Beam Dynamics of the Strong Hadron Cooler ERL at the Electron-Ion Collider

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Tuesday, September 24, 2024

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Outline

- Introduction
- Overview
- Optics
- BBU
- Energy Balance
- Summary

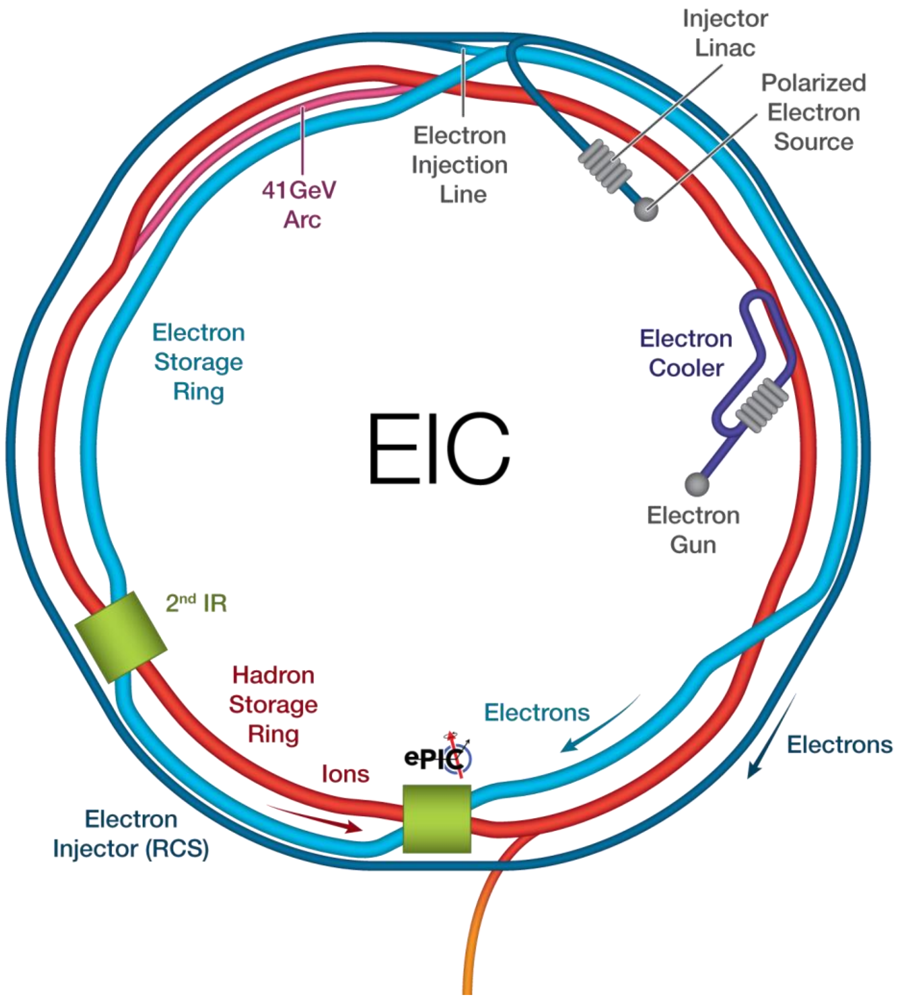
Introduction: Electron-Ion Collider

- 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 cooled (strong cooling) while collisions occur

- Cooling is necessary during collision for the target luminosity

- The Strong Hadron Cooler (SHC) ERL 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



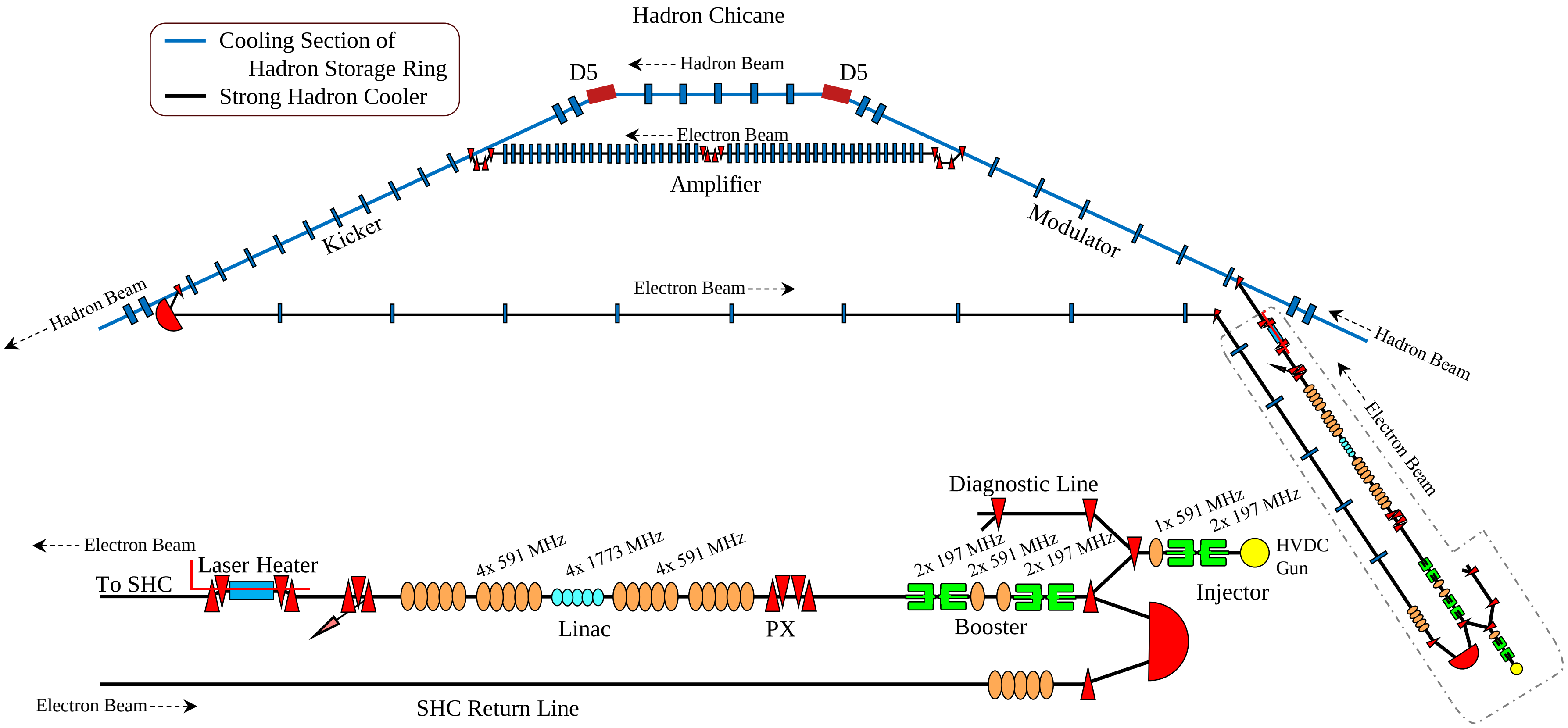
Introduction: Beam Parameters

	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

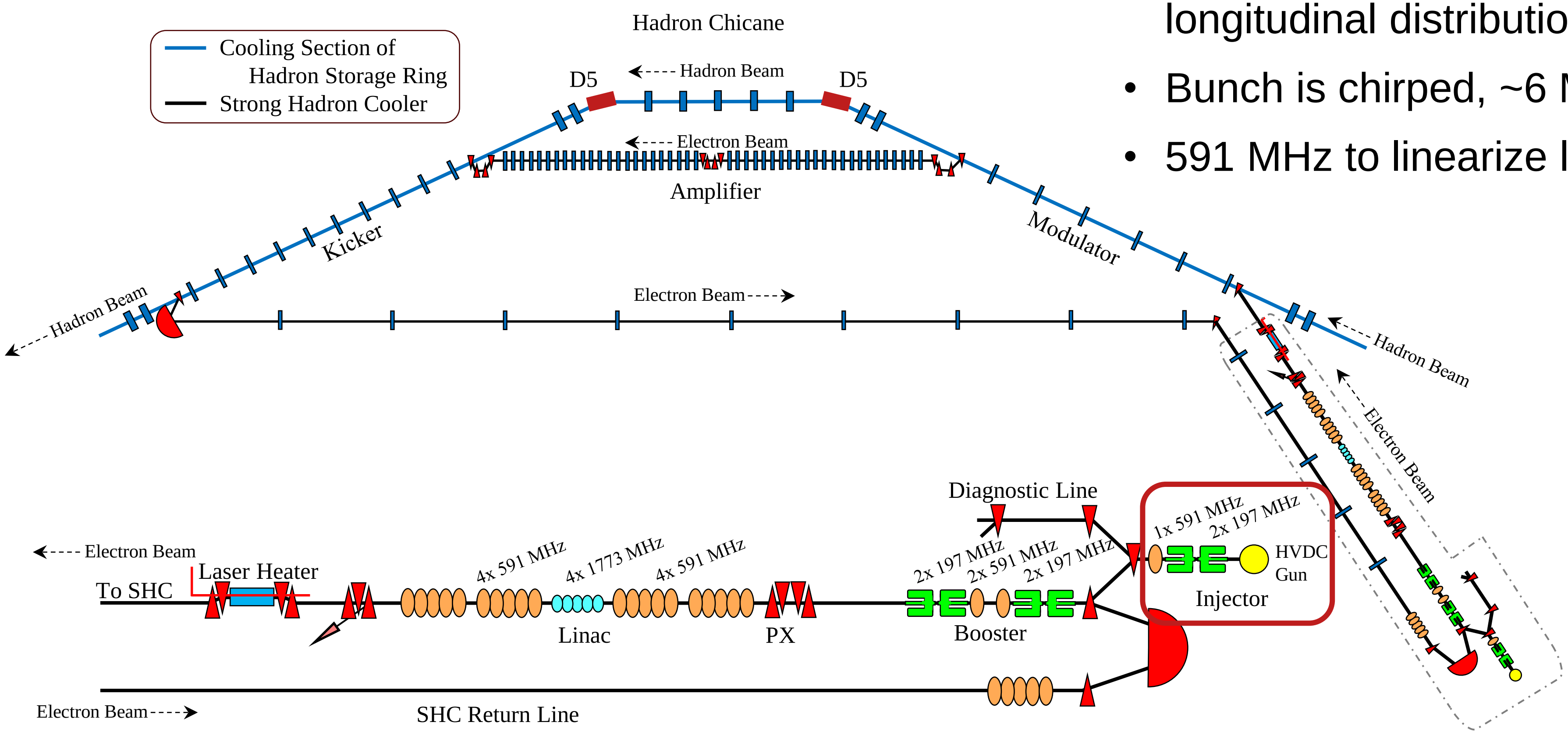
- A discussion of why these are the target parameters is outside the scope of this talk
- For an explanation, see DOI:10.18429/jacow-ipac2024-thyd1

Overview: Representative Layout

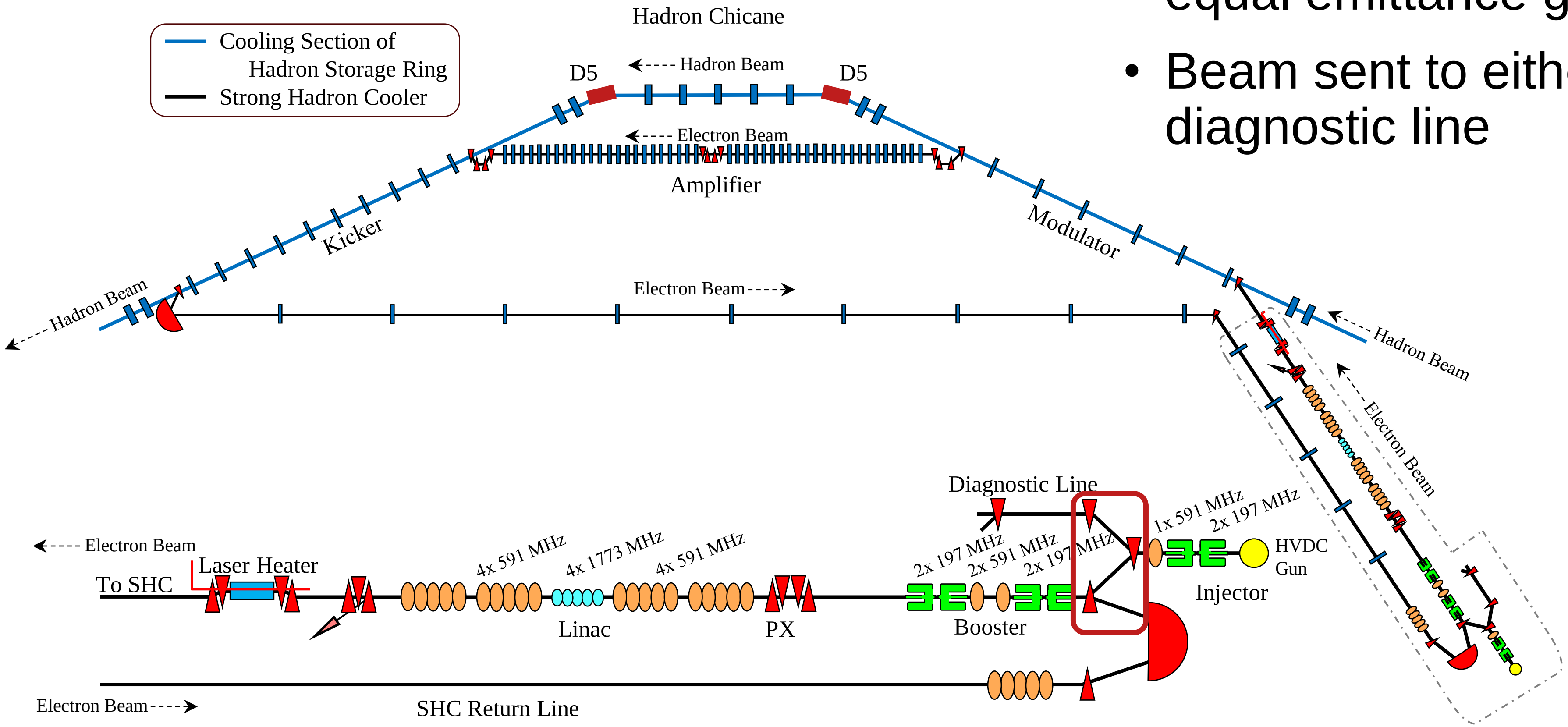


Overview: Injector

- 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

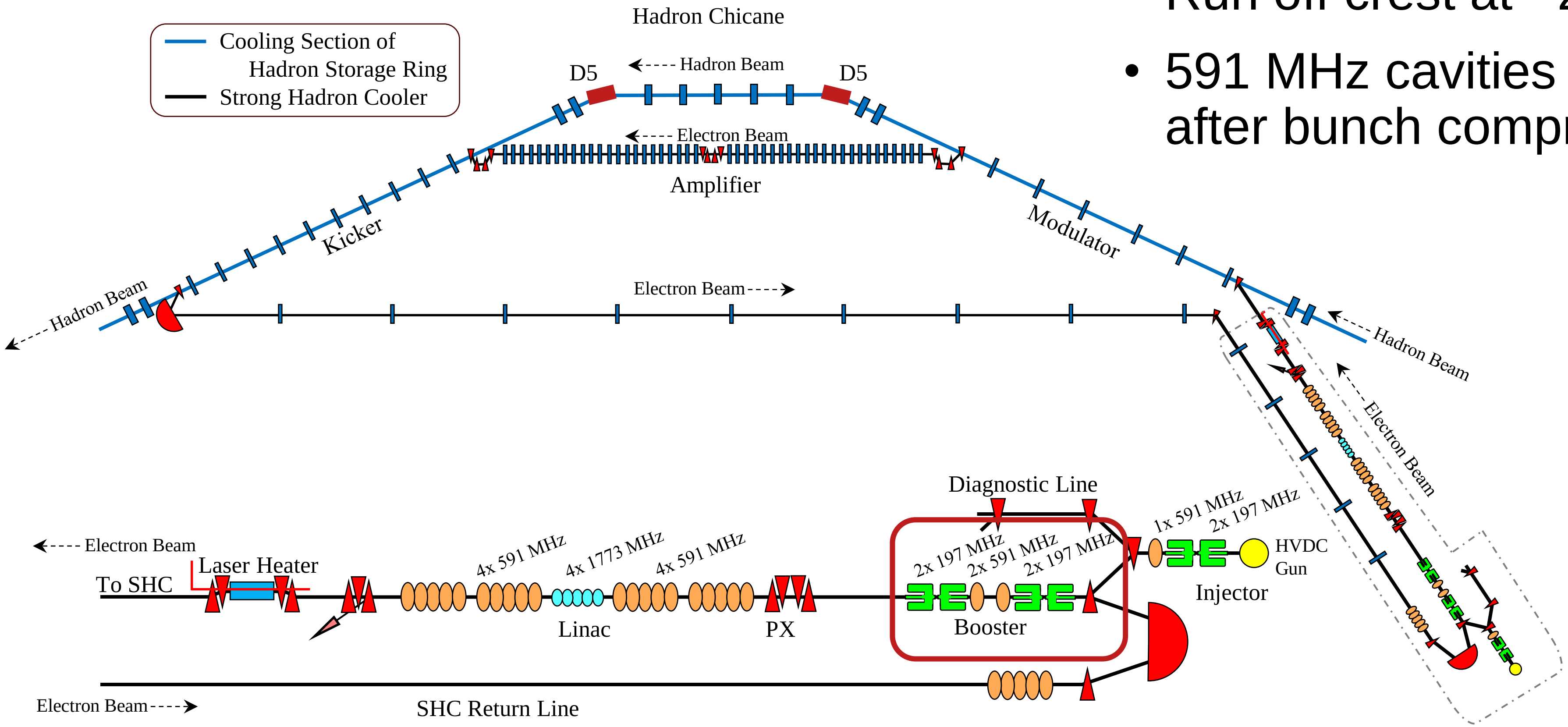


Overview: Merger



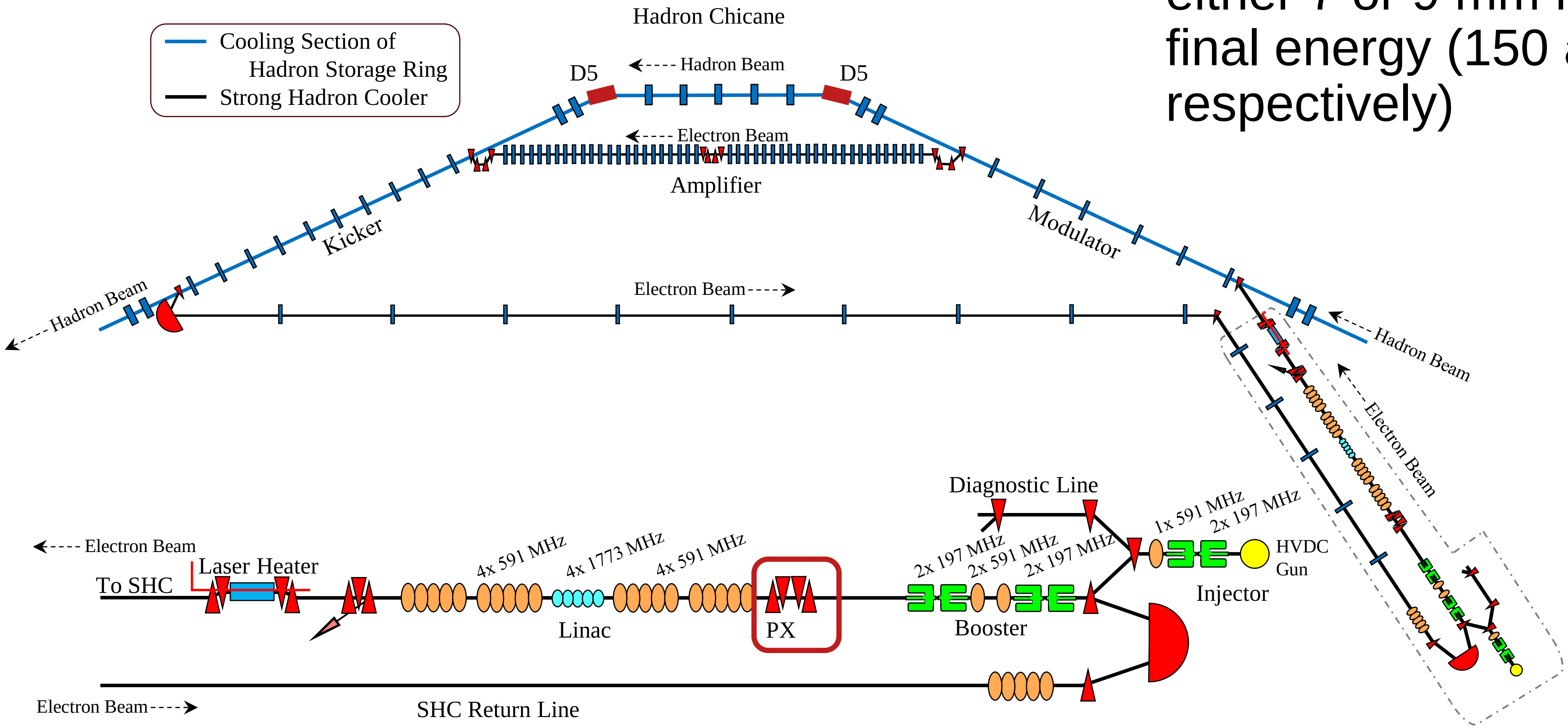
- Dogleg + (2) solenoids
- Solenoids in dispersive region result in equal emittance growth in both planes
- Beam sent to either booster or diagnostic line

Overview: Booster



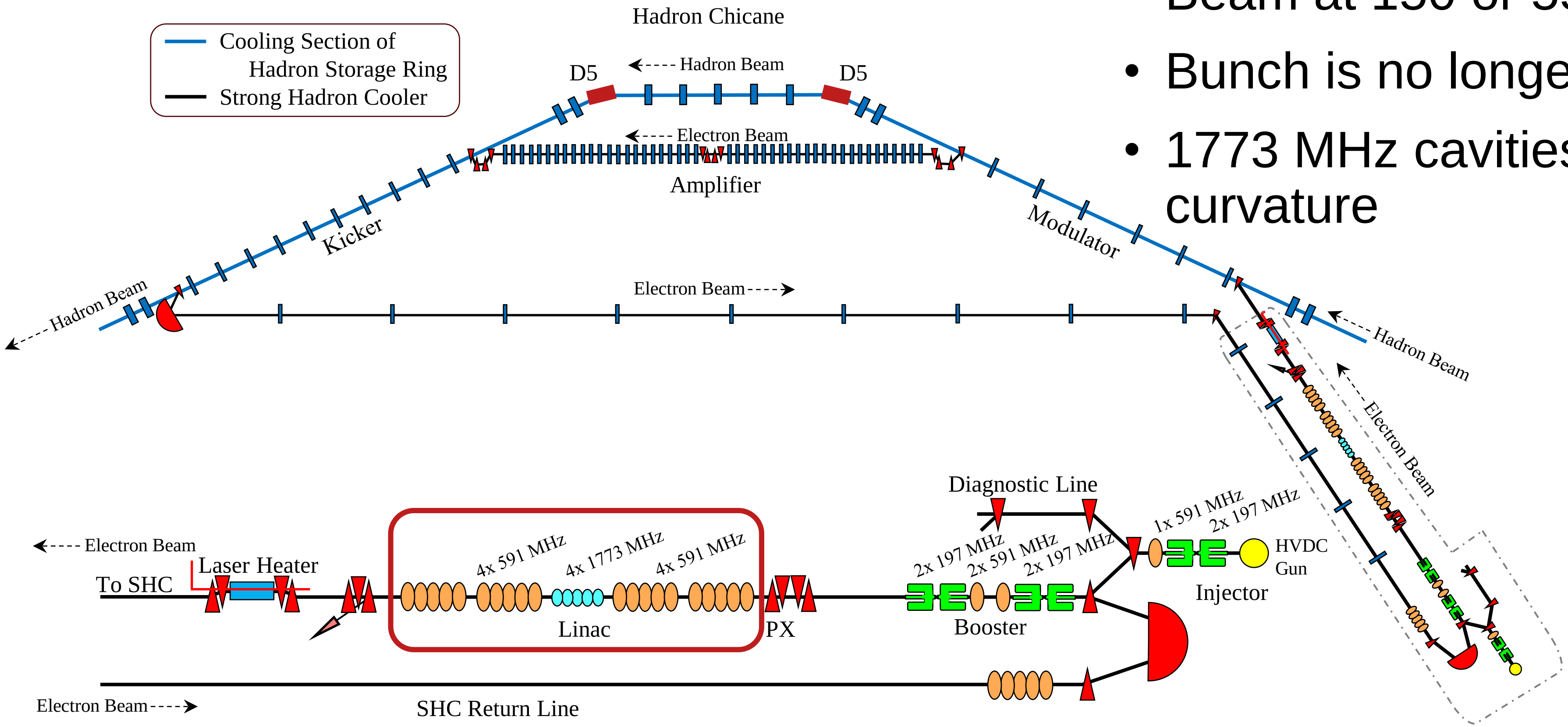
- (2) 197 MHz QWR + (2) 591 MHz single-cell+ (2) 197 MHz QWR
- Run off crest at ~25°, beam at ~13 MeV
- 591 MHz cavities linearize, evaluated after bunch compressor chicane (P1)

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

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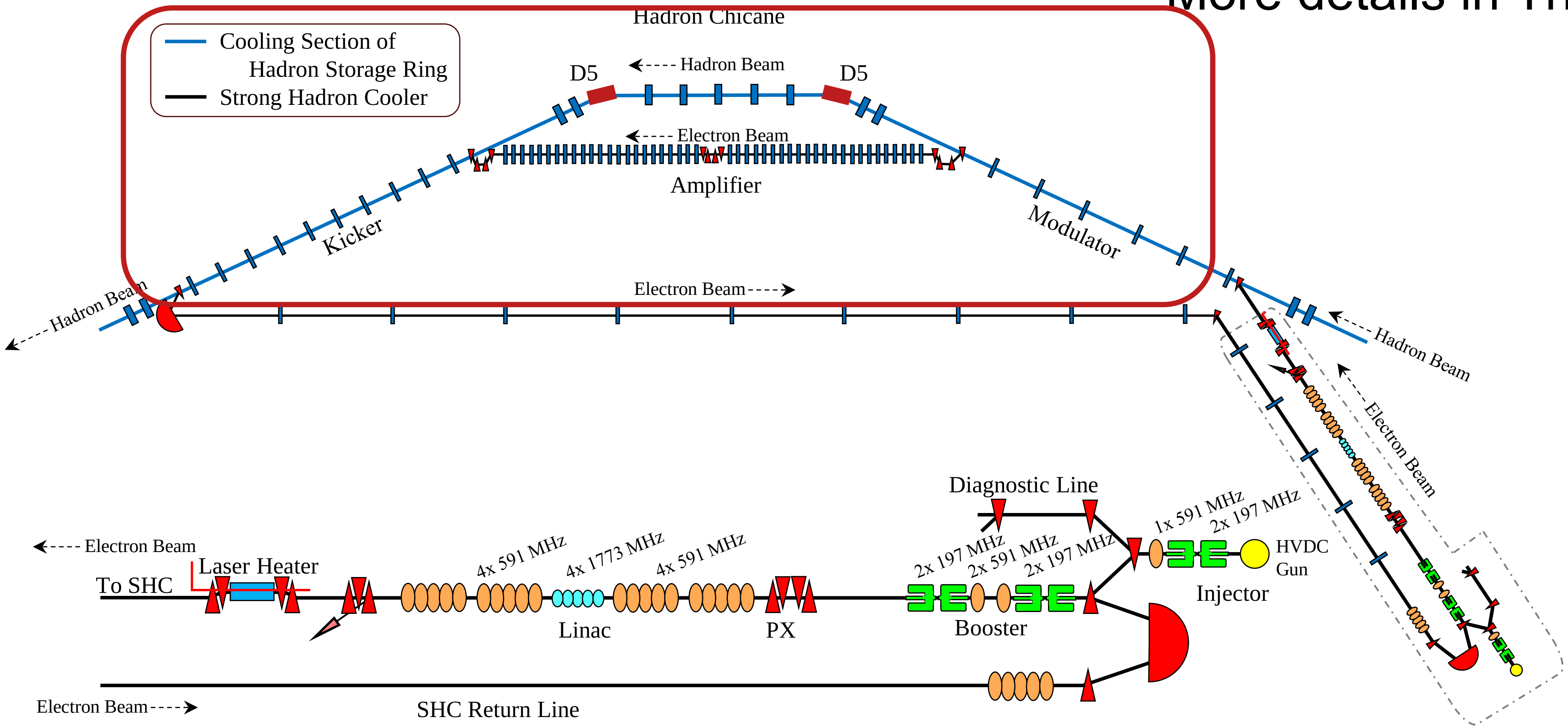
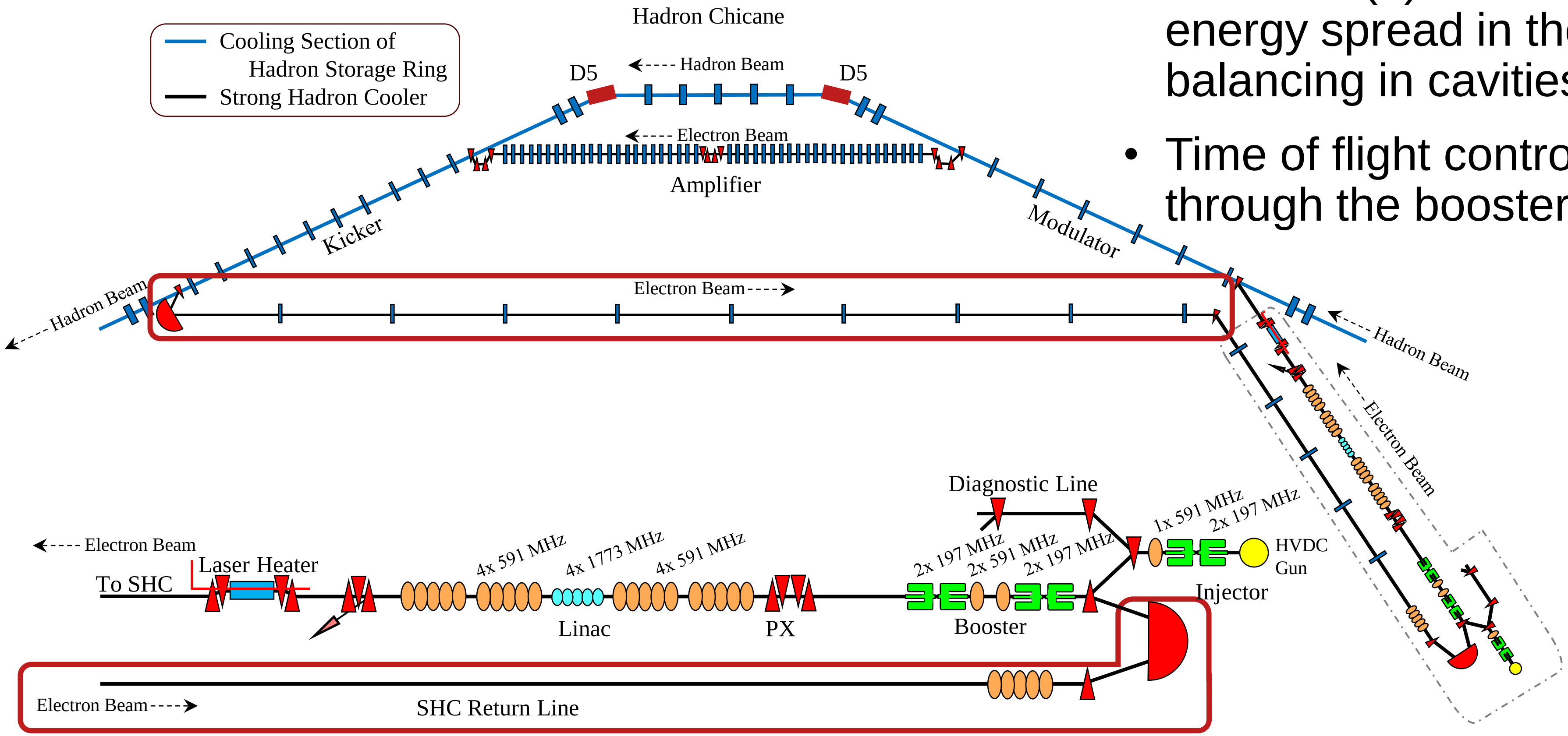
Overview: Cooler

- Beam transported to Hadron Storage Ring, merges, cools, de-merges
- More details in Thursday's talk



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

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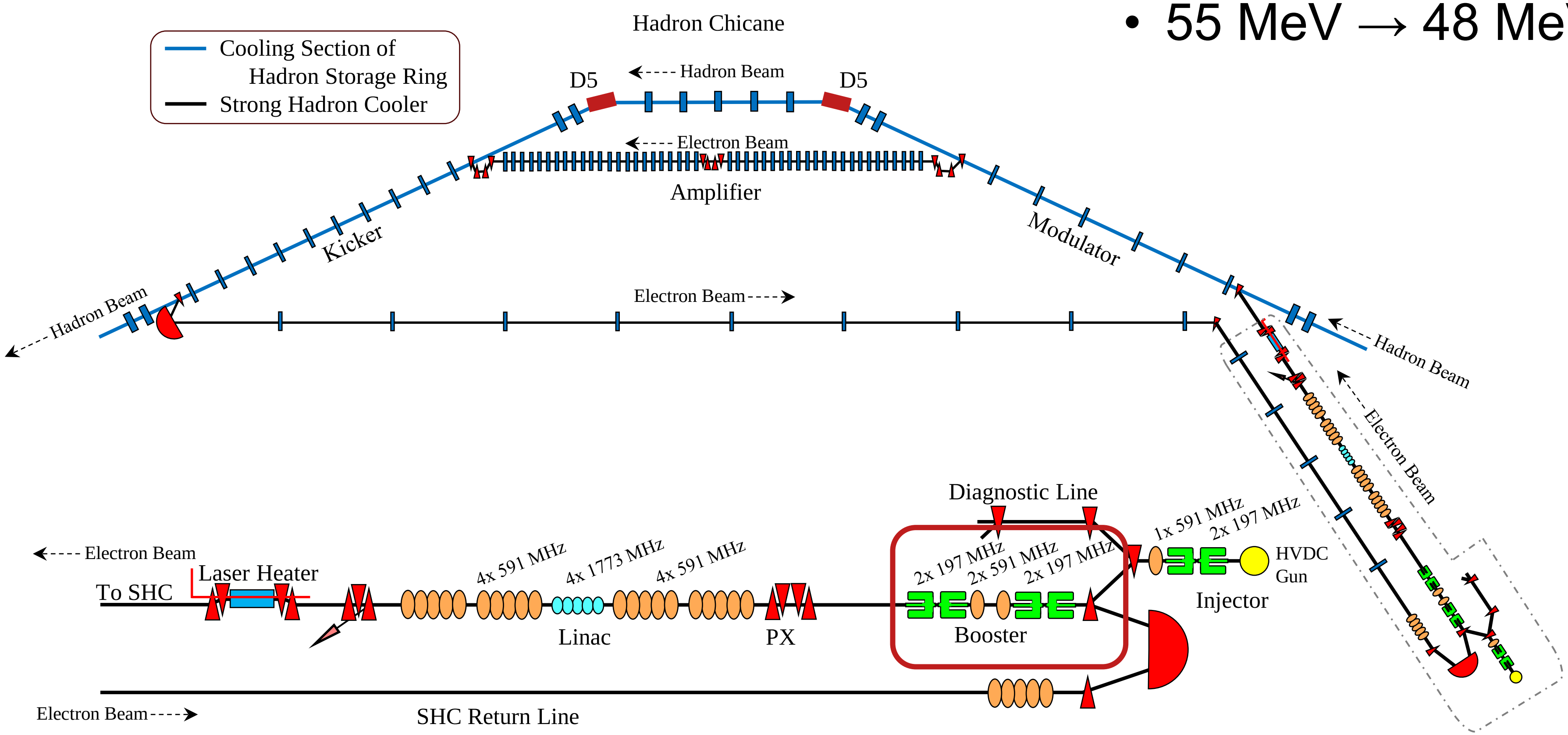
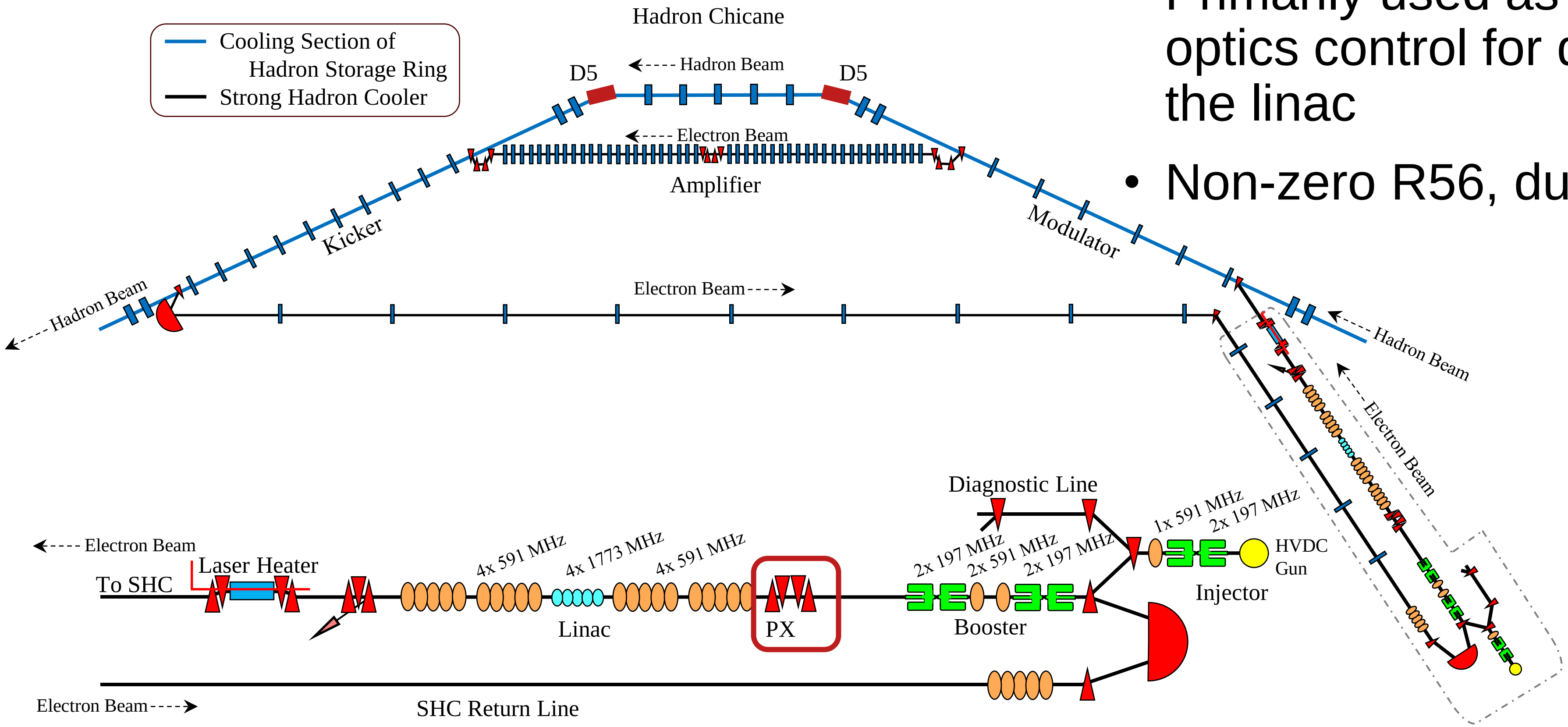
Overview: Booster (2nd Pass)

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



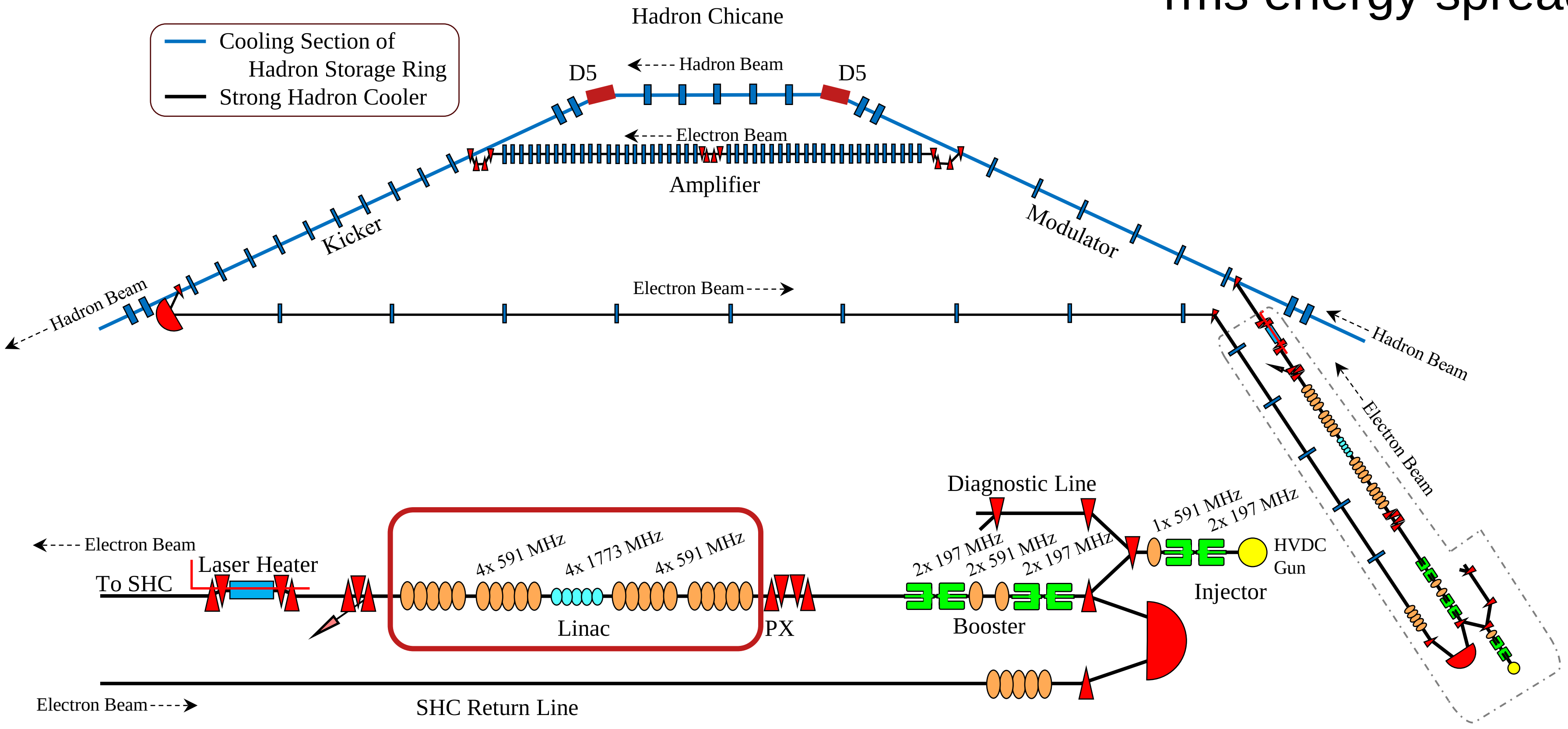
Overview: PX (2nd Pass)

- 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

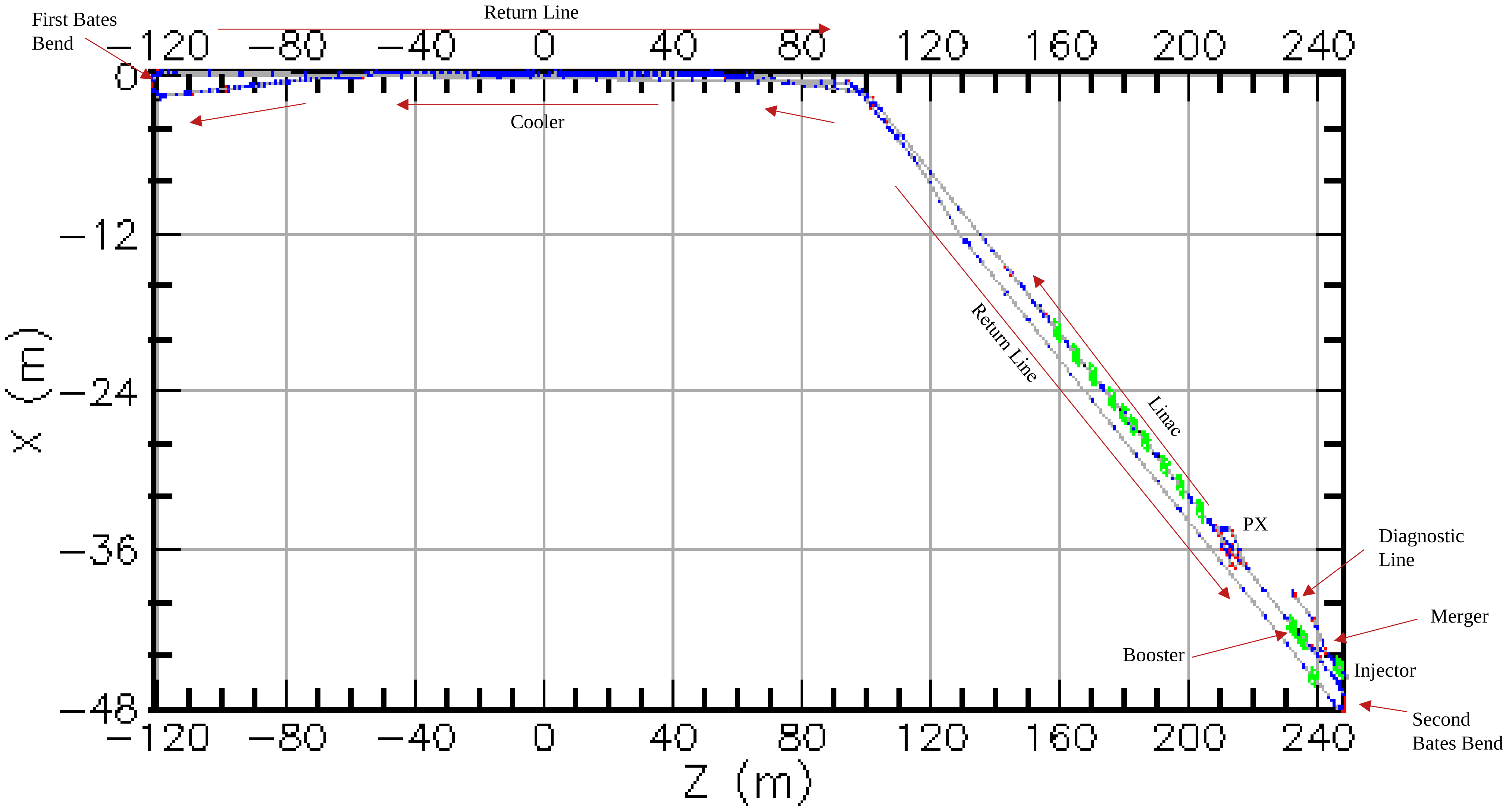


Overview: Linac (2nd Pass)

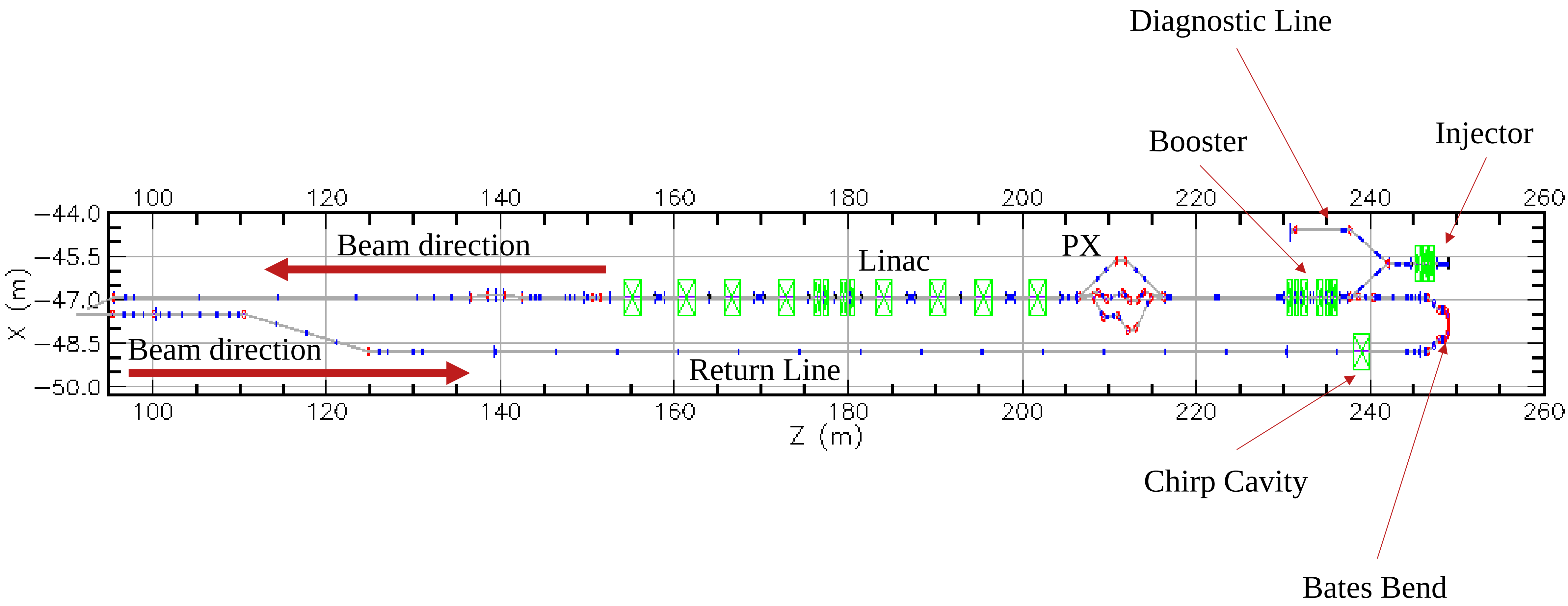
- Decelerate to 6 MeV injection energy
- Beam transported to dump with minimal rms energy spread



Overview: Actual Layout



Overview: Actual Layout



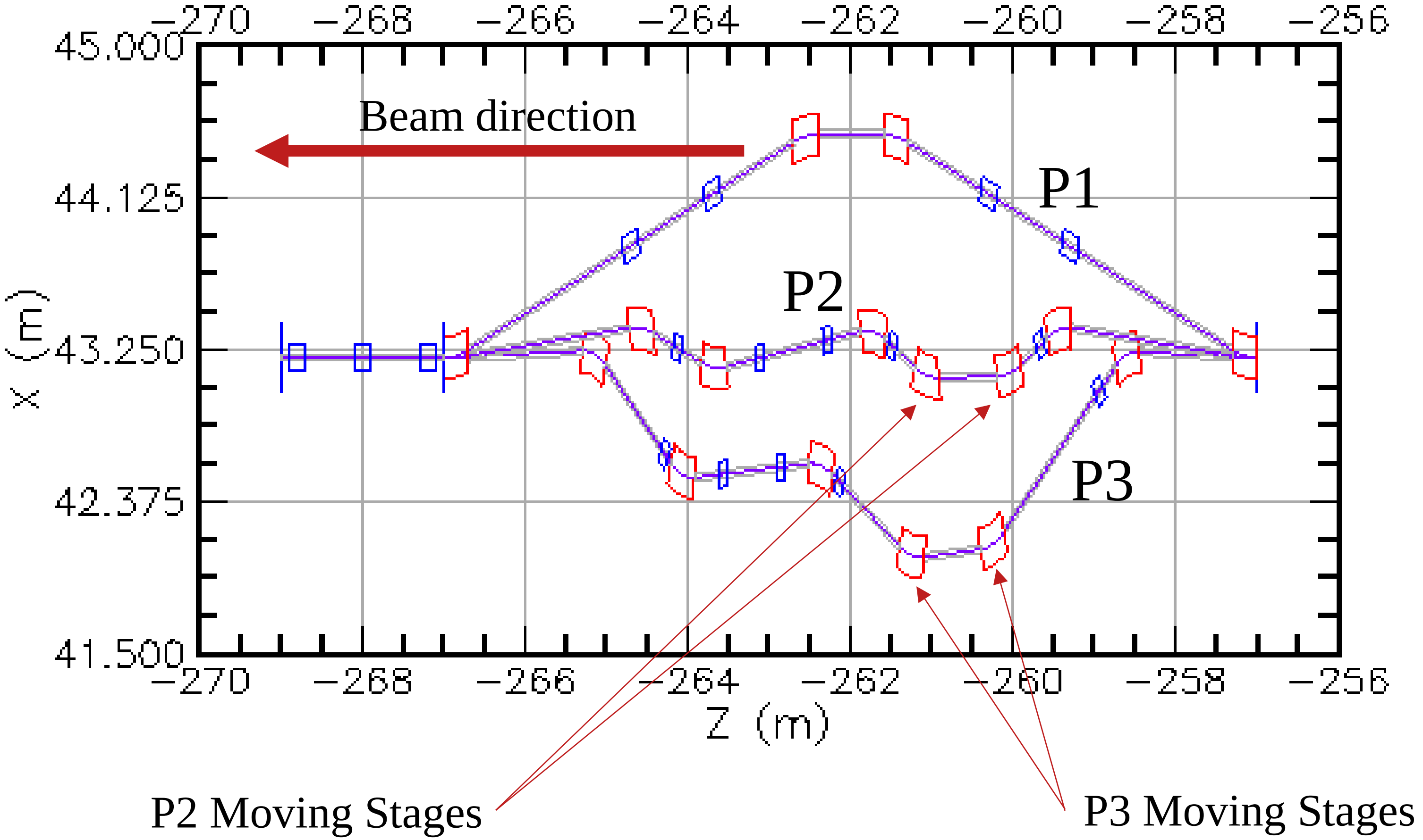
Optics: Time of Flight Requirements

- 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

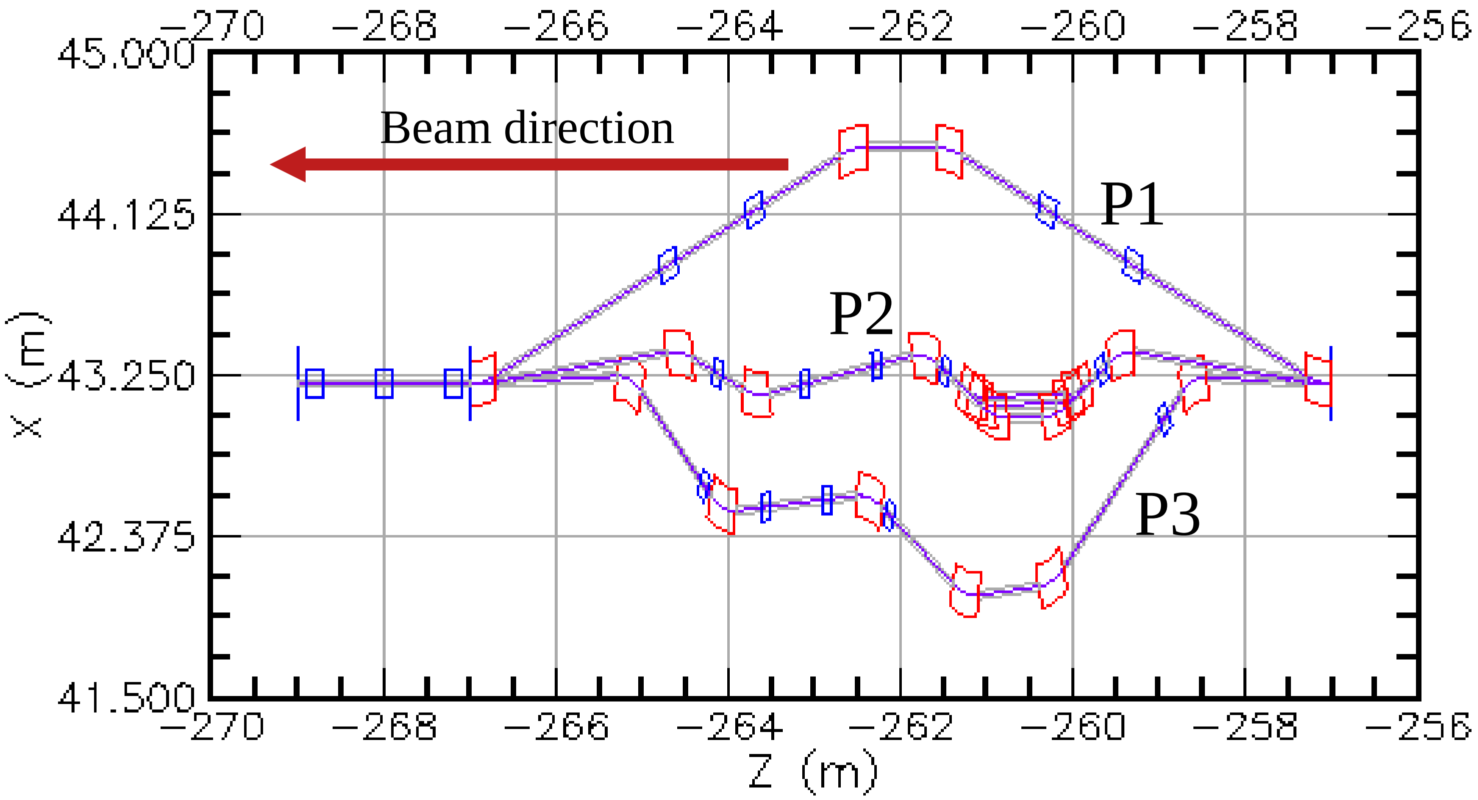
- Booster TOF needs to be correct, due to:
  - The limited range of the moving stage
  - If the decelerating beam enters P2/P3 at an energy significantly different than design, it will be lost on the beam pipe wall



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: +20°/-10°
  - P3: ±55°



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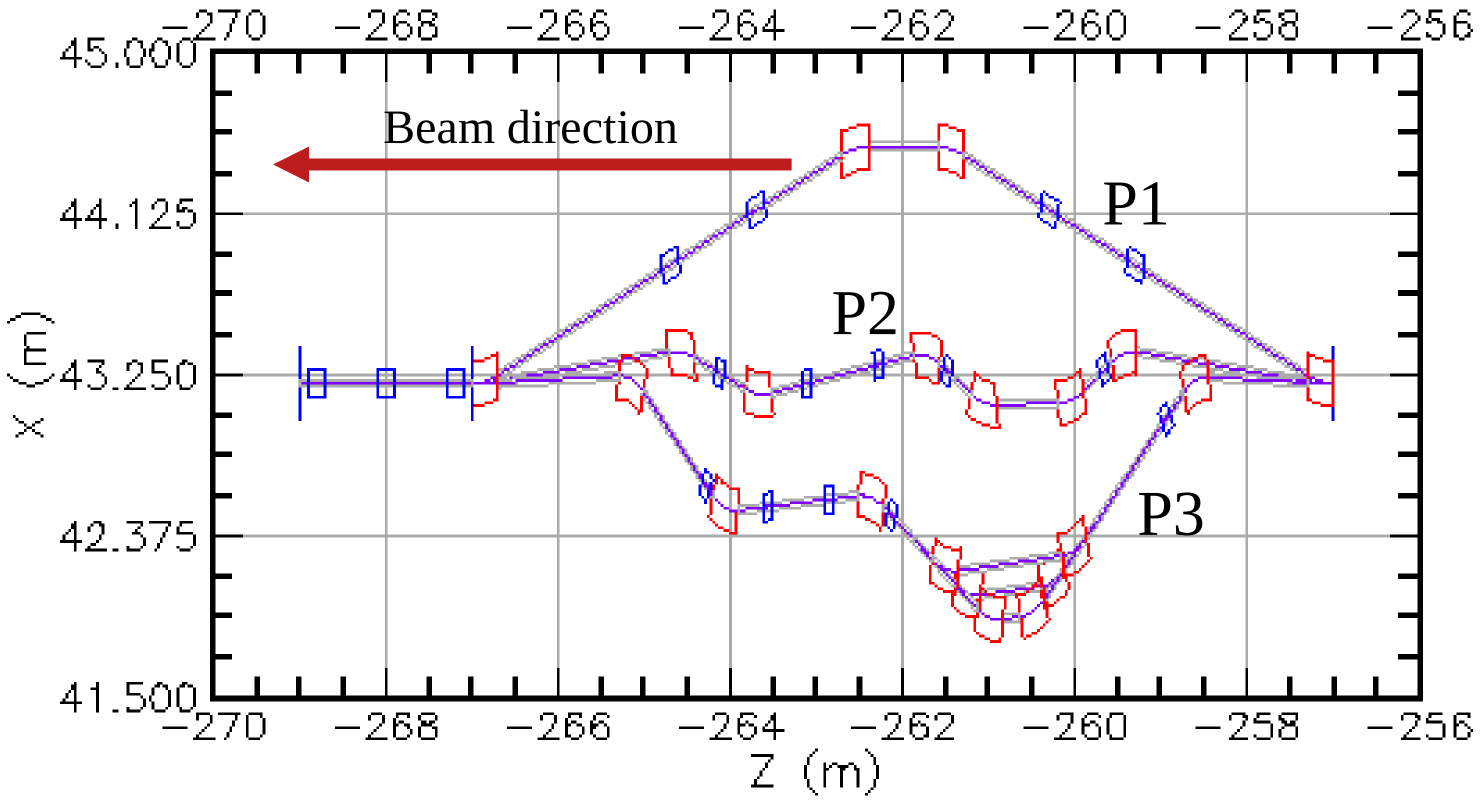

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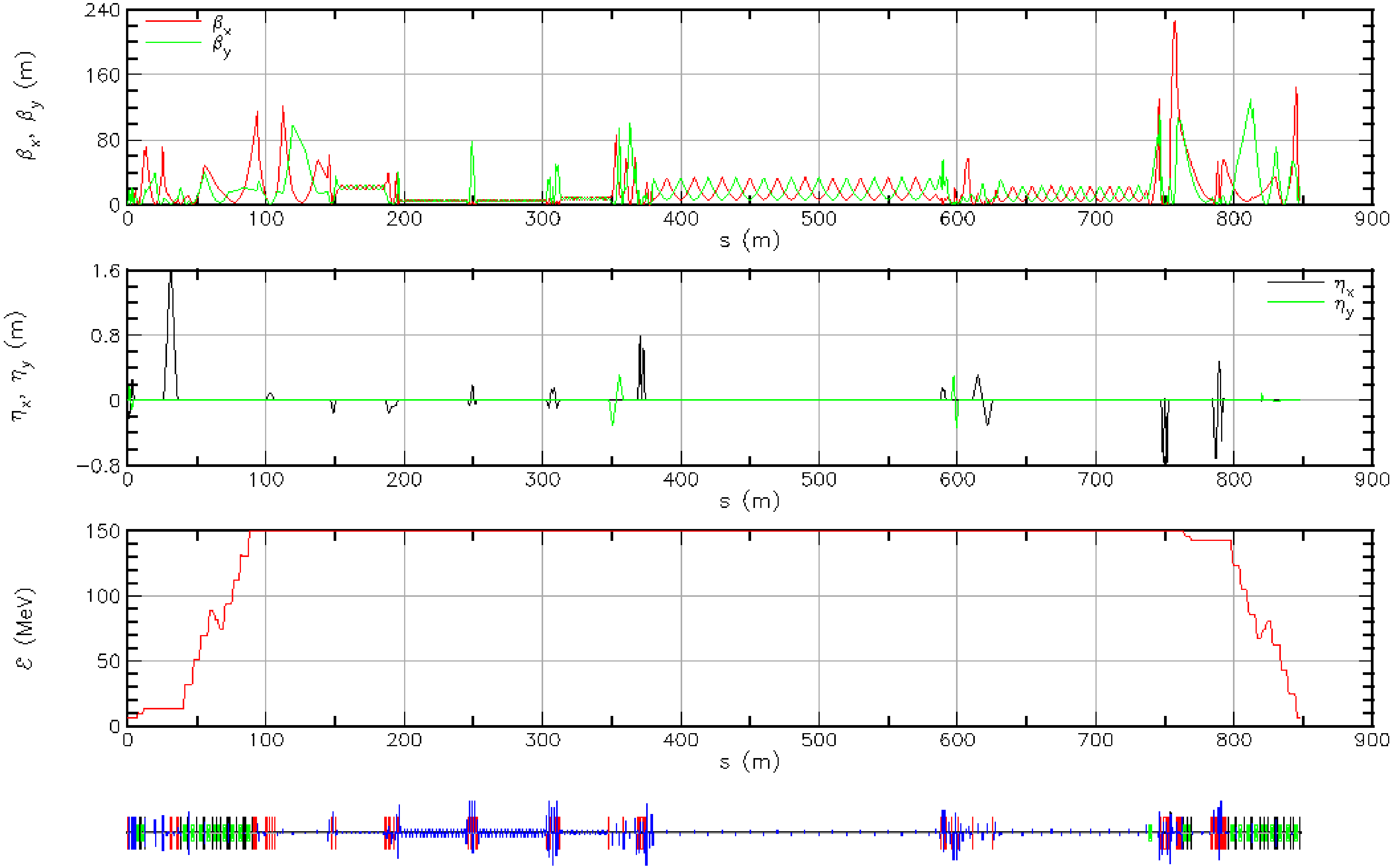
Optics: PX Section

- 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

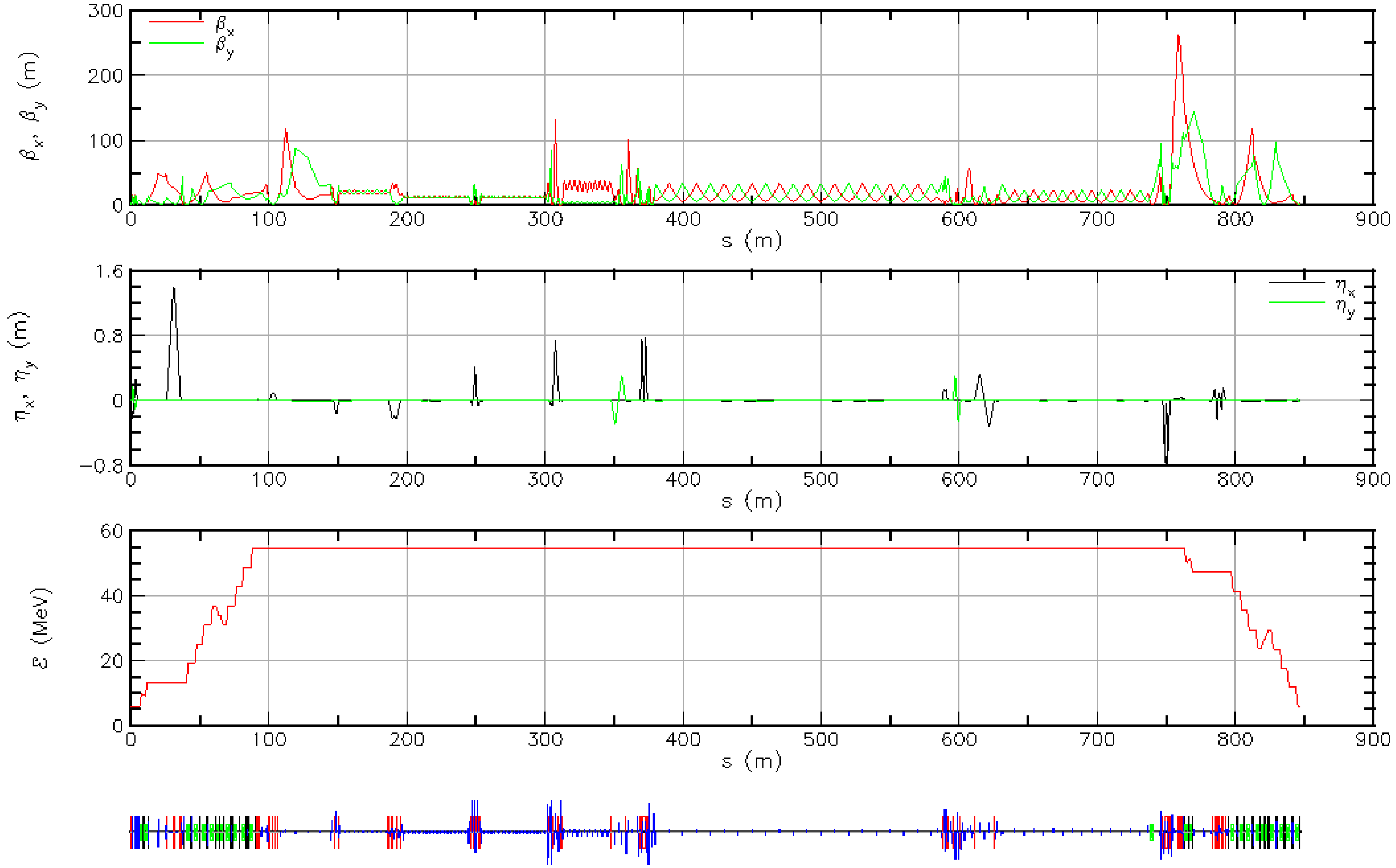
- This has significant drawbacks:
  - Lower energy efficiency
  - Higher radiation shielding requirements at the dump and the diagnostic line

- 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: Transverse



Optics at 55 MeV: Transverse



BBU Instability

- Initial evaluations of the Beam Breakup (BBU) instability have been performed using scaled Higher Order Mode (HOM) parameters from both BNL and PERLE style cavities
  - Some interest in switching to PERLE style cavities in order to reduce linac length

- BNL style cavities are more stable and have significantly higher threshold currents than the PERLE style cavities, and can handles the required average current of 98.5 mA

- PERLE style cavities do not fulfill this requirement

- However, the most dominant cavities are the highest frequency – a hybrid approach to use PERLE style cavities at the lower frequencies and BNL style at the higher frequencies may produce a shorter SRF length while maintaining a sufficiently high threshold current

- See DOI:10.18429/jacow-ipac2024-tupc45 for details

Energy Balance

- In an energy balanced cavity, the beam gains and loses the same amount of energy
- Our setup balances the energy across the booster as a unit and the linac as a unit, so some deviation from balance is seen in every cavity
- The below table gives net deviation from energy balance in kV for each cavity in both energies

	Booster @ 197 MHz						Linac @ 591 MHz											
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10	11	12
150 MeV	16	10	-5	3	-11	-14	4	13	15	16	-7	-7	-7	-7	14	12	4	-49
55 MeV	15	10	-4	3	-11	-14	12	17	18	16	-4	-4	-5	-5	14	9	-4	-65

Third Harmonics (Booster cavities 3–4)

Third Harmonics (Linac cavities 5–8)

Energy Balance

- In an energy balanced cavity, the beam gains and loses the same amount of energy
- Our setup balances the energy across the booster as a unit and the linac as a unit, so some deviation from balance is seen in every cavity

- Additionally, due to the energies involved, the difference in RF phase between the arrival times of the first and second passes are not ever the ideal of 180° in any cavity

- The below table gives arrival time deviation in degrees of RF phase from 180° for each cavity in both energies

	Booster @ 197 MHz						Linac @ 591 MHz											
	1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10	11	12
150 MeV	0.8	0.5	0.6	-1.4	-0.7	-0.9	0.1	-0.4	-0.6	-0.6	-1.7	-1.6	-1.6	-1.6	-0.5	-0.4	-0.1	2.3
55 MeV	0.8	0.5	0.6	-1.3	-0.7	-0.8	-1.3	-2.4	-2.8	-2.6	-7.0	-6.8	-6.5	-6.4	-2.0	-1.3	0.4	5.9

Third Harmonics

Third Harmonics

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Summary

- A preliminary design exists for both design energies of the Strong Hadron Cooler ERL meant to provide 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
- As collective effects and design alternatives are evaluated, we anticipate completing a mature, robust design for an ERL-driven strong cooler

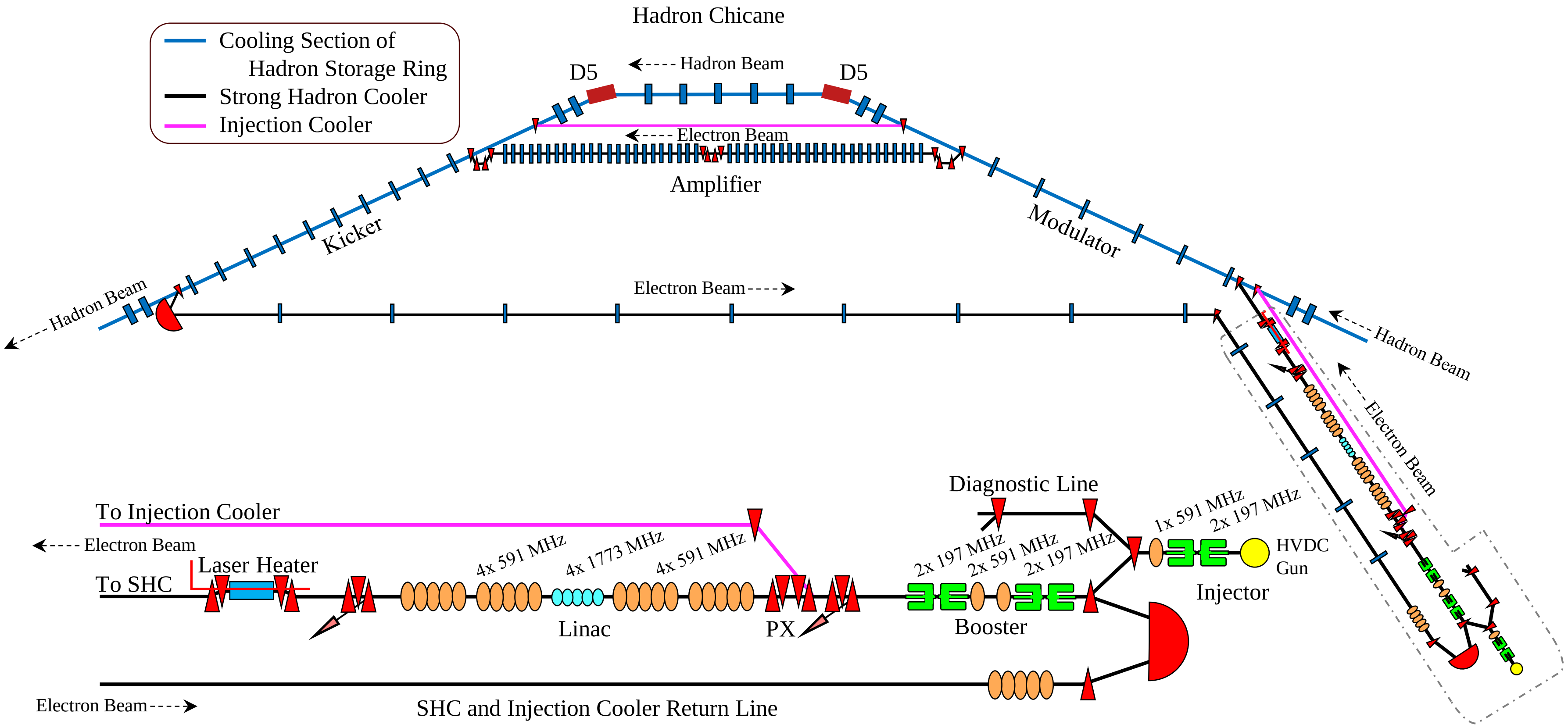
Thanks for your attention!

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_y/β_x in Modulator (m)	20.0 / 20.0	21.4 / 21.4
β_y/β_x in Kicker (m)	29.7 / 4.09	7.89 / 7.89
β_y/β_x 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) https://doi.org/10.18429/jacow-ipac2024-thyd1

Injection Cooler ERL: Layout



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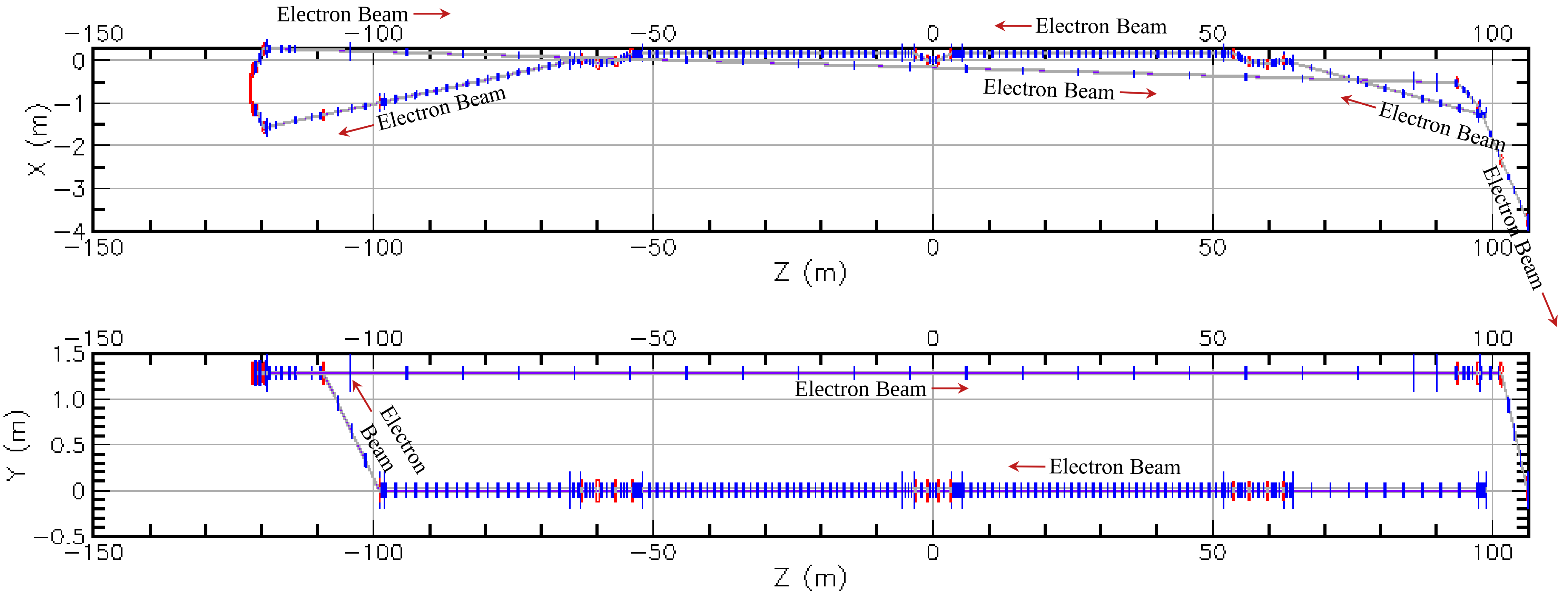
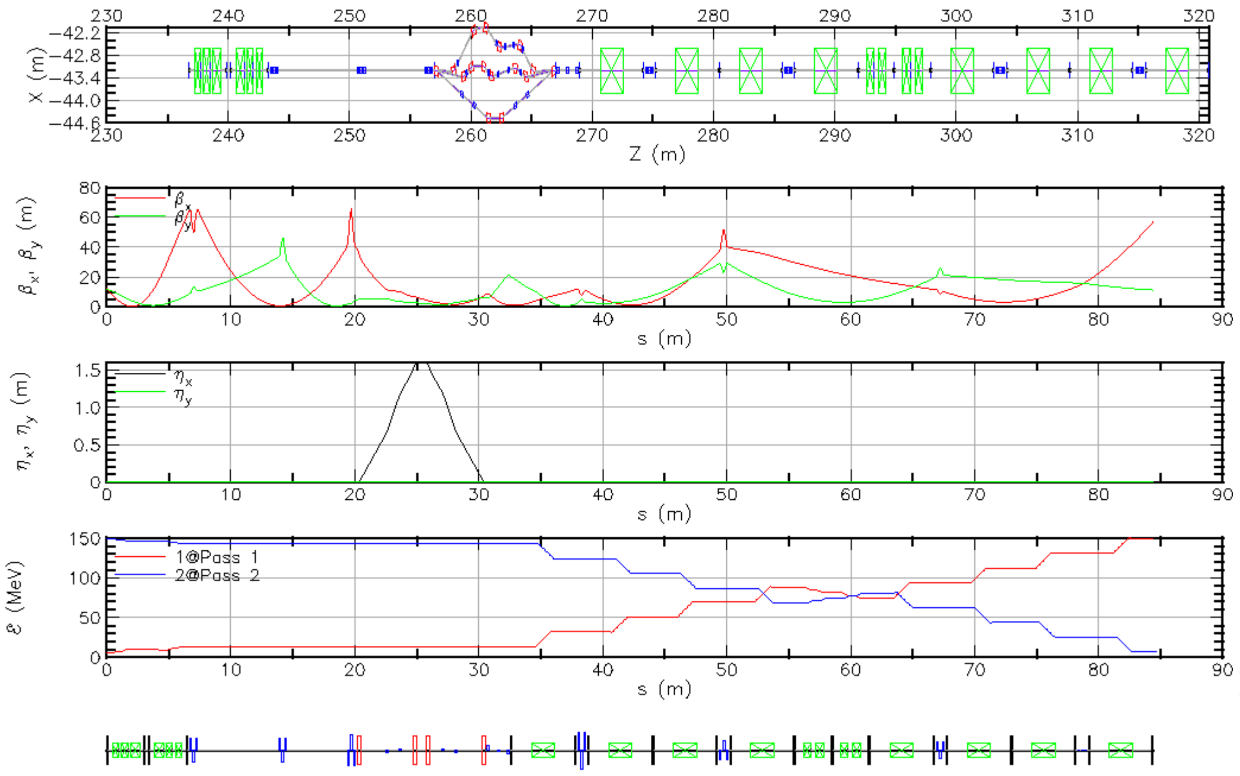
Overview: Actual Layout



- 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

Optics at 150 MeV: Both Passes [Booster:Linac]



- Top: Floor plan from beginning of booster to end of linac
- Mid top: Transverse beta for accelerating pass
- Mid bottom: Dispersion for accelerating pass
- Bottom: Energy for both passes

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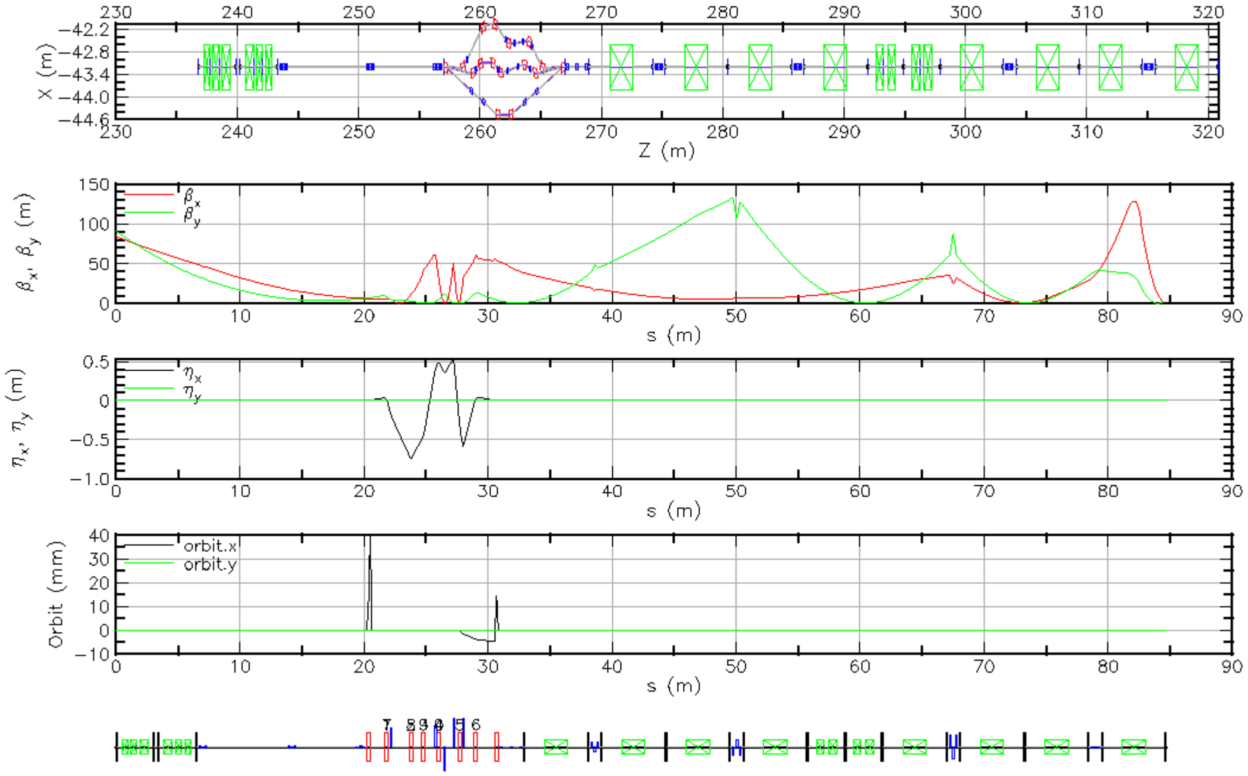
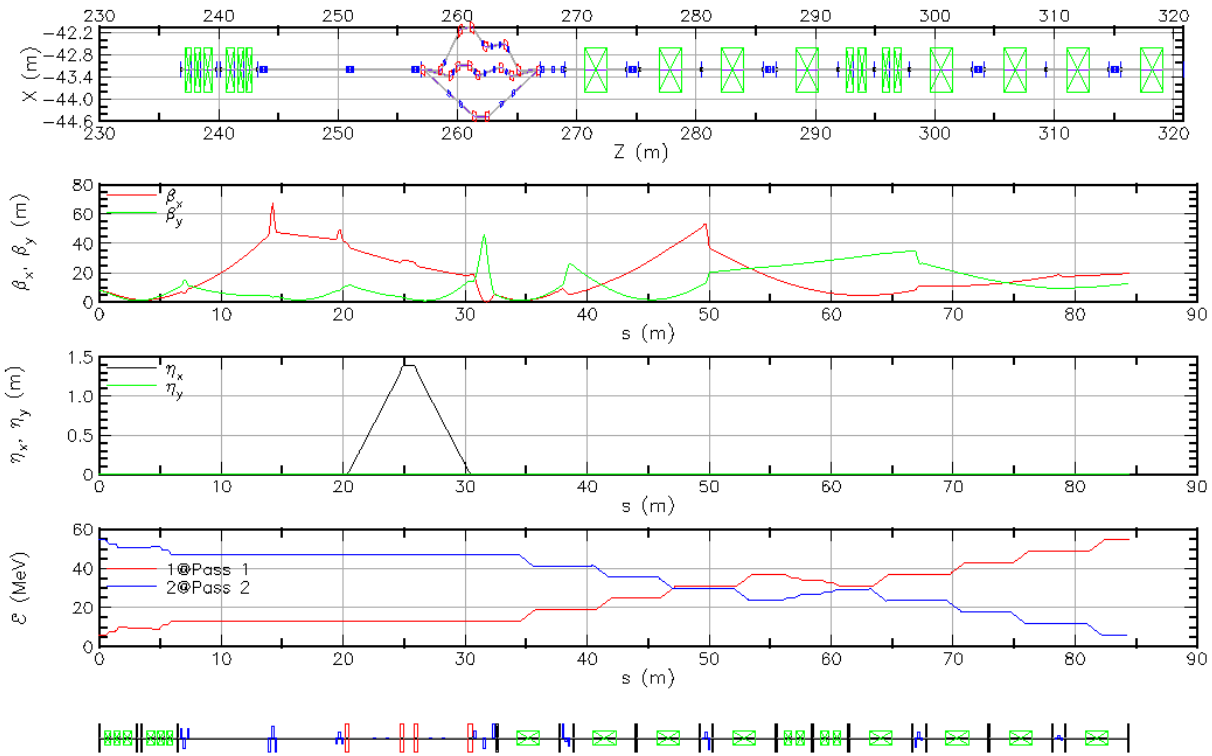


Optics at 55 MeV: Both Passes [Booster:Linac]



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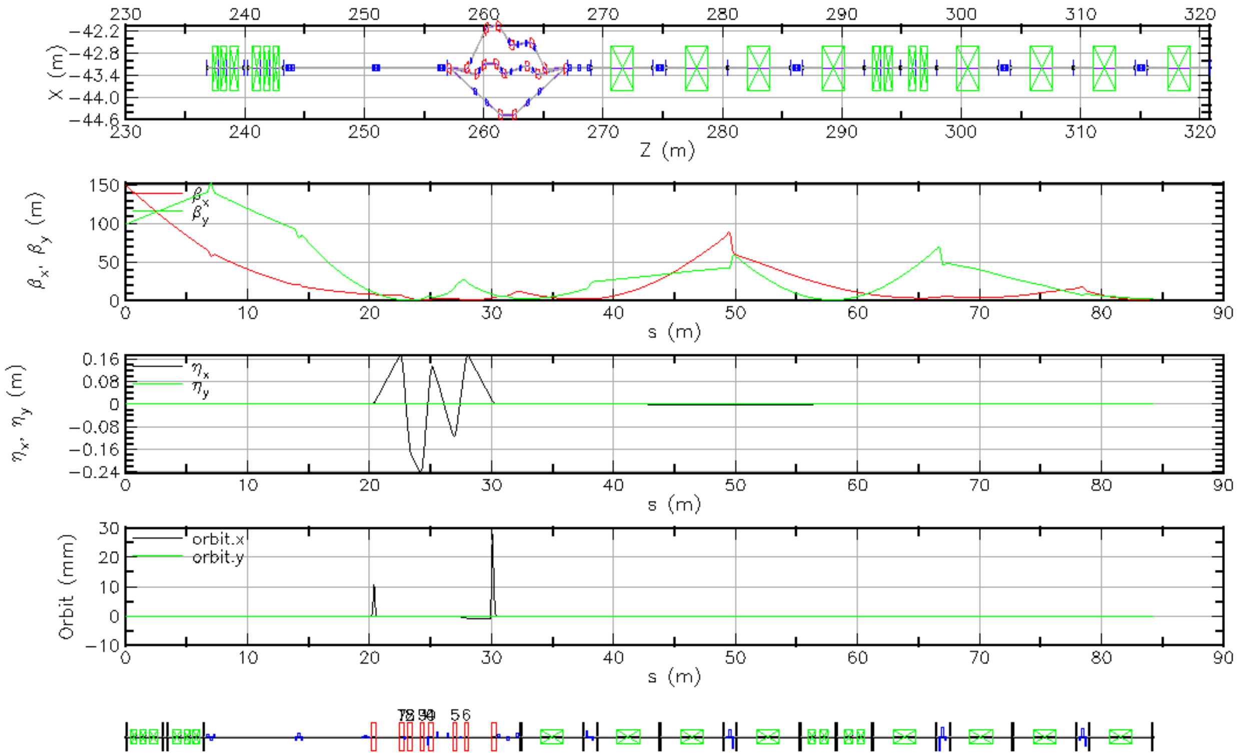

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