Two Energy Storage Ring Electron Cooler Update

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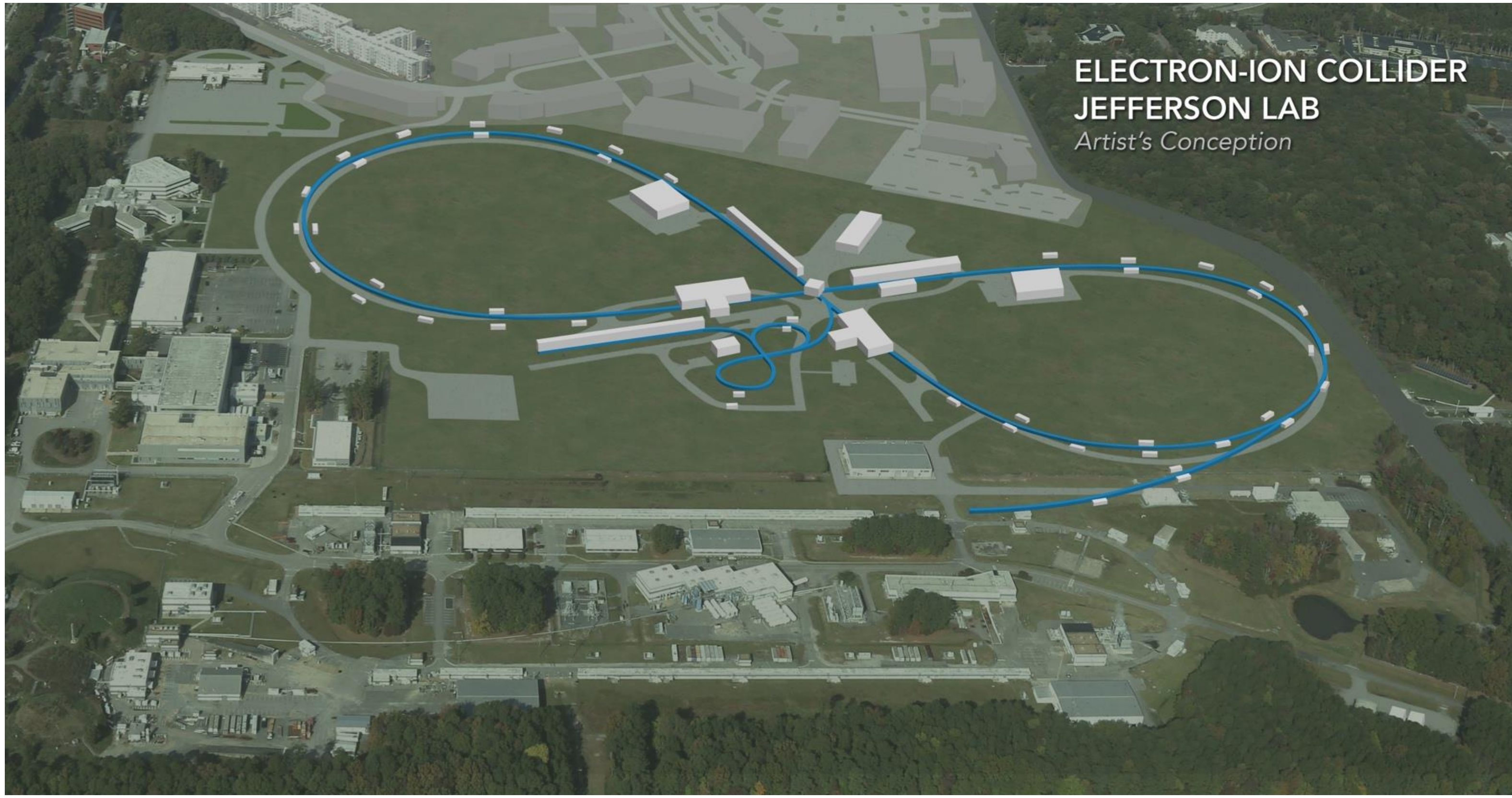

JLEIC Collaboration Meeting

April 1 - 3, 2019

Jefferson Lab

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Outline

- History
  - Proton/antiproton coolers
  - HERA idea
  - Rate estimates
- Two Energy Storage Ring FOA Activity
  - Longitudinal matching
  - Simulation problems
  - Artificial damping
- Future Work
  - Magnetized beam
  - Renieri limit (Fokker-Planck)
  - Expansion Cooling
- Summary

Proton/Antiproton Coolers

- Cline, Garren, Rubbia, Mills, et al., PAC 1979, pg. 3472

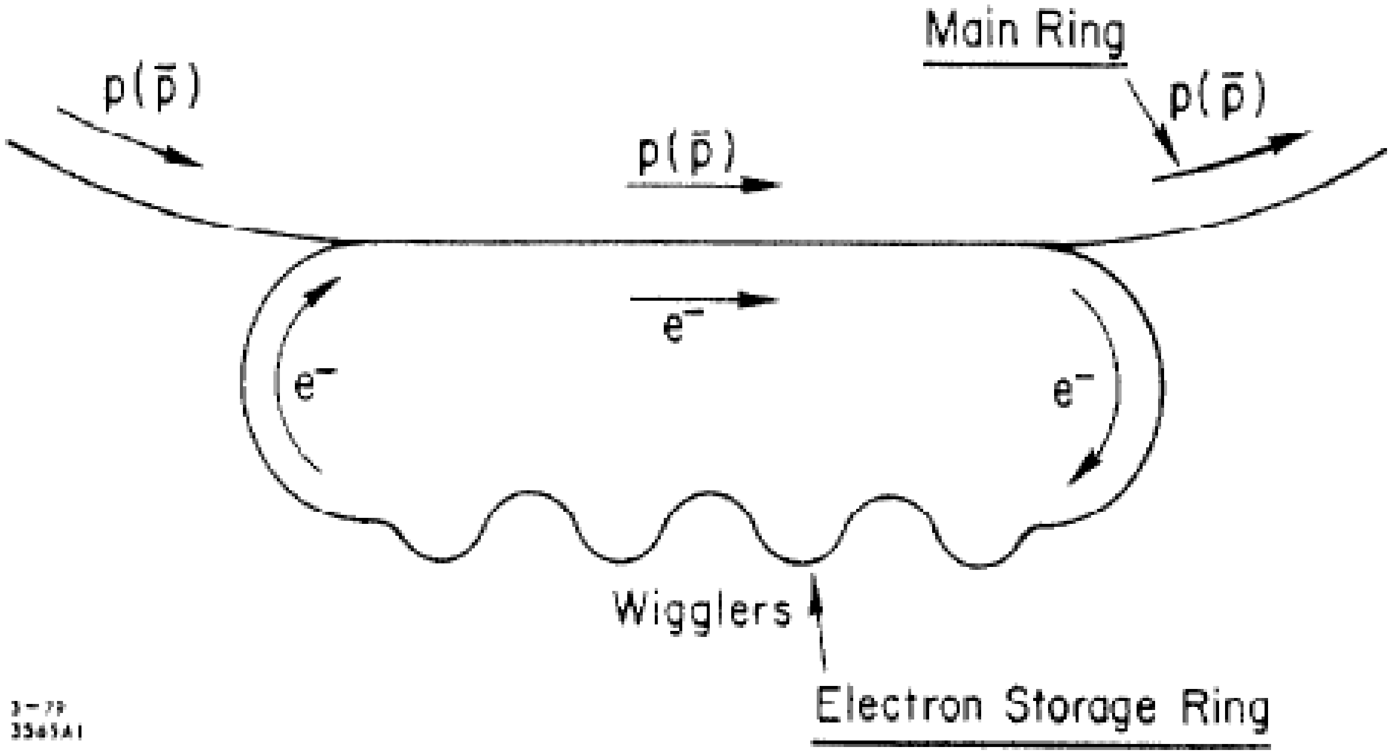

Fig. 1. High energy electron cooling plan.

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Equilibrium Conditions

- Beam temperature of equilibrium Gaussian distribution in uniform focusing channel

$$\frac{kT}{m_0c^2} = \frac{\gamma\varepsilon}{\beta} = \frac{\varepsilon_n}{\beta}$$

- Evolution equations

$$\frac{1}{\beta_p^*}\frac{d\varepsilon_p}{dt} = -\frac{2}{\tau_p}\left(\frac{\varepsilon_p}{\beta_p^*} - \frac{m_e}{m_p}\frac{\varepsilon_e}{\beta_e^*}\right) \quad (4)$$

$$\frac{1}{\beta_e^*}\frac{d\varepsilon_e}{dt} = -\frac{2}{\tau_e}\left(\frac{\varepsilon_e}{\beta_e^*} - \frac{m_p}{m_e}\frac{\varepsilon_p}{\beta_p^*}\right) \quad (5)$$

More modern

$$\frac{dT_p}{dt} = -\frac{2}{\tau_{cool}}\left[T_p - T_e\right]$$

$$\frac{dT_e}{dt} = -\frac{2}{\tau_{rad}}\left[T_e - T_p\right]$$

- Ion cooling exponential time τ_{cool} , electron synchrotron radiation cooling time τ_{rad}
- $64000 question: can one transfer the fast electron radiation damping rate to the ions?

FERMILAB Proposed Test

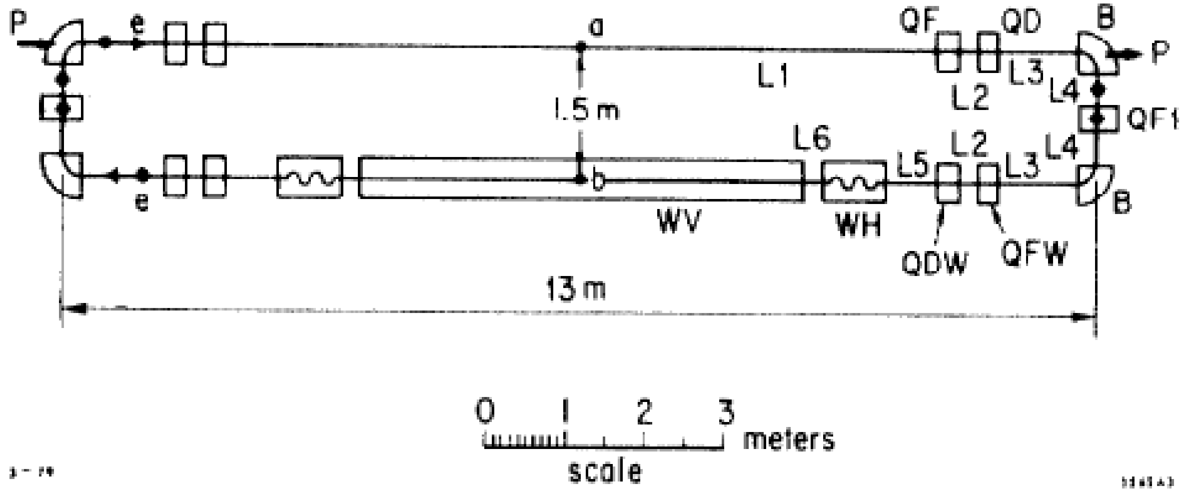

Fig. 3. Lattice of electron storage ring or cooling protons.

Table II. Operating Parameters

Energy	E	125	MeV
Magnetic Field in Main Bends	B_o	1.6678	Tesla
Rigidity	$B\rho$	0.41695	Tesla-m
Edge Angle of 90° Bands		0	Degrees
Wigglers:			
Length of One Bending Period	LWP	0.20	m
Number Periods in WH	N_n	4	
Number Periods in WV	N_v	14	
Length of Each Wiggler Pole	LWP	0.10	m
Wiggler Magnetic Field	B_w	1.6678	Tesla
Machine Circumference	$2\pi R$	28.5708	m
Average Radius	R	4.54718	m
Revolution Time	Trev	0.0953	μs
Energy Radiated/Turn (Wigglers On)	U_o	0.482	keV

- Interesting comments
  - “The proton and electron beams should have roughly equal transverse sizes and angles”
  - “the dispersion function should be zero or small in the cooling region”
  - “Electron damping times should be as short as possible. This leads to strong fields in the dipoles and the addition of wiggler magnets”
  - “it is nearly impossible to make the complete ring stable. …we propose short wiggler periods”

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HERA Era

- K. Balewski, R. Brinkmann, Y. Derbenev, et al., NIM A, **441** (2000) 274-280
  - Proposed HERA luminosity upgrade involving 2 coolers. Potential luminosity double.
  - First PETRA cooler

Table 2
Parameters of the electron cooler in PETRA

Parameter (electron cooler)	
Energy (MeV)	9.8
γ	19.2
N_e (10^{10})	3.0
$\varepsilon_{Nx}(1\sigma)$ (mm mrad)	3.0
$\varepsilon_{Ny}(1\sigma)$ (mm mrad)	3.0
$\beta_x(m)$ (cooler section)	200.0
β_y (m) (cooler section)	200.0
$\Delta p/p$ (10^{-4})	5.0
σ_z (m)	0.5
L_{cooler} (m)	50.0
L_{PETRA} (m)	2304.0
$\eta = L_{\mathrm{cooler}}/L_{\mathrm{PETRA}}$	0.022
τ_{trans} (min)	5.0
τ_{long} (min)	4.0

Table 4
Electron parameters at the end of the linac

Parameters at end of linac	
Energy (MeV)	9.8
N_e (10^{10})	3
$\varepsilon_N(1\sigma)$ (mm mrad)	2
$\Delta p/p$ (10^{-4})	30
σ_z (m)	0.017

Features
Circulator ring for (de/re)bunching electrons
Magnetized beams
"proper matching between the end of the linac and the beginning of the cooler section is mandatory"

Storage Ring Cooler

Table 5
Beam parameters for HERA-p and cooler

Parameter	HERA	Cooler ring
Energy (GeV)	820	0.45
N_p, N_e (10^{11})	1	2
$\varepsilon_x(1\sigma)$ (nm rad)	3.8	7.9
$\varepsilon_y(1\sigma)$ (nm rad)	0.9	2
β_x (m) (cooler section)	1000	1000
β_y (m) (cooler section)	250	250
$\Delta p/p$ (10^{-4})	2.1	4.4
σ_z (m)	0.31	0.22

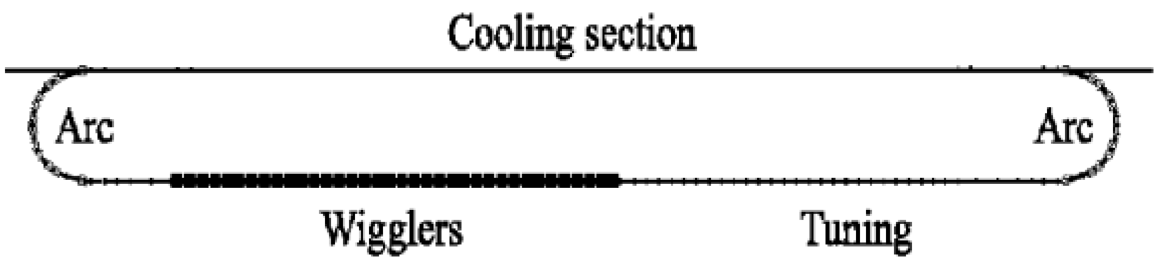


Fig. 2. Layout of electron cooler ring.

- Interesting quotes/conclusions
  - "the cooler in HERA is needed to preserve the proton beam quality achieved in PETRA"
  - "the heating of the electrons either by intrabeam scattering or by the protons in the cooler section can be compensated by radiation damping"
  - "The equilibrium electron beam parameters are no longer solely determined by radiation process, but strongly influenced by intrabeam scattering."
  - Large beta-function in the electron optics in cooler region (yielding small temperature there)

Storage Ring Optics

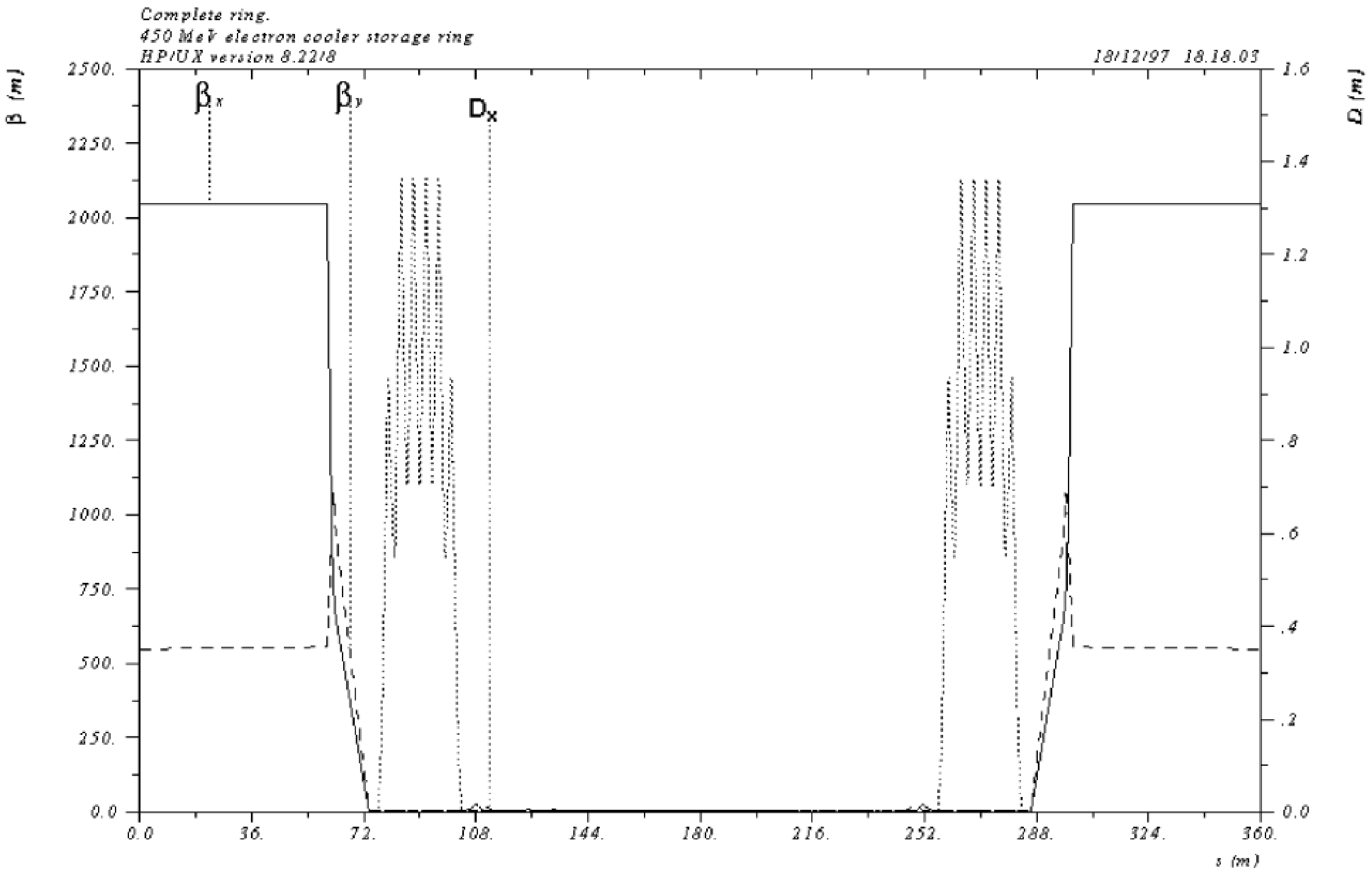


Fig. 3. Optics of electron cooler ring.

Cooling Rate Estimates

- Use simple temperature model to make turn-by-turn difference equation

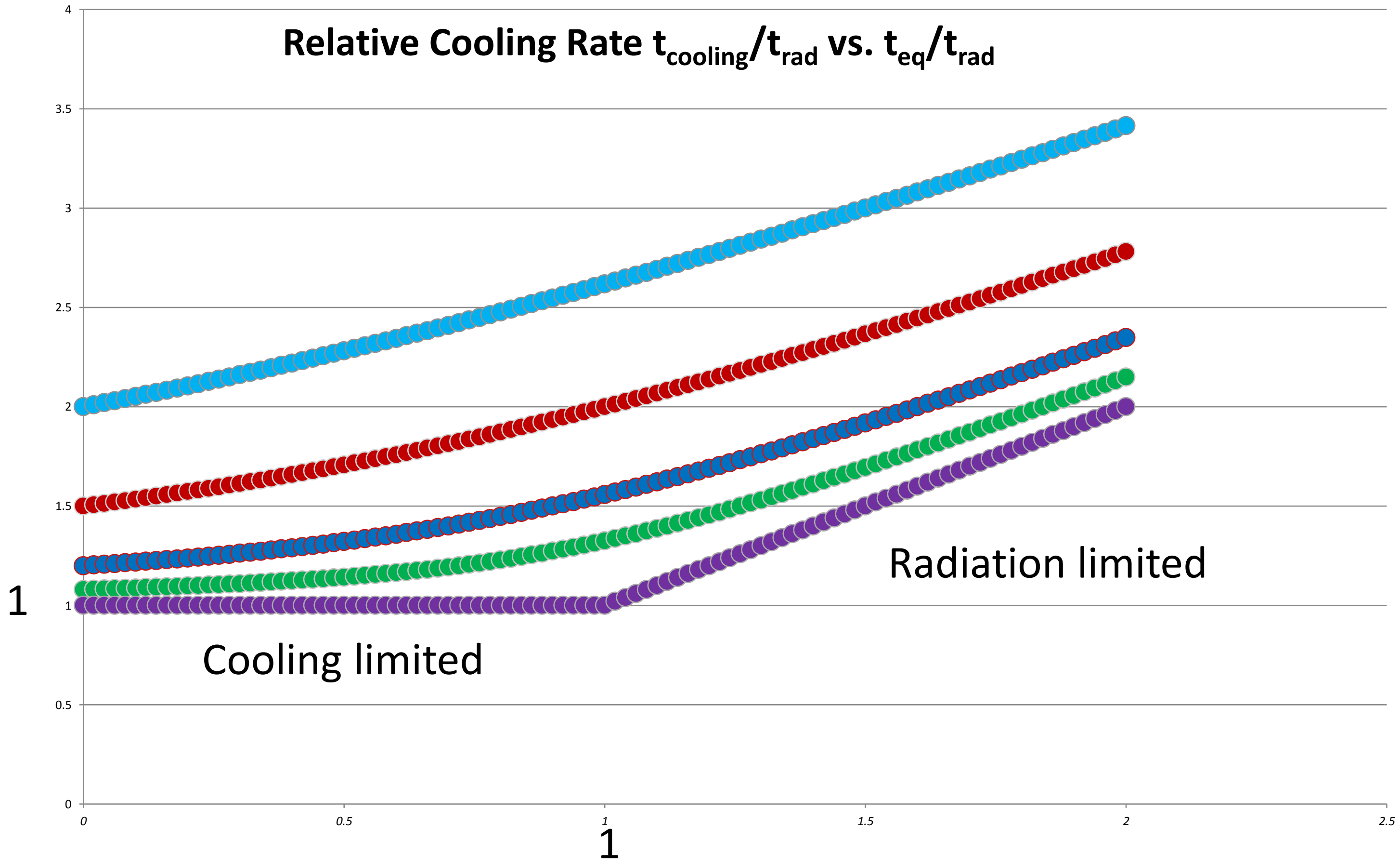


Figure 2: Relative cooling time for N_i/N_e=0 (purple), 0.08 (green), 0.2 (blue), 0.5 (brown), 1 (light blue)

Cooling Rate Estimates

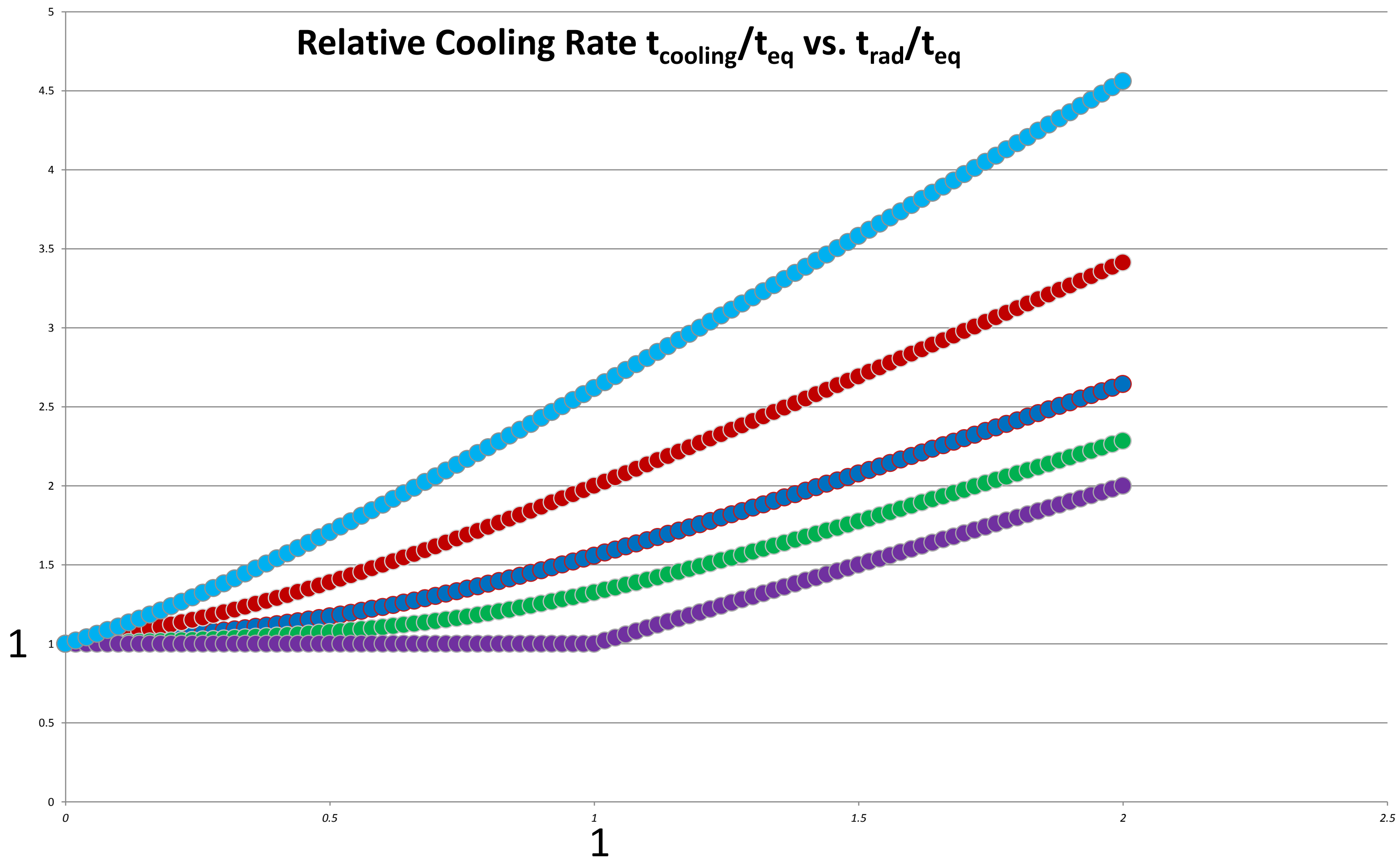


Figure 2: Relative cooling time for N_i/N_e=0 (purple), 0.08 (green), 0.2 (blue), 0.5 (brown), 1 (light blue)

Use Strong Damping at High Energy

- Ring Damping Time

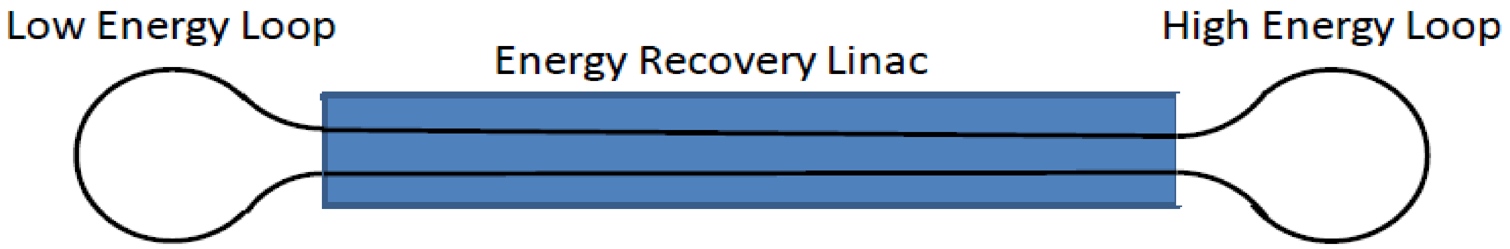
$$\frac{1}{t_{rad}} \sim \frac{1}{t_{rev}}\left[\frac{\Delta E_{rad,H}}{E_H}+\frac{\Delta E_{rad,L}}{E_L}\right] \sim \frac{1}{t_{rev}}\left(\frac{4\pi r_e}{\rho_H}\gamma_H^3+\frac{2\pi}{3}\alpha K^2\frac{L}{\lambda_{ID}}\frac{2\gamma_H}{1+K^2/2}\frac{\lambda_c}{\lambda_{ID}}+\frac{4\pi r_e}{\rho_L}\gamma_L^3\right)$$

- Optimize cost under simple model
  - Add energy instead of wiggler
  - Cooler more compact
  - Beam dynamics simpler
  - Around 500 MeV all that is needed
- Energy exchange vanishes once electron beam and ion beam at same temp

Recent FOA Activity

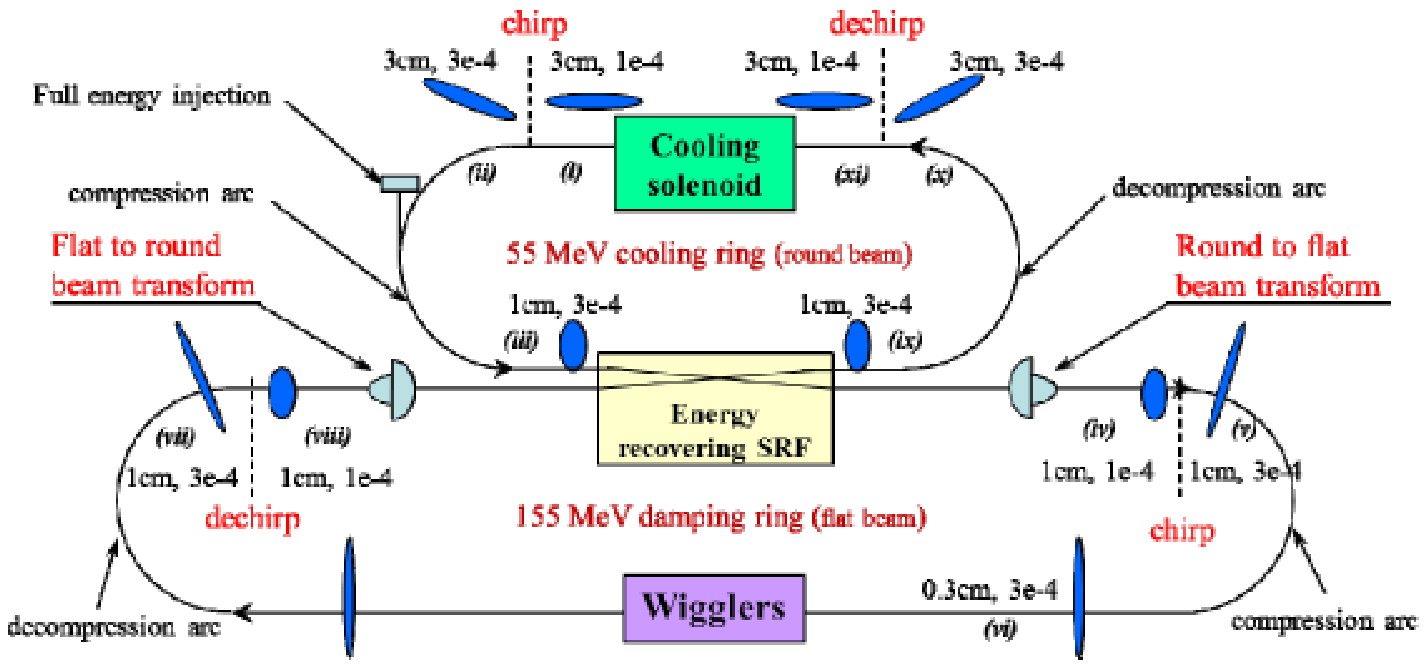
- Development of Innovative, High-energy, Magnetized Electron Cooling for an EIC (Benson, PI)
  - JLAB/ODU subproposal: Further evaluate and optimize storage ring electron coolers based on two-energy storage rings. Improve prototype linear optics of such a cooler, including properly including aspects of creating magnetized beam for the electron cooling section.

JLAB/ODU Energy Recovered Loop Accelerator



- F. Lin, et al.,

IPAC 2016



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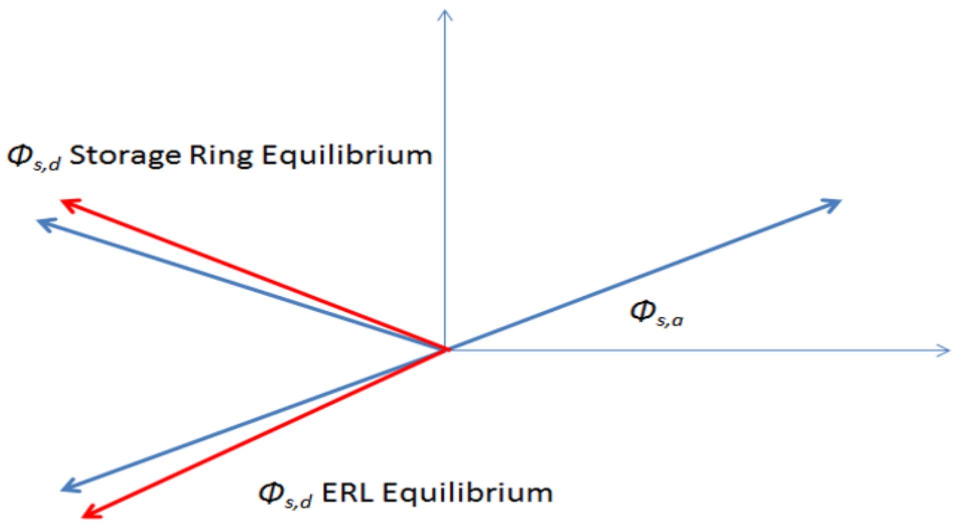
RF Voltage Phasor

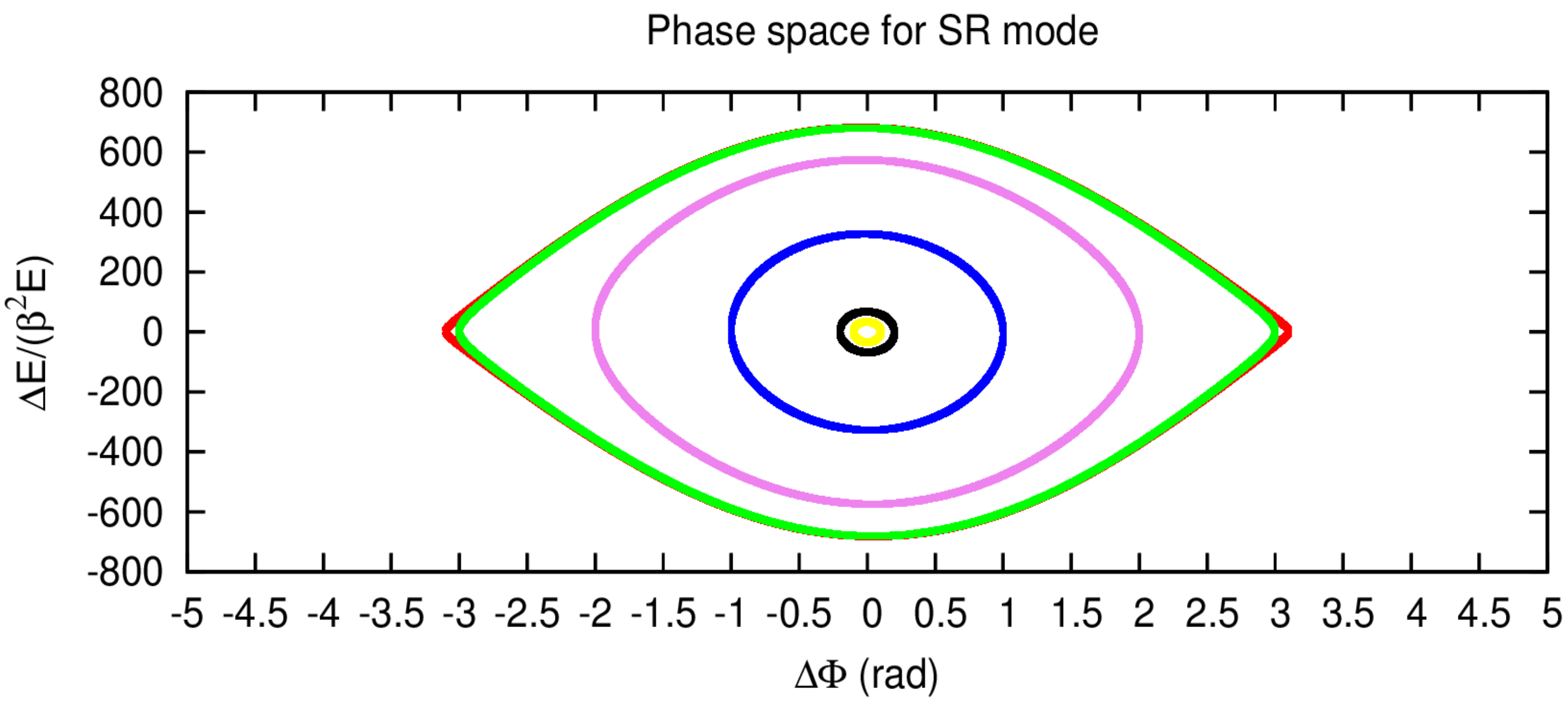


$$M=\begin{pmatrix}1 & h_L/E_L\\ 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0\\ -V\,sin\Phi_{s,d} & 1\end{pmatrix}\begin{pmatrix}1 & h_H/E_H\\ 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0\\ -V\,sin\Phi_{s,a} & 1\end{pmatrix}$$

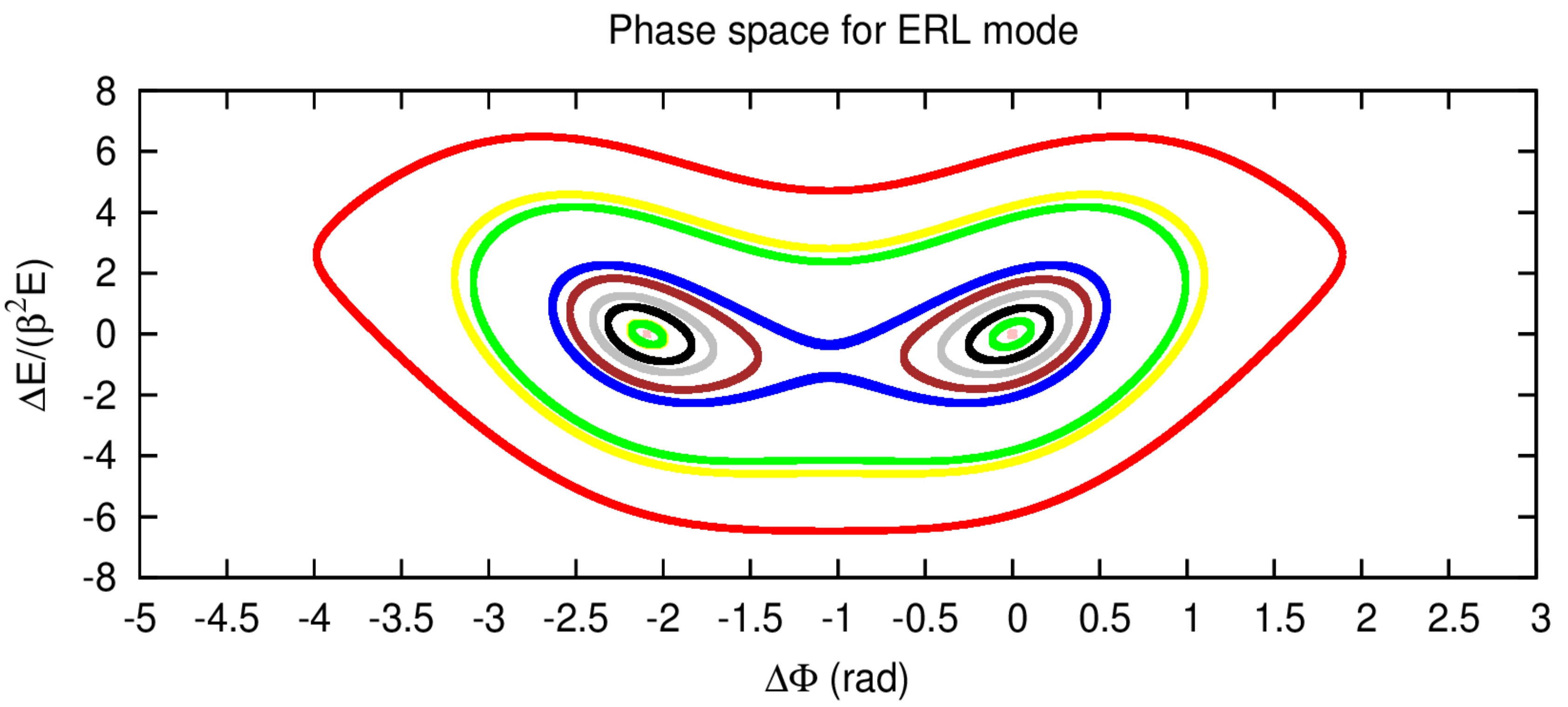
$$\mu_{SR} = \sqrt{2(h_L V\frac{sin\Phi_{s,a}}{E_L} + h_H V\frac{sin\Phi_{s,a}}{E_H})}\text{, where } h_H = \frac{2\pi h f_0 L_H \eta_H}{\beta_H^3 c}$$

$$\mu_{ERL} = \sqrt{h_L h_H\frac{V^2\sin^2\Phi_{s,a}}{E_L E_H}}$$

Phase – Space for SR Mode

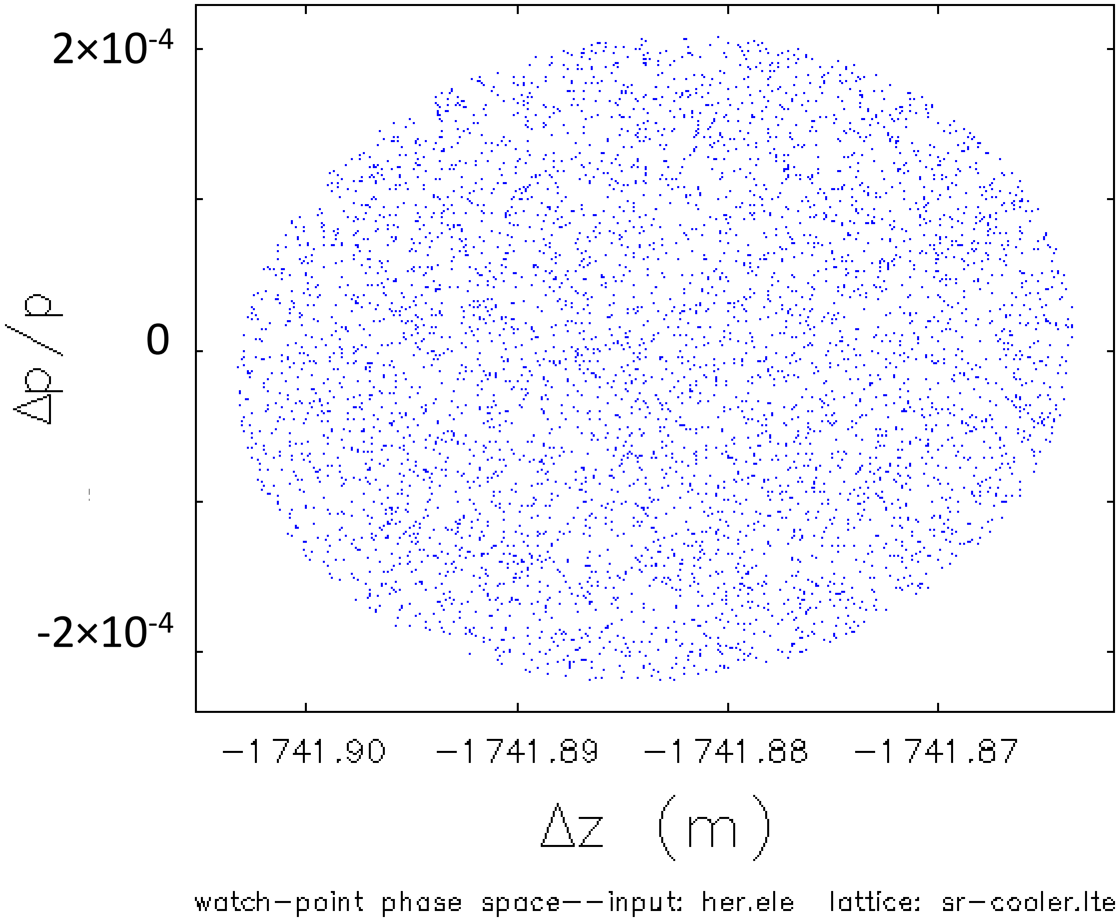


Phase – Space for ERL Mode

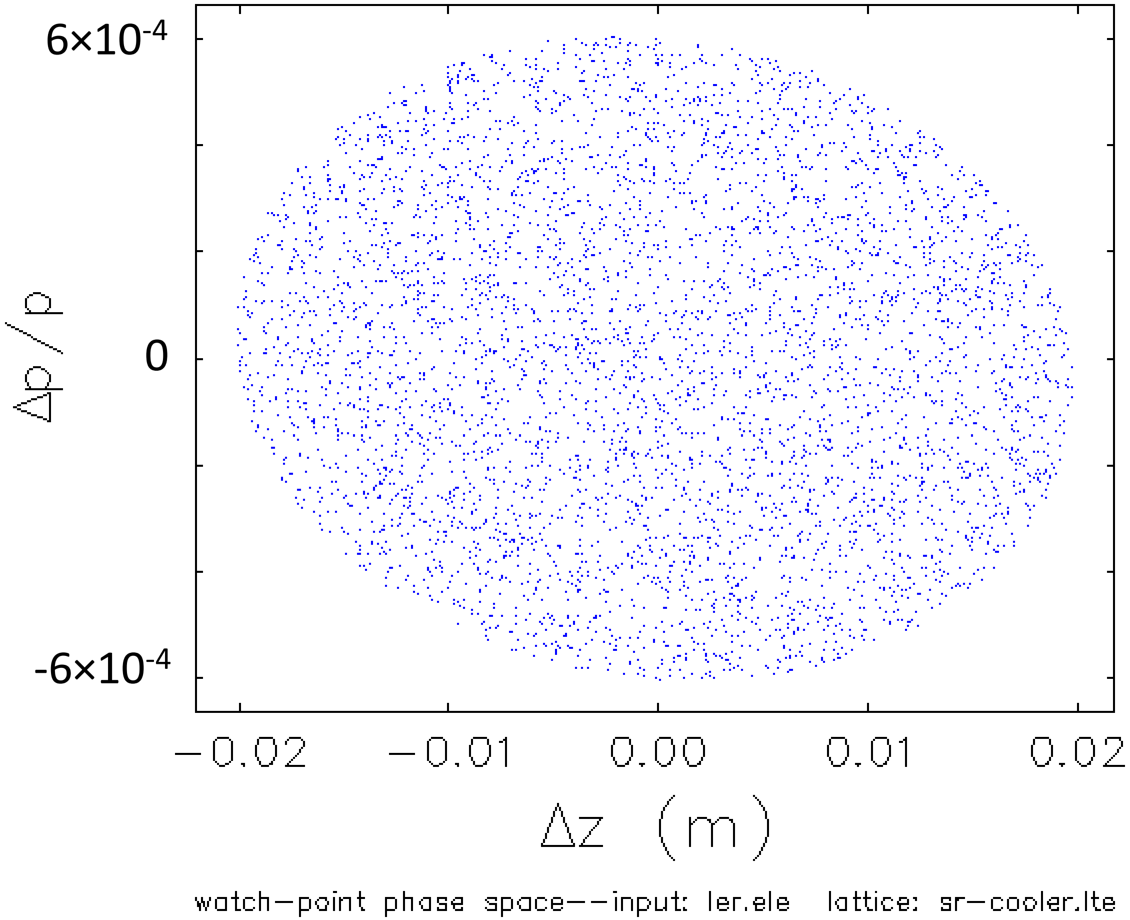


Periodic Solution

- Longitudinal periodic solution exists: Identical 15 m FODO arcs. High Energy Ring



- Low Energy Ring



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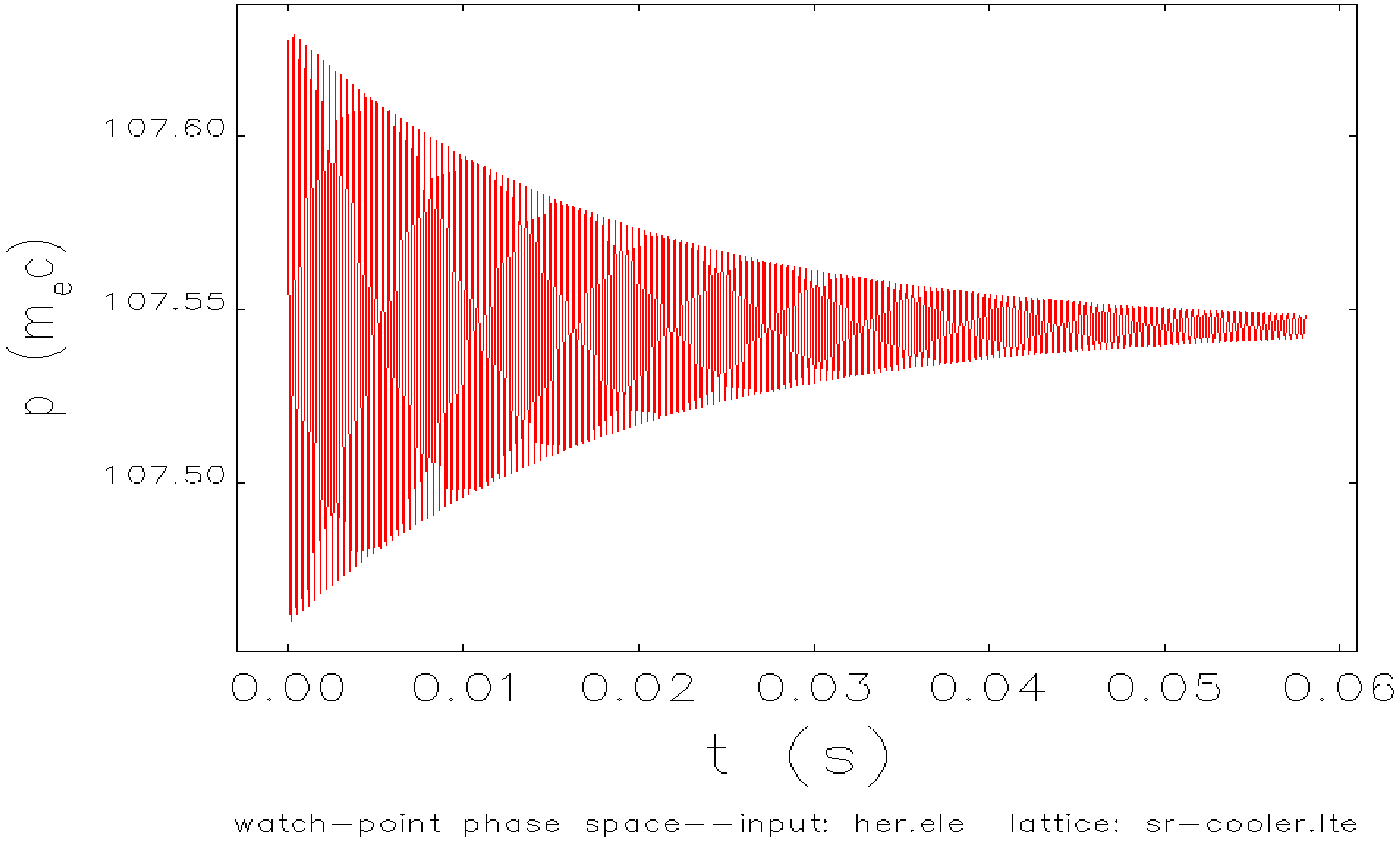
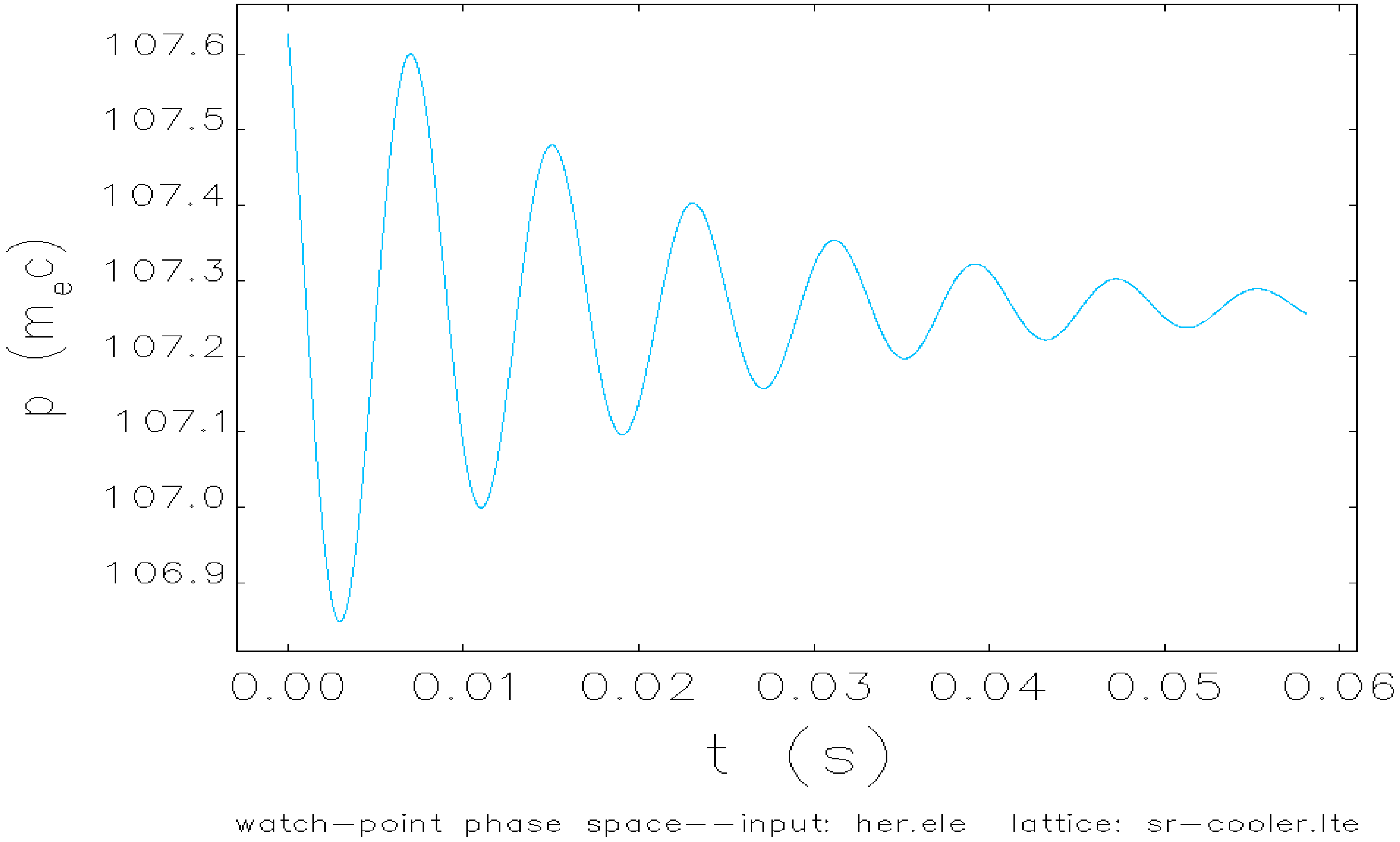
SR Mode (SR element/Artificial Damping, N=5000)



ERL Mode (SR element/artificial damping, N= 5000)



Status of the Two Energy Cooler Project

- Periodic solution for two - energy storage ring cooler. It is verified that stable periodic solution exists. Artificial damping seems to work via “elegant work-around”.
- Initiated theoretical understanding of momentum compaction and chirp/dechirp. Need much higher M_{56} than usual for significant bunch length changes for cooler
- Starting with chirping prescription, calculating the needed M_{56}. Need large value in compact ring. Once done, check RF requirements are reasonable.
- Need high performance computing to get damped emittance
- Eventually need flat beam to round magnetized beam transformations

Renieri-like Limits

- Storage ring FEL extracted power limit due to FEL's heating of electrons in ring

$$\eta = \frac{P_{FEL}}{P_{rad}} < \frac{\Delta\omega}{\omega} = \left[\frac{1}{2N_w}\right]$$

- Fokker-Planck analysis
  - Radiation event doesn't change phase. Applies to electron cooling interaction too
  - Cooling interaction much less violent than FEL interaction
  - Good models/simulations of the coupled ion cooling/electron heating problem essential for accurate predictions of limits
  - Bhawin's done when he can tell me the equivalent "Dhital" limit and writes up the paper
- Interesting comments
  - "This [increasing radiation rate] may be accomplished by increasing the working energy, or by inserting in the machine special high-magnetic-field wigglers.
  - Hutton referenced as suggested adding (damping) wigglers to increase P_{rad}!

Expansion Cooling

- Copy HERA cooling idea to make large beta-function in cooling section
- Linac provides “thermal barrier”

$$\frac{T_{e,H}}{T_{e,L}} \sim \frac{\langle \beta_L \rangle}{\langle \beta_H \rangle} \sim 100 - 1000$$

- Electron cooling rate (radiation dominated) doesn’t care about actual temperature in high energy loop
- Ion cooling rate is (perhaps!) significantly improved. Magnetic field in cooler solenoid may be quite a bit easier. Real simulation and cooling rates eventually needed.
- No self-consistent magnetized design presently (another question for Bhawin to answer!)

Summary

- Progress is being made.
- It is expected that FOA studies will lead to more certain evaluation of the considered paths.
- Independent of beam cooling applications, two ring accelerators may provide a path to short-pulse low energy accelerator beams for other applications.

- I suspect that higher energy HERs will be preferred in the end.