Design of a Microbunched Electron Cooler Energy Recovery Linac

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Outline

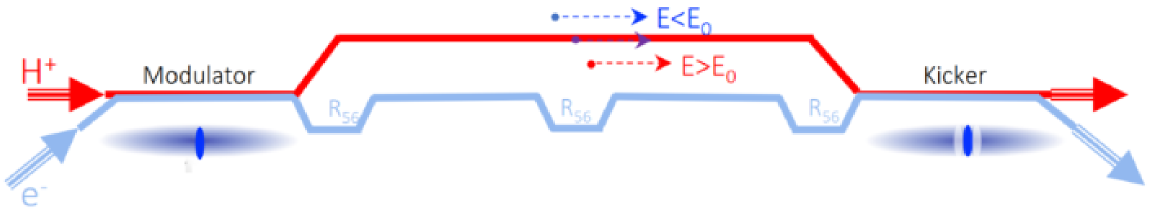
- Introduction
- Overview
- Optics
- Future Work
- Summary

Introduction: Electron-Ion Collider

- The Electron-Ion Collider (EIC) is a future accelerator currently being developed that will be built at Brookhaven National Lab (BNL) which collides electrons and hadrons
- Protons are injected, cooled (injection cooling), ramped to collision energy, and collided
- A possible future upgrade to improve the luminosity would require proton bunches to be cooled during collisions, preserving the proton beam emittance
- This ERL design is meant to deliver an electron beam which provides Coherent electron Cooling (CeC) for the two collision energies of 275 and 100 GeV – corresponding to 150 and 55 MeV electrons

Introduction: Microbunched Electron Cooling

- Coherent electron cooling (CeC) uses an electron bunch to “measure” the position of the protons, then use the same electron bunch to apply energy kicks to reduce the emittance of the proton bunch in the longitudinal and transverse directions
- Microbunched electron cooling (MBEC) is a specific type of CeC and is the mechanism proposed for the SHC-ERL to provide cooling for the EIC protons during collision



- An electron bunch with the same relativistic gamma as the protons co-propagates with the proton beam in the modulator, where the protons imprint on the electrons
- Once separated, the electrons are sent through a series of chicanes and drifts to amplify the energy modulations induced by the protons, and convert them into density modulation
- The electrons and protons co-propagate in the kicker, where the density modulation of the electrons provide a corrective kick to the protons in order to cool them

Introduction: Beam Parameters

	100 GeV	275 GeV
Gamma	107.6	294
Energy (MeV)	55	150
Bunch charge (nC)	1	
Repetition rate (MHz)	98.5	
Average current (mA)	98.5	
Bunch length, rms (mm)*	9	7
Peak current (A)	10	13
Slice energy spread (dp/p)	0.6–1.5e-4	4–8e-5
Normalized emittance (mm-mrad)	2.8	

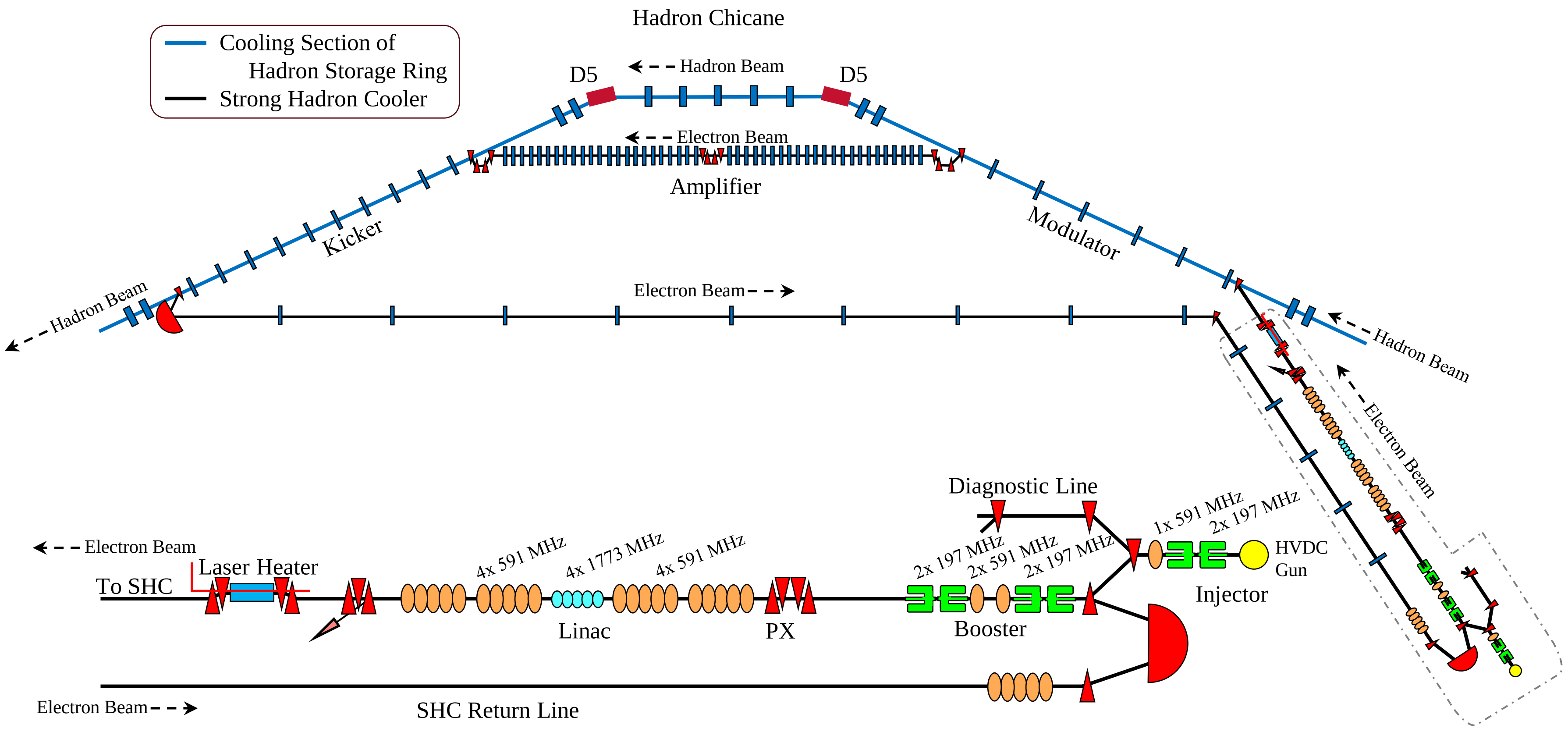
* Assumes supergaussian of order ~4

Introduction: Cooling Channel Parameters

	100 GeV	275 GeV
Gamma	107.6	294
Energy (MeV)	55	150
Modulator / Kicker Length (m)	33	
Number of Amplifier Drifts (m)	2	
Amplifier Drift Length (m)	49	
β_x/β_y in Modulator (m)	20.0 / 20.0	21.4 / 21.4
β_x/β_y in Kicker (m)	29.7 / 4.09	7.89 / 7.89
β_x/β_y in Amplifier (m)	12.0 / 12.0	4.89 / 4.89
R_{56} in First / Second / Third Chicane (mm)	23.3 / -16.7 / -18.2	12.0 / -6.66 / -6.85

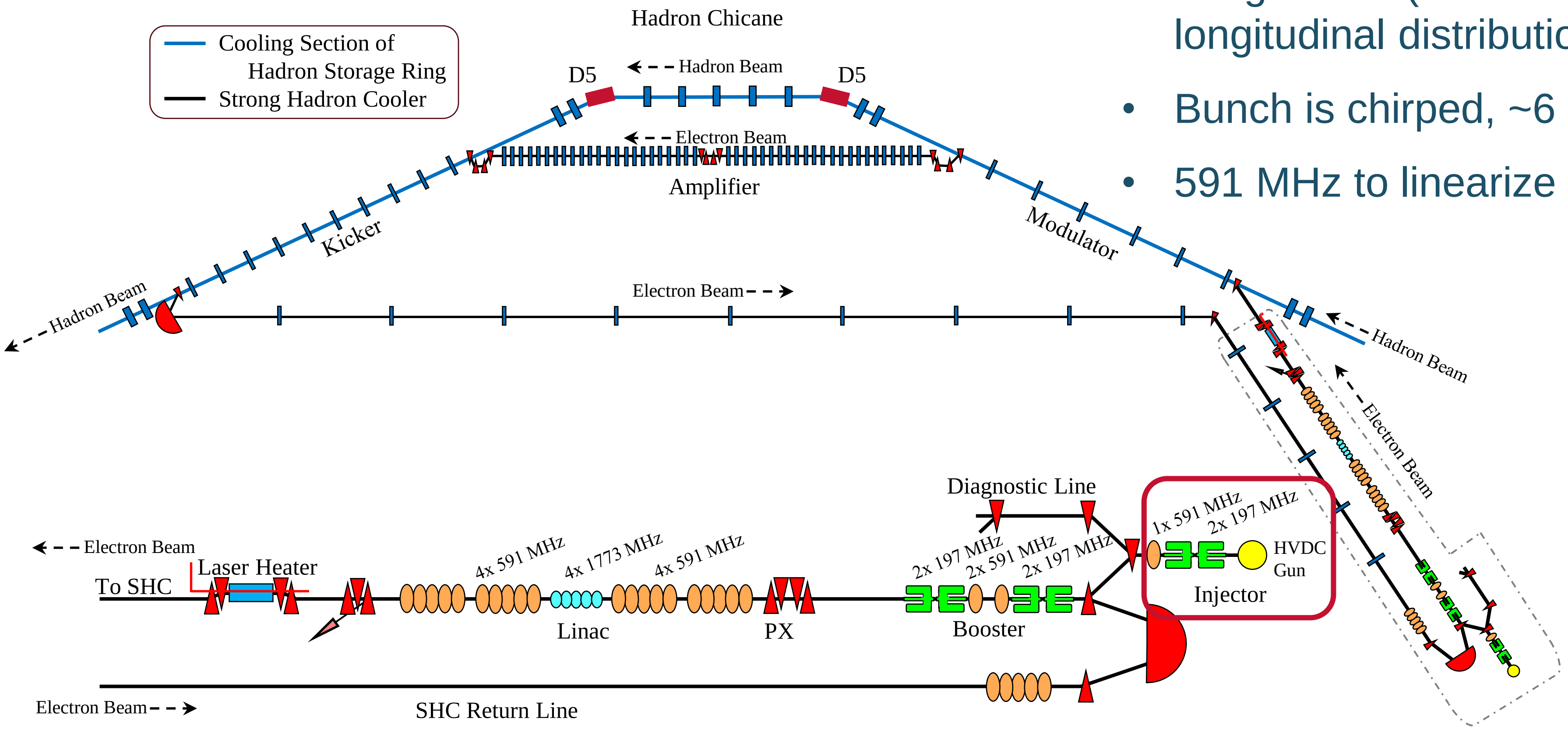
Beam parameters in the cooling channel provided by Will Bergan (BNL)
Details at DOI:10.18429/jacow-ipac2024-thyd1

Overview: Representative Layout



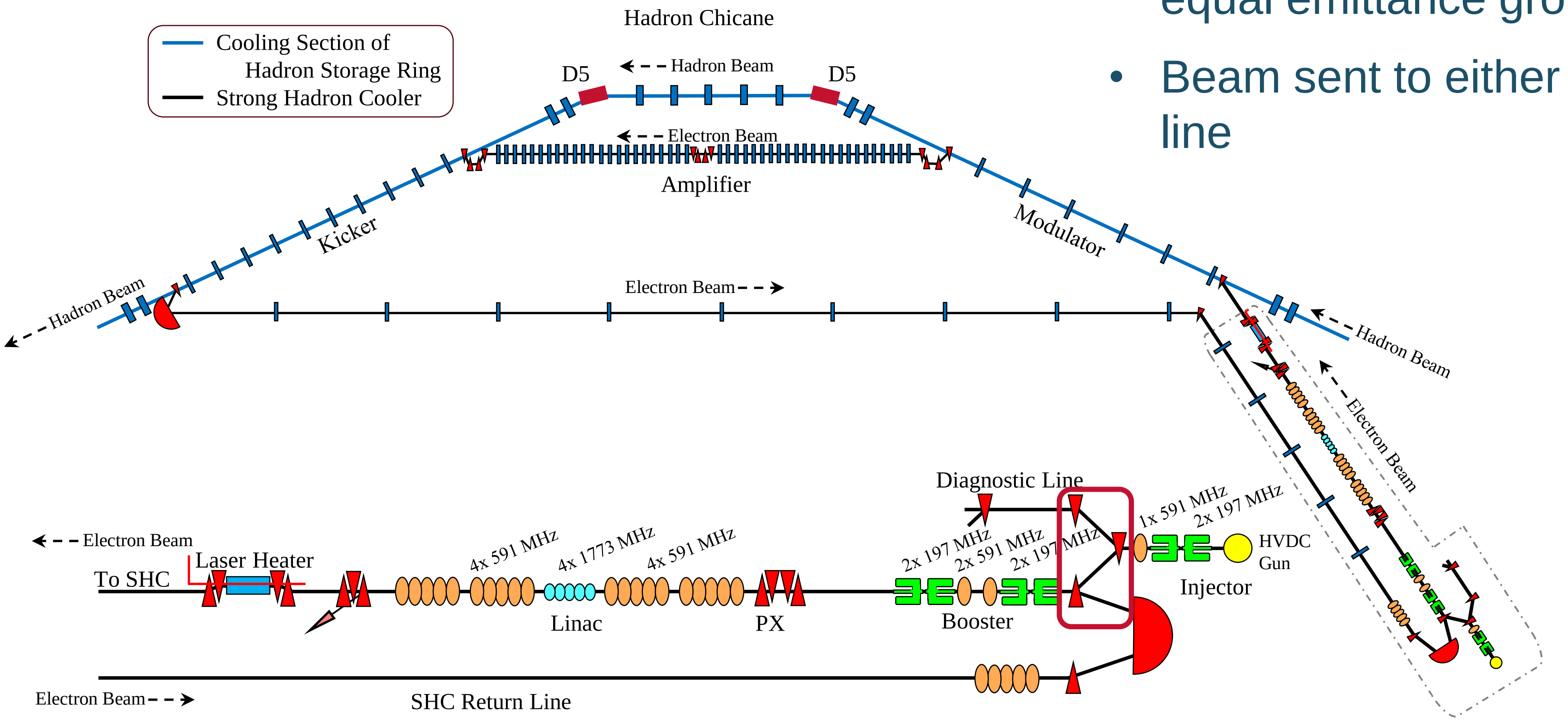
Overview: Injector

- HVDC Gun + (2) 197 MHz QWR + (1) 591 MHz single-cell
- Long bunch (~29 mm rms) with supergaussian longitudinal distribution
- Bunch is chirped, ~6 MeV
- 591 MHz to linearize longitudinal phase space



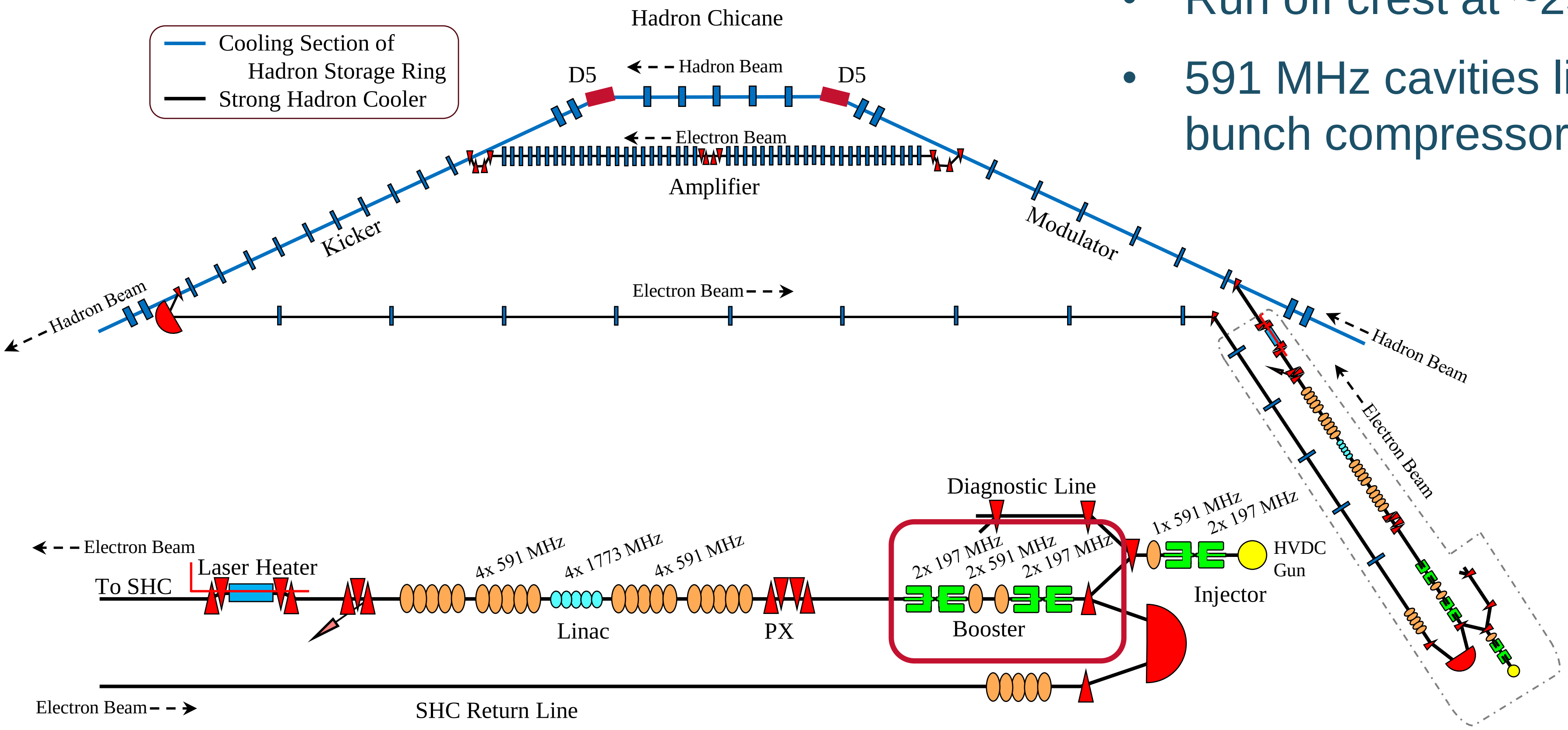
Overview: Merger

- Dogleg + (2) solenoids
- Solenoids in dispersive region result in equal emittance growth in both planes
- Beam sent to either booster or diagnostic line



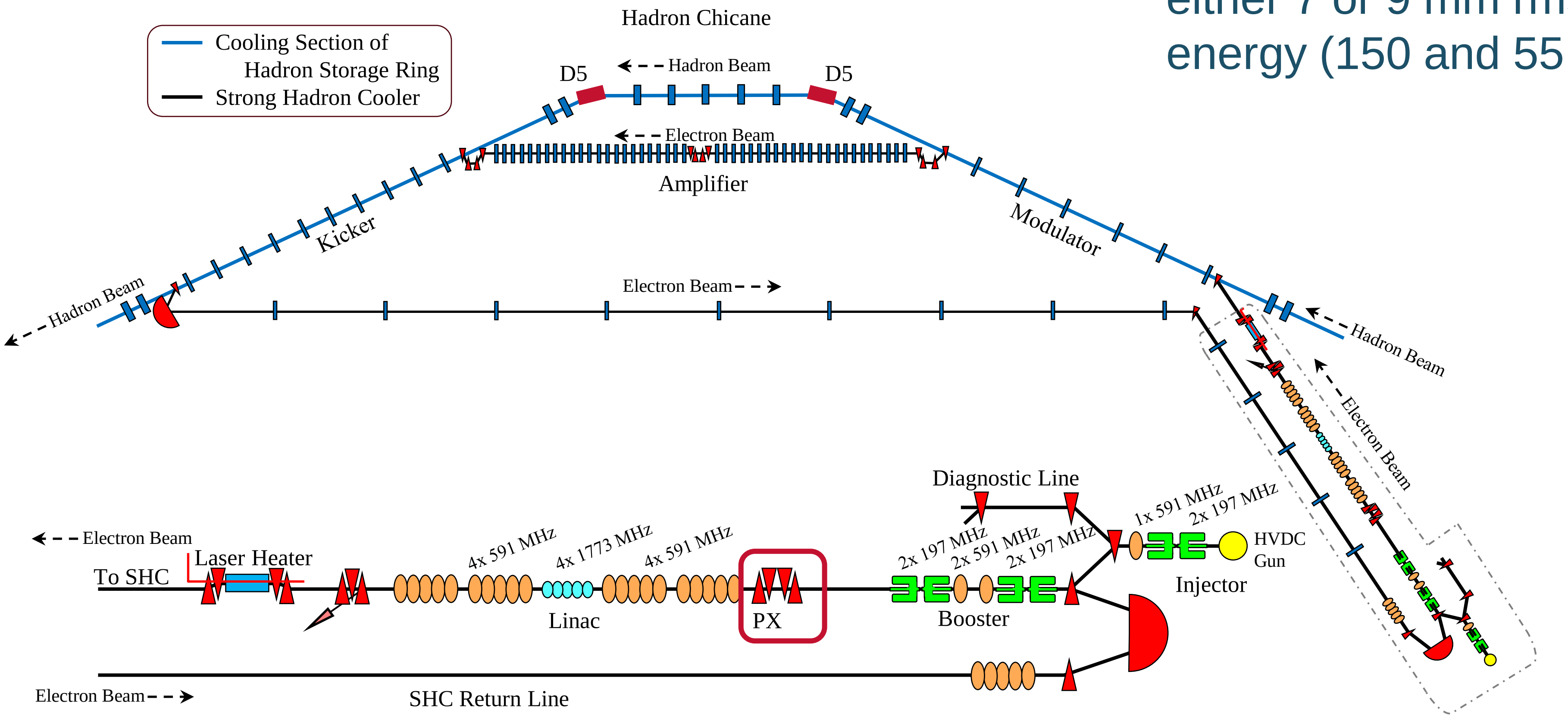
Overview: Booster

- (2) 197 MHz QWR + (2) 591 MHz single-cell+ (2) 197 MHz QWR
- Run off crest at ~25°, beam at ~13 MeV
- 591 MHz cavities linearize, evaluated after bunch compressor chicane (P1)



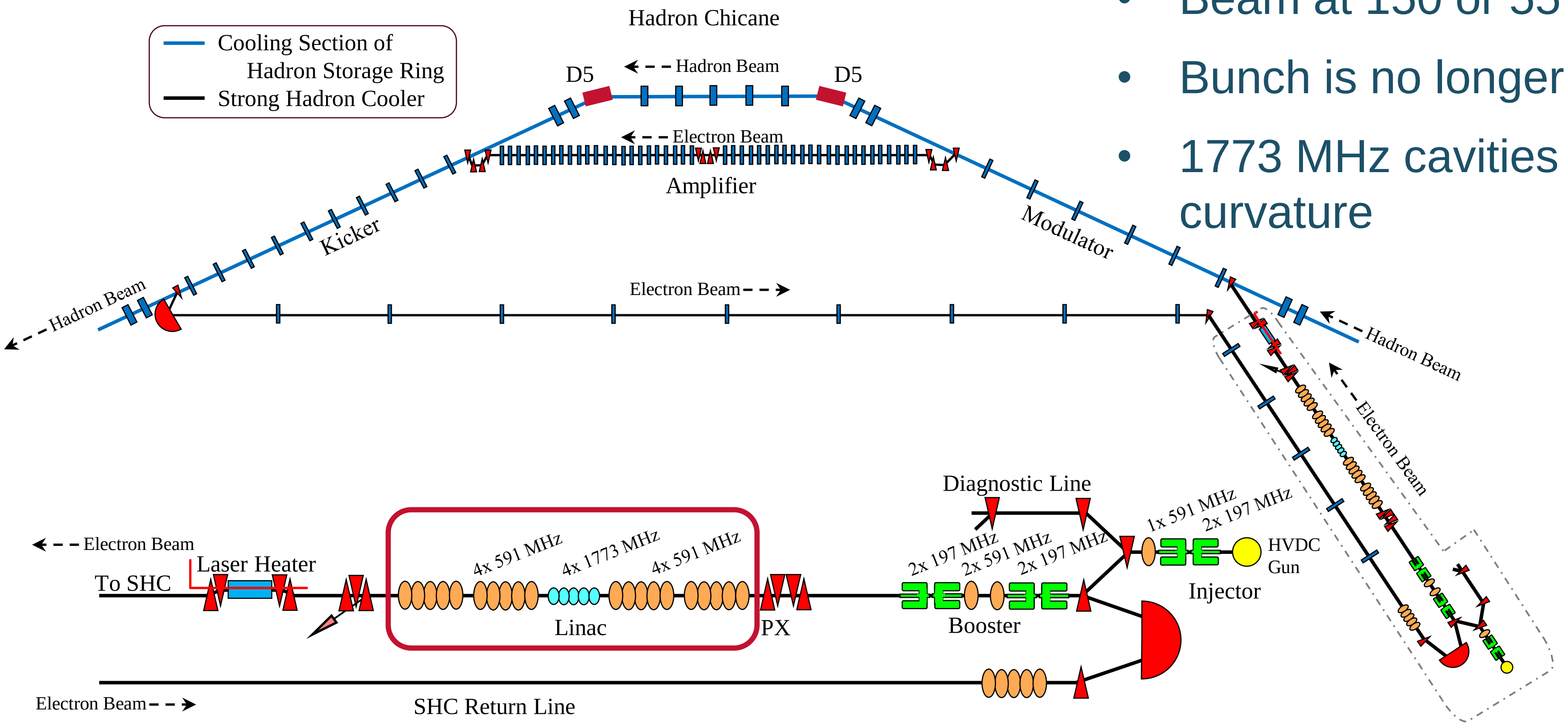
Overview: PX

- 13 MeV beam goes down P1 line
- Beam is compressed to bunch length of either 7 or 9 mm rms, depending on final energy (150 and 55 MeV, respectively)



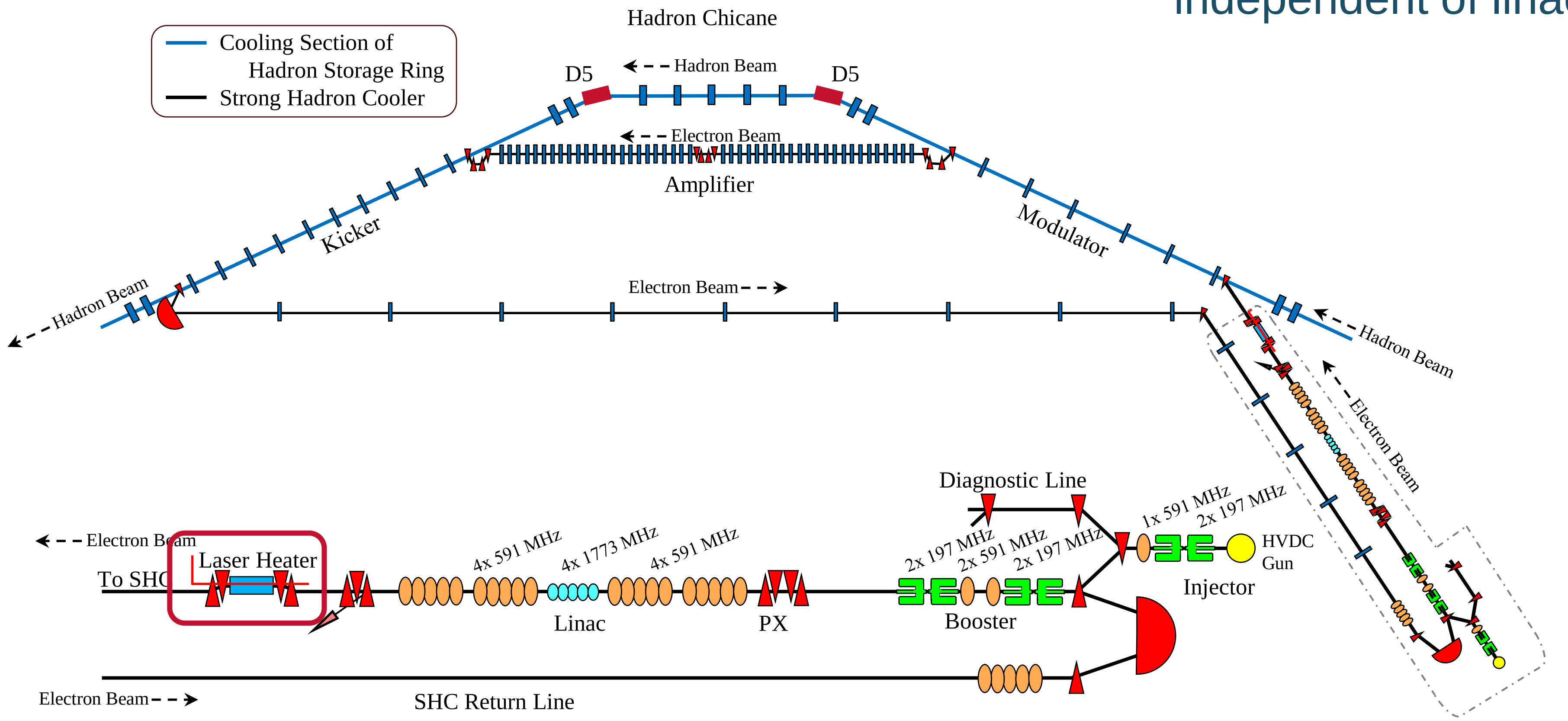
Overview: Linac

- (4) 591 MHz 5-cell + (4) 1773 MHz 5-cell + (4) 591 MHz 5-cell
- Beam at 150 or 55 MeV
- Bunch is no longer chirped
- 1773 MHz cavities minimize longitudinal curvature



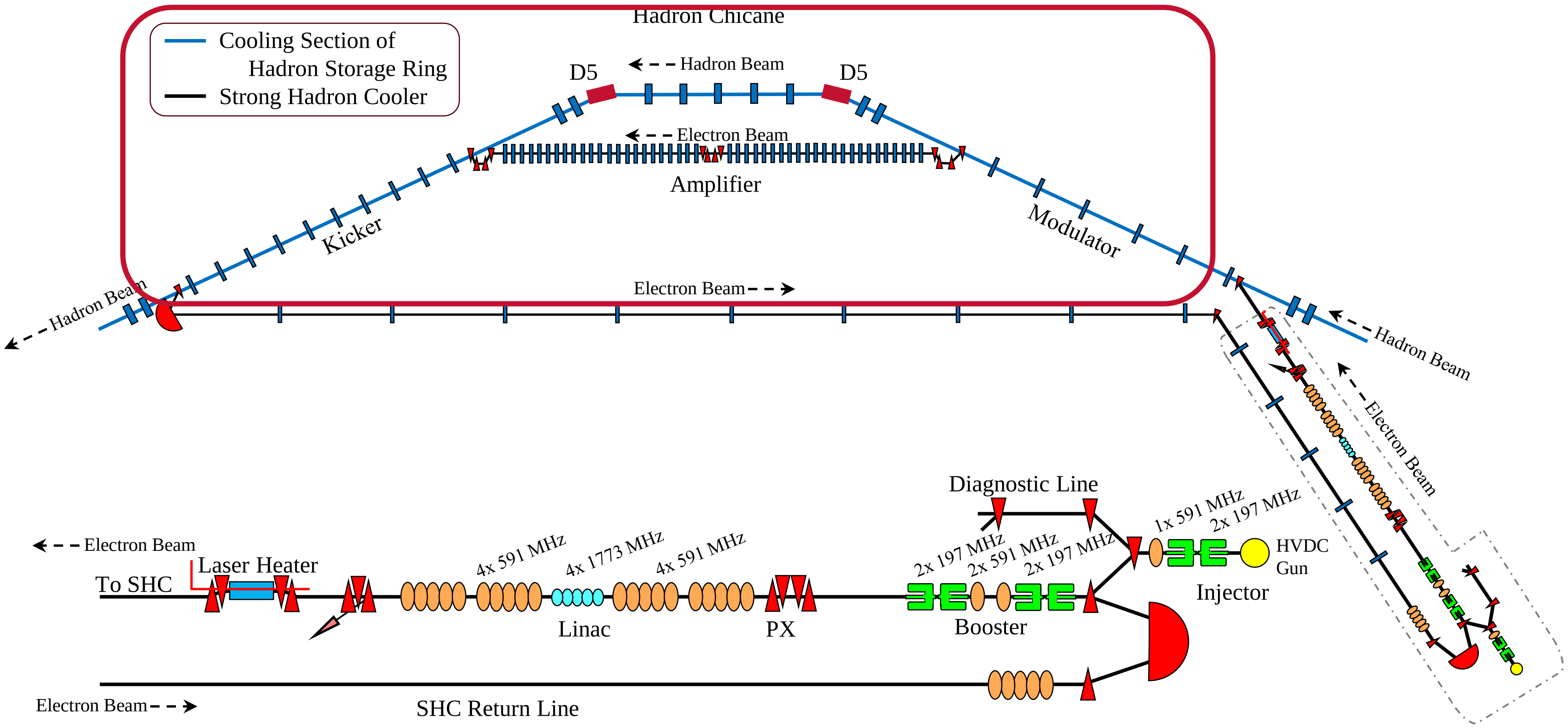
Overview: Laser Heater

- Chicane and undulator
- Provides control of slice energy spread independent of linac

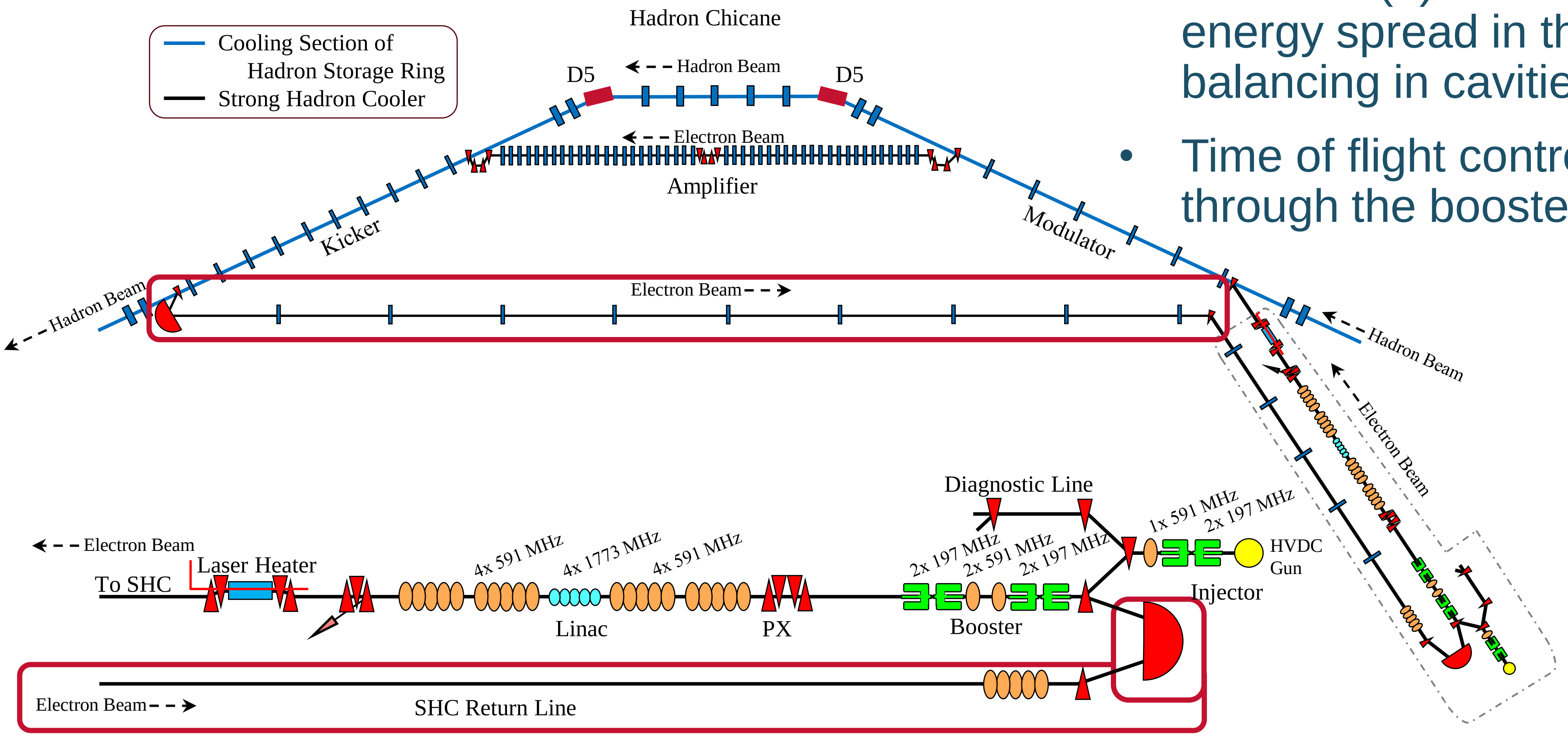


Overview: Cooler

- Beam transported to Hadron Storage Ring, merges, cools, de-merges



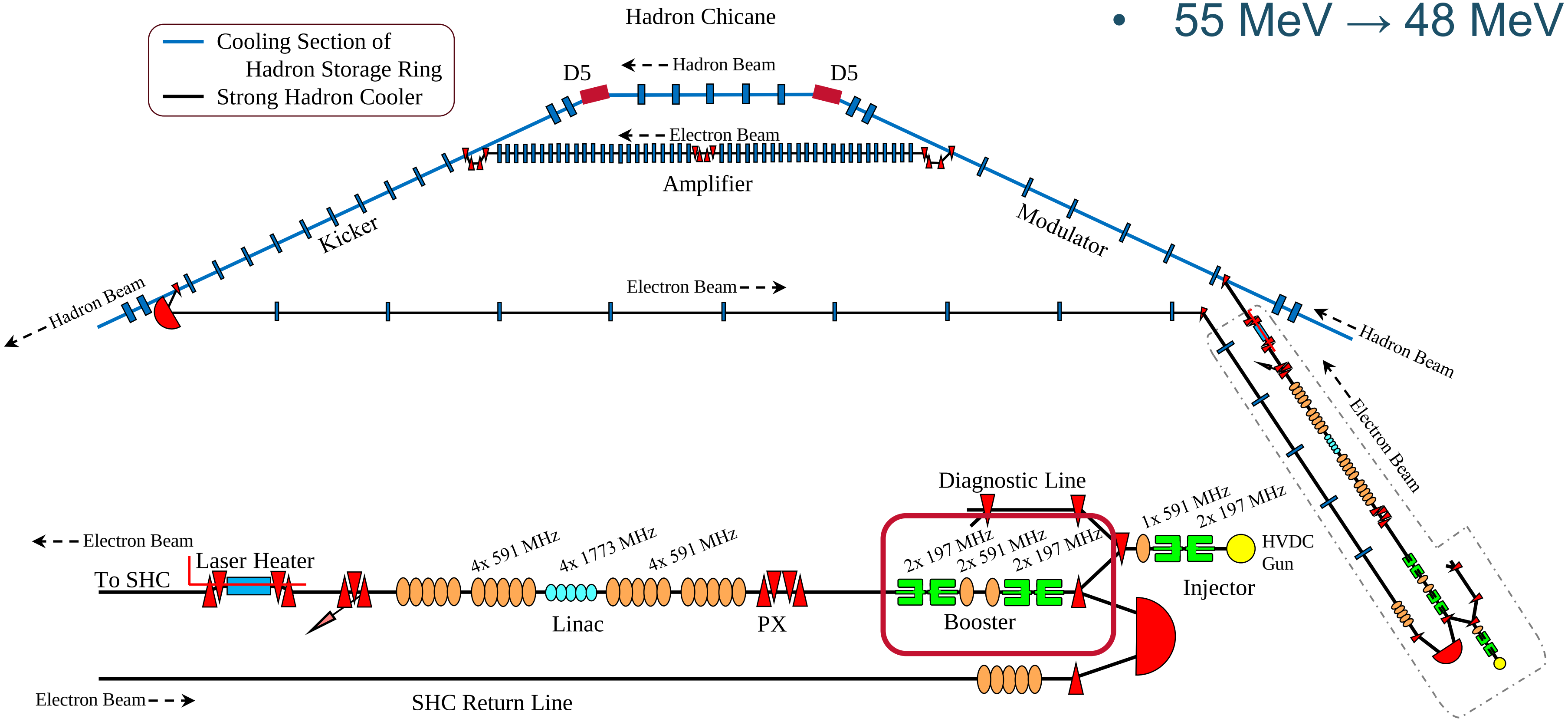
Overview: Return Line



- Bates bend + transport back to linac + Bates bend
- Contains (1) 591 MHz 5-cell to minimize energy spread in the dump while energy balancing in cavities
- Time of flight control for deceleration through the booster

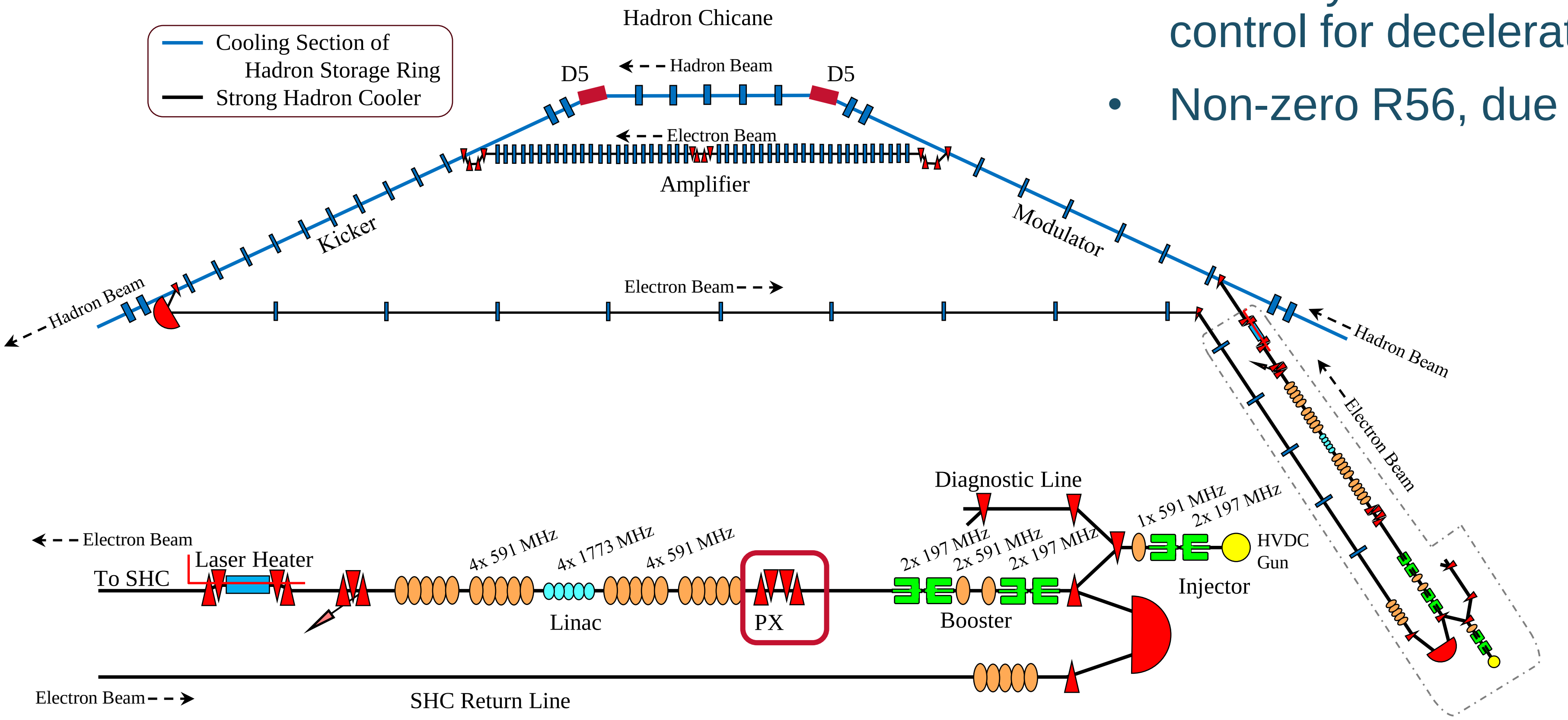
Overview: Booster (2nd Pass)

- Decelerate
- 150 MeV → 143 MeV
- 55 MeV → 48 MeV



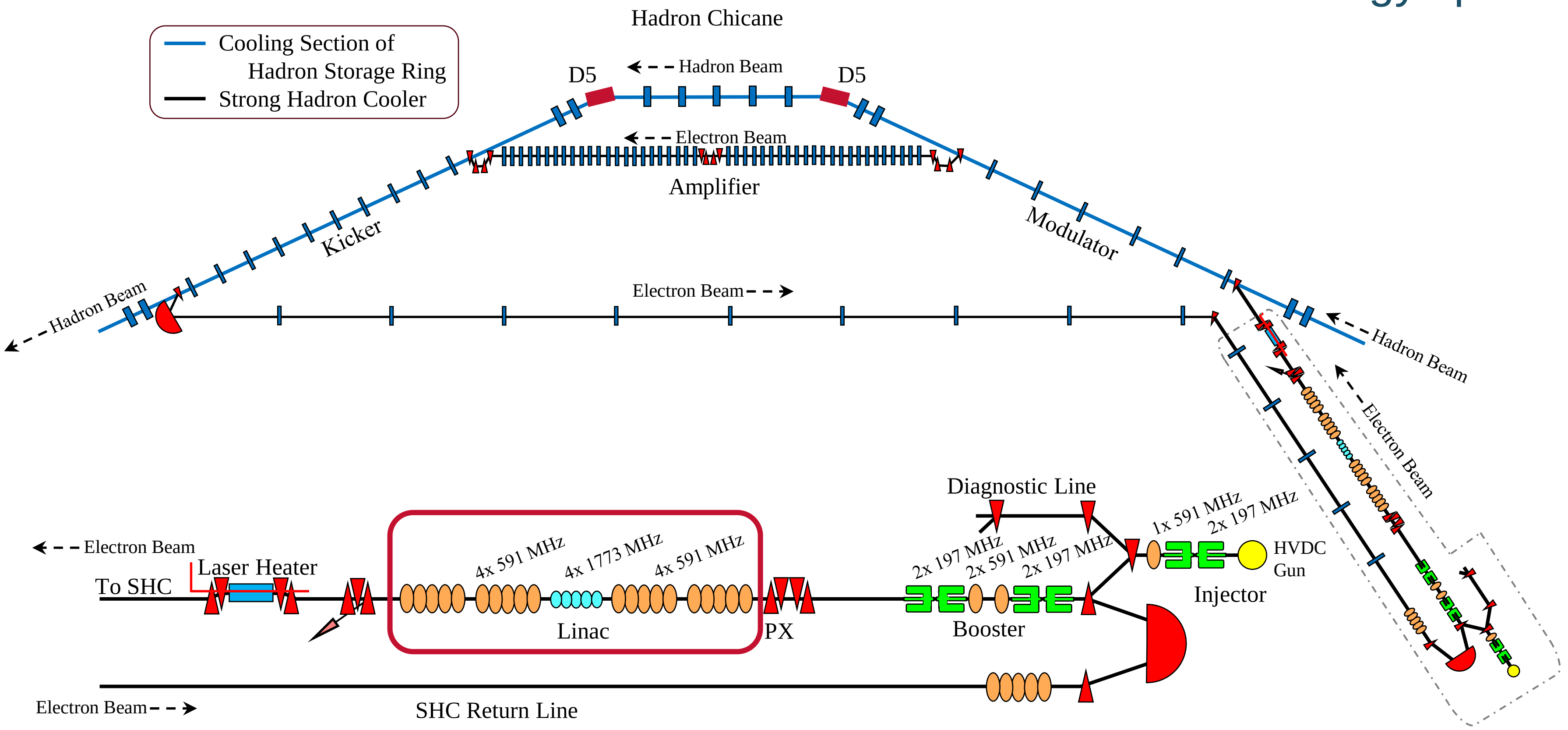
Overview: PX (2nd Pass)

- Beam takes P2 (55 MeV) or P3 (150 MeV) and bypasses compressor (P1)
- Primarily used as time of flight and optics control for deceleration through the linac
- Non-zero R56, due to constraints

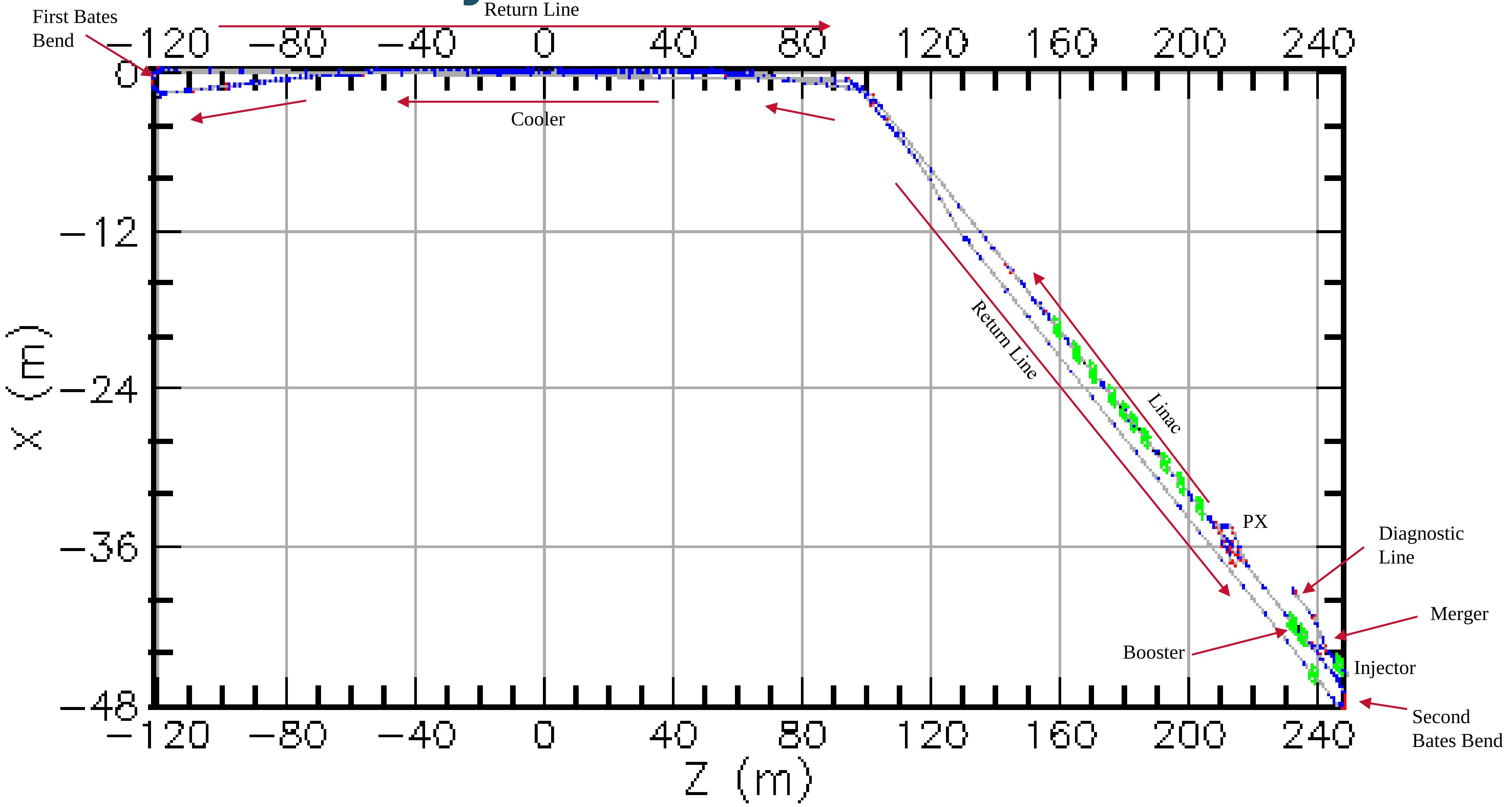


Overview: Linac (2nd Pass)

- Decelerate to 6 MeV injection energy
- Beam transported to dump with minimal rms energy spread



Overview: Actual Layout



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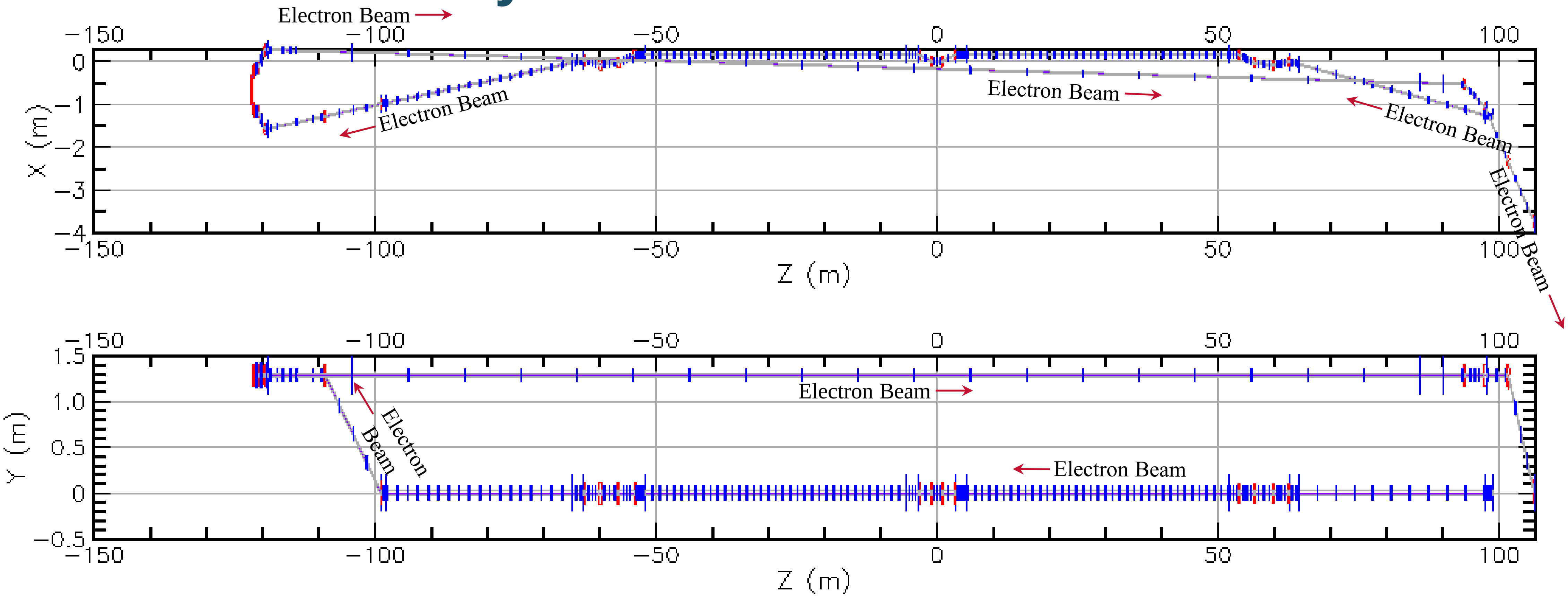
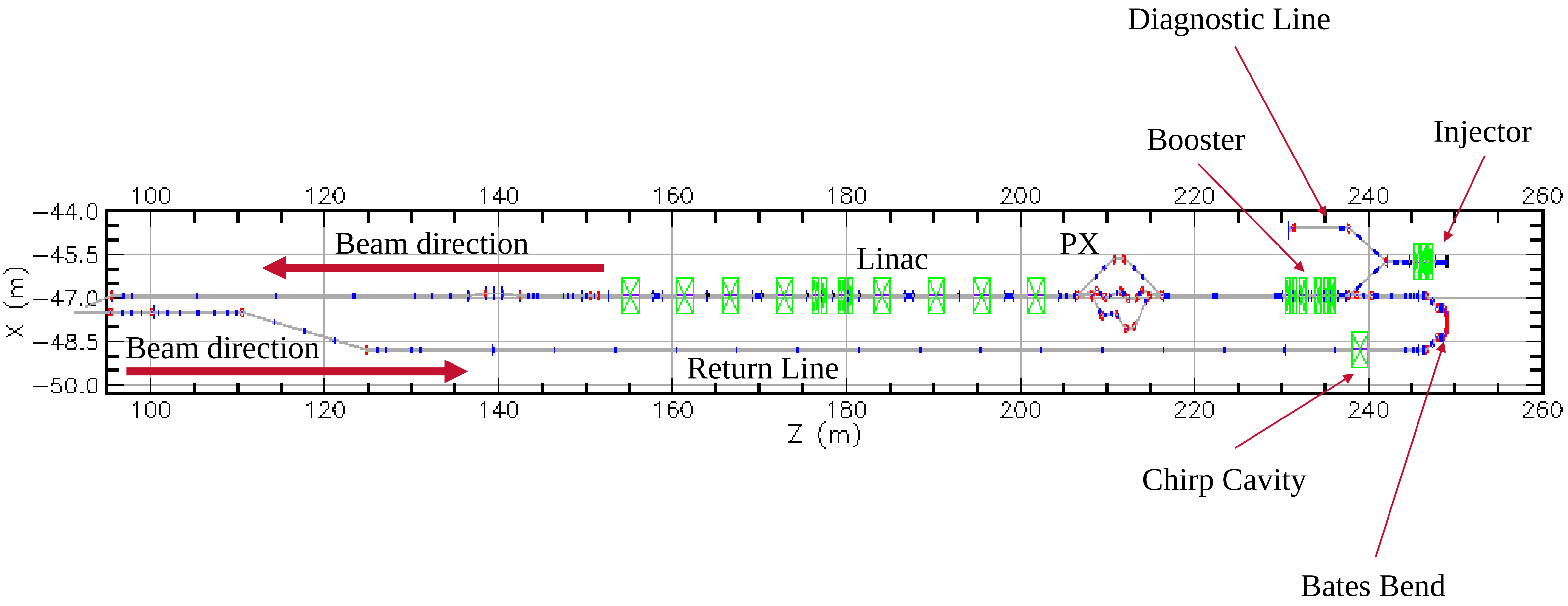


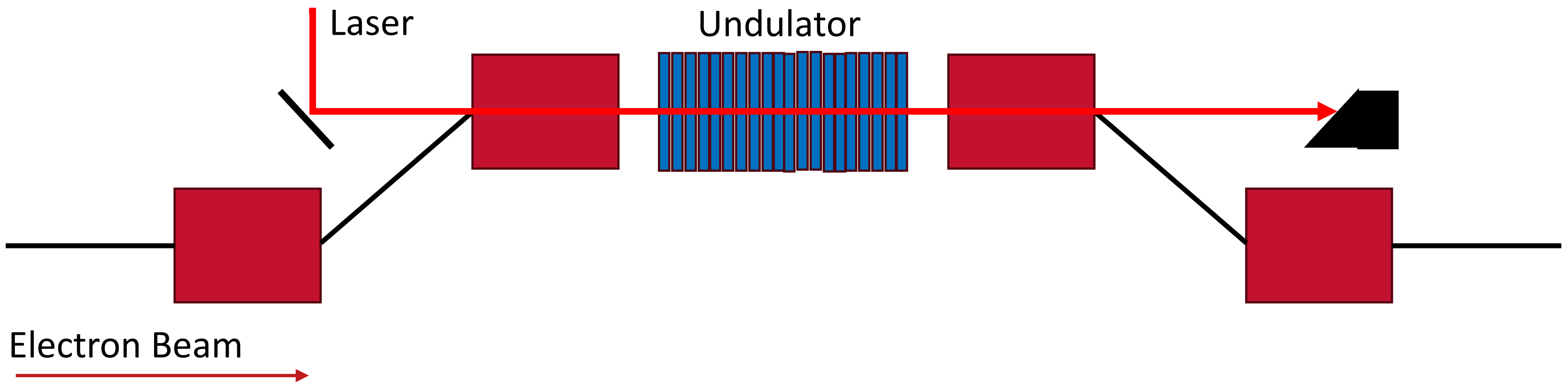
- Top: XZ view of floor plan for cooler and first part of return line
- Bottom: YZ view of floor plan for cooler and first part of return line

Overview: Actual Layout



Optics: Laser Heater

- Coherent electron cooling is highly sensitive to the slice energy spread of the electron beam – for the EIC, it must fall in a range, not just below a maximum
- To increase the slice energy spread, and provide an adjustable knob for this parameter outside of the injector, a laser heater is located between the linac and the cooler
- The layout of the laser heater involves co-propagating a laser with the electron beam inside an undulator in the center of a chicane; a simple layout is below



Optics: Laser Heater

- The momentum modulation on the electron beam resulting from the laser interaction within the undulator is smeared out in the second half of the laser heater chicane

- Given the anticipated parameters, emittance growth is negligible

- However, due to the cooling mechanism, it is critical microbunching gain does not occur before the cooler – preliminary evaluations indicate that the laser heater chicane does not result in microbunching gain, but this will have to be evaluated with full CSR simulations at a later stage

Optics: Time of Flight Requirements

- Most ERLs have a single time of flight (TOF) requirement: linac exit to linac entrance

- Because of the layout of this machine there are two:
  - Booster exit to booster entrance (Booster TOF)
  - Linac exit to linac entrance (Linac TOF)

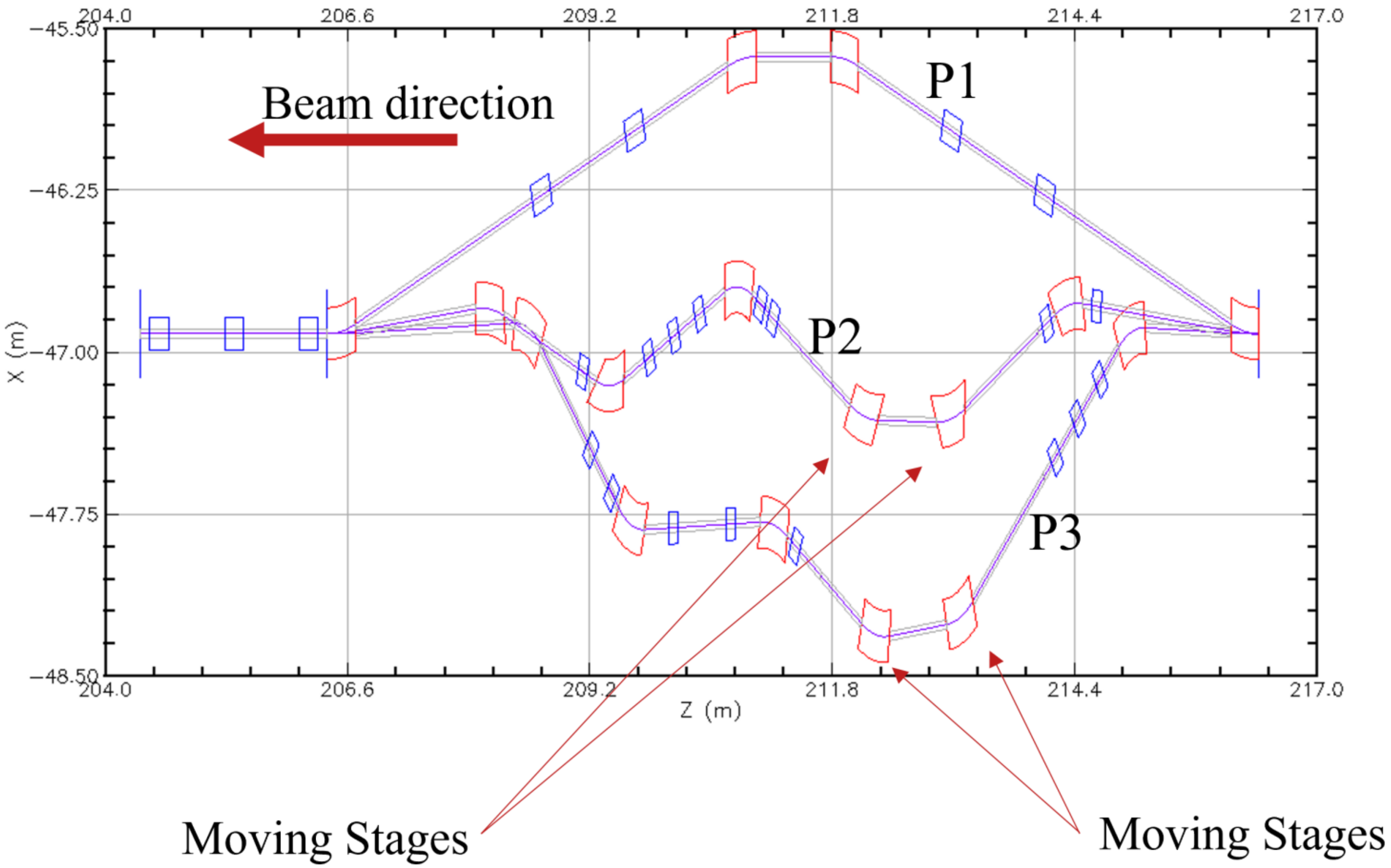
- Booster TOF uses two Bates bends for flexibility
  - At the 197 MHz fundamental frequency of the booster and a 2.5 cm maximum orbit excursion at the center of the bend, this translates to ± 11.7° per Bates bend
  - For a fixed path length of ~800 m, the TOF for the two energies differs by ~8° (at 197 MHz), but required booster TOF for deceleration is the same
  - Second Bates bend is positioned so each energy is ~4° from desired TOF when on-axis through Bates bends – by design, both energies are off-axis through the second Bates bend
  - Booster TOF flexibility becomes +27°/-19° for 55 MeV and +19°/-27° for 150 MeV

- Linac TOF handled in high energy PX lines (P2 and P3), uses moving stages for flexibility

Optics: PX Section

- Each line is energy specific
  - P1: 13 MeV
  - P2: 55 → 48 MeV
  - P3: 150 → 143 MeV

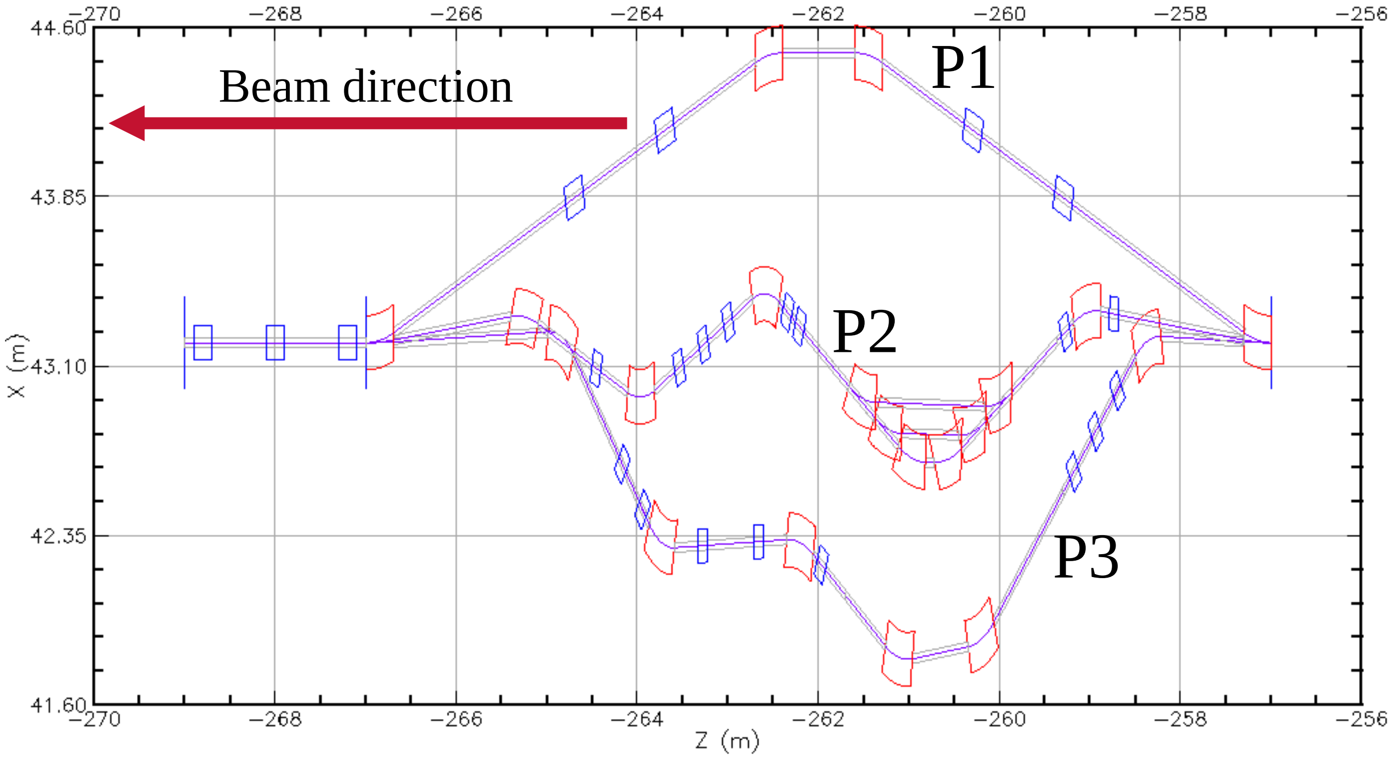
- Booster TOF needs to be correct, due to:
  - The limited range of the moving stage
  - If the decelerating beam enters P2/P3 at an energy significantly different than design, it will be lost on the beam pipe wall



Optics: PX Section

- Linac TOF for 150 and 55 MeV only differs by ~1.4° at 591 MHz – in order to minimize geometry conflicts, P3 has an added wavelength of path length

- Due to the geometry, very different TOF ranges:
    - P2: ±35°
    - P3: ±55°



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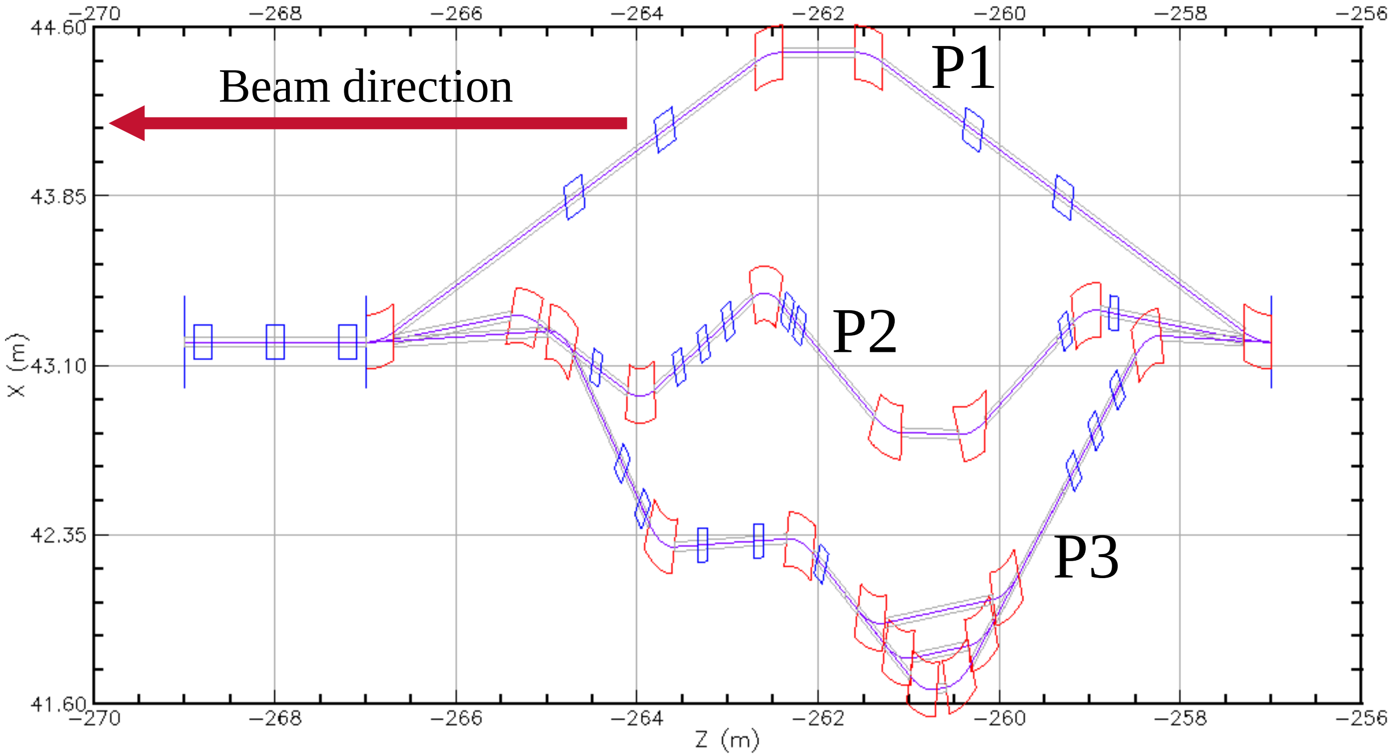
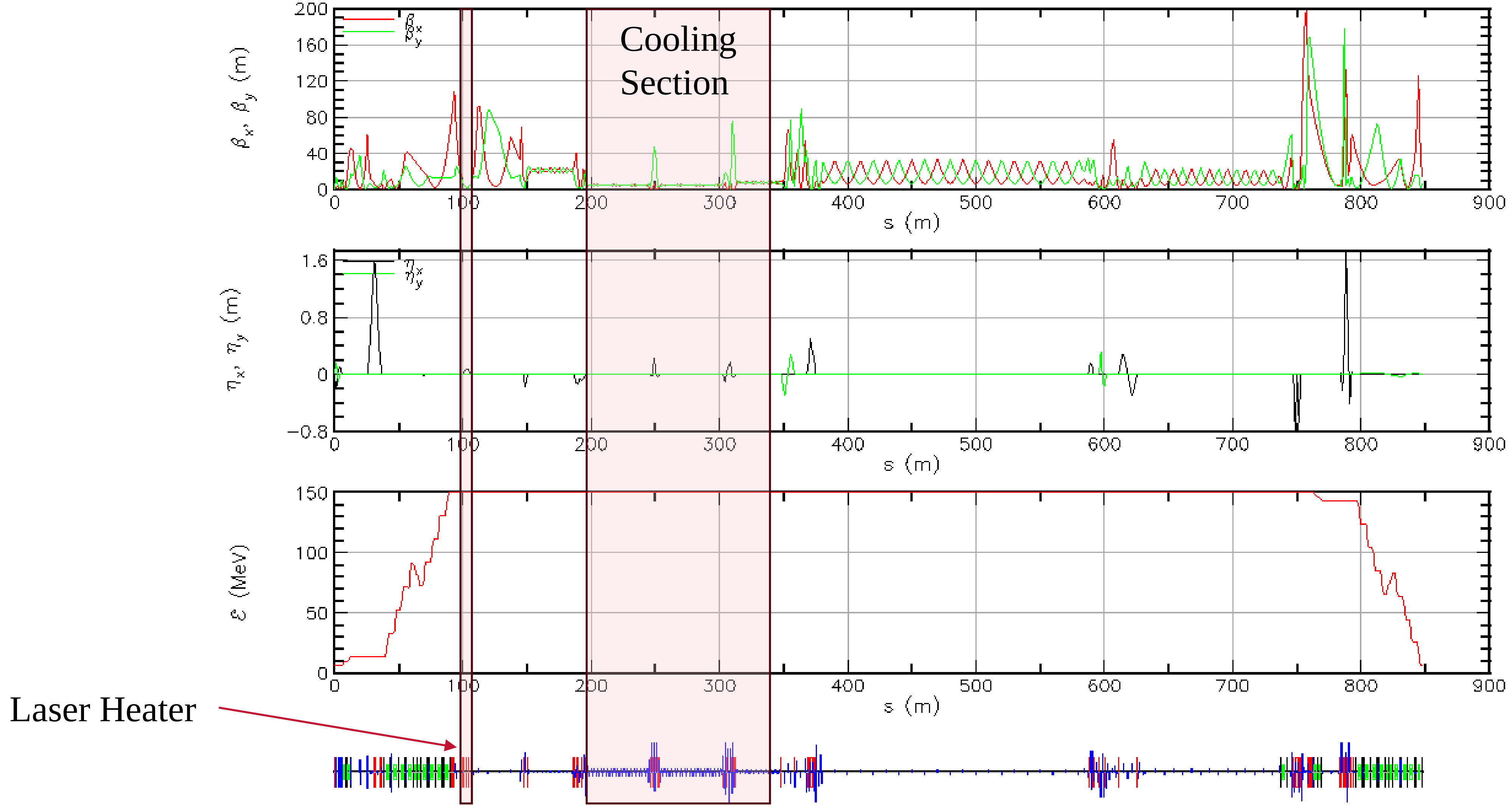


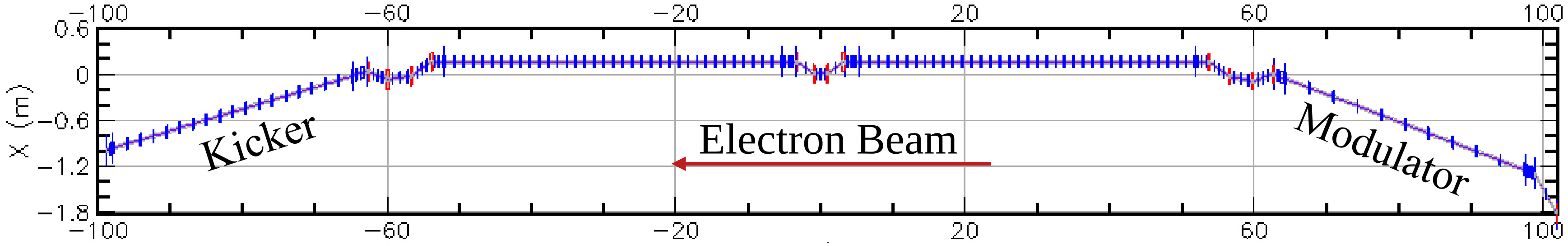
Optics: PX Section

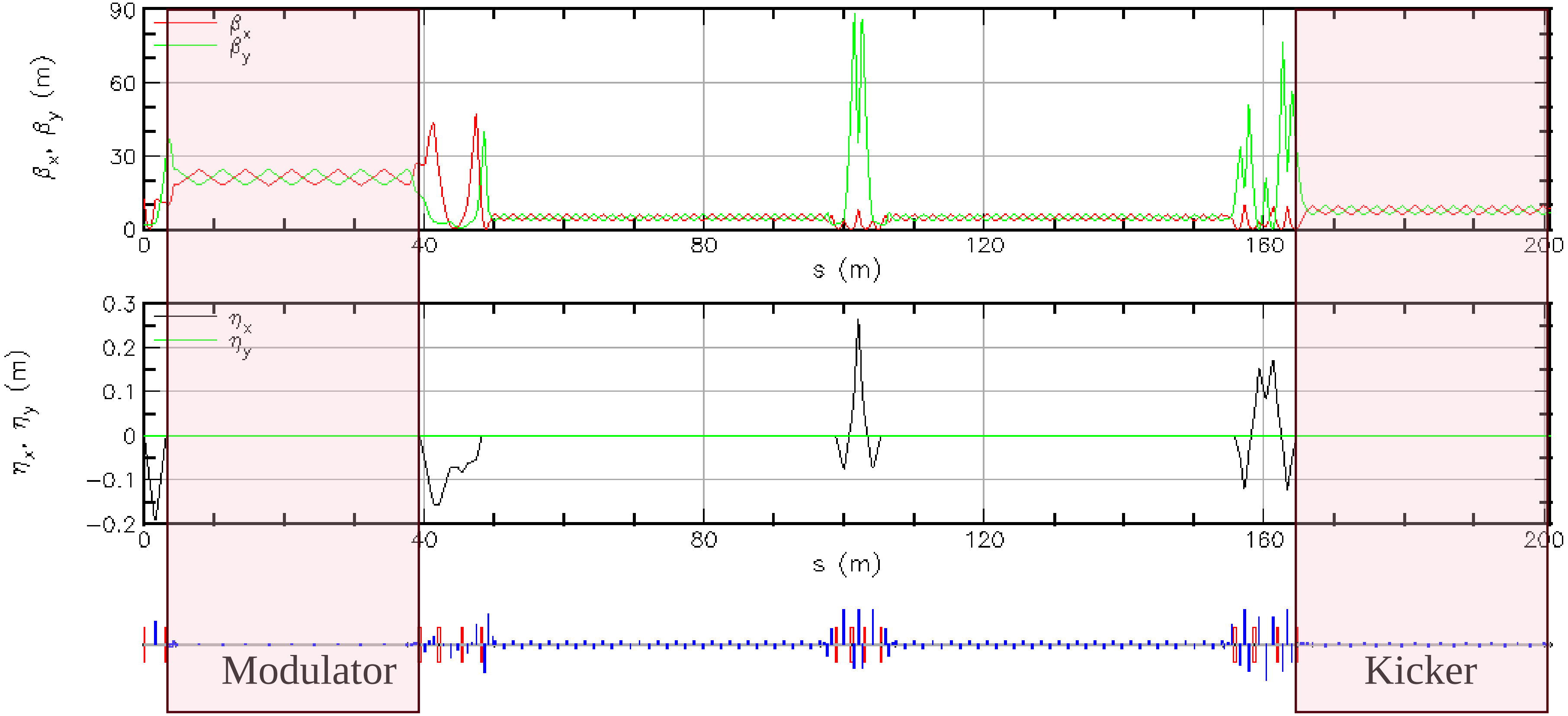
- A simpler design would have the booster and bunch compressor before the merger – why not do that?
  - Inject at 13 MeV, only one time of flight concern, no need for higher-energy bypass lines to transport the decelerating beam around the compressor chicane
- This has significant drawbacks:
  - Lower energy efficiency
  - Higher radiation shielding requirements at the dump and the diagnostic line
- Why not inject at 6 MeV after bunch compression?
  - A solution has not been found for an injector that meets all the beam parameters

Optics at 150 MeV: Complete Machine



Optics at 150 MeV: Cooler

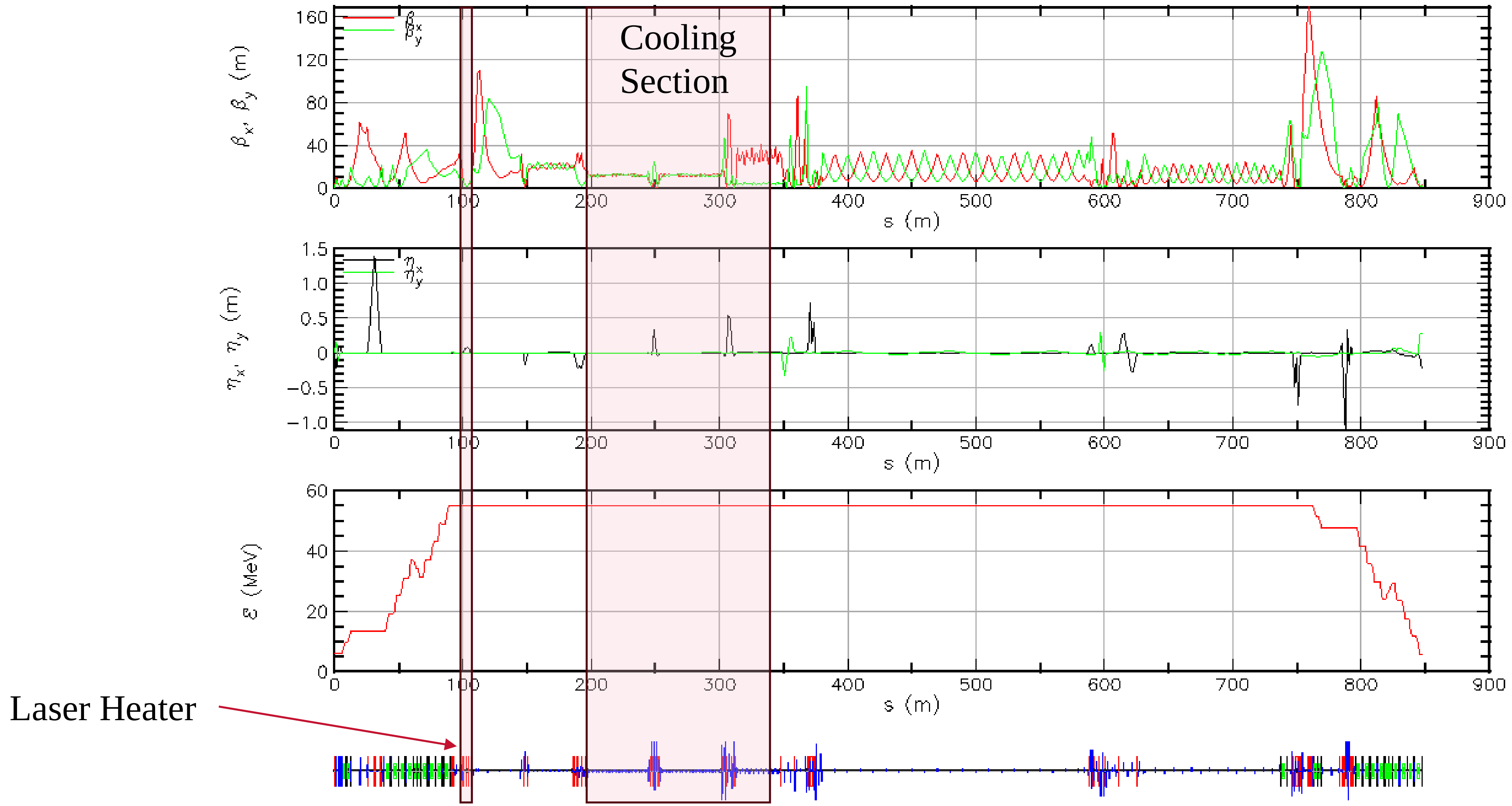




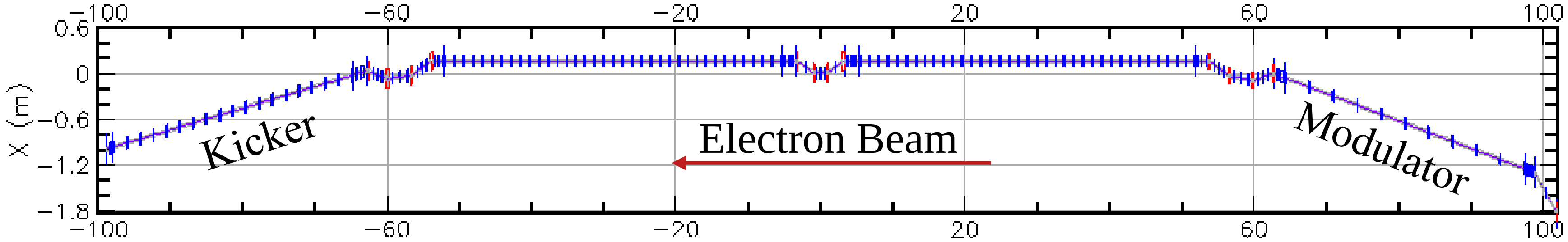
Above: Layout of cooler

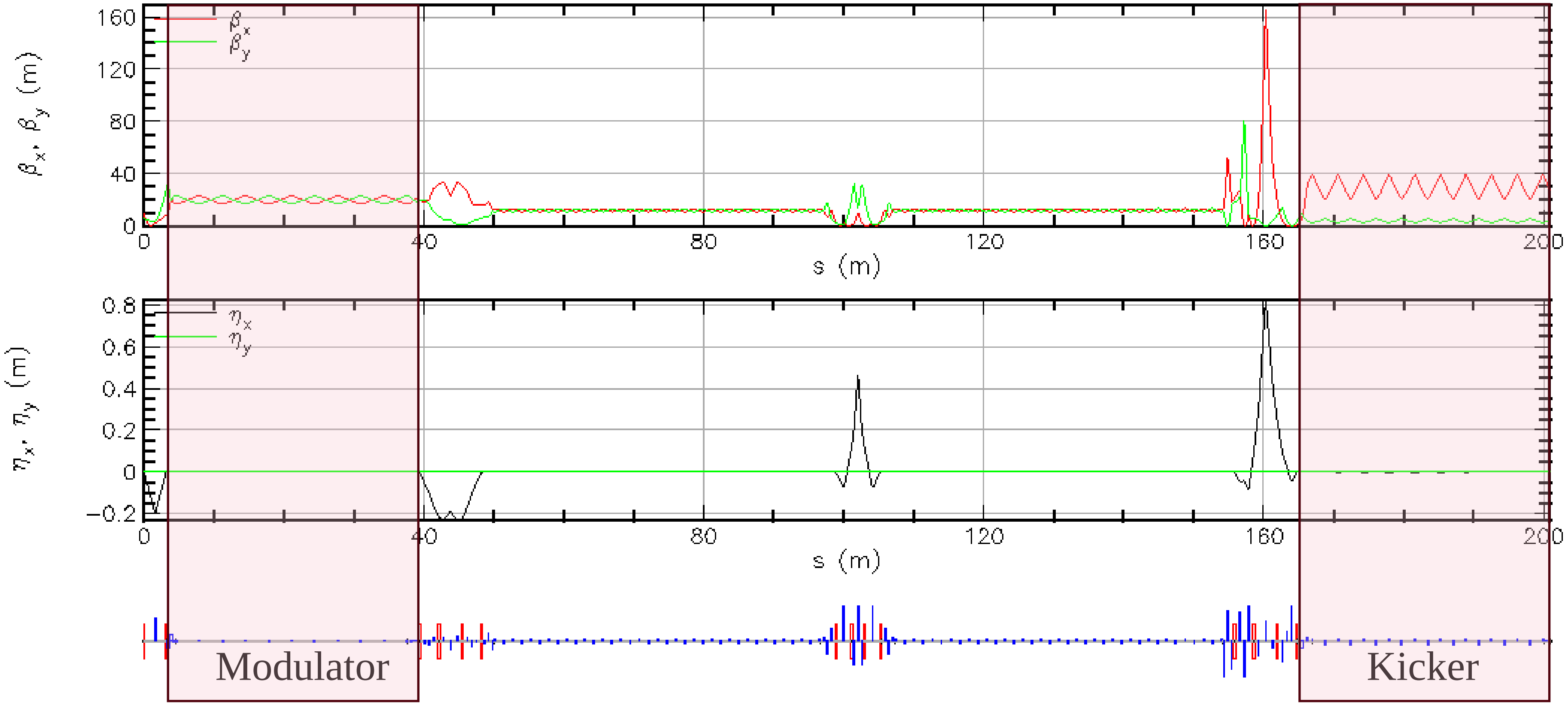
Left: Transverse optics and lattice layout

Optics at 55 MeV: Complete Machine



Optics at 55 MeV: Cooler





Above: Layout of cooler

Left: Transverse optics and lattice layout

Future Work: Alternate Cooling Scheme

- More detailed simulations have shown that MBEC is not as effective at high energy cooling for the EIC as desired
- However, others have proposed that bunched beam cooling and a circulating cooler ring (CCR) may be a prospective solution, similar to the JLEIC cooler
  - D. Kayran, A. Fedotov, and S. Seletskiy, `"Electron cooler for high-energy hadrons in the EIC based on ERL", ERL'24 https://conference-indico.kek.jp/event/225/contributions/5546/attachments/3907/5351/THO04.pdf
- ERL-driven CCR: Electron beam is accelerated to desired energy, kicked into cooling ring, circulated a small number of times to cool protons, and kicked out to be energy recovered
- The beam parameters presented for this concept require a high-brightness, high-charge injector and ERL
- The design presented is an excellent starting point, which could reasonably achieve the necessary parameters after modifications

Summary

- A preliminary design exists for both energy modes of an ERL-driven cooler capable of providing cooling during collisions at the Electron Ion Collider

- One critical success of this design is that the magnet layout stays constant between the two configurations

- Though a more complex approach than most ERLs, no show stoppers have been found

- The capability of this ERL to deliver a high-charge, high-brightness electron beam makes it a good design starting point for coolers driven by other mechanisms

Thanks for your attention!

Future Work: Alternate Cooling Scheme

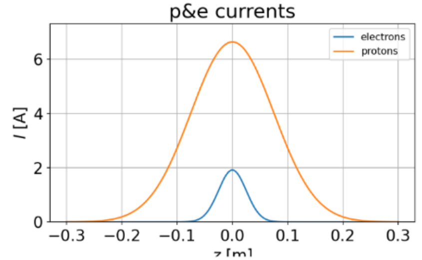
From ERL'24:

Basic required parameters for different EIC protons energies

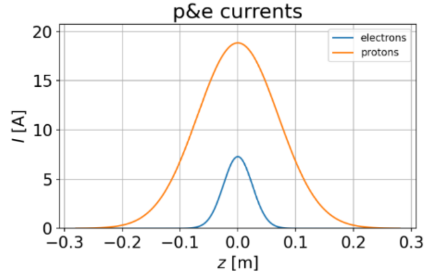
Proton Energy , GeV	275	100	41
Ne	3.00E+10	1.25E+10	4.00E+09
Qe, nC	5	2	0.64
Rms bunch length, cm	2.5	2.5	2.5
Peak Current, A	24	10	3
Rep rate, MHz	98	98	98
I ave in CS, mA	490	196	63
N _rec	7-9	3-4	1
Iav Gun, mA	70-54	65-49	63
Rms energy Spread in CS	3.00E-04	3.00E-04	3.00E-04
RMS Angular spread in CS, rad	5.20E-06	1.70E-05	2.60E-05
RMS Normilized Emittance, m	2.00E-06	1.50E-06	1.50E-06
Cooling Time_x, hrs *	1.8	1.9	2
Cooling Time_y, hrs *	3.6	3.9	1.8
Cooling Time_z, hrs *	2.9	1.6	1

*) The cooling rates assumed 177 m cooling cooling section and averaging by beta- and synchrotron oscillations of protons

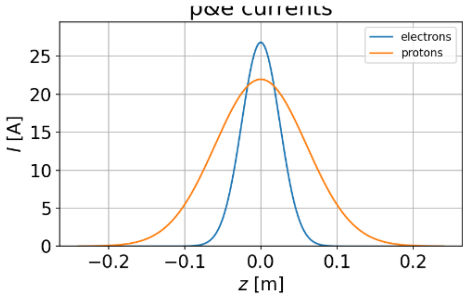
41 GeV protons



100 GeV protons



275 GeV protons



Dmitry Kayran Electron cooler for high-energy hadrons in the EIC based on ERL ERL'24, Sept 26, 2024, Japan

Future Work: Alternate Cooling Scheme

- Change supergaussian longitudinal distribution to gaussian
- Increase/decrease bunch charge
- Smaller emittance required
- Higher energy spread permitted
- Remove bunch compressor, depending on injector optimizations
- Remove laser heater, add bunch stretcher and de-chirper cavity