TEST OF OPTICAL STOCHASTIC COOLING IN THE IOTA RING

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Contents

- Introduction to Optical Stochastic Cooling
- Basics of Optical Stochastic Cooling
- Optical Stochastic Cooling at IOTA ring
- Discussion

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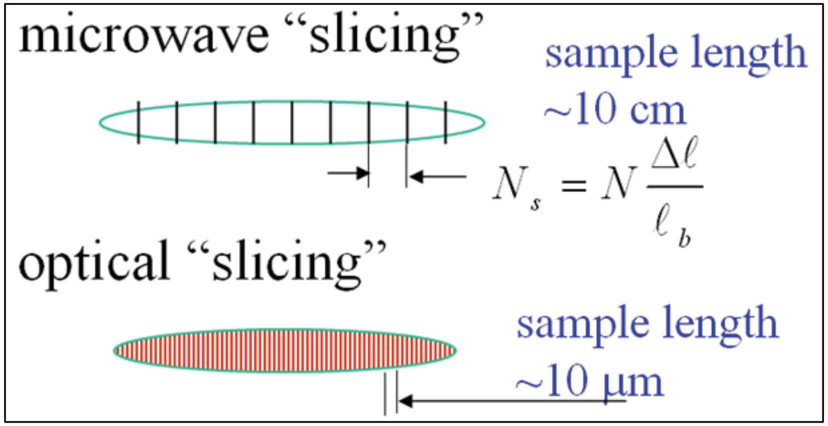
Principles of Optical Stochastic Cooling

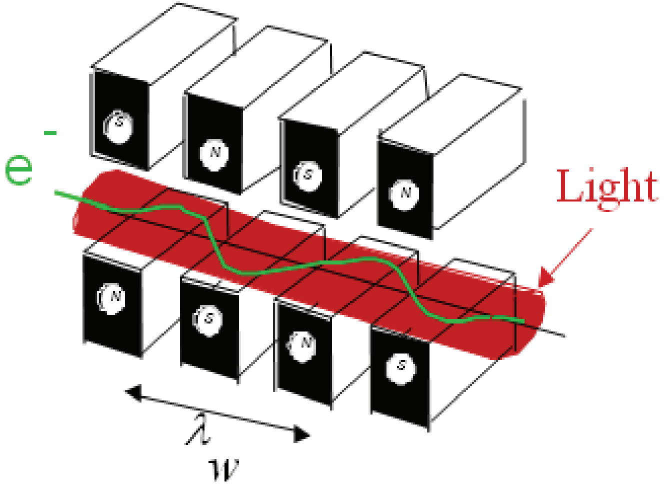
- At optimum the cooling rates of stochastic cooling are

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

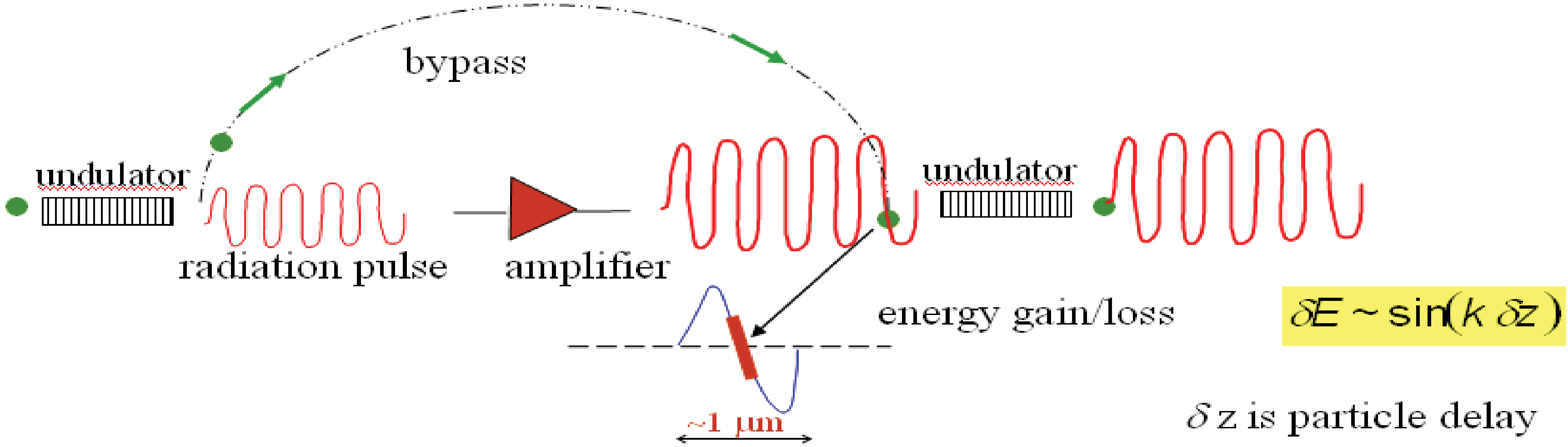


$$N_s = N\frac{\Delta\ell}{\ell_b}$$

- OSC was suggested by Zolotorev, Zholents and Mikhailichenko (1994)
- OSC obeys the same principles as the microwave stochastic cooling, but exploits the superior bandwidth of optical amplifiers ~ 10^{14} Hz
  - can deliver damping rates 4 orders of magnitude larger than usual (microwave) stochastic cooling
- Pickup and kicker must work in the optical range and support the same bandwidth as the amplifier
  - Undulators were suggested for both pickups and kickers

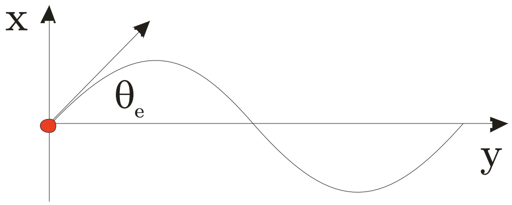


Principles of Optical Stochastic Cooling (continue)



- OSC can operate only with ultra-relativistic particles
  - Slow particles do not radiate at optical frequencies
- Radiation wave length

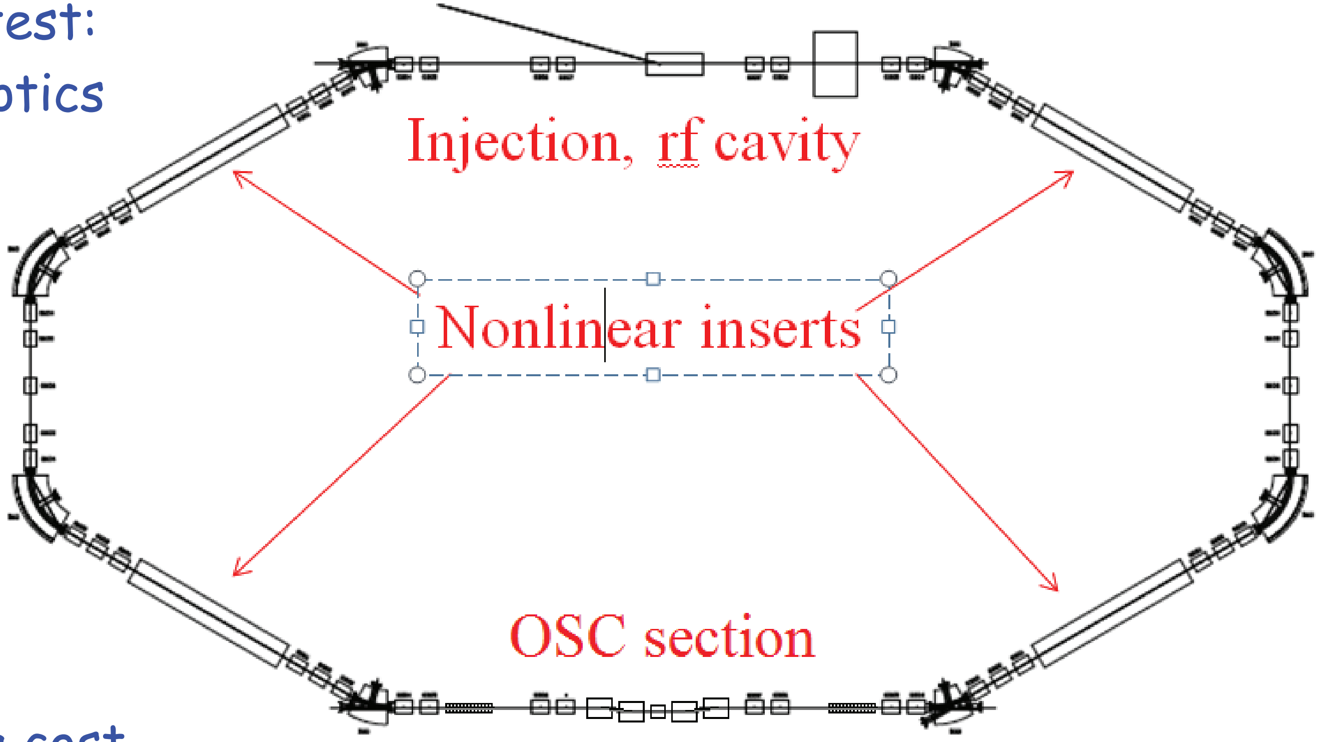
$$\lambda = \frac{\lambda_{wgl}}{2\gamma^2}\begin{cases}\left(1+\gamma^2\left(\theta_e^{\,2}+\theta^2\right)\right) & -\ helical\ undulator\\ \left(1+\gamma^2\left(\dfrac{1}{2}\theta_e^{\,2}+\theta^2\right)\right) & -\ flat\ undulator\end{cases}$$



- Correction signal is proportional to longitudinal position change on the travel from pickup to kicker
- Only longitudinal kicks are effective
  - Requires s-x coupling for L cooling and x-y coupling for ⊥ cooling

Test of OSC in Fermilab

- First attempt to test the OSC in BATES, ~2007
    - Existing electron synchrotron
    - Did not get sufficient support
- Presently Fermilab is constructing a dual purpose small electron ring called IOTA to test:
    - Integrable optics
    - OSC
- Part of ASTA program
    - Full energy injection from SC linac
- Test in a small electron ring is a cost effective way to test the OSC

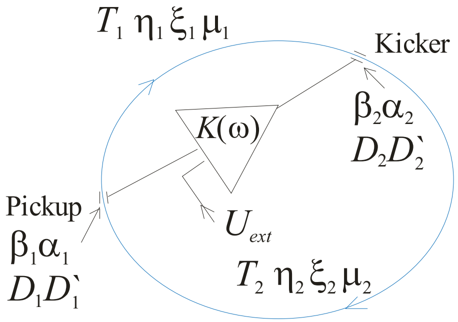


Injection, rf cavity

Nonlinear inserts

OSC section

Basics of OSC - Damping Rates



- Pickup-to-Kicker Transfer Matrix
  - Vertical plane is uncoupled and we omit it

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

M^{pk} - pickup-to-kicker matrix
M^{kp} - kicker-to-pickup matrix
M = M^{pk}M^{kp} - ring matrix

- Partial slip factor (pickup-to-kicker) describes a longitudinal particle displacement in the course of synchrotron motion

$$\tilde{M}_{56} = M_{51} D_1 + M_{52} D_1' + M_{56}$$

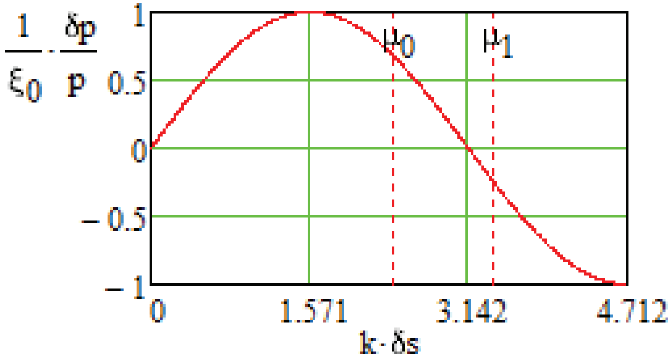
- Linearized longitudinal kick in pickup wiggler

$$\frac{\delta p}{p} = k \xi_0\, \Delta s = k \xi_0 \left(M_{51} x_1 + M_{52} \theta_{x1} + M_{56} \frac{\Delta p}{p} \right)$$

- Cooling rates (per turn)

$$\boxed{\begin{aligned} \lambda_x &= \frac{k \xi_0}{2} \left(M_{56} - \tilde{M}_{56} \right) \\ \lambda_s &= \frac{k \xi_0}{2} \tilde{M}_{56} \end{aligned}} \quad \Leftrightarrow \quad \boxed{\lambda_x + \lambda_s = \frac{k \xi_0}{2} M_{56}^{pk}}$$

Basics of OSC - Cooling Range



- Cooling force depends on Δs nonlinearly

$$\frac{\delta p}{p} = k\xi_0\,\Delta s \quad \Rightarrow \quad \frac{\delta p}{p} = \xi_0 \sin\left(k\delta s\right)$$

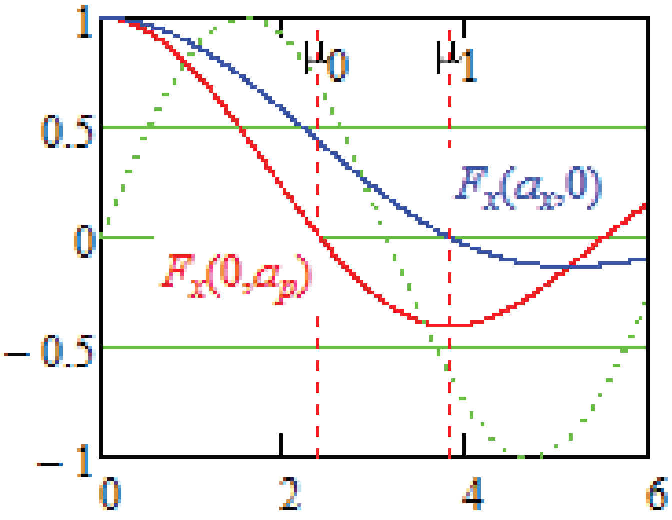
where $k\delta s = a_x \sin(\psi_x) + a_p \sin(\psi_p)$

and a_x & a_p are the amplitudes of longitudinal displacements in cooling chicane due to ⊥ and L motions measured in units of laser phase

- Averaging yields the form-factors for damping rates

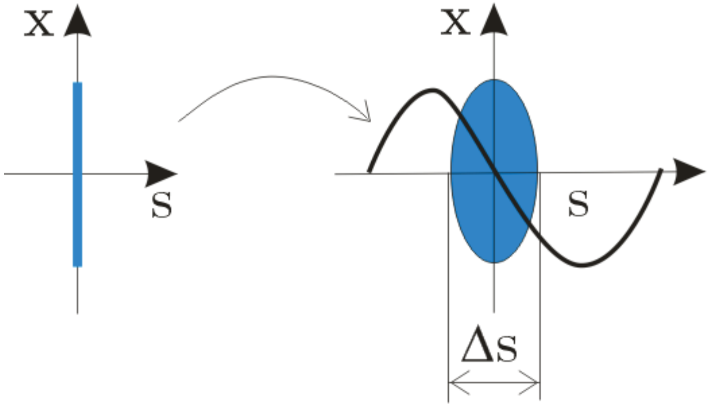
$$\boxed{\begin{aligned} \lambda_{s,x}(a_x,a_p) &= F_{s,x}(a_x,a_p)\lambda_{s,x} \\ F_x(a_x,a_p) &= \frac{2}{a_x}\mathrm{J}_0(a_p)\mathrm{J}_1(a_x) \\ F_p(a_x,a_p) &= \frac{2}{a_p}\mathrm{J}_0(a_x)\mathrm{J}_1(a_p) \end{aligned}}$$

- Damping requires both lengthening amplitudes (a_x and a_p) to be smaller than $\mu_0 \approx 2.405$



Basics of OSC - Sample Lengthening

- On the way from pickup to kicker a zero length sample lengthens on its way from pickup-to-kicker
  - Both Δp/p and ε contribute to the lengthening



$$\sigma_{\Delta s}{}^2 = \sigma_{\Delta s\varepsilon}{}^2 + \sigma_{\Delta sp}{}^2$$

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

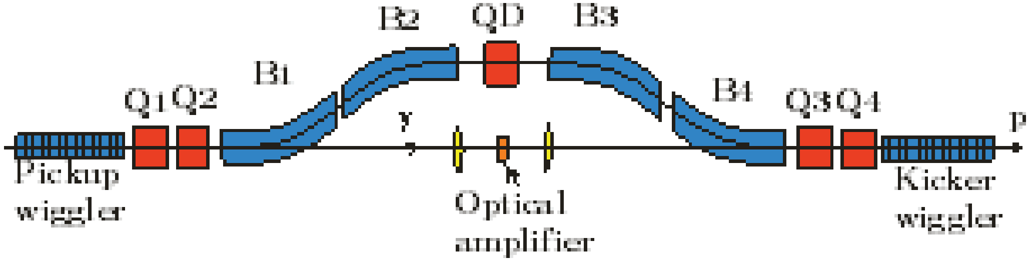
$$\sigma_{\Delta sp}{}^2 = \sigma_p{}^2\left(M_{51} D_p + M_{52} D'_p + M_{56}\right)^2$$

- While in linear approximation β_p and α_p do not affect damping rates they affect sample lengthening and, consequently the cooling range

$$\sigma_{\Delta s\varepsilon} k \le \mu_0 \qquad \mu_0 \approx 2.405$$

$$\sigma_{\Delta sp} k \le \mu_0$$

OSC Limitations on IOTA Optics



- In the first approximation the orbit offset in the chicane (h), the path lengthening (δs) and the defocusing strength of chicane quad (Φ) together with dispersion and beta-function in the chicane center (D^*, β^*) and determine the entire cooling dynamics
- δs is set by delay in the amplifier => M_{56}
- $\Phi D^* h$ is determined by the ratio of decrements => for known ε we obtain the dispersion invariant (A^*)
- An average value of A in dipoles determines the equilibrium emittance. A^* is large and A needs to be reduced fast to get an acceptable value of the emittance (ε)

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

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

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

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

$$n_{\sigma x} \approx \mu_0 / \left(2kh\Phi\sqrt{\varepsilon\beta^*}\right),$$

$$\Rightarrow \Phi D^* h \approx \frac{\mu_0}{2kn_{\sigma x}}\sqrt{\frac{A^*}{\varepsilon}} \,, \quad A^* \equiv \frac{D^{*2}}{\beta^*}$$

IOTA Optics

Main Parameters of IOTA storage ring for OSC

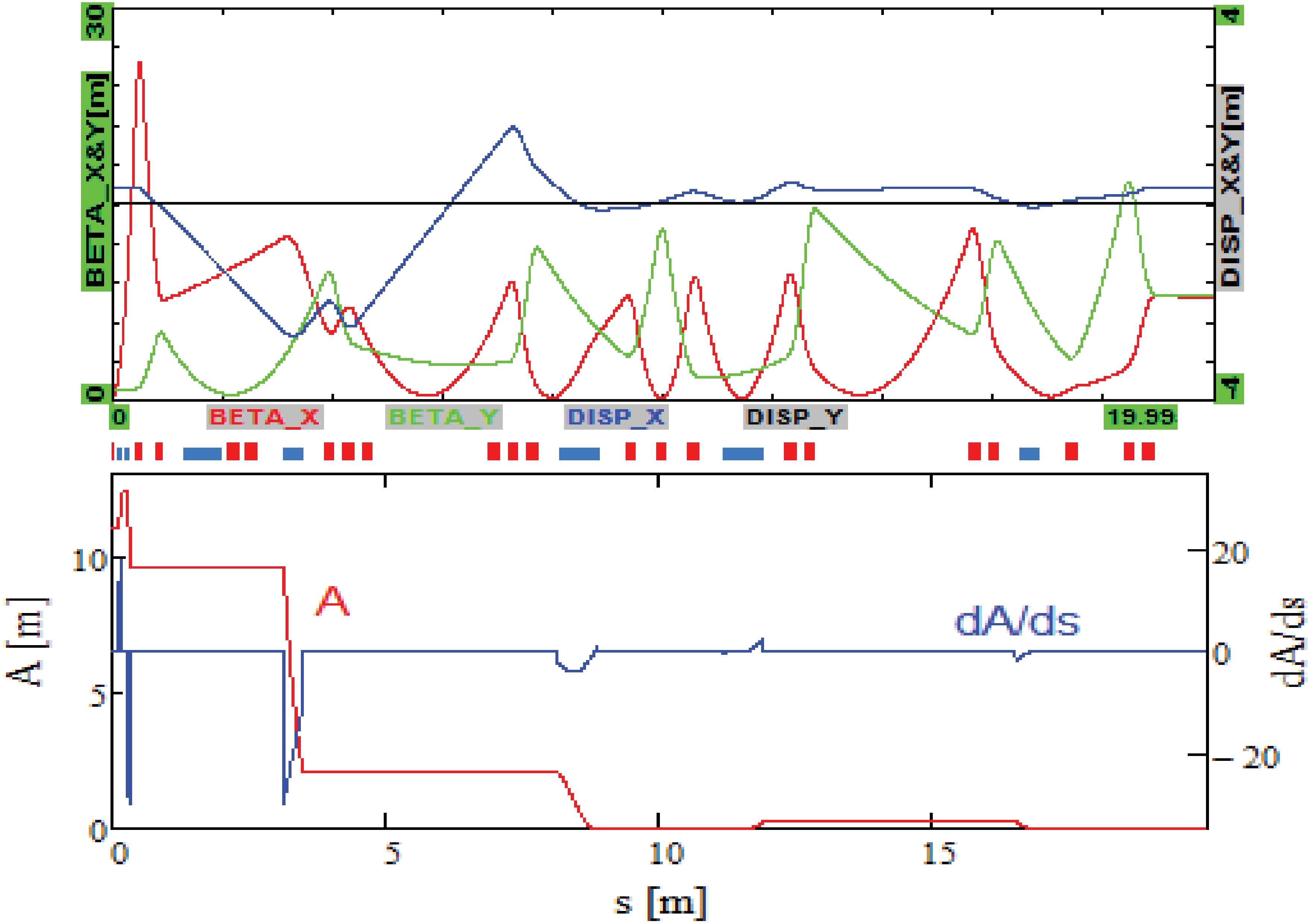
Circumference	40 m
Nominal beam energy	100 MeV
Bending field	4.8 kG
Transverse emittances, $\varepsilon=\varepsilon_x=\varepsilon_y$, rms	11.5 nm
Rms momentum spread, σ_p	$1.23\cdot10^{-4}$
SR damping times (ampl.), $\tau_s/(\tau_x=\tau_y)$	1.4 / 0.67 s

Main parameters of cooling chicane

Delay in the chicane, Δs	2 mm
Horizontal beam offset, h	20.1 mm
M_{56}	3.95 mm
D^* / β^*	307 mm / 8.59 mm
Cooling rates ratio, $(\lambda_x=\lambda_y)/\lambda_s$	1.18
Cooling ranges (before OSC), $n_{\sigma x}/n_{\sigma s}$	2.1 / 3.2
Dipole: magnetic field *length	4.22 kG * 10 cm
Strength of central quad, GdL	1.58 kG

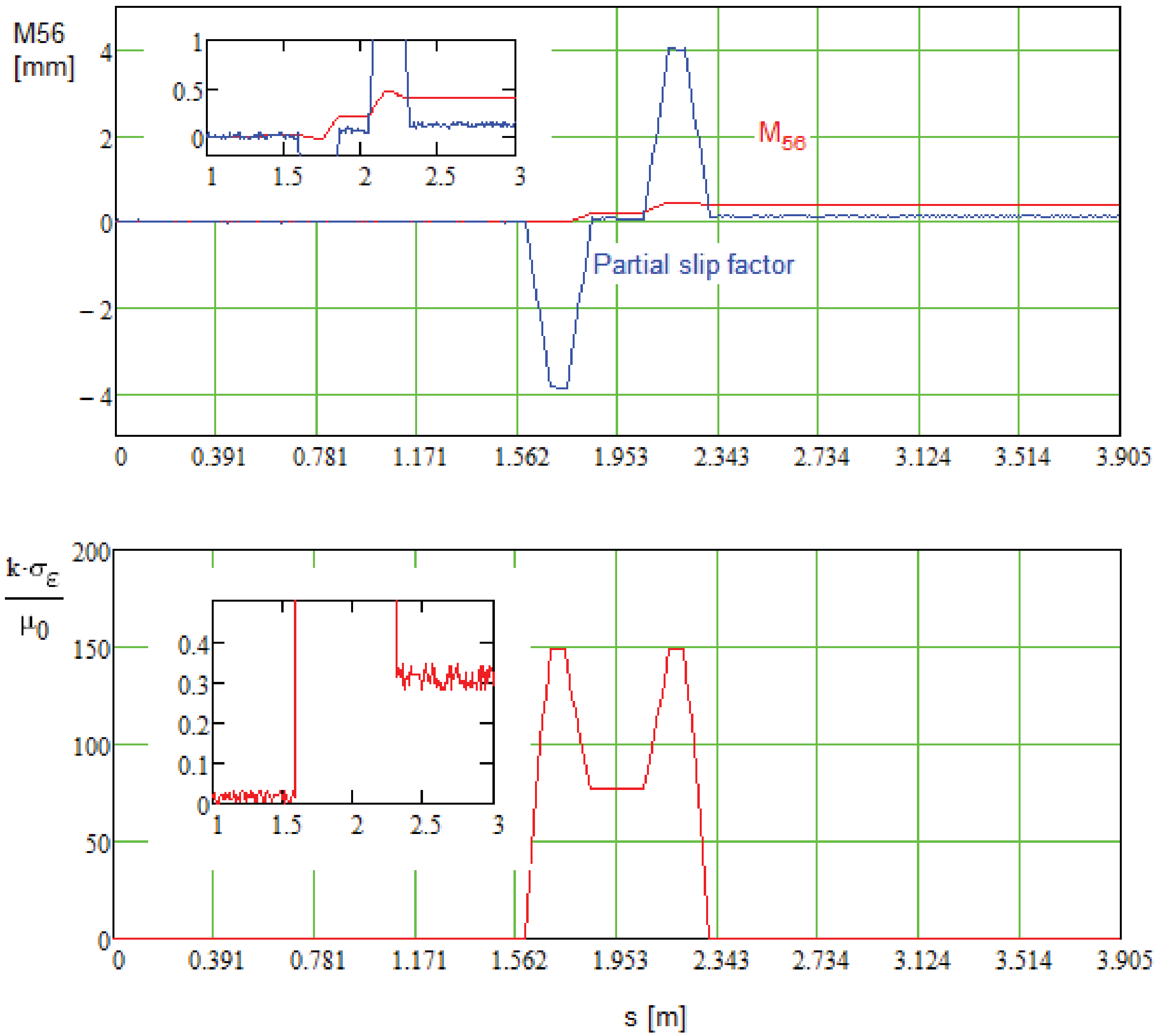
- Energy is reduced 150→100 MeV to reduce ε, σ_p and undulator period and length
- Operation on coupling resonance Q_x/Q_y= 6.36/2.36 reduces horizontal emittance and introduces vertical damping

- Small β^* is required to minimize sample lengthening due betatron motion



Optics functions and dispersion invariant for IOTA half ring

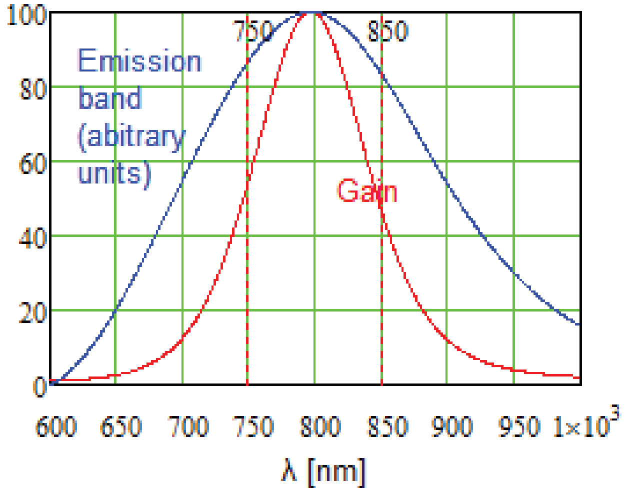
Sample Lengthening on the Travel through Chicane



Sample lengthening due to momentum spread (top) and due to betatron motion (bottom)

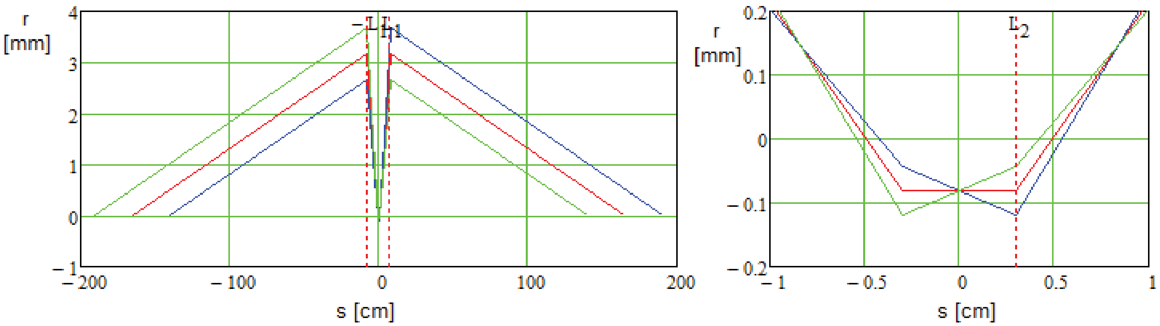
- Very large sample lengthening on the travel through chicane
- High accuracy of dipole field is required to prevent uncontrolled lengthening, $\Delta(BL)/(BL)_{dipole}<10^{-3}$

Optical Amplifier



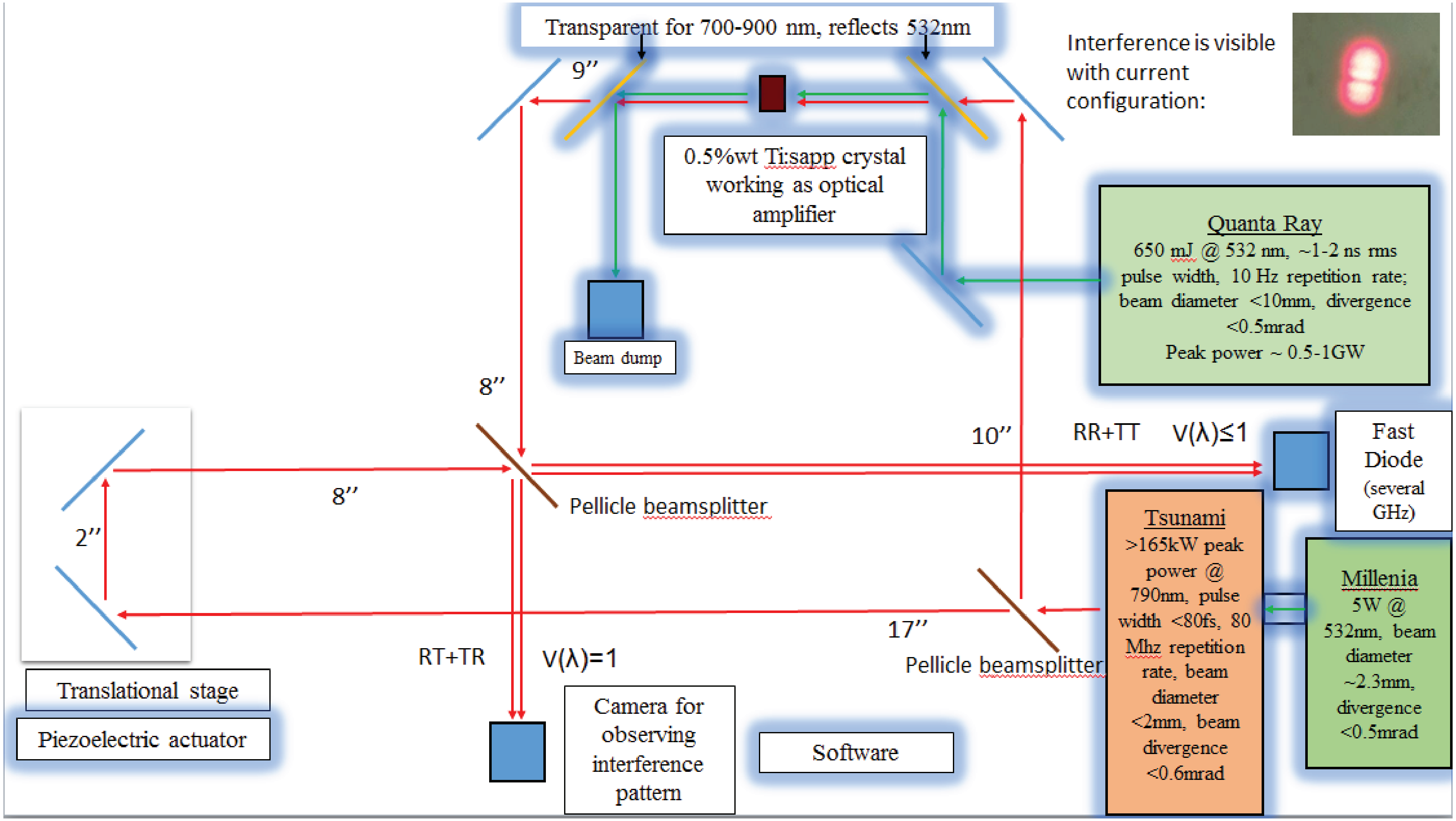
- Ti:Sapphire Optical Amplifier has a few advantages
  - Quite wide bandwidth
    - 10% FWHM at G_0=100
  - Allows operation in the CW regime
    - Decay time due to sp. rad. ~3.15 μs
  - Can deliver significant amplification with only ~1 mm signal delay.
- We bought a highly doped (0.5%wt Ti_2O_3) 2 mm thick Ti: Sapphire crystal from GT Crystal Systems for a prototype of OA
- An estimated low power gain is ~100 (20 Db) with pumping power density of 1.8 MW/cm^2
- Pumping along the direction of amplified radiation
  - P = 50 W, square profile with r = 30 μm
- Cooling the OA to the liquid nitrogen temperature is required.
  - It increases the crystal thermal conductivity
    ⇒ an acceptable ΔT across the crystal (~8K) and thermal stress
  - It reduces dn/dT ⇒
    reduces optics distortions related to high pumping power

Focusing of Beam Radiation to OA and Kicker



- Two possibilities
  - Four lens system with complete suppression of depth of field
    - Too large radiation spot on the crystal (r=120 μm) ⇒ Large P
    - Difficult to make four lenses with ~1 mm total delay time
  - Two lens system (F=8 cm, radius – 3.5 mm)
    - Reasonable compromise between 4 major requirements
    - The spot size in OA to be sufficiently small: r<30 μm
      - ⇒ diffraction limited size in OA: HWHM=6 μm or total size r≈15 μm
      - ⇒ size due to beam convergence/divergence at OA input/exit ≈25 μm
    - Requirements to suppress Depth of field effects in kicker wiggler
      - ⇒ diffraction limited size in kicker wiggler: HWHM=120 μm or total size r≈300 μm
      - ⇒ Size increase due to the depth of field for radiation radiated at the entrance or exit of pickup wiggler: 170 μm
    - To mitigate the depth of field effects the wigglers are moved from the chicane by ~50 cm

Test of Optical Amplifier Prototype



- Operation in pulsed regime ⇒ Cooling is not required
- The goal to measure the amplitude and phase of the amplifier gain

  ⇒ Interferometer for phase measurements
- Interferometer is assembled; first test was at the end of summer

Cooling Rates

- Undulator period was chosen so that $\lambda|_{\theta=0}$=750 nm
- Cooling rates were computed using earlier developped formulas(HB2012)
  - Averaging over amplifier band yielded additionally ~20% reduction of rates.
- 2 mrad angular acceptance of optical system (aperture r=3.5 mm)

  ⇒ upper boundary of the band = 850 nm
- E.-m. wave dispersion in the OA amplifier is included into the gain
  - G = 10 implies an amplitude amplification of 10

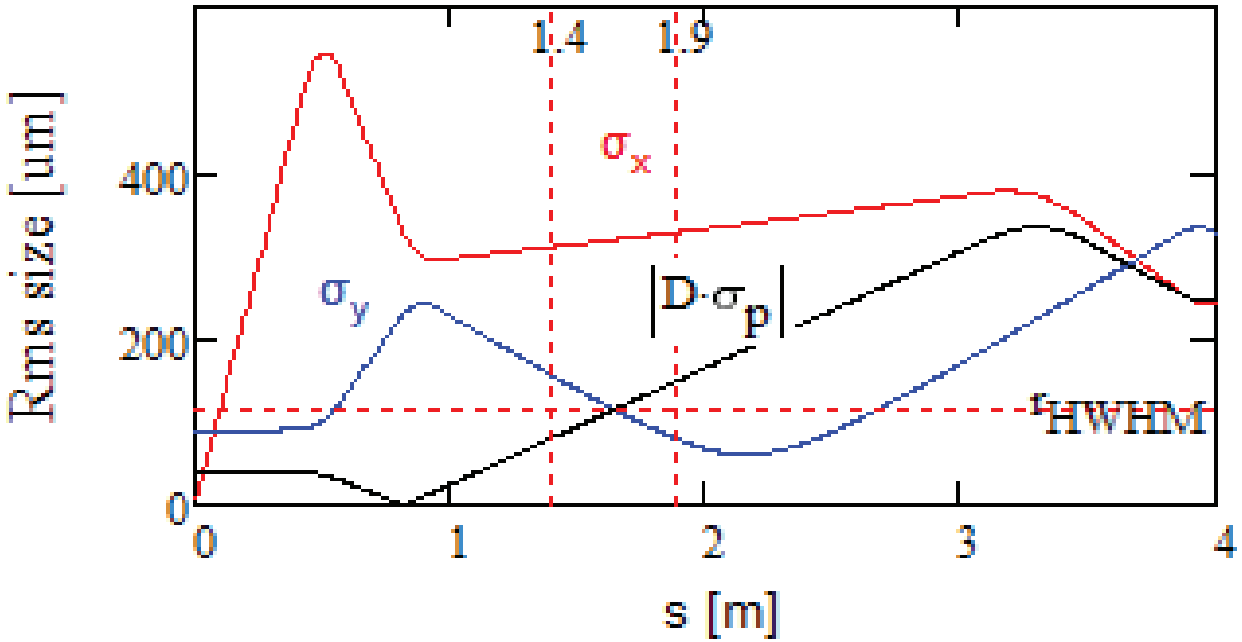
    ⇒ Dispersion makes the power gain to be somewhat larger than G^2.
- Undulator parameter K=0.6 is close to the optimal for chosen bandwidth and aperture

Main parameters of OSC

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, L_w	0.50 m
Length from OA to undulator center	1.65 m
Amplifier gain (amplitude)	10
Telescope aperture, $2a$	7 mm
Lens focal length, F	80 mm
Damp. rates (x=y/s)	160/140 s^{-1}

Effect of Beams Overlap on Cooling Rates

- In computation of cooling rates we neglected incomplete overlap of light and particle beams in the kicker undulator at the beginning of cooling process when the e-beam size is determined by SR.
- The problem is negligible for cooled beam
  - Factor of 5 reduction at the cooling beginning



Rms beam sizes (horizontal – σ_x, vertical – σ_y, and due to momentum spread - $|D\sigma_p|$) in vicinity of cooling chicane starting from the center of OSC section

Conclusions

- Optical stochastic cooling looks as a promising technique for future hadron colliders
- Experimental study of OSC in Fermilab is in its initial phase
  - It is aimed to validate cooling principles and to demonstrate cooling with and without optical amplifier
    - Even in the absence of amplification (passive system, $G = 1$) the OSC damping exceeds SR damping by more than an order of magnitude
- The beam intensity ranges from a single electron to the bunch population limited by operation at the optimum gain (10^8-10^9)
  - Single electron cooling - localization of electron wave function and essence of quantum mechanics
    - Quantum noise for passive cooling
  - Cooling at the optimal gain (ultimate cooling) gets us to otherwise hidden details of OSC, in particular, to signal suppression