Optical Stochastic Cooling for eRHIC

C. Tschalär MIT/Bates

Outline

- ERL version of eRHIC
- OSC concept and potential
- First test of OSC at Bates
- Conclusion

EIC Collaboration meeting, Stony Brook, 10 January, 2010

Linac-Ring version of eRHIC

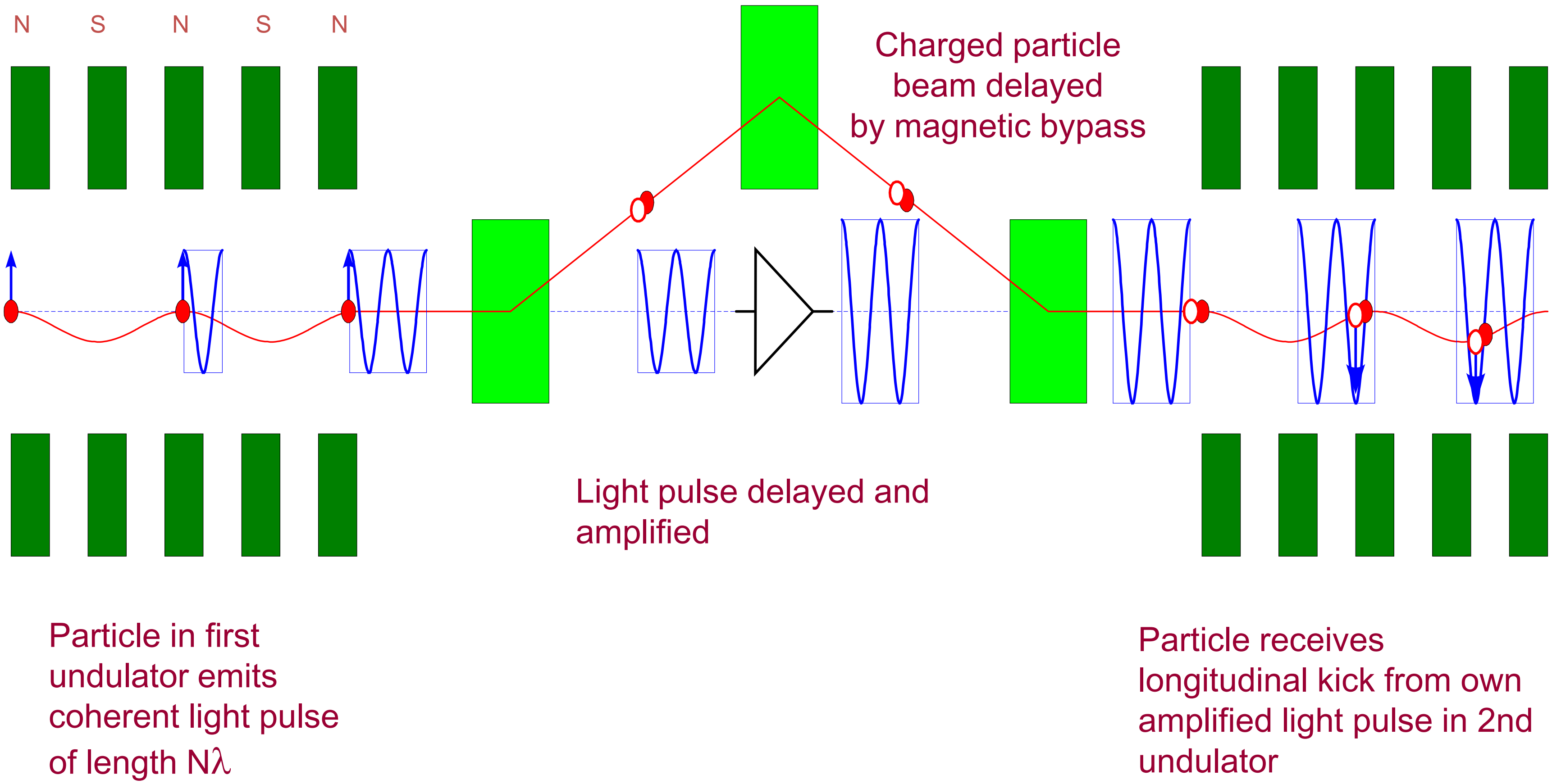
Luminosity $$L = \frac{I_e}{2\pi(1+k)}\left(\frac{N_i}{\beta_i \varepsilon_i}\right)$$

I_e limited by polarized electron source
β_i limited by beam bunch length and ring lattice

→ε_i minimized by beam cooling: Two options for cooling high-energy (250 GeV) protons:

Coherent Electron Cooling (CEC) and
Optical Stochastic Cooling (OSC)

OSC Concept



N
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Charged particle beam delayed by magnetic bypass
Light pulse delayed and amplified
Particle in first undulator emits coherent light pulse of length Nλ
Particle receives longitudinal kick from own amplified light pulse in 2nd undulator

OSC Formalism

Particle-light phase $\Delta\phi = kR_{51}x + kR_{52}\theta + kh\delta$

(wave number *k)* $h \equiv R_{56} + \eta R_{51} + \eta' R_{52} = R_{56} + 2\eta R_{51}$

R_{51}, R_{52}, R_{56} = inverse transport matrix elements of bypass

η, η' = dispersions at the kicker undulator

Optimized equal cooling rates per orbit of r.m.s beam dimensions $\bar{\delta}$, $\bar{x}$, and emittance ε:

$$\alpha_\varepsilon \equiv \Delta\bar{\delta}^2 / \bar{\delta}^2 = \Delta\varepsilon / \varepsilon = 2Gkh / \exp\left(\Delta\bar{\phi}^2 / 2\right) = 2G / \left(\bar{\delta}\sqrt{e\left(2/\upsilon^2 + 1\right)}\right)$$

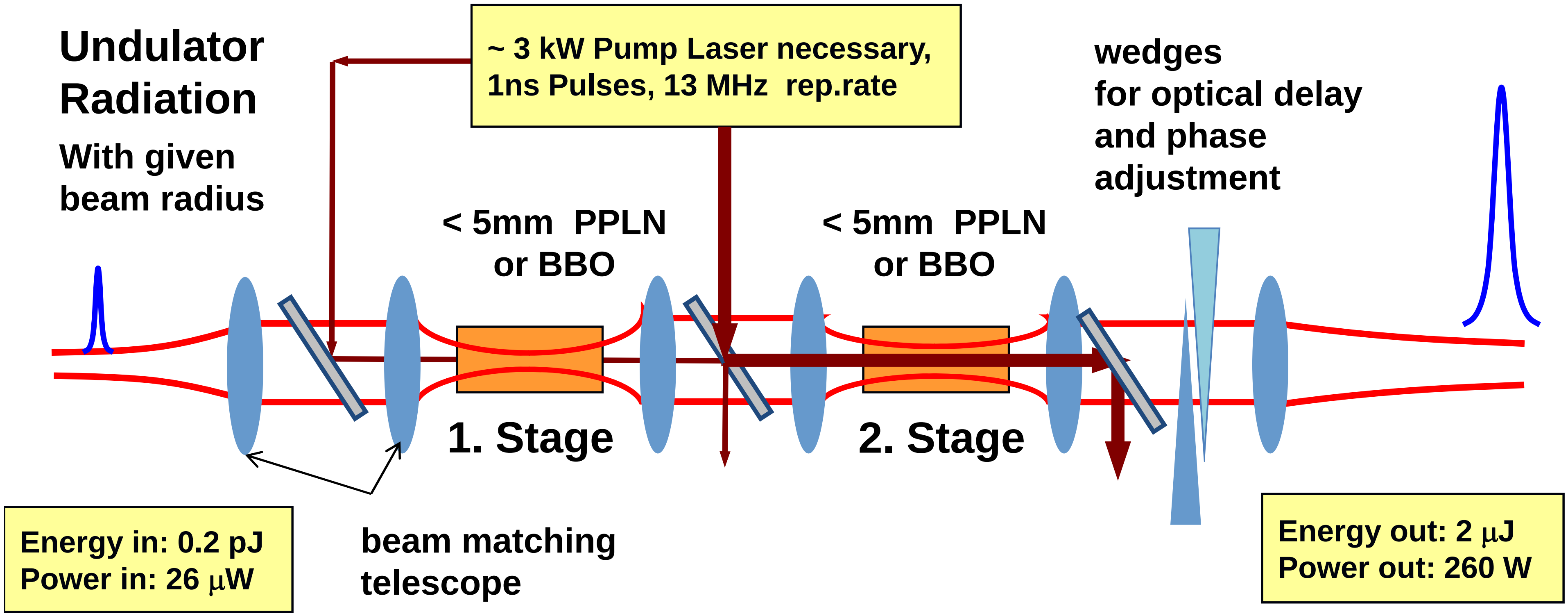
where $\Delta\bar{\phi}^2 \equiv k^2\left(R_{51}^2\bar{x}^2 + R_{52}^2\bar{\theta}^2 + h^2\bar{\delta}^2\right) = 1;$

$$\upsilon \equiv \eta\bar{\delta} / \bar{x}; \quad h = -\eta R_{51}; \quad R_{56} = 3h = -3 / \left(k\bar{\delta}\sqrt{2/\upsilon^2 + 1}\right)$$

Maximal gain factor G:

Optical Parametric Amplifier (OPA)

Schematic OPA layout for eRHIC OSC



Design to achieve total optical delay of < 2 cm possible

High Gain, G=10^7: Two stage amplifier necessary

1. Stage: G=10^5, 2. Stage: G=10^2

Critical Laser, OPA and Component R&D

Multi-kW pump laser technology

Low Risk

- **Cryogenic Yb:YAG developed at MIT Lincoln Laboratory (T. Y. Fan)**
  Fan *et al.*, JSTQE 13, 448 (2007): > 500 W (cw)
  higher performance classified (talk to T. Y. Fan)
  Brasseur *et al.*, 2.3 kW (cw), CLEO 2009

- **MIT RLE demonstrated 287 W ps-laser**
  K.-H. Hong, *et al*, Opt. Lett. 33, 2473 (2008)
  Can be easily adapted to produce 10ps-1ns pump pulse format at average power level as demonstrated in cw.
  But needs construction of 3kW Laser for OSC, estimate prize 2 Mio in 3-5 years.

The laser is not the risk!

OPA

High Risk

- **Basic performance at 2 μm demonstrated with > 600nm bandwidth, pumped with 4W demonstrated 200 mW output, 1kHz rep. rate at MIT RLE.**
- **Needs scaling to high average power handling capability**
- **Observed damage with PPLN at 100W average power pump level at 80 MHz rep. rate.**
- **Needs systematic study of OPA materials issues in PPLN, LN, BBO, … under large average power.**

OPA Potential

OPA development by MIT-RLE group (F. Kärtner) in collaboration with Lincoln Lab. (T.Y. Fan):

"Expect average output powers of 0.5 -1 kW in 5-10 years"

for $k = 2\pi / (2\mu m)$; $K = 0.14$; $I_i = 400\text{mA}$; $E_i = 250$ GeV

$$G \cong \frac{3}{E_i}\sqrt{\frac{P_{av}}{I_i / e} k(\alpha\hbar c)\frac{K^2}{K^2+2}} = 1.36 \cdot 10^{-13}\sqrt{P_{av} / \text{Watt}}.$$

For $P_{av} = 260\text{W}$; $\bar{\delta} = 1.6 \cdot 10^{-4}$; and $\upsilon = 2$:

Cooling time $\tau = T / \alpha_\varepsilon \cong 17$ minutes

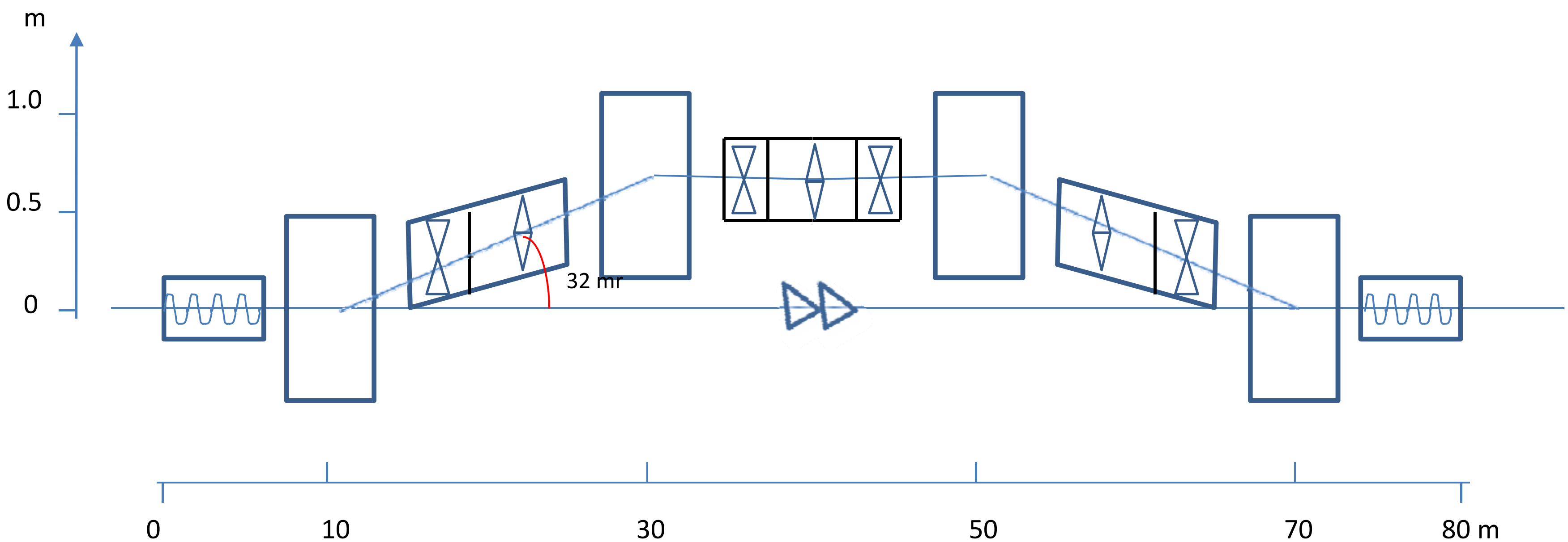
In agreement with estimates by M.Babzien et al.

OSC Bypass for RHIC

OPA is fast: Input-output delay = $L_{crystal}$ /c ≤ 20mm

→allows small-angle (32mrad) bypass with $\Delta\ell = 20$ mm

→relaxed tolerances for field and position accuracy and stability



Conceptual RHIC Bypass

For optimal cooling of 250 GeV protons beam with

$\varepsilon_{norm} = 15 \text{ mm} \cdot \text{mr}; \quad \beta = 3.4 \text{ m}; \quad \overline{\delta} = 1.6 \cdot 10^{-4}:$

$R_{51} = 8 \cdot 10^{-4}; \; R_{52} = 2.7 \text{mm}; \; R_{56} = -5 \text{mm}; \; \eta = 2 \text{m}.$

Bypass: 4 dipoles (6m, 4.5T); 8 quads (5m, 50T/m)

bending angle 32 mrad; total length 80 m;

"natural" (zero quad.) R_{56} = -40 mm.

Undulators: $B = 10 \text{ T}; \; \lambda_u = 27 \text{ cm}; \; K = 0.14; \; \lambda = 2 \mu m$

Bates OSC Verification Experiment

Rationale: Two concepts for cooling 250 GeV protons considered for Linac-Ring version of eRHIC:

CEC and OSC cooling time estimates are comparable, neither concept has been verified by experiment!

Test OSC with 300 MeV electrons at Bates South Hall Ring:

- Cooling times of 1-2 sec essential for feasibility test ("real-time" response to beam tuning)
- Much cheaper to implement than on hadron colliders
- Bates facility is available

OSC@Bates Collaboration

W. Barletta, P. Demos, K. Dow, J. Hays-Wehle*, J. van der Laan,
R. Milner, R. Redwine, S. Steadman, C. Tschalär, E. Tsentalovich,
D. Wang, F. Wang,
Massachusetts Institute of Technology Laboratory for Nuclear Science, Cambridge, MA 02139
and MIT-Bates Linear Accelerator Center, Middleton, MA 01949

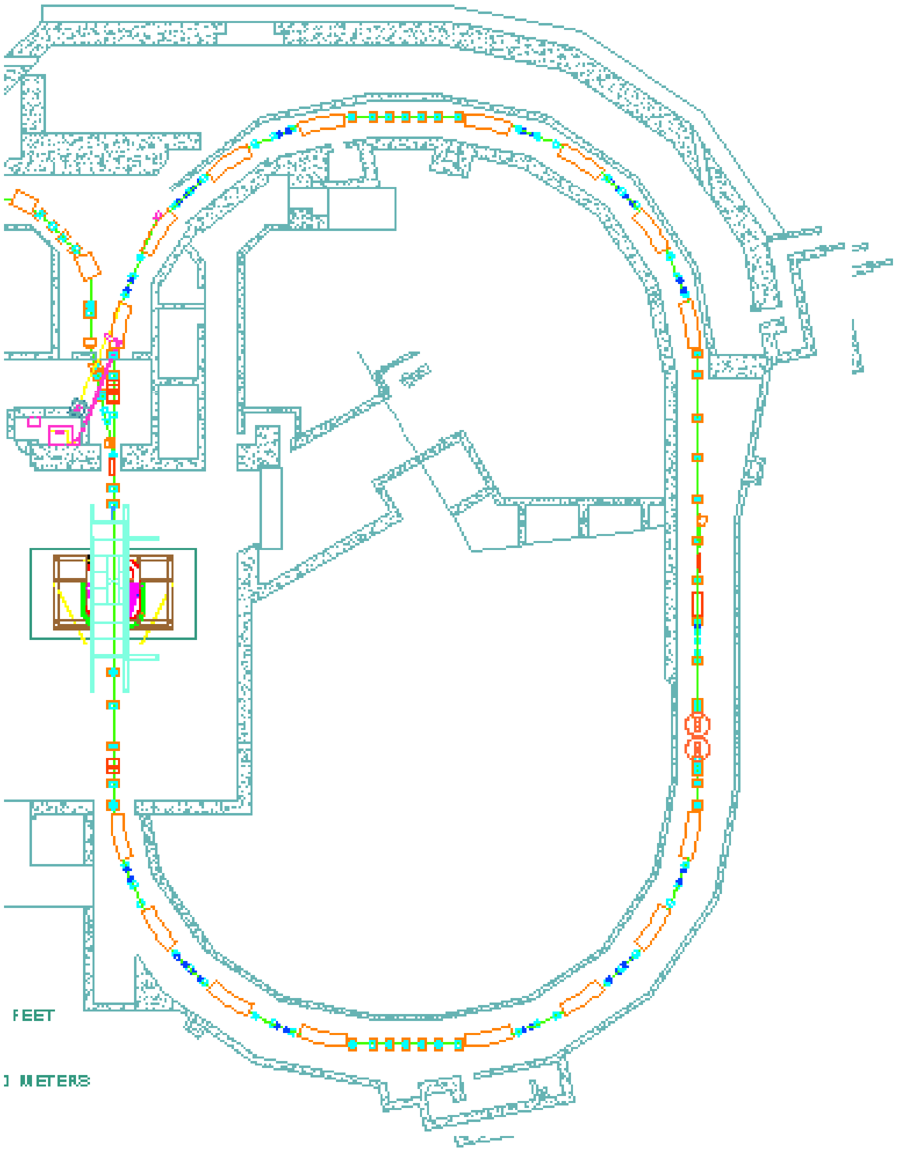
F. Kärtner, A. Siddiqui*
MIT Research Laboratory of Electronics, Cambridge, MA 02139

M. Bai, M. Blaskiewicz, W. Fischer, B. Podobedov, V. Yakimenko
Brookhaven National Laboratory, Upton, NY 11973

S.Y. Lee
Indiana University Cyclotron Facility, Bloomington, IN 47405

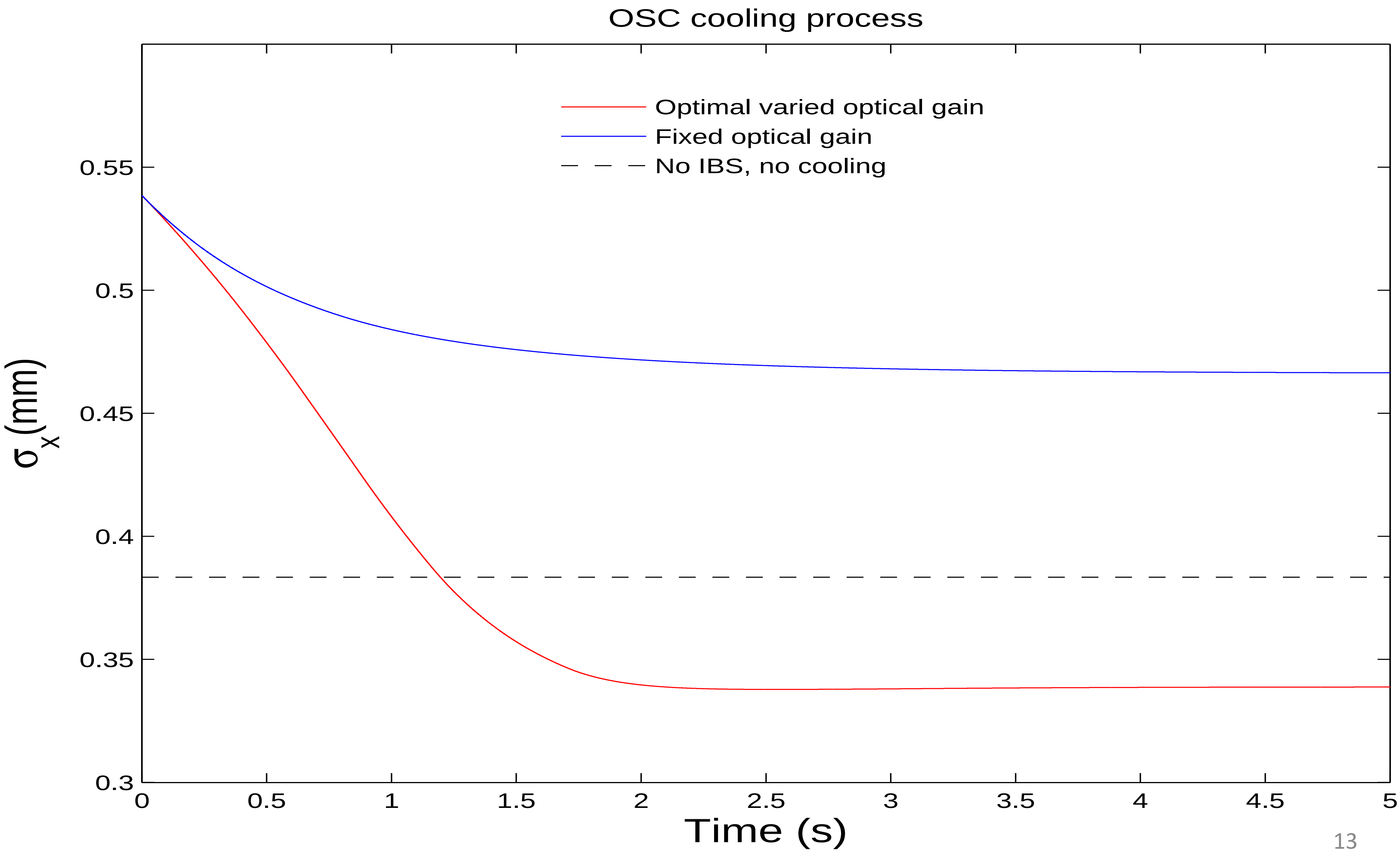
W. Wan, A. Zholents, M. Zolotorev
Lawrence Berkeley National Laboratory, Berkeley, CA 94720

Bates OSC Experiment: Layout



- Distinguish OSC from damping due to synchrotron radiation
  - Low energy electrons
  - Large dipole bend radius
- Long straight sections desirable for OSC apparatus
- South Hall Ring, e^- storage ring
  - Full energy injection at 300 MeV
- Dedicated use of South Hall Ring for first OSC demonstration
  - Design tolerances consistent with existing technology
  - Optimize for SHR environment

Estimated Transverse Cooling



Bates OSC Experiment: Proposal

- Realization plan for OSC demonstration with electrons over 3 years
  - Y1: Beam studies for OSC Lattice, amplifier bench tests
  - Y2: Install and commission OSC chicane, wigglers, amplifier
  - Y3: Experimental program to study OSC of damped electron beam
- Base OSC demonstration program
  - Measure bunch intensity, energy dependence
  - Lattice study, optimization of α_T, α_L
  - Dynamic optical gain and OSC stability
  - Simulations
- Toward heavy particle OSC
  - Diagnostics in high gain regime
  - High power amplifier development

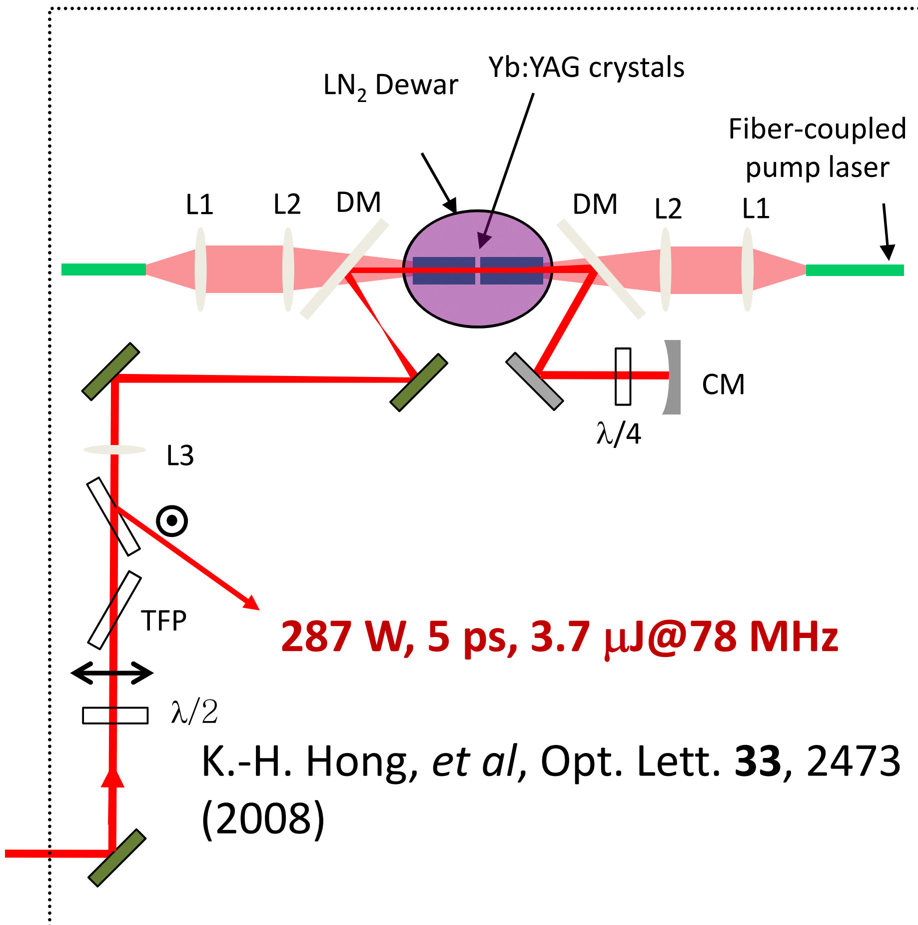
Conclusions

- With appropriate funding, OPA output powers are expected to approach the 1 kW level in 5-10 years allowing OSC cooling times well below 30 minutes for 250 GeV proton beams of eRHIC
- OSC would become competitive with other theoretical cooling concepts
- Experimental verification is essential to make OSC a proven, practical tool for eRHIC and other high-energy facilities
- The Bates SHR is the optimal site for such an experiment and the development of OSC technologies

Back-up

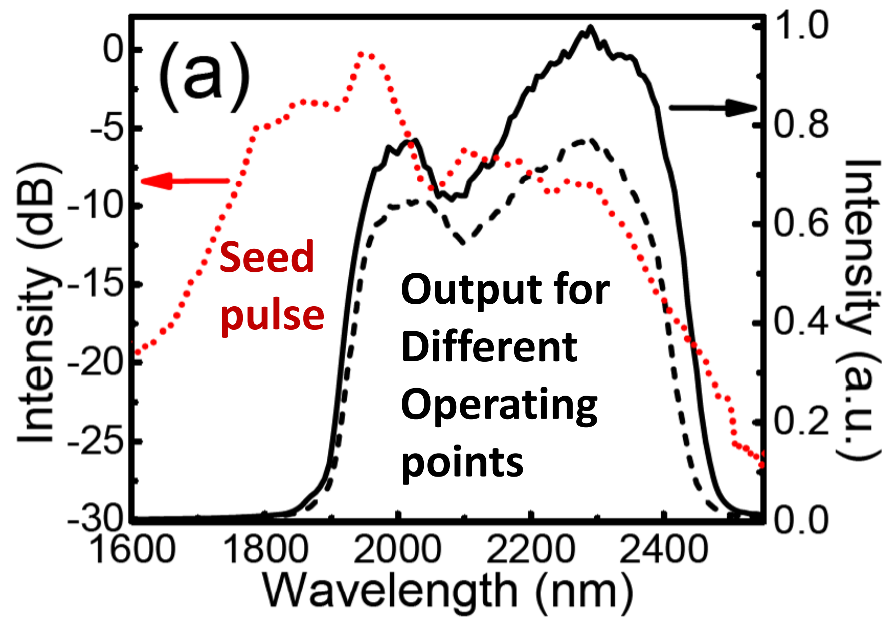
Some Details

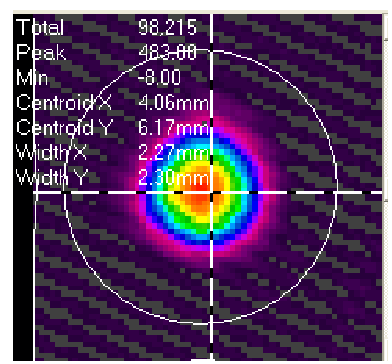
Yb:YAG amplifier



K.-H. Hong, *et al*, Opt. Lett. **33**, 2473 (2008)

2 mm OPA characteristics





Beam profile

J. Moses, et al., Opt. Lett. **34**, 1639-1641 (2009)