OPTICAL STOCHASTIC COOLING IN IOTA

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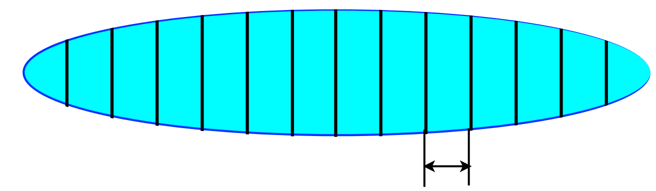
OSC PRINCIPLES

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

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

MICROWAVE SLICING

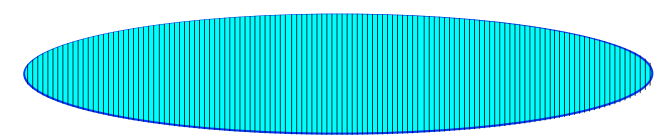


sample length: ~ 10 cm

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

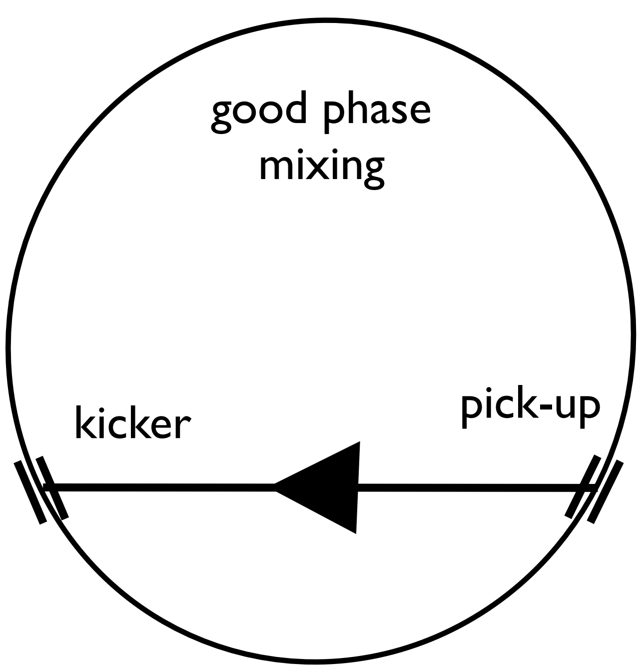
- **OSC works like** MICROWAVE STOCHASTIC COOLING, **but**
  - **exploits the superior bandwidth of optical amplifiers ~10^{14} Hz.**
  - **can deliver damping rates 4 orders of magnitude larger**

OPTICAL SLICING



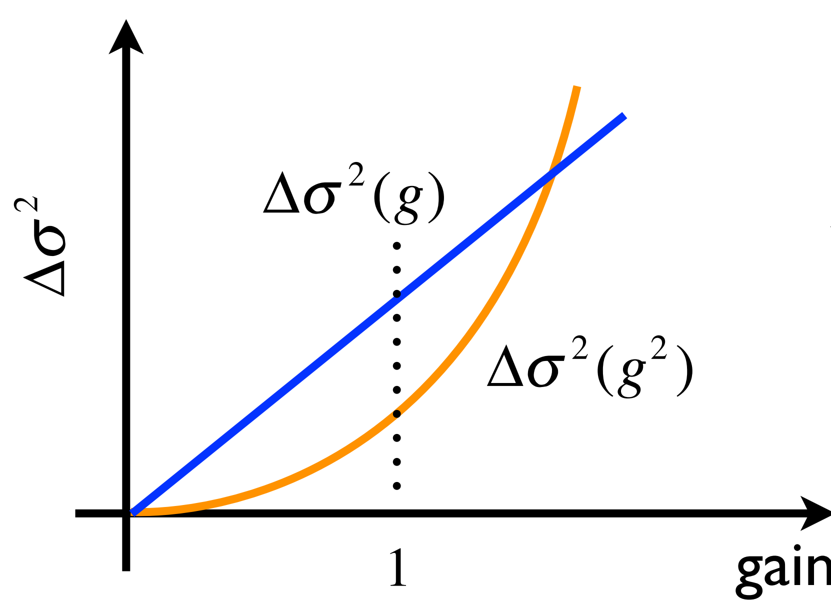
sample length: ~ 1 um

- UNDULATORS **suggested to be used for both the** PICKUP **and** KICKER **in order to support the same optical range as the amplifier**



bypass (no phase mixing)

Stochastic Cooling Basics



cooling / heating

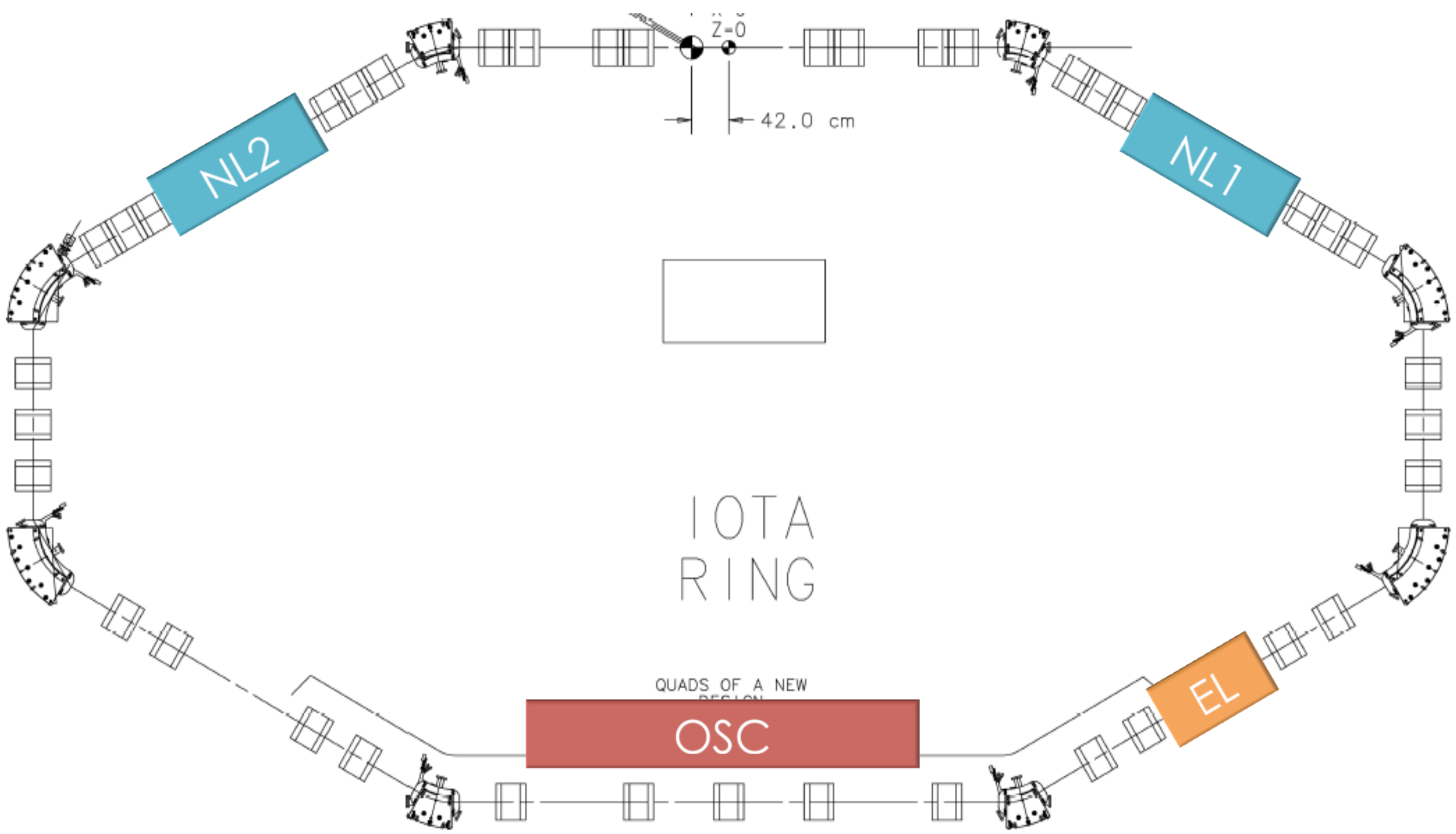
$$\Delta x(t) = \underbrace{-\frac{g}{N}x_i(t)}_{\text{cooling}} + \underbrace{\frac{g}{N}\sum_{k\neq i}^{N} x_k(t)}_{\text{heating}}$$

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

TEST OF OSC IN IOTA

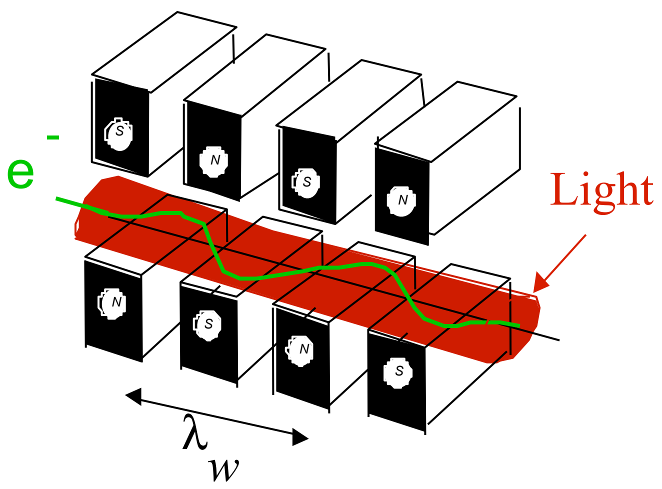
- OSC was first attempted in BATES in 2007
  - existing electron synchrotron
  - did not receive enough support
- Will be one of several tests in IOTA
  - test in small electron ring is cost effective

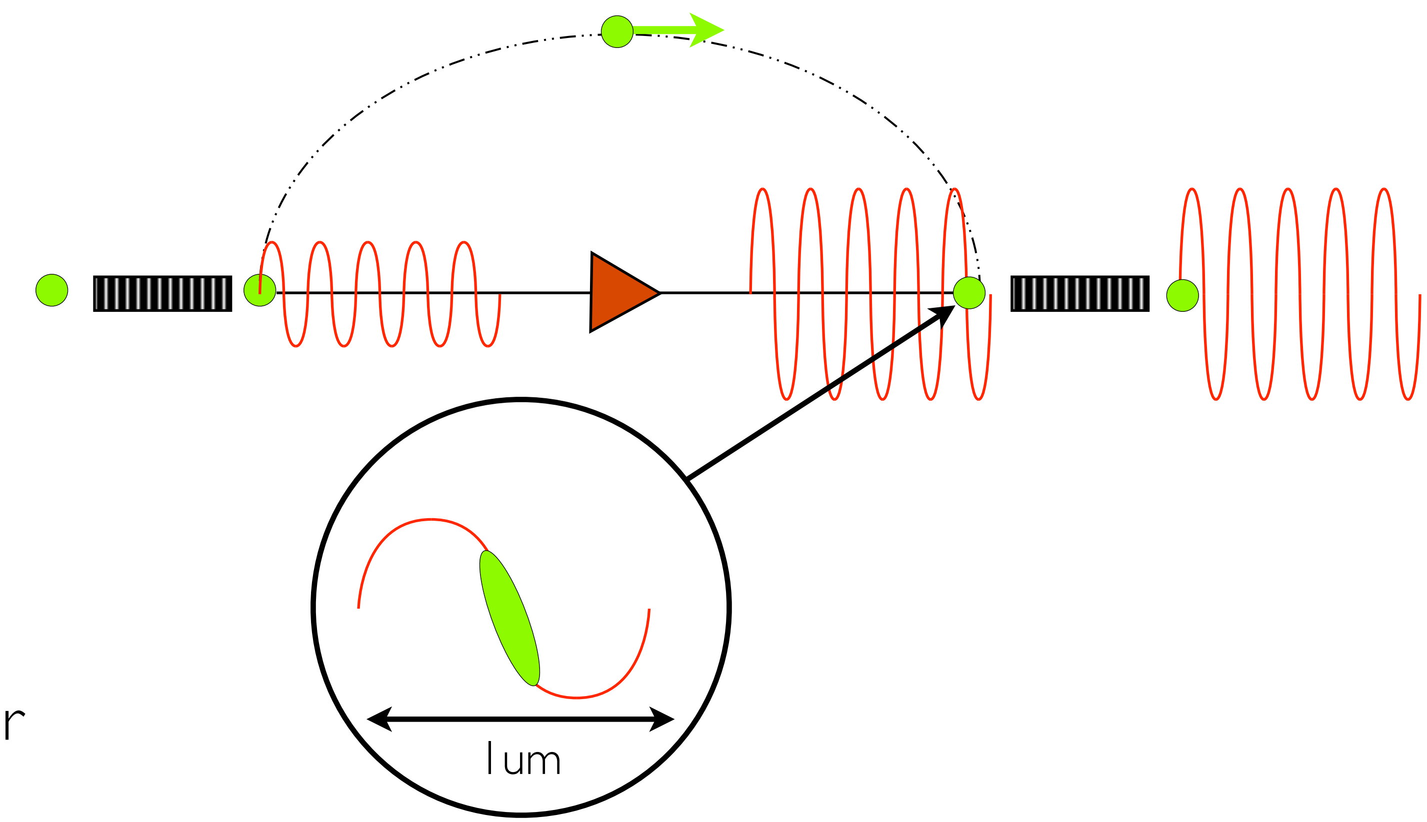
IOTA Parameters in OSC mode	Value
Circumference	40 m
Nominal Beam energy	100 MeV
Bending field	4.8 kG
Transverse RMS emittances, $\varepsilon_x=\varepsilon_y$	11.5 nm
RMS momentum spread	1.23×10^{-4}
SR damping times (ampl.),$\tau_s/(\tau_x)$	1.4 / 0.67 s



optical stochastic cooling insert

OSC PRINCIPLES





undulator period

laser wavelength

undulator parameter

$$\lambda_w = \frac{2\gamma^2 \lambda_L}{\left(1 + \frac{K^2}{2}\right)}$$

Only longitudinal kicks are effective for cooling:

cooling | heating

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

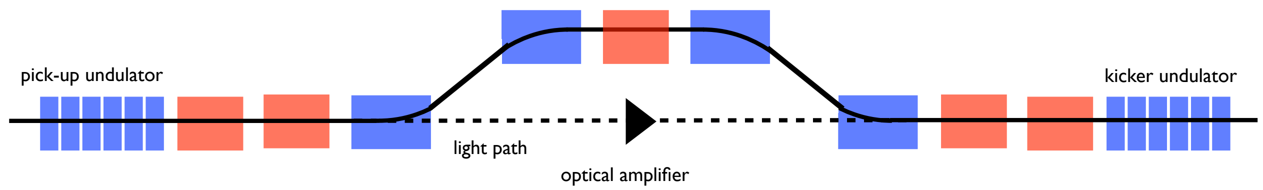
particle delay

- At optimum cooling rate is:
  - ~(bandwidth)/(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

OSC OPTICS

- 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:

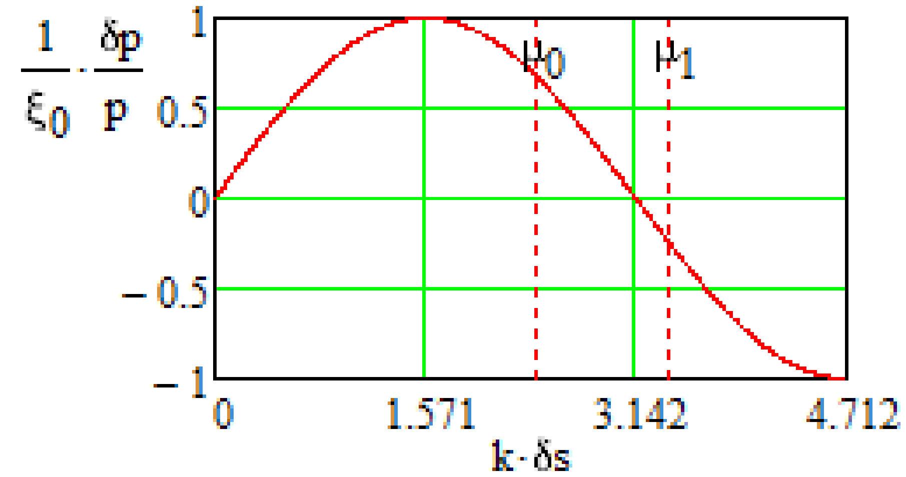
$$\Delta\delta = \kappa\Delta s = \kappa\left(M_{51}x + M_{52}\theta_x + M_{56}\tfrac{\Delta p}{p}\right)$$

- 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

Cooling Range



- Cooling force depends on Δs 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 μ_0 = 2.405 → this determines the cooling area boundary

Optical Amplifier

- Ti: Sapphire Optical Amplifier (2mm thick)
  - wide bandwith
  - can deliver significant amplification with only ~1 mm delay
  - Allows operation in CW regime

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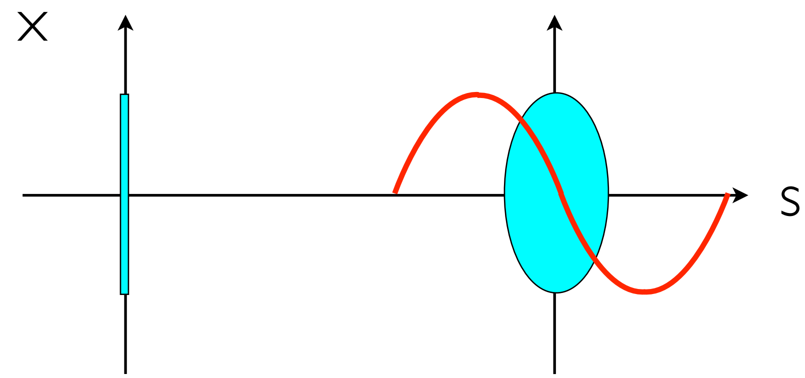
OSC OPTICS

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

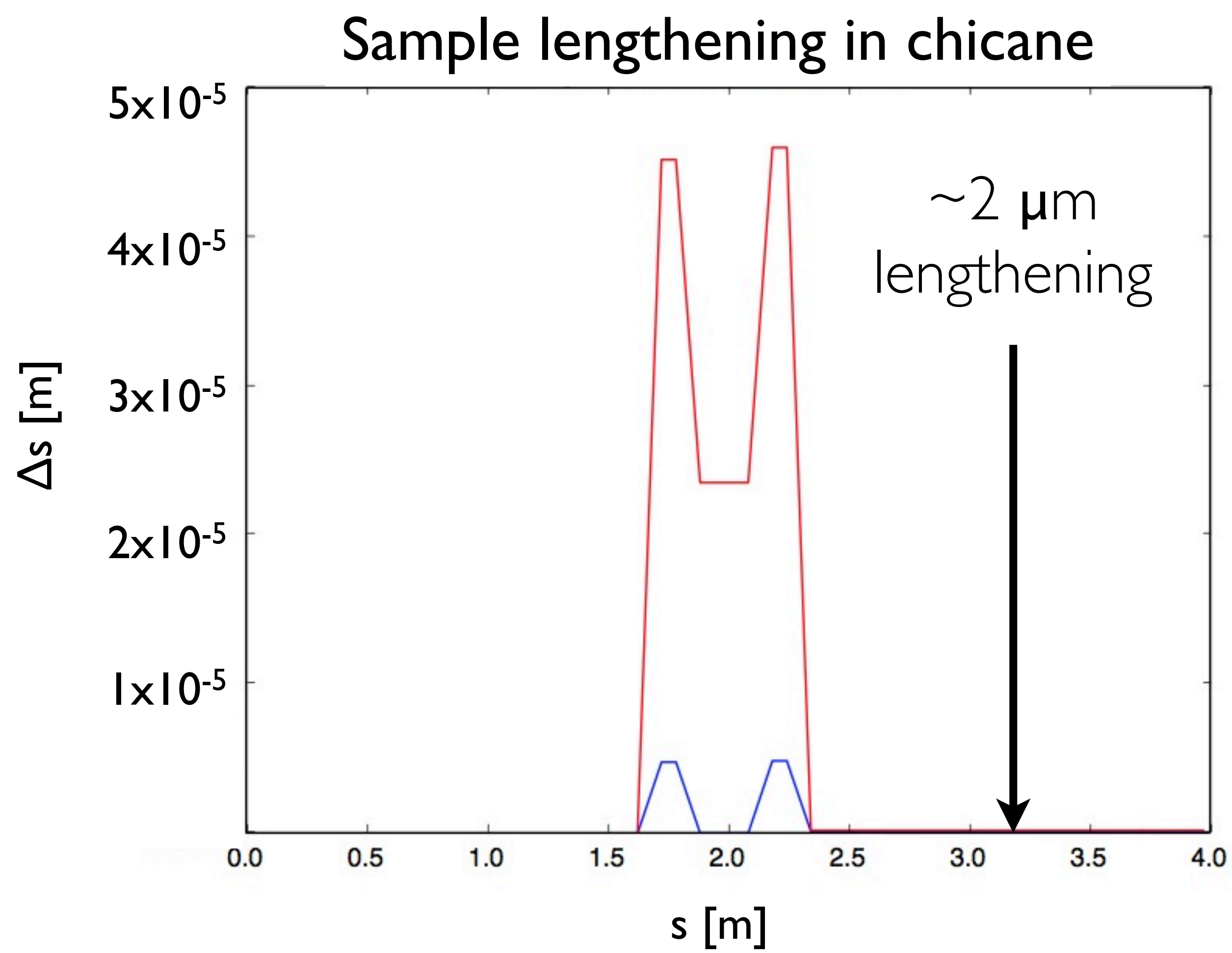


- Both Δp/p and ε contribute to the sample lengthening $\sigma_{\Delta s}^2 = \sigma_{\Delta s\varepsilon}^2 + \sigma_{\Delta sp}^2$
  - For a Gaussian distribution:

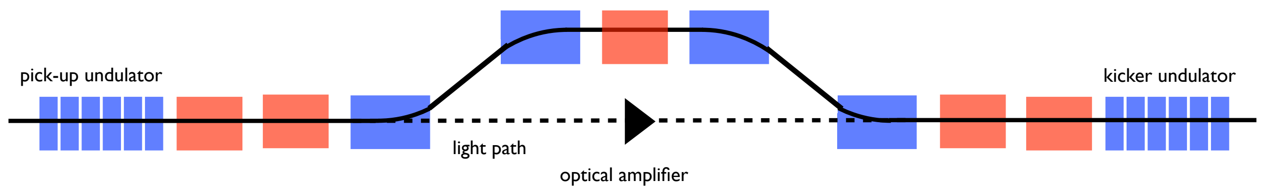
$$\sigma_{\Delta s\varepsilon}^2 = \varepsilon\left(\beta_p M_{51}^2 - 2\alpha_p M_{51} M_{52} + \gamma_p M_{52}^2\right)$$

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

- In the linear approximation, β_p and α_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, δs
  - defocusing strength of the chicane quad, Φ
  - D^* and β^* in the center of the chicane
- δs 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.

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

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

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

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

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

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

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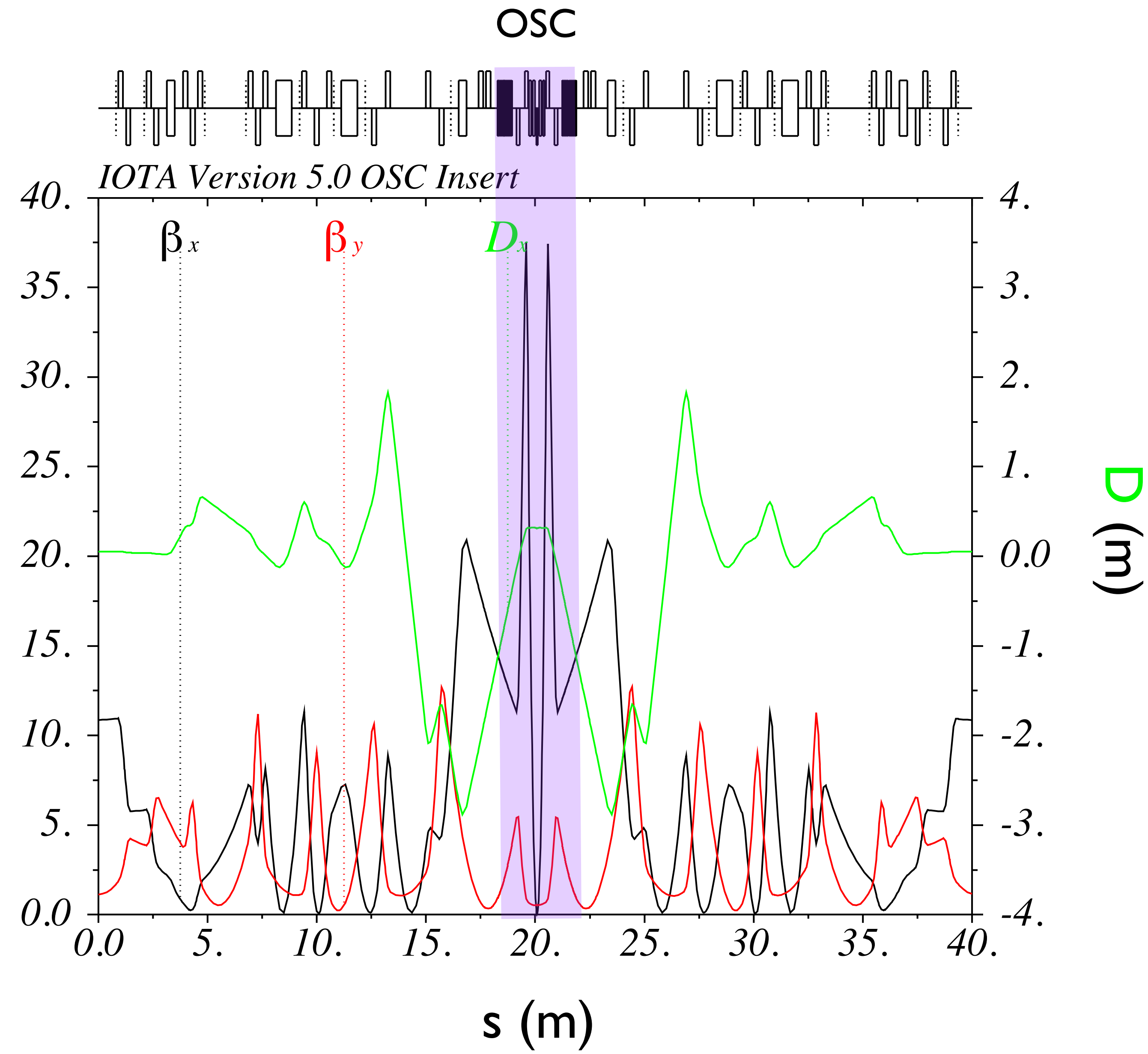
OSC OPTICS

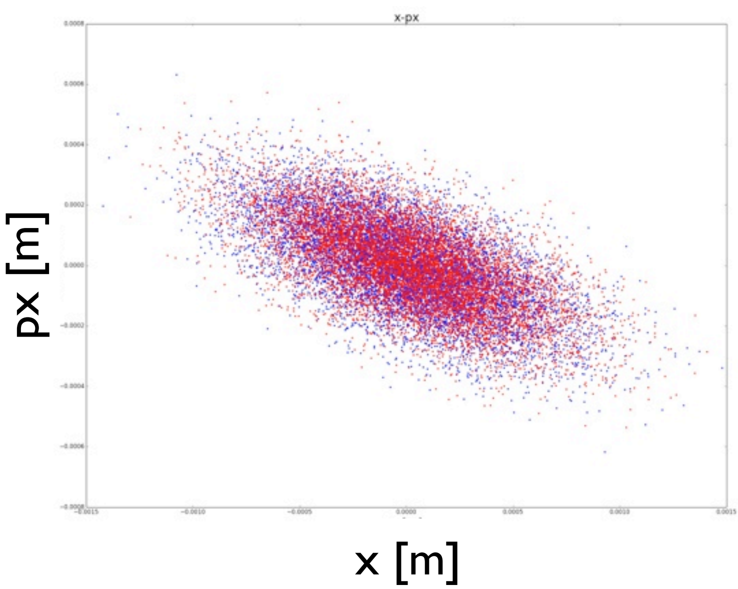
Cooling Chicane Parameters	Value
Delay in the chicane, Δs	2 mm
Horizontal beam offset, *h*	2.01 cm
M_{56}	4.8 kG
D^*/β^*	30 cm / 0.8 cm
Cooling rates ratio, $\lambda x = \lambda y / \lambda s$	1.18
Cooling ranges (before OSC)	2.1 / 3.2
Dipole: magnetic field * length	4.22 kG * 10 cm
Strength of central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



- Energy reduced from 150 MeV to reduce ε, σ_p and undulator period and length
- Operating at the coupling resonance Qx/Qy=6.36/2.36 reduces horizontal emittance and introduces vertical damping
- Small β^* is required to minimize sample lengthening due to betatron motion

OSC SECOND ORDER OPTICS

Using a realistic IOTA beam to develop second order optics



$$\Sigma_{beam} = V_{[6\times6]}\varepsilon_{[6\times6]}V^T_{[6\times6]} =$$

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[[  1.417e-07  -3.479e-08   0.          0.          1.185e-07  -1.893e-08]
 [ -3.479e-08   2.131e-08   0.          0.         -1.169e-08   1.627e-08]
 [  0.          0.          5.509e-09   7.390e-09   0.          0.       ]
 [  0.          0.          7.390e-09   3.693e-08   0.          0.       ]
 [  1.185e-07  -1.169e-08   0.          0.          1.316e-04   9.088e-12]
 [ -1.893e-08   1.627e-08   0.          0.          9.088e-12   1.427e-08]]
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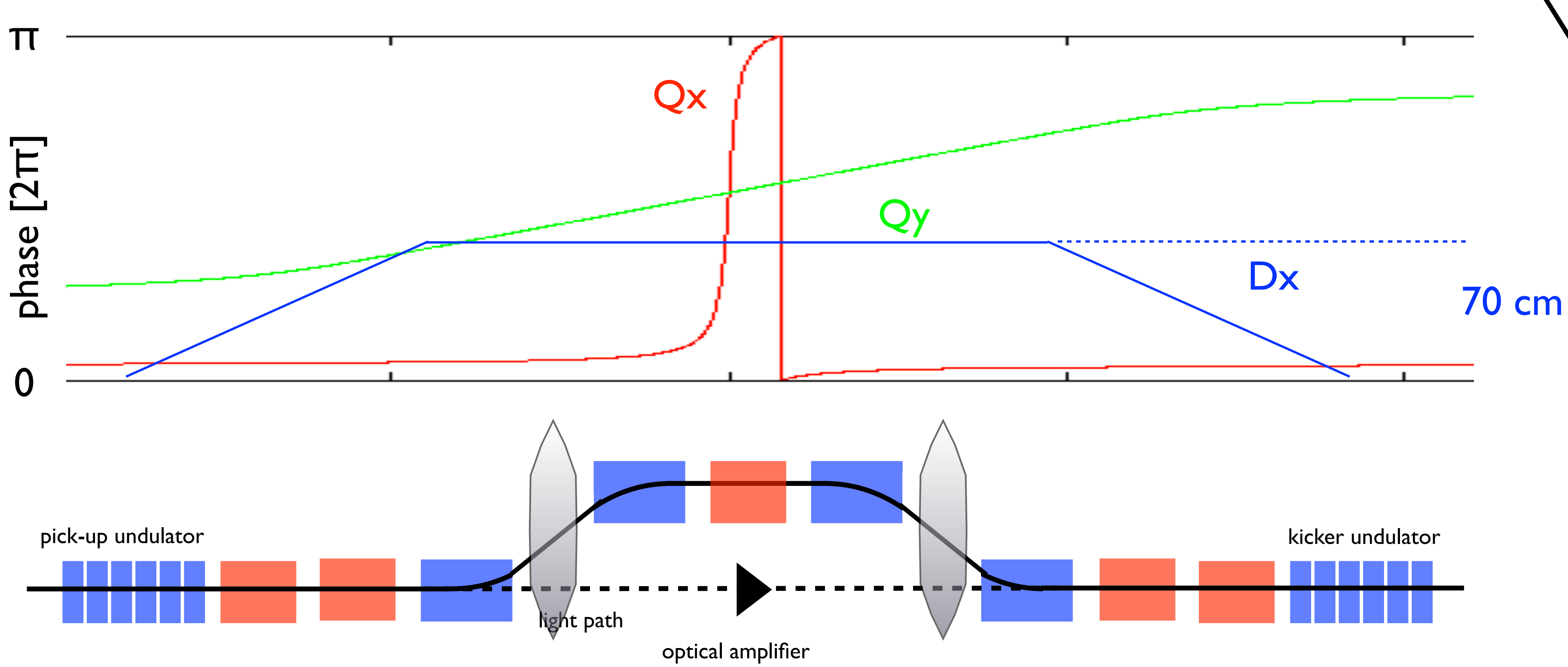
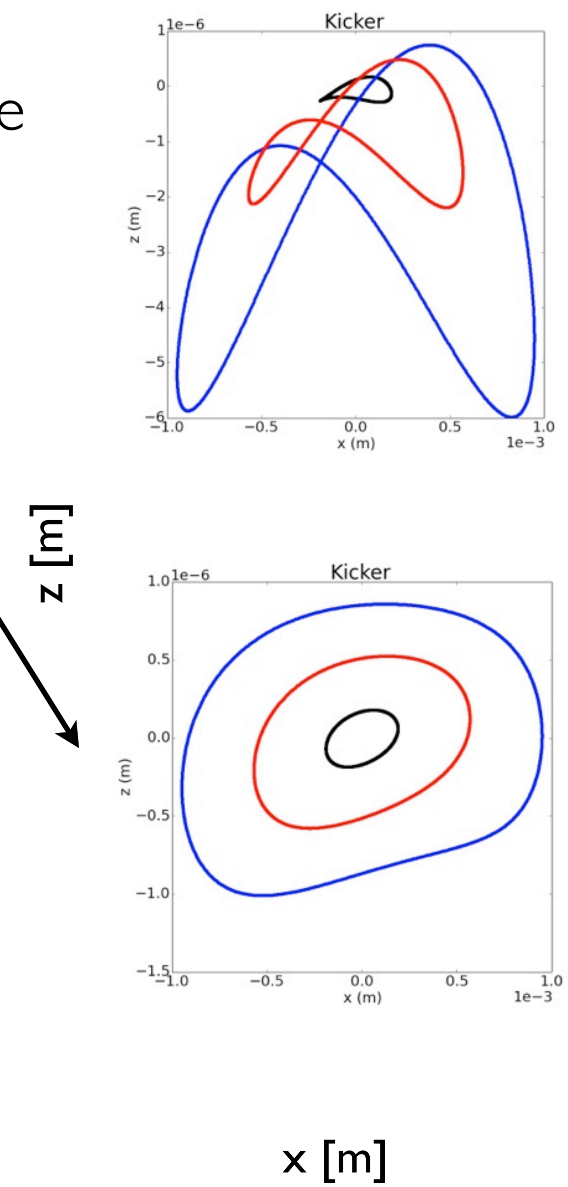
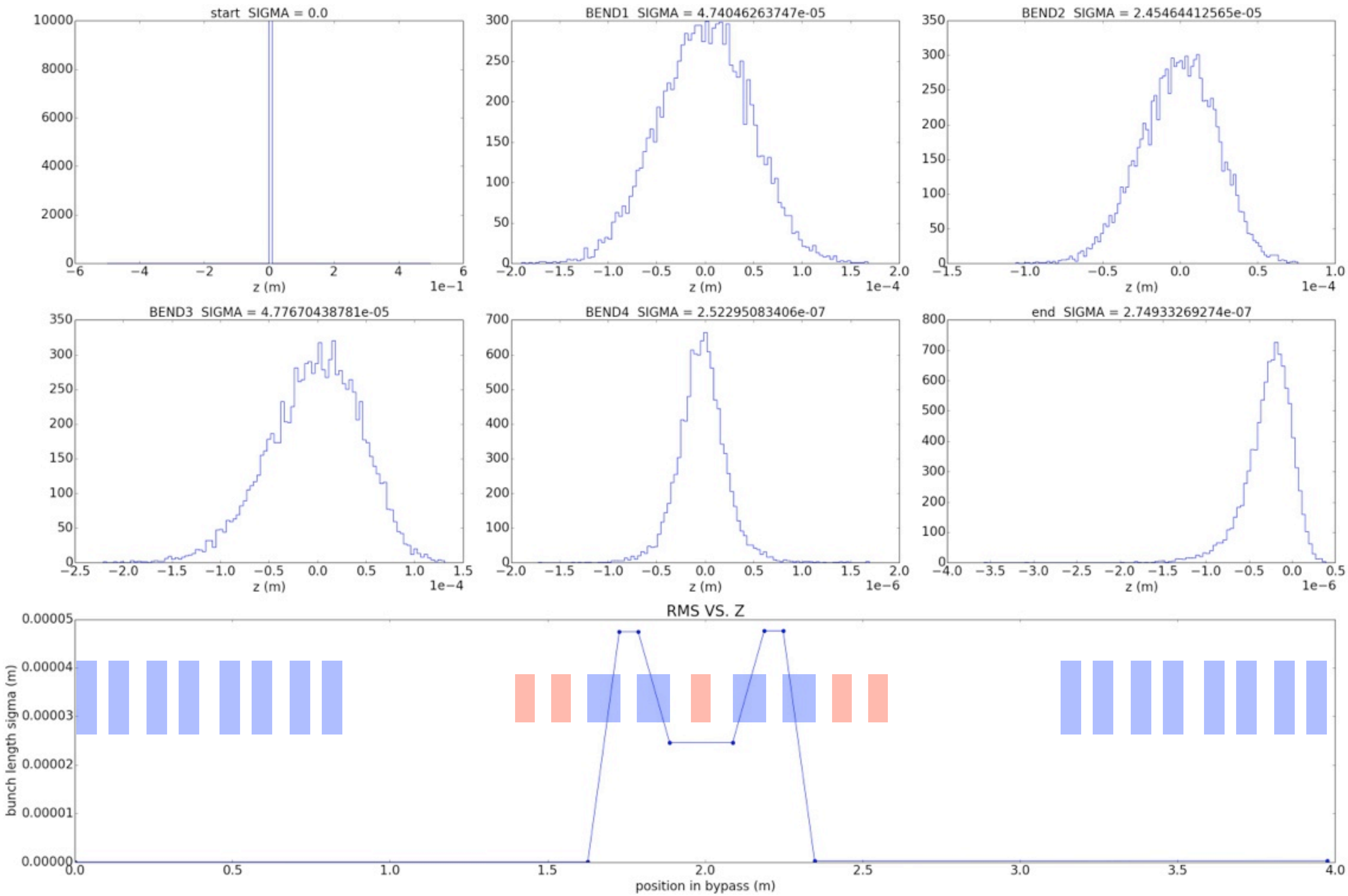
SEXTUPOLES to correct for path lengthening due to transverse emittance





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^{-1}

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

CONCLUSION

- Optics for OSC in ASTA has been developed, but the details are still being worked out; no show-stoppers have been identified.
  - will aim to demonstrate cooling with and without an amplifier; the latter having a damping time that exceeds SR damping by about an order of magnitude