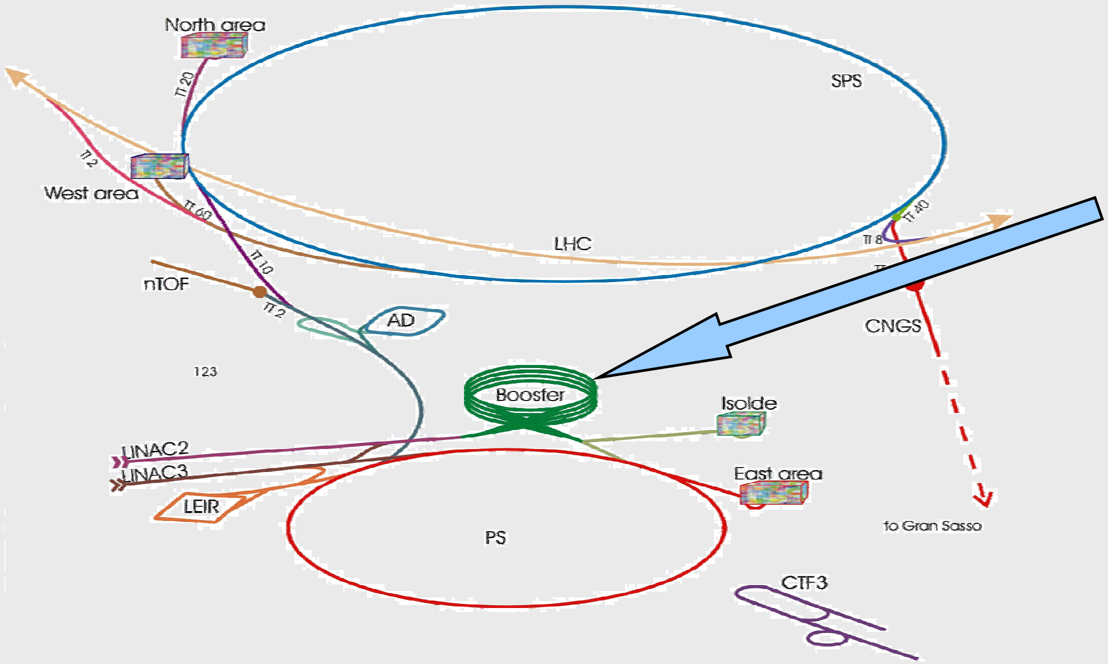
Measurement and Compensation of Betatron Resonances at the CERN PS Booster Synchrotron

Urschütz Peter (AB/ABP)

Overview

- General Information on the PS Booster Synchrotron
- Motivation for the betatron resonance analysis
- How to measure and compensate resonances?
- Measurement results
  - 2nd and 3rd order resonances
  - Alternative working point for the PS Booster
- Conclusions

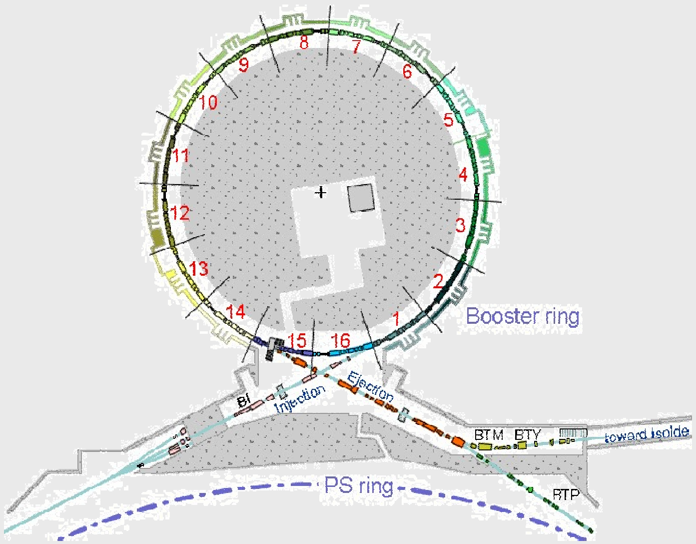
The CERN accelerator chain



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

- The PSB links the Linacs and the Proton Synchrotron (PS).
- Direct beam supplier for the On-line Isotope Mass Separator facility (ISOLDE).

PS Booster



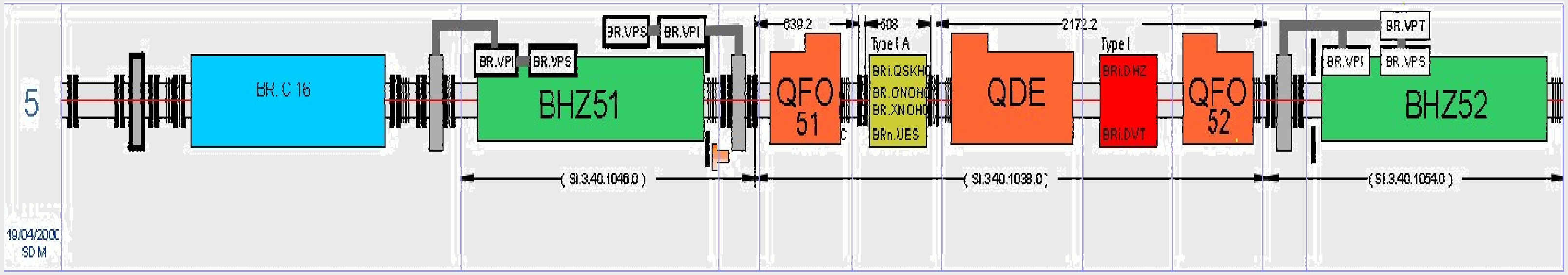
The PS Booster ring

Relevant 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)

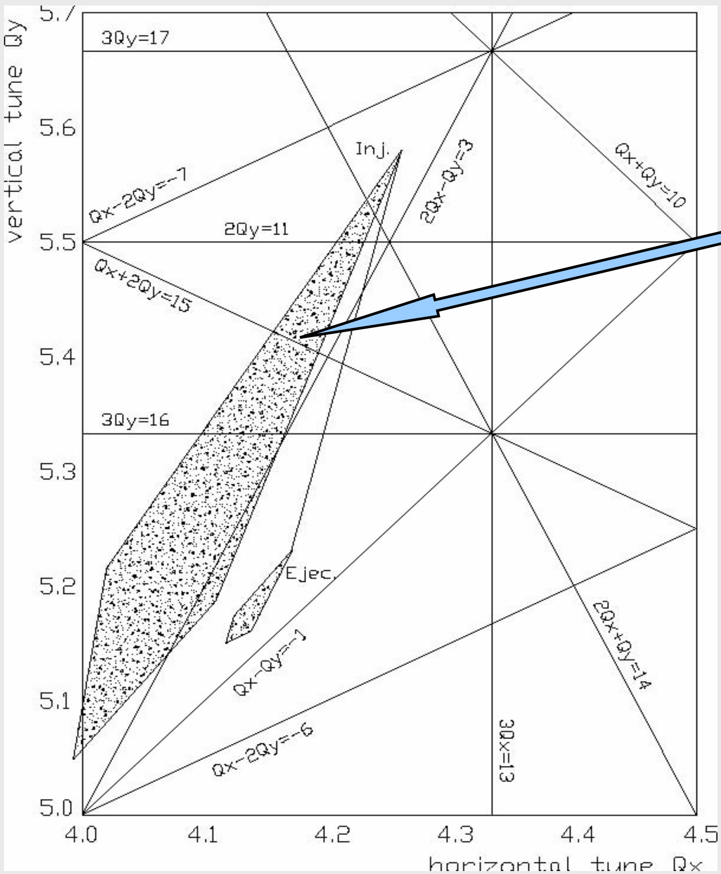
Protons:

- Energy: at injection: 50 MeV
  at extraction: 1.4 GeV
- Intensity: $5*10^9$ (LHC pilot beam)
  to $9 * 10^{12}$ (ISOLDE)



Assembly of one period

Motivation for resonance compensation



PSB tune diagram for high intensity beams.

Nominal tunes: Q_x=4.17, Q_y=5.23

At injection: Q_x=4.26, Q_y=5.58

“Necktie” shaped area (due to incoherent space charge tune spread) covers a multitude of resonances!

Resonances considered:

2^{nd} order: $Q_x – Q_y$ = - 1 (linear coupling)

$2Q_y$ = 11

3^{rd} order: $3Q_y$ = 16 (**systematic!**)

All relevant sum and difference resonances

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

Tasks & Goals

With the increasing demands for higher intensities and higher brightness beams, a revision of the existing working point with a general analysis of all relevant betatron resonances was needed.

The specific goals were:

◆ Defining an acquisition system for beam position measurement over many turns with storage and analysis.

◆ Measurement of resonance excitation and comparison to simulations.

◆ Verification and potential improvement of the existing compensation scheme.

◆ Search for an alternative new working point with a lower intrinsic excitation and efficient compensation.

Measurement set-up

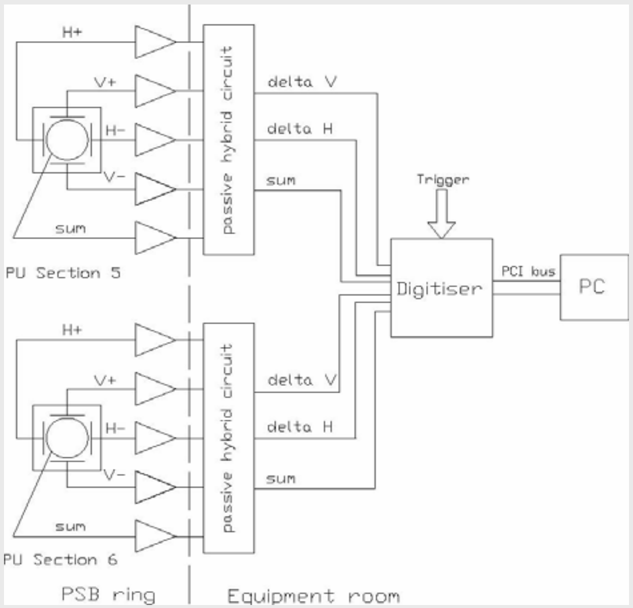
What do we need to determine resonance driving terms?

- 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 were set close to resonance condition. Chromaticity was adjusted either to zero in one plane or to reasonably low values in both planes (coupling resonances).

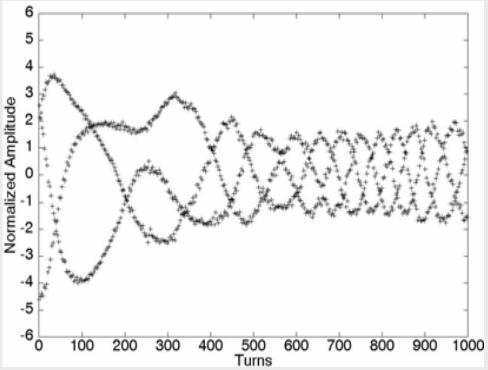
Acquisition system



- Standard closed orbit pick-ups in section 5 and 6 of rings 1 and 2 were equipped with new head amplifiers.
- Passive hybrid circuit to match impedances and to build horizontal and vertical delta signals.
- Acqiris digitiser:
  - 2 modules with each 4 channels
  - f_{sampl}=500 MS/s (~800 samples/turn)
  - memory: 2MS/channel

    → record ~**2500 turns**
- Control and Processing Program (Visual C++):
  - Controls the digitiser
  - Graphical user interface
  - Digital data is converted into real beam position

How to measure and compensate resonances ?

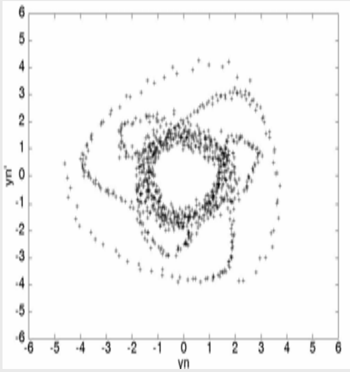


Beam position

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

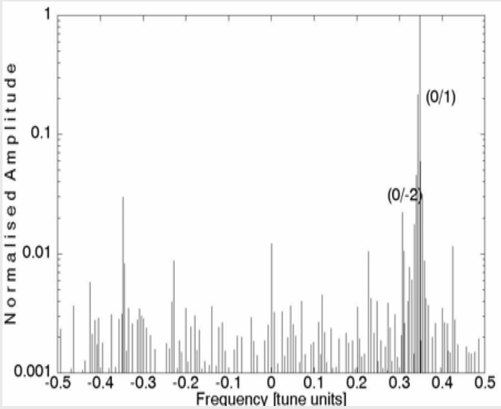
X_1, X_2 from pick-ups,

(☟❍…phase advance between pick-ups)



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].*

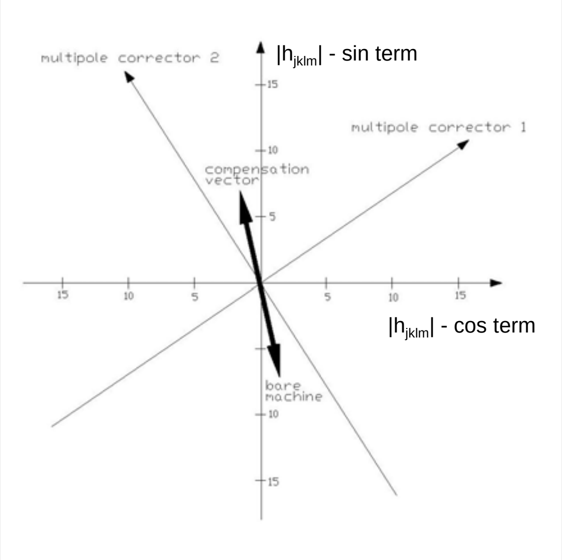
Relation between spectral decomposition of particle motion and Hamiltonian perturbation theory (Normal Form)

Driving terms: h_{jklm}

(strength and phase of the resonance)

Procedure to determine resonance driving terms

- Measurements for the bare (uncorrected) machine.
- Reference measurements with a defined multipole excitation.
- 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.: XSK2L4 = -45 A)

	measurement	simulation
$\|h_{0030}\|$ [$mm^{-1/2}$]	$15.2 \pm 1.0 * 10^{-3}$	$14.3 * 10^{-3}$
ψ_{0030}	$157.2^{o} \pm 6.7^{o}$	$347.2\ ^{o}$

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

Constraints in the PSB

1) Limitation to injection energy (50 MeV)

No dedicated kicker was available. ⟹ Injection mis-steering had to be used to obtain sufficiently large oscillation amplitudes. Resonance studies were limited to injection energy.

2) Only one sextupole family for chromaticity correction

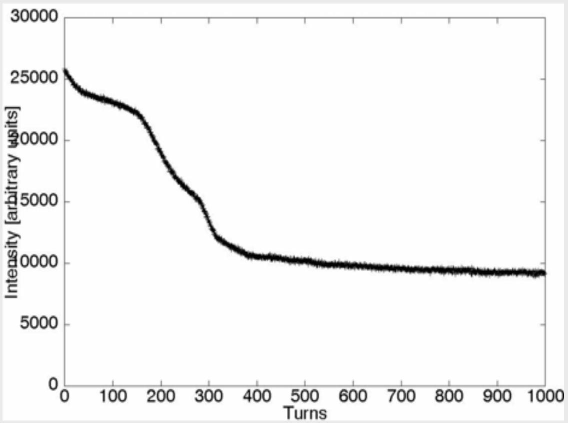
- Decoherence of one of the transverse planes is unavoidable.
(natural chromaticities: $Q'_x \sim -3.5$, $Q'_y \sim -9.3$)
- For horizontal or vertical resonances: no problem, chromaticity set to zero in one plane.
- Limitation if coupling resonances are considered, because both (horizontal and vertical) beam position signals are needed.

$3Q_y$=16 resonance

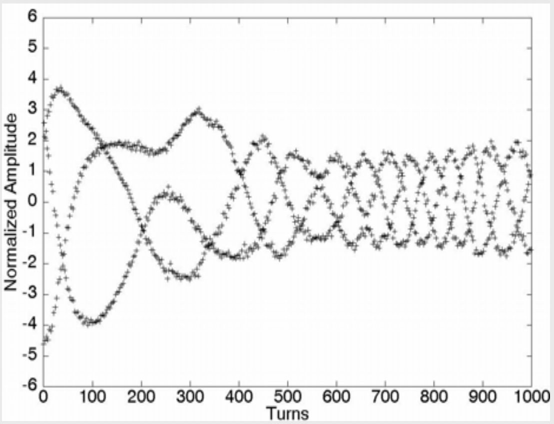
- It's a **systematic** resonance (16 periods in PSB)!
- It has to be compensated in standard operation (with skew sextupoles).
- Corresponding resonance driving term: h_{0030}
- Resonance spectral line (in vertical spectrum): (0,-2)

- 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.

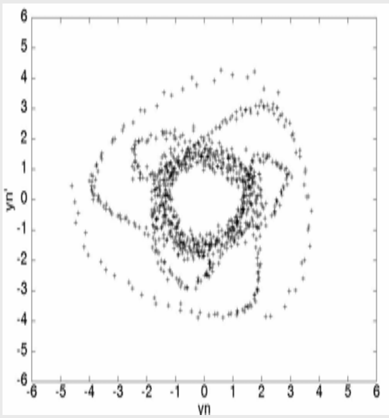
$3Q_y$=16 – bare machine



Beam intensity



Vertical beam position



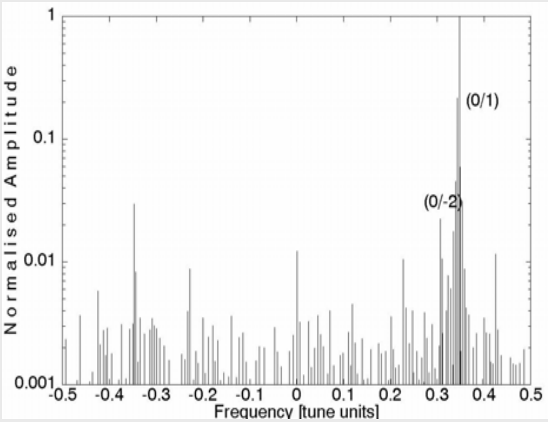
Normalised phase space

resonance strength and phase:

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

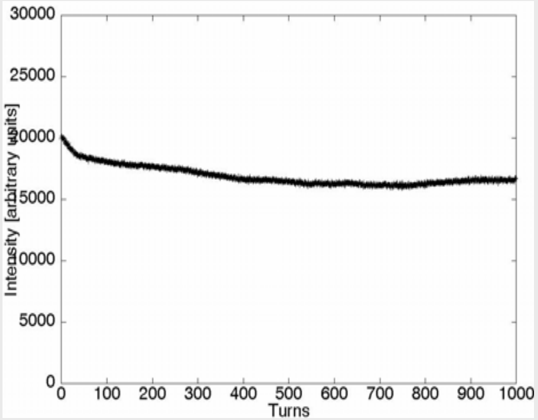
from Fourier spectra

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

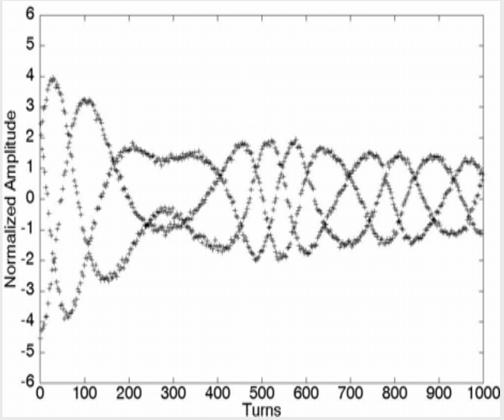


Fourier spectrum

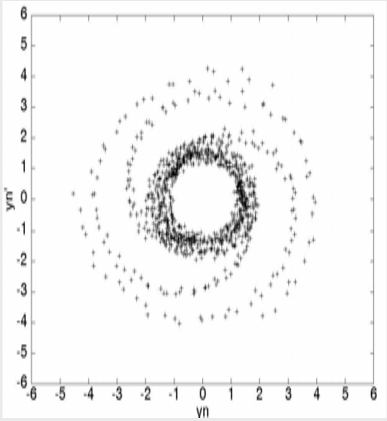
$3Q_y$=16 – compensated



Beam intensity



Vertical beam position



Normalised phase space

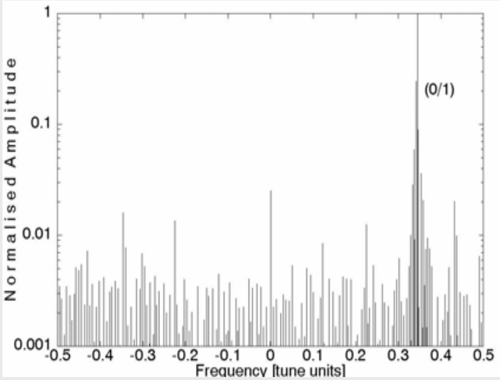
Results from the measurements:

$|h_{0030}| = 9.0 \pm 0.6 * 10^{-3}\ mm^{-1/2}$

$\psi_{0030} = -21.4^o \pm 13.9^o$

Calculated compensation currents (for two independent skew sextupoles):

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



Fourier spectrum

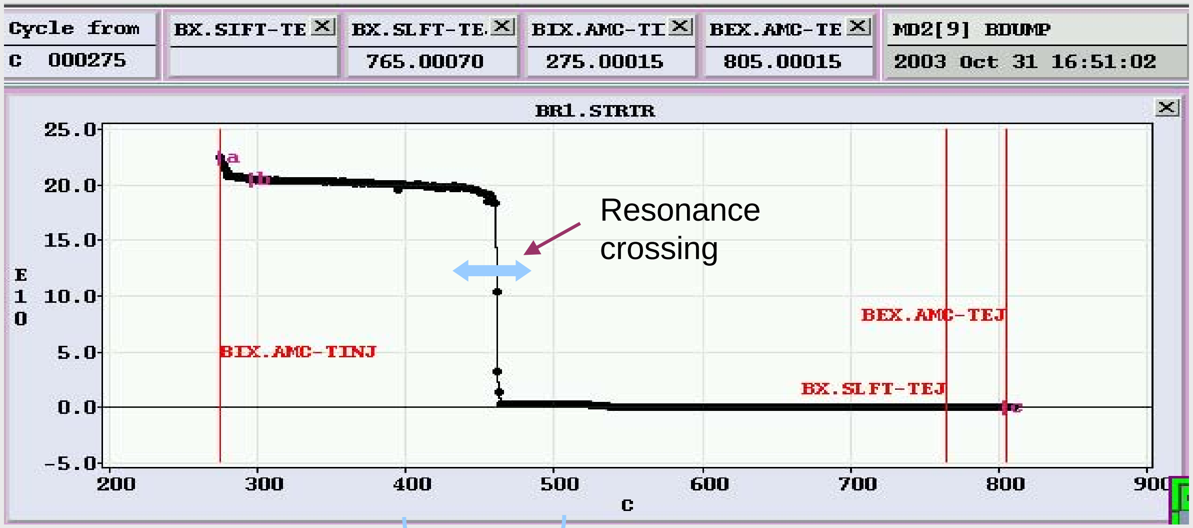
$2Q_y$=11 resonance

- In standard operation the $2Q_y = 11$ resonance has to be compensated.

  ($I_{QNO412L3}$ = + 7.1 A, $I_{QNO816L3}$ = - 3.7 A)
- Corresponding resonance driving term: h_{0020}
- Resonance spectral line (in vertical spectrum): (0,-1)

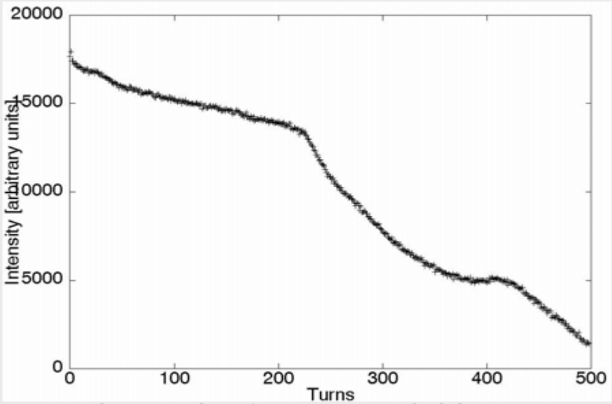
- Tunes: $Q_x \sim 4.17$, **$Q_y \sim 5.48$** (close to resonance condition: Q_y =5.5)
- Interest only in vertical particle motion.
- Chromaticity was not corrected! (Consider beam off-set in chromaticity sextupoles)

$2Q_y=11$ – bare machine



~ 60000 turns

Beam intensity over whole cycle period.



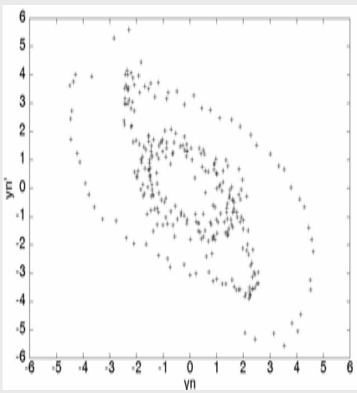
Beam intensity from acquisition system.

Beam intensity

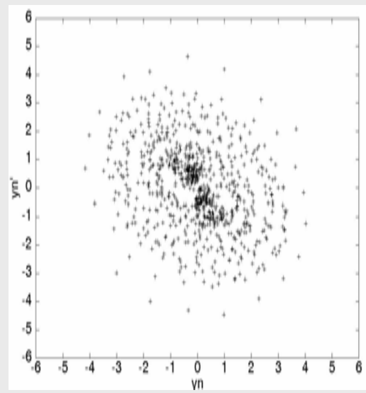
Beam is completely lost when this resonance is crossed!

$2Q_y=11$ – bare machine

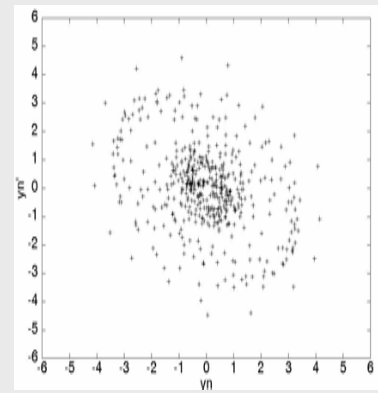
Normalised vertical phase spaces for different vertical tunes.
Tune range: $5.495 > Q_y > 5.454$



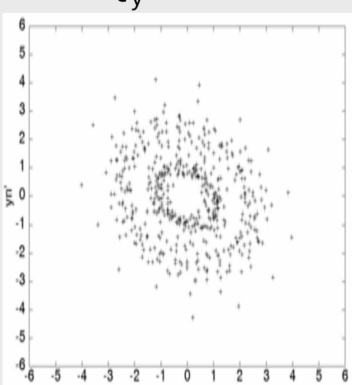
$Q_y=5.495$



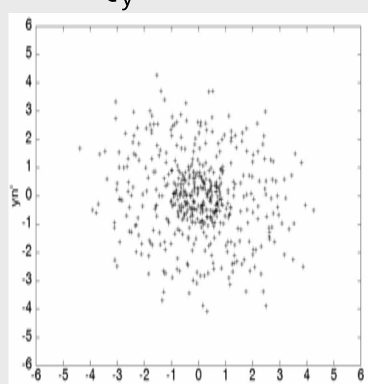
$Q_y=5.481$



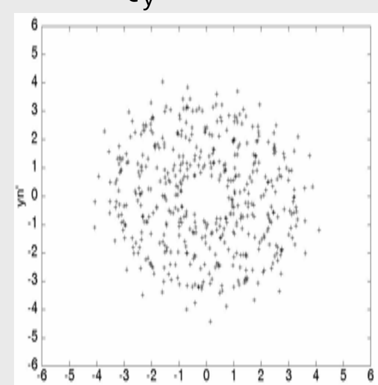
$Q_y=5.477$



$Q_y=5.470$



$Q_y=5.466$



$Q_y=5.454$

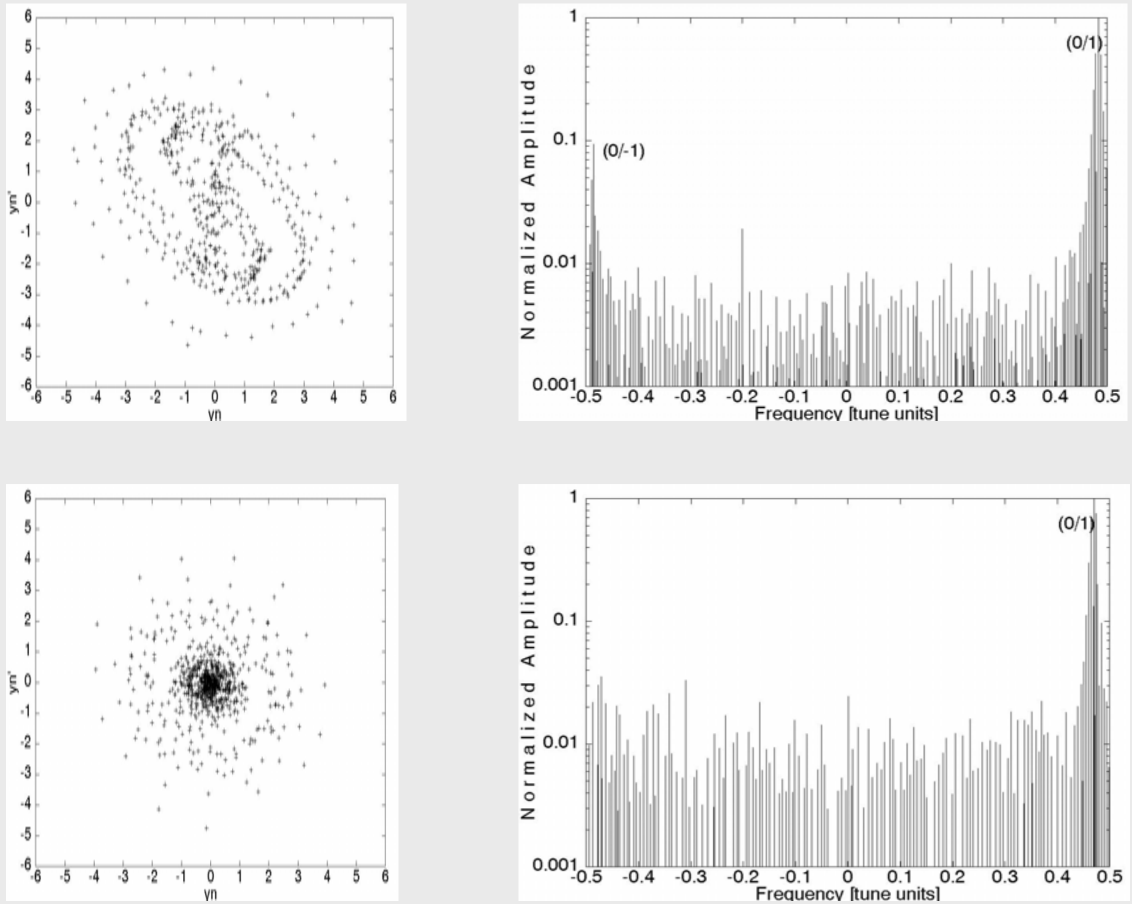
$2Q_y$=11 – bare machine & compensated

bare machine:

Calculated compensation currents:

$I_{QNO412L3}$ = + 6.3 A

$I_{QNO816L3}$ = - 2.8 A



Normalised vertical phase spaces and corresponding Fourier spectra.

Linear coupling

- In standard operation linear coupling is not compensated. Instead it is deliberately excited for an emittance exchange during the multi-turn injection.
- Difference (Q_x-Q_y= -1) and sum (Q_x+Q_y= 9 or 10) resonance have to be considered → four independent skew quadrupoles for compensation.
- In the PSB exist only two skew quadrupole families → concentration on the difference resonance, under consideration of consequences for the sum resonance.

- Tunes: Q_x ~ 4.20, Q_y ~ 5.14 (close to resonance condition)
- Equal chromaticties (horizontal and vertical beam position signal is needed): Q'_x ~ Q'_y ~ -5.3

Linear coupling – bare machine

difference resonance: Q_x-Q_y= -1

resonance strength and phase:

$$|h_{1001}| = \sqrt{\frac{a_{x1}\cdot a_{y1}}{a_{y0}\cdot a_{x0}}}\,\sin(|\hat{\phi}|)$$

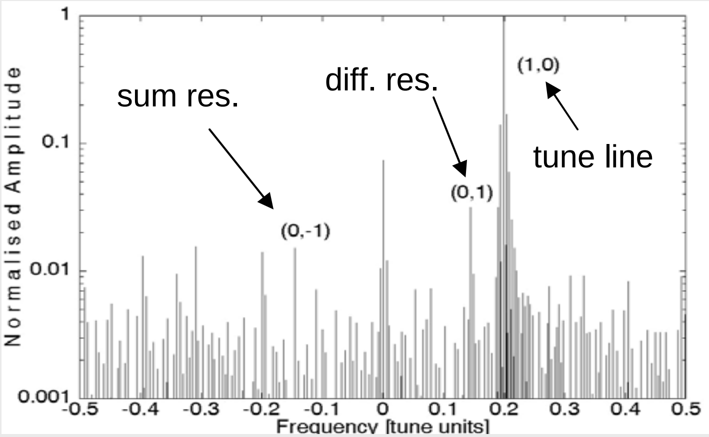
from Fourier spectra

$$\psi_{1001} = \phi_{x1} - \psi_{y0} + \frac{\pi}{2} - \mathrm{sgn}(\hat{\phi})\left(\frac{\pi}{2} - |\hat{\phi}|\right)$$

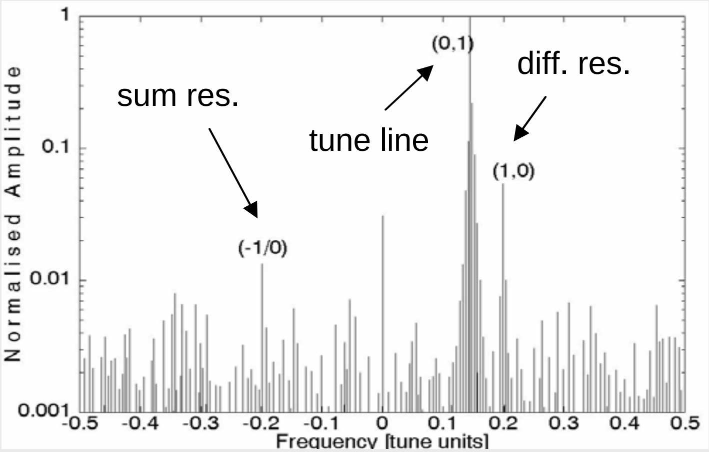
results from measurements:

diff.: $|h_{1001}| = 7.1\pm0.1 * 10^{-3}$, $\psi_{1001} = 282.8^o\pm5.2^o$

sum: $|h_{1010}| = 12.7\pm0.6 * 10^{-3}$, $\psi_{1010} = 172.9^o\pm6.9^o$



Horizontal Fourier spectrum

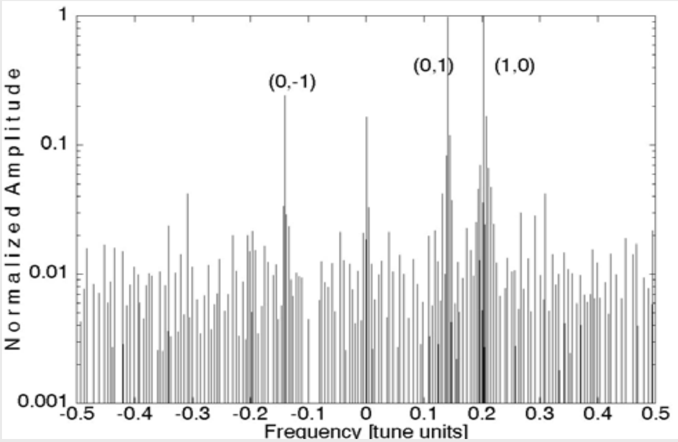


Vertical Fourier spectrum

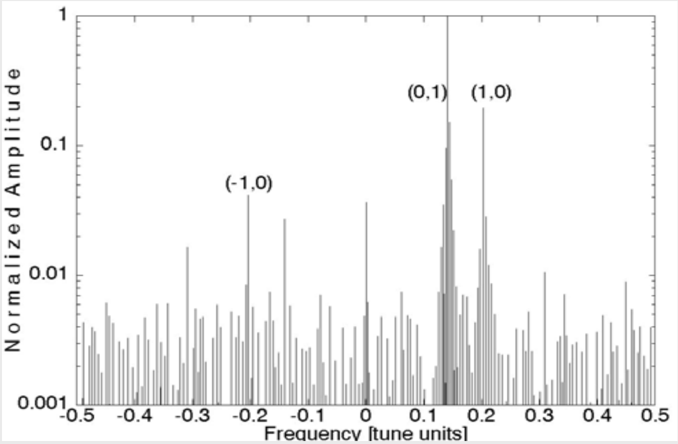
Linear Coupling - excited

- Excitation with skew quadrupole family QSK210L3: $I_{QSK210L3}$ = 35 A
- Results for difference resonance:
  - **Measurements (**bare machine contribution subtracted**):**
    - $|h_{1001}| = 9.0 \pm 0.0 * 10^{-2}$
    - $\psi_{1001} = 122.0^{o} \pm 1.1^{o}$
  - **Simulation*:**
    - $|h_{1001}| = 10.0 * 10^{-2}$
    - $\psi_{1001} = 302.7^{o}$
- Strength agree very well
- Measured phase is opposite to expectations, indicating a inversed polarity of the magnets. Confirmed by polarity measurements during shut down period.

* Single particle tracking code SixTrack and SUSSIX (for frequency analysis)



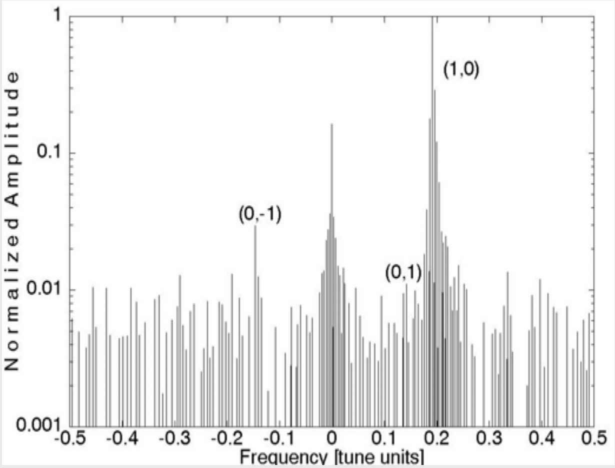
Horizontal Fourier spectrum



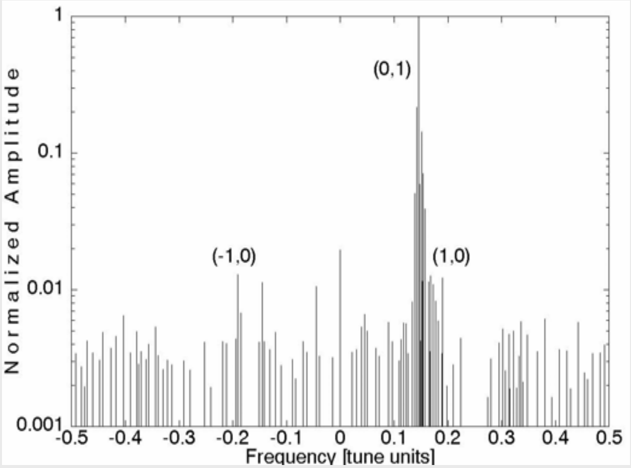
Vertical Fourier spectrum

Linear coupling - compensation

Calculated compensation currents: $I_{QSK210L3}$ = +3.6 A, $I_{QSK614L3}$ = +1.2 A



Horizontal Fourier spectrum



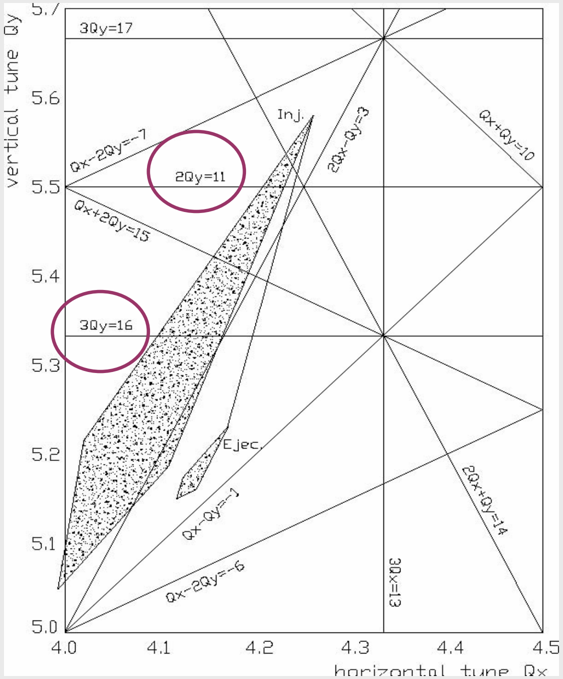
Vertical Fourier spectrum

$|h_{1001}|$ = 1.7±0.1*10^{-3}, less than 25% of initial strength

As expected, the strength of sum resonance excitation increased.

Alternative working point

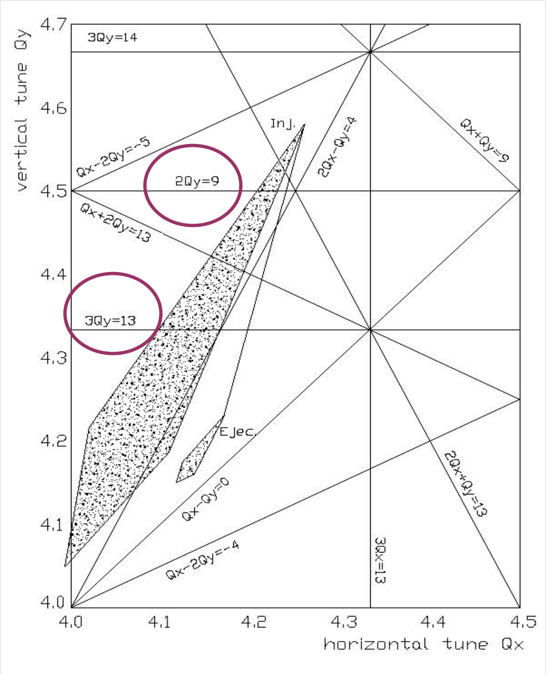
- Q_x= 4.17, Q_y= **4**.23 instead of Q_x= 4.17, Q_y= **5**.23 (Q_y is shifted one integer down)
- Main motivation: To avoid the systematic 3[rd] order $3Q_y$=16 resonance.



PSB tune diagram for standard working point.

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

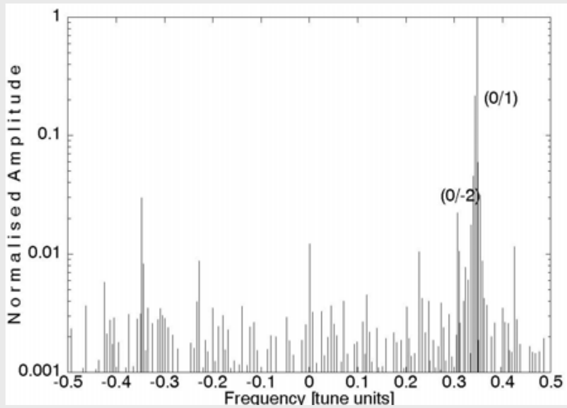
$3Q_y$=16 vs. $3Q_y$=13

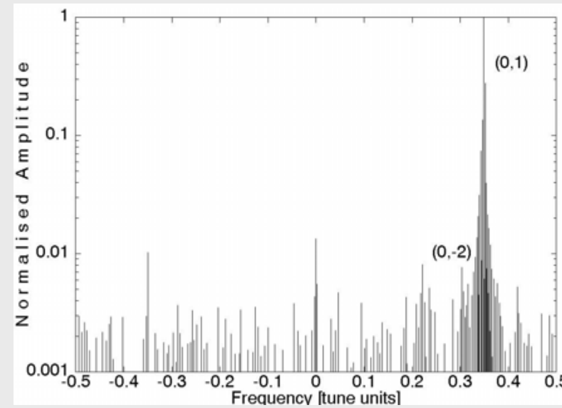


PSB tune diagram for alternative working point.

Alternative working point

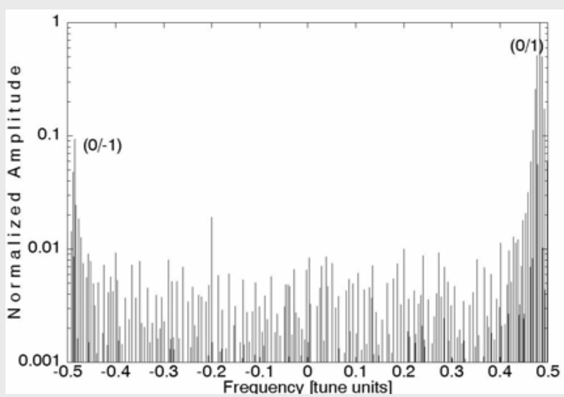
$3Q_y=16$ vs. $3Q_y=13$

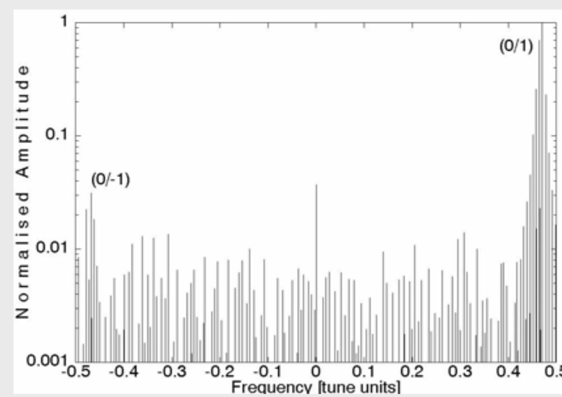




Resonance strength $|h_{0030}|$: $9.0 * 10^{-3}$ $mm^{-1/2}$ $2.2 * 10^{-3}$ $mm^{-1/2}$

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



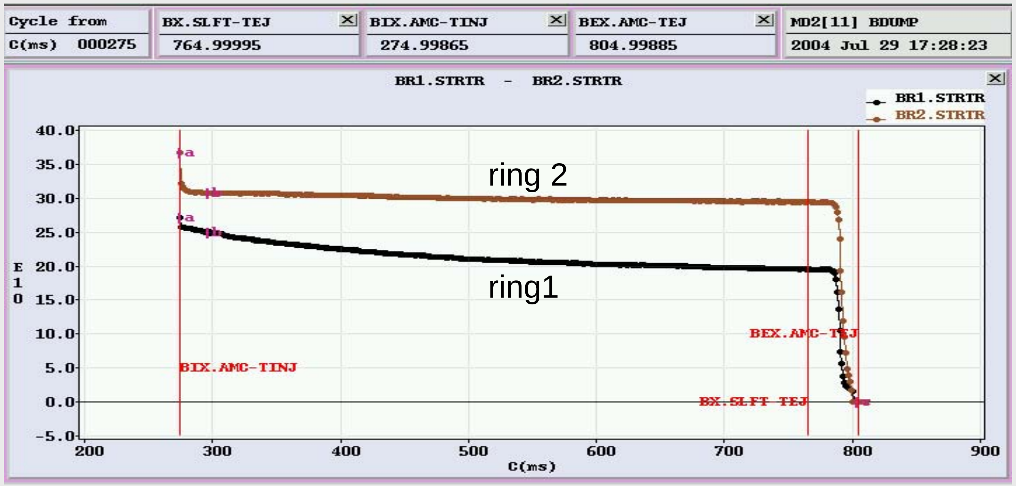


Resonance strength $|h_{0020}|$: $7.0 * 10^{-3}$ $3.2 * 10^{-3}$

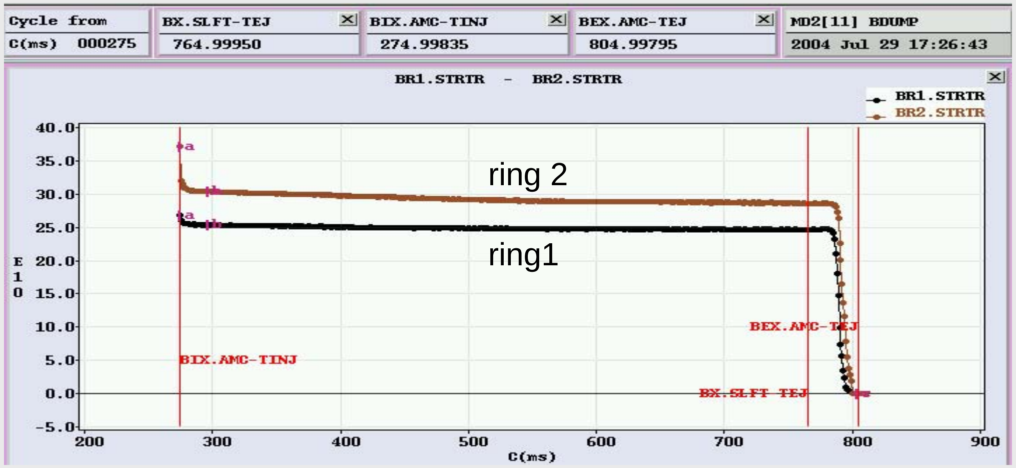
Alternative working point

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

…bare machine



…compensated



No compensation is needed for ring 2!

Conclusions

- The new acquisition system allows fast and efficient determination of resonance driving terms on the basis of turn-by-turn beam position measurements.
- All second and third order resonances relevant for operation were analysed for rings 1 and 2 of the PS Booster.
- Compensation settings were calculated and compared to the existing compensation scheme.
- Excellent agreement was found, confirming the quality of the existing scheme and underlining the validity and correctness of the new method.
- Comparative resonance driving term measurements for two different working points led to the conclusion that, from the resonance excitation point of view, a “lower” working point is preferable.
- **The start-up 2004 was done with the new working point.**
- A resonance compensation scheme for rings 1 and 2 for the new working point was established with the aid of the new method.