Optical Stochastic Cooling in Tevatron

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Objectives

- Extension of Tevatron operation to 2014
  - Looks probable, no final decision
- Is there a possibility for a luminosity upgrade?
- Can the Optical Stochastic Cooling (OSC) help?
- Do we have a fast (2-3 years) of implementation OSC?

Disclaimer

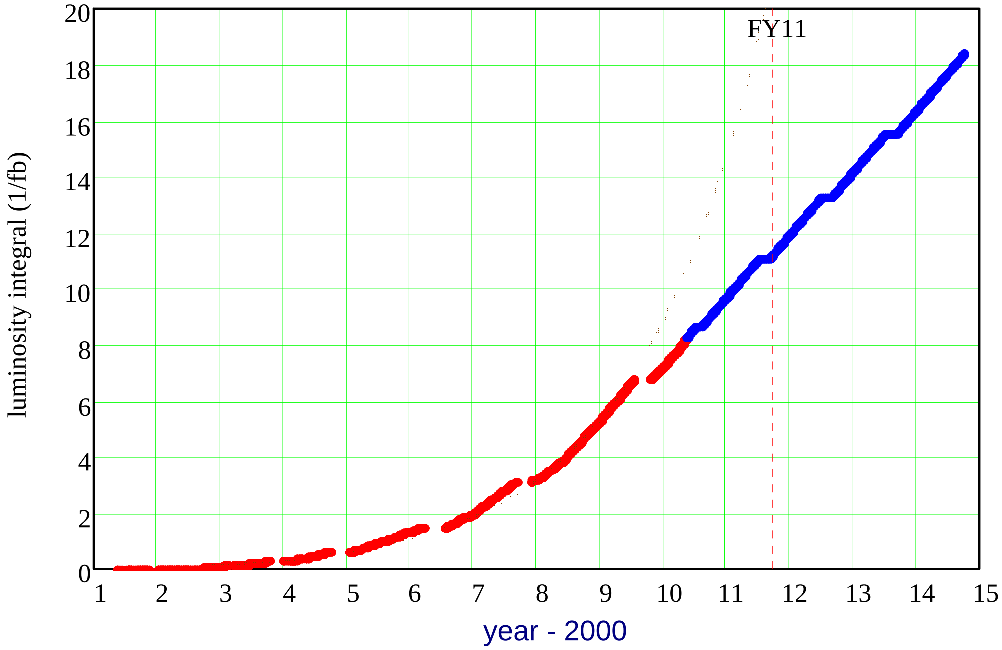
- This talk answers the above questions –
  - It does not present a coherent proposal for Tevatron OSC
  - Some advances in theory were helpful

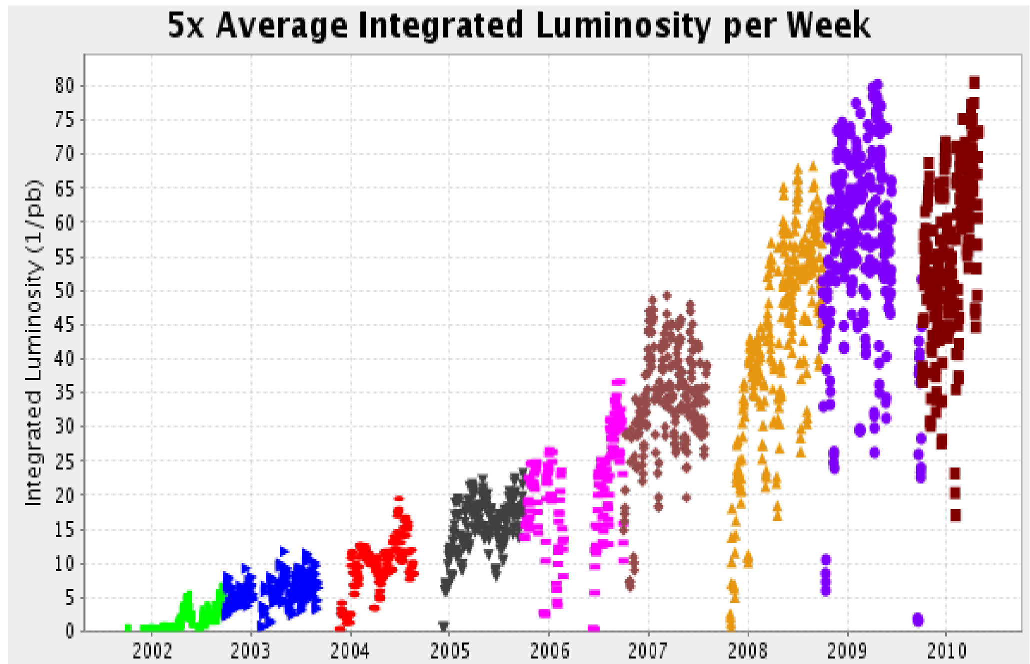
Outline

- Tevatron luminosity and its evolution
- Requirements to the cooling
- Optical stochastic cooling principles
- Damping rates and their optimization
- Kicker and optimization of its efficiency
- Requirements to the optical amplifier power
- Conclusions

Tevatron Luminosity

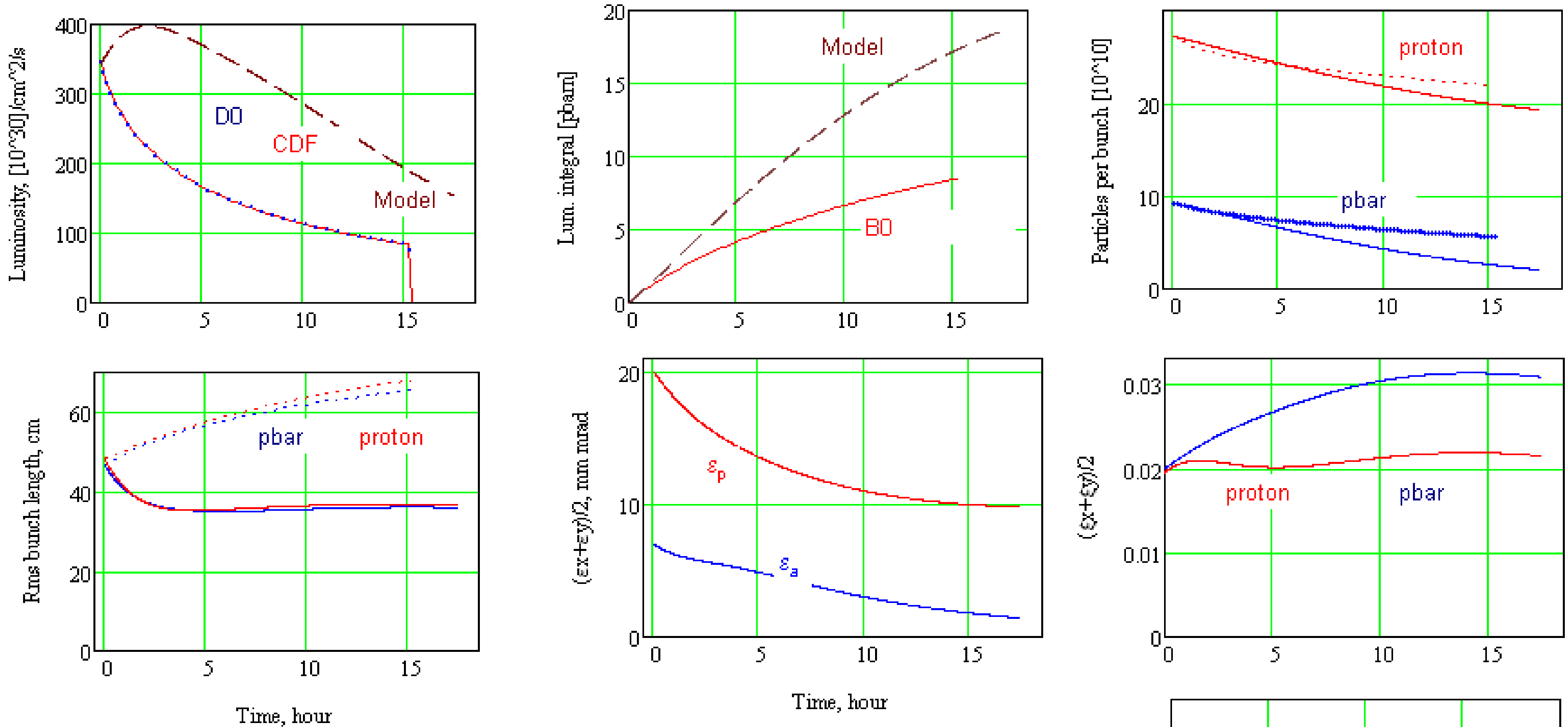
- All planned luminosity upgrades are completed in the spring of 2009
- From Run II start to 2009 the luminosity integral was doubling every 17 months
- Since 2009 average luminosity stays the same ~51 pb^{-1}/week (max ~75 …)
- The average luminosity is limited by the IBS
  - Larger beam brightness results in a faster luminosity decay



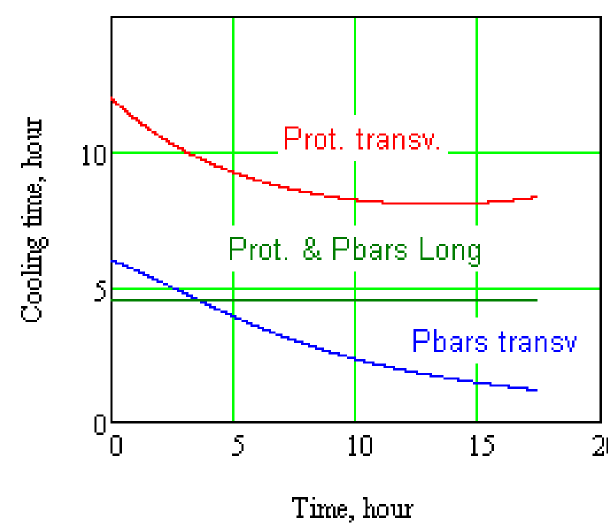


- It is impossible to make a significant improvement (~2 times) without beam cooling in Tevatron
  - 10-20% is still possible (new tunes, larger intensity beams)

Luminosity Evolution with Aggressive Cooling



- Cooling rate is limited by peak luminosity of $4 \cdot 10^{32}$ and by $\xi_{BB} = 0.03$ for pbars
  - Requires tunes closer to half-integer(0.58→.52)
- 1.96 times increase in average luminosity
  - 78% of pbars are used in luminosity – versus 40%

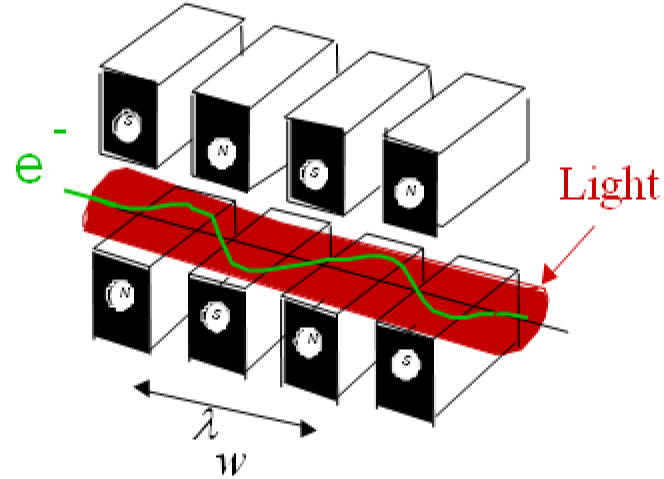


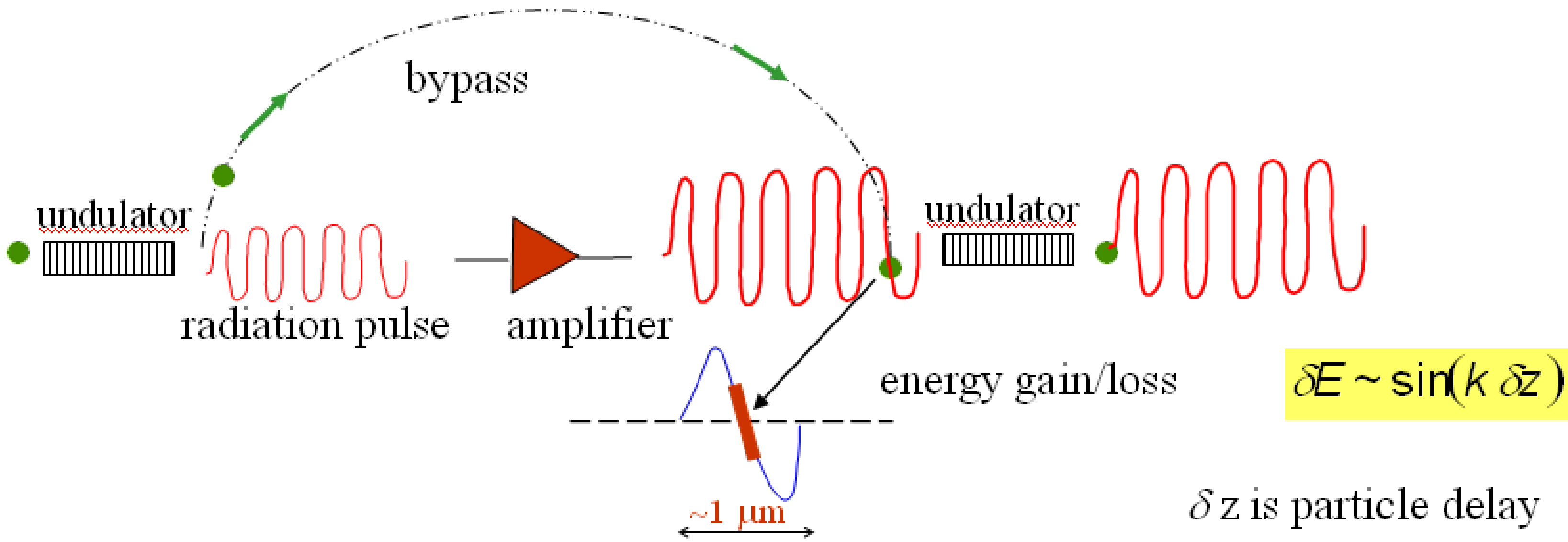
Requirements to the Beam Cooling

- Cooling time has to to be varied during the store independently for protons and pbars and transverse and longitudinal planes
  - Beam overcooling results in
    - Particle loss due to beam-beam (transverse overcooling)
    - Longitudinal instability (longitudinal overcooling)
- Simple estimate of required bandwidth based on (λ=2*W*/*N*) results in ~200 GHz
  - Well above bandwidth of normal stochastic cooling
  - Only optical stochastic cooling has sufficient bandwidth
- Cooling times (in amplitude):
  - Protons: L - 4.5 hour; $\perp$ - 8 hour
  - Antiprotons: L - 4.5 hour; $\perp$ - 1.2 hour
- Tevatron has considerable coupling and all transverse cooling can be applied in one plane
  - It requires doubling hor. cooling decrement:
    - I.e. for protons $\lambda_s = \lambda_x = 4.5$ hour

Optical Stochastic Cooling

- Suggested by Zolotorev, Zholents and Mikhailichenko (1994)
- Never tested experimentally
- OSC obeys the same principles as the microwave stochastic cooling, but exploits the superior bandwidth of optical amplifiers ~ 10^{14} Hz
- Undulator can be used as pickup & kicker
- Pick-up and Kicker should be installed at locations with nonzero dispersion to have both ⊥ and L cooling.

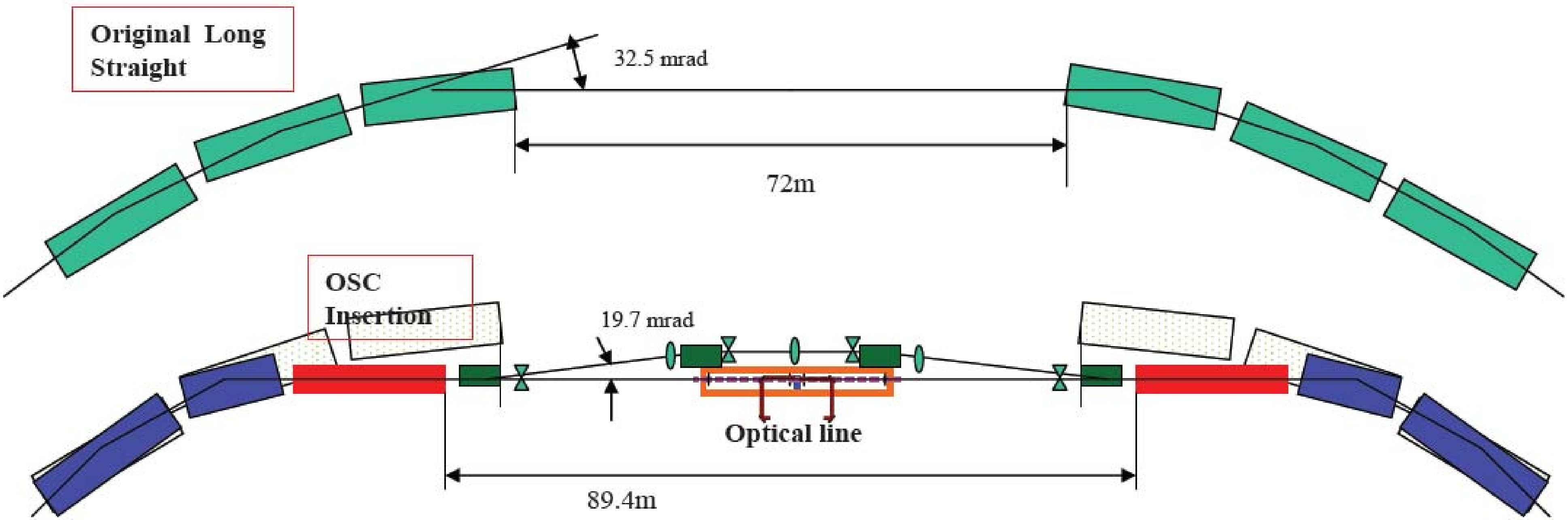




MIT-Bates Proposal (2007 presentation @ FNAL)

The Small-angle Bypass Magnetic Chicane

(conceptual design)



Dipole 4.4T, 25.6m

Dipole 8.0T

Undulator 8T, 27m

Dipole 8.2 T, 8m

Quadrupole 2m , g ≤400T/m, aperture 2cm.

Bending angle and drift space set to get:

Path delay : ΔL=10mm=30 ps

Δx=55.7cm

Ease magnet tolerances

Damping Rates (logic behind calculations)

- The optics design will be significantly simplified if the damping rates can be expressed through beta-functions, dispersions and their derivatives
  - Damping rates are expressed in terms of matrix elements of the inverse pickup-to-kicker transfer matrix in previous publications
- The sequence is
  - Express transfer matrices (6x6) through Twiss-parameters at kicker and pickup
  - Find eigen-values and eigen-vectors of the ring without cooling
  - Using perturbation theory find damping decrements
  - Determine the cooling range
    - Correction factors for the finite amplitude particles

Transfer Matrix Parameterization

- Vertical plane is uncoupled and we omit it in further equations
- Matrix from point 1 to point 2

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

$$M_{16} = D_2 - M_{11}D_1 - M_{12}D_1'$$
$$M_{26} = D_2' - M_{21}D_1 - M_{22}D_1'$$

$$M_{51} = M_{21}M_{16} - M_{11}M_{26}$$
$$M_{52} = M_{22}M_{16} - M_{12}M_{26}$$

- M_{16} & M_{26} can be expressed through dispersion
- Symplecticity ($\mathbf{M}^T \mathbf{U} \mathbf{M} = \mathbf{U}$) binds up M_{51}, M_{52} and M_{16}, M_{26}
- Partial slip factor (from point 1 to point 2) is related to M_{56}

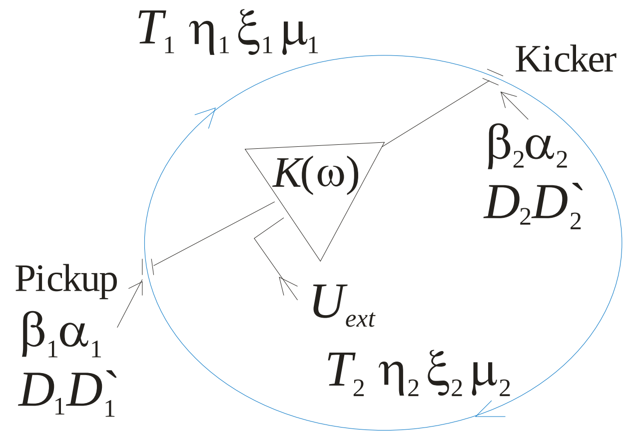
$$\Delta s_{1\to 2} \equiv 2\pi R \eta_{12} \frac{\Delta p}{p} = M_{51}D_1 \frac{\Delta p}{p} + M_{52}D_1' \frac{\Delta p}{p} + M_{56} \frac{\Delta p}{p}$$

  - where we assume the ultra-relativistic case, i.e. $\mathrm{v} = c$,
- That results in

$$\eta_{12} = \frac{M_{51}D_1 + M_{52}D_1' + M_{56}}{2\pi R}$$

=> All matrix elements can be expressed through $\beta, \alpha, D, D', \eta_{1\to 2}$

Damping Rates of Optical Stochastic Cooling



Longitudinal kick

$$\frac{\delta p}{p} = \kappa \sin\left(k\,\Delta s\right) = \xrightarrow{k\,\Delta s \ll 1} \kappa k \left(M_{1_{51}} x_1 + M_{1_{52}} \theta_{x\,1} + M_{1_{56}} \frac{\Delta p}{p} \right)$$

Or in the matrix form: $\boldsymbol{\delta}\mathbf{x}_2 = \mathbf{M}_c \mathbf{x}_1$

$$\mathbf{M}_c = \kappa \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ M_{151} & M_{152} & 0 & M_{156} \end{bmatrix}$$

M_1 - pickup-to-kicker matrix

M_2 - kicker-to-pickup matrix

$M = M_1 M_2$ – ring matrix

$\mu = \mu_1 + \mu_2$

Find the total ring matrix related to kicker location

$$\Rightarrow \quad \left(\mathbf{x}_2\right)_{n+1} = \mathbf{M}_1\mathbf{M}_2\left(\mathbf{x}_2\right)_n + \left(\boldsymbol{\delta}\mathbf{x}_2\right)_n = \left(\mathbf{M}_0 + \mathbf{M}_c\mathbf{M}_2\right)\left(\mathbf{x}_2\right)_n$$

Perturbation theory yields that the tune shifts are:

$$\delta Q_k = \frac{\kappa}{4\pi} \mathbf{v}_k^{+} \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ M_{126} & -M_{116} & 0 & M_{156} \\ 0 & 0 & 0 & 0 \end{bmatrix} \mathbf{v}_k$$

where the eigen-vector is determined by $\mathbf{M}_0 \mathbf{v}_k = \lambda_k \mathbf{v}_k$

Damping Rates of Optical Stochastic Cooling (continue)

- Expressing matrix elements and eigen-vectors through Twiss parameters one obtains the cooling rates

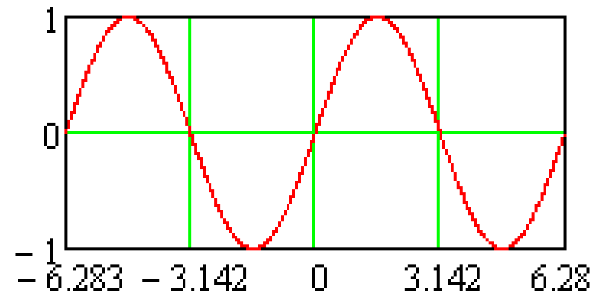
$$\lambda_1 = -k\kappa\left(\frac{M_{1_{56}}}{2} - \pi R \eta_{12}\right)$$
$$\lambda_2 = -\pi k \kappa R \eta_{12}$$

The bottom equation can be directly obtained from the definition of the partial slip factor.

- The above equations yield that the sum of the decrements is

$$\lambda_1 + \lambda_2 = -\frac{\kappa}{2} M_{1_{56}}$$

Cooling Range



- The cooling force depends on Δs nonlinearly

$$\frac{\delta p}{p} = \kappa \sin(k\delta s) = \kappa \sin\left(a_x \sin(\psi_x) + a_p \sin(\psi_p)\right), \quad \kappa = \frac{\Delta E_{max}}{E}$$

where a_x & a_p are the lengthening amplitudes due to ⊥ and L motions measured in units of laser phase ($a = k\,\delta s$)

- The form-factor for damping rate of longitudinal cooling for particle with amplitudes a_x & a_p

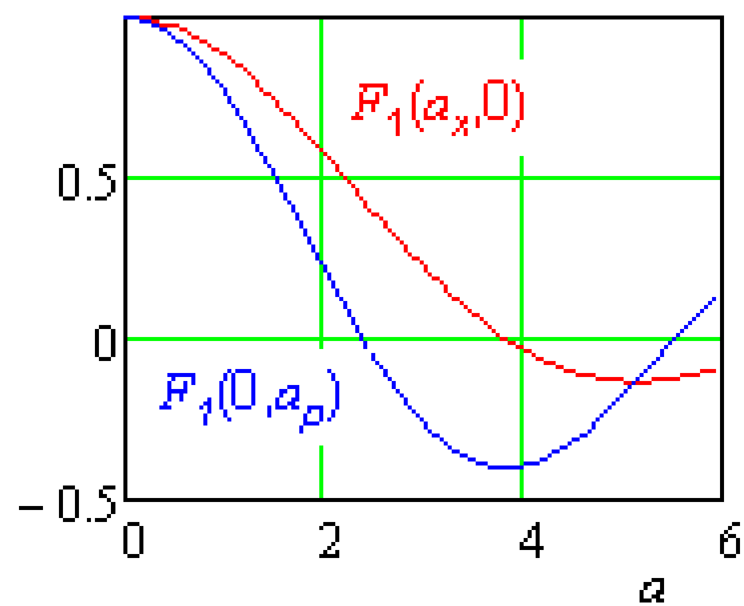
$$F_2(a_x, a_p) = \frac{2}{a_p} \oint \sin\left(a_x \sin\psi_x + a_p \sin\psi_p\right) \sin\psi_p \frac{d\psi_x}{2\pi} \frac{d\psi_p}{2\pi}$$

⇨ $$F_2(a_x, a_p) = \frac{2}{a_p} J_0(a_x) J_1(a_p)$$

- Similar for transverse motion

⇨ $$F_1(a_x, a_p) = \frac{2}{a_x} J_0(a_p) J_1(a_x)$$

- Damping requires both lengthening amplitudes be smaller $\mu_0 \approx 2.405$



Cooling of the Gaussian beam

- Averaging the cooling form-factors for Gaussian distribution yields the same result as obtained by Zholents & Zolotorev

$$F_{1G}(k\sigma_{\Delta s\varepsilon}, k\sigma_{\Delta sp}) = F_{2G}(k\sigma_{\Delta s\varepsilon}, k\sigma_{\Delta sp}) = \exp\left(-\frac{k^2\sigma_{\Delta sp}{}^2}{2}\right)\exp\left(-\frac{k^2\sigma_{\Delta s\varepsilon}{}^2}{2}\right)$$

But it ignores that the particles in the tails are undamped

Beam Optics

- Sum of decrements is proportional to the kicker-to-pickup M_{56}
  - It is determined by local optics $\Rightarrow$ Stable
- λ_2 (long) $\propto \eta_{12}$ (partial pickup-to-kicker slip factor)

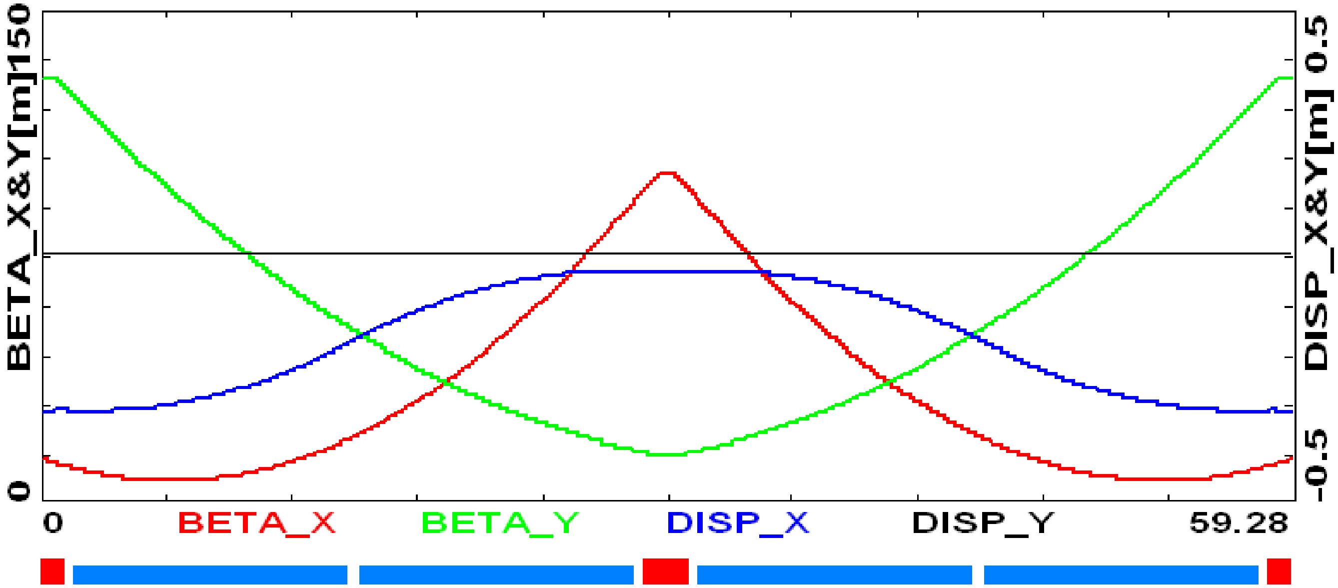
  $\Rightarrow$ Depends on the ring dispersion $\Rightarrow$ highly sensitive
- M_{56} for optimal cooling is

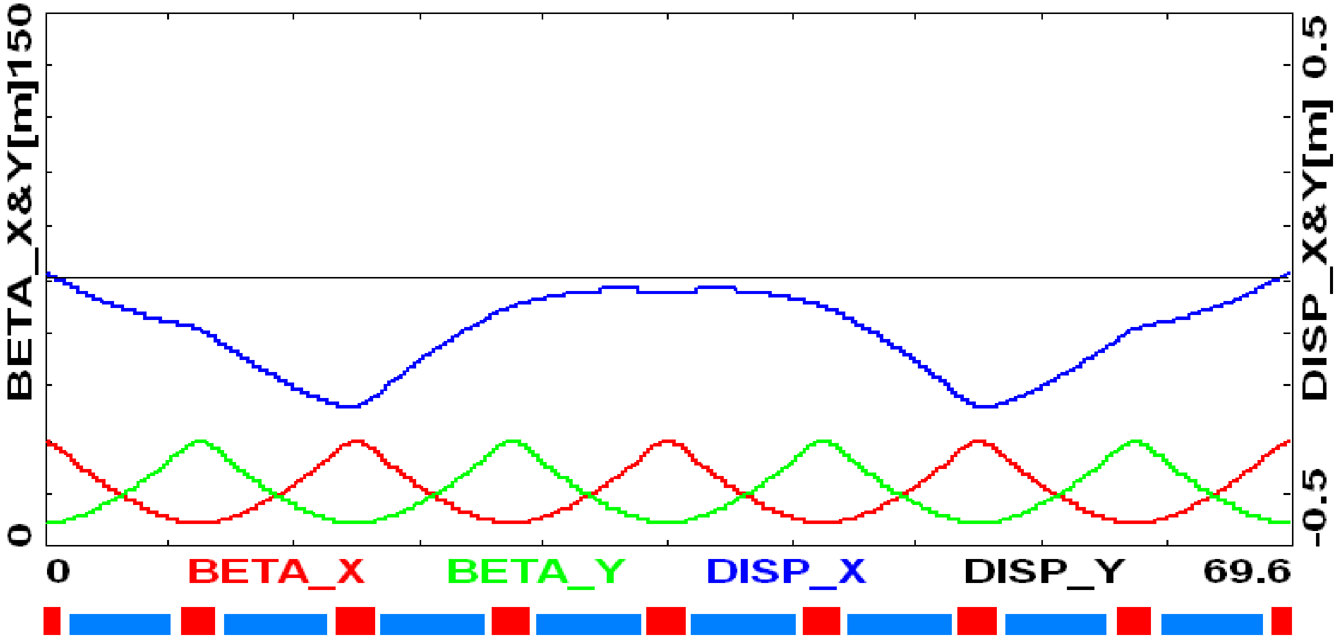
$$M_{1_{56}} = \frac{\mu_{01}\left(\lambda_1 + \lambda_2\right)}{k\lambda_1\left(\Delta p / p\right)_{\max}}$$

  - Smaller value – an increase of the optical amplifier power
  - Larger value – loss of damping for large amplitude particles
- Tevatron cooling scenario implies:
  - σ_p=1.2·10^{-4} , ε_n=3.3 mm mrad
- For 4σ and 5σ cooling ranges of L & ⊥ motions, ΔL=5.3 mm and $\lambda_1=\lambda_2$

Optical amplifier wavelength	2 μm	12 μm
M_{56} [mm]	3.2	19.2
$2\pi R\eta_{12}$ [mm]	1.6	9.6
ΔD for 10% damping rate change [cm]	0.45	1.7

Beam Optics (continue)





Without focusing

$$M_{56} \approx 2\Delta L$$

Focusing in chicane is required to obtain horizontal cooling

- weak for 12 μm M_{56}=19.2 mm
- strong for 2 μm M_{56}=3.2 mm

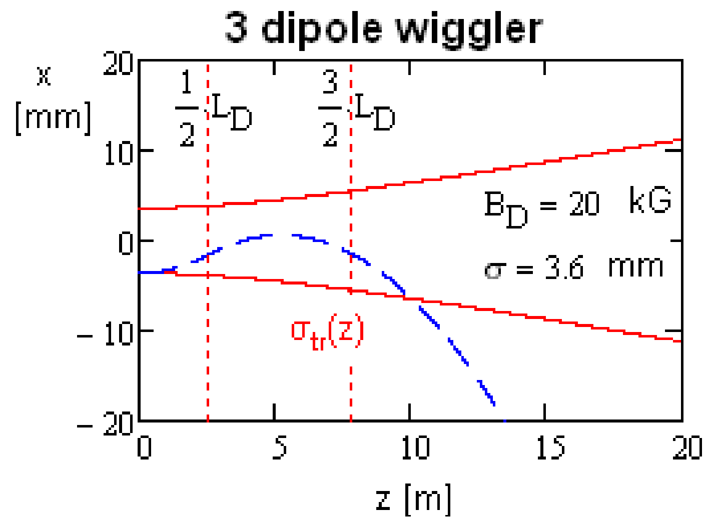
Beta-functions and dispersions in the cooling chicane for optics optimized for 12 μm (top) and 2 μm(bottom) optical amplifiers; 6T dipoles, 5.3 mm delay

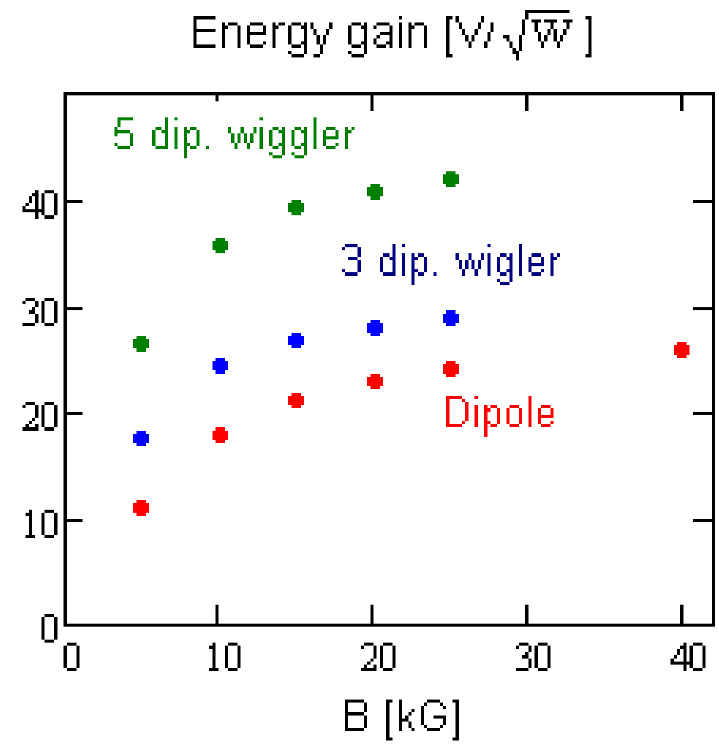
Kickers (dipole & dipole wiggler)

- Hor. polarized e.-m. wave focused at $z = 0$ to the rms size $\sigma_\perp$
- The beam is deflected in the x-plane by wiggler magnetic field
  - The beam energy change

$$\Delta E = e\int (\mathbf{E} \cdot \mathbf{v})dt$$

- Dipole wiggler consists of positive and negative dipoles which at each end are followed by dipole of the same field for further separation of beams
  - Dipole length, $\sigma_\perp$ and the beam centroid offset are adjusted to maximize the kick
  - $\sigma_\perp$ is much larger than the beam transverse size
- Because of tighter focusing of e.-m. wave the kick in a dipole is only marginally lower than in the 3 dipole wiggler





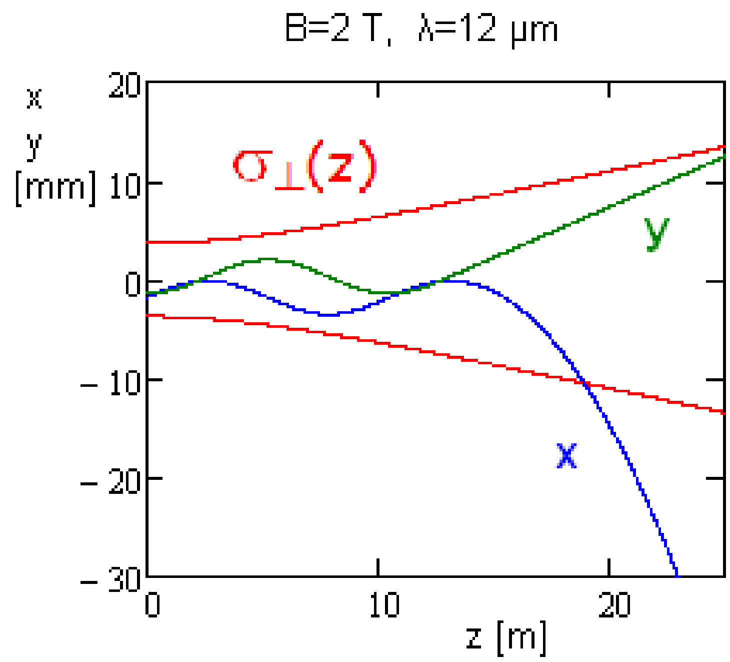
Energy Kick in Helical Wiggler

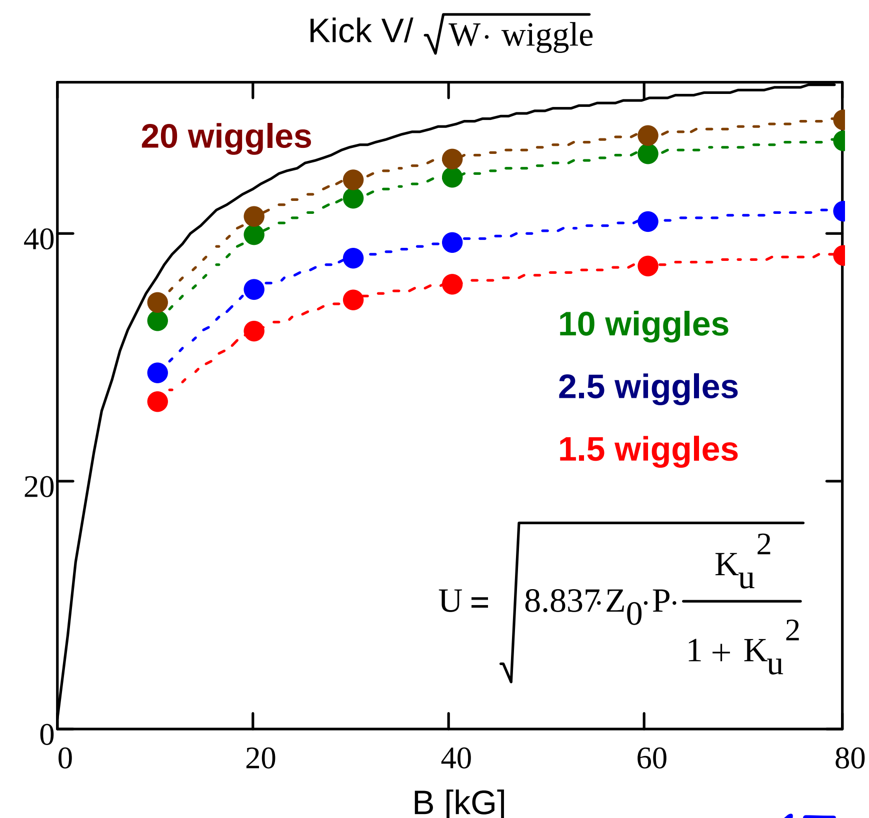
- Helical dipole suggest √2 times better kicker efficiency
  - Circular polarized light
- For large number of periods ($n_{wgl} \gg 1$) the kicker strength is[♦]

$$\frac{\Delta E_{max}}{e} \approx \sqrt{8.837 n_{wgl} P Z_0 \frac{K_u^{\,2}}{1+K_u^{\,2}}}$$

where $K_u = \frac{\lambda_{wgl}}{2\pi}\frac{eB}{mc^2}$, $Z_0=377\ \Omega$

- The waist size is growing with kicker length - $\sigma_\perp \approx \sqrt{0.946 L \lambda_w}$
- The kicker is less effective than formula prediction for small n_{wgl}
  - $\rho_{wgl} \sim \sigma_\perp$
  - Negative contribution of E_z

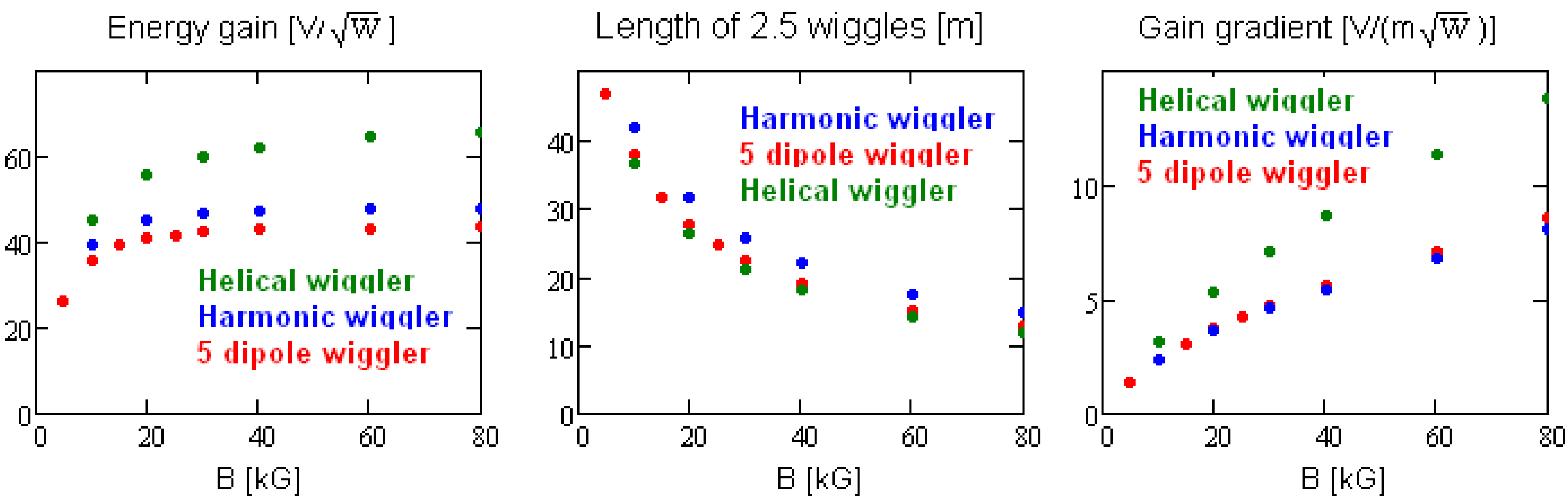




[♦]M. Zolotorev

Comparison of Different Wiggler Types

- For large wiggler period the wiggler consisting of dipoles is easier to make than a usual harmonic wiggler
  - Little loss in efficiency is compensated by shorter length
- Helical dipole wiggler is ~√2 time more efficient



Comparison of wiggler parameters for λ_w = 12 μm and different wigglers (2.5 wiggles each)

Possible Choice of OSC Parameters

Damping time 4.5 hour, N_p=3•10^{11}, n_b=36, σ_p=1.2•10^{-4} , λ_2^{-1} =4.5 hour

⇨ Amplitude of single particle kick, ΔE_{max} = 0.66 eV, $\Delta f / f_{FWHM}$ = 6%

Wave length [μm]	Wiggler type/n_{wgl}	B [T]	Total length [m]	G_{kicker} [eV/√W]	P [W]
12	Tevatron dipole/(N/A)	4	N/A	26	125
6				18	133
2				14	71
12	Helical dipole/2.5	2	40	56	28
	Helical dipole/8	8	44	132	5
6	Helical dipole/7	6	38	110	3.5
2	Helical dipole/12	6	36	116	1.05

- Peak optical amplifier power is ~100 times larger than the average one
- Bandwidth is limited by optical amplifier

Discussion

- 2 μm wavelength
  - 2 μm parametric optical amplifier is feasible (MIT-Bates)
    - 20-100 W (pumped by Nd:YAG laser)
  - Can be used with Tevatron dipoles being pickups and kickers (no wigglers), 70 W amplifier per beam
    - 2T helical wiggler (~20 m) requires ~12 W amplifier per beam
  - Optics stability and path length control are questionable
- 12 μm wavelength
  - Looks better for control of optics and the path length
  - Parametric optical amplifier pumped by 2-nd harmonic of CO_2 laser
    - Was not demonstrated yet
      - Attempt for RHIC was not quite successful
    - 5-10 W looks reasonable request
      - But R&D is required to prove feasibility
  - Requires ~6-8 T helical wiggler (≥4 years)

Conclusions

- OSC would double the average Tevatron luminosity
- There is no fast way (2-3 years) to introduce OSC in Tevatron
    - looks possible for 5-6 years
        - Cooling installation requires a modification of beam optics
            - C0 straight is available
            - New optics implies
                - new quad circuits & be new quads
                - shuffling existing and/or installation of new dipoles
                - Installation of wigglers?
            - Considerable work
                - Fractional tunes should stay the same
                - Helices should not be affected
        - Antiproton beam has less particles but requires faster cooling

          $\Rightarrow$ That results in approximately the same power requirements for optics amplifier but its larger gain

Backup Viewgraphs

Longitudinal Damping Rate

- For beam with n_b bunches and N_p particles/bunch the average laser power is

$$P_{laser} = n_b N_p f_0 \sqrt{\frac{\ln(2)}{\pi}} \frac{P_{peak}}{\Delta f_{FWHM}} = \frac{n_b N_p f_0}{\Delta f_{FWHM}} \sqrt{\frac{\ln(2)}{\pi}} \left(\frac{\Delta \mathrm{E}_{\max}}{G_{kick}} \right)^2$$

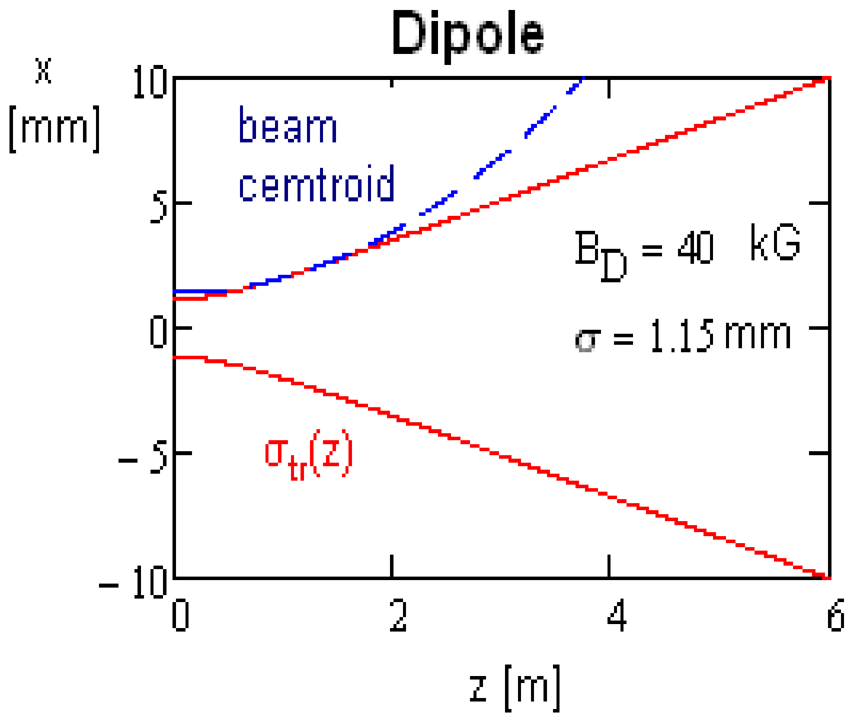
where G_{kick} is the kicker efficiency determined by the equation for monochromatic wave $\Delta \mathrm{E}_{\max} = G_{kick} \sqrt{P}$

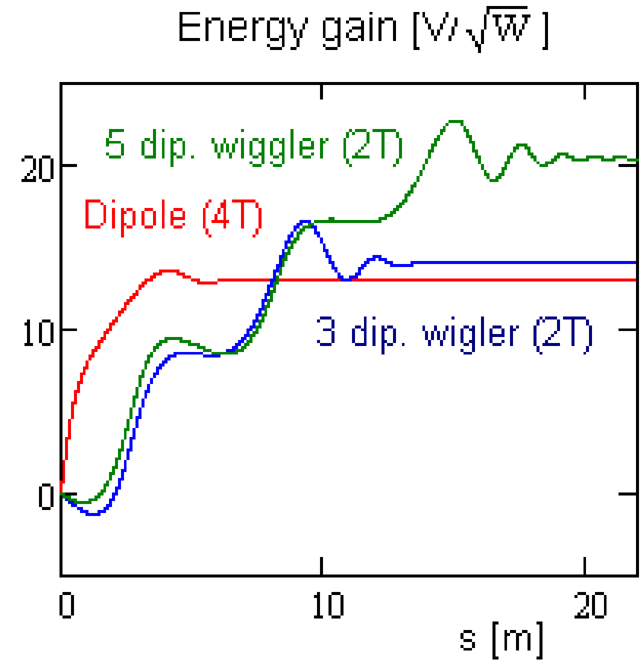
⇨ For helical dipole with large number of wiggles

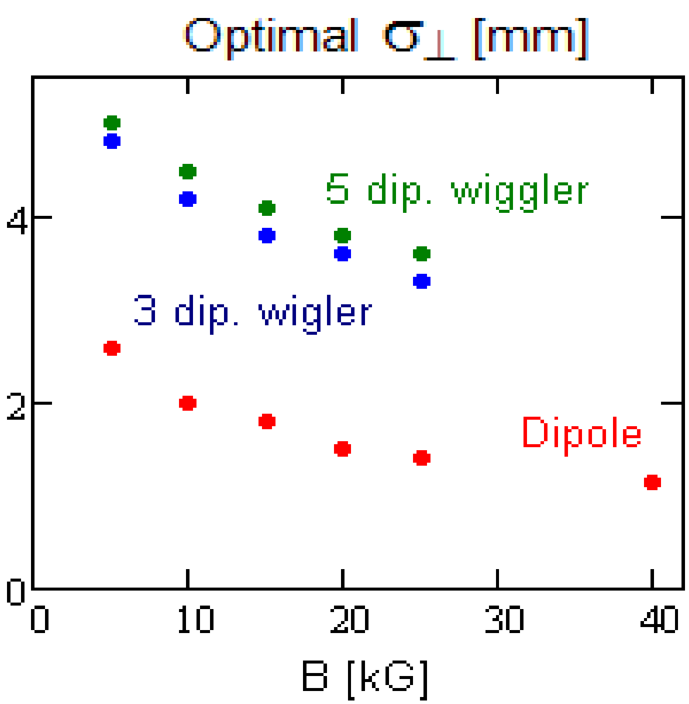
$$P_{laser} = 1.26 \left(\frac{1}{n_{wgl} (\Delta f / f)_{FWHM}} \frac{1 + K_u{}^2}{K_u{}^2} \right) \frac{n_b N_p \lambda_2{}^2 \lambda_w}{c f_0} \frac{(c p \sigma_p / e)^2}{Z_0}$$

$$\xrightarrow{K_u >> 1,\ n_{wgl} (\Delta f / f)_{FWHM} = 1} \approx \frac{n_b N_p \lambda_2{}^2 \lambda_w}{c f_0} \frac{(c p \sigma_p / e)^2}{Z_0}$$

- ♦ Number of wiggles is limited by bandwidth: $n_{wgl} \le 1/(\Delta f / f)$
- ♦ For efficient kick the undulator parameter $K_u \ge 2$
  - For larger magnetic field the kicker is shorter for same n_{wgl}
- ♦ In optimal setup ⊥ cooling does not require additional power
  - but requires an optimized optics







Beam acceleration, e∫(E•ds), starting from wiggler center

5 dipole wiggler