



# Ion Effects in High Brightness Electron Beam Linacs

Steven Full  
Cornell University  
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# Goals

- What is ion trapping?
- How do ions affect a beam?
- Is ion trapping a concern in linacs?
- How do we mitigate their effects?

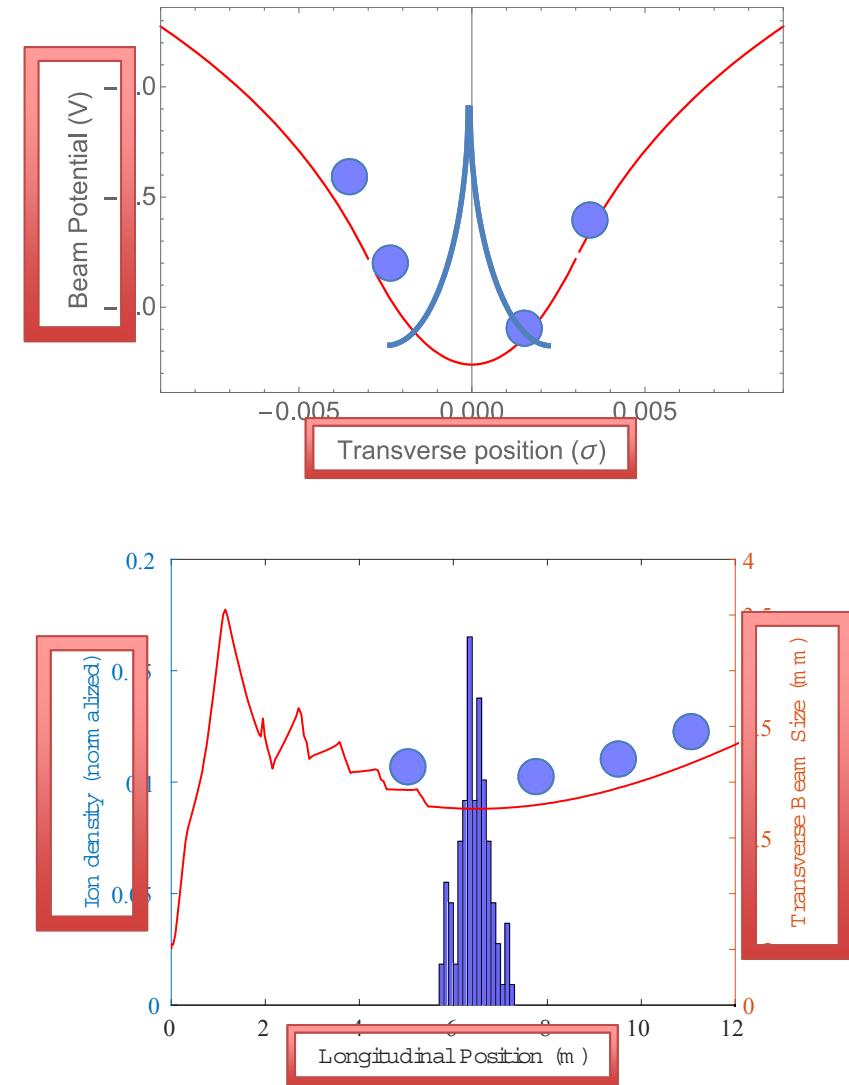


# What is ion trapping?



# What is ion trapping?

- Electron beam ionizes residual gas via collision ionization
- Ions get trapped inside the negative potential well of the beam.
- Oscillate transversely with a characteristic frequency
- Accumulate sharply in center of beam
- Also drift longitudinally towards beam potential minima



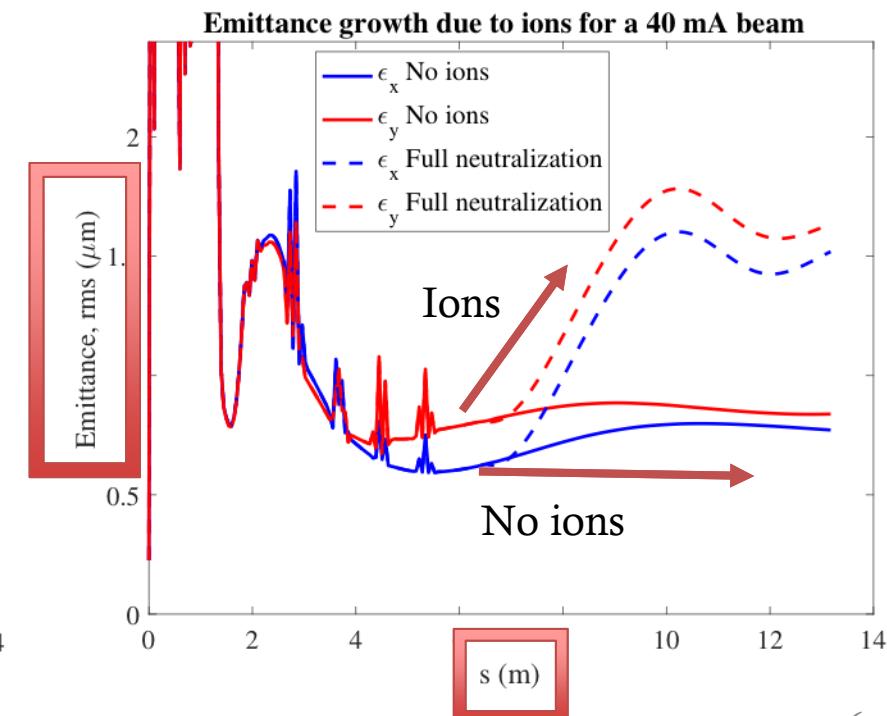
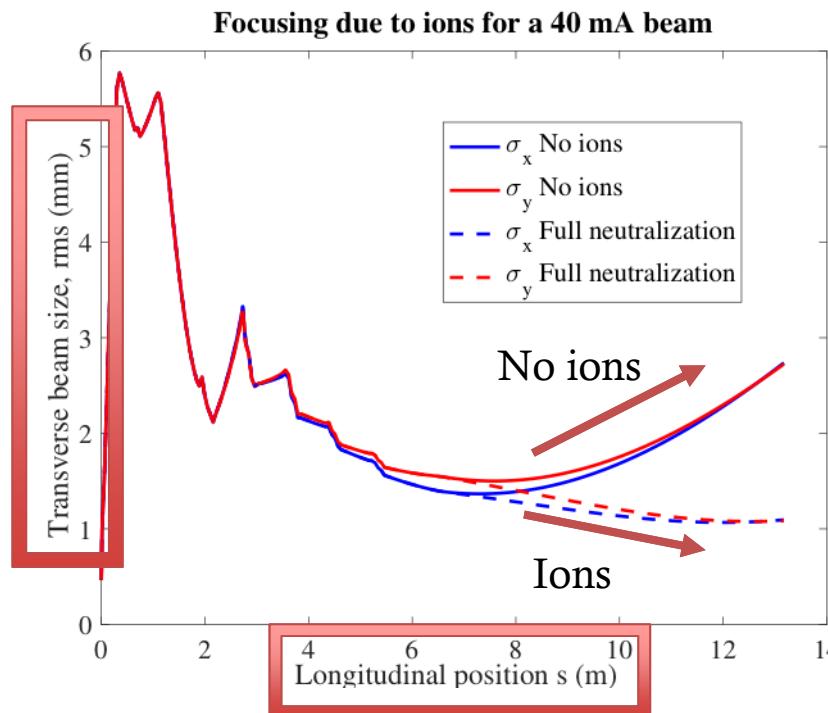


# How do ions affect a beam?



# Ion effects on beam

- Assume ion column is a very long charge distribution throughout the accelerator, with a Gaussian transverse distribution
- Ions act like a lens, leading to (non-linear) focusing
- In theory, can compensate, but in practice cannot be corrected with linear optics – so let's get rid of them
- Reducing ionization fraction to  $\sim 1\%$  eliminates focusing





# Is ion trapping a concern in linacs?



# Ion trapping conditions

Yes – ions are a problem in high current CW linacs.

- During CW, high average beam current operation ions cannot escape between bunches

Ex. synchrotron/ring



Ions are over-focused  
outward

Ions are focused



Ex. Pulsed linac, ions have time to drift



Ex. CW linac at high rep rate/high current



All ions are trapped

- Trapping observed in photoinjector **above  $\sim 10$  mA**
  - 7.7 pC bunch charge at 1.3 GHz repetition rate



# Ion trapping conditions

Two primary trapping conditions:

1) Trapped ion mass number

- Found by considering focusing in bunches and drifting outward between bunches



2) Ion oscillation frequency

- Oscillation of ion in beam's potential
- Trapping occurs if  $\omega_{ions} \ll f_{beam}$
- Experimentally verified formula

$$A_{ion} \geq \frac{n_e r_p}{4(\sigma_x + \sigma_y)\sigma_y} \Delta L_g = 0.01$$

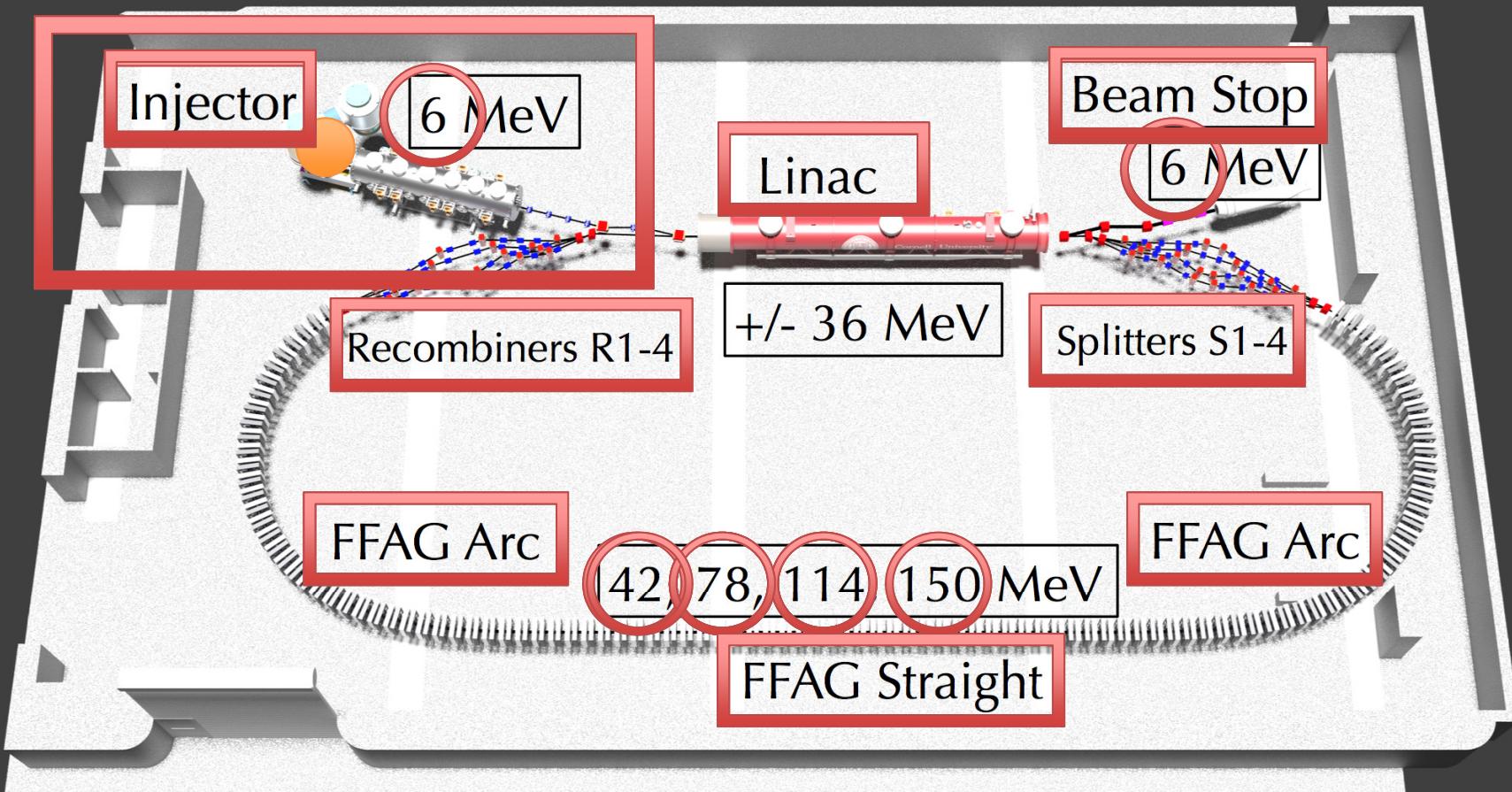
Number of electrons per bunch  
Distance between bunches

$$\omega_{ions} = \sqrt{\frac{2r_p c}{e} \frac{I_{beam}}{A_{ion} \sigma_{beam}^2}}$$

Avg. Current	Transverse Beam size	Ion oscillation frequency	Beam repetition rate
10 mA	2 mm	55 kHz ( $N_2$ )	<< 1.3 GHz

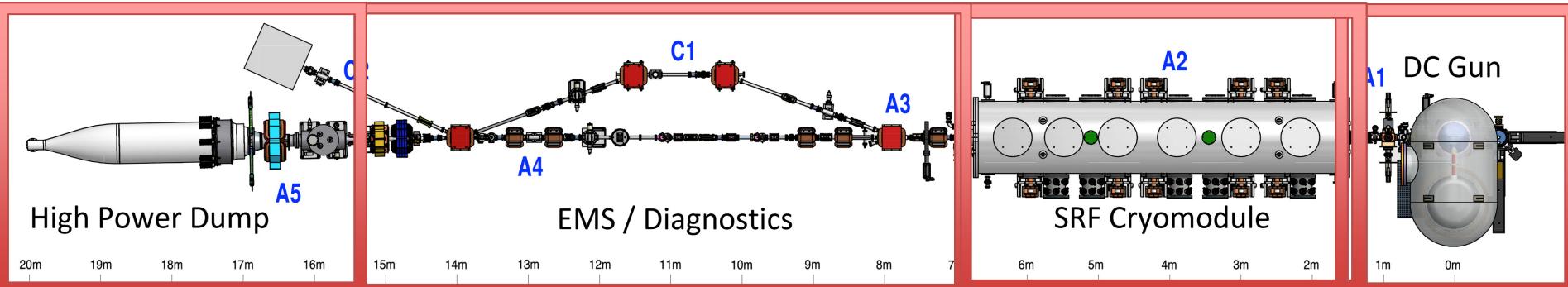


# CBETA 4 pass ERL FFAG





# Cornell ERL Photoinjector

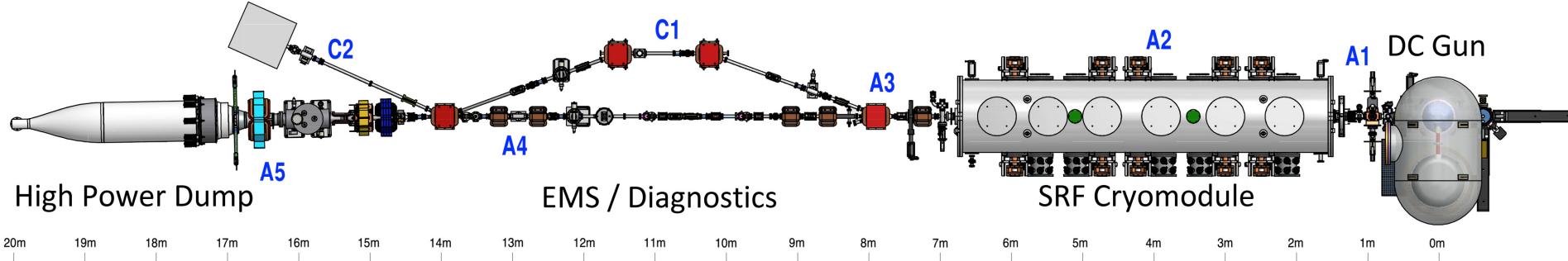


Very high average CW  
beam currents  
distinguish it from most  
other linacs.

Parameter	Experimental	Design
Avg. Current	10 – 20 mA	100 mA
Repetition rate	1.3 GHz	50 MHz or 1.3 GHz
Bunch charge	7.7 – 15.4 pC	77 pC
Beam energy	3.5 – 4 MeV	5 – 15 MeV
Beam size	1 mm – 4 mm, Round	~ mm
Bunch length	~ 3 ps	< 3 ps
Gas pressure	$1.2 \times 10^{-7}$ torr	$1 \times 10^{-10}$ torr

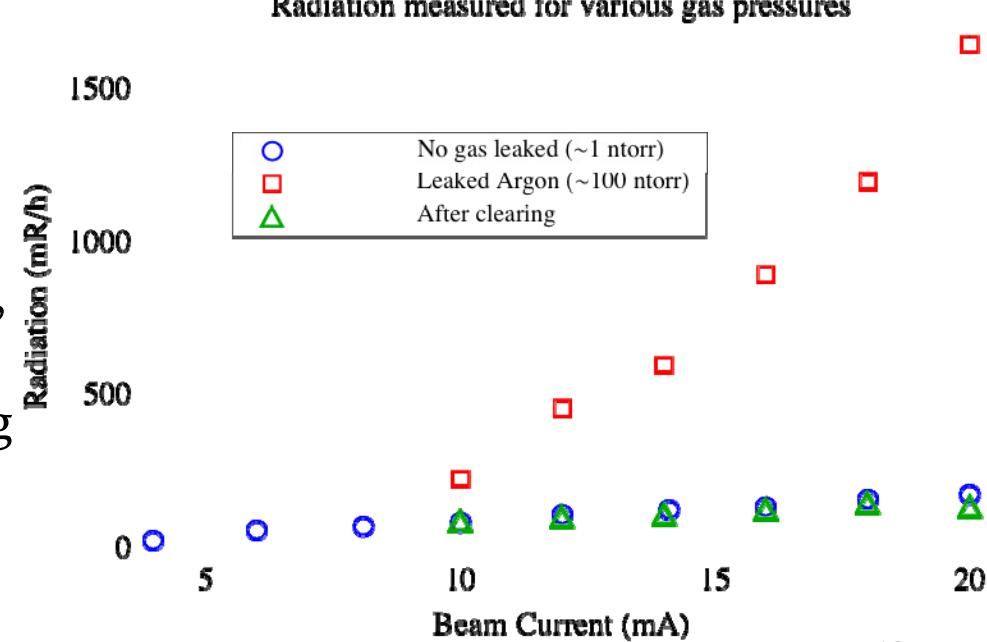


# Evidence of Ion Trapping



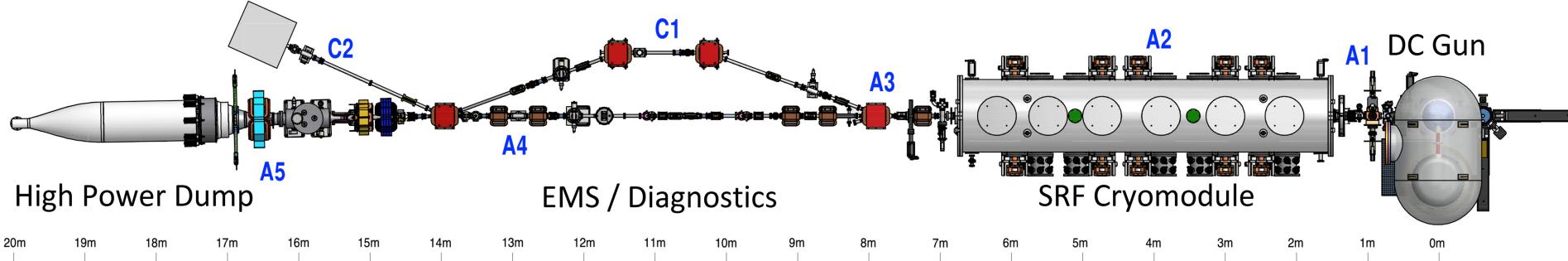
Observed ion trapping multiple times

- 1) During 75 mA, 5 MeV runs, ion clearing electrode reduced background radiation by > 50%
- 2) During low energy 350 keV runs, intermittent gun power supply trips vanished after using clearing electrode



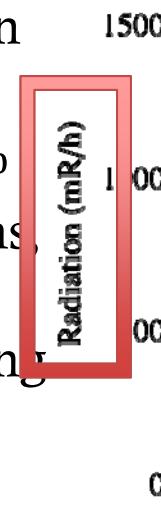


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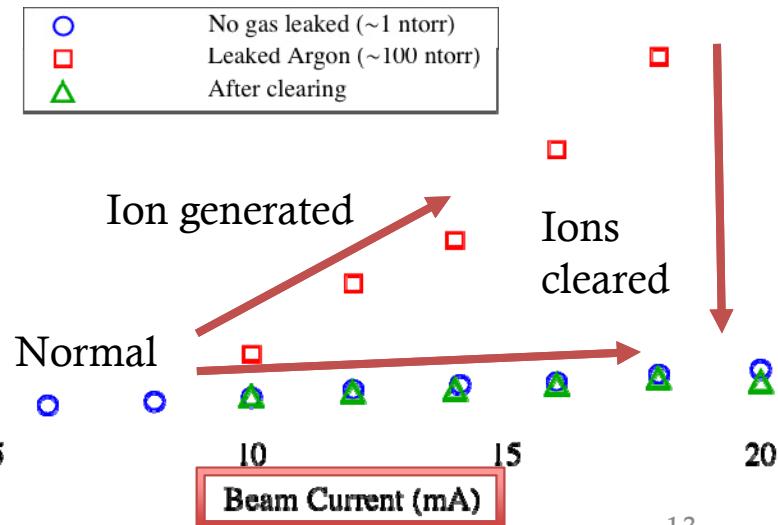


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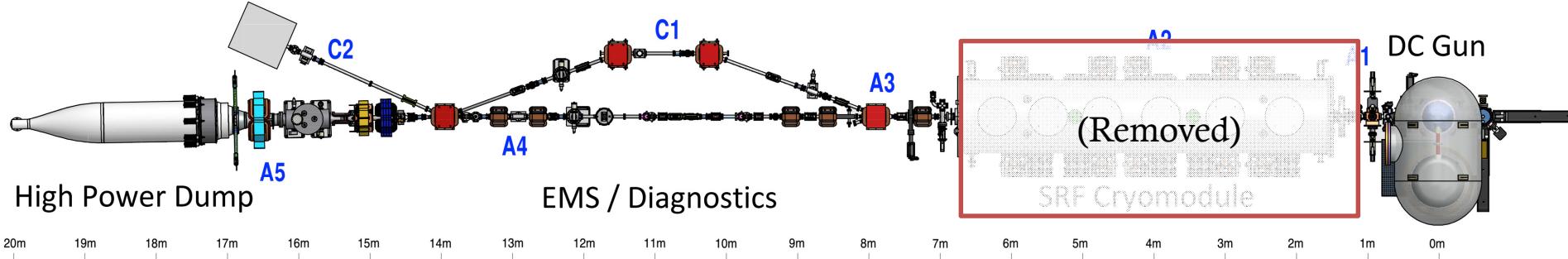


Radiation measured for various gas pressures



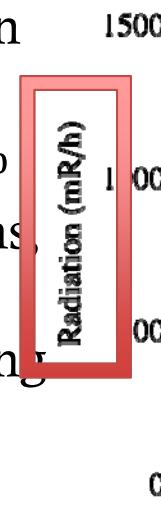


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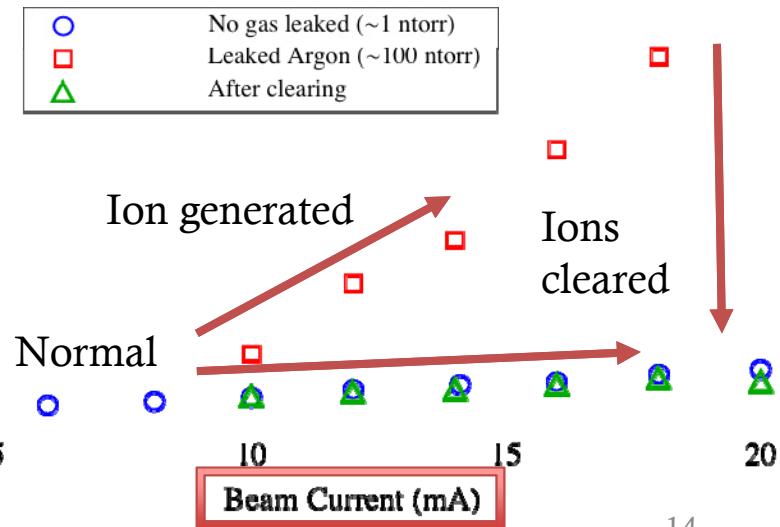


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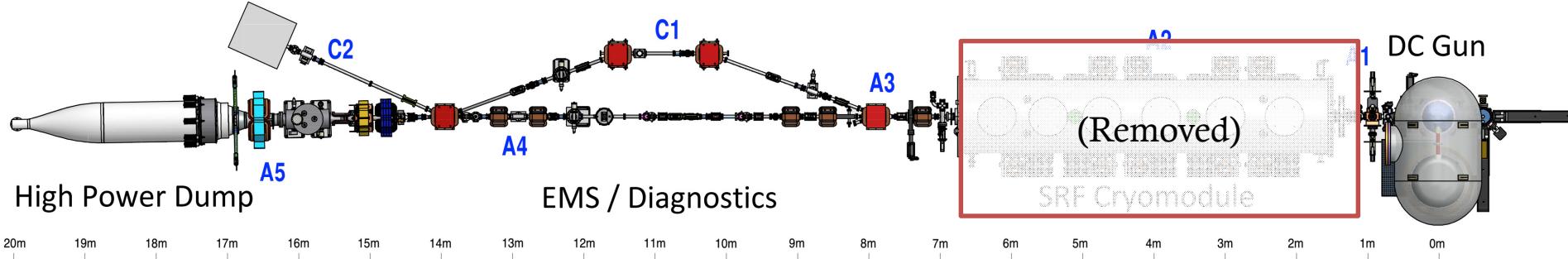


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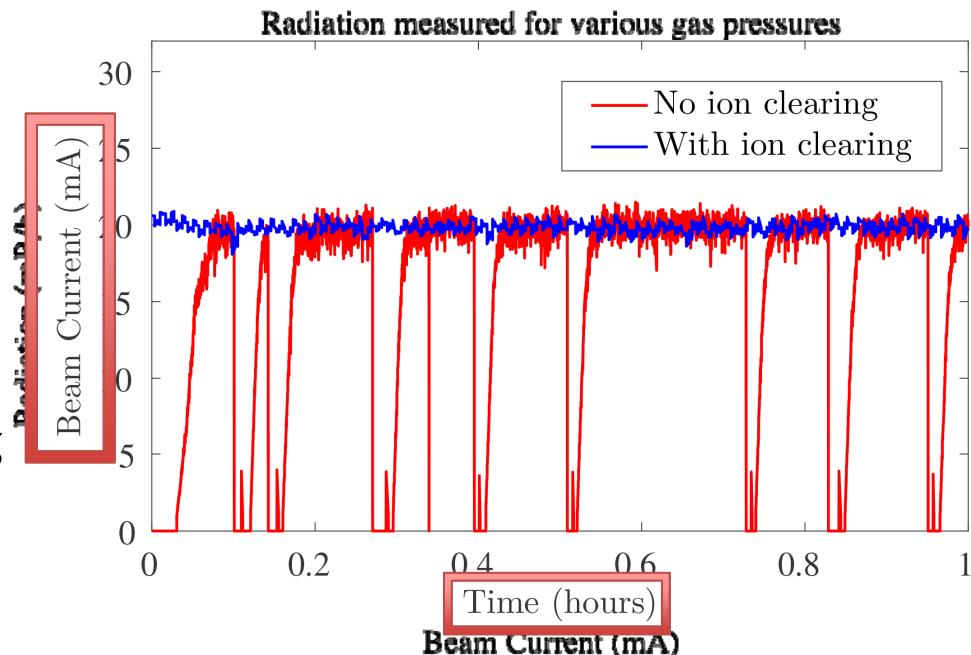


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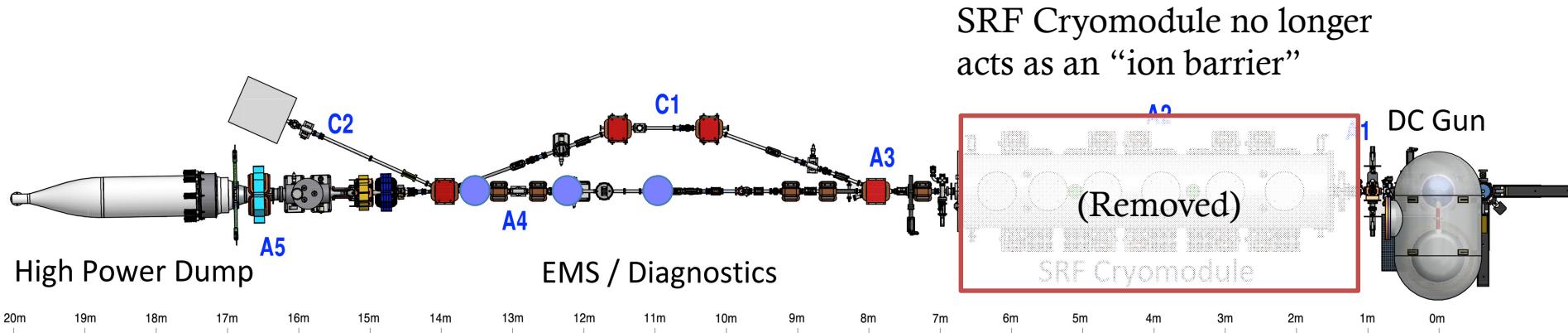
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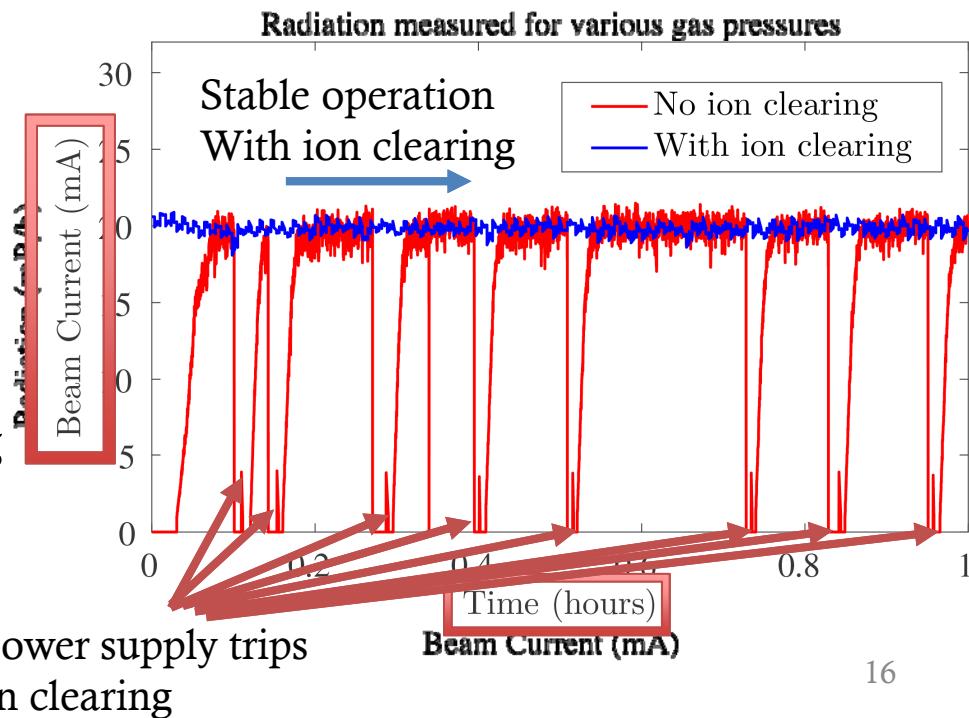


# Evidence of Ion Trapping



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# How do we mitigate ion effects?

Three methods:

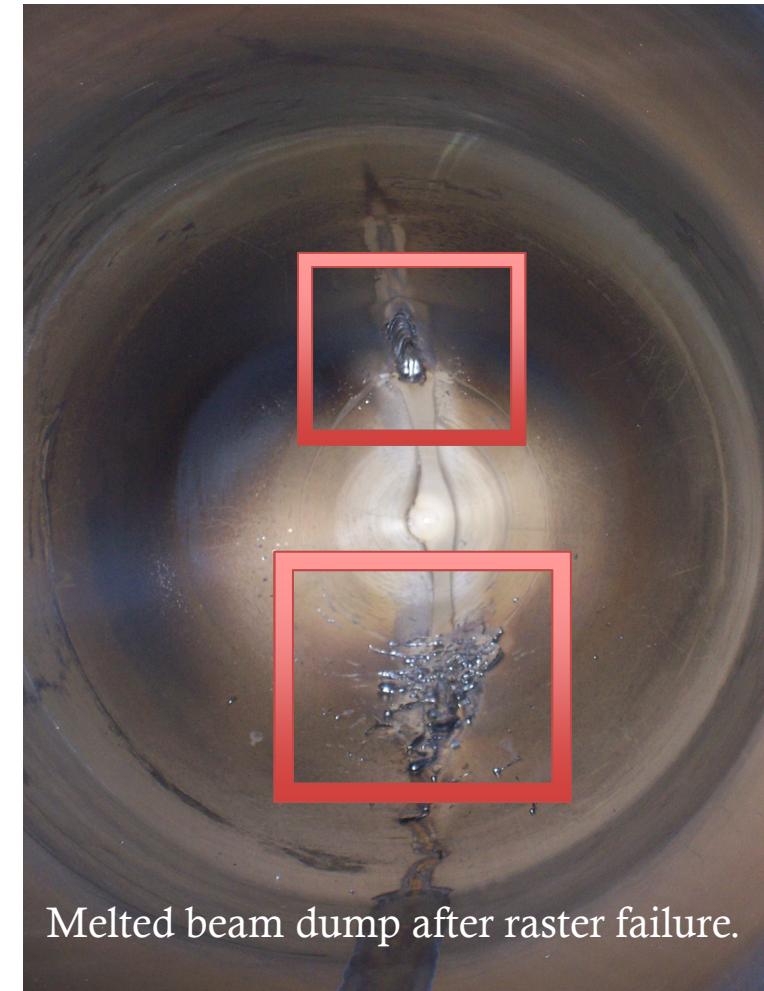
1. Clearing electrodes
2. Bunch gaps
3. Transverse beam shaking



# Testing ion clearing methods

## Measurements are challenging at high current

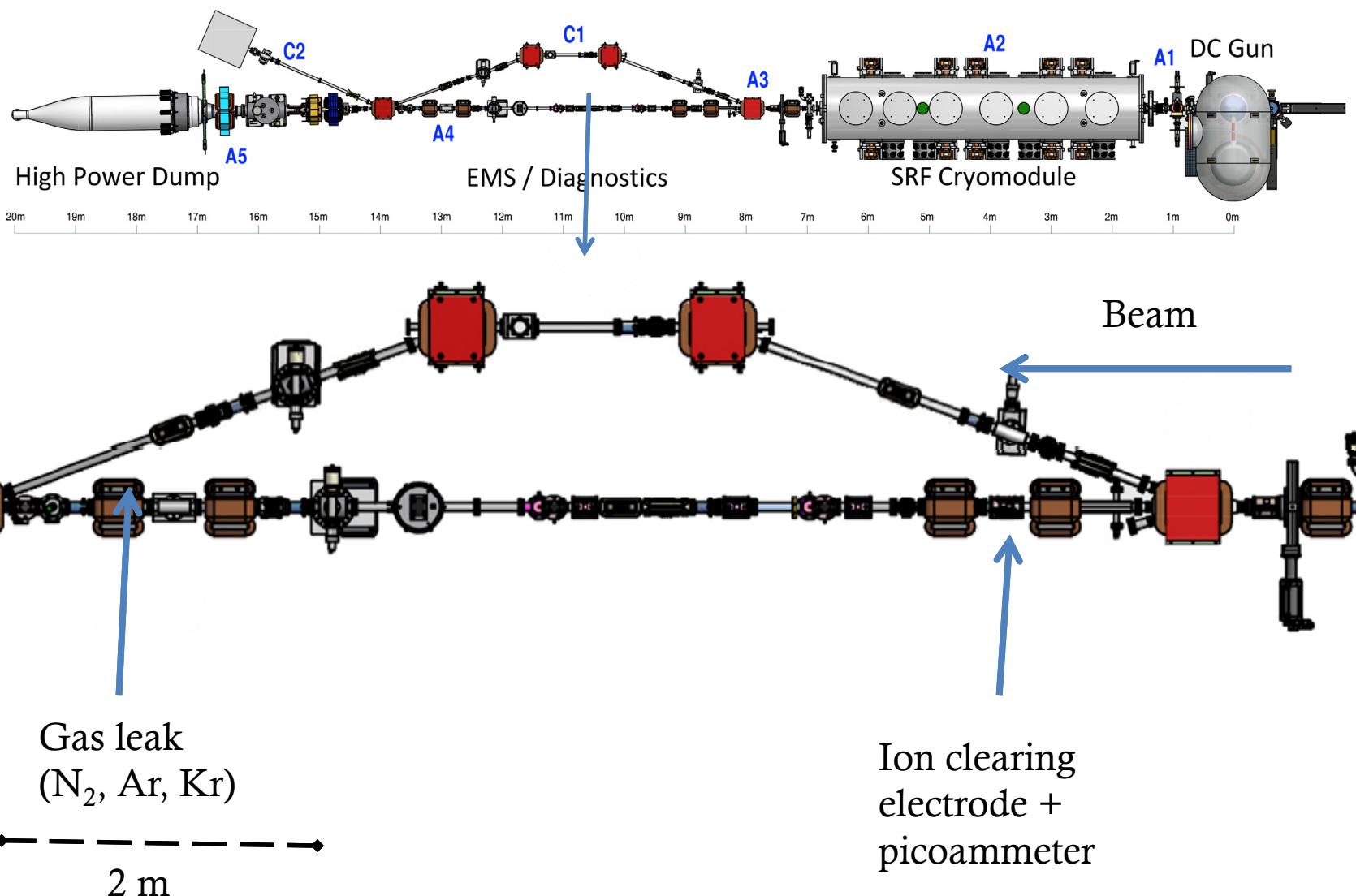
- Interceptive diagnostics melt above 1 mA
- No synchrotron/diffraction radiation (low energy linac)
- Can't measure beam directly
  - Look for ions instead
- **We used 2 diagnostics**
  - **Ion clearing electrode + picoammeter**
  - **Radiation monitors**



Melted beam dump after raster failure.



# Experimental setup



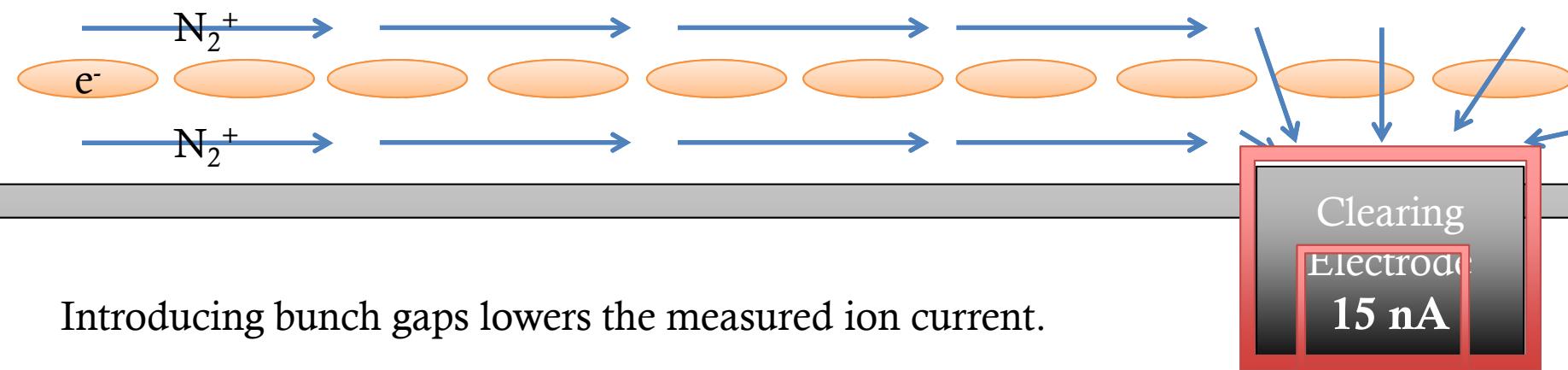


# Clearing electrode setup

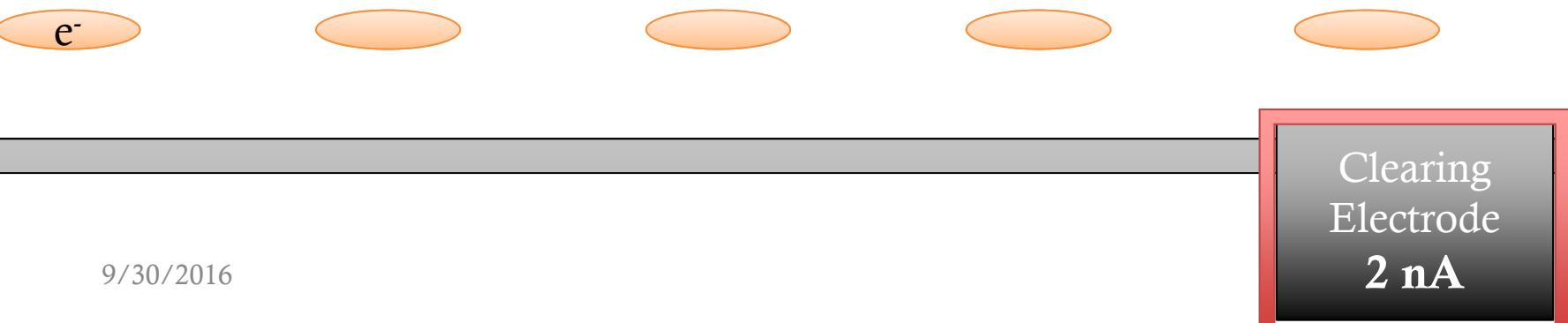
## Clearing electrode and Bunch gap measurements

During CW operation, ions remain trapped, drift towards and are measured by the clearing electrode.

Beam pipe



Introducing bunch gaps lowers the measured ion current.



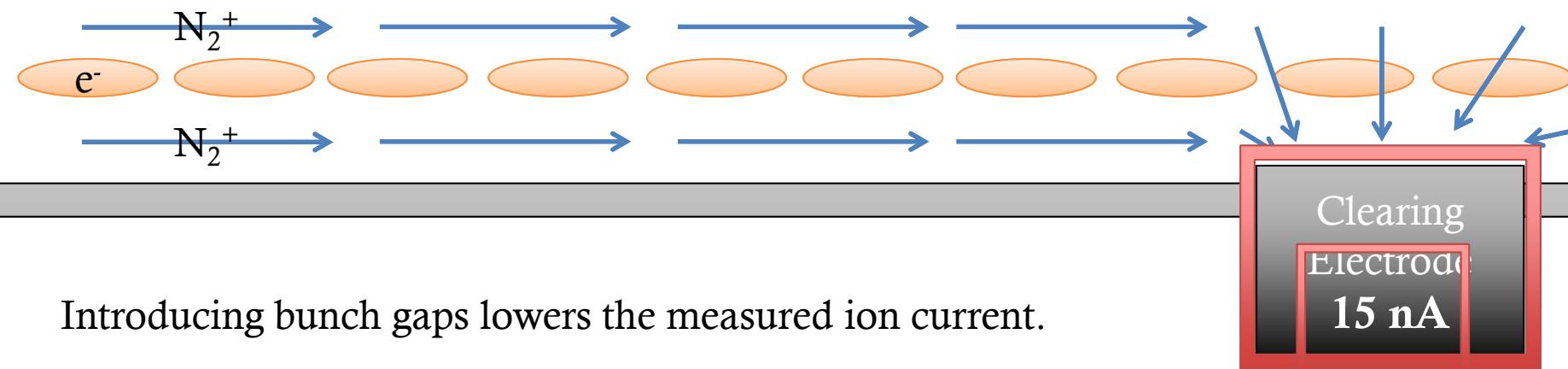


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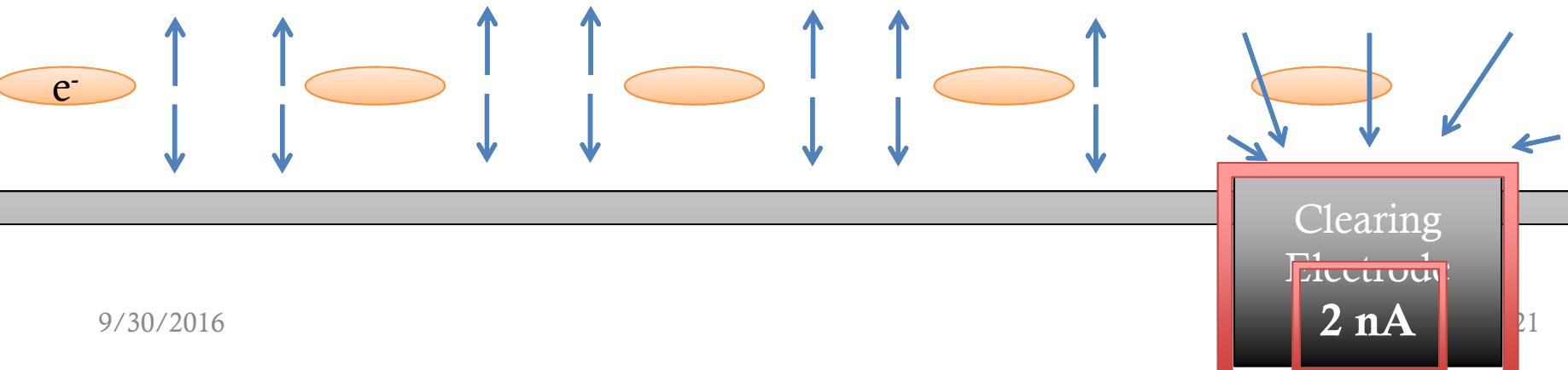
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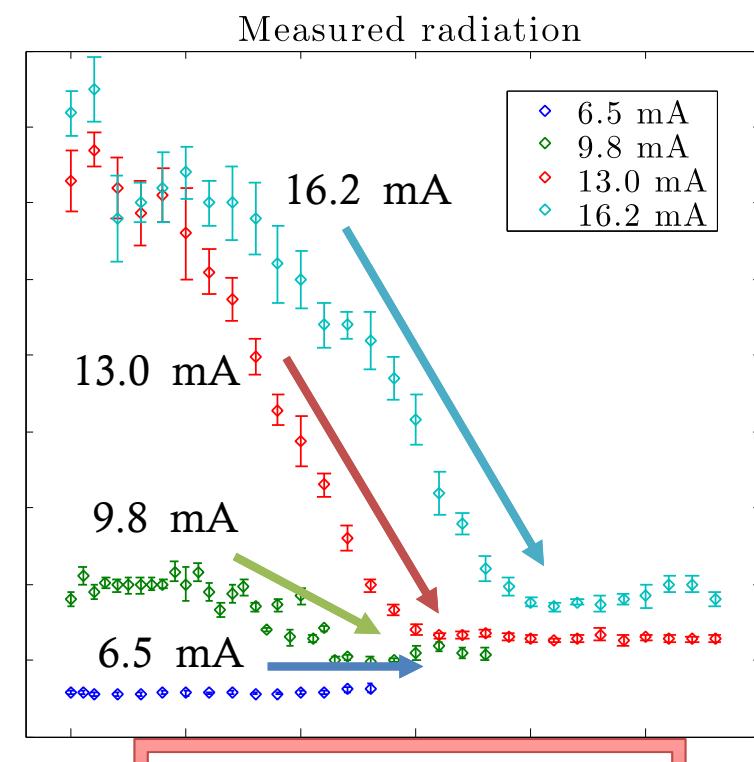
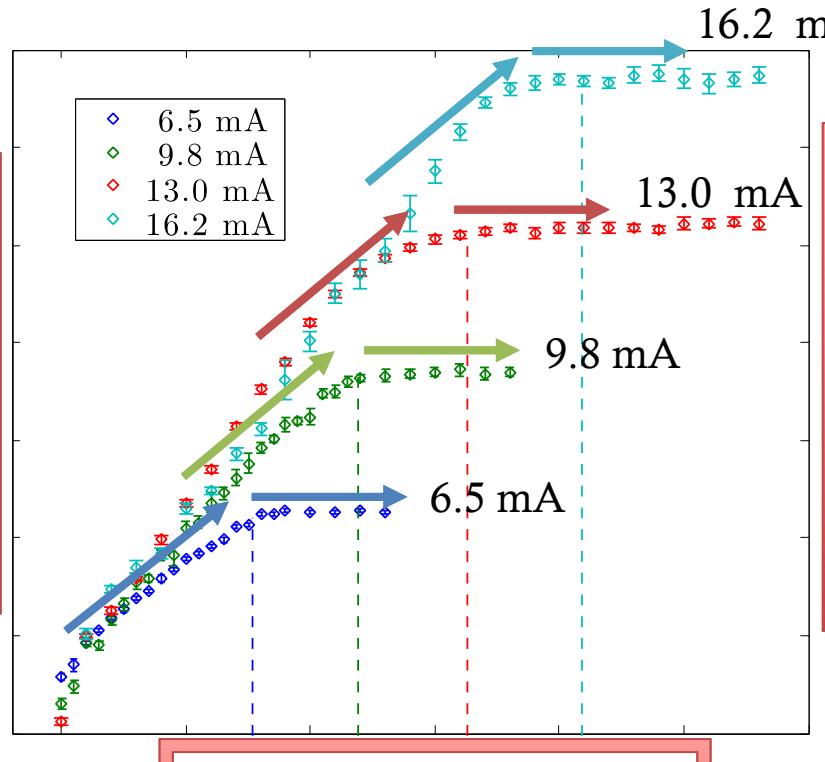
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# Clearing electrode tests

## Measured ion current striking the clearing electrode



$$V_{electrode} \geq \frac{I}{2\pi\epsilon_0 c} \frac{d}{\sigma_b}$$

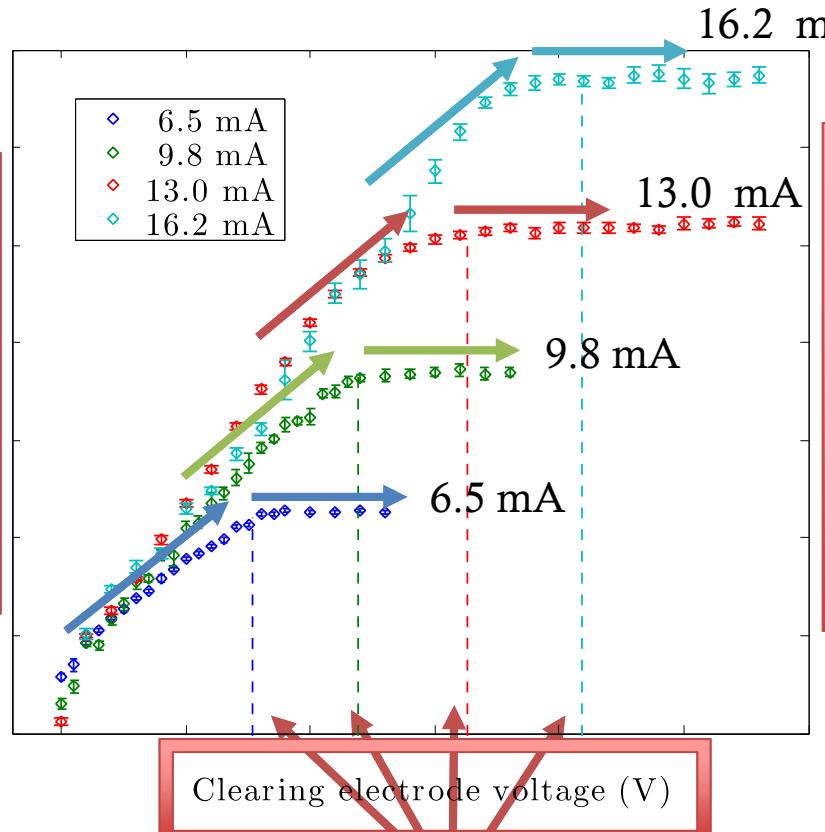
← Clearing electrode separation

← Transverse beam size



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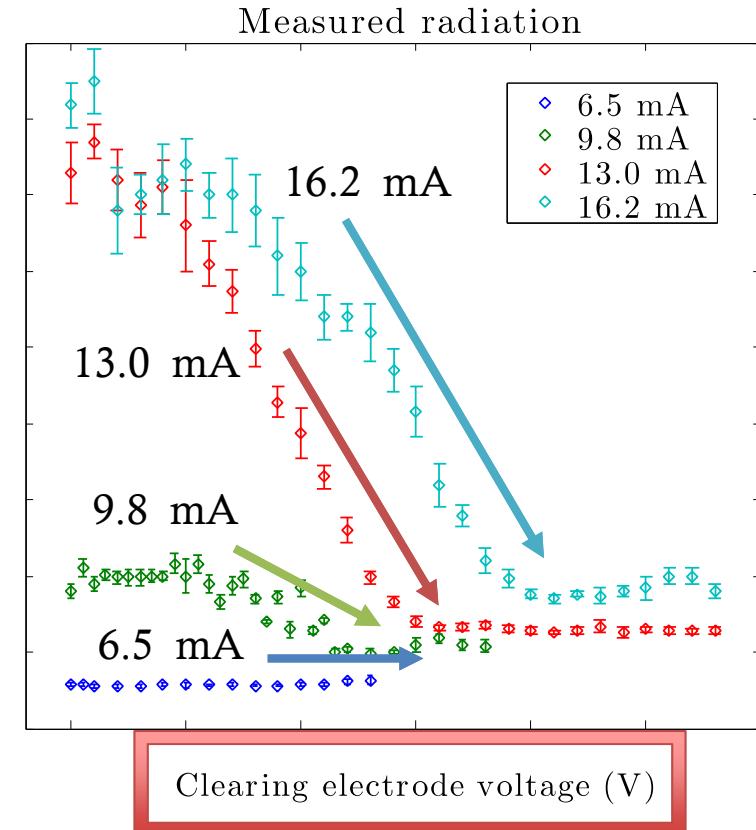
## Measured ion current striking the clearing electrode



$$V_{electrode} \geq \frac{I}{2\pi\epsilon_0 c} \frac{d}{\sigma_b}$$

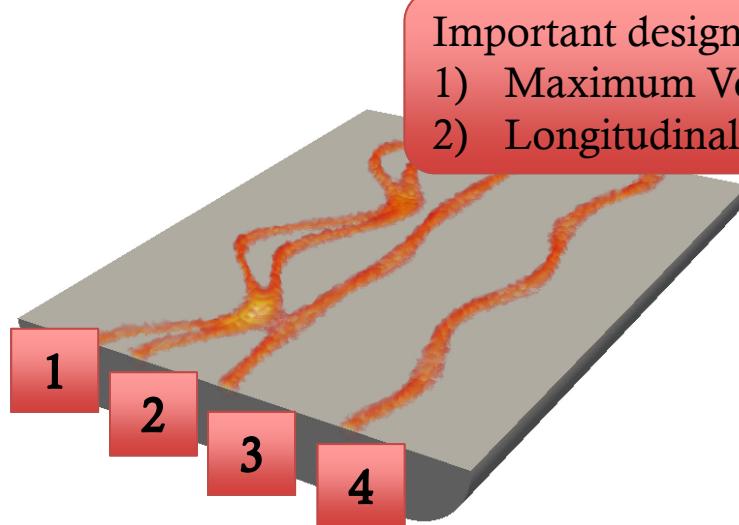
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← Transverse beam size

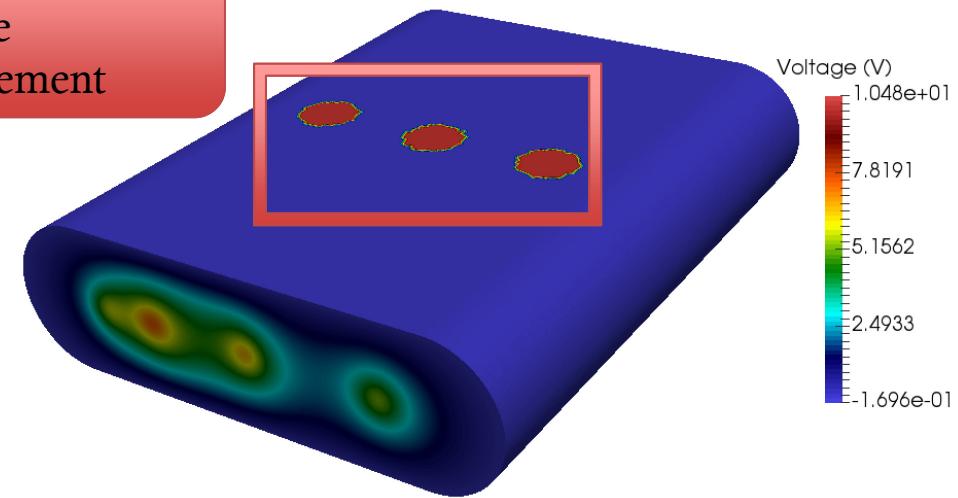




# Clearing electrode design

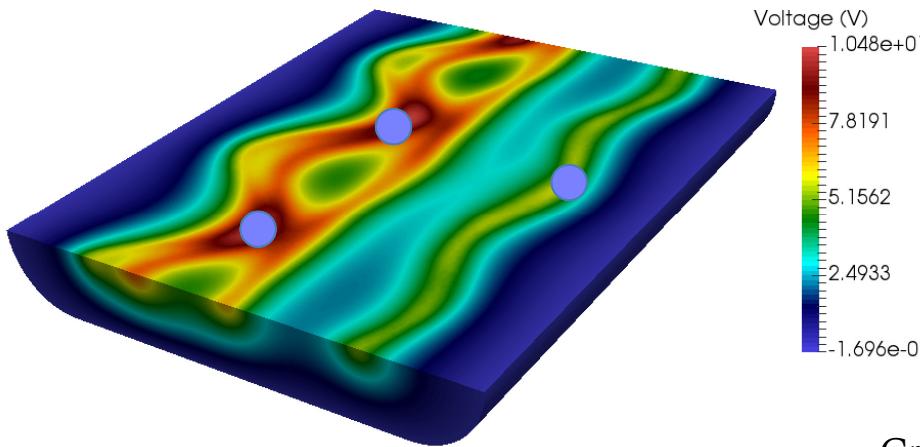


Important design considerations:  
1) Maximum Voltage  
2) Longitudinal placement

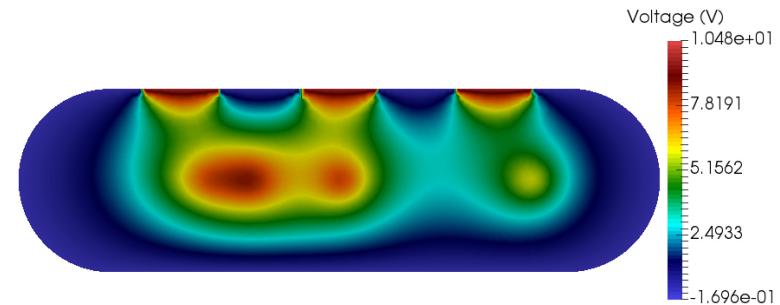


Four beams (DC approximation) in the  
CBETA beam pipe, from PDE solver FEniCS.

DC Beam potential, with three button BPMs on top.



9/30/2016 Beam potential of 4 DC beams

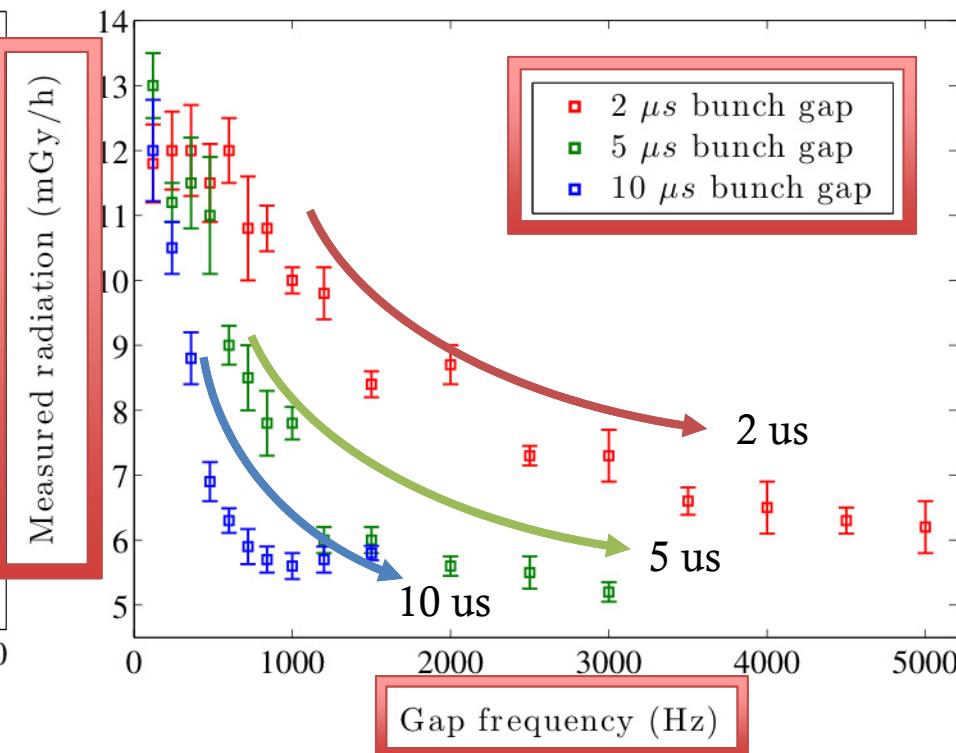
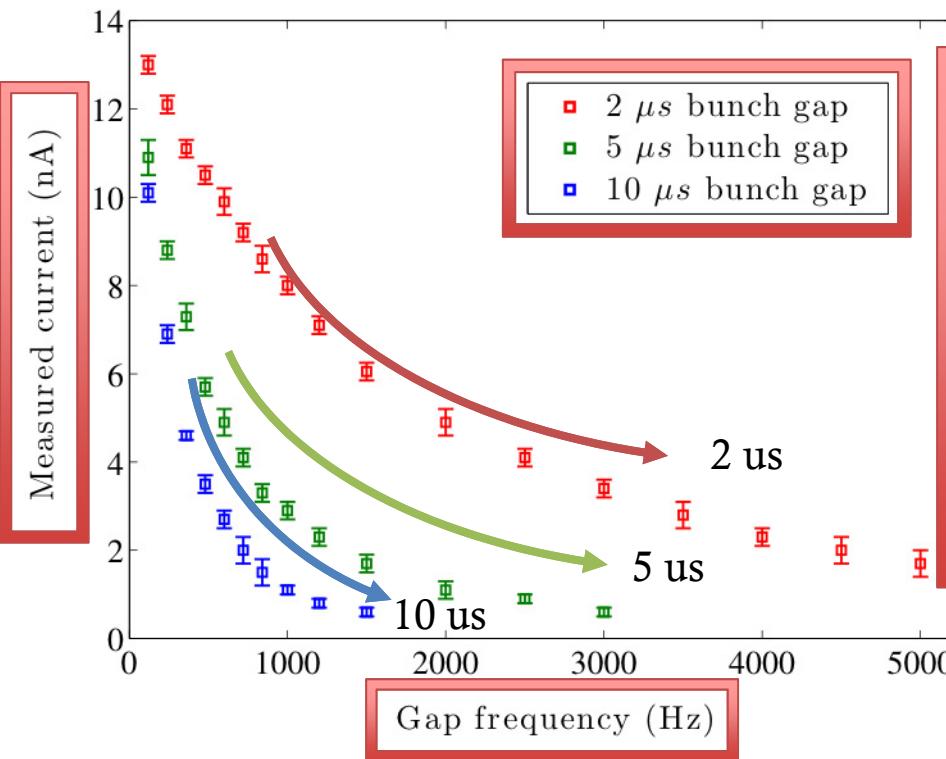


Cross section of the beam potential near the button BPMs.



# Bunch gap measurements

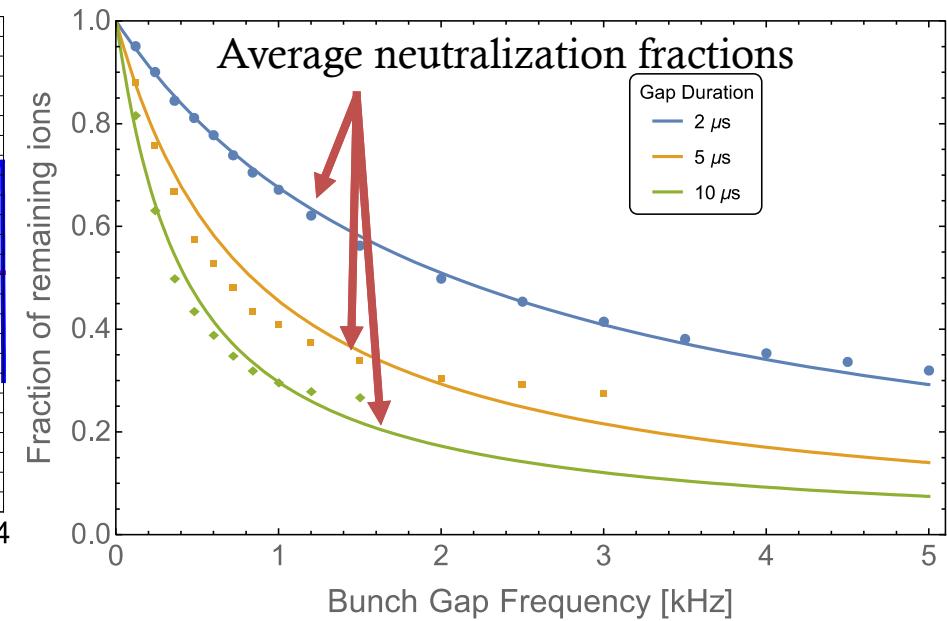
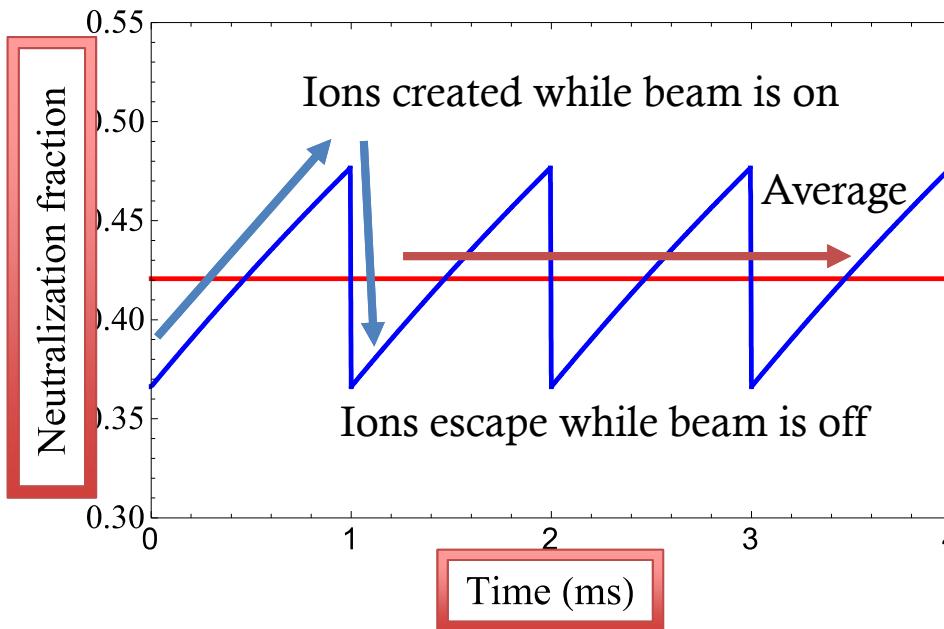
Beam current held fixed at 10 mA



Confirms that the ions are being cleared by the gaps, and not just the clearing electrode



# Measurement analysis



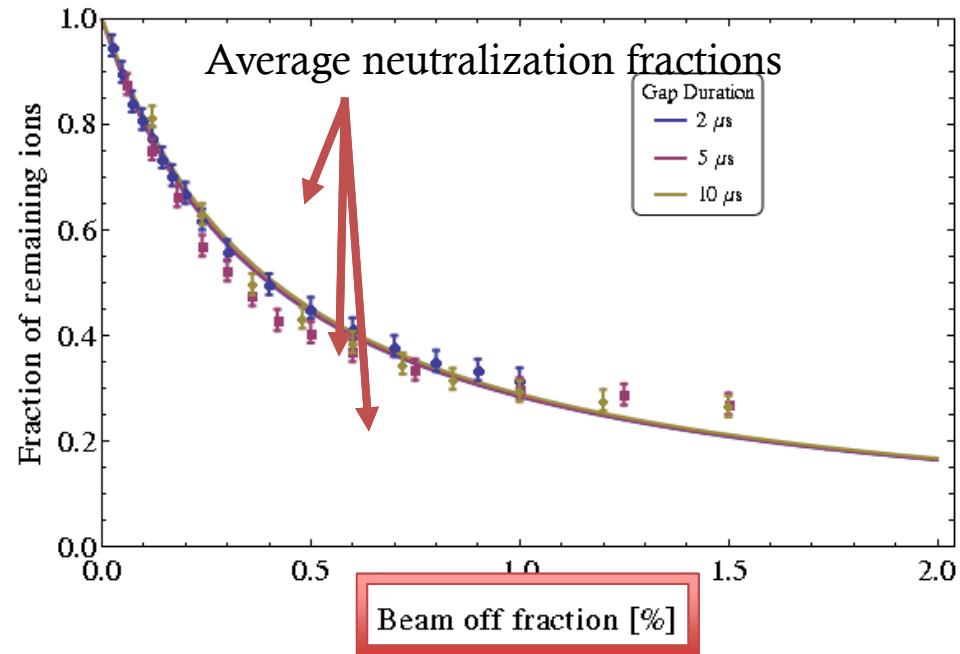
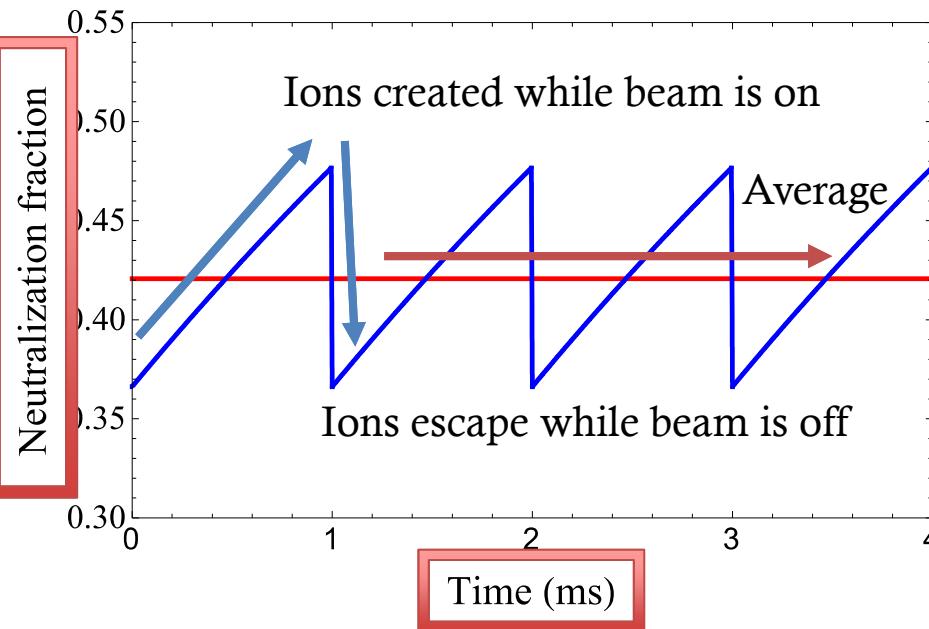
Our model: The ion density...

- 1) Increases via collision ionization while the beam is on.
- 2) Decays exponentially during the bunch gaps.
- 3) We measured the average neutralization fraction.

$$f_{avg} = \frac{1}{1 + \left(\frac{\tau_1}{\tau_2}\right)\left(\frac{T_2}{T_1}\right)}$$



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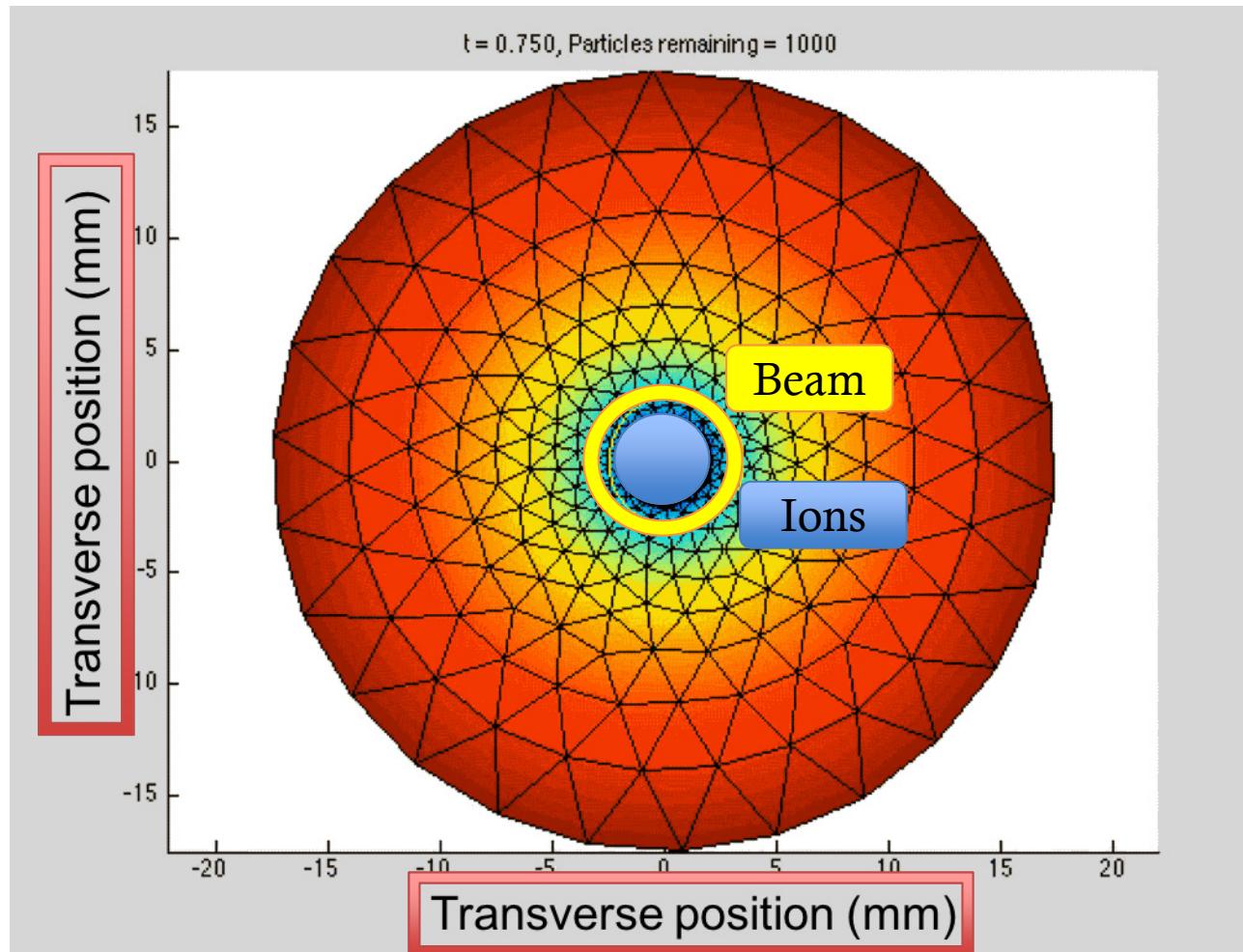
Amount of clearing depends only on total time beam is turned off.

Flexibility!



# Beam shaking

Transversely shaking the beam can drive a resonance that clears ions.





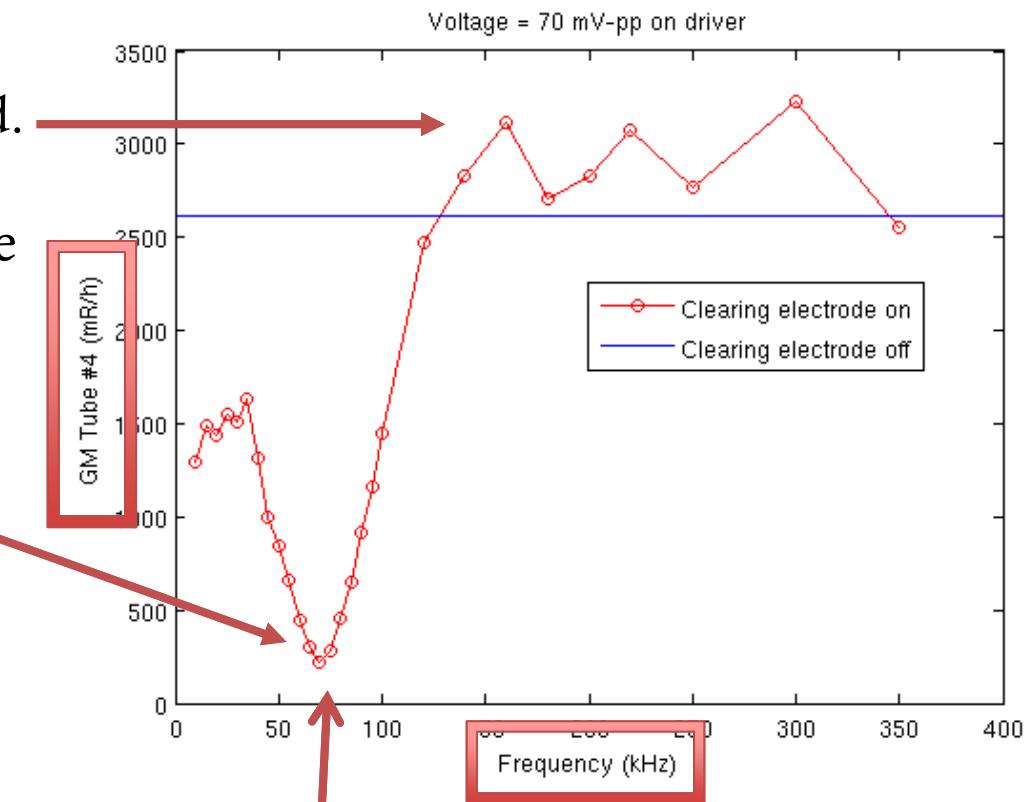
# Beam shaking

Shaking at the resonance frequency results in a reduction of background radiation.

After leaking gas, our radiation readings increased.

When we sinusoidally shake the beam with the clearing electrode at the ion oscillation frequency, the radiation levels drop significantly.

This was a known mitigation scheme in the 1980's at CERN's antiproton accumulator. MLS uses this daily also.



$$\omega_{ions} = \sqrt{\frac{2r_p c}{e} \frac{I_{beam}}{A_{ion} \sigma_{beam}^2}}$$



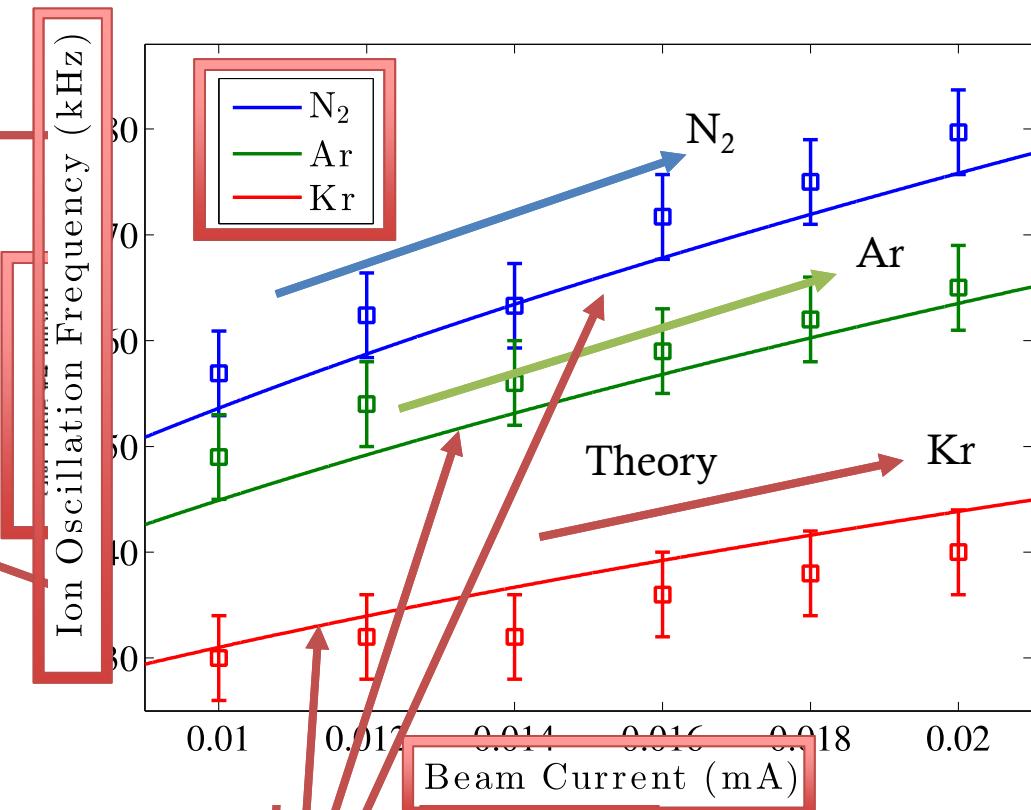
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# Take home messages

- What is ion trapping?
- How do ions affect a beam?
  - Non-linear focusing
- Is ion trapping a concern in linacs?
  - Yes, at high CW beam current
- How do we mitigate their effects?
  - Clearing electrodes, bunch gaps, beam shaking

In the future, we're taking more data with diagnostics that can withstand high beam power to see what happens to the beam!



# Thanks!

- Thanks to the ERL team:
  - Adam Bartnik, Ivan Bazarov, John Dobbins, Bruce Dunham, Georg Hoffstaetter, Tobey Moore, and Kristina Smith (REU student)
- Publication:

S, Full, et. al, “Detection and clearing of trapped ions in the high current Cornell photoinjector”

Phys. Rev. Accel. Beams, 19, 034201 (2016)