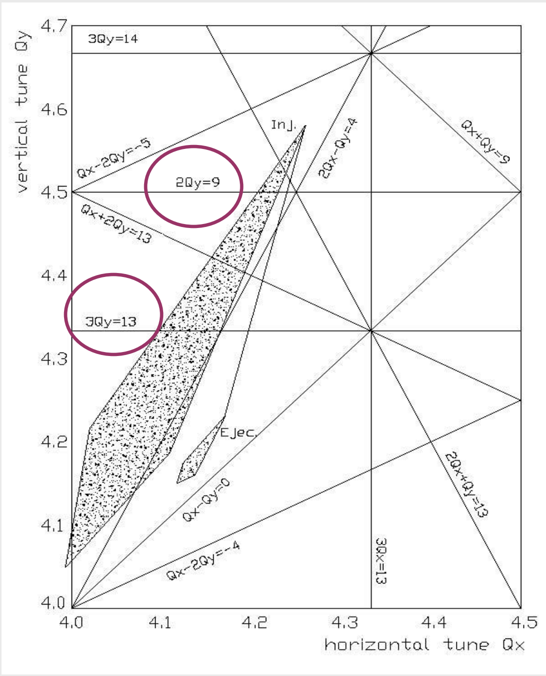
Alternative working point

- Q_x= 4.17, Q_y= **4**.23 instead of Q_x= 4.17, Q_y= **5**.23 (Q_y is shifted one integer down)
- Main motivation: To avoid the systematic 3rd order $3Q_y$=16 resonance.



$2Q_y$=11 vs. $2Q_y$=9

$3Q_y$=16 vs. $3Q_y$=13

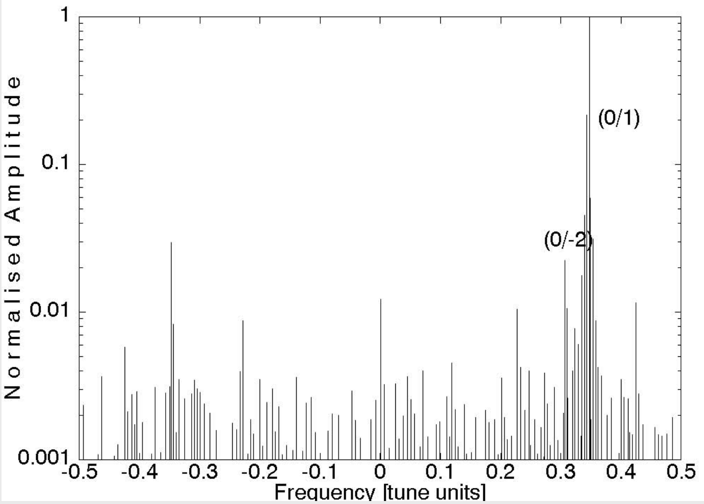


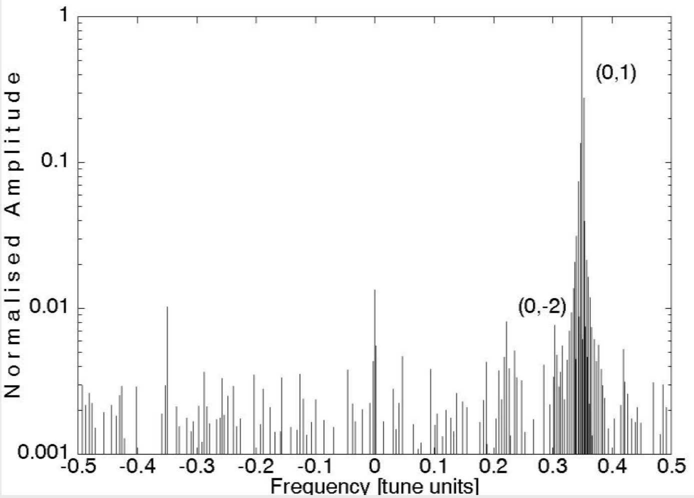
PSB tune diagram for standard working point.

PSB tune diagram for alternative working point.

Alternative working point

- Relevant resonances show clearly smaller intrinsic excitation
- Comparison of results for **$3Q_y$=16 vs. $3Q_y$=13**





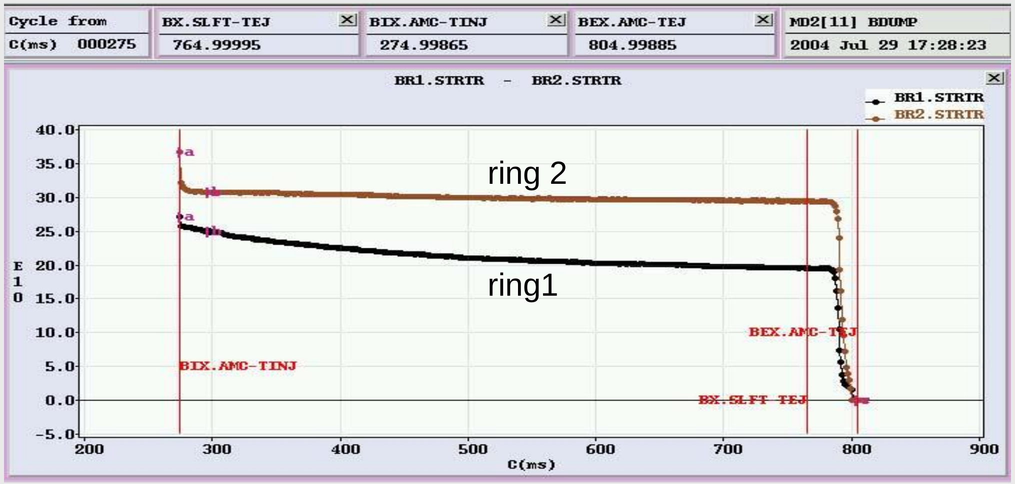
Resonance strength $|h_{0030}|$: $9.0 * 10^{-3}$ mm$^{-1/2}$ $2.2 * 10^{-3}$ mm$^{-1/2}$

- bare machine component is a factor 4 less for lower working point

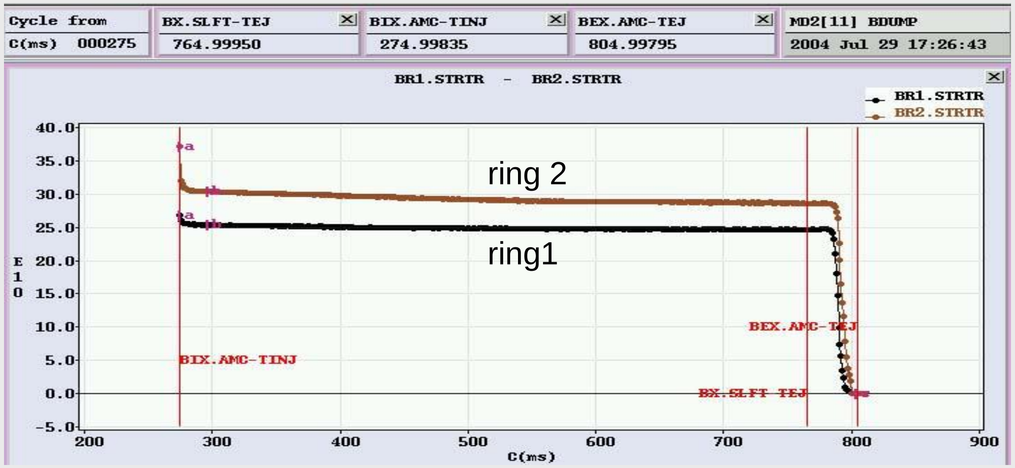
Alternative working point

Crossing of $3Q_y = 13$ in rings 1 and 2.

…uncorrected



…compensated



No compensation is needed for ring 2!

Conclusions

- All second and third order resonances relevant for operation were analyzed for rings 1 and 2 of the PS Booster.
- The acquisition system used allowed fast and efficient determination of resonance driving terms on the basis of turn-by-turn beam position measurements.
- All relevant resonances were successfully compensated
- Comparative resonance driving term measurements for two different working points; conclusion is that from a resonance excitation point of view, a “lower” working point is preferable.
- PS Booster is still operated with the lower working point.

Thank you for your attention!