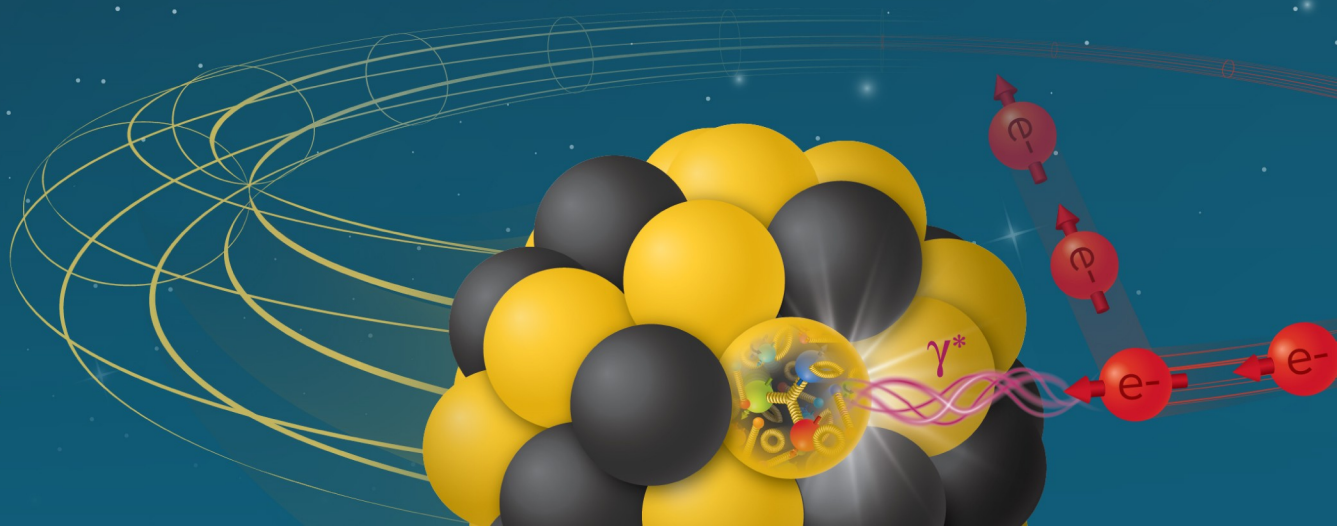
Brookhaven National Laboratory | Jefferson Lab | U.S. DEPARTMENT OF ENERGY

Minimizing Unwanted Beam Current In The Electron-Ion Collider

Arshdeep Singh on behalf of the EIC LLRF Team

2026-10-13



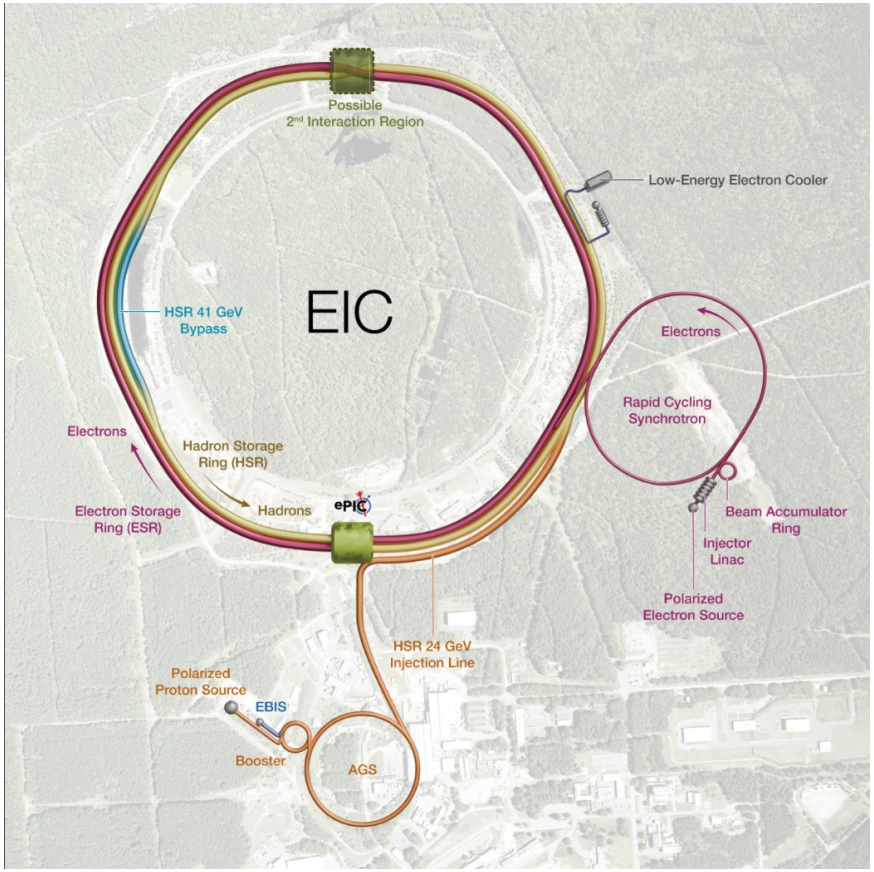
Electron-Ion Collider

Overview

- Introduction & Background
- Nominal Conditions
  - Bunch Splitting
  - Beam Current
- Beam Current Minimization
  - Strategy
  - Deviations
  - Use of feedback
- Conclusion

EIC Overview

- The EIC is a future collider to be built at BNL
  - High luminosity :
    - Between 10^{33}-10^{34} $cm^{-2}s^{-1}$
  - Wide range of COM energies :
    - ~ 20-140 GeV
  - Polarized electron and hadron (p, He-3) beams
    - ~ 70 %
- The EIC will repurpose hardware from RHIC
  - 28 MHz and 197 MHz cavities



Hadron Storage Ring (HSR) Overview

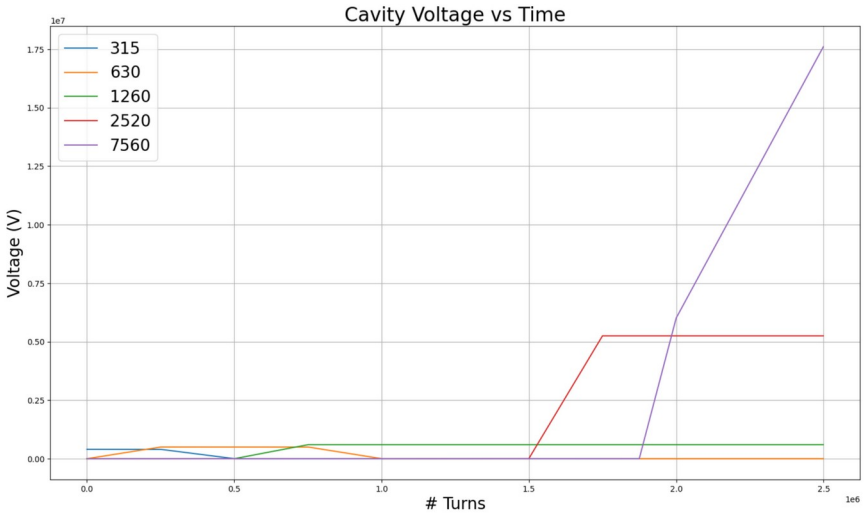
- To reach it's peak luminosity, the HSR will perform bunch splitting
  - Perform a 1 => 2 => 4 bunch split
    - From H=315 to H=1260
- The HSR will first capture and accelerate the beam, then perform bunch splitting, and finally compress the beam for collisions

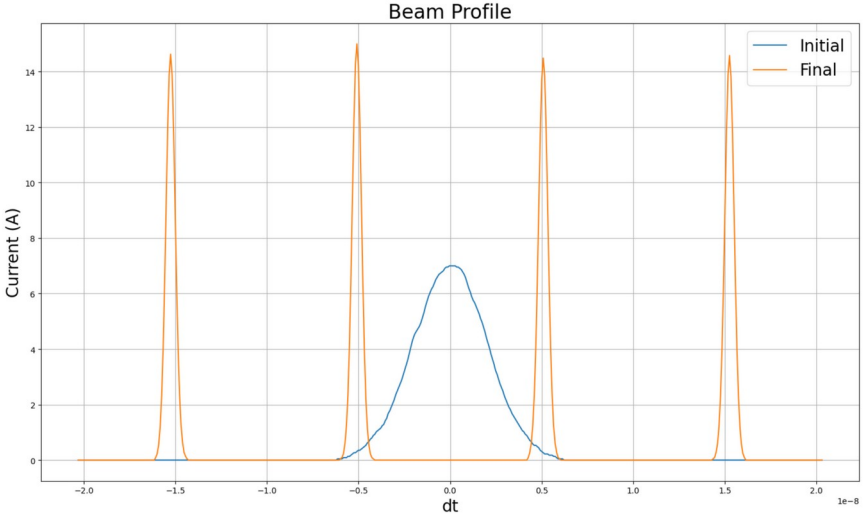
Frequency [MHz]	Function	# Cavities	V / Cavity [MV]
24.6	Capture/ Acceleration	4	0.150
49.2	Splitting	3	0.167
98.5	Splitting	4	0.150
197	Storage	8	0.750
591	Storage	4	4.0

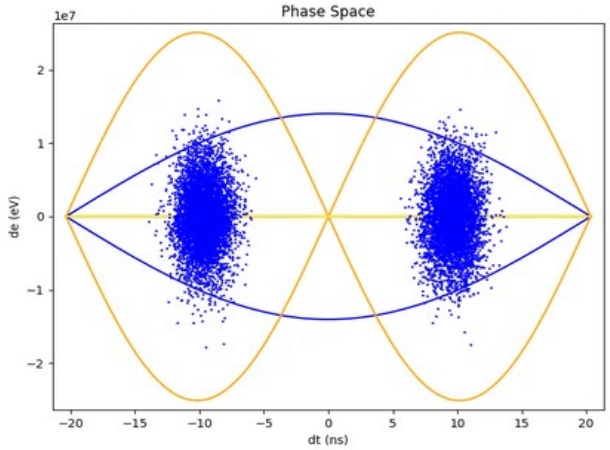
Table : Overview of RF Systems in the HSR

Nominal Bunch Splitting

- DC current of 1 A and a peak current of about 15 A



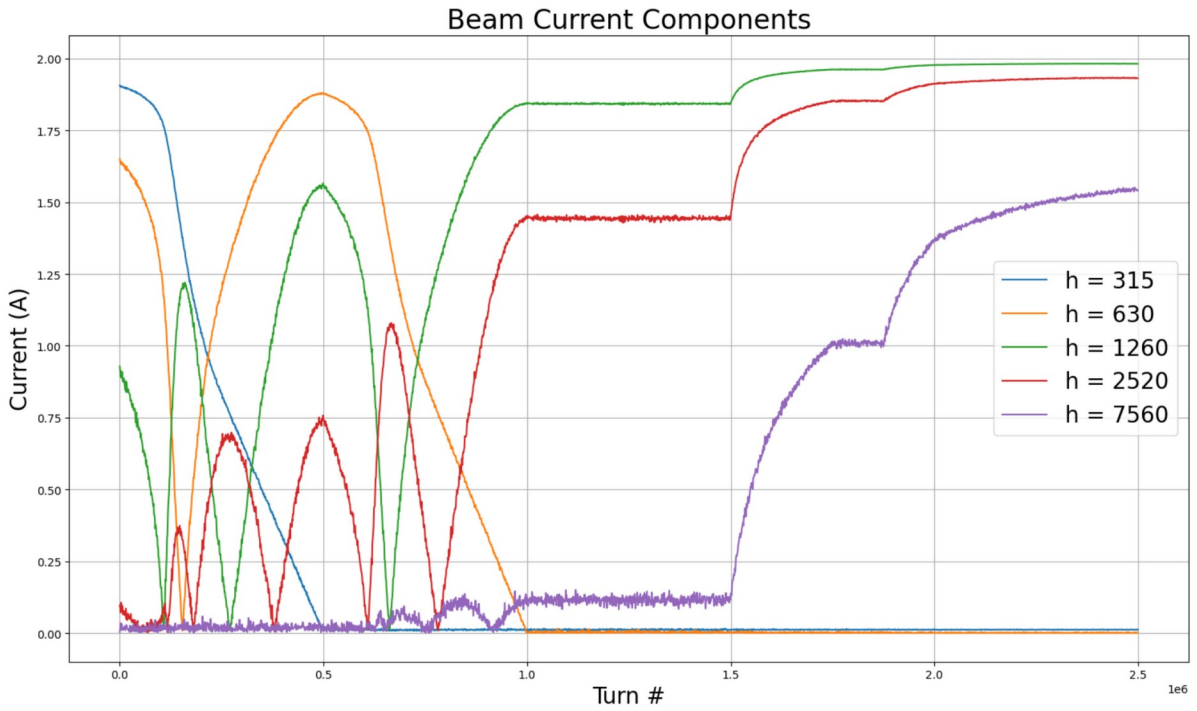




Nominal Beam Current

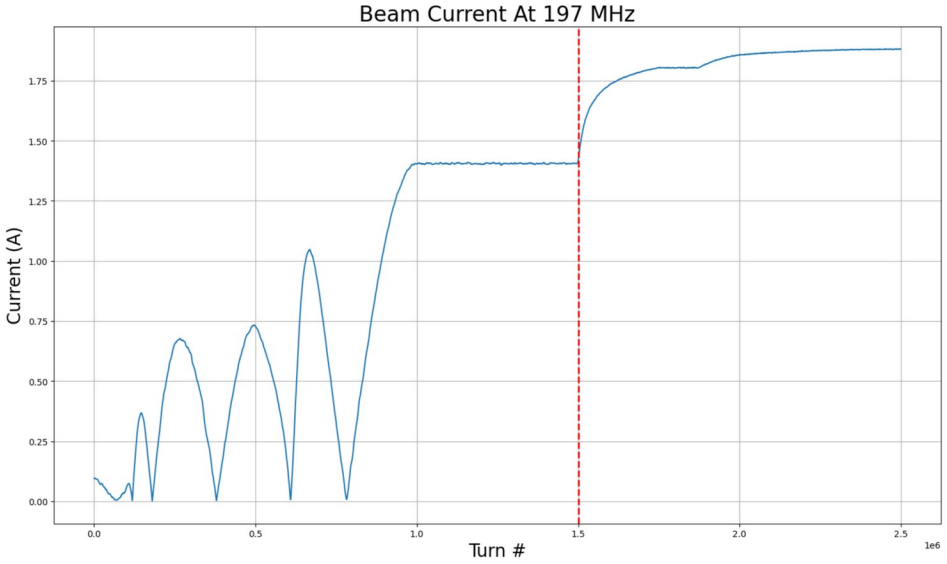
- The beam current at each RF harmonic evolves through the splitting process
- All HSR RF systems will use analog feedback for impedance reduction
  - > 35 dB loop gain, ~ 300 ns loop delay
- When V_C ~= 0 V, the PA has to be equal and opposite the beam current
  - Can run into power limitations due to high beam current in the EIC

RF beam current at each harmonic WRT turn #



197 MHz Beam Component

- The 197 MHz (H=2520) beam component is of particular concern. Doing some rough calculations:
  - The 197 MHz systems will reuse RHIC hardware, the PA is limited to around 10 A anode current
  - With a transformation ratio of 1:117 from the PA to the cavity, we get an upper limit for the generator current of about 85 mA
  - The 197 MHz beam component reaches almost 1.5 A while $V_c = 0$ V, more than 17 times what the generator can provide
  - Unmitigated beam-induced voltage will diminish achievable luminosity



The red line indicates when the voltage on the 197 MHz cavities are ramped up

Minimizing The 197 MHz Beam Component

- Instead of fighting the full beam-loading, we can minimize it
- The EIC has 8 197 MHz cavities, one of these can be counterphased and used as a “defocusing” cavity
  - **We can reshape the bunch to minimize the 197 MHz beam component** [M. Blaskiewicz]
- Most likely, the defocusing cavity cannot be converted back to a focusing cavity after the bunch splitting is complete [K. Mernick]
  - Will need to cross the cavity resonance using the tuner
    - Strong beam-loading
  - We don’t need the full voltage from 8 cavities
    - Need enough bucket area to transfer the beam to the 591 MHz bucket. Can be done with 7 focusing and 1 defocusing cavity.

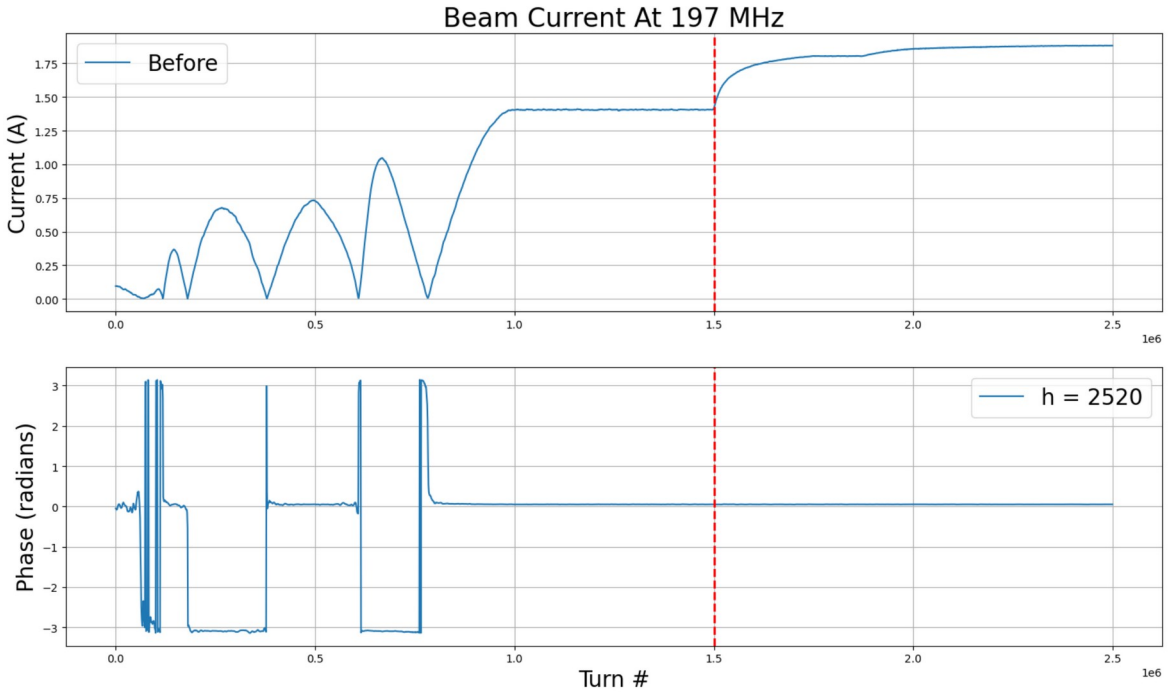
Finding The Defocusing Voltage Program

- Longitudinal tracking simulation is used to determine the defocusing voltage program:
  - At t=0, perform a voltage scan (phase is either 0 or π) and find the value which minimizes the 197 beam component
  - Then, every N turns, scan around the previous voltage value until the beam component is again minimized
  - The defocusing phase alternate between 0 and π (in accordance with the beam phase)*
- If we calculate the defocusing voltage often enough (if N is small) and if the granularity of our voltage scan is fine enough:
  - We will end up with a smooth voltage program that minimizes the beam component while preserving adiabaticity and emittance

* more details on the next slide

Note On The Defocusing Phase

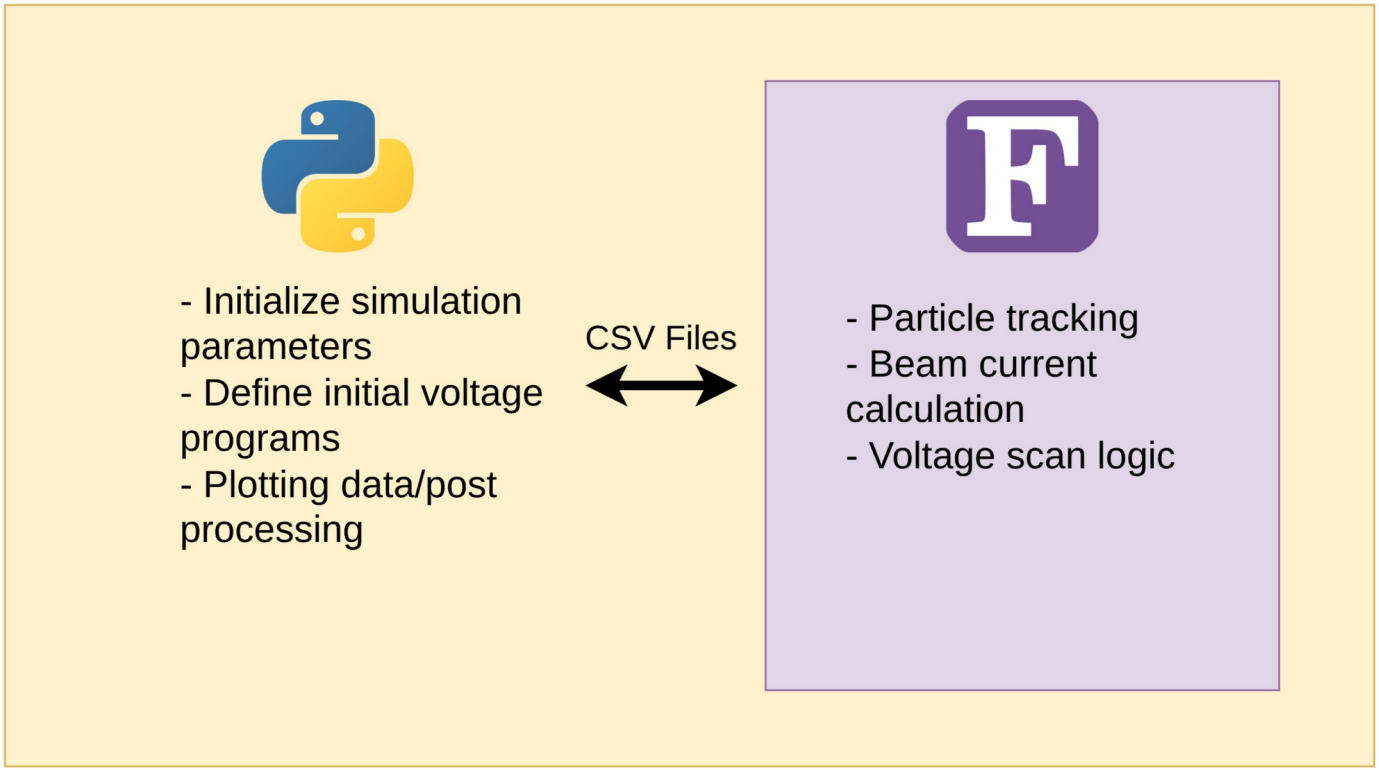
- If we look at the beam current and phase at 197 MHz during the nominal split:



- Notice the beam phase switches each time the current goes to 0
- The defocusing voltage will do the same
  - No issue with suddenly jumping between phases as the switch will happen when the voltage is at 0

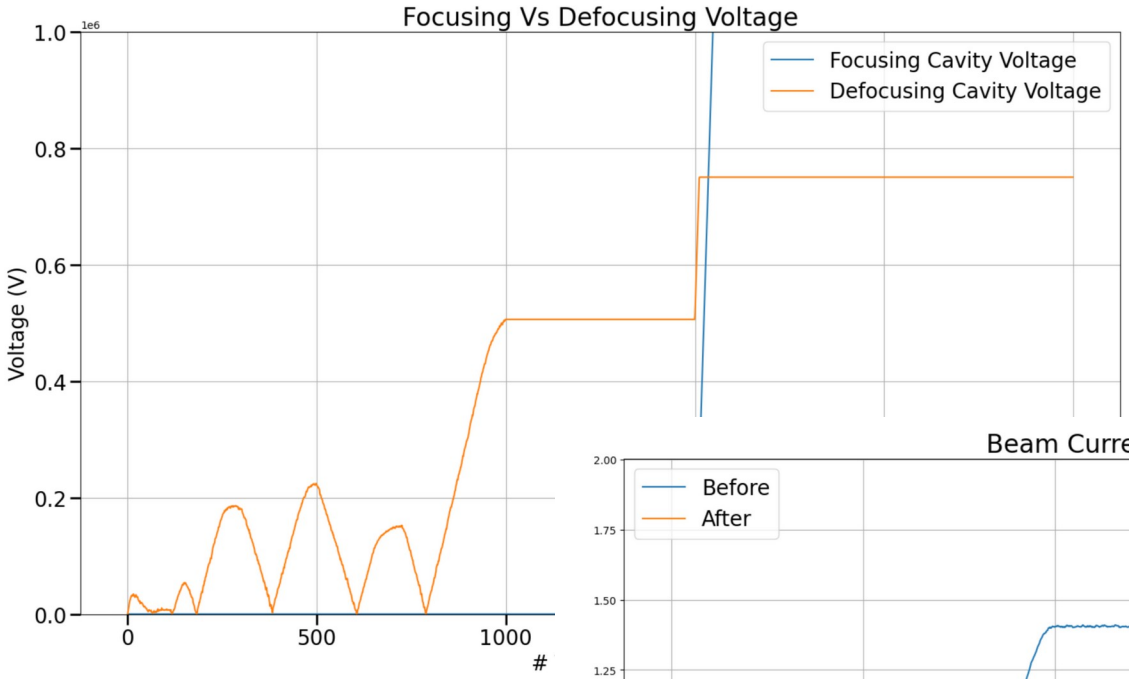
The Simulation Code

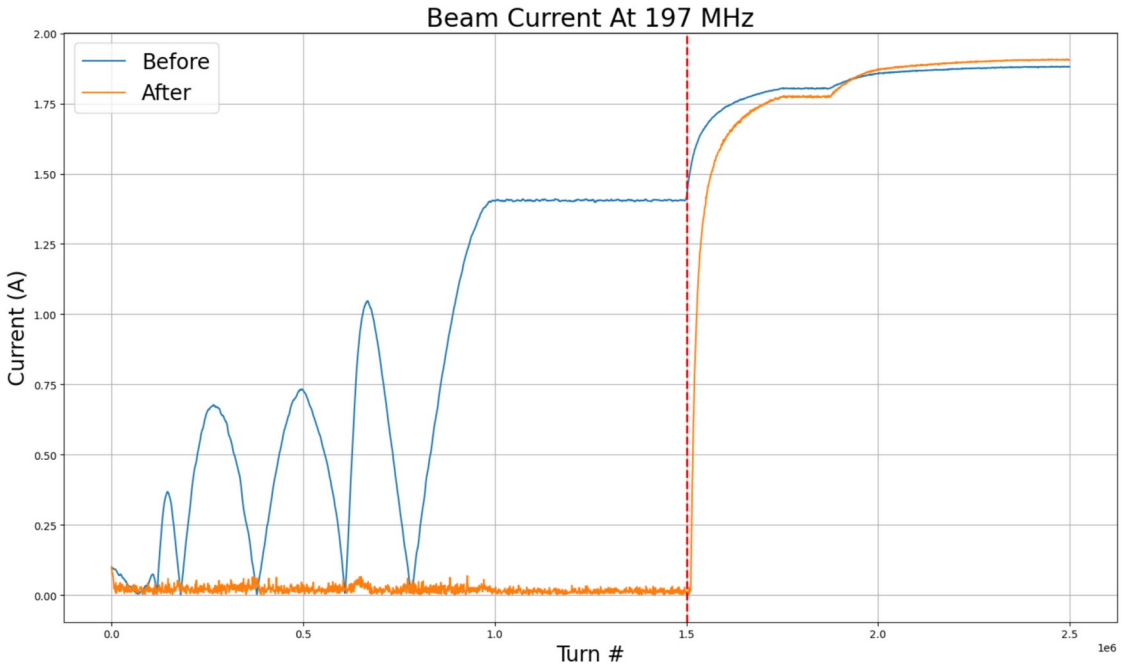
- The simulations are fairly simple : longitudinal tracking + a few calculations
- The code is written in house. It is a combination of FORTRAN wrapped in Python
  - Take advantage of OpenMP in FORTRAN for speed



Initial Results : Defocusing Voltage

- Ran simulations using 100e3 macroparticles

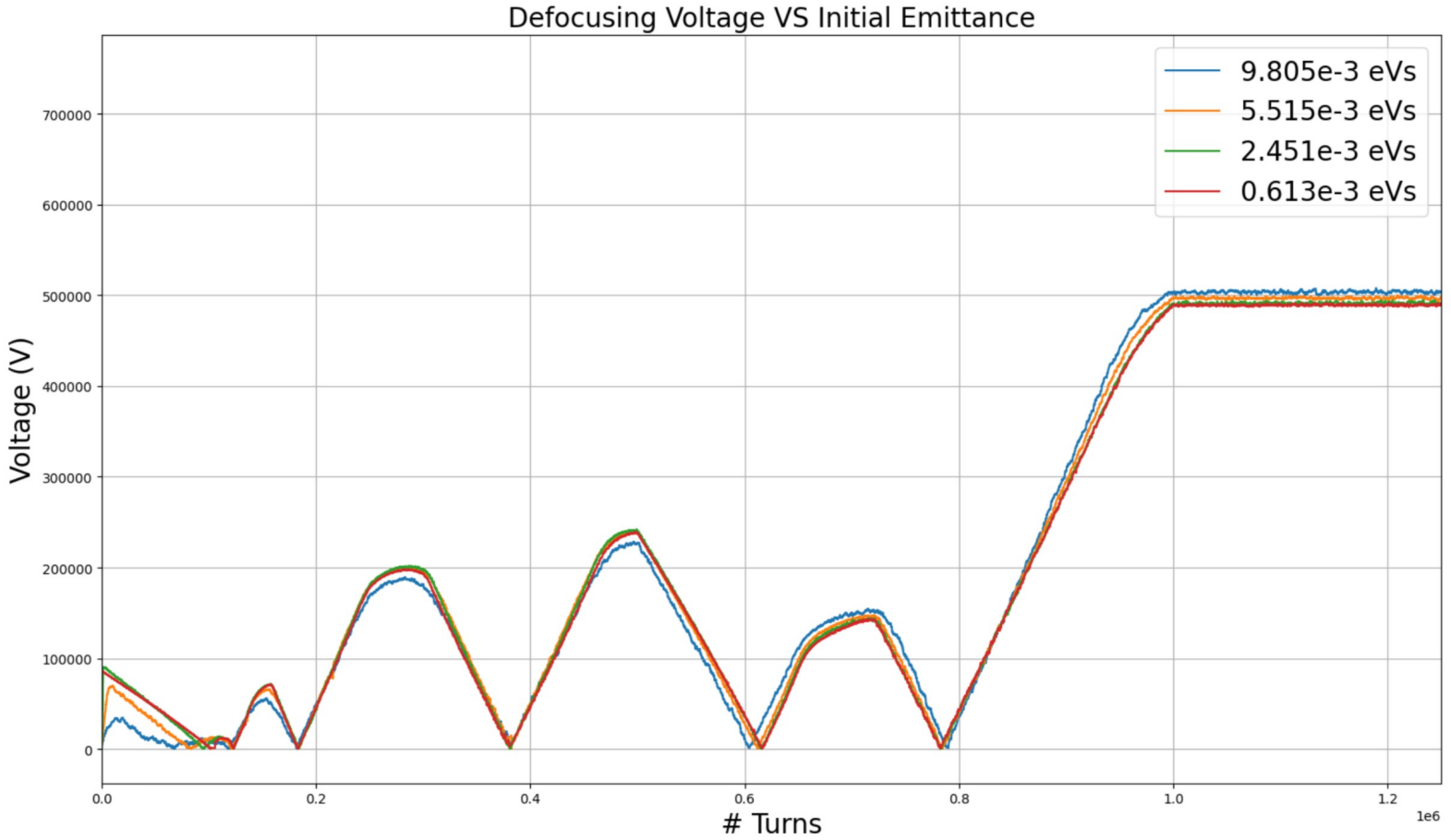




Effect Of The Initial Emittance

- Ran simulations with varying initial emittances, not significant dependence found
  - Any deviations could be corrected with feedback*

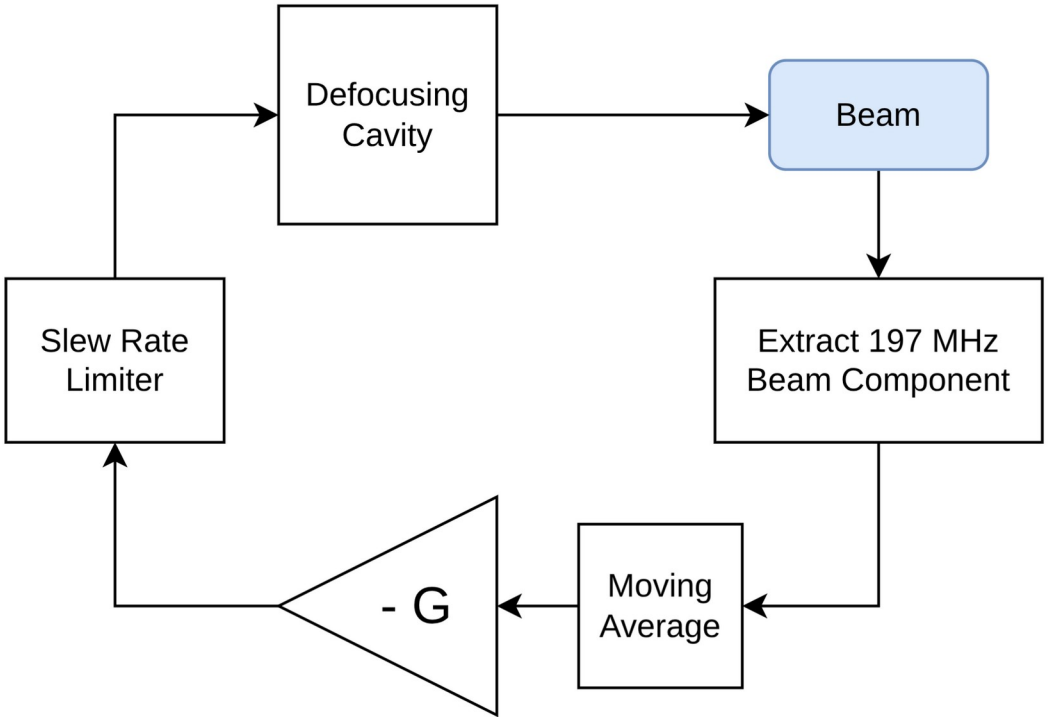
$$\epsilon_0 = \sigma_\tau \sigma_E$$



* more details on the next slide

Using Feedback For The Defocusing Voltage

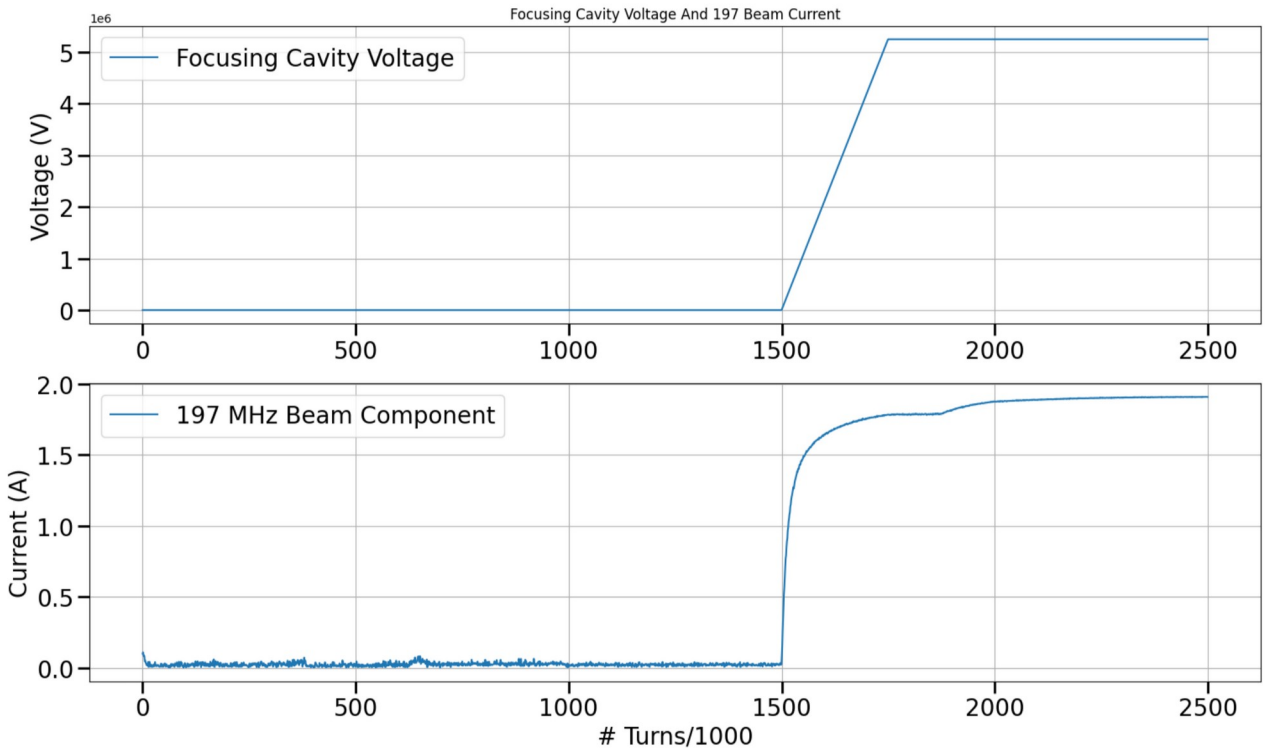
- A “standard” defocusing voltage program can be calculated based on the planned bunch splitting voltage program
- Can use feedback with low gain to regulate the defocusing voltage
  - High gain can lead to emittance blowup
  - Feedback would be enabled after the initial beam current is minimized



Bringing Up The Focusing Cavities

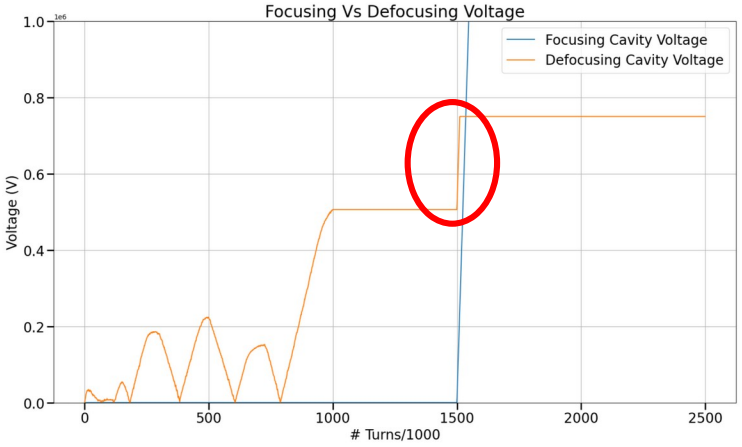
- The 197 MHz beam component quickly rises as the focusing cavities are brought up
  - We get over 85 mA when focusing cavities reach around 15 kV
    - ~ 2 kV per cavity, assuming 7 focusing cavities
  - Optimal detuning requires detuning by ~ 600 kHz

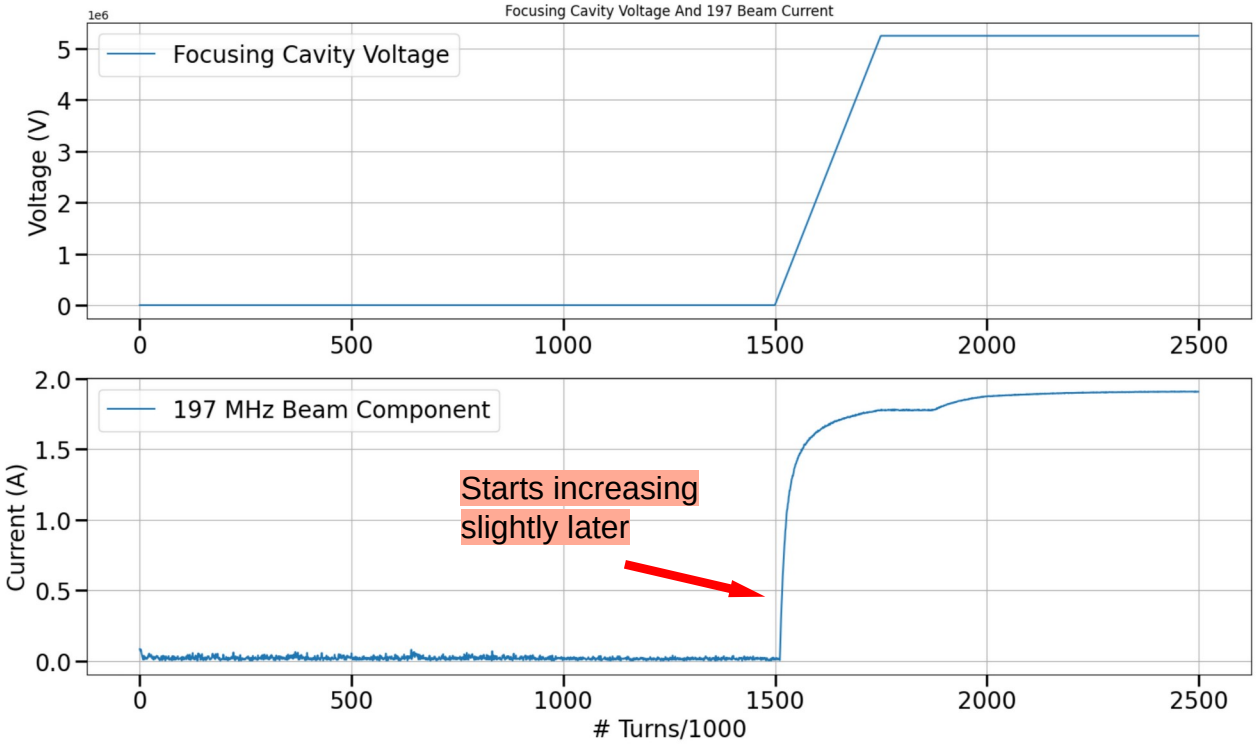
$$\Delta f_{opt} = f_{RF} \frac{\frac{R}{Q} I_{RF}}{2 V_C} \cos(\phi_s)$$



Bringing Up The Focusing Cavities (cont.)

- We can increase the voltage on the defocusing cavity as the focusing cavities are brought up
- Now we have around 37 kV (300 kV total) per cavity when beam is at 85 mA
  - Optimal detuning of ~ 32 kHz





Future Work and Conclusions

- Installed power is not enough to safely perform bunch splitting in the HSR of the EIC
- A defocusing cavity scheme is utilized to minimize beam loading and safely perform bunch splitting
- Beam-loading effects should be minimal on the defocusing cavity
  - Developing a full BLonD simulation to validate the defocusing scheme
  - Study effects of transient beam-loading

- Thank you for listening, any questions?

Acknowledgments

- Thanks to the EIC RF team for their advice, support, and feedback. S. V. Andres, M. Blaskiewicz, K. Mernick, F. Severino, G. Narayan, W. Xu, B. Xiao, S. Mai, A. Fahey and others.