Beam-based optics measurements at the ESR and at some other accelerators

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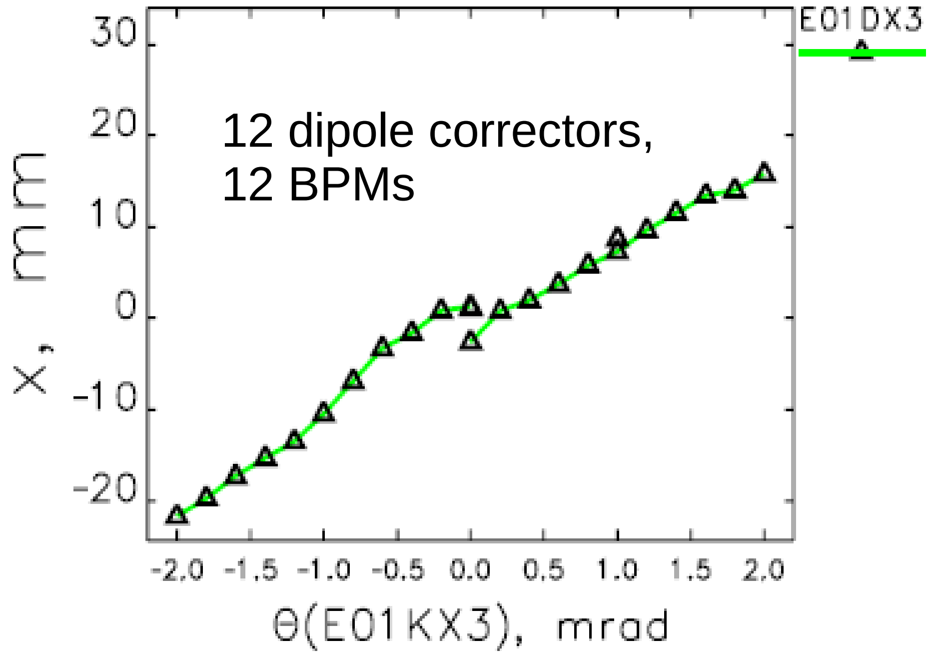
Outline:

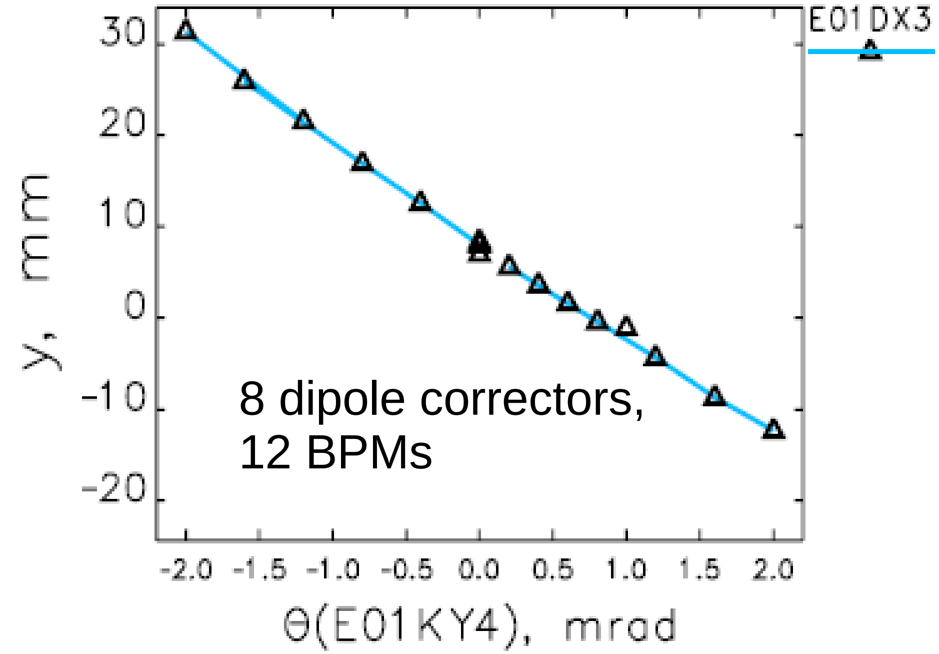
ESR:
- Linear model calibration for the ESR
- Turn-by-turn measurements
- Local bump measurements

VEPP-5 damping ring optics
Optical fiber-based beam loss monitor
Longitudinal beam slicing

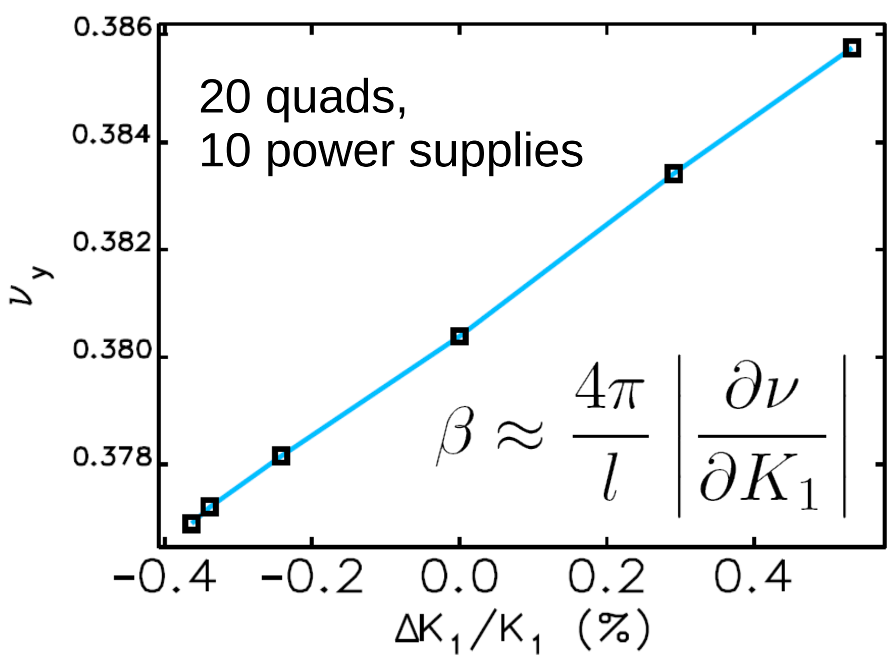
Model-Independent Analysis of BPM measurements (Tevatron, LHC)

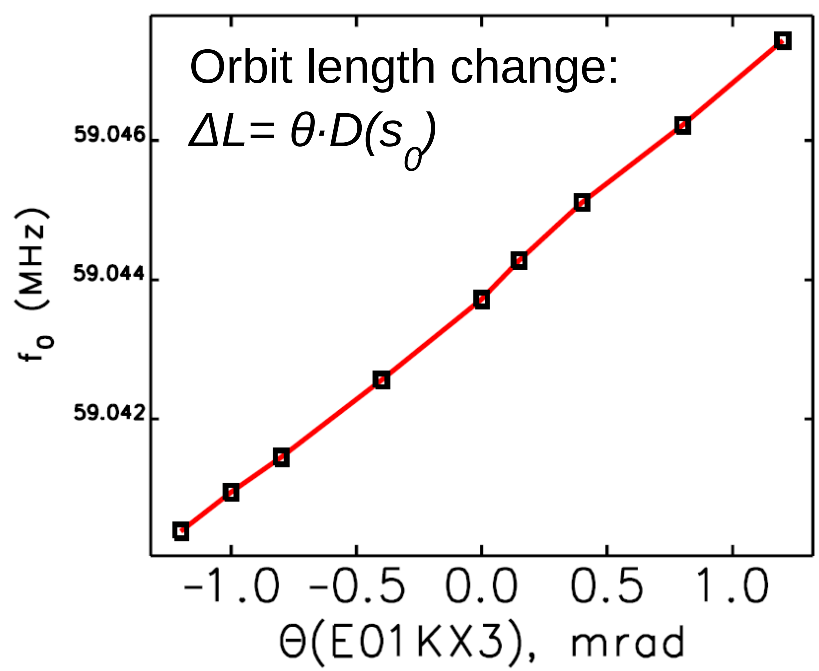
ESR orbit response measurements:





Betatron tune and revolution frequency responses:



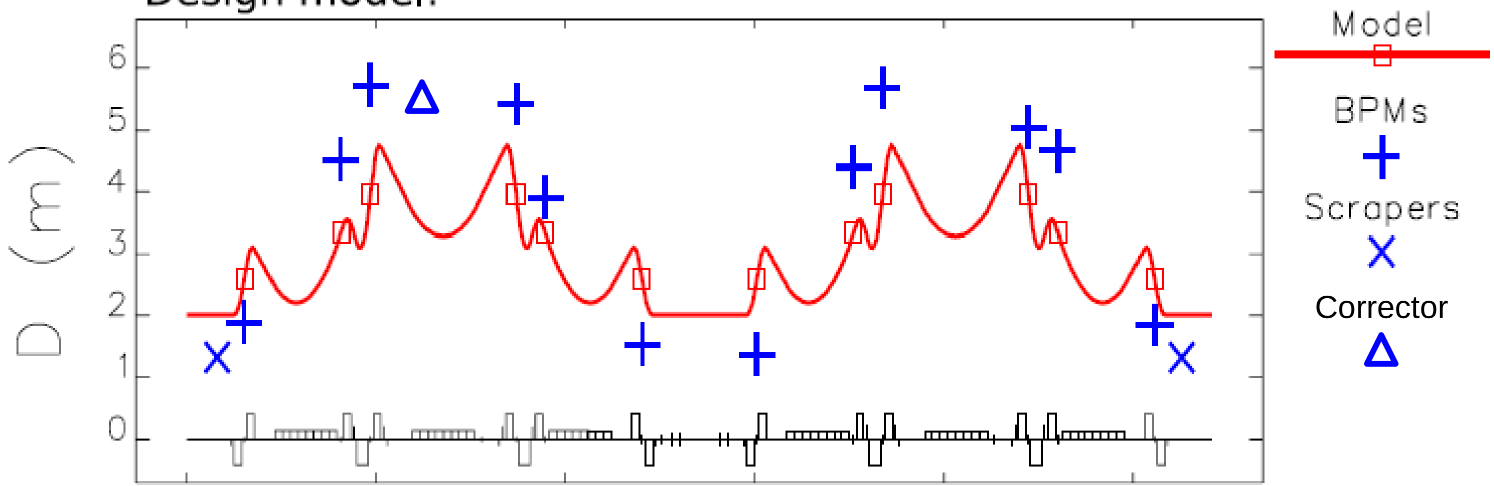


Equation for beam orbit in a storage ting with thin dipole corrector:

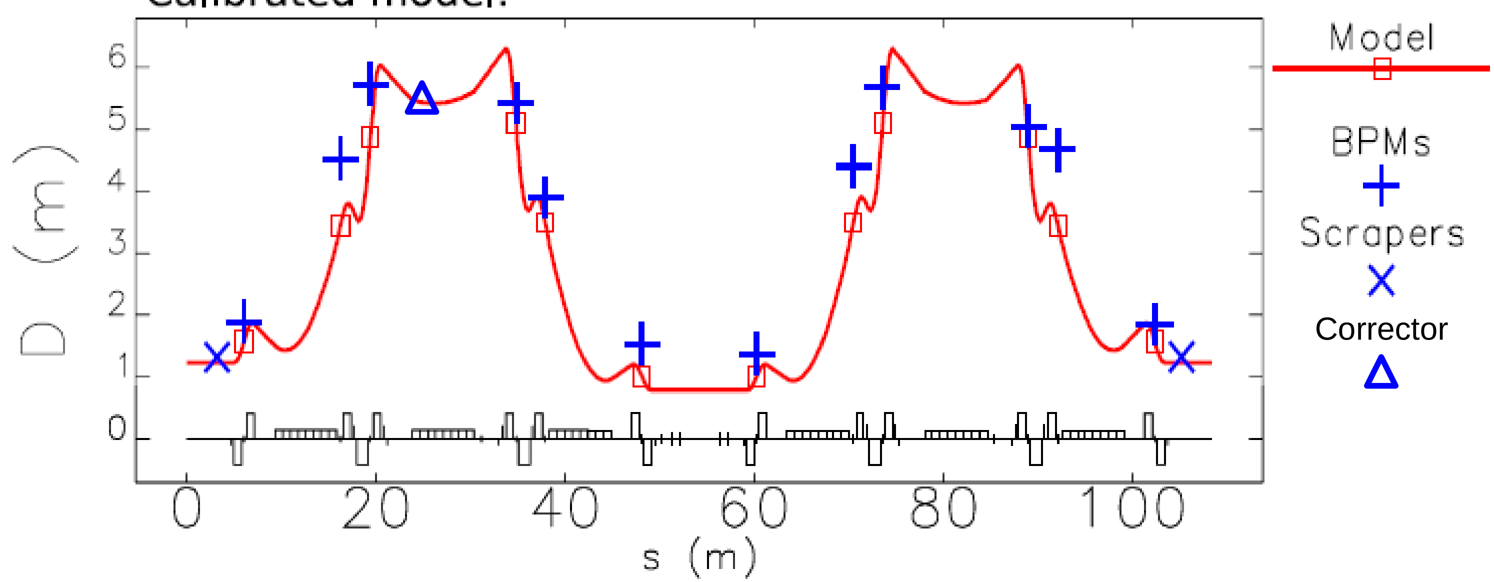
$x'' + K(s)x = \theta\delta(s - s_0)$ Solution: $x(s) = \theta G(s, s_0)$ — Green's function.

Orbit length change $\Delta L = \theta \oint \frac{G(s, s_0)ds}{\rho(s)} = \theta D(s_0)$ since $D'' + K(s)D = \frac{1}{\rho(s)}$

Design model:



Calibrated model:



Model calibration using penalty (optimization) function

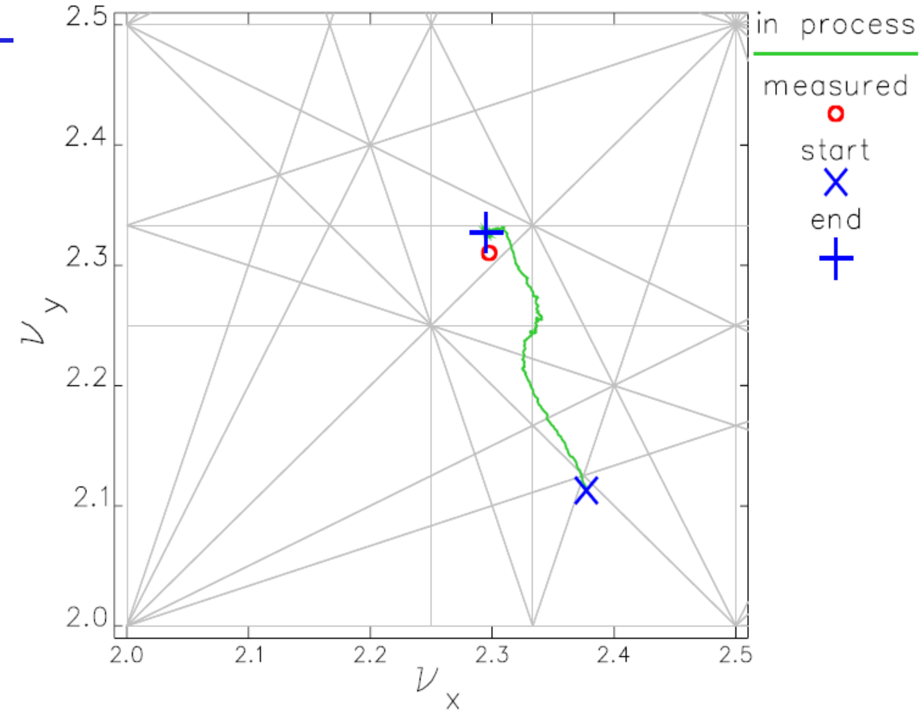
$$F = \sum_{i,j}\left[\left(\frac{\partial x_i}{\partial \theta_j}\right)_m - \left(\frac{\partial x_i}{\partial \theta_j}\right)_t\right]^2 \frac{1}{\sigma_{ij}^2}$$

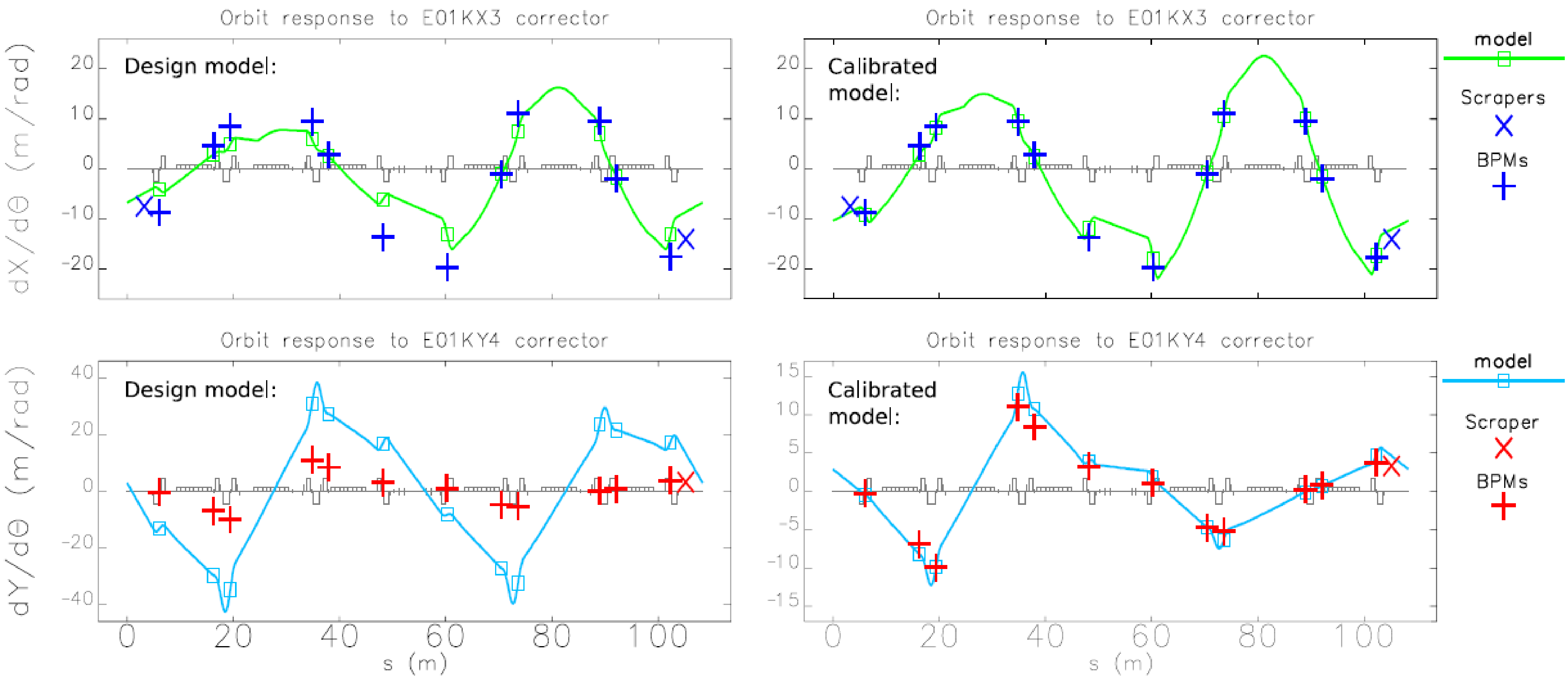
$$+ \sum_{n}\left[\left(\frac{\partial \nu_x}{\partial k_n}\right)_m - \left(\frac{\partial \nu_x}{\partial k_n}\right)_t\right]^2 \frac{1}{\sigma_n^2},$$

Measured

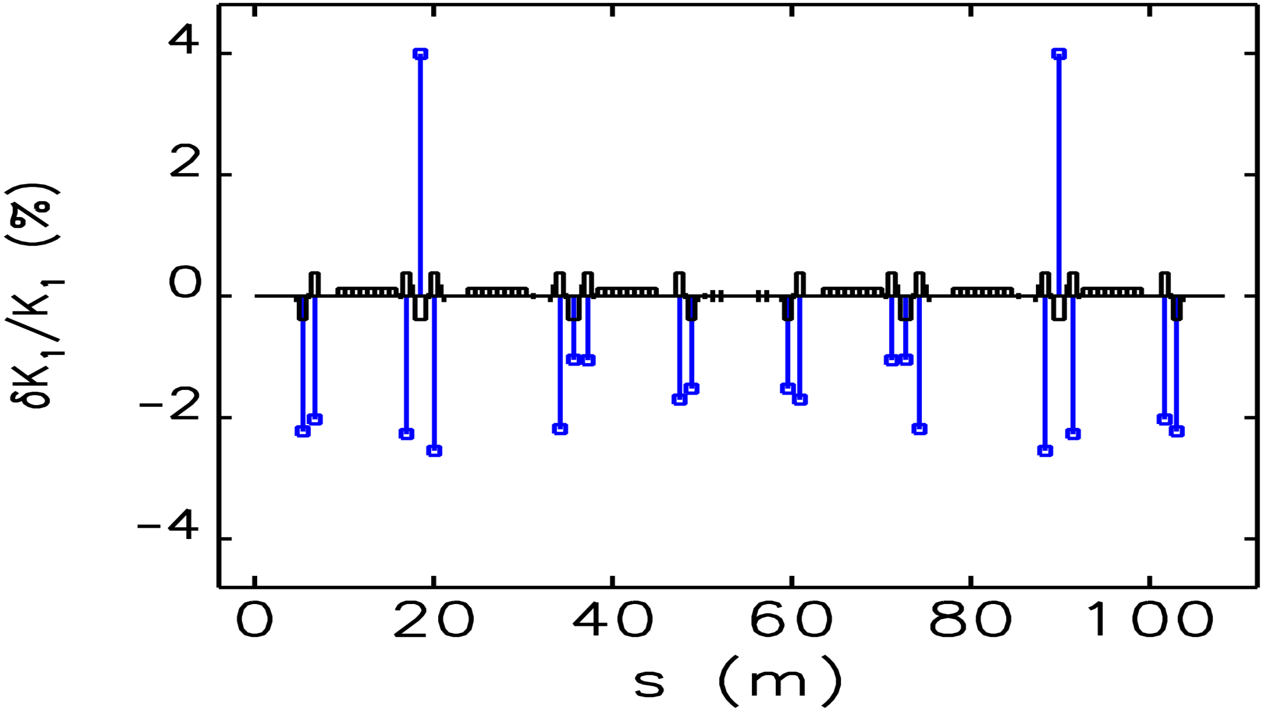
Model

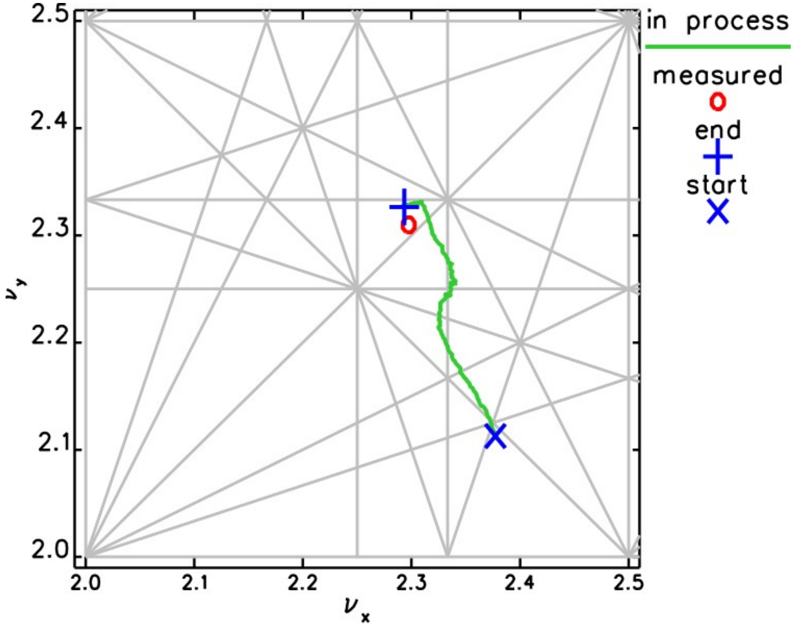
Measurement accuracy



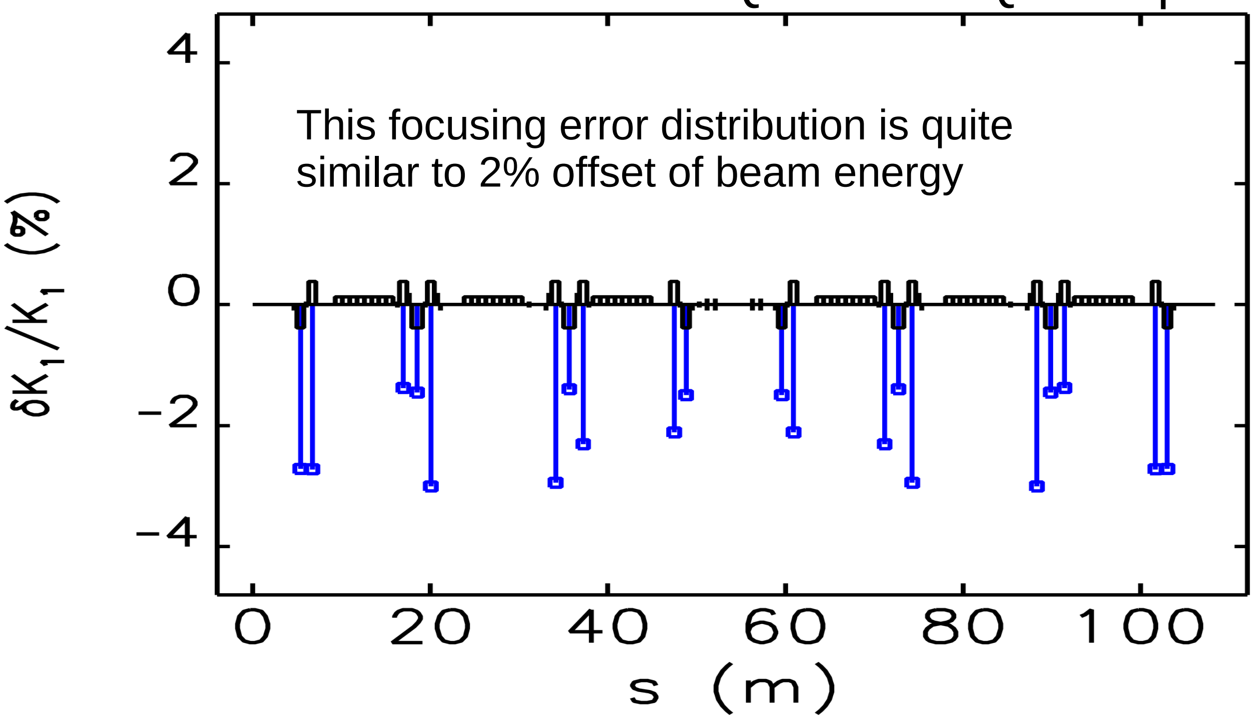


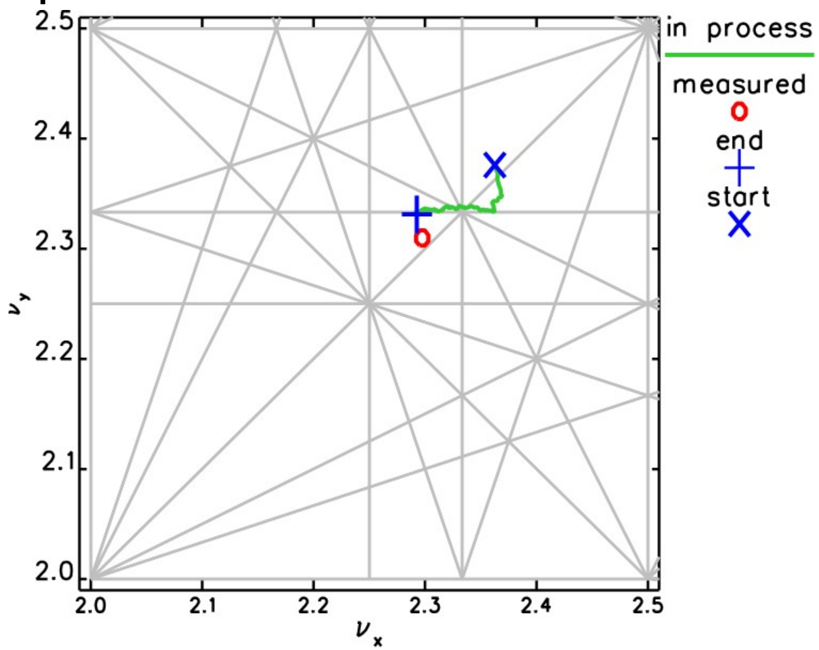
No initial error in the E01QS3D E02QS6D quadrupoles assumed:



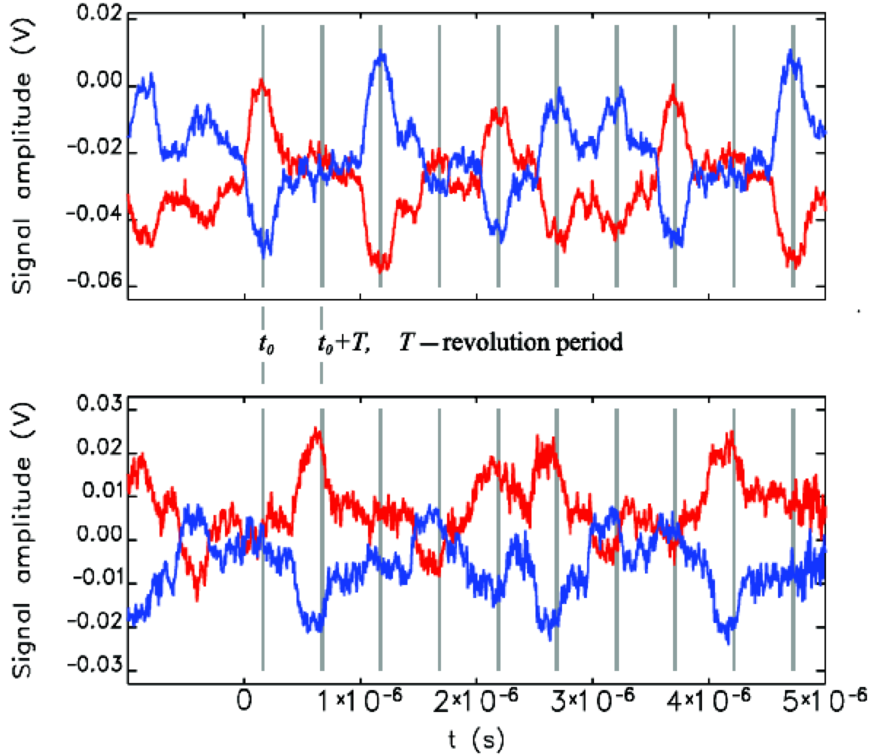


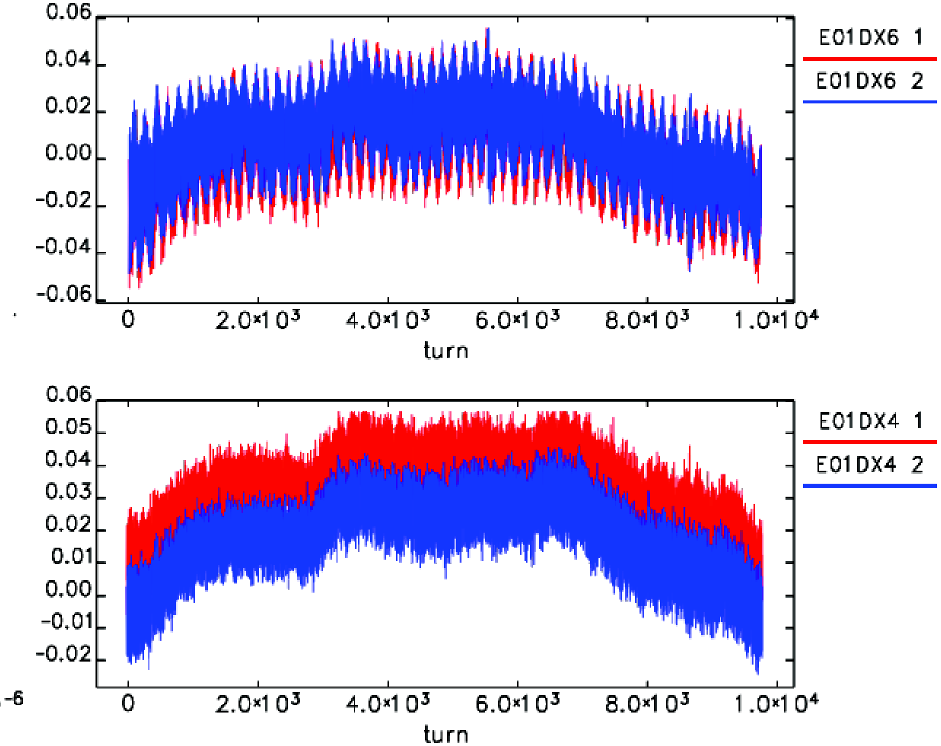
5.8% error in the E01QS3D E02QS6D quadrupoles is taken into account:

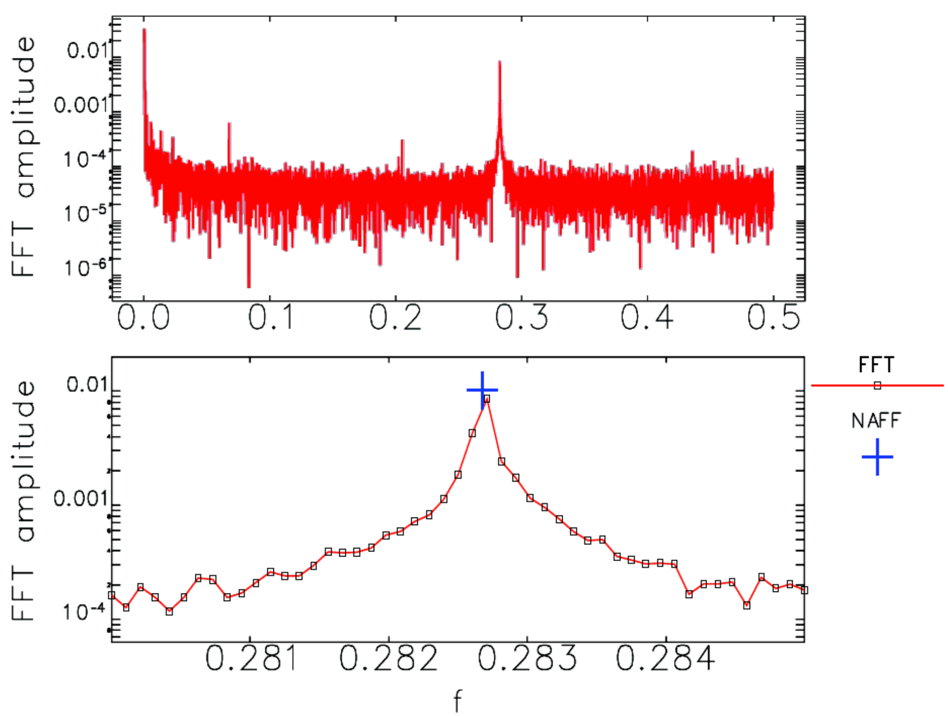


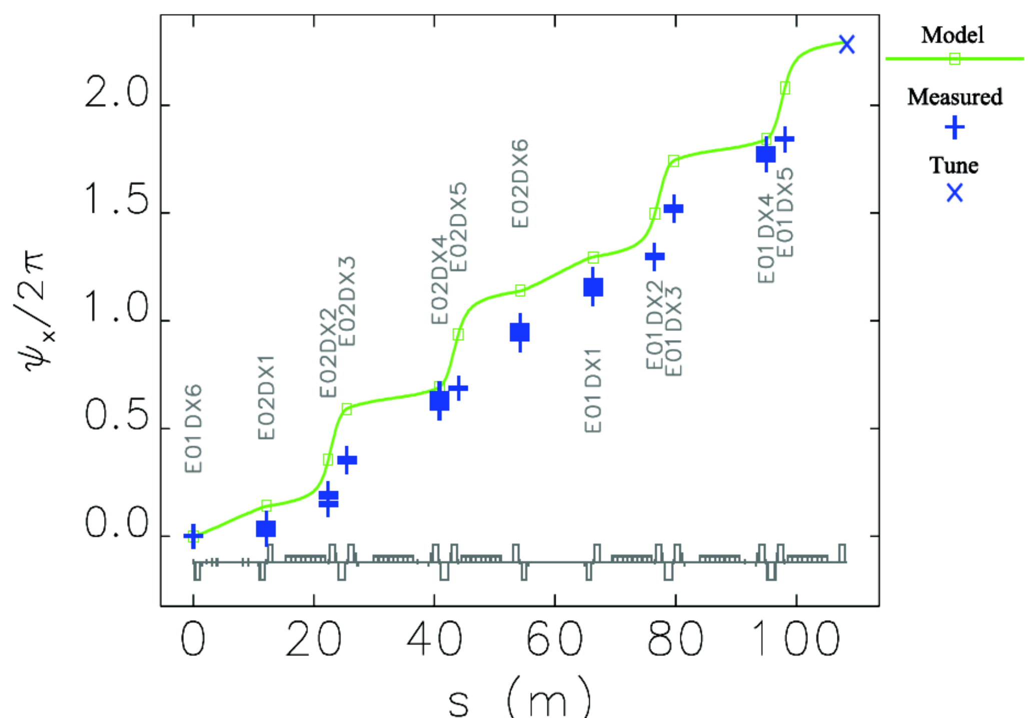


BPM signals after coasting beam is kicked on the injection orbit

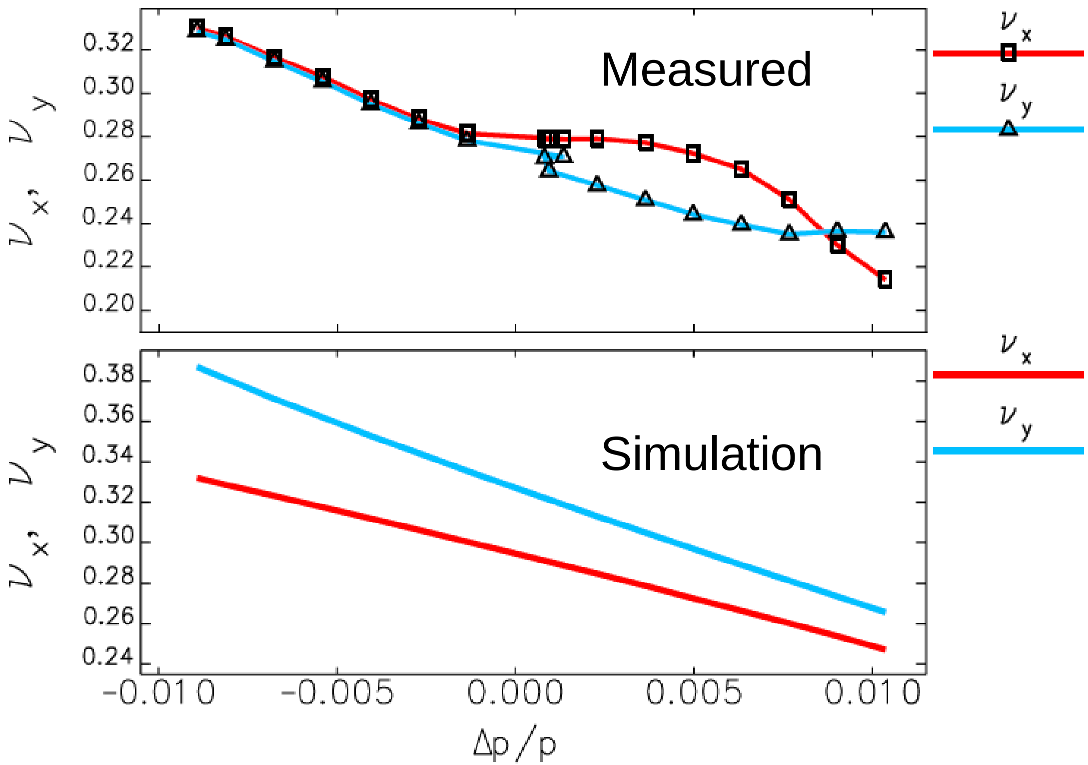




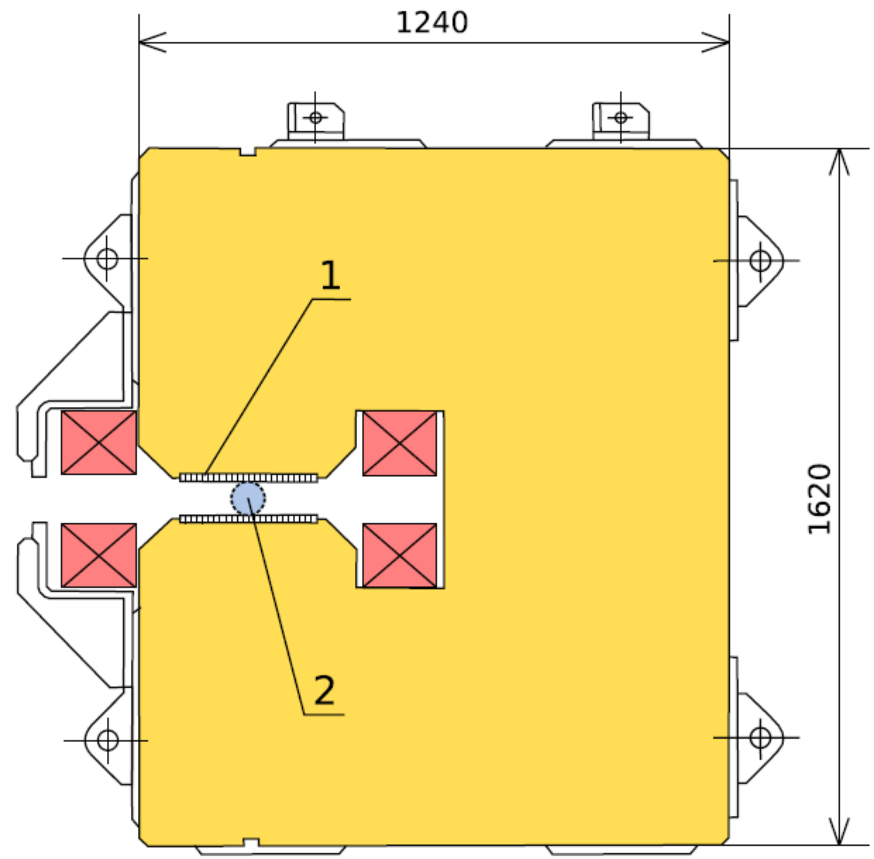




Natural chromaticity of ESR

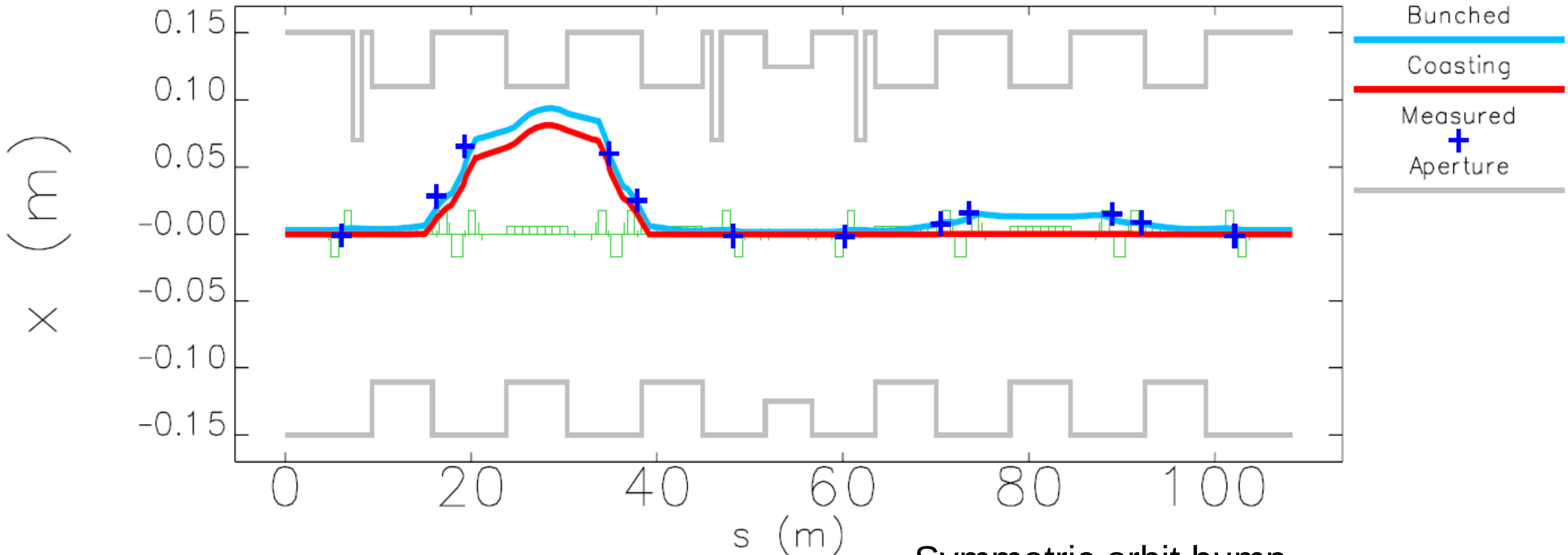


Betatron tune as a function of ion beam energy. Coasting beam energy varied with electron cooler voltage. All the ESR sextupoles were switched off.

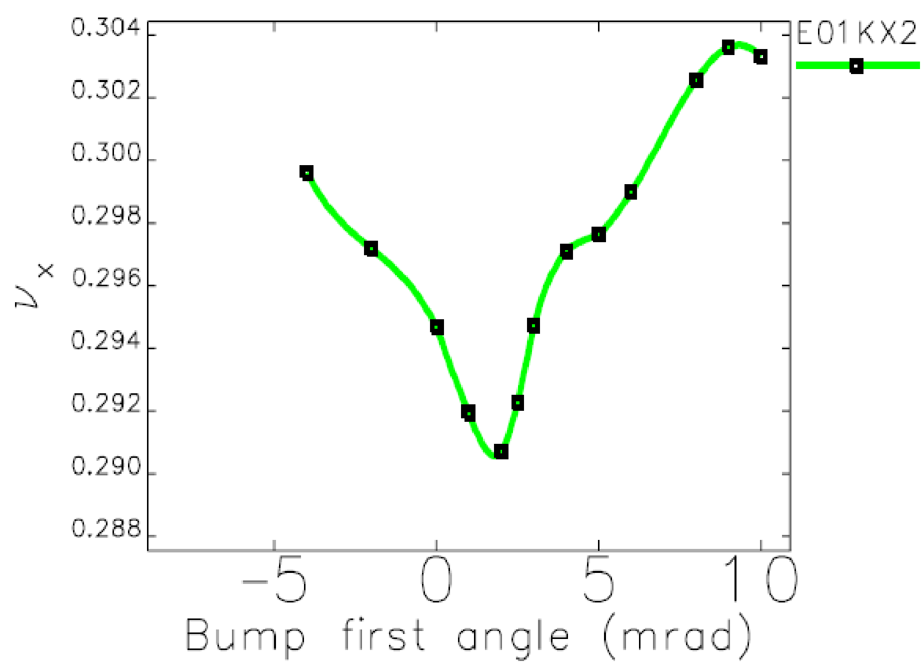


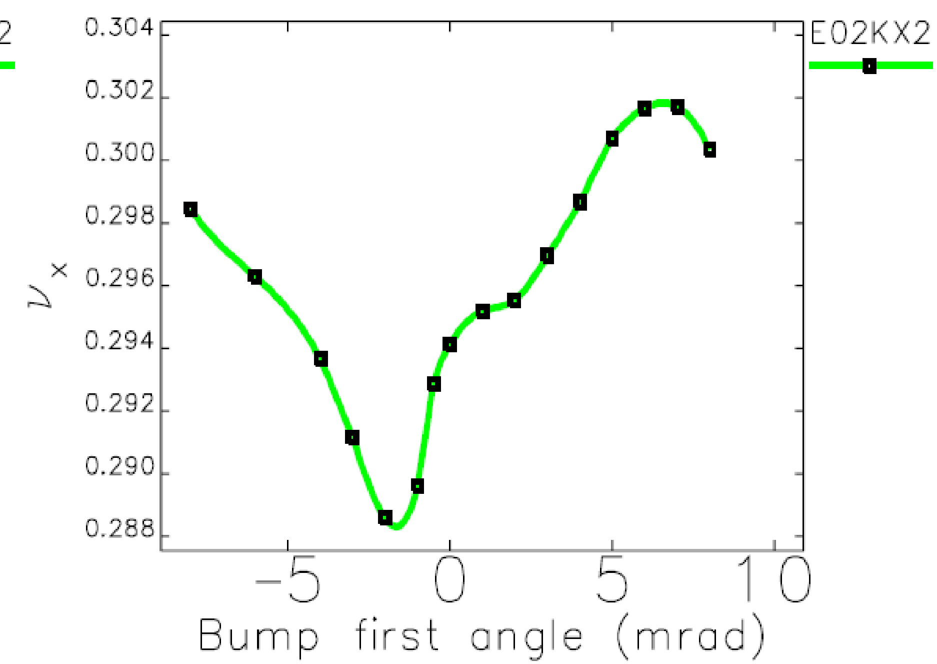
ESR dipole magnet.
1 — additional field correction coils.
2 — multipole expansion is valid only inside the circle of this size.

Local orbit bump in the ESR:

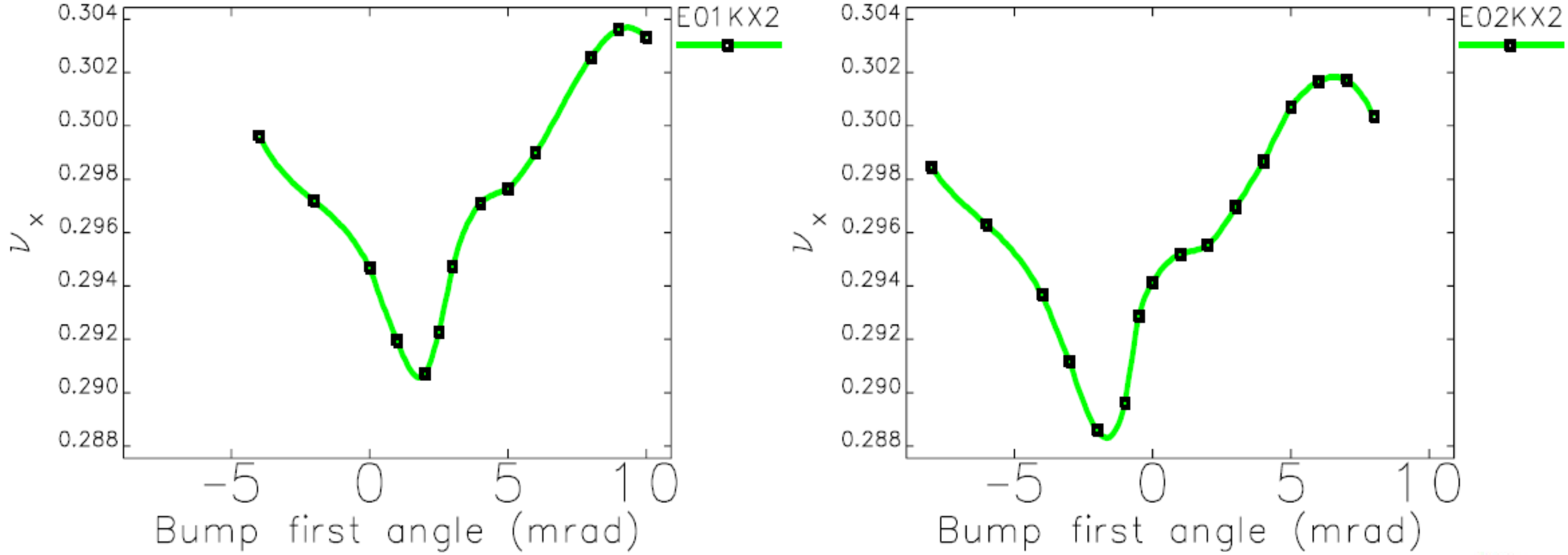


Symmetric orbit bump in the different arc of the ESR:

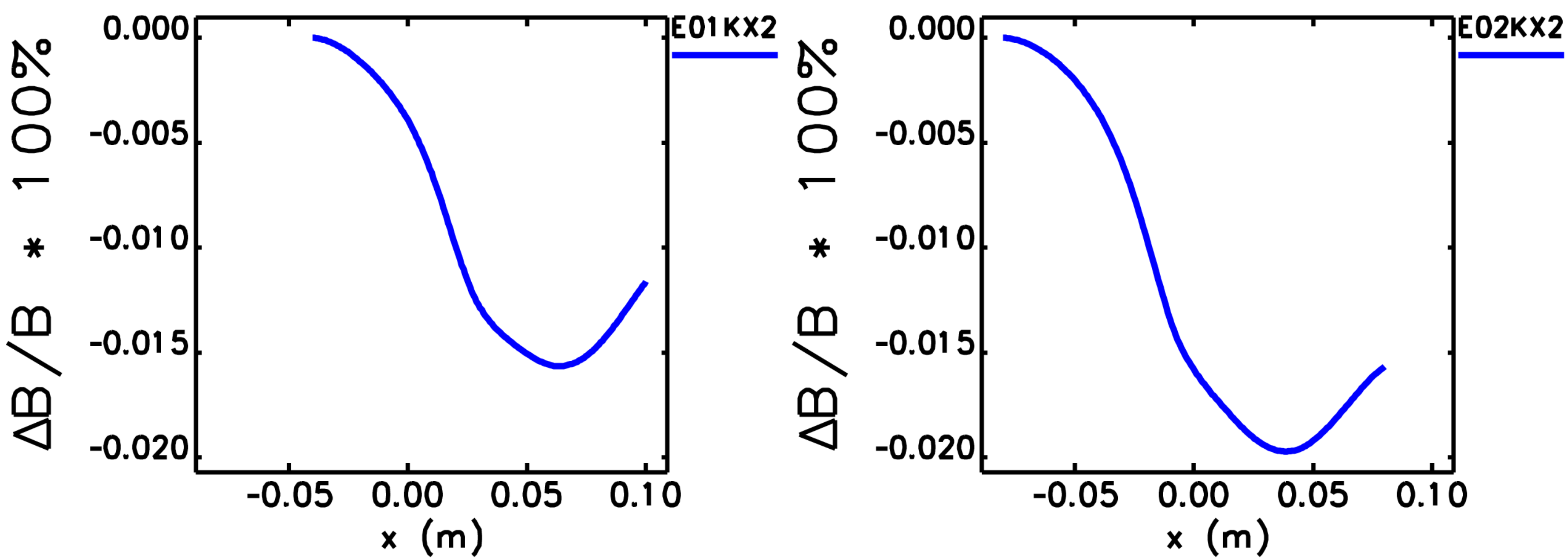




ESR dipole field profile reconstruction:



$$\frac{\partial \nu}{\partial K_1} \approx \pm \frac{l\beta}{4\pi} \qquad K_1 = \frac{1}{B\rho}\left|\frac{\partial B_y}{\partial x}\right| \Rightarrow \frac{\Delta B(x)}{B_0} \approx G_0 x + \frac{4\pi\rho}{l\beta}\int_0^x \Delta\nu(x)\,dx$$



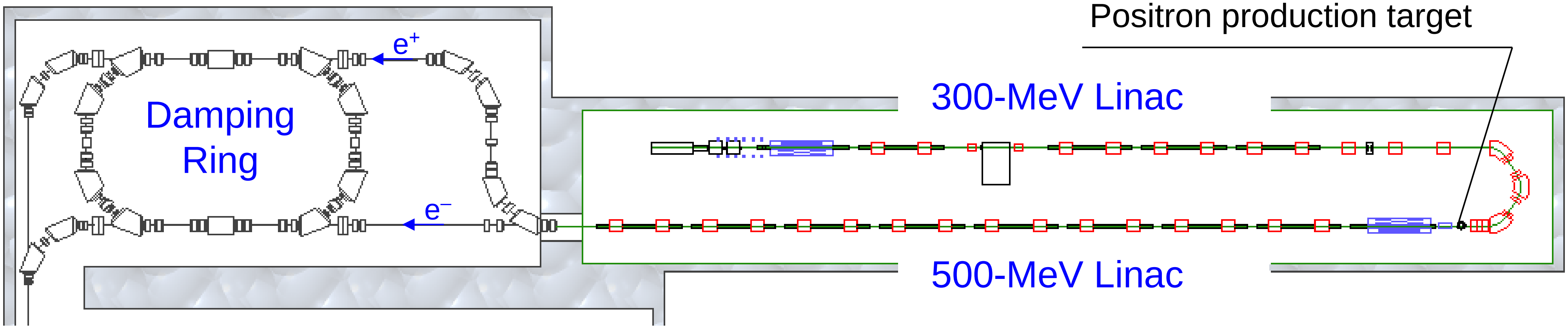
Conclusions on the ESR measurements:

1) The calibrated model proved to be good enough to make some predictions (local orbit bump, dispersion in corrector). However the causes of remaining focusing errors are still unclear, and it's not clear how different is the linear optics on injection orbit (accurate response measurements were taken only for the central orbit).

2) It would be interesting to measure dispersion function in all 12 dipole correctors (especially in the isochronous mode of the ESR). A similar measurement (also with kicked coasting beam instead of BTF) is possible in the SIS-18 — in case it is possible to vary corrector strength after RF is switched off. Dispersion + tune response data can be enough to calibrate the accelerator model, so no BPM data (i.e. orbit response matrix) with bunched beam will be required for model calibration.

3) Check the ESR dipole field profile (was it measured before?) in order to make sure it is really the cause of nonlinearity in the tune response to orbit change (and in the chromaticity). Alternative measurement with kicked coasting beam on injection orbit may be helpful. Finally it may be possible to correct the field profile with a beam based method (and see if it helps to correct the chromaticity).

VEPP-5 electron/positron source

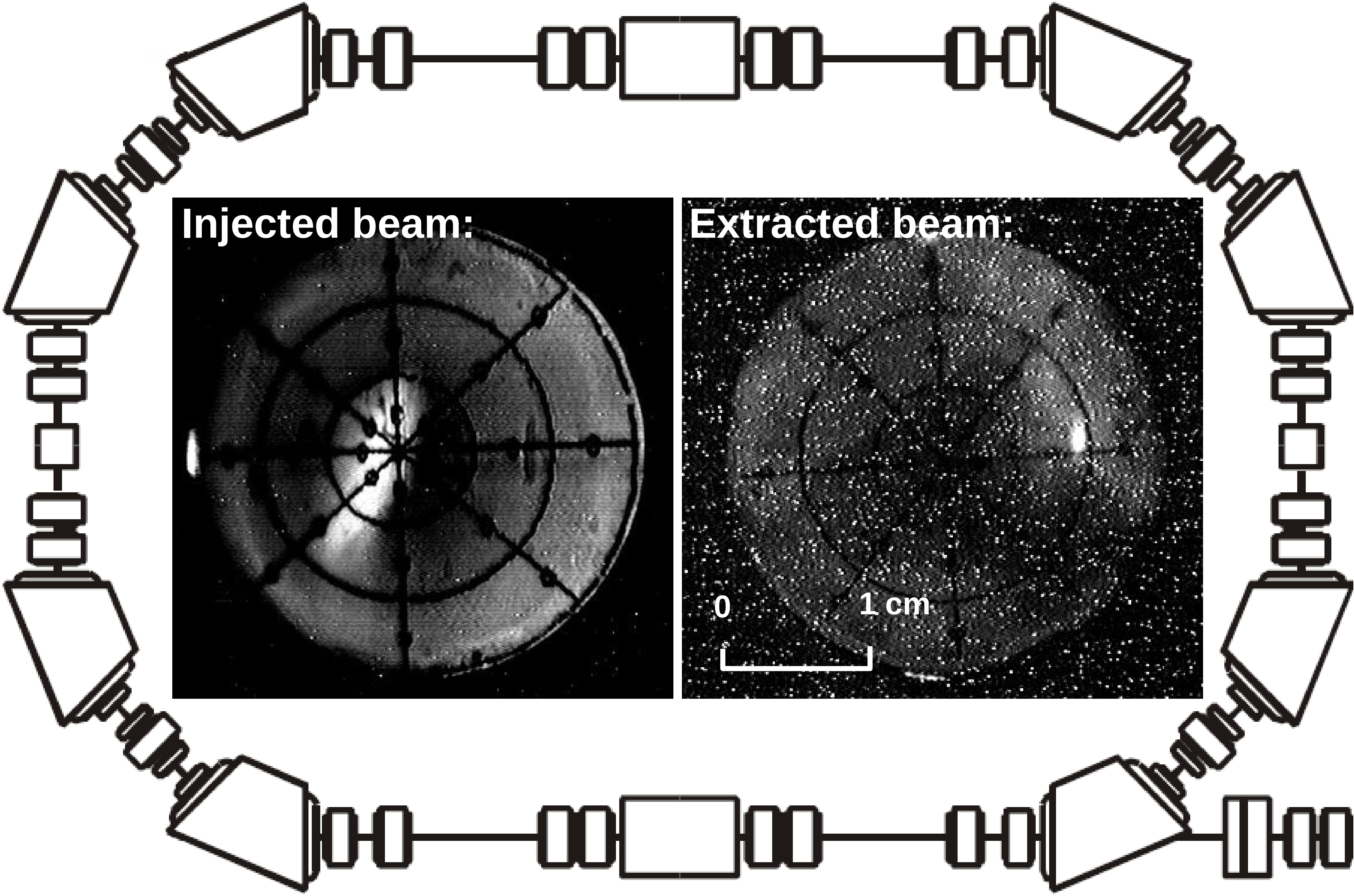


Electron beam obtained in the damping ring:

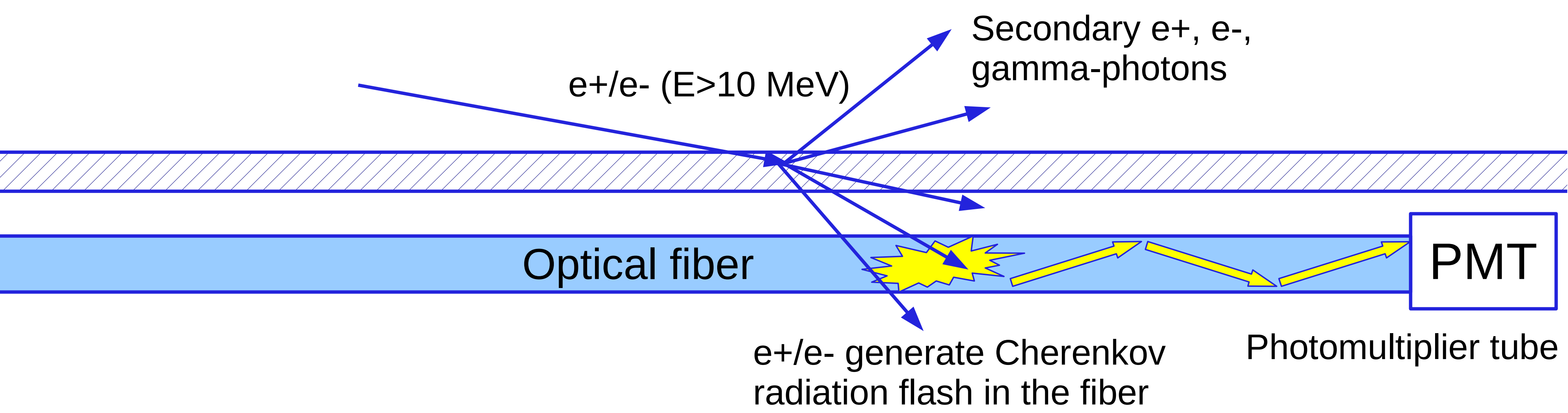
E = 200 … 400 MeV
$N(e^-)$ = $2\cdot10^{10}$
σ_S = 8 mm (I_{peak} = 50 A)

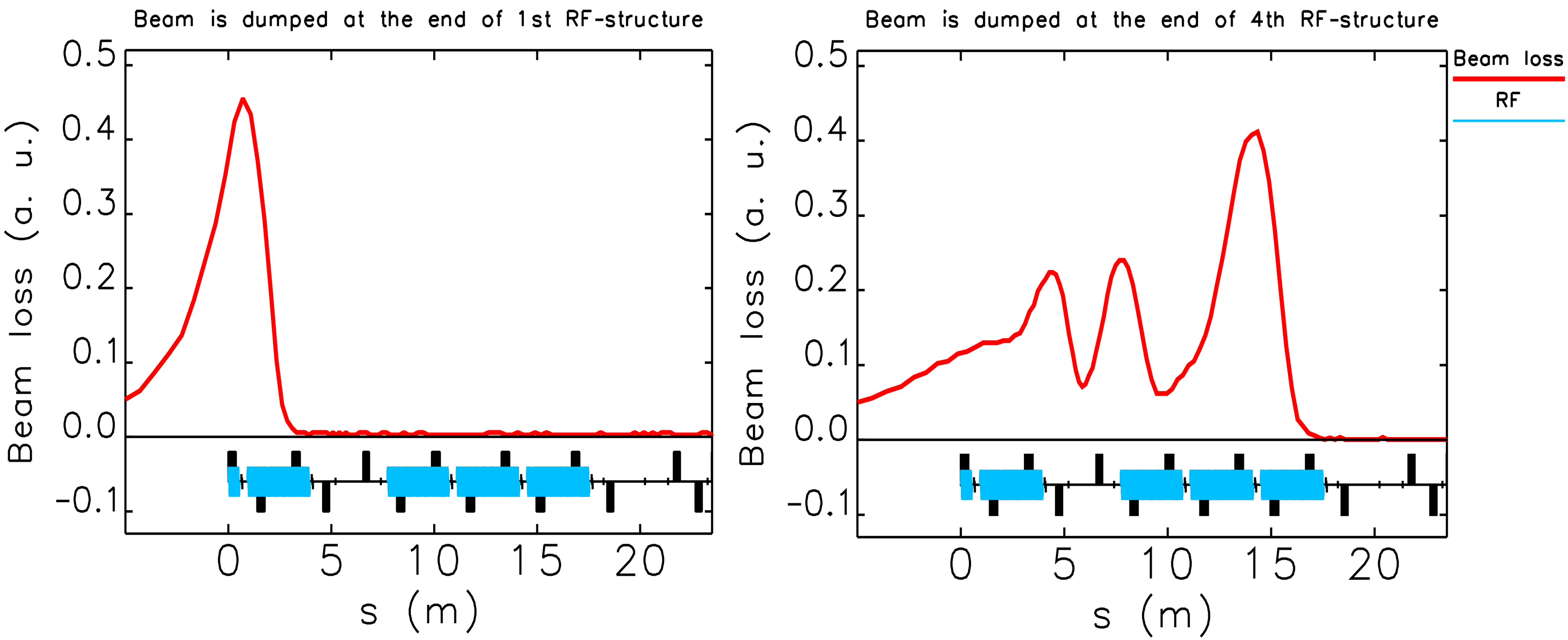
Positron beam commissioning
is scheduled for the end of 2011

Beam loss during injection is the main issue. Accurate linac and ring optics matching is required.

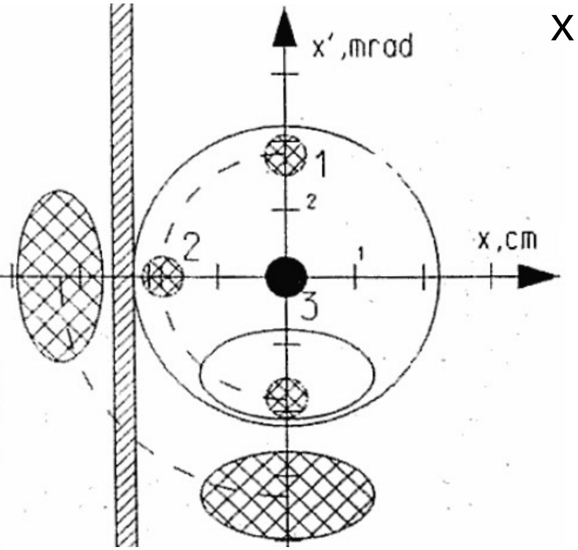


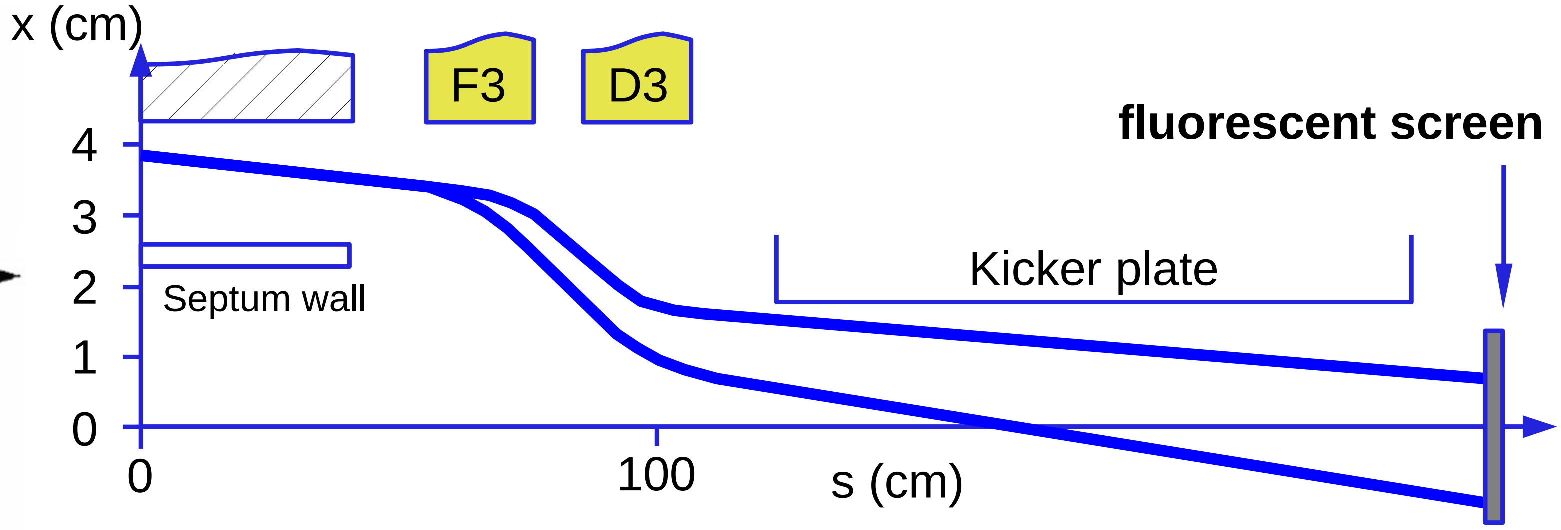
Optical fiber-based beam loss monitor

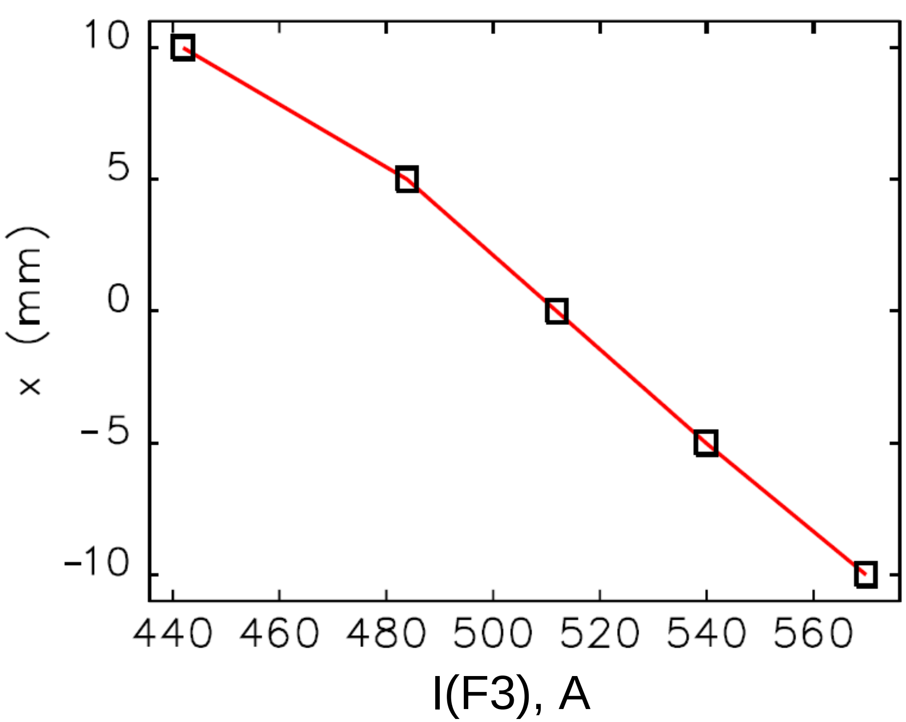




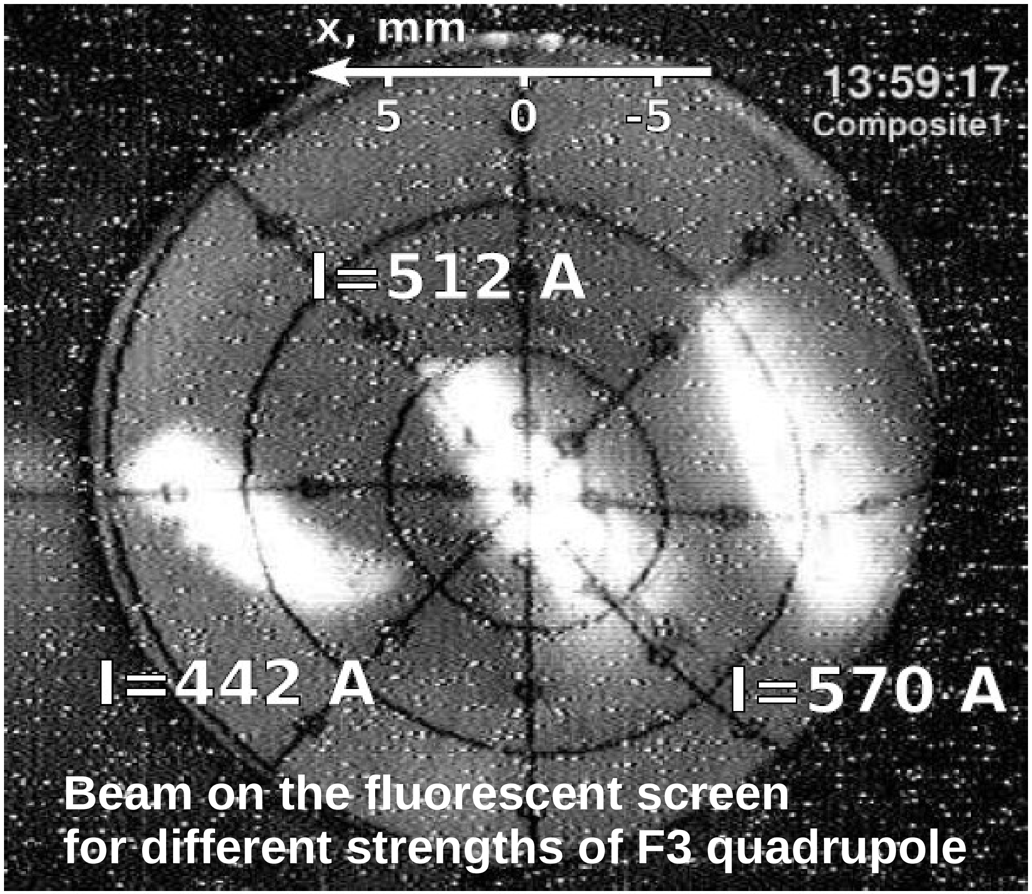
Injection angle measurement







Beam angle after septum dx/ds = −3 mrad.
Therefore F3 strength had to be decreased.

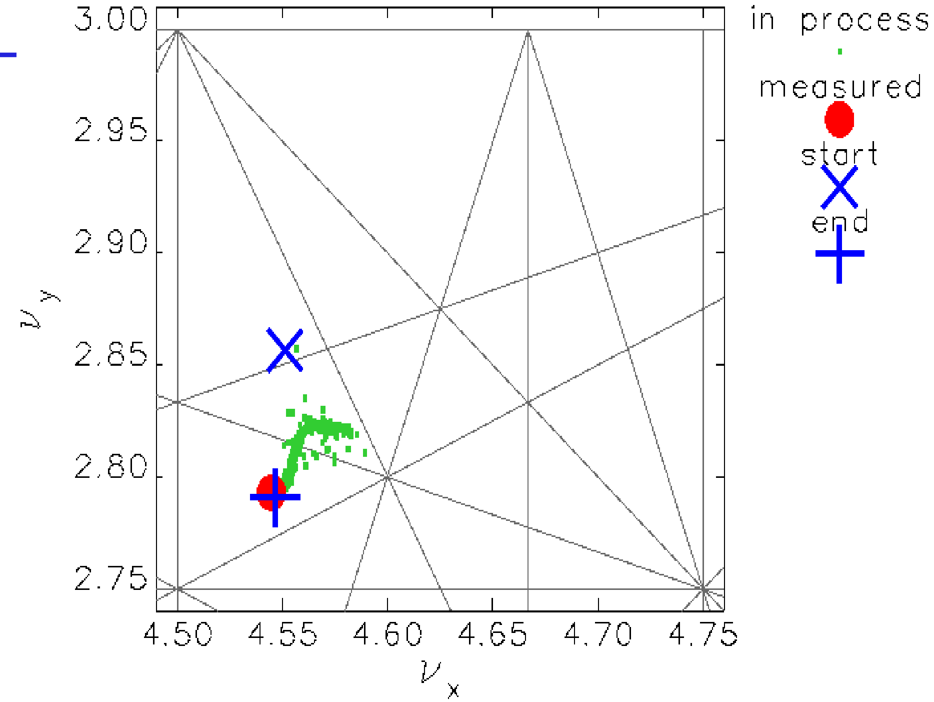


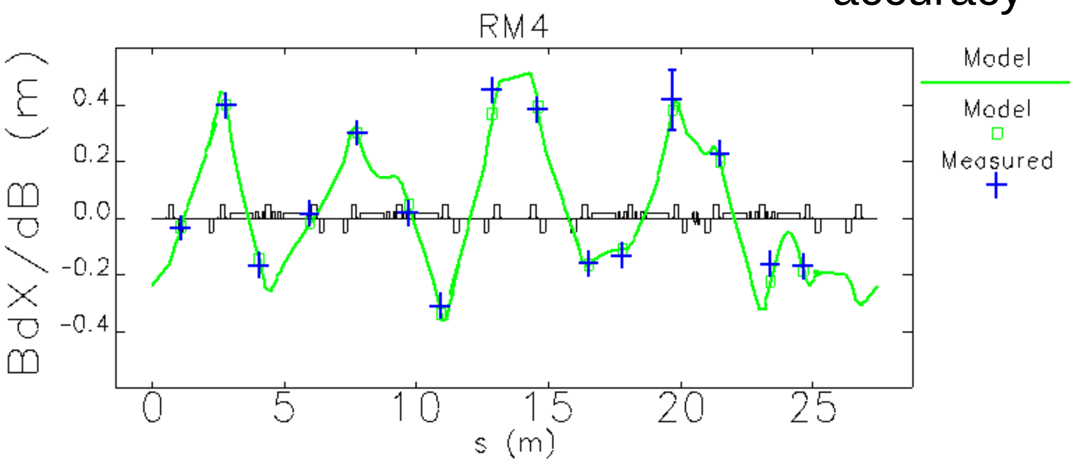
Model calibration using the penalty function

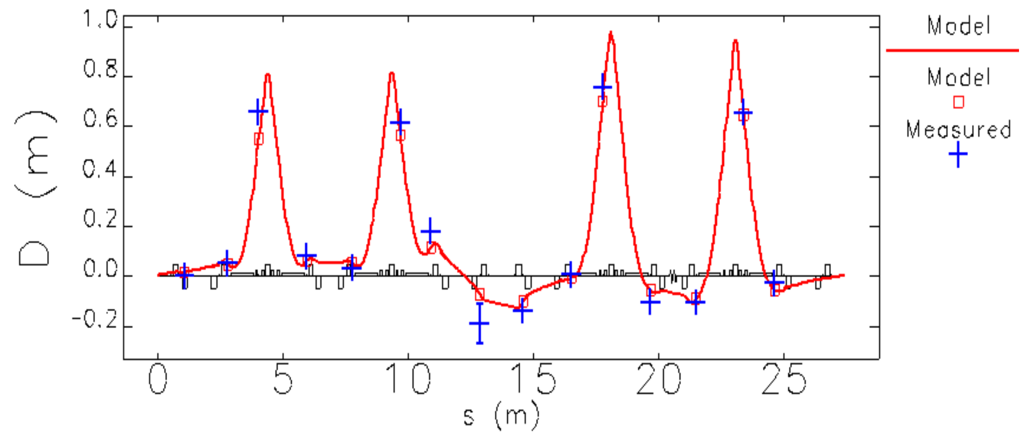
$$F = \sum_{i,j}\left[\left(\frac{\partial x_i}{\partial \theta_j}\right)_m - \left(\frac{\partial x_i}{\partial \theta_j}\right)_t\right]^2 \frac{1}{\sigma_{ij}^2}$$

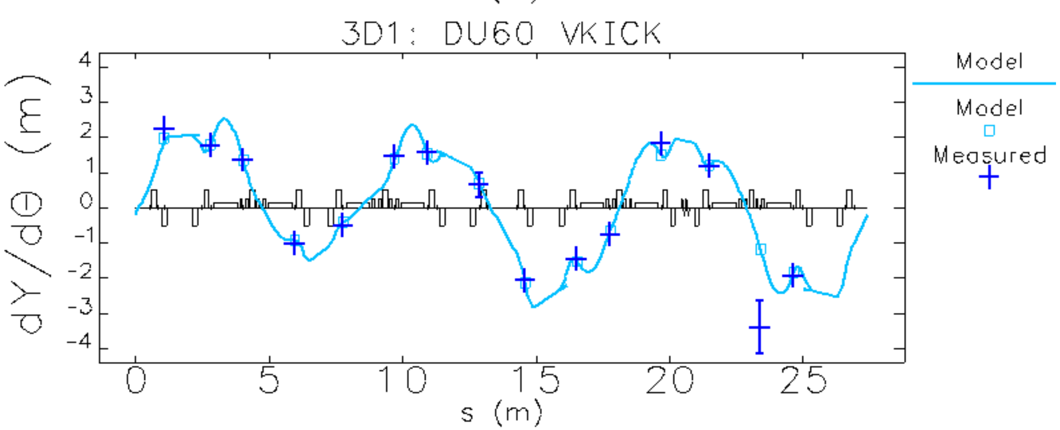
$$+ \sum_{n}\left[\left(\frac{\partial \nu_x}{\partial k_n}\right)_m - \left(\frac{\partial \nu_x}{\partial k_n}\right)_t\right]^2 \frac{1}{\sigma_n^2},$$

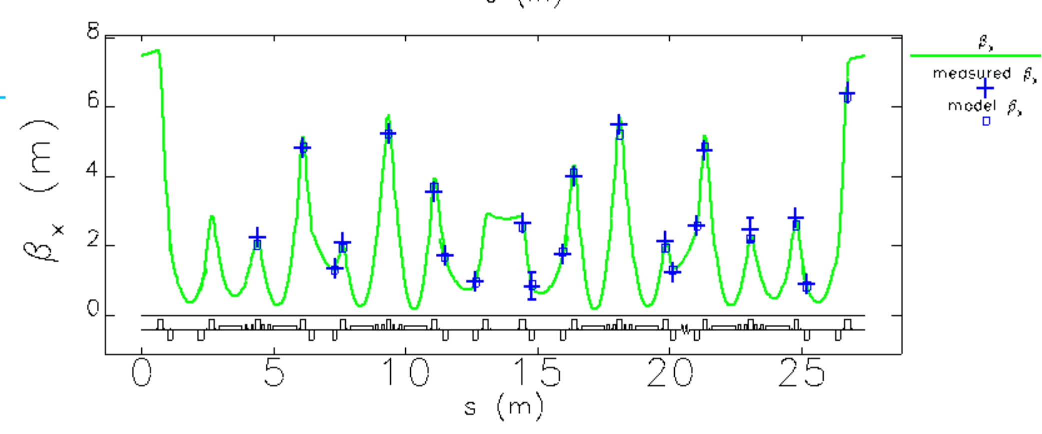
Measured Model Measurement accuracy





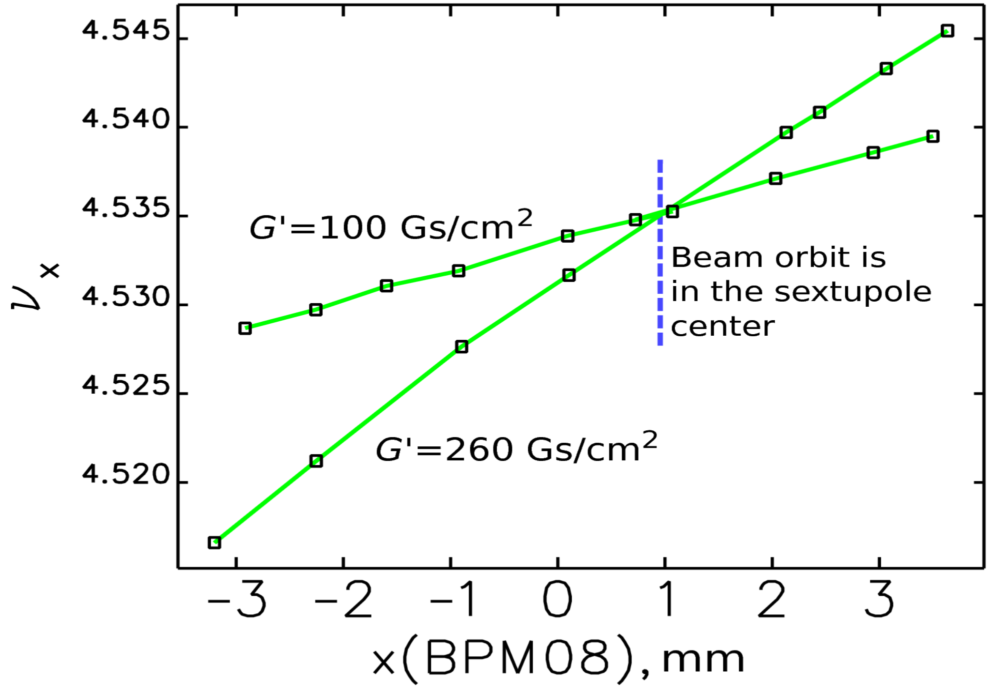




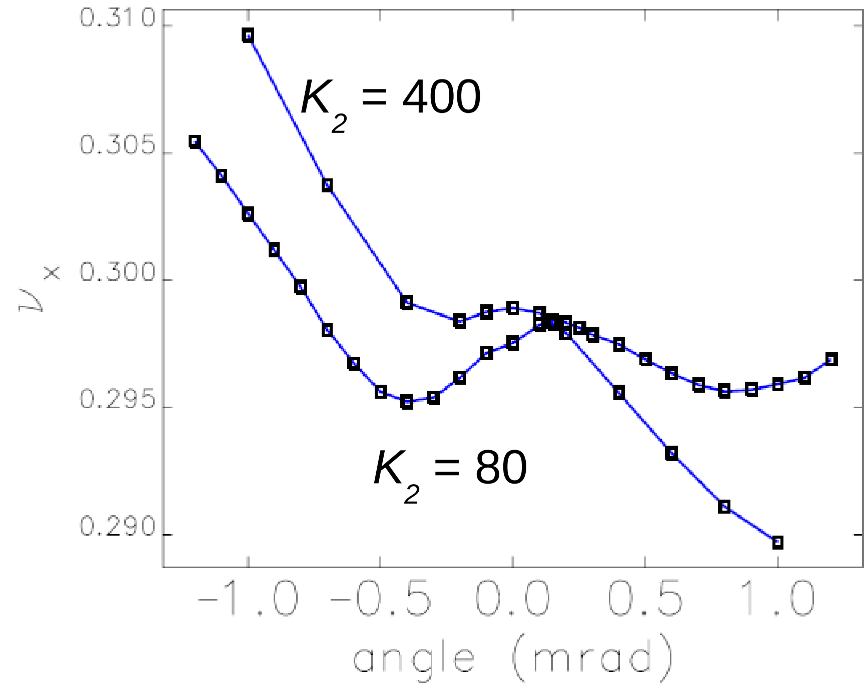


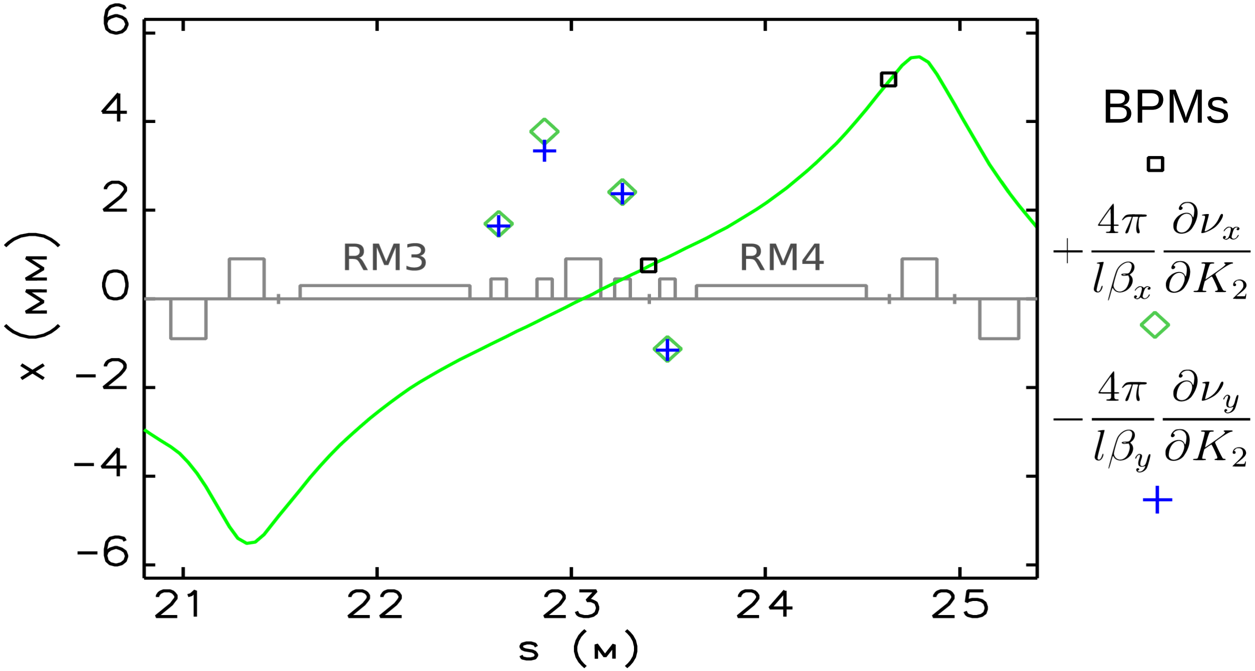
Beam orbit in sextupoles

ν_x as a function of horizontal correction for two different sextupole strengths:



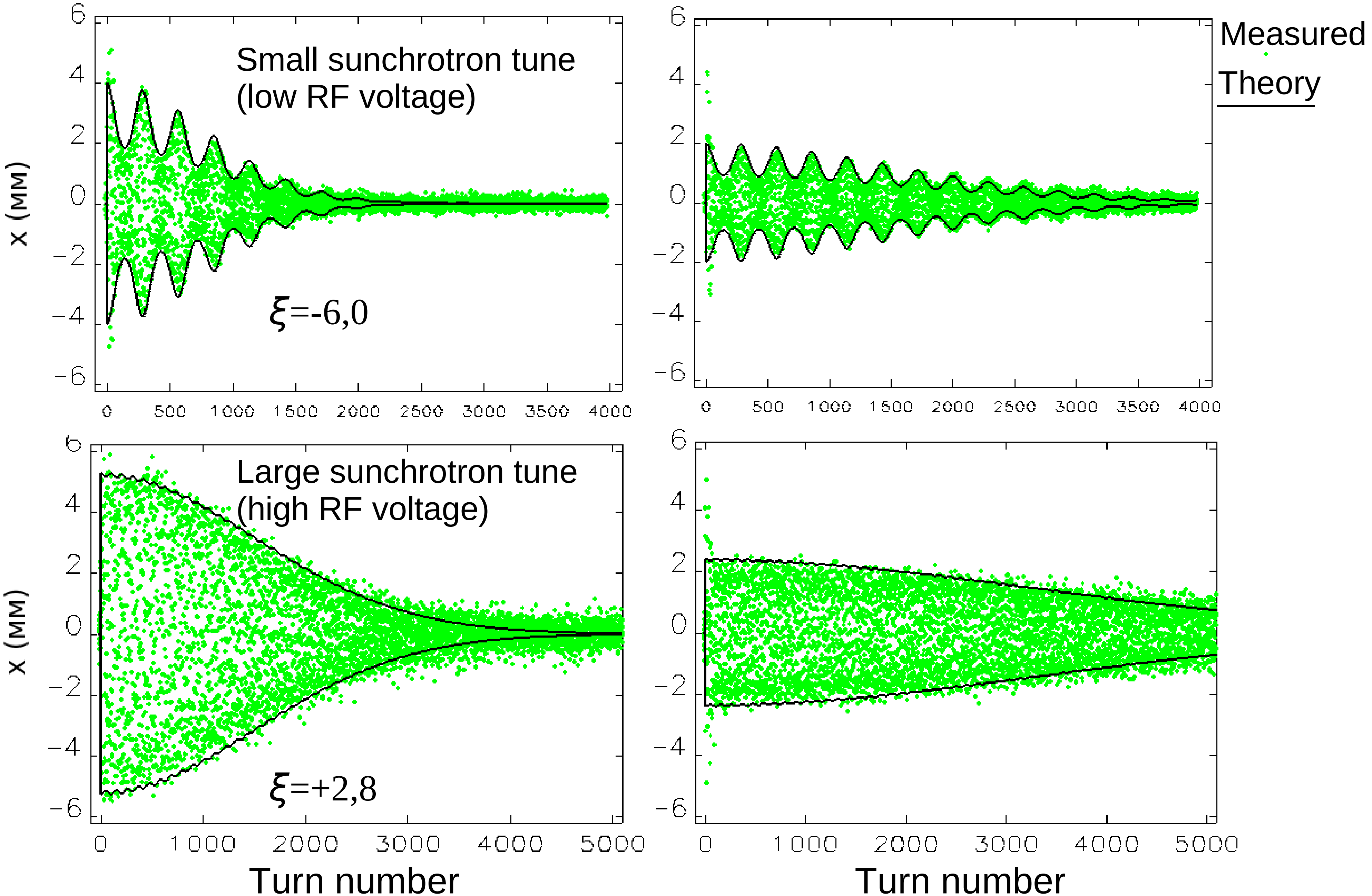
Similar measurement at the ESR:





Beam orbit offset in sextupole

Sextupole misallignments are the main focusing errors in the VEPP-5 damping ring.



Coherent beam oscillations in the VEPP-5 damping ring measured by BPM at low beam current (<1 mA)

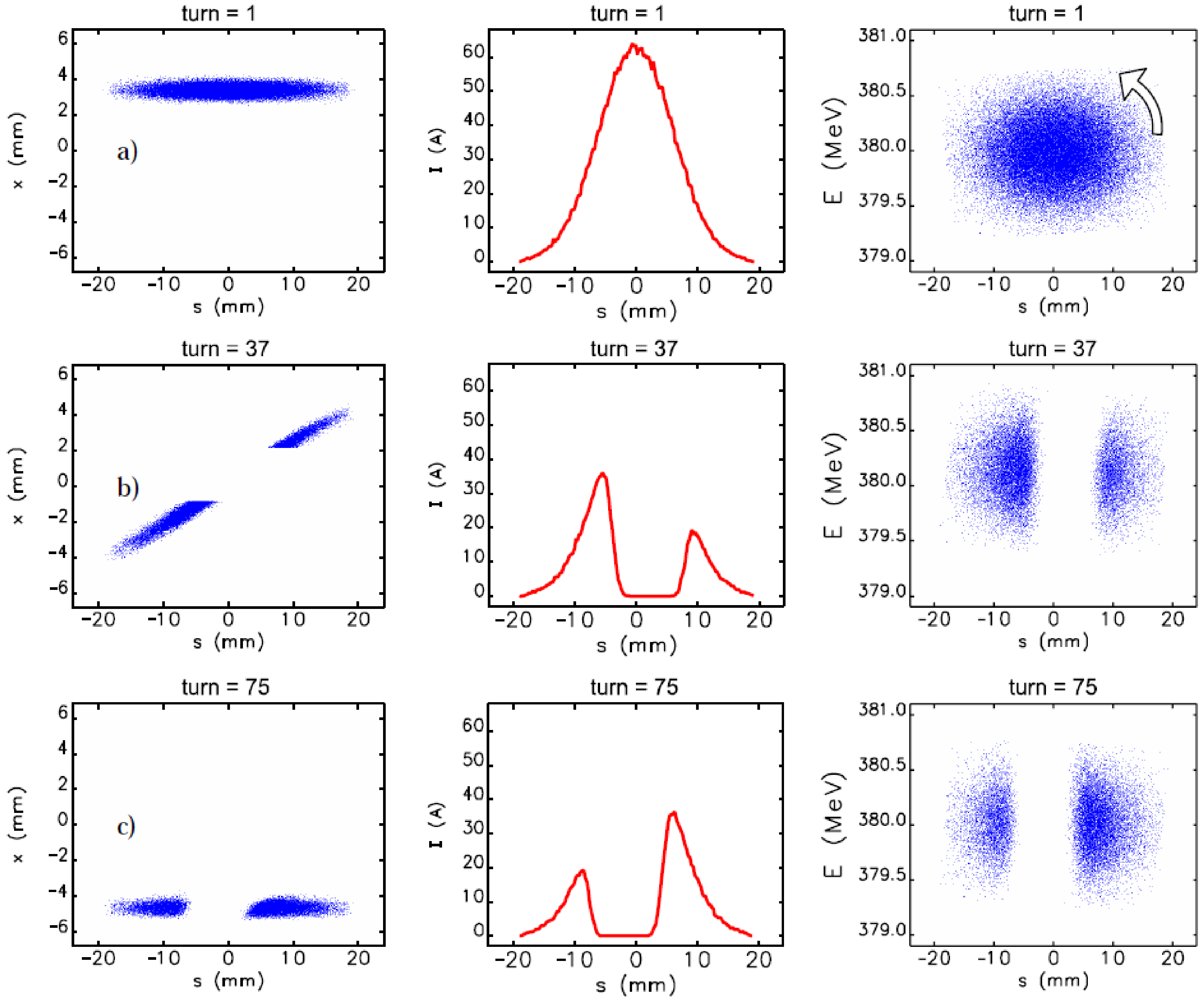


FIGURE 5. Longitudinal beam profile manipulation in the damping ring (ELEGANT simulation). a) the beam travels 1 turn after it was kicked in the horizontal plane. b) 37 beam turns after the initial kick (approximately half a period of synchrotron oscillation). At this moment two different kickers were used to create the local orbit bump in order to throw the beam at the collimator (positron septum is used as a collimator in this case). c) after about a period of synchrotron oscillation since the first kick was applied the beam can be extracted from the ring and injected into plasma. The arrow shows the direction of synchrotron motion. Horizontal chromaticity $\xi_x = +3$.

Model-Independent Analysis of Beam Position Monitor Measurements

Blind signal separation

If there are more microphones than independent signal sources it is possible to separate all the independent signals:

Mathematical formulation of the signal separation problem

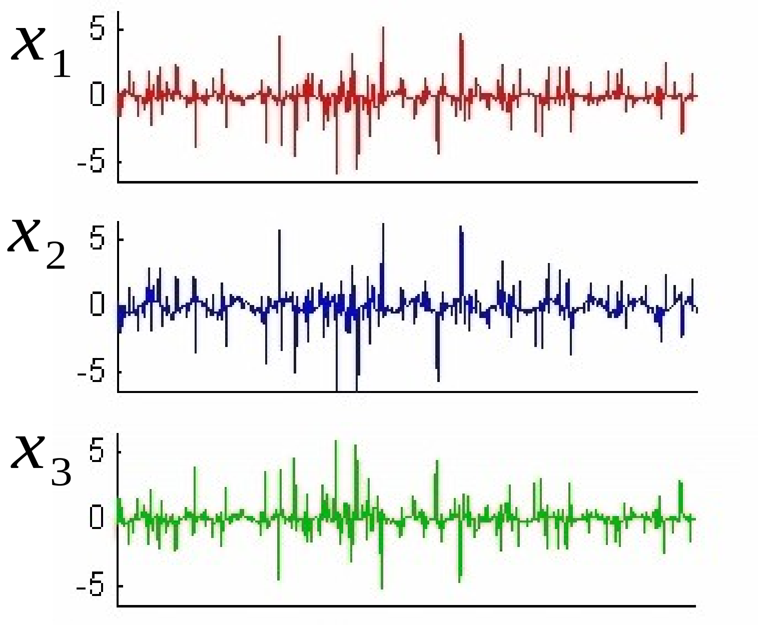
$$x_1(t) = a_{11}s_1(t) + a_{12}s_2(t)$$
$$x_2(t) = a_{21}s_1(t) + a_{22}s_2(t)$$
$$x_3(t) = a_{31}s_1(t) + a_{32}s_2(t)$$

$s_i(t)$ a_{ij} are both unknown

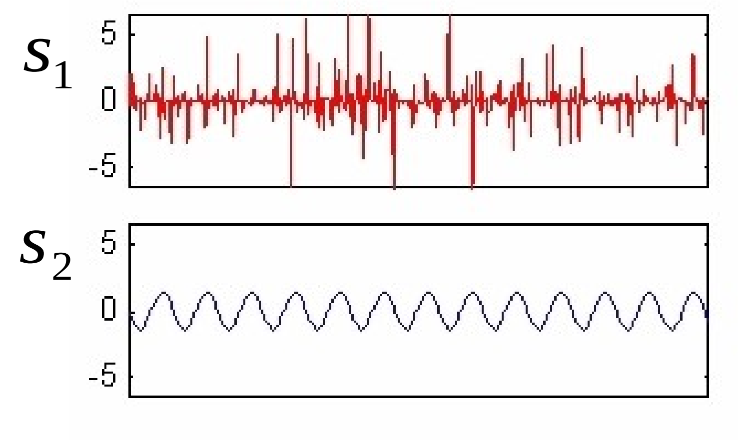
It is necessary to find such a transformation **W**, that

$$\mathbf{x} = \mathbf{A}\mathbf{s}$$

$$\mathbf{s} = \mathbf{W}\mathbf{x}$$

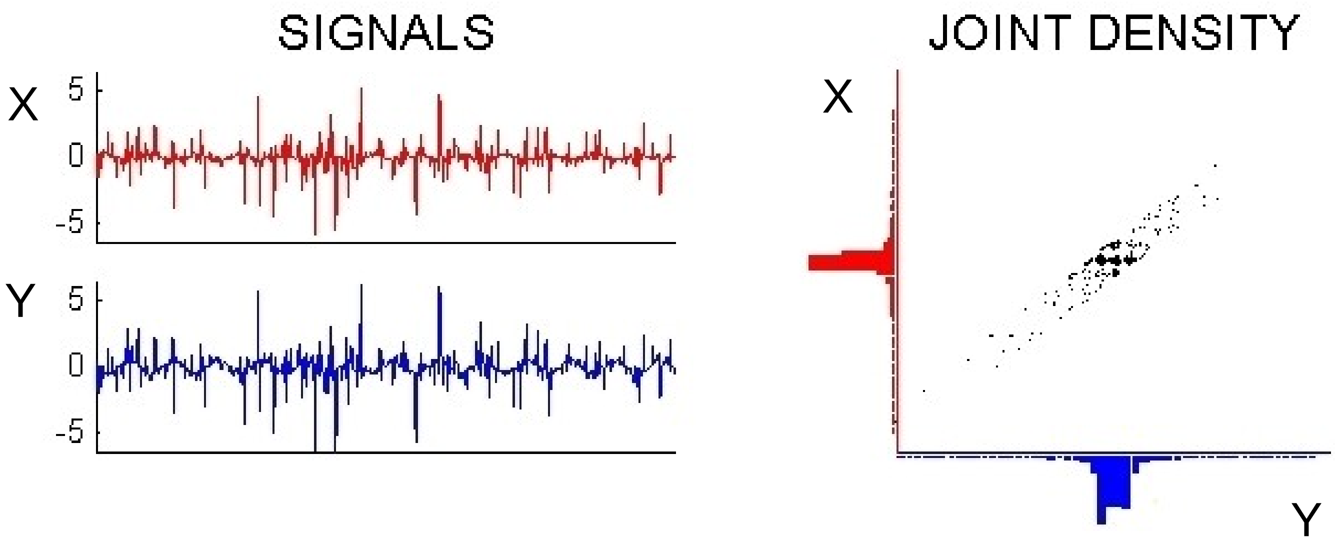


Measurements

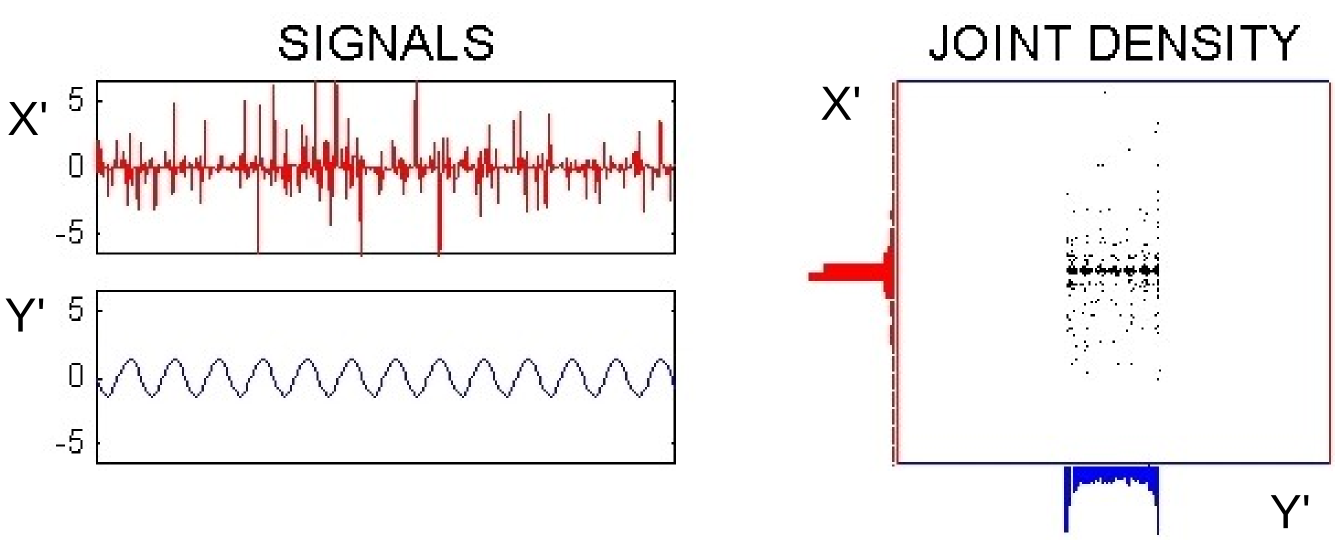


Separated signals

$$\langle s_1 s_2 \rangle = \langle s_1 \rangle \langle s_2 \rangle = 0$$

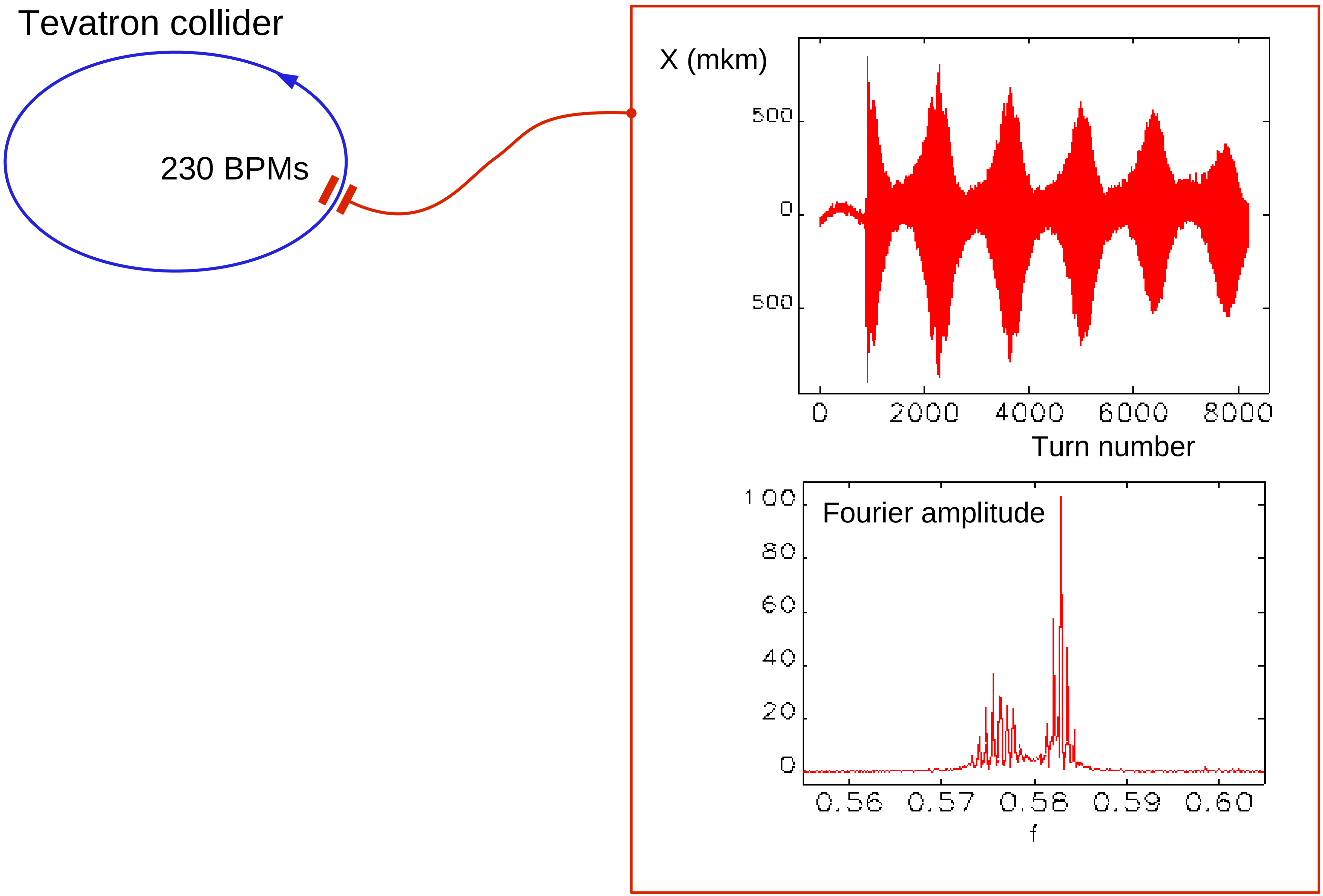


Input signals and density



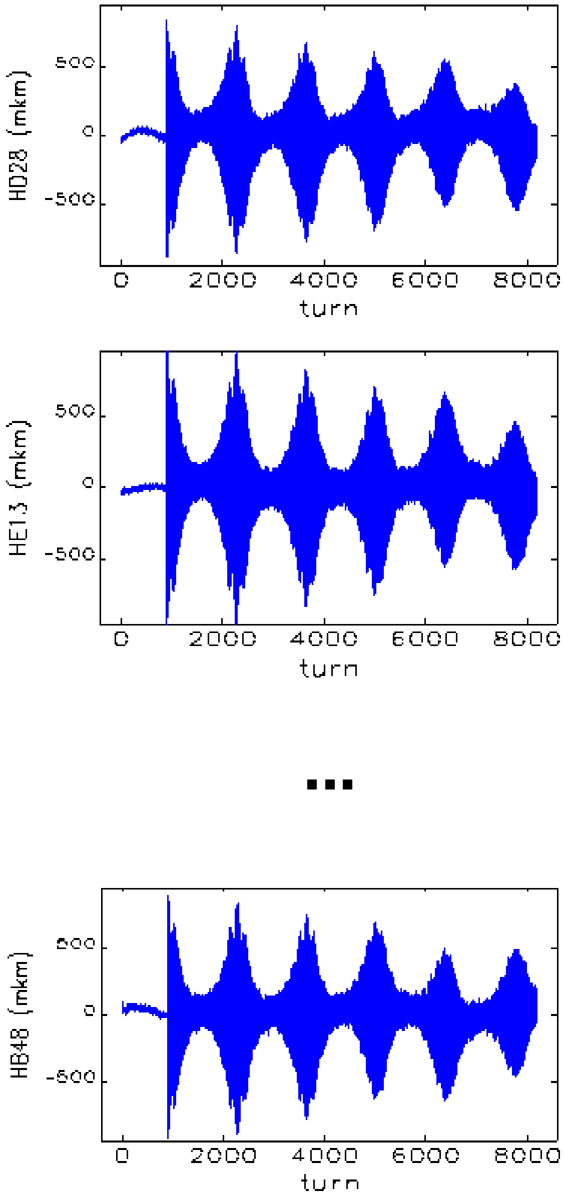
Separated signals after 5 steps of FastICA

Turn-by-turn BPM signal after beam is kicked with a horizontal kicker



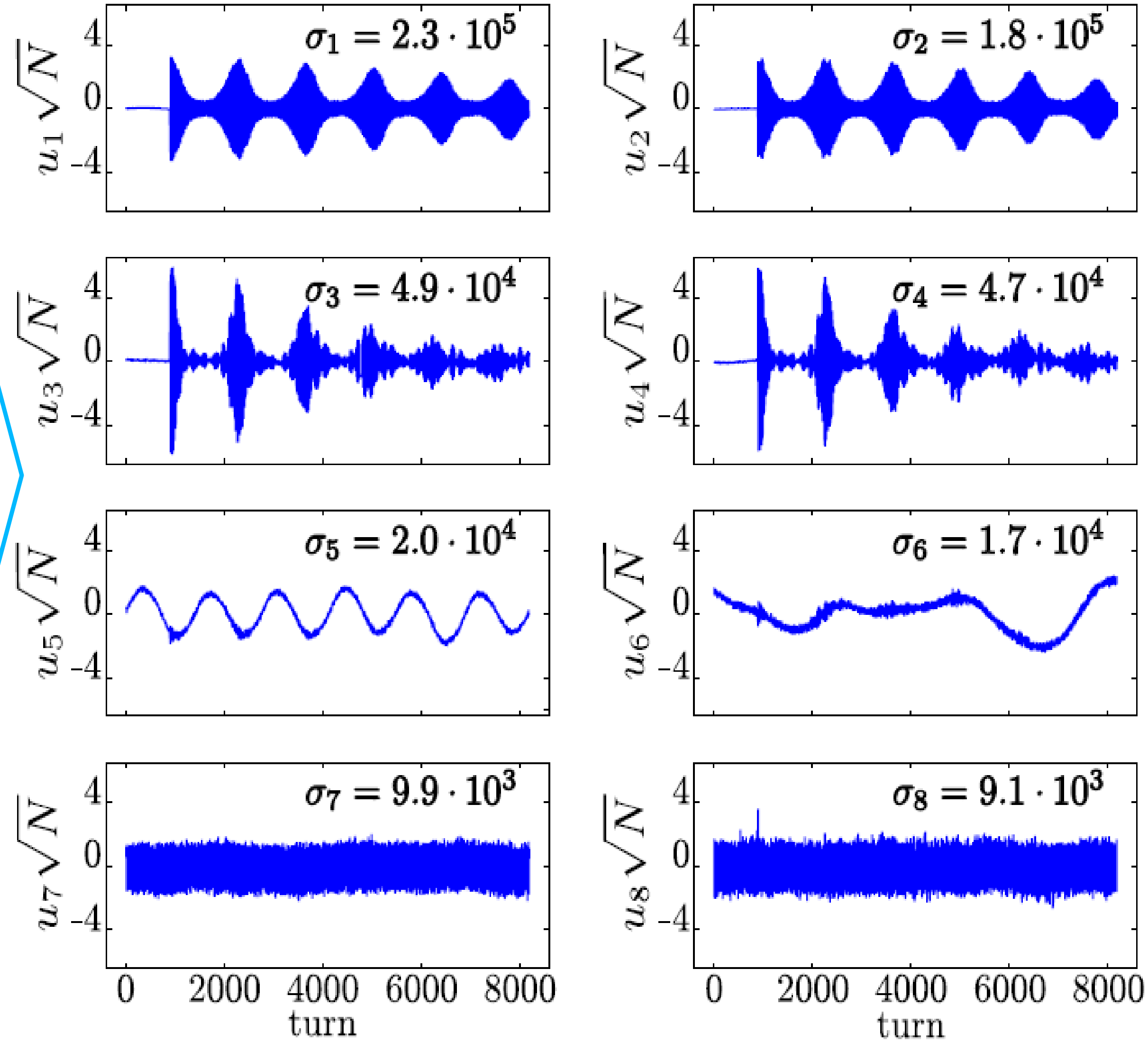
Model-Independent Analysis of BPM signals

Signal from each BPM is represented as a linear combination of a small number of mutually independent (orthogonal) components:

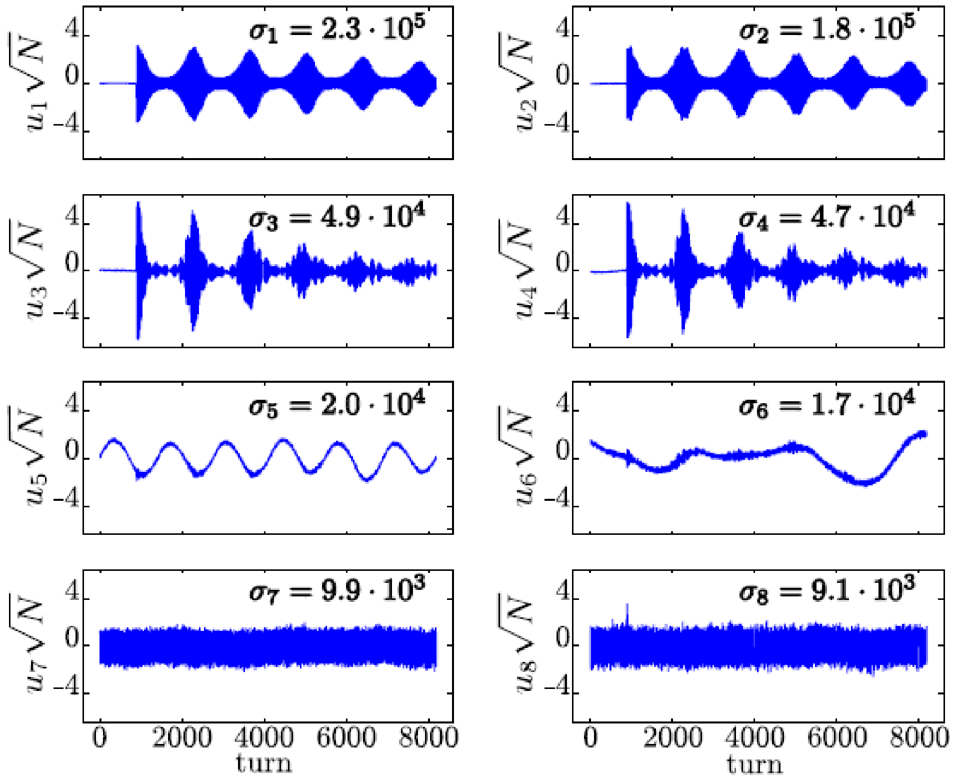


Singular
Value
Decomposition

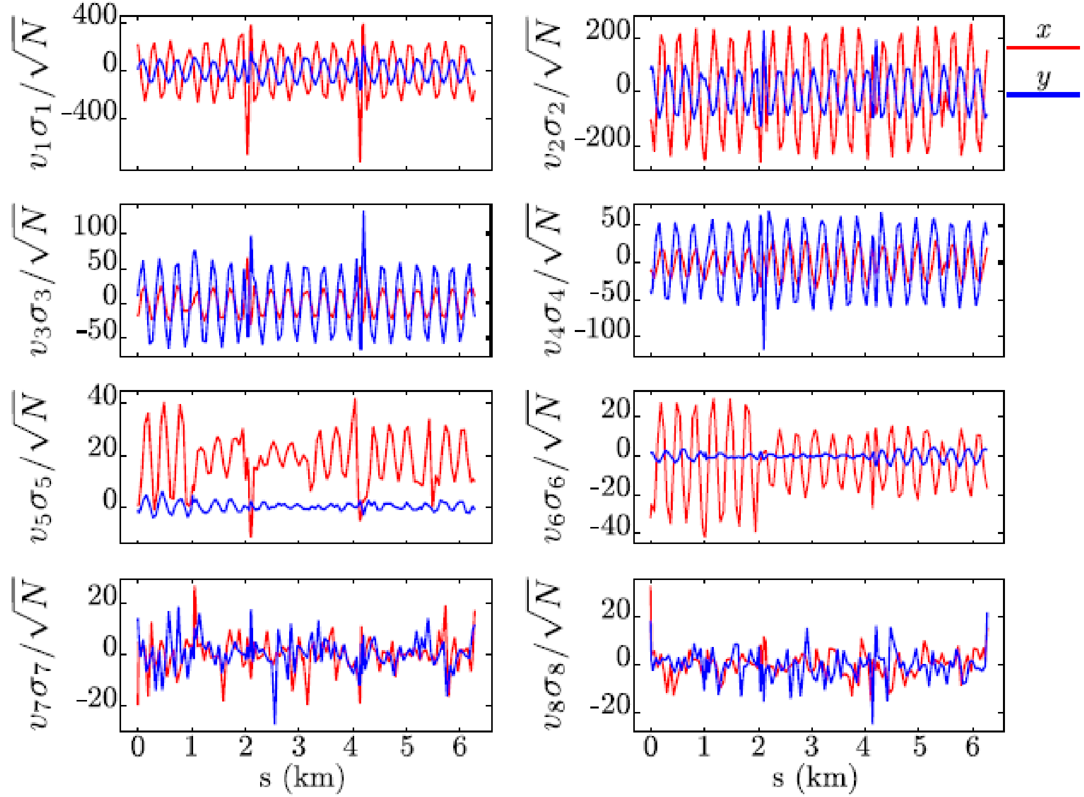
$B = U \Sigma V^T$



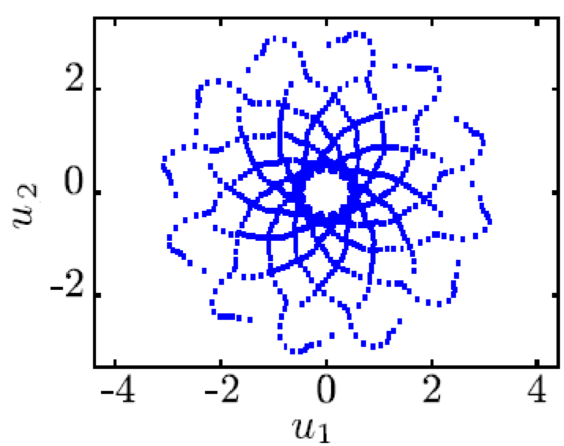
Temporal modes
(mutually independent components)



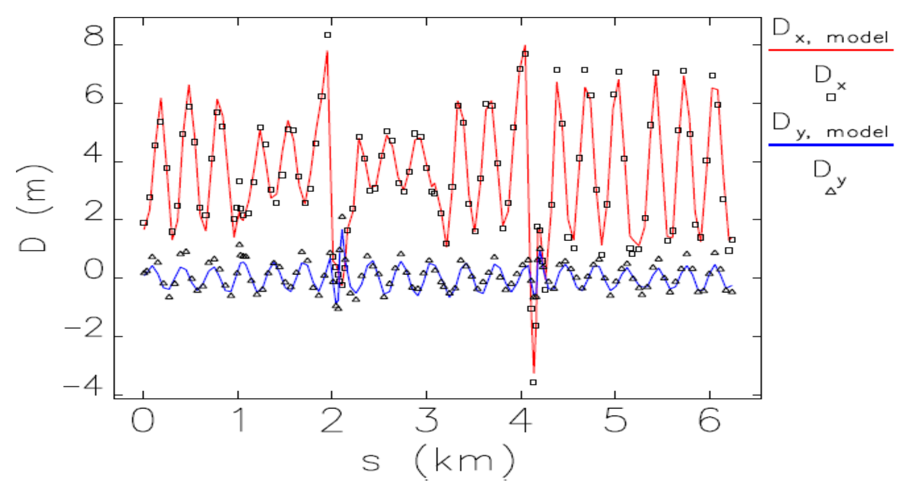
Spatial modes
(amplitude of temporal mode vs BPM position)



Beam centroid trace in phase space:



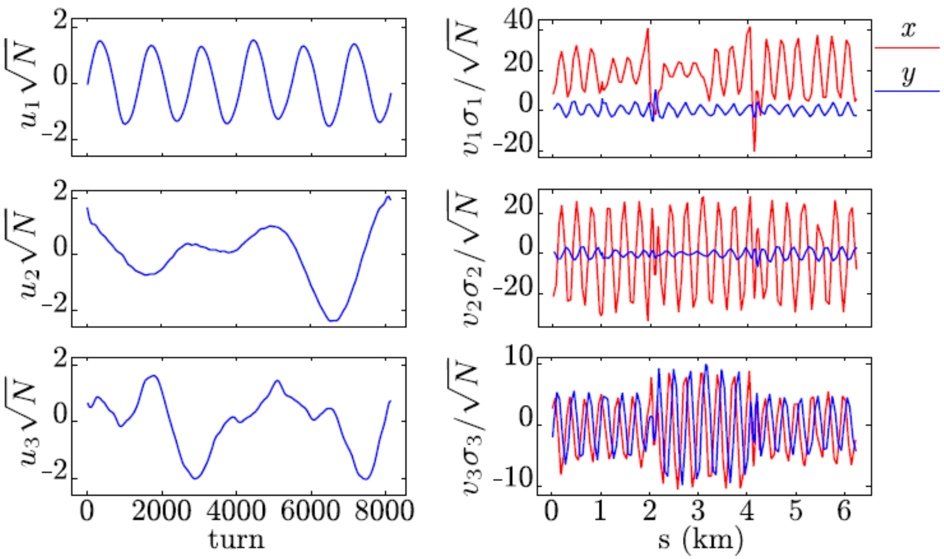
Lattice functions:



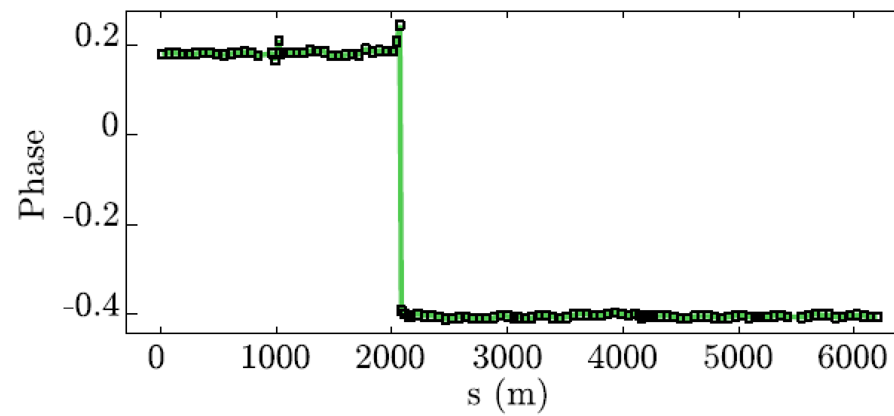
Horizontal and vertical dispersion function

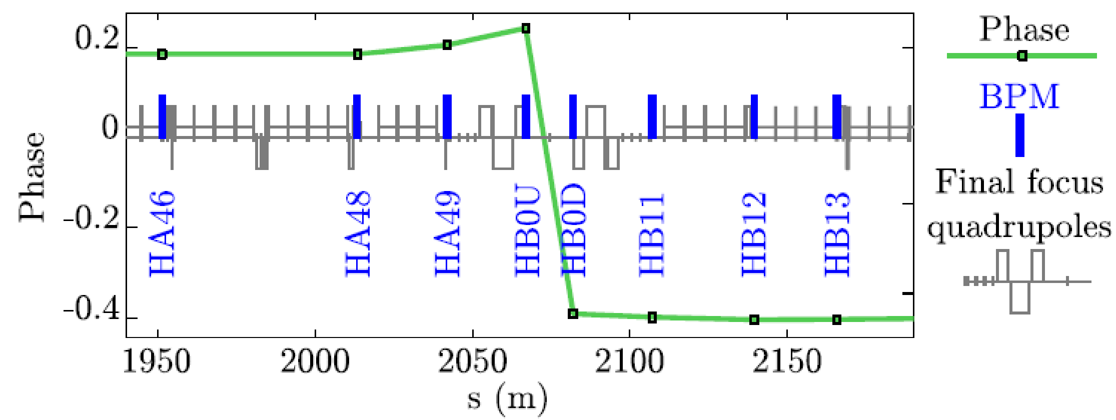
Finding the source of some modes

Slow modes (after low-pass Fourier filter)



"Betatron" phase of mode 2 (vibrational mode)





At any pair of (horizontal) BPMs any spatial mode can be represented as a linear combination of two independent orbits:

$$\begin{cases} v_{\mathrm{vibr}}(s_1) = C_1 v_{\mathrm{b1}}(s_1) + C_2 v_{\mathrm{b2}}(s_1) \\ v_{\mathrm{vibr}}(s_2) = C_1 v_{\mathrm{b1}}(s_2) + C_2 v_{\mathrm{b2}}(s_2) \end{cases}$$

$\tan(\text{Phase}) = C_1/C_2$

Elements of transport matrix between BPMs

Using any 4 linearly independent orbits (e. g. spatial modes of betatron oscillations) it is possible to calculate some of the transport matrix elements between BPMs:

$$(x_1^a x_2^b - x_2^a x_1^b)/Q_{12} + (x_3^a x_4^b - x_4^a x_3^b)/Q_{34} = \mathcal{R}_{12}^{ab}$$

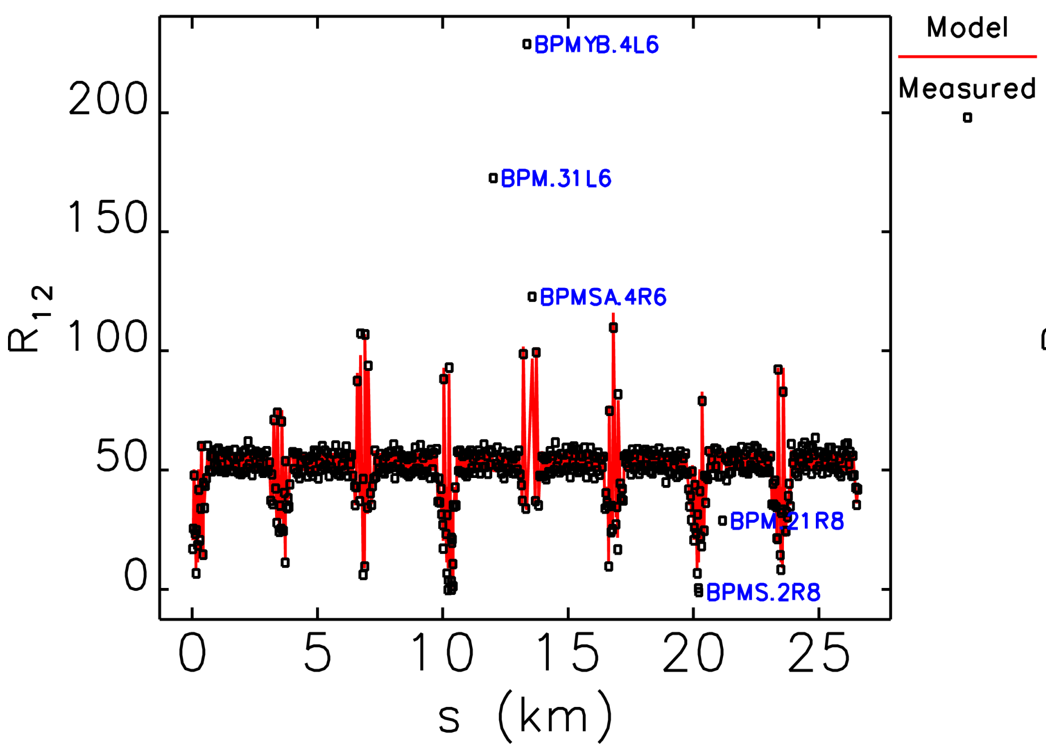
$$(x_1^a y_2^b - x_2^a y_1^b)/Q_{12} + (x_3^a y_4^b - x_4^a y_3^b)/Q_{34} = \mathcal{R}_{32}^{ab}$$

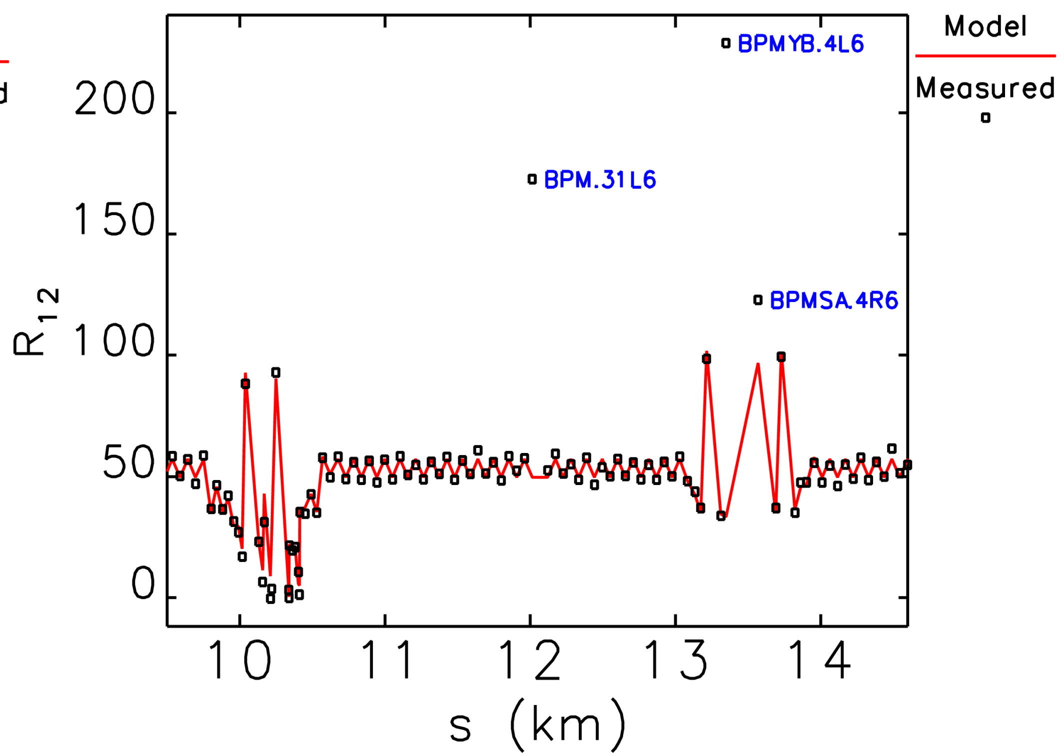
$$(y_1^a x_2^b - y_2^a x_1^b)/Q_{12} + (y_3^a x_4^b - y_4^a x_3^b)/Q_{34} = \mathcal{R}_{14}^{ab}$$

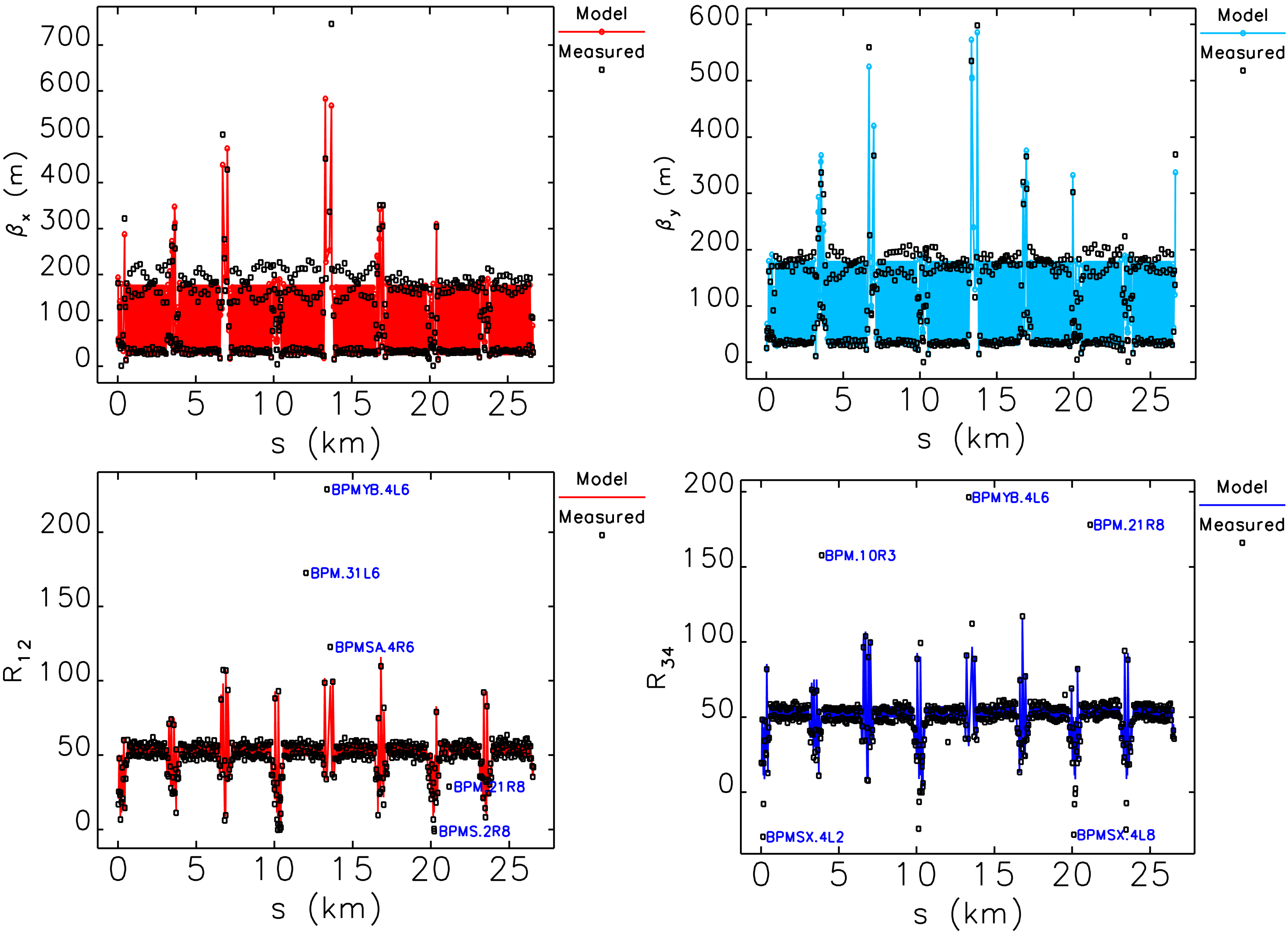
$$(y_1^a y_2^b - y_2^a y_1^b)/Q_{12} + (y_3^a y_4^b - y_4^a y_3^b)/Q_{34} = \mathcal{R}_{34}^{ab}$$

J. Irwin and Y. T. Yan, "*Beamline Model Verification Using Model Independent Analysis*", Proceedings of EPAC 2000, Vienna, Austria.

R_{12} calculated from turn-by-turn measurements (courtesy R. Miyamoto) at the LHC:






Model
Measured
β_x (m)
s (km)
β_y (m)
R_{12}
BPMYB.4L6
BPM.31L6
BPMSA.4R6
BPM.21R8
BPMS.2R8
R_{34}
BPM.10R3
BPMSX.4L2
BPMSX.4L8

Thank you for your attention!