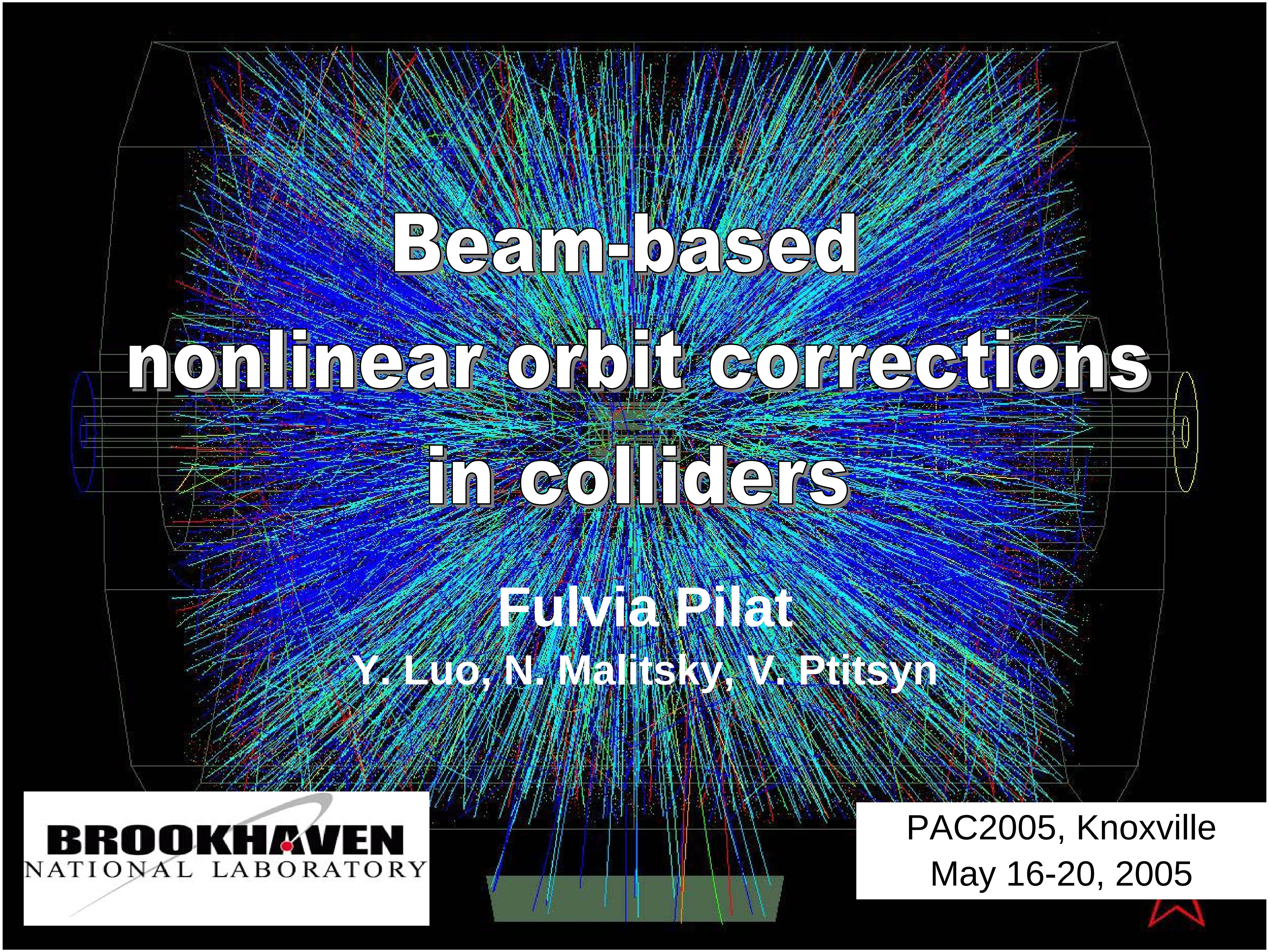

Beam-based nonlinear orbit corrections in colliders

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outline

- **Introduction**
- **Brief overview, non-linear optics correction methods**
- **IR bump correction method – theory**

  general formulation, valid to all orders

  examples: normal and skew sextupole and octupole
- **IR bump corrections – experience in operations**

  experimental set-up, machine preparation

  results for sextupole, skew sextupole, octupole and higher-orders

  validation: lifetime, dynamic aperture
- **Conclusions and outlook**

Non-linear optics corrections: motivation

Limitations collider dynamic aperture (→beam lifetime)

- Non-linear effects from magnets, in collision from IR magnets
- Beam-beam (in collision)

Correction of **non-linear optics errors**→ aperture, lifetime**,** 'cleaner' operations (i.e. steering bumps closure)

Operation experience in RHIC:

- Measured effect on lifetime – correctors on/off
- Measured dynamic aperture – correctors on/off

β^* squeeze from 1m to 0.85m during beams studies (**Run-4**), made **operational** during the **Cu-Cu operations (Run-5)** this year

Future potential: with e-cooling →reduced ε →dynamic β^* squeeze to **0.5m** → extra ~50% increase in luminosity

Nonlinear optics correction methods

'dead-reckoning'

compensate for known or measured errors

Examples:

- action-kick minimization (*Wei*) : order by-order prescription, minimize action kick from IR error terms
- driving terms compensation (*Farthouk*) needs 2 knobs for each multipole to cancel driving terms of selected resonances

'beam-based'

Use beam measurements to correct for unknown errors

Examples:

- IR bumps method (*Koutchouk, Pilat, Ptitsyn, Luo*): measure and fit tunes dependence from IR orbit bumps
- Frequency analysis (*Schmidt, Tomas, Bartolini,…):* harmonic analysis (interpolated FFT's: $1/N \rightarrow 1/N^2$) of BPM turn-by-turn data, resonance driving terms

resonance driving terms compensation → global correction

local orbit bumps → localized correction (IR' s)

IR bump method – general formulation

Local orbit distortion in a region with non-linear field→ feed-down effects to lower order harmonics

Feed-down to 0 (closed orbit) and 1st order (tunes) most useful (measurable)

Effect α size of orbit excursion (IR 3-bump. A_{bump} amplitude *at the bump center*

Tune shift: from feed-down to gradient, or from linear coupling

Tune shift **ΔQ** and linear coupling term **Δc** as a function of bump planes and multipoles:

$$\Delta Q(H, norm) = g(b_n, x_{co})$$
$$\Delta Q(V, skew, even) = -1^{n/2} g(a_n, y_{co})$$
$$\Delta c(V, norm, even) = -1^{(n-1)/2} h(b_n, y_{co})$$
$$\Delta Q(V, norm, odd) = -1^{(n-1)/2} g(b_n, y_{co})$$
$$\Delta c(H, skew) = h(a_n, x_{co})$$
$$\Delta c(V, skew, odd) = -1^{(n+1)/2} h(a_n, y_{co})$$

$$g(c_n, z_{co}) = \frac{n}{4\pi}\frac{1}{B\rho}\int \beta_z B_N c_n \frac{z_{co}^{n-1}}{R^n} ds$$

$$h(c_n, z_{co}) = \frac{n}{2\pi}\frac{1}{B\rho}\int \sqrt{\beta_x \beta_y} B_N c_n \frac{z_{co}^{n-1}}{R^n} e^{i(\mu_x-\mu_y)} ds$$

Bump	b_2	a_2	b_3	a_3	b_4	a_4	b_5
H	ΔQ	Δc	ΔQ	Δc	ΔQ	Δc	ΔQ
V	Δc	ΔQ	ΔQ	Δc	Δc	ΔQ	ΔQ

$$|C_0 + \Delta c|^2 / 4\Delta Q_{xy} << \Delta Q$$

Condition for tune shift from coupling to be negligible

IR bump method – order by order

We demonstrated that order-by –order the IR bump method is equivalent to the compensation of the relevant resonance driving terms
(***assumption*** *that* ***phase advance in triplets is ~0*** *and* ***between triplets is*** π)

Normal sextupole

total tune shift from ***sextupoles*** *in a IR region:*

Horizontal IR bump
2 sextupole correctors

$$\begin{cases} \Delta Q_x \propto \left(\sum_L k_2 \beta_x^{3/2} ds - \sum_R k_2 \beta_x^{3/2} ds\right) \cdot \dfrac{A_{bump}}{4\pi \beta_{xc}^{1/2}} \\ \Delta Q_y \propto -\left(\sum_L k_2 \beta_x^{1/2} \beta_y ds - \sum_R k_2 \beta_x^{1/2} \beta_y ds\right) \cdot \dfrac{A_{bump}}{4\pi \beta_{xc}^{1/2}} \end{cases}$$

Skew sextupole

total tune shift from ***skew sextupoles*** *in a IR region:*

Vertical IR bump
2 skew sextupole correctors

$$\begin{cases} \Delta Q_x = \dfrac{1}{4\pi} \sum k_{2s} \beta_x y_{co} ds \propto \left(\sum_L k_{2s} \beta_x \beta_y^{1/2} ds - \sum_R k_{2s} \beta_x \beta_y^{1/2} ds\right) \dfrac{A_{bump}}{4\pi \beta_{yc}^{1/2}} \\ \Delta Q_y = -\dfrac{1}{4\pi} \sum k_{2s} \beta_y y_{co} ds \propto -\left(\sum_L k_{2s} \beta_y^{3/2} ds - \sum_R k_{2s} \beta_y^{3/2} ds\right) \dfrac{A_{bump}}{4\pi \beta_{yc}^{1/2}} \end{cases}$$

IR bump method – order by order

Normal octupole

Horizontal and vertical IR bumps needed

Minimum of 3 octupole correctors/IR needed

*total tune shift from **octupoles** in a IR region:*

$$\begin{cases} \Delta Q_x = \dfrac{1}{8\pi}\sum k_3 \beta_x x_{co}^2 ds \propto \left(\sum{}_L k_3 \beta_x^2 ds + \sum{}_R k_3 \beta_x^2 ds\right)\dfrac{A_{xbump}^2}{8\pi \beta_{xc}} \\ \Delta Q_y = -\dfrac{1}{8\pi}\sum k_3 \beta_y x_{co}^2 ds \propto -\left(\sum{}_L k_3 \beta_x \beta_y ds + \sum{}_R k_3 \beta_x \beta_y ds\right)\dfrac{A_{xbump}^2}{8\pi \beta_{xc}} \end{cases}$$

$$\begin{cases} \Delta Q_x = \dfrac{1}{8\pi}\sum k_3 \beta_x y_{co}^2 ds \propto \left(\sum{}_L k_3 \beta_x \beta_y ds + \sum{}_R k_3 \beta_x \beta_y ds\right)\dfrac{A_{ybump}^2}{8\pi \beta_{yc}} \\ \Delta Q_y = -\dfrac{1}{8\pi}\sum k_3 \beta_y y_{co}^2 ds \propto -\left(\sum{}_L k_3 \beta_y^2 ds + \sum{}_R k_3 \beta_y^2 ds\right)\dfrac{A_{ybump}^2}{8\pi \beta_{yc}} \end{cases}$$

Skew octupole

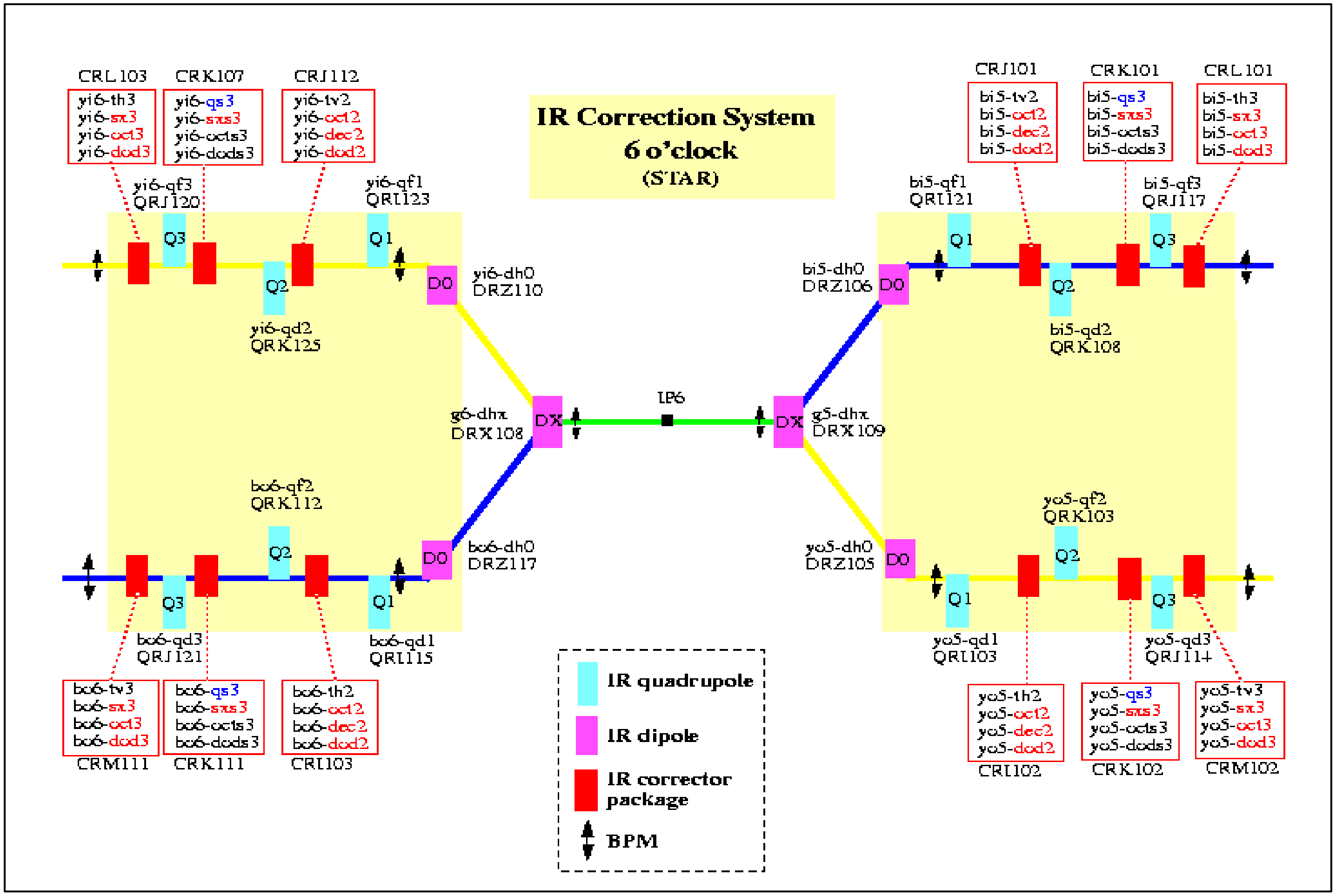
Horizontal + vertical (diagonal) bump needed

2 skew octupole Correctors/IR needed

*total tune shift from **skew octupoles** in a IR region:*

$$\begin{cases} \Delta Q_x = \dfrac{1}{4\pi}\sum k_{3s} \beta_x x_{co} y_{co} ds \propto \left(\sum{}_L k_{3s} \beta_x^{3/2} \beta_y^{1/2} ds + \sum{}_R k_{3s} \beta_x^{3/2} \beta_y^{1/2} ds\right)\dfrac{A_{bump}^2}{4\pi \beta_{xc}^{1/2} \beta_{yc}^{1/2}} \\ \Delta Q_y = -\dfrac{1}{4\pi}\sum k_{3s} \beta_y x_{co} y_{co} ds \propto -\left(\sum{}_L k_{3s} \beta_x^{1/2} \beta_y^{3/2} ds + \sum{}_R k_{3s} \beta_x^{1/2} \beta_y^{3/2} ds\right)\dfrac{A_{bump}^2}{4\pi \beta_{xc}^{1/2} \beta_{yc}^{1/2}} \end{cases}$$

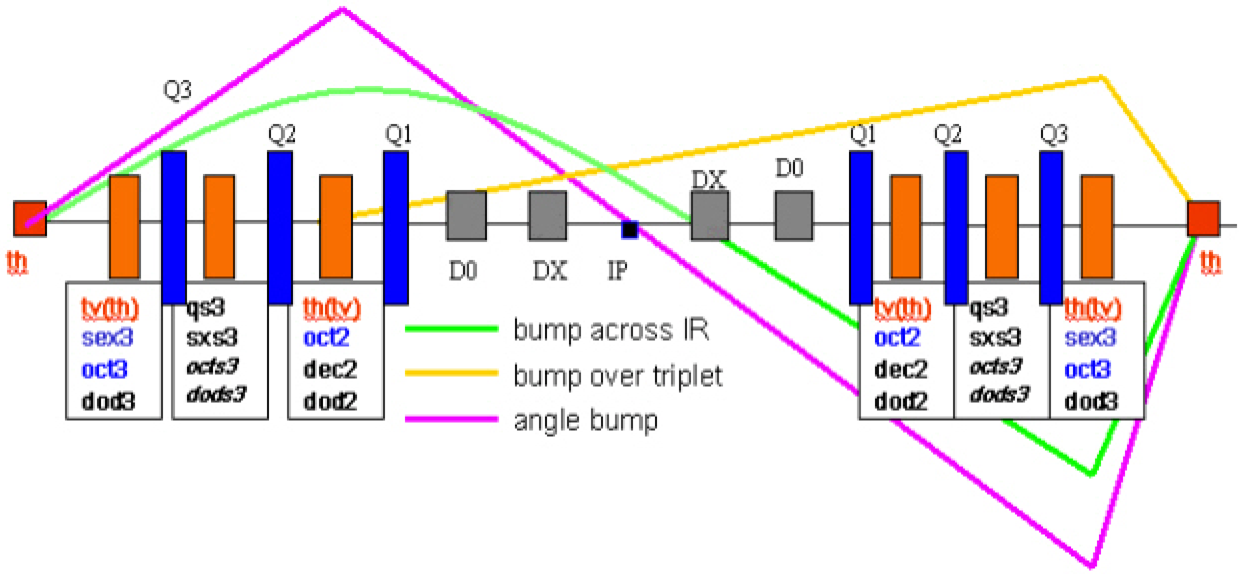
RHIC IR's - layout



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)

IR bumps: schematics



IR bumps used for correction:

- Bump across the IR: 3 dipole corrector + anti-symmetry of optics
  used for operational corrections
- Bump over single triplet: used mostly for tests and studies
- Angle bumps: used for orbit steering in operations

IR bumps: application

Tune measurements

Phase Lock Loop

245 MHz system

In high-resolution mode

< 5×10^{-5}

Data at **100 Hz**

Bump time: **60 sec**

Orbit data were used for IR linear coupling Correction

For sextupole and higher only tune shift data

Experimental set-up

- The 2 rings must be **longitudinally separated**, by at least 3 RF buckets to avoid beam-beam effects.
- Measurements are performed at the beginning of a ramp, when the **transverse emittance is small** and with **6 bunches**, to avoid risking magnet quenches in case of accidental beam loss.
- **The machine must be well decoupled**, with coupling corrected to a minimum tune separation $\Delta Q_{min} < 0.002$.
- The **tunes are separated** before the measurements by 0.01-0.012 to further minimize coupling effects.
- Good overall orbit correction with horizontal and vertical orbit rms < 1mm, and **good (<2mm) centring of the orbit in the IR triplets**, to insure symmetry during the measurement.
- The choice of **bump amplitude** is a critical one. Large bump amplitude is desirable to enhance the measured effect but this must be weighted with practical aperture considerations.

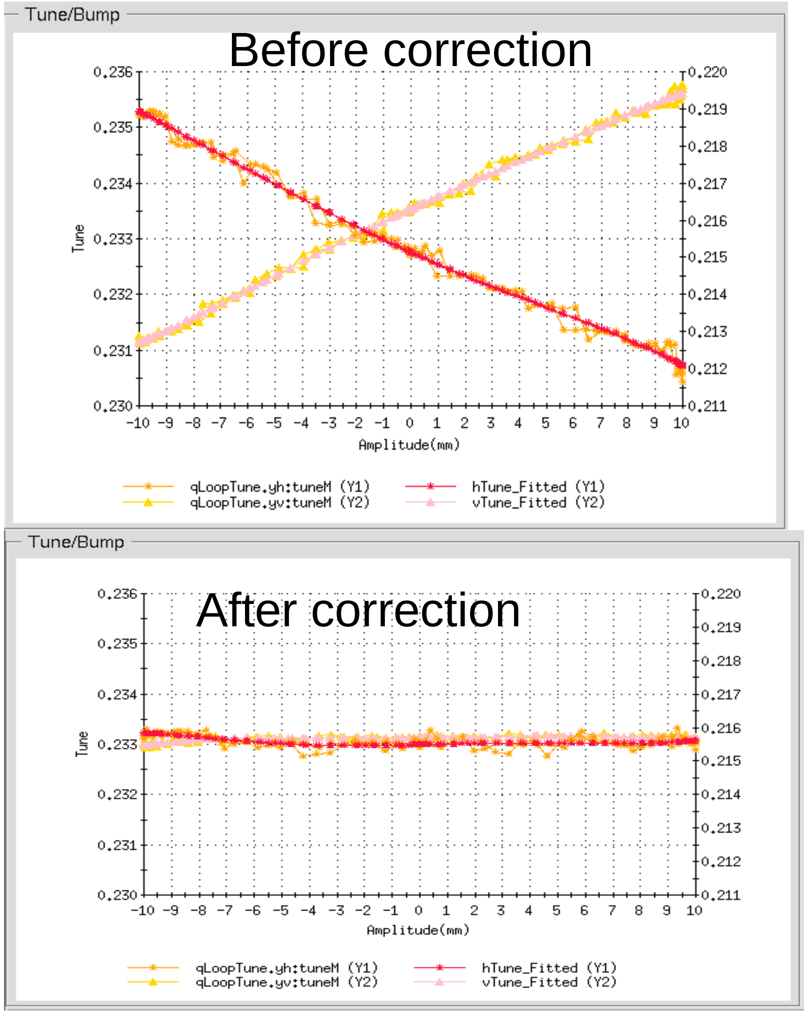
Maximum bump amplitudes of **5mm** proved enough to resolve sextupole effects, **10mm** for octupole effects, and **15mm** for higher orders.

Sextupole corrections

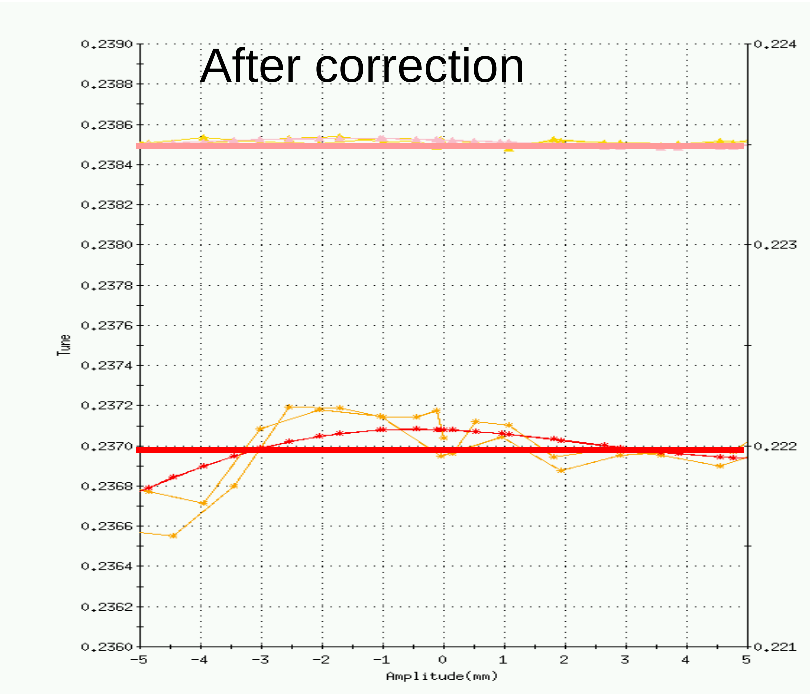
IR sextupole corrector	Run-3 d-Au β* 2m 4500A	Run-3 p-p β* 1m 2000A	Run-4 Au β* 1m 4500A	Run-4 p-p β* 1m 2000A	Run-5 Cu β* 0.9m 4500A
Yo5-sx3	-0.0014	-0.003	-0.006	-0.001	-0.007
Yi6-sx3	+0.004	0.0	+0.003	+0.001	+0.0035
Yi7-sx3	+0.003	+0.007	+0.0005	+0.001	+0.003
Yo8-sx3	-0.01	-0.038	0.0	-0.0012	-0.003
Bi5-sx3	+0.0012	+0.001	+0.0011	-0.0022	+0.0025
Bo6-sx3	-0.004	-0.003	-0.001	+0.001	-0.005
Bo7-sx3	0.0	-0.003	0.0	-0.007	-0.005
Bi8-sx3	0.0	-0.0005	0.0	+0.002	+0.0025

Local IR coupling correction in place since Run-1/2

Sextupole IR correction has been part of machine set-up for Run-4 and Run-5



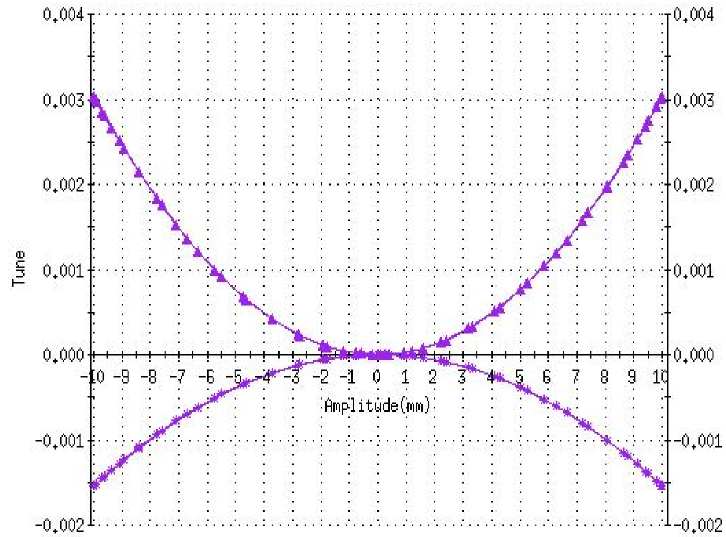
Skew-sextupole



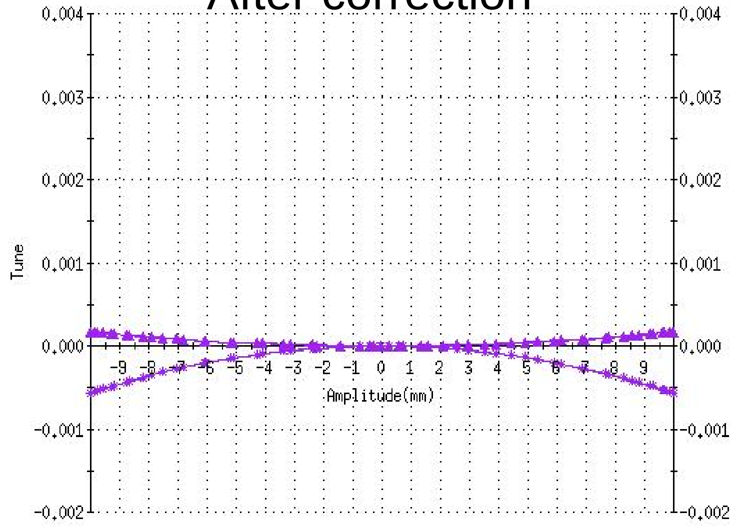
Sextupole corrections in IR8: Cu Run-5 (this year)
Skew sextupole correction (after correction of normal sextupole). **Vertical bump, 2 skew sextupoles** Needed for correction.

octupole

Before correction

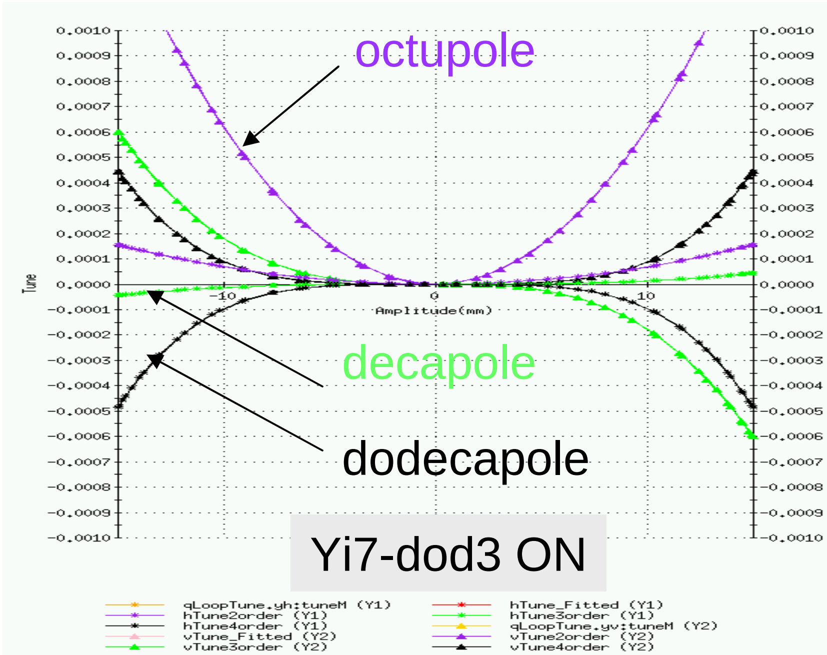


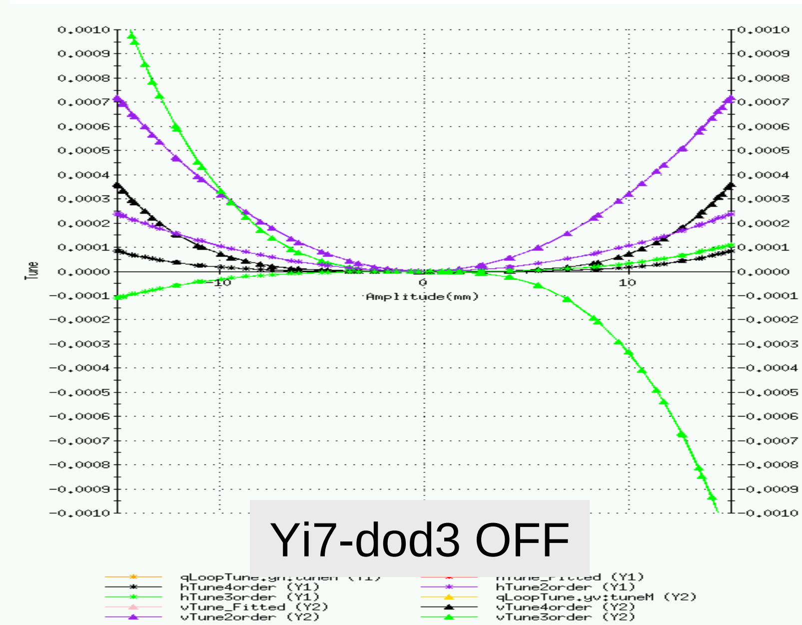
After correction



On-line polynomial fitting of tune shift vs. bump amplitude data
Example: 2nd order term (octupole) before and after test correction at an individual triplet.
10mm bump

Higher-orders



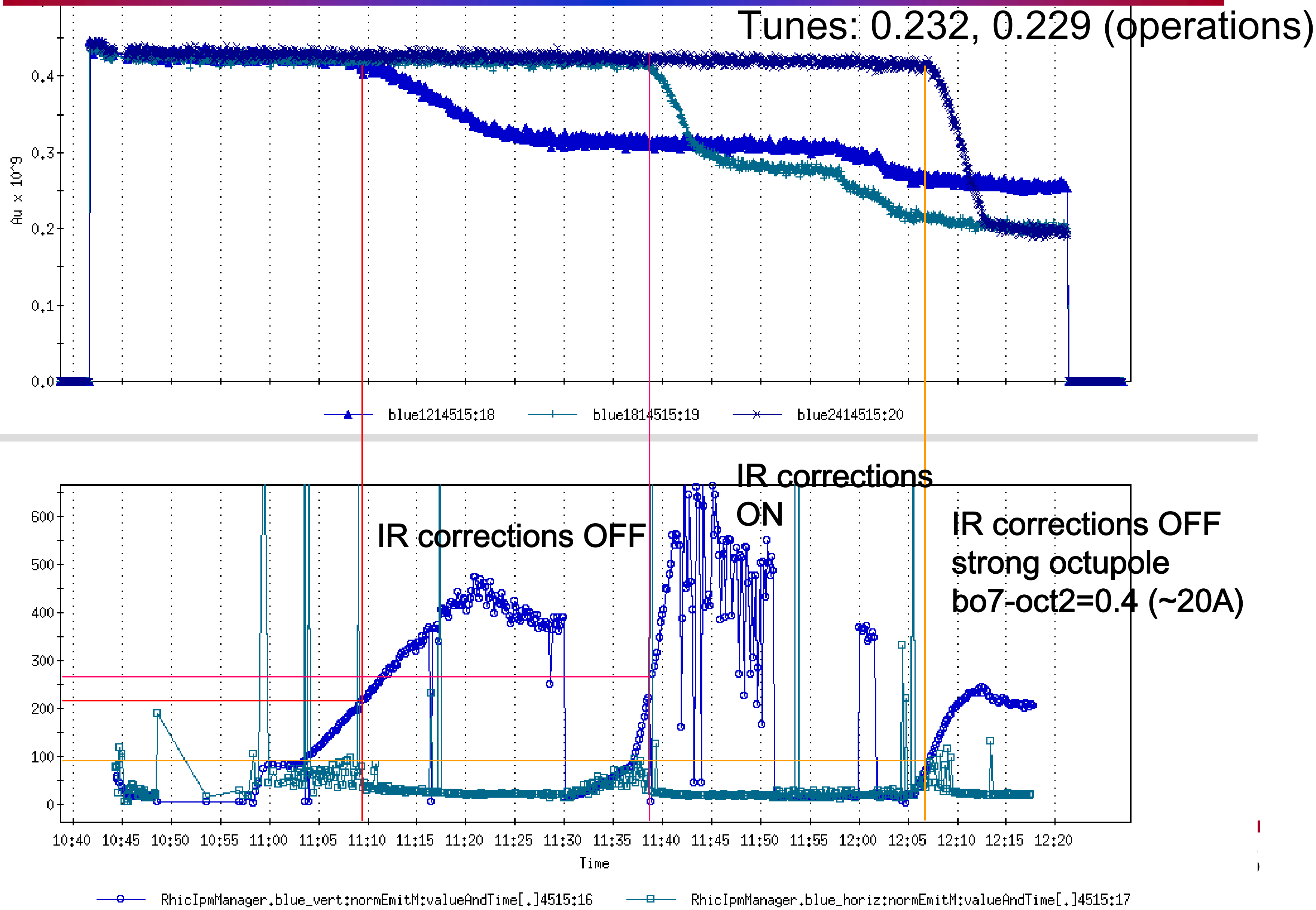


2nd (**octupole**), 3rd (**decapole**) and 4th (**dodecapole**) coefficients of tune shift after linear (sextupole) correction

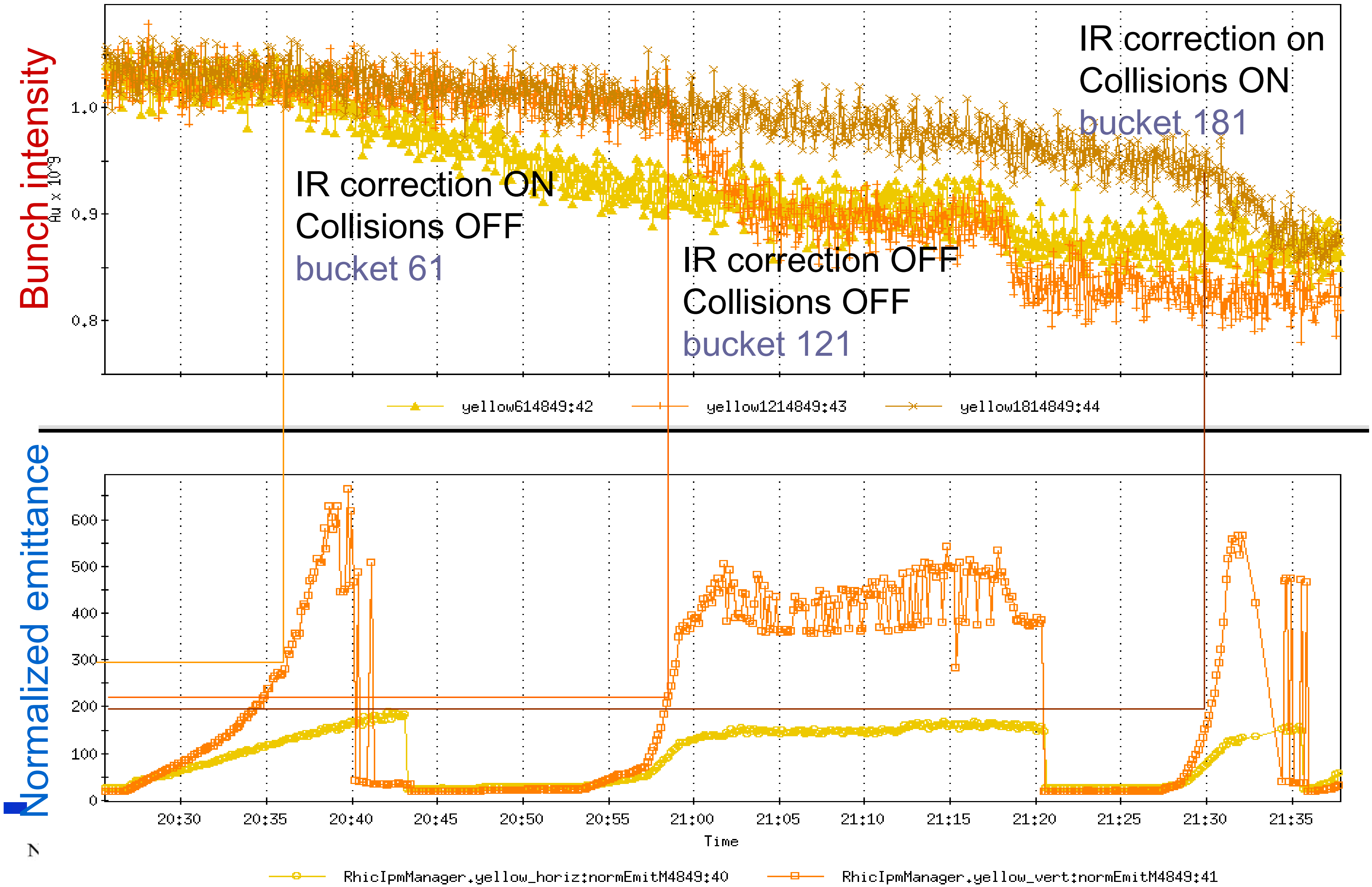
Needed **15mm IR bump** – practical limit at store with present emittance Of 10-12 π mm-mrad and β* of 85mm

Dynamic aperture – blue ring (February 11 2004)

Tunes: 0.232, 0.229 (operations)



Dynamic aperture data – yellow ring



Model

Comparison of effect based on **measured IR magnets data** and beam-based measurements
Identified sextupole **b2 errors in D0 magnets** (IR separation Dipoles) as the main source of measured sextupole effect

IR section	Measurement by IR bump	Off-line Model
Blue IR6	$-1.1\ 10^{-3}$	$-4.2\ 10^{-3}$
Blue IR8	$-2.0\ 10^{-3}$	$-2.4\ 10^{-3}$
Yellow IR6	$-3.9\ 10^{-3}$	$-3.6\ 10^{-3}$
Yellow IR8	$-0.5\ 10^{-3}$	$-2.2\ 10^{-3}$

conclusions

- Beam-based **operational corrections** have been demonstrated at RHIC
- IR local **coupling** and **sextupole** correction, **part of routine machine set-up**
- Octupole, **higher-orders** in progress (**beam experiments**)
- NOT a "critical system" but **measured improvements** in **lifetime**, dynamic **aperture**, helped in 15% β^* **squeeze**
- The method is **equivalent to resonance driving term** compensation – order-by-order – when the error sources are local (IR)
- Parallel activity on going in deriving non-liner optics corrections from **BPM turn-by-turn analysis techniques**