TOWARD THE FUTURE: UPGRADING THE ^{6}HE-CRES EXPERIMENT WITH AN ION TRAP

David McClain

^{6}He-CRES

CYCLOTRON INSTITUTE
TEXAS A&M UNIVERSITY

CENTER FOR EXCELLENCE
CENTAUR
IN NUCLEAR TRAINING AND UNIVERSITY-BASED RESEARCH

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

NNSA
National Nuclear Security Administration

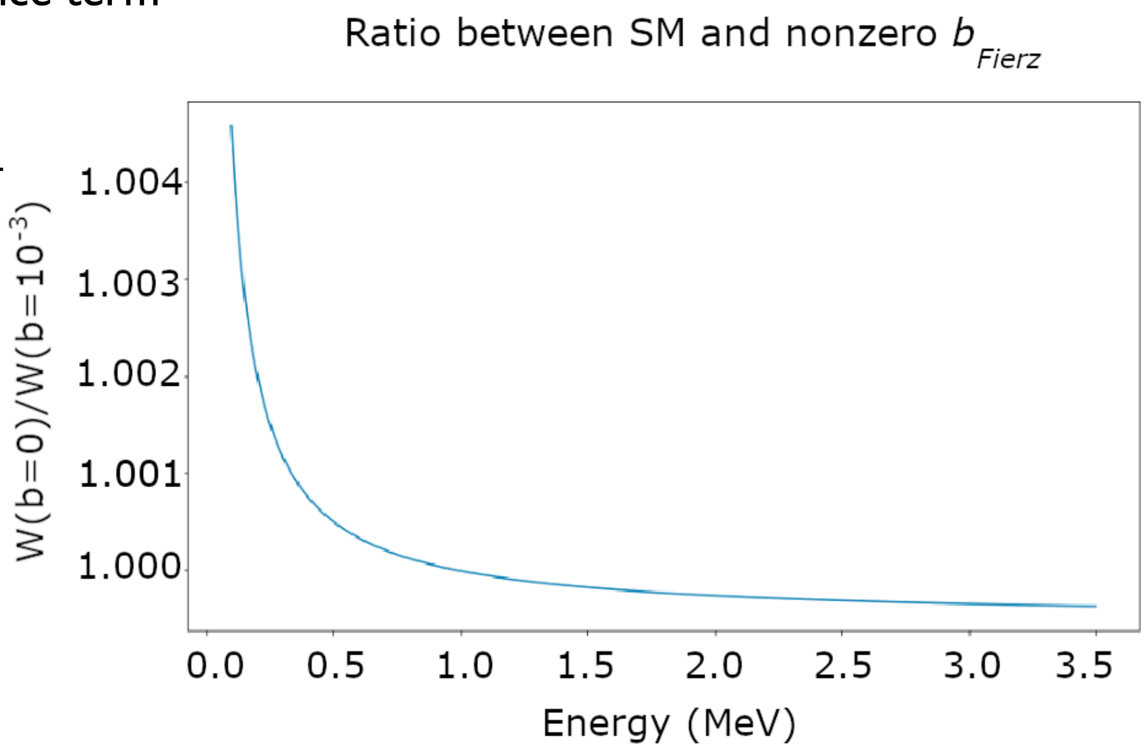
MOTIVATION

- Probe chirality-flipping couplings through the Fierz interference term

$$b = \pm \frac{2\sqrt{1-(\alpha Z)^2}\left[\frac{g_S}{g_V}\epsilon_S - 4\left(\frac{\langle\sigma\tau\rangle}{\langle\tau\rangle}\right)^2 \frac{g_T}{g_V}\frac{g_A}{g_V}\epsilon_T\right]}{1+\left(\frac{\langle\sigma\tau\rangle}{\langle\tau\rangle}\right)^2\left(\frac{g_A}{g_V}\right)^2}$$

- Where we can find b in the beta decay equation

$$WdE \propto \frac{F(\pm Z, E)}{2\pi^3} pE(E_0 - E)^2 \xi \left(1 + b\frac{m}{E}\right) dE$$



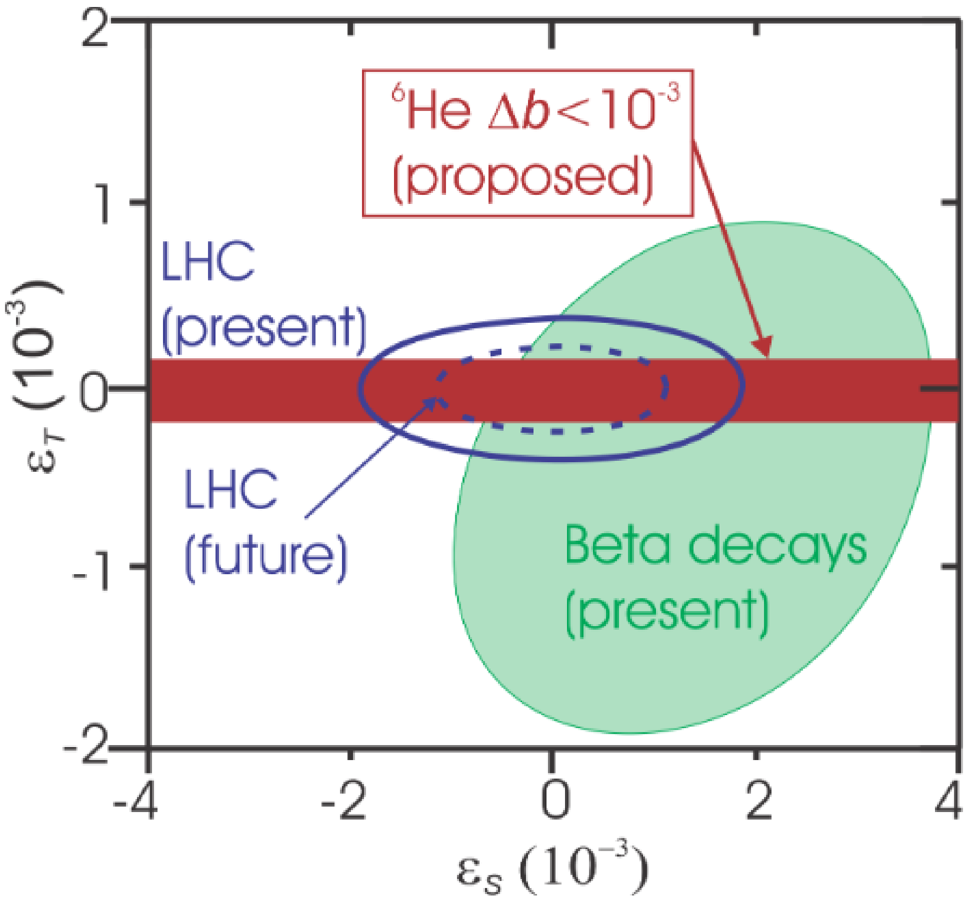
MOTIVATION

- Probe chirality-flipping couplings through the Fierz interference term

$$b = \pm \frac{2\sqrt{1-(\alpha Z)^2}\left[\frac{g_S}{g_V}\epsilon_S - 4\left(\frac{\langle\sigma\tau\rangle}{\langle\tau\rangle}\right)^2 \frac{g_T}{g_V}\frac{g_A}{g_V}\epsilon_T\right]}{1+\left(\frac{\langle\sigma\tau\rangle}{\langle\tau\rangle}\right)^2\left(\frac{g_A}{g_V}\right)^2}$$

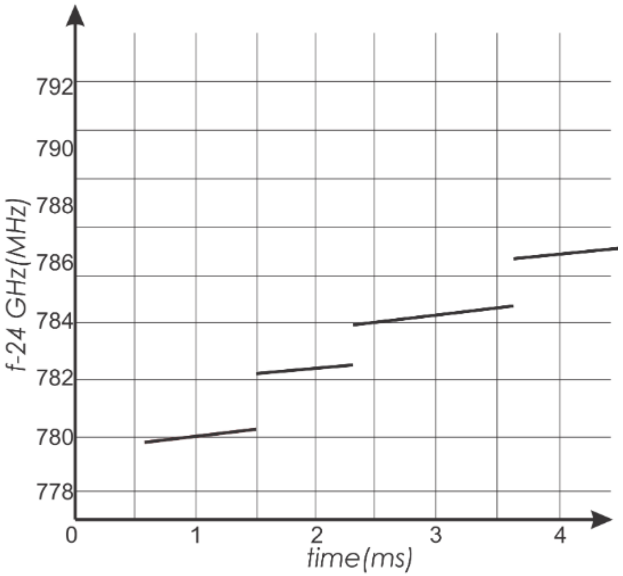
- Where we can find b in the beta decay equation

$$WdE \propto \frac{F(\pm Z,E)}{2\pi^3} pE(E_0-E)^2\xi\left(1+b\frac{m}{E}\right)dE$$



CRASH COURSE: CRES

- Cyclotron Radiation Emission Spectroscopy (CRES)
  - Developed by the Project 8 collaboration
  - Measures radiation of axially confined betas in a magnetic trap



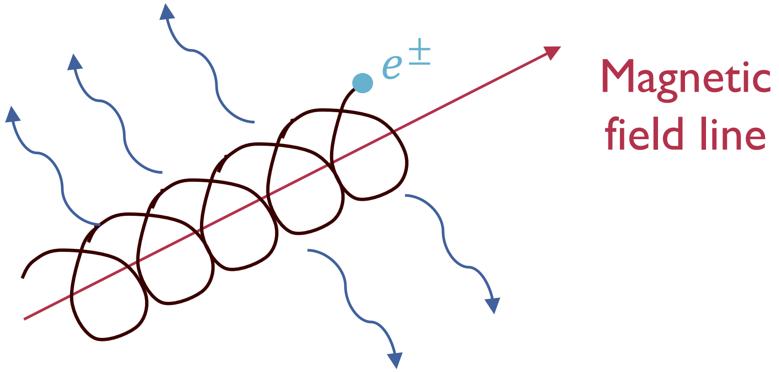
D. M. Asner, *et al.*, Phys. Rev. Lett. 114, 162501 (2015)

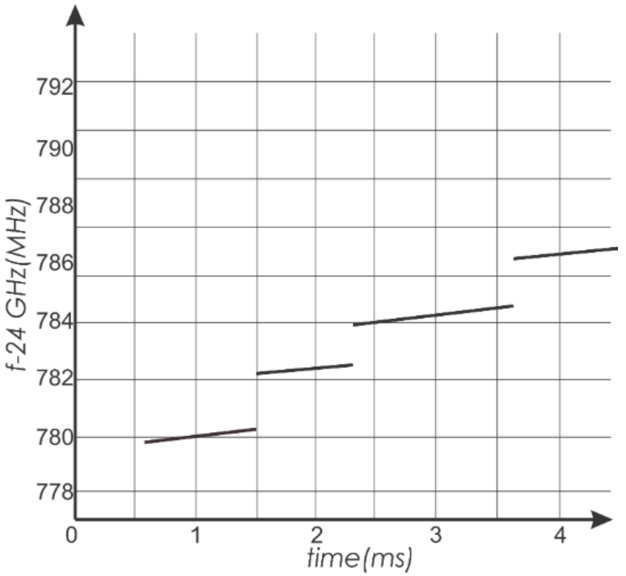
"Never measure anything but frequency!" Arthur Schawlow

CRASH COURSE: CRES

- Cyclotron Radiation Emission Spectroscopy (CRES)
  - Developed by the Project 8 collaboration
  - Measures radiation of axially confined betas in a magnetic trap
  - Linear tracks form as the beta loses energy to the emissions

$$f \propto \frac{qB}{m_e + E_e}$$





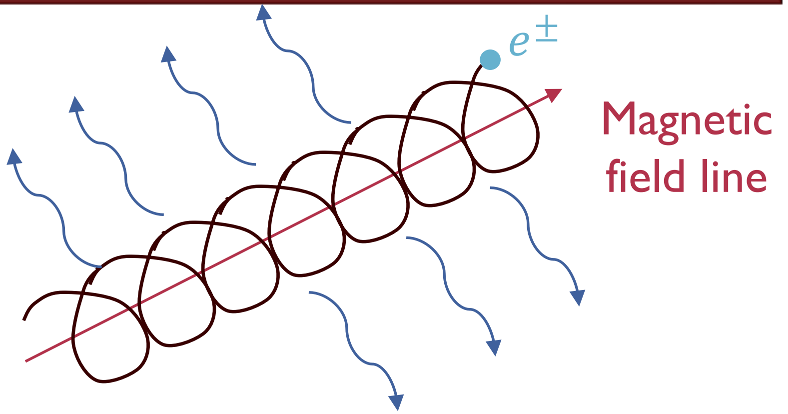
D. M. Asner, *et al.*, Phys. Rev. Lett. 114, 162501 (2015)

“Never measure anything but frequency!” Arthur Schawlow

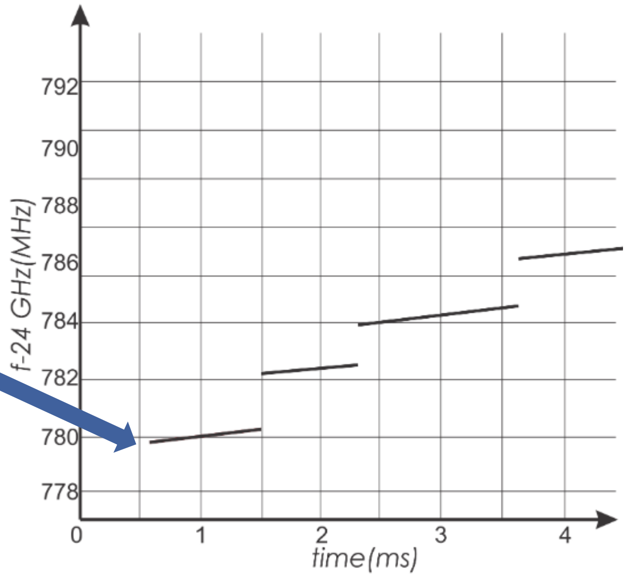
CRASH COURSE: CRES

- Cyclotron Radiation Emission Spectroscopy (CRES)
  - Developed by the Project 8 collaboration
  - Measures radiation of axially confined betas in a magnetic trap
  - Linear tracks form as the beta loses energy to the emissions

$$f \propto \frac{qB}{m_e + E_e}$$



- Retracing to the starting point of the track we can narrow our energy resolution to the eV scale!

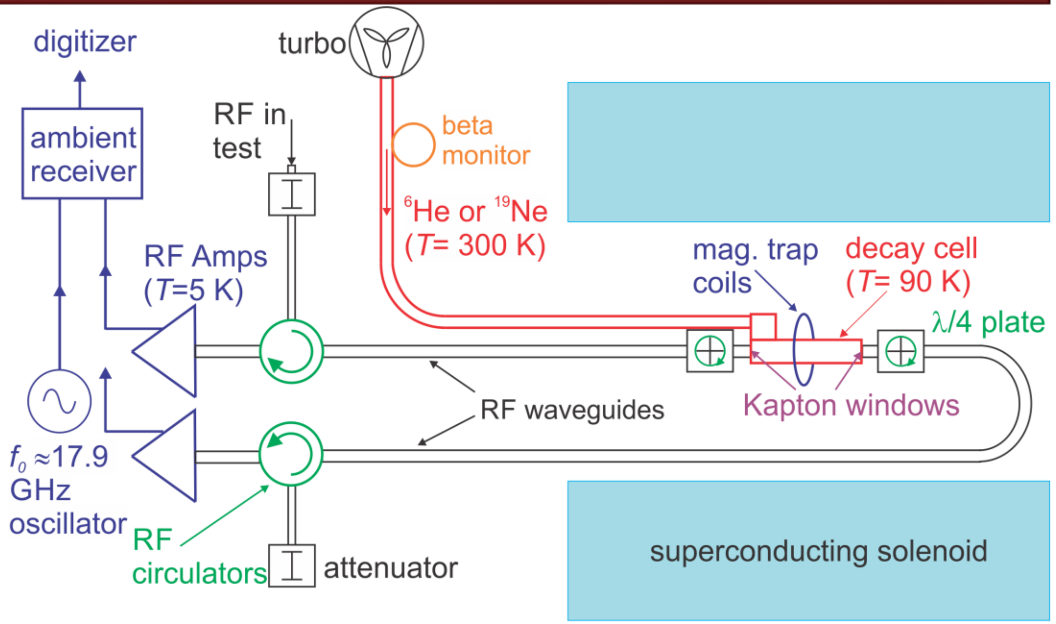


D. M. Asner, *et al.*, Phys. Rev. Lett. 114, 162501 (2015)

"Never measure anything but frequency!" Arthur Schawlow

6HE-CRES IN A NUTSHELL

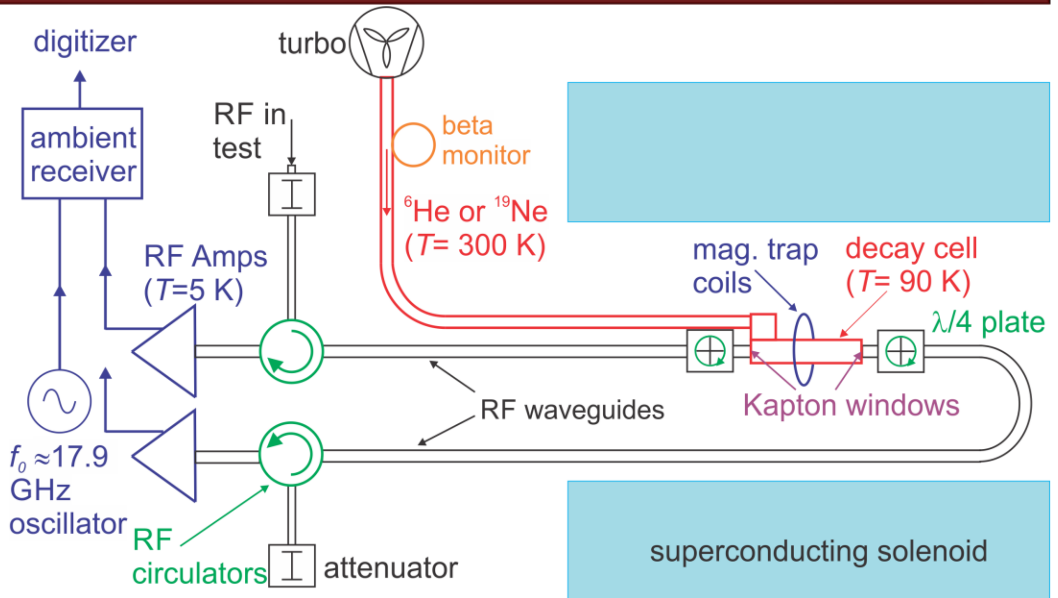
- Pumps gaseous ^{6}He and ^{19}Ne atoms into a decay cell/waveguide

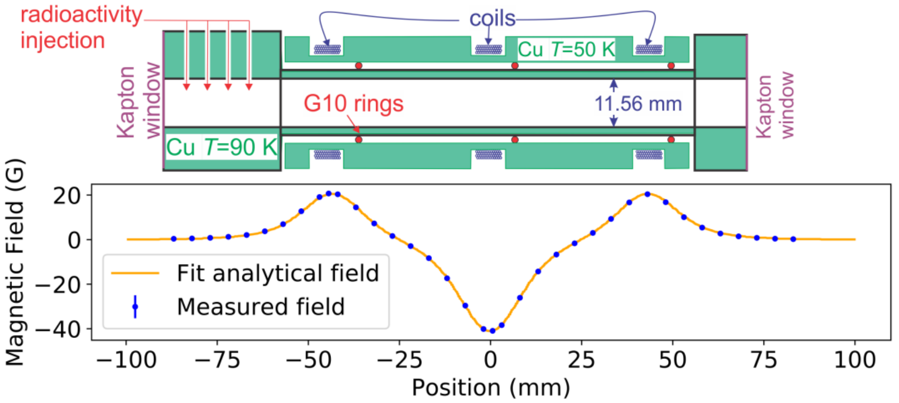


W. Byron *et al.*, arxiv:2209.02870 (2022)

6HE-CRES IN A NUTSHELL

- Pumps gaseous ^{6}He and ^{19}Ne atoms into a decay cell/waveguide
- Magnetic trap for axial confinement for betas

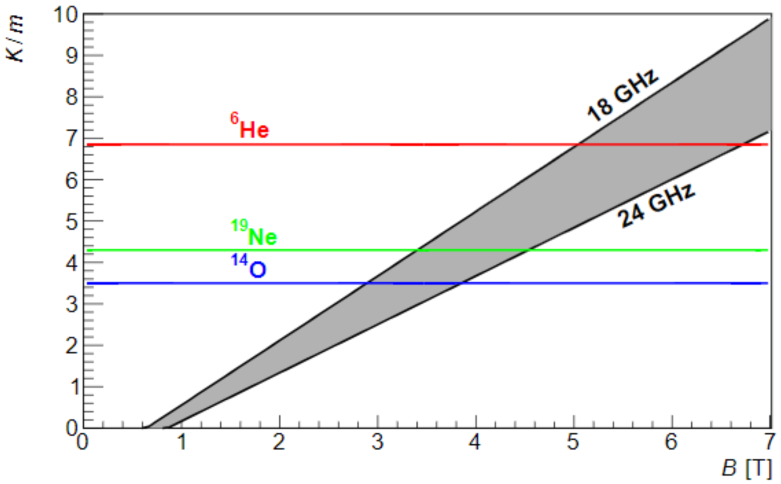


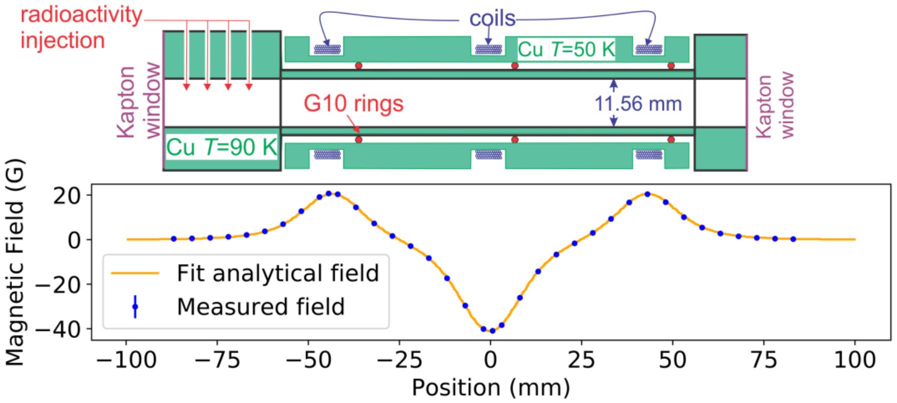


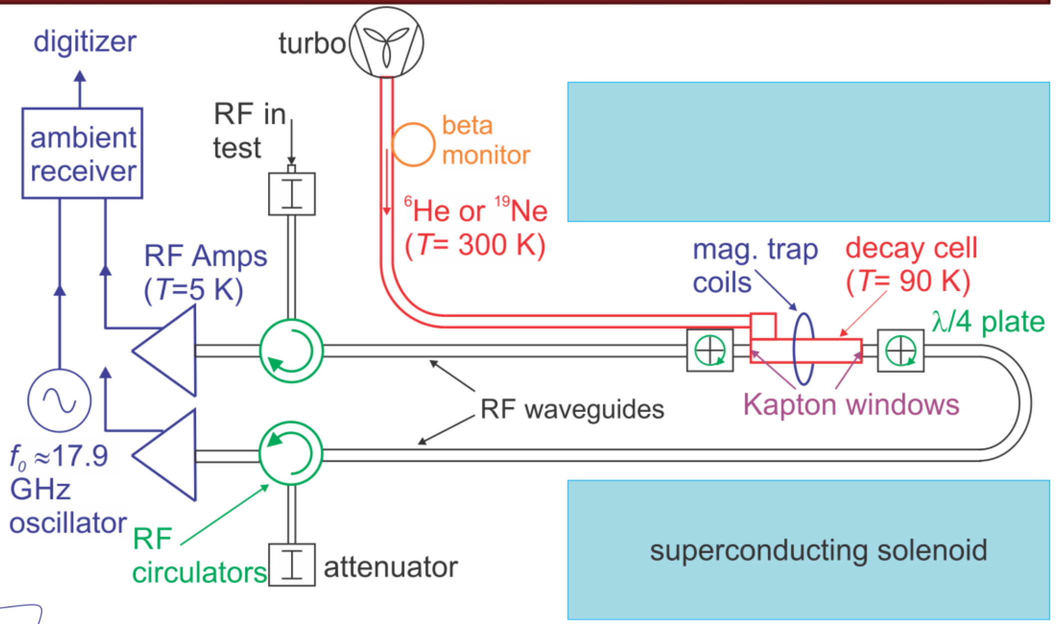
W. Byron *et al.*, arxiv:2209.02870 (2022)

6HE-CRES IN A NUTSHELL

- Pumps gaseous ^{6}He and ^{19}Ne atoms into a decay cell/waveguide
- Magnetic trap for axial confinement for betas
- Alter B-field to scan entire spectrum





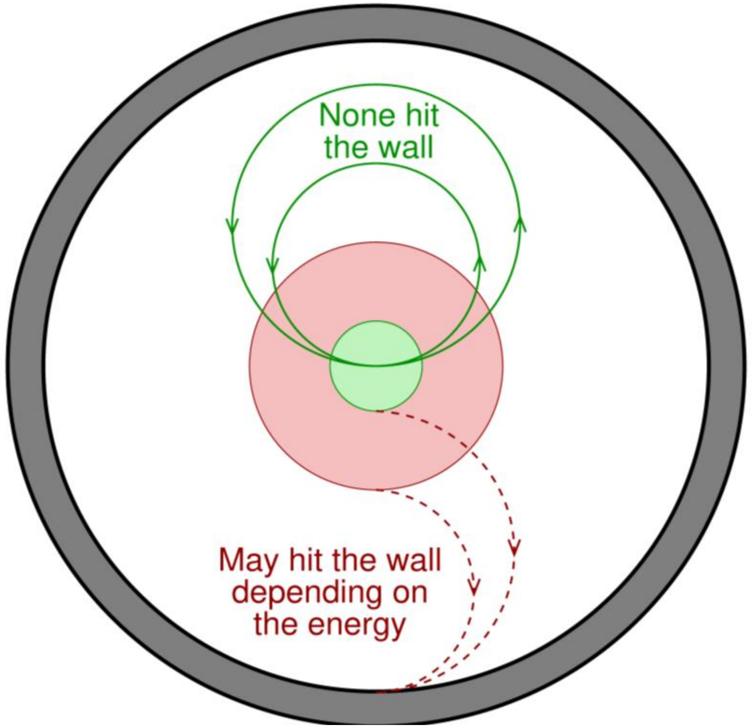


W. Byron *et al.*, arxiv:2209.02870 (2022)

WALL EFFECTS

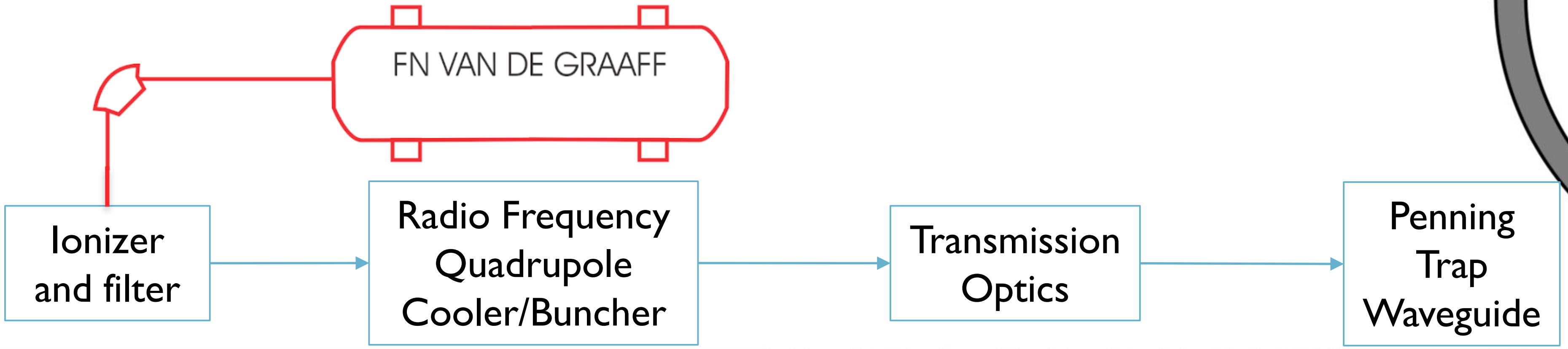
- Wall-bound betas leave insufficient tracks
  - Energy dependent spectrum shift
- Spectrum ratio cancellation (^{19}Ne and ^{6}He)

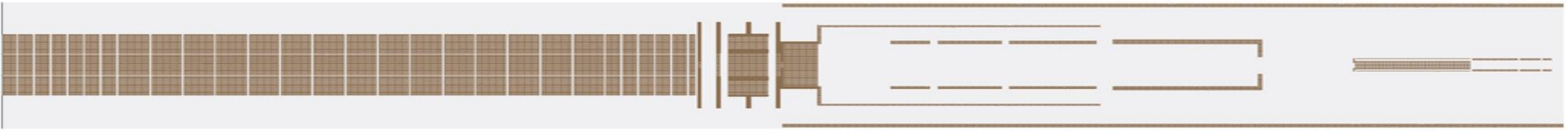
Largest and smallest electron orbits at 2 T



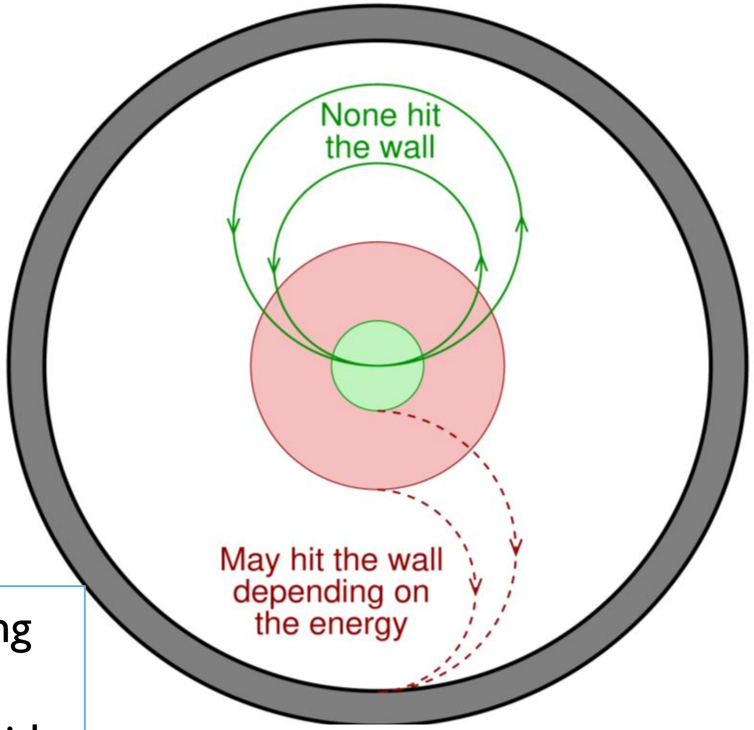
WALL EFFECTS

- Wall-bound betas leave insufficient tracks
  - Energy dependent spectrum shift
- Spectrum ratio cancellation $({}^{19}\text{Ne and } {}^{6}\text{He})$
- Radial confinement of ions with ion trap





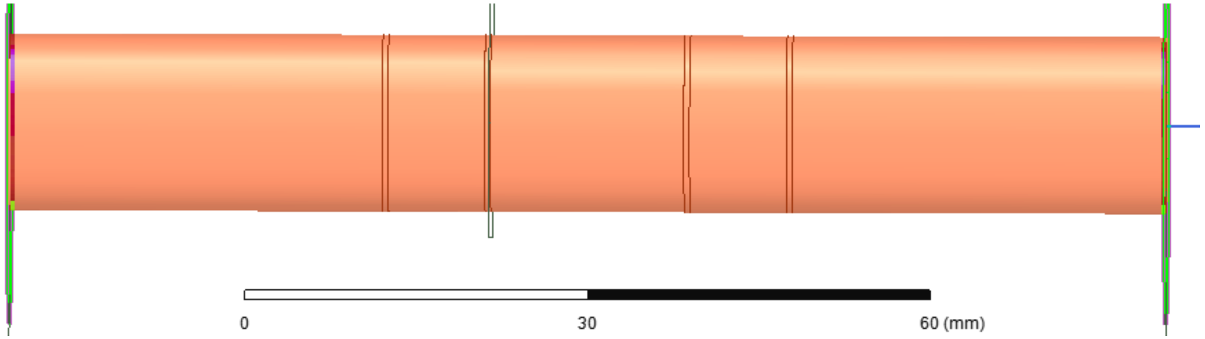
Largest and smallest electron orbits at 2 T



ION TRAP ADDITION: PENNING TRAP

Design Specifications

- Radius: $r = 5.78$ mm
- Trap Length: $l = 101.6$ mm



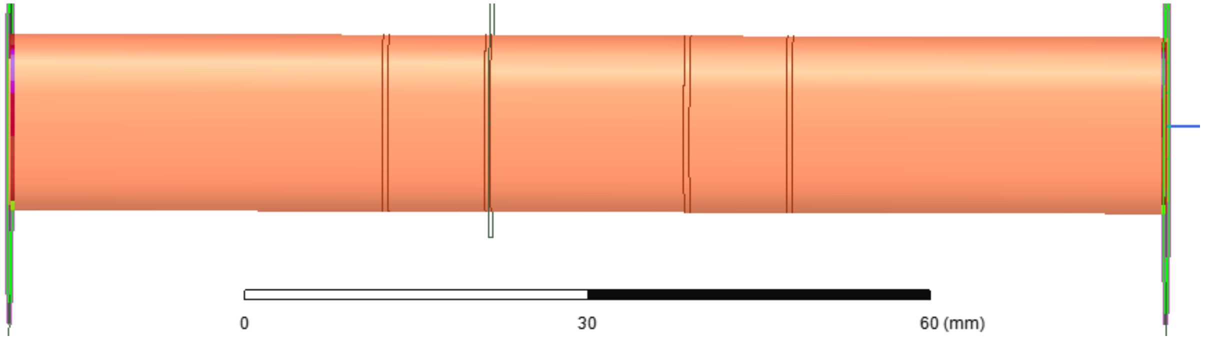
ION TRAP ADDITION: PENNING TRAP

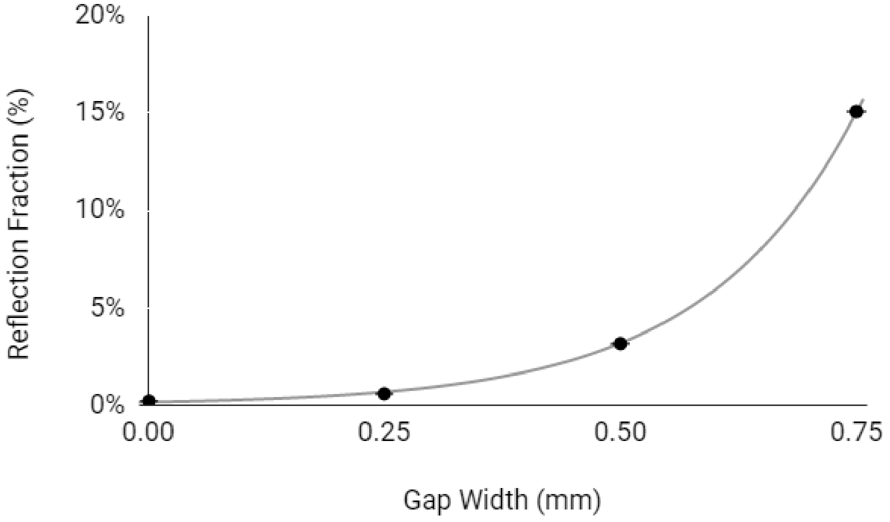
Design Specifications

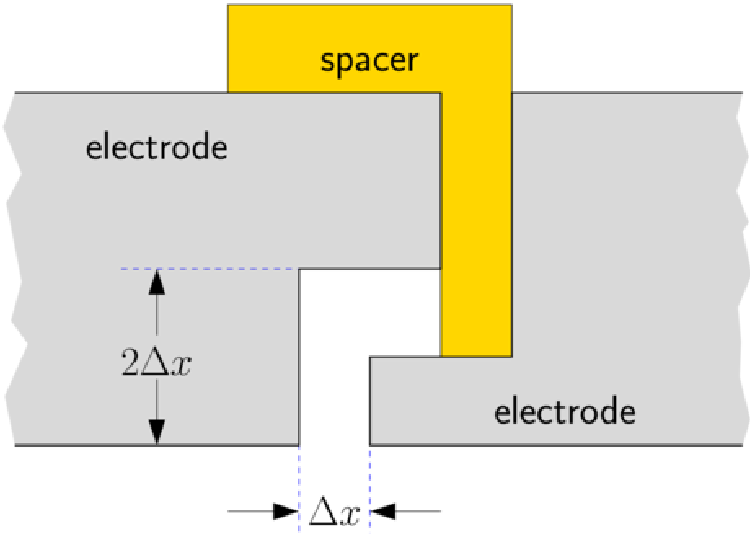
- Radius: $r = 5.78$ mm
- Trap Length: $l = 101.6$ mm

RF Considerations

- 4 electrode gaps of $\Delta x = 0.5$ mm
- Shielded insulator from RF cavity

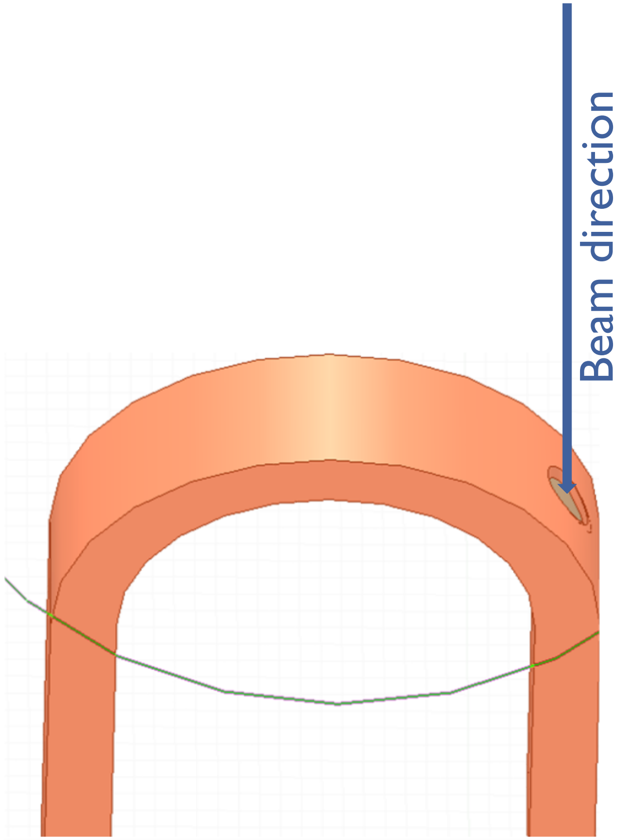






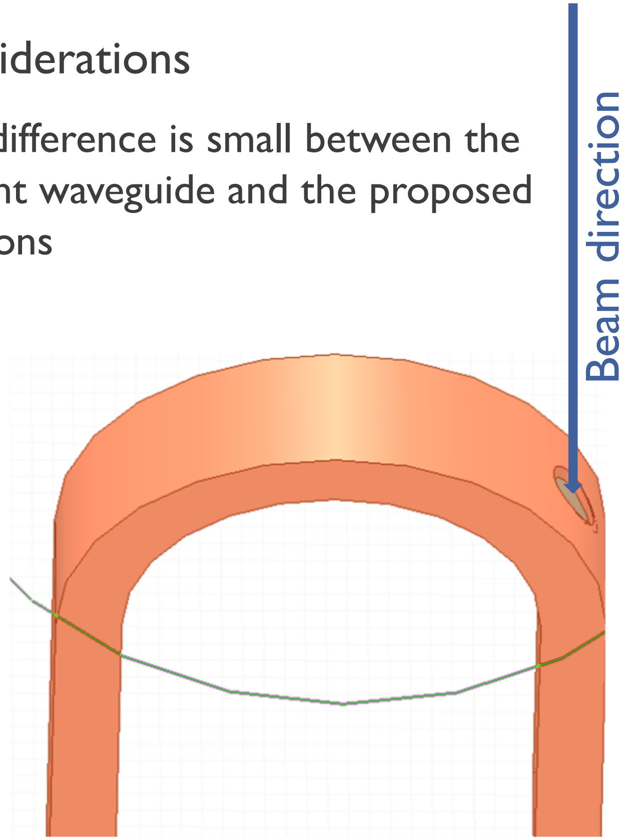
RF CONSIDERATIONS

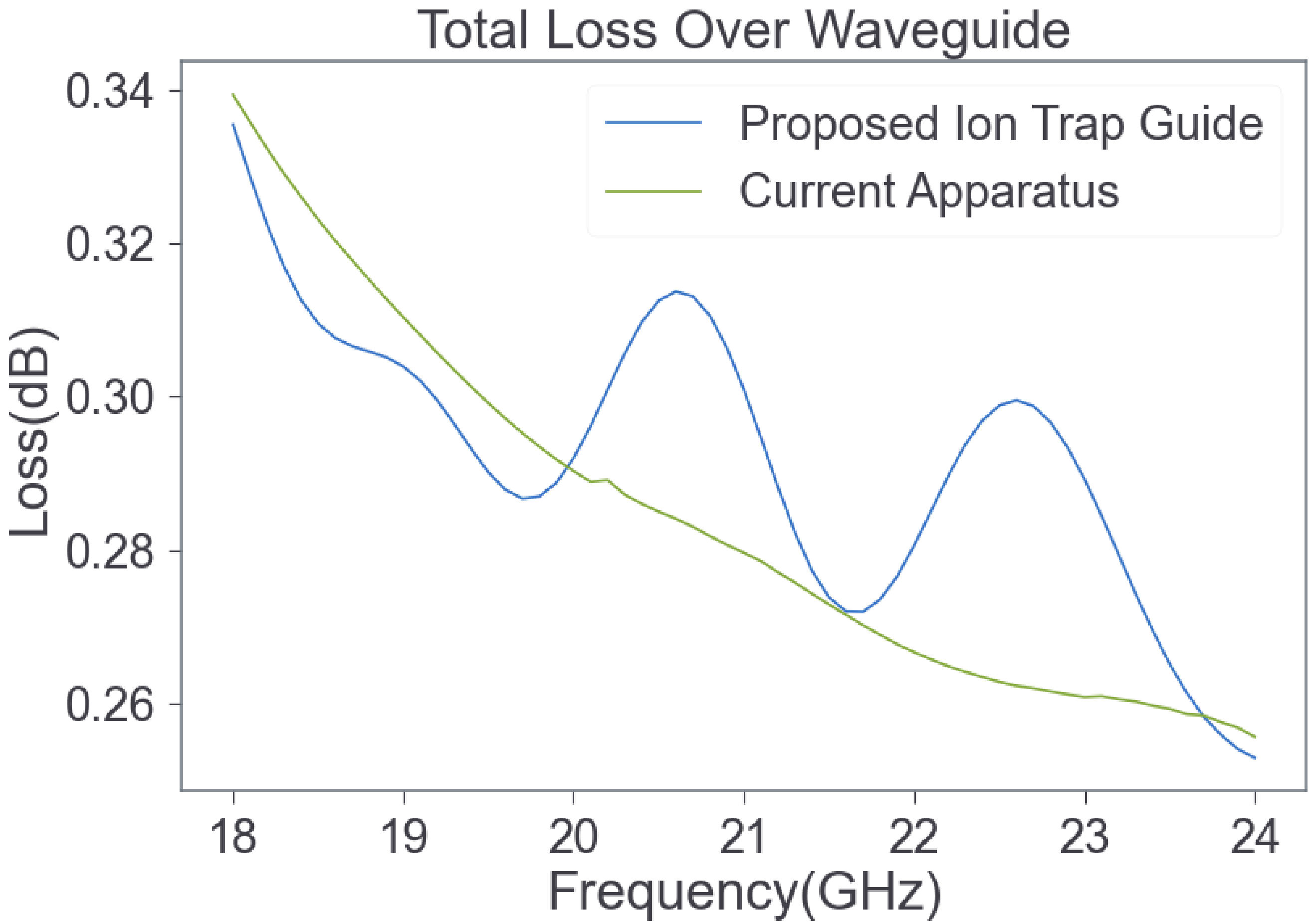
- Changes to waveguide
  - r = 2 mm hole added to the waveguide



RF CONSIDERATIONS

- Changes to waveguide
  - r = 2 mm hole added to the waveguide
- RF Considerations
  - Loss difference is small between the current waveguide and the proposed additions





ION TRAP ADDITION: RFQ

Operating Parameters

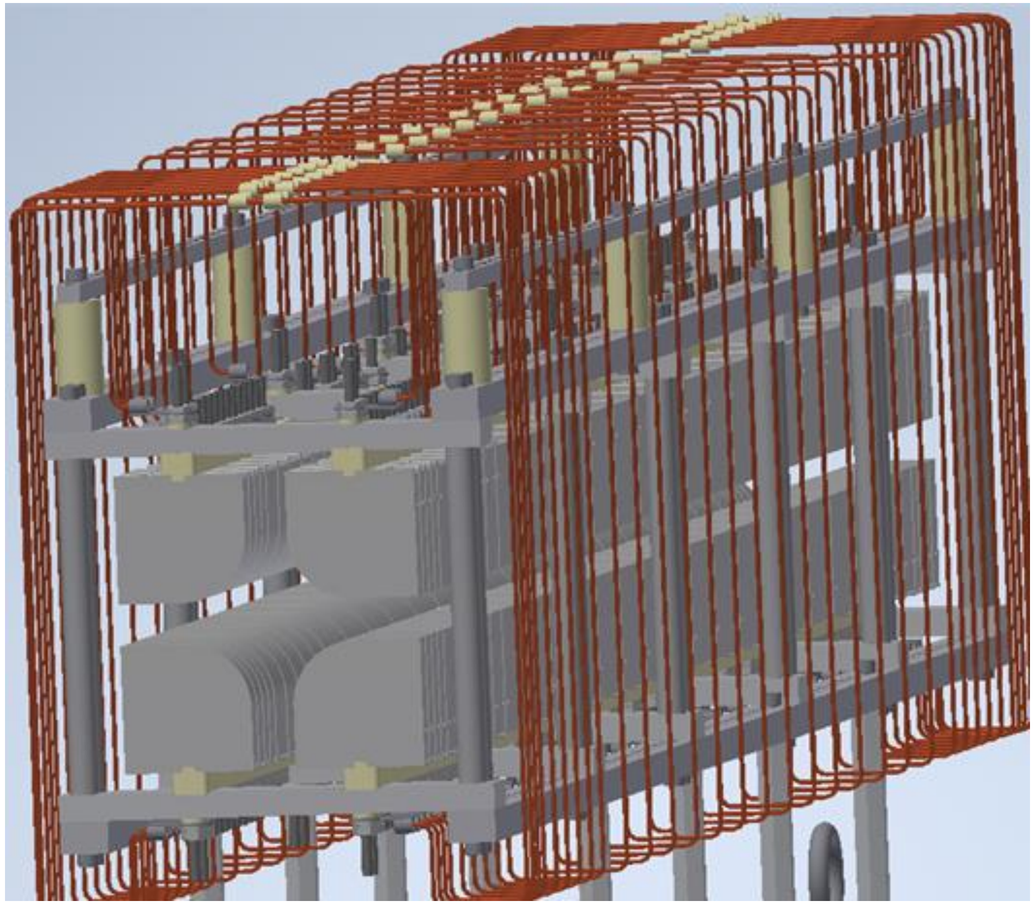
- Characteristic radius: r_0= 12 mm
- Operating frequencies: f = 1-2 MHz
- Peak-to-peak voltage: $V_{pp} = 400\,\mathrm{V}$

Resulting Bunch Characteristics

- Time spread: $\Delta t \sim 0.57\ \mu s$
- Energy spread: $\Delta E \sim 3.5$ eV
- Emittance: $\varepsilon_{rms} \sim 0.9\ \pi$ mm mrad @ 60 keV
- Transmission Rate (Within RFQ): 83%
- Estimated maximum capacity: $\mathbf{1.4 \cdot 10^4}$ **particles/bunch**

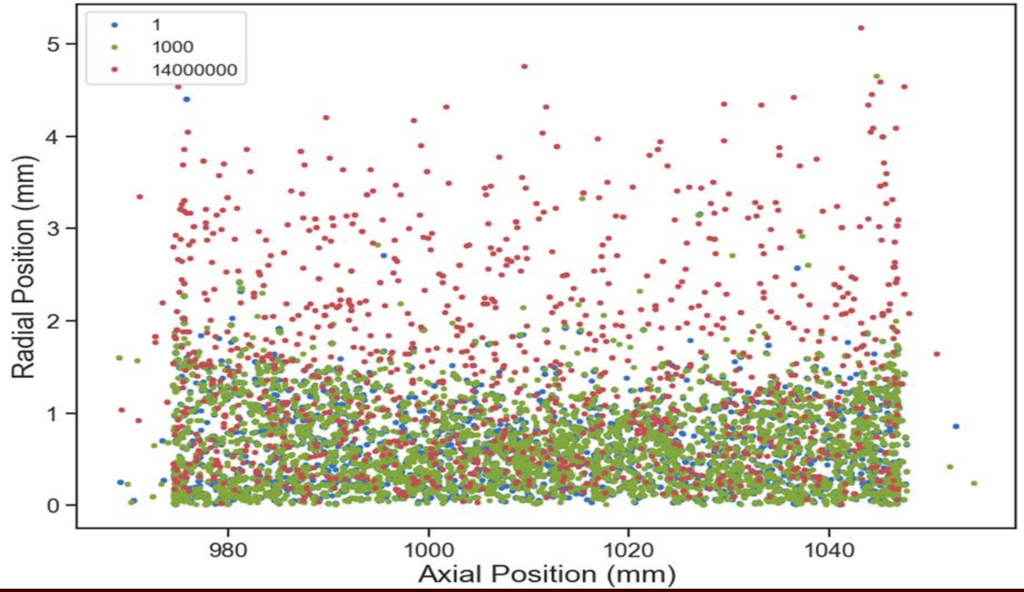
T. Brunner, *et al.*, Nuc. Inst. and Methods **676**, 32-43 (2012)

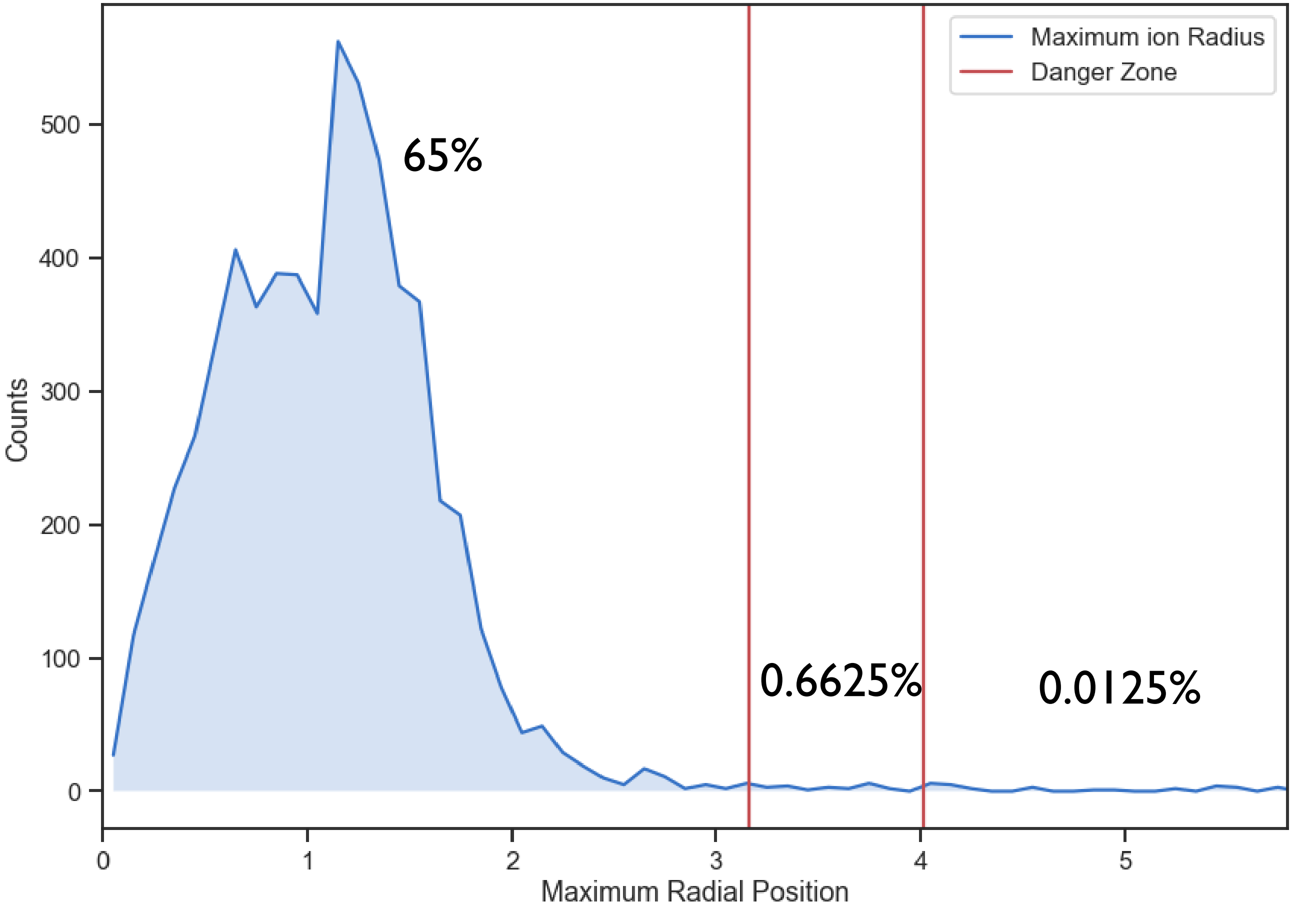
M. Mehlman, *et al.*, *Hyperfine Interact* **235**, 77–86 (2015)



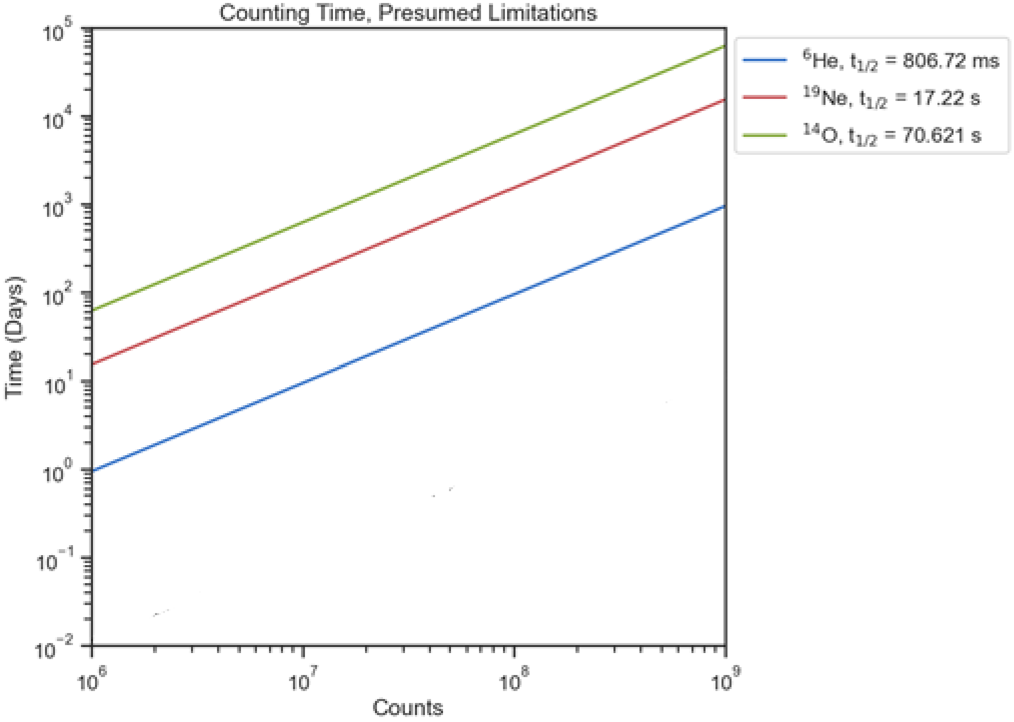
A LOOK INSIDE THE TRAP

- In the trap, we have ~65% of ions from the RFQ being captured and radially contained to avoid wall effects
- <1% of ions have a maximum radius within the "Danger Zone" that would contribute to wall effects



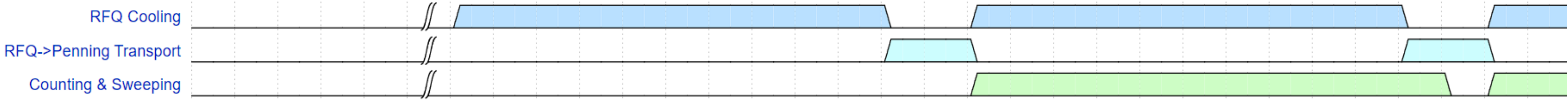


COUNT RATE

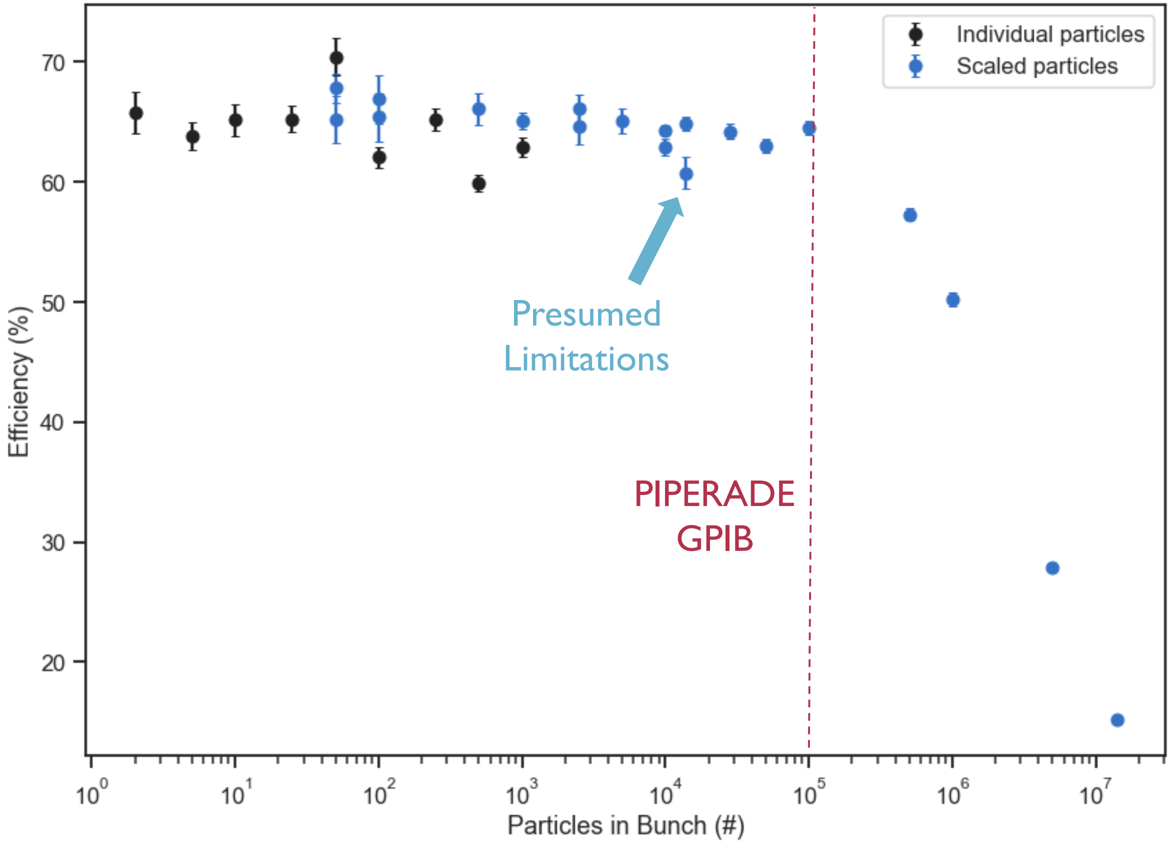


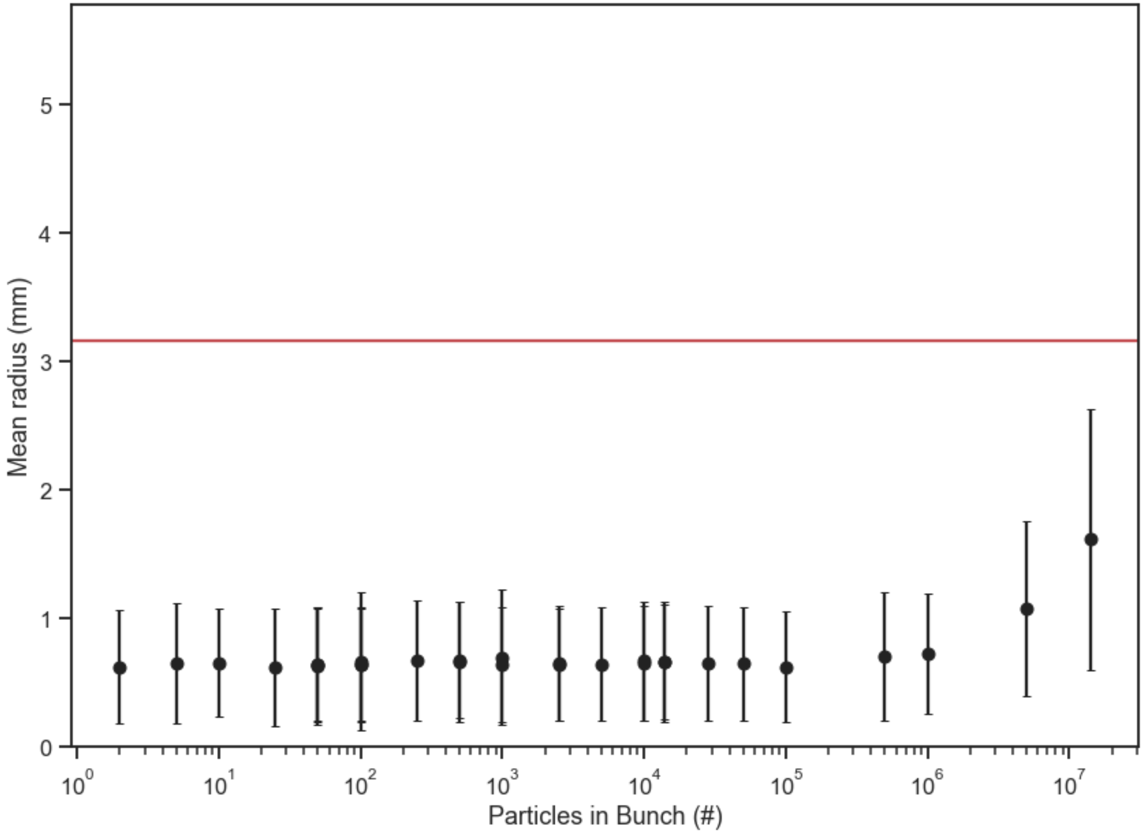
Cause of Loss	Effect
RFQ Efficiency (continuous mode)	83% efficiency
Beamline & Trap Injection	65% efficiency
Trapped Betas	3% efficiency
Events observed within frequency window	10% efficiency

- We won't be able to get to the expected count rate from the proposal given the presumed limitations of the RFQ.



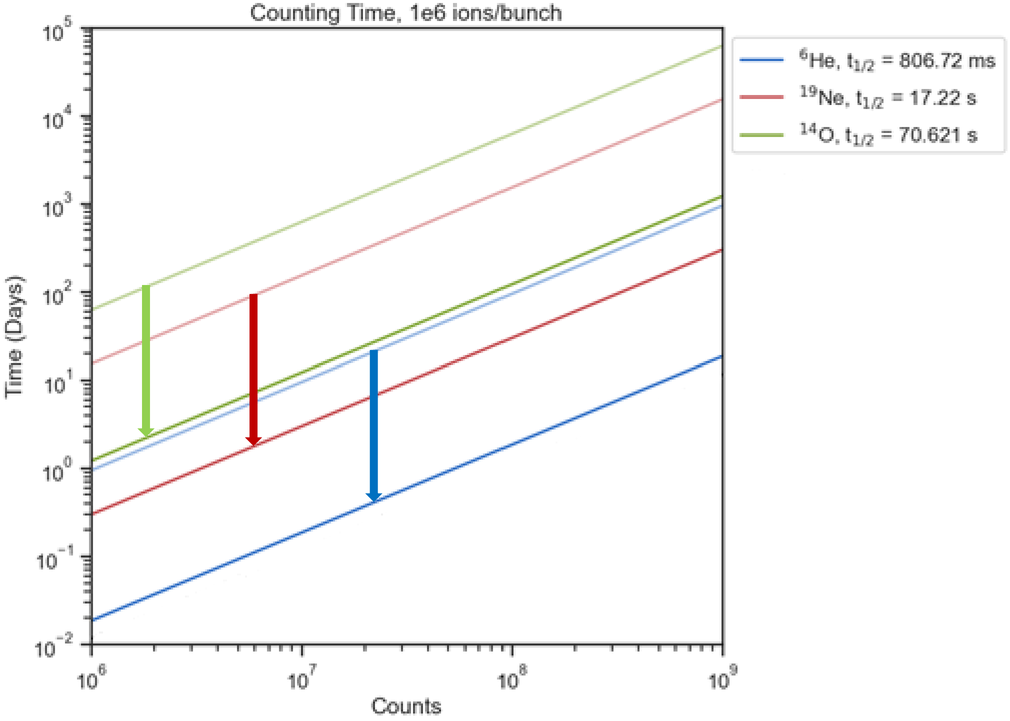
SPACE CHARGE EFFECTS





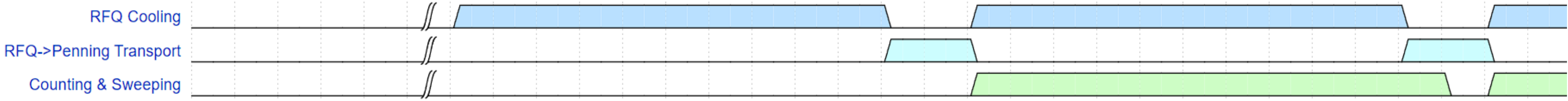
M. Gerbaux, et al.,hal-03815181 (2022)

COUNT RATE



Cause of Loss	Effect
RFQ Efficiency (continuous mode)	83% efficiency
Beamline & Trap Injection	65% efficiency
Trapped Betas	3% efficiency
Events observed within frequency window	10% efficiency

- We won't be able to get to the expected count rate from the proposal given the presumed limitations of the RFQ.



ION TRAP ADDITION: CONCLUSION

Wall effects

- ☑ Radial confinement of charged particles

RF considerations

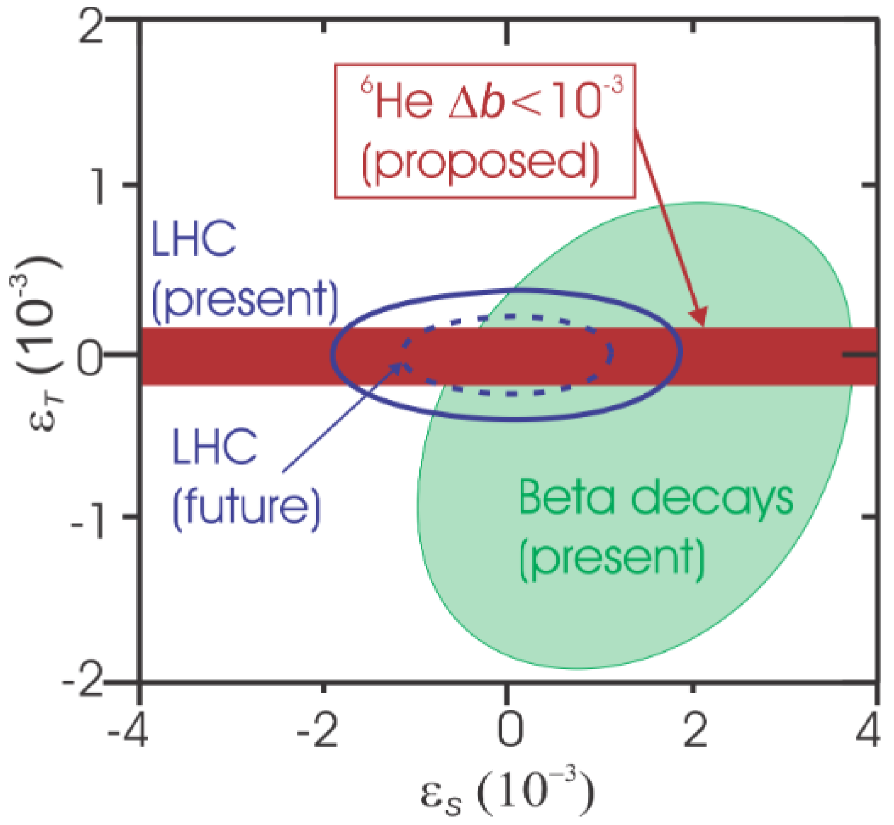
- ☑ Restricted ion trap size
- ☑ Injection hole and electrode gaps do not degrade signal

Trap injection

- ☑ RFQ designed for wide mass range

Count Rate

- ☐ Limitations of bunch size limit count rate, but simulations show that this may not be the case.



W. A. Byron, W. DeGraw, B. Dodson, M. Fertl, A. García, B. Graner, E. Hanes, H. Harrington, L. Hayen, X. Huyan, S. Hightower, M. E. Higgins, N. C. Hoppis, M. Kimsey-Lin, K. Knutsen, D. McClain, D. Melconian, P. Mueller, N. S. Oblath, R. Roehnelt, G. Savard, E. B. Smith, D. Stancil, D. W. Storm H. E. Swanson, R.J. Taylor, J. Tedeschi, B. A. VanDevender, F. Wietfeldt, and A. R. Young,

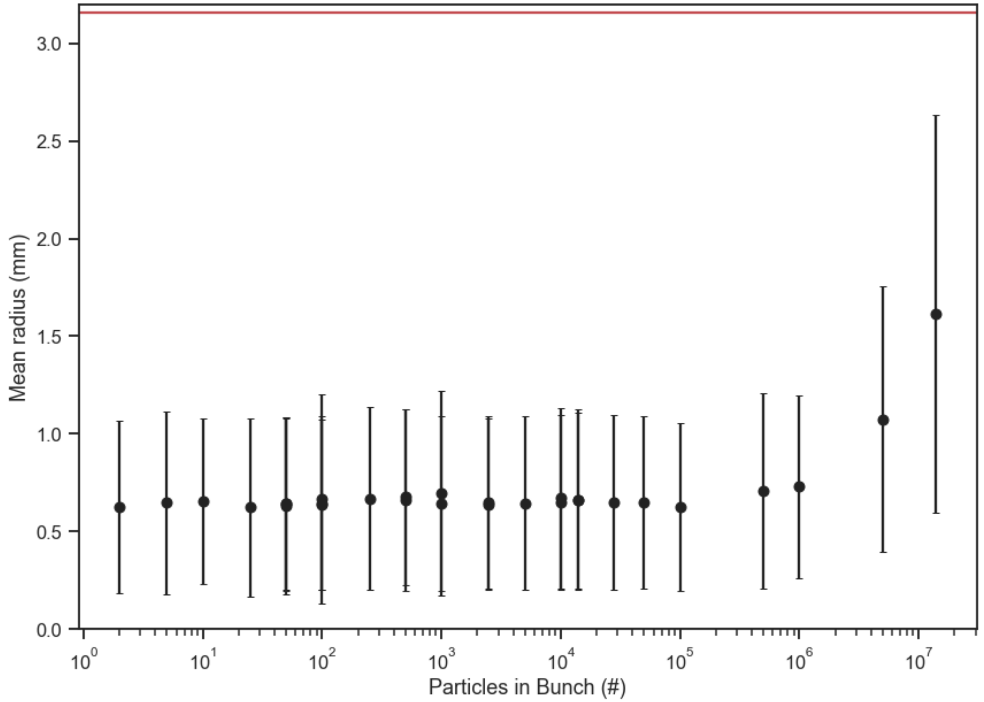
^{6}He-CRES

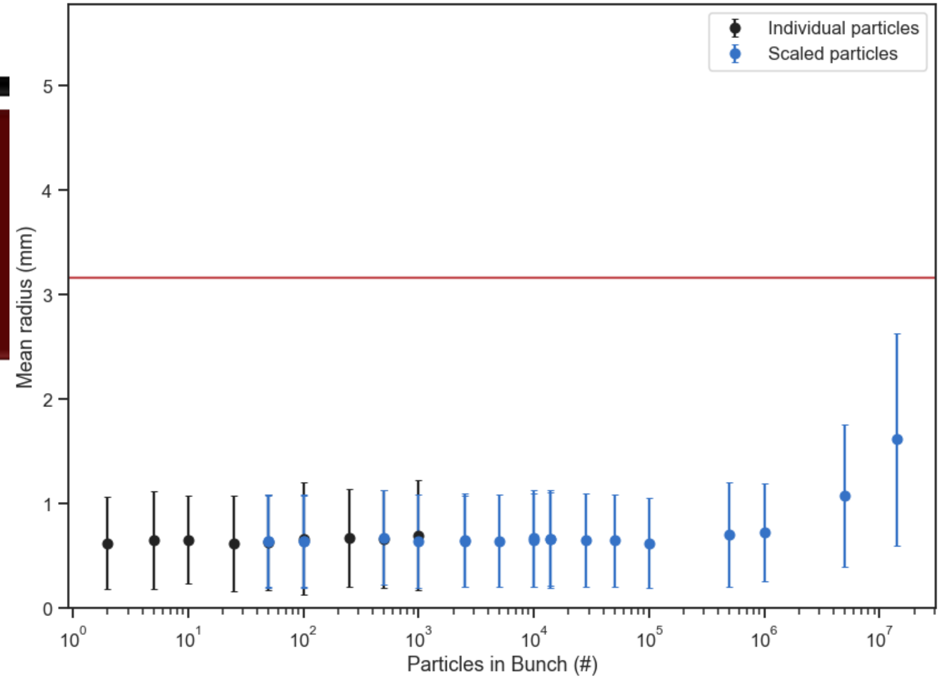
This work is supported by U.S. Department of Energy and National Nuclear Security Administration Grant No. DEFG02-93ER40773 and DE-NA0003841

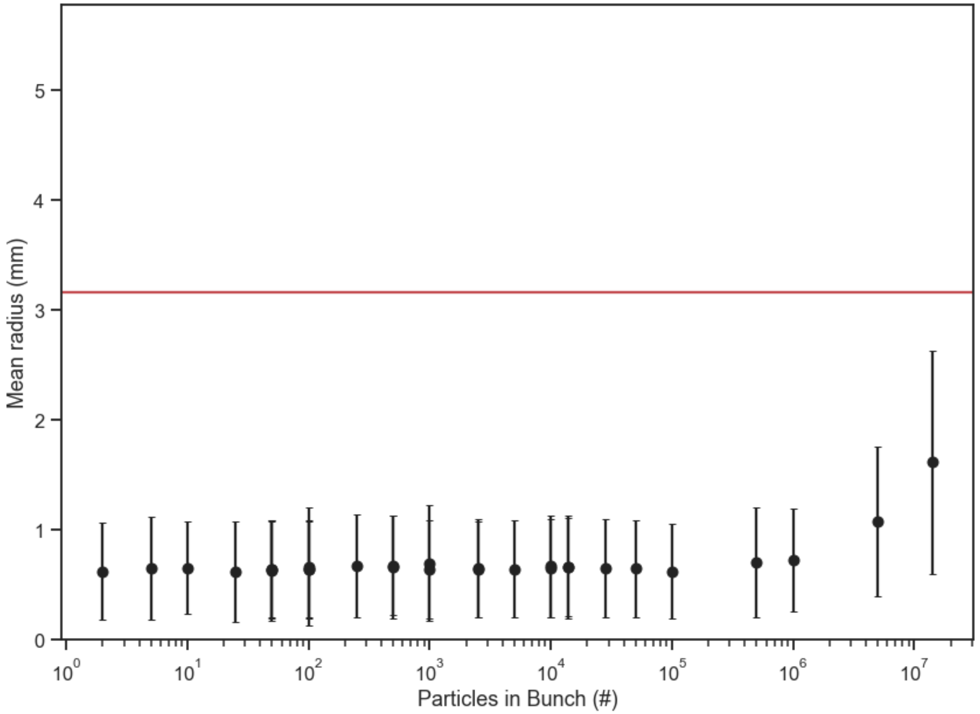
THANK YOU

Questions?

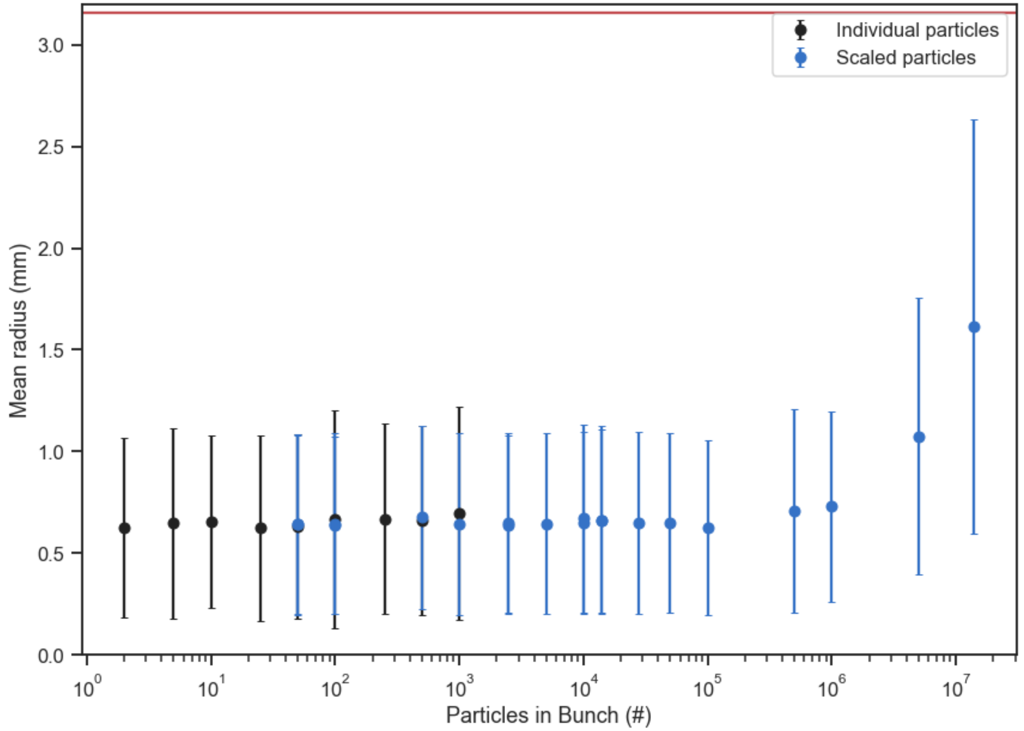
BACKUPS

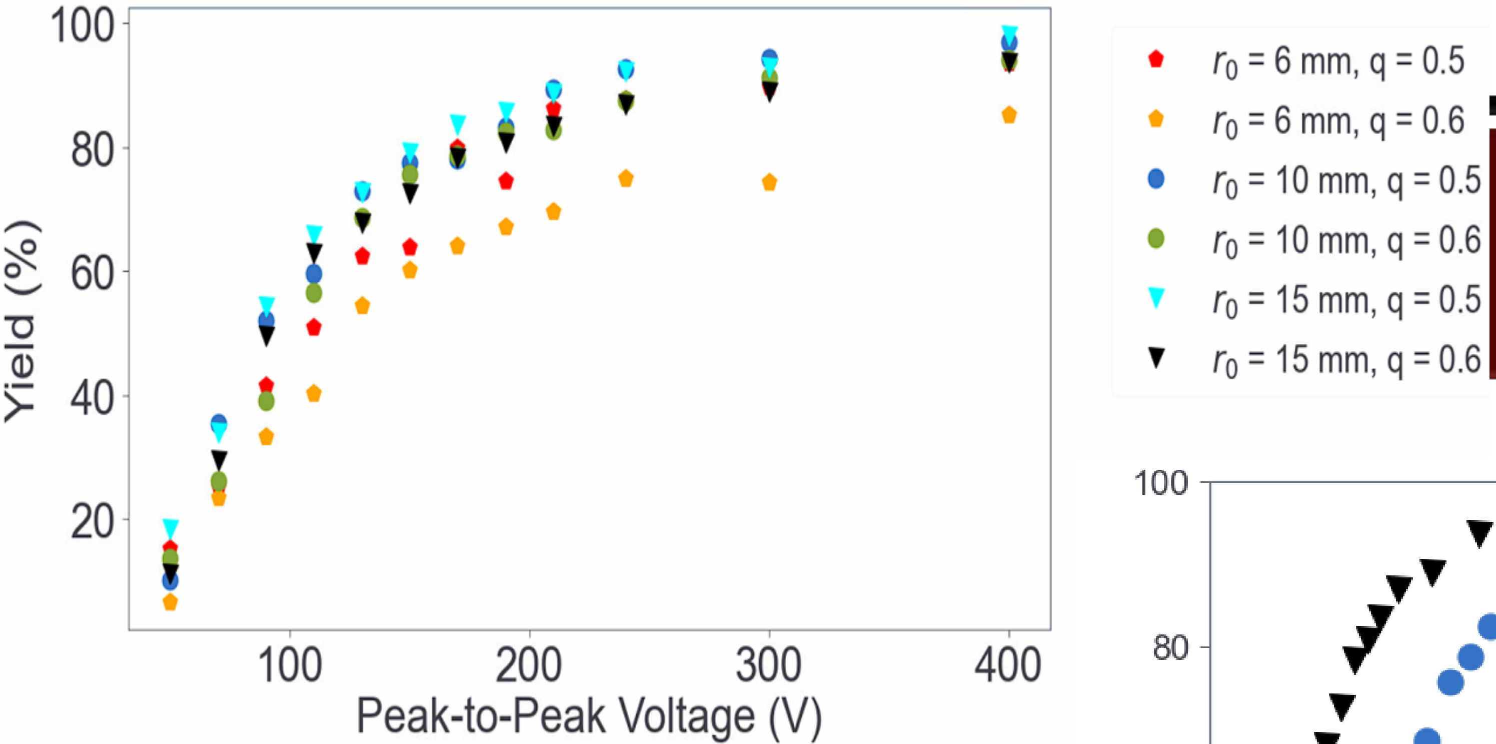

Mean radius (mm)
Particles in Bunch (#)

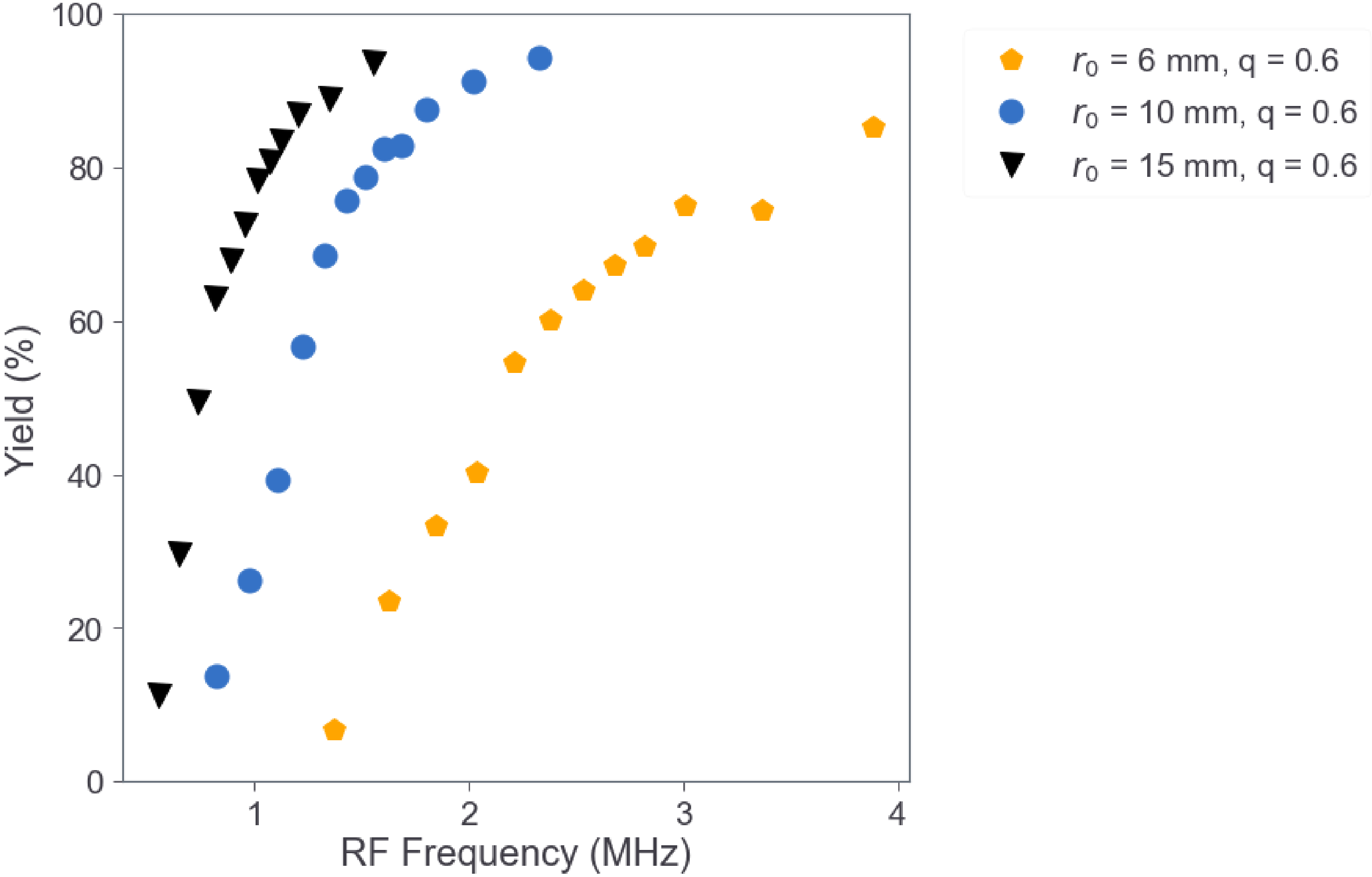

Individual particles
Scaled particles
Mean radius (mm)
Particles in Bunch (#)


Mean radius (mm)
Particles in Bunch (#)

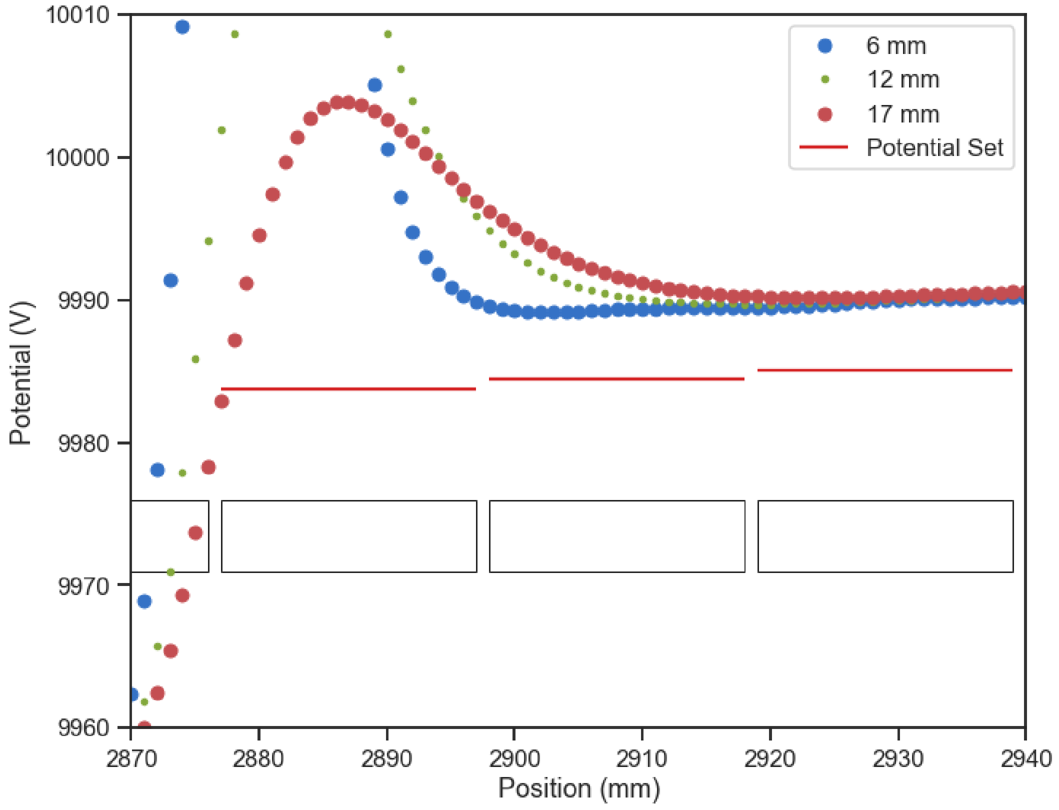
CCLAIN


Individual particles
Scaled particles
Mean radius (mm)
Particles in Bunch (#)

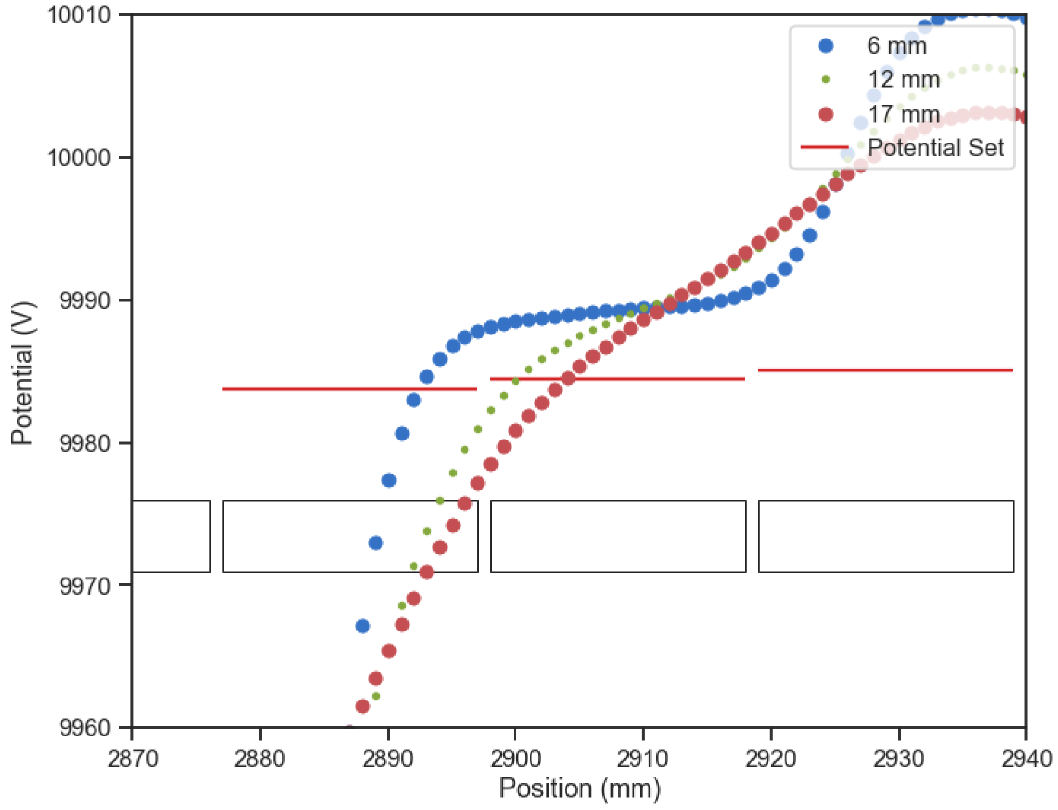

Yield (%)
Peak-to-Peak Voltage (V)
r_0 = 6 mm, q = 0.5
r_0 = 6 mm, q = 0.6
r_0 = 10 mm, q = 0.5
r_0 = 10 mm, q = 0.6
r_0 = 15 mm, q = 0.5
r_0 = 15 mm, q = 0.6

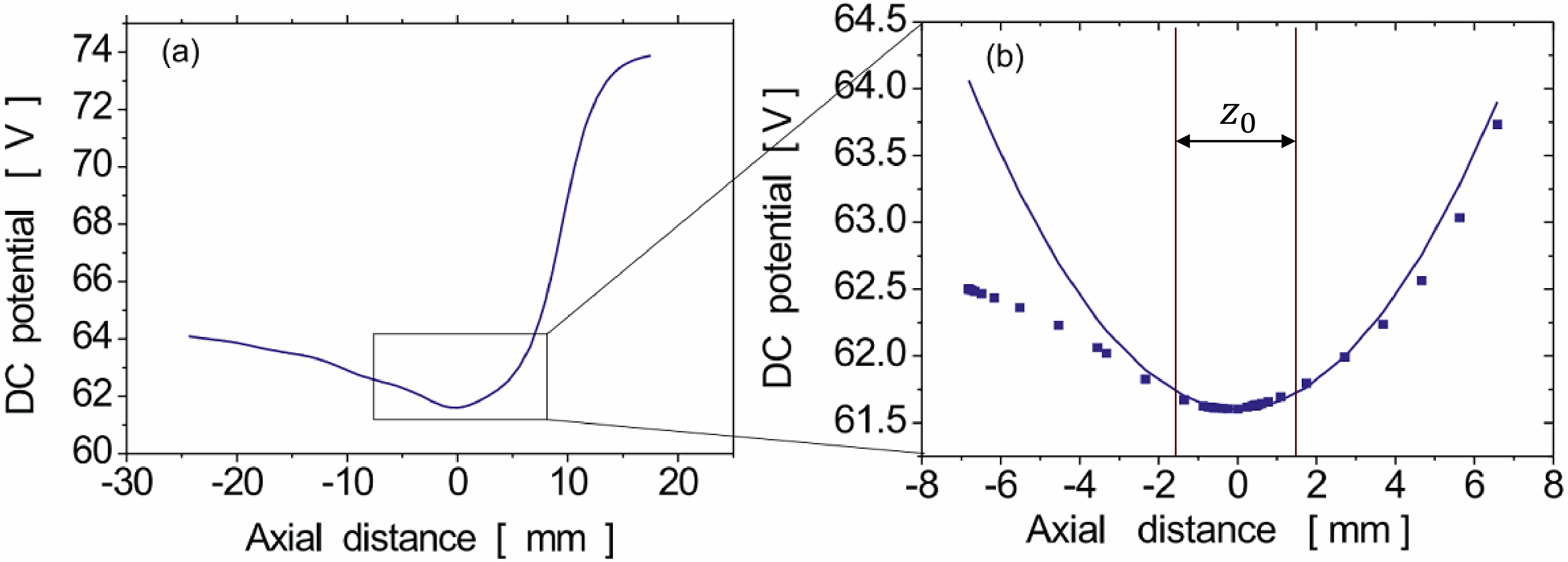

Yield (%)
RF Frequency (MHz)
r_0 = 6 mm, q = 0.6
r_0 = 10 mm, q = 0.6
r_0 = 15 mm, q = 0.6

Trap Closed



Trap Open





$$\omega_{\text{sec}} = \frac{q\omega_{\text{RF}}}{2\sqrt{2}}.$$

$$\frac{1}{2}kT = \frac{1}{2}m\omega_{\text{sec}}^2 u_{\text{sec}}^2,$$

$$u = u_{\text{sec}} - \frac{qu_{\text{sec}}}{2}\cos(\omega_{\text{RF}}t).$$

$$n = \frac{\epsilon_0}{e} \cdot q\frac{V_{\text{RF}}}{r_0^2}.$$

$$N_{max} = \pi u_{\text{total}}^2 \cdot n \cdot z_0$$

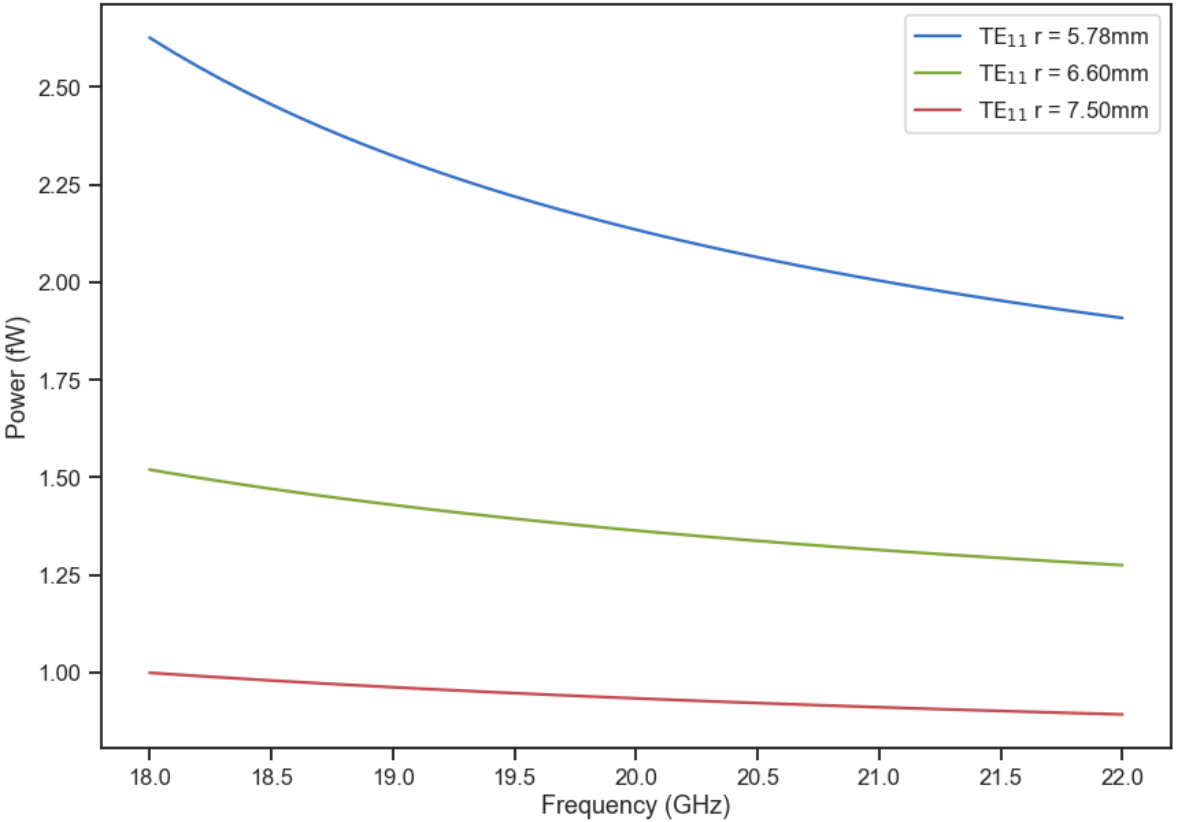
- Rubiales, D. R. (2003) *A radiofrequency quadrupole buncher for accumulation and cooling of heavy radionuclides at SHIPTRAP and high precision mass measurements on unstable krypton isotopes at ISOLTRAP*

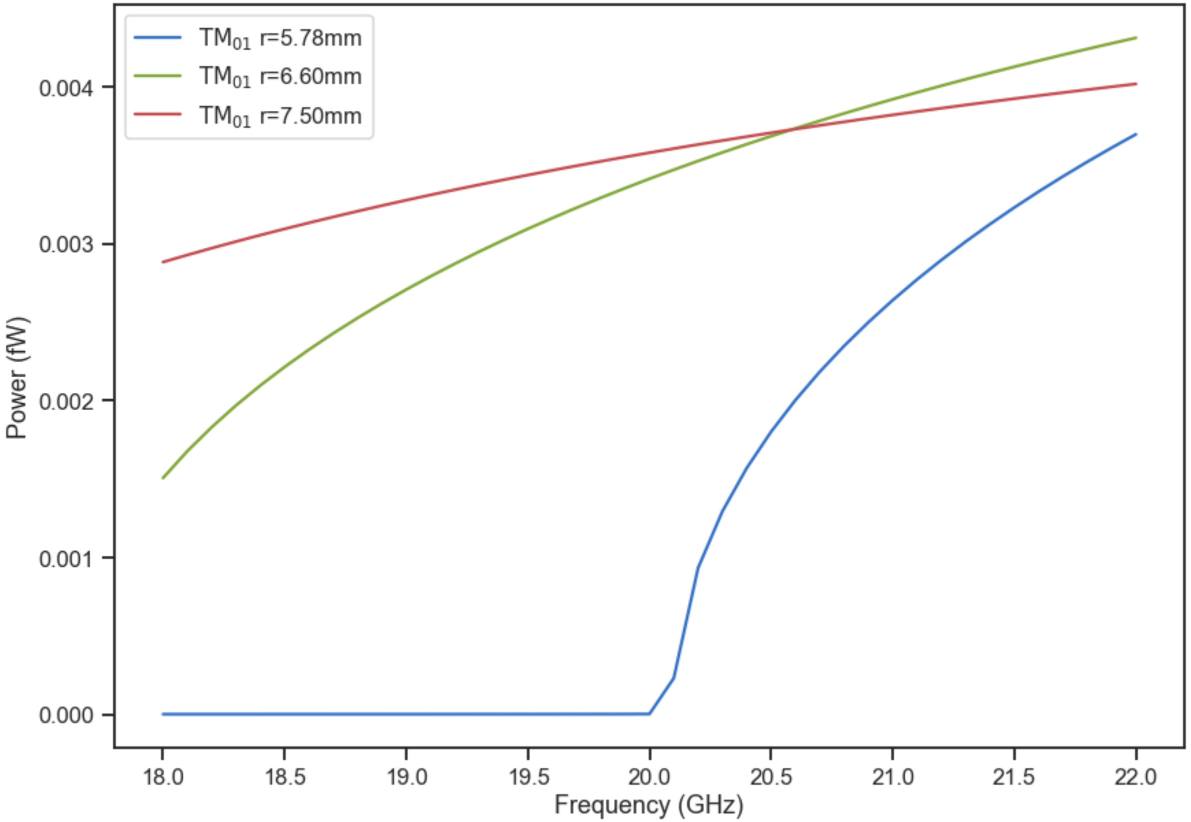
$$P_{TE_{11}} = \frac{Z_{11} e^2 v_0^2}{8\pi\alpha}\left(J_1'^2(k_c\rho_c) + \frac{1}{k_c^2\rho_c^2} J_1^2(k_c\rho_c)\right)$$

$$P_{TM_{01}} = \frac{Z_{01} e^2 v_0^2}{16\pi^2\beta} * J_0'^2(k_c\rho)$$

$$v_0 = \rho_c \Omega_c$$

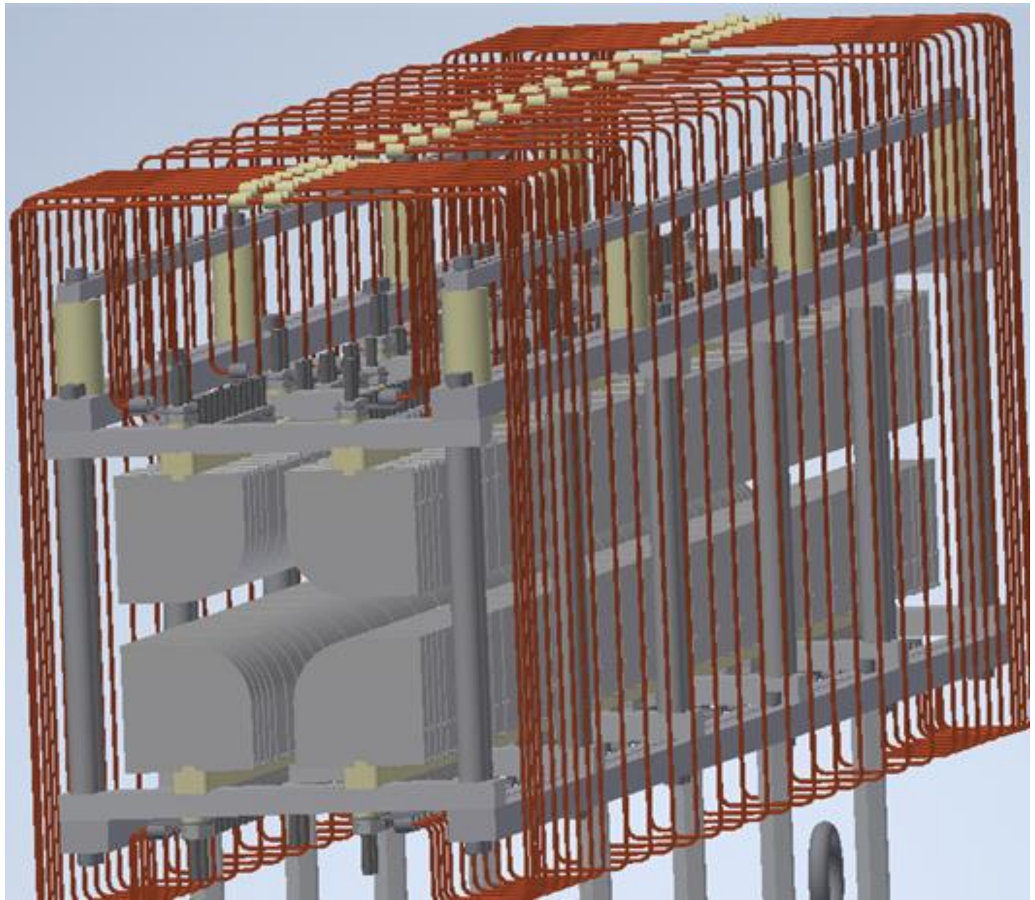
$$\alpha = 0.108858 R^2$$





GOLIATH

Gas **O**perated **L**ight-**I**on **A**tomic **T**rap for ^{6}He-CRES



^{6}He-CRES

NC STATE UNIVERSITY

L. Hayen,
D.Stancil,
R.J.Taylor,
A.Young

TEXAS A&M UNIVERSITY

D. McClain,
D. Melconian

UNIVERSITY OF WASHINGTON

W. Byron,
W. Degraw,
A. Garcia,
B. Graner,
H. Harrington,
R.G.H. Roberston,
G. Rybka,
D.W. Storm,
H.E. Swanson

Pacific Northwest NATIONAL LABORATORY

X. Huyan,
N. Oblath,
B.A.VanDevender

Argonne NATIONAL LABORATORY

P. Mueller,
G. Savard

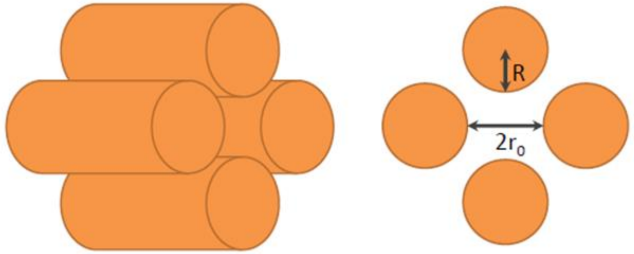
Tulane University

F. Weitfeldt

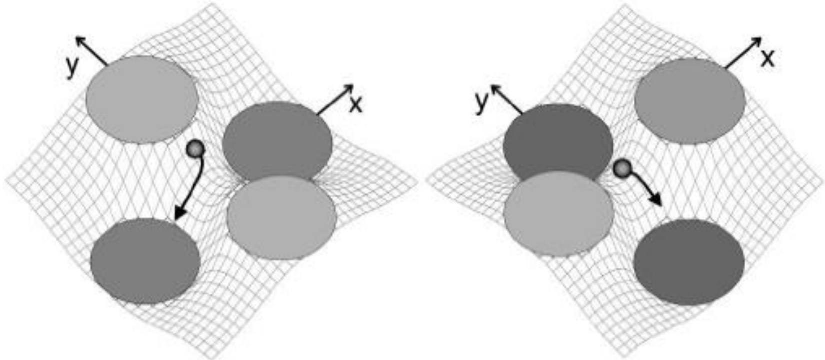
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

M. Fertl

This work is supported by U.S. Department of Energy and National Nuclear Security Administration Grant No. DEFG02-93ER40773 and DE-NA0003841



Radio frequency quadrupole trap (RFQ)



The Mathieu stability parameter q must be constrained between 0.4 < q < 0.7 from for the highest probability of retaining an ion of mass M

$$q = \frac{eV_{pp}}{\Omega^2 M r_0^2}$$

With this we constrain our operating voltage (V_{pp}) and frequency (Ω) to the characteristic distance (r_0) for a given mass.

With ions trapped in the RFQ, we use a buffer gas to cool the ions. Once the ions have sufficiently cooled, we release them from the RFQ as a singular bunch that is able to be captured by the Penning trap for measurement