Luminosity Optimization by Adjusting the β-Function in the Interaction Point at LHC and RHIC.

W. Wittmer

walter.wittmer@cern.ch

walter.wittmer@free.fr

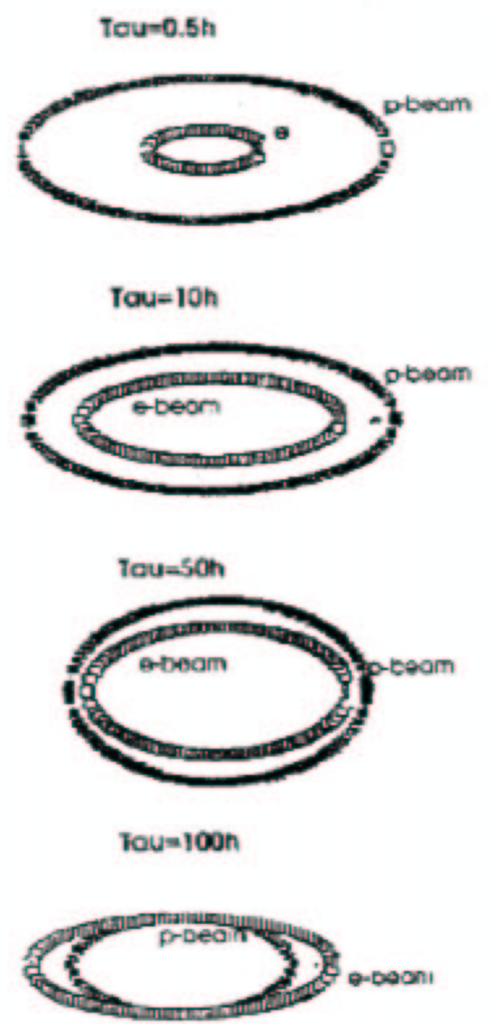
CERN AB/ABP

&

University of Technology Graz, Austria

Table of Contents

Motivation - Beam Lifetime HERA, SPS



σ_x^p (μm)	σ_x^e (μm)	σ_y^p (μm)	σ_y^e (μm)	τ_p (hrs)
410	130	20	33	0.5
410	290	120	70	10
330	290	100	70	50
210	290	50	53	100
190	200	50	53	300

$$\tau = f\left(\frac{\sigma_1}{\sigma_2}\right)$$

$$\frac{\sigma_1}{\sigma_2} \not\approx 1 \Rightarrow \left\{ \begin{array}{l} \text{poor life time due} \\ \text{to beam-beam} \end{array} \right.$$

Luminosity Optimizing for LHC Ions

- Initial beam (intensity) lifetime due to beam-beam interactions (non-exponential decay)

$$\tau_{NL} = \frac{k_b N_b}{n_{exp} L \sigma_{tot}} = \frac{22.4\text{hour}}{n_{exp}}$$

for nominal $L = 10^{27}$ cm^{-2} s^{-1} with Pb-Pb

$n_{exp} \ldots$ number of experiments illuminated

- But luminosity may be limited by experiment or quench limit

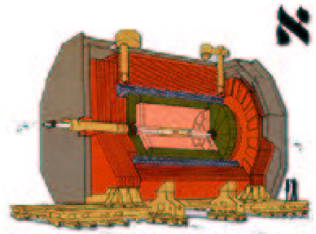
$$L = \frac{k_b N_b^2 f_0}{4\pi \sigma^{\star 2}} = \frac{k_b N_b^2 f_0}{4\pi \beta^\star \epsilon_n} \gamma$$

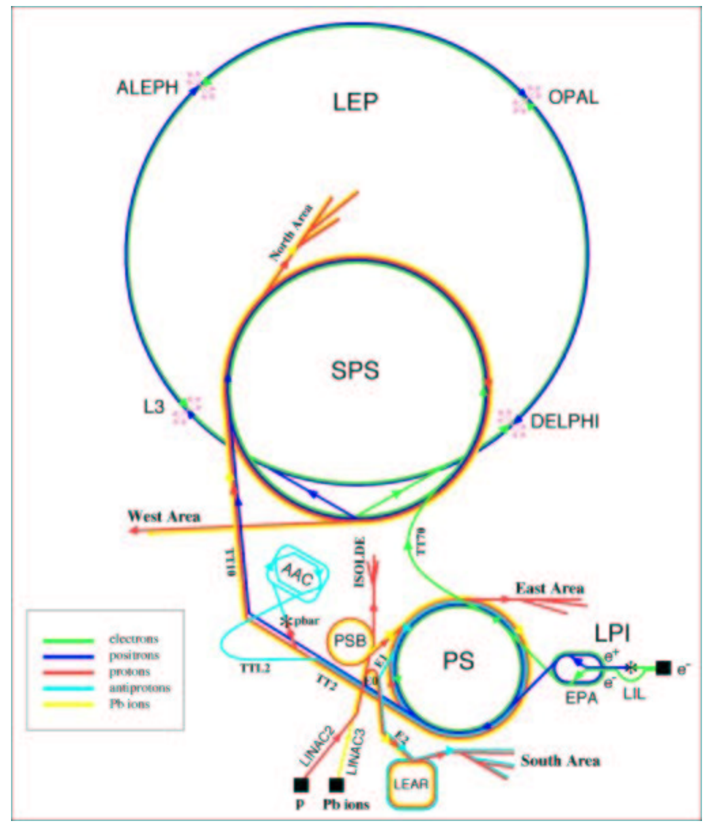
$\Rightarrow$ can have same luminosity by varying $\beta^\star \propto N_b^2$

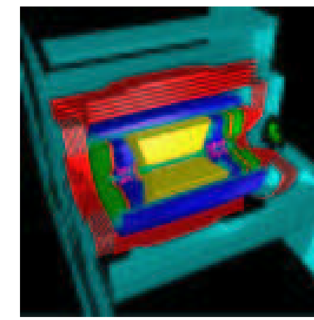
$\beta^\star$-tuning during collision to maximise integrated luminosity - especially if N_b can be increased.

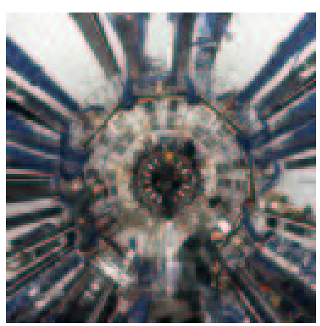
Presented by J.M.Jowett, LHC Performance Workshop, Chamonix, 19/1/2004

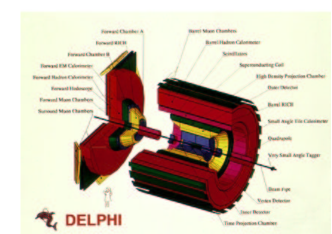
Luminosity in LEP Experiments











Each experiment requested at least the same luminosity as all the others.

Luminosity correction in LEP

In LEP closest low β quadrupoles (QS0L and QS0R) were used for correction

- Both Beams Were Equal
- Main Error Source: QS0L QS0R
- Symmetric Lattice

Luminosity correction was easy in LEP

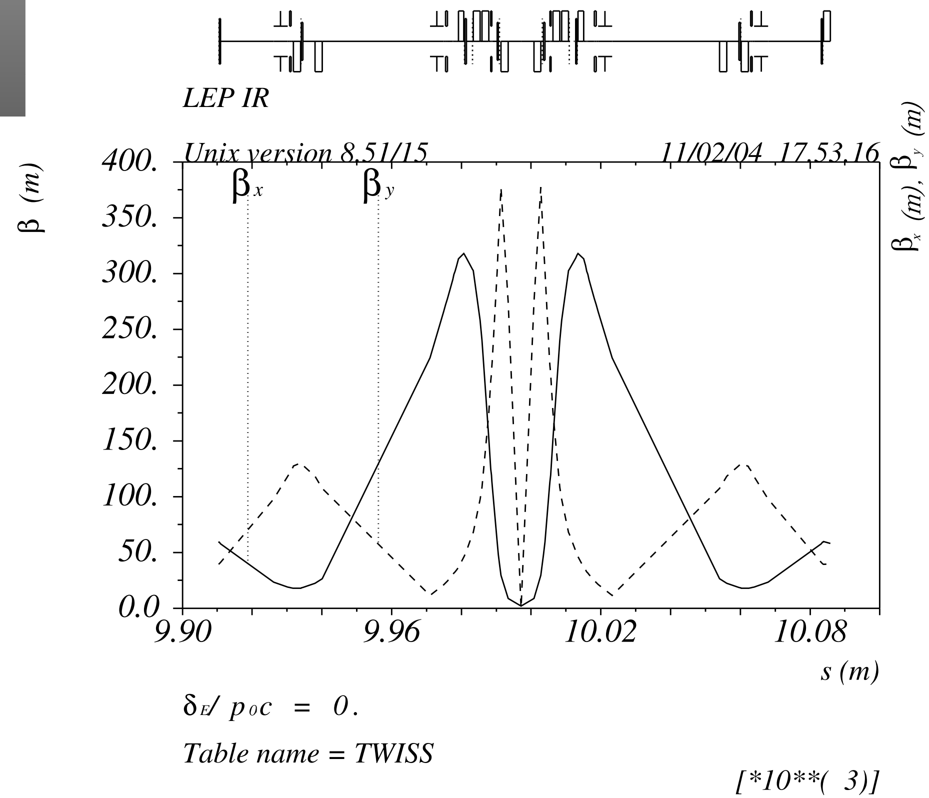
Comparison LEP and LHC-RHIC

	LEP	LHC - RHIC
beam profile	flat	round
$\Rightarrow$ lattice	symmetric	asymmetric
$\Rightarrow$ correction	1 plane	2 planes

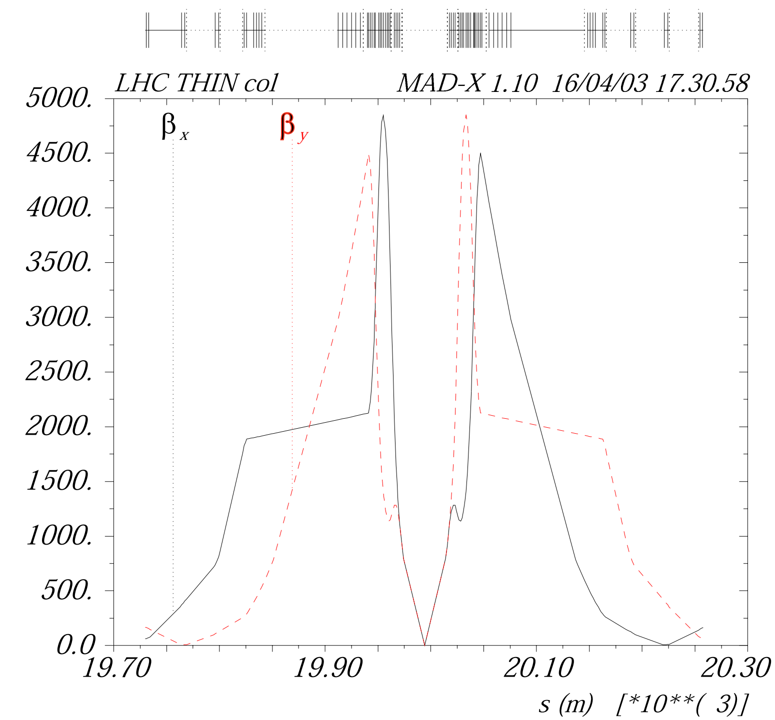
particles	e^+e^-	p p
$\Rightarrow$ beam pipe	common	mostly separated
$\Rightarrow \Rightarrow$ errors	equal	unequal

β Function LEP LHC

LEP



LHC



Motivation - Luminosity correction in LHC-RHIC

Issues of optimizing Luminosity in LHC-RHIC:

- triplet magnets cannot be used
- set of quads after separation have to be used
- beating from correction more difficult to avoid
- both planes have to be corrected orthogonally
- error source ???
- ...

If at all possible, $\beta^{\star}$ correction is extremely sophisticated!

Concept of Adjusting Luminosity and Beam Size

$$\mathcal{L} = \frac{N_1 N_2 f N_B}{4\pi \beta_x^\star \beta_y^\star \epsilon^2}$$

$$\sigma = \sqrt{\beta^\star \epsilon}$$

$\mathcal{L}$ . . . Luminosity

$N_{1,2}$ . . . number of particles per bunch

N_B . . . number of bunches per beam

f . . . revolution frequency

$\beta_{x,y}$ . . . Courant Snyder parameter

ϵ . . . emittance

σ . . . rms beam size

Principle of Adjusting $\beta^\star$

$$\Delta\beta^\star = \frac{\beta^\star}{2\sin(2\pi Q)} \sum_{s=1}^{n} \beta(s)\Delta k(s)\, l \cos(2|\Delta\mu| - 2\pi Q)$$

$\Delta\beta^\star \ldots$ change of β function at IP

$\beta^\star \ldots$ β function at IP

$Q \ldots$ tune

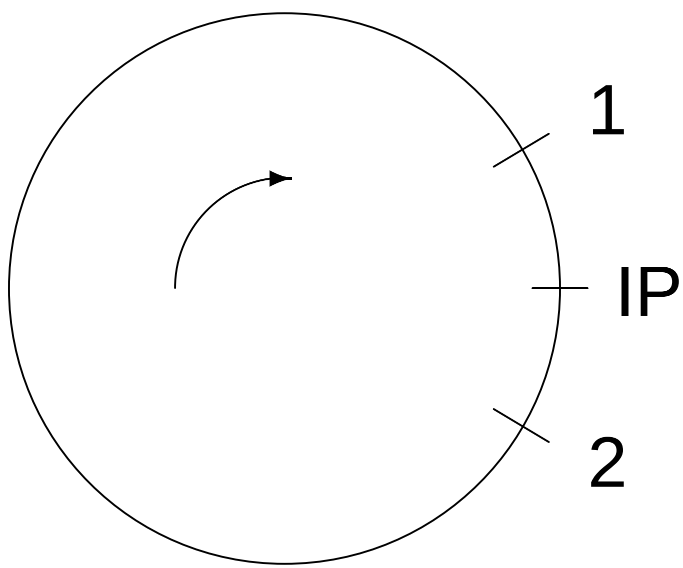
$\beta(s) \ldots$ β function at a quadrupole

$\Delta k(s)\, l \ldots$ change of integrated magnet strength

$\Delta\mu \ldots$ phase advance between quadrupole and IP

Changes - Constraints

$$M_{12} = M_{IP-2} \cdot M_{1-IP}$$



$$\left.\begin{array}{rcl} \beta_x^\star & = & \beta_x^\star + \Delta\beta_x^\star \\ \beta_y^\star & = & \text{const} \end{array}\right\} \text{at IP}$$

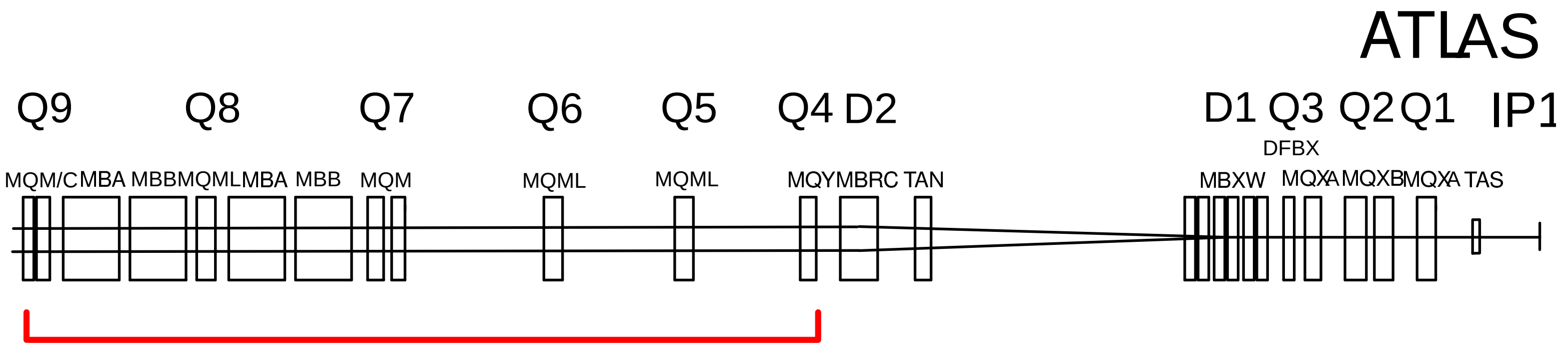
or

$$\left.\begin{array}{rcl} \beta_x^\star & = & \text{const} \\ \beta_y^\star & = & \beta_y^\star + \Delta\beta_y^\star \end{array}\right\} \text{at IP}$$

$$\left.\begin{array}{c} \beta \\ D \end{array}\right\} = \text{const at 1,2}$$

$$\left.\begin{array}{c} \alpha \\ D \end{array}\right\} = \text{const at IP}$$

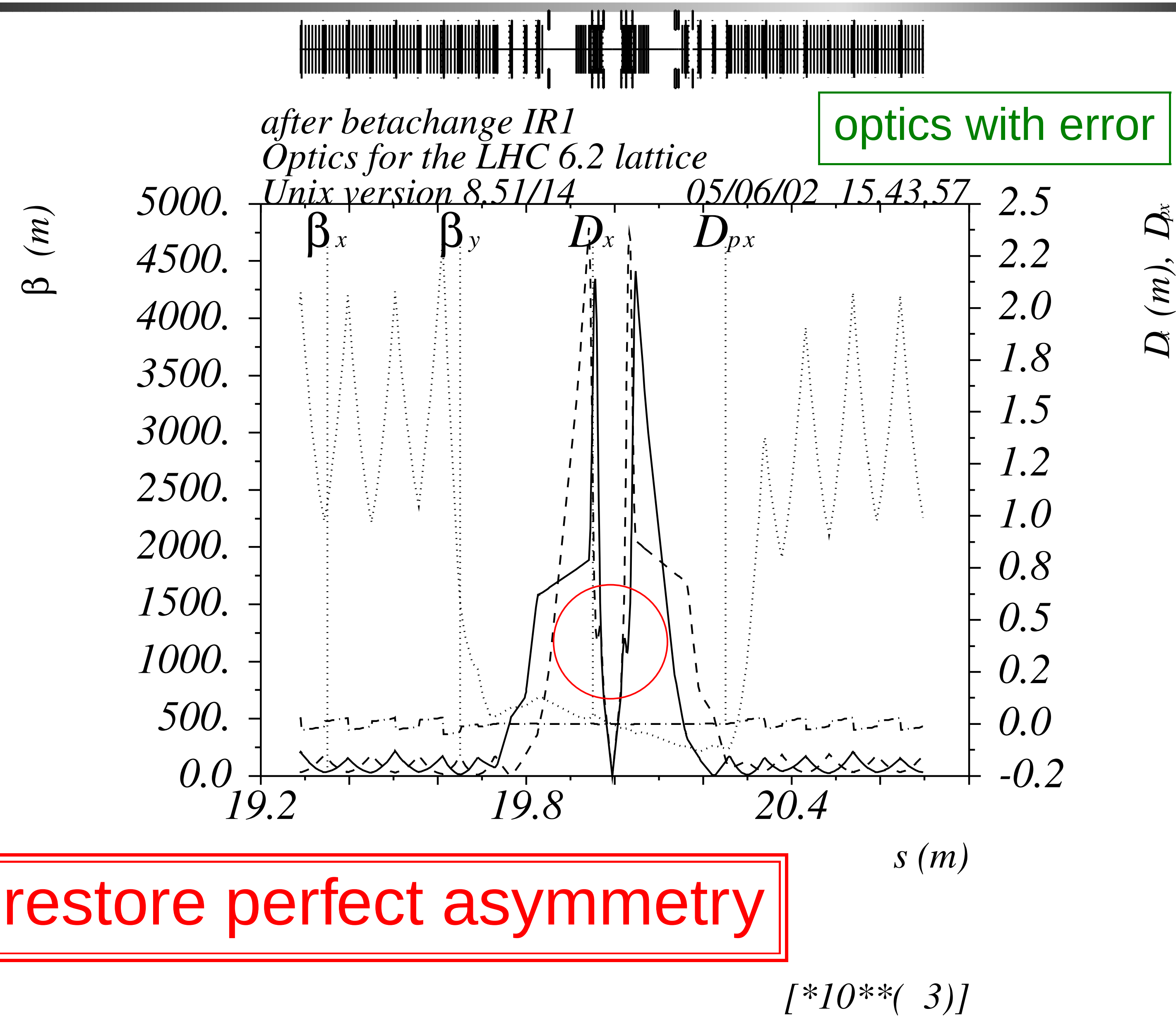
$\beta^\star$ Tuning Knobs for LHC



$$m \cdot \begin{pmatrix} \Delta K_1 \\ \Delta K_2 \\ \Delta K_3 \\ \vdots \\ \Delta K_n \end{pmatrix} \longrightarrow \Delta\beta_{x,y}$$

$$\boxed{m = 1 \qquad \Longleftrightarrow \qquad \Delta\beta_{x,y} = 1m}$$

Concept of non Local Correction using Tuning Knobs



goal: restore perfect asymmetry

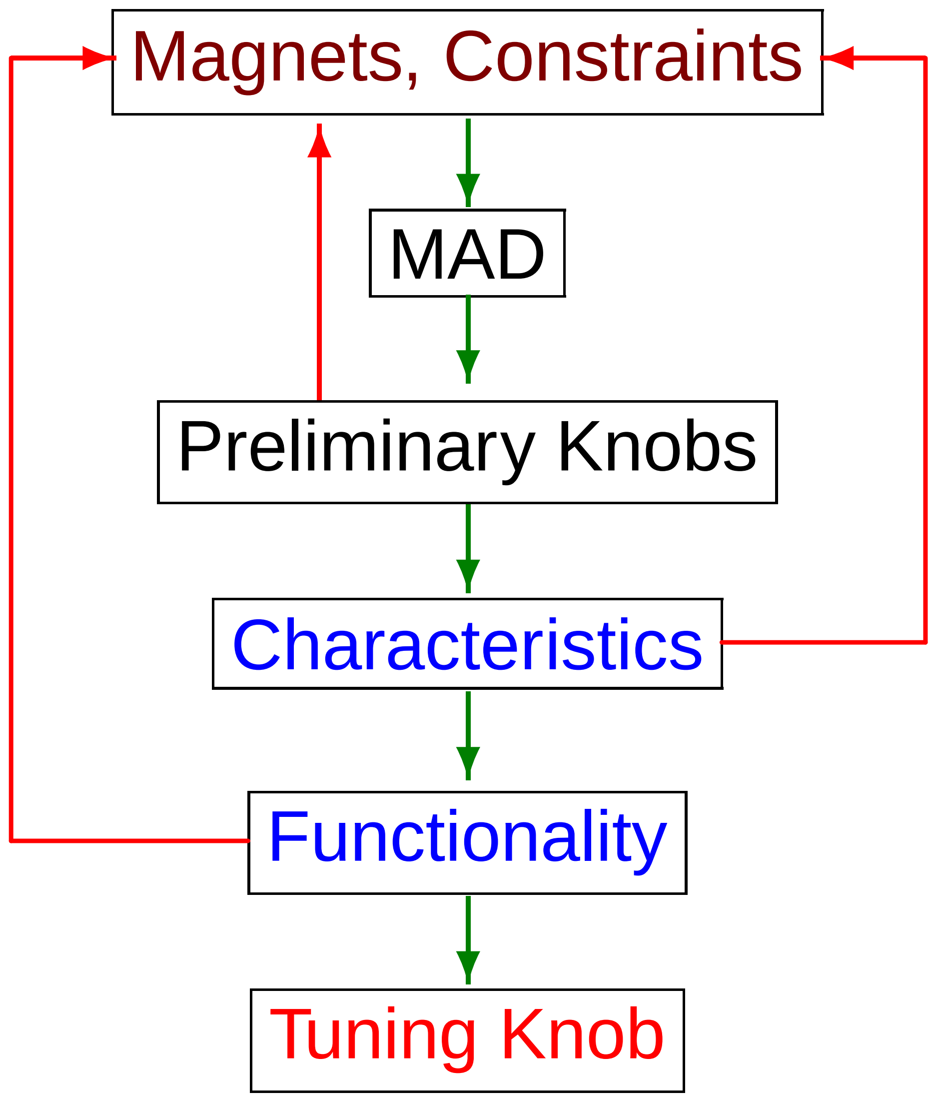
Goal of $\beta^\star$ Tuning Knobs

- Change β function at the IP.
- Confine changes to selected area (IR).
- Minimize perturbation to other optics functions.
  - Constraints
  - Observables

Methods of Calculating $\beta^\star$ Tuning Knobs

- MAD Matching (empirical)
  - direct
  - linear fit $\Delta K = f\left(\beta\right)$
- Response Matrix (analytical)

MAD MATCHING



Magnets - Constraints for MAD MATCH

	Magnets	Constraints
available	LHC $\left\{\begin{array}{c}\text{KQ4-KQ13}\\ \text{R+L}\end{array}\right.$ RHIC $\left\{\begin{array}{c}\text{K(1-3)A8}\\ \text{K(4-6)A8(I,O)}\\ \text{K(4,56)M8, K7A8}\\ \text{K(D,F)AA8, KFBA8}\end{array}\right.$	$\alpha, \beta, D, D', X, (pX), Y, (pY)$ at IP1 and IP5 or $\left\{\begin{array}{l}\alpha, \beta, D, D', X, (pX), Y, (pY) \text{ at IP1}\\ \beta, D, X, Y, \text{ at I, II}\\ \text{with (I)} \xrightarrow[k=0,1\ldots]{\Delta\mu=\frac{\pi}{4}(2k+1)} \text{(II)}\end{array}\right.$ and Q, Q'
finally used LHC	KQ4 - KQ9 (KQ13) R+L	α, β, D at IP1 and IP5
finally used RHIC	KQ4-KQ6, L+R K7A8, KFBA8 KDAA8, KFAA8	$\alpha, \beta, (D)$ at IP8 and IP6 Q

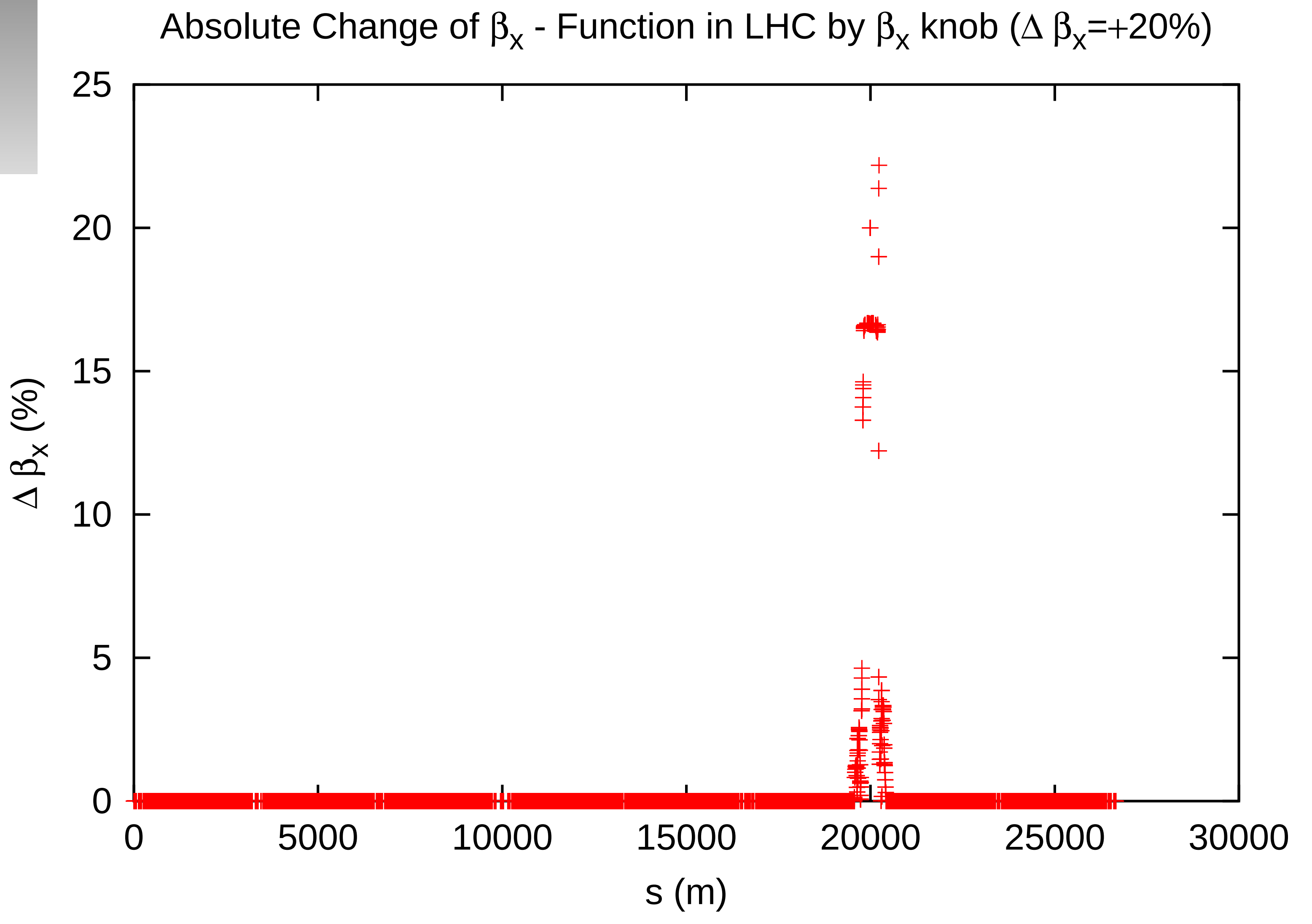
MAD matching: no. magnets = no. constraints (12,10)

Allowed Variation of Constraints & Observables.

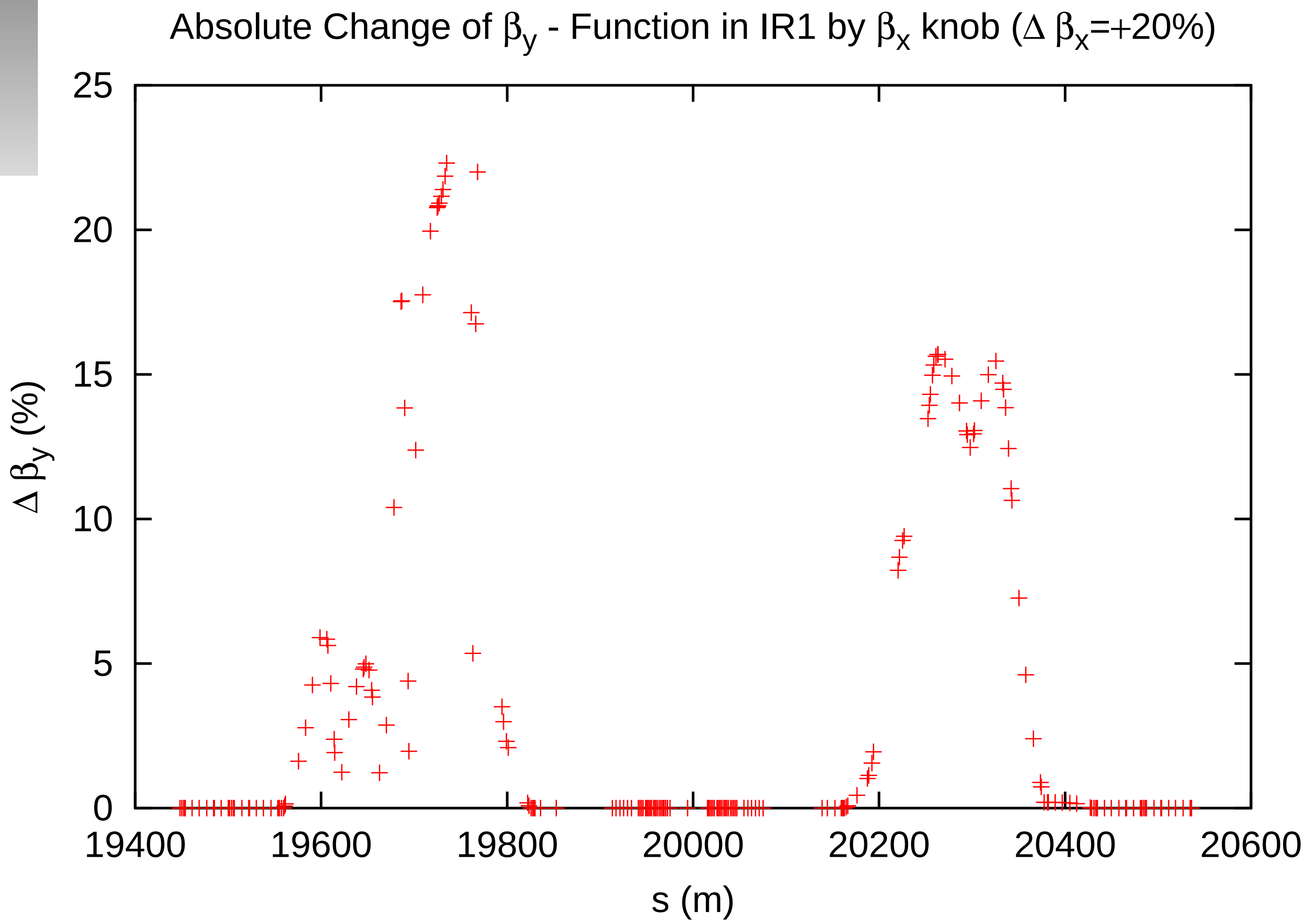
operative range of knobs $\Longrightarrow$ 10 % of nominal value ($\beta^\star$=0.5m).

constraint observable	allowed variation
$\lvert\alpha^\star\rvert$	< 0.1
$\beta^\star_\perp$	$< 1\%$ of $\Delta\beta^\star$
$\lvert D^\star\rvert$	$< 3 \cdot 10^{-2} m$
$X^\star, Y^\star$	$< 16.0 \cdot 10^{-6} m$
$pX^\star, pY^\star$	$< 10\%$
Q	$< 0.025(0.1)$

Global Constraints behavior β_x

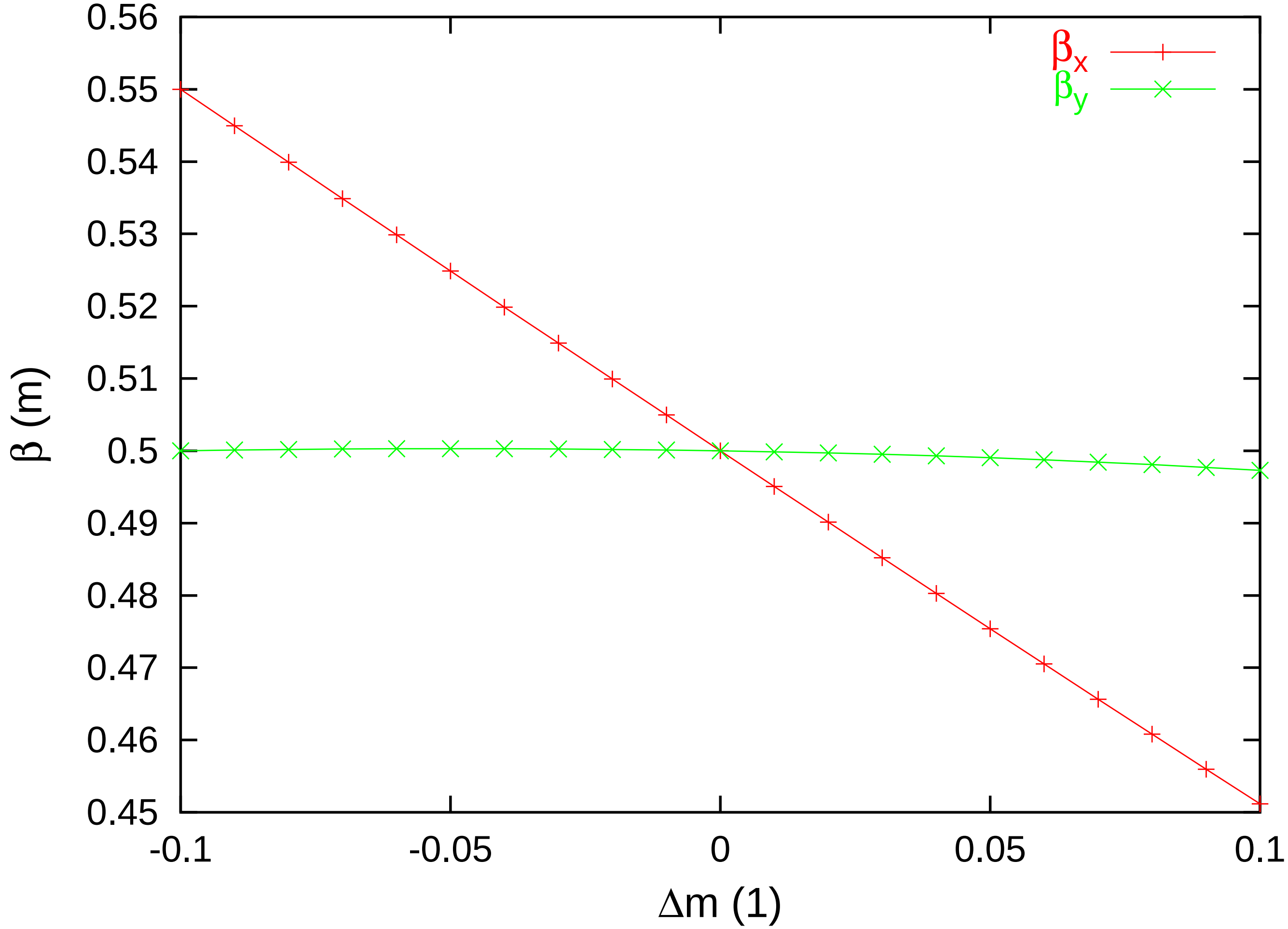


IR1 Constraints behavior β_y



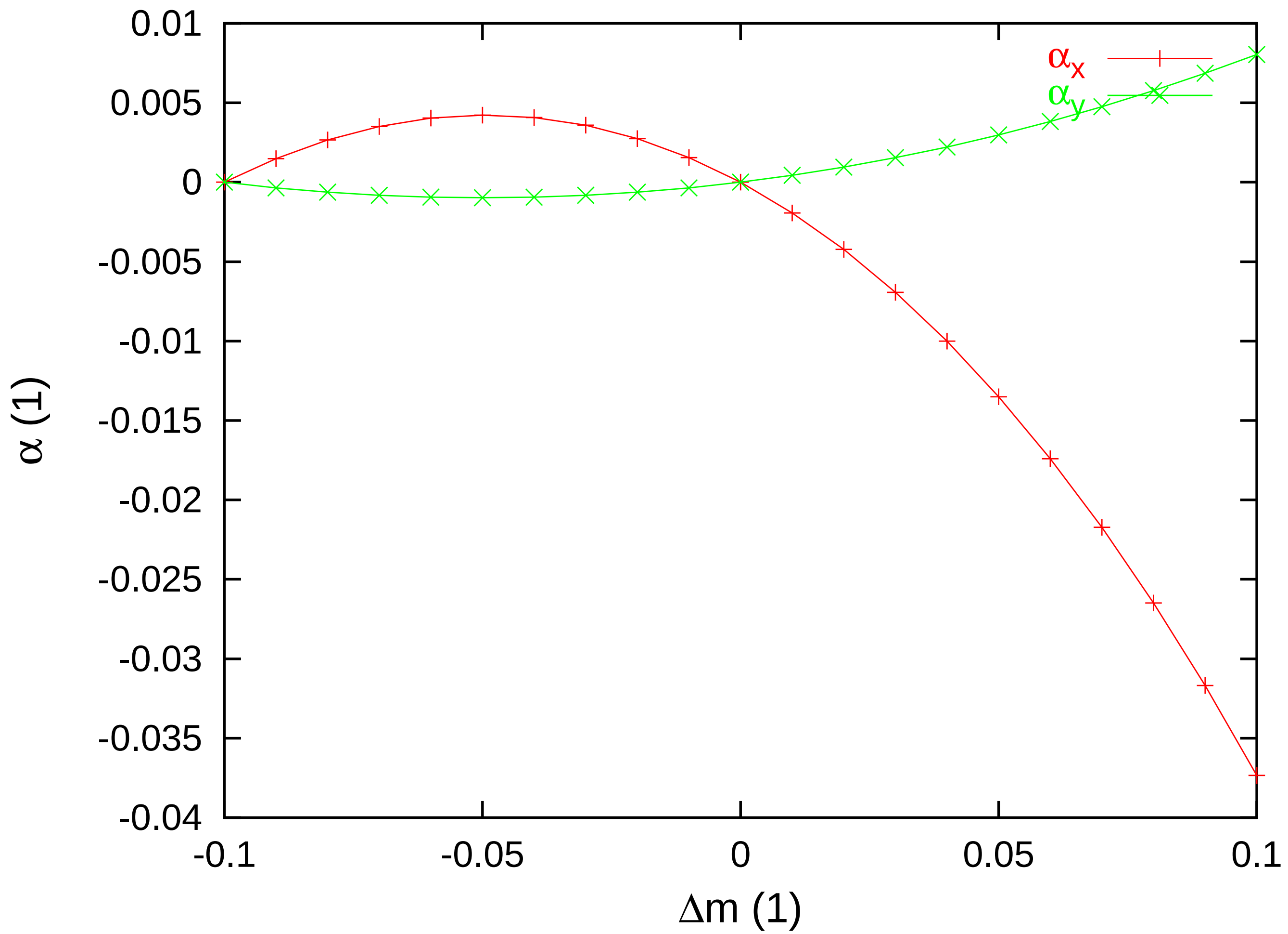
Result with Direct Method

$\beta^\star$ as a function of Δm

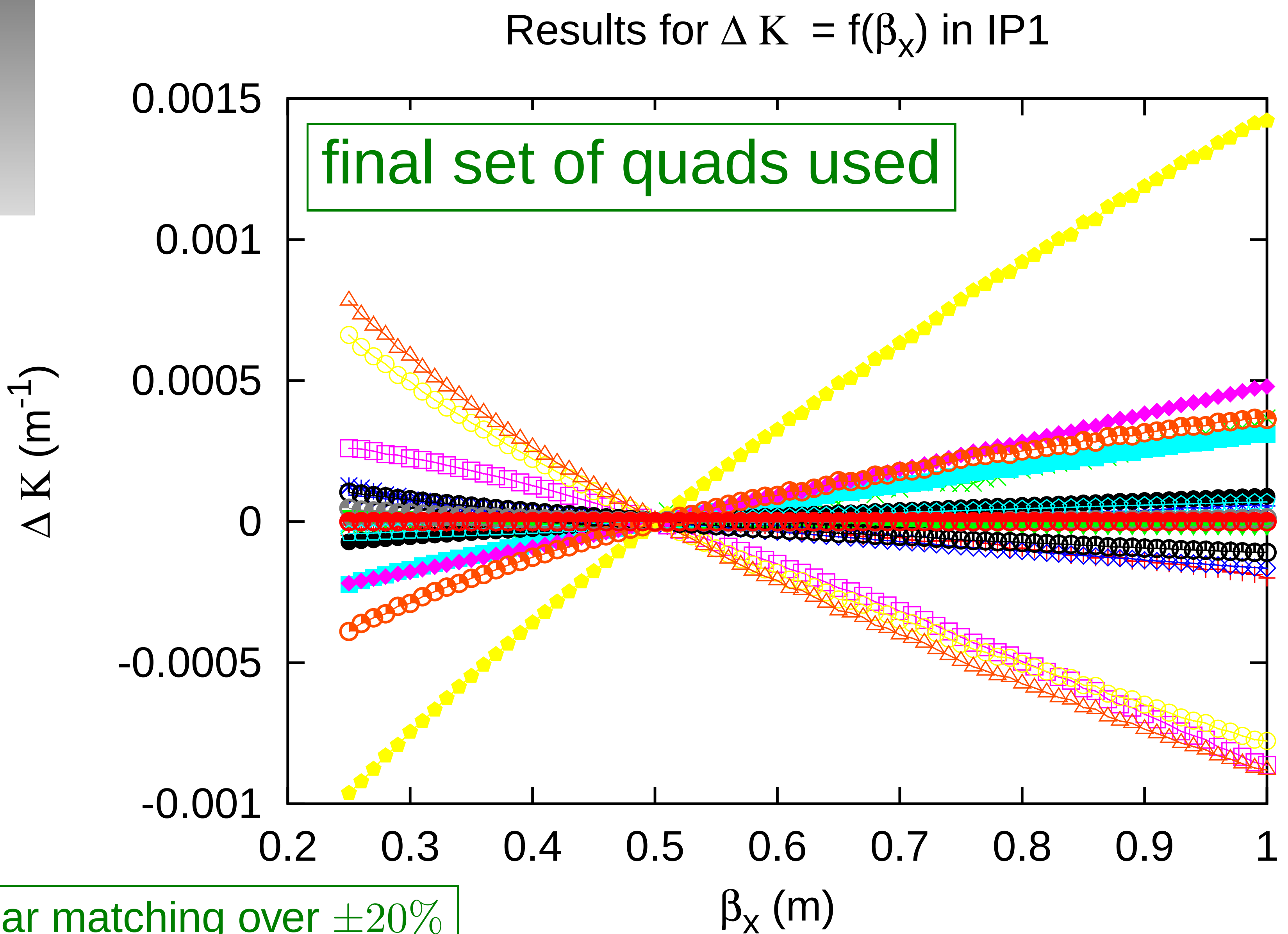


Result with Direct Method

$\alpha^\star$ as a function of Δm

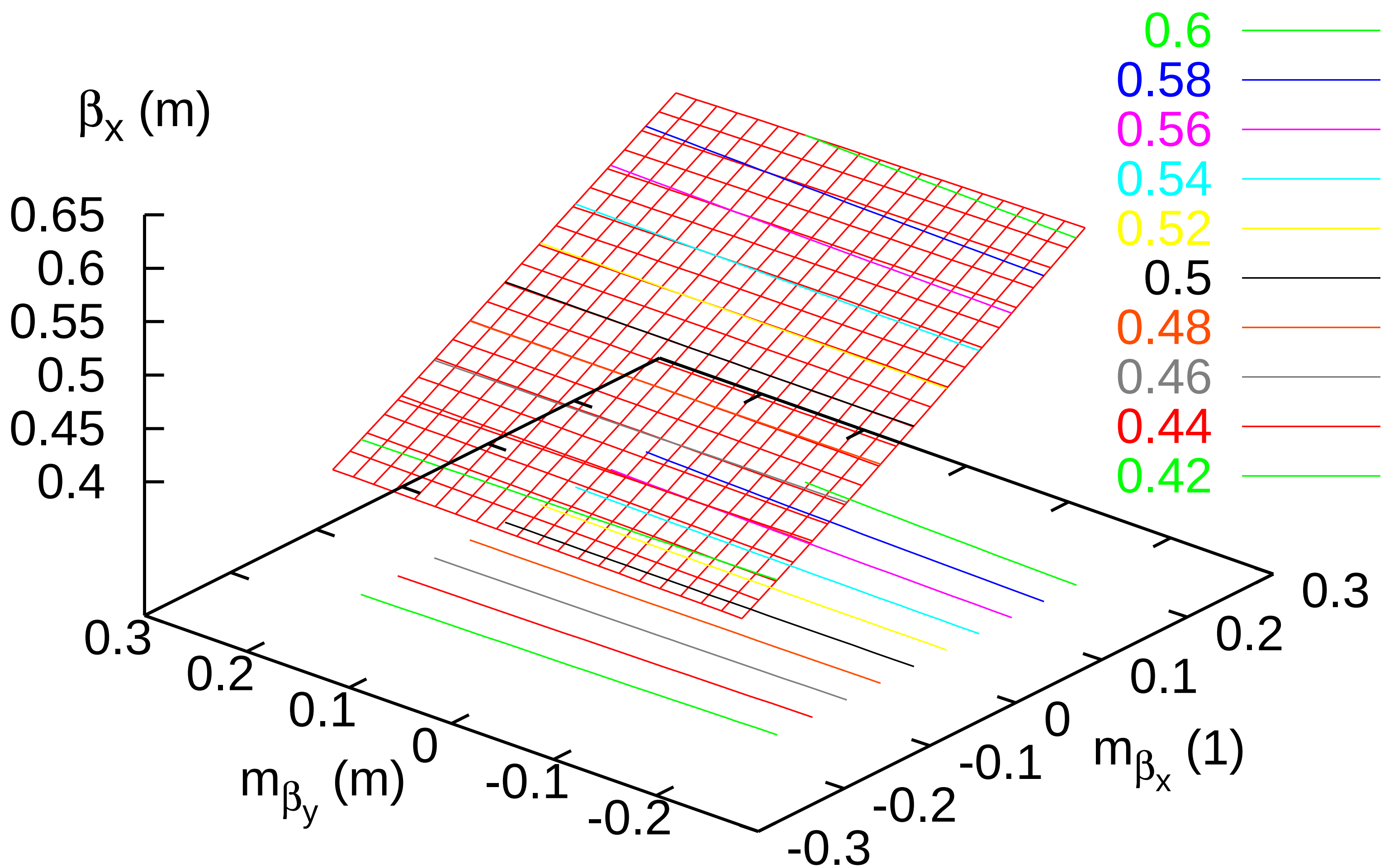


Matching Results with MAD - $\Delta K = f\left(\beta\right)$

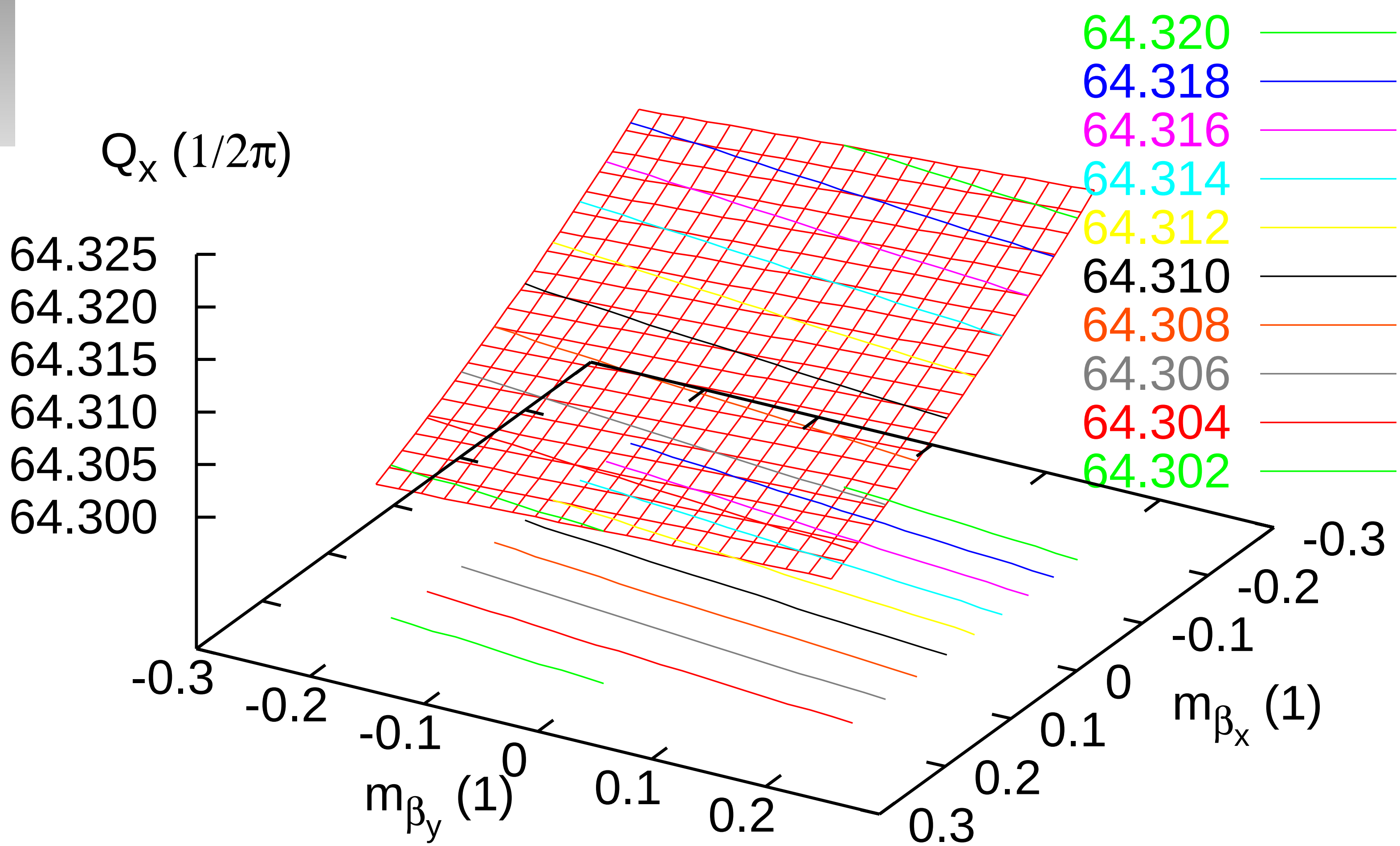


linear matching over $\pm 20\%$

Characteristic: $\beta_x = f(m_{\beta_x}, m_{\beta_y})$



Characteristic: $Q_x = f(m_{\beta_x}, m_{\beta_y})$



Summary Characteristic

K_{β_x} (m)	K_{β_y} (m)	β_x (m)	β_y (m)	α_x (1)	α_y (1)	D_x (m)	D_y (m)	Dp_x (1)
-0.1	-0.1	4.00e-01	4.06e-01	3.16e-02	-3.45e-02	6.14e-03	6.72e-03	3.20e-02
0.1	-0.1	6.05e-01	4.10e-01	2.15e-02	-1.76e-02	1.50e-02	6.53e-03	3.23e-02
-0.0	0.0	5.00e-01	5.00e-01	2.71e-09	-4.20e-09	1.03e-02	6.73e-03	3.11e-02
-0.1	0.1	4.05e-01	6.14e-01	2.20e-02	-2.35e-02	6.19e-03	7.29e-03	2.86e-02
0.1	0.1	5.97e-01	6.05e-01	2.42e-02	-3.61e-02	1.46e-02	7.30e-03	2.91e-02

K_{β_x} (m)	K_{β_y} (m)	Dp_y (1)	X (m)	Y (m)	pX (1)	pY (1)	Q_x $(1/2\pi)$	Q_y $(1/2\pi)$
-0.1	-0.1	2.14e-02	5.25e-13	3.56e-08	-5.80e-13	1.50e-04	64.3187	59.3240
0.1	-0.1	2.15e-02	8.55e-13	1.56e-07	-3.59e-13	1.50e-04	64.3012	59.3252
-0.0	0.0	1.92e-02	5.38e-13	-1.53e-10	-7.02e-13	1.50e-04	64.3100	59.3200
-0.1	0.1	1.72e-02	4.92e-13	-1.55e-07	-1.90e-13	1.49e-04	64.3215	59.3158
0.1	0.1	1.79e-02	5.29e-13	-3.74e-08	-8.30e-13	1.50e-04	64.3027	59.3140

K_{β_x} (m)	K_{β_y} (m)	$Bmag_x$ (1)	$\beta_y beat_{max}$ (%)	$Bmag_y$ (1)	$\beta_y beat_{max}$ (%)
-0.1	-0.1	1.000101	0.014218	1.000035	0.008416
0.1	-0.1	1.000064	0.011279	1.000005	0.003278
-0.0	0.0	1	0	1	0
-0.1	0.1	1.000049	0.009932	1.000004	0.002981
0.1	0.1	1.000127	0.015964	1.000073	0.012092

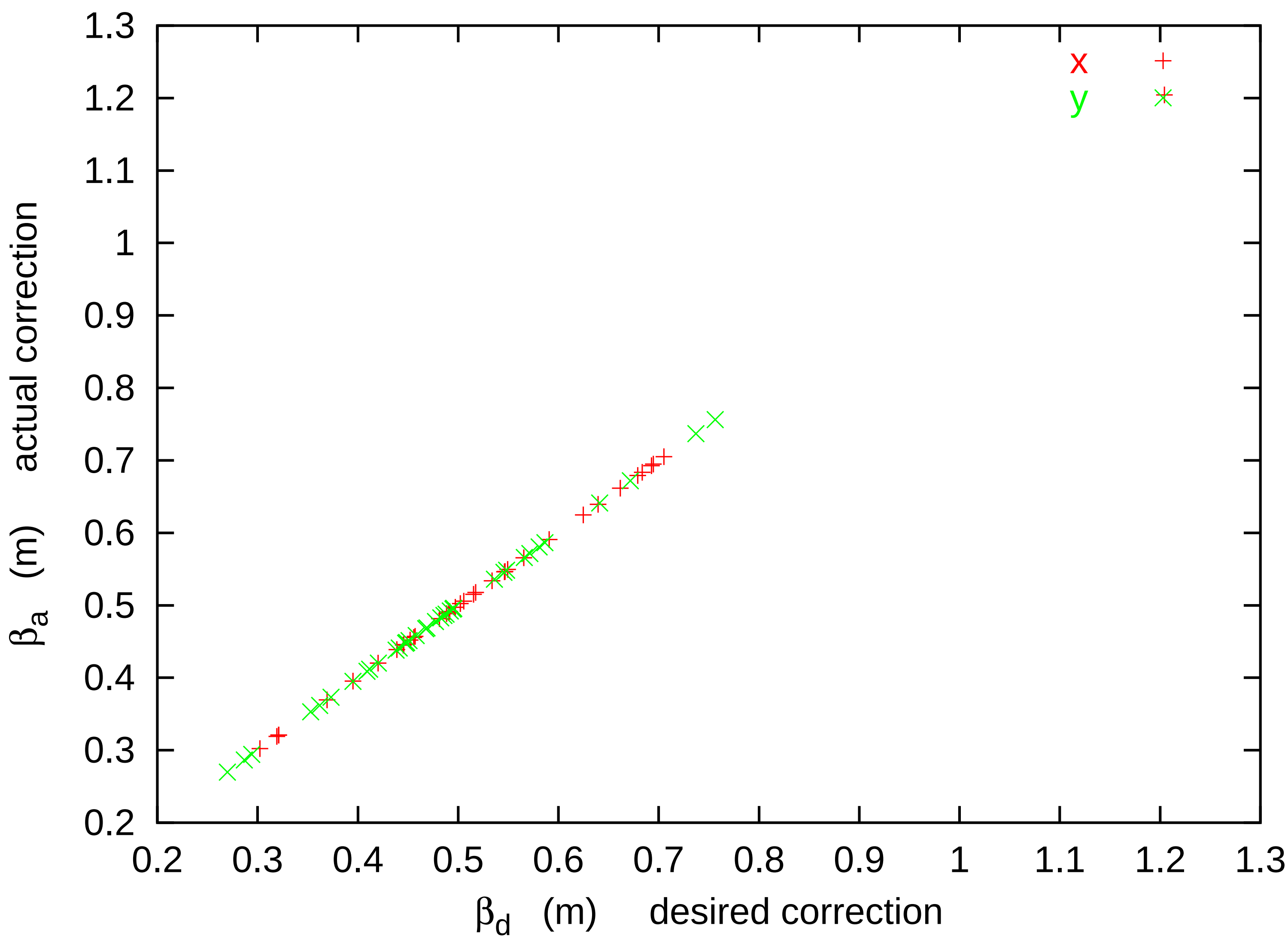
Functionality: Error Test

Main Area of Application

error source		field error type
main arc quadrupoles	MQ	gradient error
triplet quadrupoles	MQX	b2 , a2

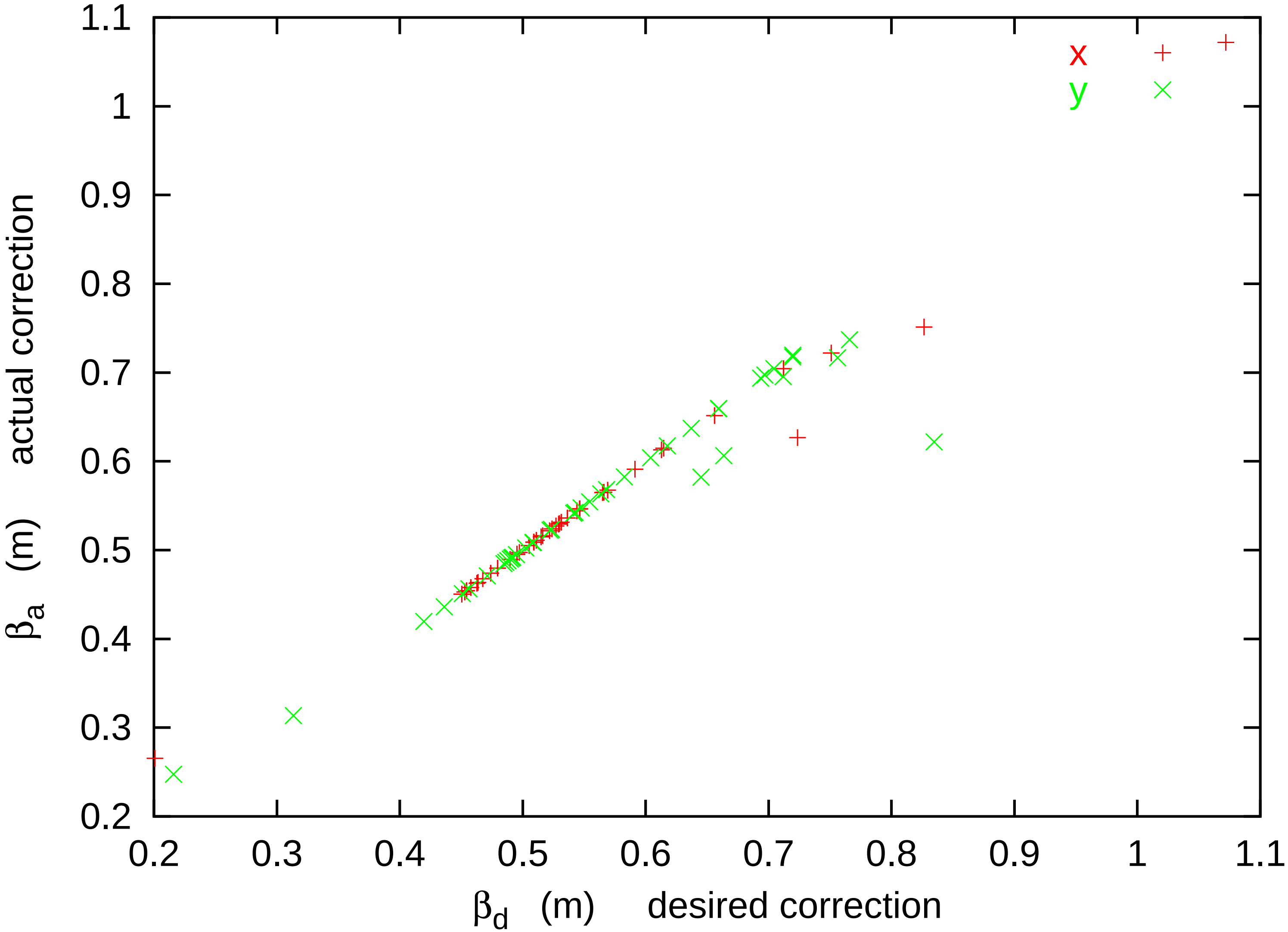
tested were: b1 - b12, a2 - a12

Evaluate Results MQ



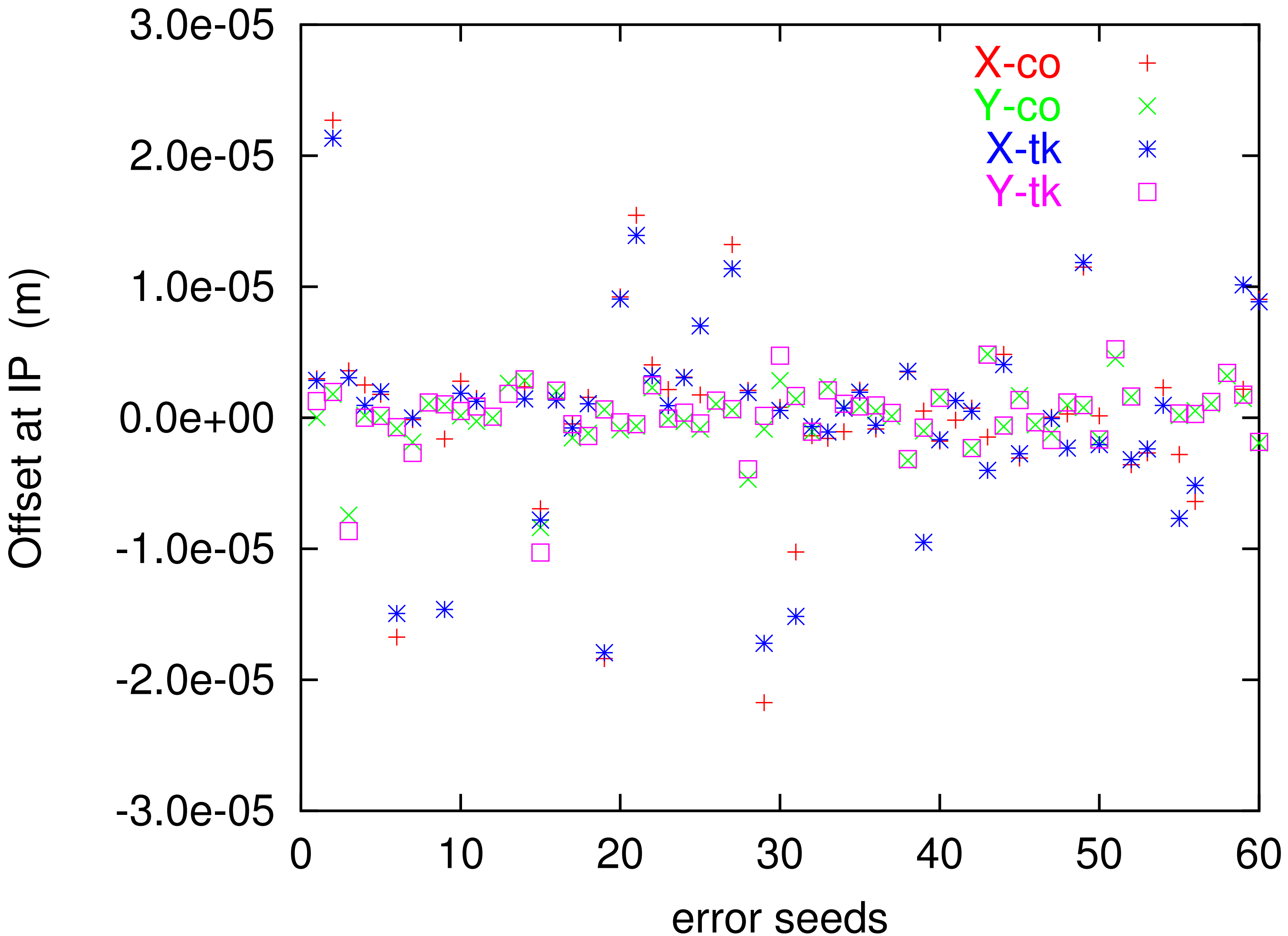
all error seeds corrected

Evaluate Results MQX



error seeds with $\Delta\beta < \pm 20\%$corrected

Evaluate Results Steering Effect of Knobs



All steering errors caused by knobs $< 16\mu m$.

Monitoring Critical Points

Monitoring changes of constraints created by applying knobs for correction in IP1:

- Experiments IP2, IP5, IP8
- acceleration cavities in IR4
- cleaning insertions IP3, IP7

$$\boxed{\begin{array}{c} |\Delta\beta_{max}| < 2(\%) \\ |\Delta D_{max}| < 0.7(m) \end{array}}$$

Summary MAD Match

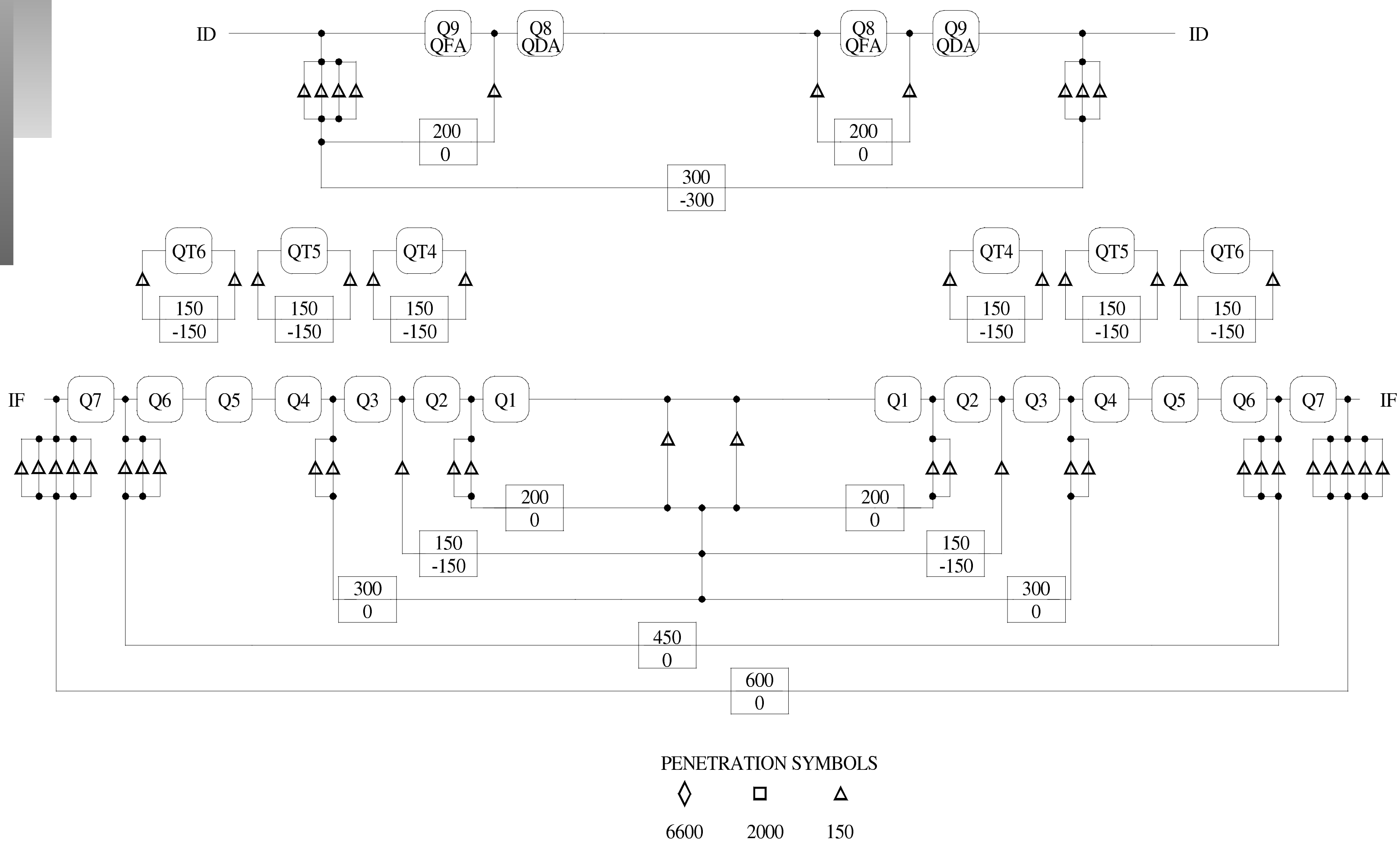
- Characteristics: Knobs achieve desired changes in a range of $\pm 20\%$ of nominal value. The perturbations of other optics function lie within the specification.

- Correction Efficiency: All errors coming from the arc can be corrected. Errors from triplet magnets can be corrected within a range of $\pm 20\%$.

Comparison RHIC - LHC

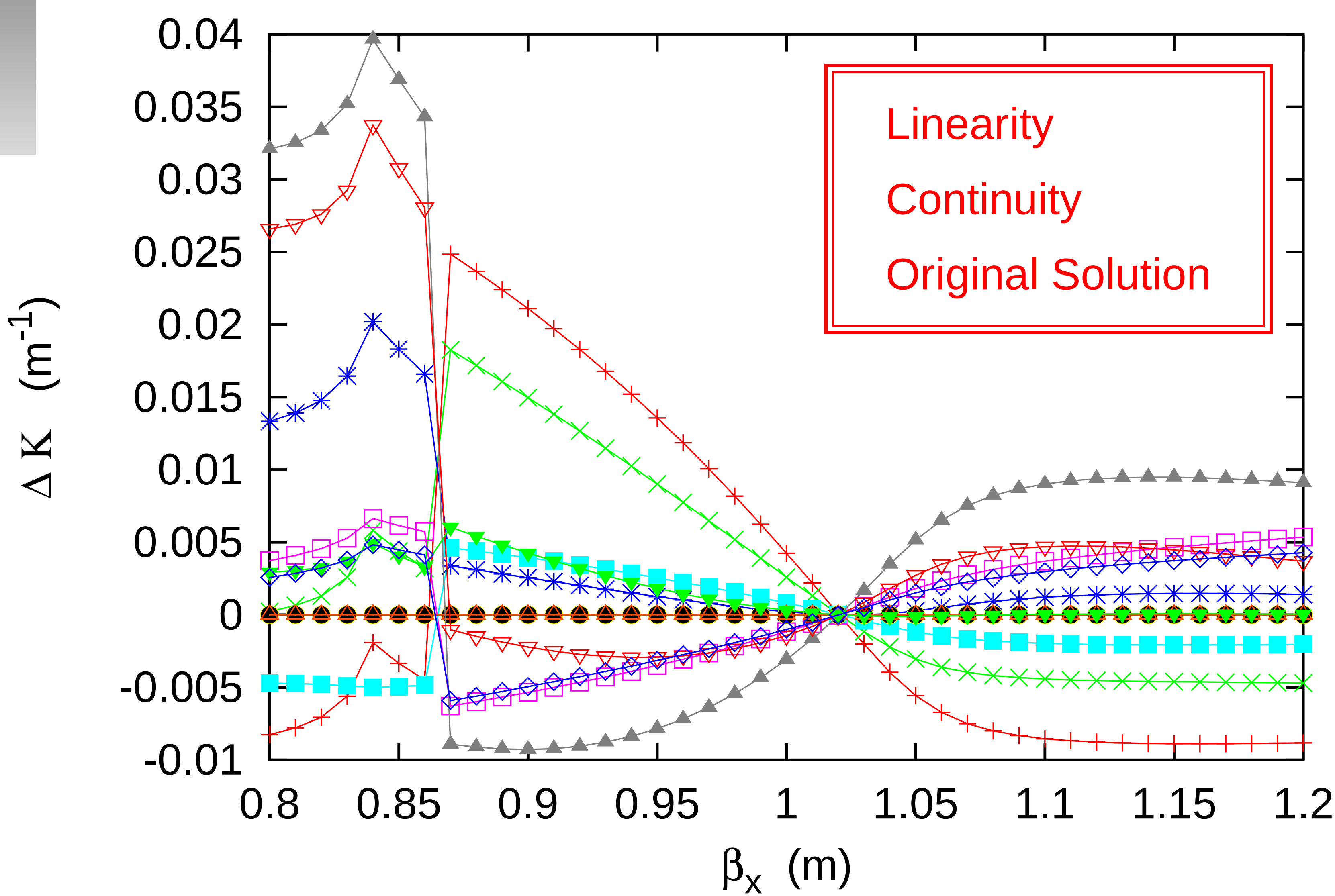
item	accelerators	
	RHIC	LHC
lattice	asymmetric	
beam pipe	mostly separated	
beam pipe triplet	separate	common
Xing	no	yes
power supply	nested	separate

RHIC - Nested Power Supply System

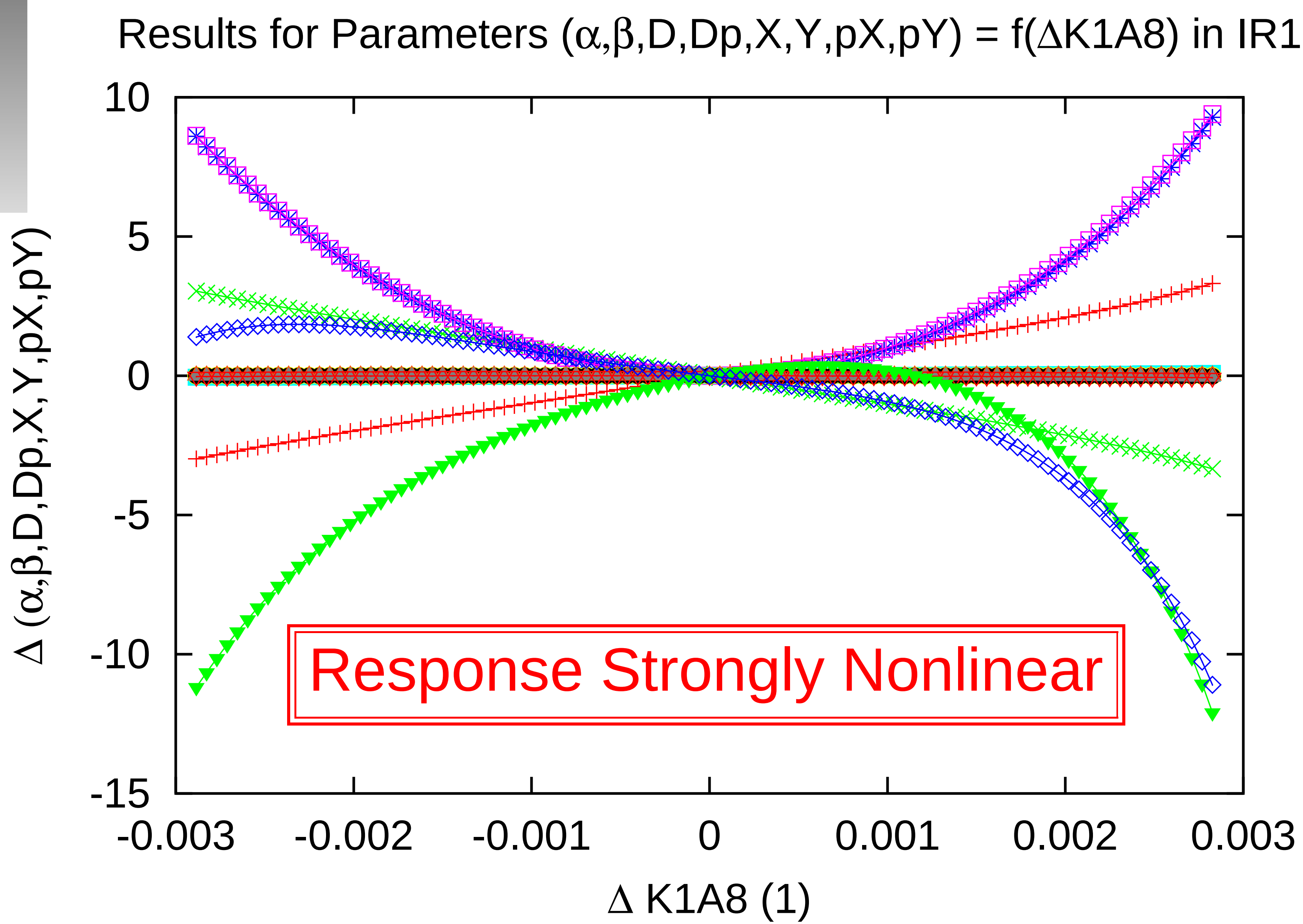


RHIC - MAD Matching Results

Results for $\Delta K = f(\beta_x)$ in IR8

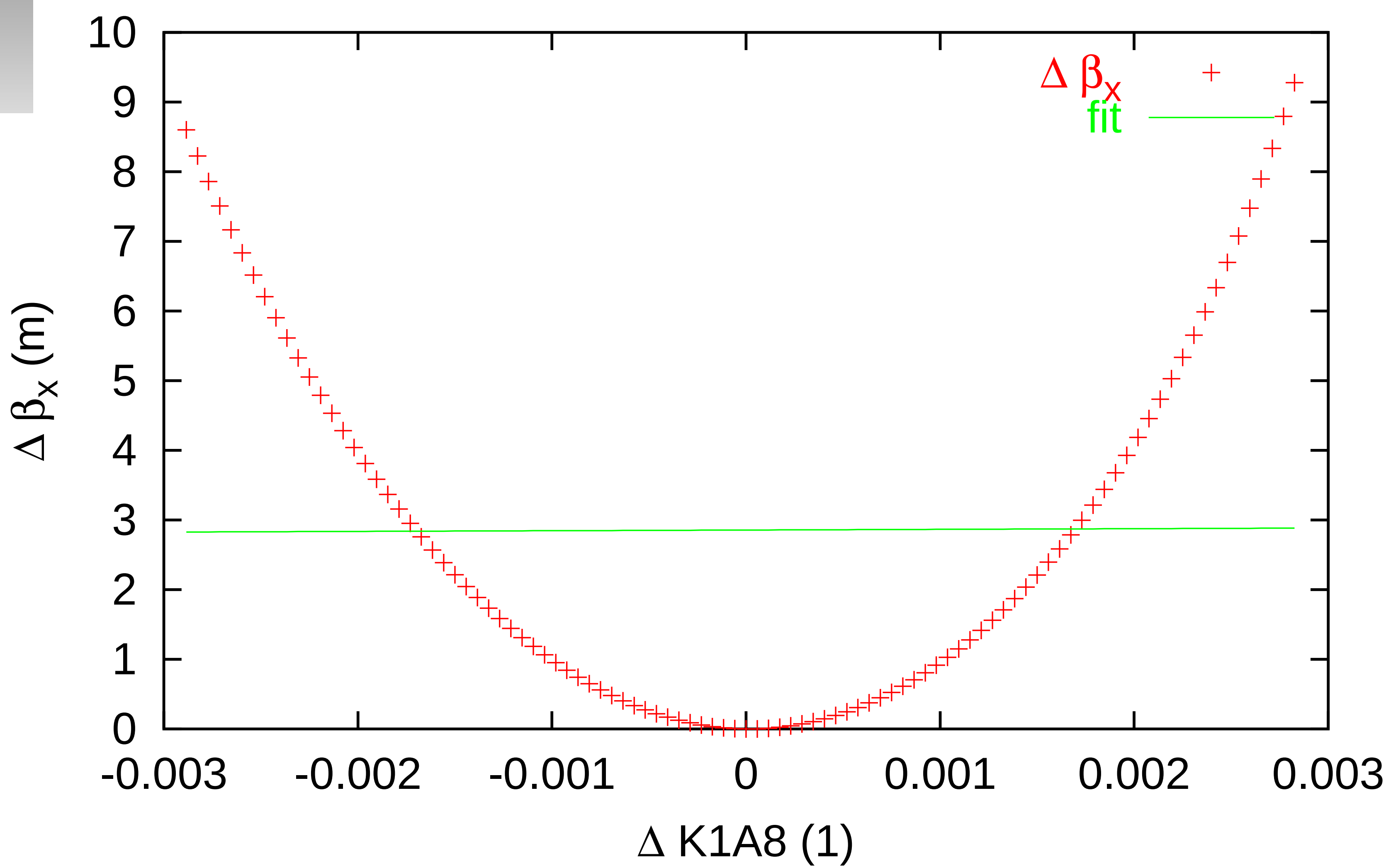


ΔK_{Quad} **Response**



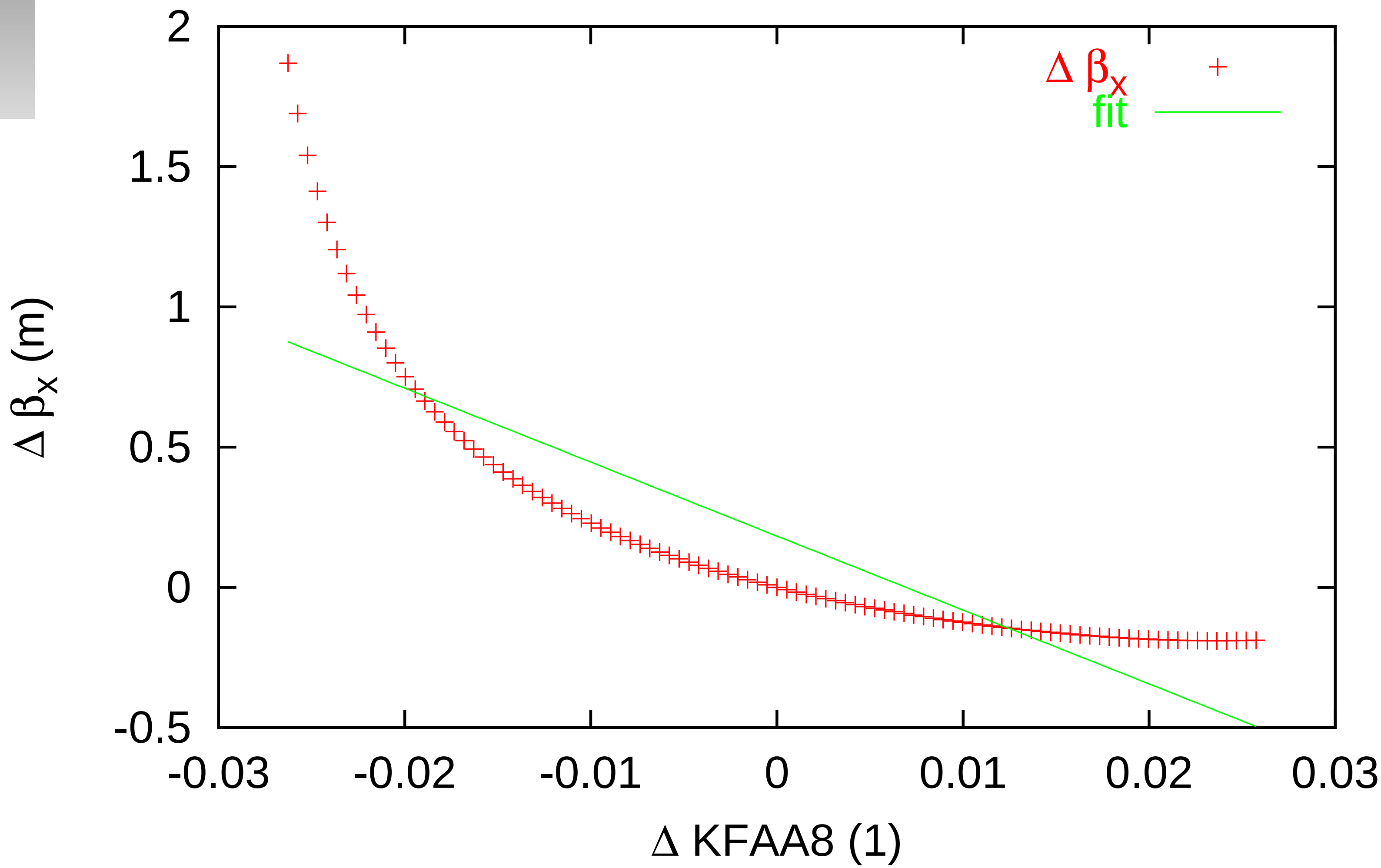
Response Matrix Analysis - Magnet Category 1

Results for $\Delta\ \beta_x$ = f(ΔK1A8) in IR8. Plot results for linear fit: f(x) = k*x + b
k = 9.74396. b = 2.85552



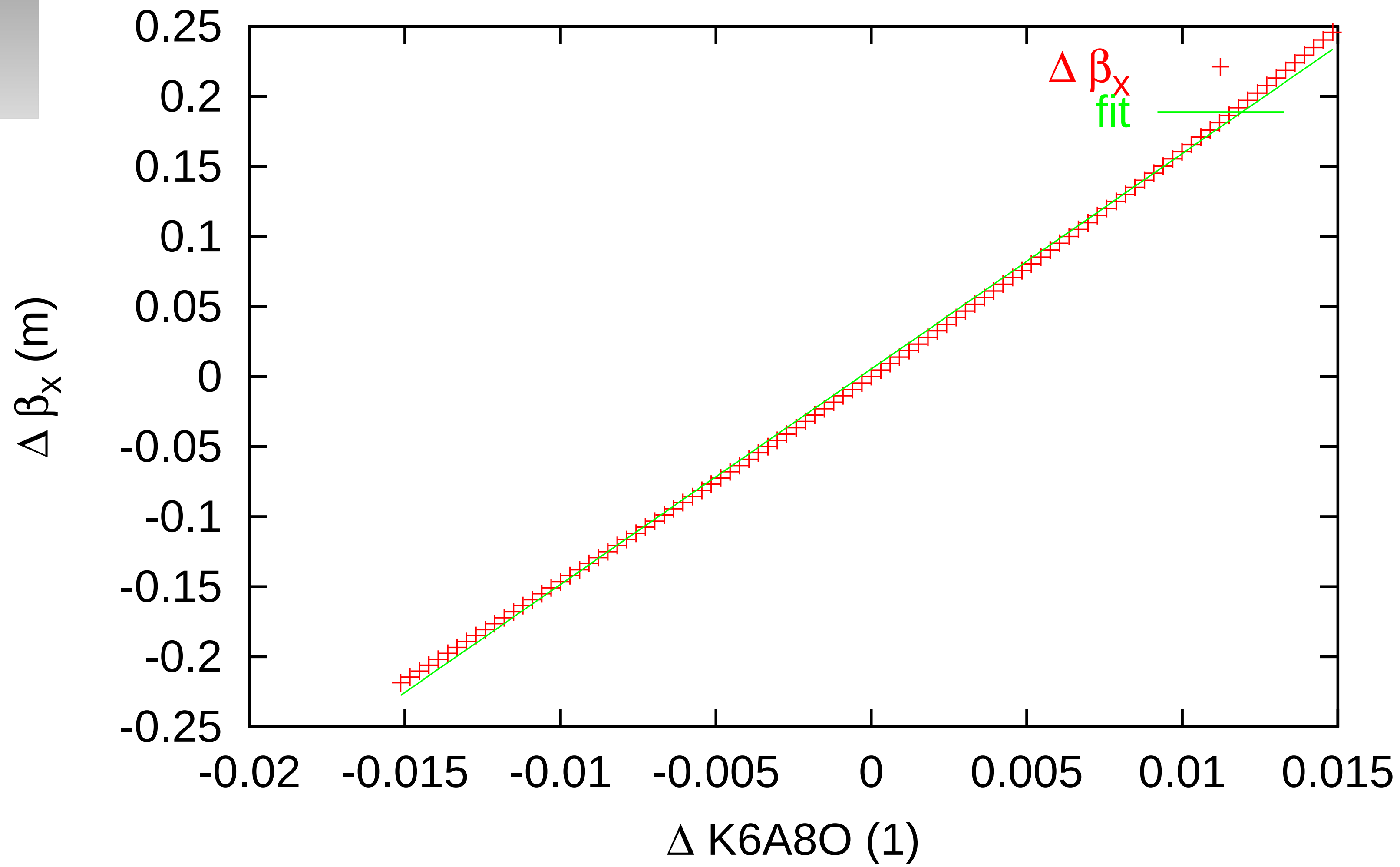
Response Matrix Analysis - Magnet Category 2

Results for $\Delta\,\beta_x = f(\Delta \mathrm{KFAA8})$ in IR8. Plot results for linear fit: $f(x) = k*x + b$
$k = -26.3685.\ b = 0.182956$



Response Matrix Analysis - Magnet Category 3

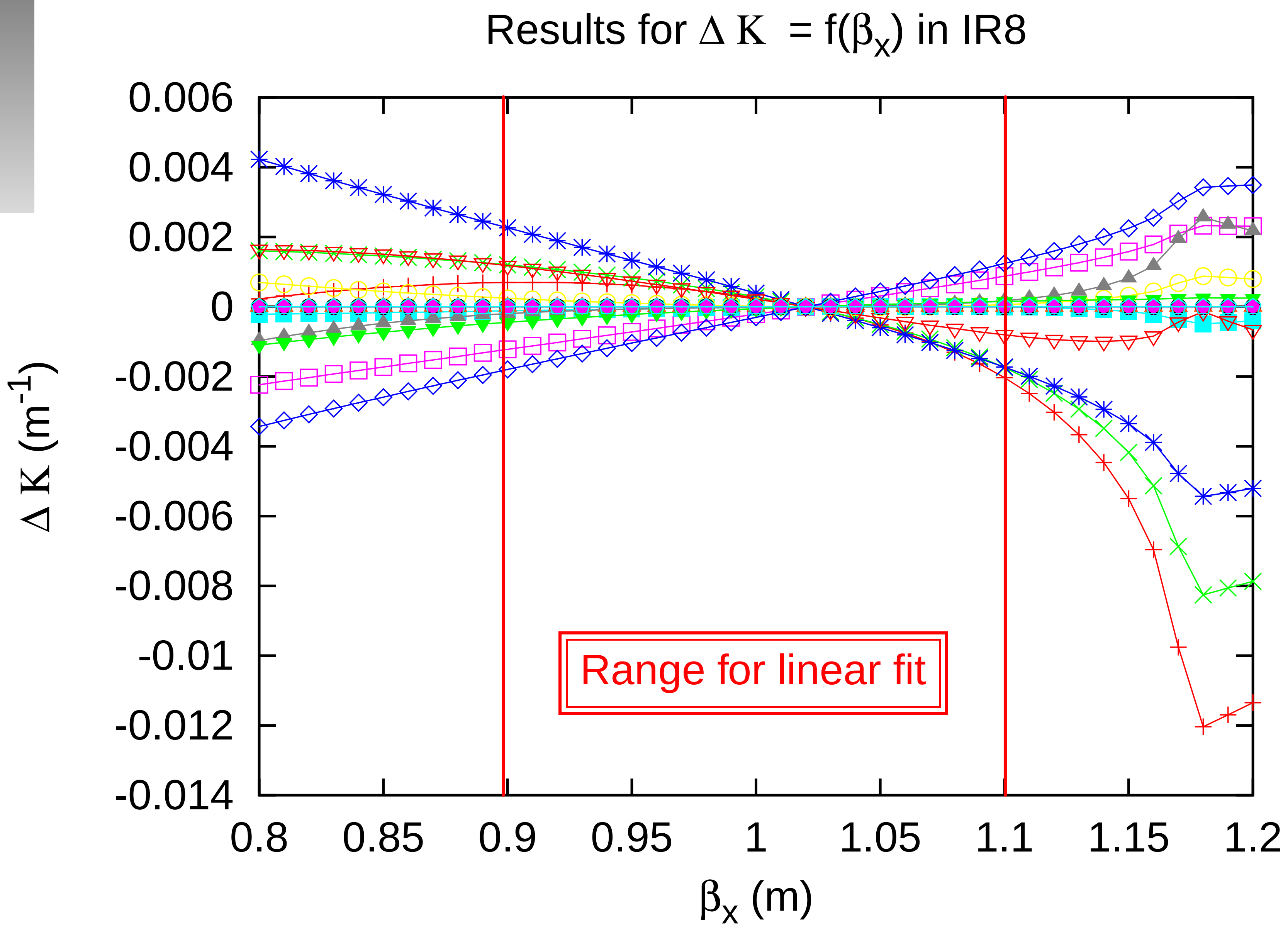
Results for $\Delta\,\beta_x = f(\Delta K6A8O)$ in IR8. Plot results for linear fit: $f(x) = k*x + b$
$k = 15.391.\ b = 0.00538547$



Result from Response Analysis

name	cat	usable range	name	cat	usable range
K1A8	1	-	K5A8O	3	$\pm 50\%$
K2A8	1	-	K6A8I	3	$\pm 50\%$
K3A8	1	-	K6A8O	3	$\pm 50\%$
K4A8I	3	$\pm 50\%$	K7A8	2	$\pm 5\%$
K4A8O	3	$\pm 50\%$	KDAA8	2	$\pm 5\%$
K4M8	1	-	KFAA8	2	$\pm 5\%$
K56M8	1	-	KFBA8	2	$\pm 5\%$
K5A8I	3	$\pm 50\%$			

Result ΔK_{Quad} Response Combined with MAD MATCHING



Benefit of Response Matrix Analysis

- learn about the behavior of parameters $\Longrightarrow$ choice of constraints.
- try inversion to solve the problem but remember non linear problem

Response Matrix

$$\mathbf{R} = \begin{pmatrix} \frac{\partial \alpha_x}{\partial K_{K1A8}} & \frac{\partial \alpha_x}{\partial K_{K2A8}} & \frac{\partial \alpha_x}{\partial K_{K3A8}} & & & & \frac{\partial \alpha_x}{\partial K_{KDAA8}} \\ \frac{\partial \alpha_y}{\partial K_{K1A8}} & \frac{\partial \alpha_y}{\partial K_{K2A8}} & \frac{\partial \alpha_y}{\partial K_{K3A8}} & \cdots & \cdots & \cdots & \frac{\partial \alpha_y}{\partial K_{KDAA8}} \\ \frac{\partial \beta_x}{\partial K_{K1A8}} & \frac{\partial \beta_x}{\partial K_{K2A8}} & \frac{\partial \beta_x}{\partial K_{K3A8}} & & & & \frac{\partial \beta_x}{\partial K_{KDAA8}} \\ & \vdots & & \ddots & & & \\ & \vdots & & & \ddots & & \\ & \vdots & & & & \ddots & \\ \frac{\partial dQ_2}{\partial K_{K1A8}} & \frac{\partial dQ_2}{\partial K_{K2A8}} & \frac{\partial dQ_2}{\partial K_{K3A8}} & \cdots & \cdots & \cdots & \frac{\partial dQ_2}{\partial K_{KDAA8}} \end{pmatrix}$$

$$\Delta\vec{K} = \mathbf{R}^{-1}\Delta\vec{P}$$

Methods of Matrix Inversion

- Direct Inversion (numerical)
  - condition of matrix
  - dimensions of matrix
- Singular Value Decomposition

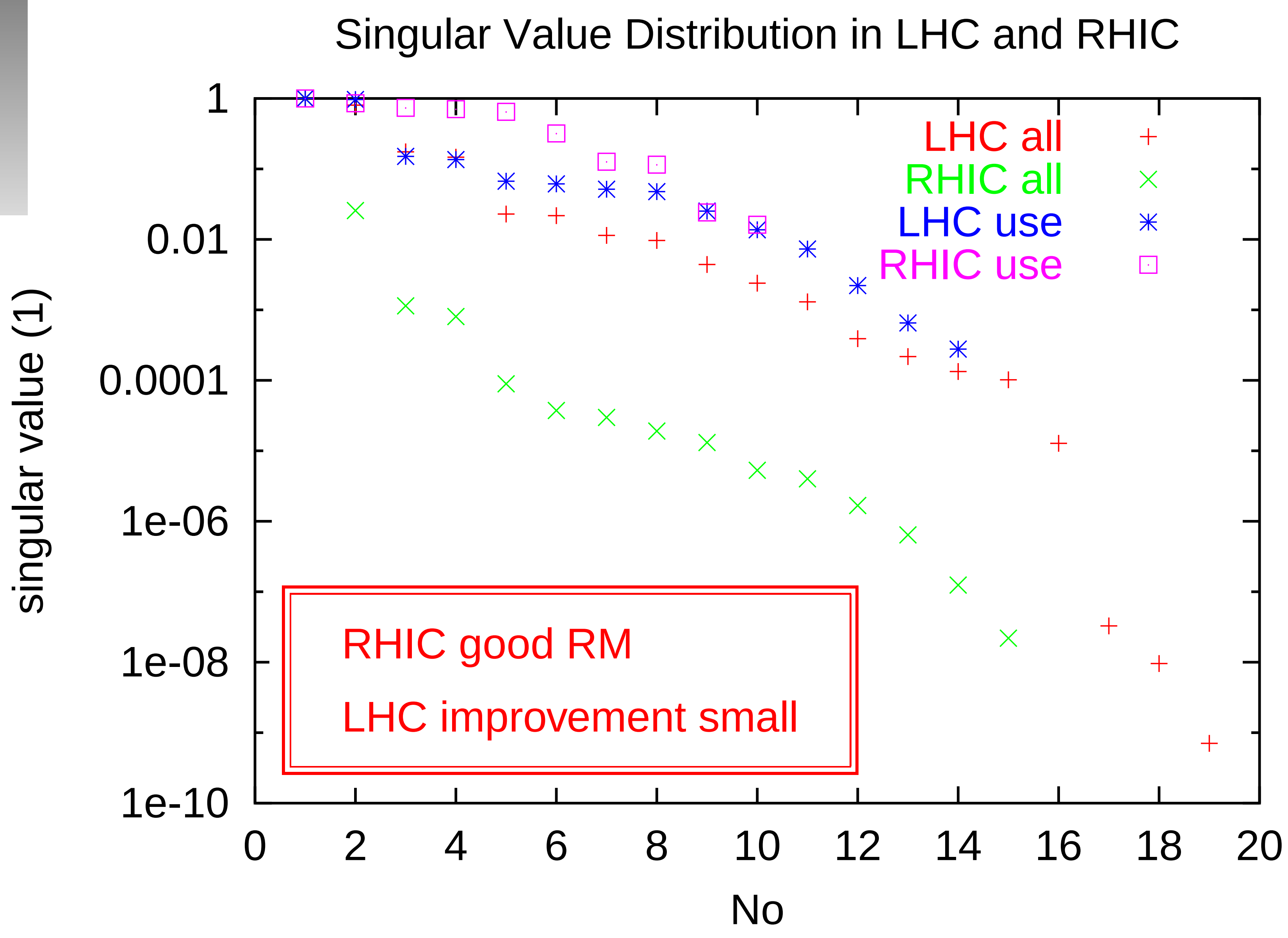
SVD Singular Value Decomposition

$$\mathbf{A} = \mathbf{U}\mathbf{S}\mathbf{V}^T$$

$$\begin{pmatrix} & & \\ & \mathbf{A} & \\ & & \end{pmatrix} = \begin{pmatrix} & & \\ & \mathbf{U} & \\ & & \end{pmatrix} \cdot \begin{pmatrix} s_1 & & & \\ & s_2 & & \\ & & \ddots & \\ & & & s_m \end{pmatrix} \cdot \begin{pmatrix} & & \\ & \mathbf{V}^T & \\ & & \end{pmatrix}$$

$$\mathbf{A}^{-1} = \mathbf{V}\mathbf{S}^{-1}\mathbf{U}^T$$

Singular Value Distribution



Approach to Solve Problem of Non Linearity

Problem: Linear methods are used to solve a non linear problem.

Possible Solution: By minimizing the $\Delta\vec{K}$ vector the error introduced by non linearity is minimized.

Drawback: This has to be achieved at the cost of the constraints.

Advantage: The overall performance can improve significantly.

Summary LHC

operative range of knobs: $\pm 0.1m$ at $\beta^\star = 0.5m$

$$
\begin{aligned}
|\alpha^\star_{max}| &= 3.1 \cdot 10^{-3} \\
\Delta\beta^\star_{\perp_{max}} &= 0.34\% \text{ of } \Delta\beta^\star \\
|D^\star_{max}| &= 1.5 \cdot 10^{-2} m \\
X^\star_{max} &= 8.5 \cdot 10^{-13} m \\
Y^\star_{max} &= 1.6 \cdot 10^{-7} m \\
\Delta p Y^\star_{max} &= 0.2\% \\
\Delta Q_{max} &= 0.01 \\
\beta^{beat}_{max} &= 1.6\% \\
D^{beat}_{max} &= 0.7m
\end{aligned}
$$

Summary RHIC

operative range of knobs: $\pm 0.2m$ at $\beta^\star = 1m$

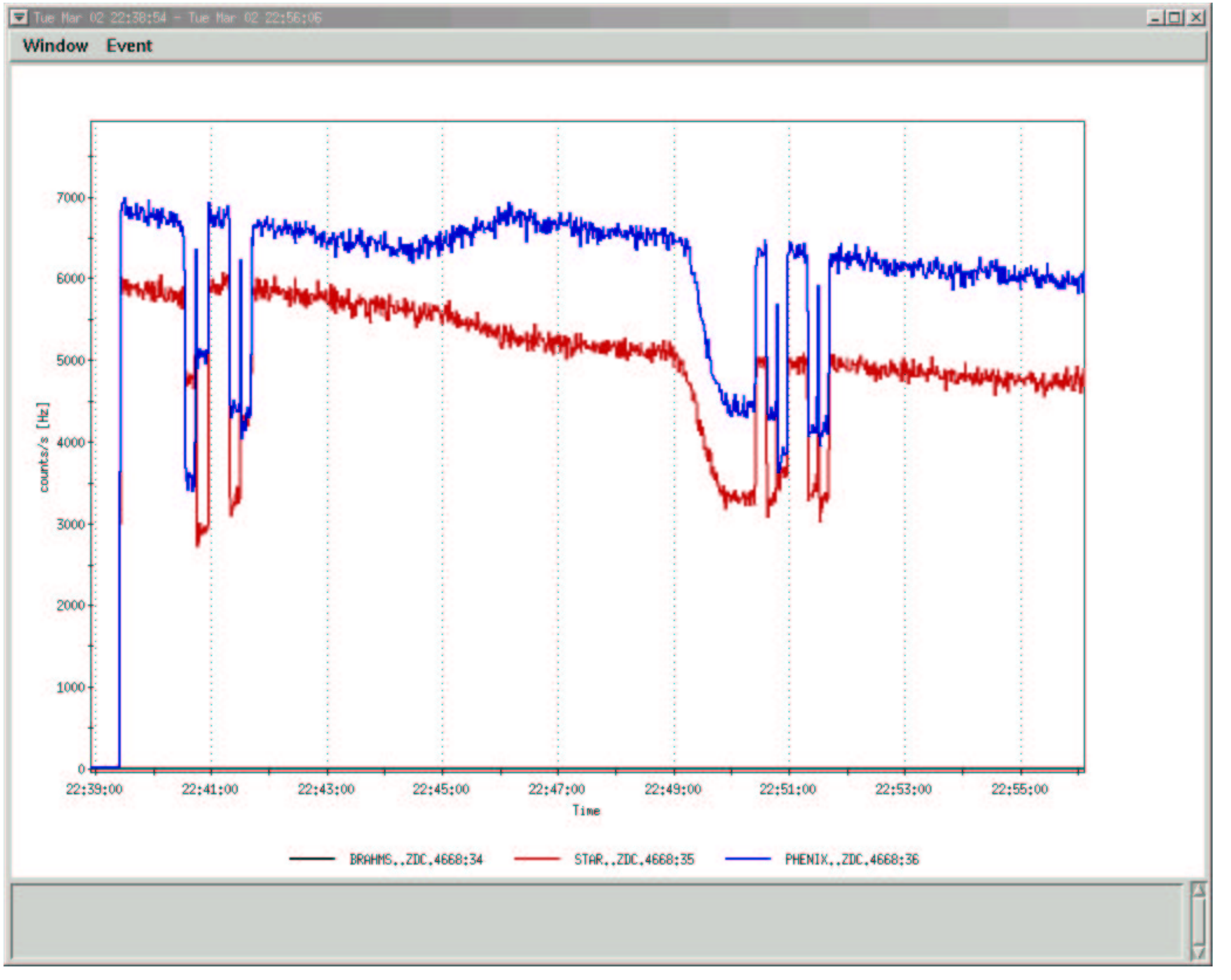
$$
\begin{aligned}
|\alpha^\star_{max}| &= 1.6 \cdot 10^{-2} \\
\Delta\beta^\star_{\perp_{max}} &= 0.17\% \text{ of } \Delta\beta^\star \\
|D^\star_{max}| &= 1.9 \cdot 10^{-2} m \\
\Delta Q_{max} &= 0.003
\end{aligned}
$$

RHIC Beam Experiment

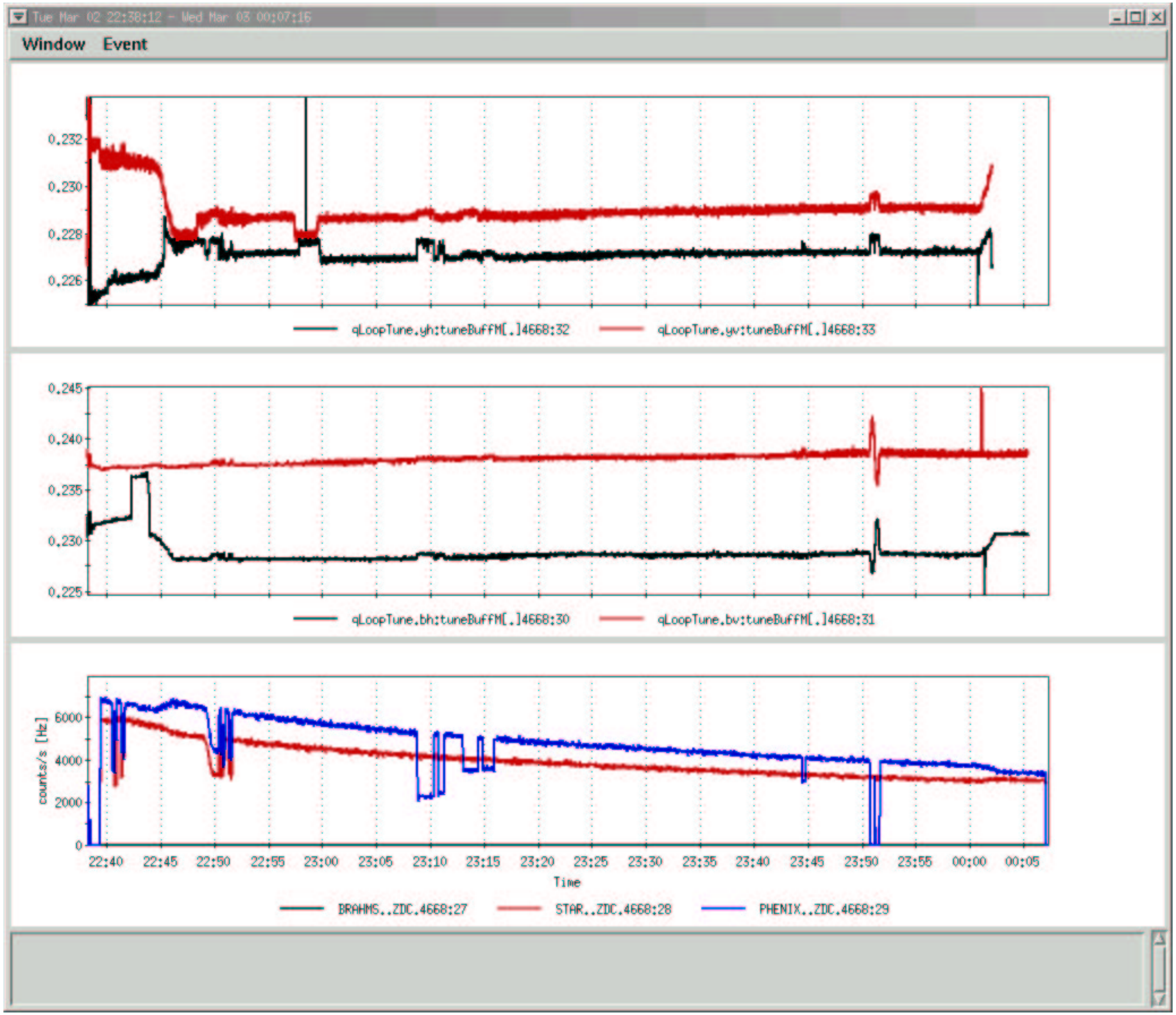
Response Matrix approach based on
Online Model Johannes

Goal : Squeeze $\beta^\star$ as much as possible

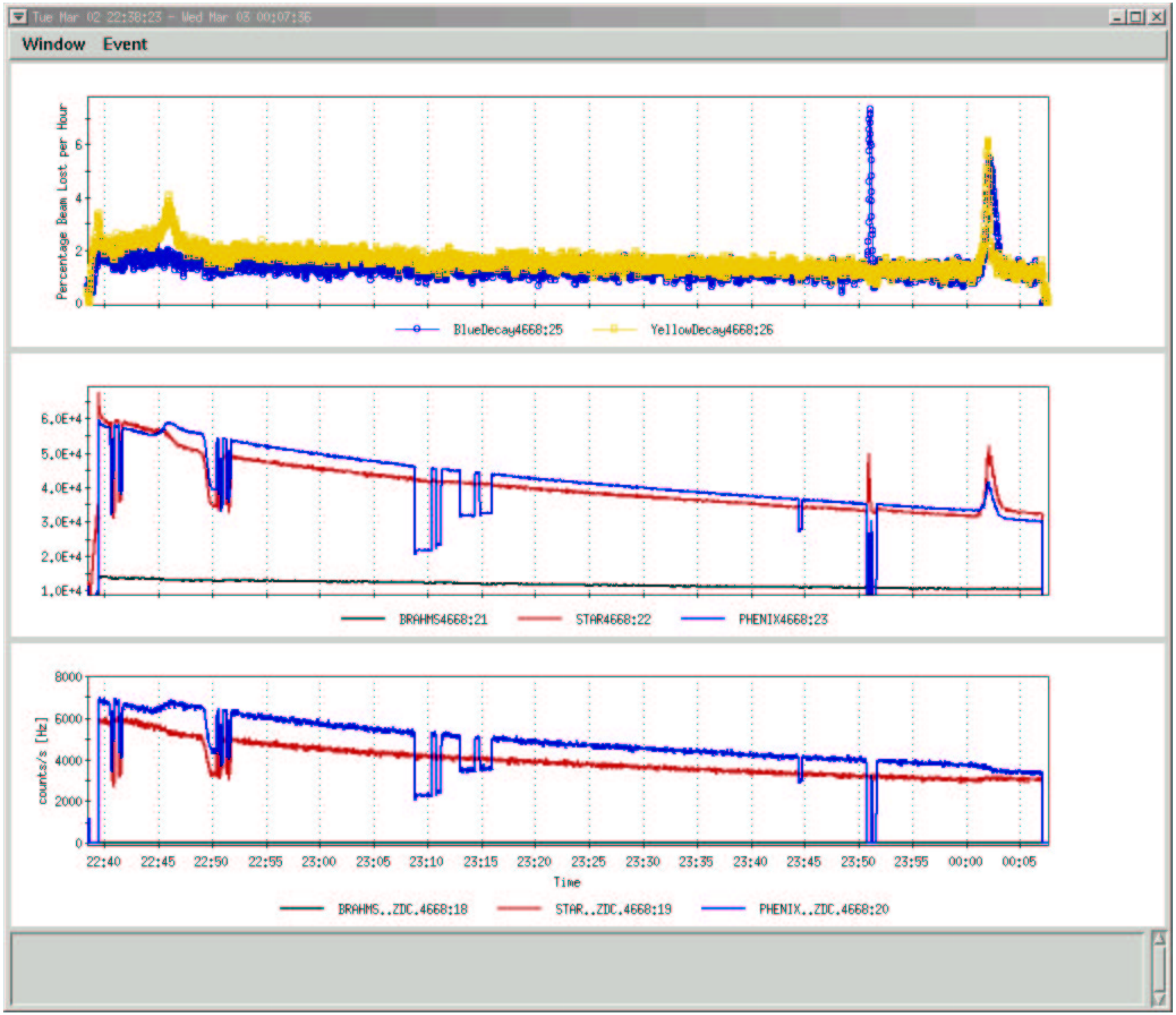
Beam Experiment Results RHIC - Rates



Beam Experiment Results RHIC - Rates and Tunes



Beam Experiment Results RHIC - Rates, Background and Tunes



Beam Experiment Results RHIC - Dispersion Measured and Model

Preliminary Summary RHIC Beam Experiment

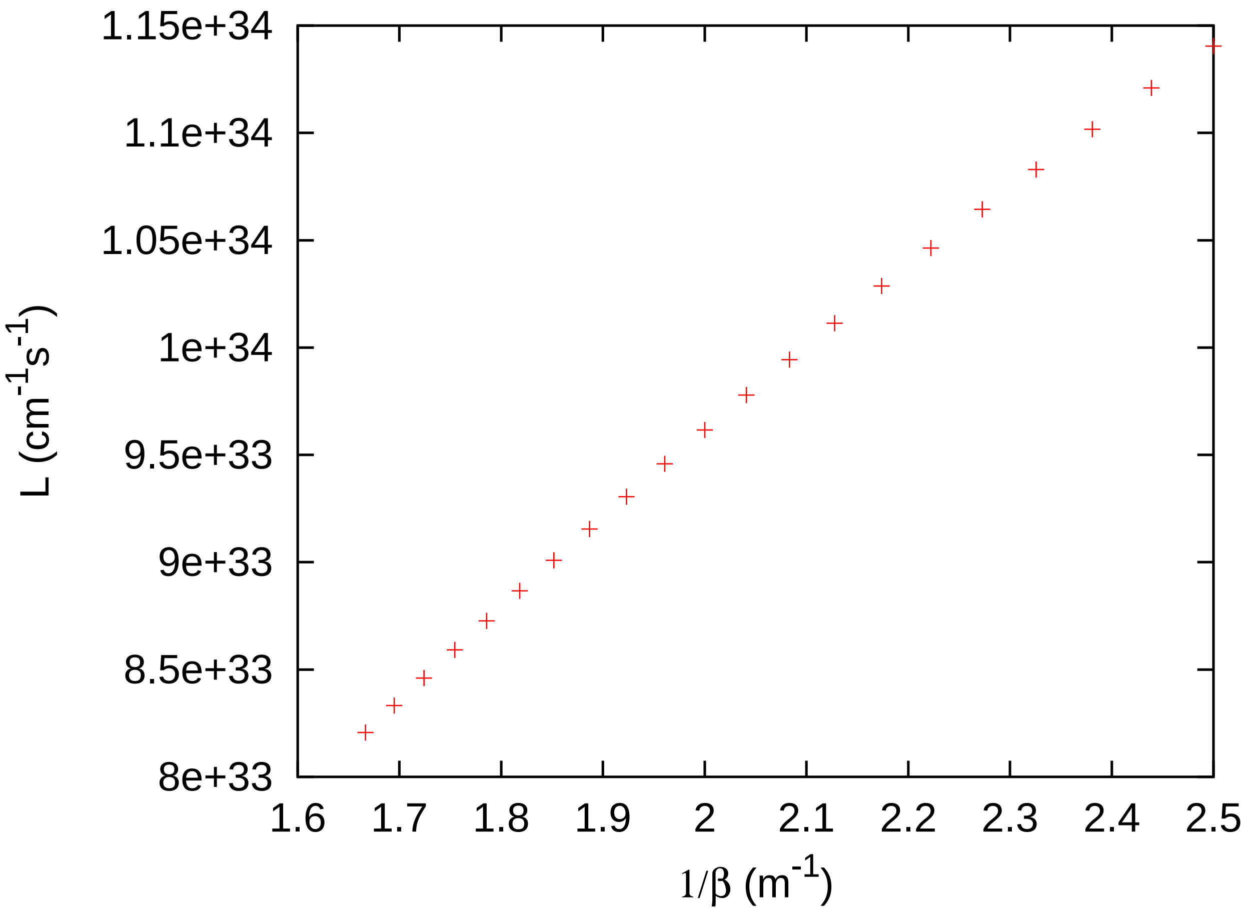
operative range of knobs: $m > -0.12$ at $\beta^\star \approx 1m$

$$
\begin{aligned}
\Delta\beta^\star &= -10\% \text{ ?} \\
|\Delta D^\star_{max}| &= \text{?} \\
\mathcal{L}_{Phenix} &\approx +10\% \text{ ?} \\
\mathcal{L}_{Star} &\approx -2\% \text{ ?} \\
\Delta Q_{max} &= 0.003
\end{aligned}
$$

Further covered Topics

- $\beta^\star$ Measurement Utilizing Tuning Knobs
- Influence of the Knobs on
  - Closed Orbit
  - Crossing Angle
  - Beam-Beam (MAD)
  - Parasitic Beam-Beam (Train)

Increase LHC Luminosity with Tuning Knobs



Long range and head on beam-beam effects do not prevent luminosity gains when using tuning knobs to sqeeze the β functions at the IP.

References

‘Luminosity Optimization by Adjusting LHC $\beta^\star$ at Collision.’ CERN Proceedings Nanobeam 2002 Lausanne, Switzerland, 2-6 September 2002,p 199-205, see also the nanobeam web page: http://icfa-nanobeam.web.cern.ch/icfa-nanobeam/paper/wittmer.pdf

W. Wittmer, A. Verdier, F. Zimmermann ‘Correcting the LHC $\beta^\star$ at Collision’ CERN-LHC-Project-Report-647, see also http://warrior.lbl.gov:7778/pacfiles/papers/WEDNESDAY/AM_POSTER/WPAB083/WPAB083.PDF

Adjusting the β-functions in PHENIX of RHIC. to be published