Single and Two Energy Storage Ring Electron Coolers

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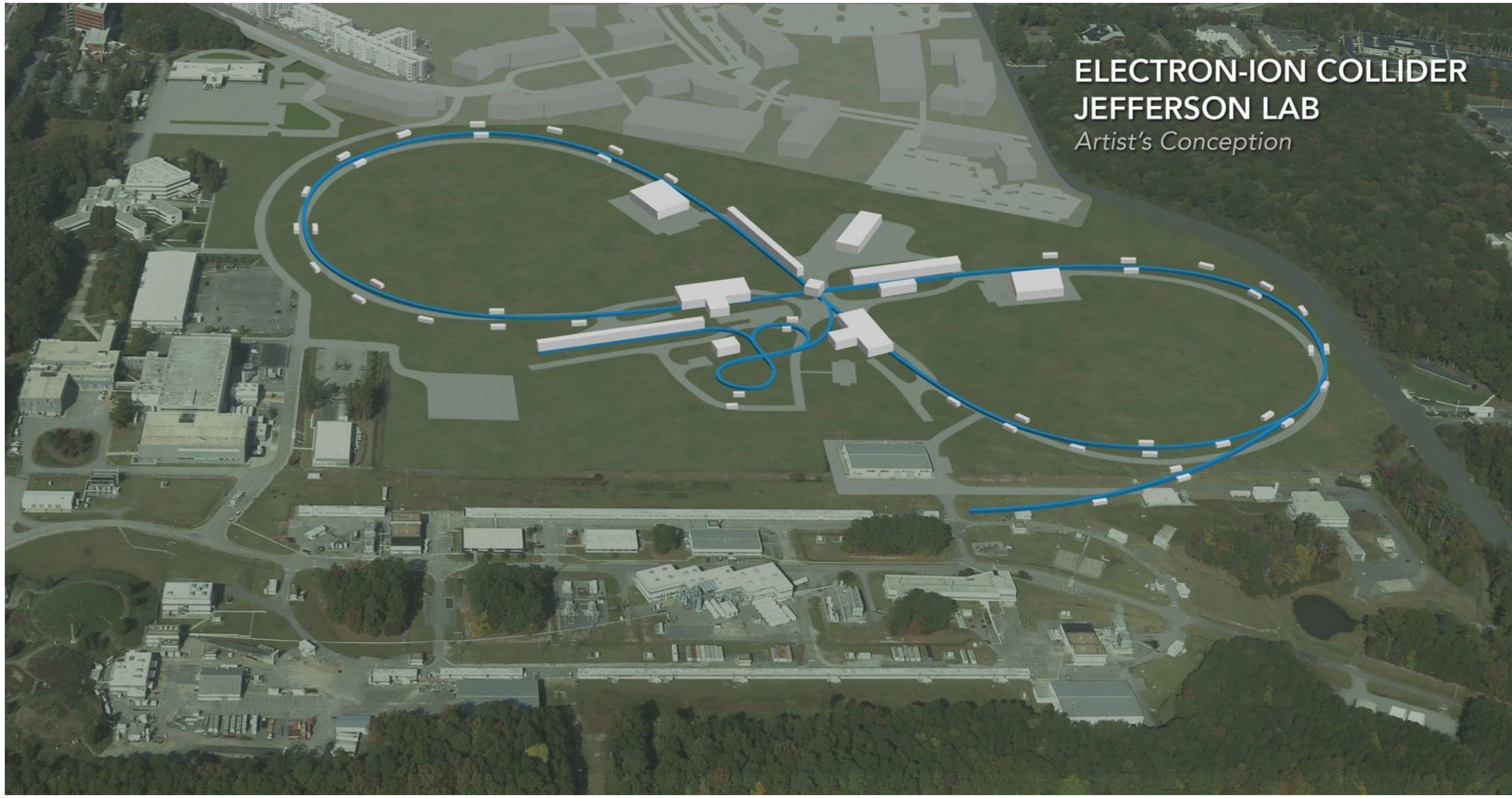

EIC Accelerator Collaboration Meeting

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Jefferson Lab

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Outline

- Ancient History
  - Proton/antiproton coolers
  - HERA idea
- NP FOA Activity
  - Argonne Lab
  - Brookhaven Lab
  - Jefferson Lab
- Future Work
  - Renieri limit (Fokker-Planck)
  - Expansion Cooling
- Summary

Proton/Antiproton Coolers

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

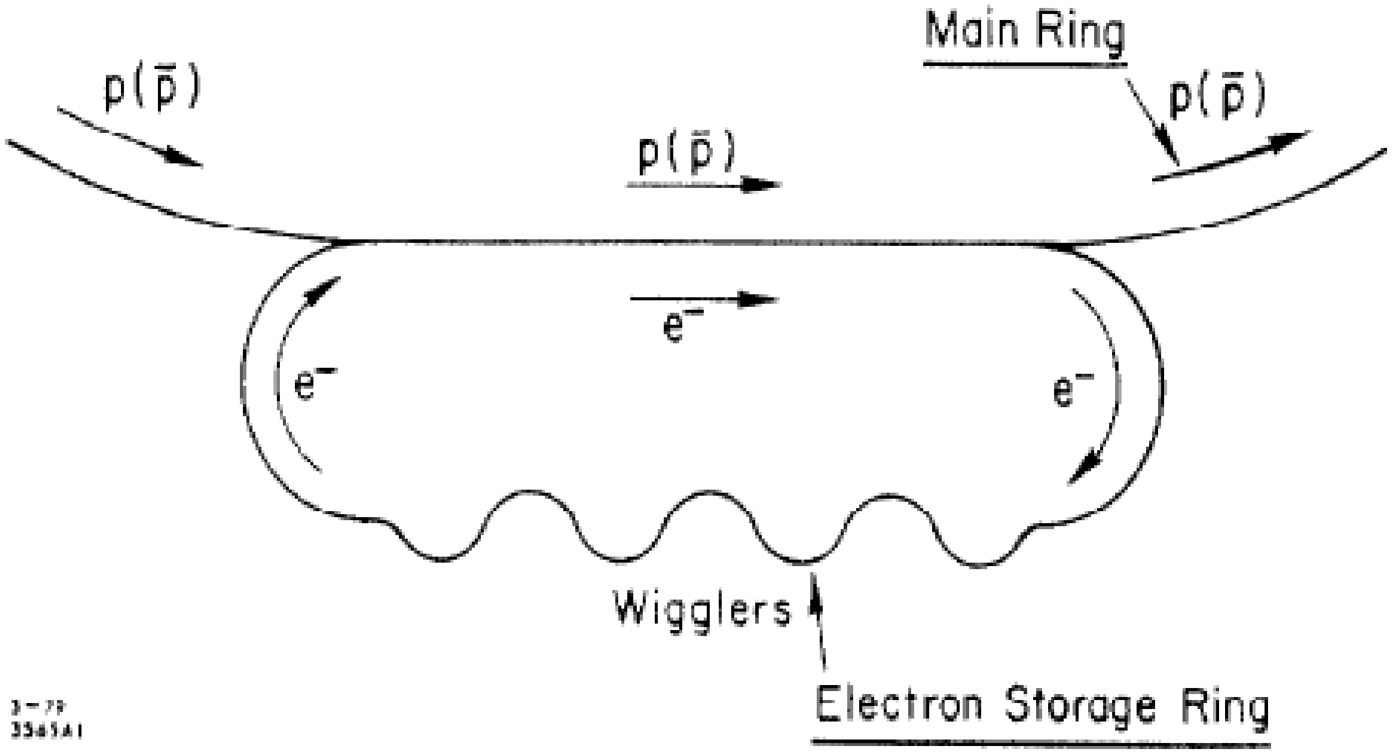

Fig. 1. High energy electron cooling plan.

Equilibrium Conditions

- Beam temperature of equilibrium Gaussian distribution in uniform focusing channel

$$\frac{kT}{m_0 c^2} = \frac{\gamma \varepsilon}{\beta} = \frac{\varepsilon_n}{\beta}$$

- Evolution equations

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

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

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

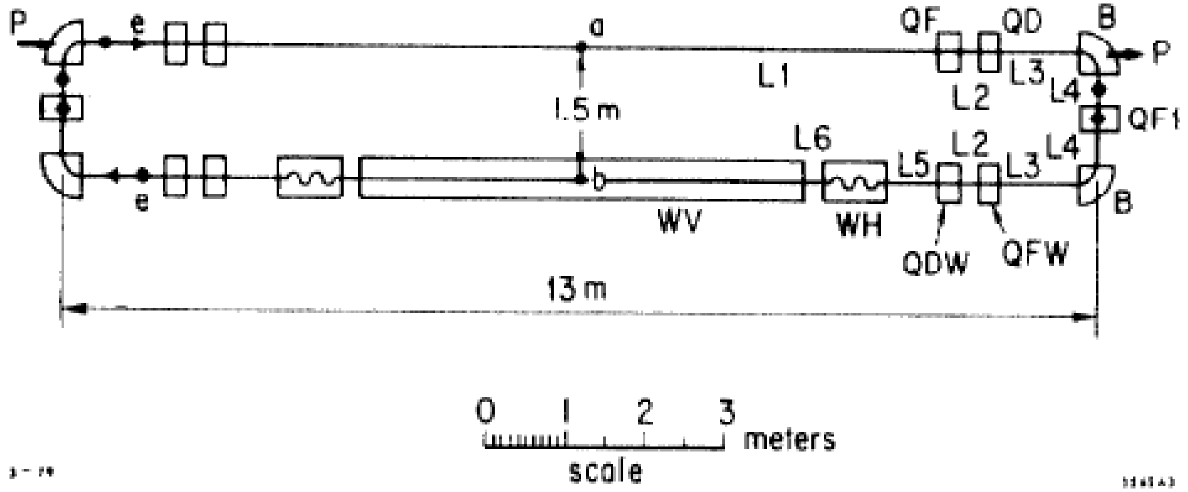

Fig. 3. Lattice of electron storage ring or cooling protons.

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
$\eta = L_{\text{cooler}}/L_{\text{PETRA}}$	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

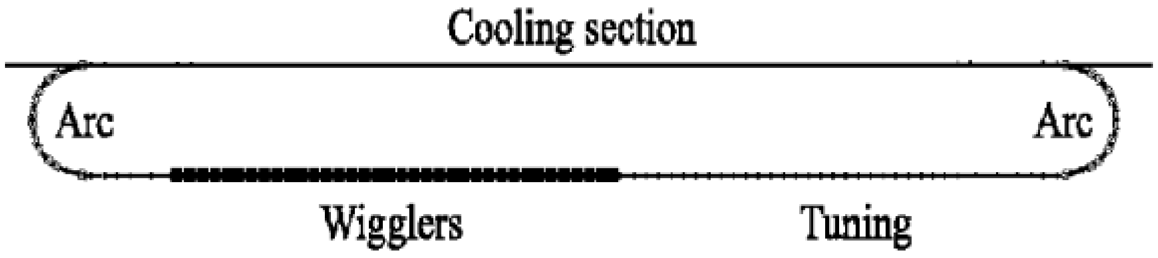

Fig. 2. Layout of electron cooler ring.

- 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

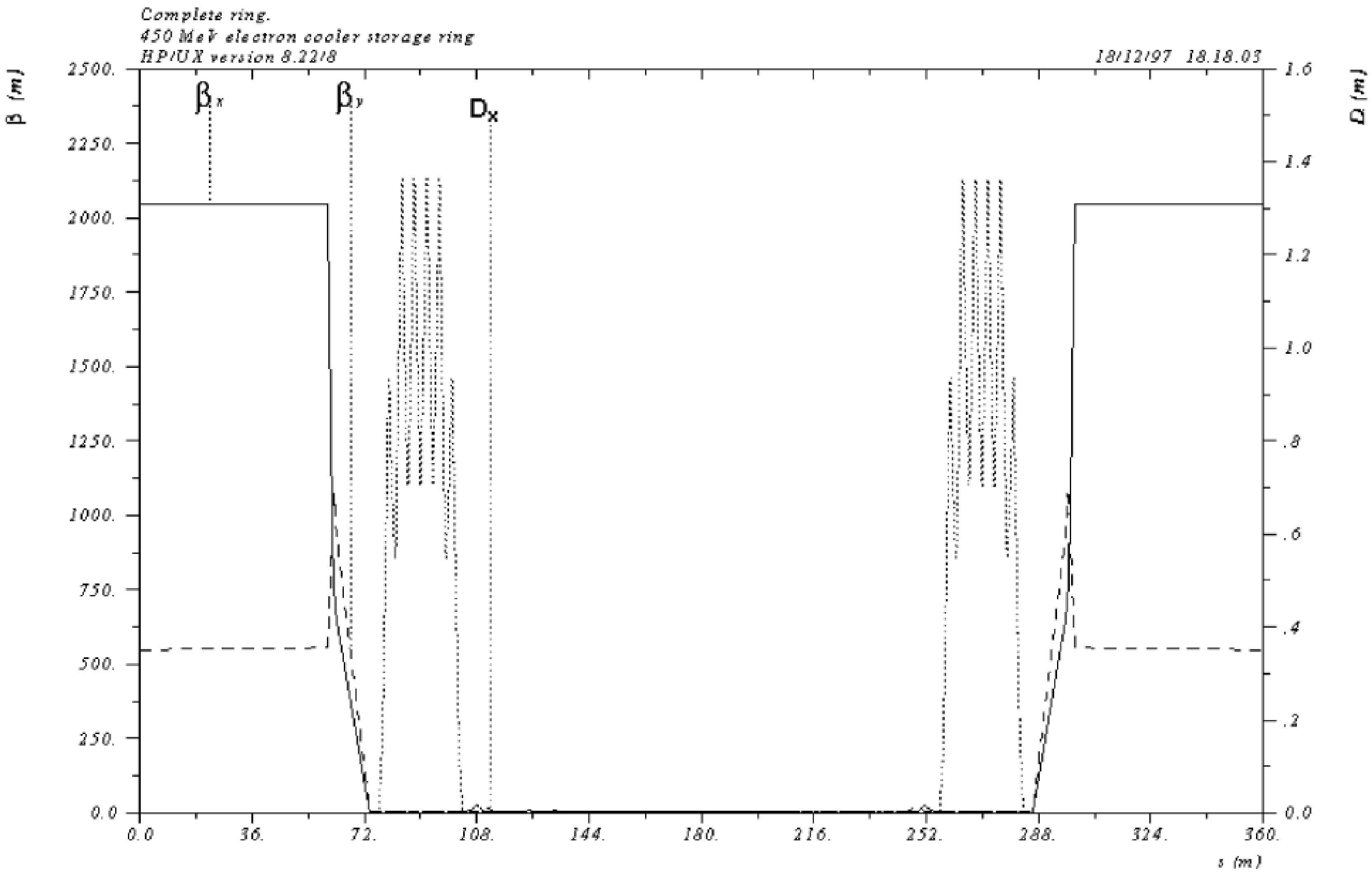

Fig. 3. Optics of electron cooler ring.

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Recent FOA Activity

- New activity on storage ring coolers is funded through two of the approved NP-FOA-0001848 proposals for
- Strong hadron cooling with micro-bunched electron beams (Willeke, PI)
  - Argonne subproposal: Analyze and compare possible options for electron cooling in a storage ring including the radiation damping and/or optical stochastic cooling. Explore the possibility and challenges of using a ~ 250 MeV electron storage ring
- Development of Innovative, High-energy, Magnetized Electron Cooling for an EIC (Benson, PI)
  - BNL subproposal: In the proposed work we will revisit the fundamental physics of processes determining the equilibrium electron emittance in storage rings by applying numerical techniques that include collisional processes, radiation damping, and quantum excitation. The applicability of high energy electron storage ring cooling to eRHIC will be evaluated by analyzing a specific design in detail.
  - 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.

ASSUMPTIONS

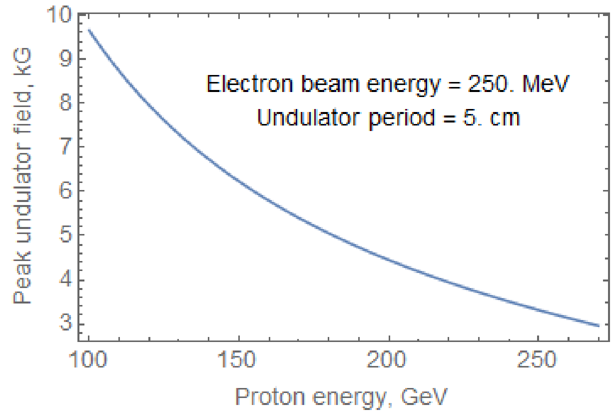
- Protons interact with electrons inside an undulator instead of a drift.
- Tune electron longitudinal velocity inside undulator to the proton longitudinal velocity, i.e.,

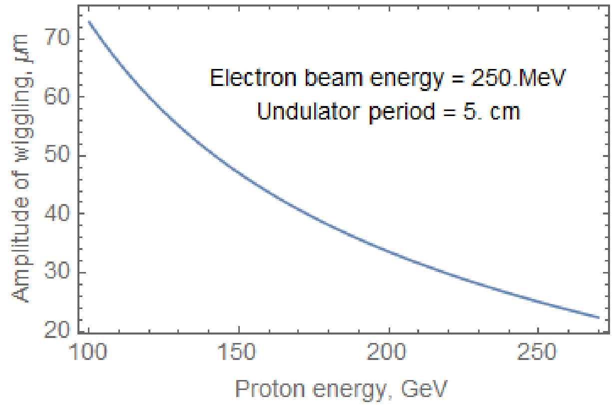
$$\gamma_0^2 = \gamma_z^{*2}\left(1+K^2\right)$$

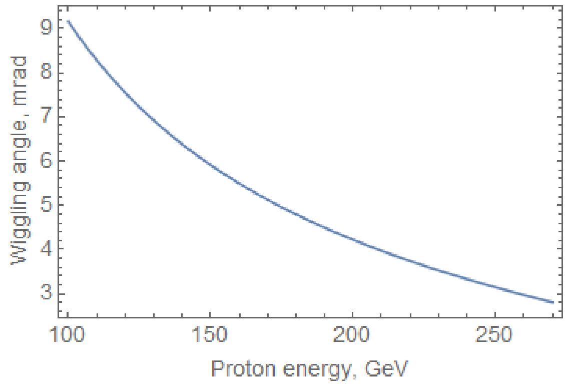
$$\gamma_{z_p} = \gamma_{z_e}$$

$$\gamma_{z_e}^{*2} = \frac{\gamma_0^2}{\left(1+K_e^2\right)}$$

- Question: can energy transferred from protons to electrons be radiated away by undulator radiation in the electron ring?







OPPORTUNITIES FOR THE RING WITH THE SYNCHROTRON RADIATION DAMPING

- Yes, but:
  - Obtaining fast electron cooling and maintaining a low energy spread in the electron beam requires a long wiggler

  - “I found that a ring with ~600 m total length of wigglers with a peak magnetic field of 1.6 T can maintain 10^{-4} energy spread in the electron beam when rms energy transfer from protons to each electron per turn is of the order of 300 eV”

- Conclusion: Technique doable for slow proton cooling of the order of 50 hours at the cost of a long wiggler, but for proton cooling under one hour afforded by amplification of electron microbunching, “there is simply no chance to use synchrotron radiation for cooling since the rms energy transfer from protons to each electron per turn approaches 20000 eV”.

- Follow-on work continuing

Introduction

- It is estimated that cooling more than doubles the peak luminosity of the eRHIC ring-ring collider. Improving the luminosity lifetime will have additional benefits.
- Stochastic cooling has been used in RHIC since 2007. It won't work for protons. It should be OK for heavy ions.
- We have accurate simulations that have been extended to our Low Energy Electron Cooling program and recently implemented for ring cooling in eRHIC. Calculations must be sufficiently accurate to design with confidence.

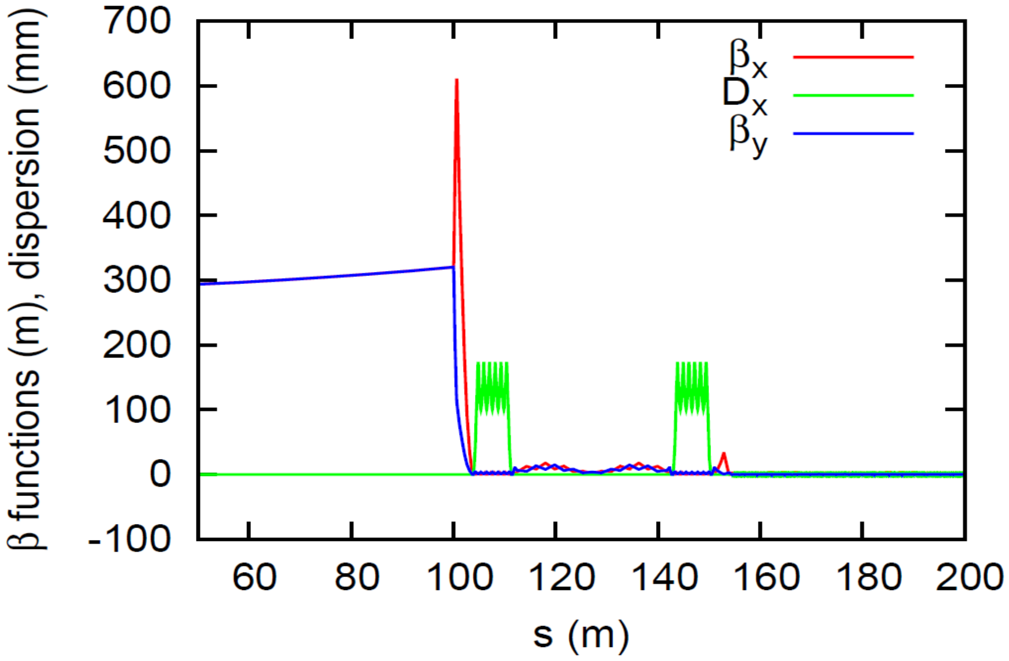
Introduction

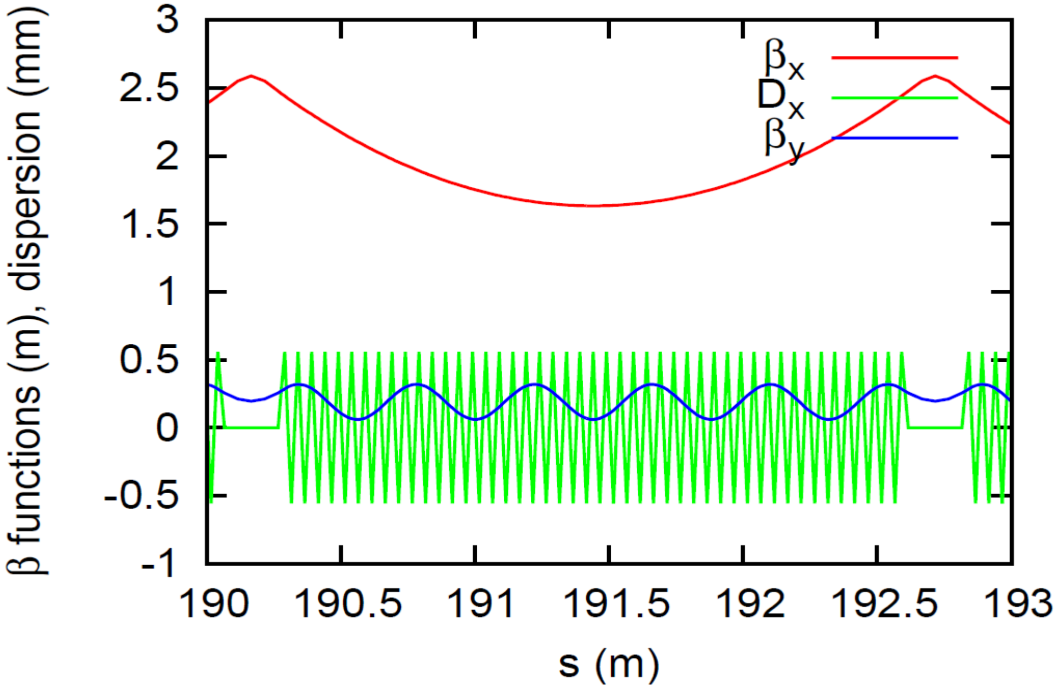
- Have 330 bunches of 2.4×10^{11} protons with initial normalized emittance $\varepsilon_x = \varepsilon_y = 2.5\mu m$, $\varepsilon_s = \sigma(E)\sigma(t) = 0.047$ eV-s
- For high luminosity we need two longitudinal splits that conserve longitudinal emittance and to cool the vertical emitttance to $\varepsilon_y = 0.38\mu m$ while maintaining initial ε_x and ε_s .
- We need to maintain this against 2 hour intrabeam scattering times.
- Hardware required must be realistic.
- We are not at this stage yet.

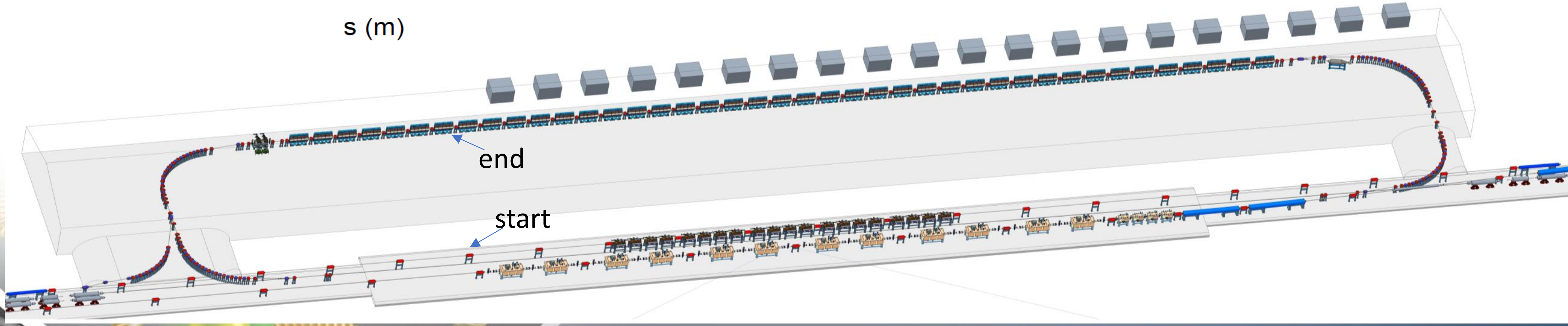
Ring Cooler

- The electron dynamics are dominated by IBS and radiation damping.
- Need to program effect of hadrons heating e^-.
- Only round electron beams considered so far.
- We took aggressive parameters.
- Take $\Upsilon=293$
- 200m, 4T H wiggler with 5 cm period
- arcs with 15 m radius and good focusing
- Get 48 nC, $\varepsilon_{x,y}$= 5.2nm, σ_s=18cm, $\sigma(E)/E=1\text{x}10^{-3}$.
- ΔQ_{sc}=0.5, microwave threshold $|Z/n|=0.07\Omega$.

Lattice Design







Lattice Issues

- The vertical chromaticity is too negative.
- Edge focusing in the wiggler is the source.
- To combat electron IBS we need radiation damping of

$$\frac{\dot{\varepsilon}_x}{\varepsilon_x} \sim \frac{\dot{\varepsilon}_y}{\varepsilon_y} \sim \frac{\dot{\varepsilon}_s}{2\varepsilon_s} \sim -240s^{-1}$$

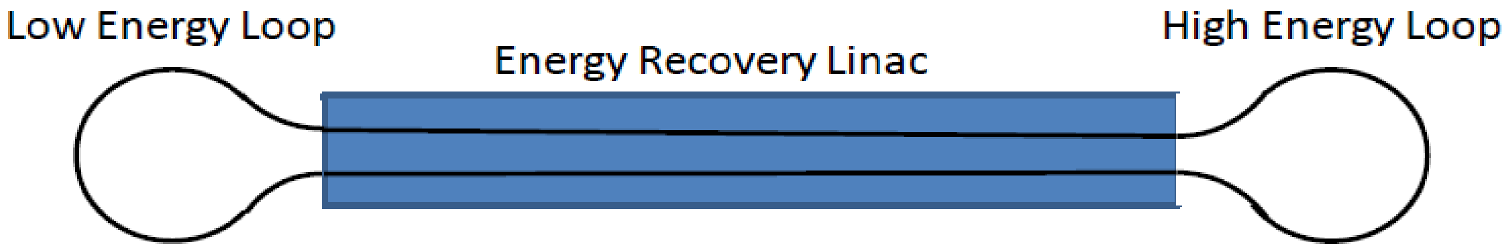
- Suggestions are welcome!

parameter	value
γ_T	47.6
Q_x	25.2
Q_y	204.7
Q_x'	25.5
Q_y'	-239
$\rho_{wiggler}$	12.5 cm
x_{max}	0.63 mm

Areas For Additional Effort

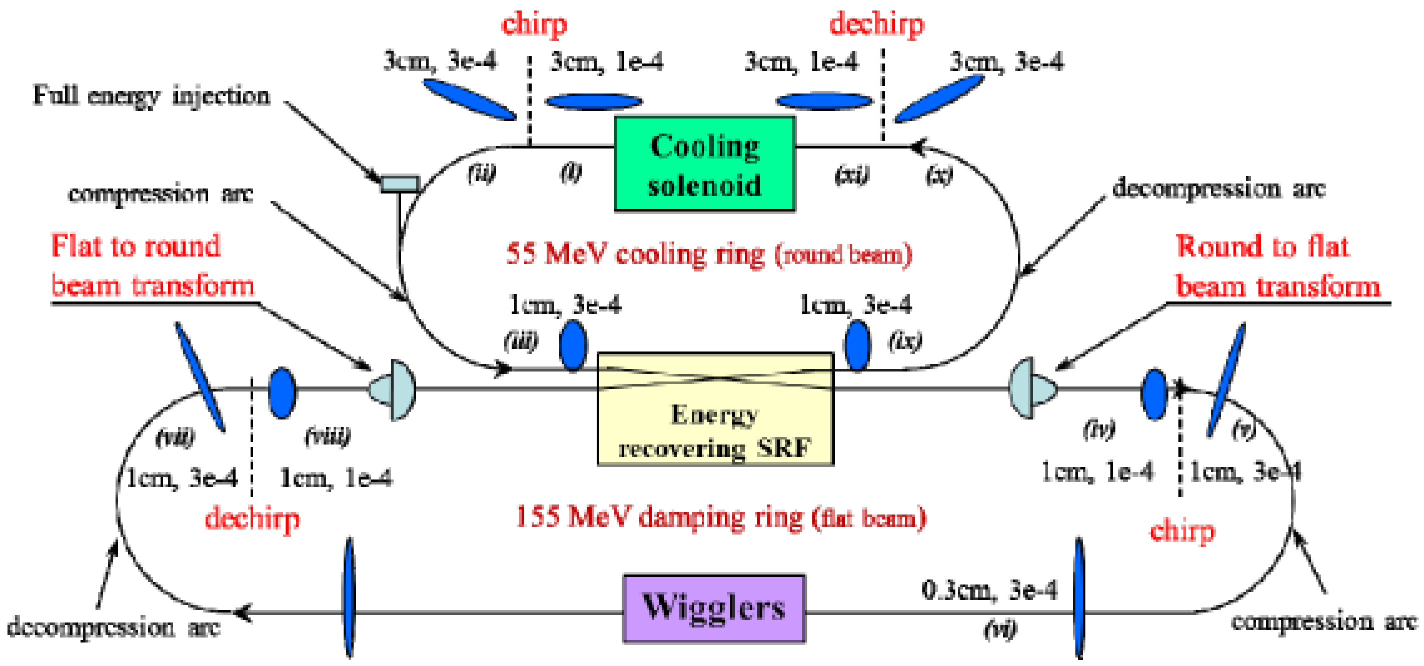
- Langevin simulations show the cooler will easily maintain the emittance of the initial bunch.
- Have not found a path to [cool to] 0.38μm. We have not yet found a way to maintain the initial horizontal emittance starting with ε_y=0.38μm. Triaxial distribution needs study.
- We must include triaxial distributions and hadron heating in incoherent cooling estimates.
- We need to find a viable ring cooler lattice and model electron beam survival.
- We need to extend calculations to lower energies.
- Recent studies suggest 1μm proton emittance is possible. Implications need study.

JLAB/ODU Energy Recovered Loop Accelerator



- F. Lin, et al.,

IPAC 2016



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Cooling Rate Estimates

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

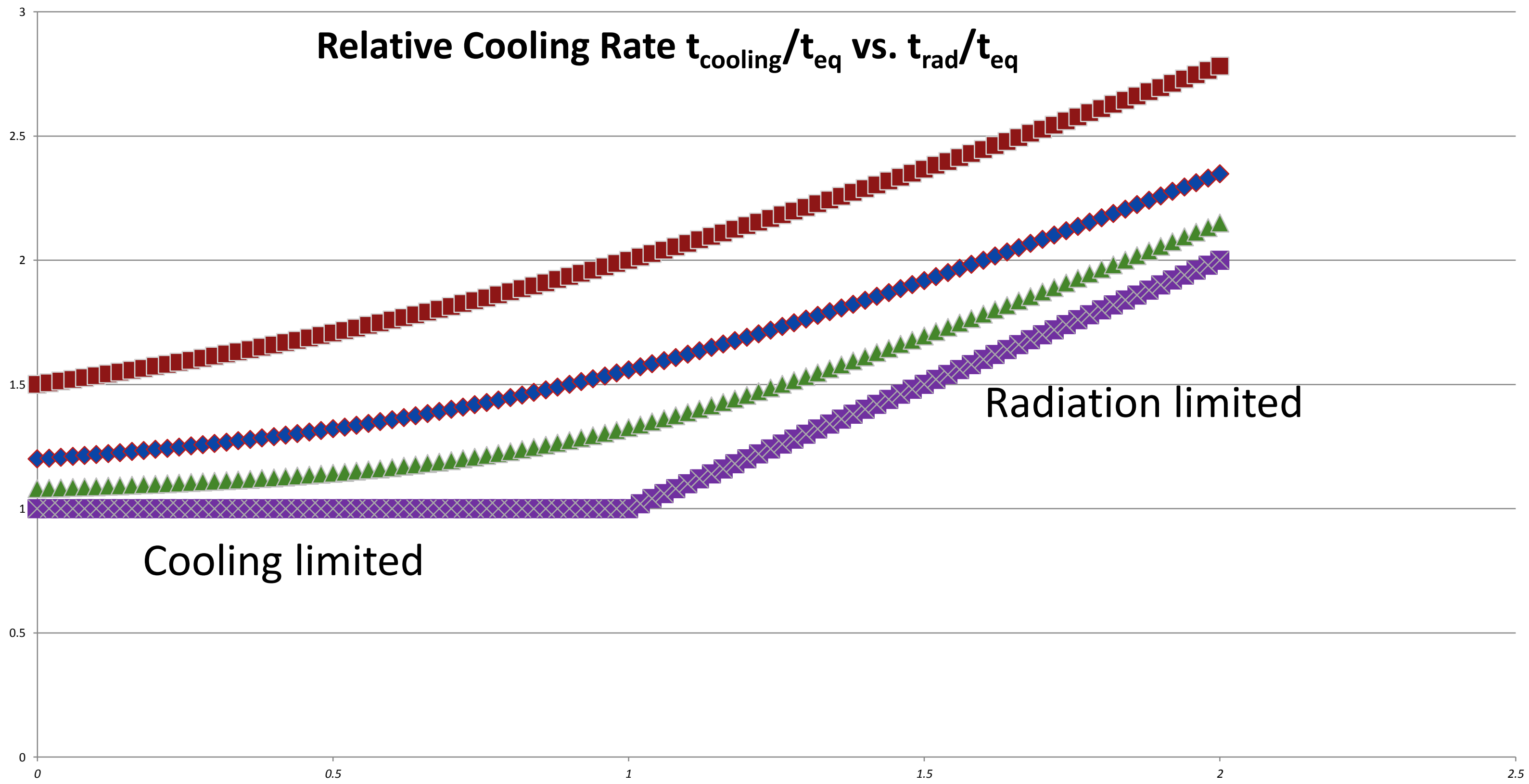
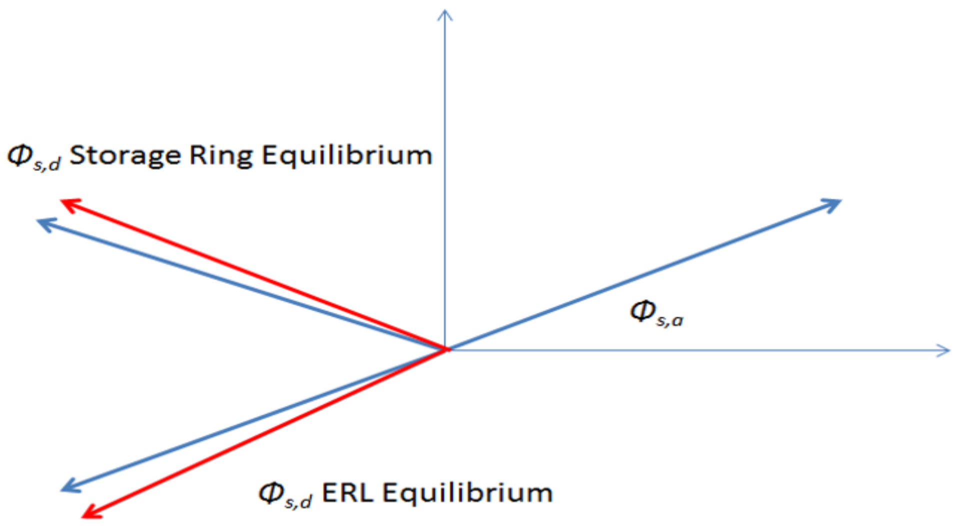


Figure 2: Relative cooling time for N_i/N_e=0 (purple), 0.08 (green), 0.2 (blue), 0.5 (brown)

RF Voltage Phasor



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

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

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

Bucket Height for SR and ERL Modes

- We use two cavities (same peak voltage but different phases for acceleration and deceleration)
- We use linac language throughout
- For SR mode, ϕ_a (accelerating phase) = 60^0
- For SR mode, ϕ_d (decelerating phase) = 120^0
- For ERL mode, ϕ_a = 60^0, ϕ_d = 240^0
- Cavity peak voltage = 1690 MV
- In storage ring language, ϕ_a = 150^0, ϕ_d = 210^0 for SR mode and ϕ_a = 150^0, ϕ_d = 330^0 for ERL mode

$$\Delta\phi_2 = \Delta\phi_0 + \frac{h_L}{E_L}\Delta E_0$$

$$\Delta E_2 = \Delta E_0 + V(\cos(\phi_a + \Delta\phi_2) - \cos\phi_a)$$

$$\Delta\phi_4 = \Delta\phi_2 + \frac{h_H}{E_{Hs}}\Delta E_2$$

$$\Delta E_4 = \Delta E_2 + V(\cos(\phi_d + \Delta\phi_4) - \cos\phi_d)$$

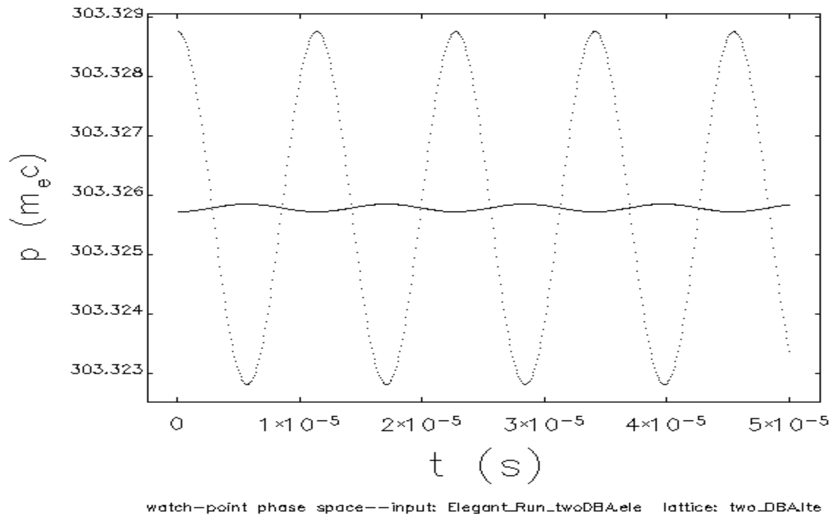
155 MeV to 1 GeV

- RF voltage = 1690 MV
- SR mode (Radiation off)

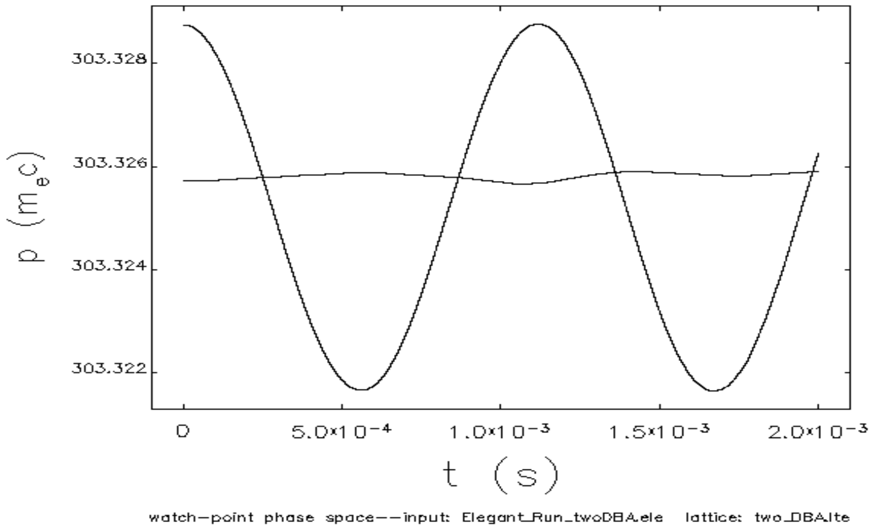
- % difference in tune =3.79

- ERL mode (Radiation off)

- % difference in tune = 4.24

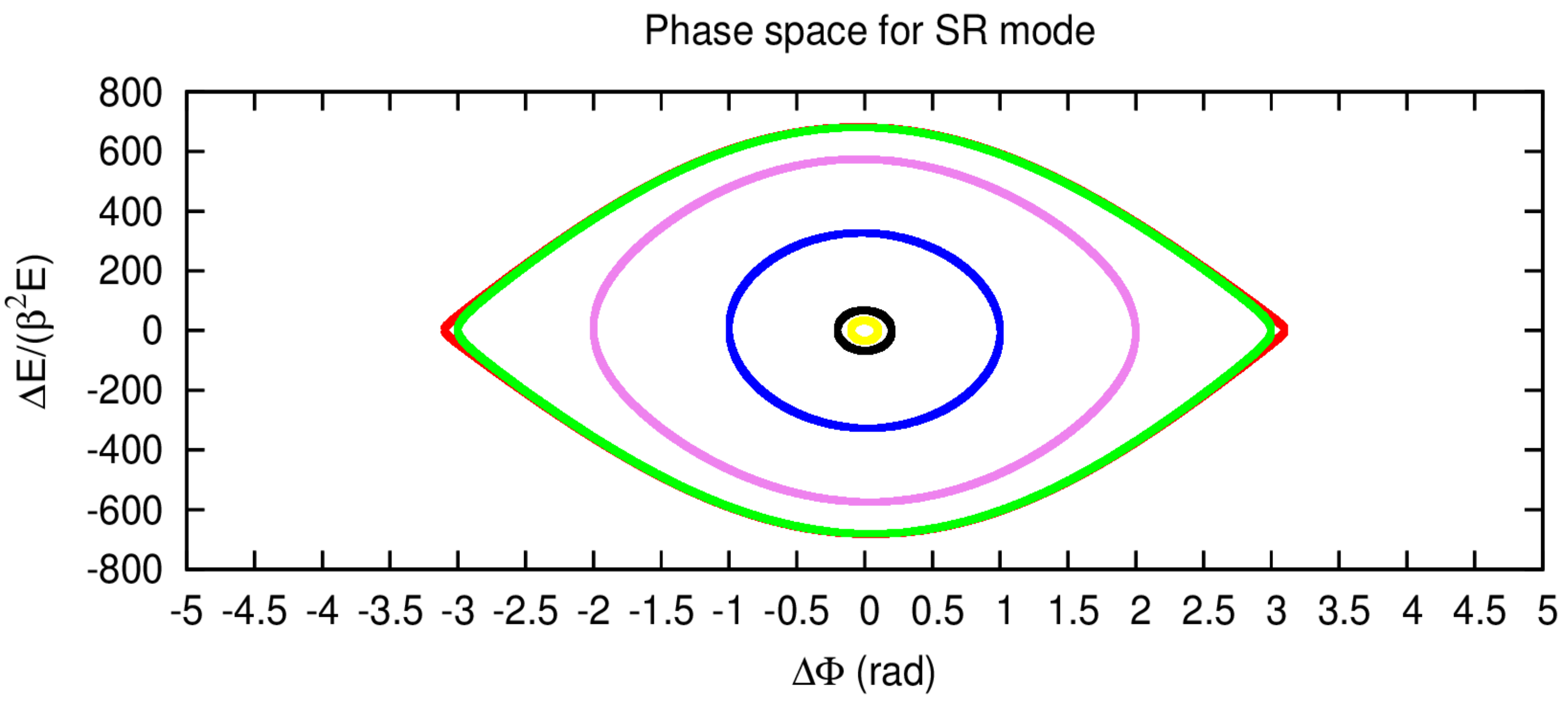


SR mode

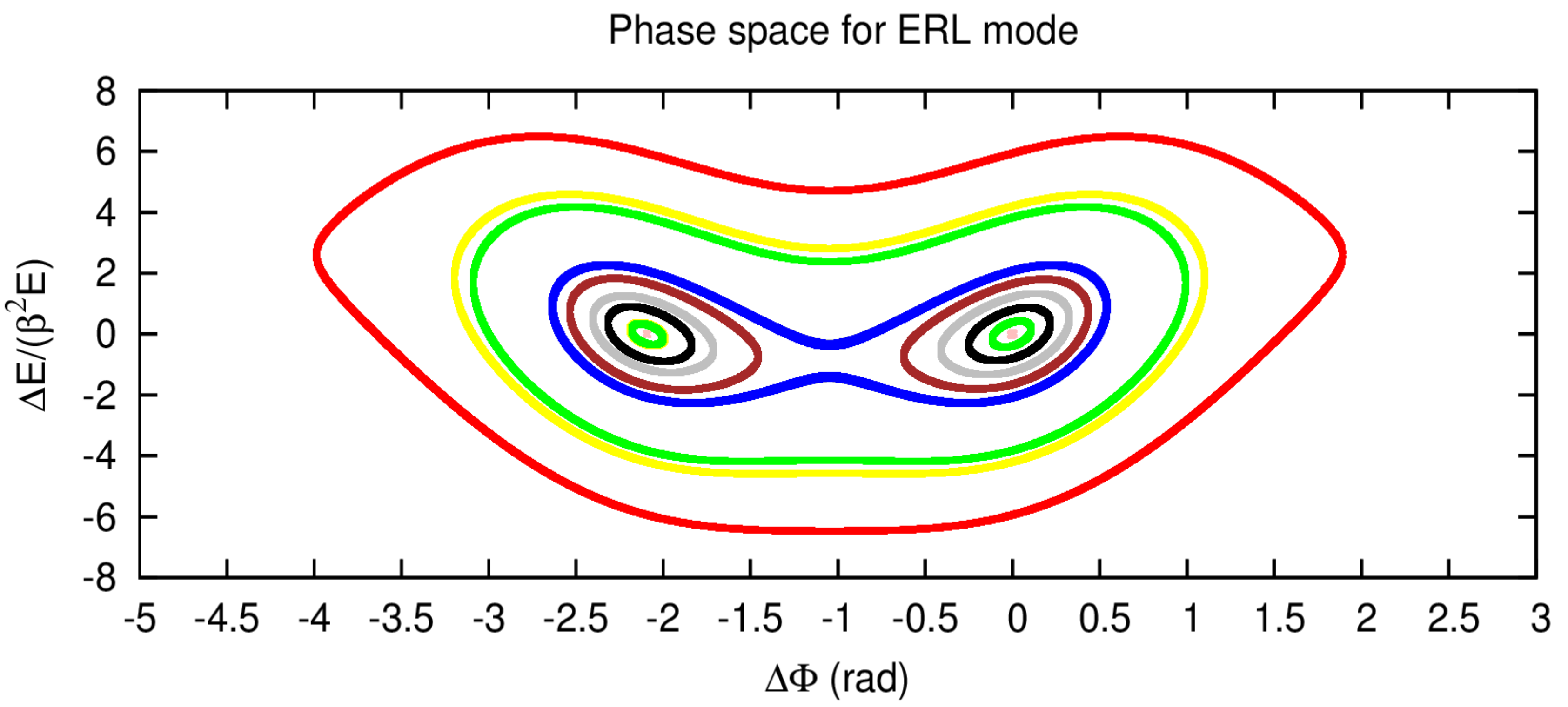


ERL mode

Phase – Space for SR Mode



Phase – Space for ERL Mode



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}!

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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

- New projects to evaluate storage rings as coolers have been initiated at Argonne, Brookhaven, and Jefferson Lab. Researchers are looking into both single energy ring extensions and two energy ring designs.
- Cooling in eRHIC potentially doubles the peak luminosity
- Maintaining the peak luminosity and losing beam only to burn off will improve performance.
- Ring cooling looks promising from a technical point of view but the lattice is very hard and the collective effects are challenging.
- As projects have just started, totally self consistent designs not complete at present. It is still difficult to assess whether these ideas provide either complementary capability or a viable alternative to other beam cooling systems.
- Progress is being made on all fronts.
- 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.