Direct Measurement of Resonance Driving Terms at SPS

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History

1988 J. Bengtsson, “Non-linear transverse dynamics for storage rings with applications to the Low-Energy Antiproton Ring (LEAR) at CERN”.

1992 J. Laskar, C. Froeschlé and A. Celletti, “The measure of chaos by the numerical analysis of the fundamental frequencies. Application to the standard mapping”.

1998 R. Bartolini and F. Schmidt “Normal Form via tracking or Beam Data”.

Introduction

-Beam based detection of lattice errors?

$\Rightarrow$ Resonance driving terms

-Can they be measured?

$\Rightarrow$ Pick-up system

-Can one localise the lattice errors?

$\Rightarrow$ Pick-ups around the ring

-Does it work for realistic beams?

$\Rightarrow$ Multiparticle considerations

-Real application:

$\Rightarrow$ Experiment at the SPS

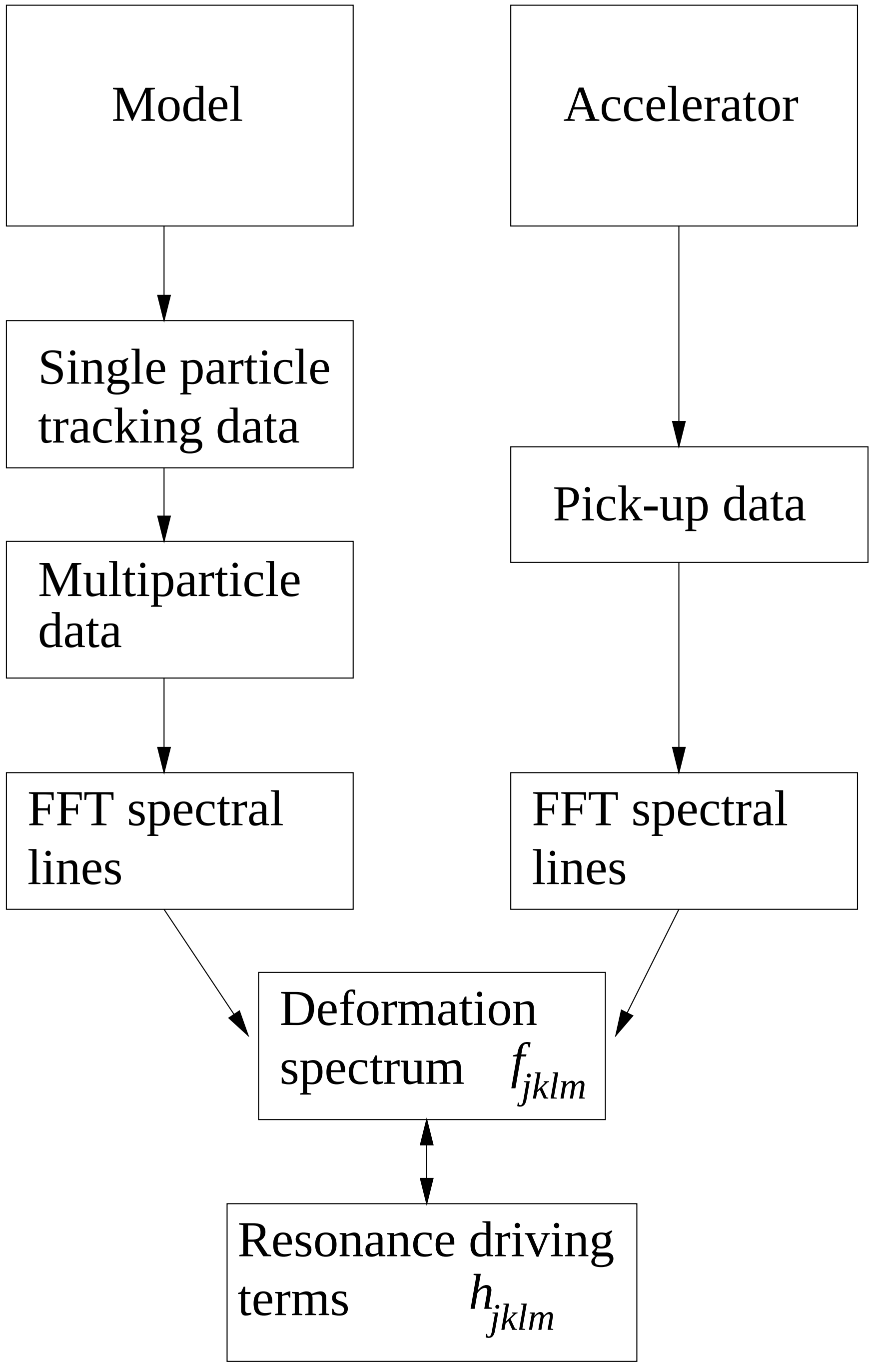
-Outlook for the PS Booster, RHIC and LHC

Resonance driving terms

- They provide a way to find linear and non–linear lattice errors:
  - Coupling (a_2)
  - Beta–beating (b_2)
  - Detuning with amplitude (b_3^2, b_4,...)
  - Non–linear resonances (b_3, b_4,...)

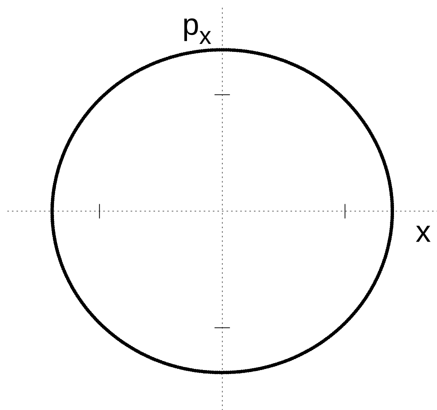
- and minimise them by use of correction circuits.

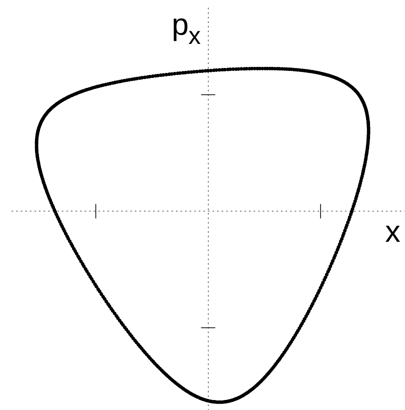
Technique overview



Example of phase space deformation

Linear motion | Non-linear motion





Relation between resonances and spectral lines

-Resonance (p,q) means:

$$\mathrm{p}Q_x + \mathrm{q}Q_y = n, \text{ with } n \in \mathrm{N}$$

-The spectral line (u,v) has the frequency:

$$\mathrm{u}Q_x + \mathrm{v}Q_y$$

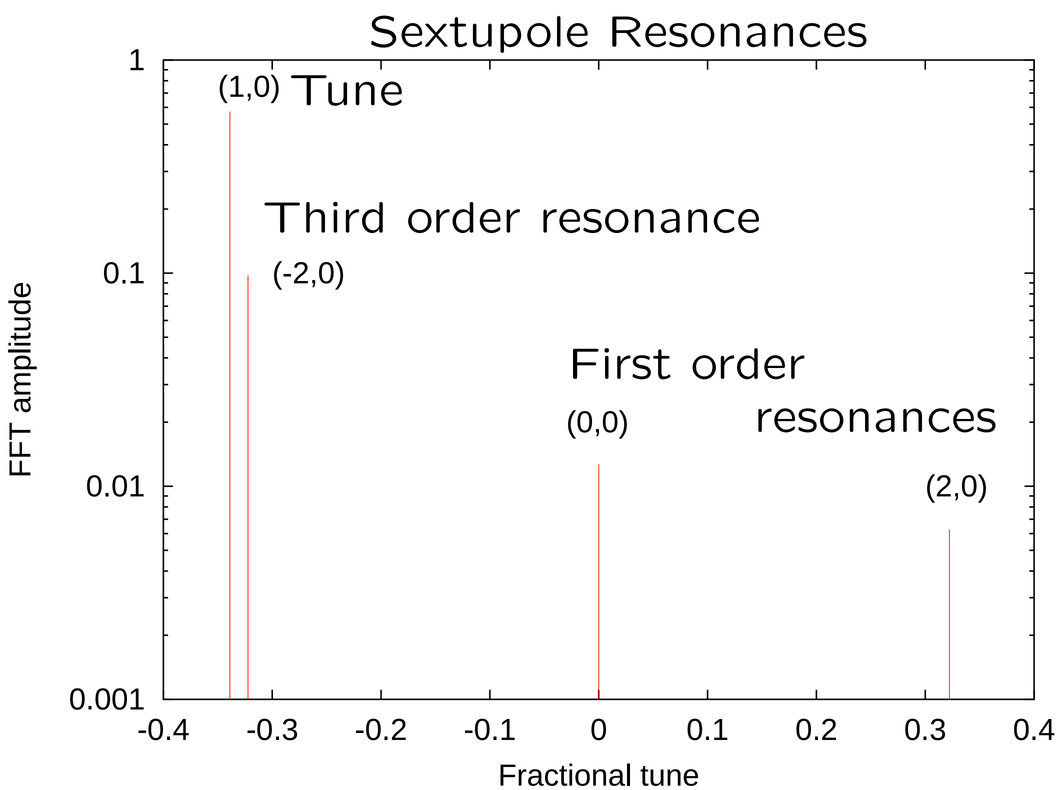
-The resonance (p,q) introduces the following spectral lines:

- (u,v)=(1−p,−q) in the spectrum of the horizontal motion,

- (u,v)=(−p,1−q) in the spectrum of the vertical motion.

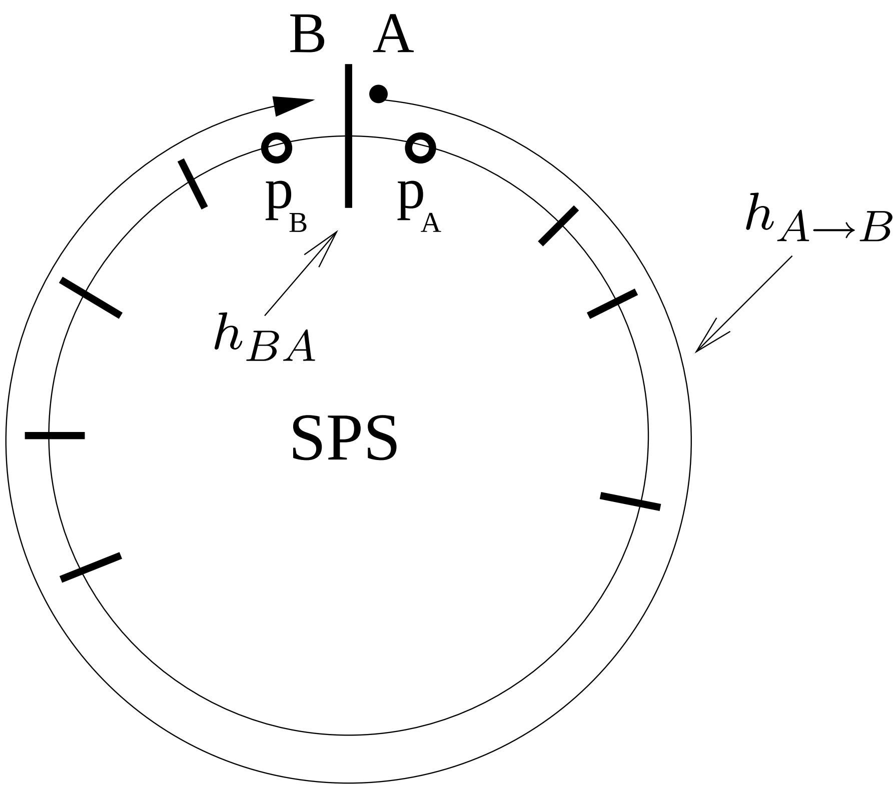
Example of a Fourier spectrum

Fourier spectrum of simulation data of a particle close to the third order resonance.



Spectral line (u,v)	Resonance term h_{jklm}	Resonance (p,q)
(-2,0)	h_{3000}	(3,0)
(0,0)	h_{2100}	(1,0)
(2,0)	h_{1200}	(1,0)

Longitudinal variation of resonance terms (I)



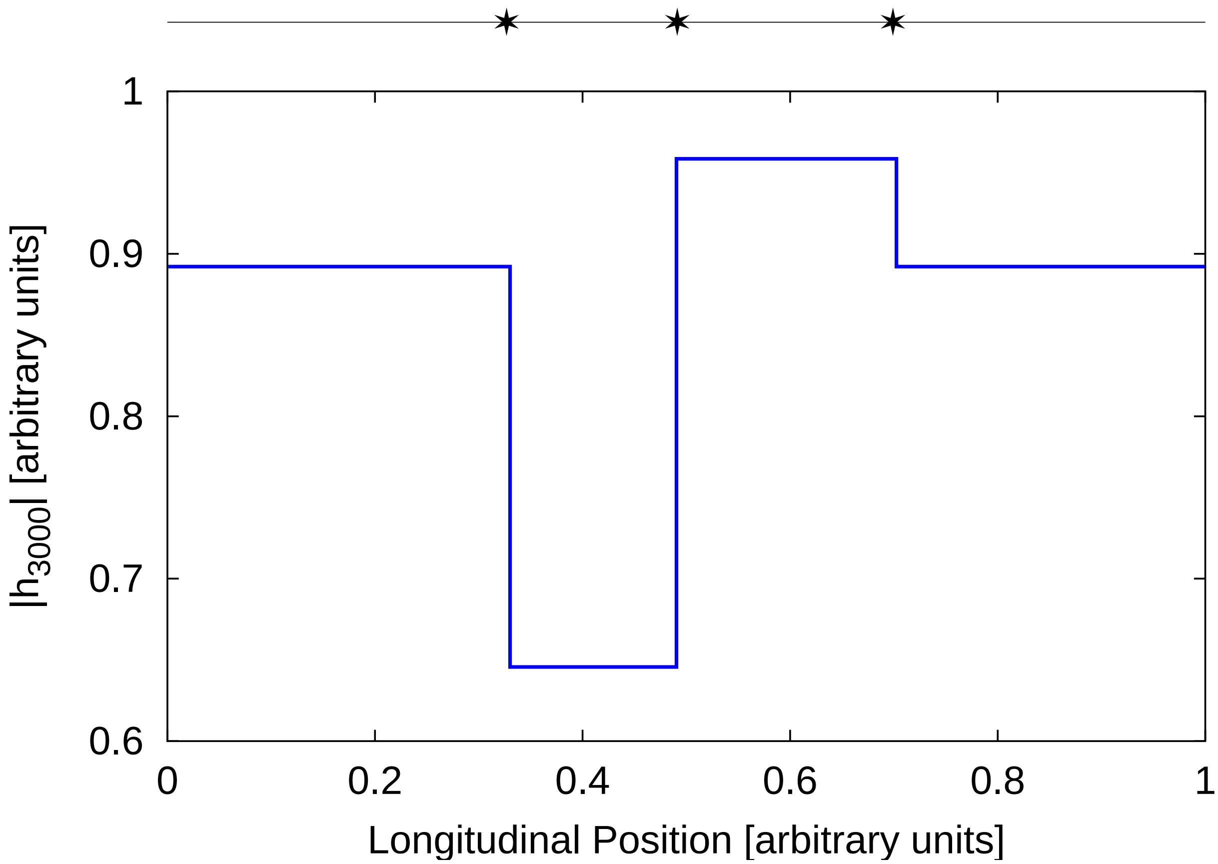
$$\left.\begin{array}{l} h_A = h_{A\to B}\circ h_{BA} \\ h_B = h_{BA}\circ h_{A\to B} \end{array}\right\} h_A \neq h_B$$

$\Rightarrow$ Amplitude of Driving Terms not the same

$\Rightarrow$ Amplitude constant between lattice errors

Longitudinal variation of resonance terms (II)

Tracking simulation of FODO lattice with 3 sextupoles:



$\Rightarrow$ Localisation of multipoles.

Effect of particle distributions

The motion of the centroid of the beam differs from that of a single particle when decoherence processes take place. The most relevant sources of decoherence are:

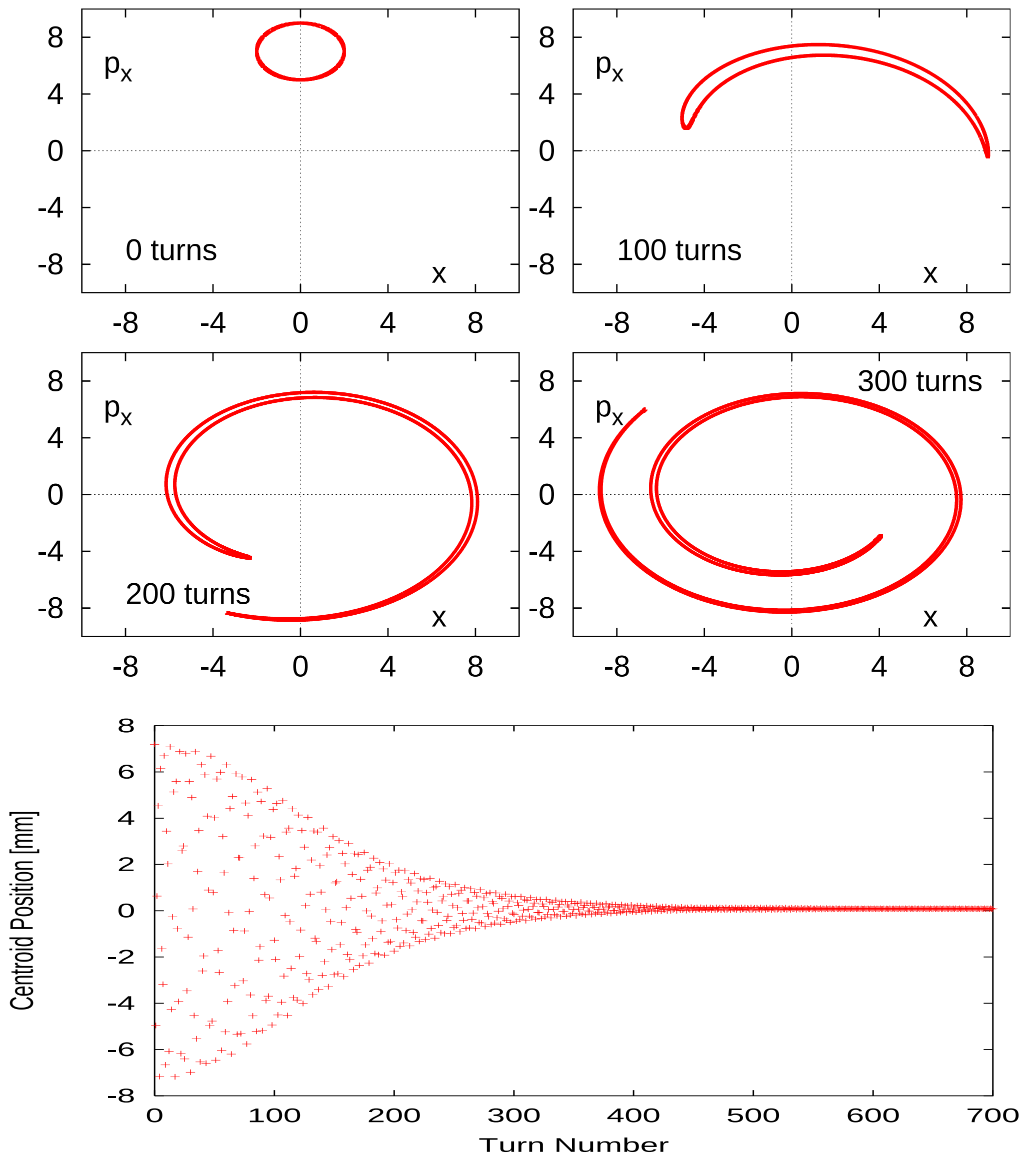
- Amplitude detuning

$$Q_x = Q_{x\circ} + g_x(A_x, A_y)$$

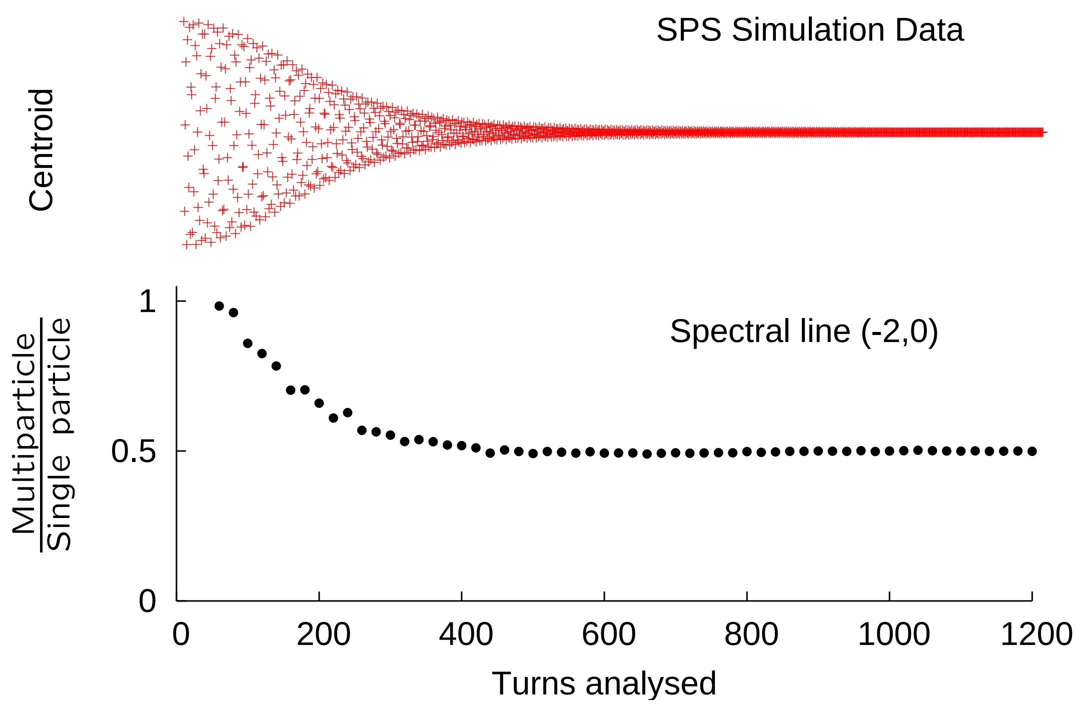
- Chromaticity

$$\Delta Q_x = Q'_x \frac{\Delta p}{p}$$

Amplitude detuning



Multiparticle versus single particle

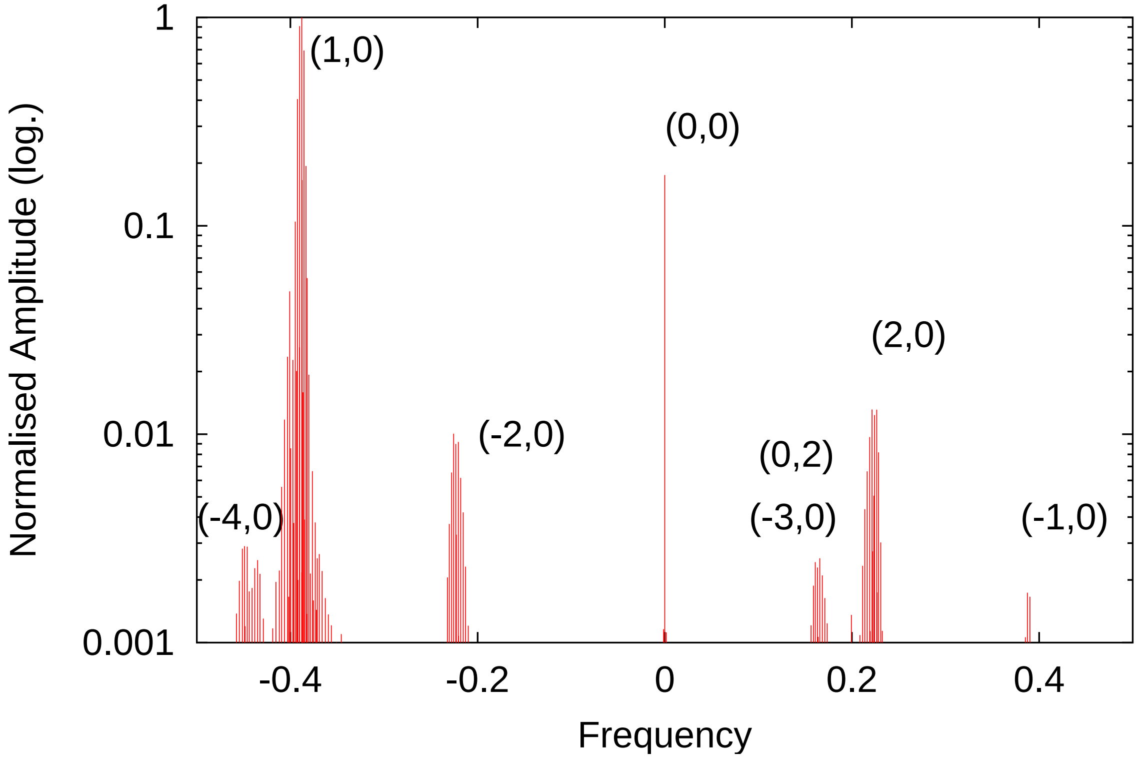


Reference: CERN–SL–2001–39

$\Rightarrow$ The spectral line (u,0) of a decohered signal is reduced by a factor of $|u|$ compared to the single particle case.

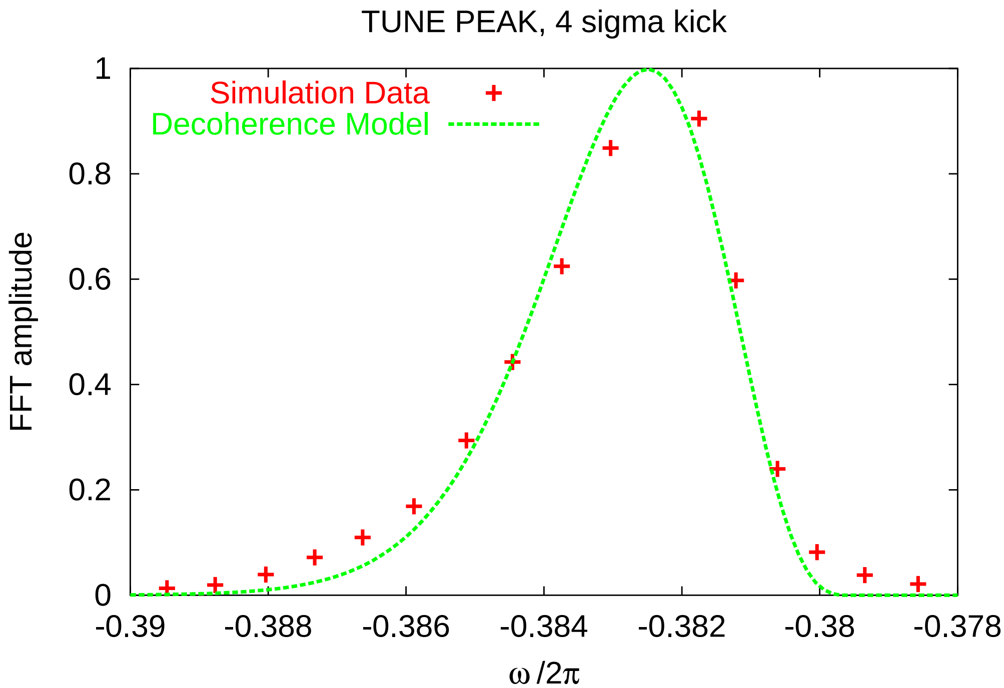
Multiparticle spectrum

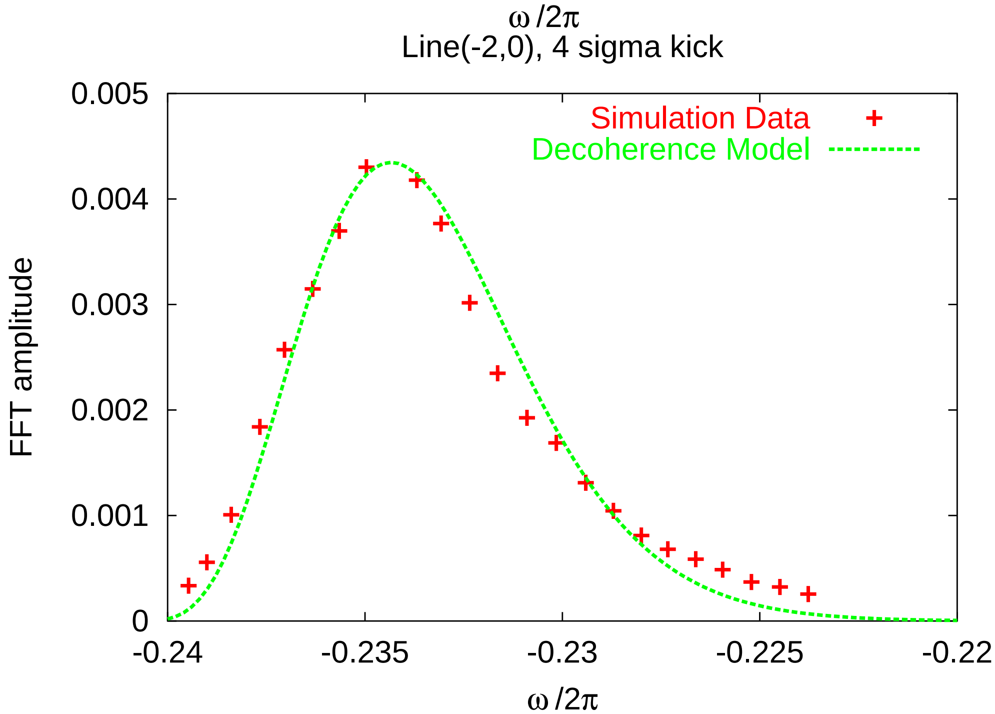
SPS simulation.



⇒ The spectral lines become distributions instead of spikes.

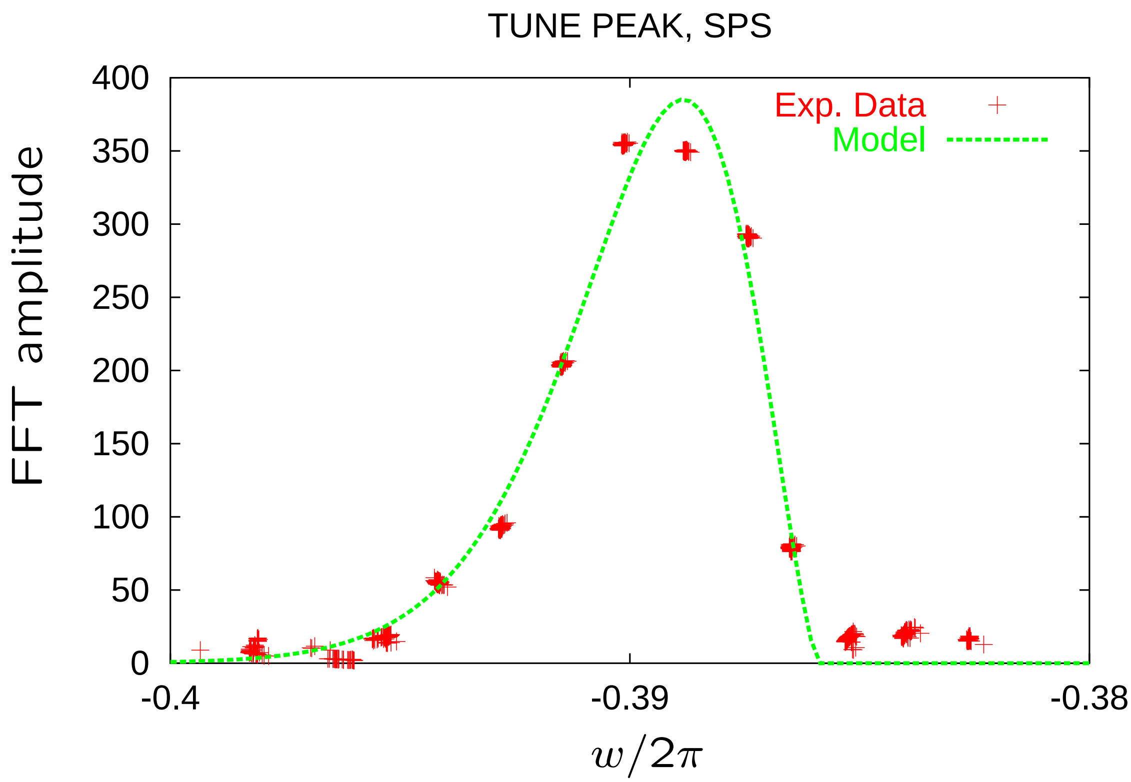
Model versus simulation





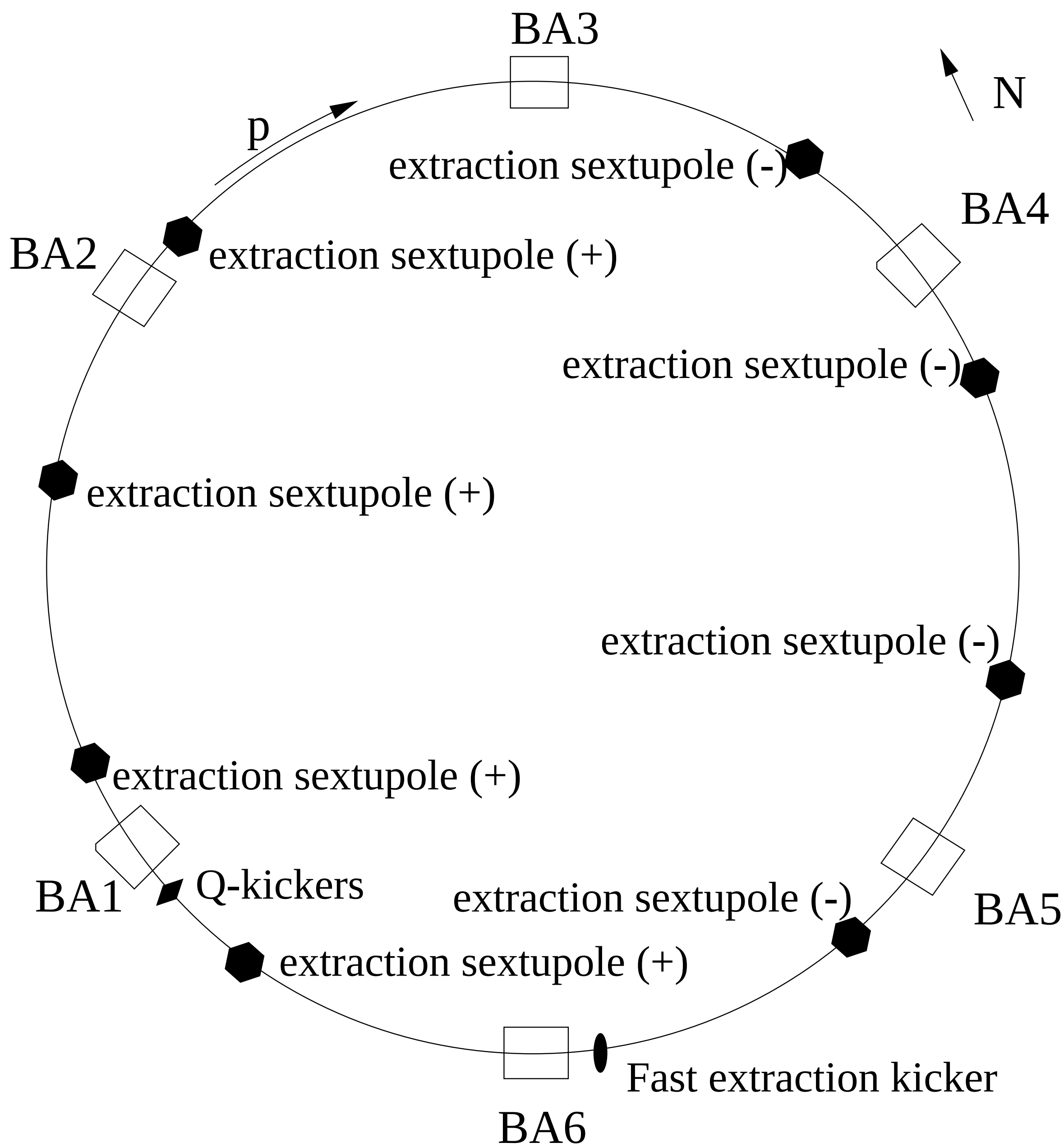
Application: SPS 120 GeV (2000)

Fitting tune line distribution:



Observable	Fit result	Classic Meth.
Q_{x0}	$-0.38593 \pm 5 \cdot 10^{-5}$	-0.3859
$(\Delta Q_x)_{1\sigma_x}$	$(-3.6 \pm 0.1) \cdot 10^{-4}$	$-3.71 \cdot 10^{-4}$
$\sigma_x[mm/\sqrt{\beta_x}]$	0.266 ± 0.008	

$\Rightarrow$ Measurement of these observables from a single kick


BA3
N
p
extraction sextupole (-)
BA4
BA2
extraction sextupole (+)
extraction sextupole (-)
extraction sextupole (+)
extraction sextupole (-)
extraction sextupole (+)
BA1
Q-kickers
extraction sextupole (-)
BA5
extraction sextupole (+)
Fast extraction kicker
BA6

Technique:

1. Transverse beam oscillation excited by a single kick.

2. FFT of turn–by–turn signal constructed from 2 consecutive pick-ups.

Experiments:

- 2000: E=120 GeV, 84 bunches, 2×10^{12} protons, Qx=26.62 and Qy=26.58.

- 2001: E=26 GeV, single bunch, 2×10^{10} protons, same tunes.

- 2002: E=26 & 80 GeV, single bunch, 2×10^{10} protons, Qx=26.18 and Qy=26.22.

Linear Coupling: description

The coupling resonance (1,-1) is driven by the deformation term f_{1001} and produces secondary spectral lines $(0,1)_H$ and $(1,0)_V$ (the tune lines $(1,0)_H$ and $(0,1)_V$).

$$2 \times |f_{1001}| = \sqrt{\frac{(0,1)_H}{(1,0)_H}\frac{(1,0)_V}{(0,1)_V}}$$

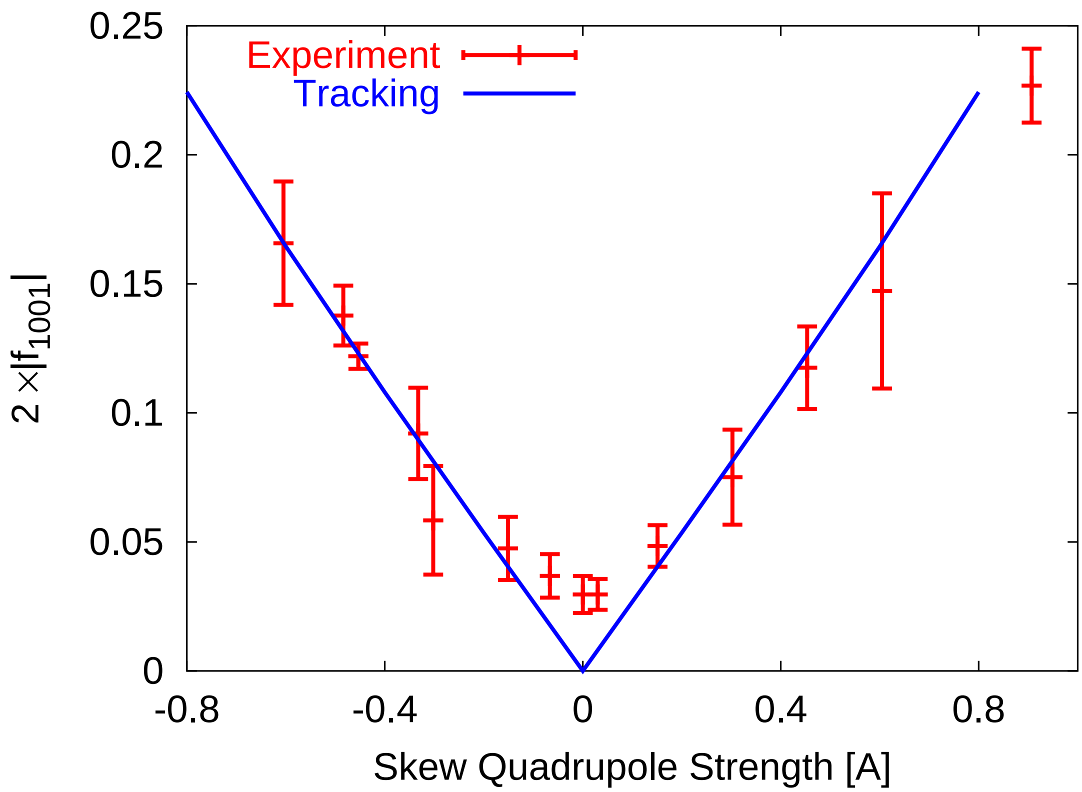
This measurement of $|f_{1001}|$ is independent of pick-up calibrations and oscillation amplitudes.

The horizontal tune line $(1,0)_H$ depends on the horizontal kick and the secondary horizontal line $(0,1)_H$ depends on the vertical kick.

$\Rightarrow$ We kick in both planes.

Linear Coupling in SPS (2001)

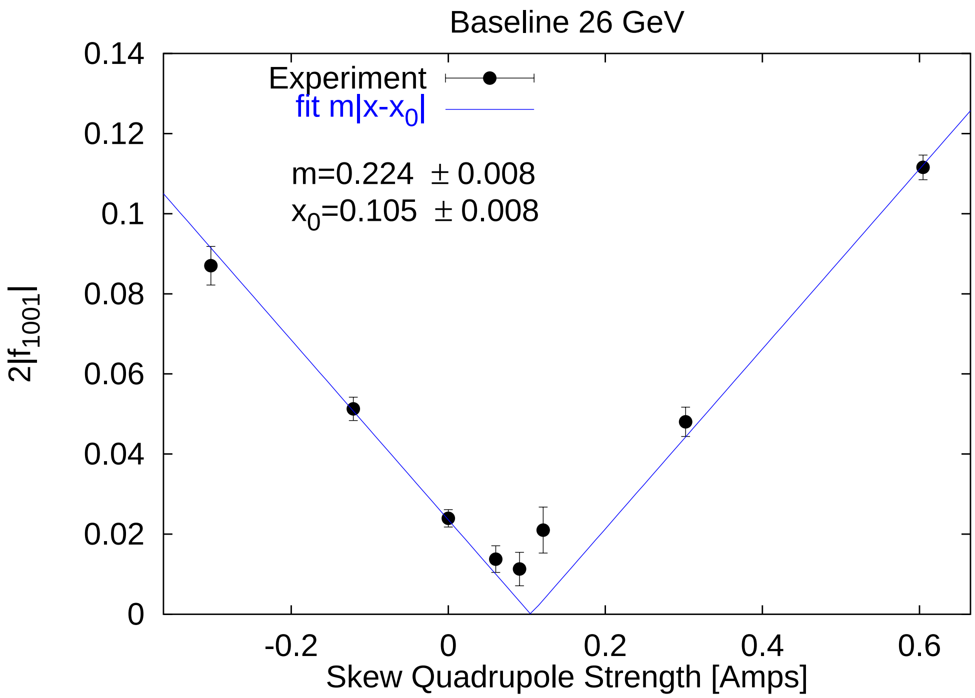
The coupling term $|f_{1001}|$ is plotted as function of the strength of the skew quadrupoles:

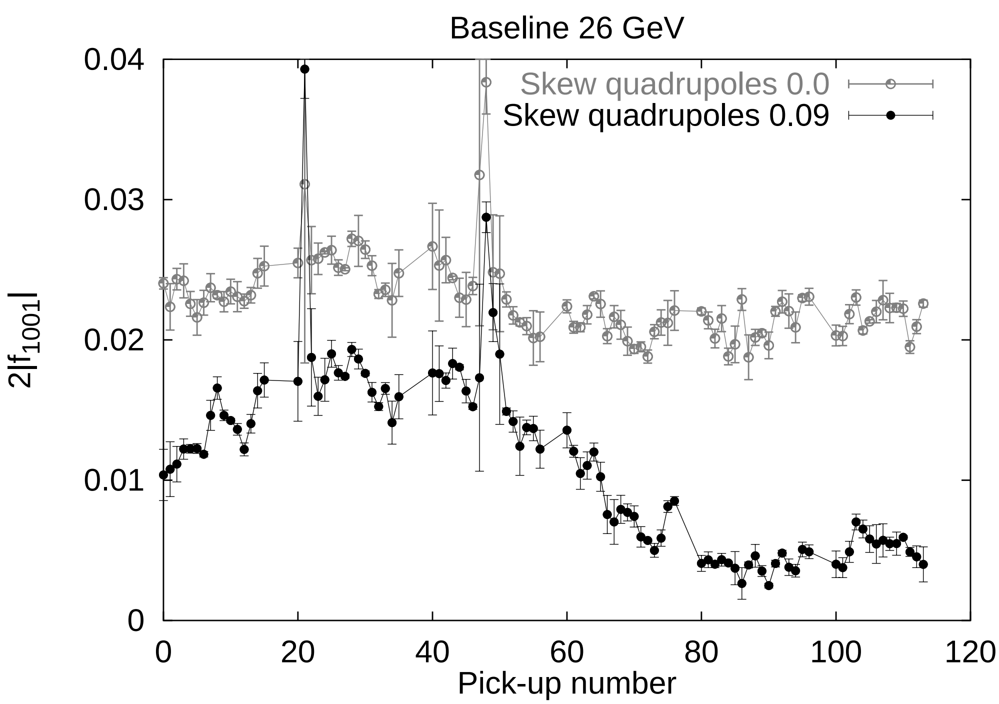


⇒Model and experiment are in excellent agreement.

⇒This shows that SPS is decoupled in this particular case.

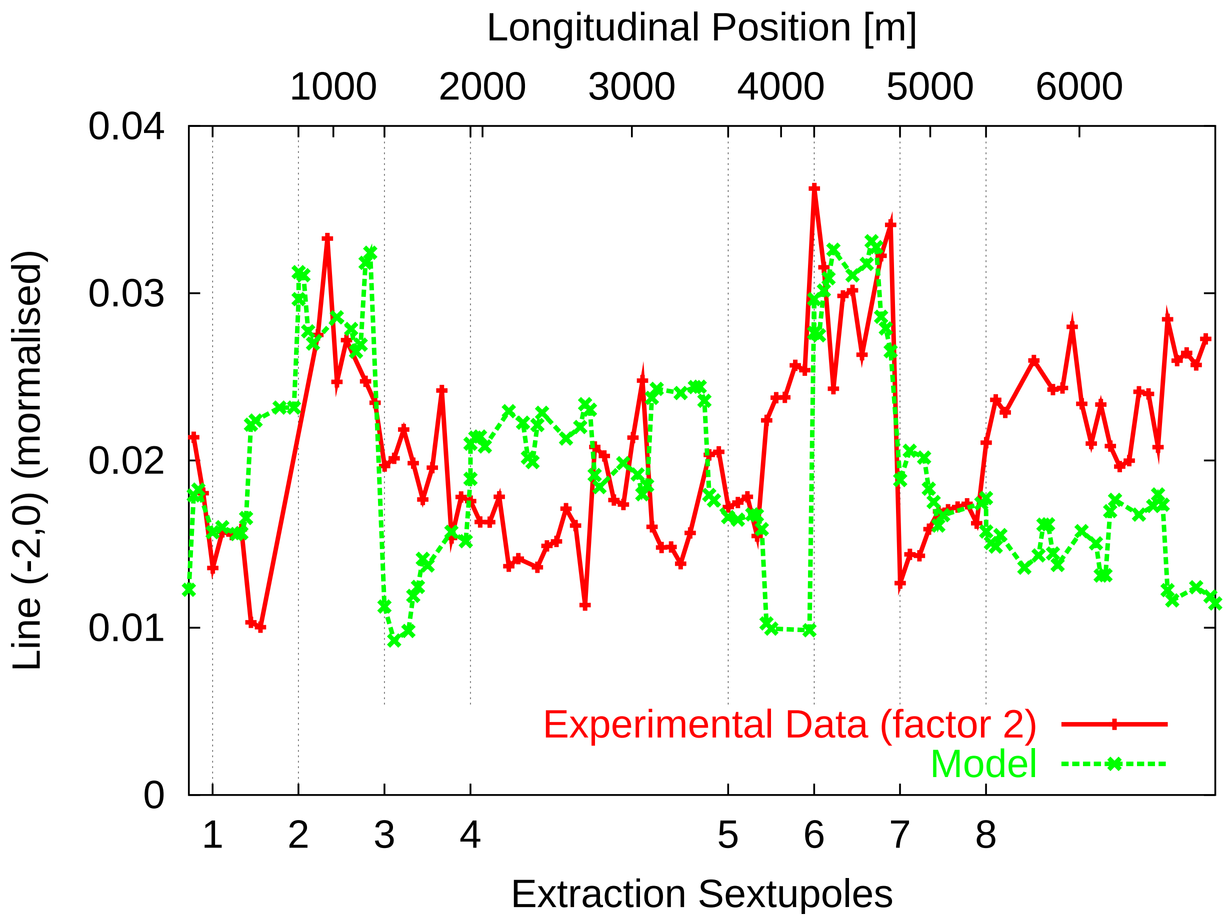
Linear Coupling in 2002





Sextupolar driving terms in SPS (2000)

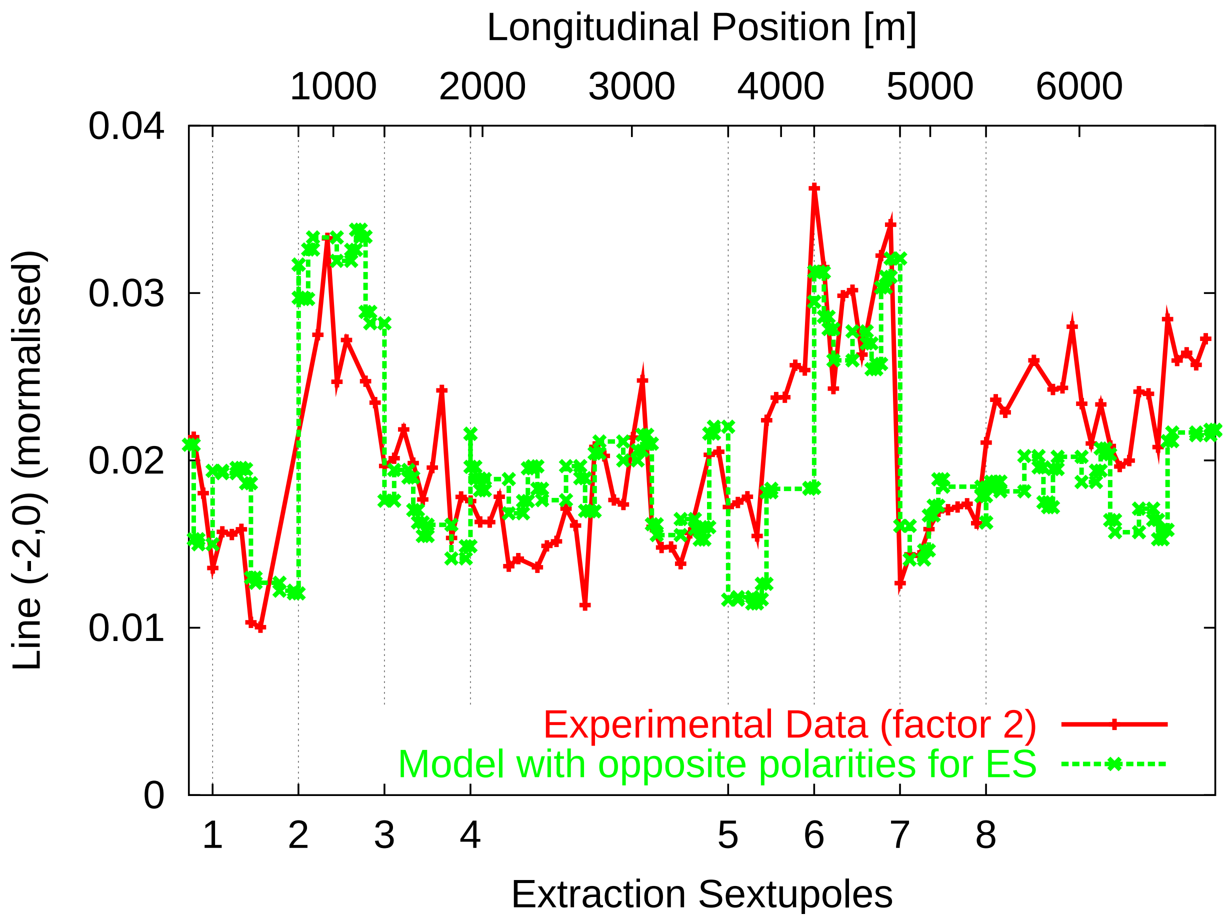
The resonance (3,0) introduces the spectral line (-2,0).



$\Rightarrow$ We have a problem!

Solution

Change polarities of the extraction sextupoles?

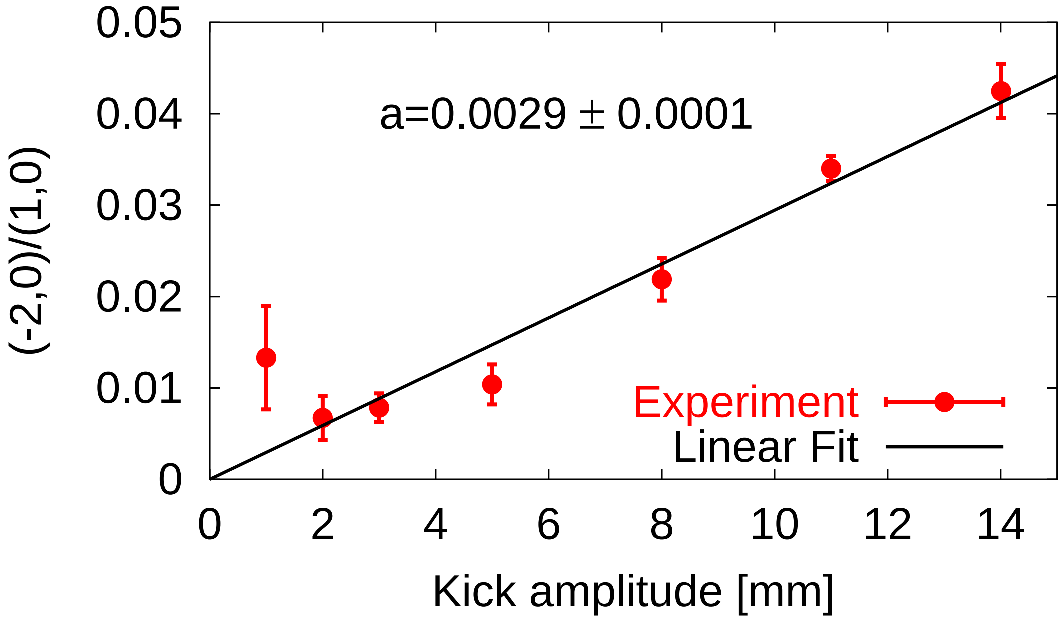


Hardware checks confirmed that these sextupoles had opposite polarities.

⇒ First success of this technique!

Line to Resonance conversion

The resonance (3,0) is driven by the deformation term f_{3000} and produces the spectral line (-2,0).



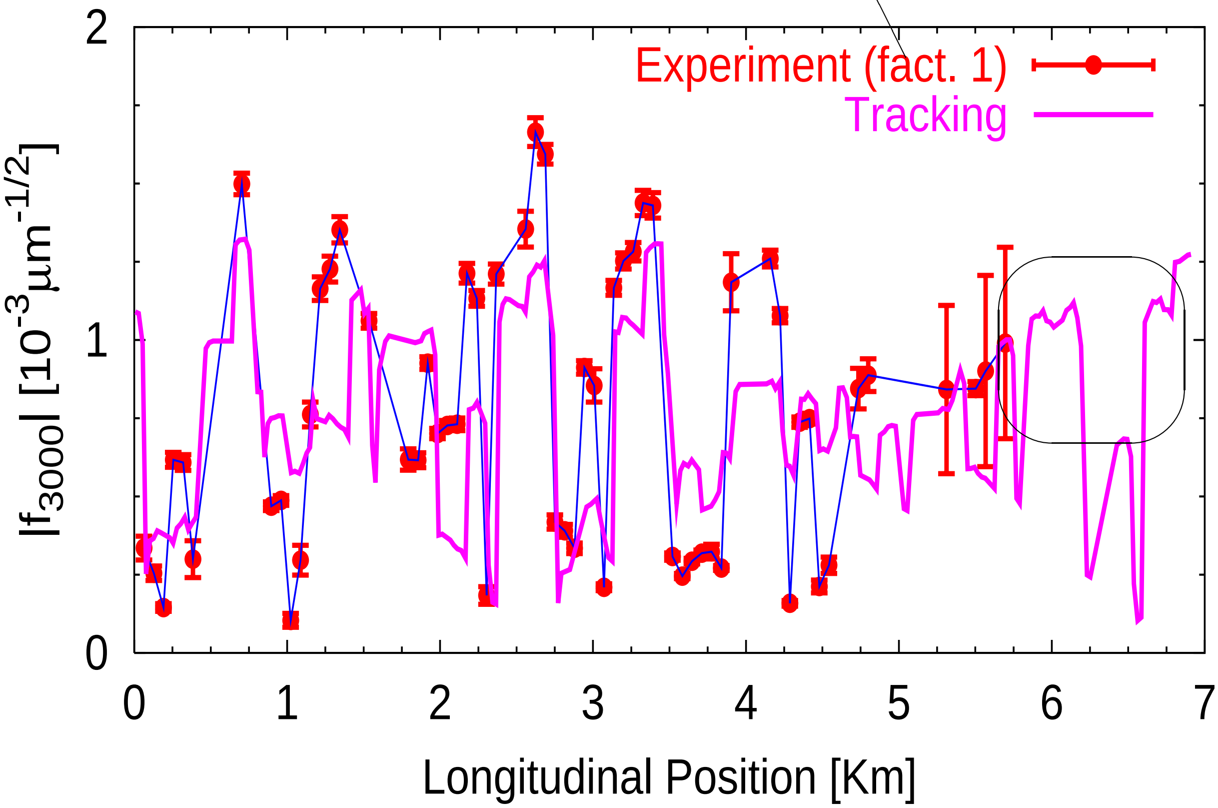
$$|f_{3000}| = \frac{1}{6} \mathrm{a} \sqrt{\beta_e} \ [\sqrt{\mu m}]$$

$$\sqrt{\beta_e} = 10.6 \ [\sqrt{m}]$$

$\Rightarrow |f_{3000}|$ is obtained around the ring by doing this fit for all the pick-ups.

A. Sextupolar Driving Terms 2001

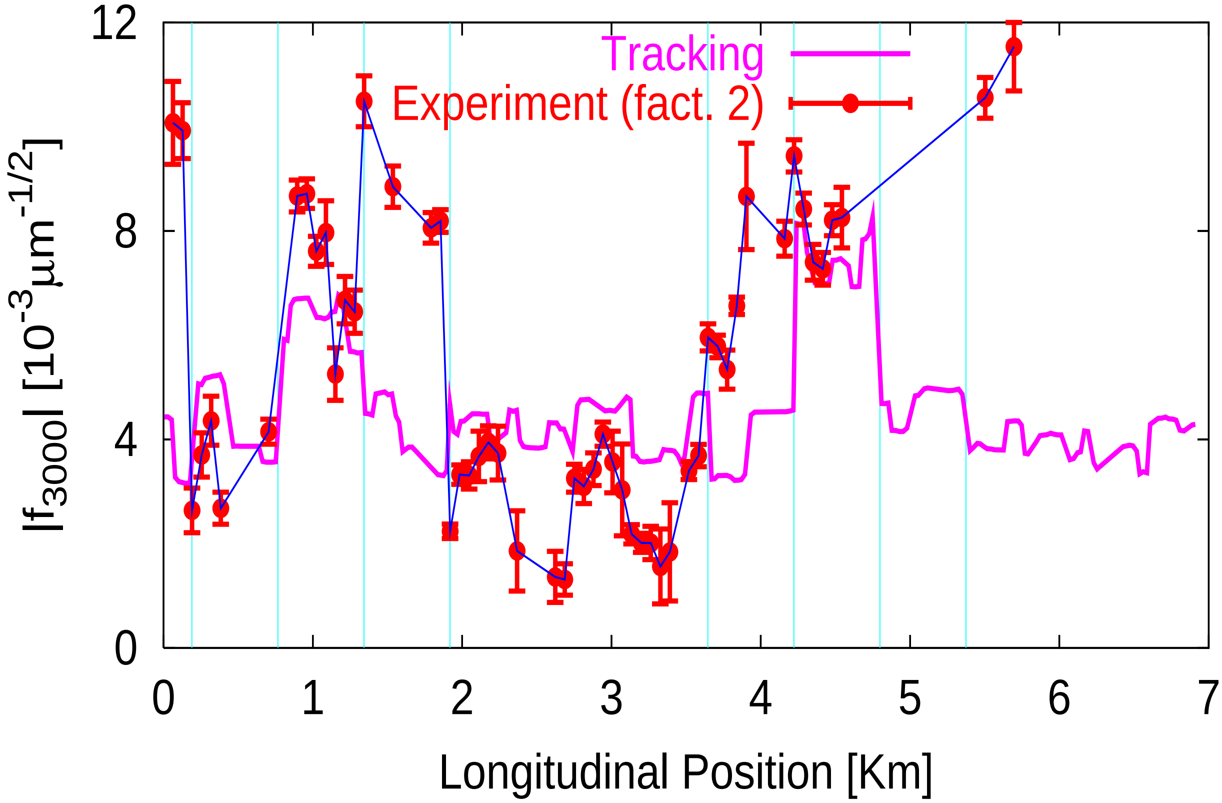
Bare SPS, Qx=26.62 (No decoherence).



⇒ Local discrepancies may be due to unknown sextupole sources.

B. Introduction of artificial lattice errors

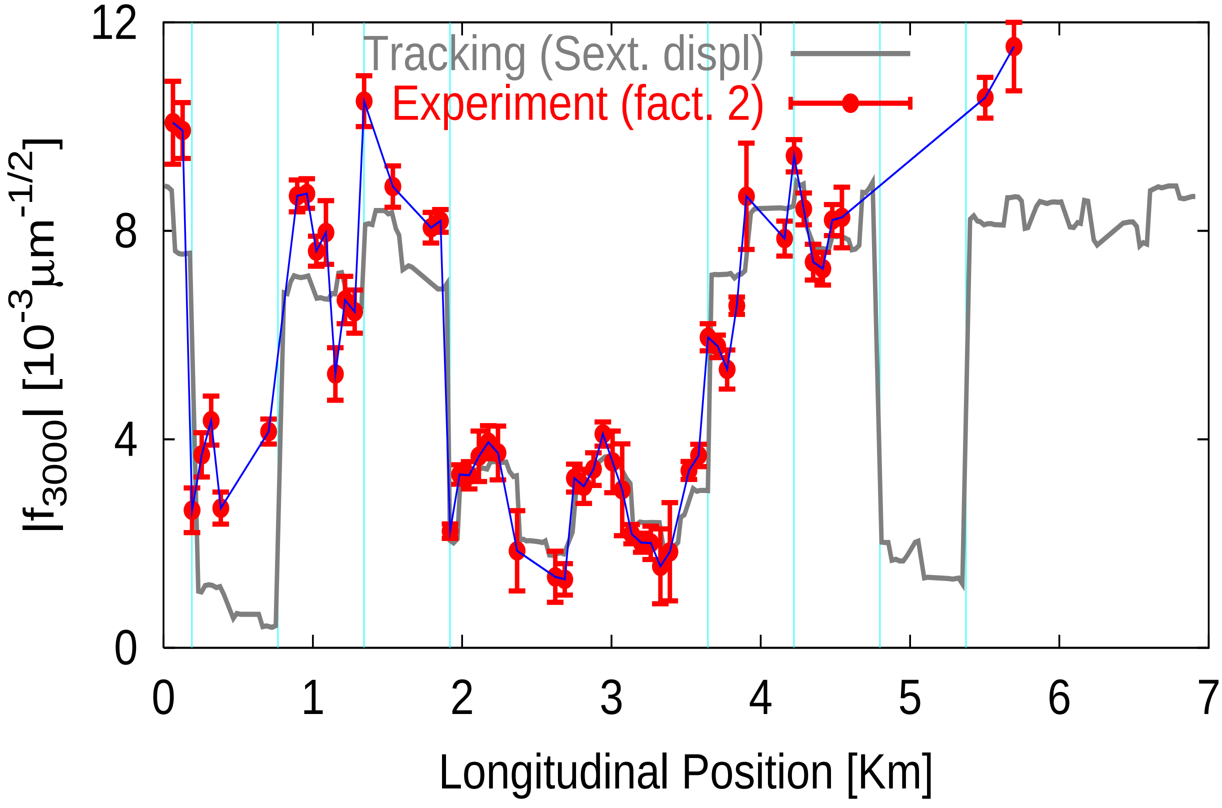
Extraction Sextupoles powered to $++++-----30$ A.
Data fully decohered ⇒ Line reduced by a factor 2.



⇒Large discrepancies: We have a problem!

C. Solution

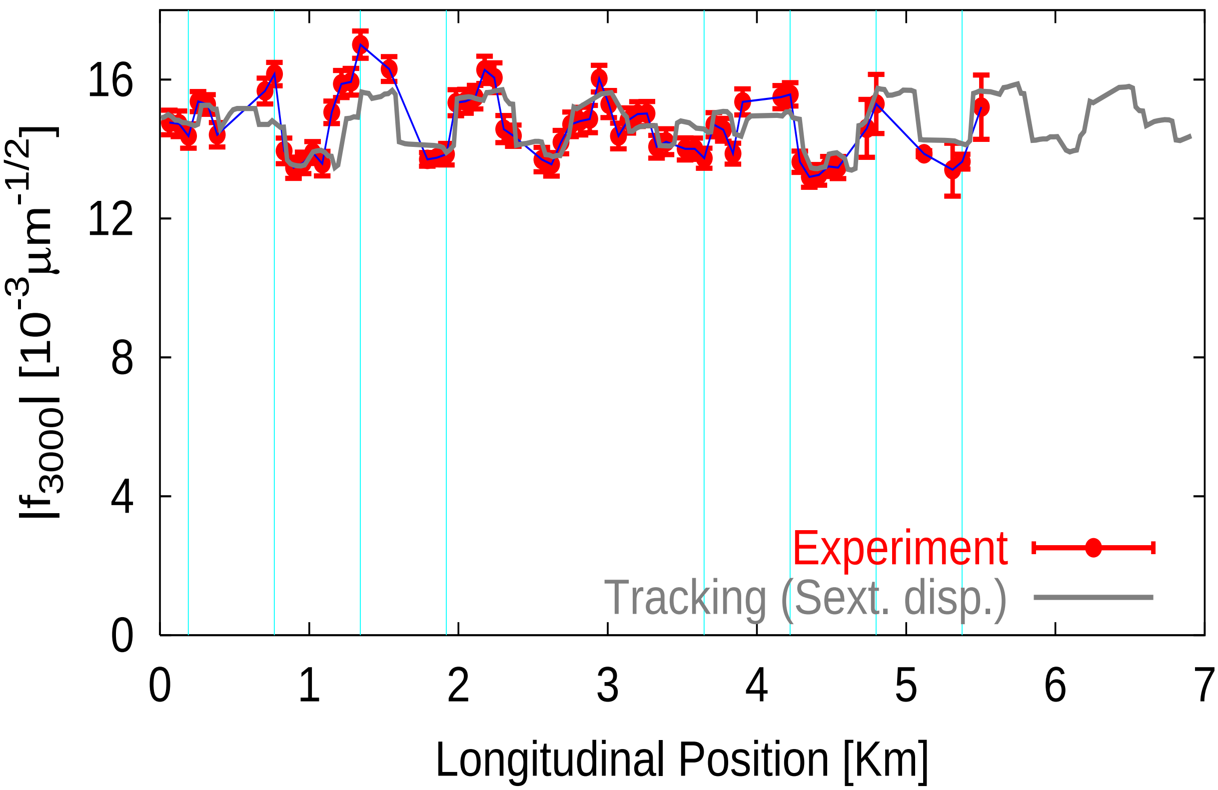
The closed orbit as measured from pick-ups is introduced at the extraction sextupoles in the model.



⇒ Improvement due to beta–beating and phase differences in the model.

D. Close to the (3,0) resonance

Extraction Sextupoles powered to ++++++++++3 A. Qx=26.662.
Data fully decohered ⇒ Line reduced by a factor 2.

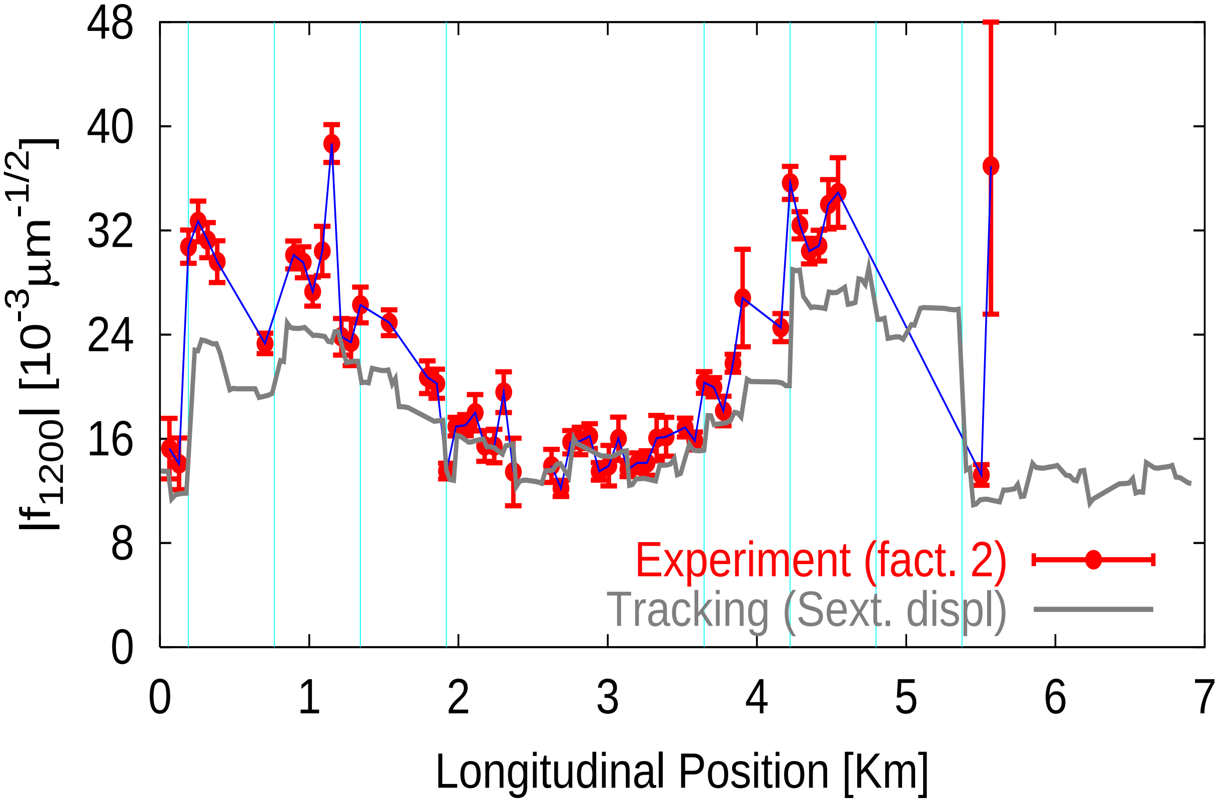


⇒ Smaller variations due to the tune.

E. Resonance(1,0)

The resonance (1,0) is driven by the term f_{1200} and produces the spectral line (2,0). Extraction Sextupoles powered to $++++-----30$ A. Qx=26.69.

Data fully decohered $\Rightarrow$ Line reduced by a factor 2.



$\Rightarrow$ Good agreement.

Conclusions

- A method to measure and correct the linear coupling has been developed. It has the advantage of being faster than the traditional closest tune approach.

- For the first time sextupolar resonance terms have been measured around the SPS:
  - Correct sextupole polarities were found.
  - The overall agreement between model and experiment is good after introducing the closed orbit at the sextupoles.
  - The reduction of lines due to decoherence is experimentally confirmed.
  - Decoherence also has an advantage.
  - A tool for the on–line analysis of the data has been developed for SPS, ready for implementation.

Outlook

- Similar studies have been started at the PS Booster and at RHIC.

- This method has even larger potential in conjunction with an AC dipole instead of a single kick:
  - Non destructive measurement
  - No decoherence

- A realistic model of LHC showed that this technique could be applied to measure and correct linear and non–linear resonances.