

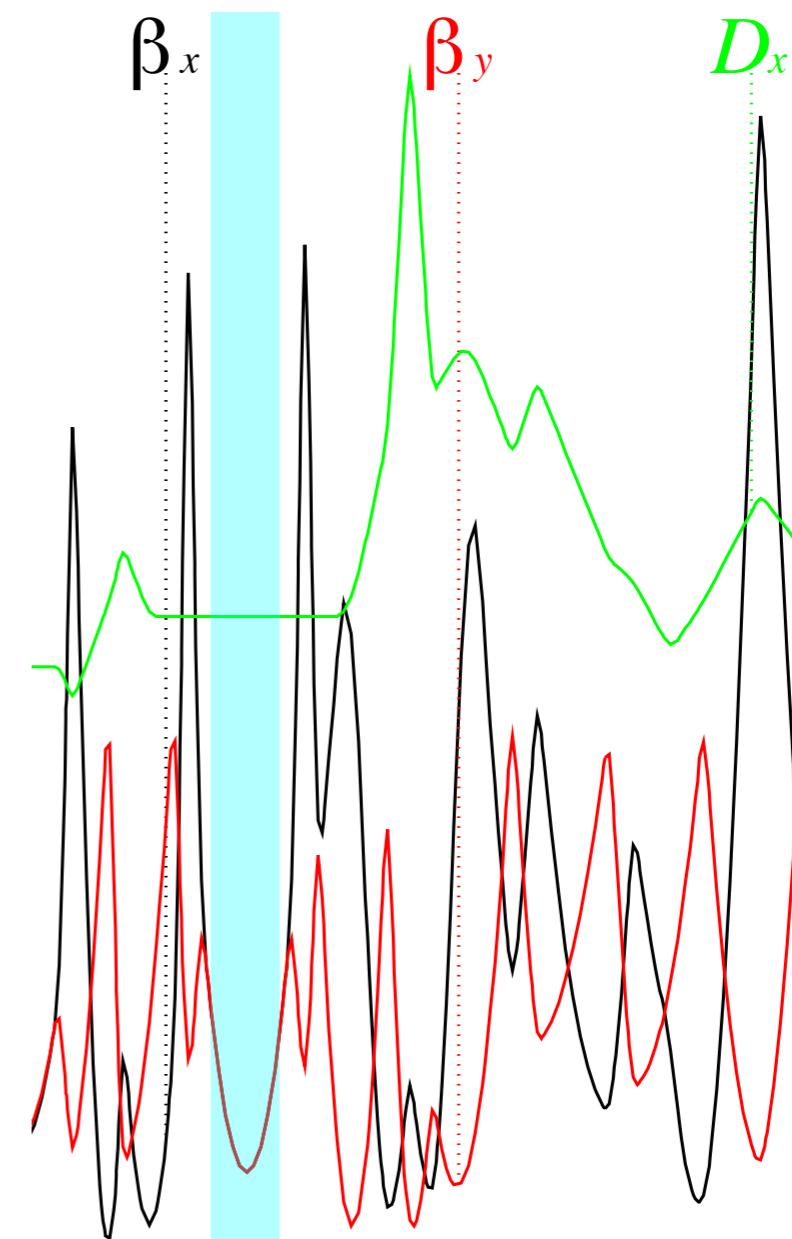
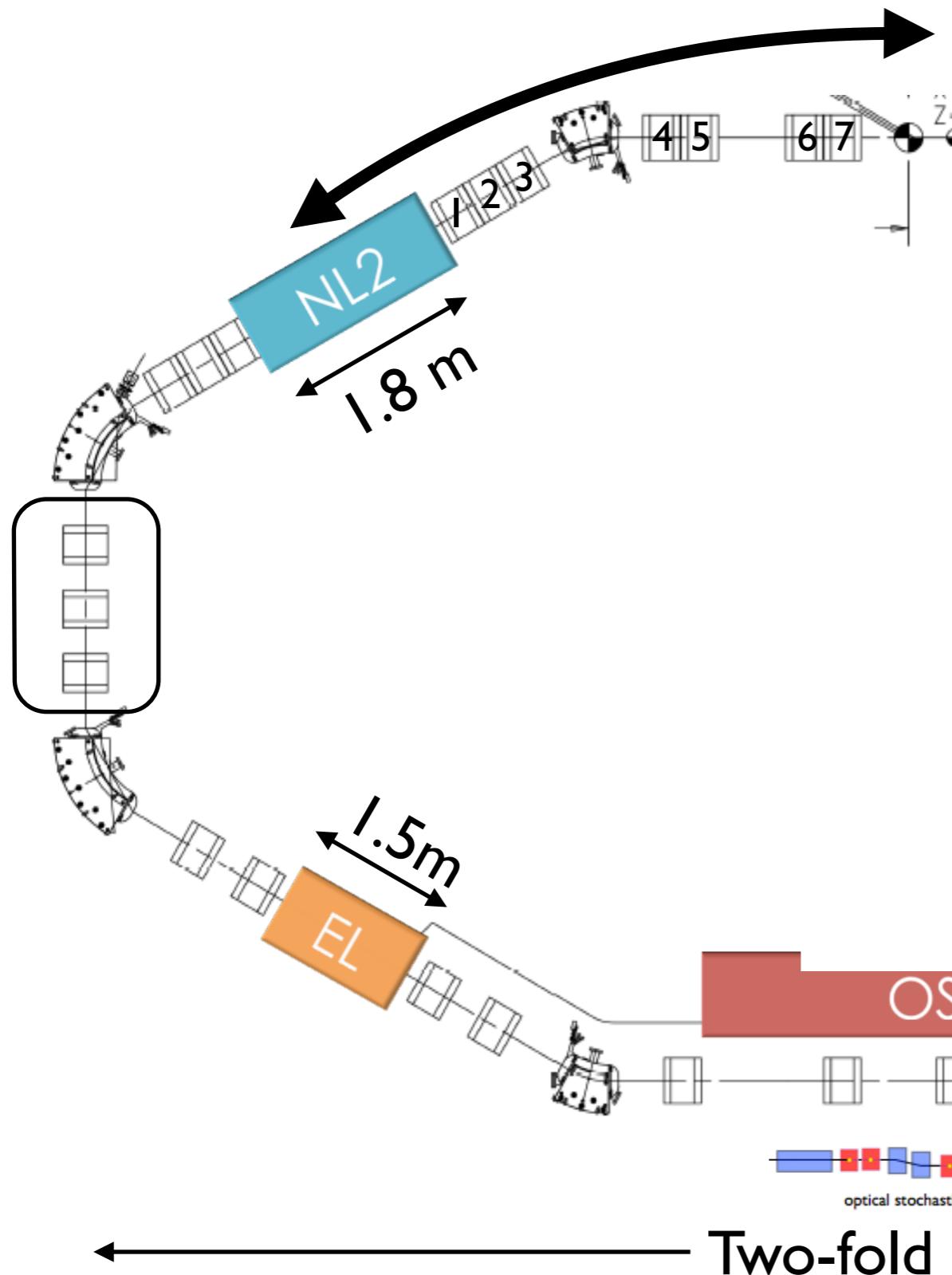
# DESIGN OF THE IOTA RING

**Gene Kafka (IIT/ FNAL), Sasha Valishev, Valeri Lebedev**

# IOTA DESIGN

7 constraints between injection and middle of

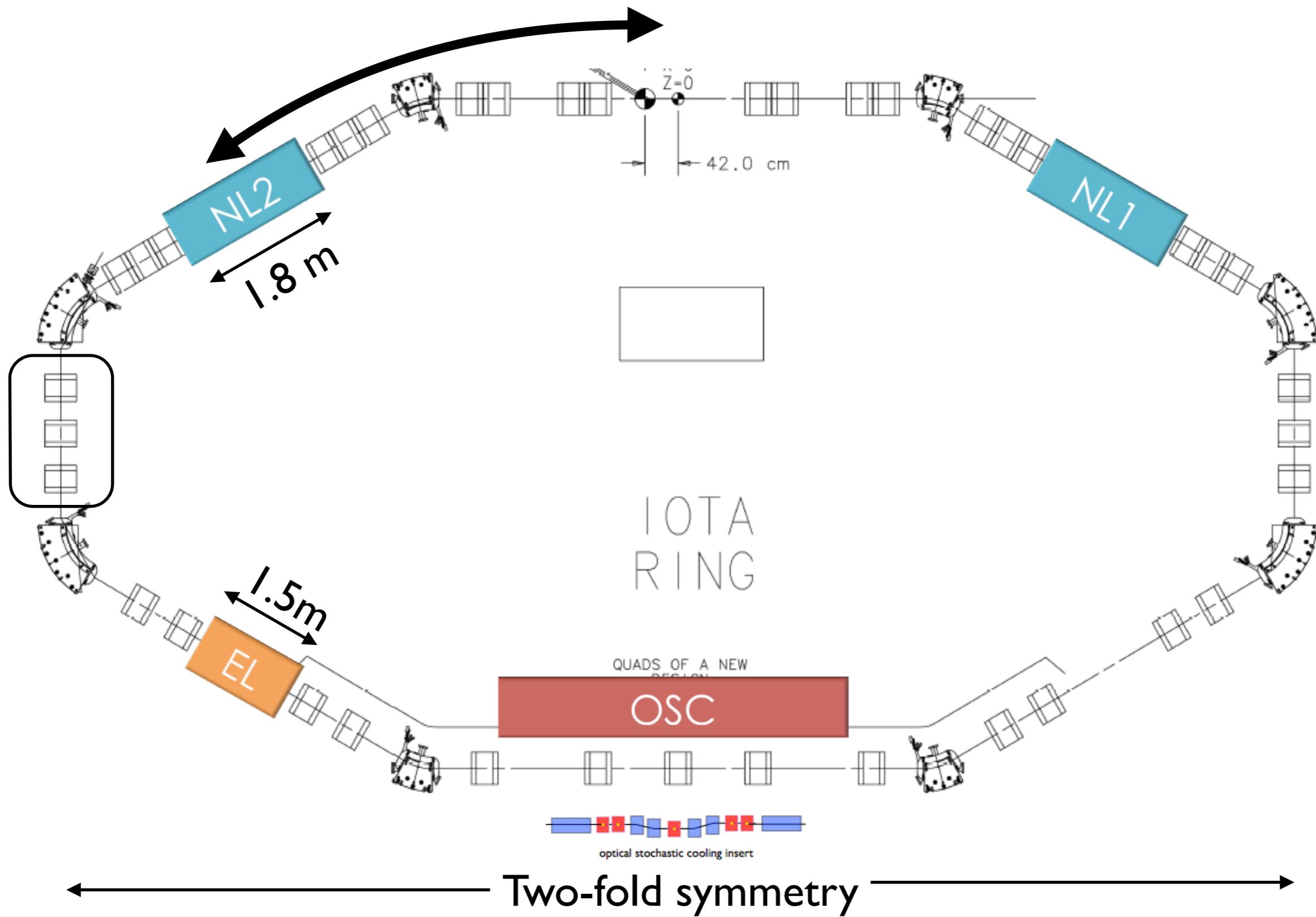
NL drift:  $\beta_x$  (max),  $\beta_y$  (max),  $\alpha_x$ ,  $\alpha_y$ ,  $D'_x$ ,  $Q_x$ ,  $Q_y$



# IOTA DESIGN

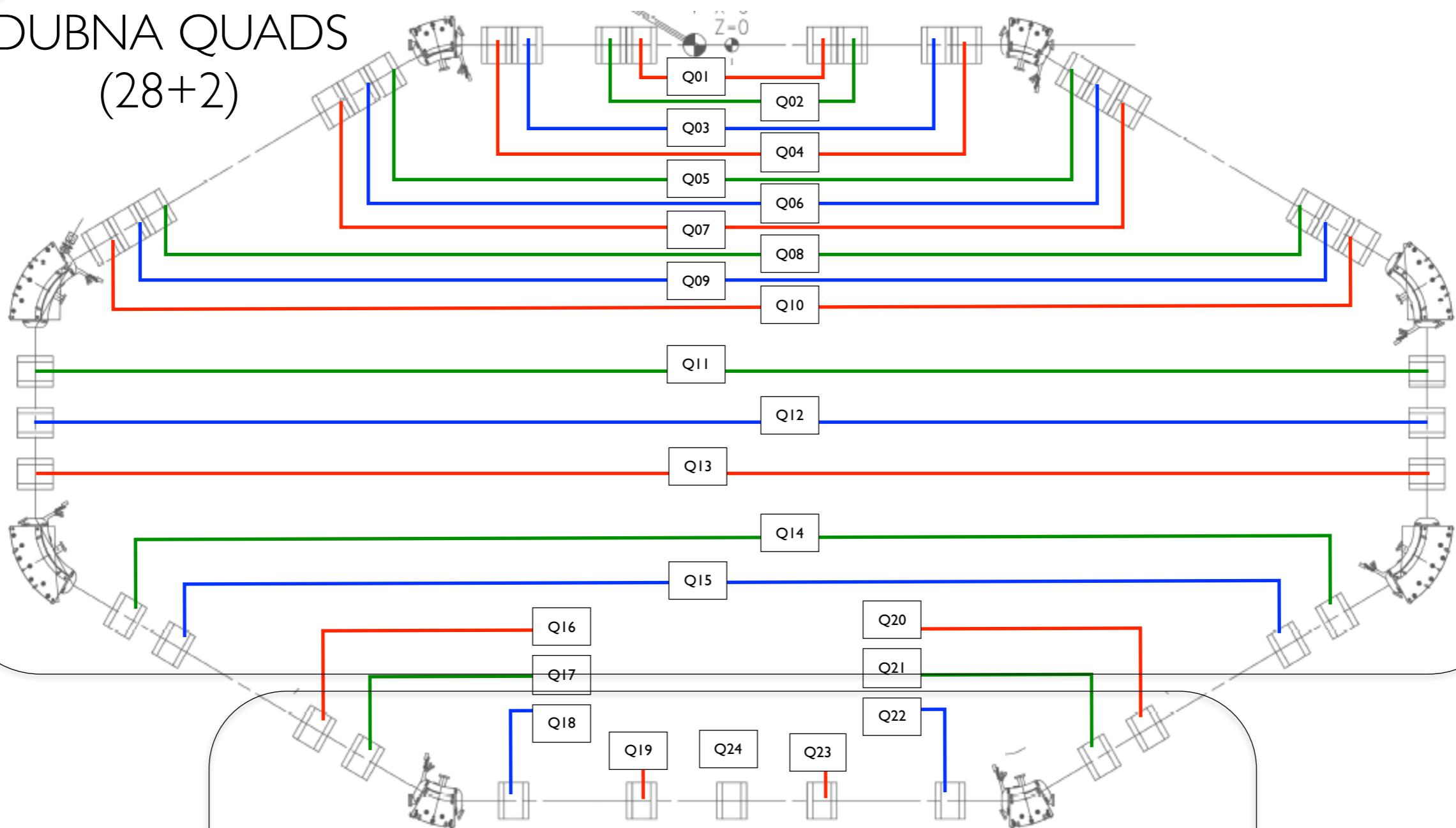
7 constraints between injection and middle of

NL drift:  $\beta_{x(max)}$ ,  $\beta_{y(max)}$ ,  $\alpha_x$ ,  $\alpha_y$ ,  $D'_x$ ,  $Q_x$ ,  $Q_y$



# IOTA DESIGN

## DUBNA QUADS (28+2)

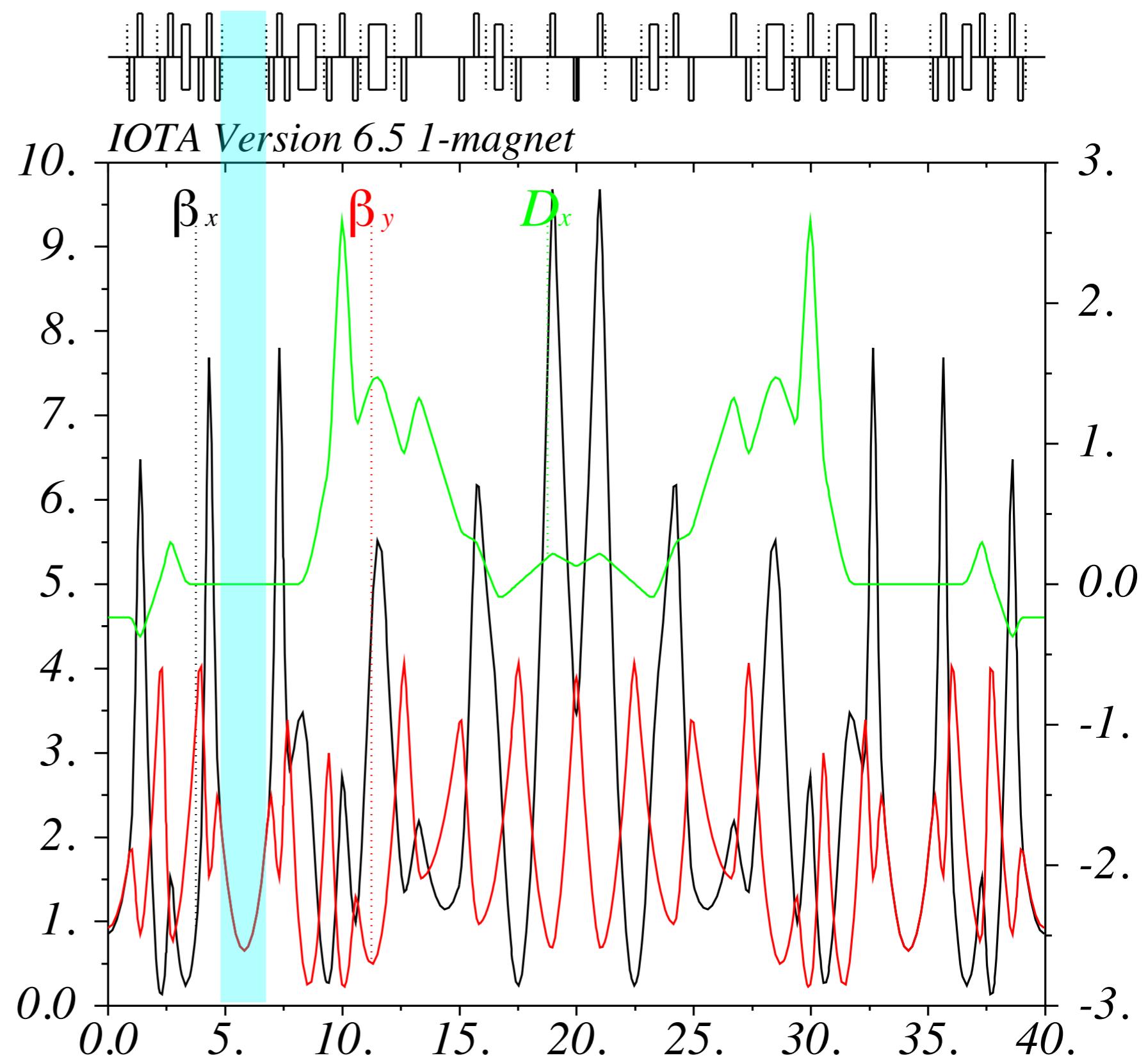


Custom QUADS Configuration

	Gradient [kG/cm]	Current [A]
Dubna Quads	0.3 - 1.0	60.5 - 127.3
Custom Quads	0.019 - 0.282	39.6 - 54.1

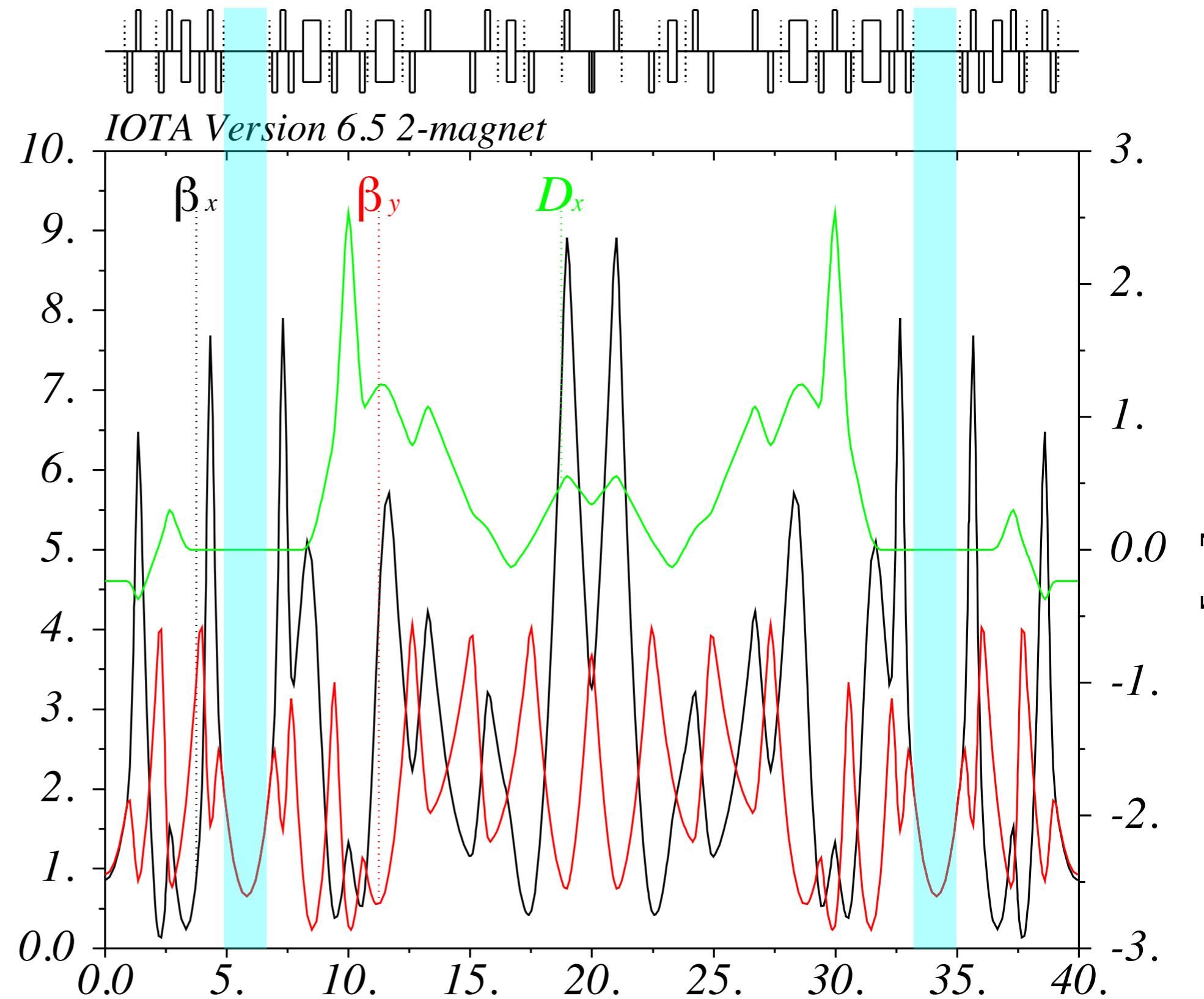
# I NONLINEAR MAGNET LATTICE

- Equal beta-functions, matched in NL
- $Q_x=5.3; Q_y=5.3$
- Dispersion=0 in NL
- Max amplitude in NL=11 mm
- $\alpha=0.08$



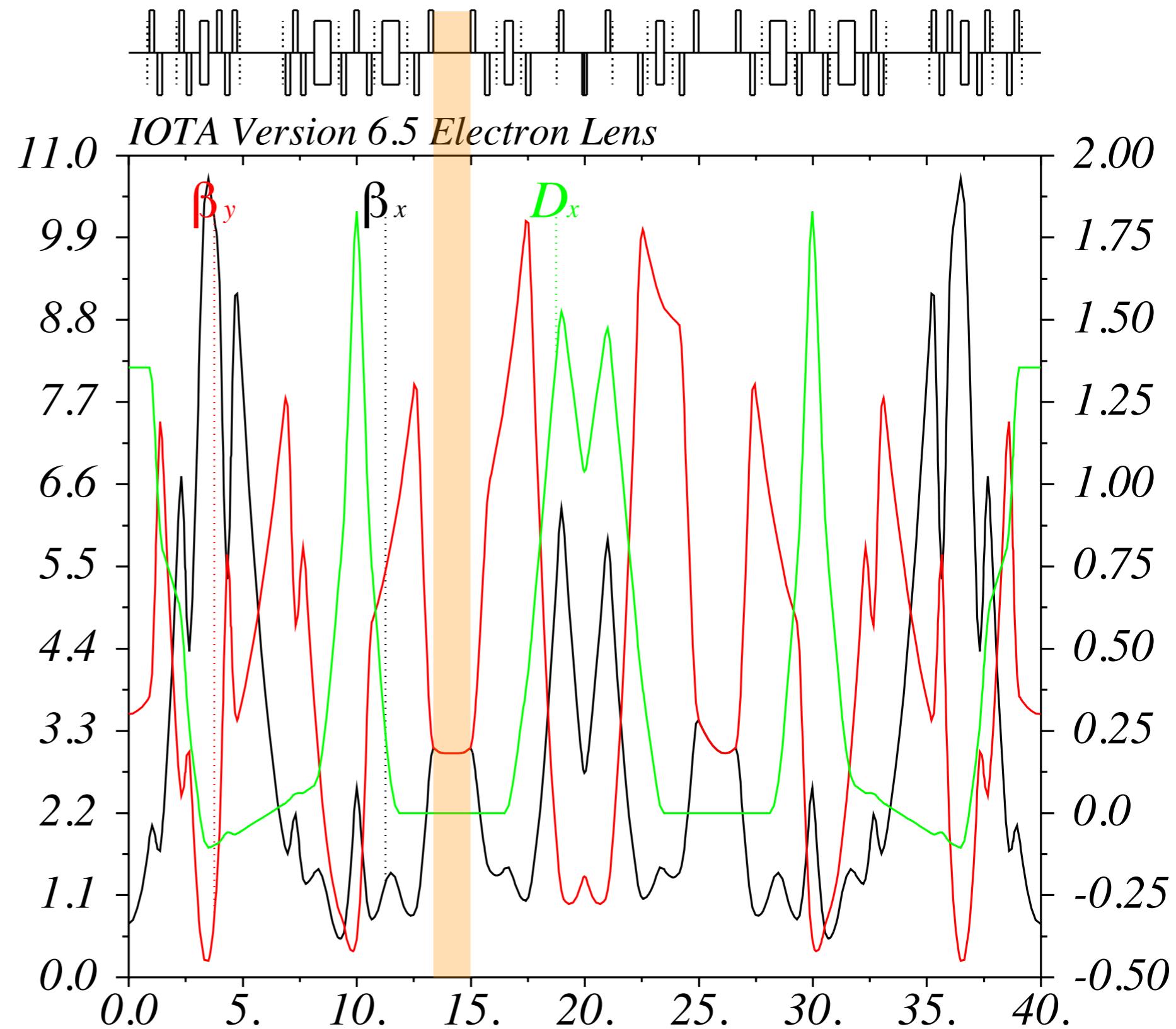
## 2 NONLINEAR MAGNET LATTICE

- Equal beta-functions, matched in NL
- $Q_x=5.1; Q_y=5.1$
- Dispersion=0 in NL
- Max amplitude in NL=11 mm
- $\alpha=0.08$



# ELECTRON LENS LATTICE

- Equal beta-functions, matched in the solenoid.
- $Q_x=3.5$ ;  $Q_y=3.0$
- Dispersion=0 in Elens
- Max amplitude in the Elens=17 mm



# IOTA PARAMETERS

Nominal e 150 MeV, (100 MeV for OSC)

Nominal e  $1 \times 10$

Circumference 40. m

Bending field 0.7 T

Beam pipe aperture 50 mm dia.

Maximum b-function (x,y) 10, 4 m (NL)

Momentum compaction  $0.02 \div 0.1$

Betatron tune  $3 \div 5$

Natural chromaticity  $-5 \div -10$

Transverse emittance r.m.s. 0.1 mm

SR damping time 0.6s ( $5 \times 10$ )

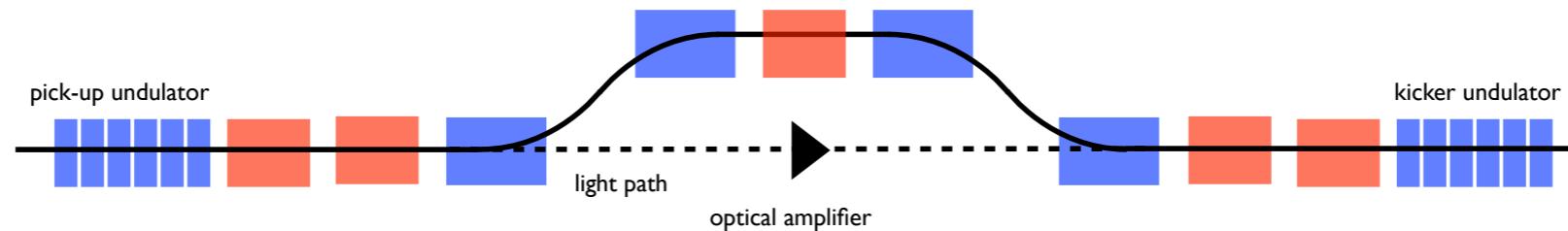
RF V,f,q 1 kV, 30 MHz, 4

Synchrotron tune 0.0009

Bunch length, momentum spread 1-2 cm,  $1.4 \times 10$

# SUMMARY OF OSC PARAMETERS

Cooling Chicane Parameters	presented @AAC	Sept 4, '14
Delay in the chicane, $\Delta s$	2 mm	3 mm
Horizontal beam offset, $h$	2.01 cm	3.740 cm
$M_{56}$	3.95 mm	4.92 mm
$D^*$	30 cm / 0.8 cm	15 cm / 1.4 cm
Cooling rates ratio, $\lambda_x = \lambda_y / \lambda_s$	1.18	3.851
Cooling Ranges: $N\sigma_p / N\sigma_x$	2.1 / 3.2	6.2 / 4.8
Dipole: magnetic field * length	4.22 kG * 10 cm	1.32 kG * 28 cm
Strength of central quad, GdL	1.58 kG	0.355 kG
RMS momentum spread	$1.23 \times 10^{-4}$	$1.11 \times 10^{-4}$
Transverse RMS emittances,	11.5 nm	1.23 nm
RF harmonic, voltage	8, 25kV	4, 100V
Bunch Length	2 cm	18 cm
Sample Lengthening	2.7 um	2.0 um



# PROBLEMS WITH OSC LATTICE

RING Parameters	Sept 4, '14
Particles per bunch	$2.5 \times 10$
IBS / SR rate (Longitudinal)	1.78
IBS / SR rate (Horizontal)	3.32
Decrease Number of Particles:	
Particles per bunch	$0.75 \times 10$
IBS / SR rate (Longitudinal)	0.52
IBS / SR rate (Horizontal)	0.97

- I. Better vacuum is needed.
2. OSC will operate with **low intensity** beam ( $\sim 10^6$  particles)—what are the **implications for instrumentation?**
3. change of chicane (not in baseline design)

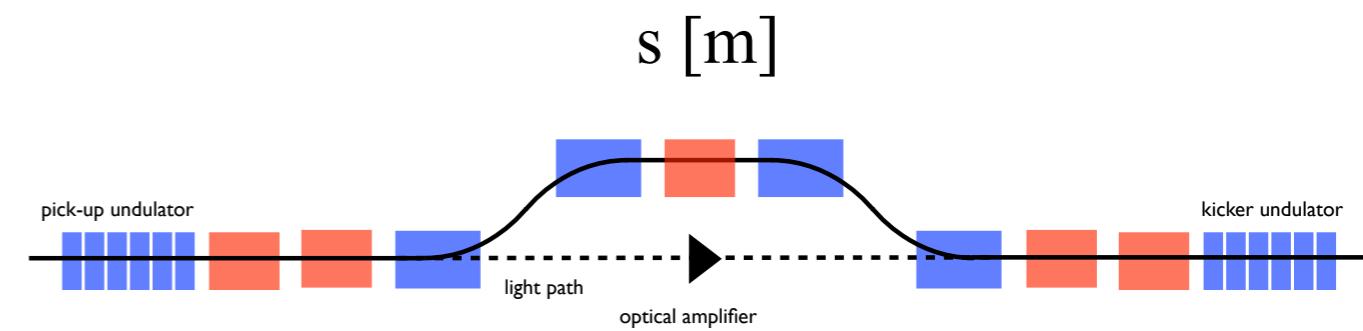
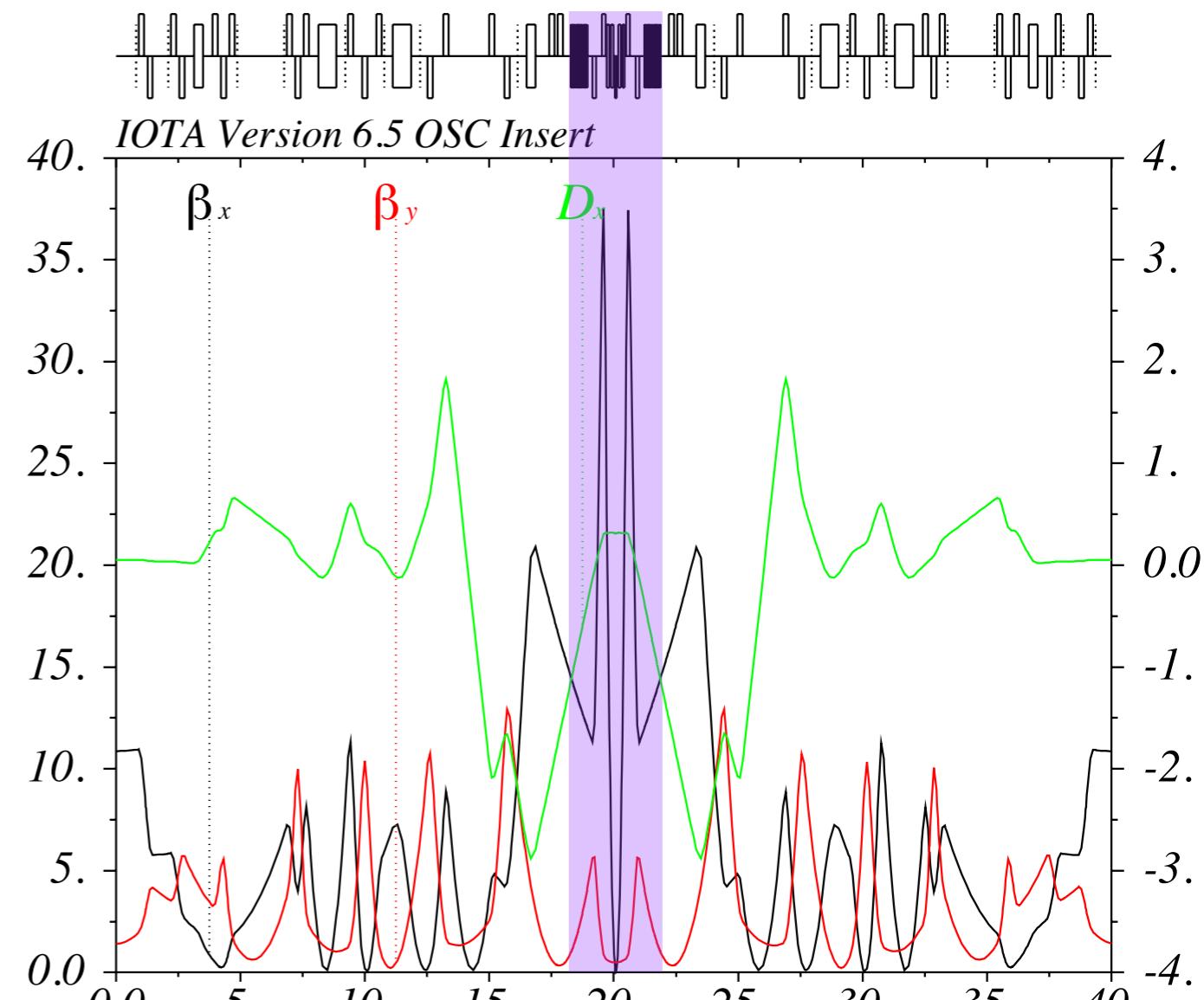
# 2 NONLINEAR MAGNET LATTICE

## IOTA Parameters in OSC mode

	Value
Circumference	40 m
Nominal Beam energy	100 MeV
Bending field	4.8 kG
Transverse RMS emittances,	11.5 nm
RMS momentum spread	$1.23 \times 10^{-6}$
SR damping times (ampl.),	1.4 / 0.67 s

## Cooling Chicane Parameters

	Value
Delay in the chicane, $\Delta s$	2 mm
Horizontal beam offset, $h$	2.01 cm
$M_{56}$	4.8 kG
$D^*$	30 cm / 0.8 cm
Cooling rates ratio, $\lambda_x = \lambda_y / \lambda_s$	1.18
Cooling ranges (before OSC)	2.1 / 3.2
Dipole: magnetic field * length	4.22 kG * 10 cm
Strength of central quad, GdL	1.58 kG



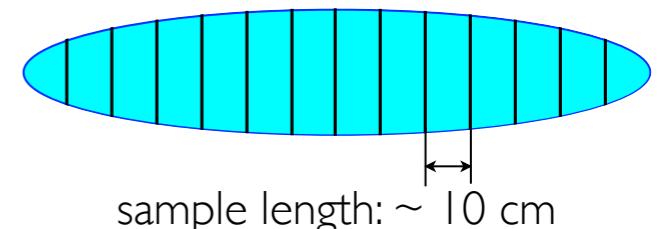
# OSC PRINCIPLES

- ▶ Microwave stochastic cooling suggested by Van der Meer (1969)
- ▶ OSC was suggested by Zolotorev, Zholents and Mikhailichenko (1994)

$$\lambda f_0 \approx \frac{W}{N} \Leftrightarrow \lambda \approx \frac{1}{N_{sample}}$$

- ▶ OSC works like MICROWAVE STOCHASTIC COOLING, but
  - exploits the superior bandwidth of optical amplifiers  $\sim 10^{14}$  Hz.
  - can deliver damping rates 4 orders of magnitude larger
- ▶ UNDULATORS suggested to be used for both the PICKUP and KICKER in order to support the same optical range as the amplifier

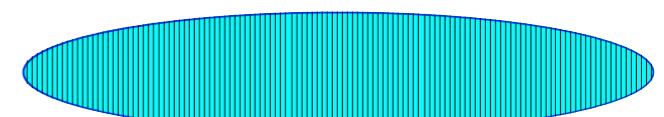
MICROWAVE SLICING



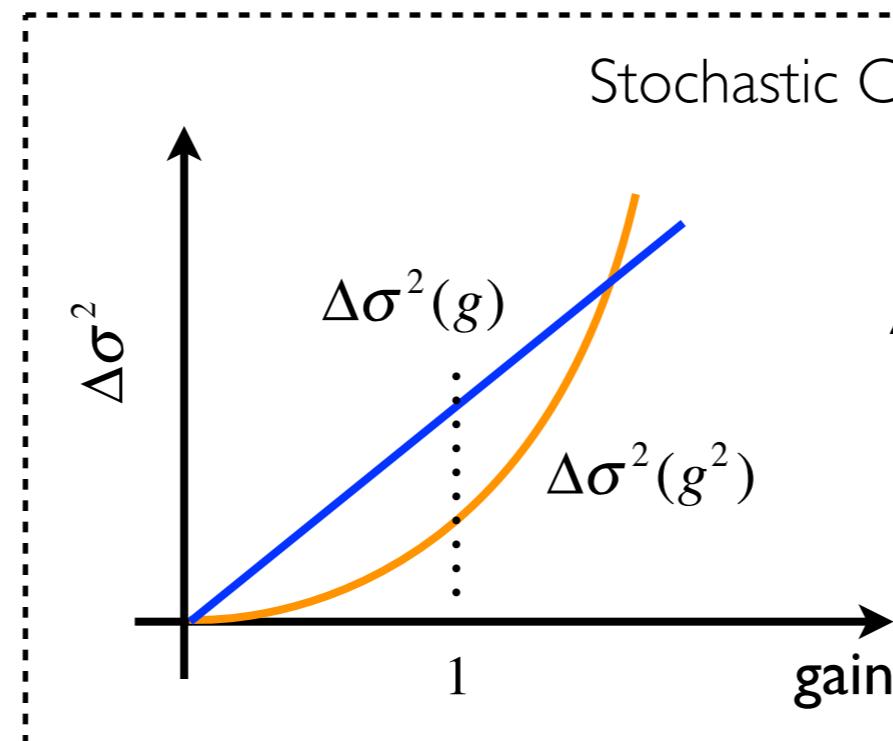
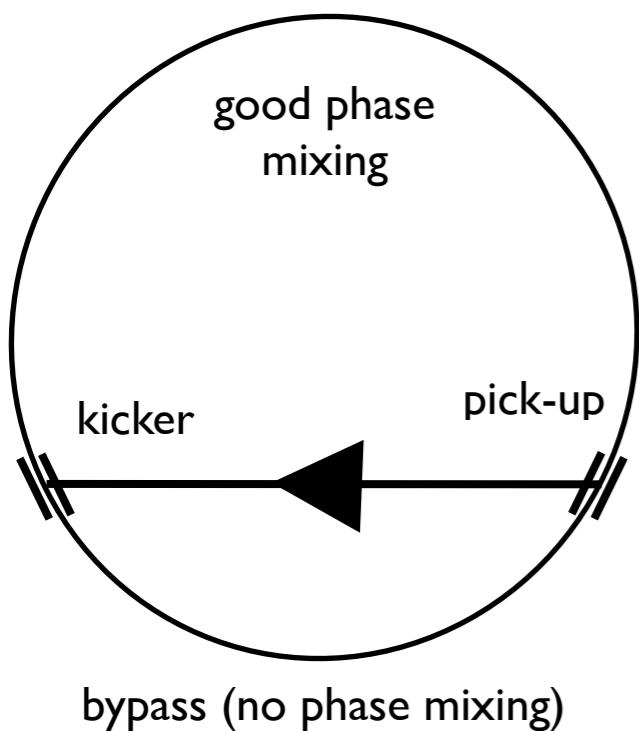
sample length:  $\sim 10$  cm

$$N_{sample} = N \frac{\Delta\ell}{\ell_b}$$

OPTICAL SLICING



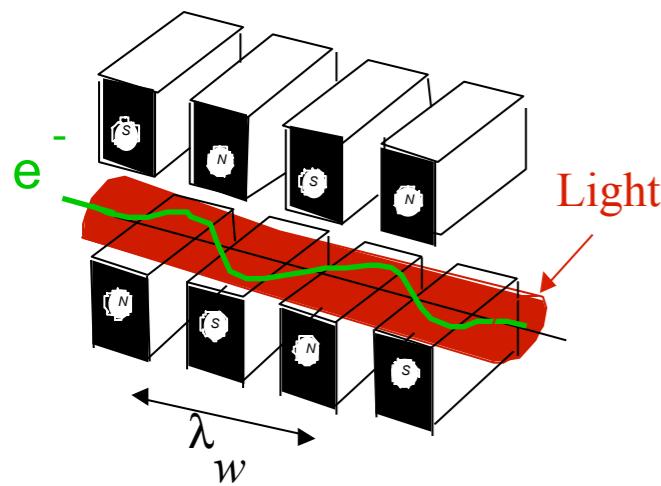
sample length:  $\sim 1$  um



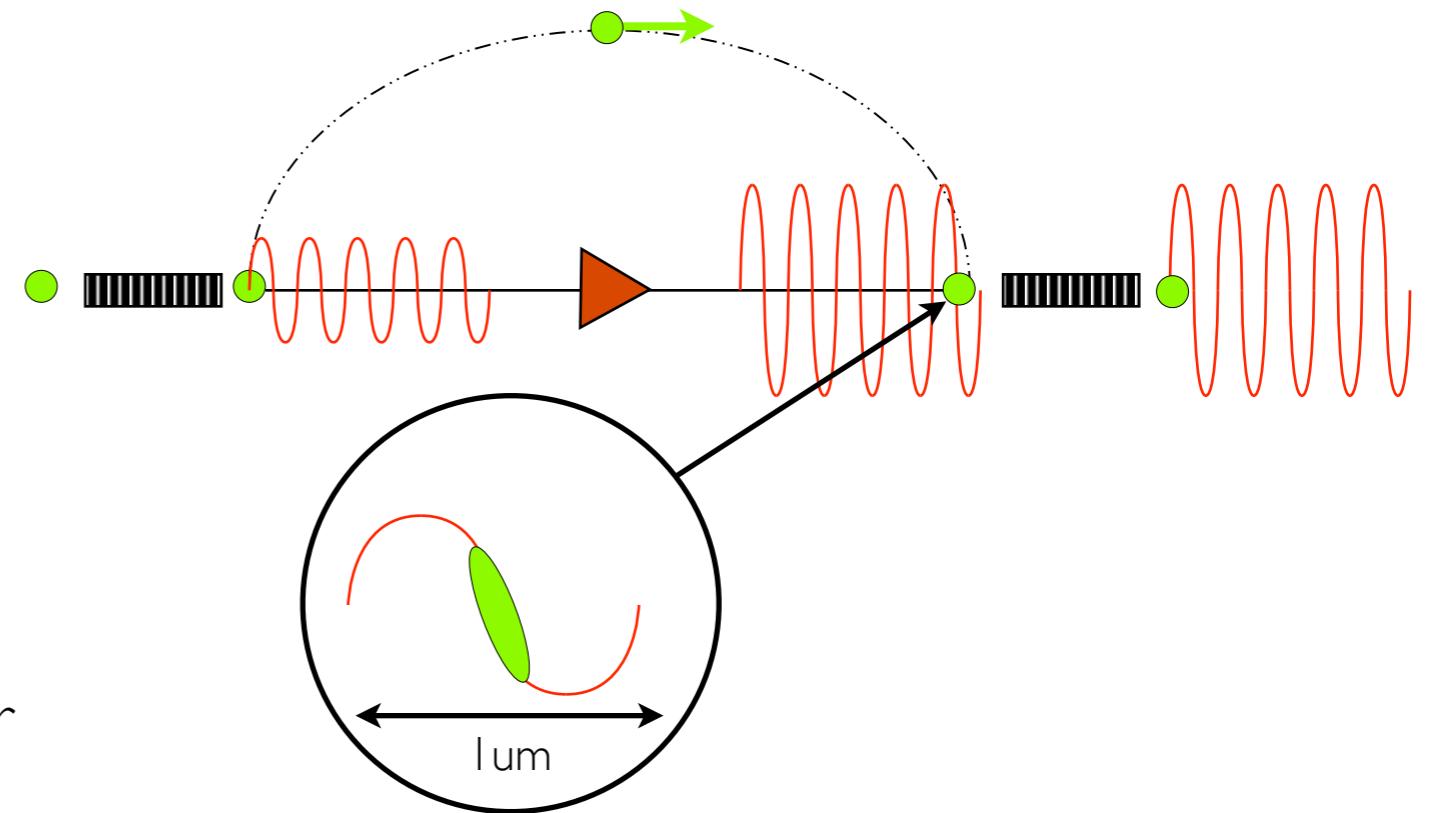
$$\Delta x(t) = -\frac{g}{N} x_i(t) + \frac{g}{N} \sum_{k \neq i}^N x_k(t)$$

$$-\frac{\Delta(x^2)}{x_{rms}^2} = \frac{2g - g^2}{N_S}$$

# OSC PRINCIPLES



$$\text{undulator period} \downarrow \quad \lambda_w = \frac{2\gamma^2 \lambda_L}{\left(1 + \frac{K^2}{2}\right)} \quad \begin{matrix} \text{laser wavelength} \\ \text{undulator parameter} \end{matrix}$$



Only longitudinal kicks are effective for cooling:

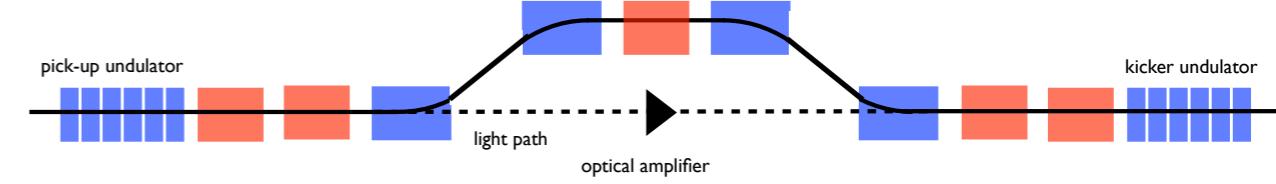
$$\Delta\delta_i = \kappa \sin(k\Delta s_i) - \kappa \sum_{k \neq i}^N \sin(k\Delta s_i + \psi_{ik})$$

↑  
particle delay

- ▶ At optimum cooling rate is:
  - $\sim(\text{bandwidth})/(\text{number of slices in the sample})$
- ▶ Correction signal is proportional to longitudinal position change
- ▶ Only longitudinal kicks are effective
  - longitudinal cooling requires s-x coupling
  - transverse cooling requires x-y coupling

► Pickup-to-kicker Transfer Matrix (vertical plane is uncoupled and omitted)

$$\begin{bmatrix} x \\ \theta_x \\ s \\ \Delta p / p \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & 0 & M_{16} \\ M_{21} & M_{22} & 0 & M_{26} \\ M_{51} & M_{52} & 1 & M_{56} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ \theta_x \\ s \\ \Delta p / p \end{bmatrix}$$



► Partial slip factor (pickup-to-kicker) describes a particle's longitudinal displacement

$$\tilde{M}_{56} = C\eta_{pk} = M_{51}D_p + M_{52}D'_p + M_{56}$$

► First order approximation of the longitudinal kick in the pickup:

$$\Delta\delta = \kappa\Delta s = \kappa \left( M_{51}x + M_{52}\theta_x + M_{56} \frac{\Delta p}{p} \right)$$

► Cooling rates per turn:

$$\begin{bmatrix} \lambda_x \\ \lambda_s \end{bmatrix} = \frac{\kappa}{2} \begin{bmatrix} M_{56} - \tilde{M}_{56} \\ C\eta_{pk} \end{bmatrix}$$

► x-y coupling outside the bypass allows for redistribution of horizontal damping rate into both transverse planes

# OSC PRINCIPLES

## Cooling Range

- ▶ Cooling force depends on  $\Delta s$  nonlinearly:

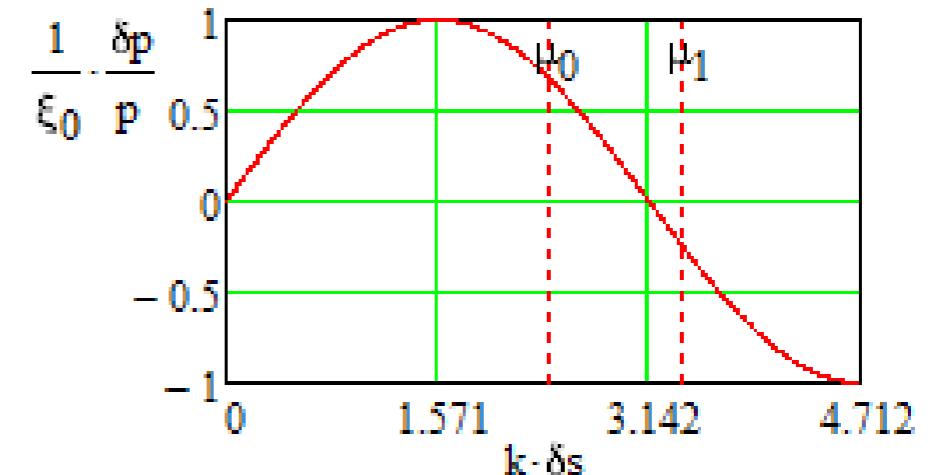
$$\Delta \delta = \kappa \sin(k\Delta s)$$

- ▶ where  $k\Delta s = a_x \sin(\psi_x) + a_p \sin(\psi_p)$

- ▶  $a_x$  and  $a_p$  are the amplitudes of longitudinal displacements in cooling chicane due to transverse and longitudinal motions (betatron and synchrotron radiation) in units of laser space
- ▶ Damping requires both lengthening amplitudes ( $a_x$  and  $a_p$ ) to be smaller than  $\mu_0 = 2.405 \rightarrow$  this determines the cooling area boundary

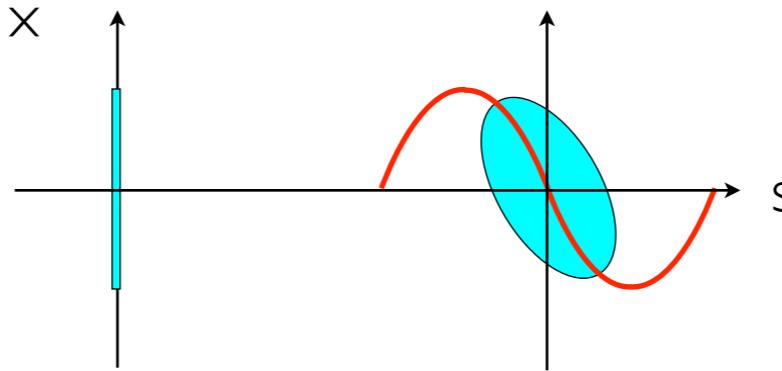
## Optical Amplifier

- ▶ Ti: Sapphire Optical Amplifier (2mm thick)
  - ▶ wide bandwidth
  - ▶ can deliver significant amplification with only  $\sim 1$  mm delay
  - ▶ Allows operation in CW regime



# OSC OPTICS

- A zero length sample will lengthen on its way from the pickup to the kicker



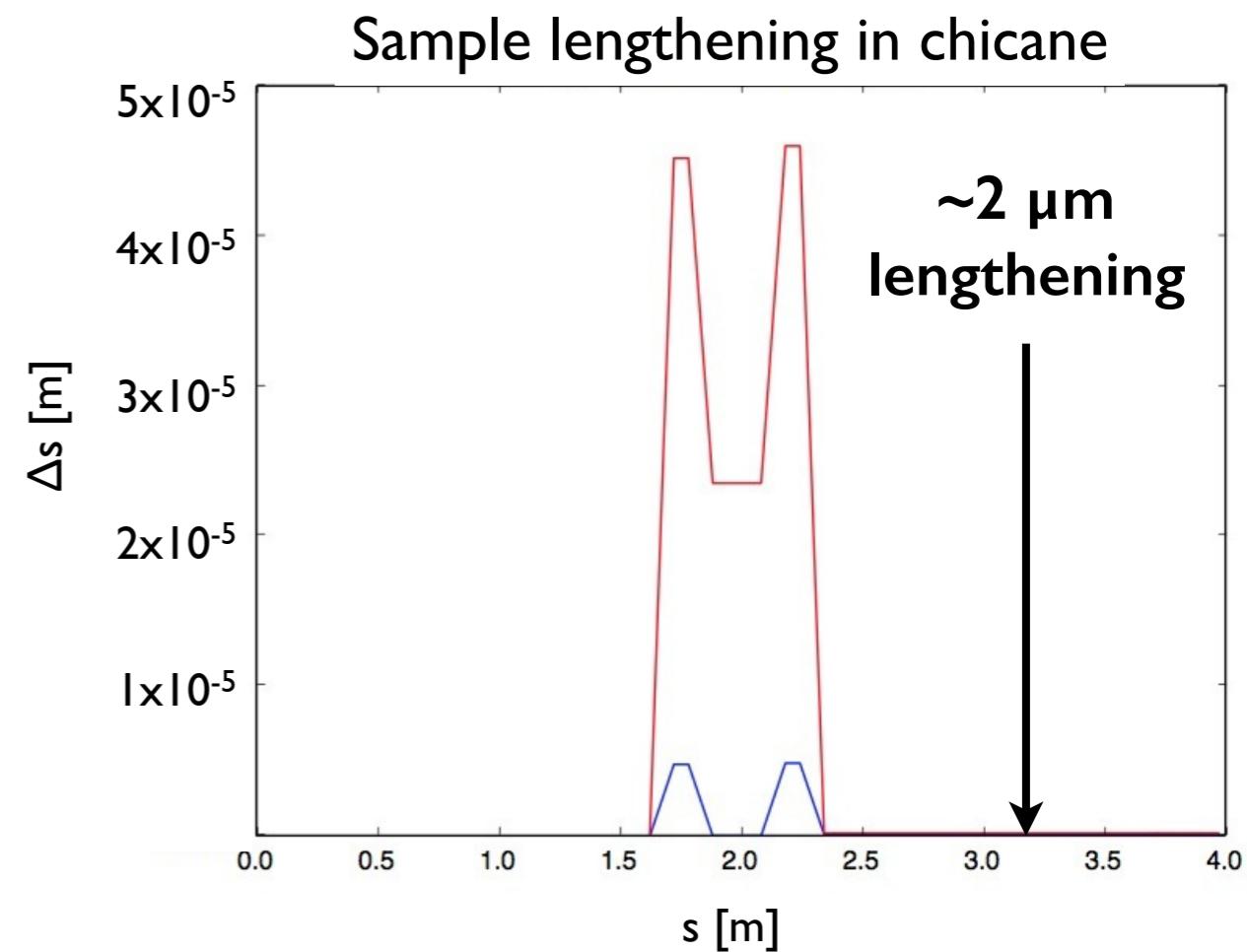
- Both  $\Delta p/p$  and  $\varepsilon$  contribute to the sample lengthening  $\sigma_{\Delta s}^2 = \sigma_{\Delta s\varepsilon}^2 + \sigma_{\Delta sp}^2$

- For a Gaussian distribution:

$$\sigma_{\Delta s\varepsilon}^2 = \varepsilon (\beta_p M_{51}^2 - 2\alpha_p M_{51}M_{52} + \gamma_p M_{52}^2)$$

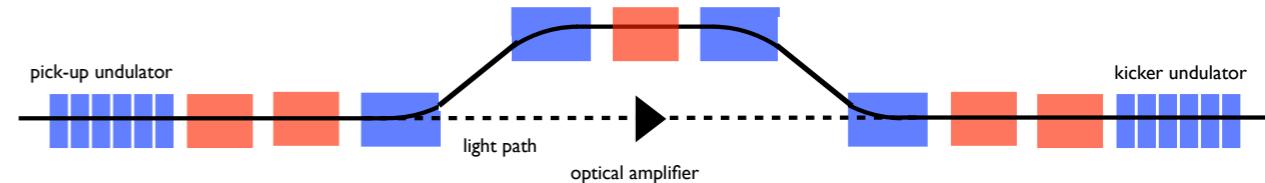
$$\sigma_{\Delta sp}^2 = \sigma_p^2 (M_{51}D_p - M_{52}D'_p + M_{56})^2$$

- In the linear approximation,  $\beta_p$  and  $\alpha_p$  do not affect damping rates, but affect sample lengthening and consequently the cooling range



# OSC OPTICS

- ▶ The first approximation of cooling dynamics are determined by the:
  - orbit offset,  $h$
  - path lengthening,  $\delta s$
  - defocusing strength of the chicane quad,  $\Phi$
  - $D^*$  and  $\beta^*$  in the center of the chicane
- ▶  $\delta s$  is set by the delay in the amplifier
- ▶  $\Phi D^* h$  is set by the ratio of decrements
- ▶ The dispersion invariant,  $A$ , in the dipoles determines the equilibrium emittance.



$$M_{56} \approx 2\Delta s,$$

$$\tilde{M}_{56} \approx 2\Delta s - \Phi D^* h,$$

$$\lambda_x / \lambda_s \approx \Phi D^* h / (2\Delta s - \Phi D^* h),$$

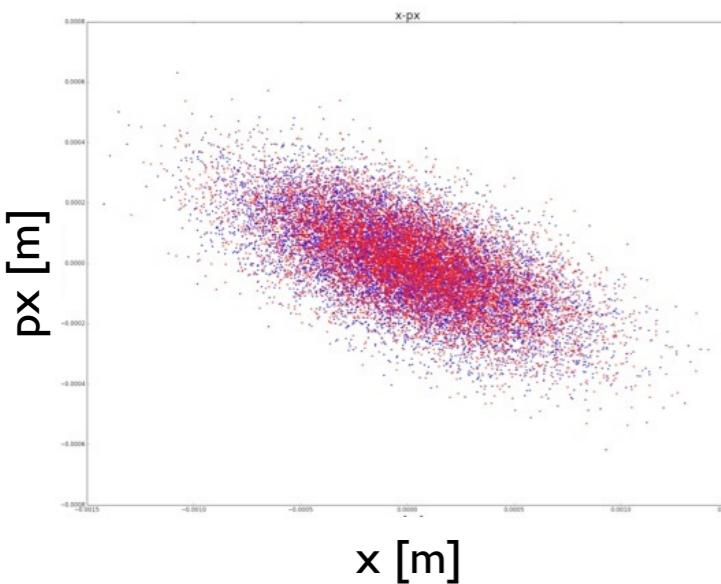
$$n_{\sigma x} \approx \frac{\mu_0}{k\sigma_p} (2\Delta s - \Phi D^* h),$$

$$n_{\sigma x} \approx \frac{\mu_0}{2kh\Phi\sqrt{\varepsilon\beta^*}},$$

$$\Phi D^* h \approx \frac{\mu_0}{2kn_{\sigma x}} \sqrt{\frac{A^*}{\varepsilon}}$$

# OSC SECOND ORDER OPTICS

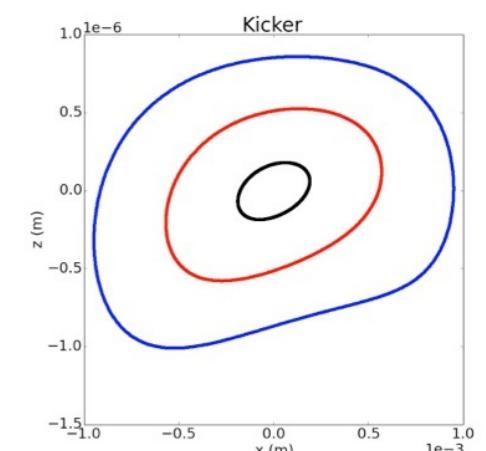
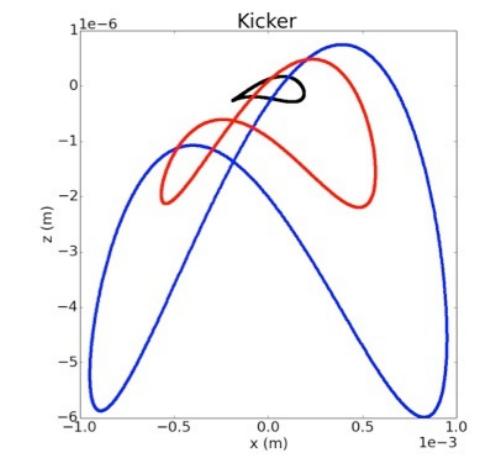
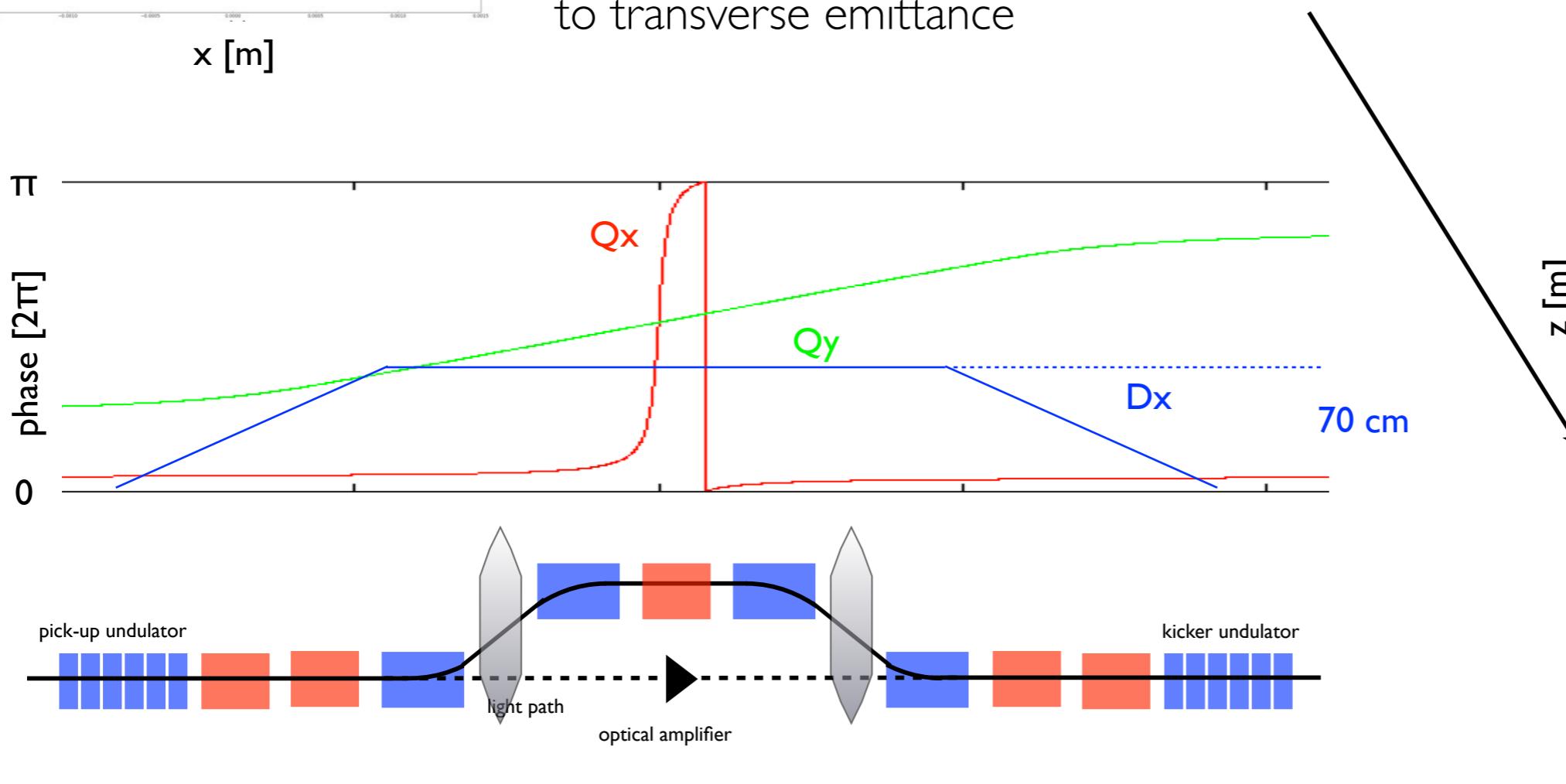
Using a realistic IOTA beam to develop second order optics



$$\Sigma_{beam} = V_{[6 \times 6]} \mathcal{E}_{[6 \times 6]} V^T_{[6 \times 6]} =$$

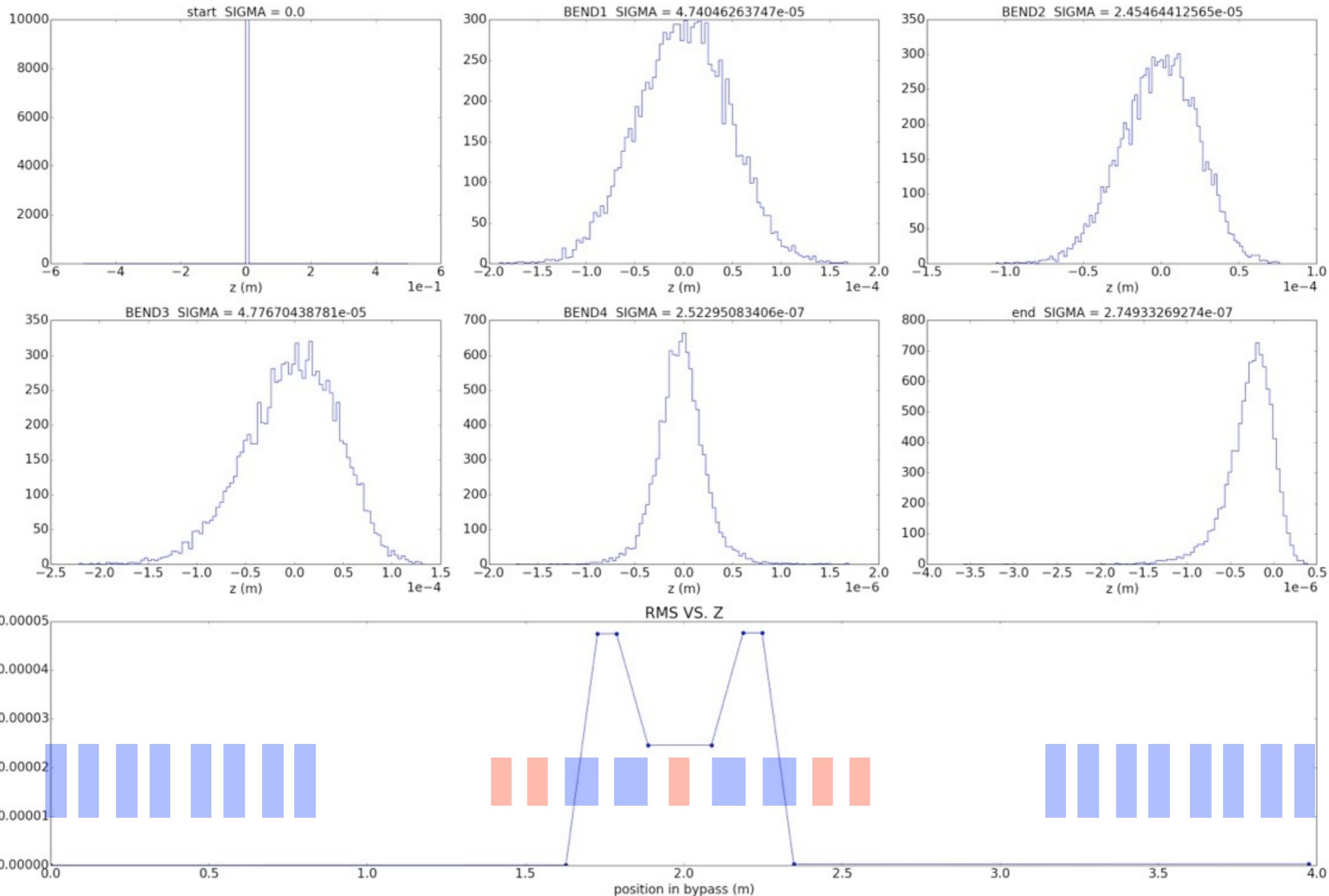
$$[[ 1.417e-07 \quad -3.479e-08 \quad 0. \quad 0. \quad 0. \quad 1.185e-07 \quad -1.893e-08 \\ -3.479e-08 \quad 2.131e-08 \quad 0. \quad 0. \quad 0. \quad -1.169e-08 \quad 1.627e-08 \\ 0. \quad 0. \quad 5.509e-09 \quad 7.390e-09 \quad 0. \quad 0. \quad 0. \\ 0. \quad 0. \quad 7.390e-09 \quad 3.693e-08 \quad 0. \quad 0. \quad 0. \\ 1.185e-07 \quad -1.169e-08 \quad 0. \quad 0. \quad 0. \quad 1.316e-04 \quad 9.088e-12 \\ -1.893e-08 \quad 1.627e-08 \quad 0. \quad 0. \quad 0. \quad 9.088e-12 \quad 1.427e-08 ]]$$

**SEXTUPOLES** to correct for path lengthening due to transverse emittance



$x$  [m]

# OSC BUNCH LENGTHENING



# OSC PARAMETERS

OSC Parameters	Value
Undulator parameter, K	0.6
Undulator period	4.92 cm
Radiation wavelength at zero angle	750 nm
Number of periods, m	10
Total undulator length, Lw	0.5 m
Length from OA to undulator center	1.65 m
Amplifier gain (amplitude)	10
Telescope aperture, 2a	7 mm
Damping rates (x=y/s)	160/140 s

- ▶ OSC will be tested with and without an optical amplifier