Detection and clearing of trapped ions in the Cornell ERL photoinjector

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ERL Workshop 2015
June 11th, 2015

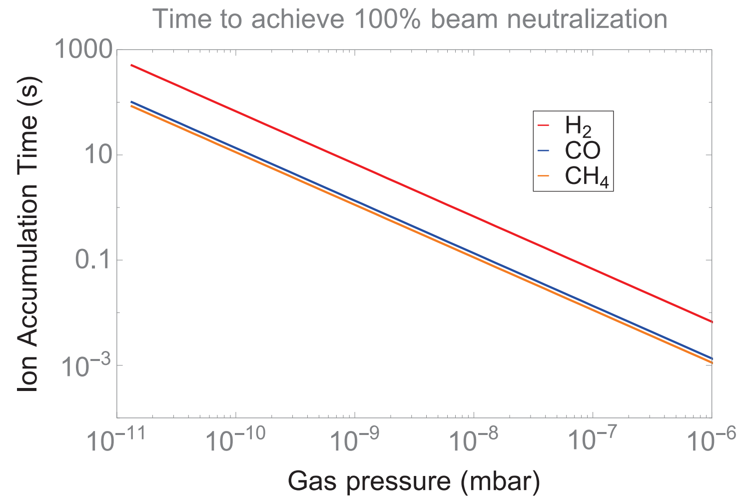
Goals

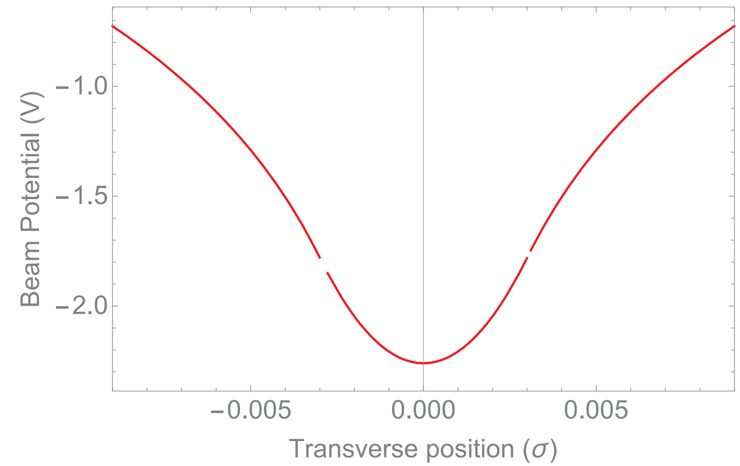
- Explain why ions are a problem
- Show experimental results for 3 clearing techniques
  - Clearing electrodes
  - Beam shaking
  - Bunch gaps

Ions trapping

- Ions accumulate rapidly via collision ionization
- Ions get trapped inside the negative potential well of the beam.
- They oscillate with a characteristic frequency

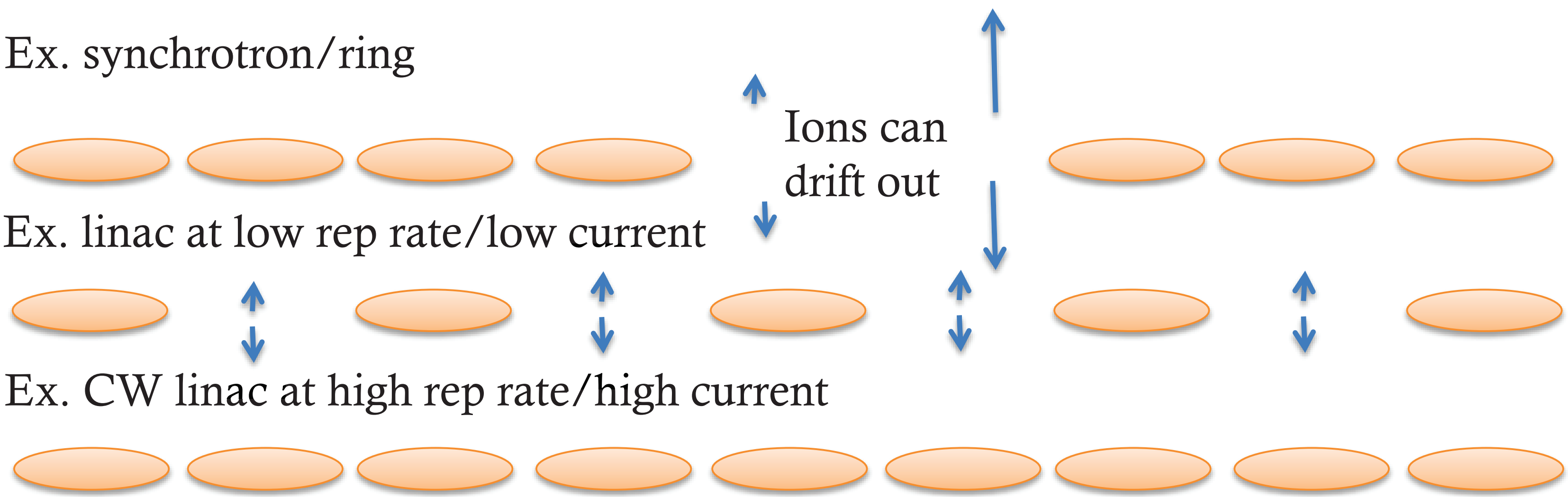
$$\omega_{ions} = \sqrt{\frac{2r_p c}{e}\frac{I_{beam}}{A_{ion}\sigma_{beam}^2}}$$





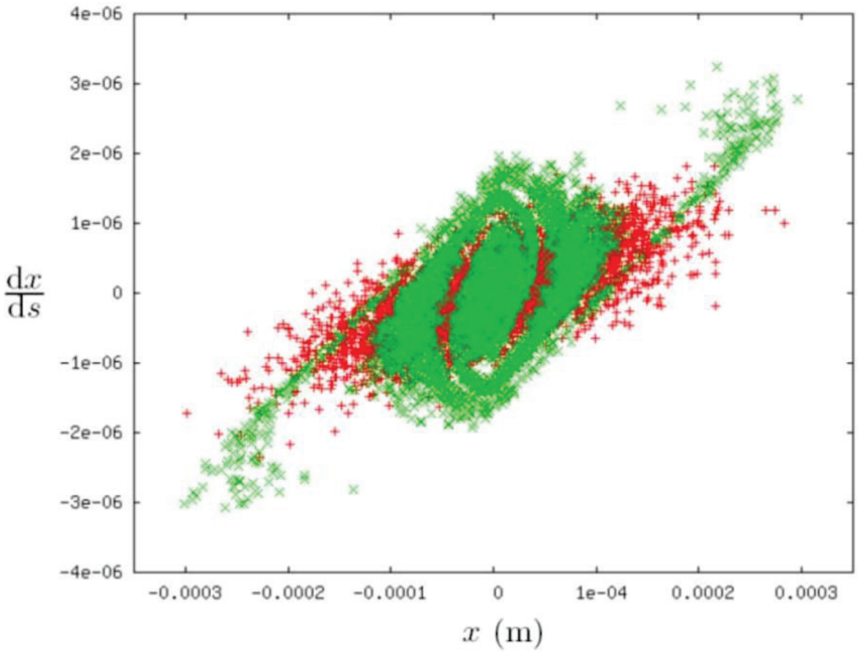
This is a problem in ERLs/linacs

- During CW, high repetition rate operation ions cannot escape between bunches
  - Introducing bunch gaps causes beam loading problems in ERLs
- Anecdotally we know ions are in the photoinjector:
  - Beam-ion interactions generate bremsstrahlung
  - Ion clearing electrodes reduced radiation by >50% when approaching 70 mA.



Ions do scary things in ERLs

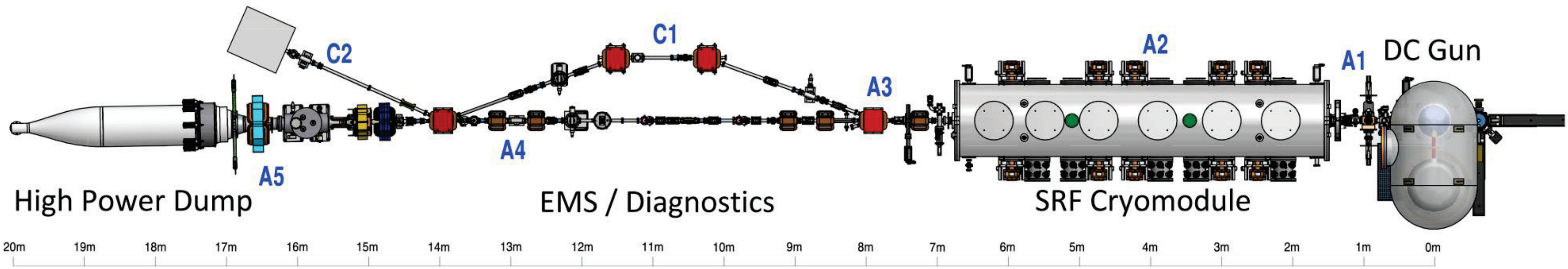
- Beam halo/losses
- Incoherent tune shifts/spread
- Betatron phase errors (ion focusing)
- Charge neutralization (can be good)
- Beam instabilities (ex. Fast Ion Instability)



Simulated Phase space in Cornell ERL design
Green – After traversing 200 m ion field
Red – Normal operation

G.H. Hoffstaetter, C. Spethmann , Phys. Rev. ST AB, Volume 11, 014001 (2008)

Cornell ERL photoinjector



Ions have been studied quite a bit in simulations up until this point.

We present some of the first experiments looking at ions in this high current parameter regime.

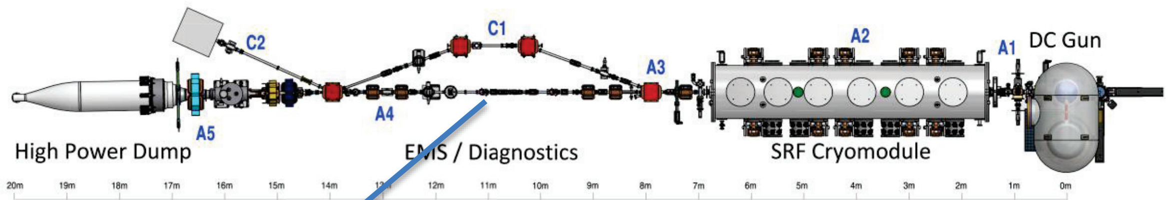
Parameter	Experimental	Nominal
Beam energy	3.5 - 4 MeV	5-15 MeV
Beam size	1 mm – 4 mm, Round	~ mm
Bunch length	~ 3 ps	< 3 ps
Bunch charge	7.7 – 15.4 pC	77 pC
Current	10 – 20 mA (100 mA)	100 mA
Repetition rate	1.3 GHz	50 MHz or 1.3 GHz
Gas pressure	1.2 x 10^{-7} torr	1 x 10^{-10} torr

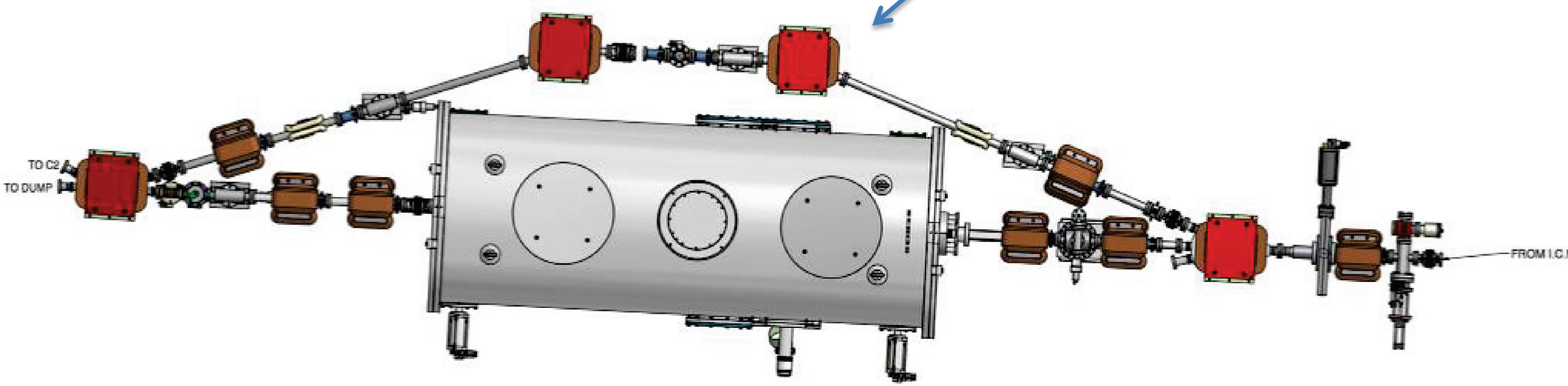
Measurements are challenging at high current

- We can't measure beam directly
  - Interceptive diagnostics melt above 1 mA
  - No synchrotron/diffraction radiation (low energy linac)
  - New fast wire scanner wasn't available
- We look for ions instead
- **We used 3 diagnostics**
  - **BPM + spectrum analyzer**
  - **Ion clearing electrode + picoammeter**
  - **Radiation monitors**

Melted beam dump after raster failure.

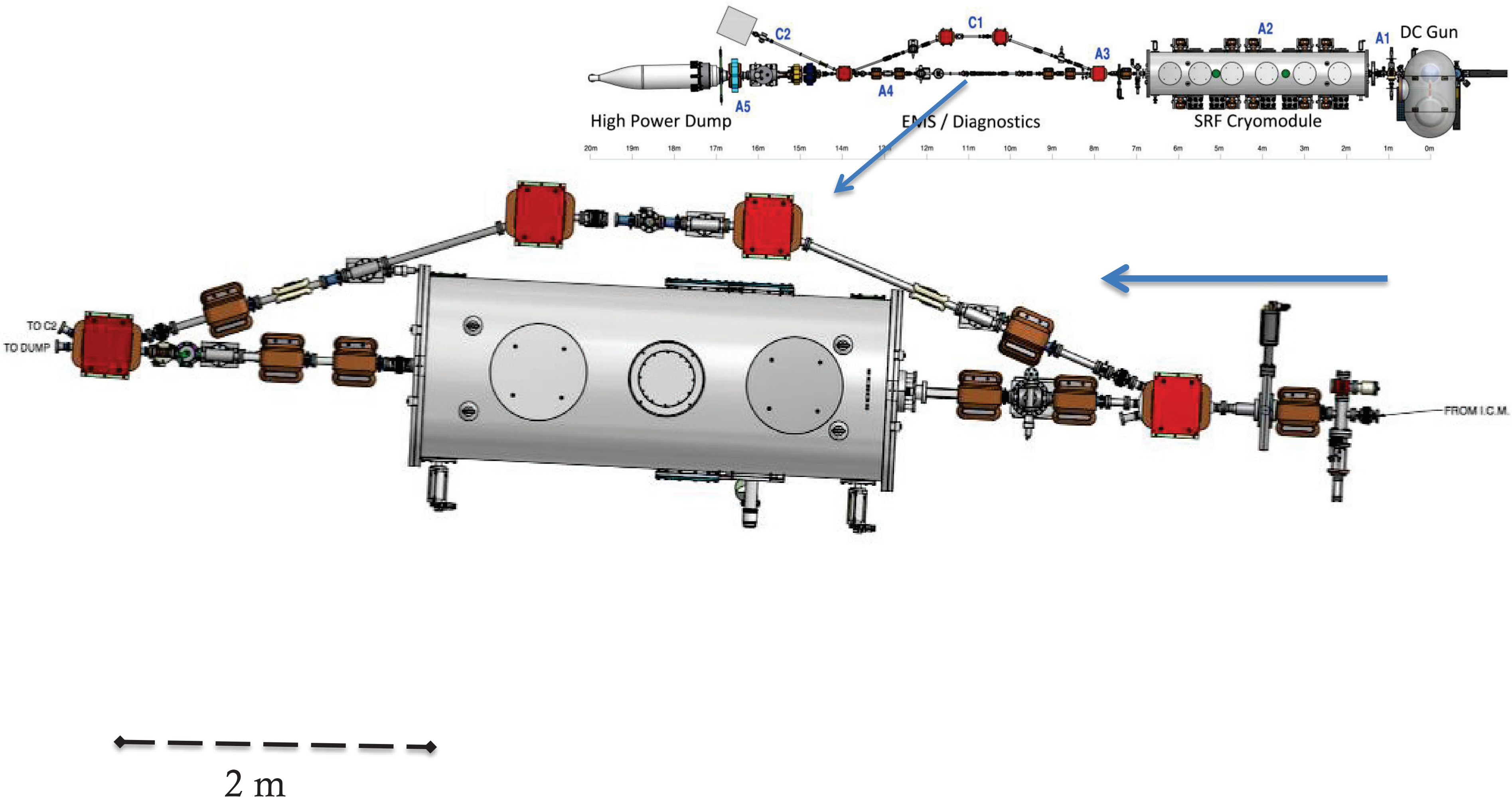
Experimental setup





2 m

Experimental setup



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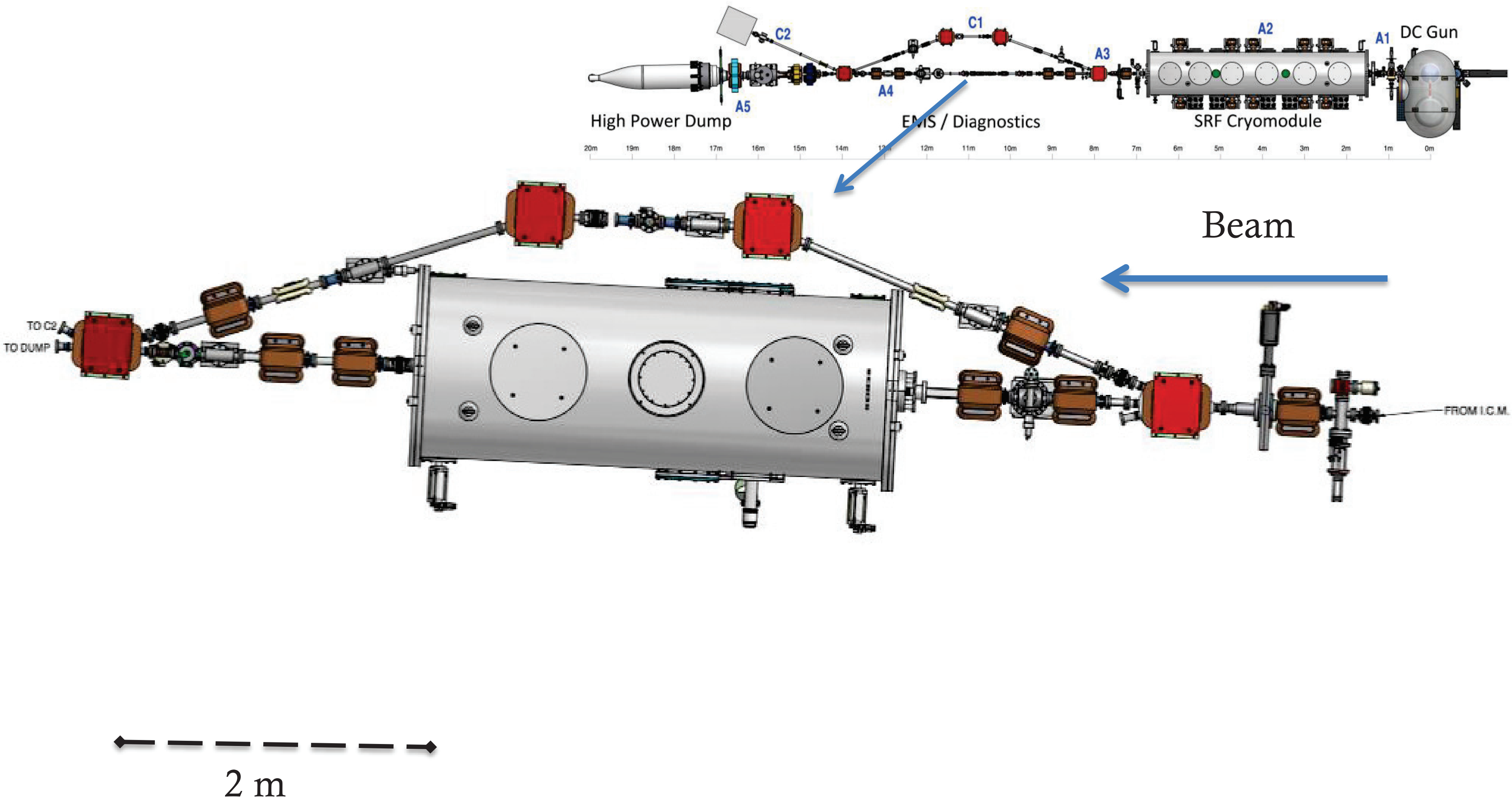

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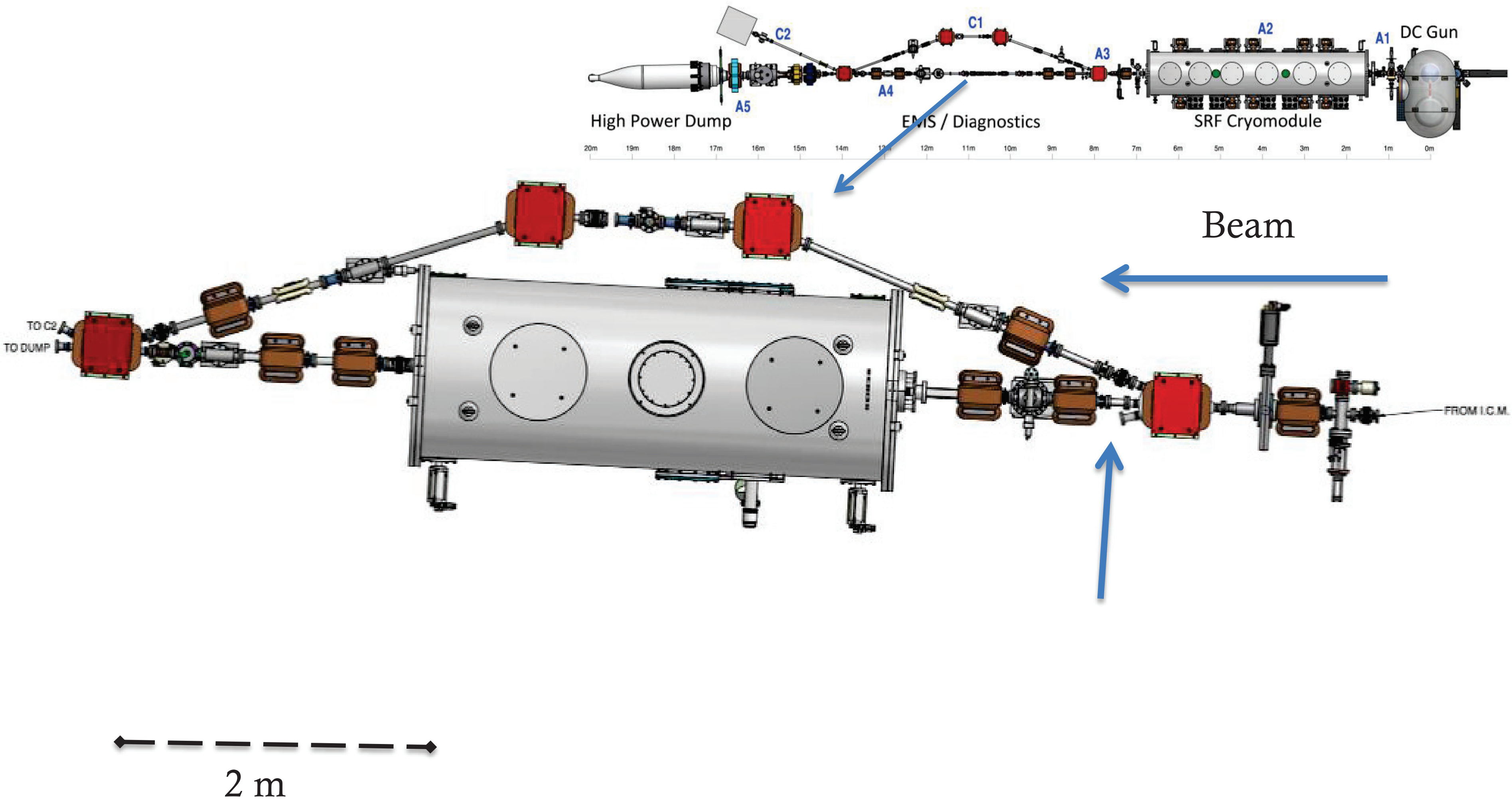

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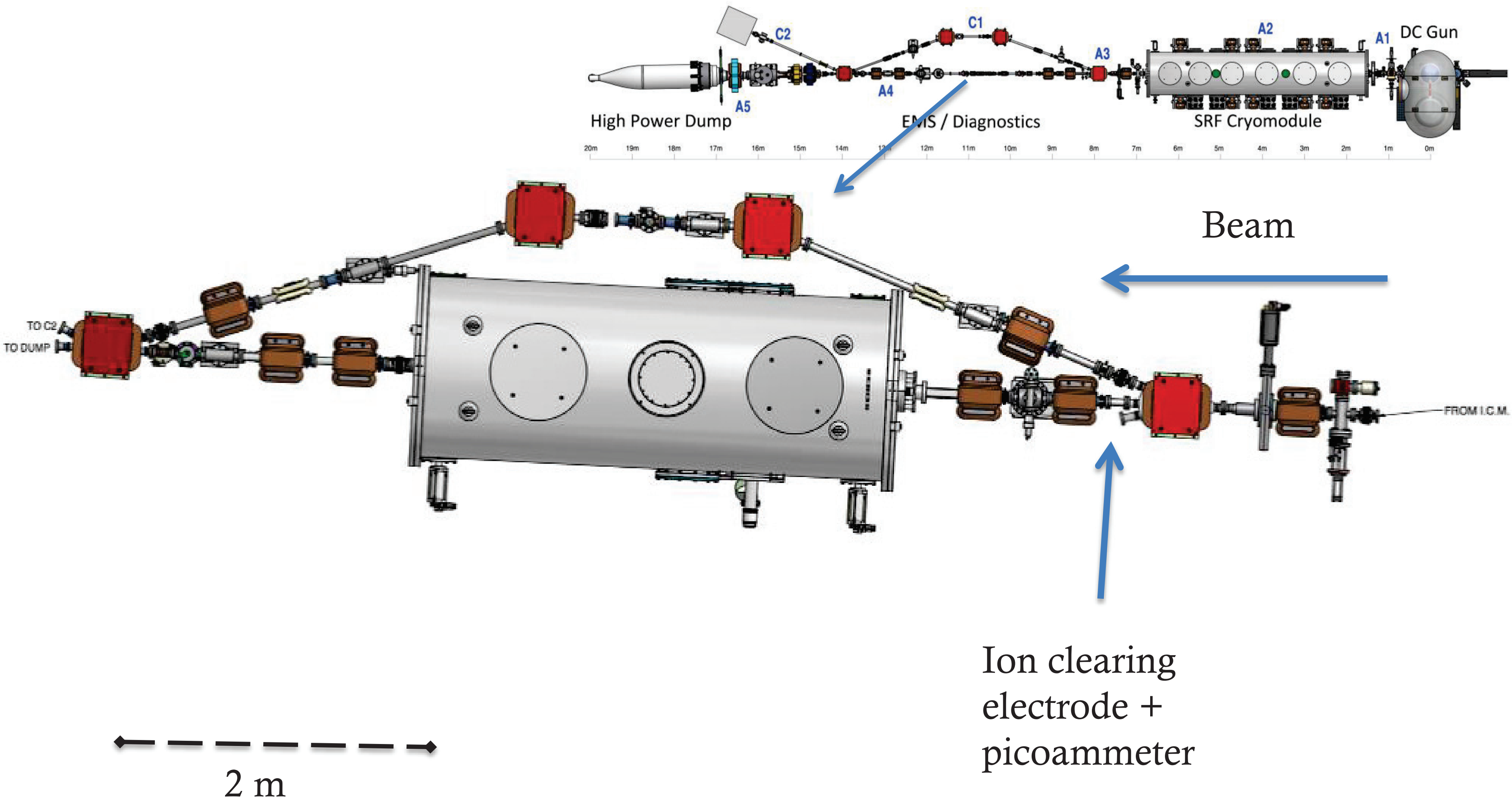

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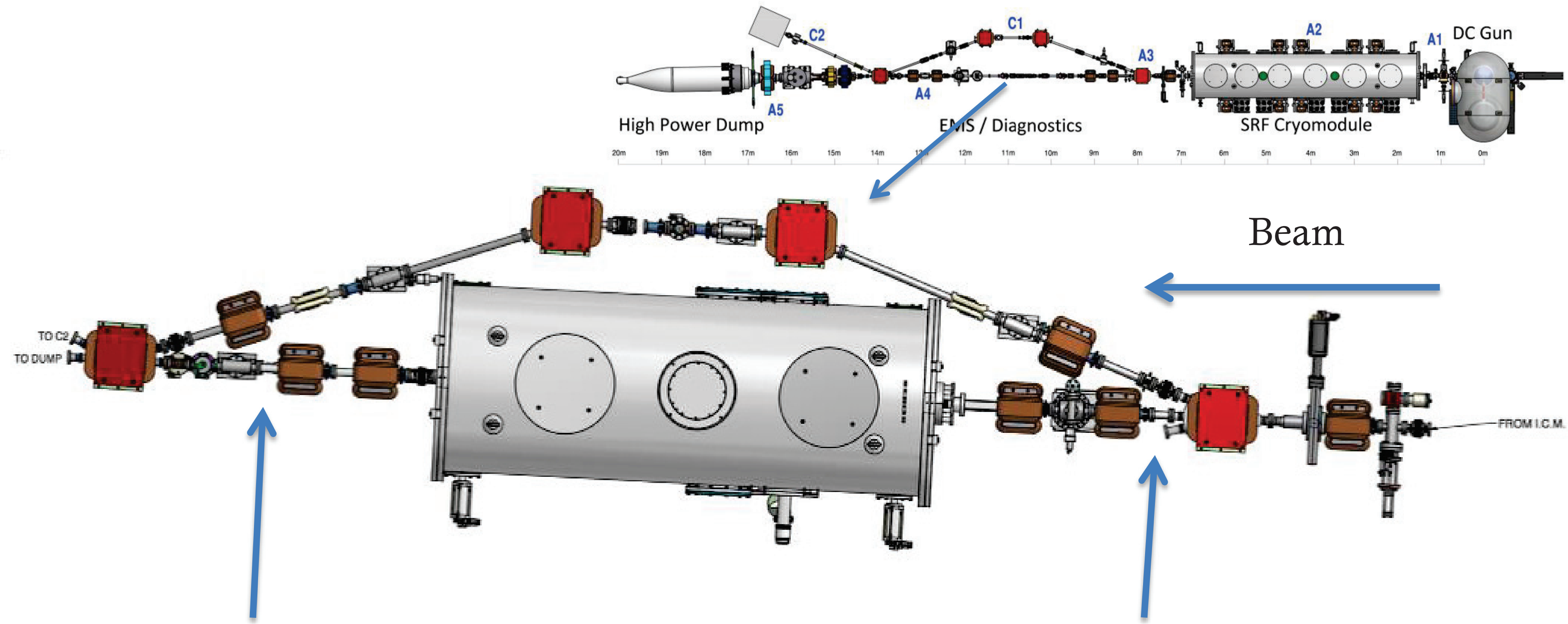
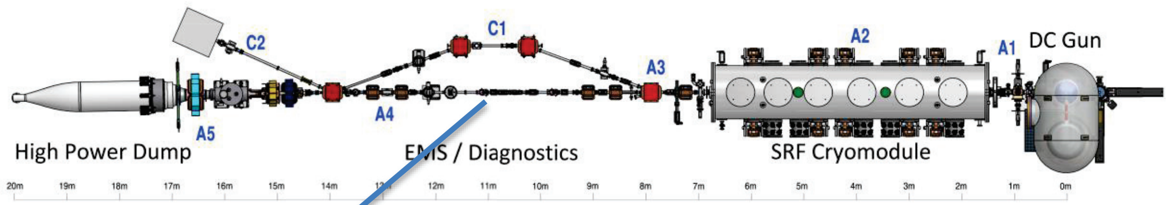


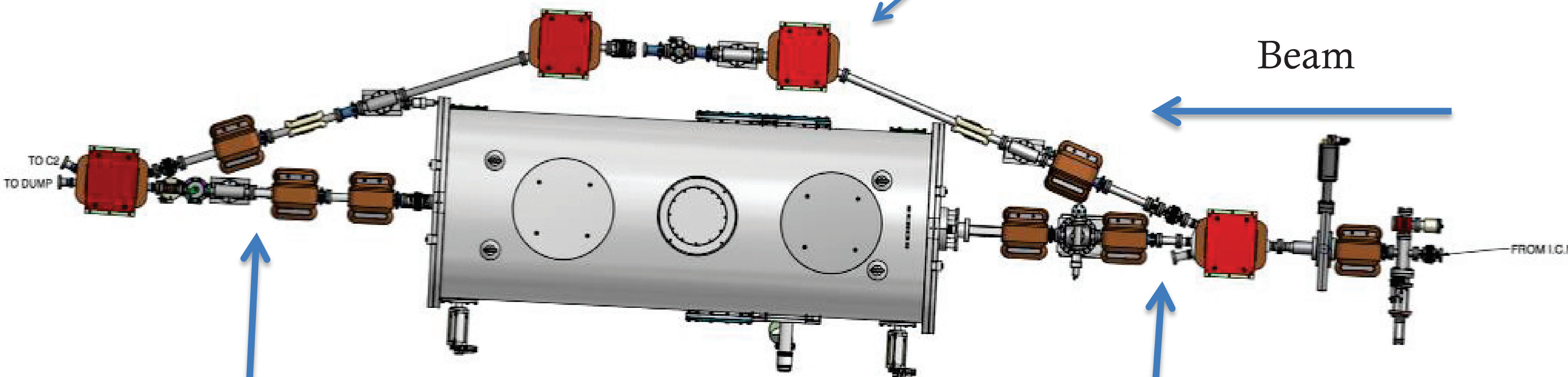
Ion clearing electrode + picoammeter

2 m

Experimental setup



Beam

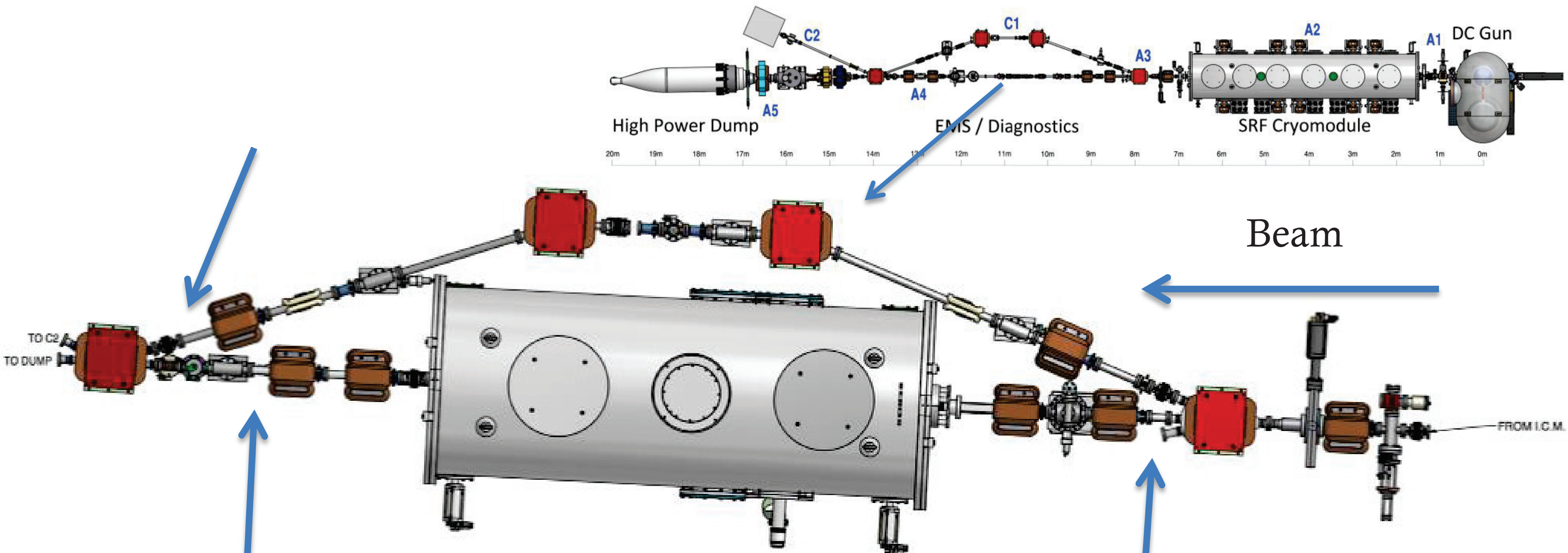


Gas leak
(N_2, Ar, Kr)

2 m

Ion clearing
electrode +
picoammeter

Experimental setup



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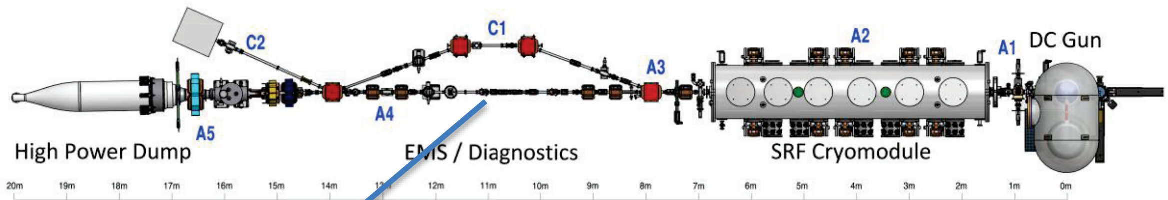
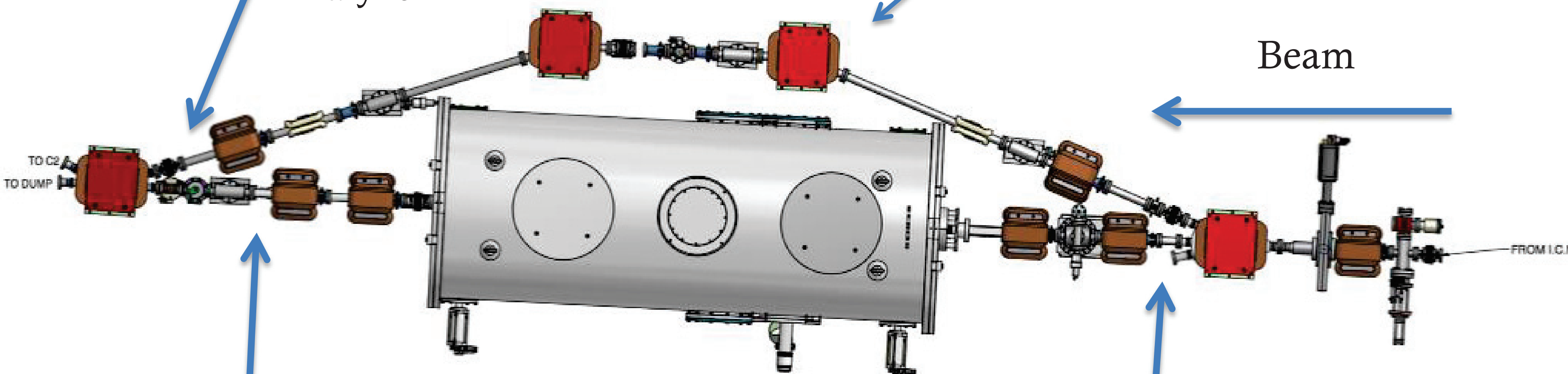


BPM +
Spectrum
Analyzer

Beam



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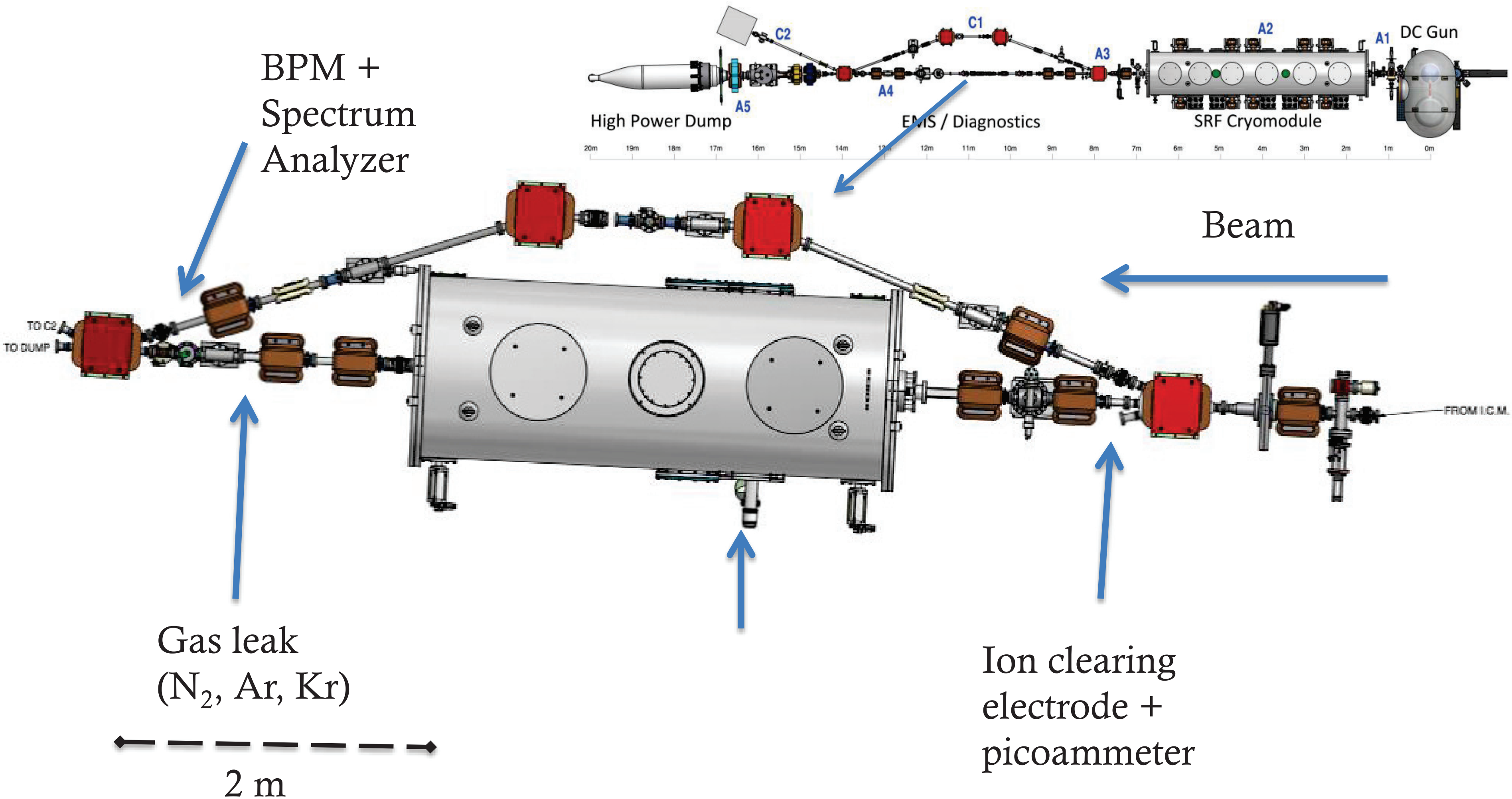

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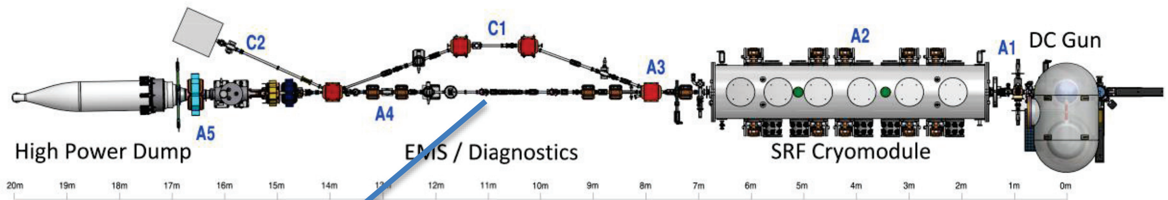
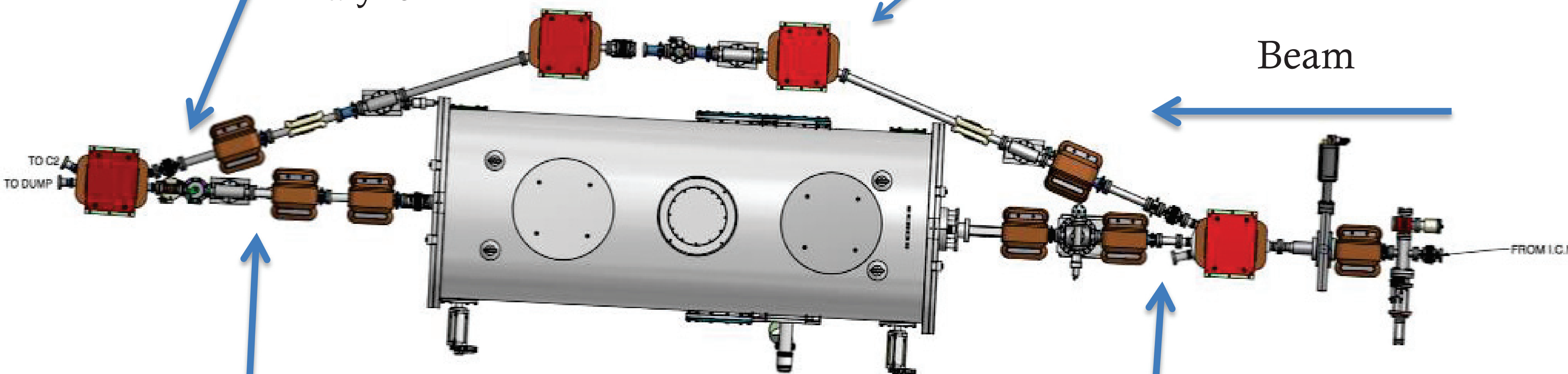


BPM + Spectrum Analyzer

Beam



Gas leak (N_2, Ar, Kr)

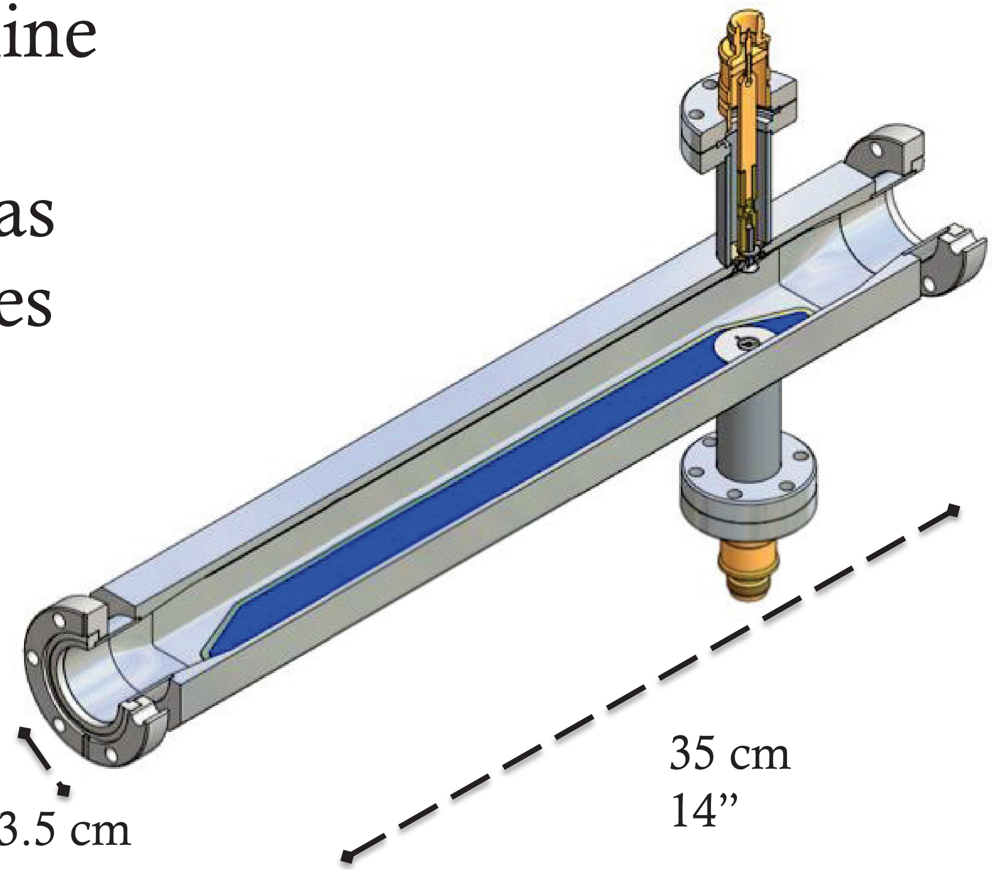
2 m

Superconducting RF Cavity (HTC - Horizontal test cryomodule)
Present only during beam shaking experiments

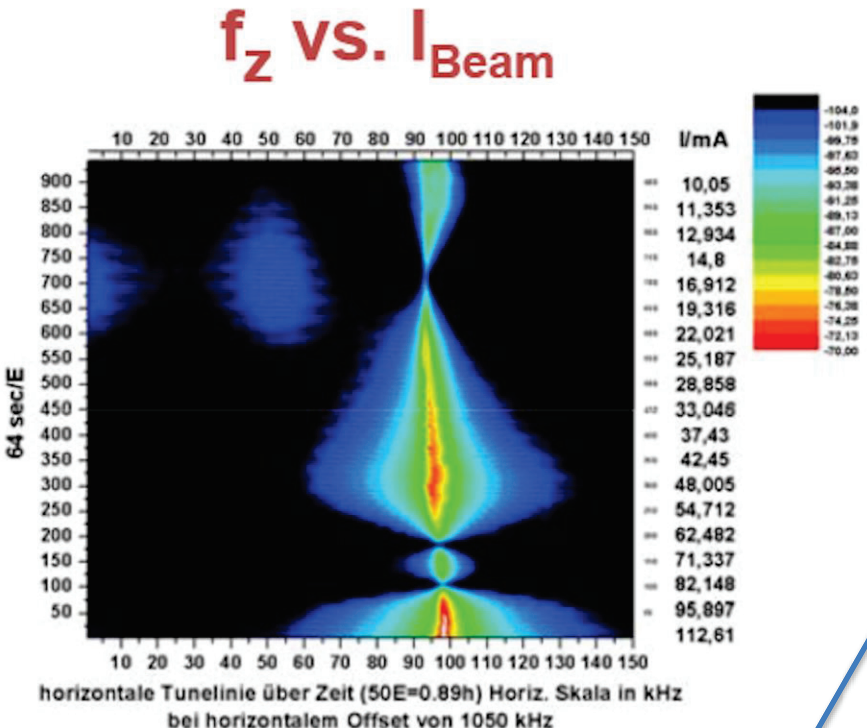
Ion clearing electrode + picoammeter

Ion clearing electrode design

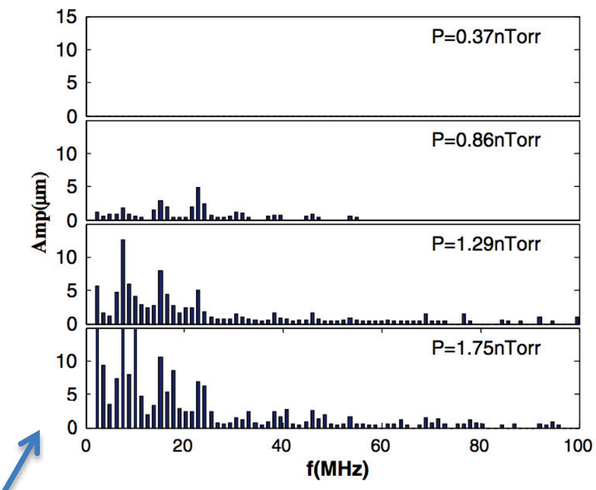
- Button and stripline BPMs are commonly used as clearing electrodes
- We use a special design



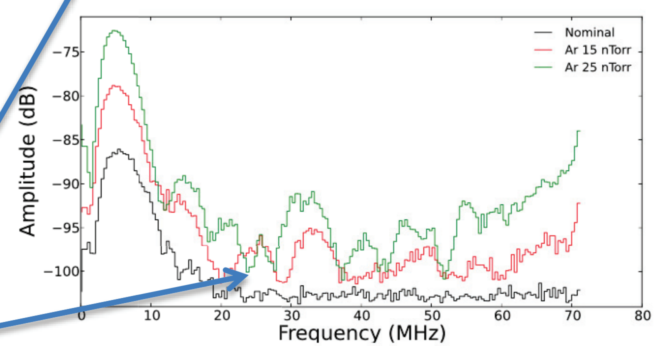
First step: Sidebands around the tune are a clear signature of ions in most rings.



MLS (Feikes)



SPEAR3 (Wang)

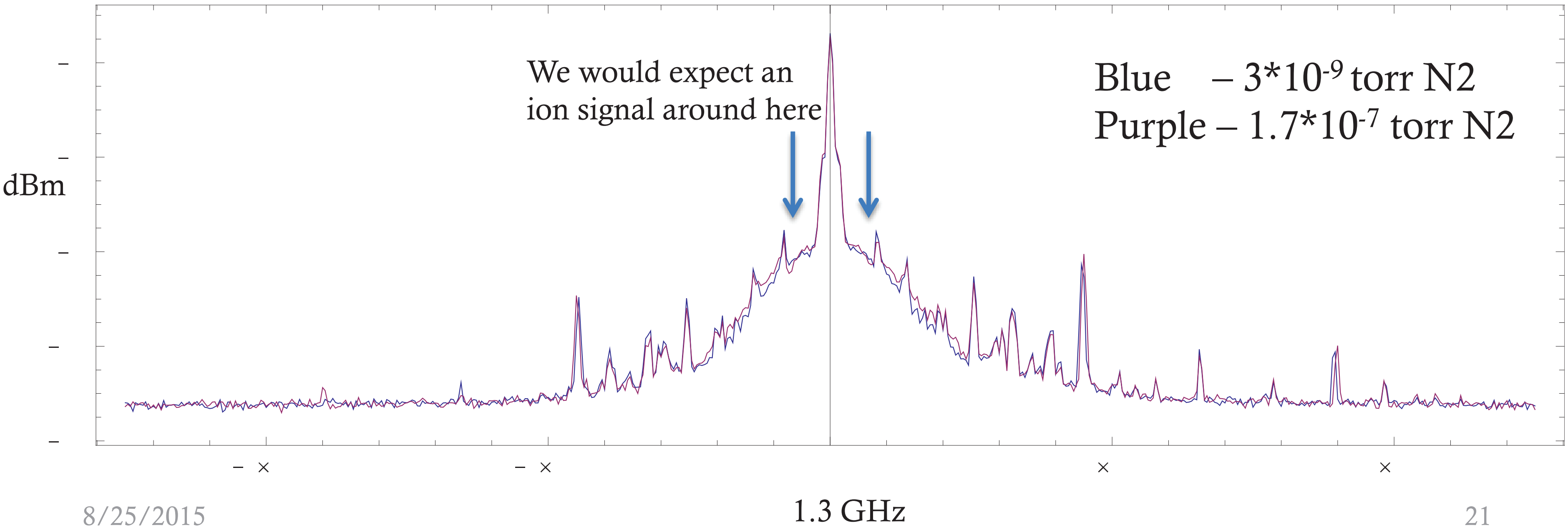


CESR (Chatterjee)

Result of beam-ion coupled oscillations.

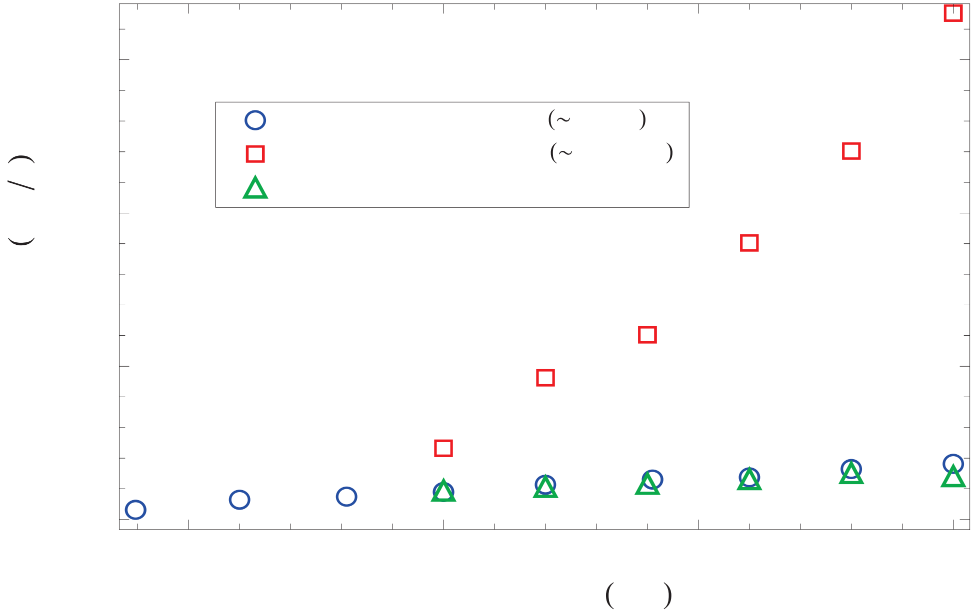
No observed sidebands in injector

- Leak gas, then examined BPM + spectrum analyzer
  - No changes before and after leak
  - No changes when implementing clearing methods
- Two reasons why we didn't observe any changes:
  - There's **too much noise** in the 50 – 100 KHz region where you would expect to observe ion peaks
  - Only a ~2 m interaction region, which is too short
    - Beam-ion coupling would need to be noticeable after ~20 ns



As beam current is increased, background radiation increases.

- Leaking gas shows that this radiation is caused by gas/ions.
- Clearing electrodes help mitigate the radiation, further suggesting it's caused by ions.
- Note: The radiation due to ions (without gas leaks) becomes noticeable at ~70 mA.

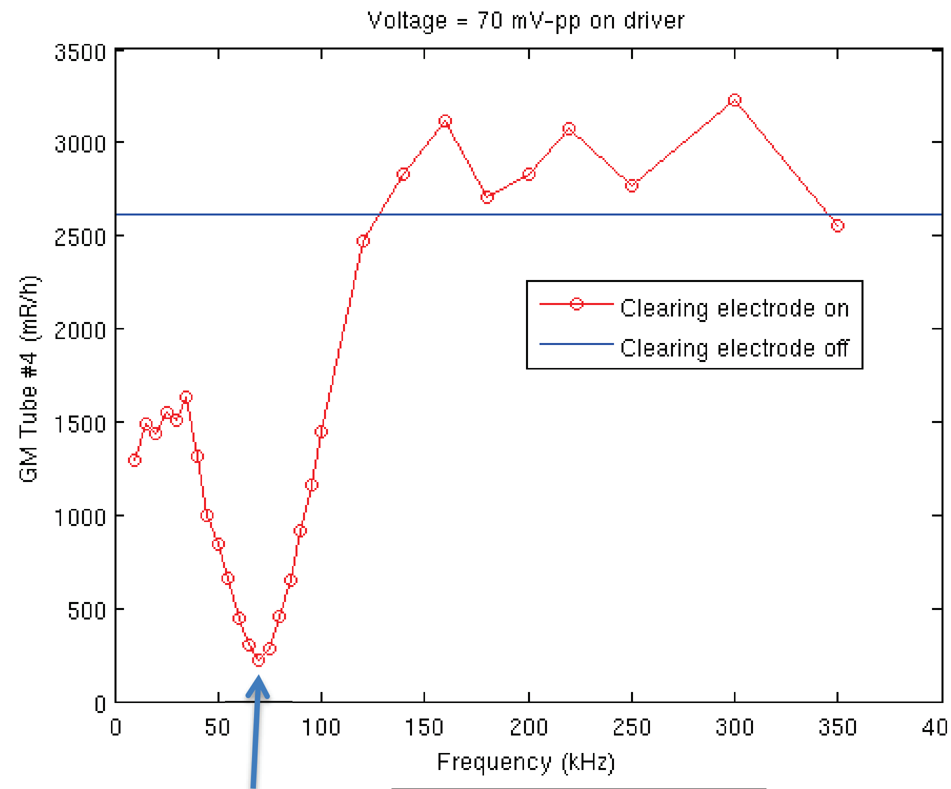


Shaking at the resonance frequency results in a reduction of background radiation.

After leaking gas, our radiation readings increased.

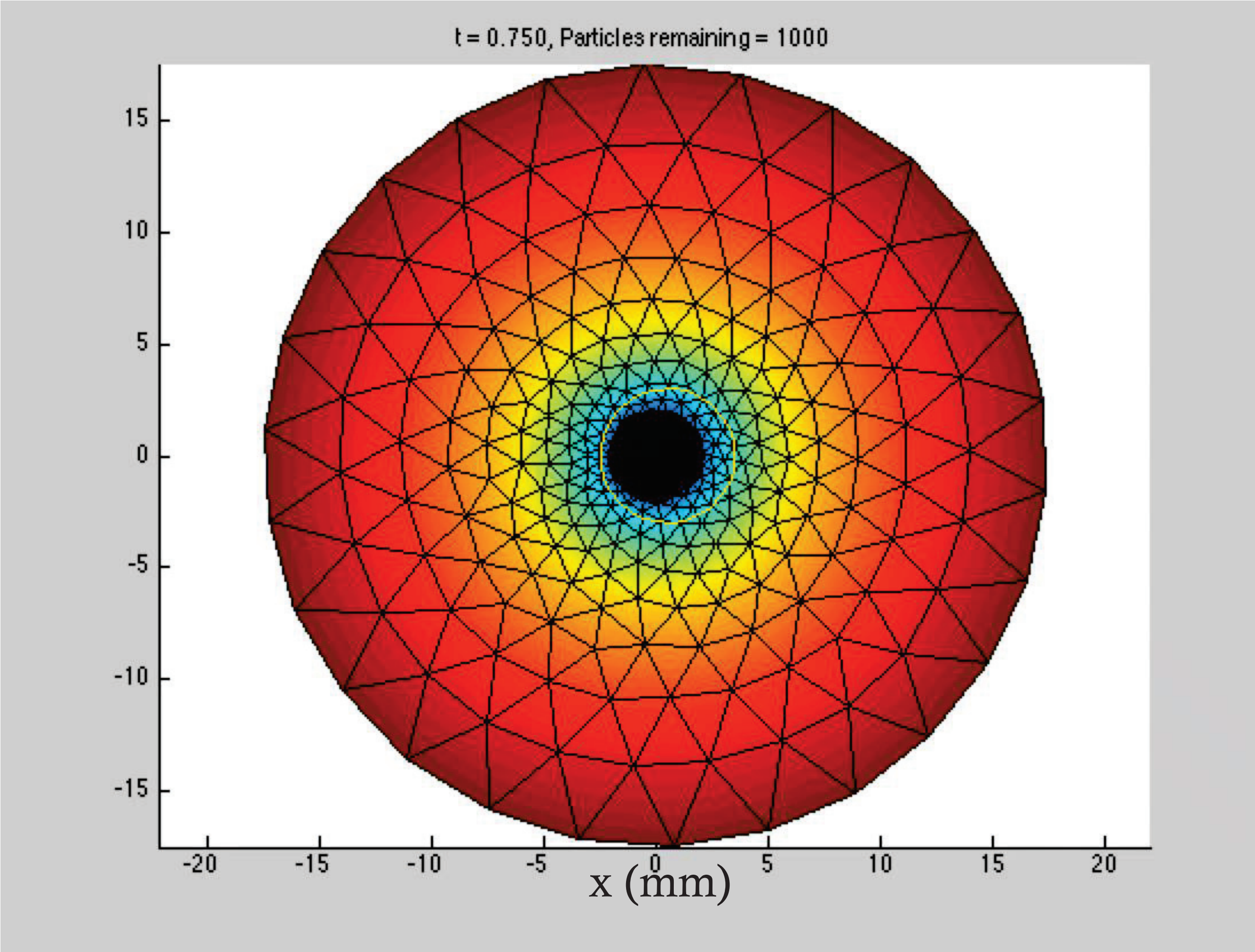
When we sinusoidally shake the beam with the clearing electrode at the ion oscillation frequency, the radiation levels drop significantly.

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



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

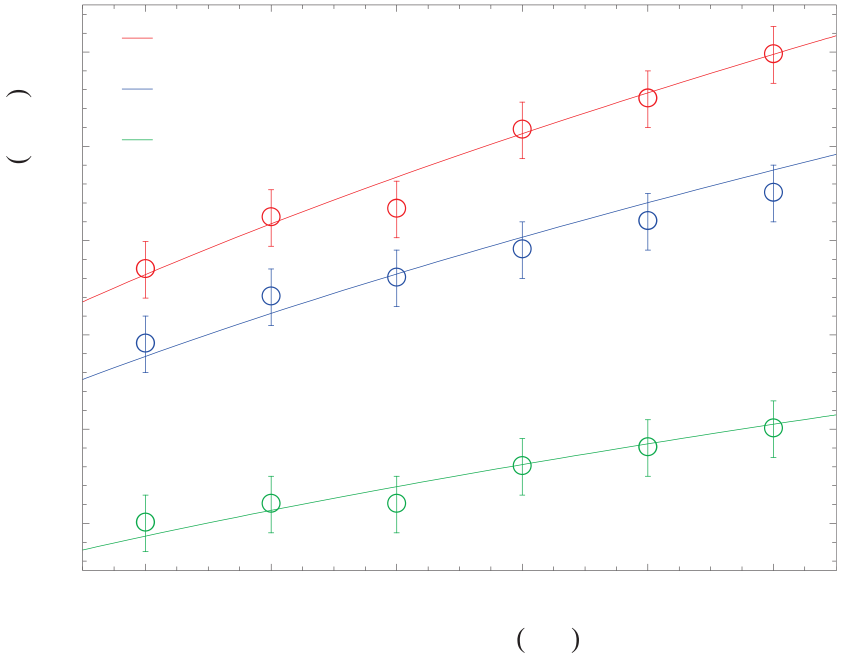
Movie of beam shaking using a Poisson solver

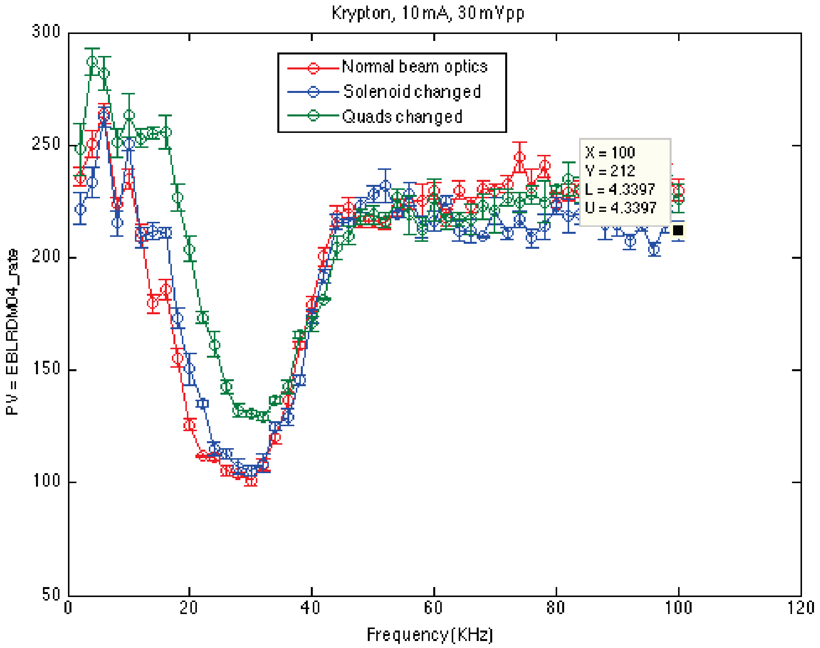


Frequency scales correctly with beam current, ion mass, but not beam size.

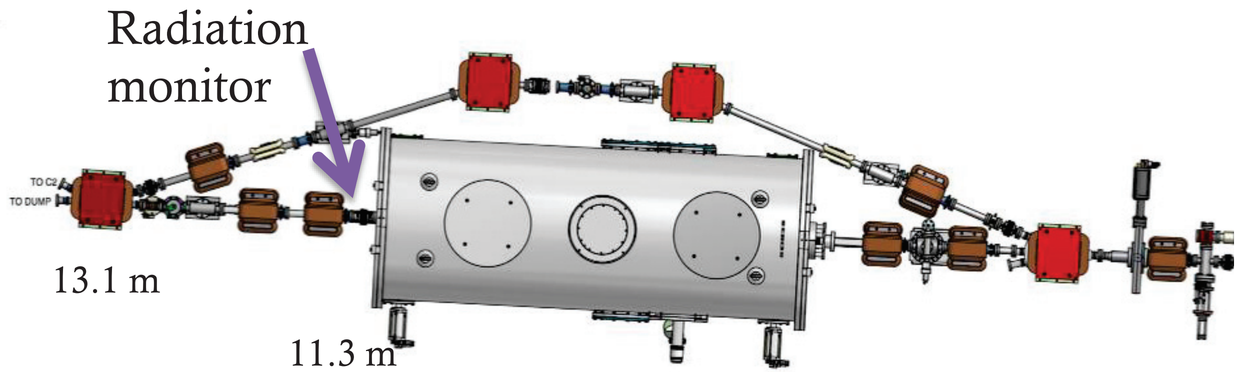
$$\omega_{ions} = \sqrt{\frac{2r_p c}{e} \frac{I_{beam}}{A_{ion}\sigma_{beam}^2}}$$

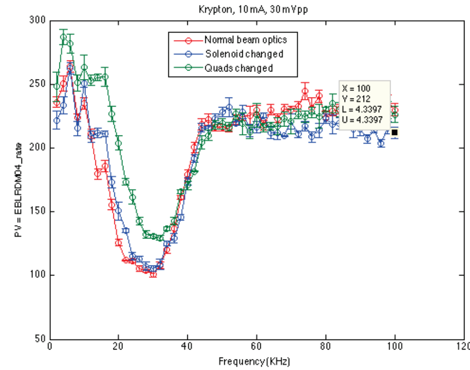
Changing the beam size by over a factor of 3 did NOT change the resonance frequency… Still a mystery

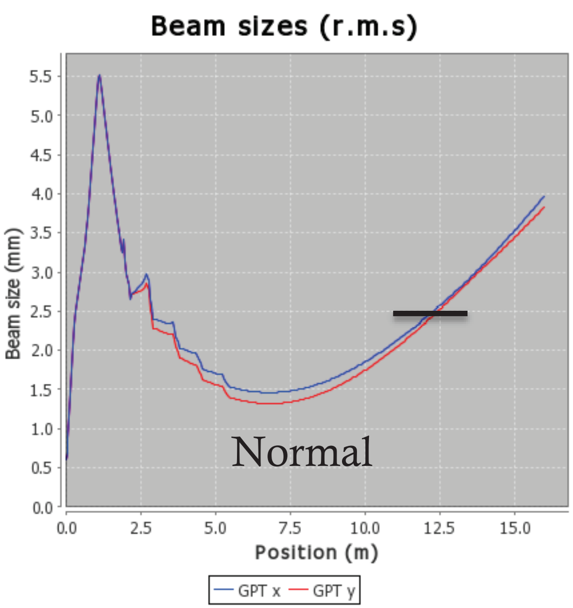


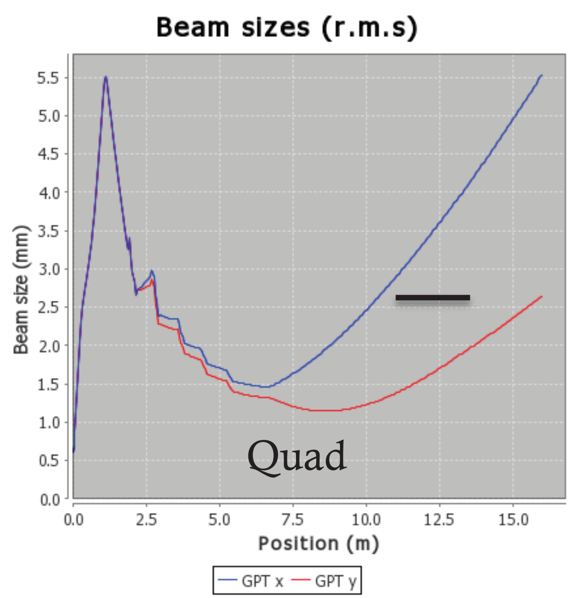


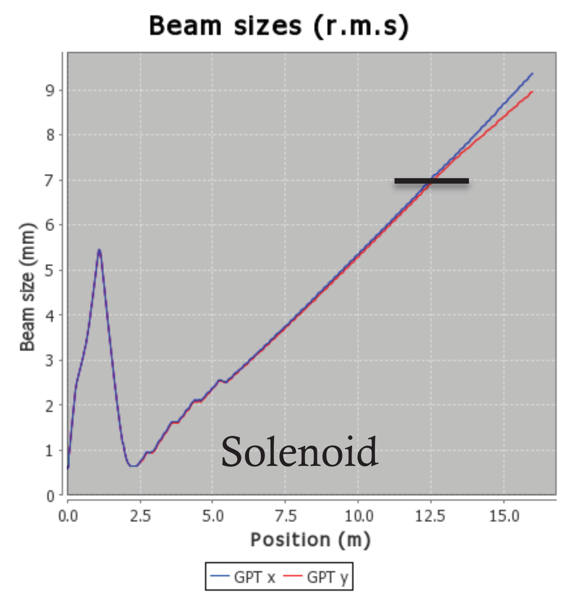
Simulated beam size using GPT



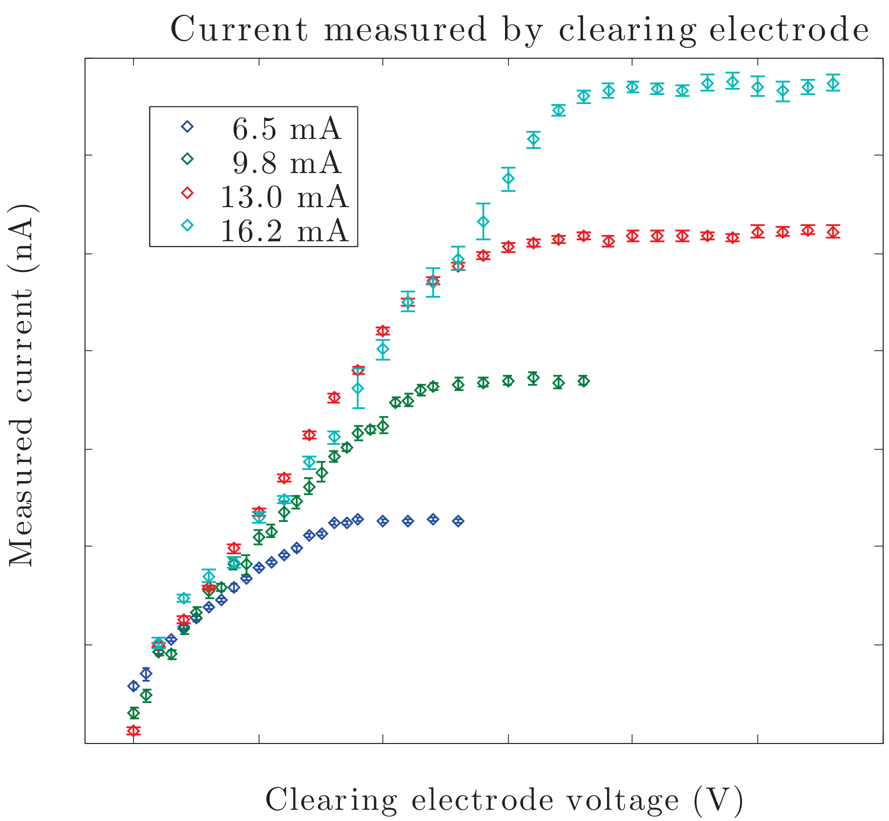


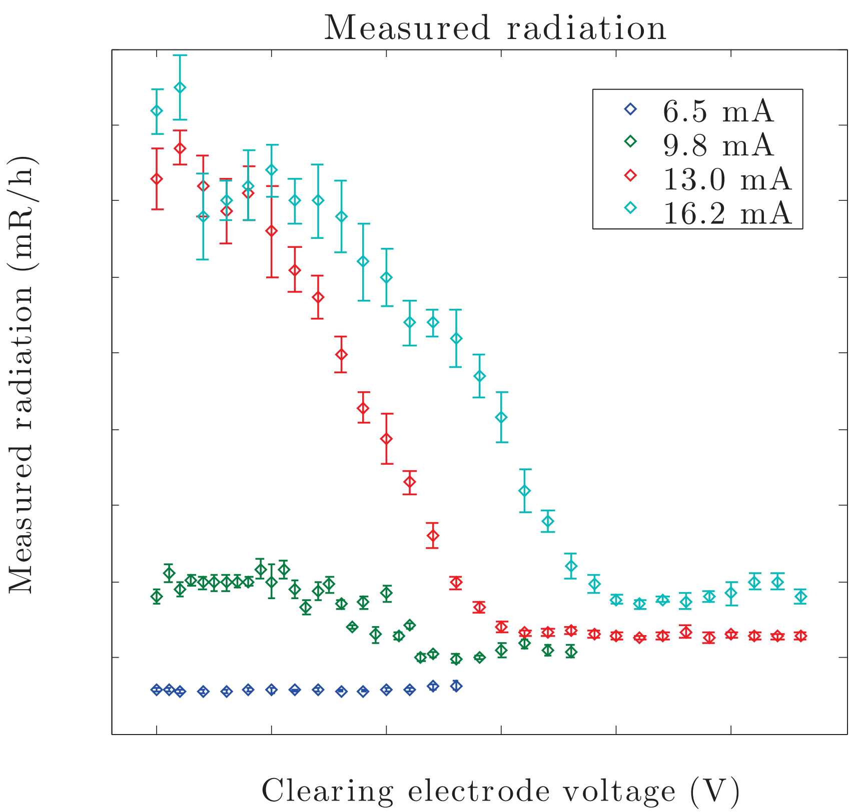






Measured current striking the clearing electrode





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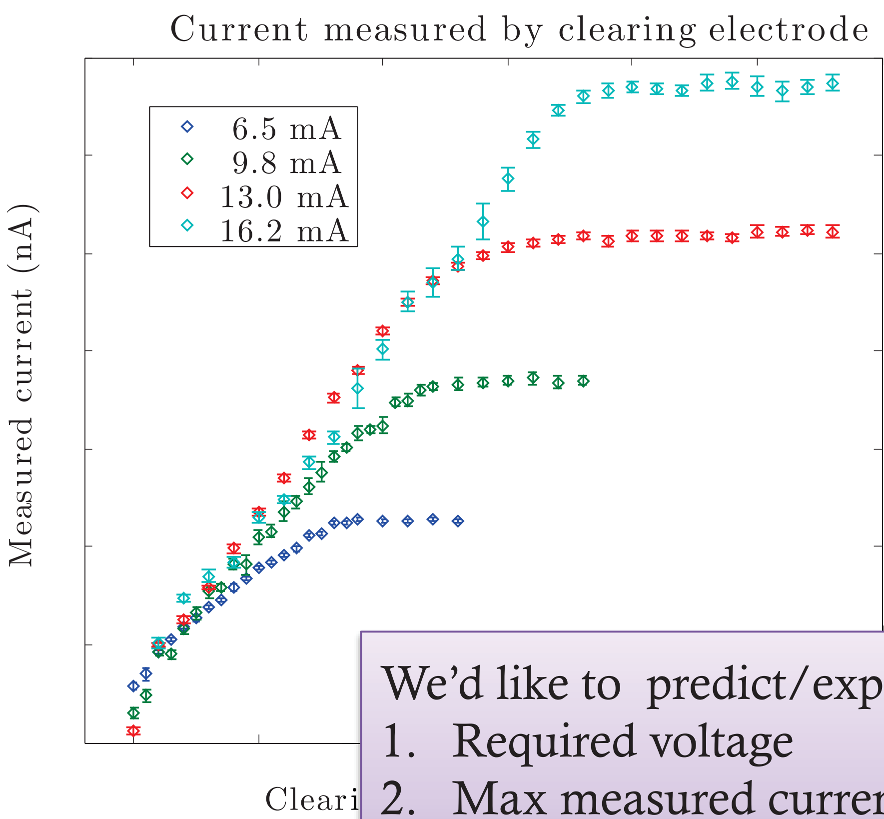
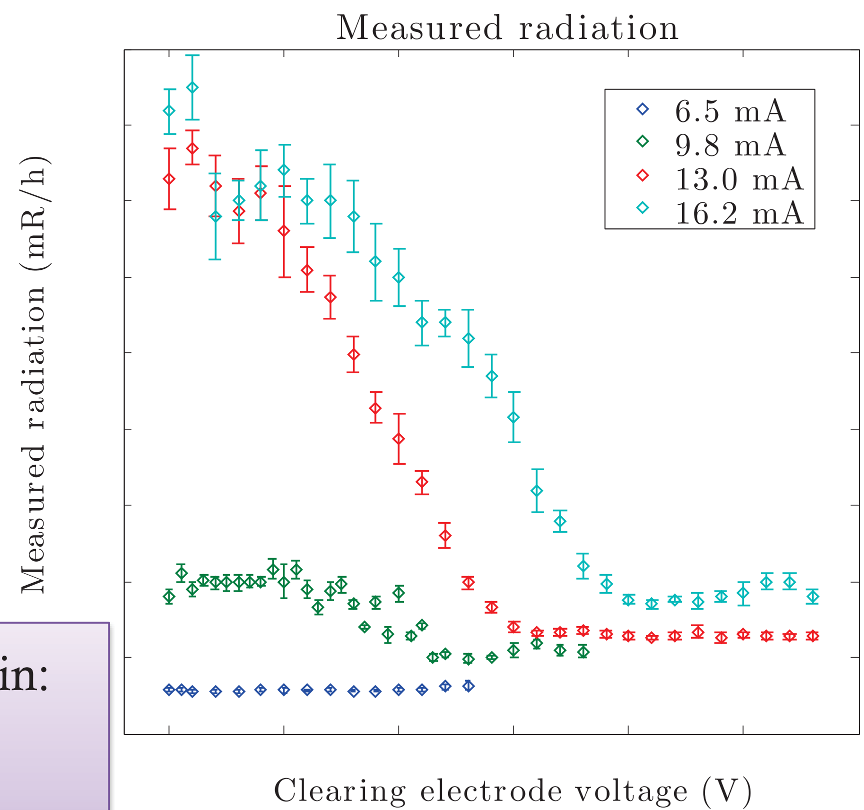
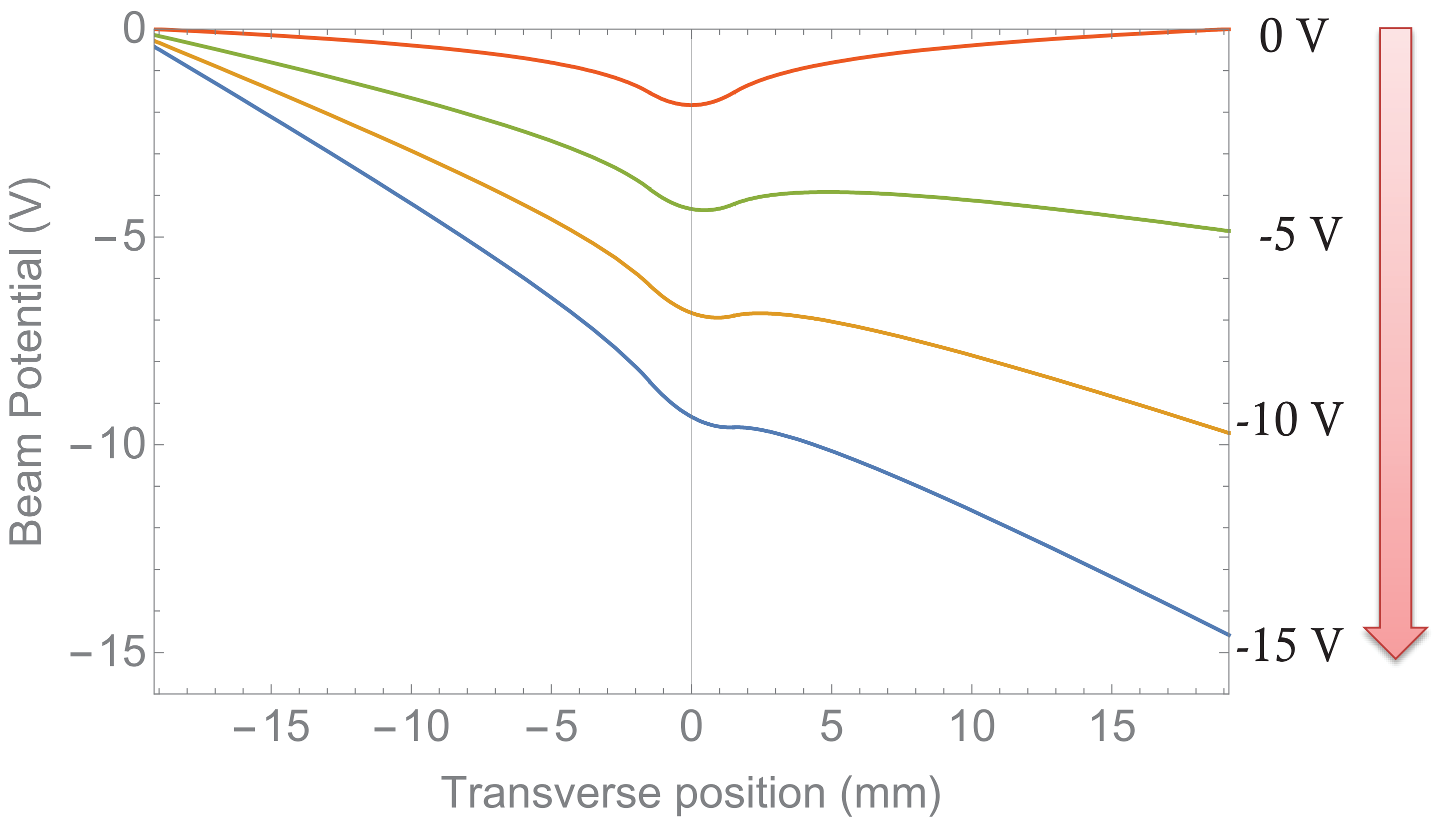




We'd like to predict/explain:

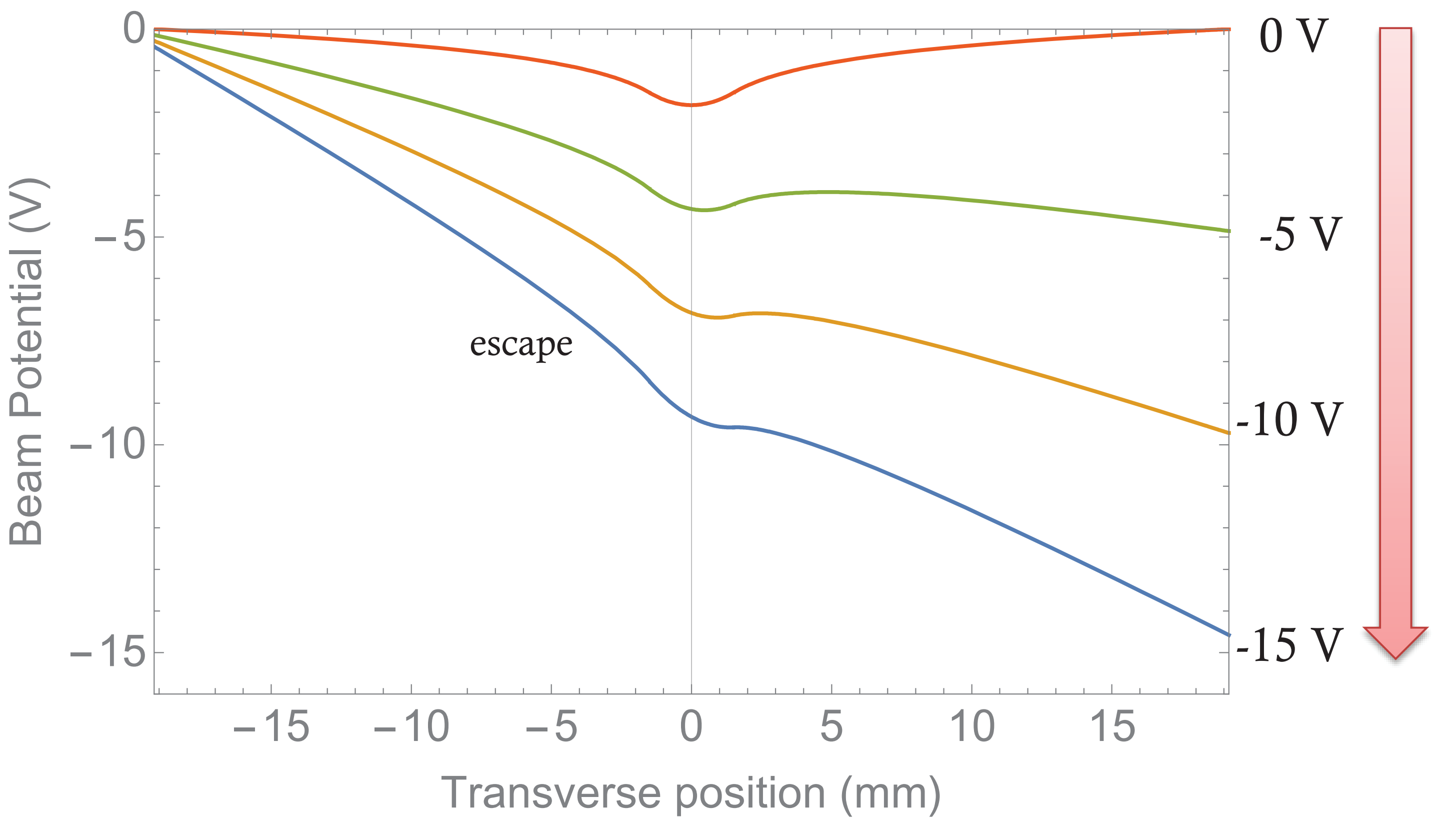
1. Required voltage
2. Max measured current
3. Slope

Clearing electrodes reduce the trapped ion density



Increasing the applied voltage suppresses the transverse beam potential, allowing more ions to escape.

Clearing electrodes reduce the trapped ion density



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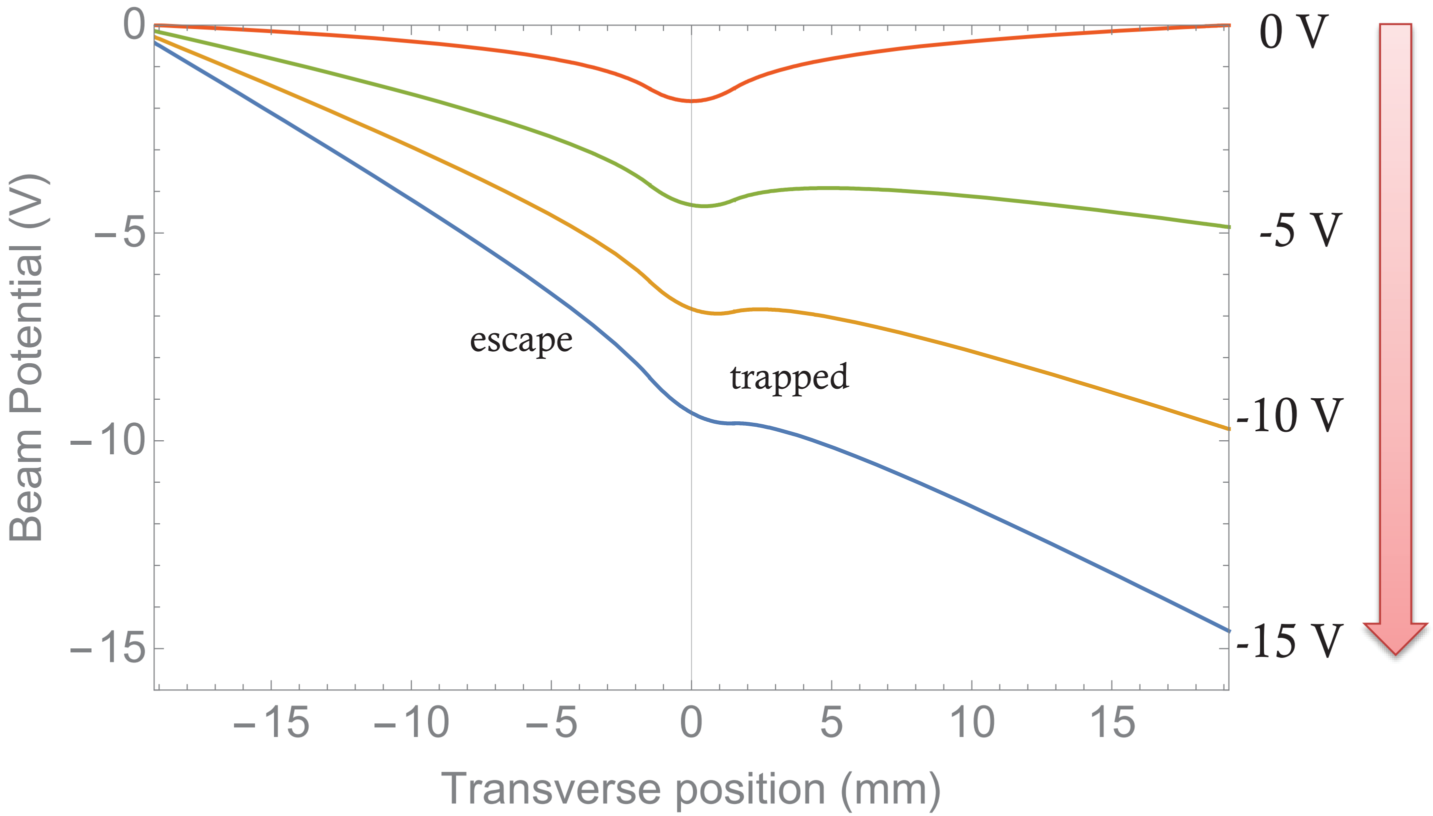

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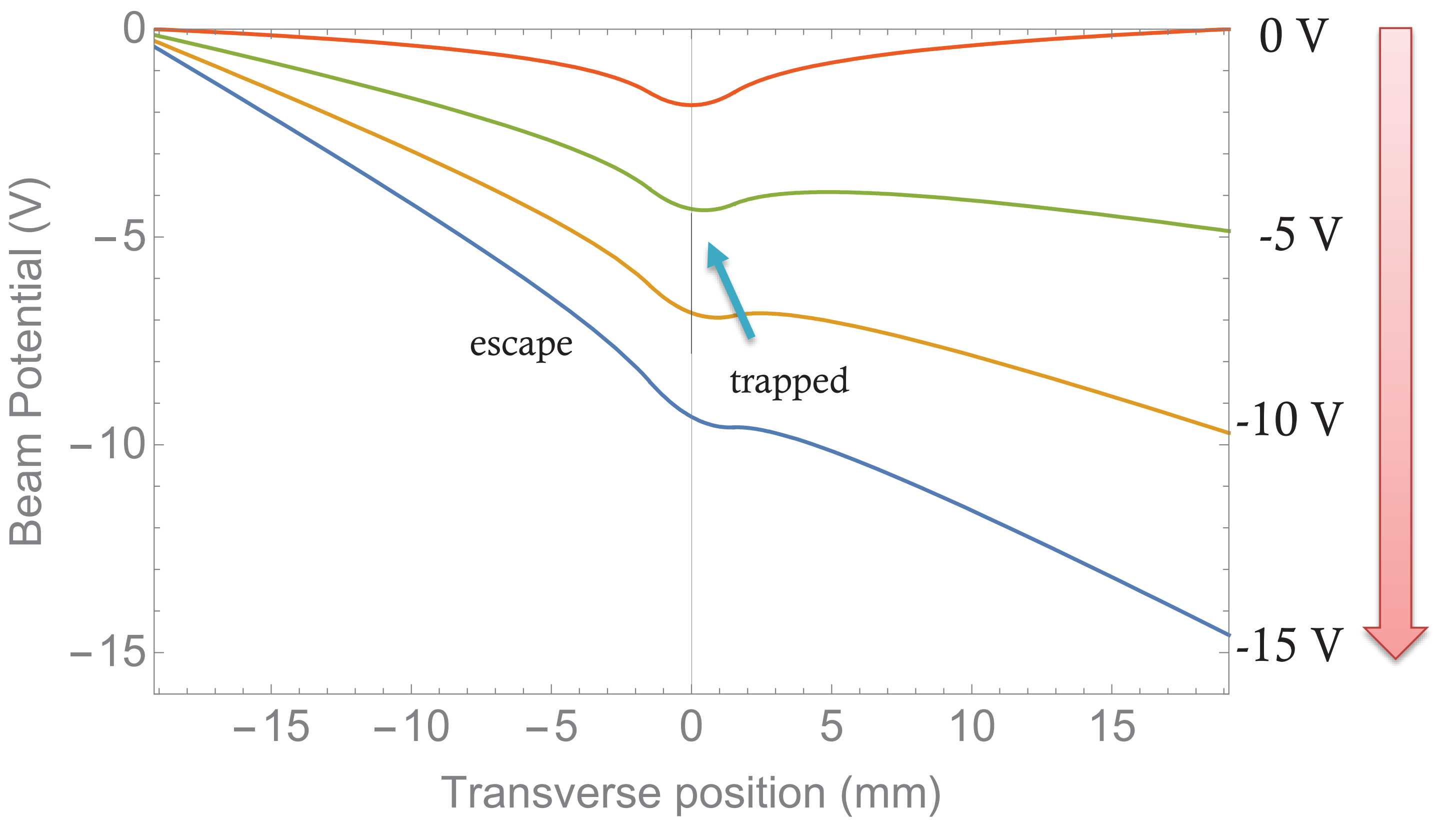

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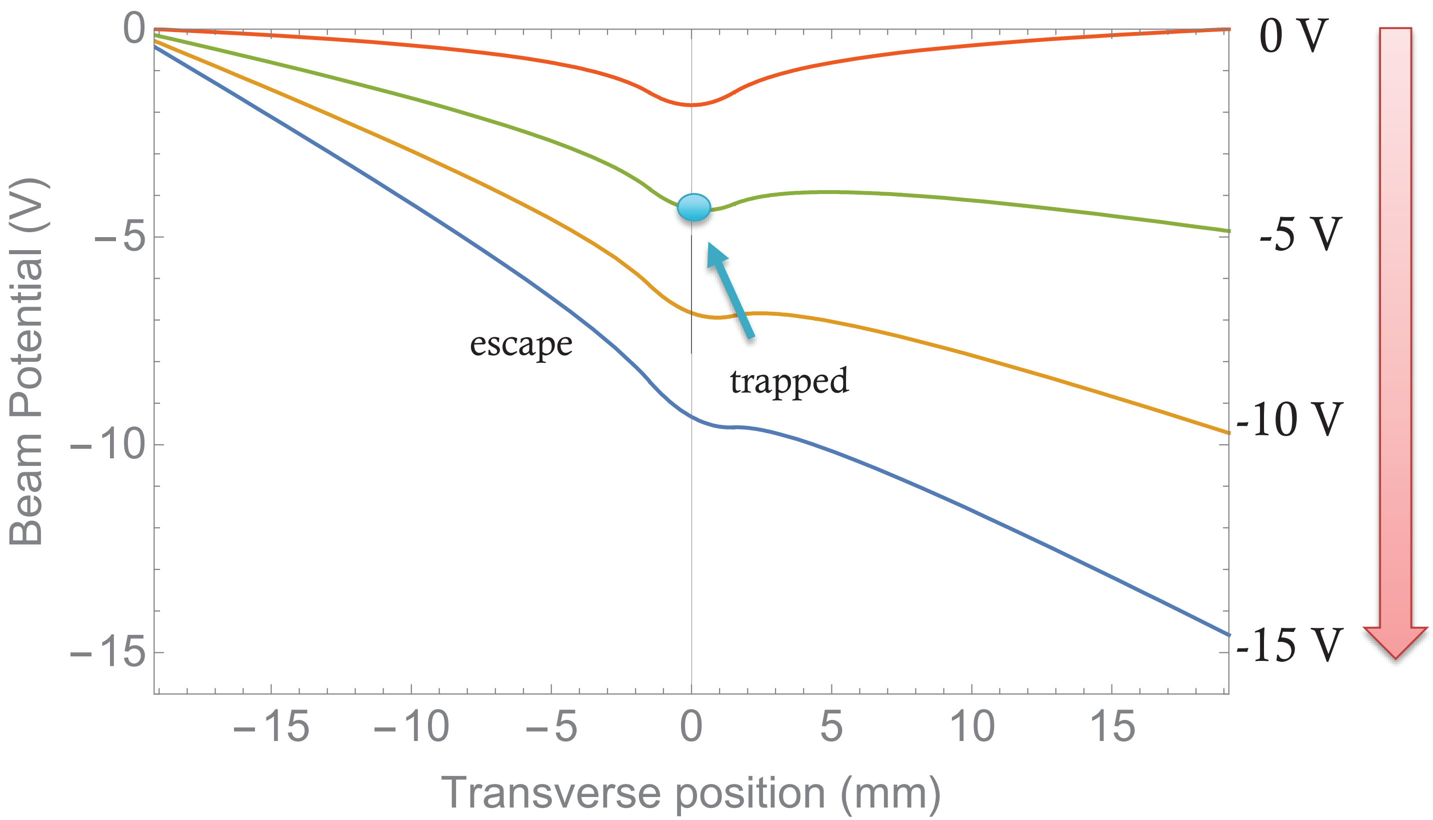

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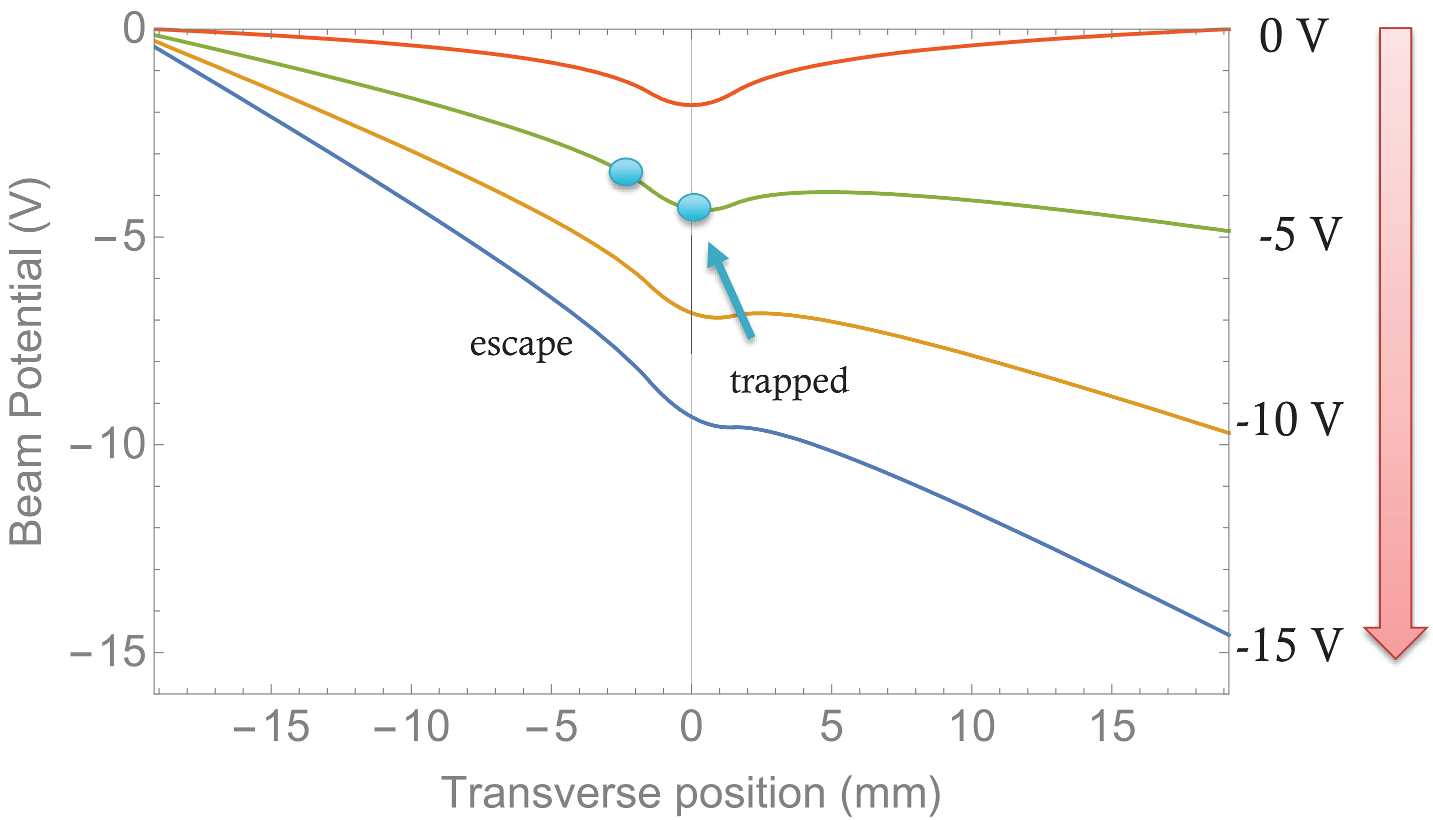

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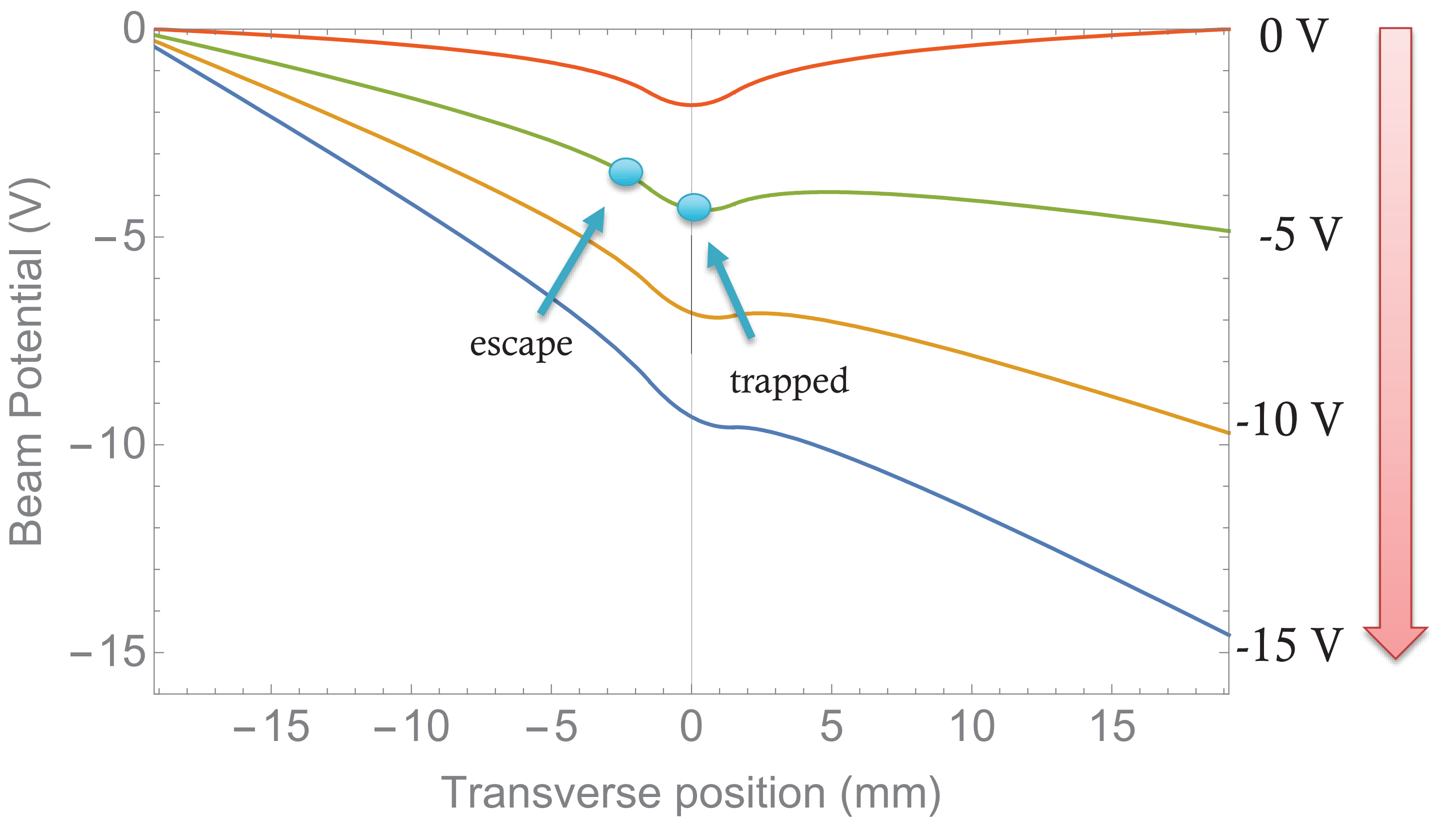


Increasing the applied voltage suppresses the transverse beam potential, allowing more ions to escape.

Predicting the minimum required voltage for full ion clearing.

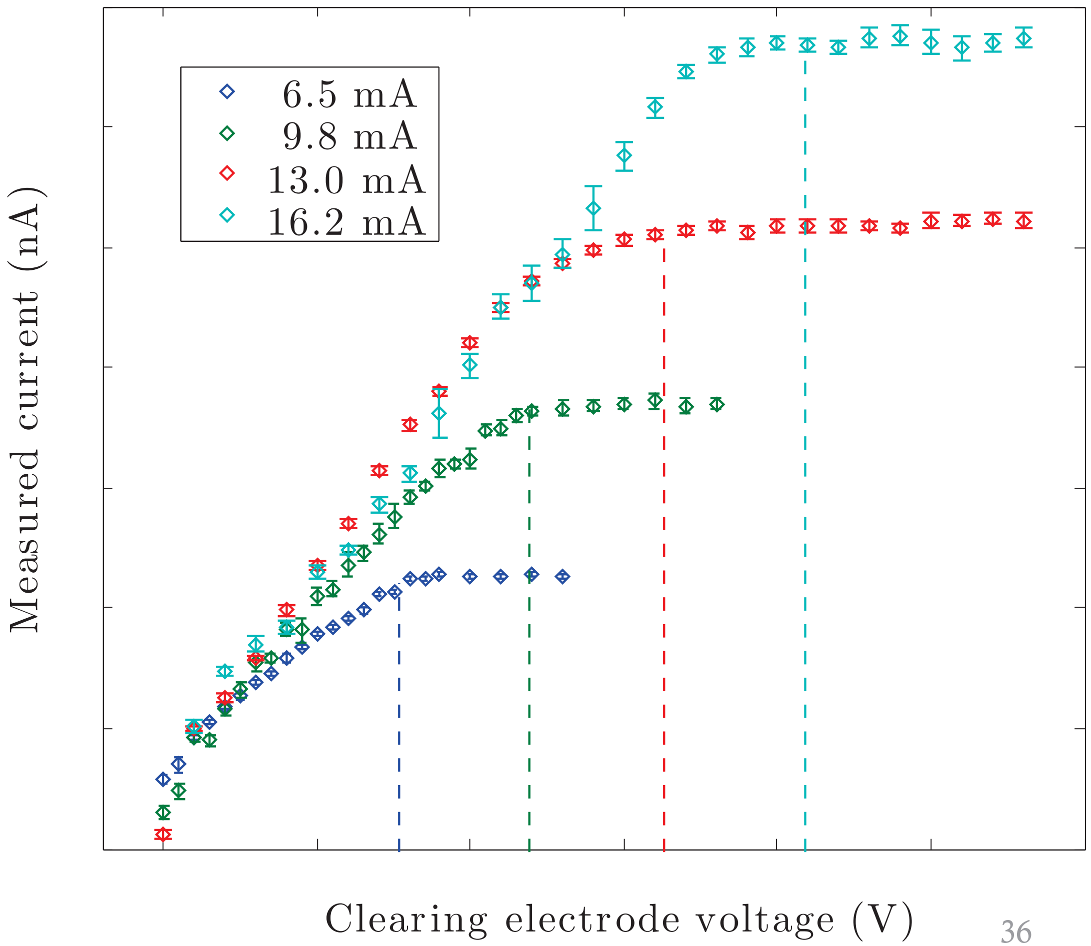
Full clearing occurs when the clearing electrode field overwhelms the beam's peak electric field , i.e.:

$$E_{clear} \geq E_{beam}$$

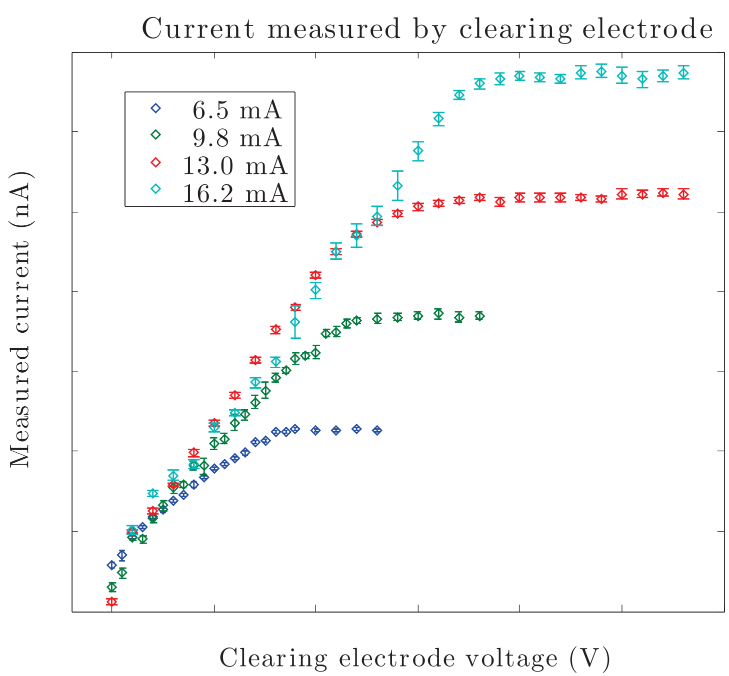
Clearing electrode separation

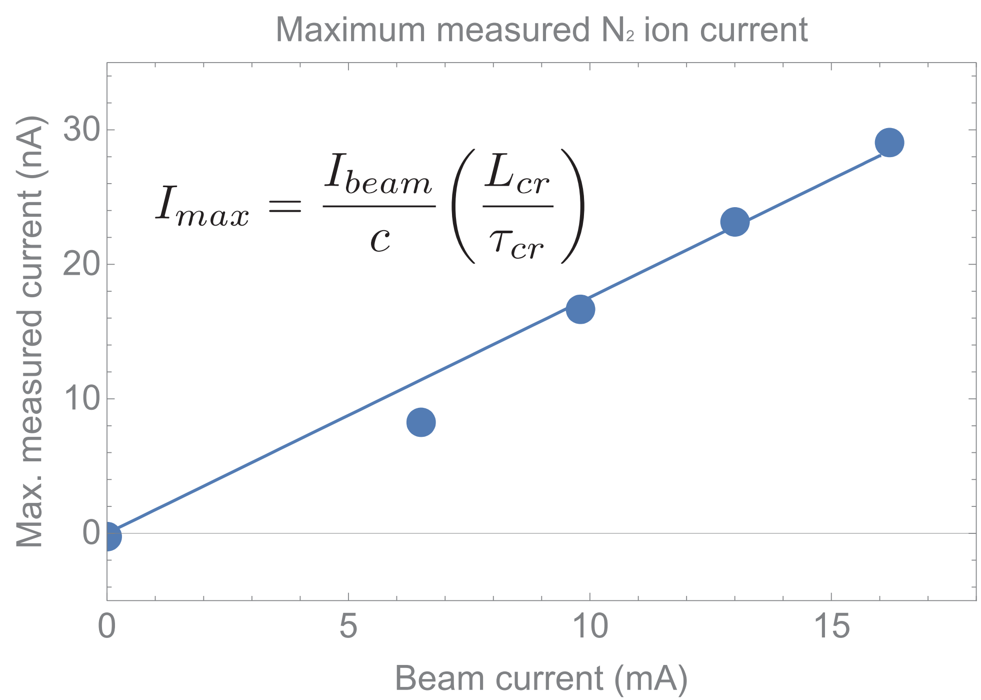
$$V_{electrode} \geq \frac{I}{2\pi\epsilon_0 c}\frac{d}{\sigma_b}$$

Transverse beam size



Measured current striking the clearing electrode using a picoammeter



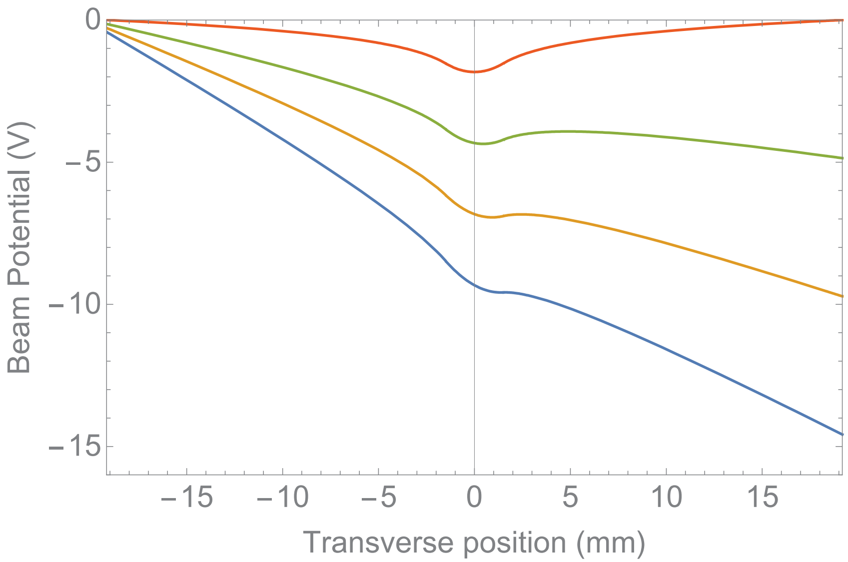


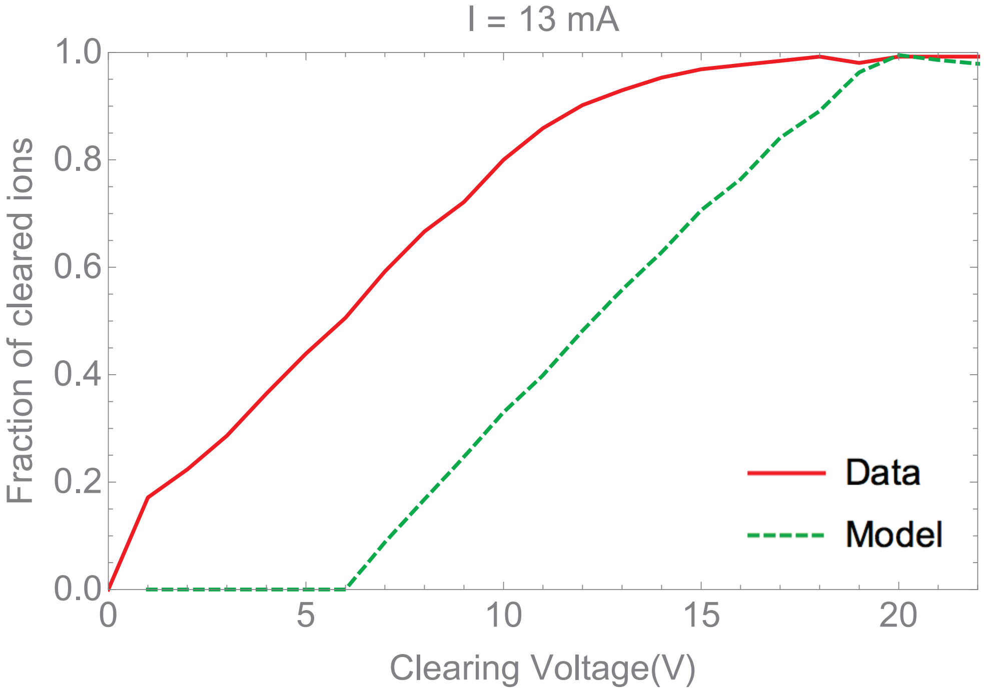
τ_{cr}	Creation time
L_{cr}	Creation region

$$\tau_{col} = \frac{1}{\sigma_{col}\rho_{gas}c} = 5.2ms$$

$$L_{cr} = 2.9m$$

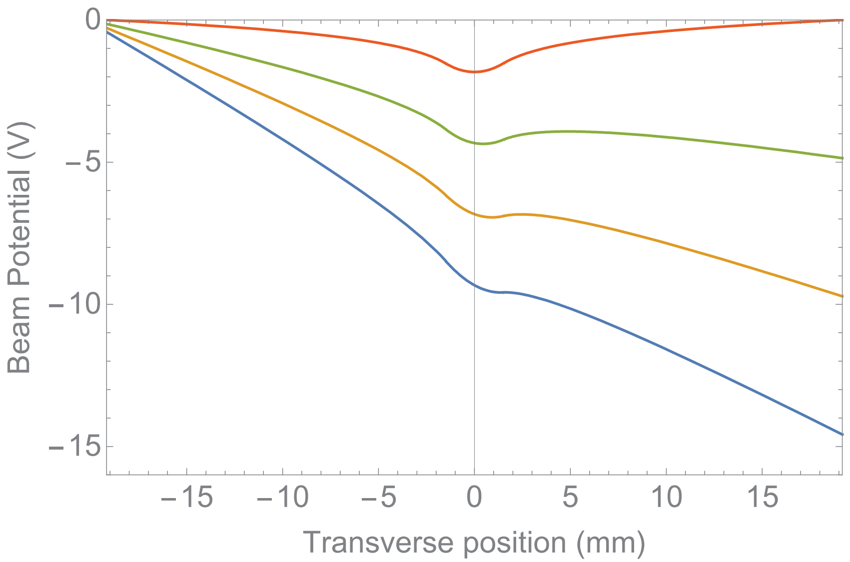
Slope predictions using a simple model

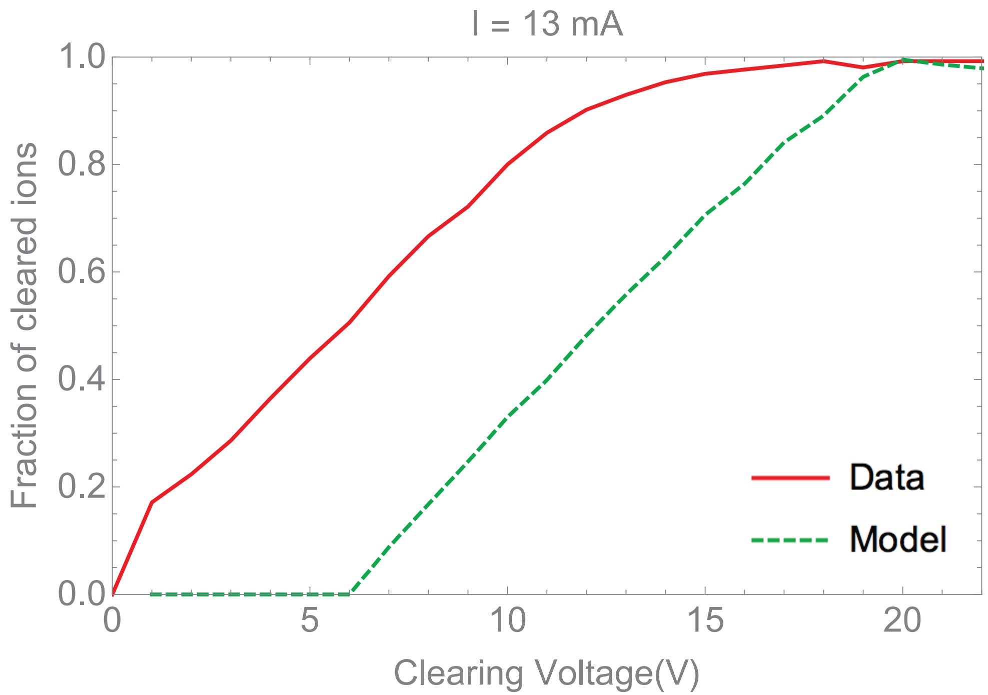




Slope predictions using a simple model

- Round, constant charge distribution beam
- Create ions inside the beam, using a constant distribution
- Increase voltage and count how many ions "leak out"





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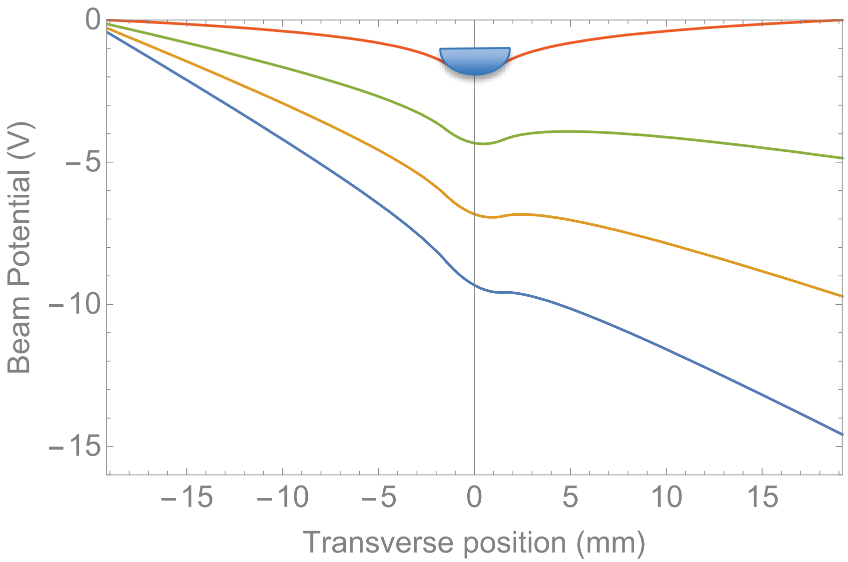

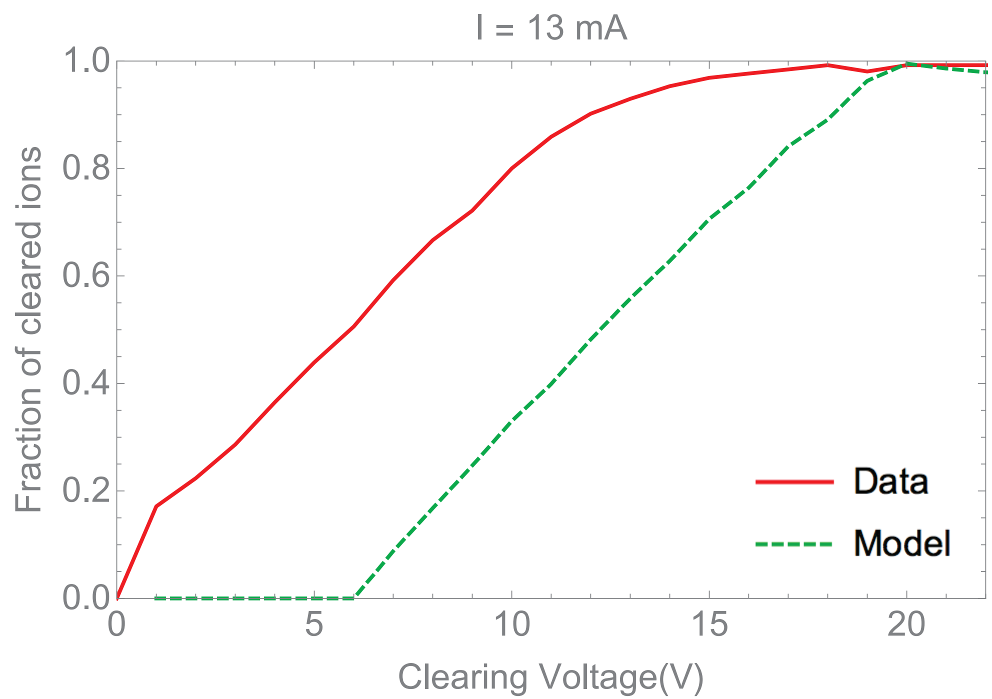

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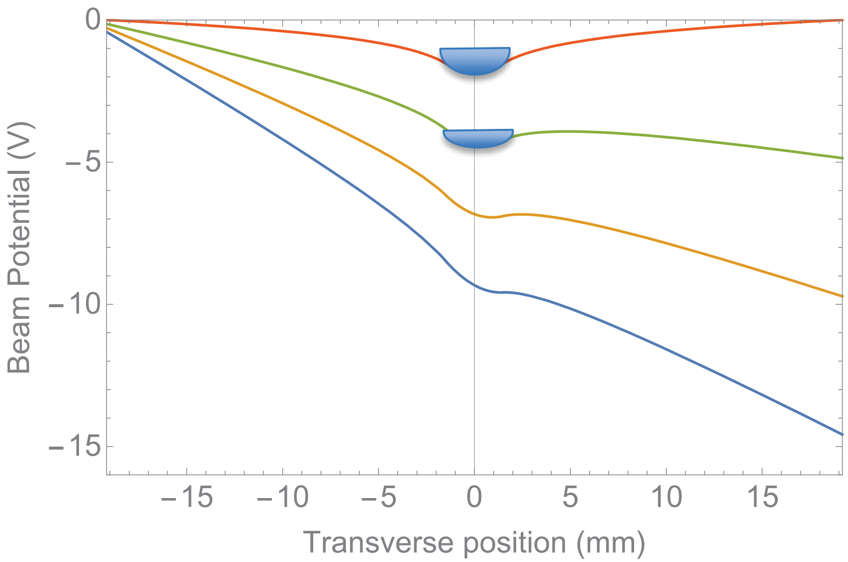

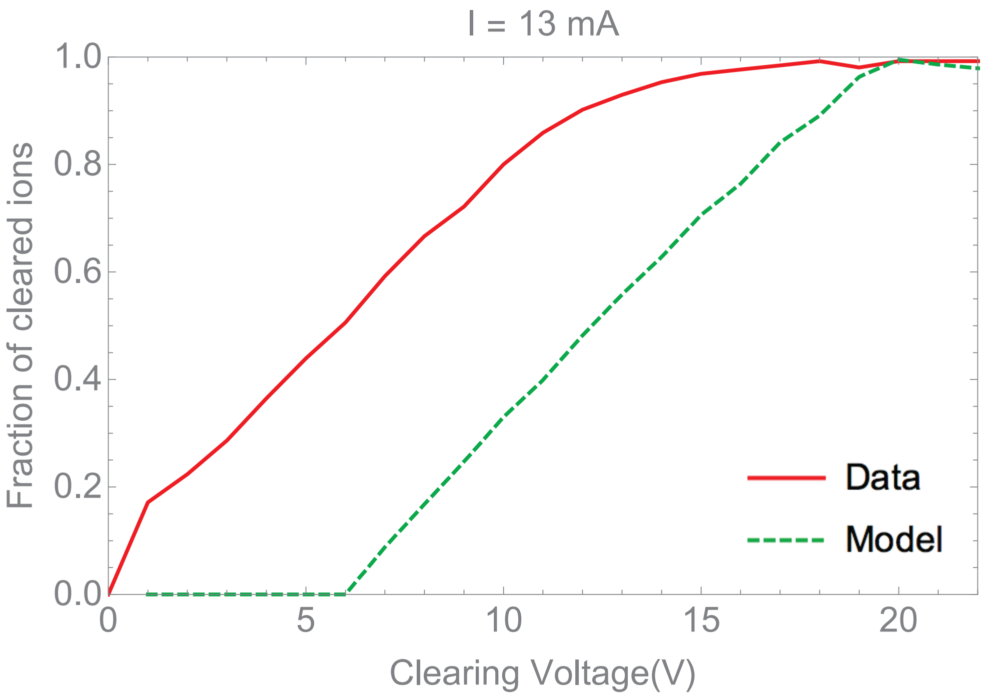

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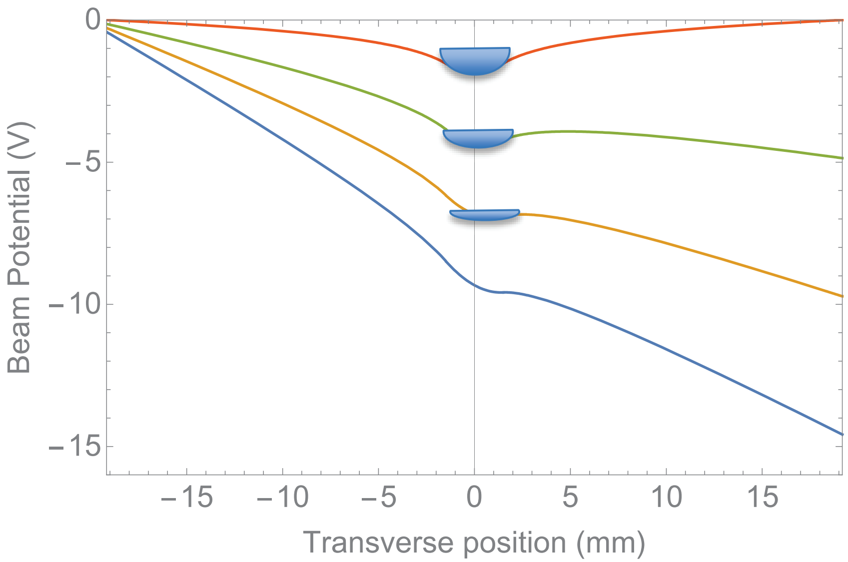
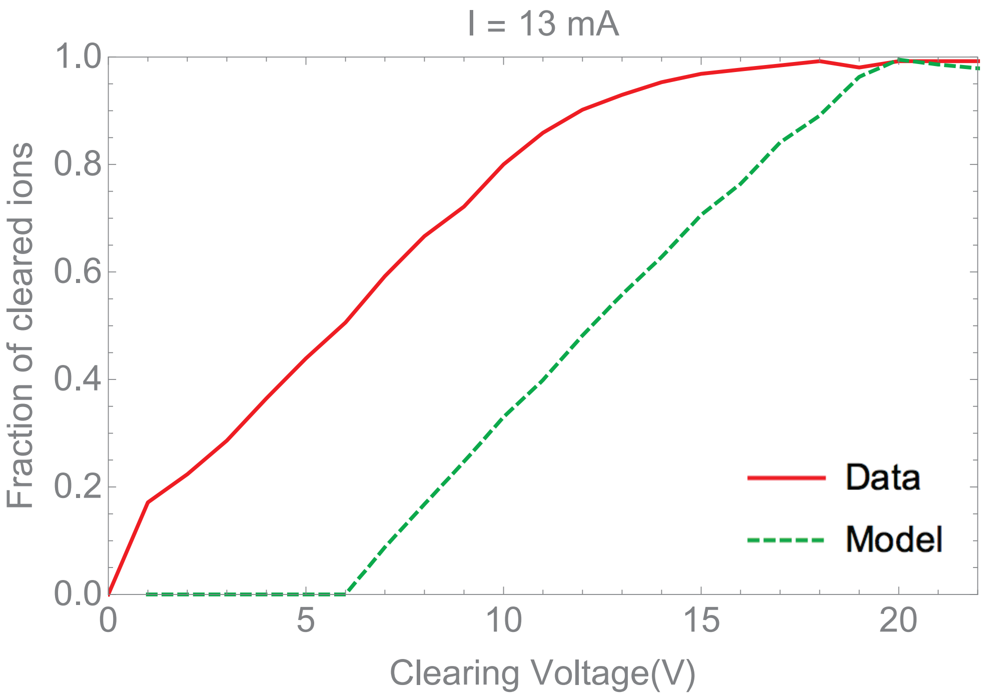
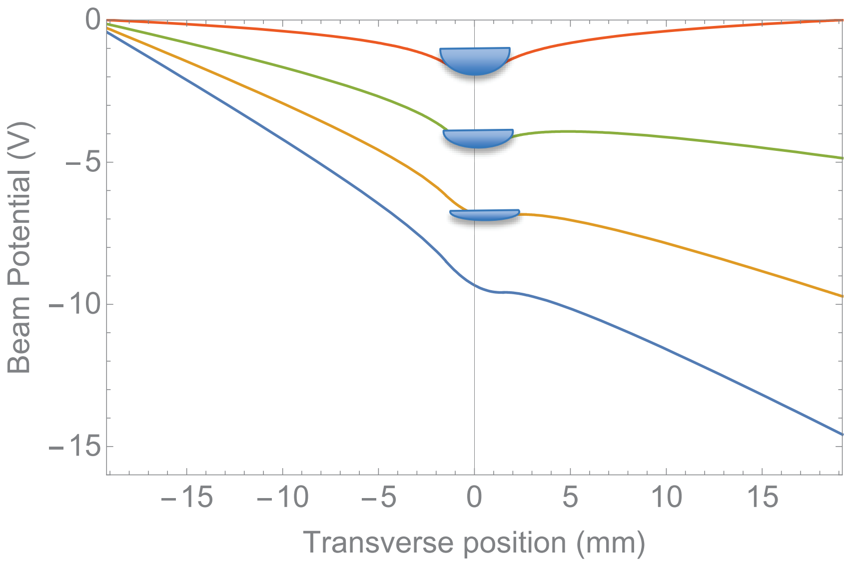
- Increase voltage and count how many ions "leak out"

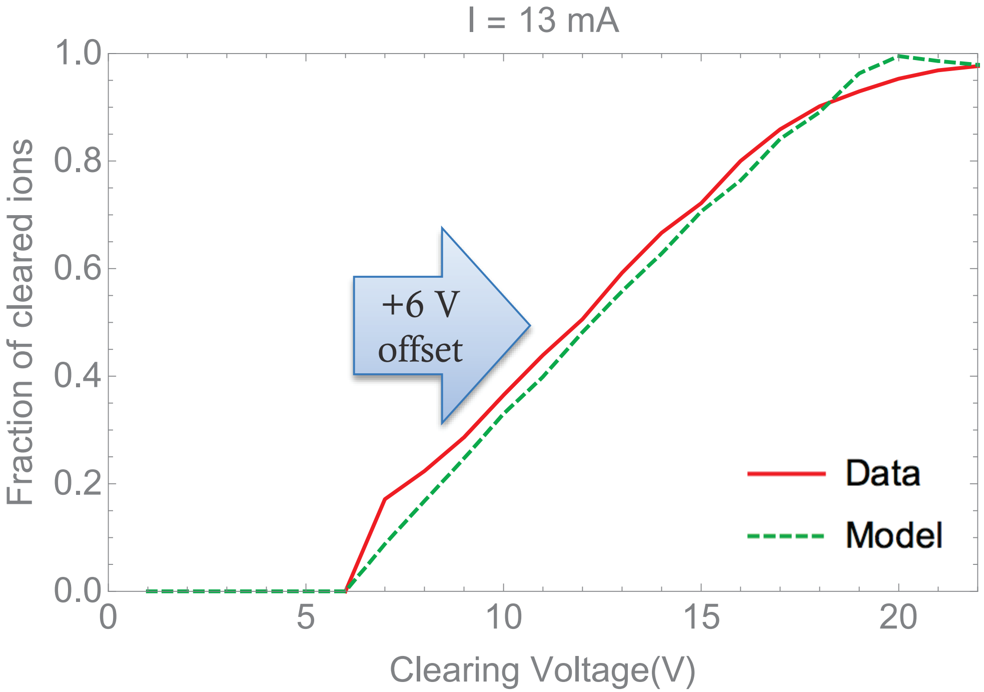




Slope predictions using a simple model

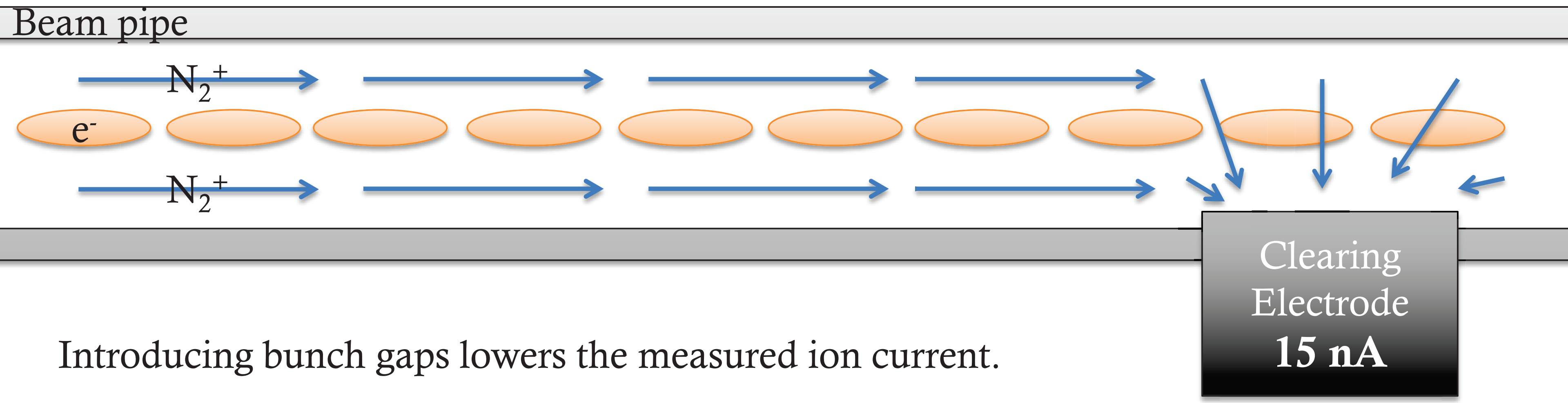
- Round, constant charge distribution beam
- Create ions inside the beam, using a constant distribution
- Increase voltage and count how many ions "leak out"



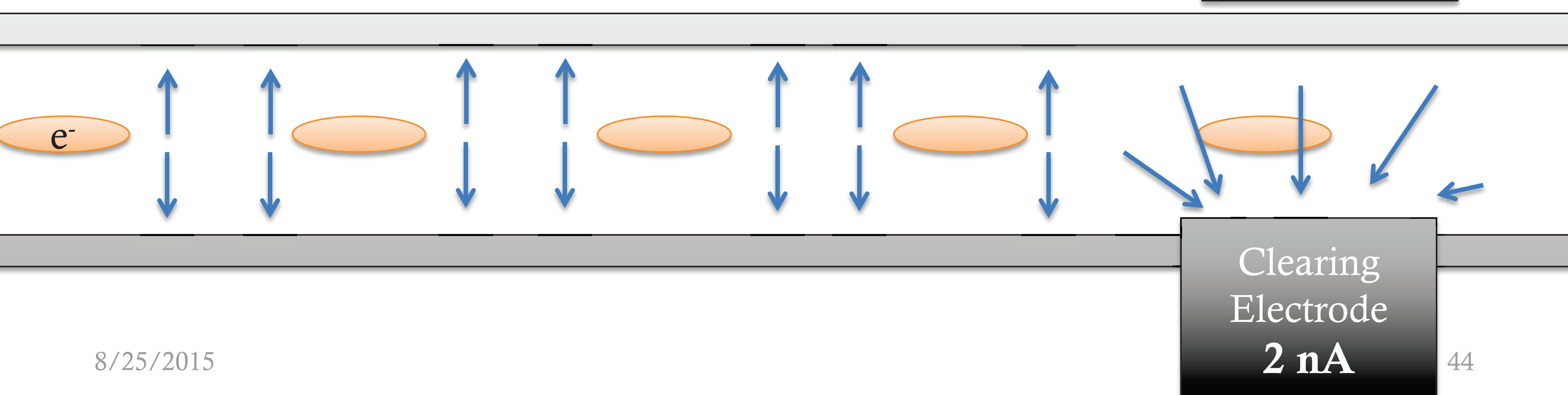


Clearing electrode and Bunch gap measurements

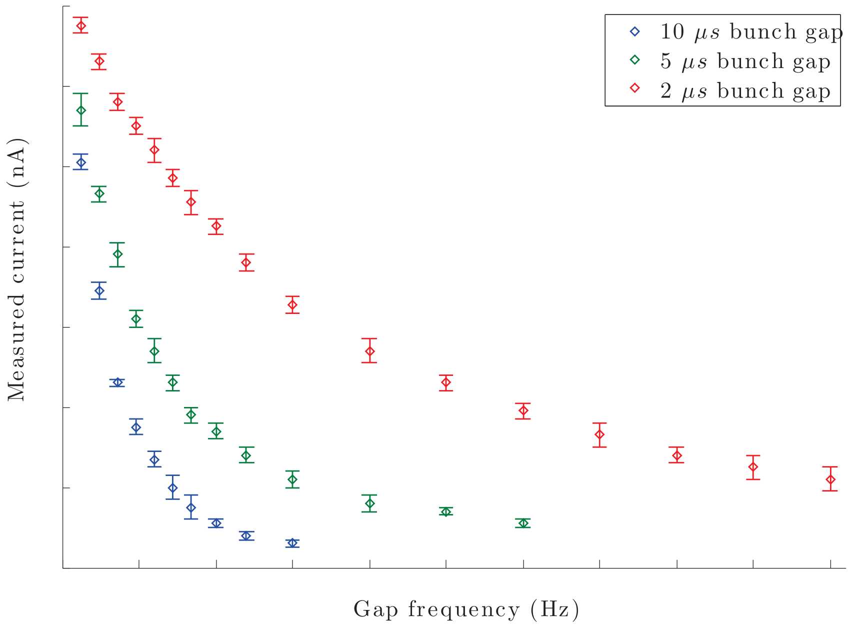
During CW operation, ions remain trapped, drift towards and are measured by the clearing electrode.

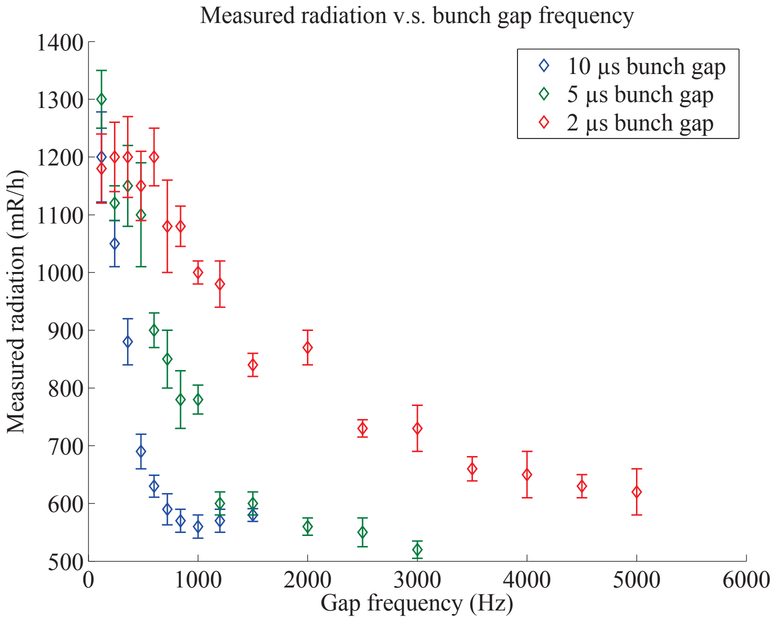


Introducing bunch gaps lowers the measured ion current.



Bunch gap measurement raw data





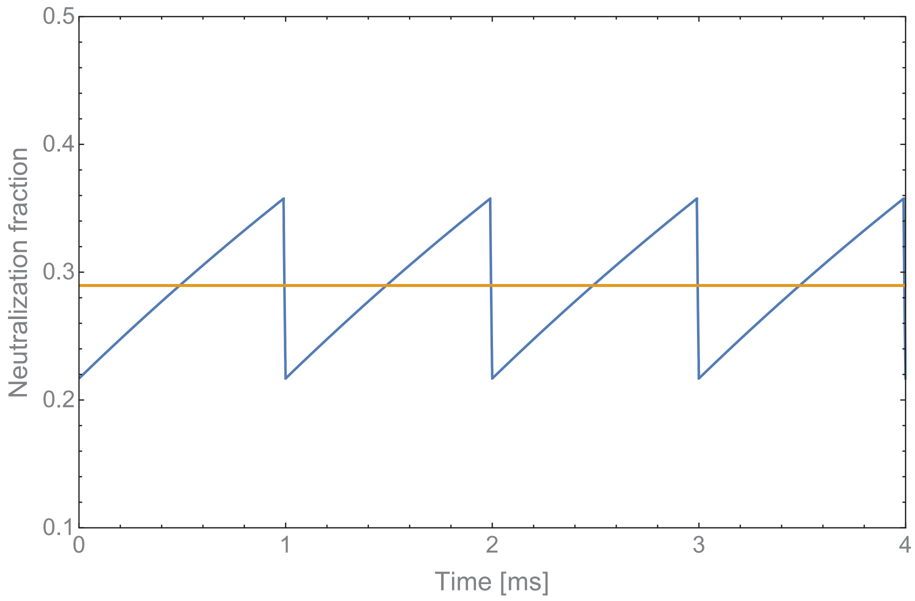
Clearing electrode current measurements

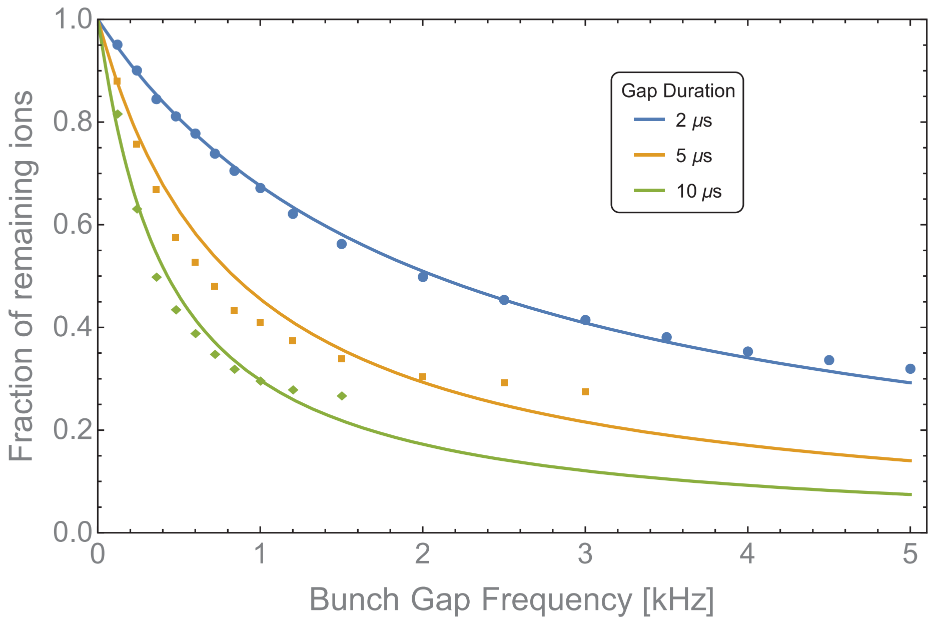
Introducing bunch gaps reduces the number of trapped ions.

Radiation levels

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

Measurement analysis





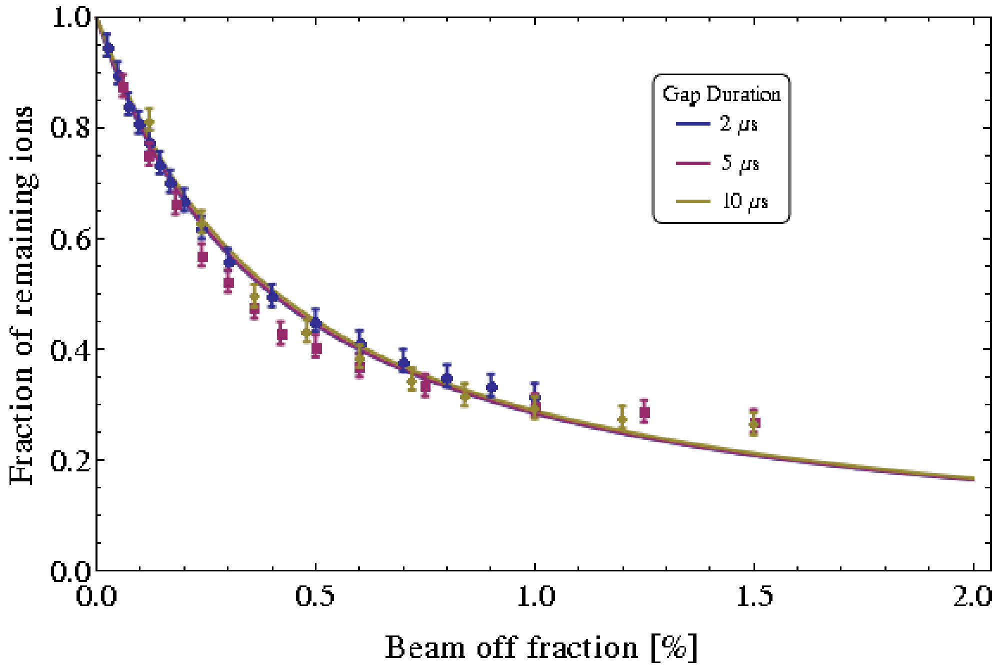
Our model: The ion density…
1) Increases via collision ionization while the beam is on.
2) Decays exponentially during the bunch gaps.

Lines are the average remaining ion fraction calculated from our model.

Only the **total time the beam is off** determines the amount of clearing.

According to our data, a 1% reduction in beam current reduces the ionization fraction by about 70%.

A 30% reduction in beam current would be required for 99% reduction in ionization fraction. But this is a large extrapolation of our data.



	Data	**Extrapolation**
Reduction in beam current	1%	30%
Reduction in ions	70%	99%

Required bunch gaps appear shorter than predicted via theory.

Trapping condition predicts all ions will remain trapped with short ≤ 10 μs gaps.

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

An estimate using the oscillation period (confirmed by experiment) suggests you need over 20 μs gaps to clear ions.

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

So how low can we go?
What's the shortest possible bunch gap?
Can we avoid beam loading?

Trapping condition from:
G.H. Hoffstaetter, M. Liepe / Nuclear Instruments and Methods in Physics Research A 557 (2006) 205–212

Take home messages

- Hopefully this gives you some idea of mitigation options
  - Clearing electrodes voltages for full clearing can be predicted
  - Beam shaking is a viable option
  - Bunch gaps merit further study
    - Maybe we can avoid beam loading problems??

- Possibilities during the next round of experiments
  - Beam size measurements to compliment data
  - Explore smaller bunch gaps

Thank you for listening!

Keep an eye out for future publications.

Thanks to the Cornell team for making this experiment possible:
Ivan Bazarov
Georg Hoffstaetter
Adam Bartnik
John Dobbins
Bruce Dunham

Also thanks to Atoosa Meseck from HZB for helping out with suggestions, especially at the beginning of these experiments.

Contact: Steve Full at sf345@cornell.edu
This work was supported by the financial assistance from the National Science Foundation and Department of Energy (Grant No. DMR-0807731 and DGE-0707428).