Development of a Bunched Beam Electron Cooler based on ERL and Circulator Ring Technology for the Jefferson Lab Electron-Ion Collider

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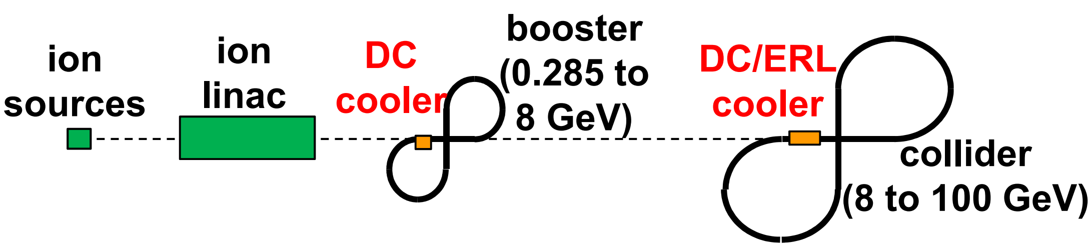
Outline

- Basic design concepts
- Cooling Physics Simulation Issues
- Cooler design specifications
- Cooling partition issue
- ERL design
- S2E results for ERL
- CCR design issues.
- Injection/extraction scheme
- The injector
- Summary (future work)

Multi-Step Cooling for High Luminosity

- **Cooling of JLEIC proton/ion beams**
  - Achieving very small emittance (**~10x reduction**) & very short bunch length **~1 cm** (with SRF)
  - Suppressing IBS induced emittance degradation
  - high cooling efficiency at low energy & small emittance



Pre-cool when energy is low

$$\tau_{cool} \sim \gamma^2 \frac{\Delta\gamma}{\gamma} \sigma_z \varepsilon_{4d}$$

Cool when emittance is small (after pre-cool at low energy)

Ring	Functions	Proton kinetic E (GeV)	Lead ion kinetic E (GeV/u)	Electron kinetic E (MeV)	Cooler type
booster ring	Accumulation of positive ions		0.1 (injection)	0.054	DC
collider ring	Maintain emitt. during stacking		2 (injection)	1.1	DC
	Pre-cooling for emitt. reduction	7.9 (injection)	7.9 (ramp to)	4.3	DC
	Maintain emitt. during collision	Up to 100	Up to 40	Up to 54.5	ERL

Can't reduce emittance due to space charge limit

Pre-cooling both protons and lead ions

ERL cooler can't reach energy below 20 MeV

Why Magnetized Electron Cooler?

- At cathode immersed in solenoid, the gun generates almost parallel (laminar) beam state of a **large** size (electron Larmor orbits are very small compared to beam size)
- This beam state is then transplanted to the solenoid in cooling section (while preserving the canonical emittances: the ***drift*** and the Larmor emittances)
- The solenoid field can be controlled to match the e-beam size to the ion beam size
- We do not maintain the solenoid field from cathode to dump.

Magnetization results in the following critical advantages

(compared to a non-magnetized gun/cooling solenoid):

- Have significantly stronger cooling than non-magnetic case.
- Tremendous reduction (by a factor 20 – 30) of the regional and global deleterious Space Charge transverse impact on dynamics in the CCR (tune shift)
- Strong mitigation (suppression) of the CSR micro-bunching/energy spread growth (though CSR can still increase the correlated energy spread).
- Suppression of deleterious impact of high electron transverse velocity spread and short-wave misalignments to cooling rates (thanks to ion collisions with "frozen" electrons at large impact parameters)

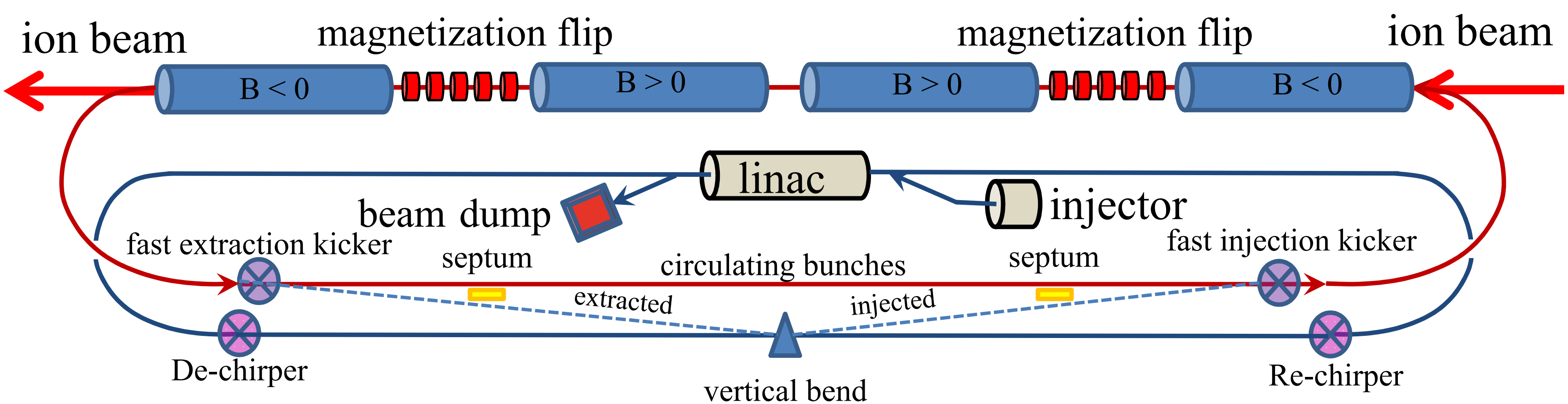
Cooling Simulations

- Basic cooling model is similar to Betacool
  - Currently using Parkhomchuk friction model
- Have added turn-by-turn capability
- Working on new cooling formulas from Derbenev thesis
- Developing segmented beam approach to alter the cooling partition to match the IBS heating.
- Anchoring the code to experiment at IMP (poster yesterday)

Baseline Design is Cooling Ring Fed by ERL

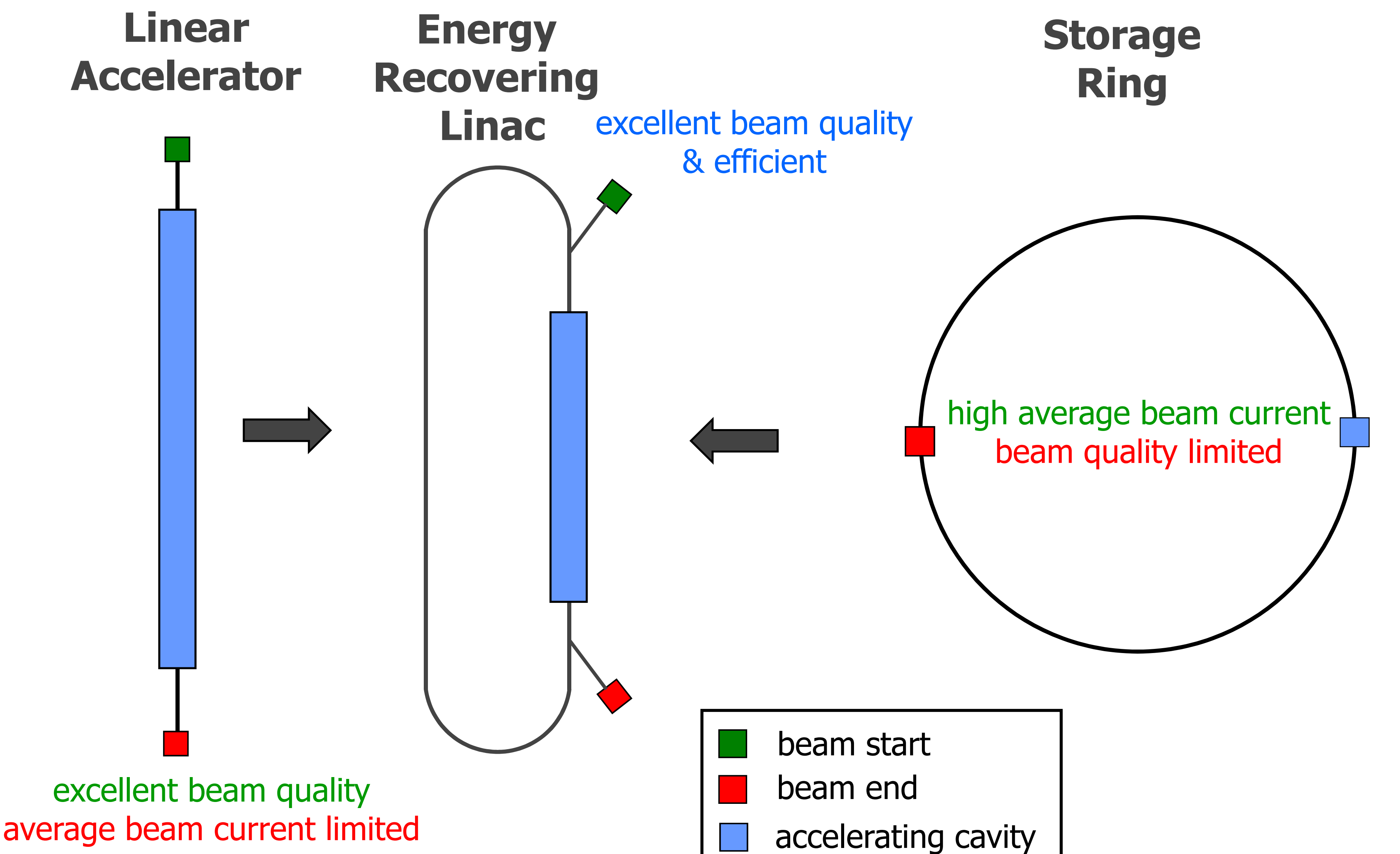
- Net zero longitudinal field in the ion ring to minimize spin rotation
- Uses harmonic kicker to inject and extract from CCR (divide by 11)
- Assumes high charge, low rep-rate injector (w/ subharmonic acceleration and bunching)
- Same-cell energy recovery in 952.6 MHz SRF cavities

top ring: CCR

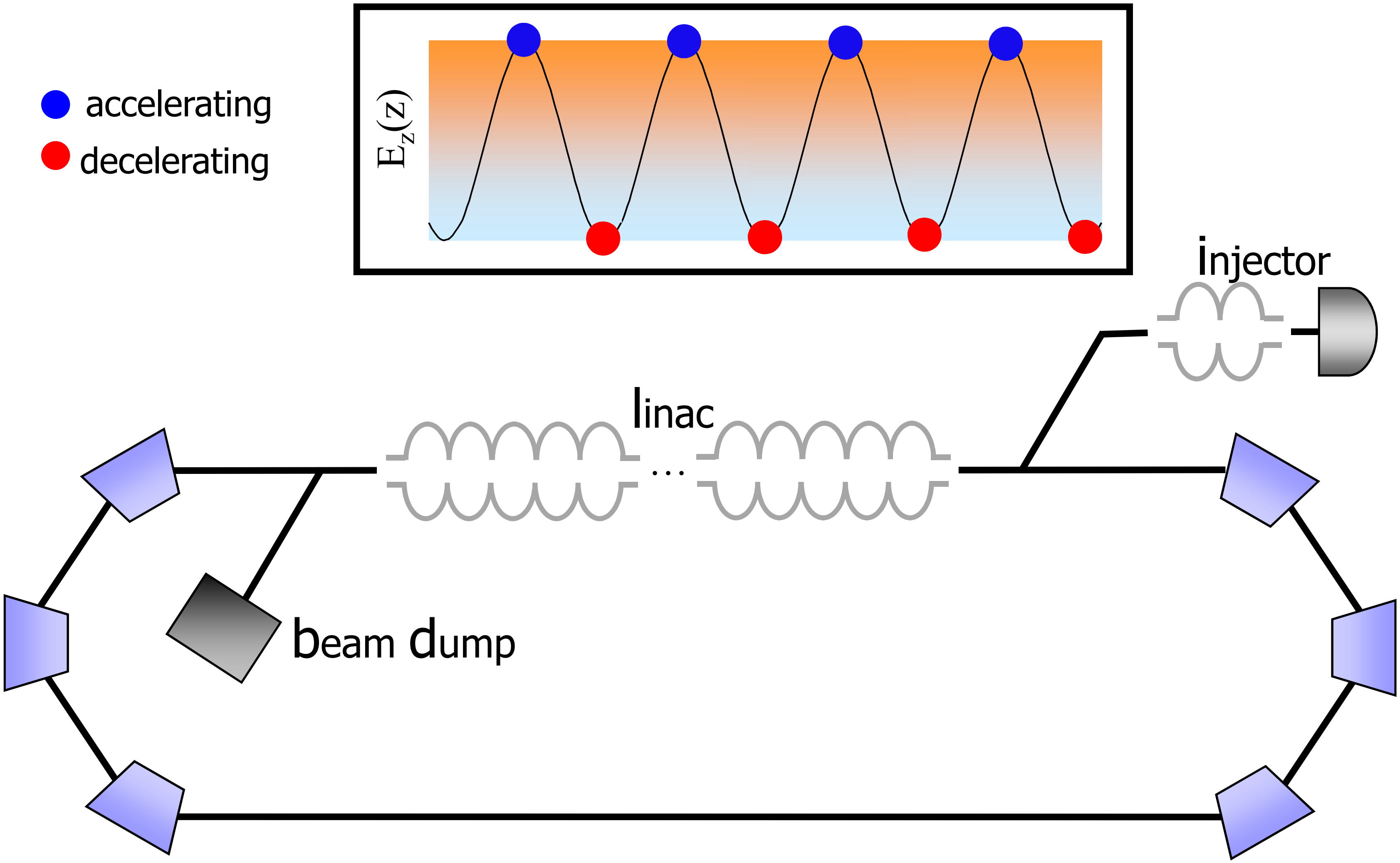


bottom ring: ERL

Accelerator Architectures

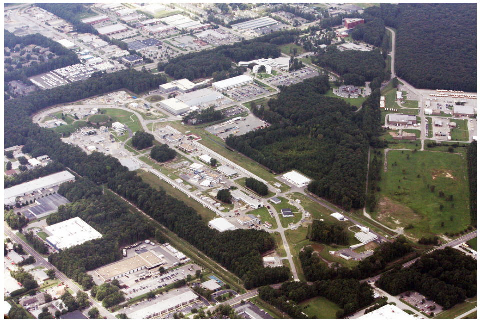


Generic ERL

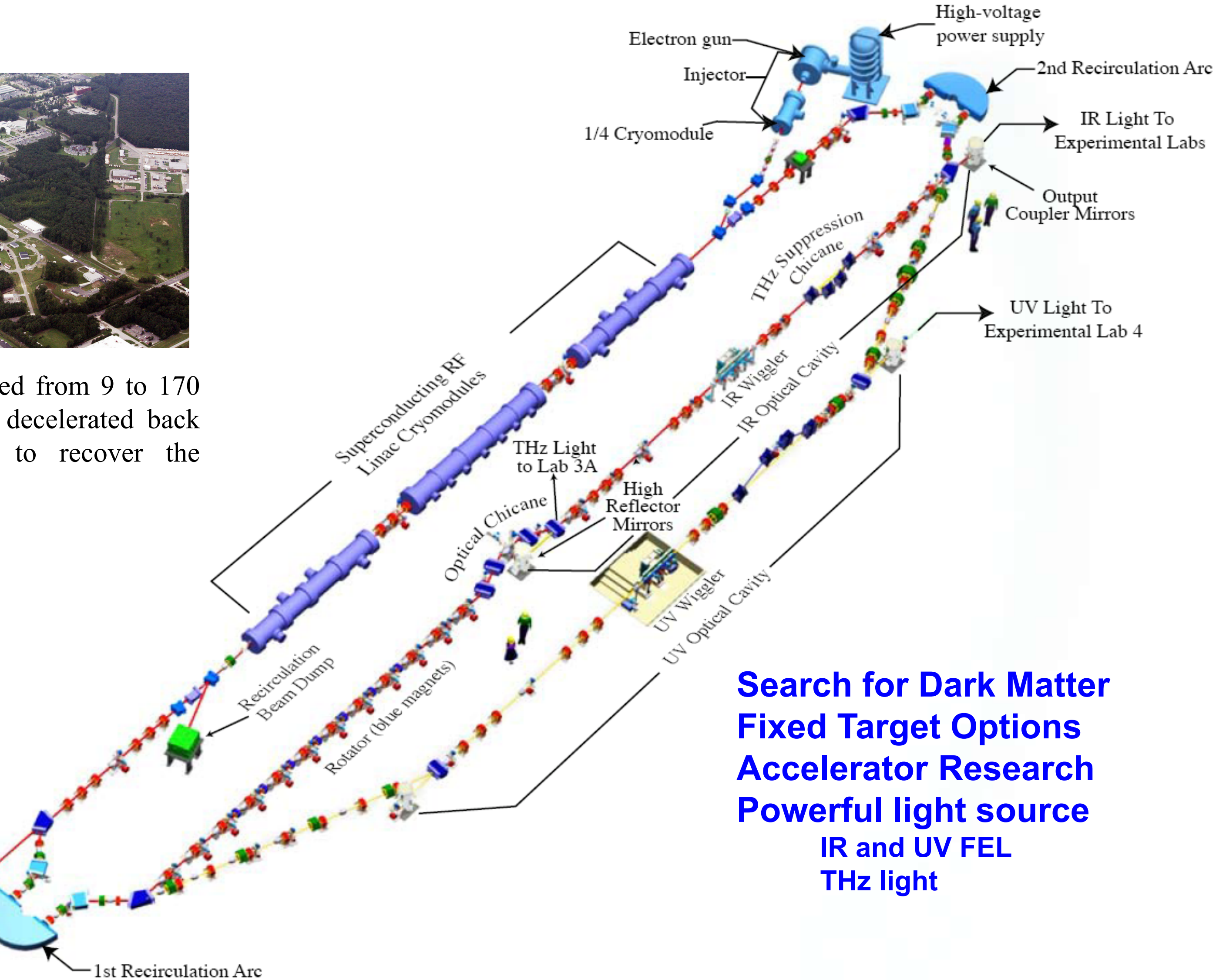


Note: ERLs are time-of-flight spectrometers. Always start with the longitudinal match.

JLAB ERL: Low Energy Research Facility (LERF)

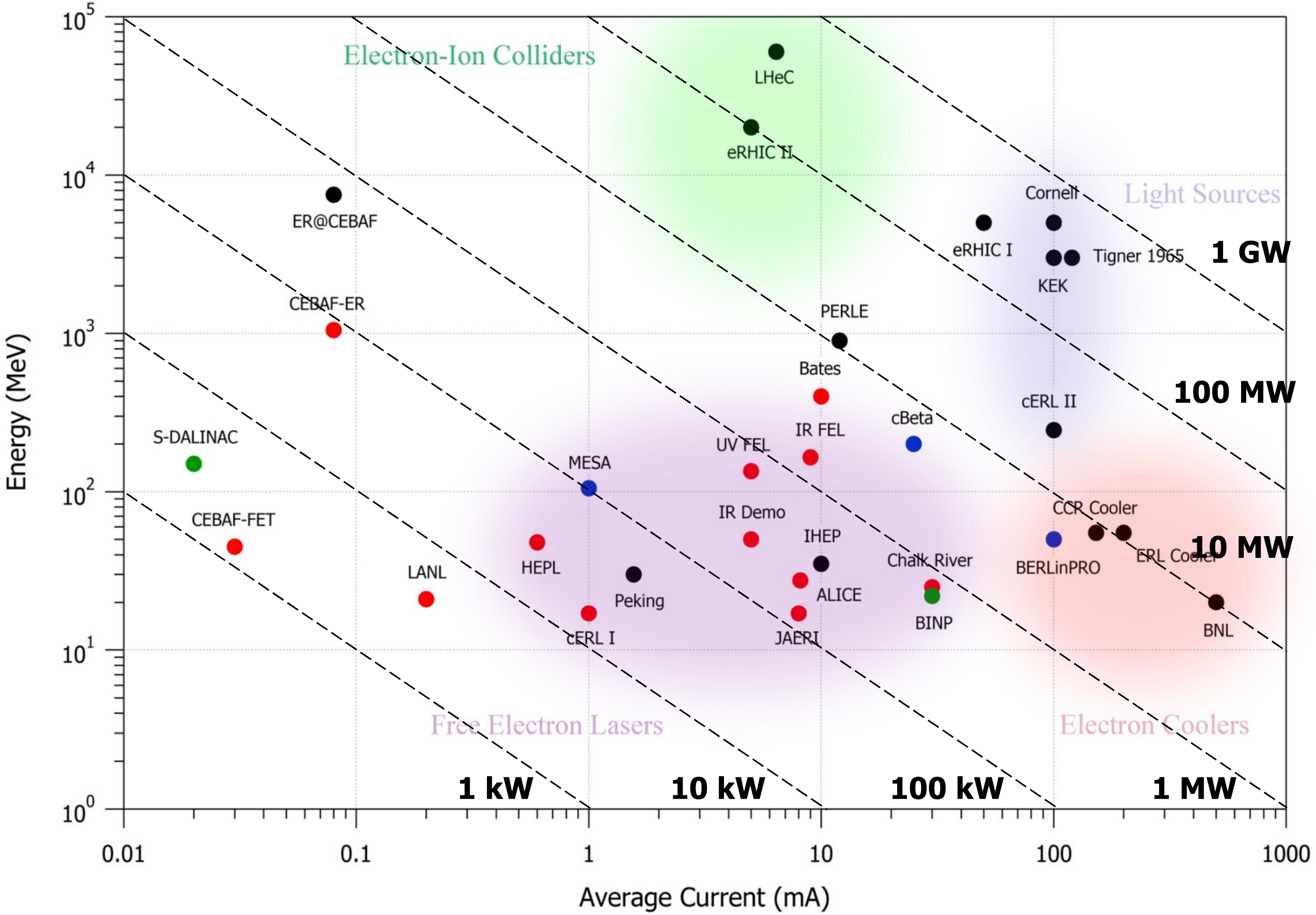


Beam accelerated from 9 to 170 MeV and then decelerated back to ~10 MeV, to recover the energy



Search for Dark Matter
Fixed Target Options
Accelerator Research
Powerful light source
- **IR and UV FEL**
- **THz light**

Generations of ERLs



ERL Concept

- ERLs advantages:
  - They can provide high current without high RF power
  - They can tolerate losses on the order of 10^{-4} without instability.
  - They can provide high brightness at low energy where storage rings have no damping.
  - Can produce very short bunches.
- ERL disadvantages
  - Must provide CW high current electron source (lifetime may be a problem)
  - They can tolerate losses on the order of 10^{-4} without instability (but this can be kWs of beam power lost).
  - May have more difficulties handling ion trapping.

Strong Cooler Specifications (Electrons)

• Energy	20–55 MeV
• Charge	3.2 nC
• CCR pulse frequency	476.3 MHz
• Gun frequency	43.3 MHz
• Bunch length (tophat)	2 cm (23°)
• Thermal emittance	<19 mm-mrad
• Cathode spot radius	2.2 mm
• Cathode field	0.1 T [3]
• Gun voltage	400 kV
• Normalized hor. drift emittance	36 mm-mrad
• *rms* Energy spread (uncorr.)*	3×10^{-4}
• Energy spread (p-p corr.)*	$<6\times10^{-4}$
• Solenoid field	1 T
• Electron beta in cooler	37.6 cm
• Solenoid length	4x15 m
• Bunch shape	beer can

Cooler Specifications (protons)

Case 1 – 63.3 GeV center of mass energy

• Energy	100 GeV
• Particles/bunch	2.0×10^{10}
• Repetition rate	158.77 MHz
• Bunch length (rms)	2.5 cm
• Normalized emittance (x/y)	1.2/0.6 mm-mrad
• Betatron function in cooler	100 m (at point between solenoids)

Case 2 – 44.7 GeV center of mass energy

• Energy	100 GeV
• Particles/bunch	6.6×10^{9}
• Repetition rage	476.3 MHz
• Bunch length (rms)	1.0 cm
• Normalized emittance (x/y)	1.0/0.5 mm-mrad
• Betatron function in cooler	100 m (at point between solenoids)

Ion ring lattice may be coupled or dispersed in solenoid. Ion beam may be partially offset from the electron beam.

Electron Cooling (CM Energy 63.5 GeV)

Proton beam (CM energy 63.5 GeV)

Electron beam 3.2 nC

	Units	x	y	z
Cooling rate	10^{-3} 1/s	-0.431	-1.434	-1.605
IBS rate	10^{-3} 1/s	3.192	0.102	0.618
Total rate	10^{-3} 1/s	2.761	-1.332	-0.987

- In horizontal direction, cooling is about one order weaker than IBS.

To find equilibrium:

- Apply dispersion at cooler to transfer longitudinal cooling to transverse directions
- Apply transverse coupling to transverse horizontal IBS to vertical direction
- Increase proton beam emittance
- Study the possibility of emittance exchange
- Decrease proton beam current

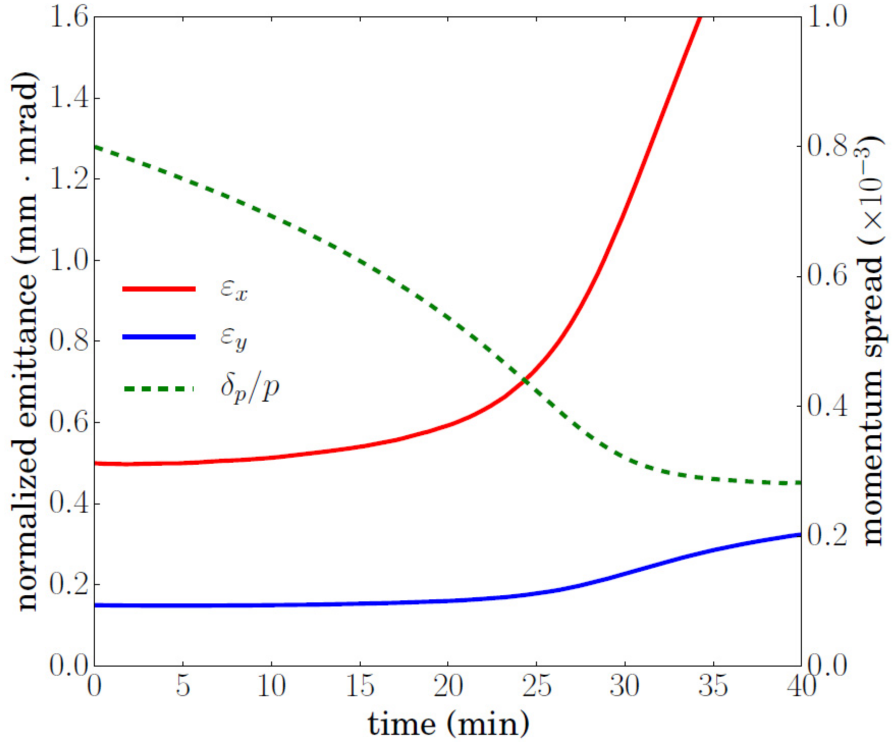
Electron Cooling (CM Energy 44.7 GeV)

- Proton beam (CM energy 44.7 GeV):
  - Energy: 100 GeV
  - Proton number: 0.804x10^{10} (82%)
  - Normalized emit. (rms): 0.50/0.15 μm
  - Beta function in cooler: 60/200 m

Longitudinal overcooling reduces the bunch length, which increases the charge density and thus the IBS rate. Transverse equilibrium is broken.

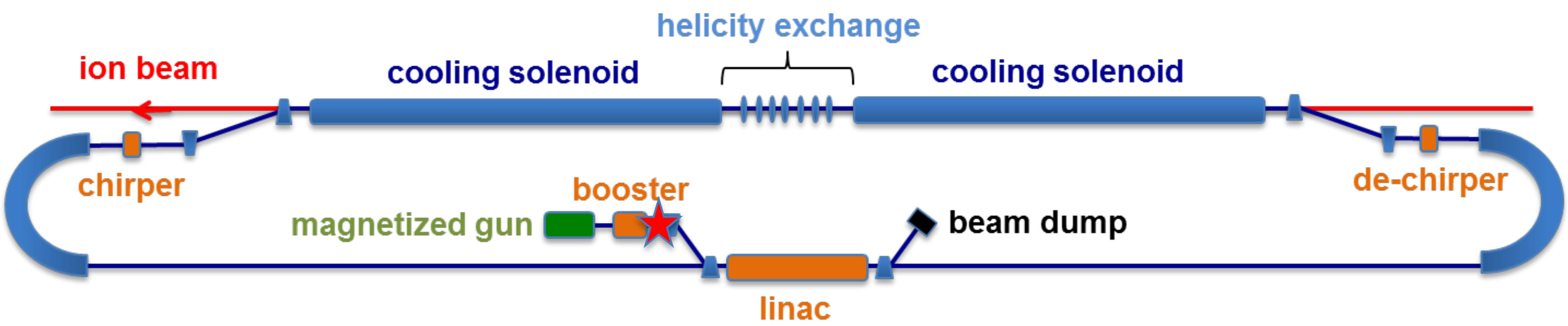
Could decrease RF to keep bunch long.

Electron beam 3.2 nC



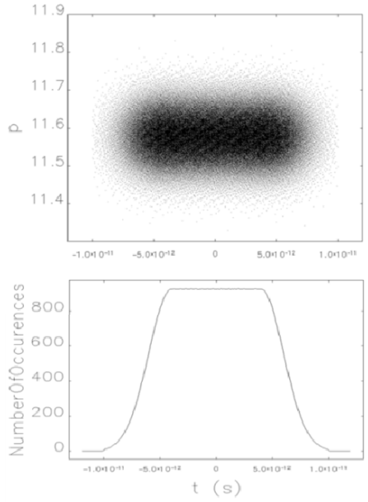
ERL Design Status

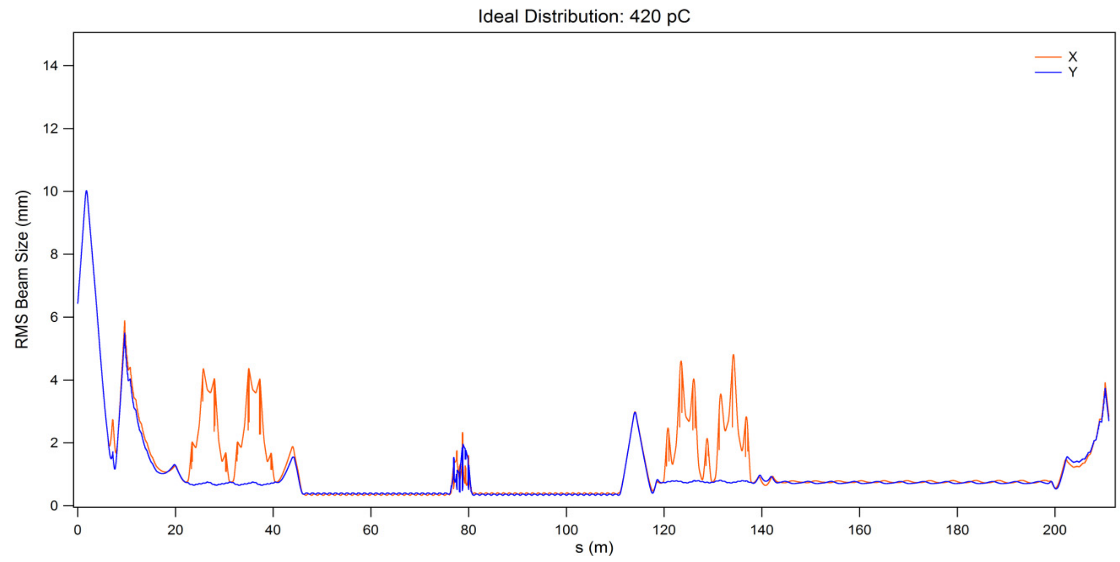
- Charge is 420 pC at 476.3 MHz
- All transport is locally symmetric
- Have completed S2E and I2E simulations for ERL design
- Would eventually want to use two helicity exchanges and four solenoids.
- Have not yet included the cooling leg merger and demerger.
- I2E looks good but we have not been able to produce the initial distribution from injector simulations.



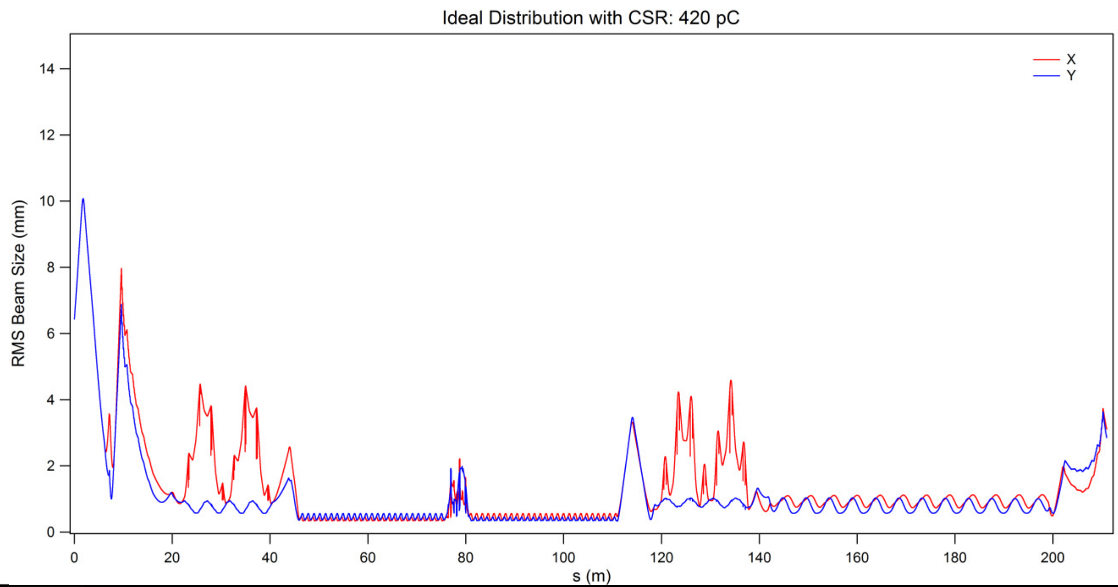
★ Start of Injector to end simulations

Transverse performance in ERL (Ideal beam)





- Start with ideal distribution at booster exit (above).
- Find *rms* beam size vs. distance without (top) and with (bottom) CSR
- No re-optimization performed with CSR.



Larmor emittance X2 vs. Distance

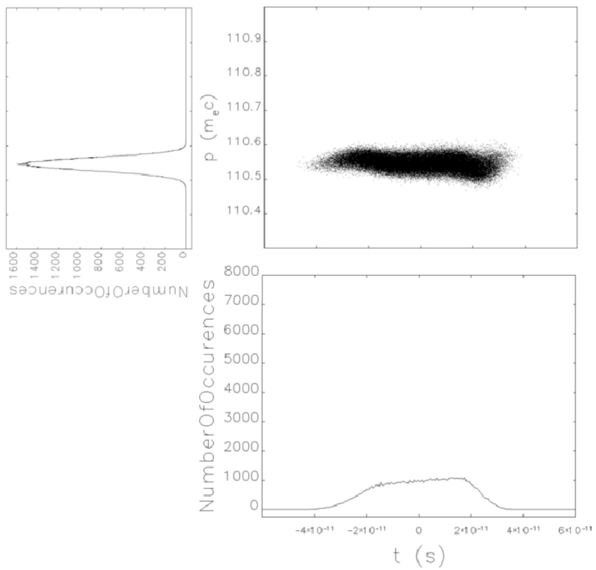
We list here the vertical emittance after a round-to-flat transform on the electron beam. The vertical emittance is twice the Larmor emittance Specification is that the Larmor emittance be less than 19 mm-mrad. So we want the vertical emittance to be less than 38 mm-mrad.

Location	Ideal 420 pC	Ideal 420 pC + CSR	Real 420 pC	Ideal 2 nC
Initial Distribution	4.0	4.0	4.0	4.0
Merger Exit	6.01	14.48	5.43	31.92
Linac Exit	5.74	14.18	5.58	47.18
Arc 1 Exit	6.06	14.63	5.60	44.84
Solenoid Entrance	6.04	14.51	5.52	44.89
Arc 2 Exit	6.92	13.19	7.95	44.38
Linac Exit	8.87	15.57	8.11	45.83

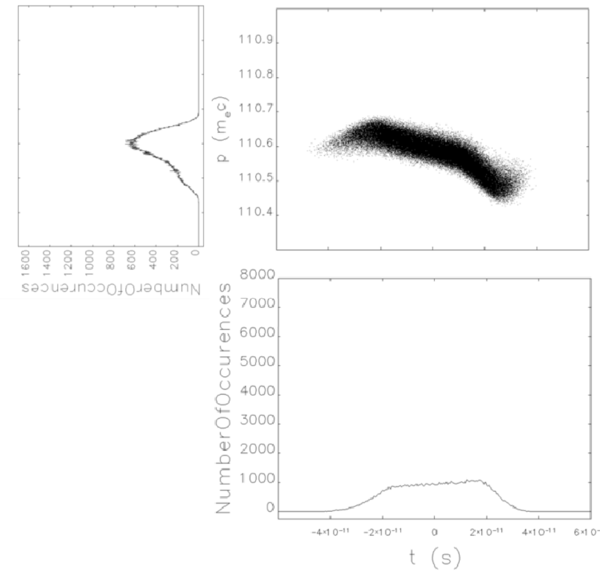
Big challenge: preserving the emittance in the injector merger.

Longitudinal Behavior

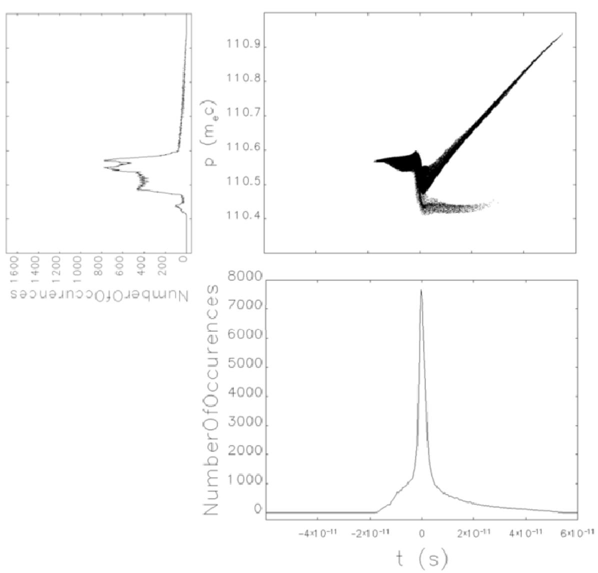
420 pC
ideal



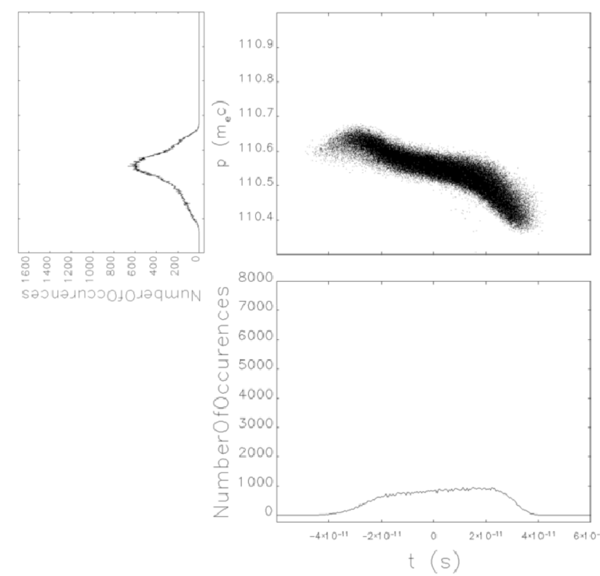
420 pC
ideal
w/CSR



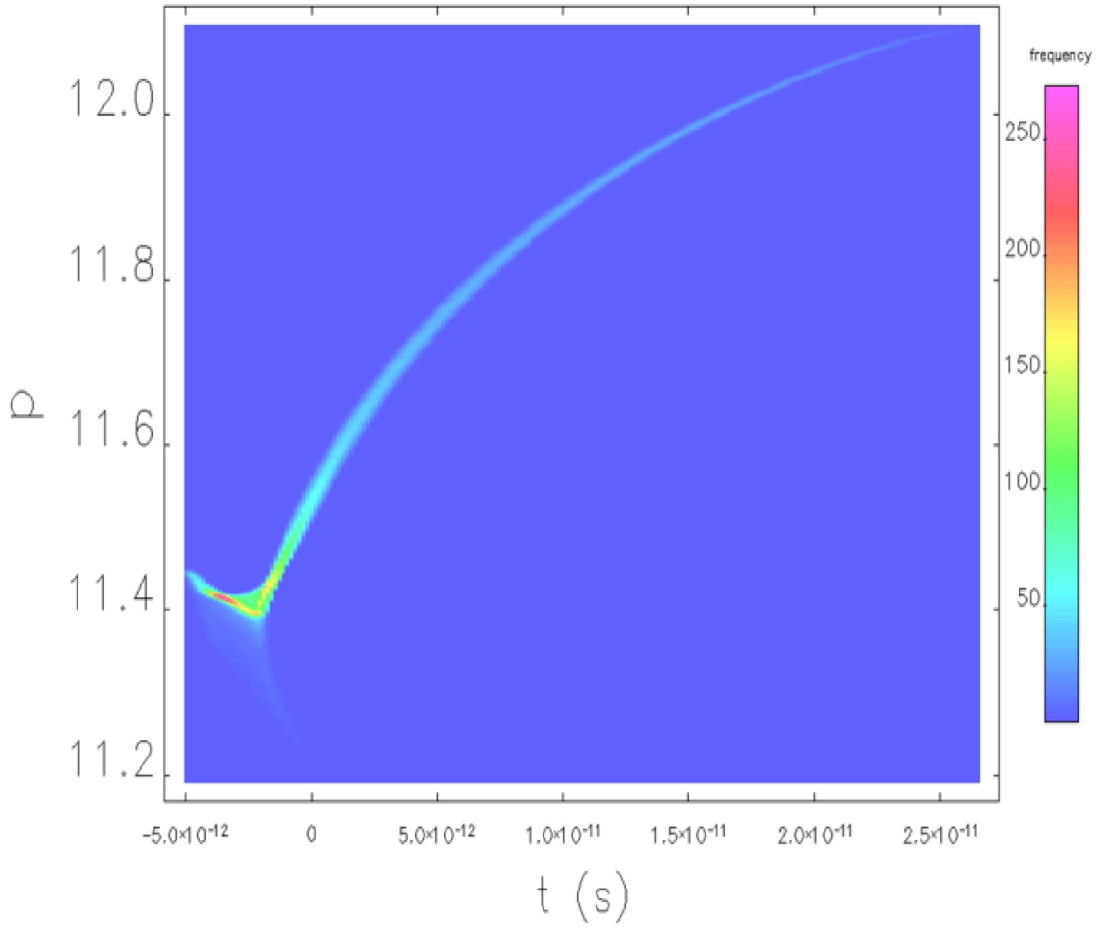
420 pC
S2E



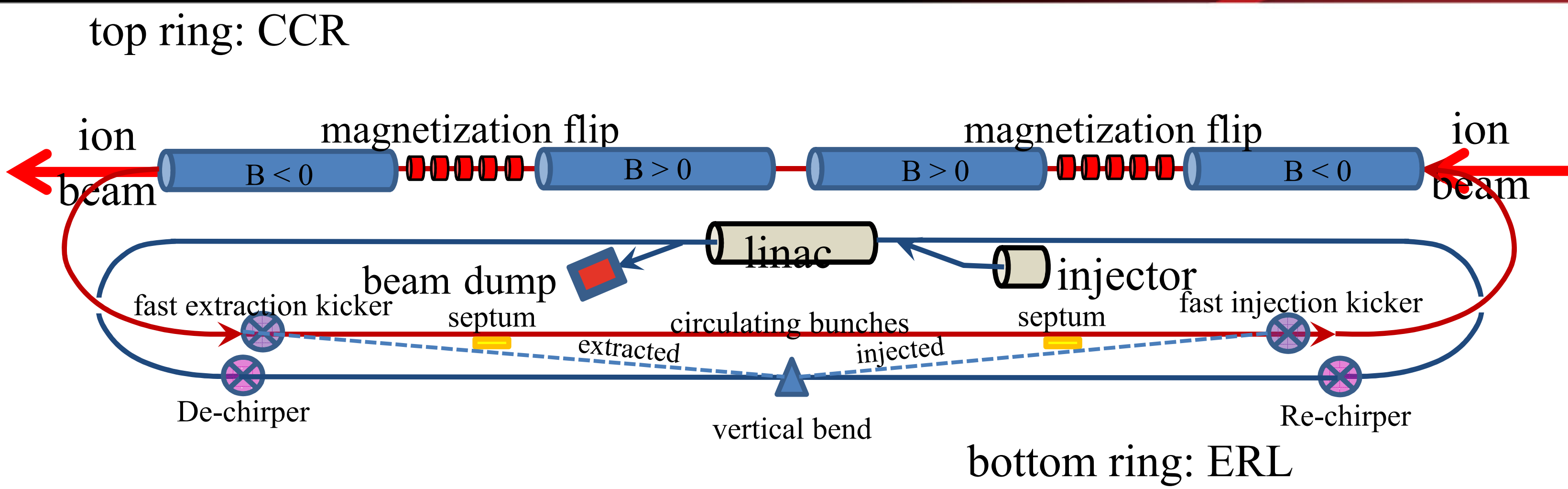
2 nC
ideal



S2E beam after Booster

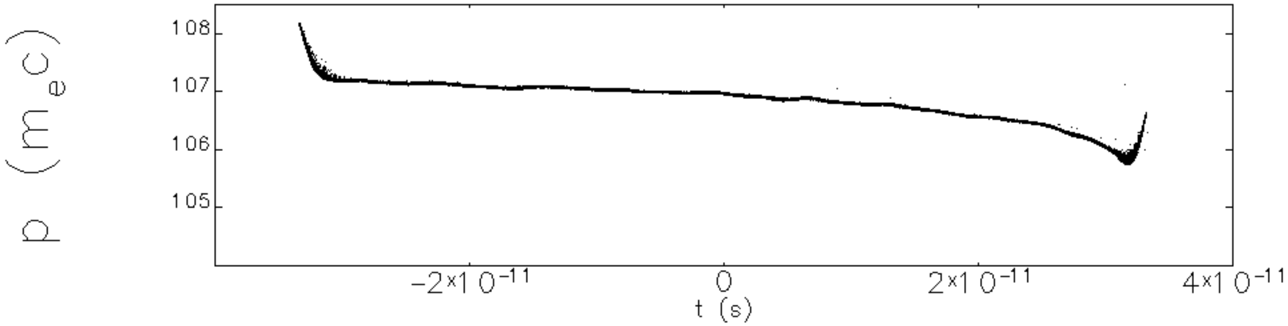


Challenges in the Strong Cooling Design

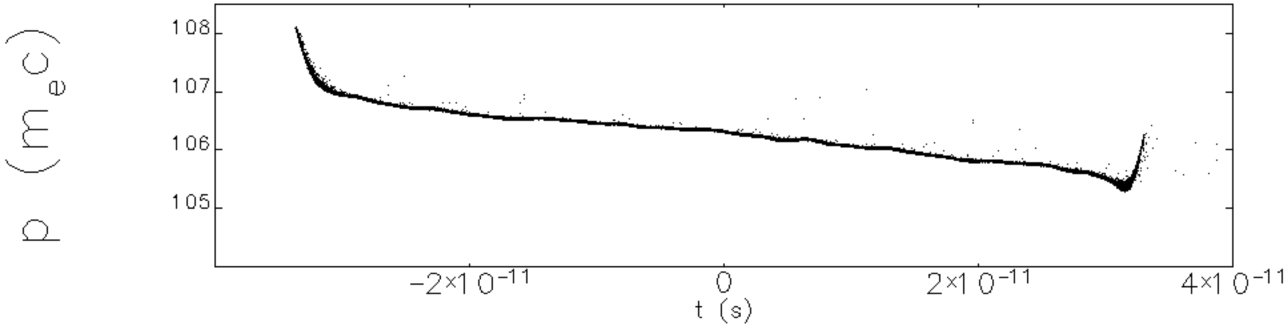


- Increased charge enhances space charge and CSR forces, but long pulse raises the possibility of shielding the CSR.
- Locally symmetric arcs are difficult at 55 MeV (if you want to keep the length modest so as to avoid space charge nastiness...). Globally symmetric arcs can work but must be tested one-by-one.
- Need tools for simulating the system Want CSR, LSC, and shielding.
- Beams are big and halo loss will be a problem.

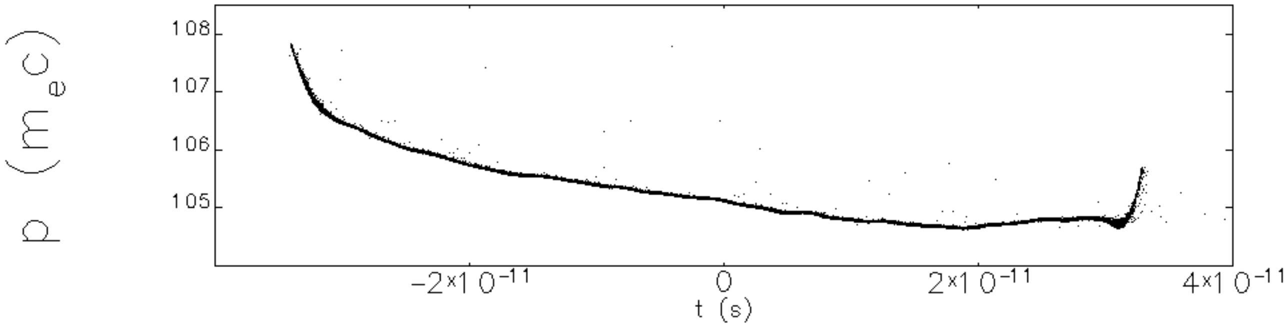
(t,p) Evolution – *Zoomed View*



5-turns



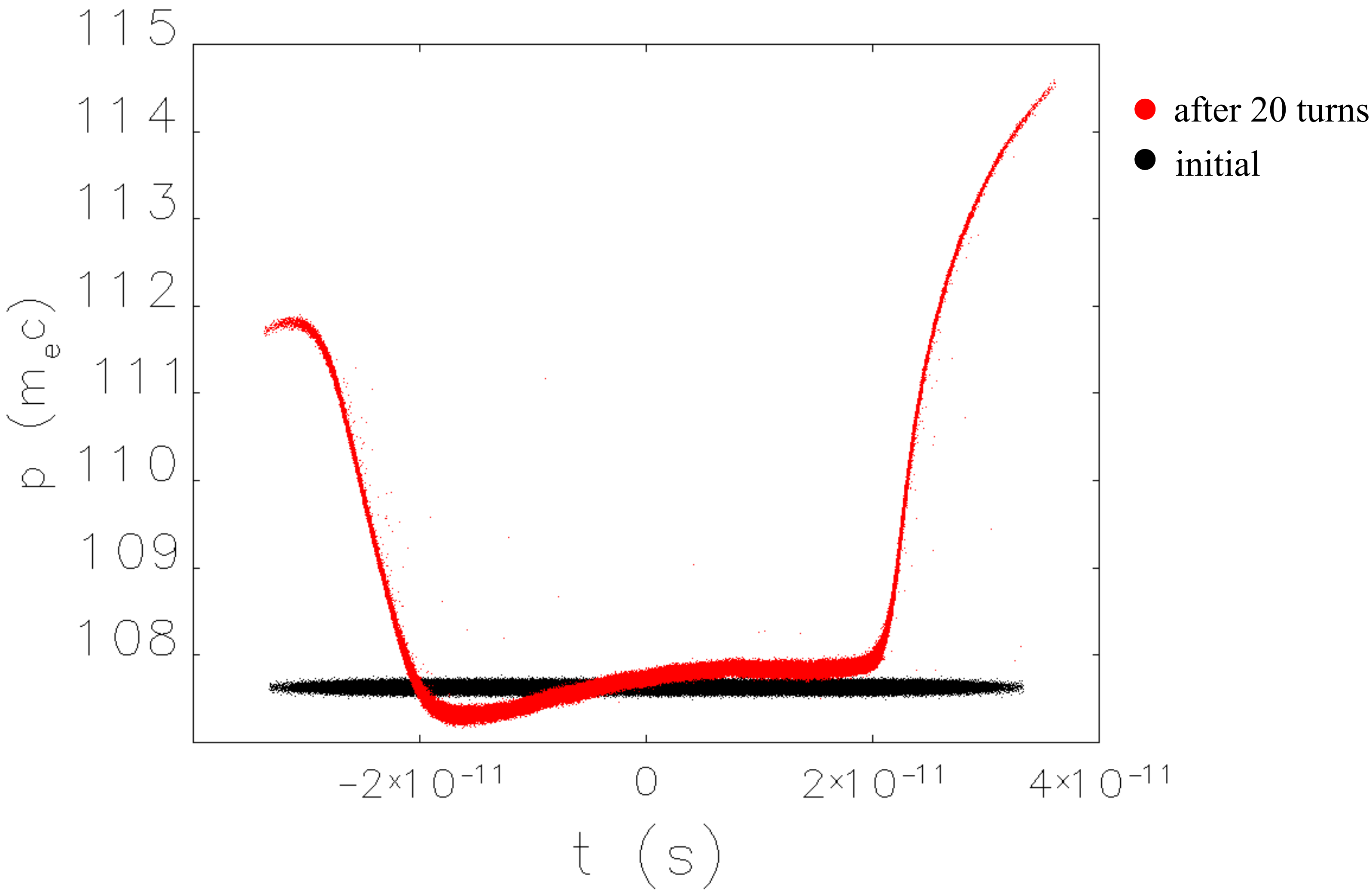
10-turns



20-turns

Initial bunch assumed to be super-Gaussian profile

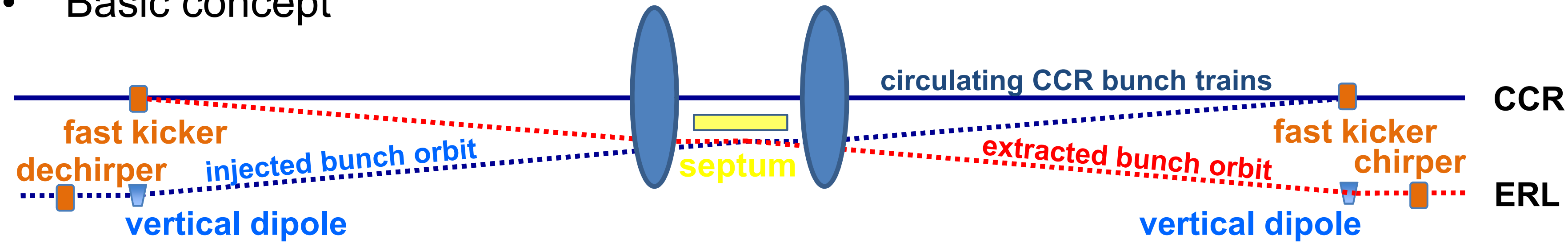
Longitudinal Phase Space: 200 kV



Use RF cavity to remove chirp and reaccelerate the beam.

Exchange Region Layout

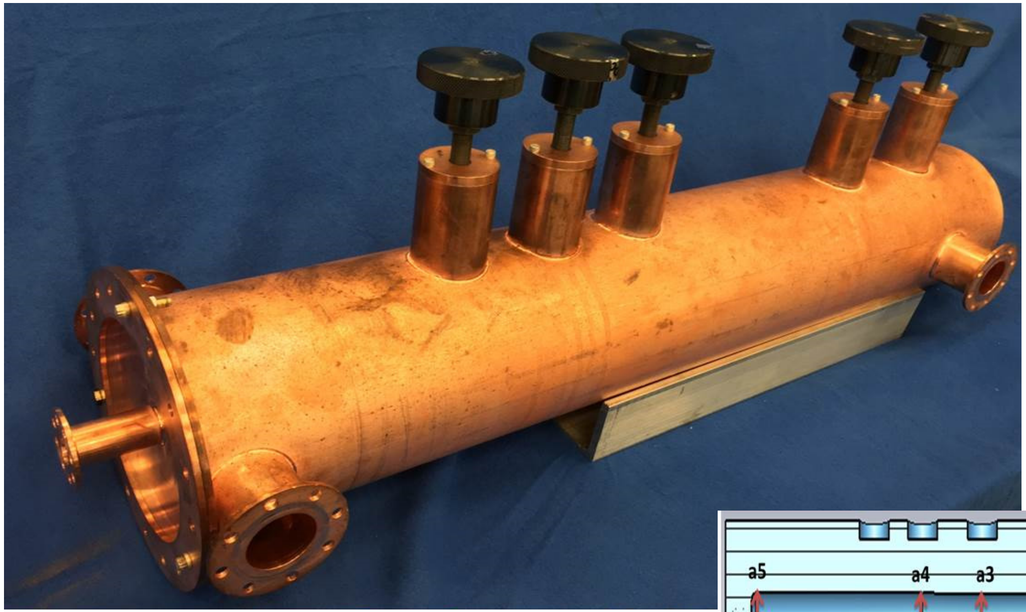
- Basic concept

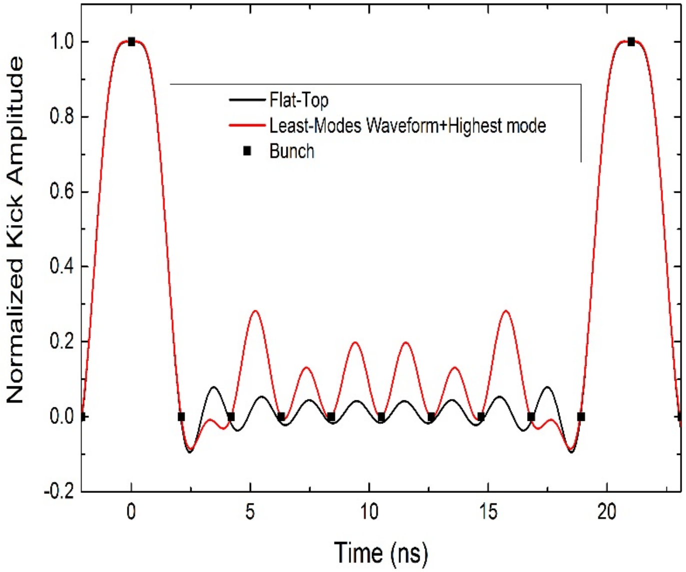


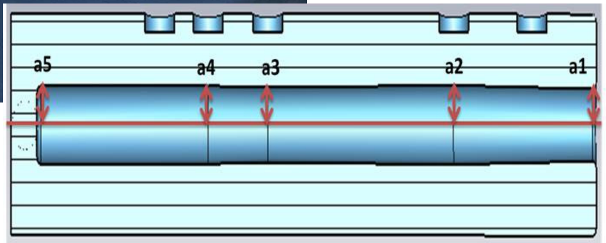
- Additional “details”
  - “pre-kicker” and “post-kicker” in ERL
    - suppress bunch length/kicker nonlinearity – driven distortion
  - dispersion management in vertical translation
  - focusing pattern/optics constraints amongst various kickers
  - betatron matching
    - various beams (injected, extracted, recirculated) must match to one another when split and merged
    - all beams must match to acceptance of ERL, CCR when at start/end of exchanges
  - length/height scales
    - clearance between CCR recirculation/exchange focusing and dispersion management focusing

Harmonic Kicker

- Harmonic Beam Kicker. A first 952.6 MHz copper cavity has been prototyped, bench measured, and satisfies beam dynamic requirements for a Circular Cooler Ring design for the bunched electron cooler.

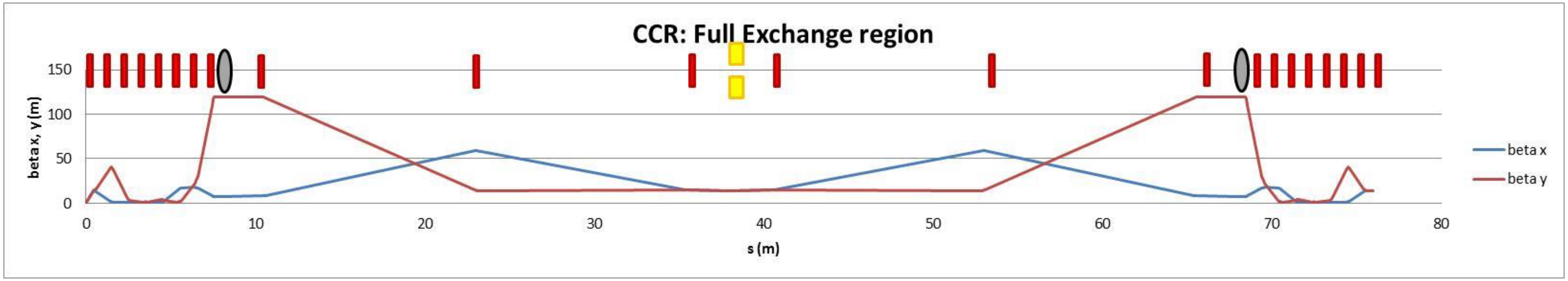




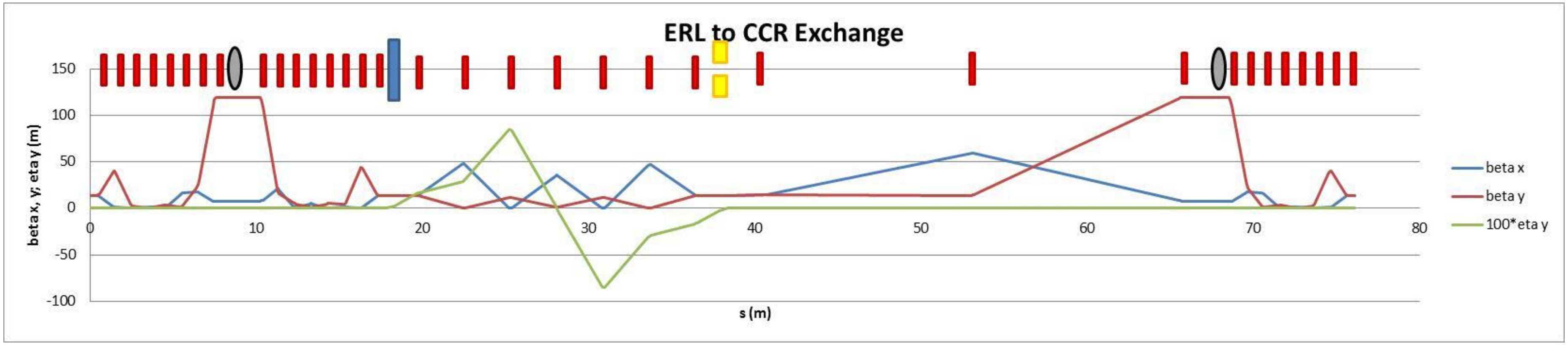


Twiss Parameterization

- CCR back leg

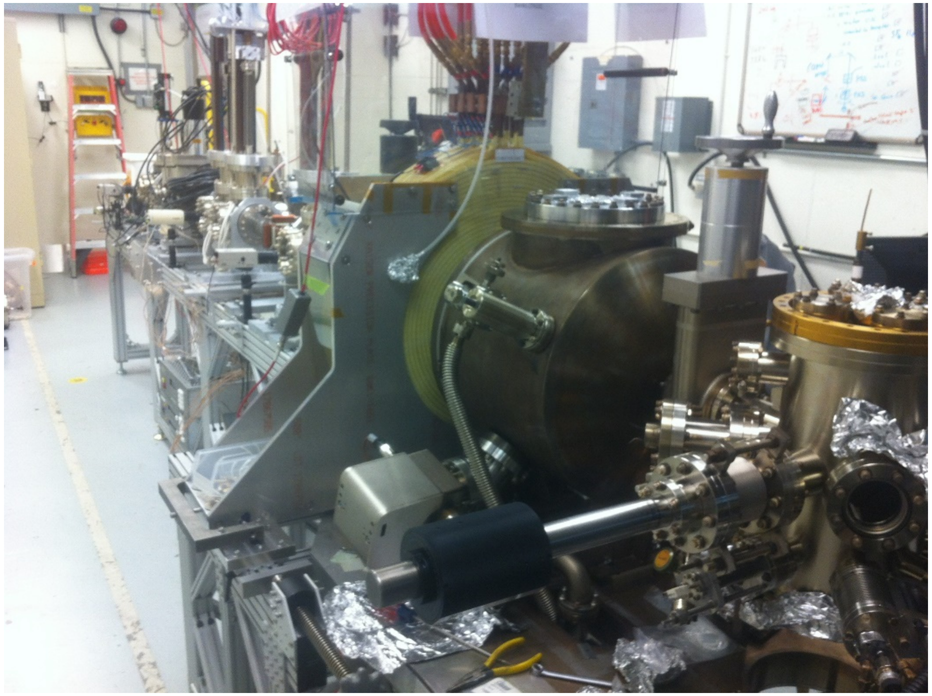


- ERL to CCR



Hardware Development

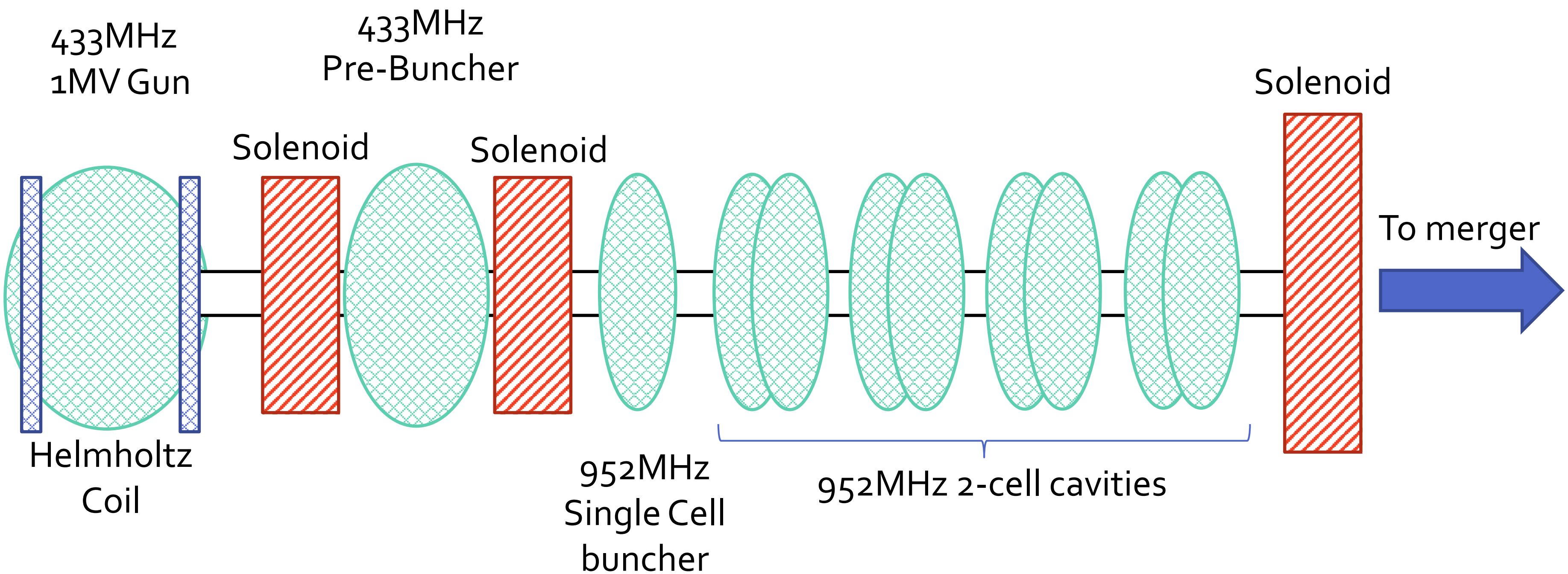
- Magnetized Source for e-cooler at 32 mA: A high charge (420 pC) magnetized source is funded by the Jefferson Lab LDRD program that should operate up to 32 mA average current. This project concludes in 2018.



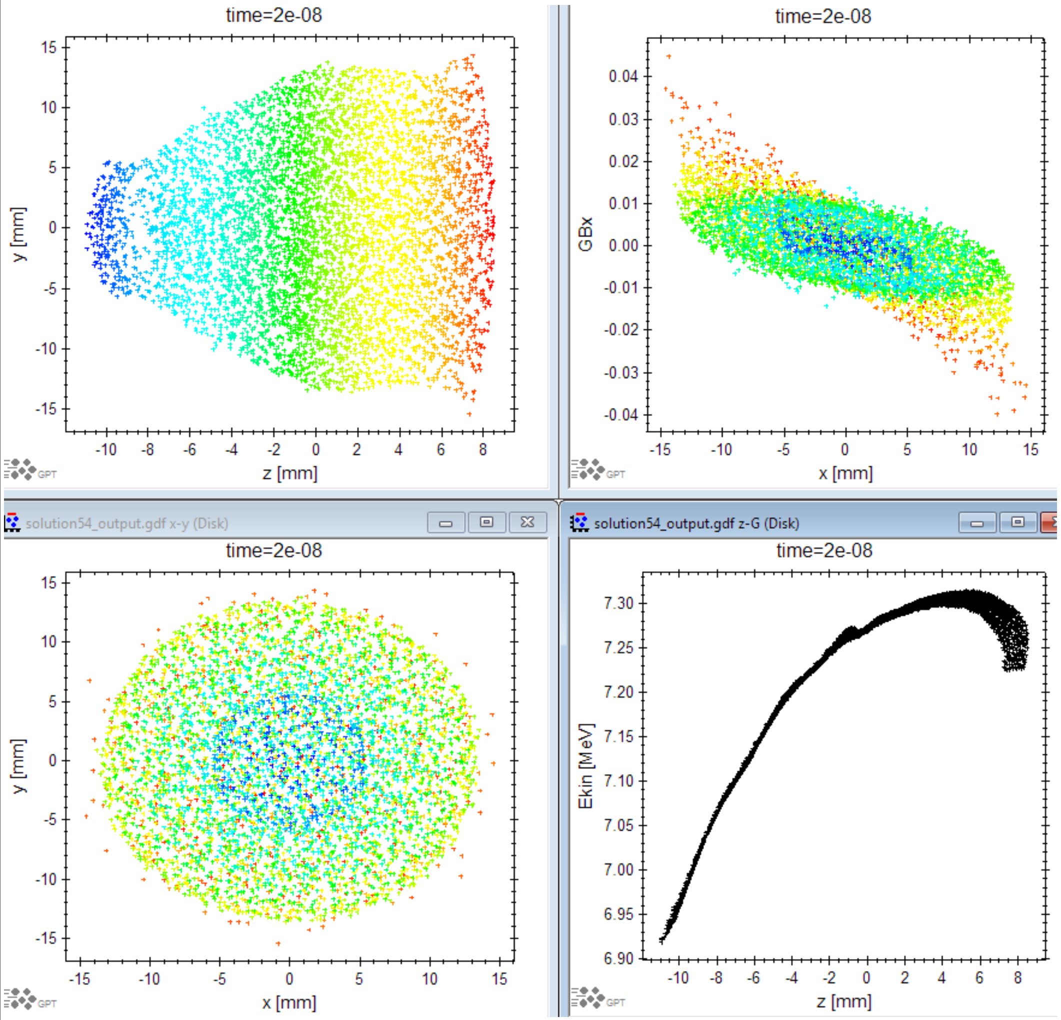
Magnetized beam parameters:

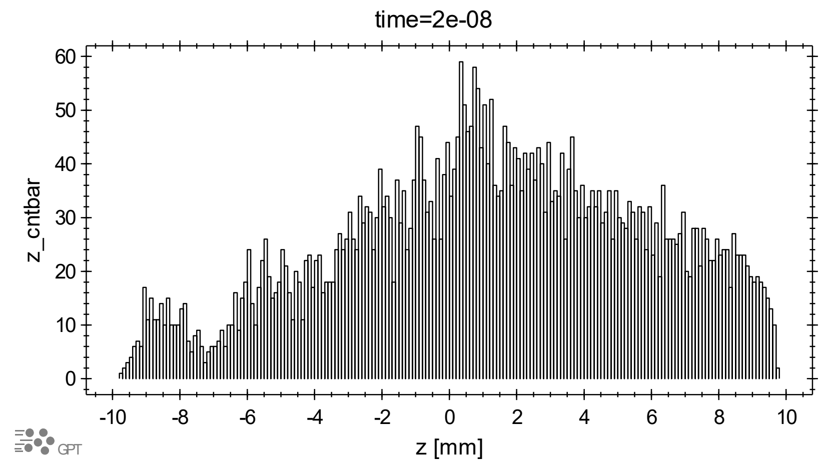
- a_0 = 1 – 5 mm, B_z = 0 – 2 kG
- Bunch charge: 1 – 500 pC
- Frequency: 15 Hz – 476.3 MHz
- Bunch length: 10 – 100 ps
- Average beam currents up to 32 mA
- Gun high voltage: 200 – 350 kV

Injector Design



Start to Merge





Ez = 648keV ps
Dp/p = 0.01
<Ek> = 7.2MeV
Chirp = -1.19 ps-1
s_z = 4.53mm, s_t = 14.4ps

Summary: Where are We?

- ERL Design is mostly done. Need further injector optimization.
- CCR beam exchange region is designed and looks reasonable.
- Injector design is good for each slice (magnetization is preserved up to end of booster).
- CCR core beam meets specifications (tails might be a problem)
- Microbunching gain is low.

Summary: Where Do We Go from Here?

- Have to partition the cooling to match IBS.
- Need to simulate CCR with CSR shielding
- Need to add space charge to CCR simulations (bunch tails are an issue)
- Continue injector optimization (lower frequency)
- Calculate the usual suspects:
  - Ion trapping
  - HOM damping in linac.
  - BBU
  - Wakes
- Experimental tests (e.g. collimation)

Test Facility for ERL-Circulator Cooler

- Demonstrate the ERL-Circulator cooler design concept
- Develop/test key technologies (magnetized gun, fast kickers, etc.)
- Study dynamics of the cooling bunches in a circulator ring
- Using the existing ERL with only minor upgrade, adding a new ring