Control of the Driving Terms: A Perspective

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11/03/06

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1.0 Background

WEPCH096 Proceedings of EPAC 2006, Edinburgh, Scotland

MEASUREMENT AND CORRECTION OF THE 3RD ORDER RESONANCE IN THE TEVATRON

Y. Alexahin, V. Lebedev, D. Still, A. Valishev, FNAL, Batavia, IL 60510, F. Schmidt, CERN

For the first time in 1988 [4] the accelerator community has started using TBT data to evaluate the sextupole strength in a real accelerator. Further studies have shown [5] that, in first order approximation, each line in a complex FFT of the TBT data can be related to a resonance. Specifically, the TBT spectra of complex

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Measurement vs. Control:

G. Gardner, Y. Shoji, L. Ahrens, J.W. Glenn, Y.Y. Lee, T. Roser, A. Souka, W. van Asselt, W.T. Weng "Observation and Correction of Resonance Stopbands in the AGS Booster" PAC93.

G. Gardner, Y. Shoji, G. Danby, J.W. Glenn, J. Jackson, A. Soukas, W. van Asselt, C. Whalen "Analysis of Resonance-Driving in the AGS Booster" EPAC94.

J. Bengtsson "The Sextupole Scheme for the Swiss Light Source (SLS): An Analytic Approach" SLS Note 9/97.

R. Bartolini, L.H.A. Leunissen, Y. Papaphilippou, F. Schmidt, A. Verdier "Measurement of Resonance Driving Terms from Turn-by-Turn Data" PAC99.

F. Schmidt, R. Tomás "Measurement of Driving Terms" PAC01.

M. Bai, M. Blaskiewicz, A. Lehrach, T. Roser, F. Schmidt, W. van Asselt "Measurement of Non-Linearities Using Spectrum Analysis of Driven Betatron Oscillation" PAC01.

M. Hayes, F. Schmidt, R. Tomás "Direct Measurement of Resonance Driving Terms at SPS at 26 GeV" EPAC02.

V. Ptitsyn, A.V. Fedotov, F. Pilat "The Observation and Compensation of Nonlinear Resonances in RHIC" EPAC02.

F. Schmidt, M. Hayes, R. Tomás "Completion of the Sextupole Driving Terms Measurements at the SPS" PAC03.

W. Fischer, F. Schmidt, and R. Tomás "Measurement of Sextupolar Resonance Driving Terms in RHIC" PAC03.

M. Bai, F. Pilat, T. Satogata, R. Calaga "Measurement of Linear Coupling Resonance in RHIC" PAC03.

M. Benedikt, C. Carli, M. Chanel, F. Schmidt, P. Urschütz "Betatron Resonance Studies at the CERN PS Booster by Harmonic Analysis of Turn-by-Turn Beam Position Data" EPAC04.

P. Urschütz “Measurement and Compensation of Second and Third Order Resonances at the CERN PS Booster” EPAC04.

V.A. Kvardakov, T.B. Levichev, A.I. Naumenkov, P.A. Piminov “The Study of 2D Sextupole Coupling Resonances at VEPP-4M” EPAC04.

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2.0 A Case Study

NON-LINEAR TRANSVERSE DYNAMICS FOR STORAGE RINGS
WITH APPLICATIONS TO THE
LOW-ENERGY ANTIPROTON RING (LEAR) AT CERN

Johan Bengtsson

CERN 88-05
Proton Synchrotron Division
1 August 1988

Question: what's the betatron spectrum for a particle near a single resonance?

Frequency	Amplitude	Phase
$Q_x + \Delta Q_x$	$\sqrt{2 J_{2x} \beta_x(s_0)}$	$\phi_{2x}(s_0)$
$(n_x - 1)(Q_x + \Delta Q_x) + n_z(Q_z + \Delta Q_z)$	$\sqrt{2 J_{2x} \beta_x(s_0)}\, j\, \Delta_x$	$(n_x - 1)\, \phi_{2x}(s_0) + n_z \phi_{2z}(s_0) + \phi_\kappa$
$(n_x + 1)(Q_x + \Delta Q_x) + n_z(Q_z + \Delta Q_z)$	$\sqrt{2 J_{2x} \beta_x(s_0)}\, k\, \Delta_x$	$(n_x + 1)\, \phi_{2x}(s_0) + n_z \phi_{2z}(s_0) + \phi_\kappa$

Frequency	Amplitude	Phase
$Q_z + \Delta Q_z$	$\sqrt{2 J_{2z} \beta_z(s_0)}$	$\phi_{2z}(s_0)$
$n_x(Q_x + \Delta Q_x) + (n_z - 1)(Q_z + \Delta Q_z)$	$\sqrt{2 J_{2z} \beta_z(s_0)}\, l\, \Delta_z$	$n_x \phi_{2x}(s_0) + (n_z - 1)\, \phi_{2z}(s_0) + \phi_\kappa$
$n_x(Q_x + \Delta Q_x) + (n_z + 1)(Q_z + \Delta Q_z)$	$\sqrt{2 J_{2z} \beta_z(s_0)}\, m\, \Delta_z$	$n_x \phi_{1x}(s_0) + (n_z + 1)\, \phi_{2z}(s_0) + \phi_\kappa$

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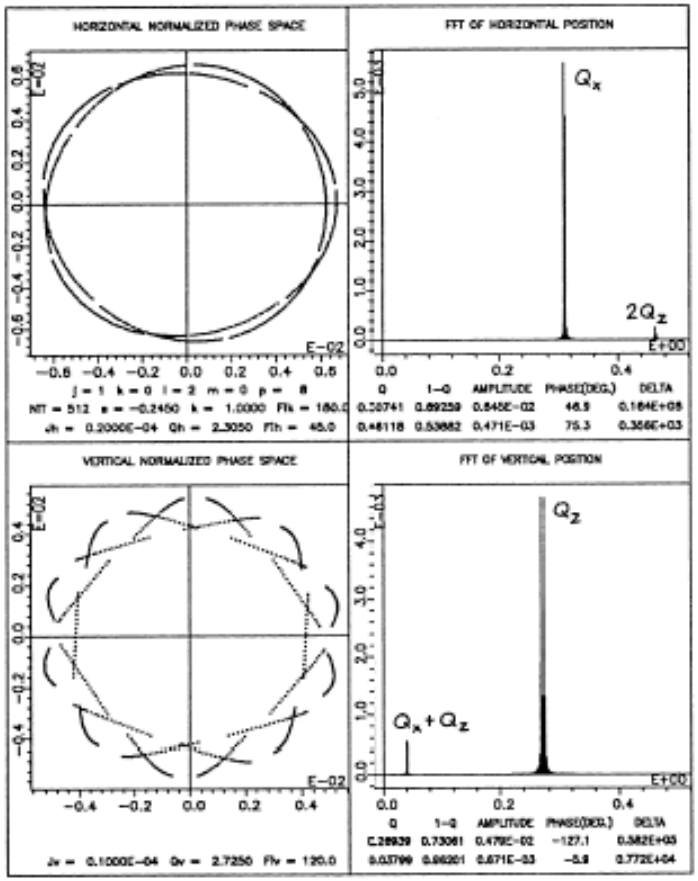

Figure 5: Simulation of a sextupolar sum resonance

$\sqrt{2\beta_x(s_0)J_{2x}}$	6.38×10^{-3}	6.45×10^{-3}
$\phi_{2x}(s_0)$	46.9°	46.9°
ΔQ_x	2.19×10^{-3}	2.41×10^{-3}
$\sqrt{2\beta_x(s_0)J_{2x}}\,\Delta_x$	2.19×10^{-4}	4.71×10^{-4}
$2\phi_{2z}(s_0)+\phi_x$	74.4°	75.3°
$\sqrt{2\beta_z(s_0)J_{2z}}$	4.63×10^{-3}	4.79×10^{-3}
$\psi_{2z}(s_0)$	127.2°	127.1°
ΔQ_z	5.25×10^{-3}	5.61×10^{-3}
$\sqrt{2\beta_z(s_0)J_{2z}}\,2\Delta_z$	6.03×10^{-4}	6.71×10^{-4}
$\phi_{2x}(s_0)+\phi_{2z}(s_0)+\phi_x$	$-5.9°$	$-5.9°$

FIGURE 1. Simulation and Data Analysis of $\nu_x + 2\nu_y = 8$.

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- **Validate the turn-by-turn BPM data acquisition system (2 channels) and the interpolation techniques required to obtain sufficient resolution from the FFT:**

Table 5: Phase advance

Pick-ups	Measured phase advance (degrees)	Calculated by COMFORT (degrees)
UEH13 – UEH14	15.4	16.0
UEH14 – UEH23	192.1	191.2
UEH21 – UEH22	120.7	118.3
UEH22 – UEH23	34.1	36.3
UEH23 – UEH24	15.9	16.0

TABLE 1. Optics Model Calibration.

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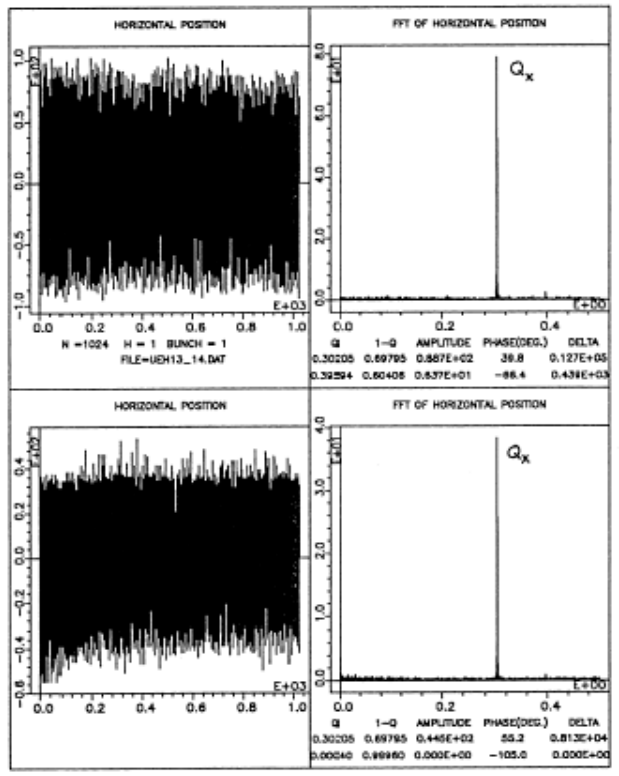

Figure 6: Measurement of the phase advance

FIGURE 2. Measurement and Signal Processing at Injection.

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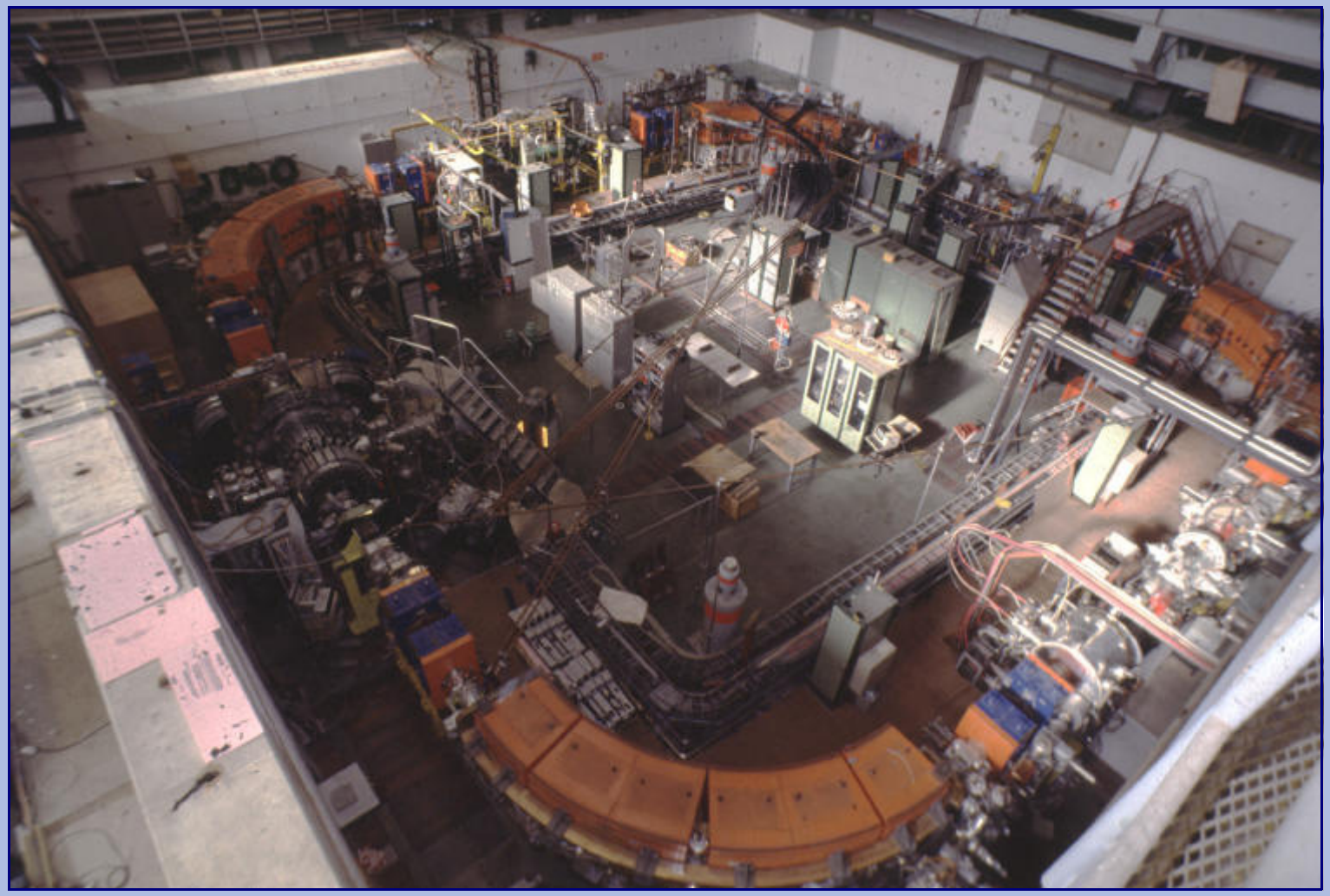

FIGURE 3. The Low Energy Antiproton Ring (LEAR).

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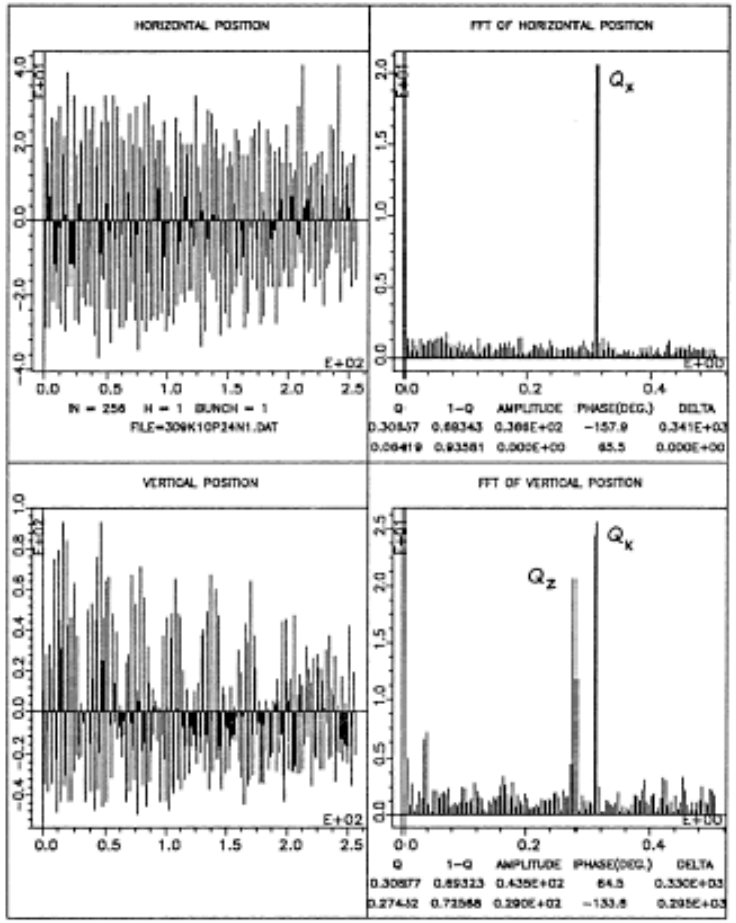

Figure 12: Measurement done before compensation, e = 0.032

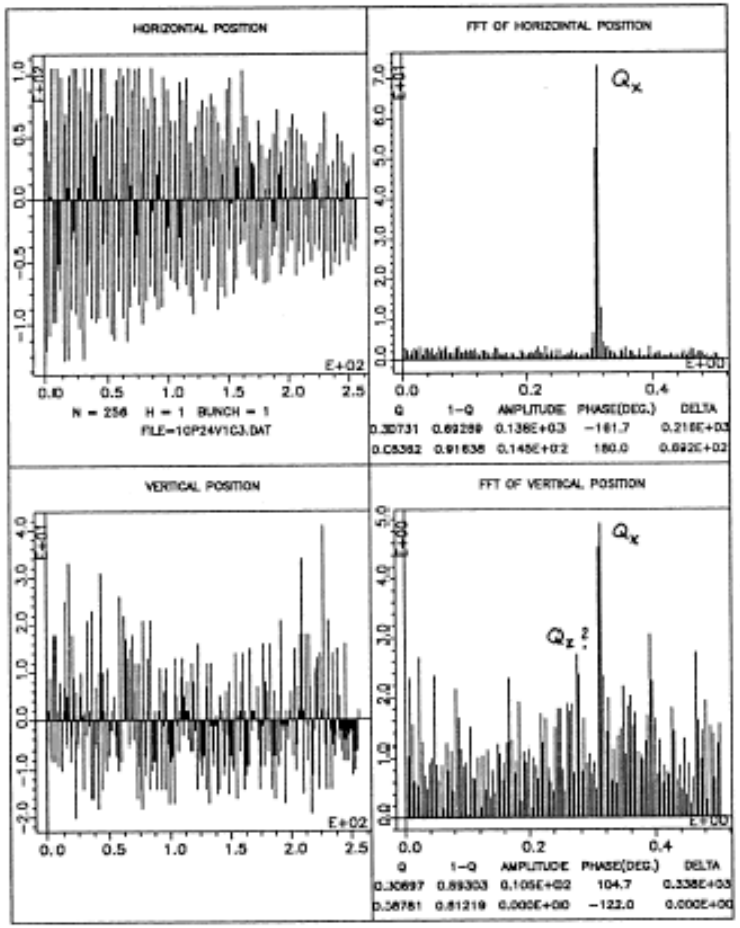

Figure 13: Measurement done after compensation, e = 0.033

FIGURE 4. Correction of the $\nu_x + \nu_y = 5$ Resonance in LEAR.

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- Since LEAR did not have skew quadrupoles, correction was made by tilting a normal quadrupole at the proper location (in 3 steps, using a big wrench).
- However, roll errors could not account for the correction (3.2 mrad).

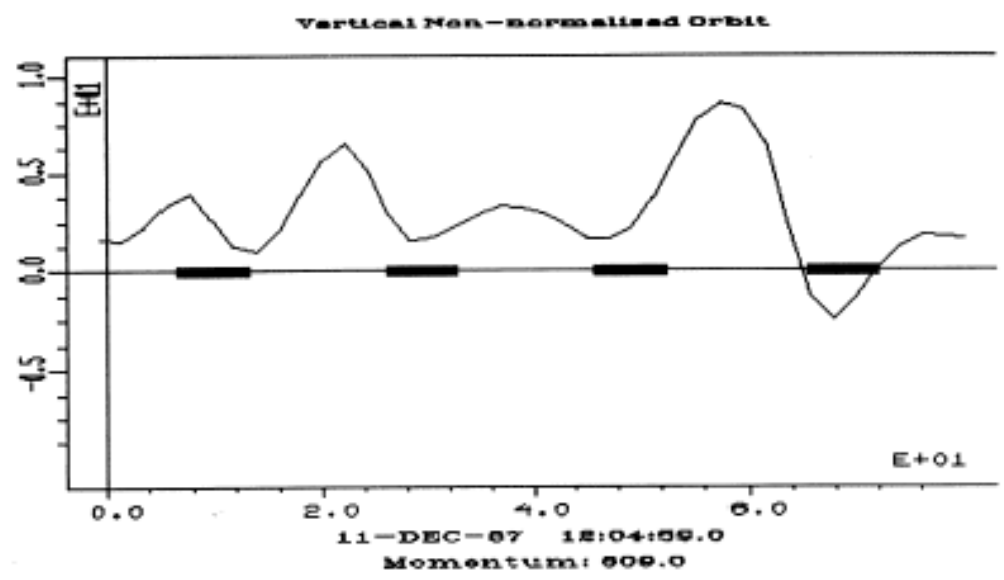

Figure 17: Vertical closed orbit distortions

FIGURE 5. Source of the $\nu_x + \nu_y = 5$ Resonance in LEAR.

- So, instead, the dominant sextupoles (2) were moved onto the orbit.

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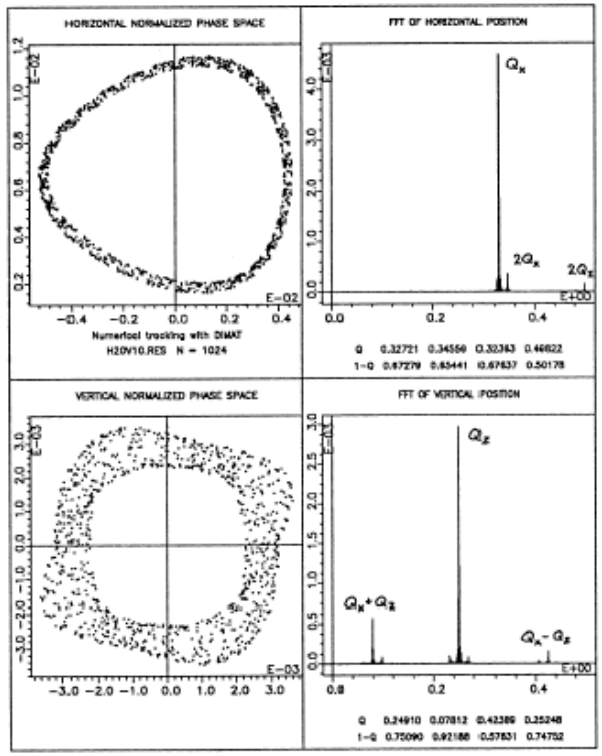

Figure 21: Tracking with DIMAT, $J_x = 10$, $J_z = 5$

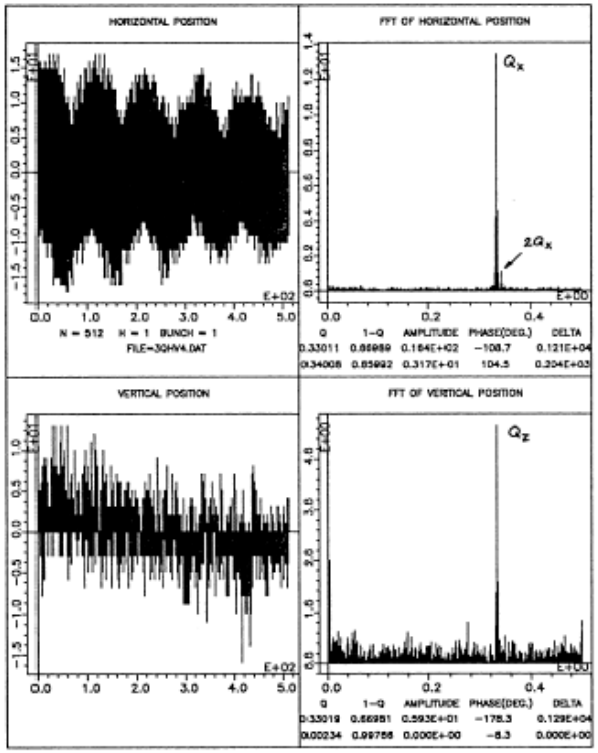

Figure 24: Measurement of $3Q_x = 7$

FIGURE 6. Study of the Extraction Resonance $3\nu_x = 7$ for LEAR.

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Note, control of the $3\nu_x = 7$ resonance used for the ultraslow extraction (1-4 hrs) was done by:

- **first zeroing it (by accelerating through the resonance),**
- **and then incrementing it to design values (without driving the other terms).**

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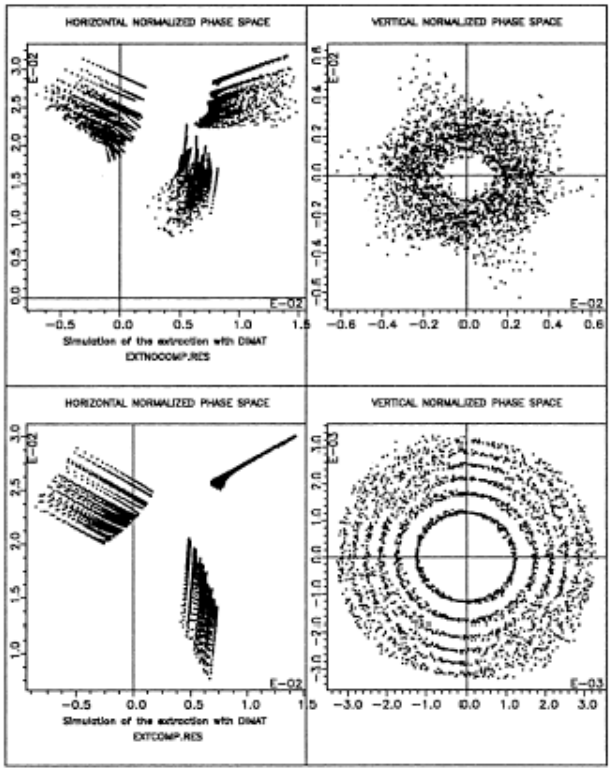

Figure 23: Simulation of the extraction by DIMAT

FIGURE 7. Simulation of the Ultraslow Extraction for LEAR: with- and without Correction of $\nu_x + 2\nu_y = 8$.

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Eventually:

1995: from antiparticles to antimatter

After making antinuclei, naturally the next question was: can antielectrons stick to antinuclei to make antiatoms?

In fact the answer was only revealed quite recently, thanks to a very special machine, unique to CERN, the **Low Energy Antiproton Ring** (**LEAR**). Contrary to an accelerator, LEAR actually "slowed down" antiprotons. Physicists could then try to force a positron (or antielectron) to stick to an antiproton, making an antihydrogen atom, a real antimatter atom.

Towards the end of 1995, the first such **antiatoms** were produced at CERN by a team of German and Italian physicists. Although only 9 antiatoms were made, the news was so thrilling that it made the front page of many of the world's newspapers.

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Preliminary analysis of turn-by-turn BPM data from the recent RHIC proton run:

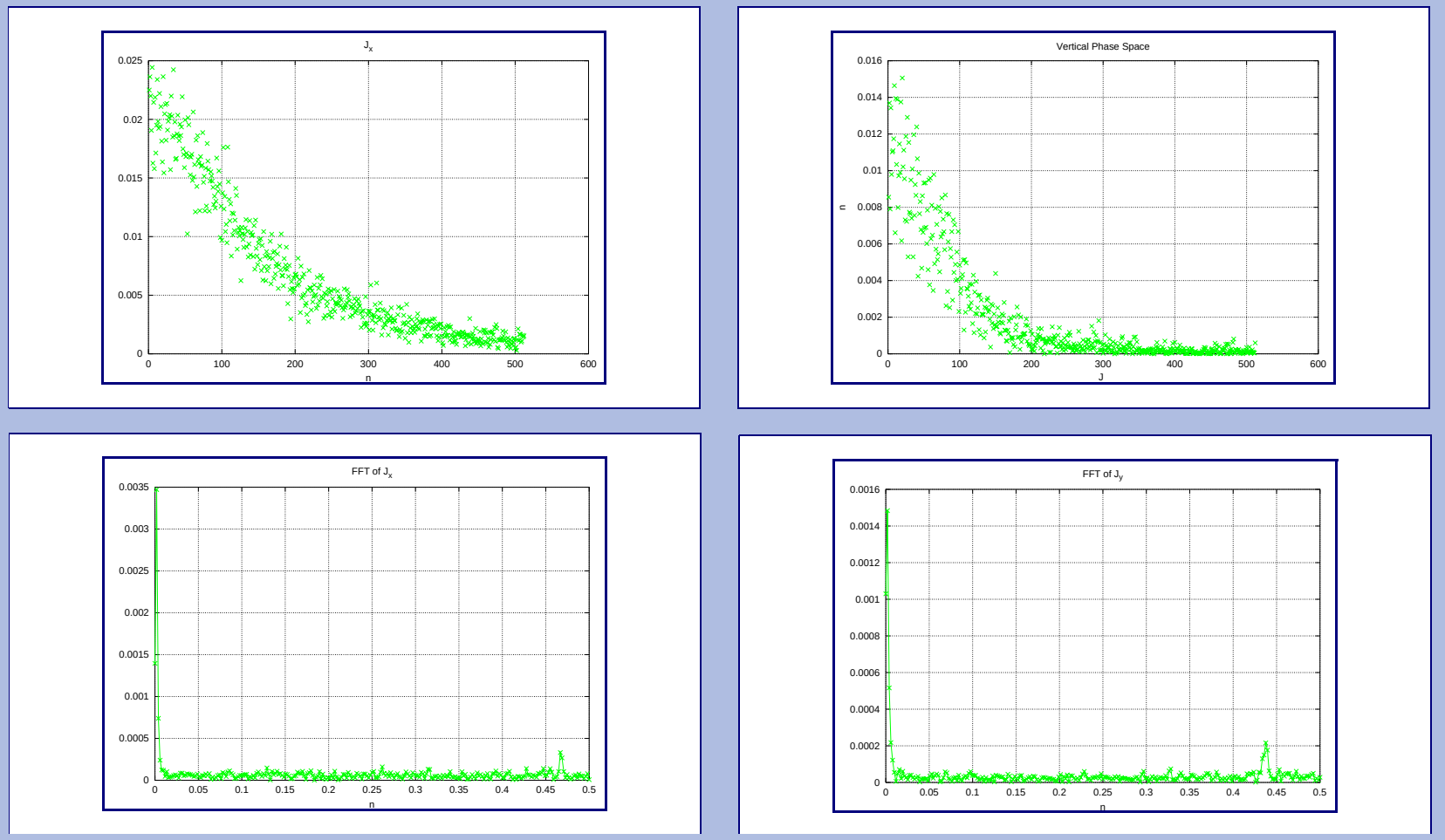

FIGURE 8. FFT of $J_{x,y}$ at Injection.

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- Use AC-dipole to drive the beam.
- Implement on-line tools for signal processing.

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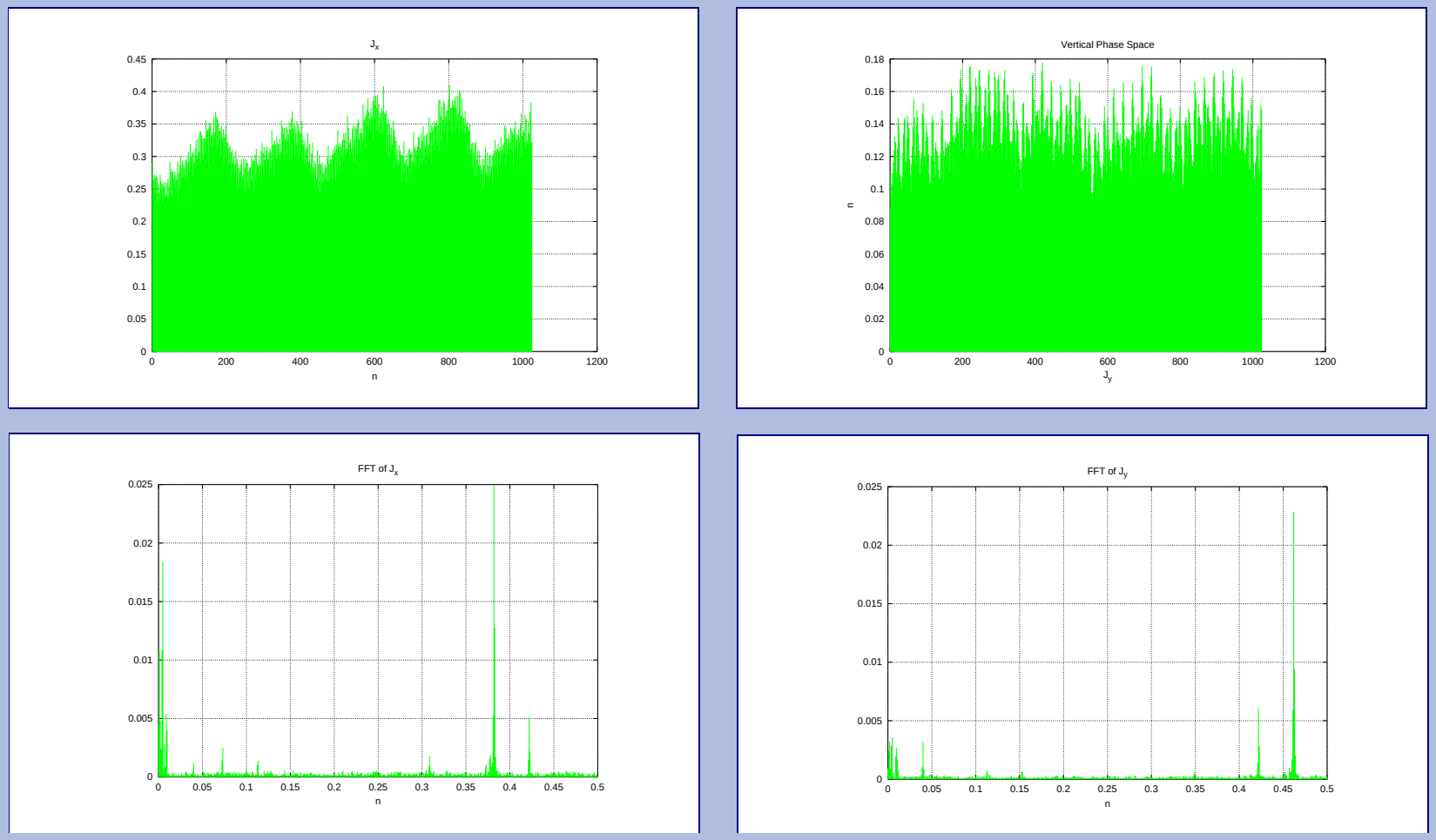

FIGURE 9. AC-Dipole Data for $J_{x,y}$.

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Peak	f_x	A_x	ν_x	ν_y	Δf_x
0	-0.00001	5.923e-01			
1	0.38201	4.038e-02	2	0	0.00001
2	0.00465	3.057e-02	~~0~~	~~0~~	~~0.00465~~
3	0.00109	1.711e-02	~~0~~	~~0~~	~~0.00109~~
4	0.00912	9.479e-03	~~4~~	~~-1~~	~~-0.02386~~
5	0.42197	8.110e-03	1	1	-0.00004
6	0.00680	4.458e-03	~~4~~	~~-1~~	~~-0.02618~~
7	0.07302	4.112e-03	3	0	0.00002

TABLE 2. Signal Processing of $J_{x,y}$: $\nu_x = 0.69100$, $\nu_y = 0.73101$.

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• **Implement on-line tools to control individual driving terms:**

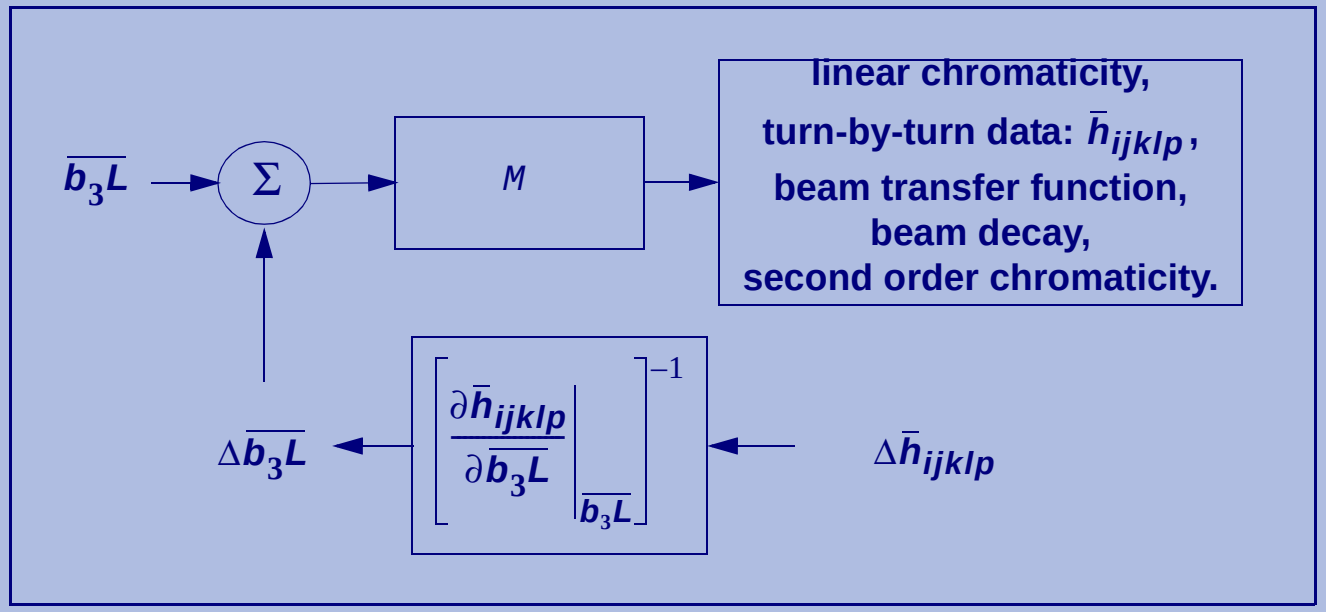

FIGURE 10. The inverted "sextupole response matrix" (i.e. Jacobian).

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3.0 Comments

- Measurement vs. control.
- Modeling- and signal processing tools need to be on-line.
- Simulate how to improve the nonlinear dynamics for a realistic lattice.
- Optics model calibration: feed-down, beta- and phase advance beat.
- Injection studies: signal decay.
- AC-Dipole studies: complexity.
- Beam decay: simplicity.
- Estimate the precision of the measurement/data analysis techniques from simulations for a realistic lattice.
- Close-the-loop: insert estimated source terms back into the model.
- Control individual driving terms on-line by implementing the inverted “sextu-pole response matrix”.

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