First Experimental Demonstration of Optical Stochastic Cooling with the MIT-Bates South Hall Ring

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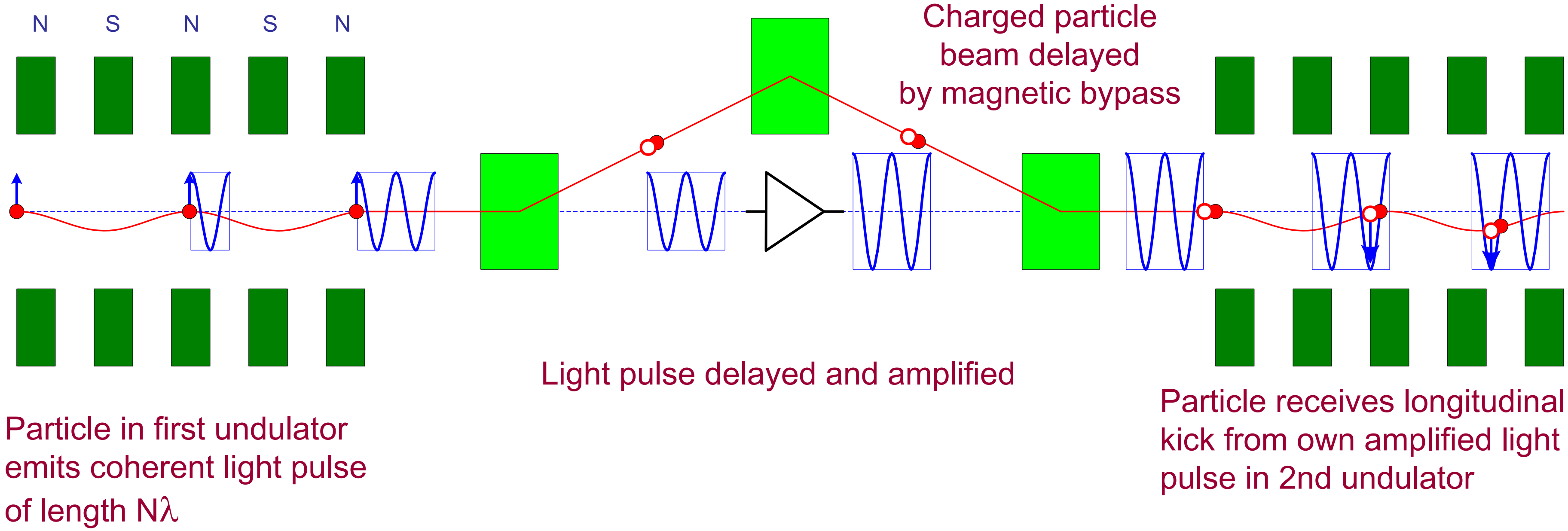
Reference: M.S. Zolotorev and A.A. Zholents, Phys. Rev. E 50, 3087 (1994)

Why Optical Stochastic Cooling?

- Beam cooling essential for maximizing luminosity in modern colliders
- Existing techniques diminish in effectiveness for beams at high energy and high brightness
- Optical stochastic cooling holds promise for this regime
- Relevant to LHC, RHIC, EIC/eRHIC, etc.
- Potential application to high brightness light sources
- Involves delicate manipulation of beams with light
- Bates experiment seeks to demonstrate this new technique for the first time

Introduction to OSC

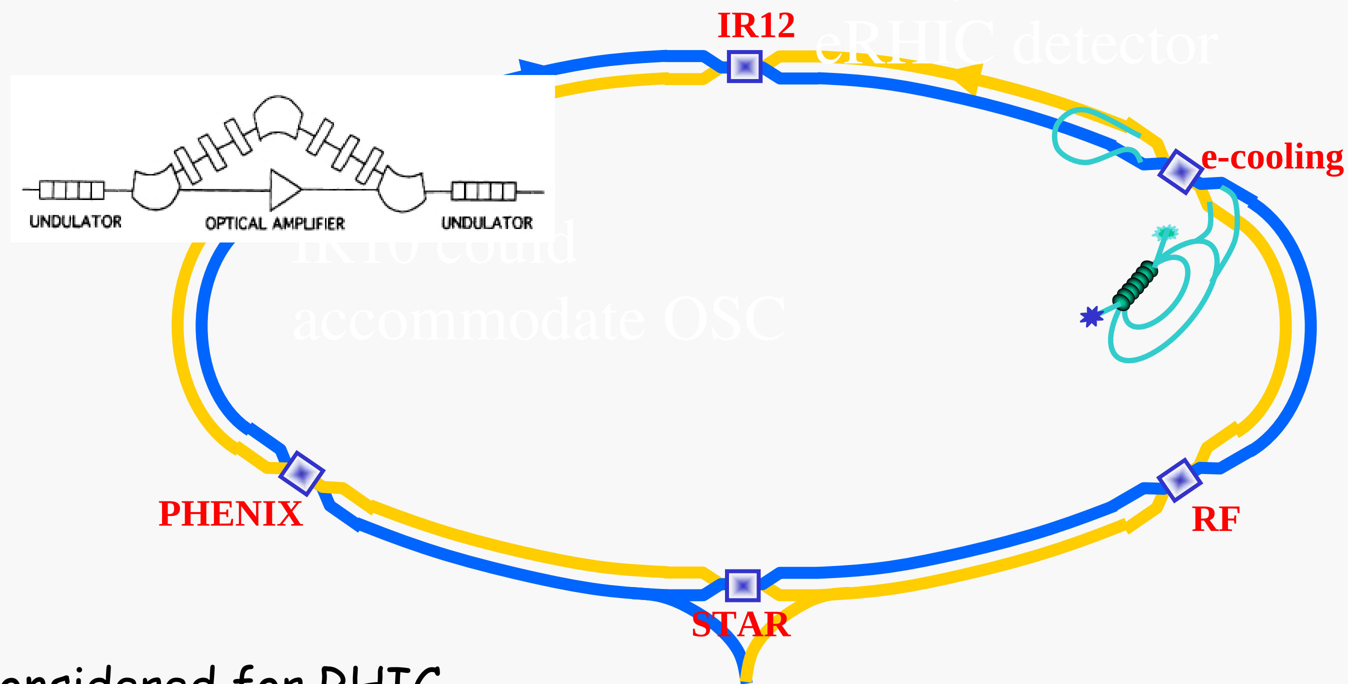
- Transit-time method of optical stochastic cooling:
  - Reduce momentum spread; transverse cooling through dispersion
- Analogous to stochastic cooling using undulator radiation
- Increase of system bandwidth by 4 orders of magnitude compared with microwave stochastic cooling reduces cooling time



Formalism not explicitly dependent on charged particle type

OSC in RHIC

- Estimates of OSC made for RHIC {M. Babzien *et al*, Phys Rev STAB 7, 012801 (2004)}
  - Increased beam lifetime and time-averaged luminosity for p and Au ions by counteracting the beam spreading from IBS and beam-beam interactions
  - Reduces tails and detector background (complements electron cooling)



- OSC considered for RHIC
  - IP10 could accommodate OSC apparatus
  - **Preliminary estimates indicate that a factor of 2 increase in luminosity seems possible, but this estimate depends strongly on achievable experimental parameters.**

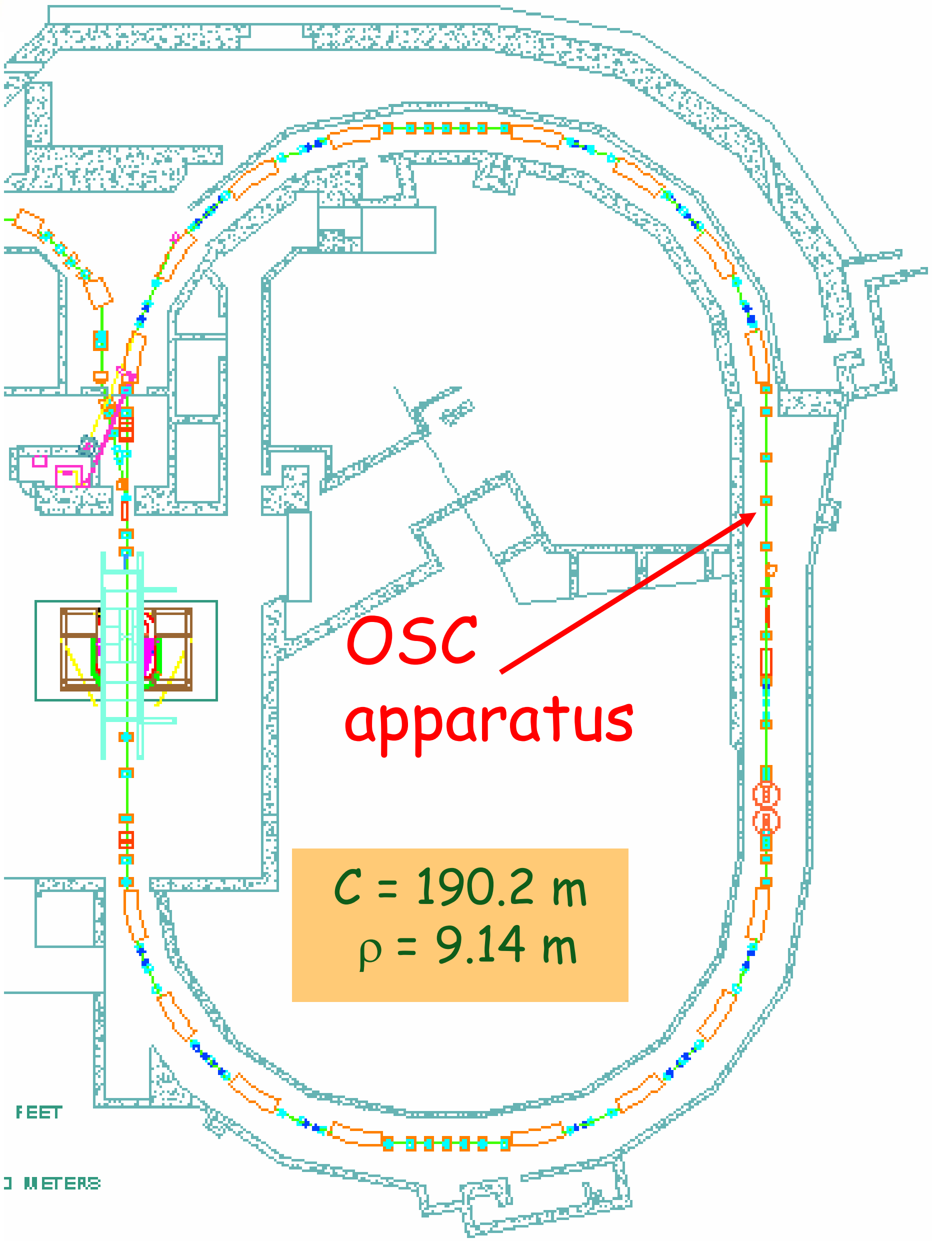
OSC Demonstration with Electrons

- OSC never demonstrated in practice
- Technical requirements for cooling of heavy particles are very severe
  - Bypass optics must be synchronized with amplified light within 1 μm (fraction of λ)
  - Very strong wiggler fields needed for bending heavy particles (~10 T peak)
  - Amplifier output saturates far below optimal gain
  - Diagnostics capable of detecting OSC required (cooling time ~ hours)
- Demonstration of OSC with electrons could point way to cooling beams at very high energy and high bunch population
  - OSC of electrons much faster (seconds) than for hadron beams (hours)
  - Modest technical requirements (wiggler, amplifier, bypass chicane)
  - Develop techniques and diagnostics needed to achieve OSC in practice
  - Evaluate prospects for OSC in high-energy, high-brightness regimes

MIT-Bates Linear Accelerator

- Bates operated by MIT for US DOE as nuclear physics user facility since 1974; program ended in 2005 with very successful BLAST program using polarized electron beam and polarized targets in South Hall Ring
- Buildings and accelerator transferred from DOE ownership to MIT in 2005

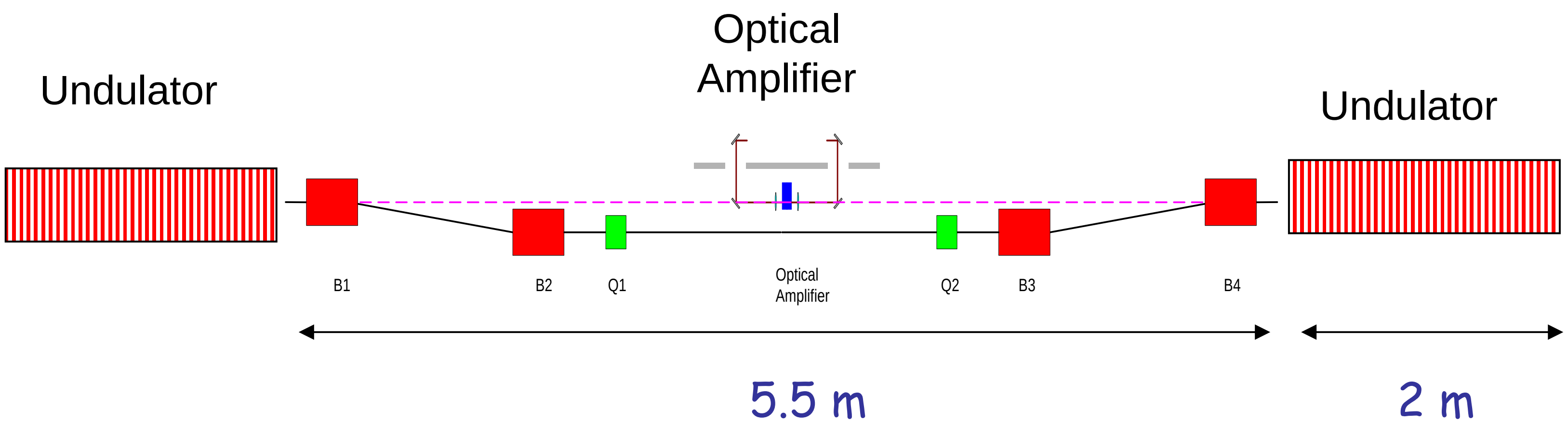
MIT-Bates South Hall Ring



- 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

OSC Apparatus Overview

- Broadband optical parametric amplifier (developed by MIT-RLE)
  - Large dispersion-free linear amplification in short medium
  - Total delay ~20 ps with control to a fraction of an optical cycle
- Small angle (65 mrad) OSC bypass with 6 mm path length change makes the setup robust
  - Fixed optics with achievable magnet tolerances
  - Minimize effects of synchrotron radiation and required changes to SHR RF
- Undulators matched to amplifier wavelength (2 μm), bandwidth (~10%)
- All readily integrated within 10 m of SHR east straight section



OSC Beam Design for Optimal Experimental Conditions

Parameter	Symbol	Design Value
Beam Energy	E	300 MeV
SR transverse damping time (sec.)	τ_x	4.83 s
Particles/bunch	N_b	$1.0 * 10^8$
SHR bunch frequency	f_b	18.9 MHz
SHR average current	I	0.3 mA
SHR horizontal emittance	ε_x	98π nm rad
SHR relative momentum spread	σ_p	$1.67 * 10^{-4}$

- Design parameters for an OSC demonstration experiment
  - Choose lowest viable energy with bunched beam
  - Very different operation from NP stored beam (cw, 850 MeV)
- OSC beam study (April-May 2007)
  - Viability of complete accelerator (first beam since June 2005)
  - Established stored beam at 325 MeV (lowest energy stored in SHR)

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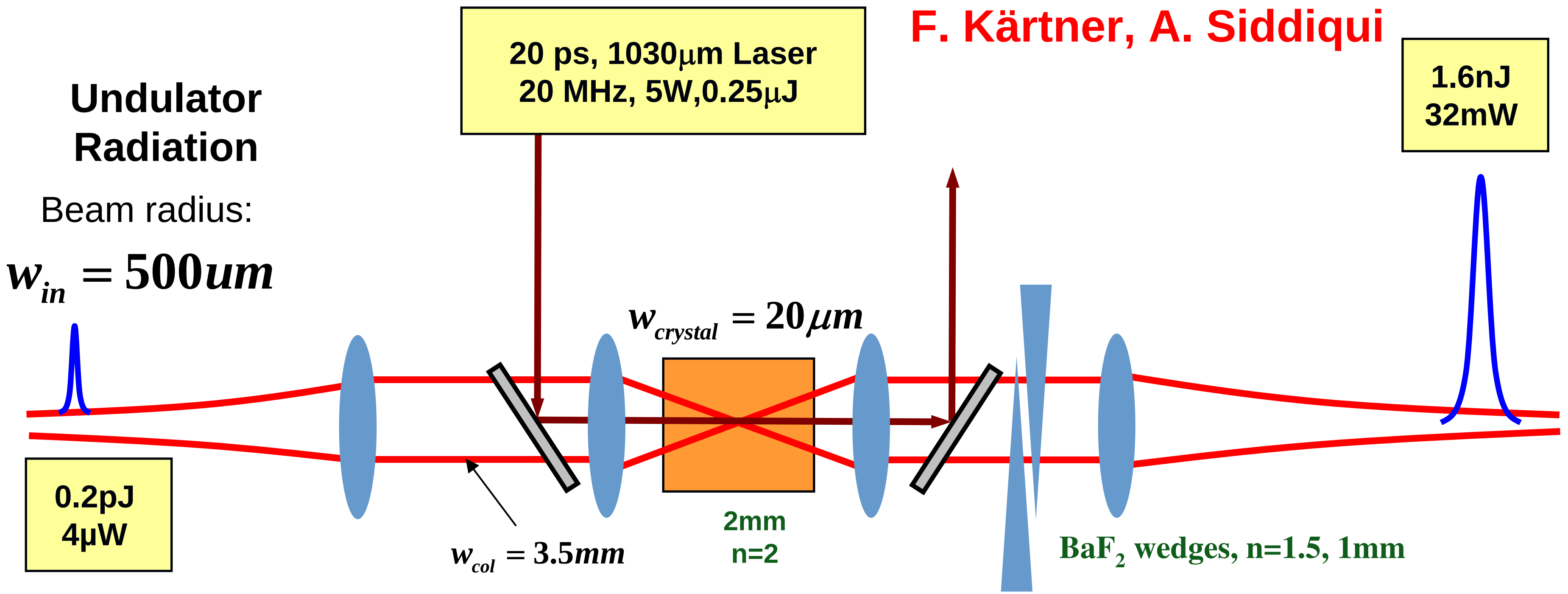
- Beam development
  - Pulse spacing of stored beam consistent with amplifier rep rate
  - Optimize lattice using large emittance and high dispersion to increase sensitivity to OSC
- Experimental approach
  - Equilibrium when IBS growth rate matches synchrotron damping
  - Optically cool damped beam in equilibrium
  - Expect observable OSC effects primarily on on transverse beam profile

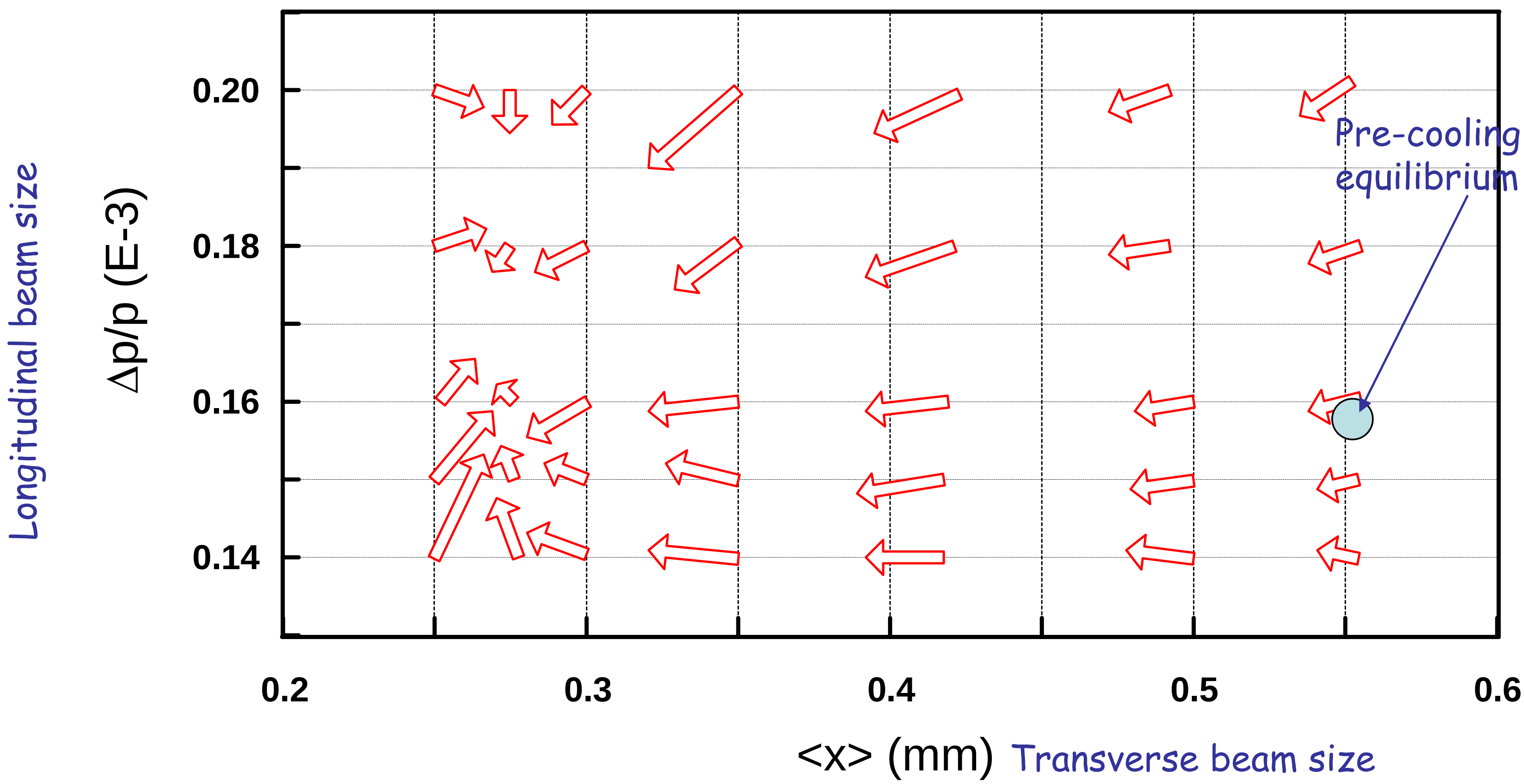
Undulator Radiation



- Amplification in periodically poled lithium niobate crystal (PPLN)
- Pump laser controls gain; phase-locked to stored electron beam
- Optics internal to SHR vacuum system; remotely actuated
- Fine phase control allows interferometry in 2nd undulator for achieving OSC

OSC Numerical Modeling

Change in profile of the beam bunch in 50 ms



- Measure beam size vs. time with synchrotron light diagnostics
- OSC gives rapidly observable transverse reduction to new equilibrium

OSC Experiment at Bates

- Applied for funding to build apparatus, run experiment
  - Rated as "Compelling" by RHIC Accelerator Physics Review Panel
  - MIT discretionary funds for just completed beam study (April-May 2007)

- Realization plan over 3 years
  - Develop beam tune for OSC enhancement (OSC Lattice)
  - Develop and install OSC chicane
  - Install wigglers and amplifier

- Experimental program to study OSC of damped electron beam
  - Measure OSC as function of bunch intensity, lattice, and amplifier parameters
  - Develop new diagnostics for OSC optimization

Summary

- OSC is a promising cooling technique for high energy beams.
  - Only known method for cooling high-energy hadrons
  - Also potentially useful for muon collider
- Demonstration and development of technique prohibitive in cost at hadron facilities; should use electron storage ring as first step
- MIT-Bates South Hall Ring provides ideal environment with eager collaboration for this study
- Study OSC for varying bunch intensity, lattice, amplifier parameters
- Investigate new diagnostics for OSC optimization

Backup

OSC Chicane

- Bypass optics control path length difference between electrons and light
- Response matrix for chicane modeled with TRANSPORT, MAD
  - Dipole bend angle couples path length change to momentum (**R_{56}**)
  - Field lens couples to transverse props (**R_{51}, R_{52}**) for nonzero dispersion
- Absolute setting demands R51, R52, R56 setting within ~±5%
  - Power supply current accuracy {± 1%}, magnet positioning {± 10 mm}
- Stability (~1 hour) demands variation for central orbit length ≤ 0.1 μm = 20° phase
  - Current stability {10-5}, position stability {50 μm}
- Higher order coefficients calculated, effects small (COSY)

	X mm	x' mrad	y mm	y' mrad	l mm	Δp/p %
X	1.02632	6.07987	0.00000	0.00000	0.00000	-0.02580
x'	0.00877	1.02632	0.00000	0.00000	0.00000	-0.00860
Y	0.00000	0.00000	0.84246	5.72468	0.00000	0.00000
y'	0.00000	0.00000	-0.05070	0.84246	0.00000	0.00000
l	**0.00086**	**0.00258**	0.00000	0.00000	1.00000	**-0.01200**
Δp/p	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000

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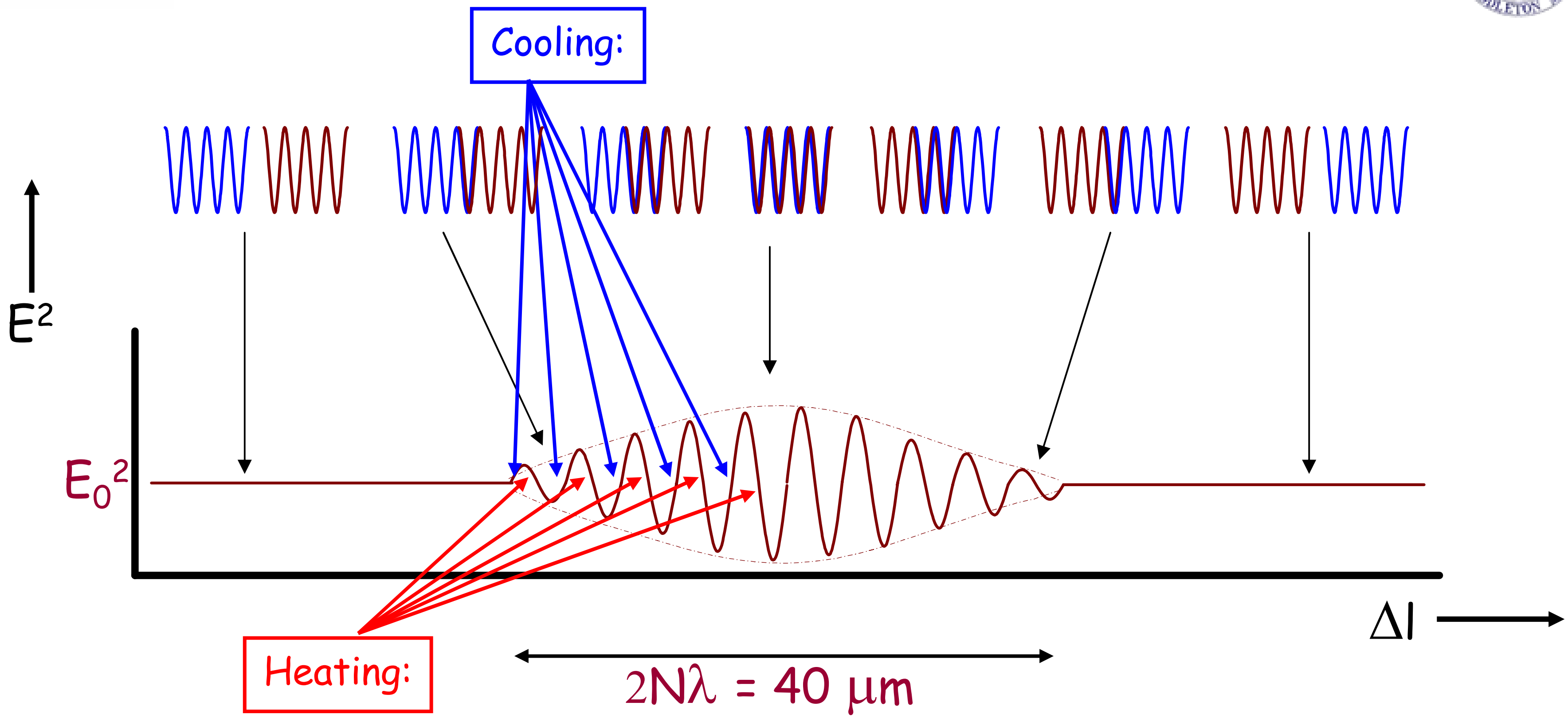
- Developing injection scheme to populate selective (1-12) SHR RF buckets
  - Pulsed amplifier for OSC (f < 40 MHz) and multi-bunch instabilities
  - Built mode-locked fiber laser for photoinjector, locked to RF & OSC amp
- Verified linac transport for OSC conditions
  - Low beam loading and average current for diagnostics
  - Existing RF systems accommodate path length changes for OSC chicane

"Synchronized Lightpulse" Signal



- Interference signal maximal when light amplitudes same ($A_1=A_2$)
- E^2 is maximal for $\Delta\phi = 0$ ($\Delta\phi = \pi/2$ for OSC)
- Initial alignment with amplifier gain off
- Possible use in feedback system if signal locked

OSC Estimates in RHIC

- OSC presently limited by laser estimates (large uncertainty in effect)
- Assume that OSC can curtail emittance growth from heating effects
- Complementary to electron cooling

Future Cooling possibilities RHIC p beams (W. Fischer, BNL)	Uncooled (present)	Cooled (overcome IBS, beam-beam)	
Luminosity lifetime	~3 h	10 h	30 h
Time between stores	1.5 h		
Optimum store length	2.6 h	5 h	9 h
Store length	5 h	5 h	9 h
Time average/peak luminosity	37%	61%	74%
Integrated luminosity gain		60%	100%