IR optics compensation

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LARP Collaboration Meeting

Danfords, September 16-18, 2003

outline

- **IR optics compensation** (introduction, motivation)
- **Optics measurements**
- **Local IR correction**
  - RHIC and LHC IR correction systems
  - Linear compensation (data RHIC Run 2000 and 2001)
  - Non-linear correction methods
    - IR bumps method →results RHIC run 2001
    - IR bumps application → results RHIC run 2003
- **Beta* knobs**
- **Non-linear chromaticity**
- **Dynamic aperture**
- **LARP areas of activity**: commissioning, IR upgrade

IR Correction systems

Motivation:

- ❑local correction of **linear errors** (**coupling**, **gradient**)
- ❑Local correction of **nonlinear errors** (IR magnets **field errors**)

→**Beta squeeze**, **crossing angle**

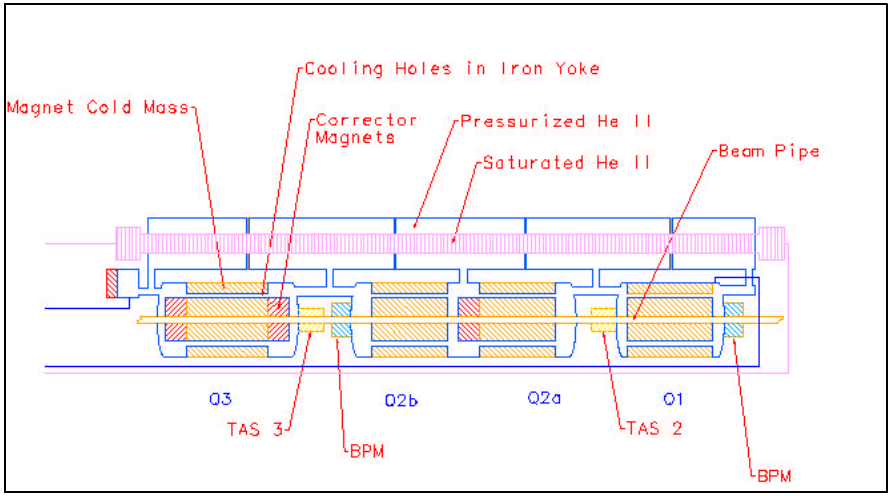
→Beam control, luminosity

Design:

- ❑**Multi-layer corrector packages** installed next to IR triplet quadrupoles
- ❑Typically, dipole → dodecapole
- ❑Independently powered

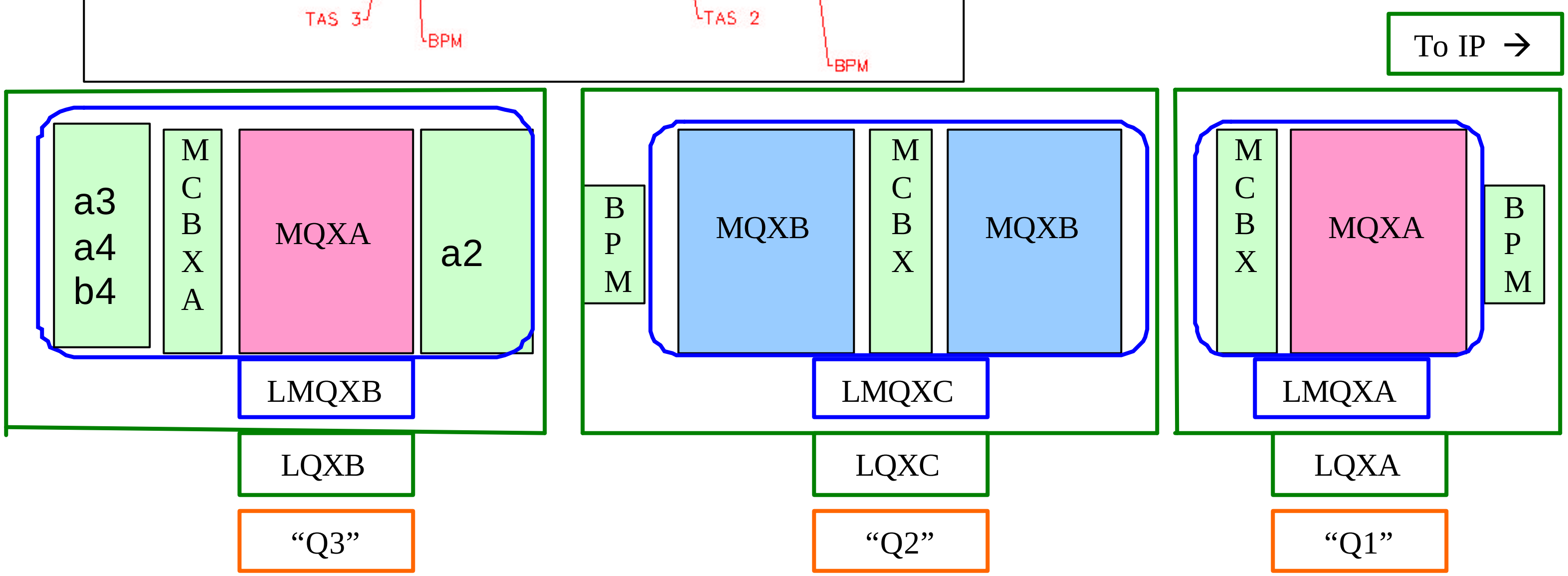
RHIC → LHC → (VLHC)

LHC inner triplet - correctors

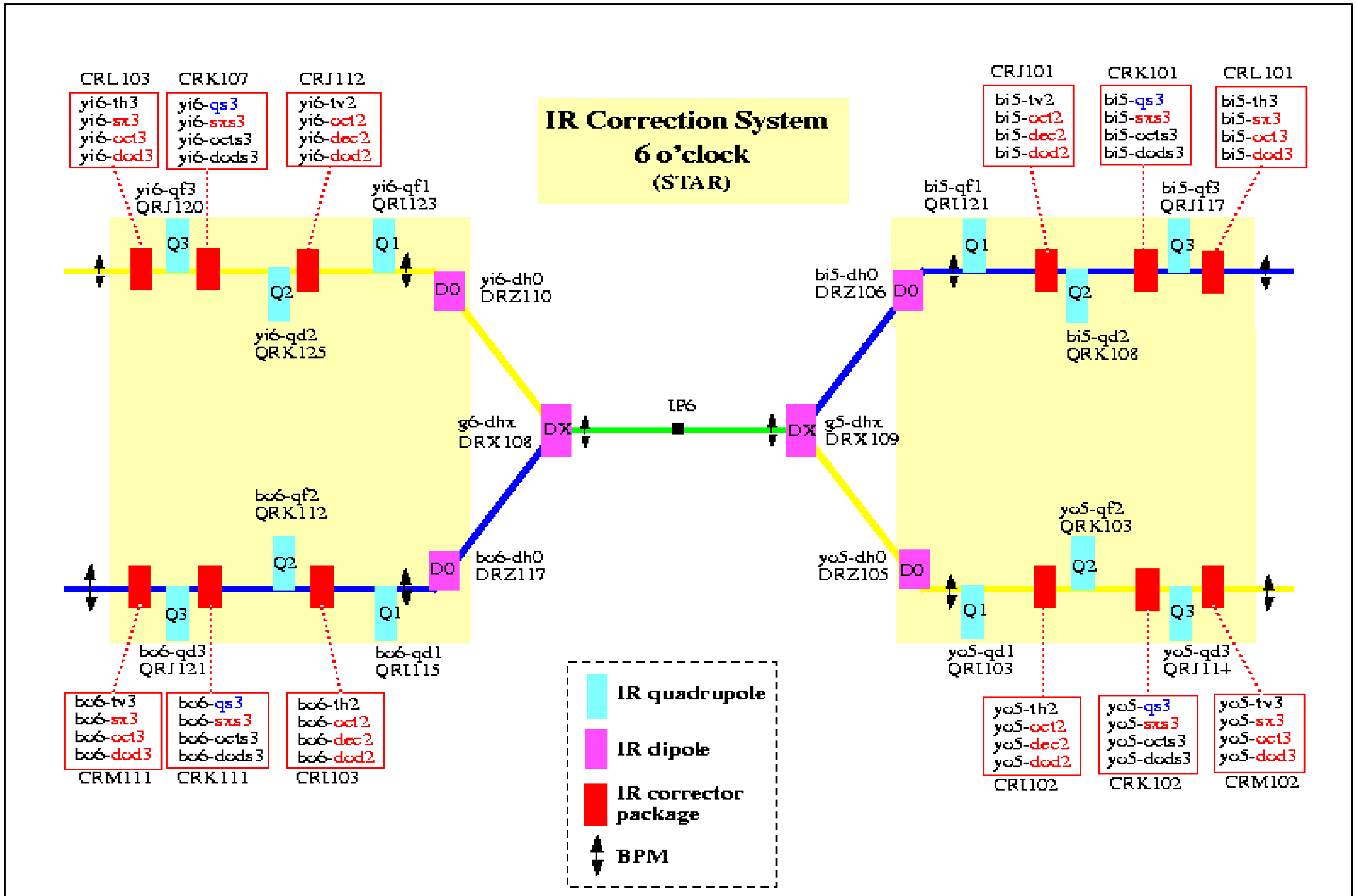


MCBX: b1 a1
MCBX: b1 a1
MQSXA: a2 a3 a4 b4
→ a2 + a3 a4 b4
MCBXA: a1 b1 b3 b6

Optimization process:
Magnet design – correction system



RHIC IR's - layout



6 o'clock IR
8 o'clock IR:

- ❑Dipole correctors
- ❑Skew quadrupoles
- ❑Nonlinear

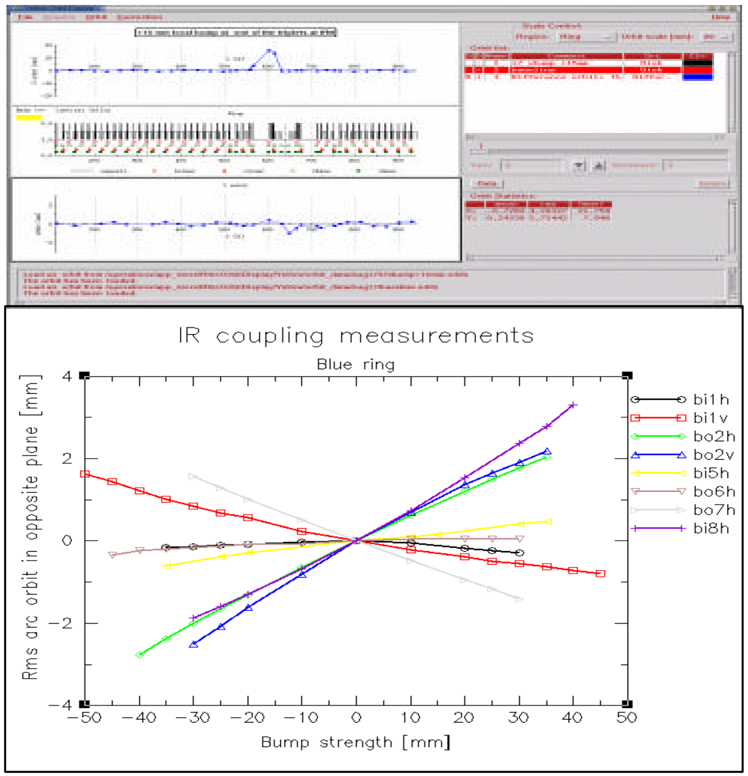
Other IR's:

- ❑dipole correctors
- ❑Skew quadrupoles

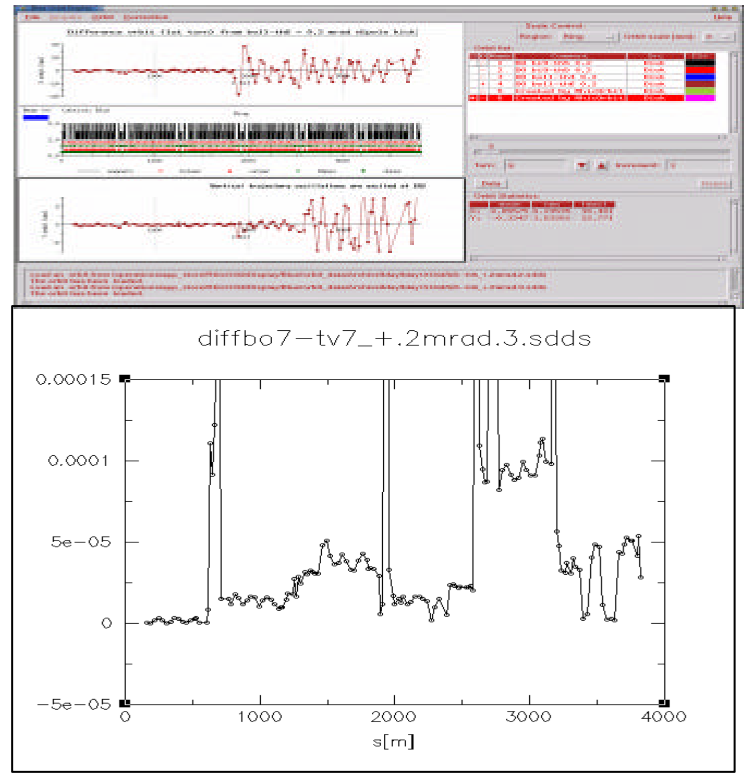
(nonlinear layers exist but no PS yet)

Run 2000 – IR correction linear

Determine local IR skew quadrupole correction strenghts (Cardona, Ptitsyn, Pilat)



IR bump method



Action-jump method

IR Correction - linear

- From Run 2000 **IR bump** data and **action jump** data, we had **predictions** for the **12 IR skew quad correctors** in each ring
- The results from the 2 methods **agree** (5-10%)
- The **predicted values** from the 2000 data analysis agree with the corrector settings found **operationally in 2001**
- The **residual coupling** in the machine (not arising from the IR triplets) is corrected with **skew quadrupole families** by correcting the coupling resonance (minimum tune separation)

Configuration 2001 (blue ring)	$\Delta Q(\min)$
Uncorrected	0.009
Local correction IR8, IR10,IR2	0.019
Local correction in all IR's	0.008
Local correction + global correction	0.0005 (tune meter resolution)

IR nonlinear correction methods

Dead reckoning: → action-kick minimization (Wei)

order-by-order prescription, assumes field errors known
(off-line code – “IR filter”- to set corrector strengths)

↓

driving terms compensation (Farthouk)

needs 2 knobs for each multipole to cancel selected DT for both beams:
a2 (1,1) **a2**(1,-1) **b3** (1,2) **a3**(0,3) **b4**(4,0) **b4**(0,4) **a4**(1,3) **a4**(3,1) **b6**(6,0) **b6**(0,6)

operational: beam based + off-line analysis

IR bumps: measure and fit **observables vs. bump amplitude**:

(Koutchouk) rms orbit (BPM’s, linear, sextupole)

(Ptitsyn, Pilat) tunes (Tune Meter, up to dodecapole)

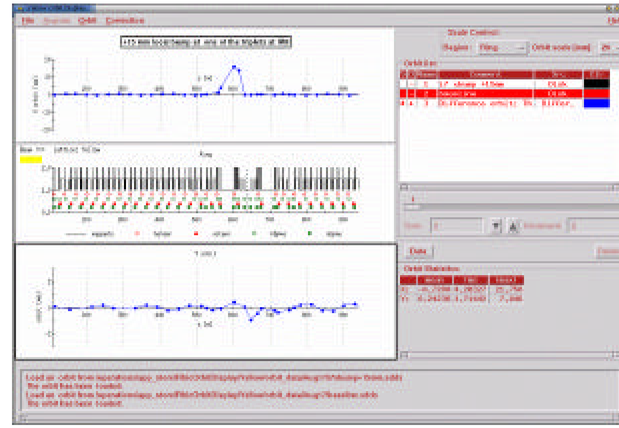
(tune spread) (Schottky, octupole, dodecapole?)

frequency analysis: “better FFT” detect and correct nonlinear resonance driving terms

(Schmidt, Tomas)

SUSSIX

IR bumps method - principle



Closed local orbit bump (triplet)
Observable as function of bump amplitude:
rms orbit outside the bump
z=(x,y) $c_n=(a_n,b_n)$ z_{ba}=bump amplitude

$$z(rms) = f(c_n, z_{ba}) = \frac{\sqrt{b_{z-arc}}}{2\sqrt{2}\sin pQ_z} \frac{B_N}{Br} \int \sqrt{b_z}\, c_n \left(\frac{z_{ba}}{R}\right)^{n-1} ds$$

The orbit perturbation depends on the **plane of the bump** (H,V)
And the **parity of the multipole order**

tune shift
Arises from normal gradients (ΔQ) or repelling effect of linear coupling (measured by c)

$$\Delta Q = g(c_n, z_{ba}) = \frac{n-1}{4p} \frac{B_N}{Br} \int b c_n \frac{z_{ba}^{n-2}}{R^{n-1}} ds \qquad \bar{c} = h(c_n, z_{ba}) = \frac{n-1}{2p} \frac{B_N}{Br} \int \sqrt{b_x b_y}\, a_n \frac{z_{ba}^{n-2}}{R^{n-1}} e^{i(m_x - m_y)} ds$$

Selection of one or the other effect depends on the **plane of the bump**, whether the multipole is **skew or normal** and on the **parity of the multipole order**

IR bumps: simulation, performance

Use MAD to compute orbit and tune response to H and V orbit bumps in the LHC IP5, assuming:
0.1% gradient error ($\Delta\beta/\beta$~20%), 1 mrad roll (c~0.04)
Multipoles set to 10 units in Q2B.

Orbit response:
(assuming 20 data points)

Perturbation	BPM resolution
roll 0.1 mrad	15 μm rms
b3 = 7.6 10^{-4}	8 μm rms
b4 = 7.2 10^{-4}	3.5 μm rms

Tune response:
Assuming 20 measurements and tune resolution of 2 10^{-4}
→ resolve multipoles up to b6 (dodecapole)

DC offset of BPM can be eliminated by subtracting 2 orbits

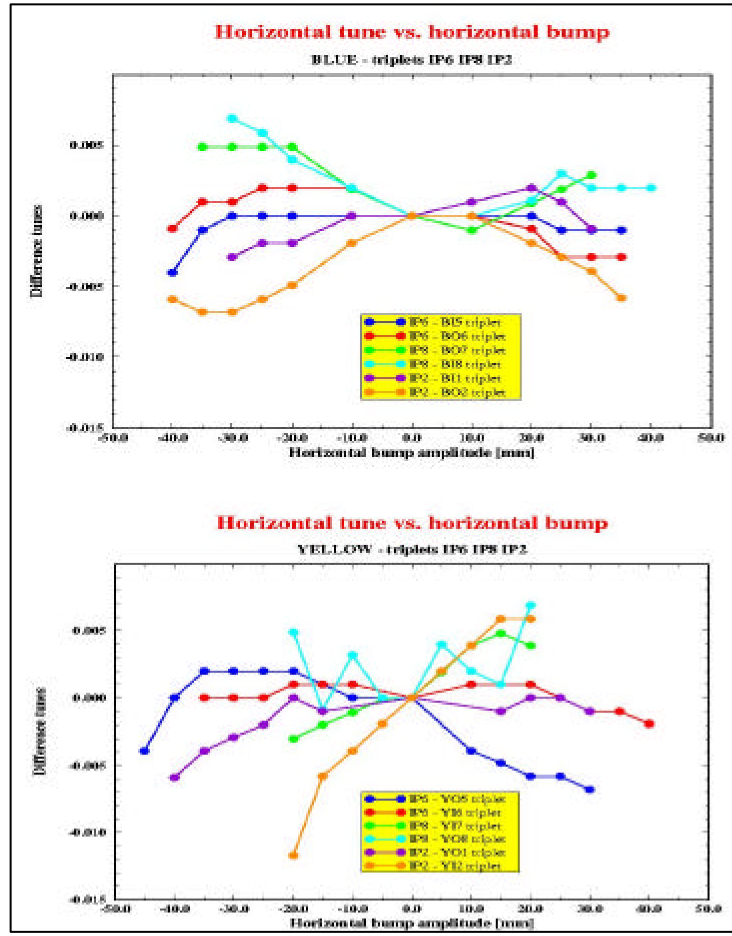
Accuracy can be improved by increasing the number of measurements

Run 2000–IR correction nonlinear

RHIC IR bumps – beam experiment

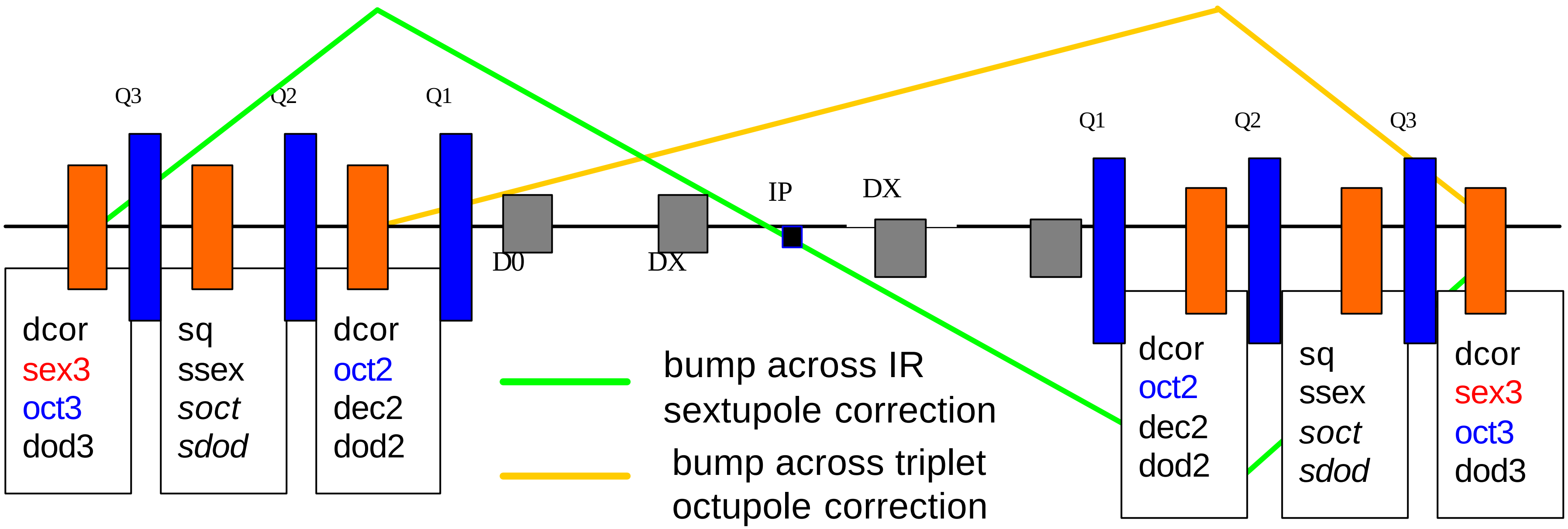
- ❑Bump data at IR2, IR6, IR8, blue & yellow
- ❑Mostly H bumps, some V bumps
- ❑Tune resolution run 2000: 0.001
- ❑Bump amplitude typically to **6s**
- ❑Orbit→ linear, sextupole
- ❑Tune→ 5th order polynomial

triplet	b3	a3	b4	b5	a5	b6
YO5	0.94	-0.55	0.03	-0.08	0.11	-0.01
YI6	-0.95	0.14	0.36	0.03	-0.06	-0.03
YI7	**1.01**	-0.22	0.81	0.36	-0.17	-0.15
YO8	**3.81**		-0.47	-1.85		0.06
YO1	0.32	-0.14	0			0
YO2	**1.51**		0.76	-0.75		-0.21



Tune resolution 2001 (0.0002)→ decapole
dodecapole?

IR corrections: run 2003



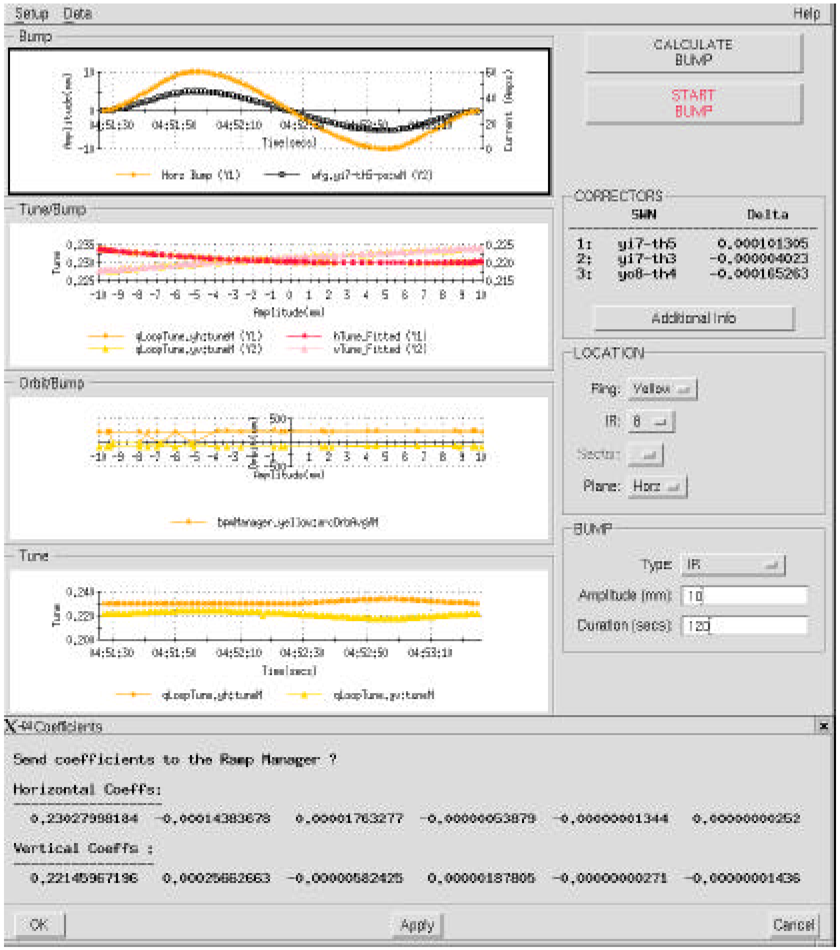
Orbit bumps at triplets and across IR
→rms **orbit** and **tunes** vs. bump amplitude

PLL ~10^{-5} resolution

Motivation:

- **Dynamic aperture**
- **Operations** (closure of steering bumps)

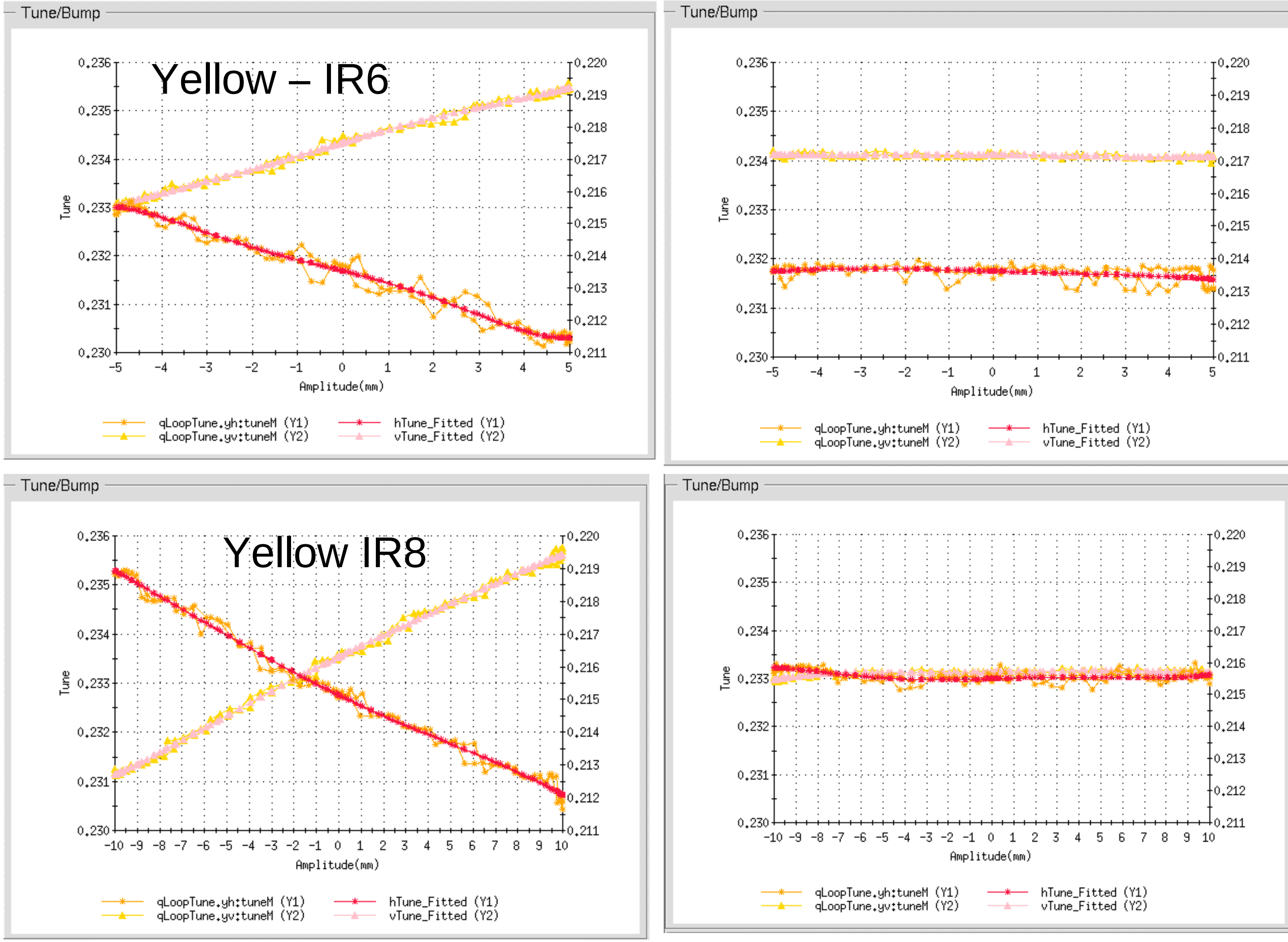
IR bumps application



IR bump application:

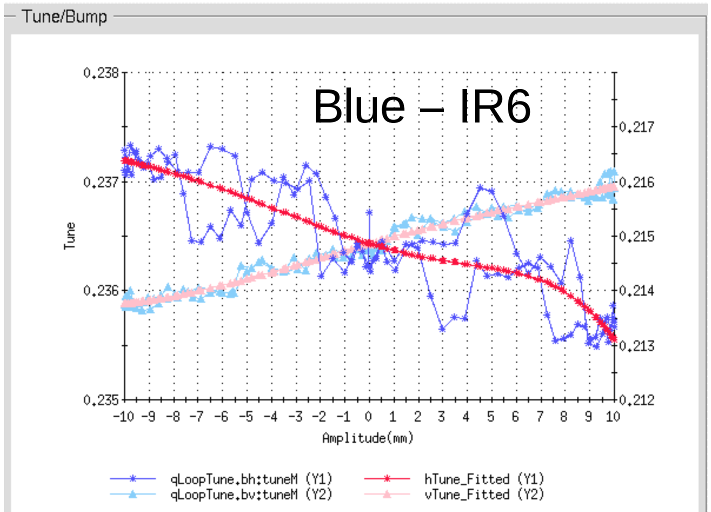
- **set-up** and **ramp-up** of IR and triplet bumps in specified time (1-2 minutes)
- Tune and power supply monitoring
- Plot orbit rms and **tunes as a function of bump amplitude**
- **Polynomial fitting** up to 5th order of tunes versus amplitude → **coefficients**→nonlinear **corrector settings**

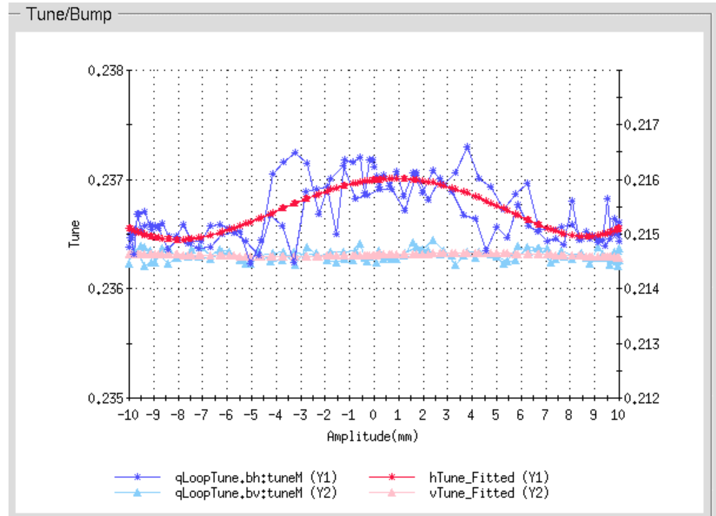
Run 2003: sextupole correction yellow ring

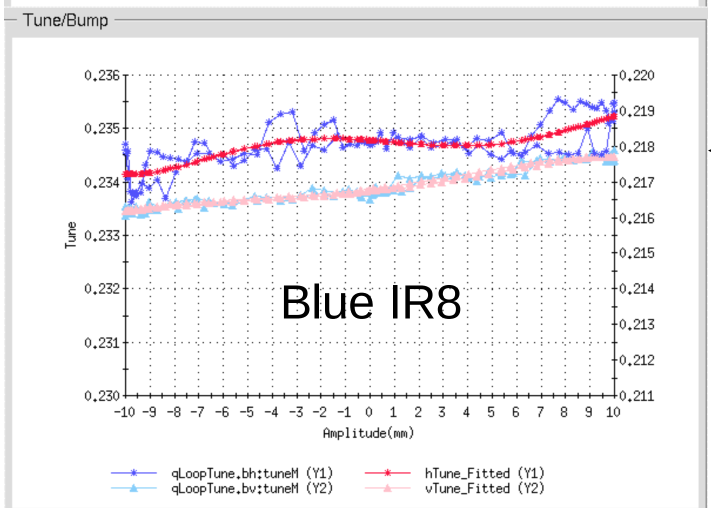


after correction

Run 2003: octupole correction blue ring





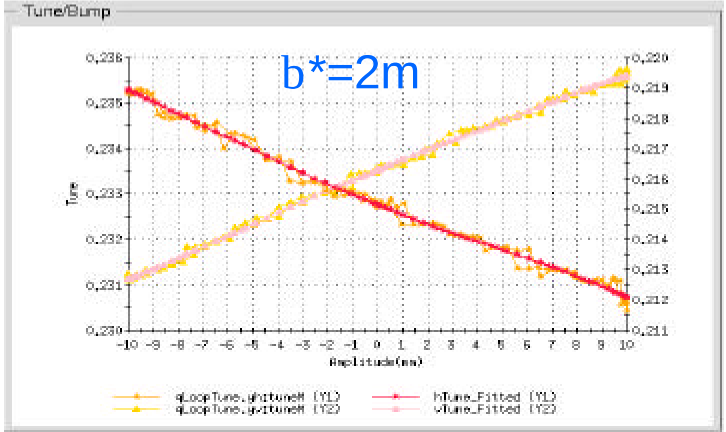


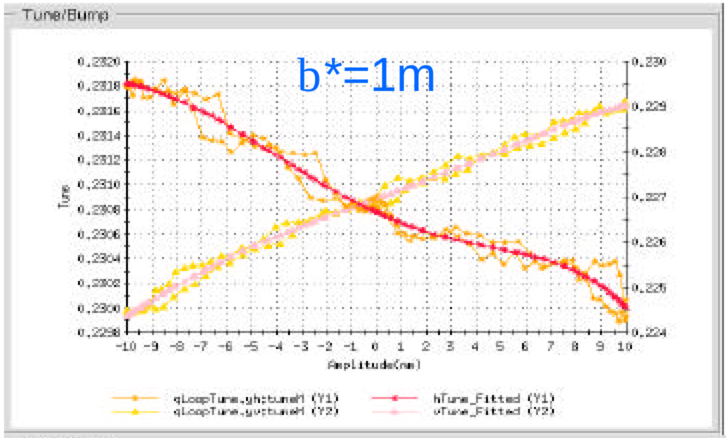
small effect

left uncorrected

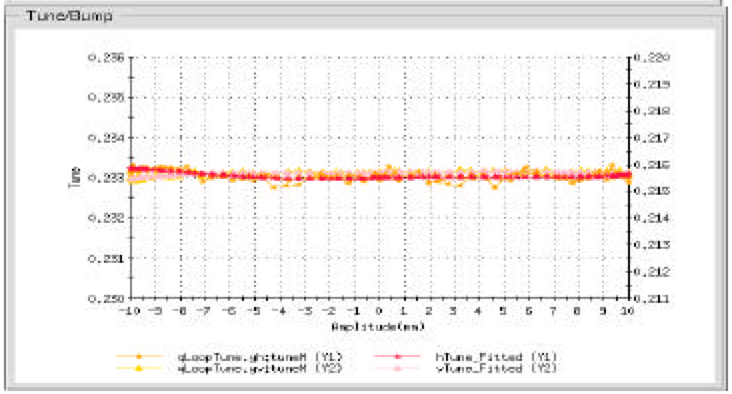
Run 2003: β*=2m vs. 1m

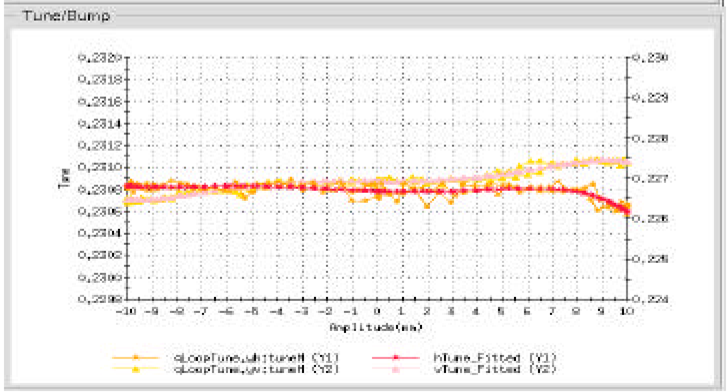
Yellow IR8





before sextupole correction





after sextupole correction

- **Sextupole correction** at **IR6** and **IR8** – blue and yellow rings beta*=1m and 2m
- test of **octupole correction** at **YIR8** (2 octupoles allow individual triplet correction) feed-down octupole→sextupole, to be repeated: octupole first, then sextupole
- **Current dependence** of field harmonics (left 5000A, right ~2000A)

IR correctors - results

Fit coefficients ($x10^{-3}$) before and after correction – beta*=2m

IR	plane	Sextupole BC	Sextupole AC	Octupole BC	Octupole AC
Y IR8	**H**	**0.22209**	**0.01347**	**0.00535**	**0.00093**
	V	**-0.33559**	**0.00595**	**-0.00388**	**0.00119**
Y IR6	**H**	**-0.23338**	**-0.02673**	**-0.00968**	**-0.00051**
	V	**0.41028**	**-0.00042**	**-0.00745**	**-0.00251**
B IR8	**H**	**-0.03204**	***-0.03204***	**-0.00557**	***-0.00557***
	V	**0.07865**	***0.07865***	**0.00646**	***0.00646***
B IR6	**H**	**-0.06853**	**0.02713**	**0.00536**	**-0.01491**
	V	**0.12877**	**0.01121**	**-0.00176**	**0.00002**

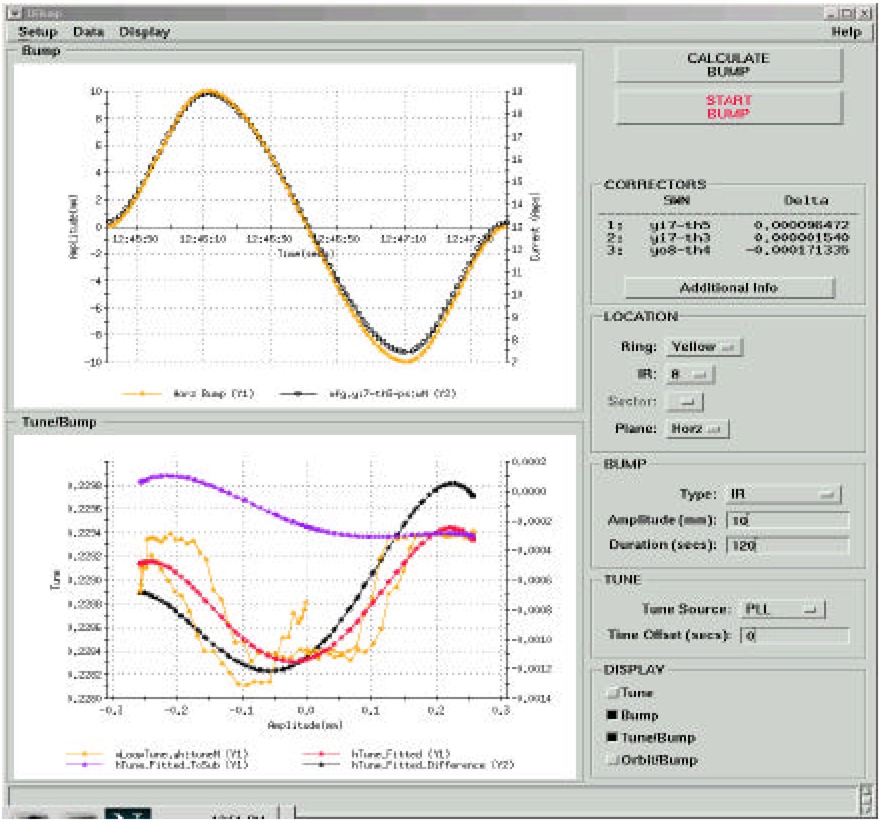
- Similar tables for beta*=1m
- Full set of measurements taken in IR10 and IR2 (to evaluate b* options at Phobos and Brahms)

IR corrector strengths 2m vs 1m

Sextupole corrector	Strength b*=2m ~5000 A	Strength b*=1m ~2000 A
yo5-sx3	-0.014	-0.003
yi6-sx3	0.004	0
yi7-sx3	0.003	0.007
yo8-sx3	-0.01	-0.038
bi5-sx3	0.012	0.001
bo6-sx3	-0.004	-0.003
bo7-sx3	0.0	-0.003
bi8-sx3	0.0	-0.0005

- Difference in strength due mainly to the current dependence of the triplet field errors (if the effect is local).
- The **b*=2m strengths** can be used as a **starting point for correction next year Au-Au run** + readjustment when needed (**b*=1m at ~5000A**)

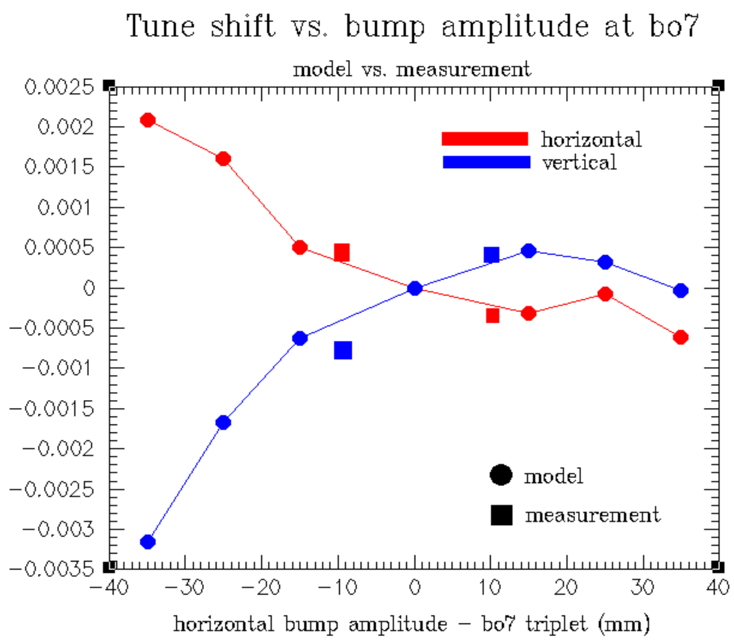
IR bumps – tune shift vs.crossing angle



Test of using the IR bump application to speed up the measurement of **tune shift vs. crossing angle** at the IP. (compare **cogged vs. un-cogged beams**)

Promising – to be repeated with beams better centered in the triplets

Model predictions



Started comparison of experimental data with RHIC model (including measured individual field errors in triplet cold masses and alignment errors)

R.Tomas working on RHIC modeling with beam-beam and IR errors (→working point)

Nonlinear chromaticity

Correct **linear chromaticity** to 0

Separate tunes (reduce coupling effects)

Compare radial steering shift to bpm

Tried various radial steering ramps

Radial steps (chrom app)

5 and 10 steps

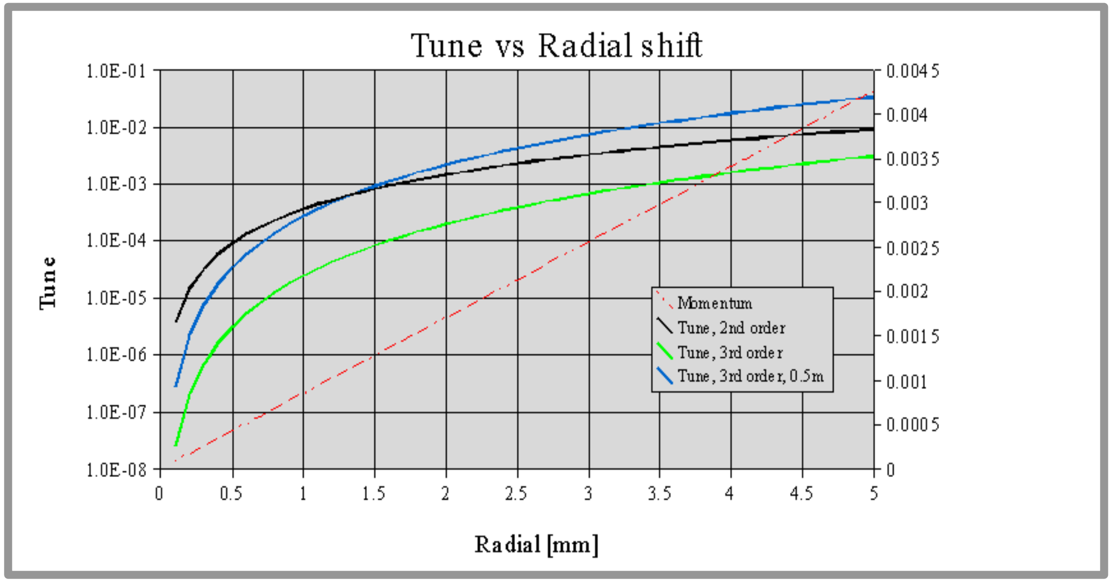
Radial modulation (PLL)

0.4mm amplitude at 1Hz

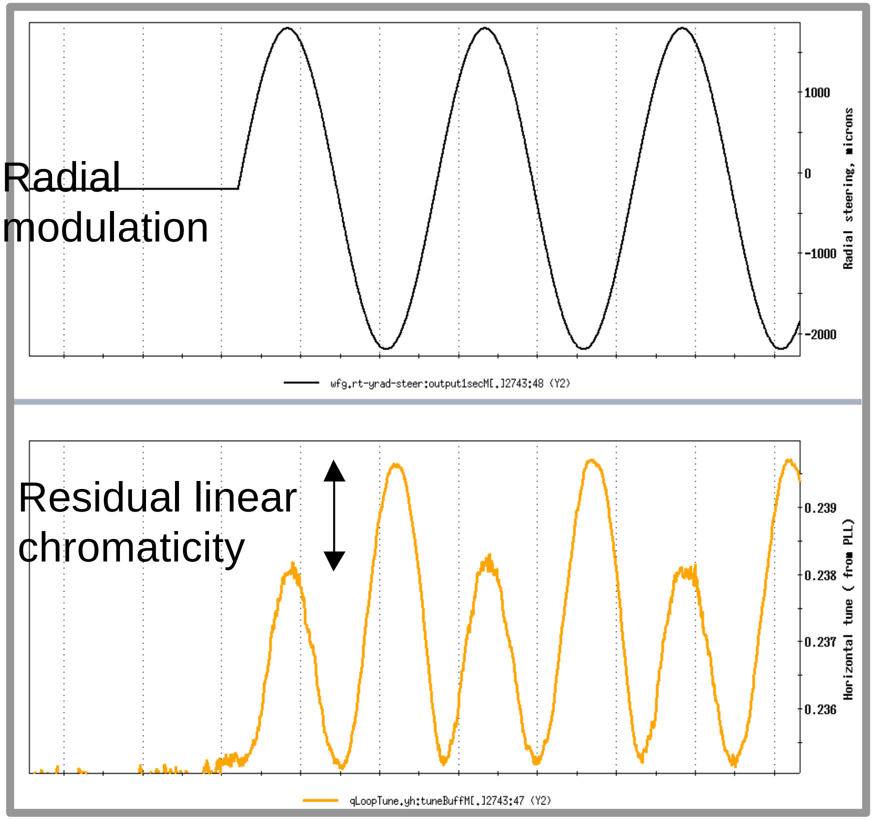
1mm amplitude at 0.4Hz

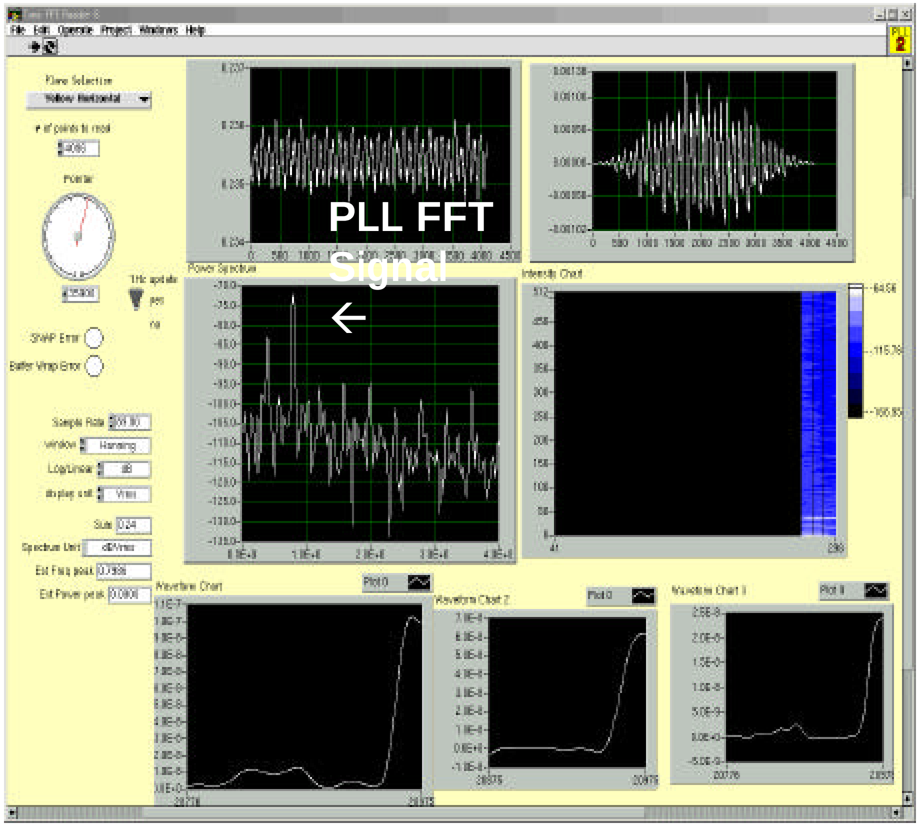
2mm amplitude at 0.2Hz

Prediction from model:



Nonlinear chromaticity - 2





Nonlinear chromaticity - results

Ring	b*	run	date	x2x	x2v
blue	2m	d-Au	Feb 5 2003	**999 +/- 158**	212 +/- 202
yellow	2m	d-Au	Feb 26 2003	271 +/- 179	81 +/- 463
blue	1m	p-p	May 23 2003	**884 +/- 179**	**988 +/- 79**
yellow	1m	p-p	May 23 2003	-720 +/- 218	743 +/- 281

		X			**Y**	
Tune Data	**Fit Order**	? 2	?	**Correlation**	? 2	?
PLL	2	1085	37	0.995972	107	66
	3	1124	33	0.997336	117	71
	4	925	24	0.998808	421	66
	5	782	17	0.999545	562	71
Artus	2	1008	66	0.988581	187	98
	3	1008	48	0.994650	187	104
	4	1225	46	0.995868	-47	109
	5	1226	48	0.996159	-47	111

analysis of
PLL and Artus data

(Dynamic) aperture measurements

<u>Goal</u>: collect data to compare with (up-to-date) model

<u>Method</u> used:

ramp **6 bunches** (avoid possible emittance blow-up), **nominal tunes**

use **scrapers** to confirm **halo beam size** (PIN diodes) and **core beam size** (DCCT and WCM, beam intensity)

increase H emittance of bunches selectively via **tune meter kicks (1 Hz)**

measure continuously emittance with **IPM** and **Schottky**

emittance **'saturation'** defines **aperture**

use scrapers to confirm beam size

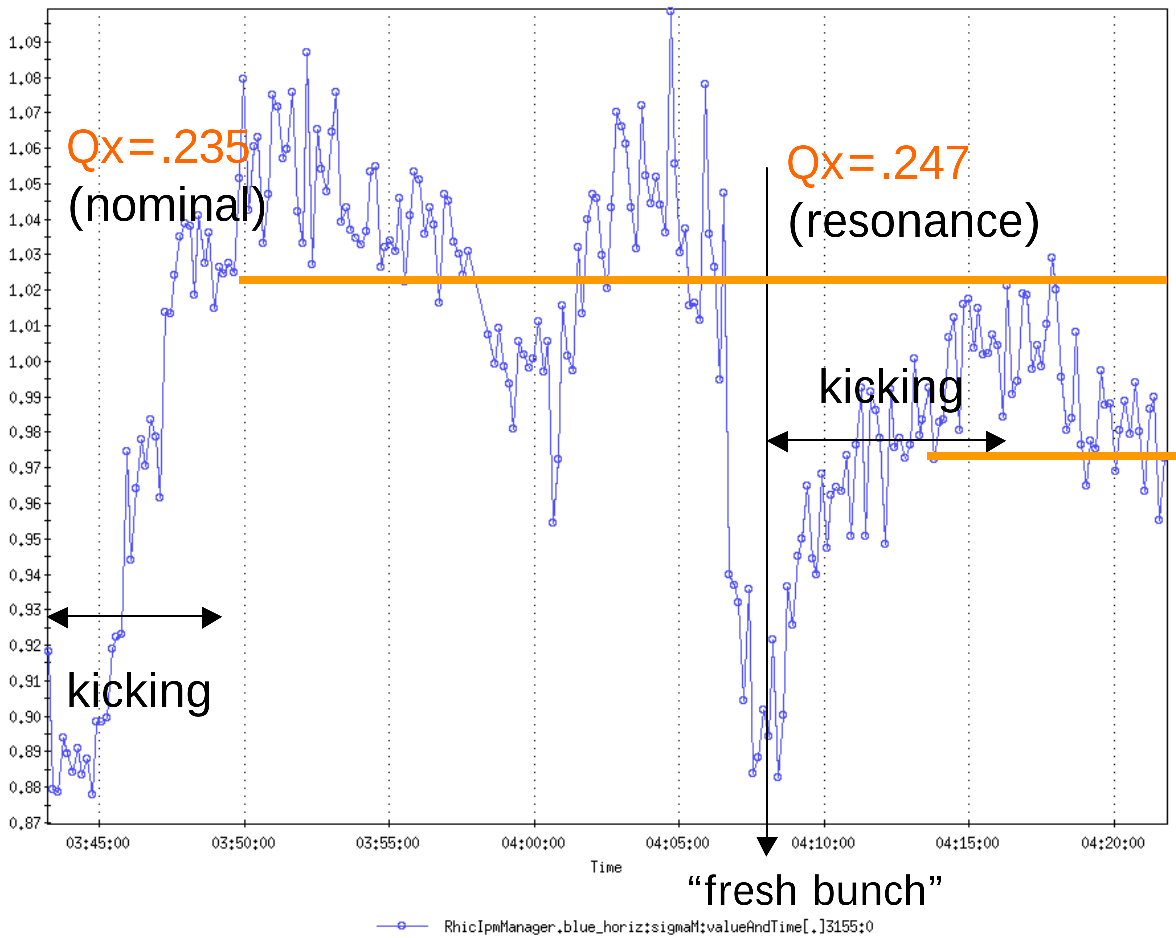
check **loss** pattern and use **orbit** to <u>discriminate **physical** **from** **dynamic aperture**</u> **(physical typically at the abort, and triplets)**

repeat procedure for **vertical emittance**

repeat procedure for horizontal **<u>tune close to the 0.25 resonance</u>**

Dynamic aperture, blue, β*=2m

Blue ring - β^* = **2m** in IP6 and IP8



Dynamic aperture
(nominal tune) ~**4.5 sigma**
By rescaling the emittance
To the initial one

Dynamic aperture
(resonant tune) ~**3.6 sigma**

data to compare
with simulation

b* tuning "knobs"

For **b*< 2m** we b* tuning "knobs" are desireable
Tuning knobs = (quasi) **orthogonal** quadrupole vectors able to produce **matched** changes in **b*** in a range of about **+/-20%**

Necessary:

- Find the appropriate orthogonal knobs
- Verify **orthogonality** and **matching** (offline)
- **Online model** with beta, dispersion, coupling in order
- Implementation in RE (**online matching** capability – cfr. JVZ talk)
- **Optics measurements** with 5-10% resolution

Existing work for LHC ("Correcting the LHC b* at collision – Wittmer Verdier, Zimmermann, PAC2003)

- Calculation & matching
- Tested orthogonality
- Tested performance in simulation (with errors)

They have the RHIC lattice with 2m and 1m beta star and agreed to repeat the study for RHIC, possible test in run 2003 if study is successful.

LARP-related IR activities

IR optics compensation is necessary for the **IR upgrade** and to enhance the **baseline machine performance**

- Development of **operational IR correction techniques** capabilities for the LHC (application, analysis) – correction system testing at RHIC
  1. IR bumps 2. Resonance driving terms
- Test of **LHC simulation IR filter** (compensation of selected driving terms) at RHIC: apply filter in simulation and measure driving terms with before and after correction (RHIC beam experiment)
- **Test of LHC b* tuning knobs** at RHIC
- Precise **beta function measurements** with AC dipole
- Measurement techniques for **non-linear and skew chromaticity**
- **Dynamic aperture measurements**
- **Test of b* squeeze 1m -> 0.5m optics at RHIC**
  (LHC IR upgrade also factor~2 in b*) – possible with p at 100 GeV without change in power supplies