EIC Crab Cavity Low-Level RF Design

Research in the Physics Department

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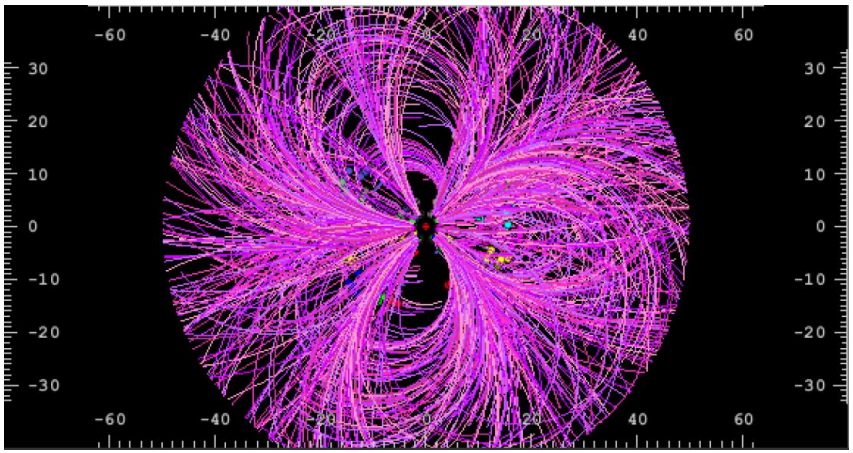
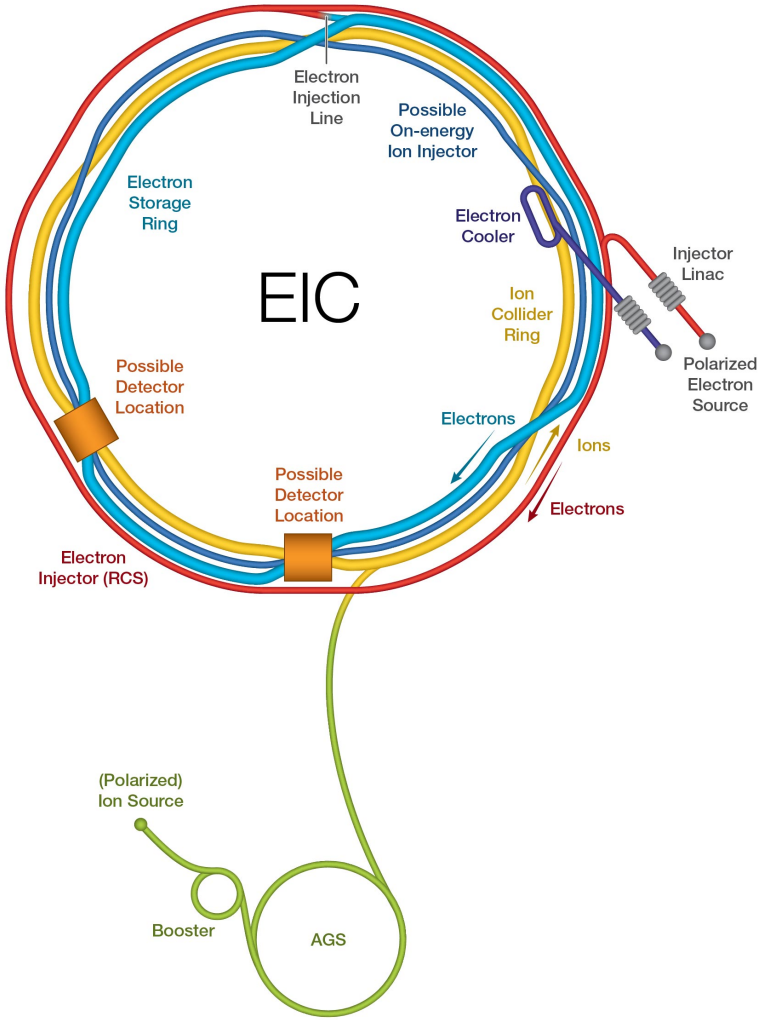
What is a Particle Accelerator

- Accelerators propel particles to near the speed of light
- Used for particle physics research
  - Discovering new particles
  - Testing new theories of particle interaction
  - Investigate dark matter theories
- Used as sources of high energy x-rays for experiments in biology, chemistry, medicine, materials science, and more.



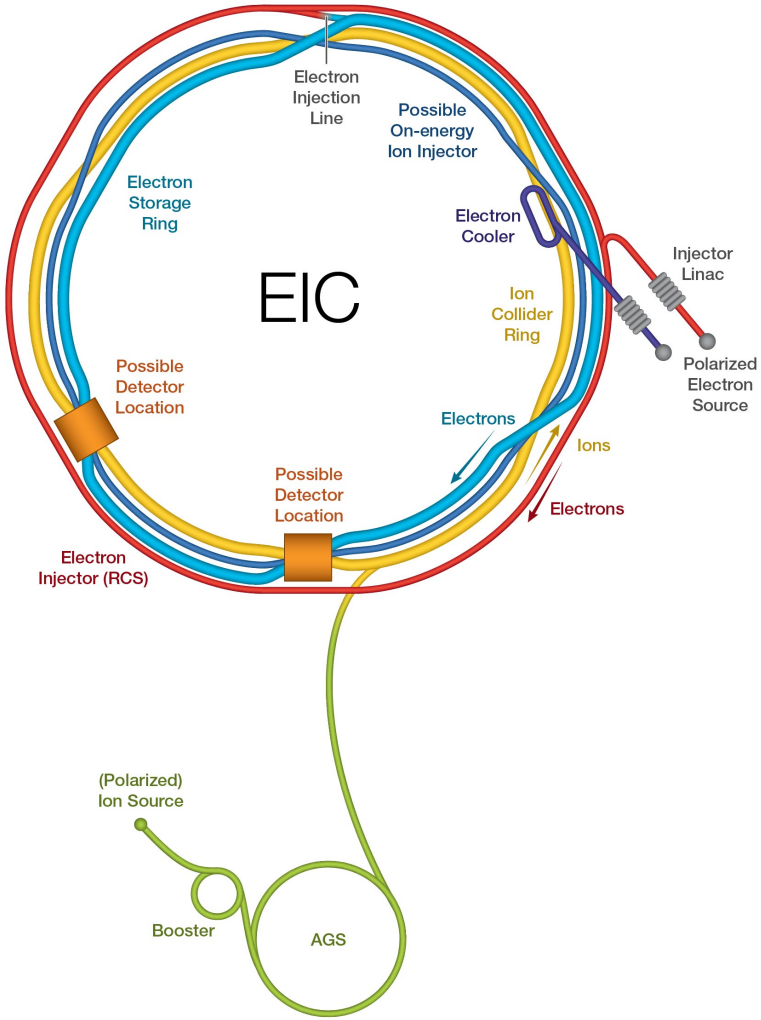
The Scale of the EIC

- The next big US accelerator, the Electron-Ion Collider (EIC), at Brookhaven National Lab, NY (within the 2030s).
- 3.8 km circumfrence ring
- 10^{34} collisions per square centimeter per second
- Particles going around $\sim 80,000$ times per second
- Estimated cost of $\$1.6 - \$2.6$ billion



Main Parts of a Particle Accelerator

- Magnets (steering)
- Detectors (for collecting collision data)
- Electromagnetic cavities (for accelerating particles)



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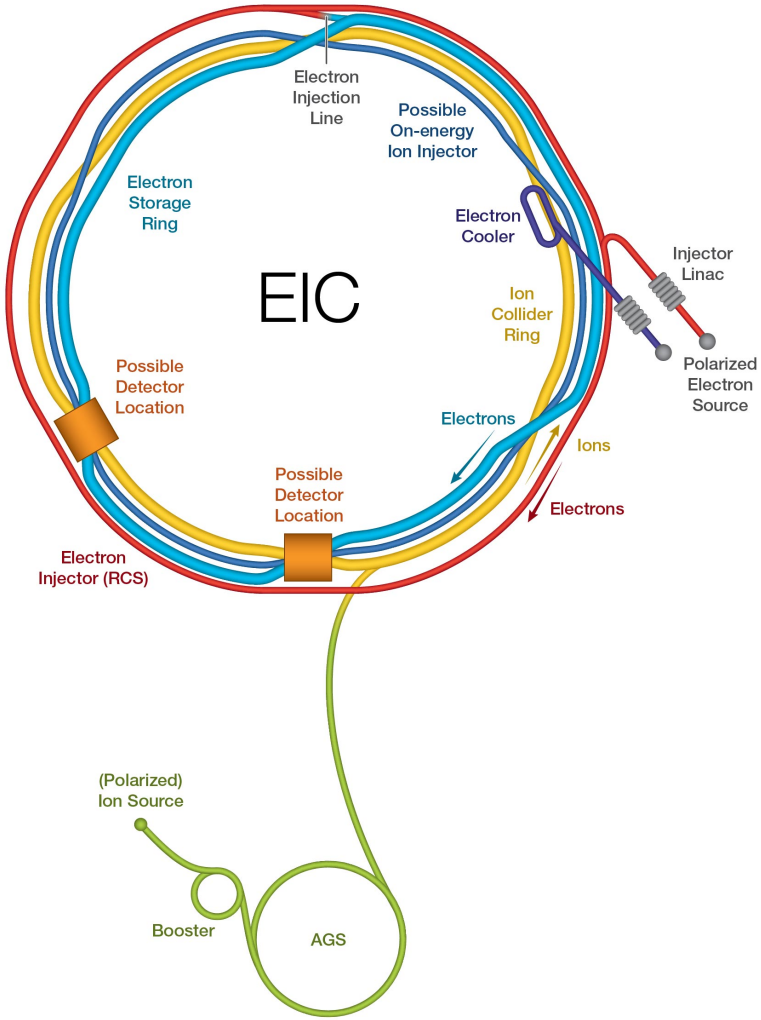

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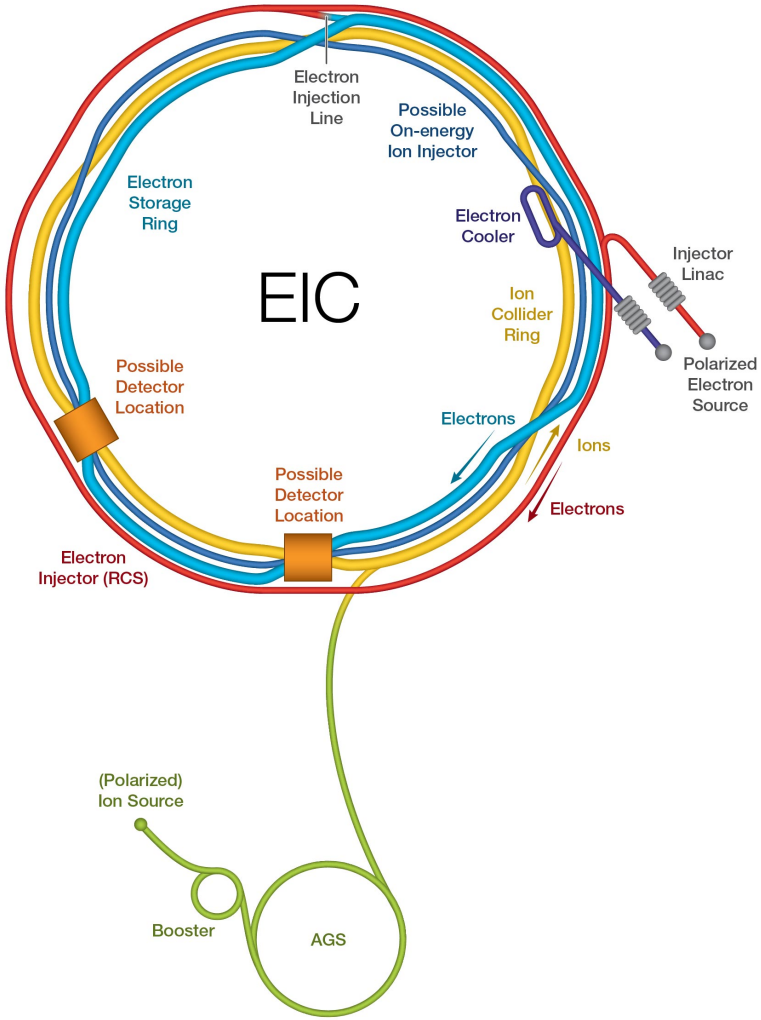

New Technology

- Future accelerators will incorporate new technologies to increase the energy of collision and the collision rate.
- An important developing technology are Crab Cavities
  - Used once before at KEKB in Japan in 2007 (with marginal success and a lot of operational issues).
  - Will be used in the High Luminosity Large-Hadron Collider (HL-LHC) at CERN, Geneva, Switzerland ($\approx$2029).
  - They will also be used in the EIC. [2]
- The crab cavity field will have to be regulated precisely through the action of feedback systems $\rightarrow$ our research

A Crab Cavity

- A crab cavity is an electromagnetic resonator that will rotate the particle cloud (bunch) around its center, so that it moves sideways (transversely), like a crab.
- After crabbing the beam, it must be uncrabbed
- Why would we want to do this?
  - More collisions → more data

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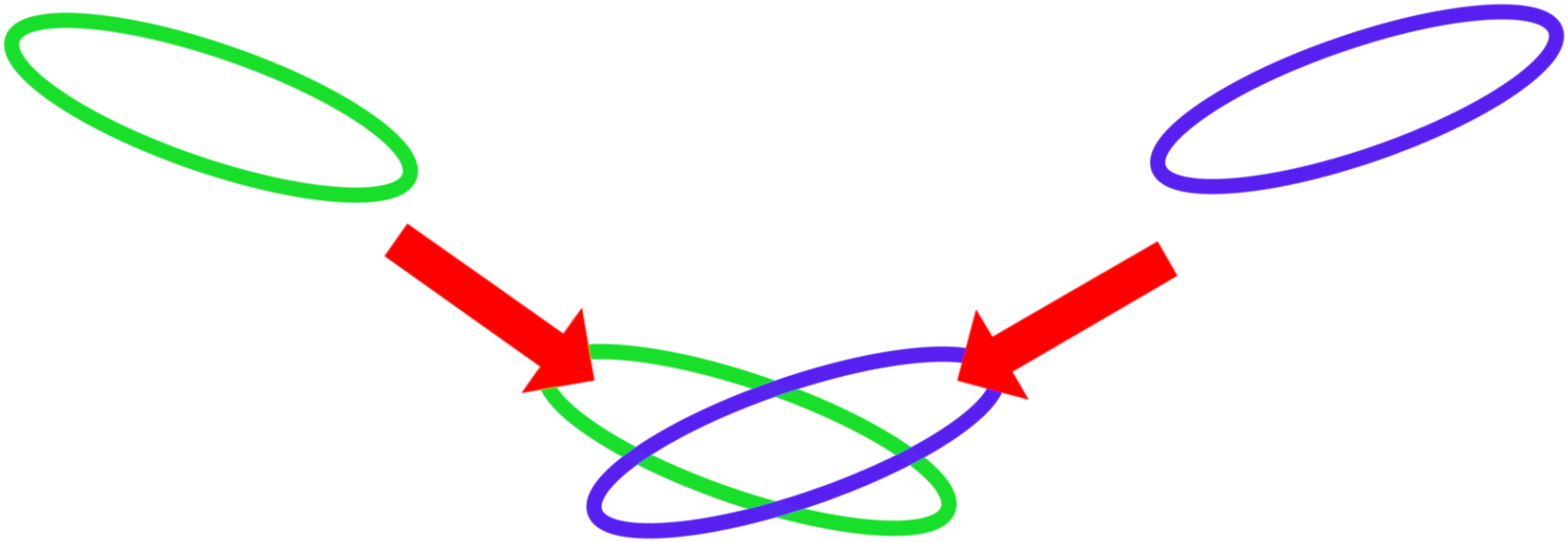

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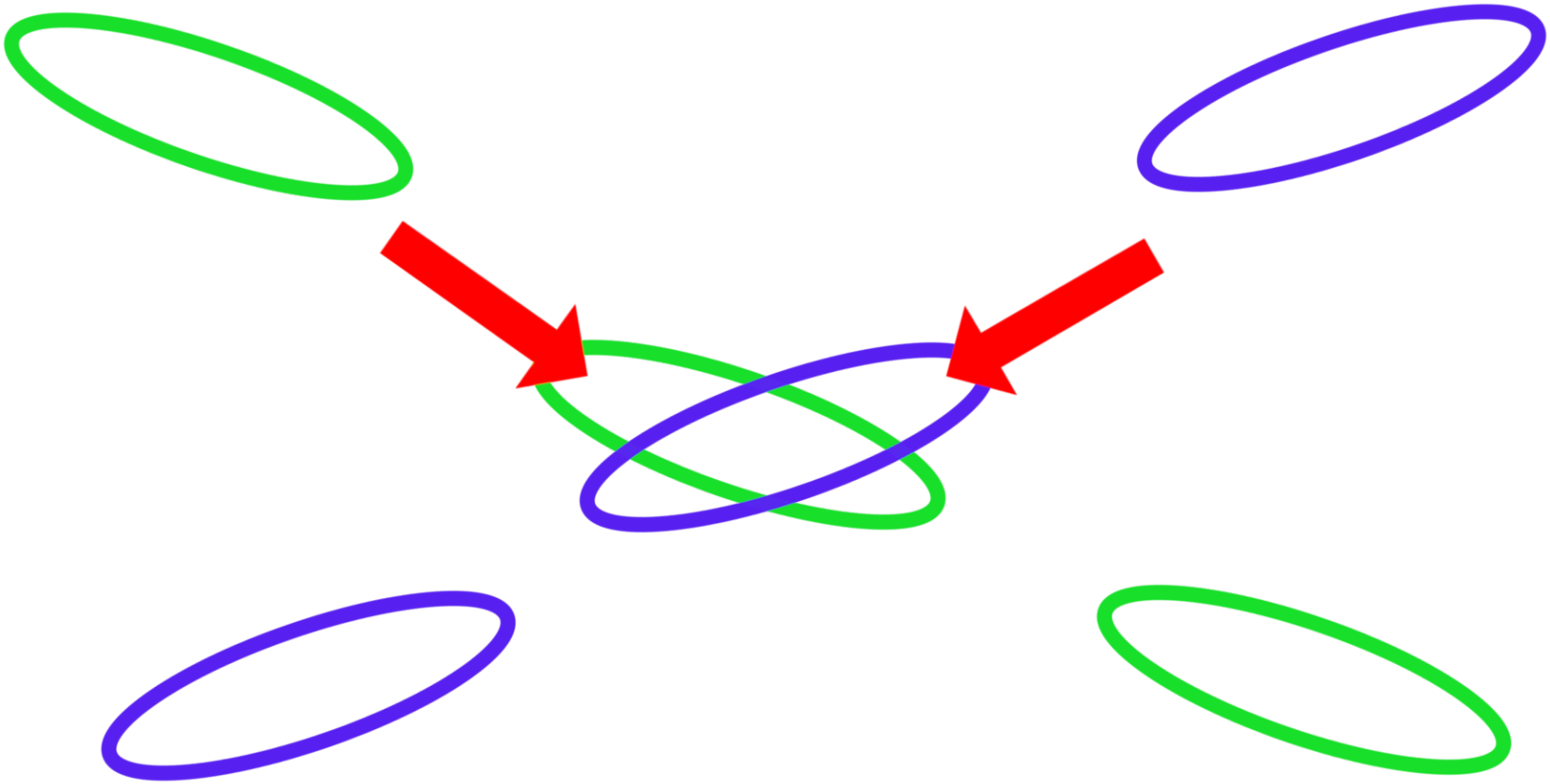

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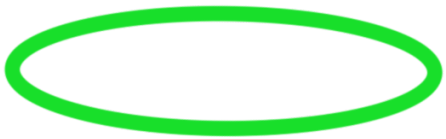

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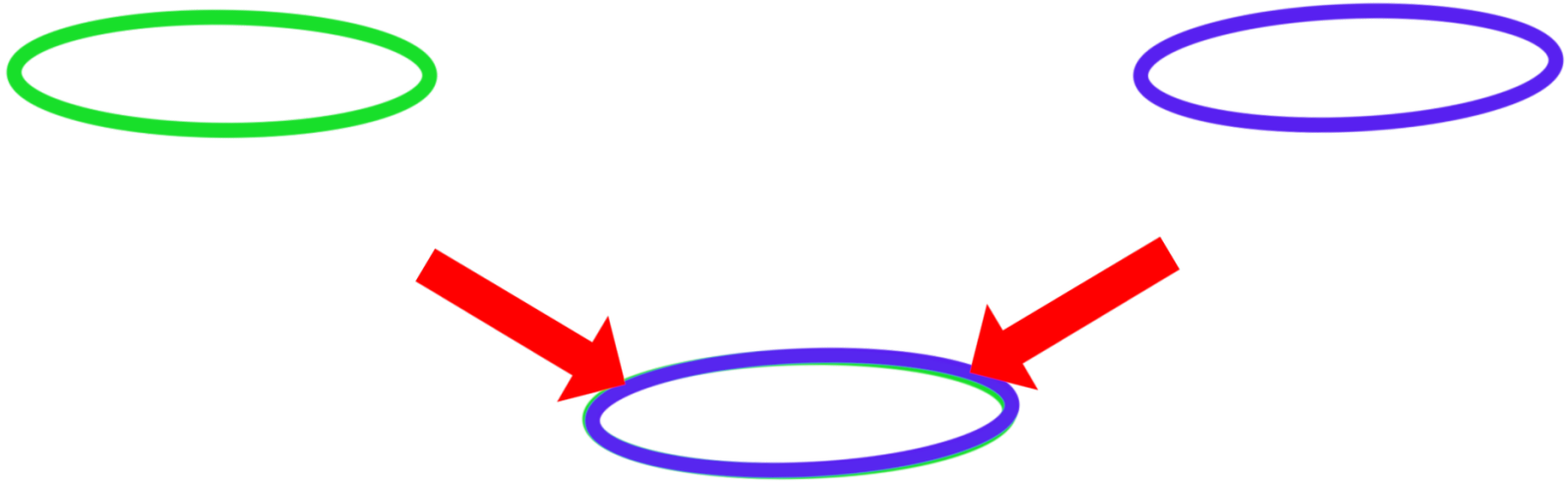

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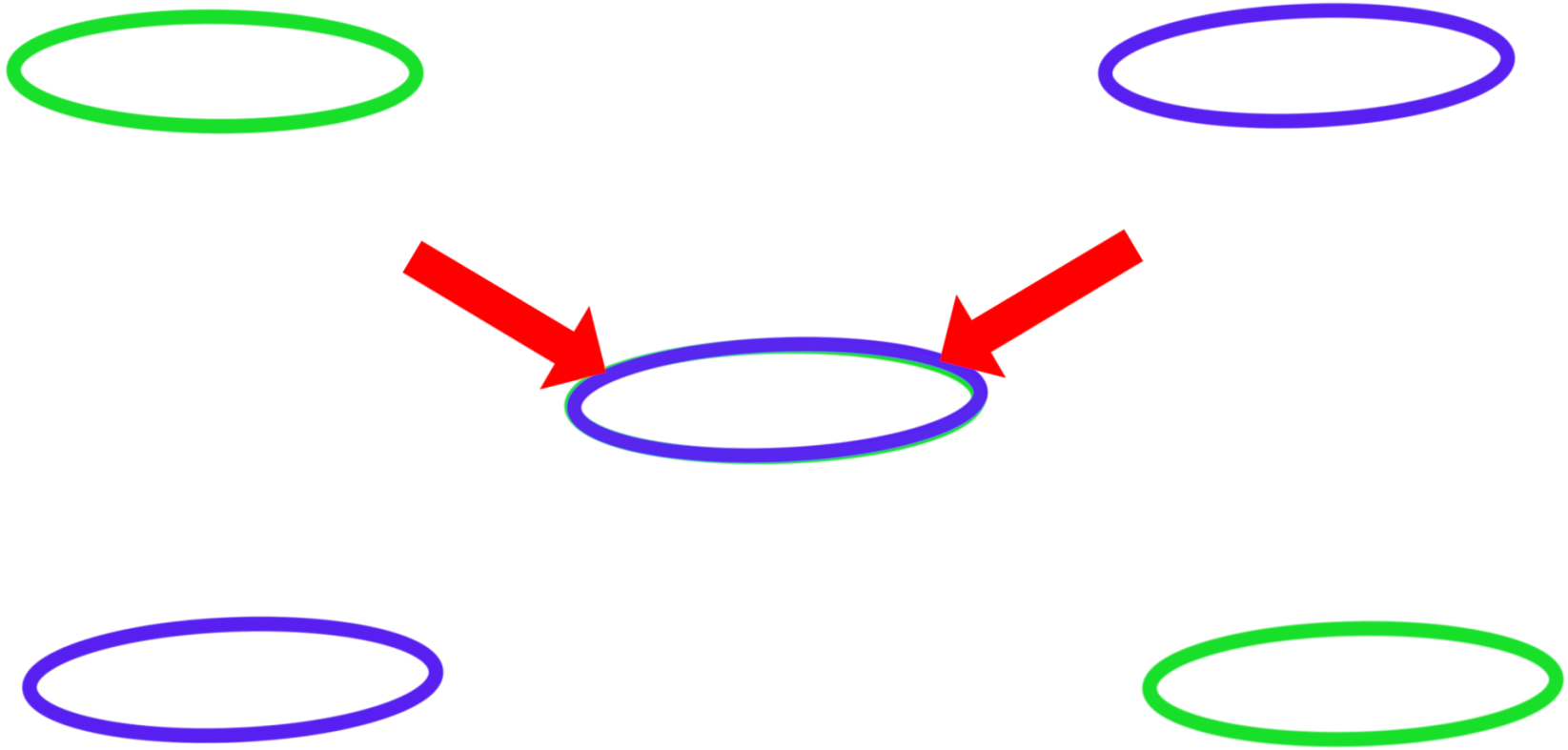
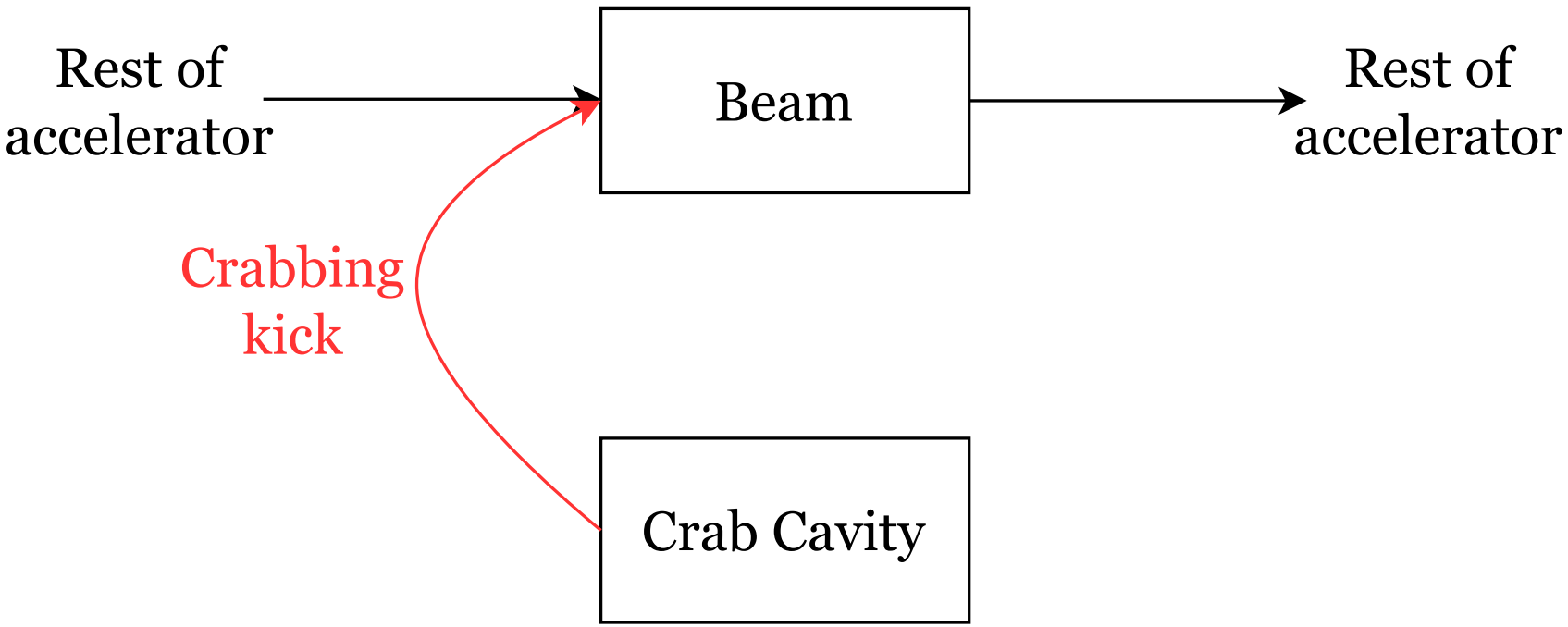


The Drawbacks

- Crab cavities significantly increase the commissioning and operational complexity of the system
  - More things to go wrong
  - More interactions $\rightarrow$ harder to model
- We have to move a millimeter thick beam going at the speed of light $(300,000,000\frac{\mathrm{m}}{\mathrm{s}})$ with micrometer precision

The Feedback Loop



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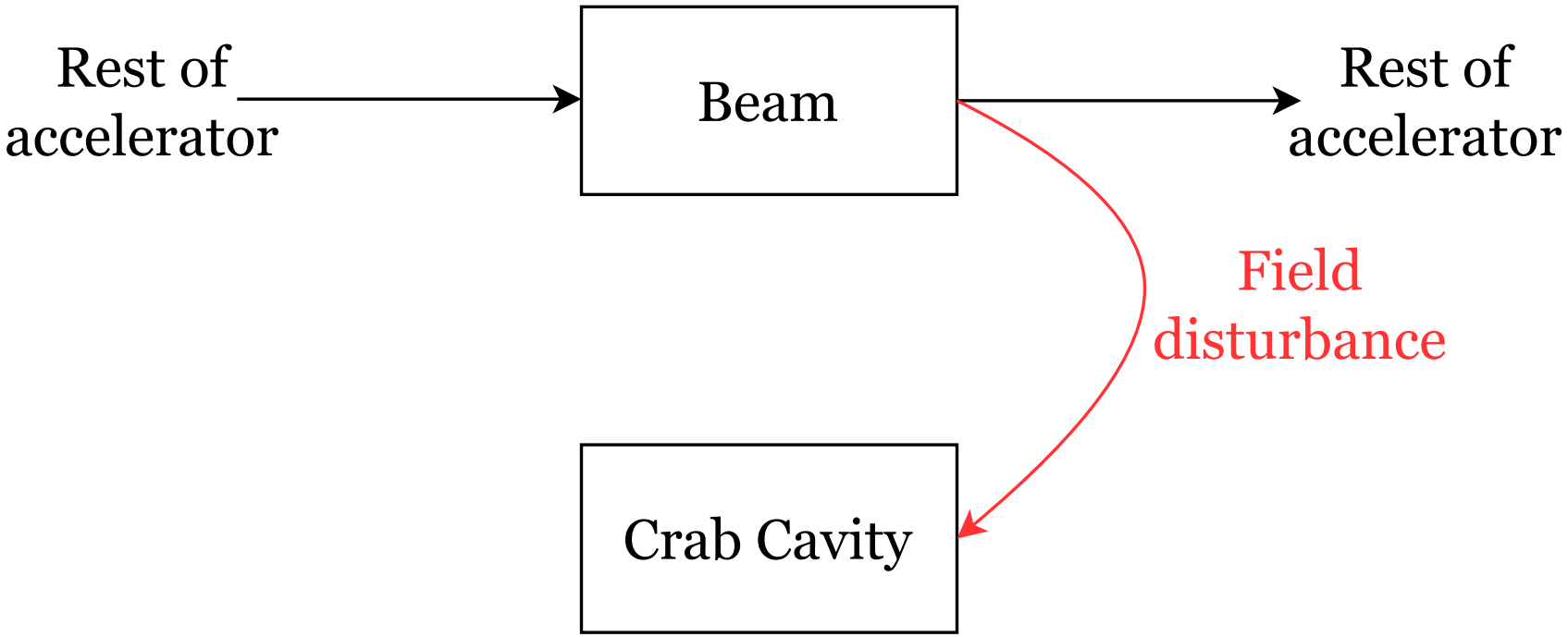
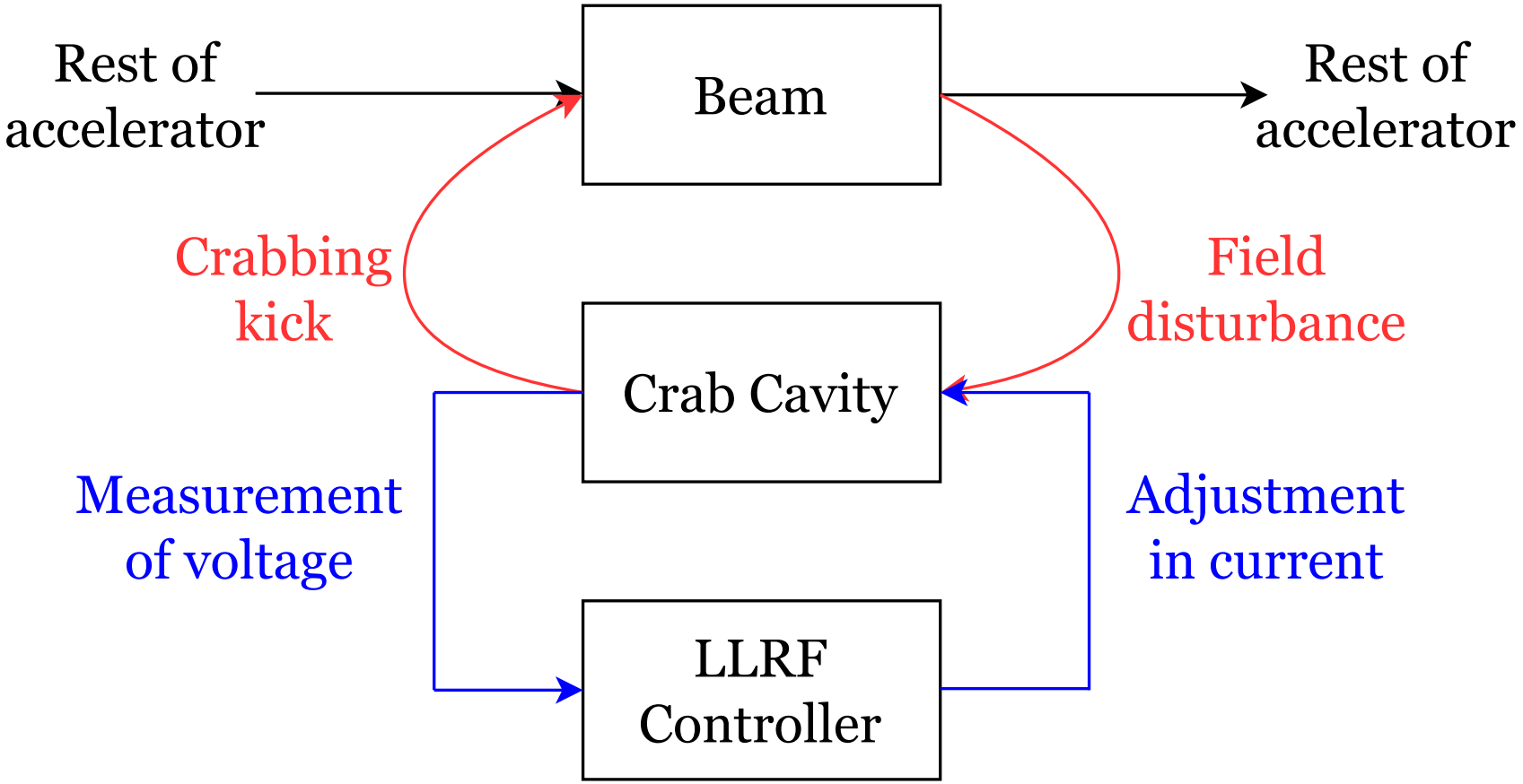


The Feedback Loop (with controller)



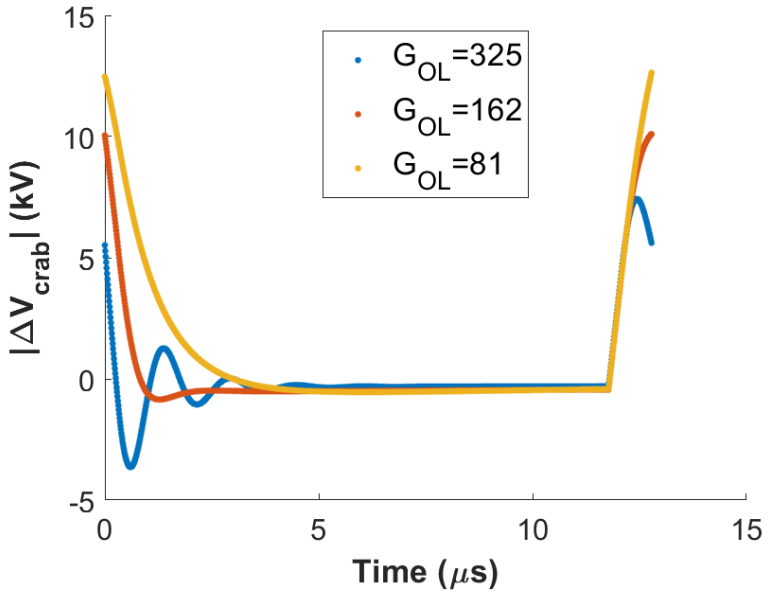
Simulation Description

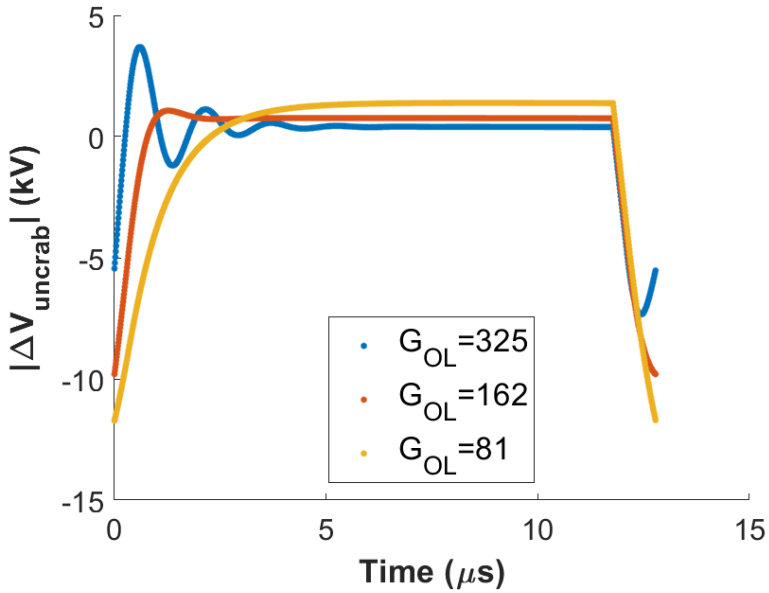
- We created and verified a simulation of the system including
  - Particle beam
  - Crabbing and uncrabbing cavities
  - Controller
  - Transmitter (affecting controller action)
- Implemented and run in MATLAB/Simulink
- We have two main takeaways from the simulation
  - Is controlling the loop possible with current technology?
  - If so, what is the best configuration for the controller? Metrics include beam performance and transmitter power requirements.

What we studied

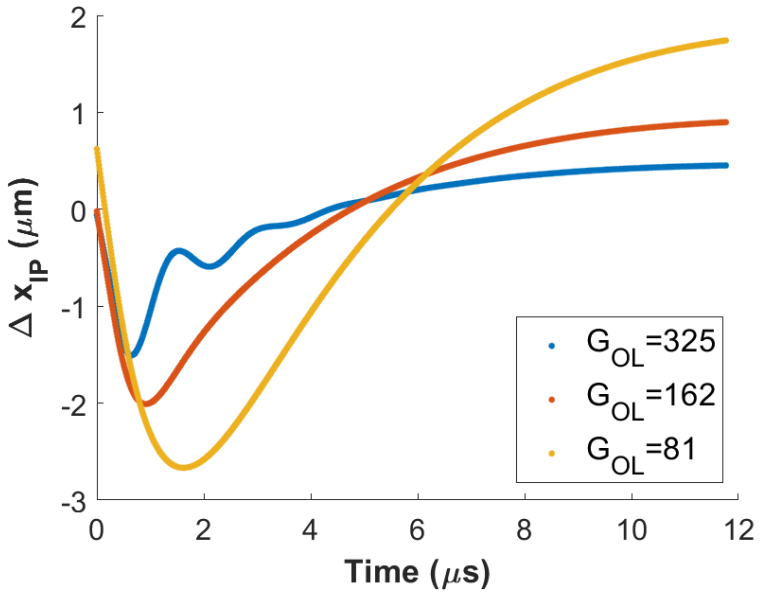
- We have conducted extensive studies on the effect of
  - Different controller architectures
  - Different noise levels
  - Additional controllers (such as the One-turn feedback and a controller acting on crabbing/uncrabbing cavities concurrently)
- Due to time limitations I will present one quick example, the main controller gain effect on performance

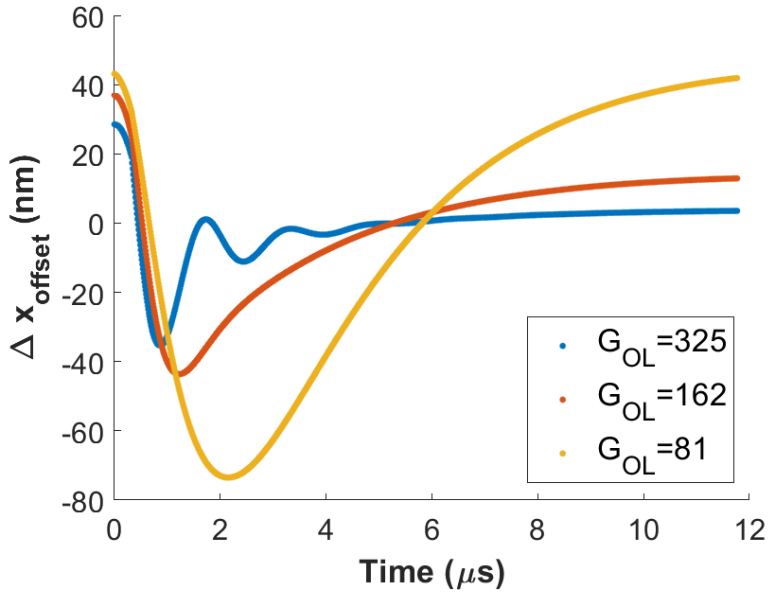
Results


15
10
5
0
-5
0
5
10
15
$|\Delta V_{crab}|$ (kV)
Time (μs)
G_{OL}=325
G_{OL}=162
G_{OL}=81


5
0
-5
-10
-15
0
5
10
15
$|\Delta V_{uncrab}|$ (kV)
Time (μs)
G_{OL}=325
G_{OL}=162
G_{OL}=81

Results (cont.)





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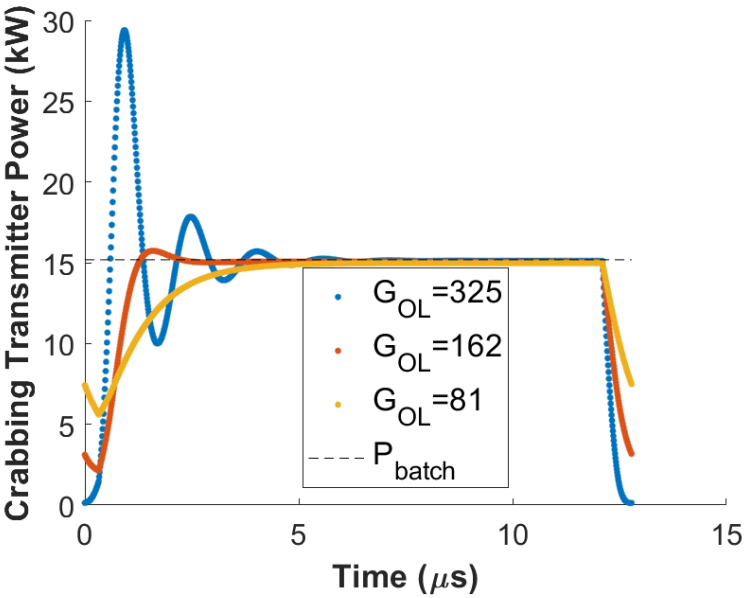

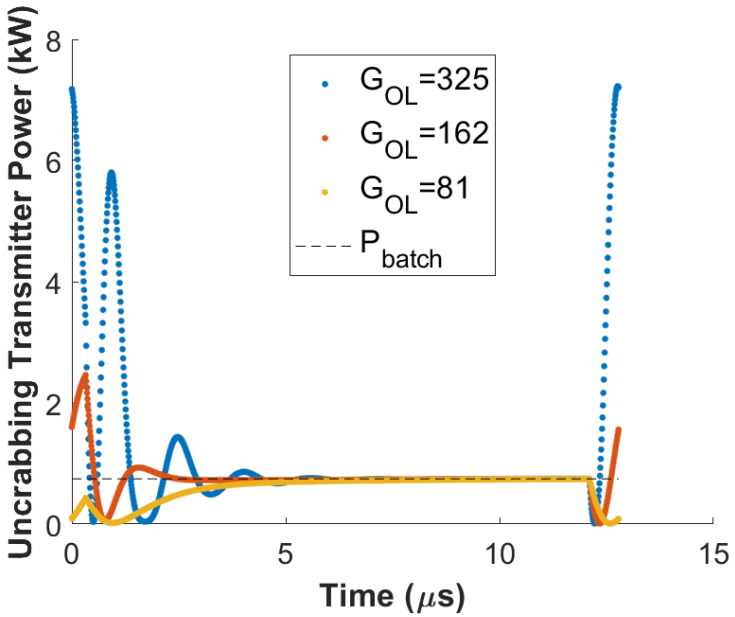

Additional studies

- We will combine the results from this work with two previous EIC studies from our group to design the crab cavity controller:
  - Study on the noise created by the accelerating cavities (completed) [1]
  - Study the beam/crab cavity interaction to determine bunch stability (ongoing)

Acknowledgements

- This work was conducted under Dr. Themis Mastoridis in the physics department
- This work was conducted alongside Trevor Hidalgo and Matti Toivola

References

[1] K. Smith, T. Mastoridis, P. Fuller, P. Mahri, and Y. Matsumura.
Eic transverse emittance growth due to crab cavity rf noise: Estimates and mitigation.
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[2] F. Willeke and J. Beebe-Wang.
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Image Sources

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