ERL Cooling Ring Concepts for the MEIC

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Outline

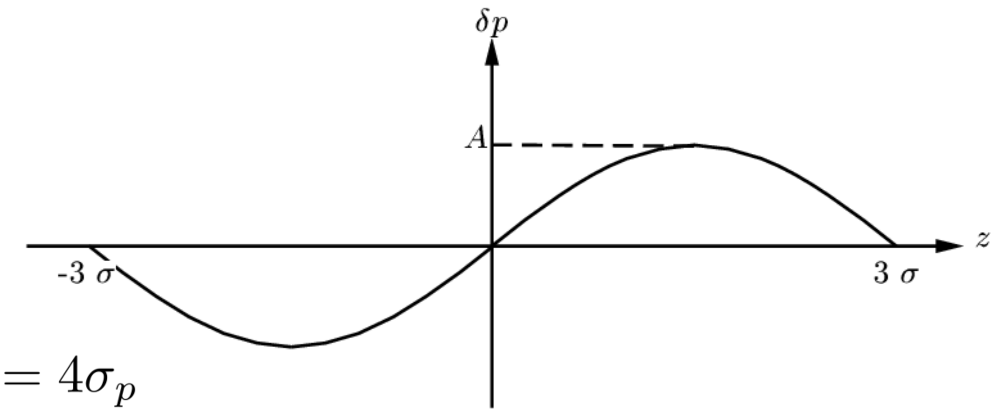
- Cooler specifications
- Statement of the problem
- Can we bend the beam?
- Can we not bend the beam?
- Where do we go from here?

Cooler Specifications

• Energy	20-55 MeV
• Charge	420 pC
• Repetition rate	476 MHz
• *rms* Bunch length	70 psec
• *rms* emittance	30 mm-mrad
• *rms* Energy spread (uncorr.)*	$3x10^{-4}$
• Energy spread (p-p corr.)*	$<2x10^{-3}$
• Solenoid field	2 T
• Solenoid length	30 m
• Injector	Magnetized!!

Model of the Correlated Electron Beam

$$\delta p = A \sin\left(\frac{z}{3\sigma} \cdot \pi\right)$$



δ_p is the drift momentum.
At the entrance of the cooler: $A = 4\sigma_p$
At the end of the cooler: $A = 8\sigma_p$
Assume A increases linearly inside the cooler.

An ion only sees the electrons around itself.

In the co-moving frame, the electrons get a drift velocity.

In the local electron beam frame, the ion get a drift velocity. $V{\downarrow}\|$ is replaced as $V{\downarrow}\| - v{\downarrow}d$, with $v{\downarrow}d$ the drift velocity.

Cooling Rate vs. Momentum Spread

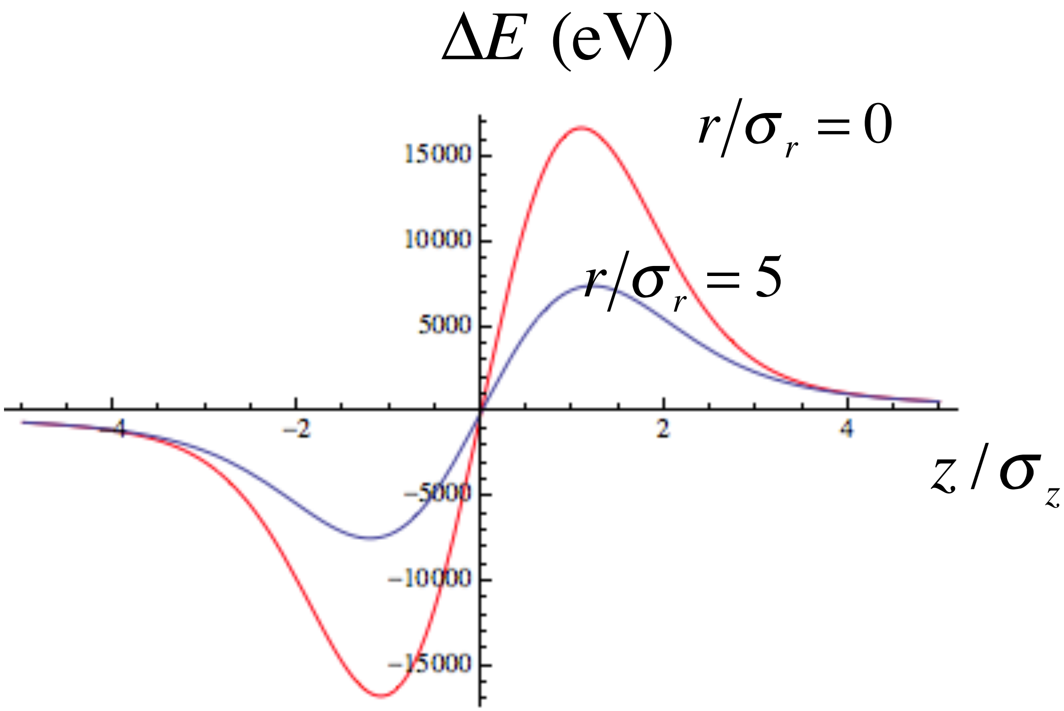
- Monte Carlo model.
- Enough samples to make sure the result is stable till the third effective digit .

δ_p		Uncorrelated			Correlated		
-4	eV		R_y	R_z	$R_x(\times10^{-3})$	$R_y(\times10^{-3})$	$R_z(\times10^{-2})$
1	0.0051	1.59	1.59	1.66	1.53	1.53	1.22
2	0.0204	1.54	1.54	1.50	1.33	1.33	0.66
3	0.0460	1.48	1.48	1.34	1.14	1.14	0.39
4	0.0818	1.41	1.41	1.19	0.99	0.99	0.25
5	0.1278	1.34	1.34	1.06	0.87	0.87	0.17

Cooling rate is severely reduced, especially in the longitudinal direction.

LSC-induced Energy Change Accumulated in the Linac (8m) and the Following Matching Section (4m)

parameters	
$E_e = 5 \sim 55$ MeV	$\gamma = 10 \sim 107$
$Q_b = 420$ pC	$N_e = 2.6\times 10^9$
$\sigma_p = 10^{-4}$	$\Delta E_e = 5.5$ keV
$\sigma_z = 1.5$ mm, $\sigma_r = 1$ mm	$w = 4\times 10^{-3}$ (E=5MeV)
Drift Length	$L = 8+4$ m



Here is an under-estimated result:

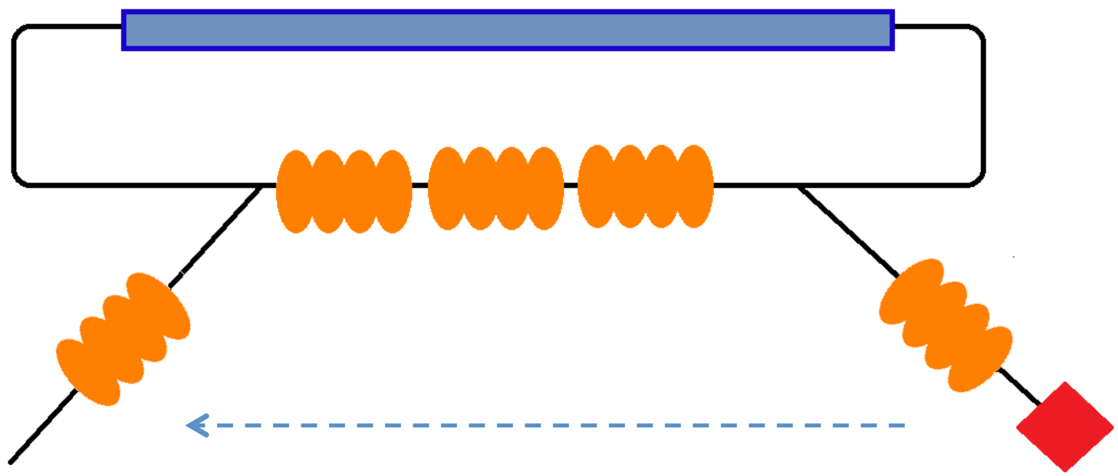
$$\text{Relative energy change} = \frac{15\ \text{keV}}{55\ \text{MeV}} = 2.7\times 10^{-4}$$

So What is So Hard about This?

- Have to run very high current
  - Must have energy recovery or cost is too high
  - Also need SRF cavities but this means no magnetic fields in the cavities.
- The current varies with position in the micro-bunch so space charge forces vary and cannot be perfectly compensated.
- Any realistic design must bend the beam with discreet magnet elements.
- No micro-pulsed high current source has been demonstrated
- Bunch is very long in the cooler solenoid.

Architecture: Traditional ERL

- Same-cell energy recovery
- Bends
- Possible R2F/F2R with space charge
- Dump energy



Can We Bend the Beam?

Optical principles of beam transport for relativistic electron cooling

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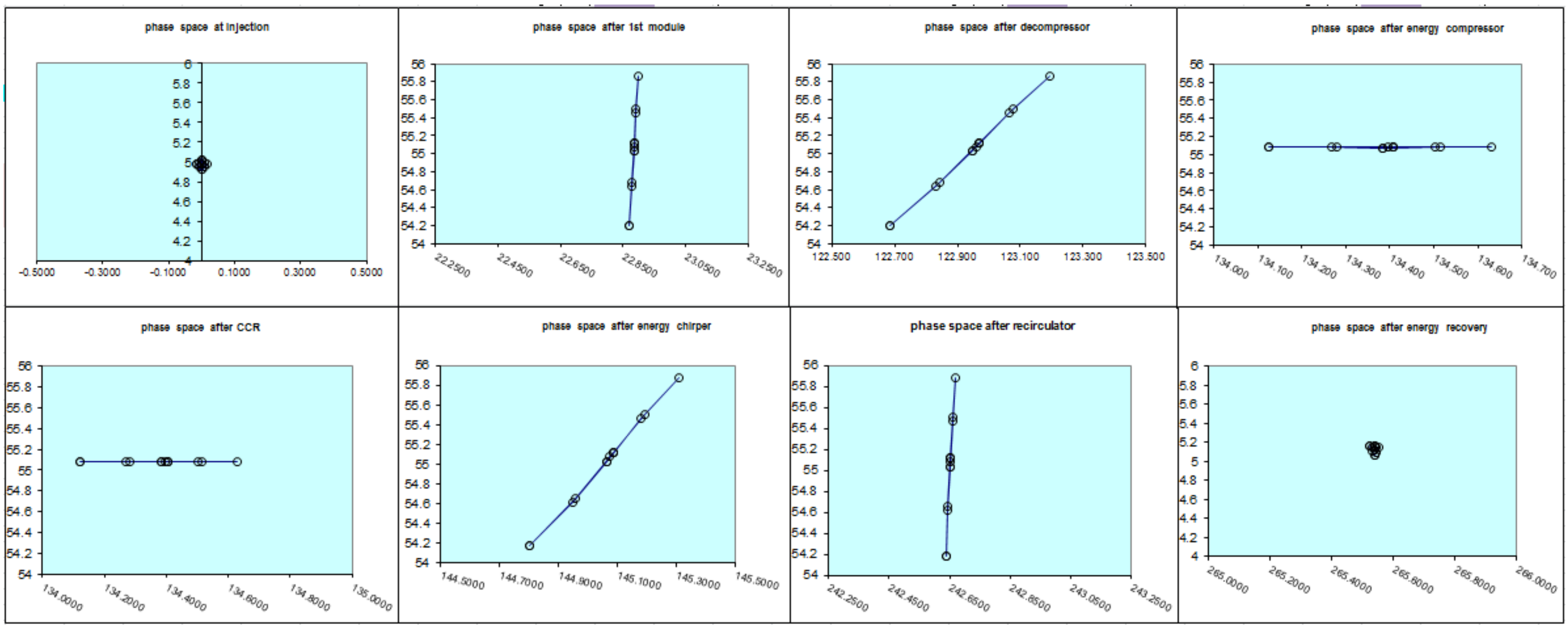
In conventional low energy electron coolers, the electron beam is immersed in a continuous solenoid, which provides a calm and tightly focused beam in a cooling section. While suitable for low energies, the continuity of the accompanying magnetic field is hardly realizable at relativistic energies. We consider the possibility of using an extended solenoid in the gun and the cooling section only, applying lumped focusing for the rest of the electron transport line.

We can transport beams and keep them "calm" if we use solenoids to focus and n=1/2 dipoles to bend the beam. This is all for a DC beam. What about for a pulsed beam?

Longitudinal Match

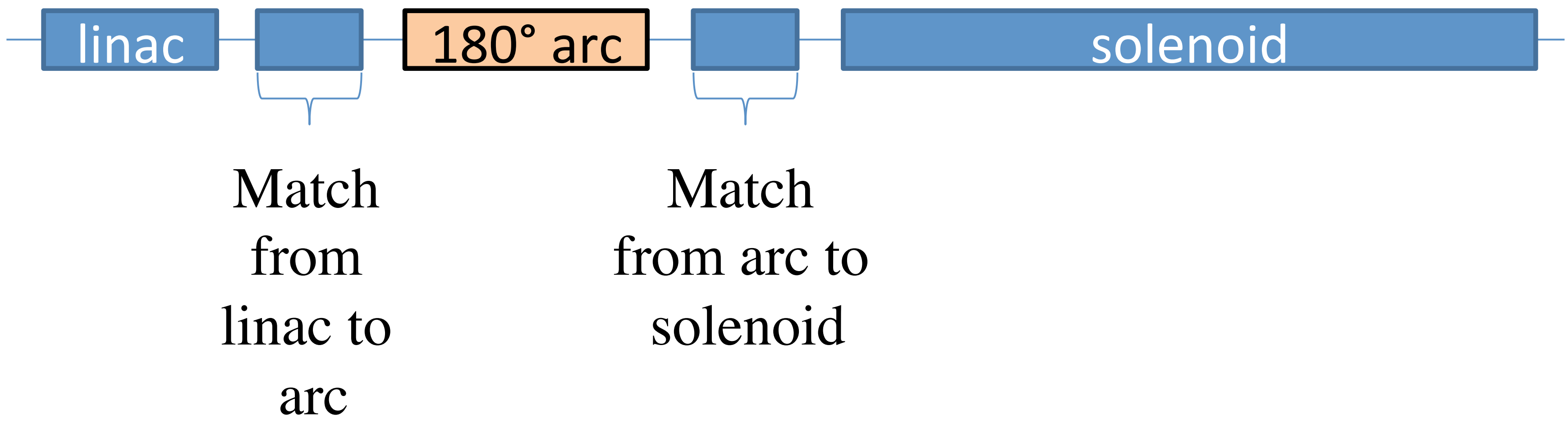
- Accelerate off-crest, decompress, energy compress → cooling channel



(courtesy D. Douglas)

Lattice for Study

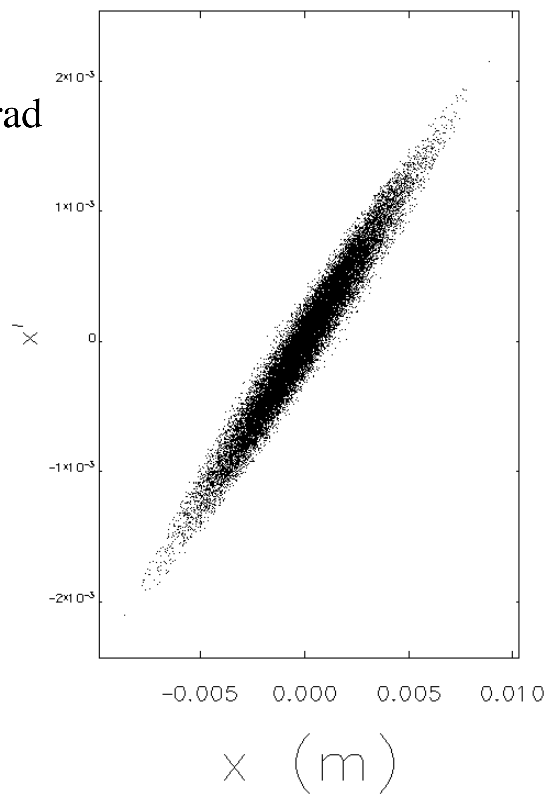
- Schematic of modules for the **round beam**

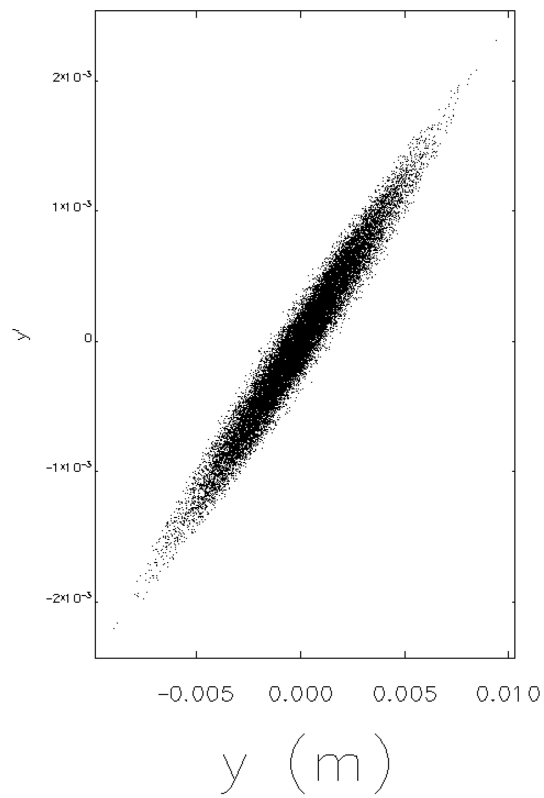


Linac Exit: Round Beam

- Modeled in TStep with space charge effects (420 pC)
  - Acceleration 20° *before* crest
- Input transverse match: $b_{x=y}$ = 6.0 m, $a_{x=y}$ = -2.0

b_x = 17.57 m
a_x = -4.33
e_x = 30.3 mm-mrad

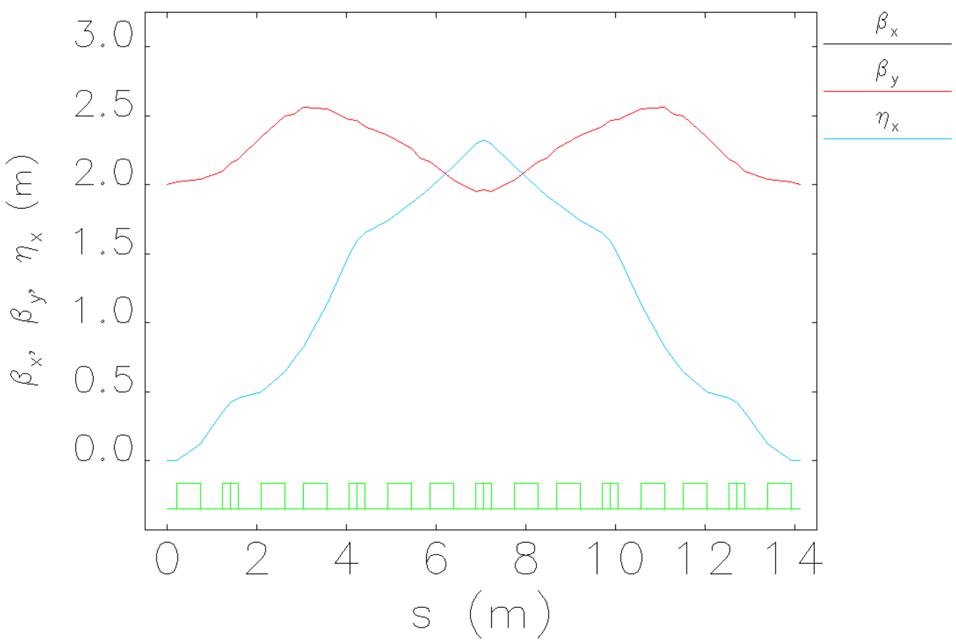


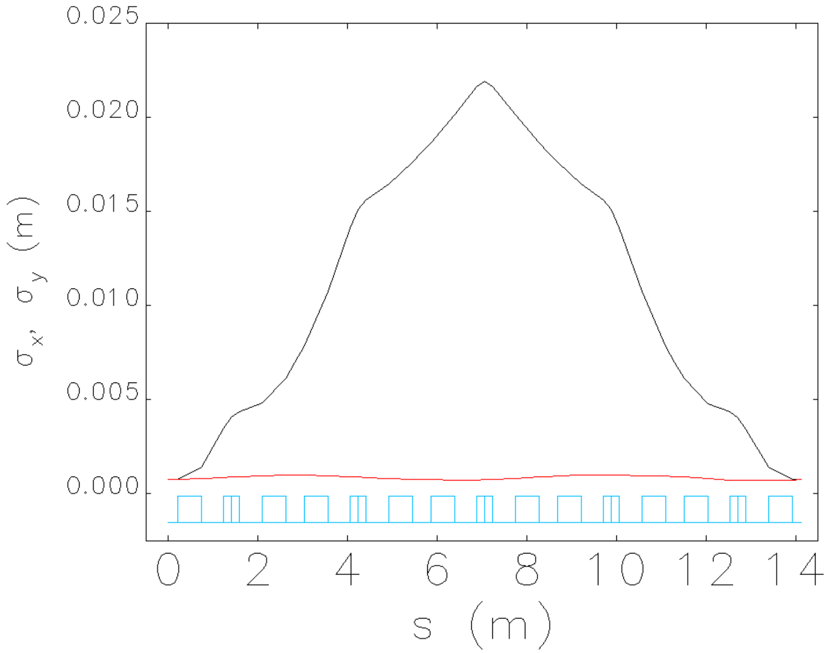


b_x = 17.60 m
a_x = -4.34
e_x = 30.3 mm-mrad

Recirculation Arc

- Utilize indexed dipoles to provide azimuthally symmetric focusing
- Three bend achromats with *reversed* center bend to increase the focusing per unit bending
- 5th-integer (tune of 0.2) in both planes

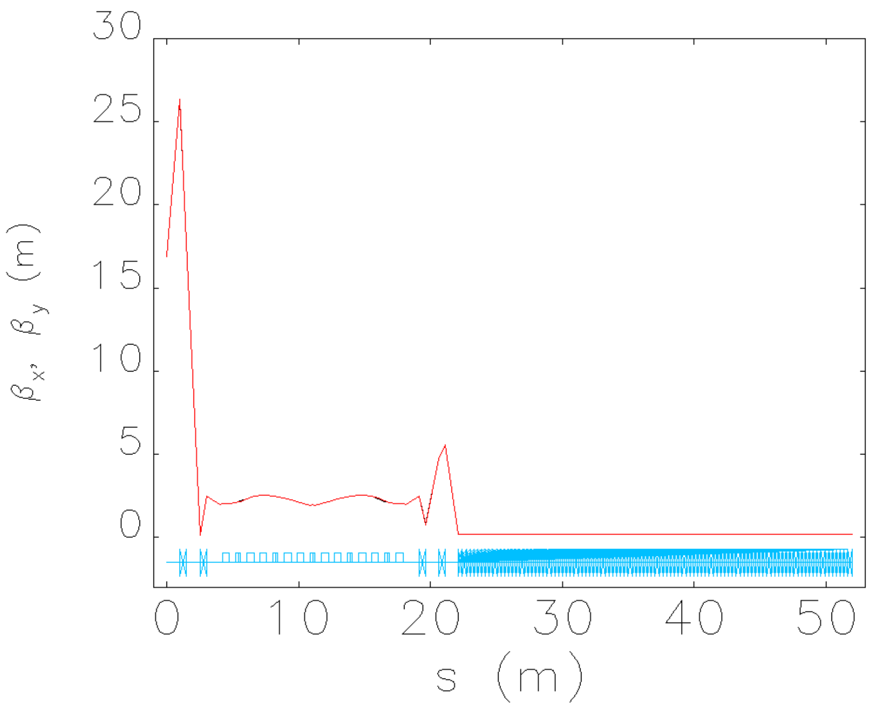


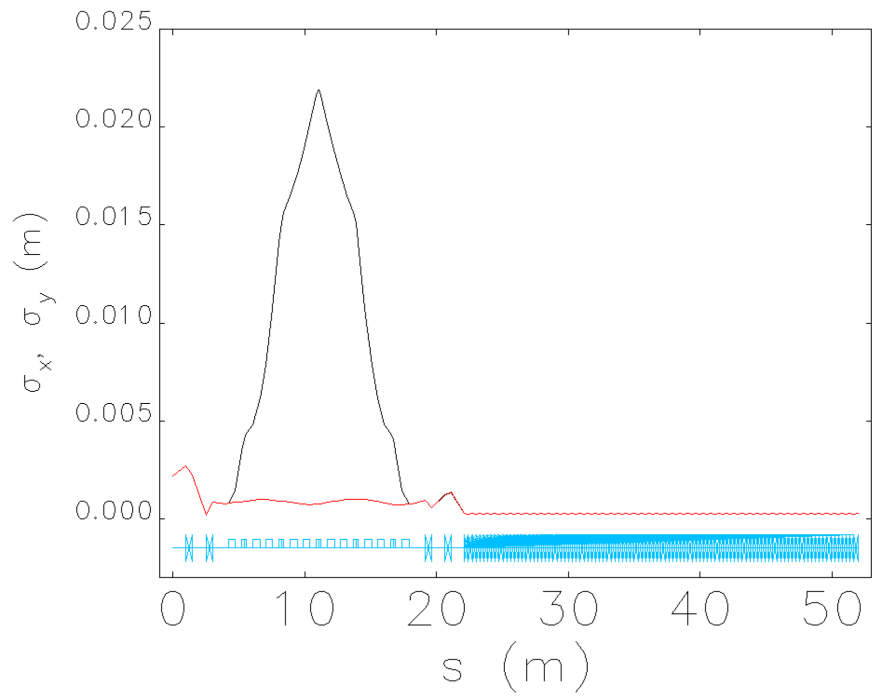


(design by D.Douglas)

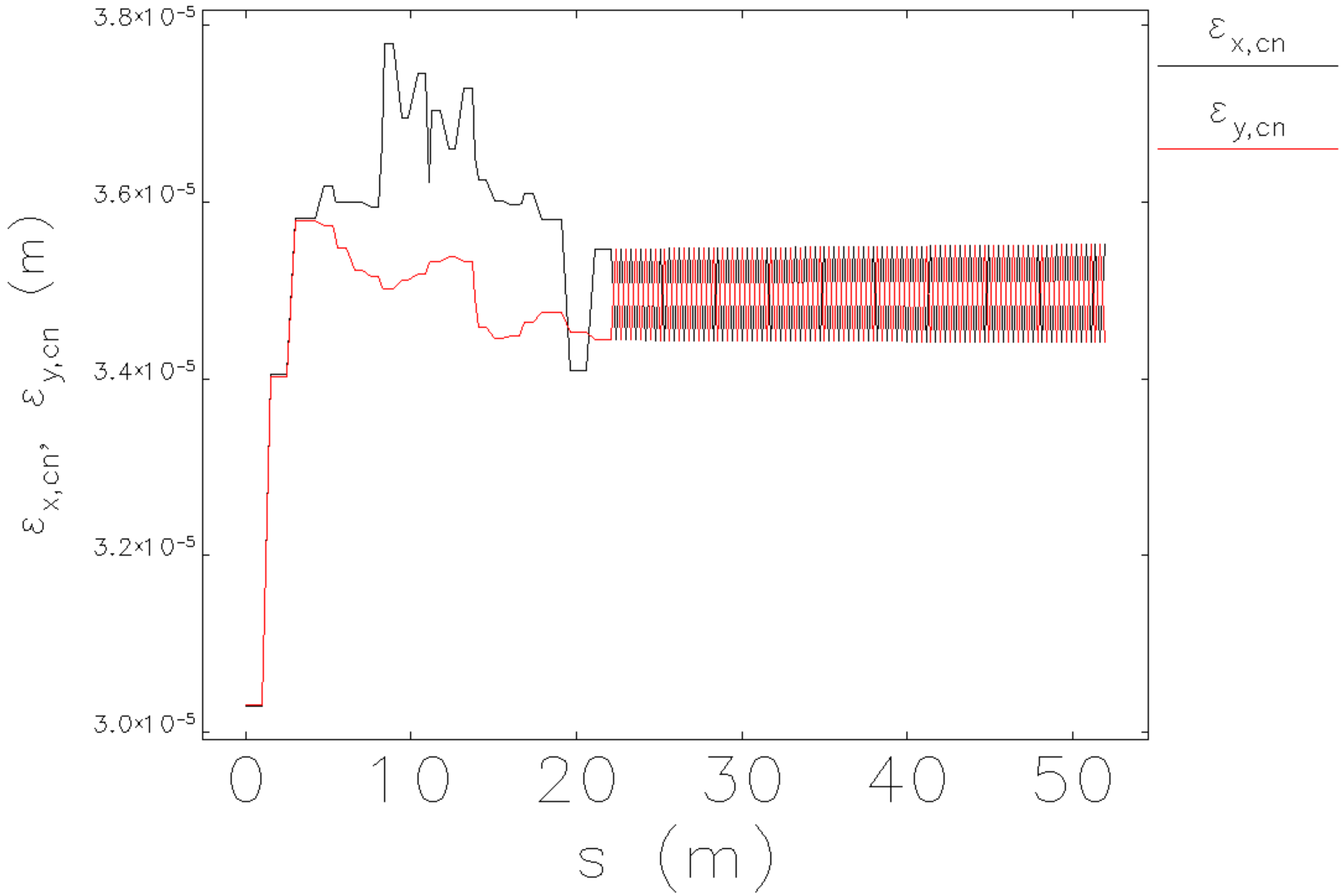
Lattice

- From the exit of the linac to the exit of a 30 m solenoid (B=2T)



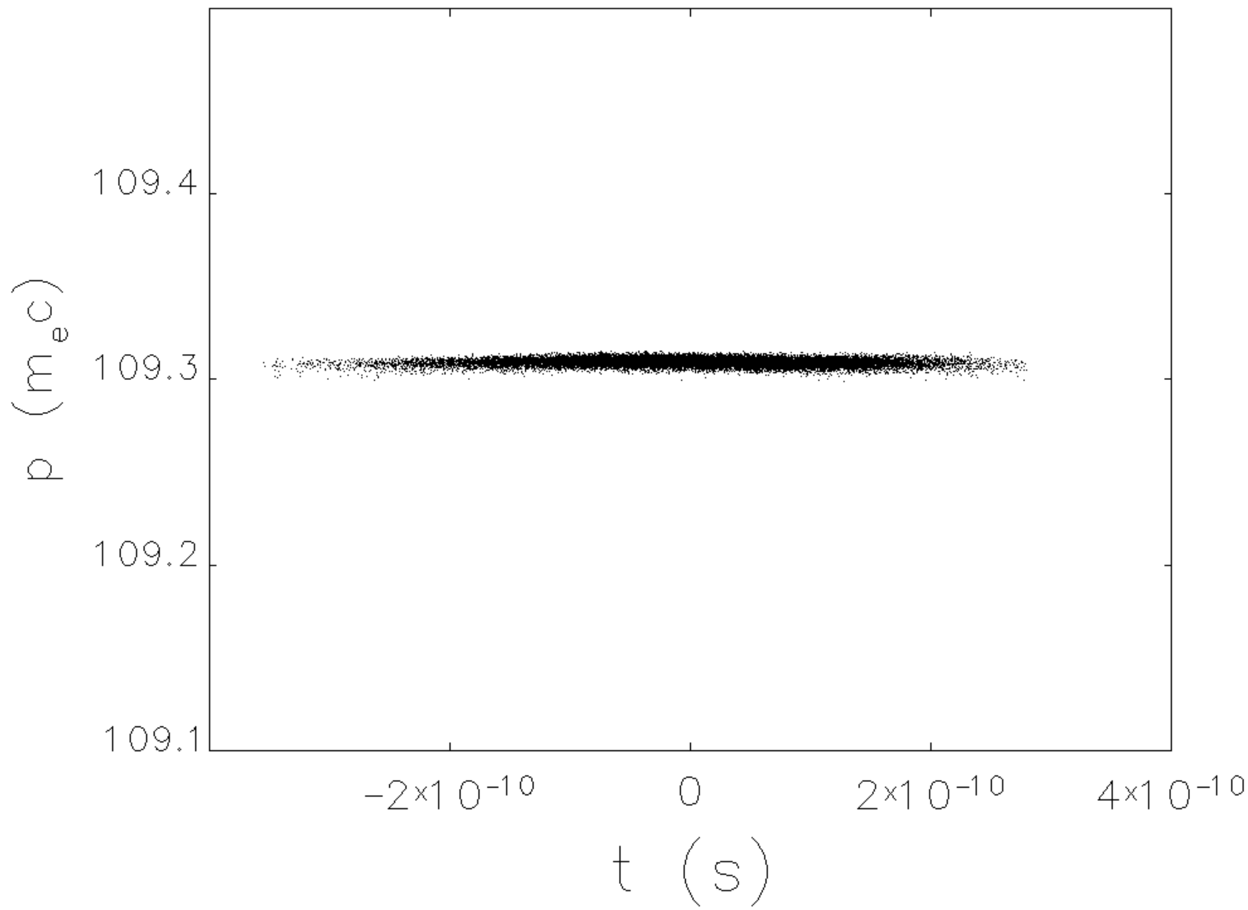


Lattice: Emittance Evolution



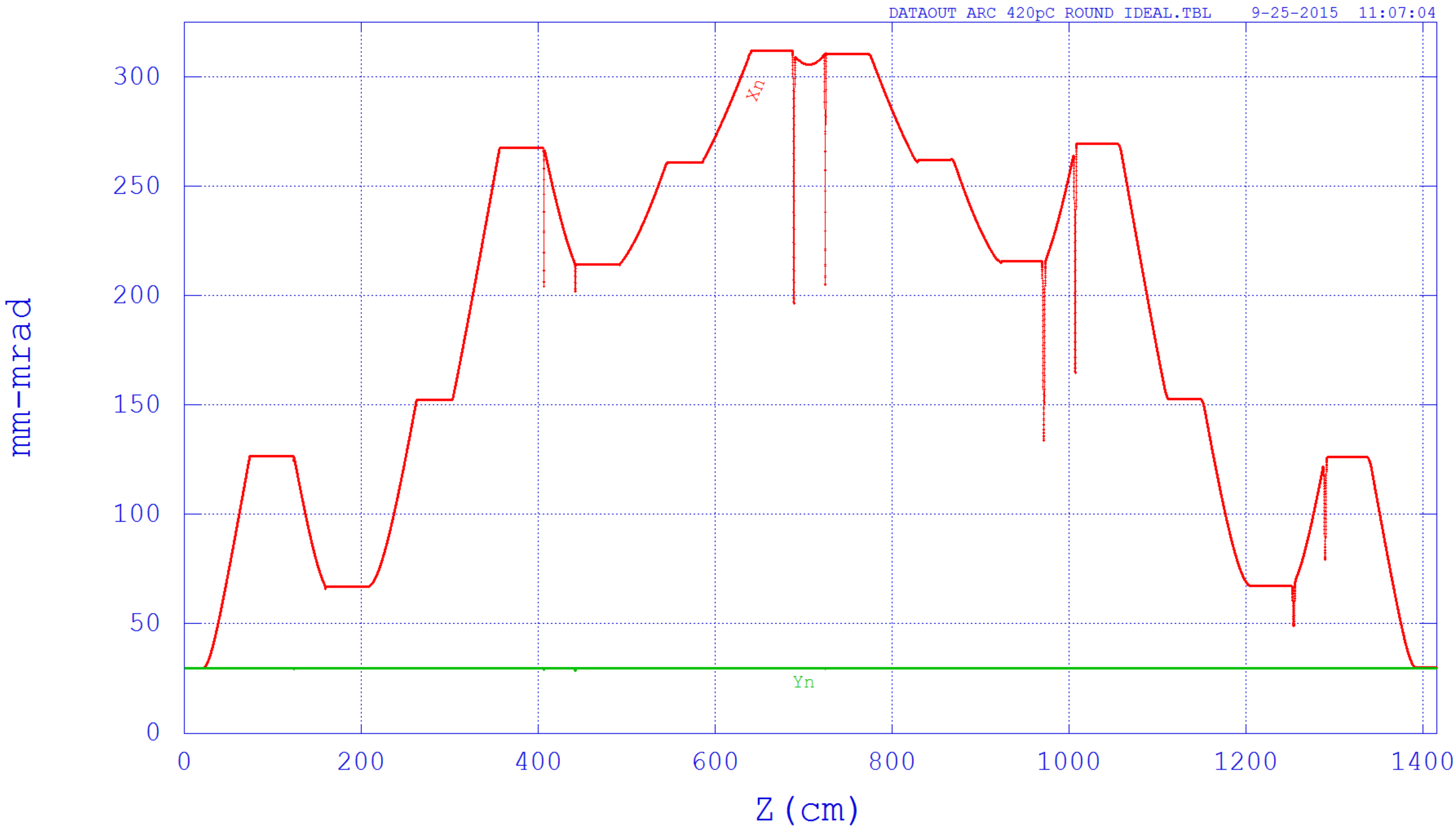
Lattice: (t,p) Phase Space

- Longitudinal phase space at entrance to cooling solenoid
  - Note: energy spread actually order of magnitude *smaller* than spec



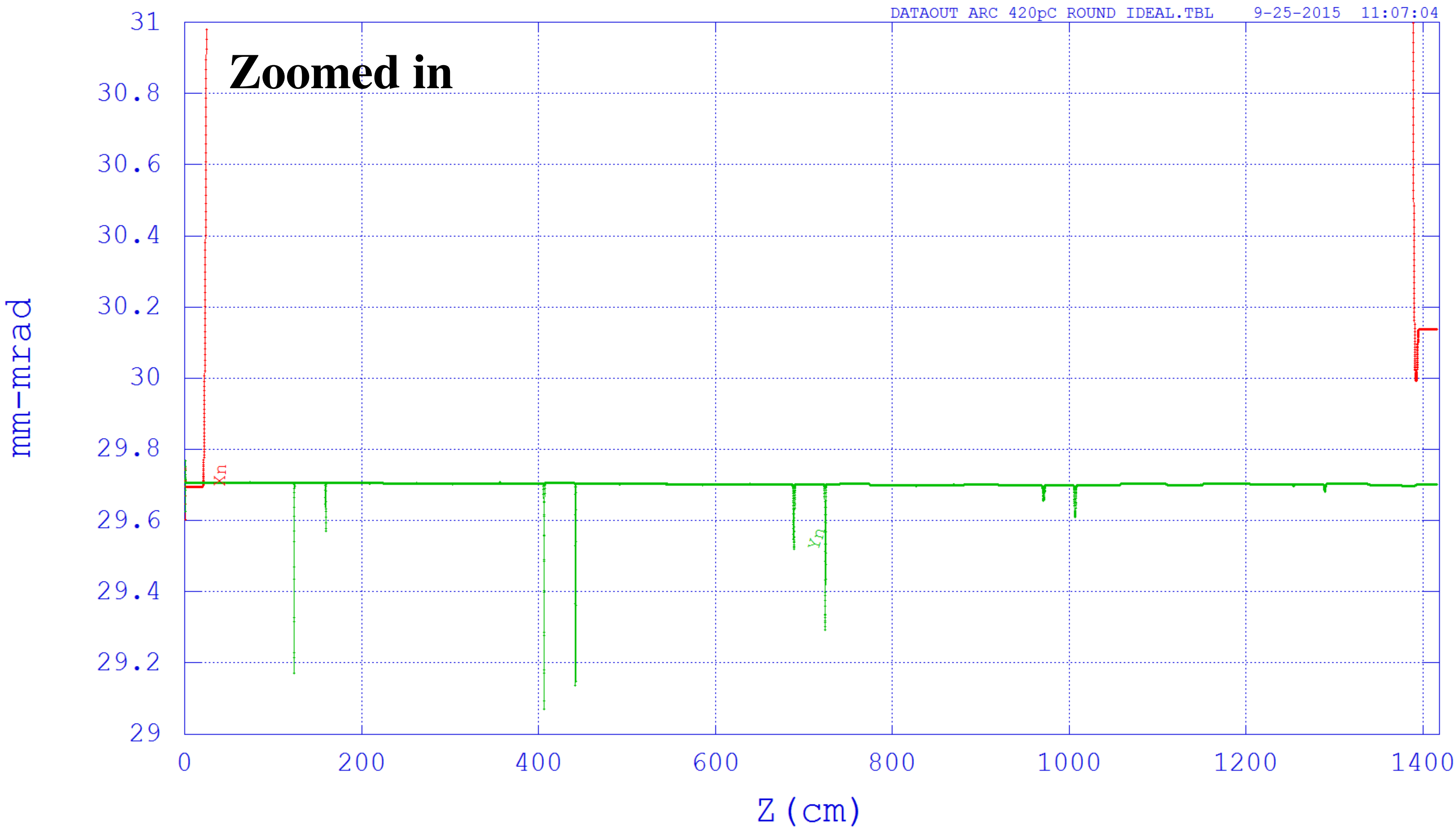
TStep Output

Normalized emittance of an ideal, round beam through a 180 deg. arc with 420 pC (space charge on)



TStep Output

Normalized emittance of an ideal, round beam through a 180 deg. arc with 420 pC (space charge on)

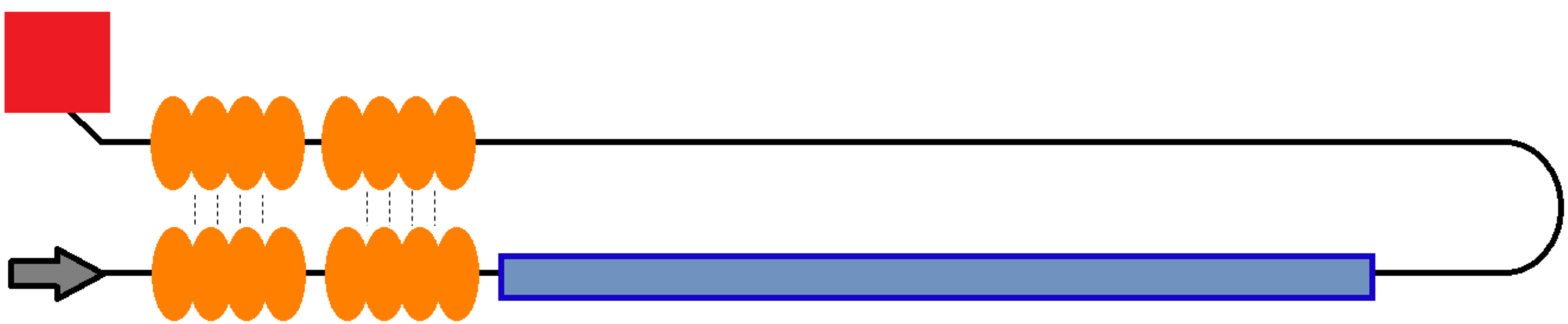


But We Have Cheated

- Elegant simulations have no space charge.
- Tstep Started with ideal distribution.
- The de-chirper was just a mathematical construct rather than a real RF cavity.
- Have not demonstrated cathode to cooler transport

Architecture: Linac to Linac ER

- No merger
- Up and down are linked in the same way as traditional ERL
- Bend happens after the cooling solenoid
- May need bends for bunch stretcher
- Cavity phasing and positioning important



Possible Dual Axis Design

Asymmetric Dual Axis Energy Recovery Linac for Ultra-High Flux sources of coherent X-ray/THz radiation: Investigations Towards its Ultimate Performance

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(Dated: September 15, 2015)

Truly compact and high current, efficient particle accelerators are required for sources of coherent high brightness and intensity THz and X-Ray radiation to be accepted by university or industrial R&D laboratories. The demand for compactness and efficiency can be satisfied by superconducting RF energy recovery linear accelerators (SRF ERL) allowing effectively minimising the footprint and maximising the efficiency of the system. However such set-ups are affected by regenerative beam-break up (BBU) instabilities which limit the beam current and may terminate the beam transport as well as energy recuperation. In this paper we suggest and discuss a SRF ERL with asymmetric configuration of accelerating and decelerating cavities resonantly coupled. In this model of SRF ERL we propose an electron bunch passing through accelerating and decelerating cavities each once and we show that in this case the regenerative BBU instability can be minimised allowing high currents to be achieved. We study the BBU start current and property of in such an asymmetric ERL via analytical and numerical models and discuss the properties of such system.

I. INTRODUCTION

The next generation light sources are to be compact, highly efficient, have high repetition rates and high-brilliance radiation pulses. One of the candidates to satisfy all these requirements are light sources based on energy recovery linac (ERLs) driven by photo-injection sources. Linacs parameters such as: emmitance, repetition rate and bunch charge, in this case are driven by an electron photo-injector which is based on photoemission and laser technologies. Both these technologies have improved dramatically in the last twenty years and such linac drivers capable of generating femtosecond pulses can be routinely bought from specialised companies [1]. To generate a high-power, high brilliance beam either in THz or X-ray ranges, a high charge electron beam is required and new developments are now bringing Ampere class injectors to reality [2]. The increase of the bunch charge will lead to an increase of photon yield and brilliance during x-ray Compton scattering [3] and power generated by THz source [4]. The power ranges of a power supply required to drive 100mA (a typical current in such accelerators) to reach THz and X-ray regions are $0.5 - 1$ MW and $0.1 - 1$ GW respectively and it is clear that even at THz ranges, energy recovery is required to meet the demand for energy efficient systems. However, adding an energy recovery stage, while increasing the beam charge and repetition rate, leads to the appearance of so called beam break-up (BBU) instabilities [5]. These instabilities result in beam trajectory shifts, energy recovery degradation, and ultimately, termination of the beam transportation. The regenerative BBU instability is especially damaging to ERL systems and originates from parasitic excitation of transverse higher order modes (HOMs) inside the cavities. The use of the same cavity [6] or strongly coupled cavities [7] means that the positive feedback between the transverse momentum imparted by the HOM, and hence beam displacement and the HOMs amplitude is readily established. A circulating beam through such a system results in a growth in the beam displacement and dephasing with each bunch.

In this paper we discuss a single turn SRF ERL system [8] i.e. the beam is transported through the accelerating section, interaction point (IP) and deceleration section only once. In this model, the beam is accelerated inside the acceleration section while in the deceleration section most of the beam energy is extracted and guided through a resonantly coupled section back into the acceleration section. In FIG. 1, we show a schematic illustration of a compact source of coherent radiation driven by a single turn SRF ERL. Both sections consist of the same number of cells but adjusted in such way to insure that only the operating mode of both sections are fully overlapping each other creating a single operating mode of the cavity while the rest of the HOM frequencies are separated in the frequency domain.

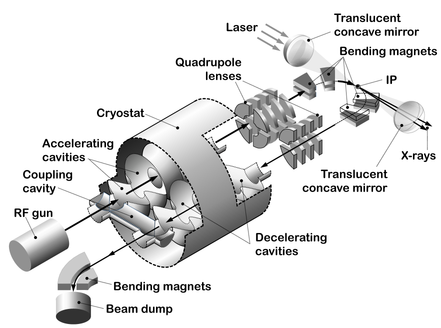
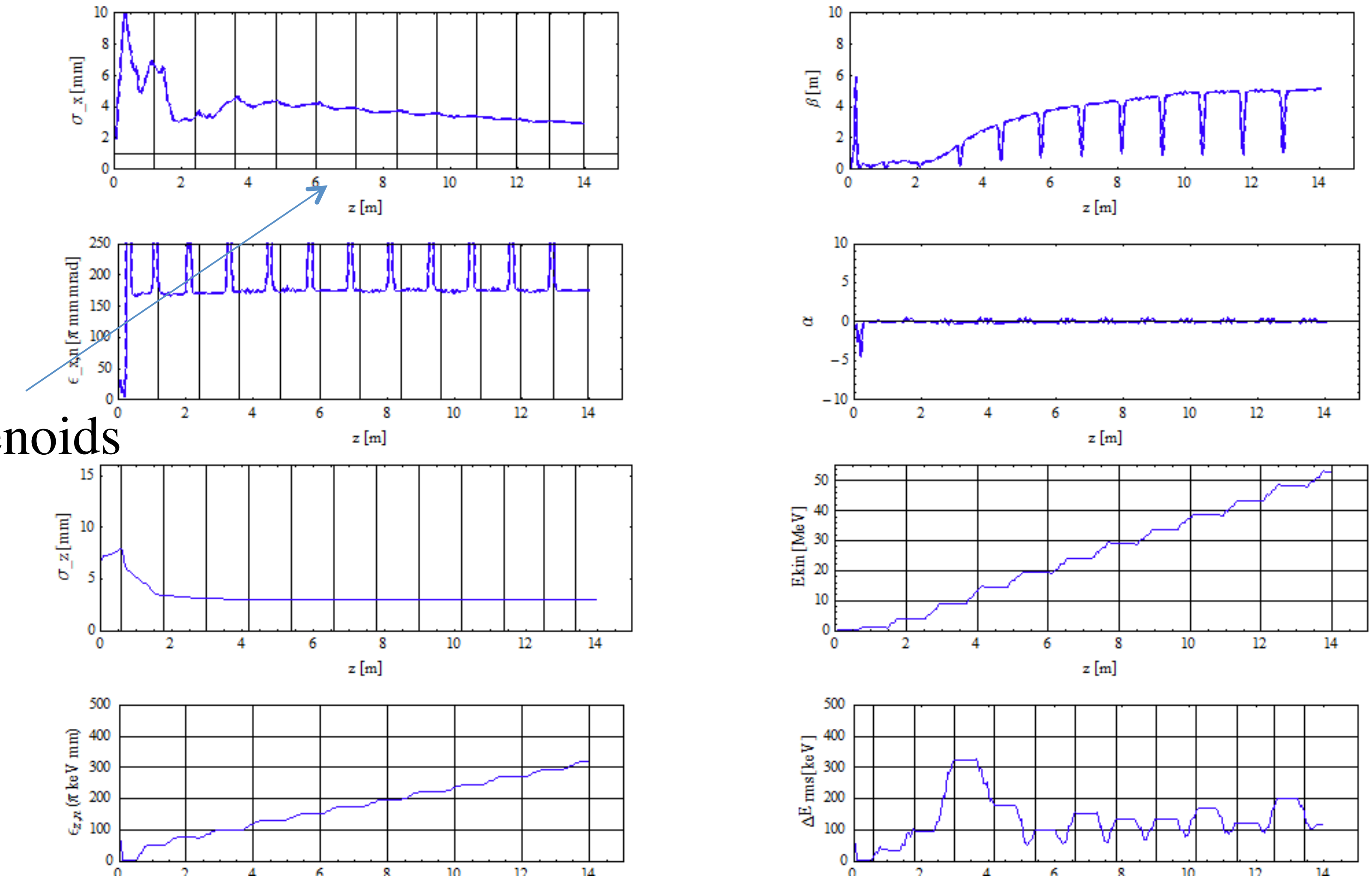


FIG. 1. A schematic of possible single turn ERL system.

Linac to Linac ER



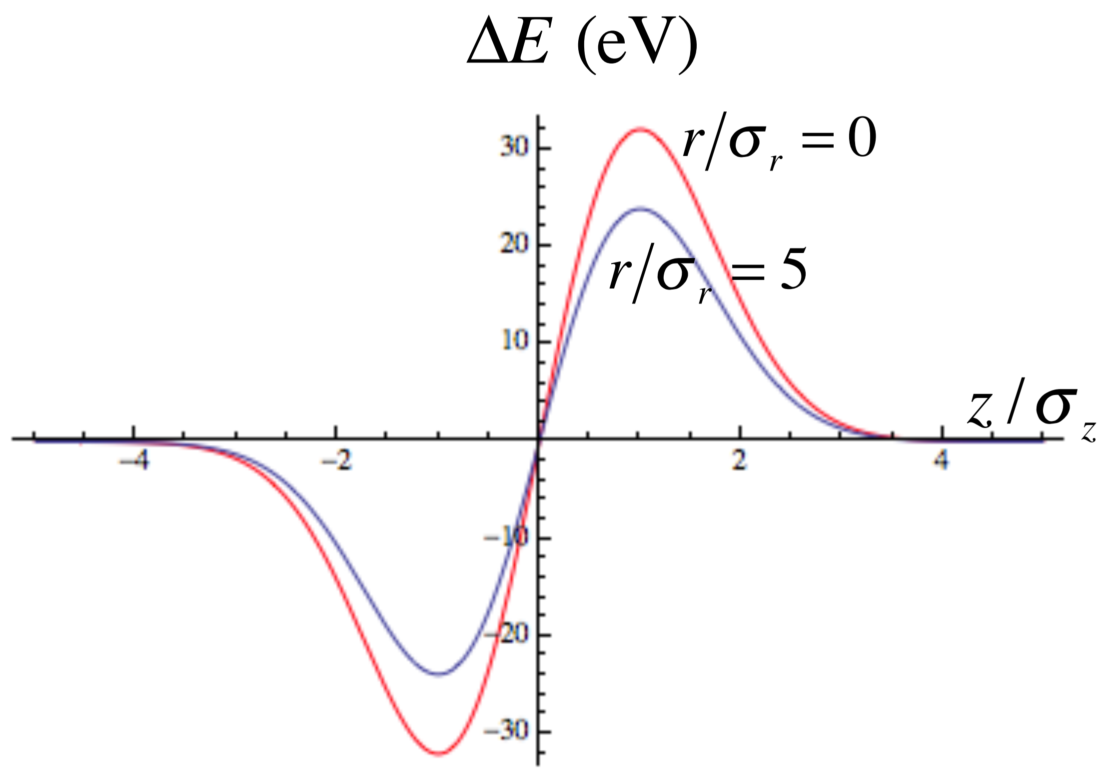
Where Do We Go From Here?

- Need Gun Design (see Matt Poelker's talk)
- Need to understand how arbitrary bunch profile causes emittance growth.
- Need Merger Design for traditional ERL layout.
- Down select single cell or dual cell architecture
- Need to incorporate realistic de-chirper and chirper
- Consider non-linear effects (see Rui Li's talk)
- Do Start to End (cathode to dump)
- Look at lower energy

Questions?

LSC-induced Energy Change accumulated in the Cooling Channel

parameters	
$E_e = 55$ MeV	$\gamma = 107$
$Q_b = 420$ pC	$N_e = 2.6 \times 10^9$
$\sigma_p = 10^{-4}$	$\Delta E_e = 5.5$ keV
$\sigma_z = 3$ cm, $\sigma_r = 1$ mm	$w = 9 \times 10^{-8}$
Drift Length	$L = 30$ m



$$\text{Relative energy change} = \frac{30 \text{ eV}}{55 \text{ MeV}} = 5 \times 10^{-7}$$