# Barium Ion Transport in High Pressure Xenon Gas using RF Carpets

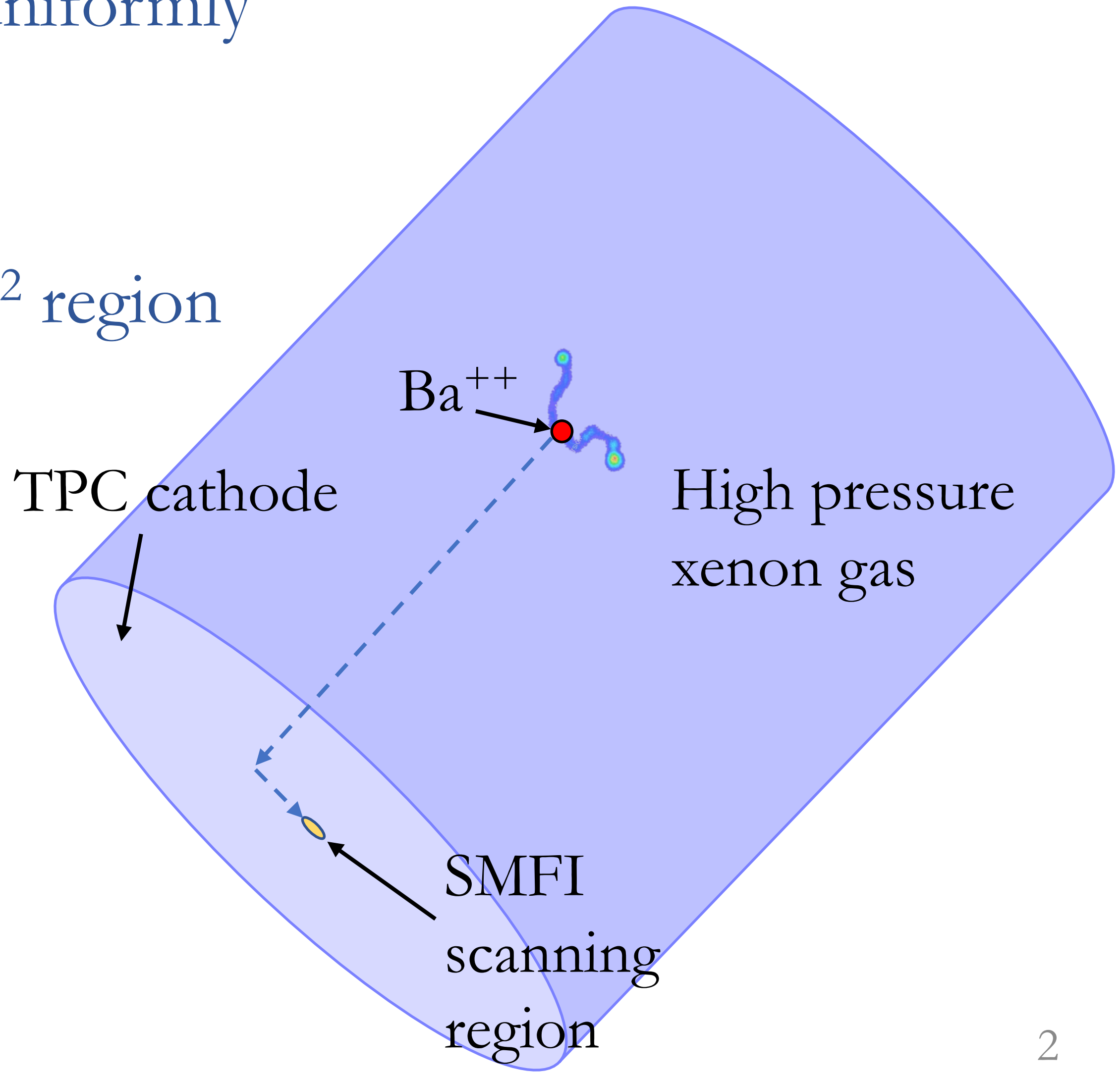
Katherine Woodruff

for the NEXT Collaboration

SMI 2019

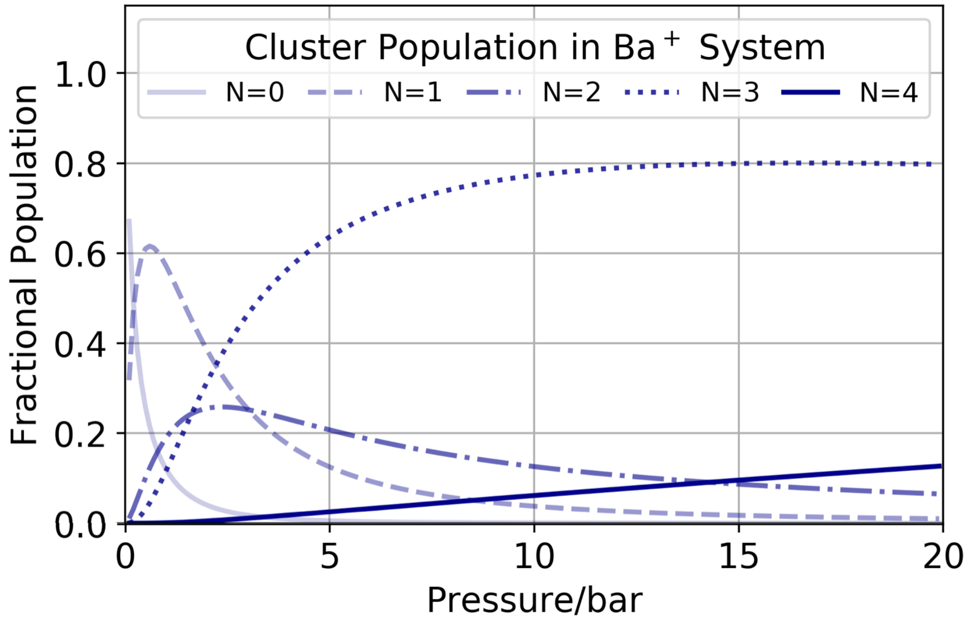
# NEXT ton-scale

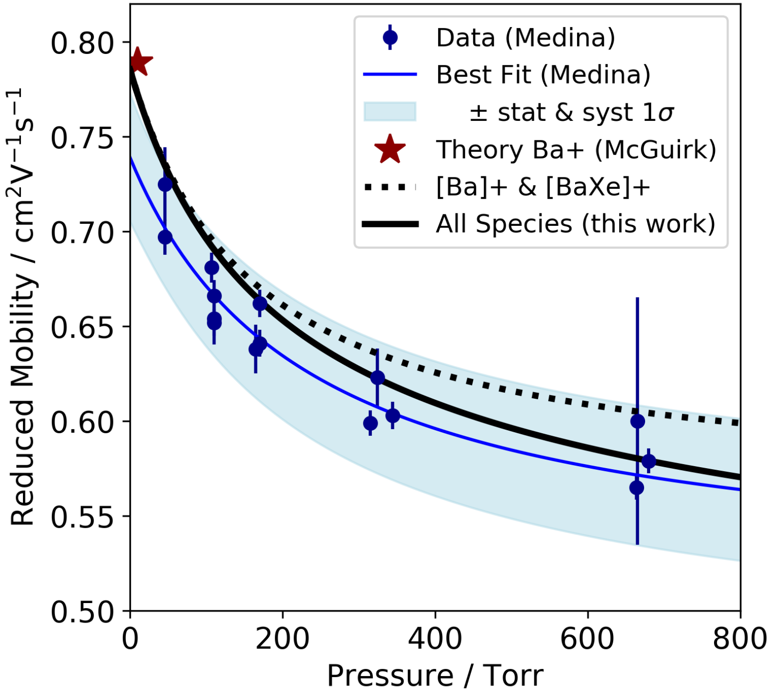
- Xenon-136 double beta decay happens uniformly in the detector
  - 1 ton of xenon at 10 bar is **55 m³**
- Need to transport the Ba++ ion to ~cm² region for SMFI
- TPC drift field will deliver ion to the cathode
- Use an RF carpet to transport across the cathode



# Barium ion mobility in xenon

- Barium doesn't drift as a single ion
  - $Ba^+ + Xe + Xe \leftrightarrow BaXe^+ + Xe$
- Predict $Ba^+/Xe$ cluster formation using density functional theory (DFT)
  - Excellent agreement with data



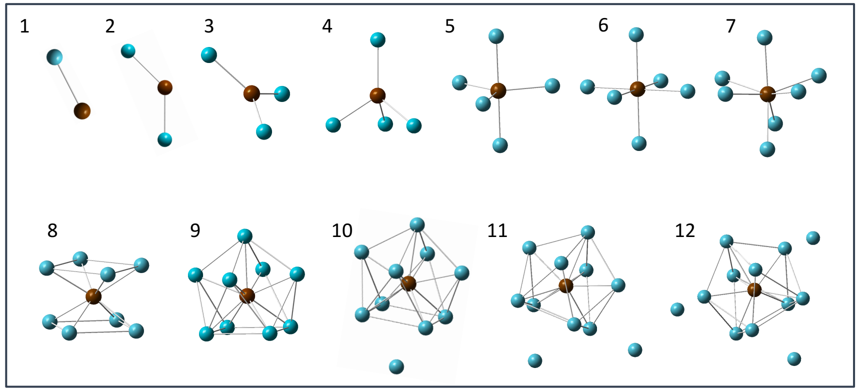

**Mobility and Clustering of Barium Ions and Dications in High Pressure Xenon Gas**

E. Bainglass, B.J. P. Jones, et. al. Phys.Rev. A97 (2018) no.6, 062509

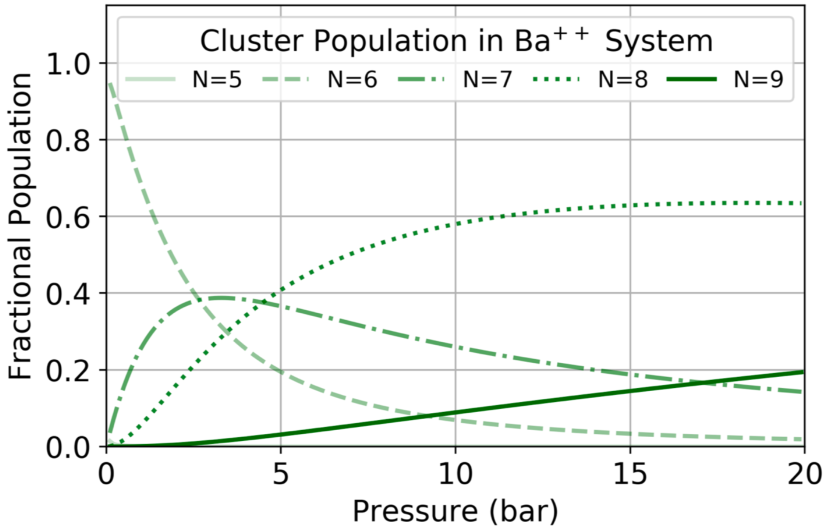
# $Ba^{++}$ mobility in xenon

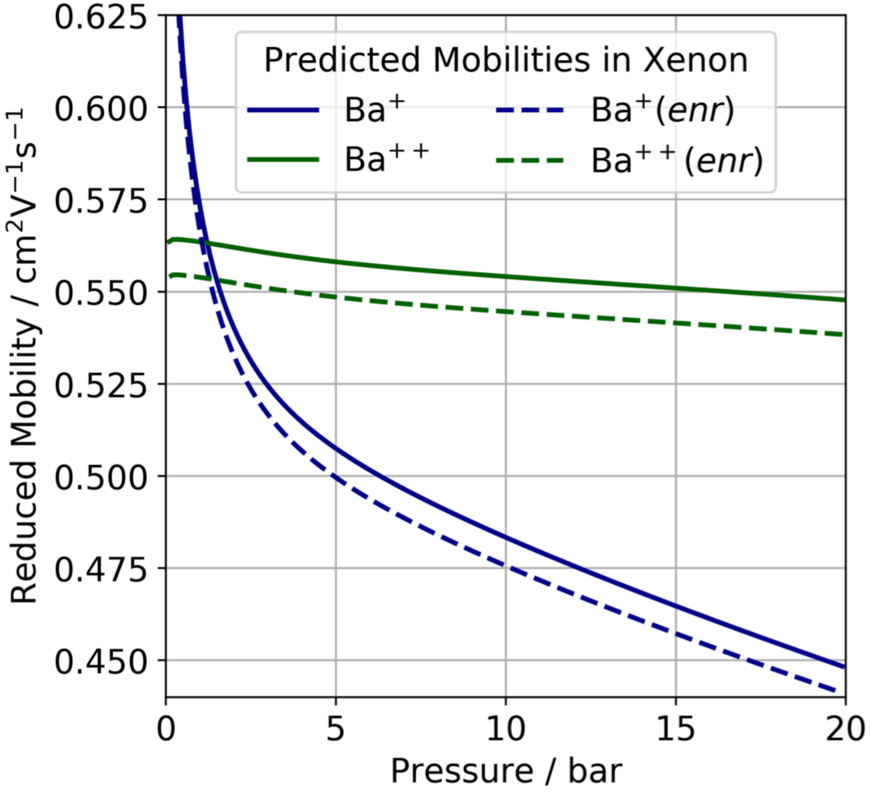
- Use the same theory to predict $Ba^{++}$ mobility in Xe
  - Bigger clusters more similar to each other, so less pressure dependence in $Ba^{++}$ than $Ba^{+}$

Calculated $Ba^{++}$ clusters:



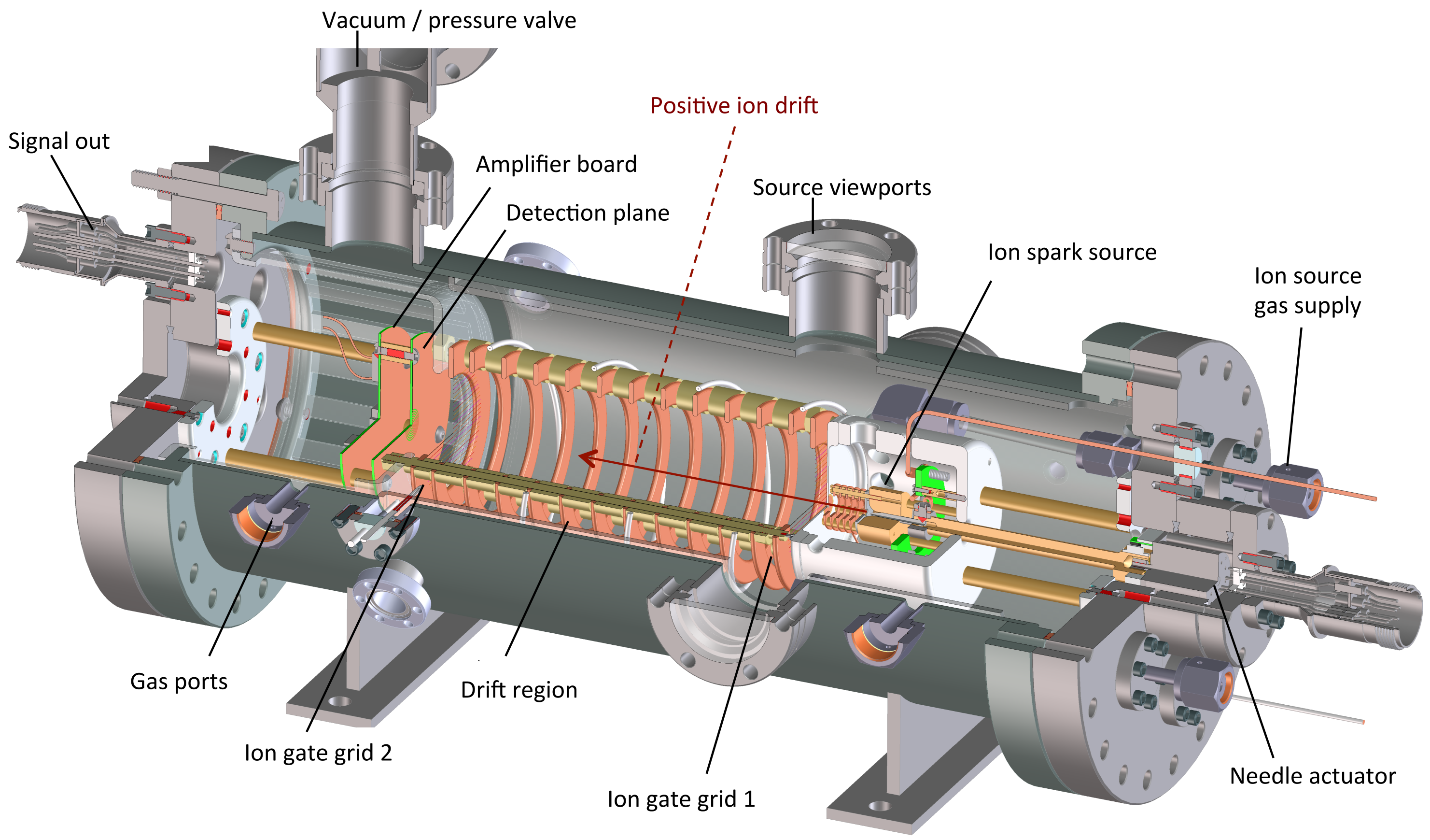

- Isotopic composition changes scattering kinematics, so %-level differences with enriched xenon



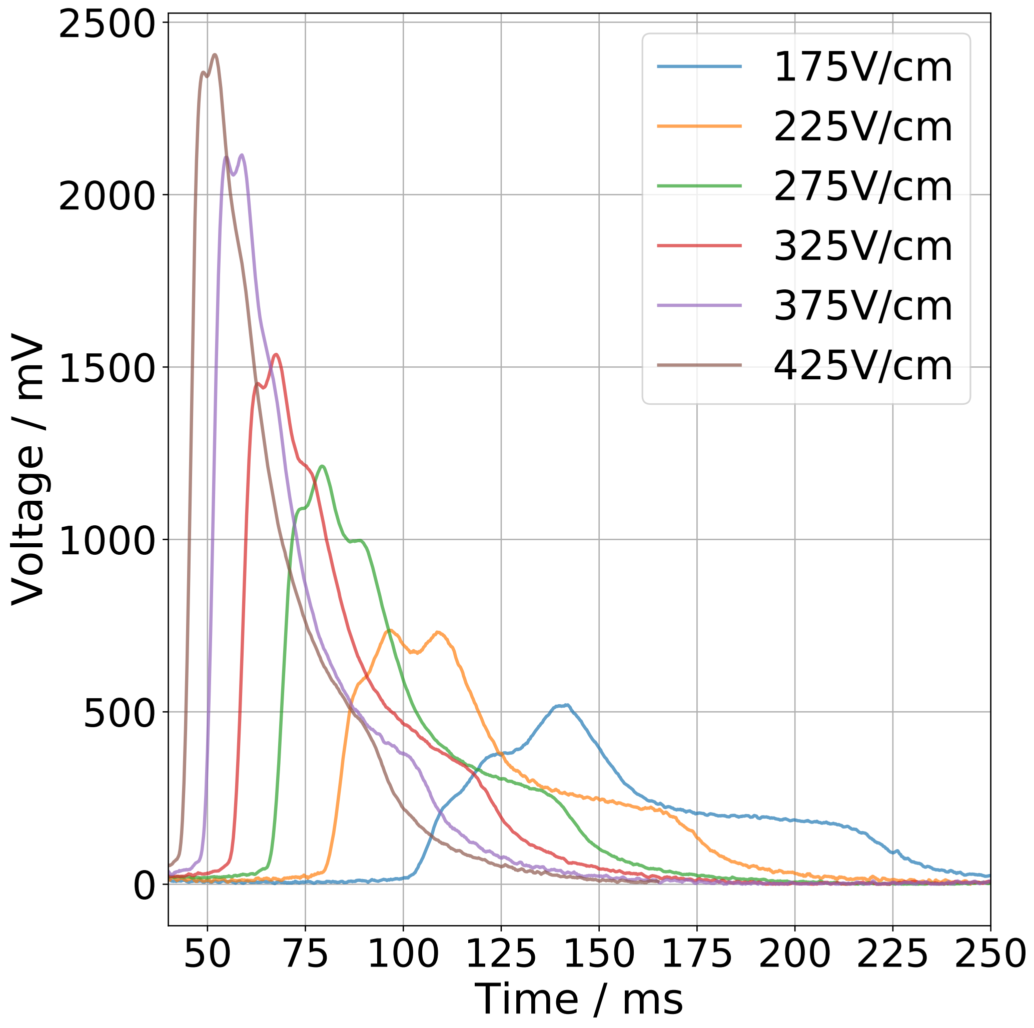
# Ion drift experimental studies

- Made an ion drift chamber with a spark source to study drift properties in high pressure
- Sparking electrodes are made of tungsten
  - Ionizes the gas in spark chamber
- Using DC voltage source to produce DC drift fields up to 425 V/cm
  - Drift region is 13 cm



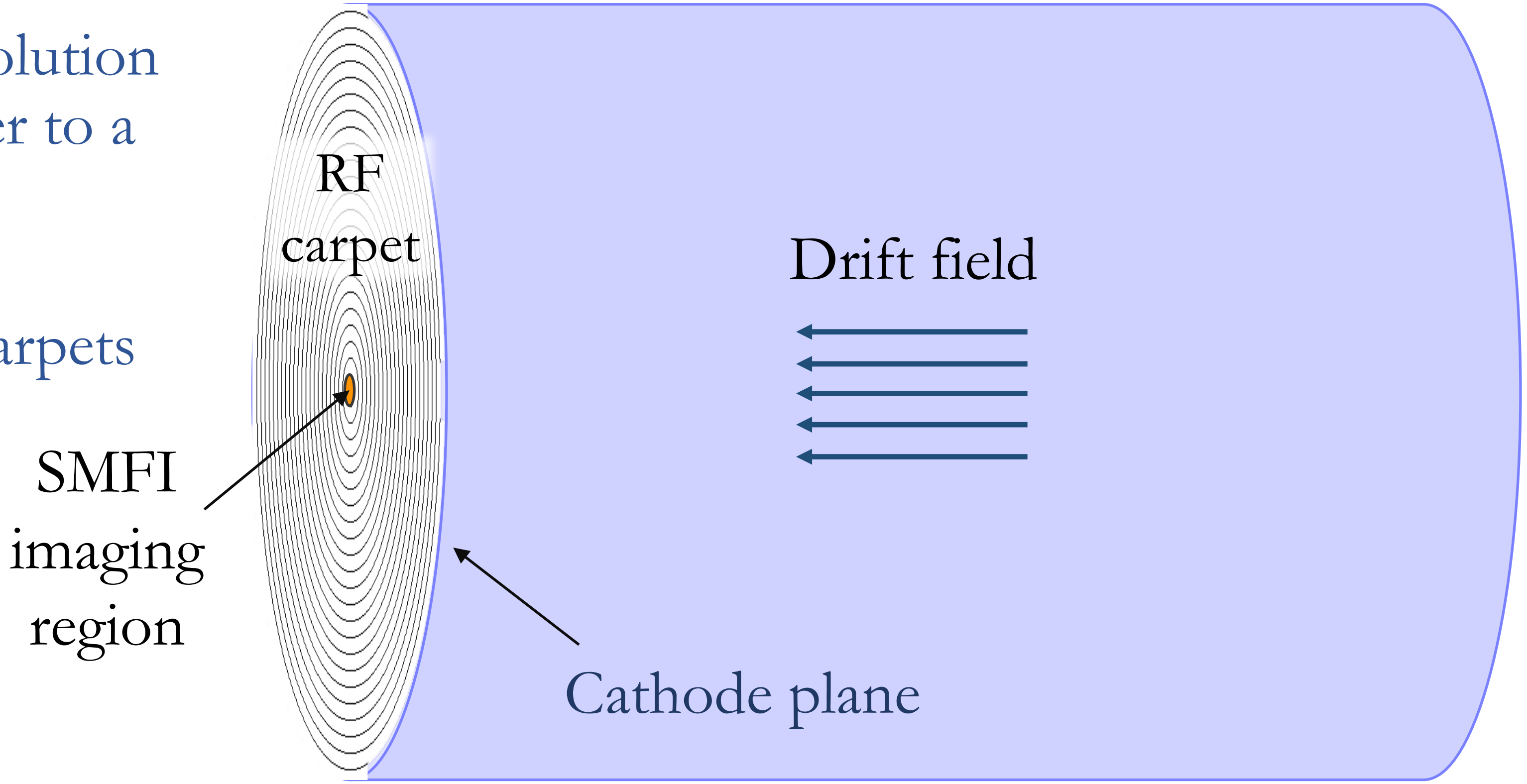
# Ion drift experimental studies

- Sparked in argon gas at 3 bar
- Expect argon ions at the detection plane
- We see several populations in the ion packets reaching the cathode
- This requires further study



# RF carpets cathode transport

- Use RF carpets to transport the ions across the cathode
- The final design will have several CCD camera scanning regions and RF carpet systems
  - This gives some spatial resolution to match the decay daughter to a two-electron event in the tracking plane
  - The number of cameras/carpets will depend on the background coincidence probability



# Two-neutrino decay coincidences

- Both $2\nu\beta\beta$ and $0\nu\beta\beta$ decays will produce a daughter barium ion
  - We want the probability of a random coincidence between a barium ion from $2\nu\beta\beta$ and a misidentified radioactive background event to be less than $3\sigma$ ($p_{3\sigma} \sim 0.0027$)
  - The coincidence rate is driven by the decay $2\nu\beta\beta$ decay rate

$$\tau_{2\nu\beta\beta} = 2.11\times10^{21}\text{ years}$$

- There are $4.02\times10^{27}$ xenon atoms in 1 ton:

$$R_{2\nu\beta\beta} = 1.32\times10^{6}\text{decays/ton/year}$$

(~2.5 decays/minute in 1 ton of xenon)

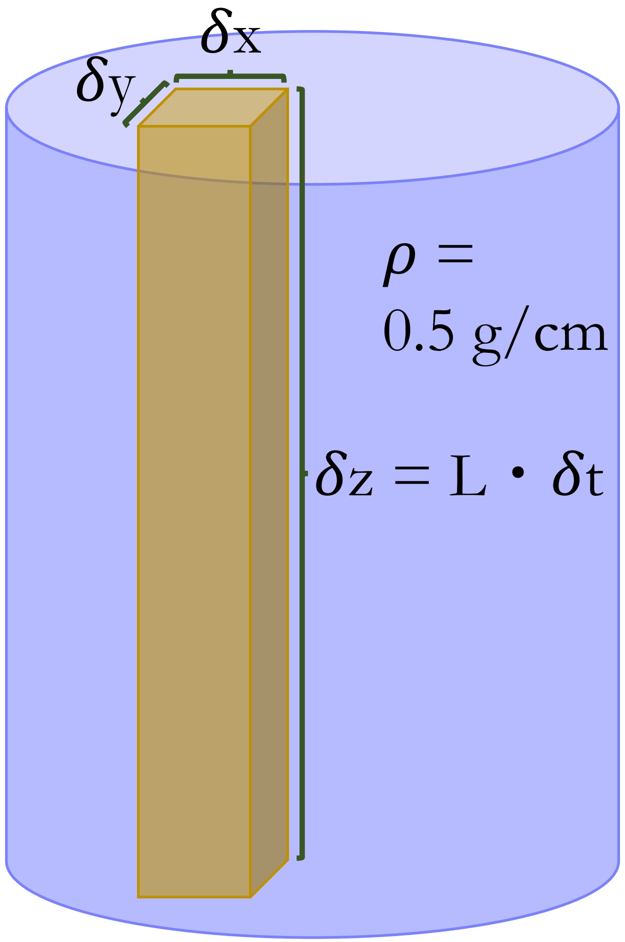
# Two-neutrino decay coincidences

- The SMFI timing resolution will be ~1s
- The number of $2\nu\beta\beta$ decays in a given volume will be:

Rate × volume × density

$$R_{2\nu\beta\beta} \times (\delta x \times \delta y \times L \cdot \delta t) \times \rho < p_{3\sigma}$$
$$\Longrightarrow \delta x \times \delta y \lesssim 4500 \text{ cm}^2$$

- This is a circle with a 43 cm diameter
- Could cover a 2.6 meter cathode with ~15 carpet/camera systems



# RF carpet transport requirements

This has been demonstrated:
[MSU thesis (Pang 2011)]

Demonstrated up to 300 mbar:
NIM B: 376:221–224 (Gehring *et al.* 2016)

| Parameter | NEXT constraints |
|---|---|
| Size | ~40 cm diameter |
| Buffer gas | Xenon-136 |
| Gas pressure | 10 bar |
| Push field | 300 V/cm |

Stability depends on ion mobility

This is affected by the clustering of $Ba^{++}$ in high pressure xenon gas

PRA: 97:062509
Bainglass *et al.* (2018)

About 10x higher than typical fields

- Are all of these requirements achievable?

# RF carpet effective potential

IJMS 299:2 71-77 (Schwarz 2010)

Location of effective potential minimum (approximation):

$$y_{\min} = -\frac{a}{2\pi}\ln\left(\underbrace{E_{\mathrm{p}}\, a(\Omega^2 + D^2)\frac{\pi}{8\sin(\pi\gamma/2)}\frac{m_i}{q}\left(\frac{\gamma a}{2V}\right)^2}_{y_{\min} \text{ is large when argument is near zero}}\right)$$

- NEXT constraints:
  - $E_p$: electric push field
  - $m_i$: barium ion mass
  - $q$: barium ion charge
  - $D$: damping constant

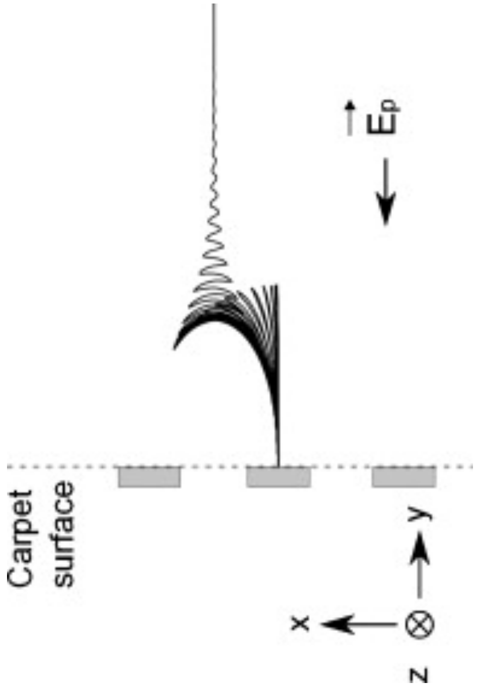
$$D = \frac{q}{m_i}\frac{1}{K_0}\frac{p}{p_0}\frac{T_0}{T}$$

- Controllable parameters:
  - $a$: electrode pitch
  - $\gamma$: gap to pitch ratio
  - $\Omega$: RF frequency
  - $V$: RF voltage

# Stable ion motion

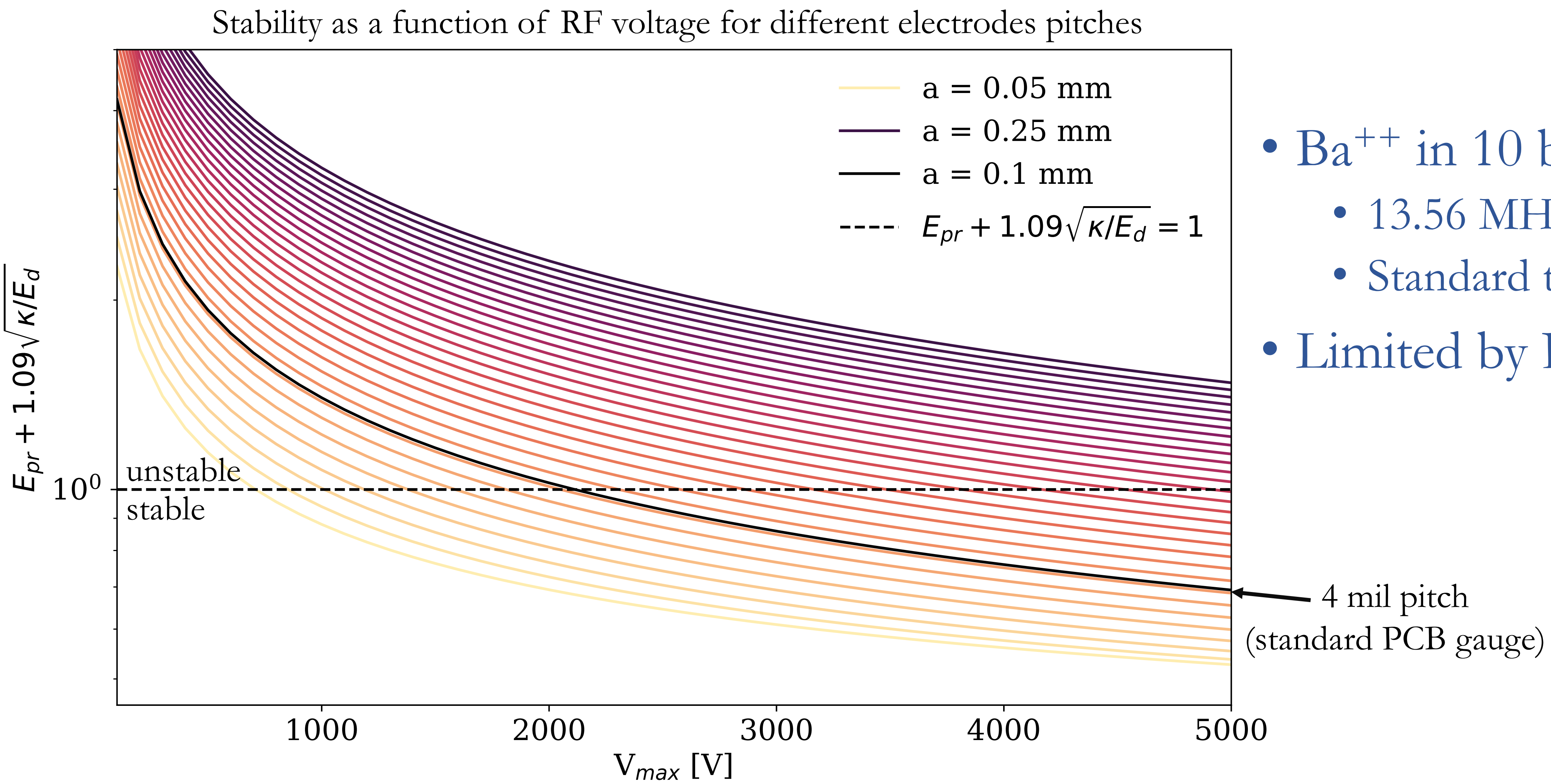
- Ion stability is determined by the electric field perpendicular to the carpet
  - The ion motion is stable when the repelling force of the carpet is strong enough to keep the ion from touching the electrode
  - An empirical fit to the approximated electric field gives the stability requirement:

$$E_{\mathrm{pr}} + 1.09\sqrt{\kappa/E_{\mathrm{d}}} < 1$$




- $E_{\mathrm{pr}} = \frac{q}{m_i}\frac{1}{\Omega^2}\frac{\pi}{a}E_{\mathrm{p}}$ (reduced push field)
- $E_{\mathrm{d}} = \frac{q}{m_i}\frac{1}{\Omega^2}\frac{8V}{\gamma a^2}\sin\left(\pi\frac{\gamma}{2}\right)$ (dimensionless RF field component)
- $\kappa = D/\Omega$ (reduced damping parameter)

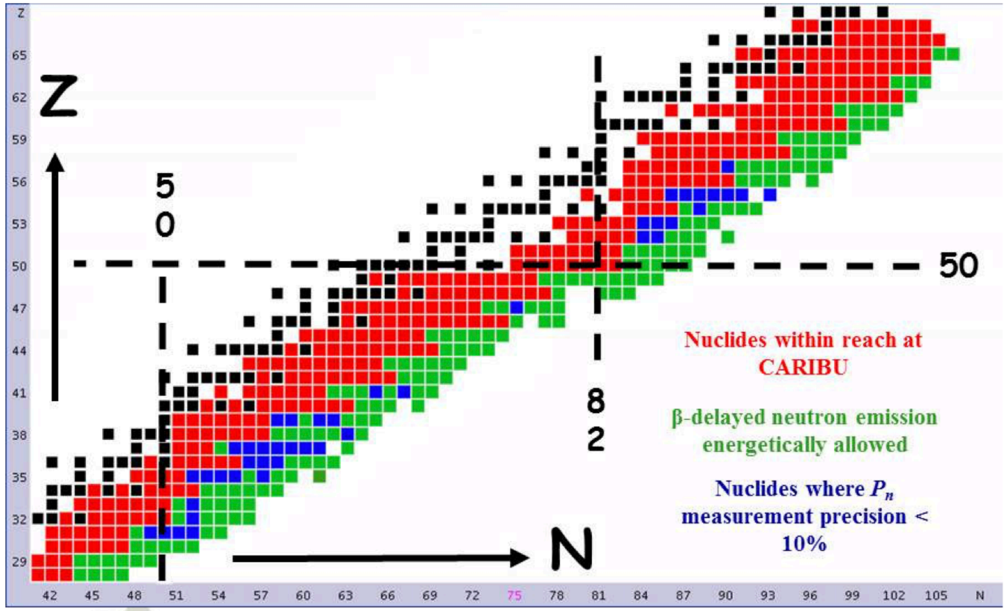
# Stable ion motion




- $Ba^{++}$ in 10 bar xenon
  - 13.56 MHz RF
  - Standard temperature
- Limited by Paschen's law

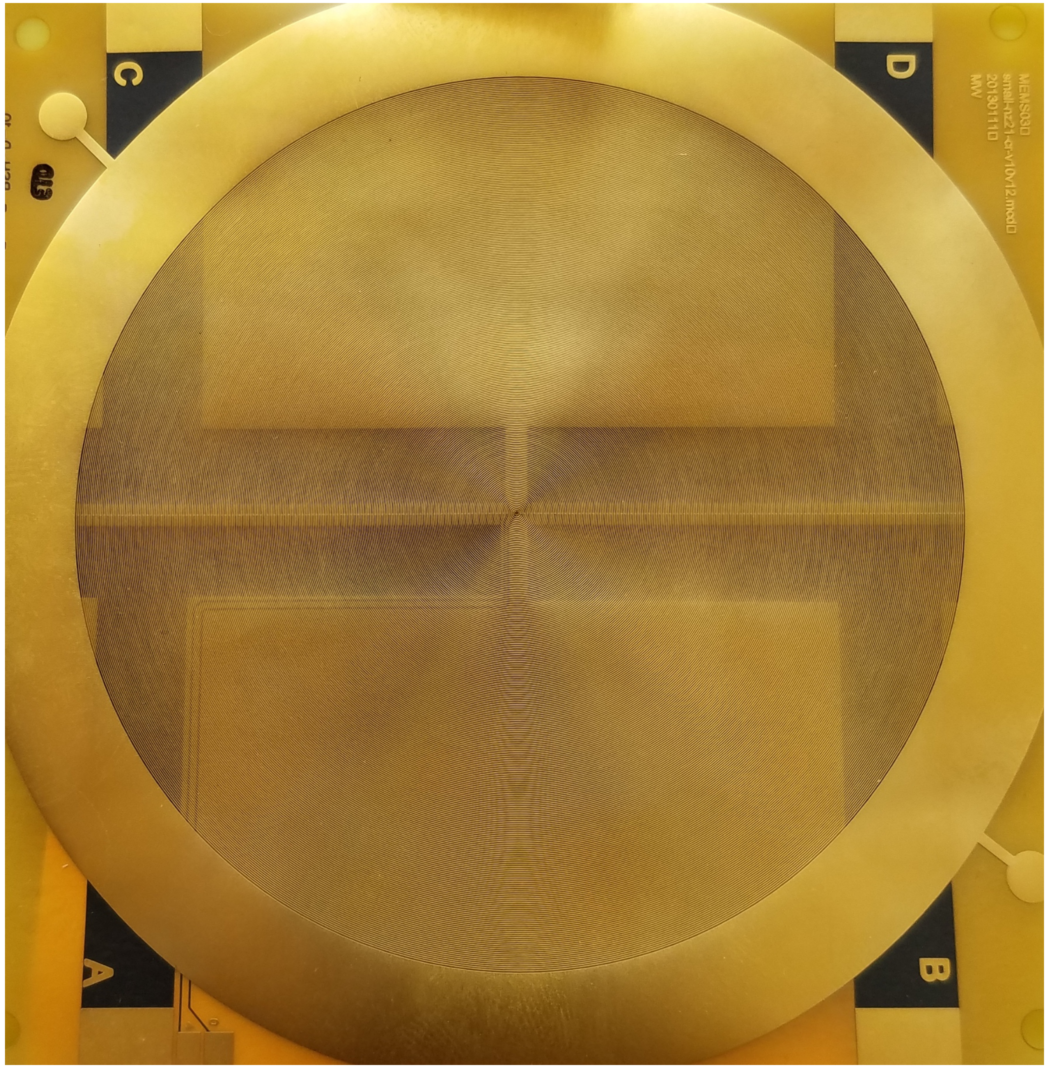
# CARIBU RF carpet tests at ANL

- We have been given priority I ranking for time in the CARIBU beamline
  - Working with RF carpet expert at ANL, Guy Savard
  - Use barium beam to test RF carpet transport in high pressure
  - We will test up to 1 bar of pressure with a 30 V/cm push field
    - Fill with helium, then argon, then xenon
    - If successful, we will propose tests at higher pressures and push fields



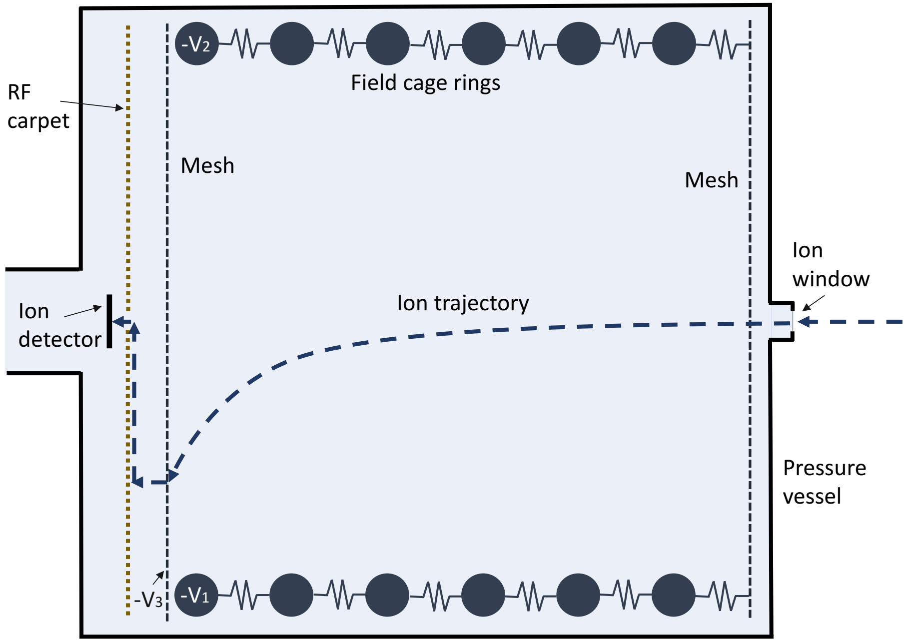
# RF Carpet

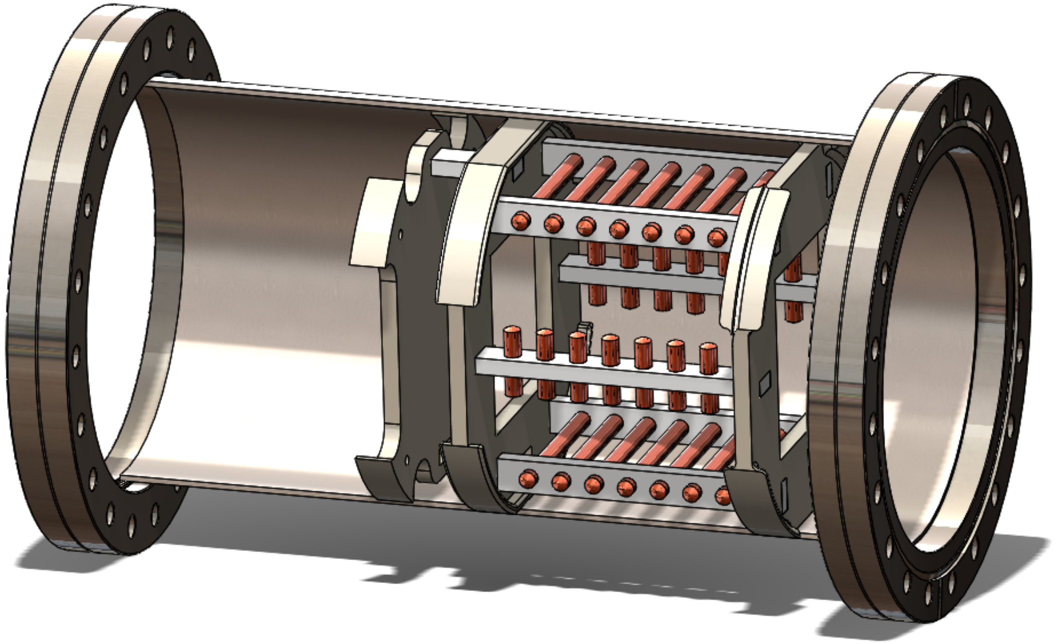
- RF carpet from Notre Dame via ANL (Guy)
  - 252 electrodes with 0.16 mm pitch
  - 8 cm active diameter
  - 0.32 mm center hole diameter
  - Transports ion using surfing wave
    - Surfing wave can be produced with a function generator
    - Full period every four electrodes
    - Couple to the RF signal inside the chamber

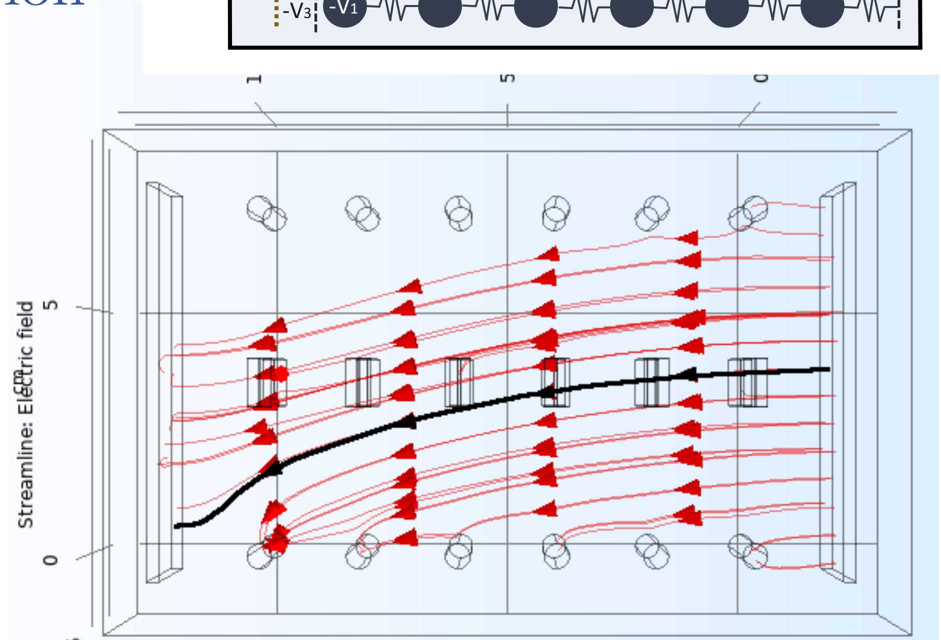


# Steerable drift field

- Asymmetric electric field cage
  - One side is has a higher voltage than the other at the cathode end of the field cage
  - We can control the relative voltages from outside
  - Allows us to change the position of the barium ion on the RF carpet



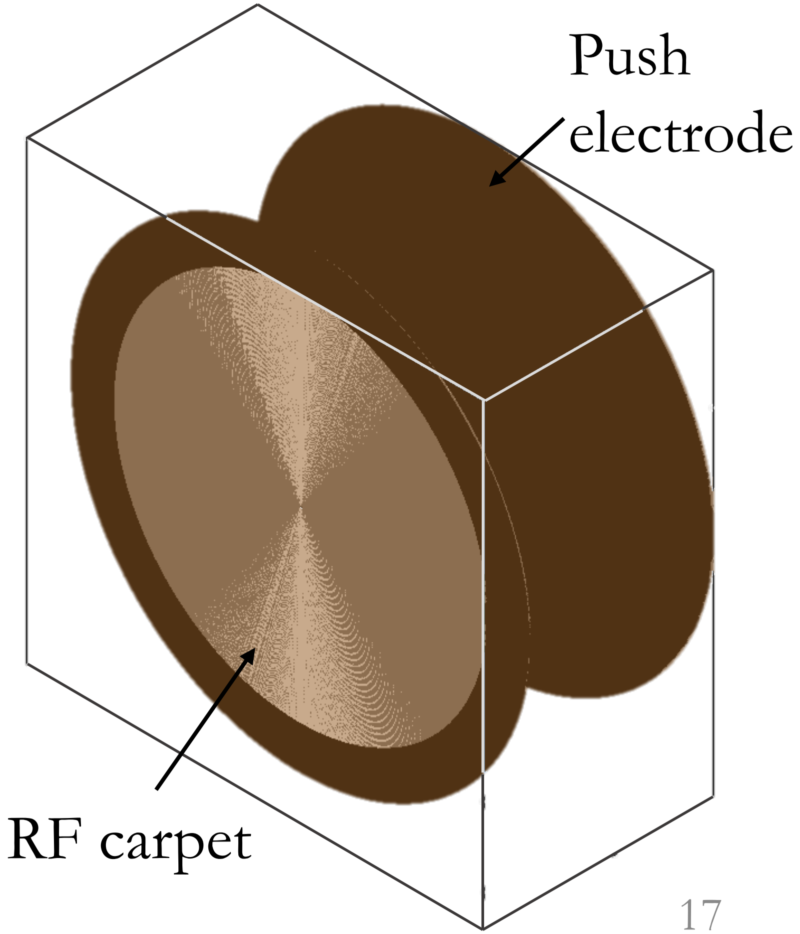





COMSOL simulation of electric field

# SIMION ion simulations

- Using SIMION to study different conditions
- RF carpet geometry:
  - 252 electrode rings
    - 0.16 mm spacing
    - 8 cm active diameter
  - Push electrode 4 cm from carpet surface
- Simulating $Ba^{++}$ ions in He, Ar, and Xe
  - Determining possible operating parameters for first CARIBU tests
    - Pressures up to 1 bar
    - Push field up to 30 V/cm
  - Will continue to higher pressures and push fields



# SIMION simulation details

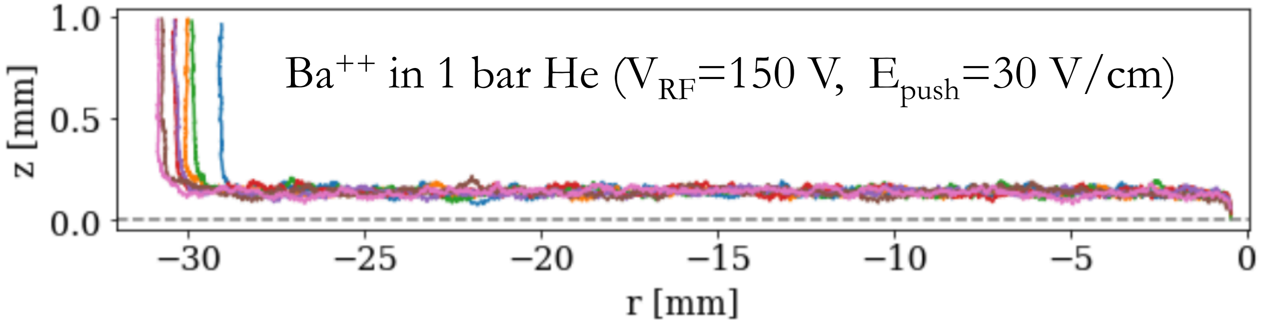
- Using a hard-sphere collision model with modified cross sections
  - The cross sections are modified based on the $Ba^{++}$ mobilities in helium, argon, and xenon found in LXCat database:
    - $Ba^{++}$ in He: $K_0 = 18\ \mathrm{cm}^2/\mathrm{Vs}$
    - $Ba^{++}$ in Ar: $K_0 = 2.06\ \mathrm{cm}^2/\mathrm{Vs}$
    - $Ba^{++}$ in Xe: $K_0 = 0.55\ \mathrm{cm}^2/\mathrm{Vs}$

McGuirk, *et al.* J. Chem. Phys. 130 (2009) 194305
Buchachenko, *et al.* J. Chem. Phys. 148 (2018) 154304
(via LXCat database)

Bainglass, *et al.* Phys. Rev. A **97**, 062509

- 13.56 MHz RF with 100 kHz (4-phase) surfing wave
  - Ion time-step (sampling rate) 0.0092 $\mu$s (8 steps per RF period)
  - $Ba^{++}$ ions generated 1 cm from surface of carpet
    - In a random 1cm-diameter area, 30 cm from the carpet center:

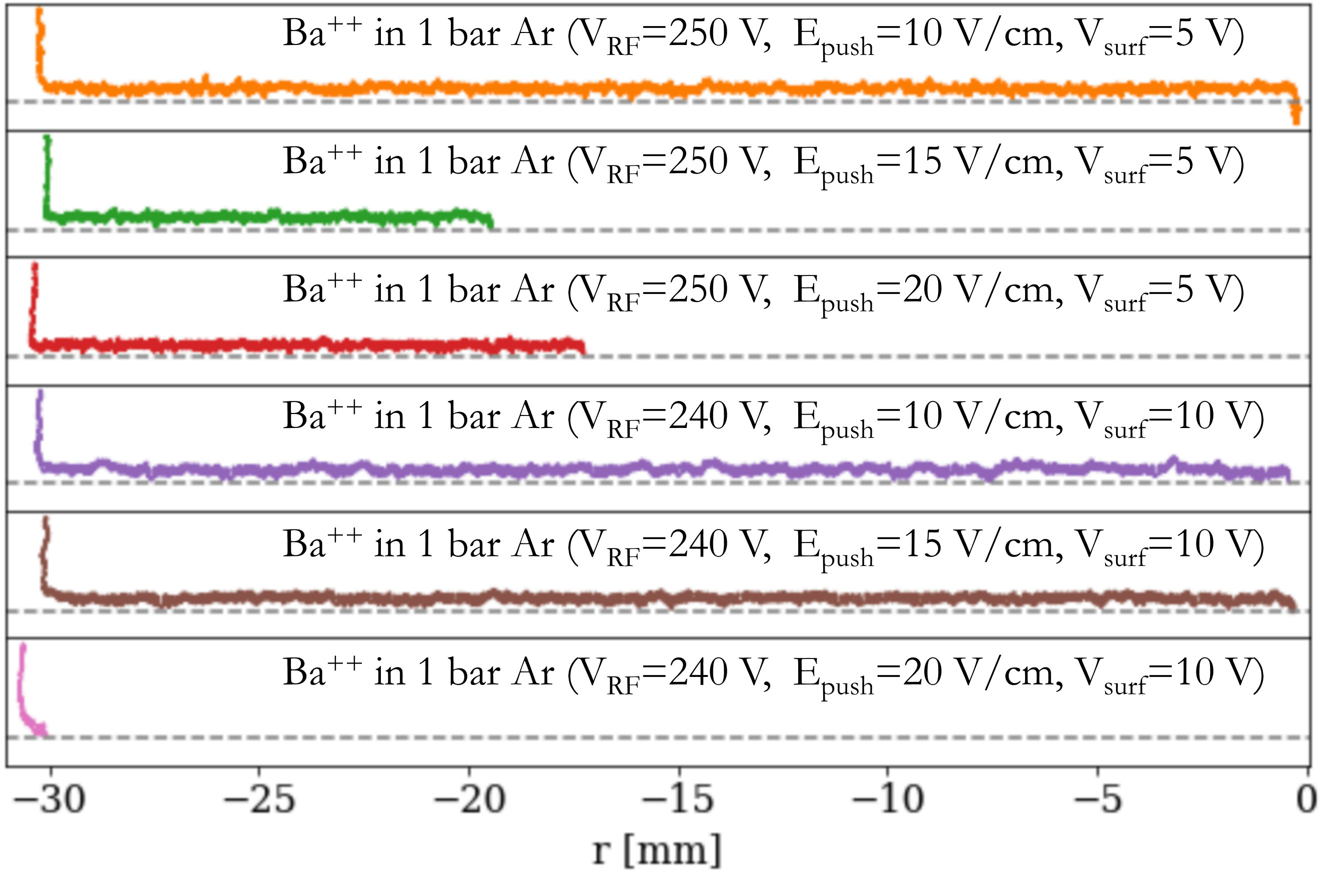
Example in helium:



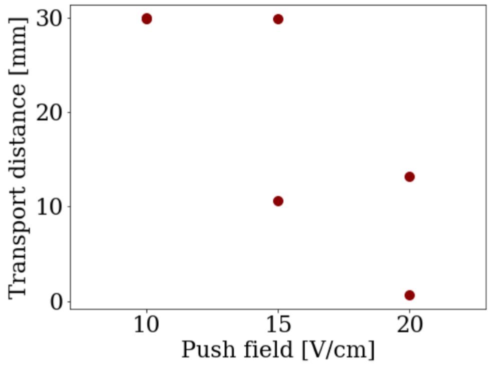
# First simulations in argon at 1 bar

- Stable ion transport is more difficult in argon
  - We have been able to find some stable operating conditions for argon at 1 bar
  - Beginning to map out the $Ba^{++}$/Ar parameter space

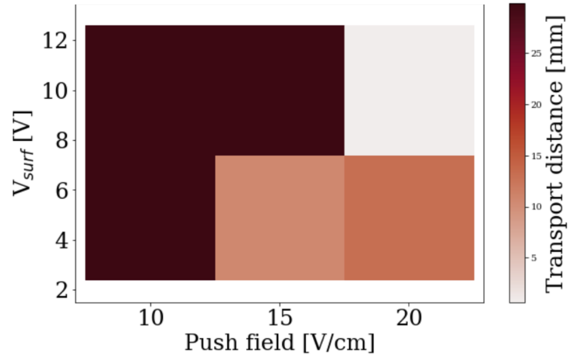
Examples in argon:

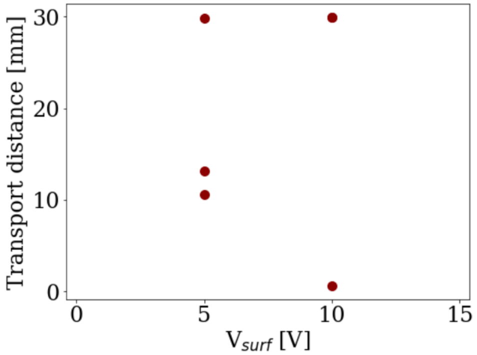


# First simulations in argon at 1 bar

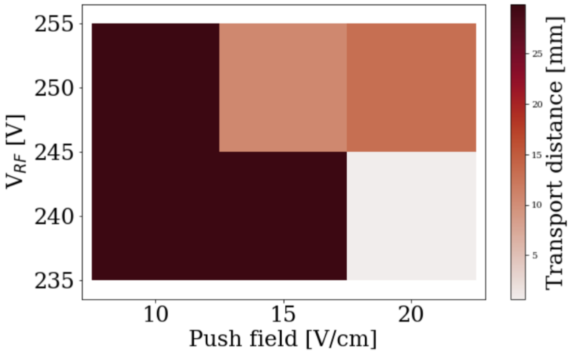


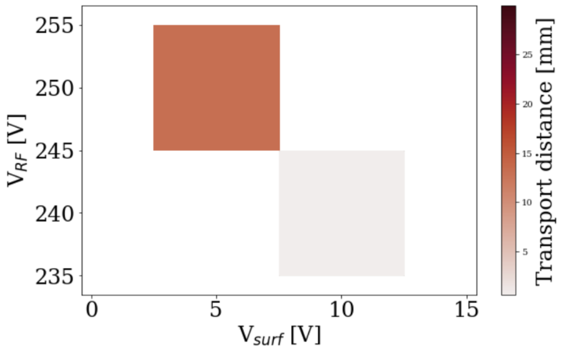

- Varying the push field, RF and surfing wave amplitudes
  - Only changing the parameters tunable in first CARIBU tests
  - Comparing the average transport distance

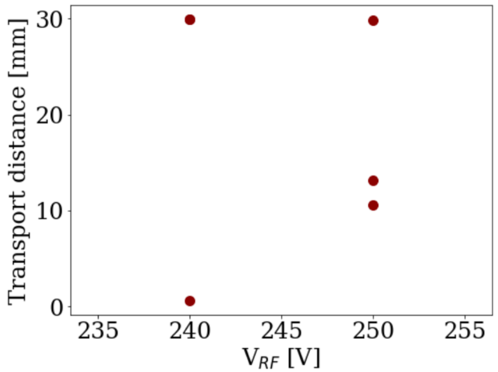



- The simulations are on the border of stability
  - (stable ions make it the full 30 mm)
- Very dependent on RF voltage
  - We need to confirm the voltage breakdown with our RF frequency in laboratory conditions

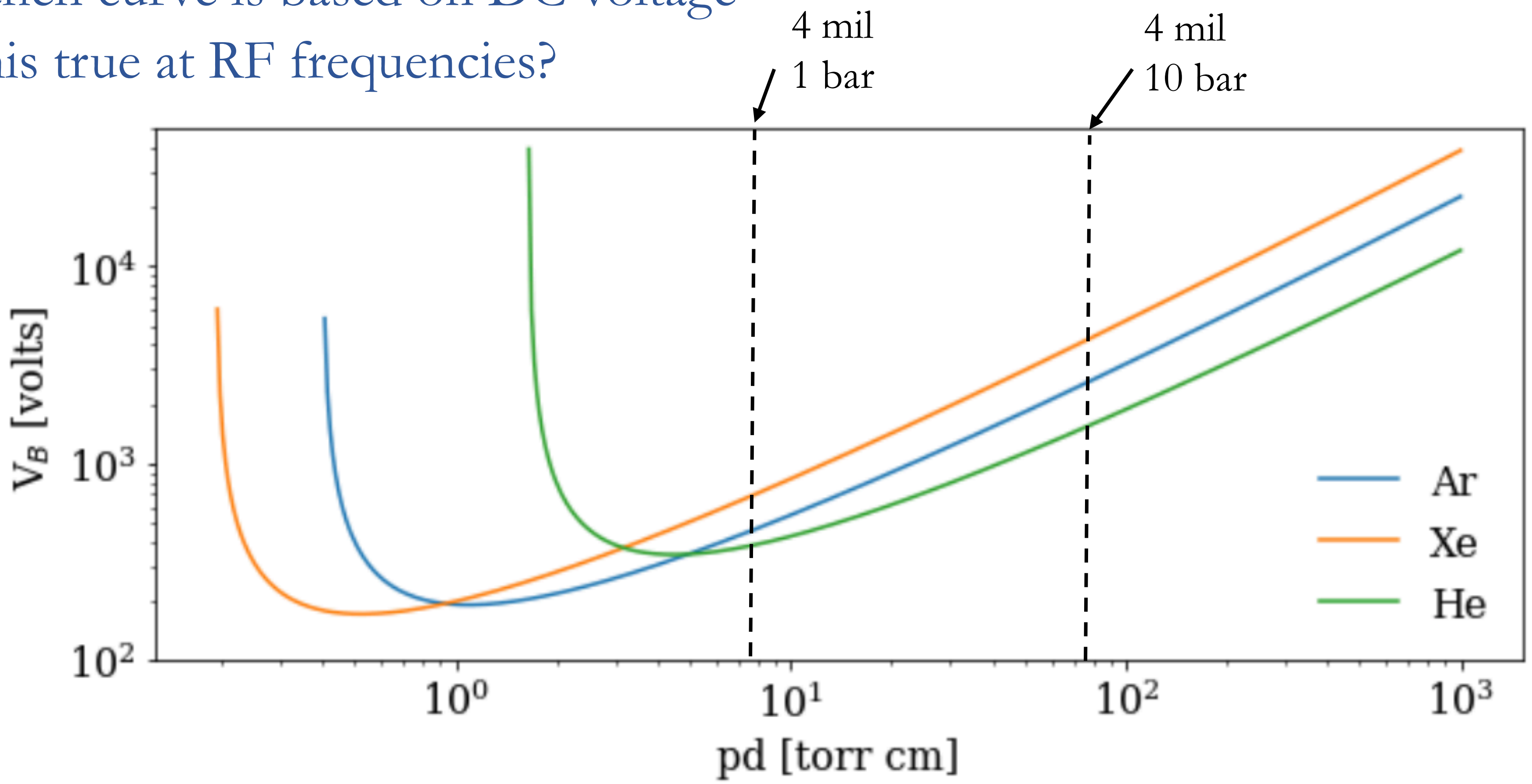


# RF Paschen curve

- Our simulations and plans assume that we need to stay well below the Paschen curve
  - Paschen curve is based on DC voltage
  - Is this true at RF frequencies?



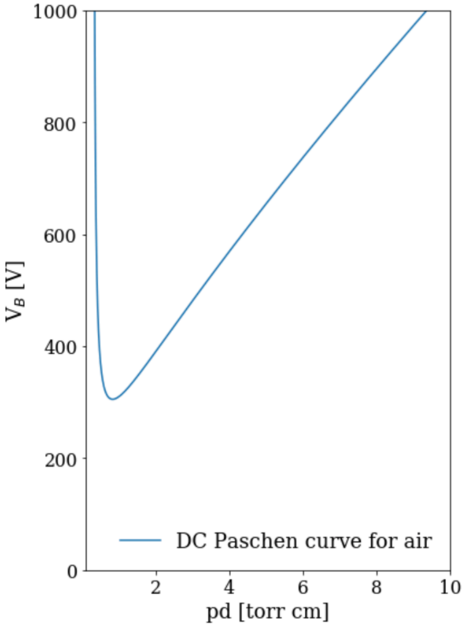
# Similarity principle

- We are operating at 13.56 MHz with ~0.01 cm (4 mil) spacing
- Similarity principle:
  - RF Paschen curve depends on frequency x gap
  - Our *fd* ~ 0.14 MHz-cm
  - Near DC, but not exactly

**The Electrical Breakdown of Gases in Uniform High Frequency Fields at Low Pressure**

By W. G. TOWNSEND† and G. C. WILLIAMS‡
Department of Physics, University College of Swansea

*Communicated by F. Llewellyn Jones ; MS. received* 18*th June* 1958, *and in final form* 21*st July* 1958



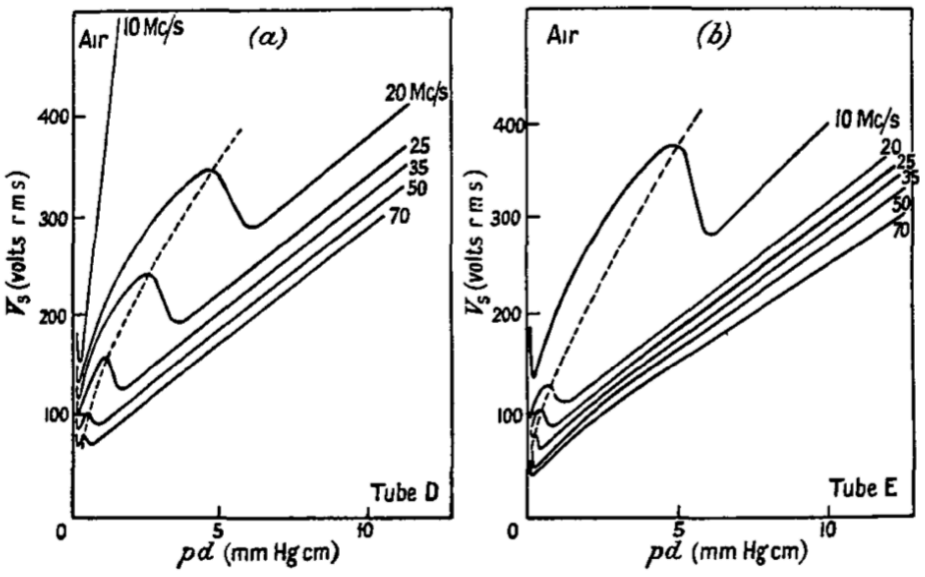
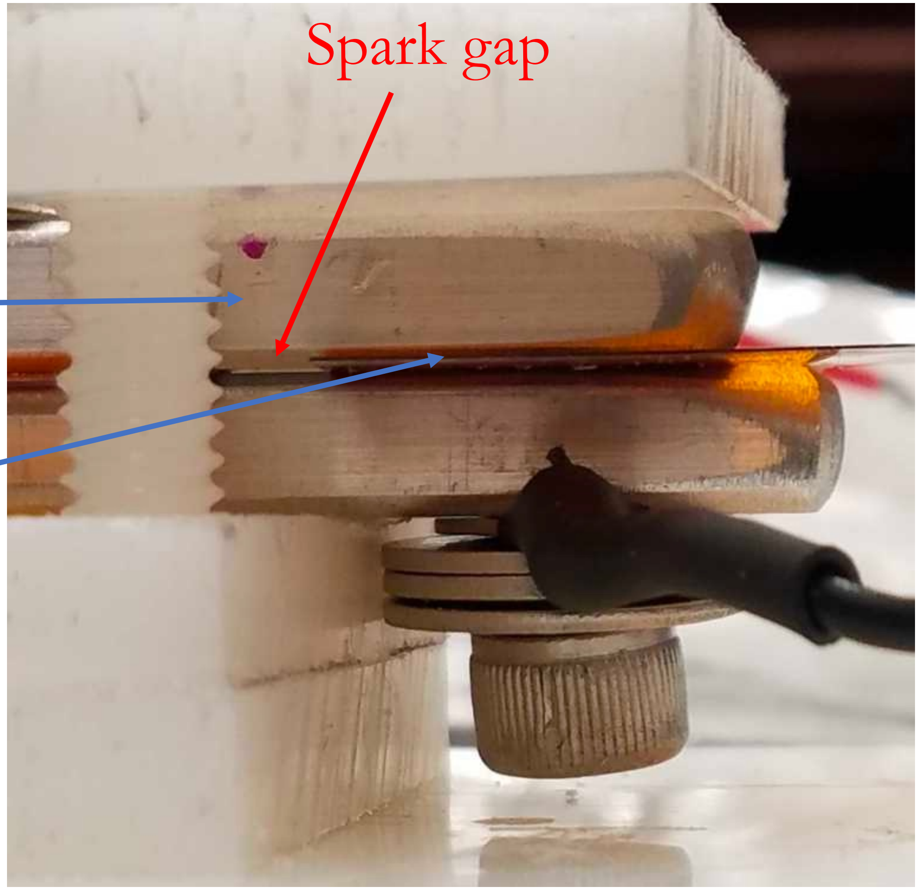




Figure 1. ($V_s$, $pd$) curves for air for high frequency fields.

# RF high voltage tests in high pressure

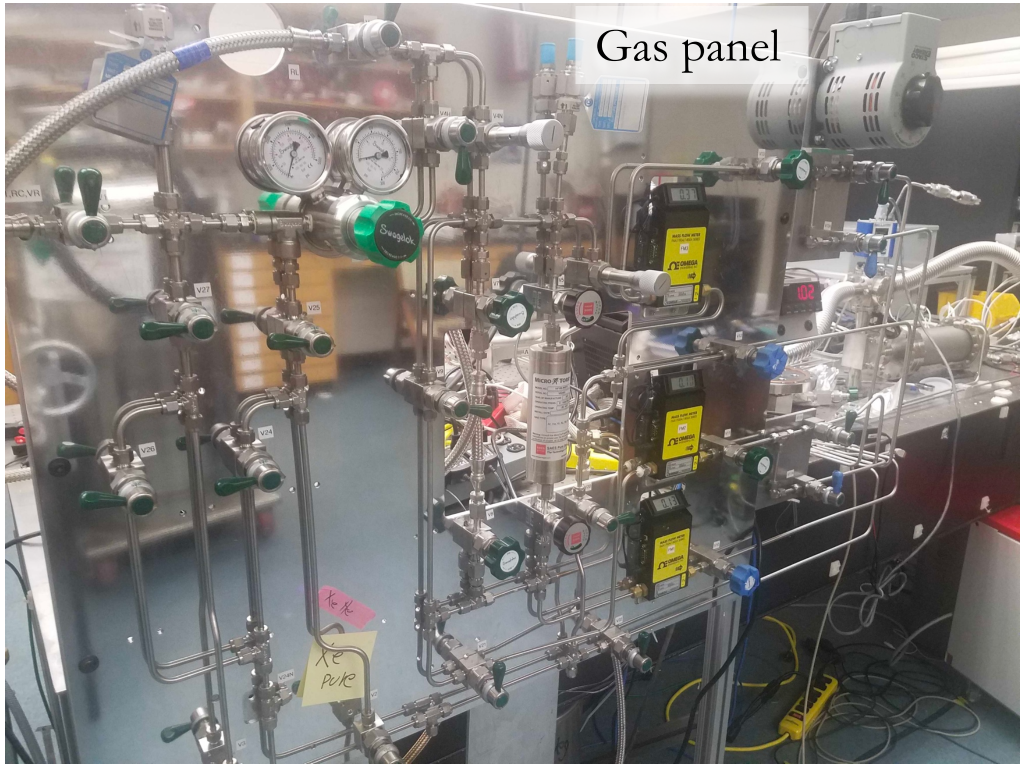
- Testing the RF breakdown strength in high pressure gases

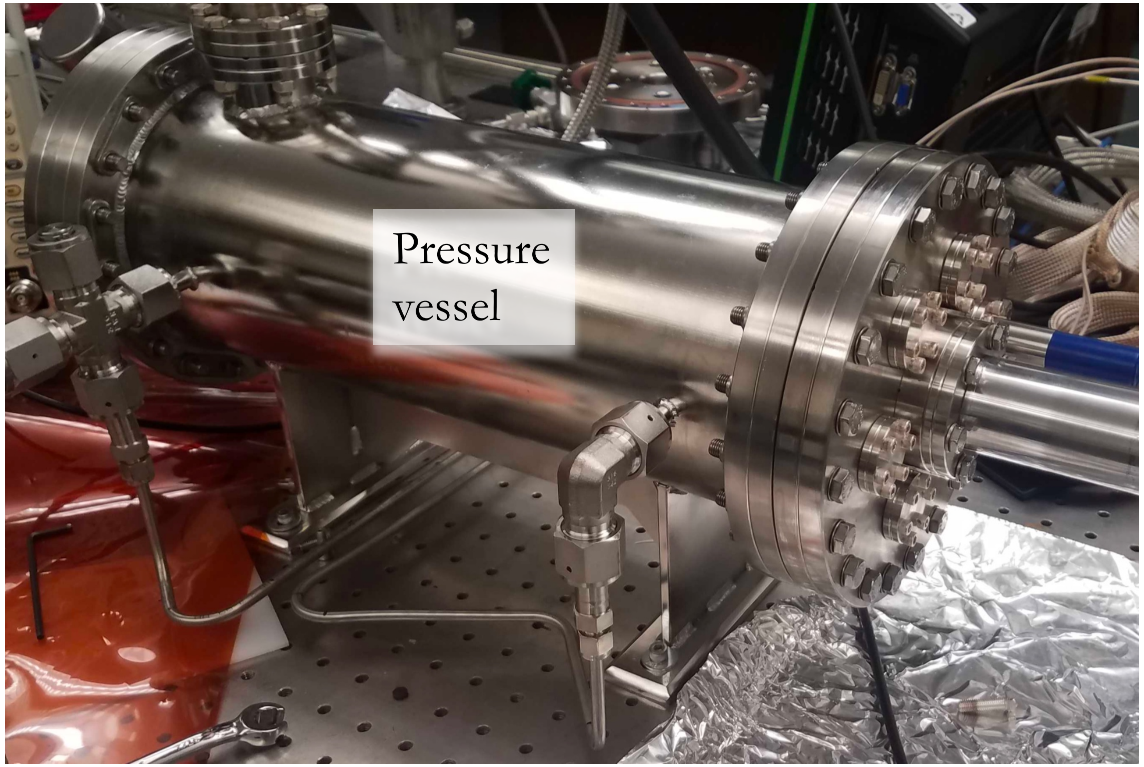
- Test setup:
  - Two 1/4" thick steel electrodes
    - One held at ground, the other at RF HV
  - 5 mil Kapton sheets for gauges
    - Use 1-3 sheets (5-15 mil)
    - Kapton is sandwiched between electrodes



# UTA gas system

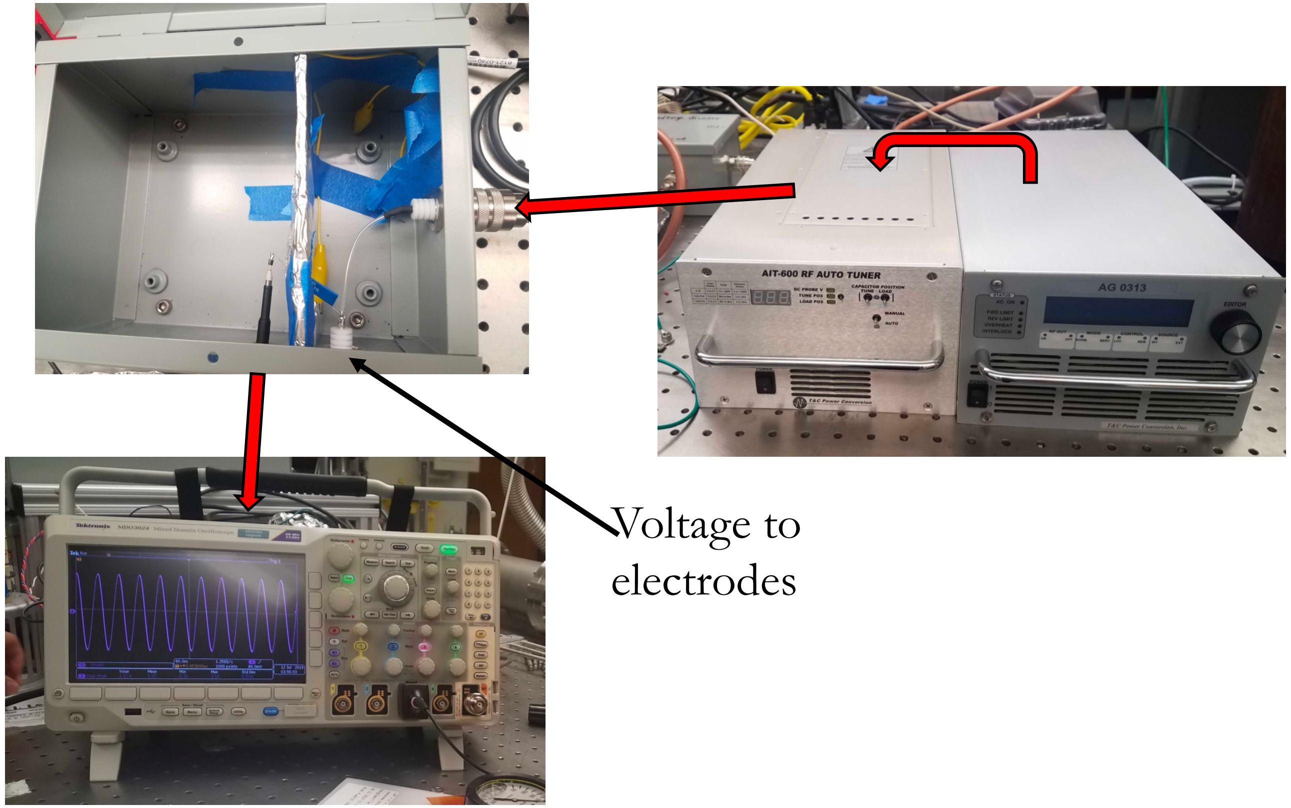
- Gas system at UTA can go up to 10 bar
- Testing with helium, argon, and xenon
  - Pressures from 100 mbar to 10 bar



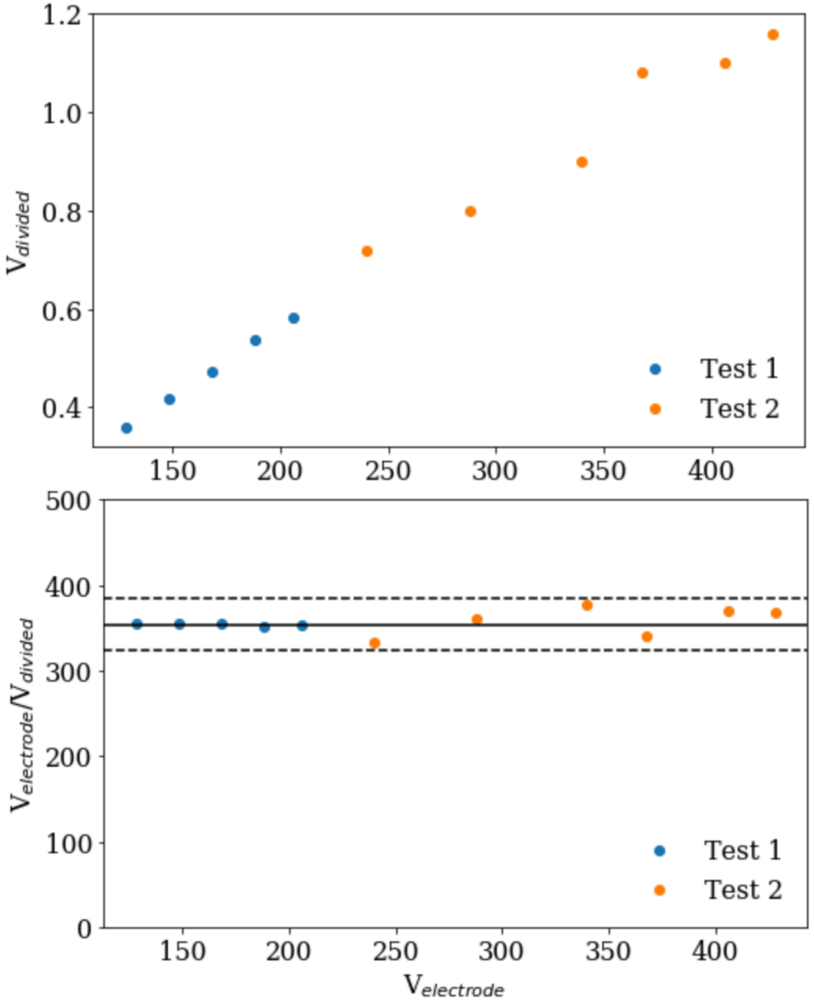



# High voltage RF signal

- 300-watt 13.56-MHz generator + impedance tuner
- Signal goes to both application and potential divider for monitoring

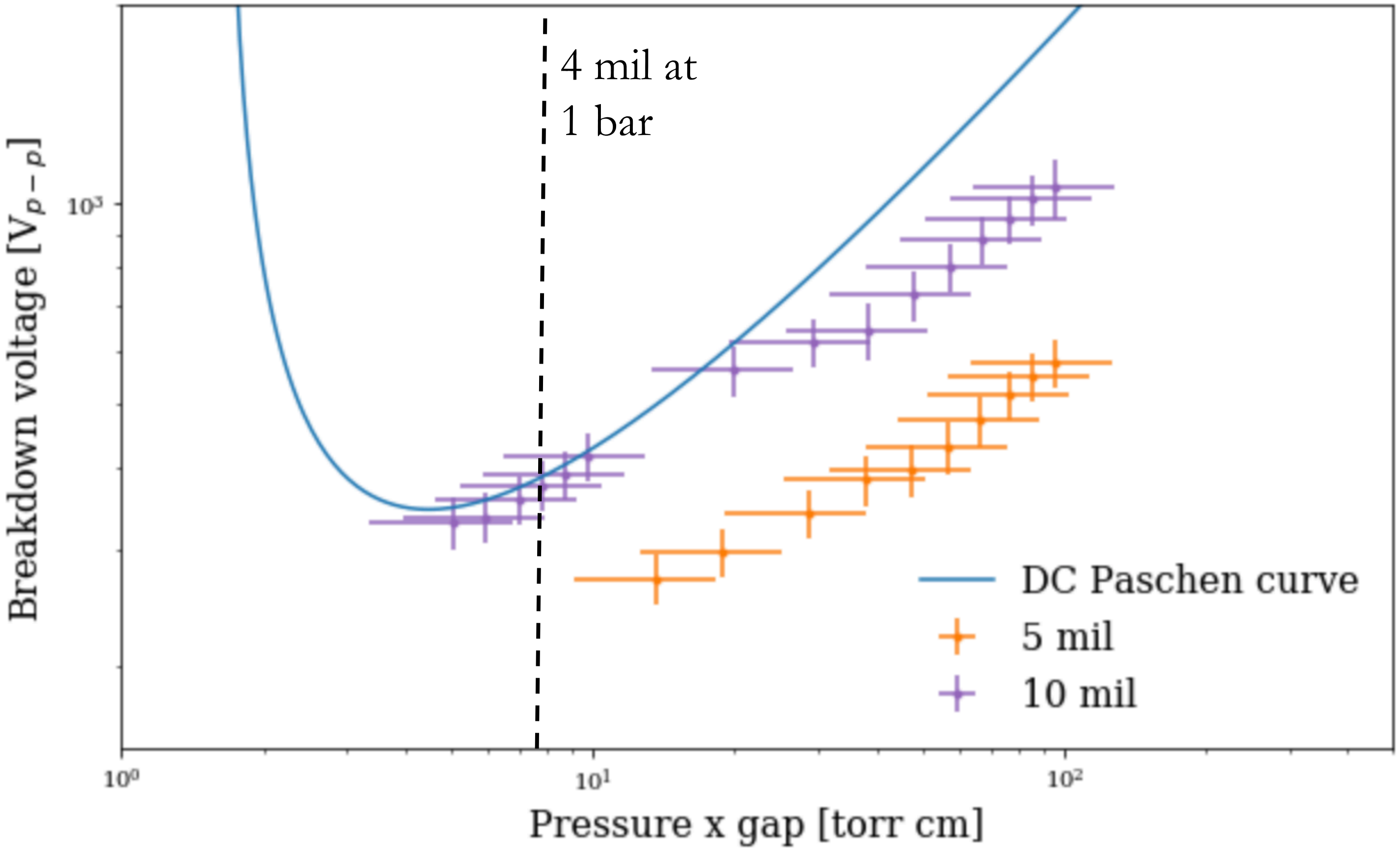



Tested the relationship in air at 10 mil spacing:



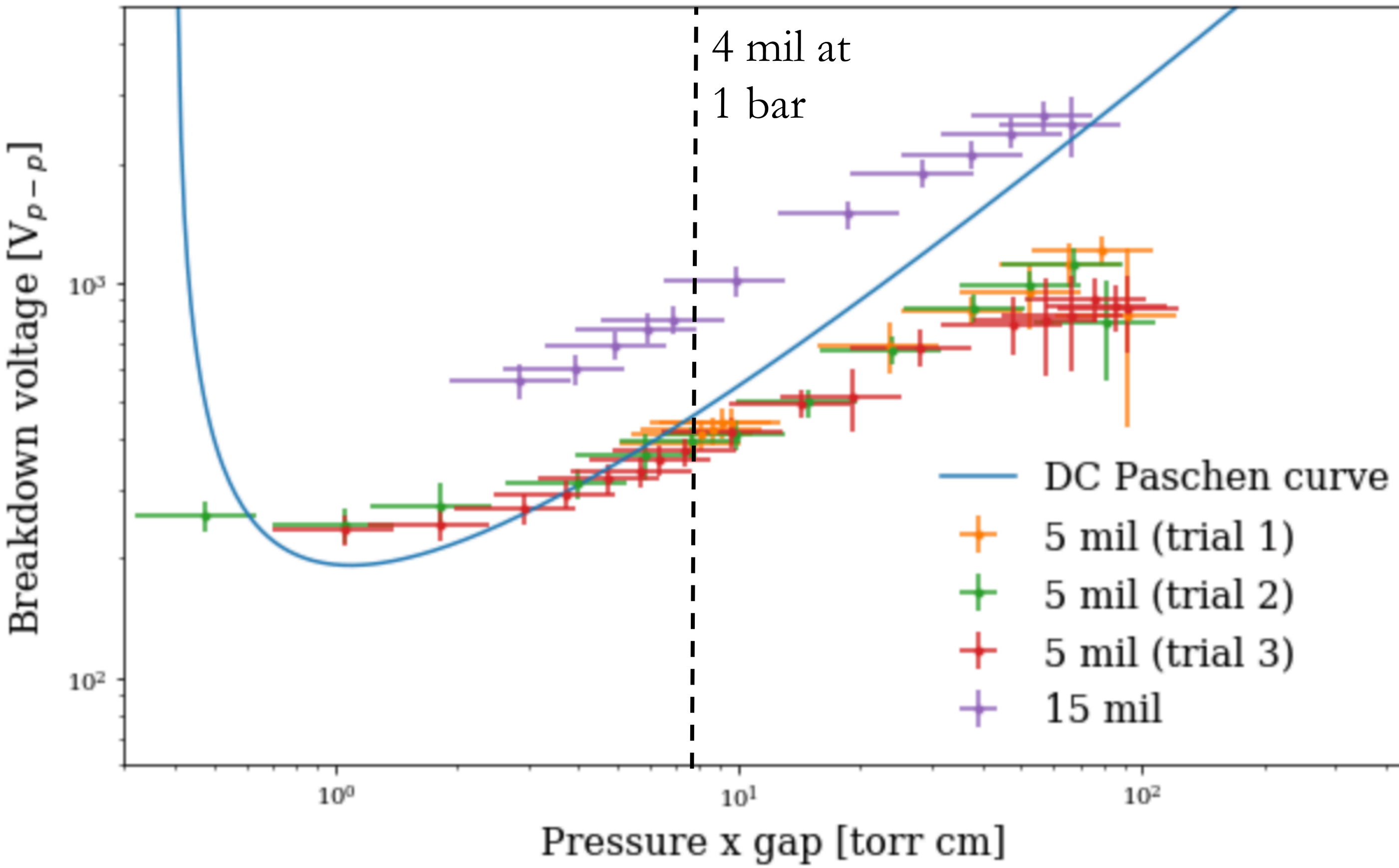
# RF breakdown in helium

- We see different relationships for different spacings
  - Breakdown voltage is higher for larger gaps
  - It's possible that the potential divider may behave differently at different spacings



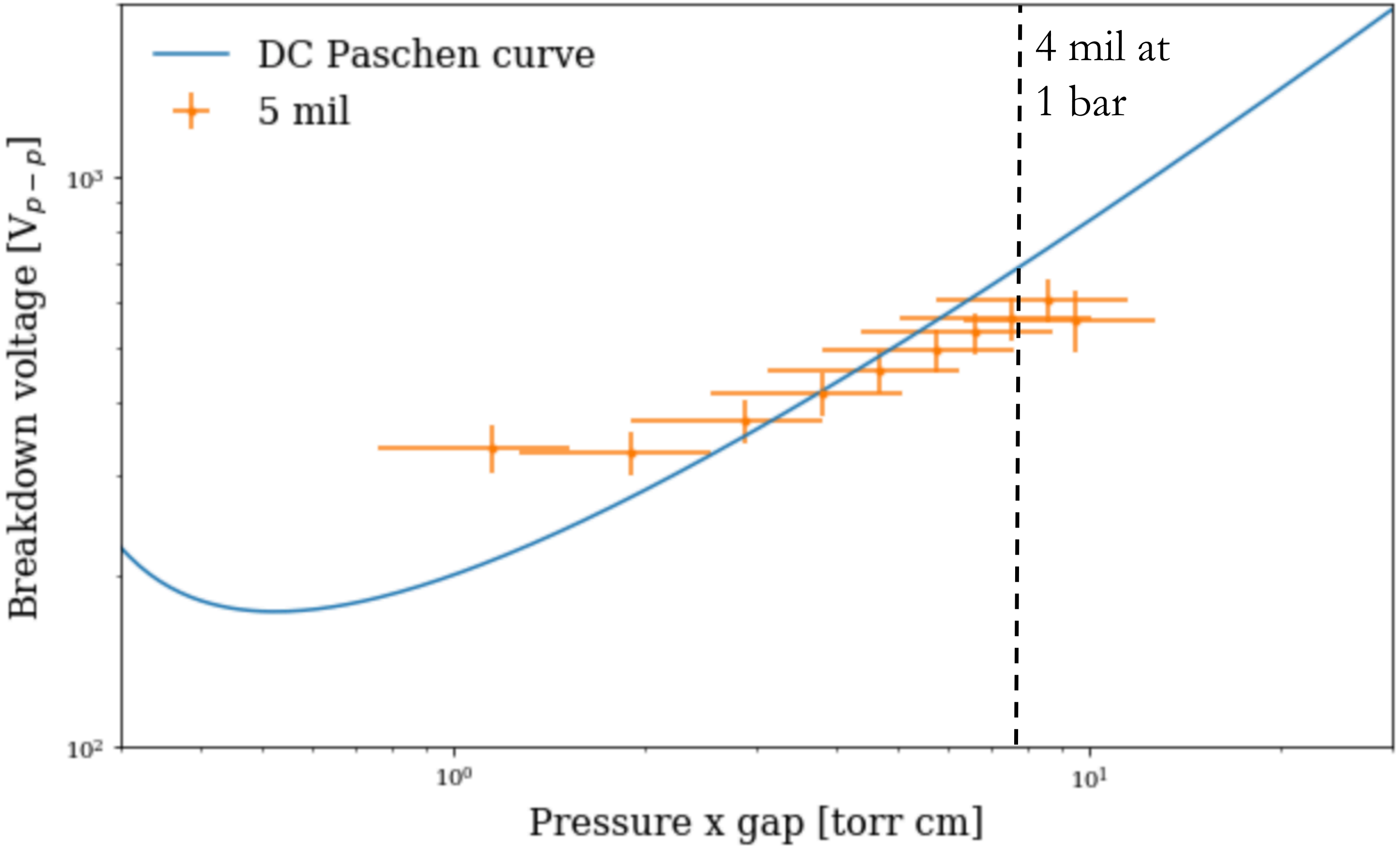
# RF breakdown in argon

- Similar difference between spacings
- Overall closer to the DC Paschen curve
- Limited by the breakdown through the Kapton spacers



# RF breakdown in xenon

- Closer to the DC Paschen curve at smaller spacings
  - The data looks very promising for high pressure xenon!



# Next steps

- Make a test stand that doesn't require material between the electrodes
- Understand the behavior of the voltage divider better
  - Is it spacing, pressure, voltage dependant?
- Have PCB made that mimics the RF carpet
  - How will the Kapton substrate effect the inter-electrode breakdown?

# Summary

- Can potentially use RF carpets to transport barium ions across the NEXT cathode to an SMFI imaging region
- Operating at 10 bar in xenon will be a major challenge
  - Approximate calculations show that it may be possible with high enough voltage and small enough electrode spacing
  - Using SIMION to further explore the possible operating space
- Our first tests at 1 bar will be done in a barium beam at CARIBU
- Testing the RF breakdown voltages at small distances
  - Will determine exactly how high we can safely push the RF voltage at high pressure
  - Early data looks very promising for high voltage in xenon gas!

Thank you!