Two Energy Storage Ring Cooler

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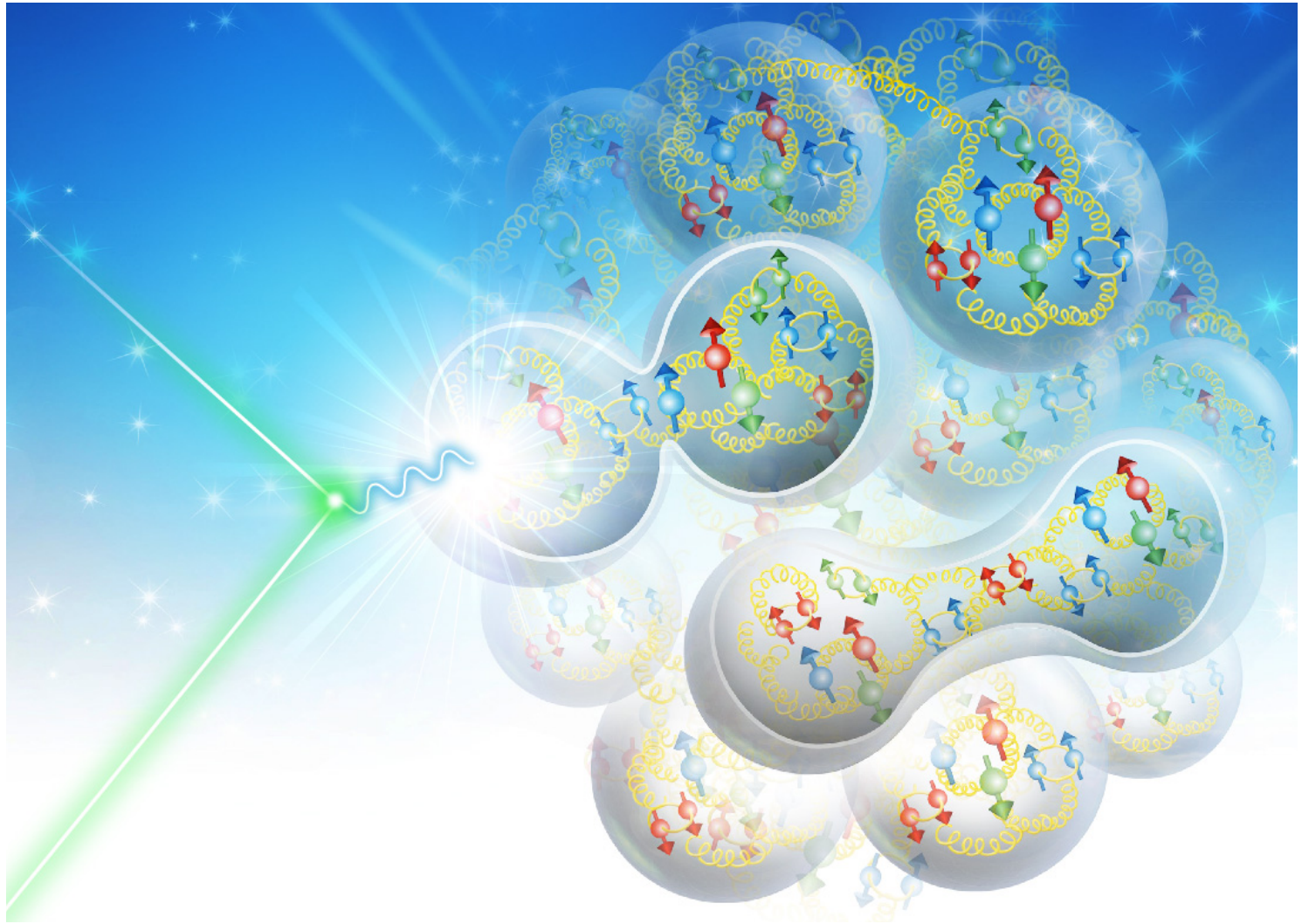
on behalf of Bhawin Dhital, Slava Derbenev, David Douglas, Geoff Krafft, Vasiliy Morozov, Yuhong Zhang

EIC Hadron Cooling Workshop,
October 7-8, Fermilab, 2019



Jefferson Lab
OLD DOMINION UNIVERSITY

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Outline

- Motivation
- History
- Two Energy Storage Ring Cooler
  - Introduction of the whole system
  - Design goals and work plan
  - Study of longitudinal stability
- New High Level Design Idea
- Summary and Plan

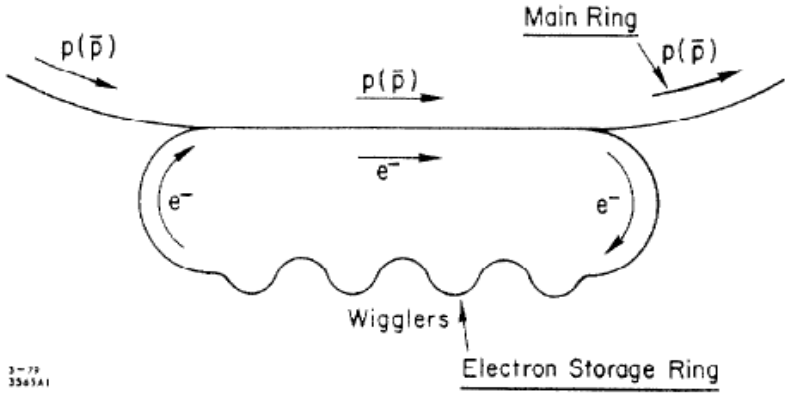
Motivation

- Cooling of ion beams to reduce the beam emittance and compensate the IBS emittance degradation is crucial to deliver high luminosity and extend luminosity lifetime in EIC in low or medium ion energy ranges (a few to a few hundred GeV).

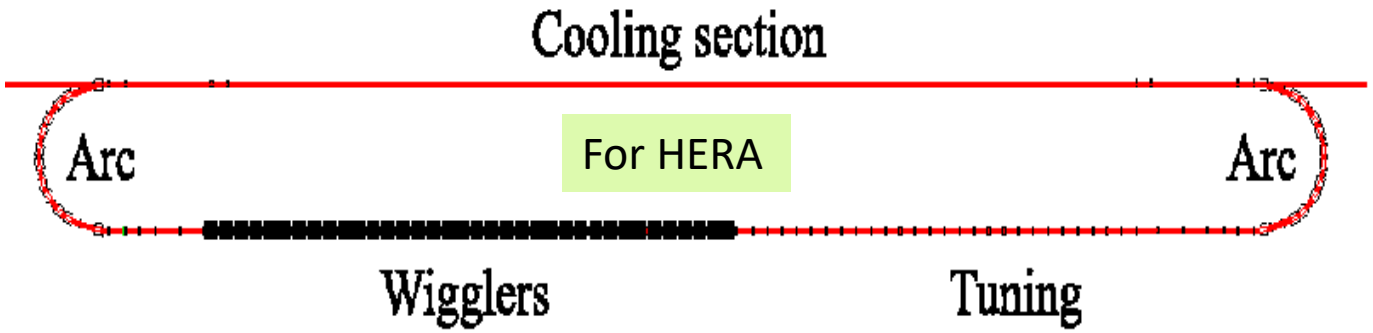
- We propose a **two-energy** storage ring cooler, where the electron beam is stacked and circulates. Cooling beam has
  - a high beam current of ~1 A,
  - a long storage time, and
  - a good beam quality through **enhanced** synchrotron damping counteracting the heat of electron beam due to intra- and inter- beam scattering

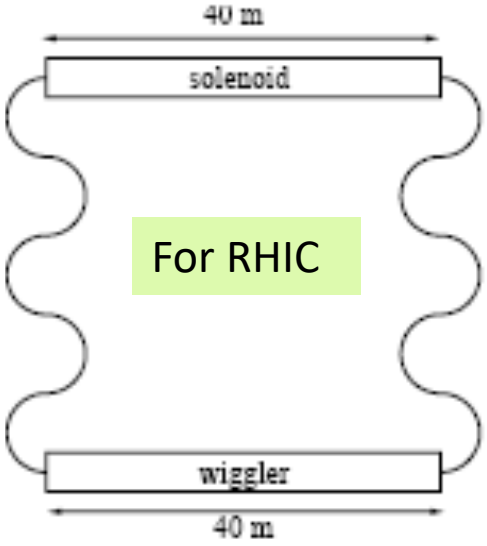
Highlights of Storage Ring Cooler Ideas

- Proposed electron cooling for proton/antiproton by Cline et al. in late 70s (PAC 1979, p3472)



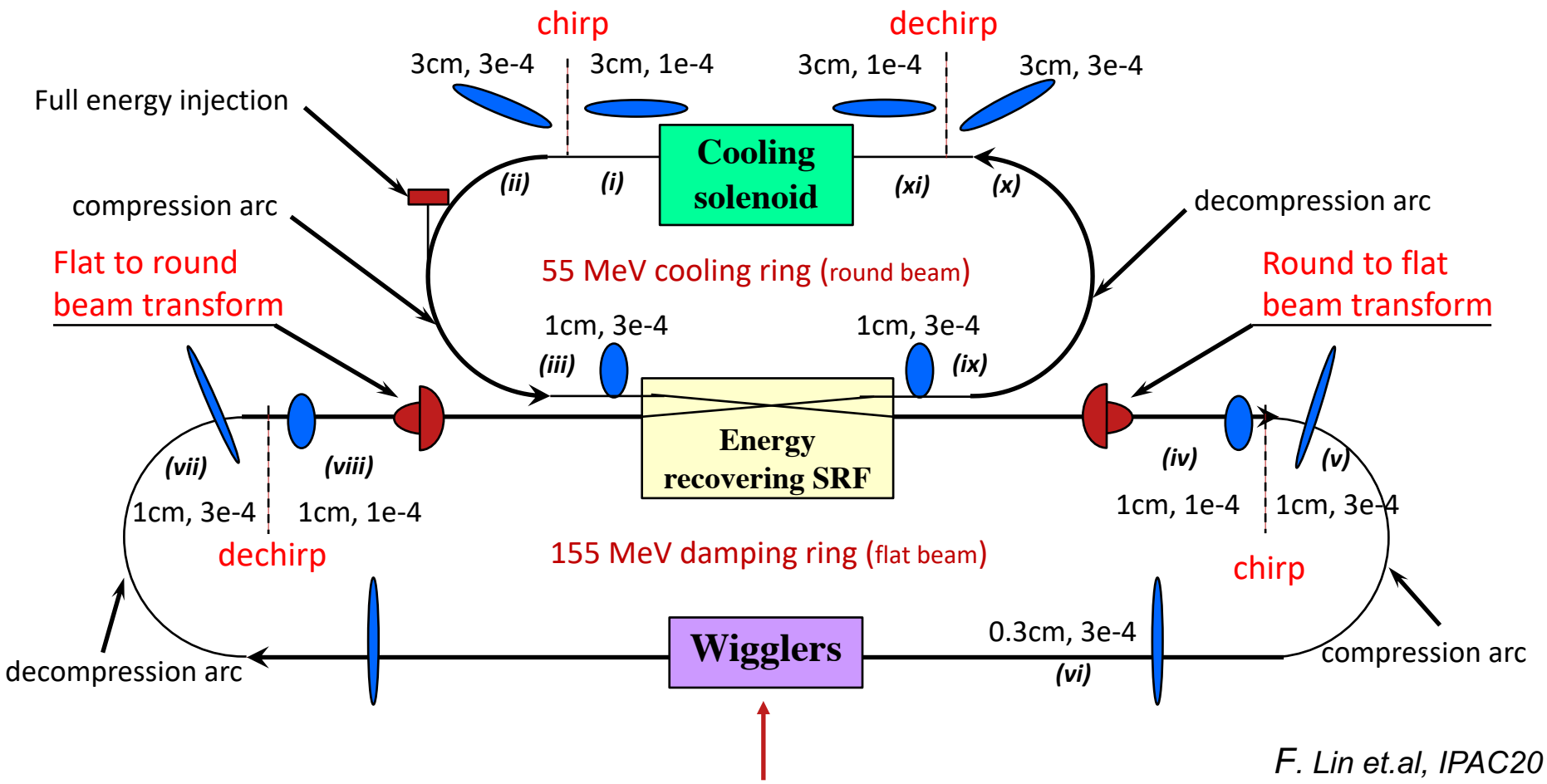
- Proposed electron cooling for HERA and RHIC by Derbenev et al. in late 90s (Nuc. Inst. and Meth. Phys. Res. A 424(1999)277-295, FERMILAB-TM-2058).





- Proposed two-energy storage ring electron cooling by Y. Zhang, inspired by discussions with D. Douglas et al., in 2015

Proposed Storage Ring Cooler: Schematic Diagram



F. Lin et.al, IPAC2016, Busan, Korea

Proposed Idea: Add wigglers to decrease damping time

Design Goals and Work Plan in Founded FOA Proposal

Item	Unit	Value
Energy	MeV	20-55 (110)
Current	A	0.5-1
Repetition rate	MHz	476
rms bunch length	cm	3 (~1)
Normalized emittance*	μm-rad	100-500 (72)
Energy spread	10^{-4}	1
Solenoid field	T	2 (1)
Solenoid length	m	20-30

Year I:

- Improvement of prototype linear optics of a storage-ring electron cooler, including properly including aspects of creating magnetized beam for the electron cooling section
- Optimization of cooler parameters
- Analytic estimation of intra-and-inter beam scattering and space charge effects

Year II:

- Estimation of equilibrium emittances
- Initial single-particle tracking
- Analysis of HOM impedance requirements for the SRF structure
- Identify potential issues such as coherent synchrotron radiation and beam break up
- Publish Journal paper on Recirculated Linac Coolers

Longitudinal Stable Modes

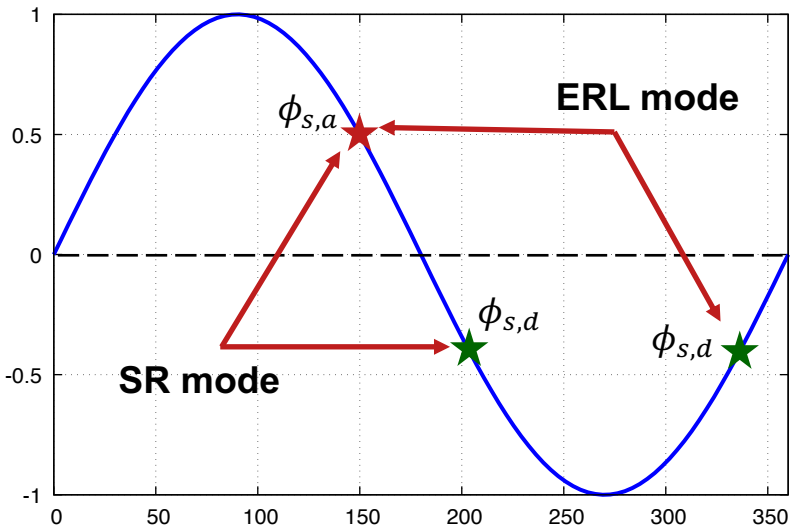
- Storage Ring (SR) mode: longitudinal focusing in both accelerating and decelerating passes

$$\phi_{s,d} = \pi + (\pi - \phi_{s,a})$$

- ERL mode: longitudinal focusing occurs in one of accelerating and decelerating passes, while the other is defocusing

$$\phi_{s,d} = \pi + \phi_{s,a}$$

(* $\Delta\phi$ needs to be added if synchrotron radiation is considered)



- Linear transfer matrix for $(\Delta\phi, \Delta E)$:

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

$$Q_{SR} = \frac{1}{2\pi}\sqrt{2\left(h_L V \frac{-\cos\phi_{s,a}}{E_L} + h_H V \frac{-\cos\phi_{s,a}}{E_H}\right)}$$

$$Q_{ERL} = \sqrt{h_L h_H \frac{V^2 \cos^2\phi_{s,a}}{E_L E_H}}$$

Here $h_{L,H} = \frac{2\pi f_0 L_{L,H}\eta_{L,H}}{\beta_H^3 c}$

	SR mode	ERL mode
Qs from formula	0.03448	0.001627
Qs from simulation	0.03415	0.001631
Difference in %	0.9	0.2

G.A. Krafft et.al, Jlab technote

Stability Criteria

- One turn matrix is used to find stability criteria

SR mode

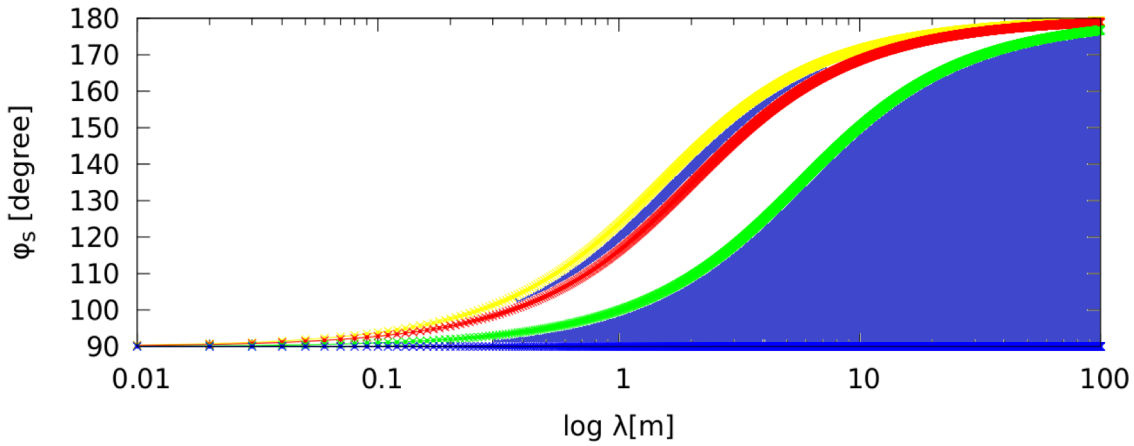
$$\phi_{s,a} \in \left(\pi - \tan^{-1}\left(\frac{\Delta P \cdot 2|M_{56}| \cdot 2\pi}{P_2 \lambda_{rf}\left(A + \sqrt{A^2 - \frac{16}{B}}\right)}\right), \pi - \tan^{-1}\left(\frac{\Delta P \cdot |M_{56}| \cdot 2\pi}{P_2 \lambda_{rf} A}\right)\right)$$

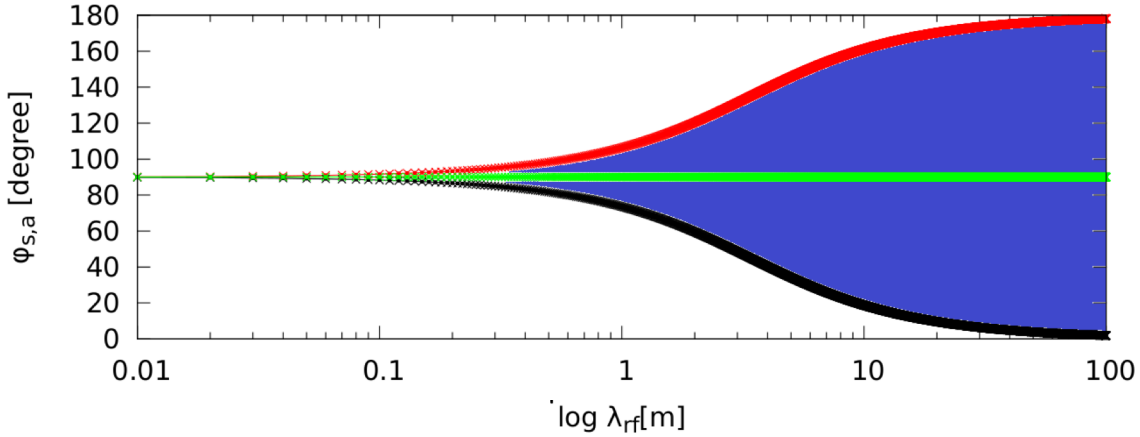
and $\phi_{s,a} \in \left(\frac{\pi}{2}, \pi - \tan^{-1}\left(\frac{\Delta P \cdot 2|M_{56}| \cdot 2\pi}{P_2 \lambda_{rf}\left(A - \sqrt{A^2 - \frac{16}{B}}\right)}\right)\right)$

ERL mode

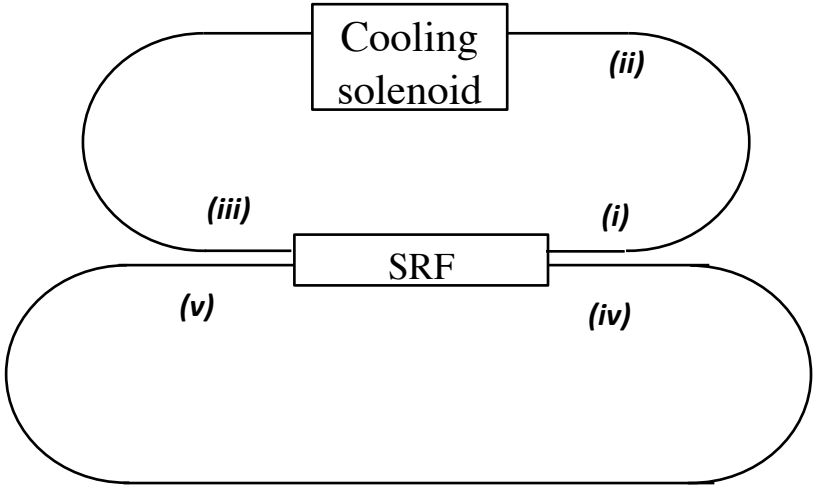
$$\phi_{s,a} \in \tan^{-1}\left(\frac{\Delta P \cdot \sqrt{B}|M_{56}| \cdot \pi}{P_2 \lambda_{rf}}\right) < \phi_{s,a} < \tan^{-1}\left(\frac{-\Delta P \cdot \sqrt{B}|M_{56}| \cdot \pi}{P_2 \lambda_{rf}}\right)$$

Here $B = \frac{P_2}{P_1}, A = \frac{2(1+B)}{B}, P_1 = 55MeV, P_2 = 155MeV$

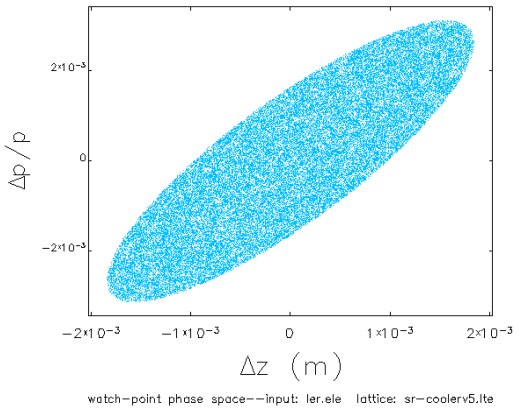


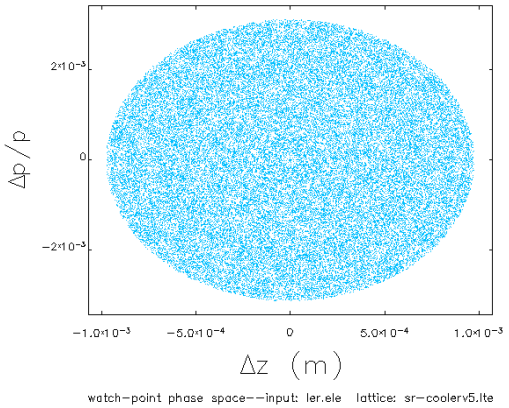


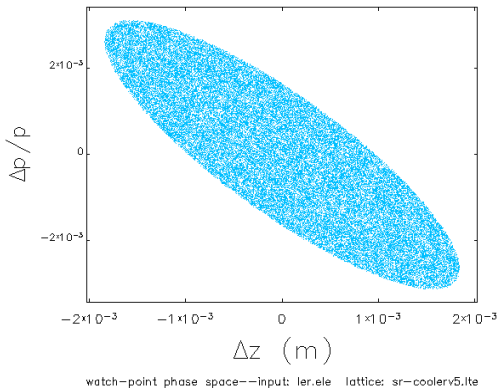
SR Mode Periodic Solution



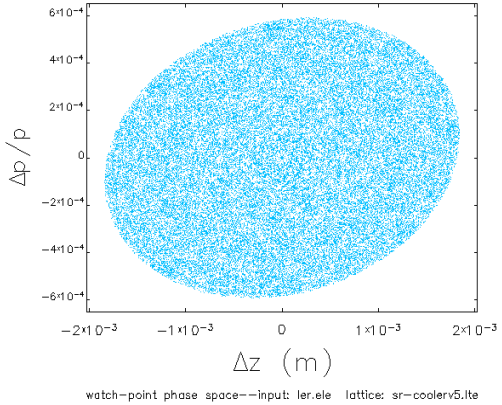
(i) (ii) (iii)

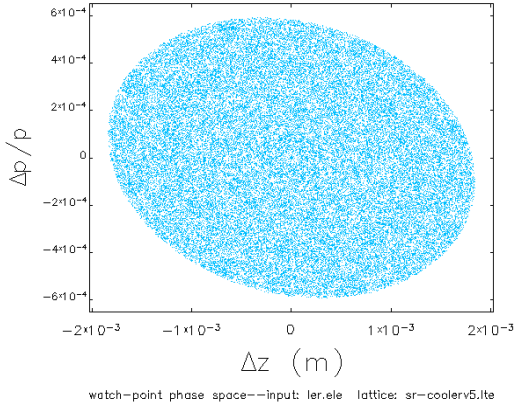


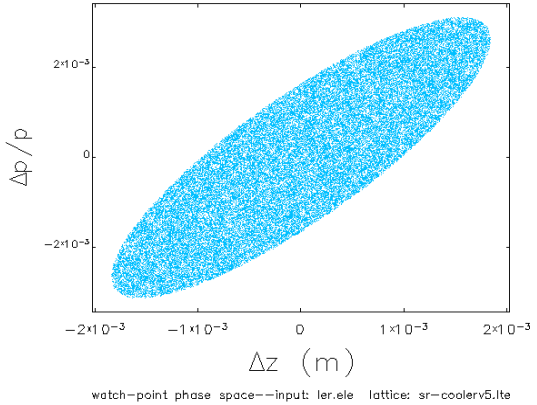




- Simulation conditions:
  - $\phi_{s,a} = 95^0, \lambda_{rf} = 0.629816$ m, M_{56}/arc ~ -0.5m, $E_{cooling}$=55 MeV, $E_{damping}$=155 MeV
- Result: $\Delta z \sim 1mm$, $\frac{\Delta p}{p} \sim 3\times10^{-3}$ @ cooling solenoid

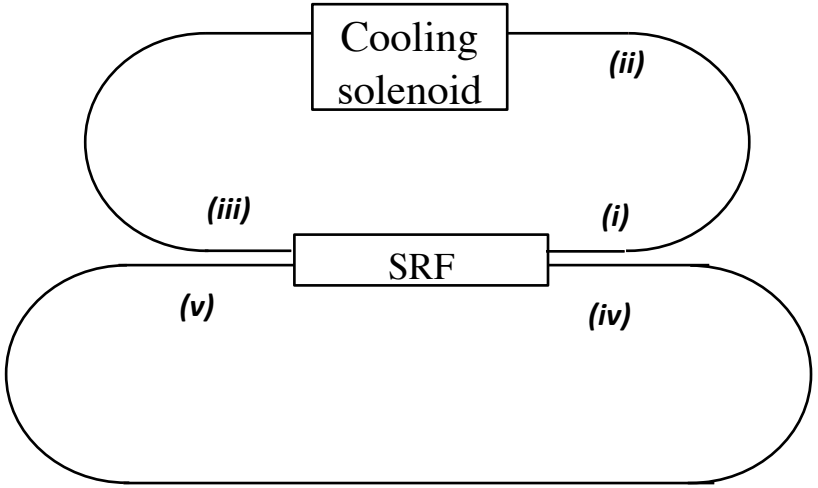


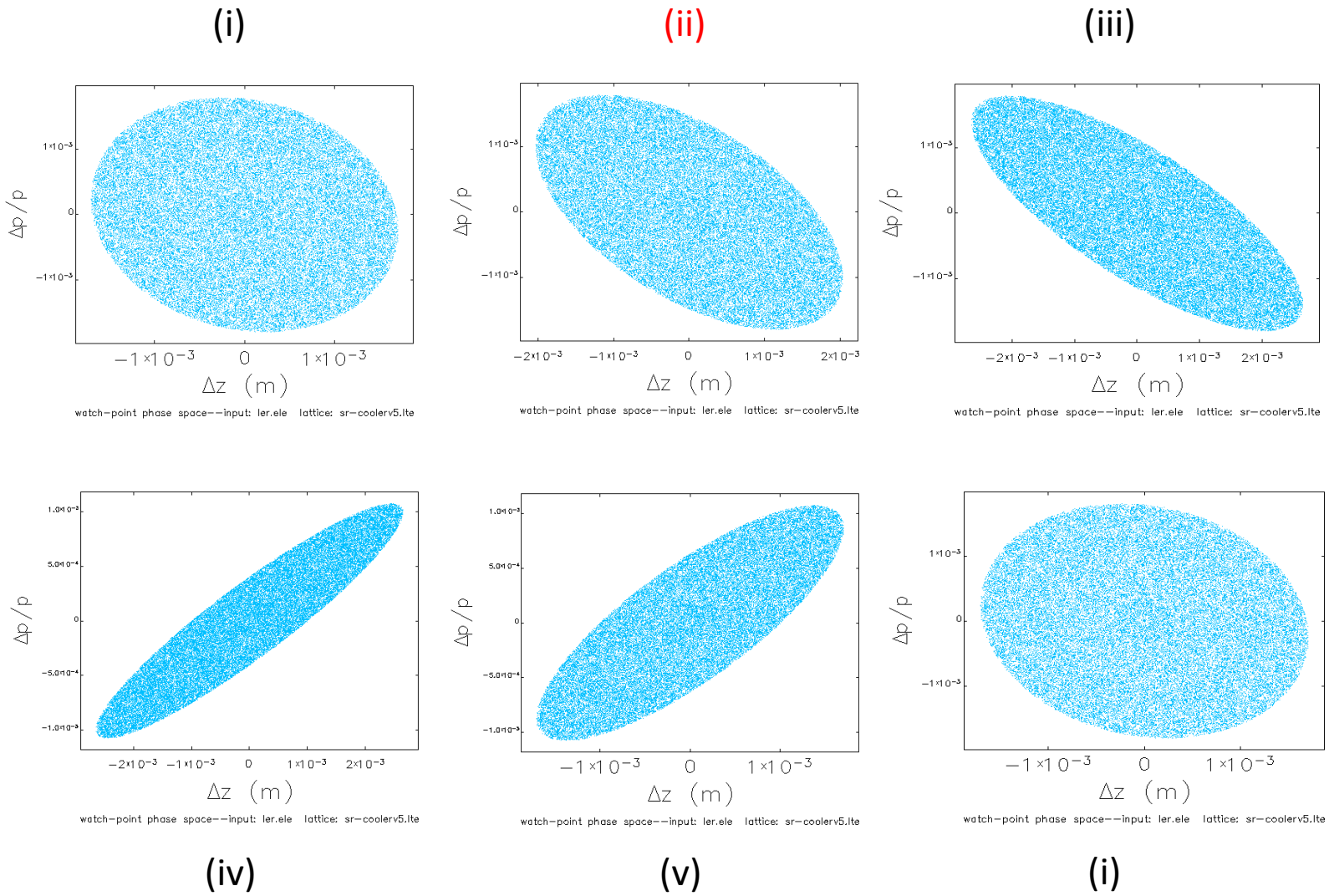




(iv) (v) (i)

ERL Mode Periodic Solution





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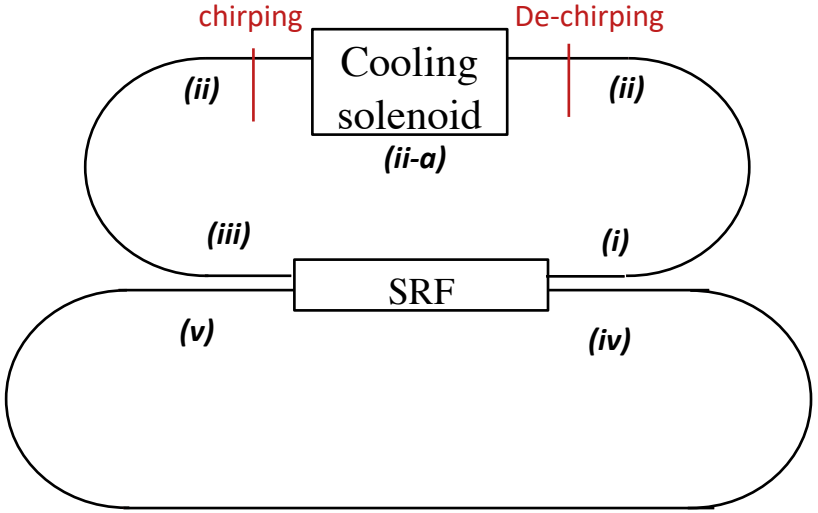
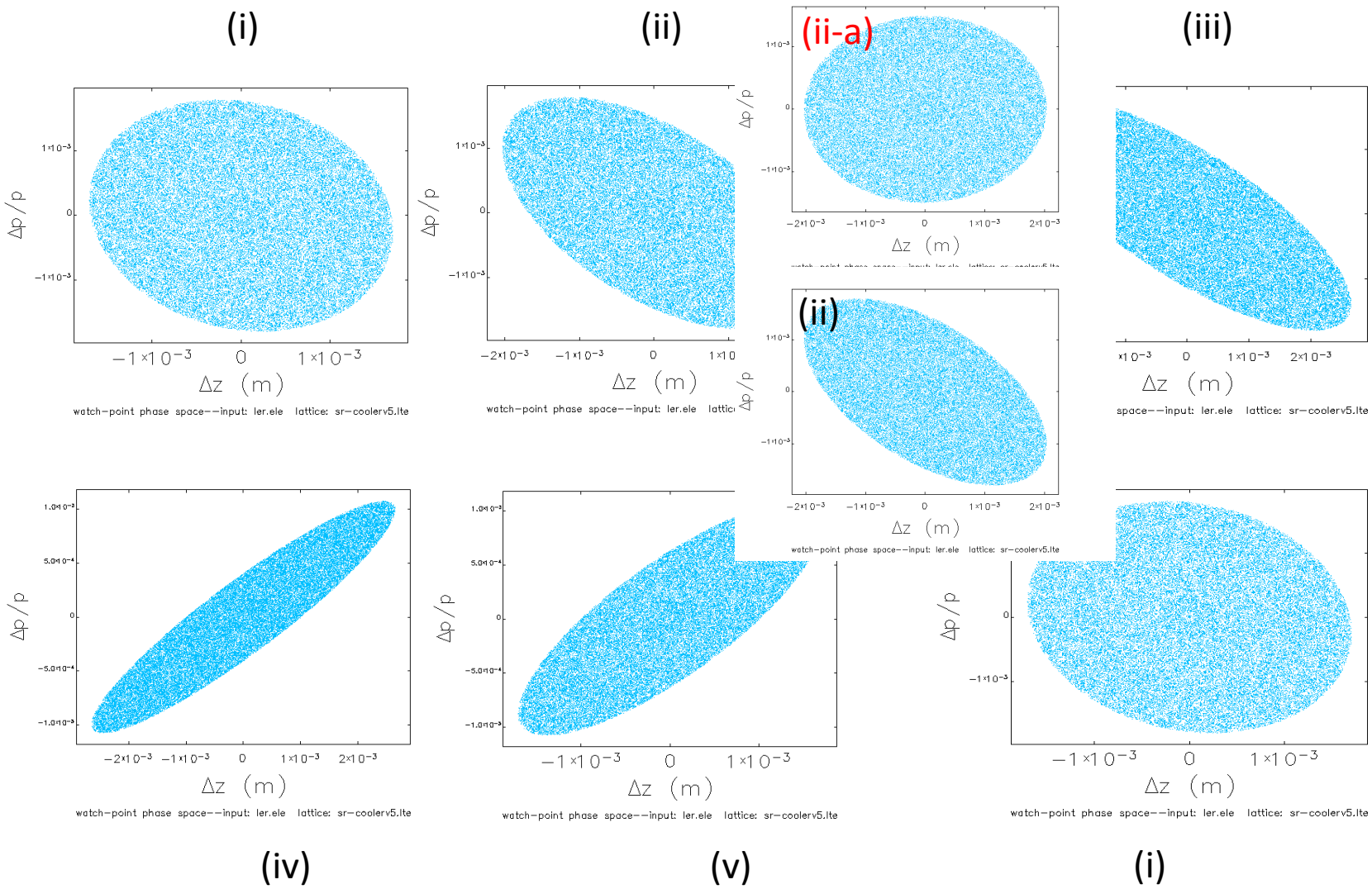
- Result: $\Delta z \sim 2mm$, $\frac{\Delta p}{p} \sim 1.8\times10^{-3}$ @ cooling solenoid

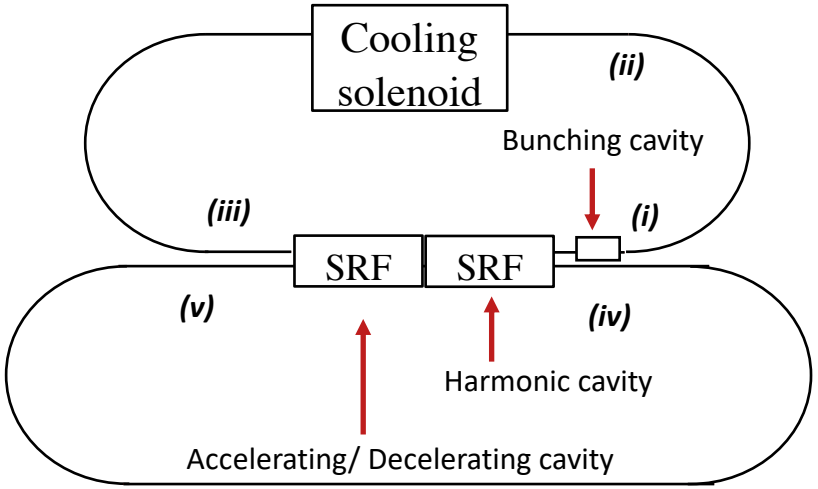
ERL Mode Periodic Solution with Chirping and De-chirping



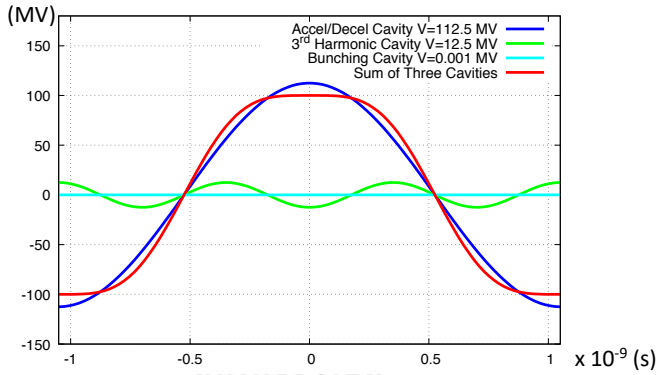


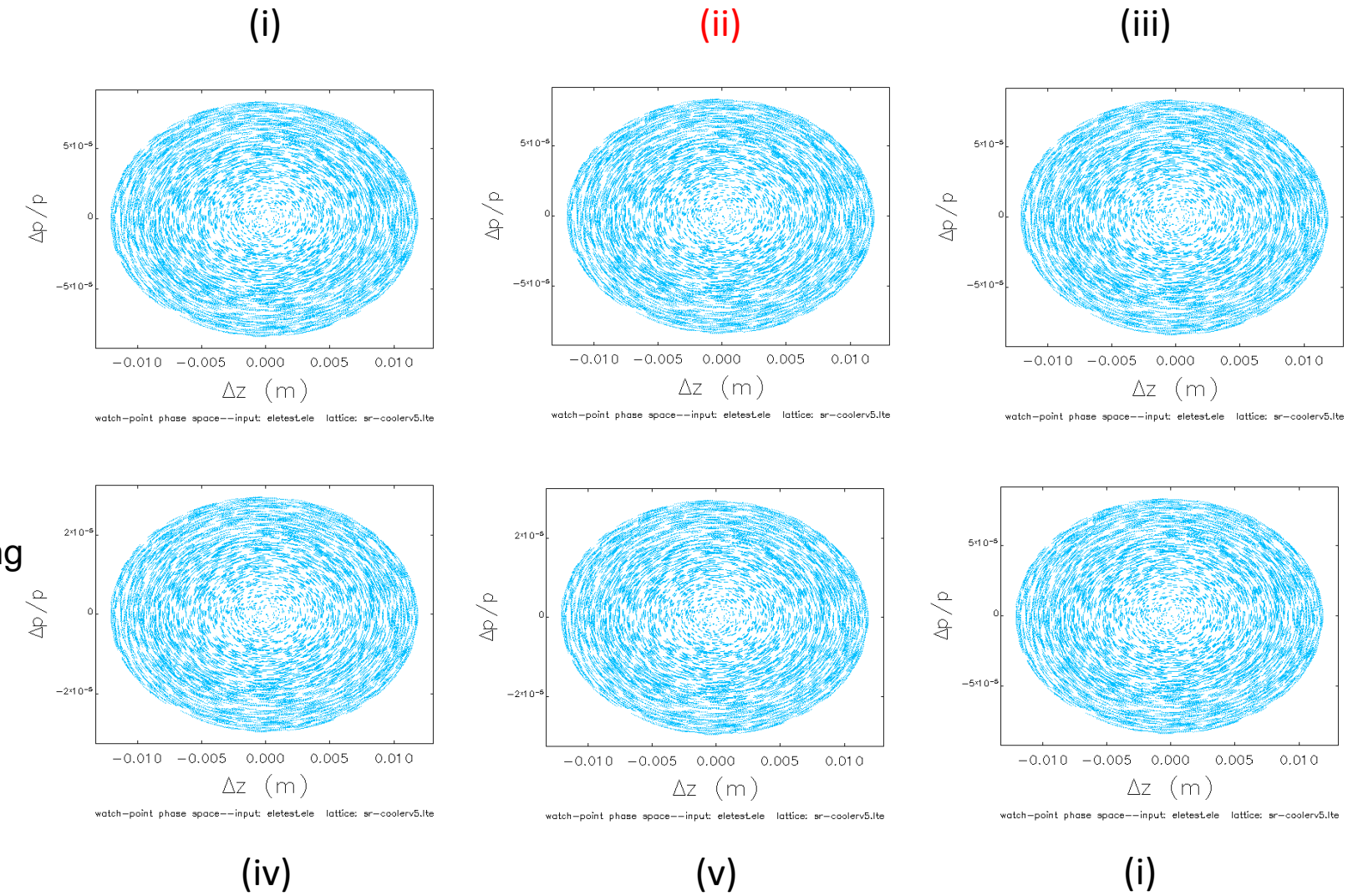
- Simulation conditions:
  - $\phi_{s,a} = 95^0, \lambda_{rf} = 0.629816$ m, M_{56}/arc ~ -0.5m, $E_{cooling}$=55 MeV, $E_{damping}$=155 MeV
  - V_{chirp}=$V_{de\text{-}chirp}$=2.8MV
- Result: up-right beam with $\Delta z \sim 2mm$, $\frac{\Delta p}{p} \sim 1.8\times10^{-3}$ @ cooling solenoid

Lengthen the Bunch Using Harmonic Cavity

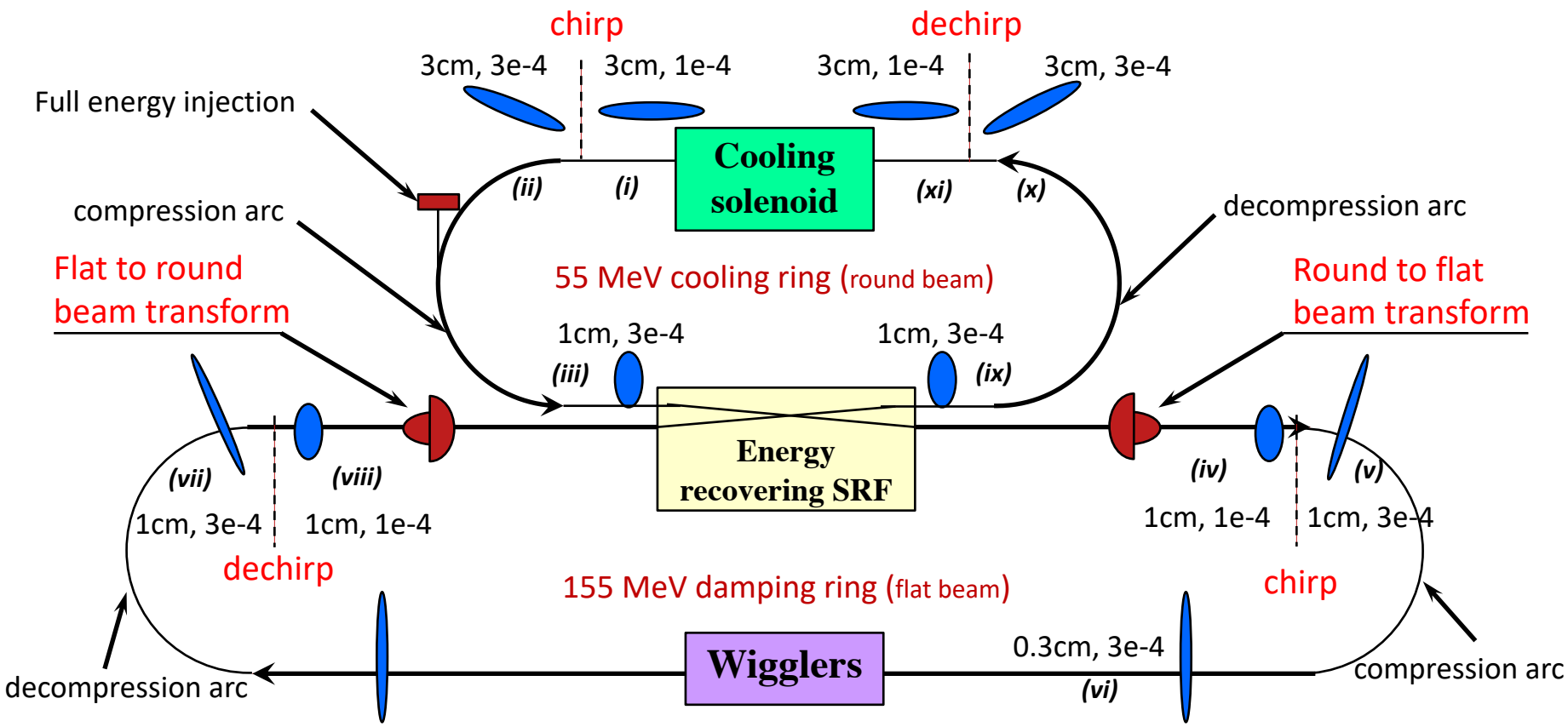


- Acc./Dec. cavity + harmonic cavity both run on the crest to lengthen the bunch
- Bunching Cavity creates a long. Focusing
- Result: up-right beam with $\Delta z \sim 1cm$, $\frac{\Delta p}{p} \sim 5\times10^{-5}$ @ cooling solenoid



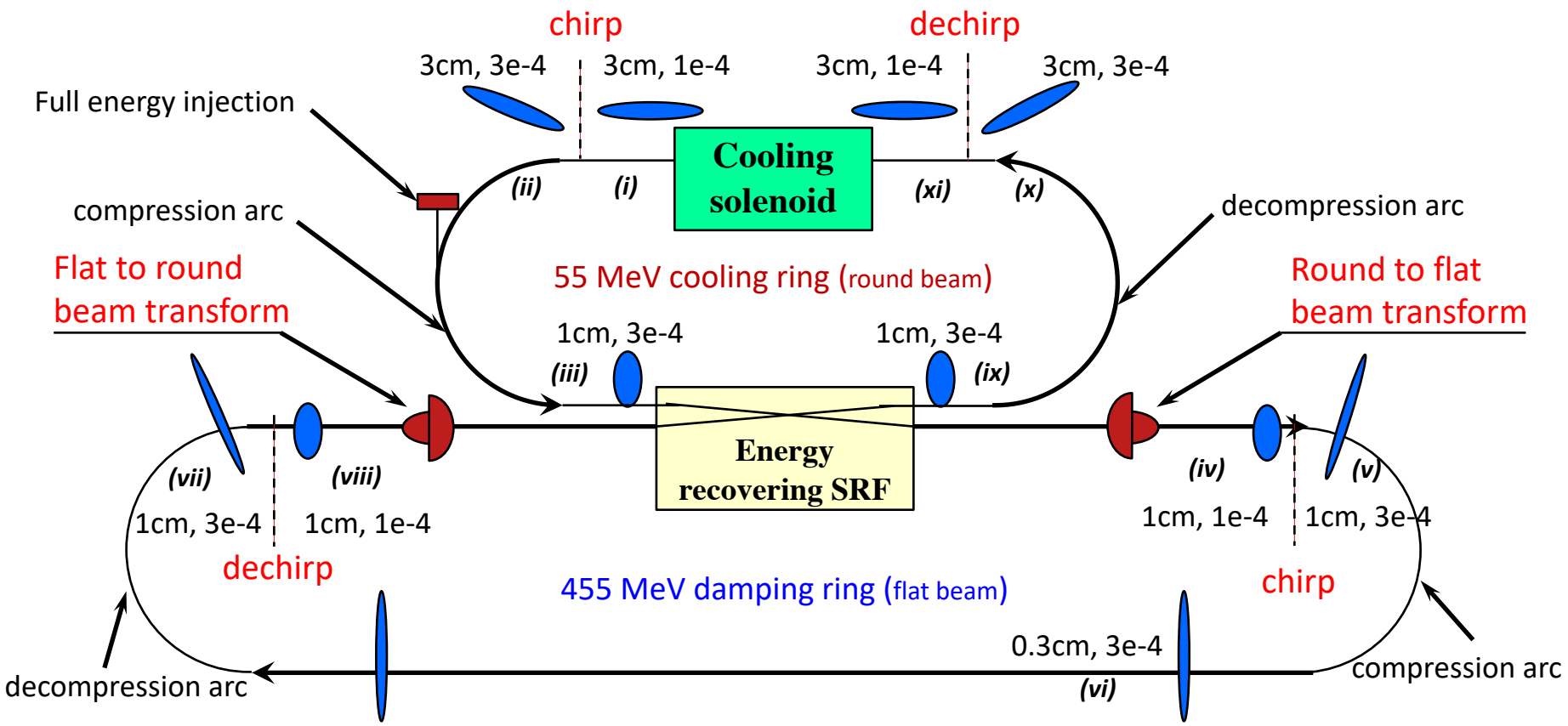


Original Storage Ring Cooler: Schematic Diagram



Original Proposed Idea: add wiggler to decrease damping time

New Storage Ring Cooler: Schematic Diagram

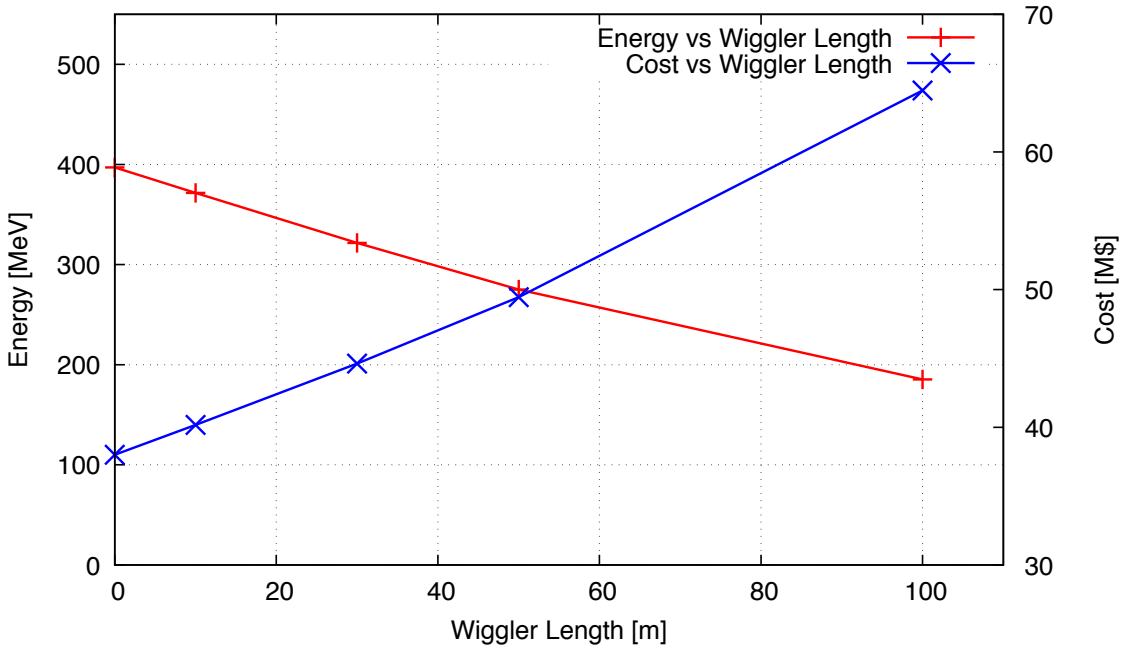


New Idea: increase beam energy in the damping ring to decrease damping time

Parameter Choices to Reach 600ms Damping Time

- Damping time for a two-energy ring: $\frac{t_{rev}}{\tau_{rad}} = \frac{t_{rev,LE}}{\tau_{rad,LE}} + \frac{t_{rev,HE}}{\tau_{rad,HE}} \approx \frac{t_{rev,HE}}{\tau_{rad,HE}} \sim \frac{\Delta E_{rad}}{E} = \frac{4\pi r_e}{3\rho_H}\gamma_H^3 + \frac{2\pi}{3}\alpha K^2 \frac{L_w}{\lambda_{ID}} \frac{2\gamma_H}{1+{K^2}/{2}} \frac{\lambda_c}{\lambda_{ID}}$

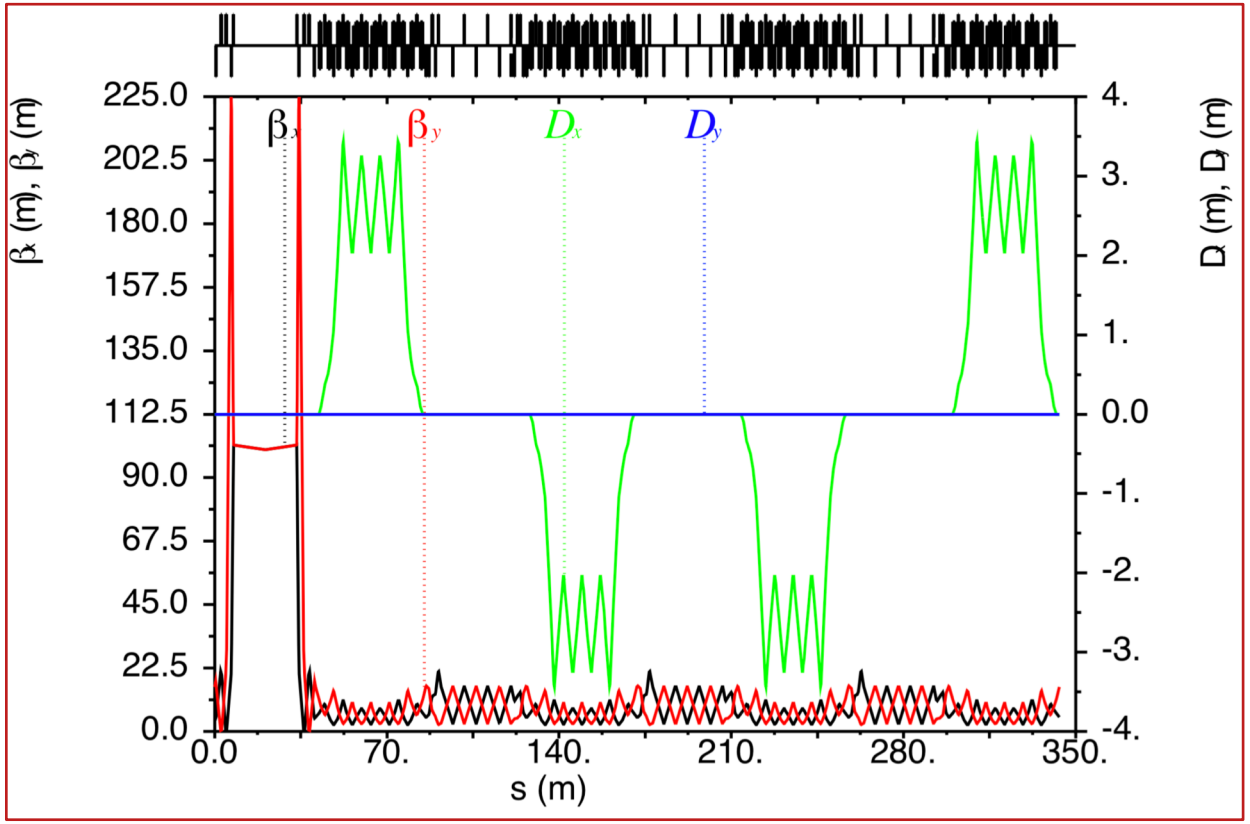
- Simple cost model: $C(\gamma_H, L) = \frac{511kV}{0.9}\left(\frac{10\$}{100V}\right)\left(\gamma_H + \frac{CL_w}{\lambda_{ID}}\right) - \frac{511kV}{0.9}\left(\frac{10\$}{100V}\right)\gamma_L$

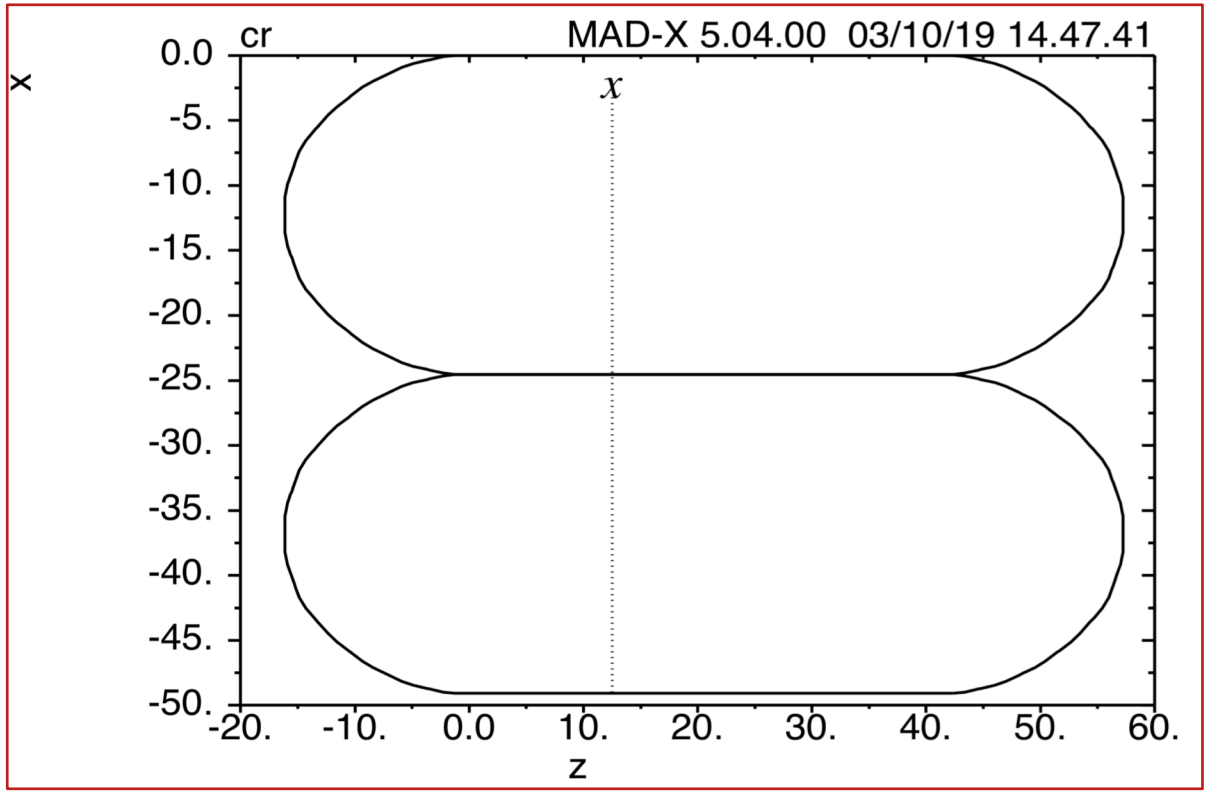


Item	Unit	Value	
Cooling Ring Energy	MeV	**55[1]**	**10.9[2]**
γ_L		107.8	21.3
Damping Ring Energy	MeV	**418**	**418**
γ_H		818	818
Total Gradient	MeV	363	407
Horizontal Damping Time	ms	**600**	**600**
Longitudinal Damping Time	ms	300	300

[1] to cool proton beam at 100 GeV
[2] to cool proton beam at 20 GeV

Two Energy Storage Ring Cooler Optics and Geometry





* Note that, flat to round (and round to flat beam) transform has been design as a module. This will be integrated into the optics.

High Level Optics and Beam Parameters

Item	Units	Value
Circumference	m	343.4
Horizontal / vertical tunes $\nu_{x,y}$		9.(69) / 9.(13)
Horizontal / vertical chromaticities $\xi_{x,y}$		-16.81 / -25.44
Maximum hor. / ver. β functions $\beta_{x,y}$	m	101.64 / 224.95
Maximum hor. / ver. dispersions $D_{x,y}$	m	3.44 / 0
Momentum compaction factor α		0.074
Transition energy γ_{tr}		3.68
M^{56}/arc		-6.32

Item	Units	Value
Cooling ring energy	MeV	55
Energy loss per turn	MeV	2.4e-7
SR power	MW	1.2e-7
Horizontal damping time	ms	263923
Longitudinal damping time	ms	131962
Normalized horizontal emittance	um	0.9
Energy spread		2.3e-5
Damping ring energy	MeV	418
Energy loss per turn	MeV	8.0e-4
SR power	MW	4.0e-4
Horizontal damping time	ms	602
Longitudinal damping time	ms	301
Normalized horizontal emittance	um	391.6
Energy spread		1.7e-4

Assume:

Beam Energy	MeV	418
Beam current	A	0.5
Nor. horz. emittance	um	392
Nor. vert. emittance	um	78.4
Energy spread		1.7e-4
Bunche length	cm	1

IBS		
Longitudinal time	s	1.07
Horizontal time	s	31.38
Vertical time	s	-1.8e6

Summary and Plan

- For the concept of a two-energy storage ring cooler, we
  - verified the longitudinal stability with accelerating and deaccelerating cavities,
  - established chirping and de-chirping properly,
  - explored mechanisms to length the bunch,
  - initiated front-to-end numerical simulations,
  - improved the linear optics design and estimated new parameter choices.
- Future Plan
  - perform the longitudinal simulation using the improved optics design
  - perform simulations with synchrotron radiation included
  - optimize the cooler parameters
  - improve the linear optics design
  - identify potential issues such as HOM impedance, coherent synchrotron radiation and beam break up, etc.

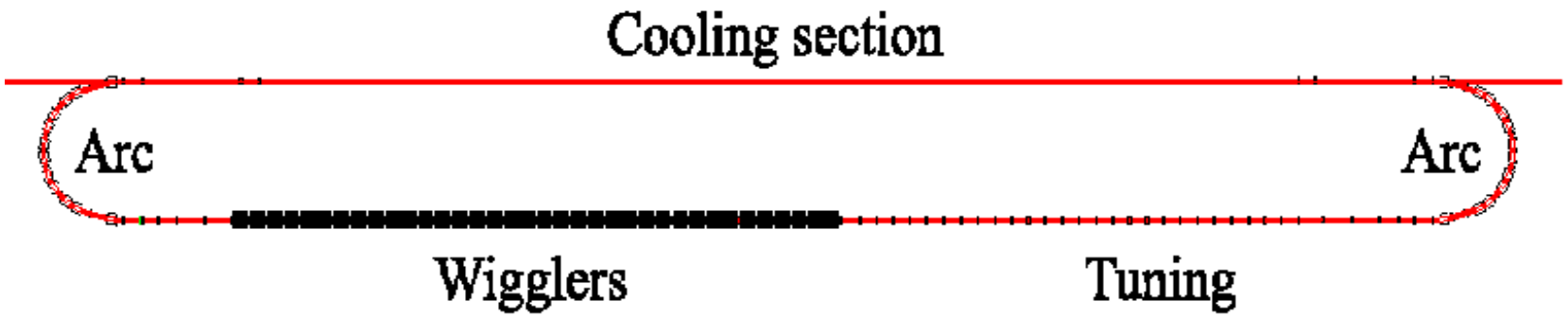
Thank You for Your Attention !

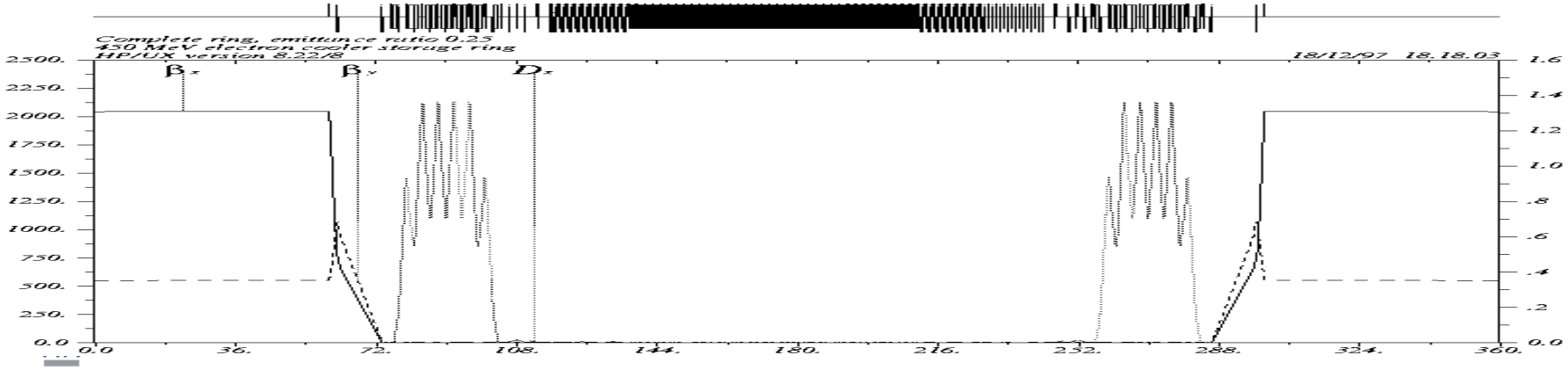
Back Up

HERA High Energy Cooler

- Cooling section: high beta insertion (L=120m)
- arcs: diameter 16m (tunnel 5.2m) ⇔ sextupol strength
- wiggler section: dispersion free, 37 wigglers, B = 1T
- tuning section: adjusting tunes, coupling - rf cavities

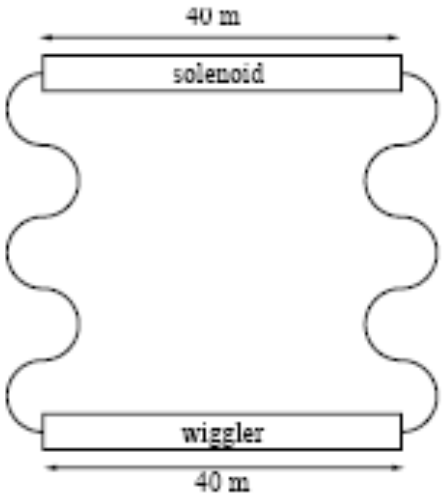
M. Gentner, R. Brinkmann, Ya. Derbenev, D. Husmann, C. Steier, NIMA 424 (1999)
K. Balewski@Snowmass 2001



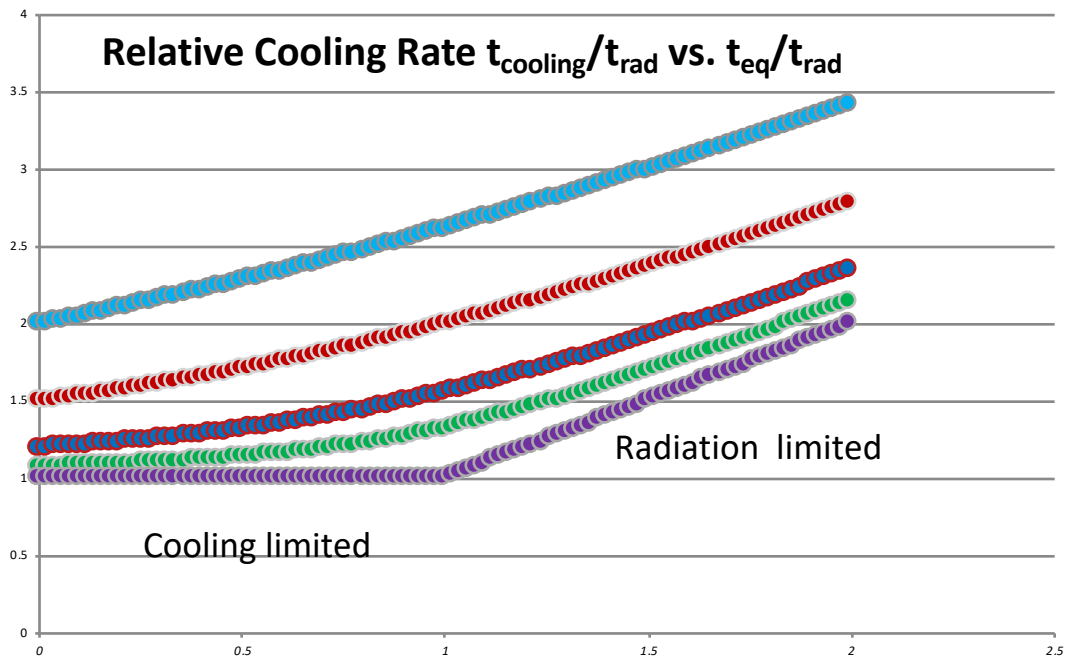


RHIC Cooler

A. Burov, V. Danilov,
P. Colestock, Ya. Derbenev,
FERMILAB-TM-2058 (1998)



MAIN PARAMETERS OF THE ELECTRON COOLER	
Energy E_e (MeV)	55.4
Relativistic factor γ	108.4
Electrons per bunch N	$1.5 \cdot 10^{10}$
Bunch length σ_{es} (cm)	15
Number of bunches n_b	60
Circumference C (m)	200
Radiation damping time:	
longitudinal (s)	0.014
horizontal (s)	0.12
vertical (s)	0.038
Momentum compaction factor α	0.15
Synchrotron tune ν_s	0.01
Relative energy spread δ_{eE}	$2.9 \cdot 10^{-4}$
Hor. rms emitt., unnorm. ϵ_x(cm)	$4 \cdot 10^{-5}$
Vert. rms emitt., unnorm. ϵ_y(cm)	$2 \cdot 10^{-7}$
Solenoid, length(m) / field(Gs)	40 / 390
Wiggler, length(m) / field(T)	40 / 3.6
Lifetime (min)	0.6
Ion $\beta-$functions in solenoid (m)	160
Electron angles in solenoid	$\leq 1 \cdot 10^{-5}$
Ions longitudinal cooling time (min)	8
Ions transverse cooling time (min)	28

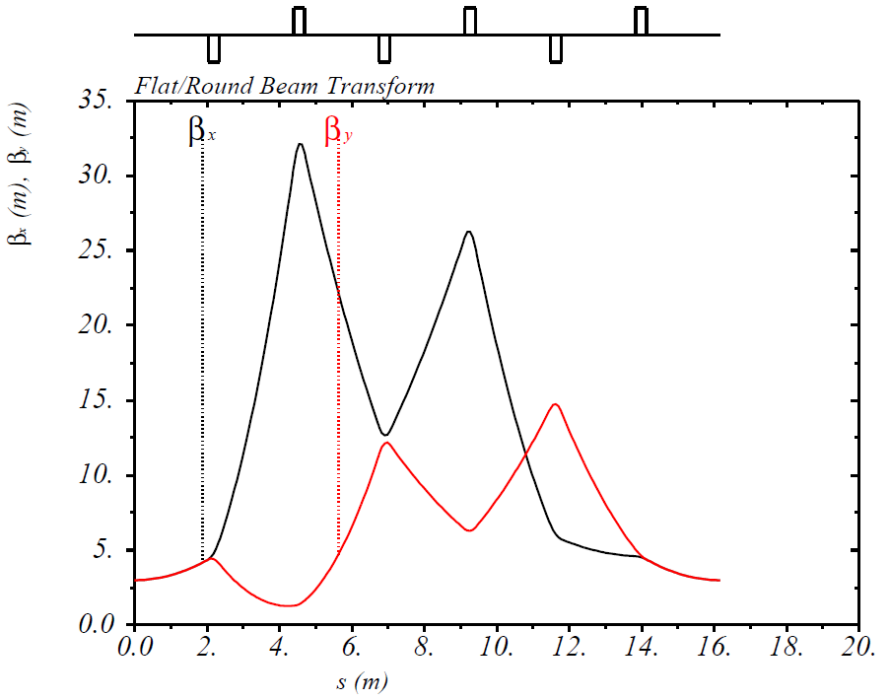


Relative cooling time for N_i/N_e=0 (purple), 0.08 (green), 0.2 (blue), 0.5 (brown), 1 (light blue)

$\phi_{s,a}$ vs M56 for SR Mode

$\lvert M_{56} \rvert$ (m)	$\phi_{s,a}$ (degree)
1.0	(107.0086 – 112.5110), (90.00 – 96.1948)
2.0	(98.6959 – 101.7071), (90.00 – 93.1065
3.0	(95.8221 – 97.8654), (90.00 – 92.0721)
4.0	(94.3731 – 95.9153), (90.00 – 91.5543)
5.0	(94.7338 – 93.5009), (90.00 – 91.2436)
6.0	(92.9186 – 93.9513), (90.00 – 91.0364)
7.0	(92.5021 – 93.3883), (90.00 – 90.8884)
8.0	(92.1898 – 92.9656), (90.00 – 90.7773)
9.0	(91.9466 – 92.6365), (90.00 – 90.6910)
10.0	(91.7521 – 92.3732), (90.00 – 90.6219)

- Design an uncoupled betatron stable beam transport module imaging (β, α) back to the same (β, α), with transverse tunes split by a quarter integer.
- Rotate the system by 45° about the reference orbit
- Apply it to the flat beam to generate a magnetized beam.



Flat to round or round to flat beam transform (based on D. Douglas's presentation in the JLEIC R&D meeting on 2015-07-09).