ION TRAPPING FOR CRES EVENTS: A GOLIATH UPGRADE TO THE HE6-CRES EXPERIMENT

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^{6}He-CRES

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

NNSA
National Nuclear Security Administration

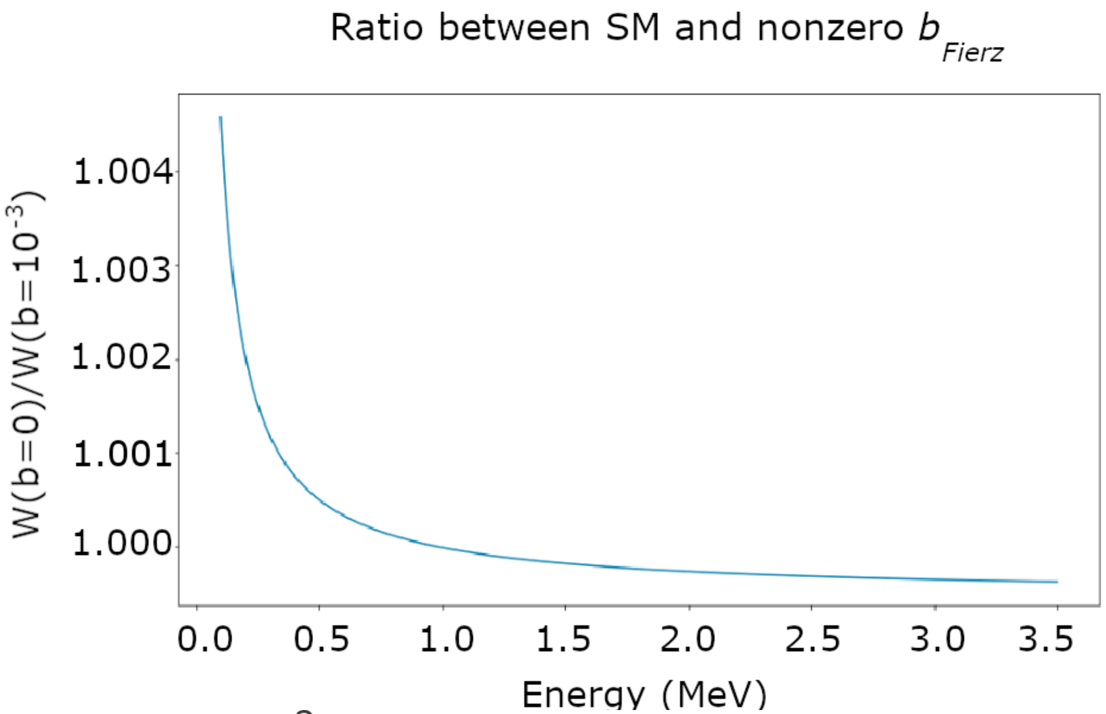
PHYSICAL MOTIVATION

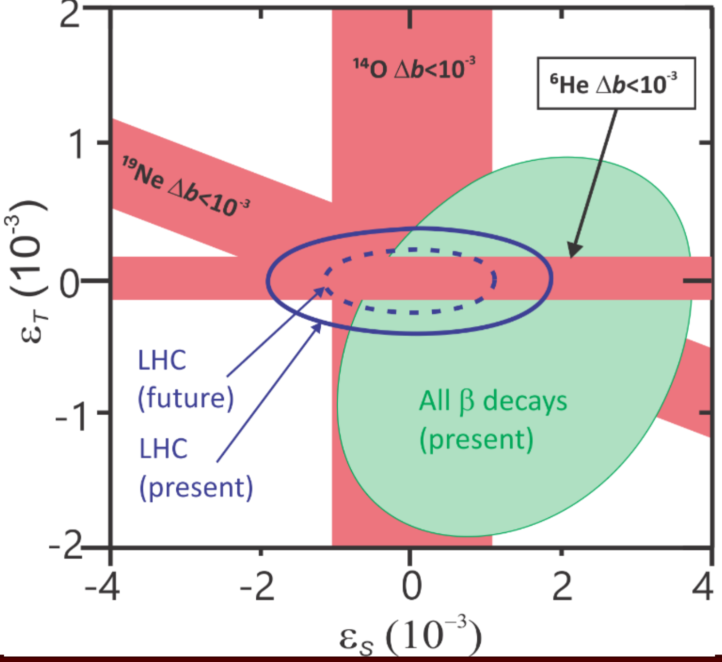
- Probe chirality-flipping couplings through the Fierz interference term

$$b \approx \pm \frac{2\sqrt{1-\alpha^2 Z^2}}{1+|\tilde{\rho}|^2} Re\left(\frac{g_S \epsilon_S}{g_V(1+\epsilon_L+\epsilon_R)} - 4|\tilde{\rho}|^2 \frac{g_T \epsilon_T}{g_A(1+\epsilon_L-\epsilon_R)}\right)$$

- Where we can find b in the beta decay equation as the only effect in the beta spectrum shape

$$W(E_e)dE_e = \frac{F(\pm Z, E_e)}{2\pi^3} \mathrm{p_e E_e (E_0 - E_e)^2 dE_e} \xi \left(1 + b\frac{m_e}{E_e}\right)$$

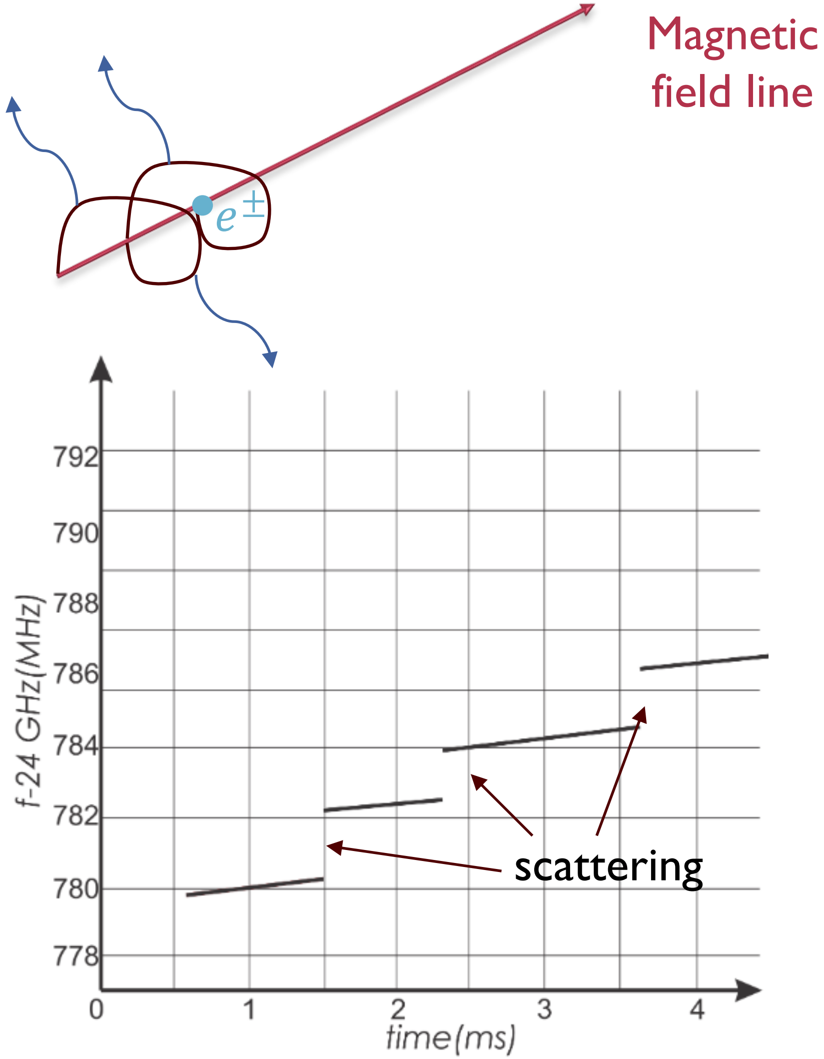




CYCLOTRON RADIATION EMISSION SPECTROSCOPY (CRES)

"Never measure anything but frequency!" - Arthur Schawlow

- Developed by the Project8 collaboration
- Measures the frequency of radiation from betas in a magnetic field



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

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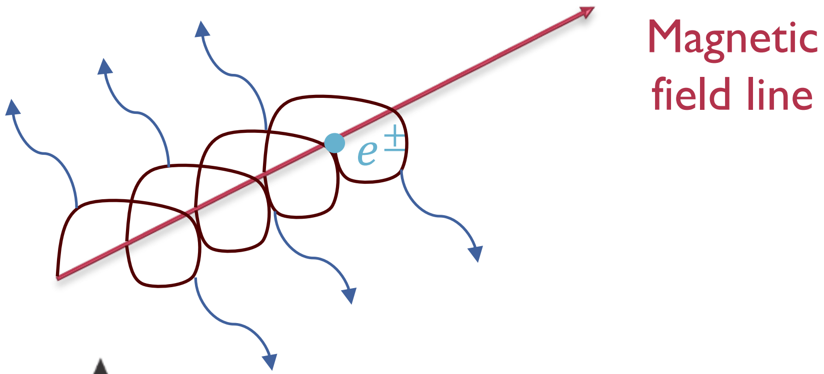
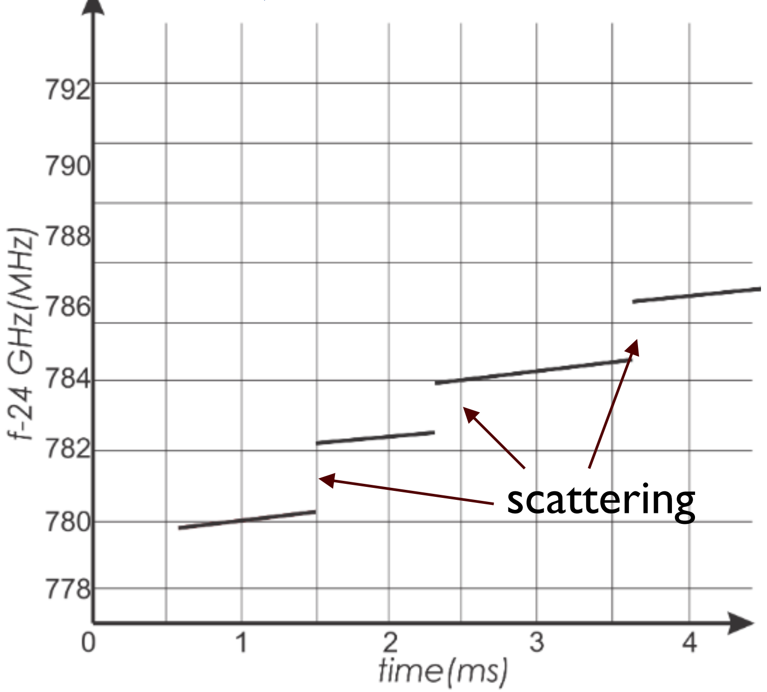


- Developed by the Project8 collaboration
- Measures the frequency of radiation from betas in a magnetic field
- Linear tracks form as the beta loses energy to the emissions

$$f_c = \frac{qB}{2\pi\left(m_e + \frac{E_e}{c^2}\right)}$$



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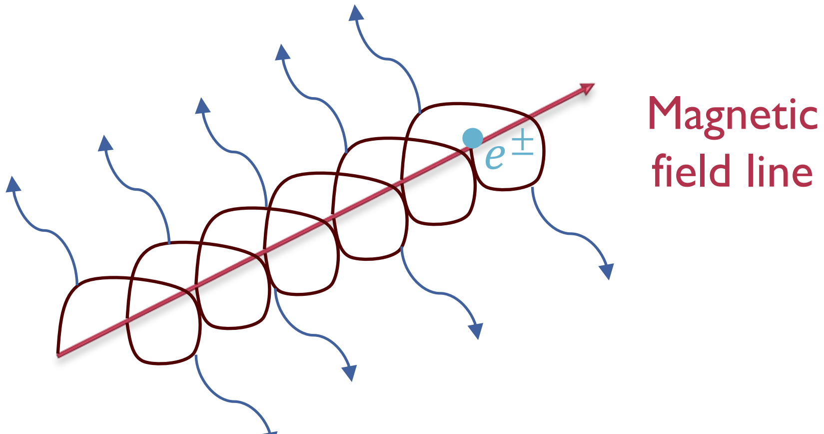

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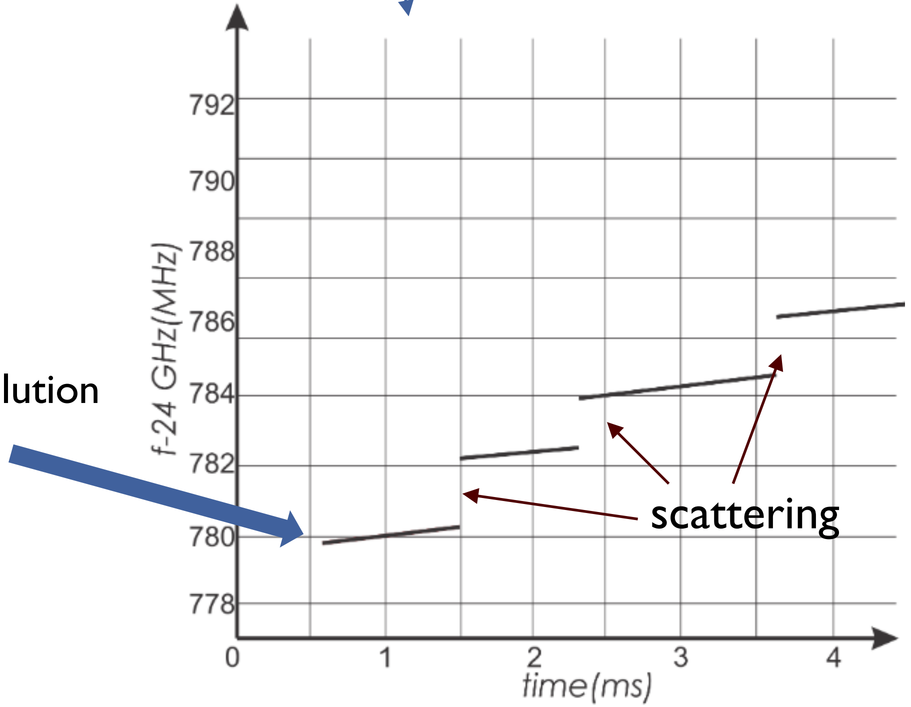
- Measures the frequency of radiation from betas in a magnetic field
- Linear tracks form as the beta loses energy to the emissions

$$f_c = \frac{qB}{2\pi\left(m_e + \frac{E_e}{c^2}\right)}$$

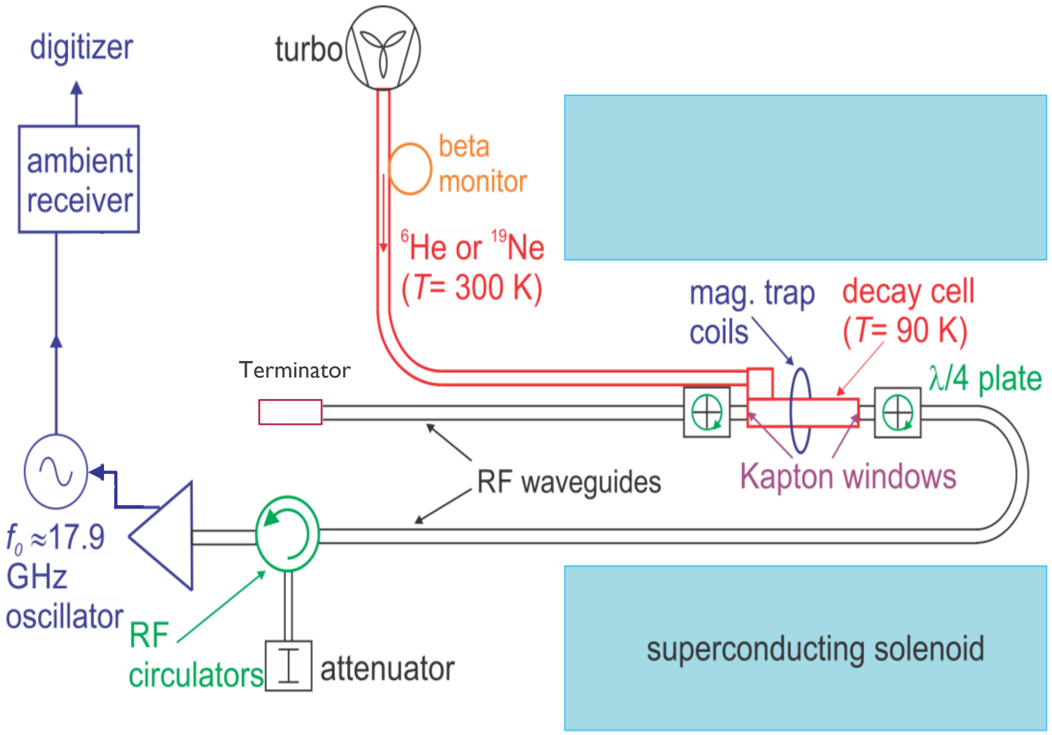
  - Retracing to the starting point of the track we can narrow our energy resolution to the eV scale!



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

^{6}He-CRES IN A NUTSHELL

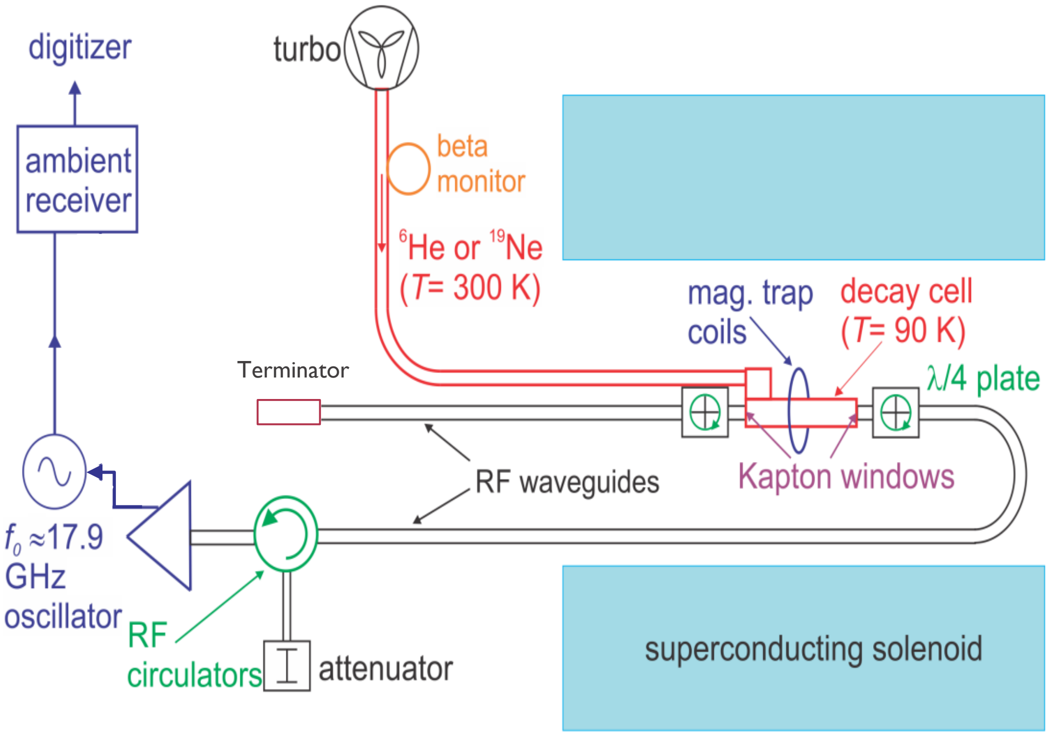
- Pumps gaseous ^{6}He and ^{19}Ne atoms into a decay cell/waveguide

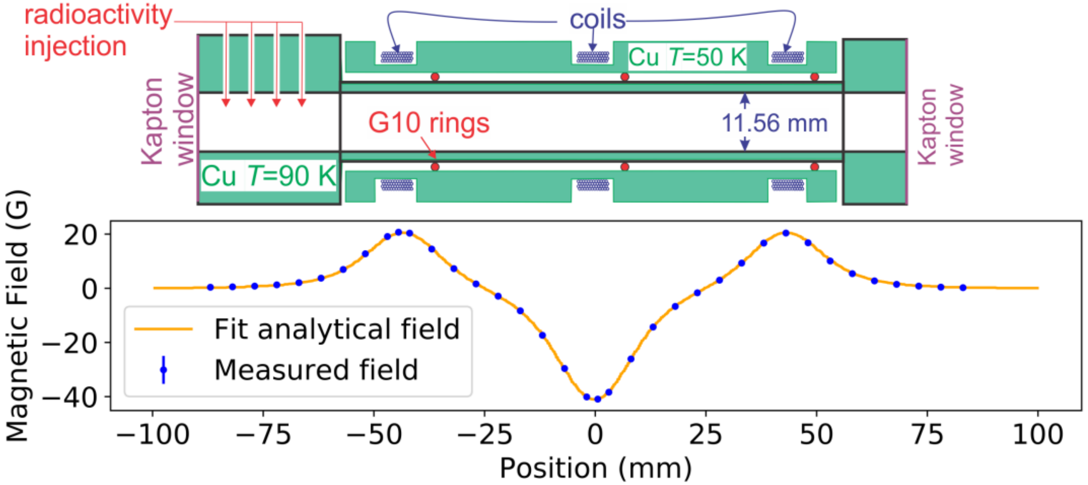


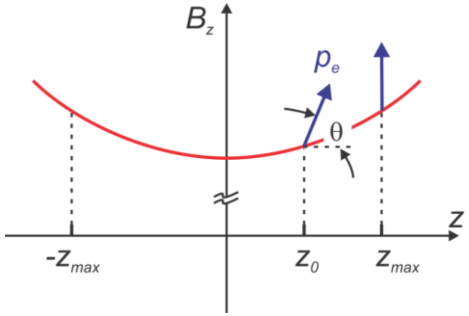
^{6}He-CRES

IN A NUTSHELL

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





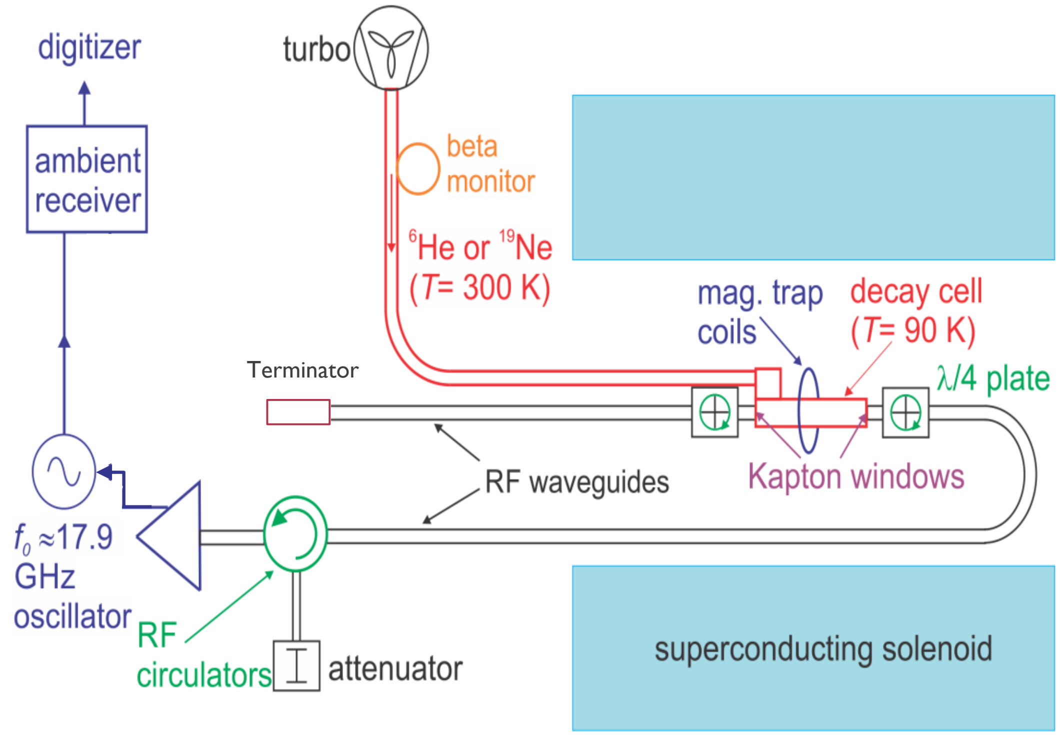


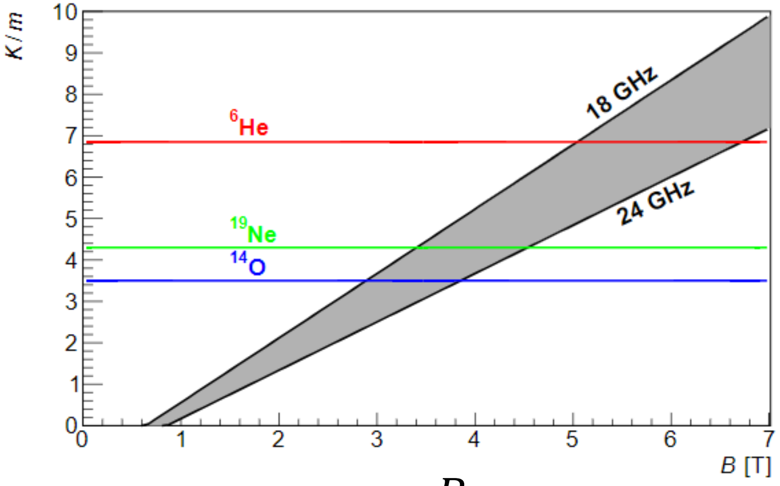
^{6}He-CRES

IN A NUTSHELL

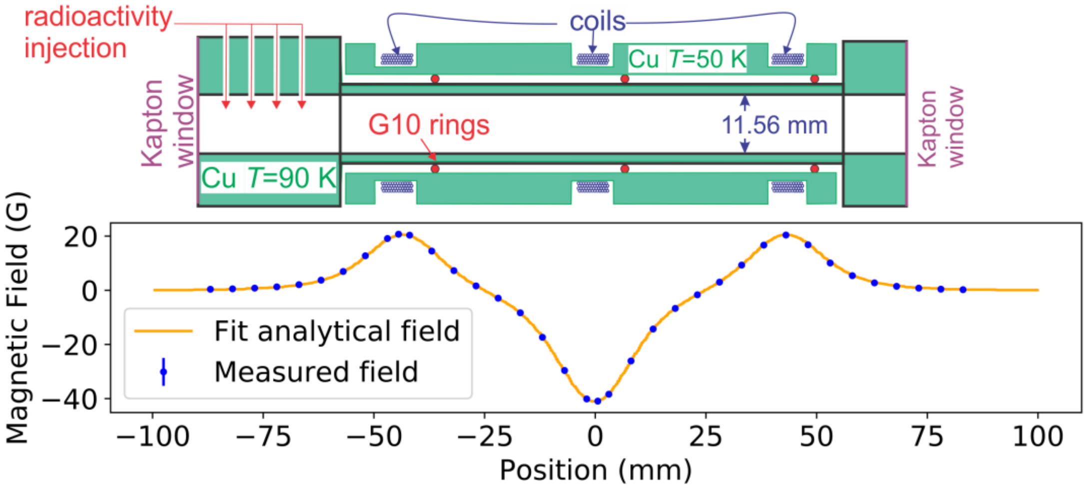
- Pumps gaseous ^{6}He and ^{19}Ne atoms into a decay cell/waveguide
- Magnetic trap for axial confinement
- Alter B-field to scan entire MeV scale spectrum

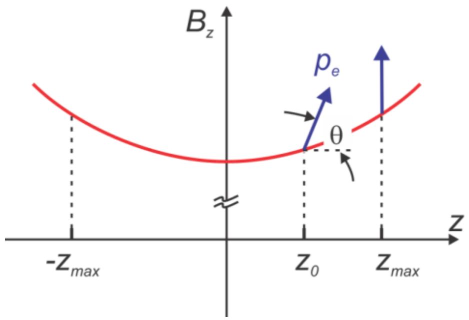
W. Byron *et al.* (He6-CRES Collaboration)
Phys. Rev. Lett. **131**, 082502 (2023)





$$f_c \propto \frac{qB}{E_e}$$

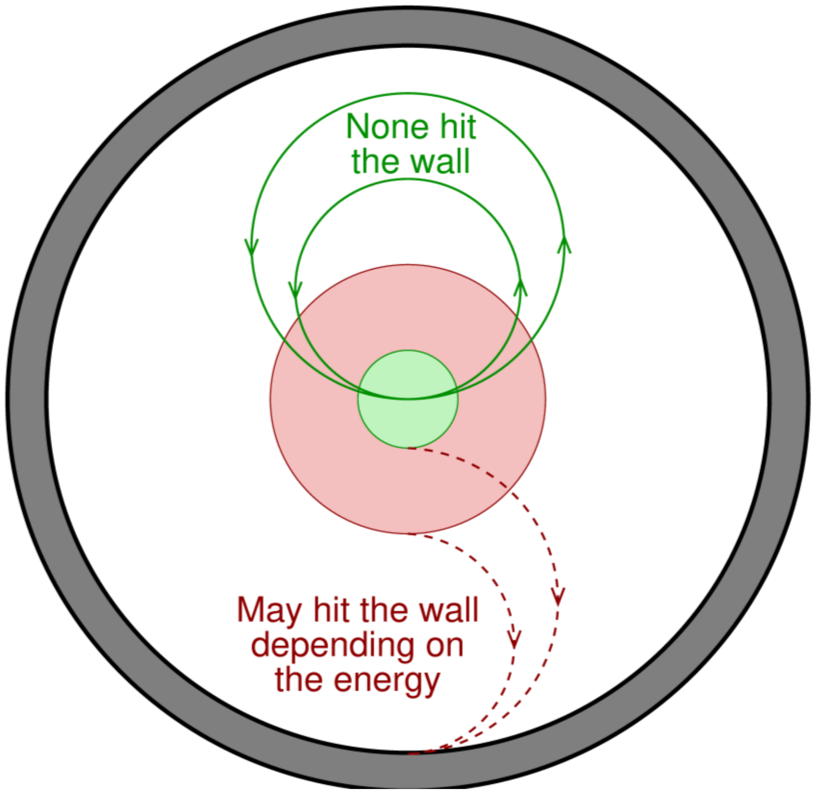




WALL EFFECTS

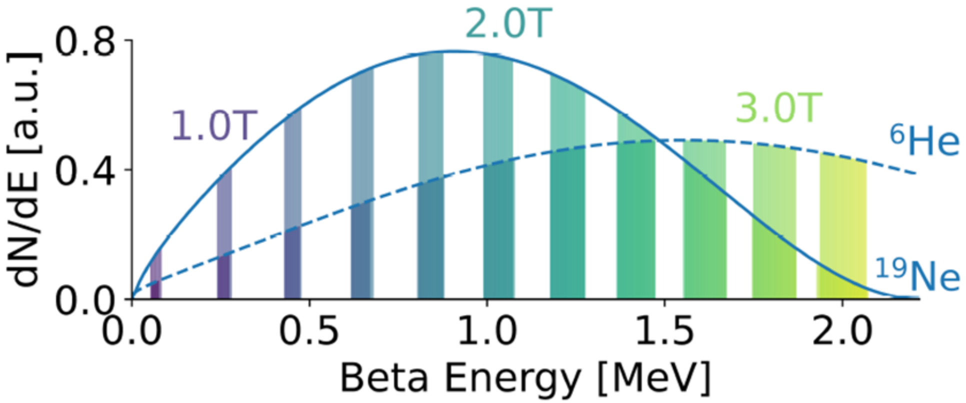
- Wall-bound betas leave insufficient tracks
  - Energy dependent effective geometry

Largest and smallest electron orbits at 2 T



WALL EFFECTS

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



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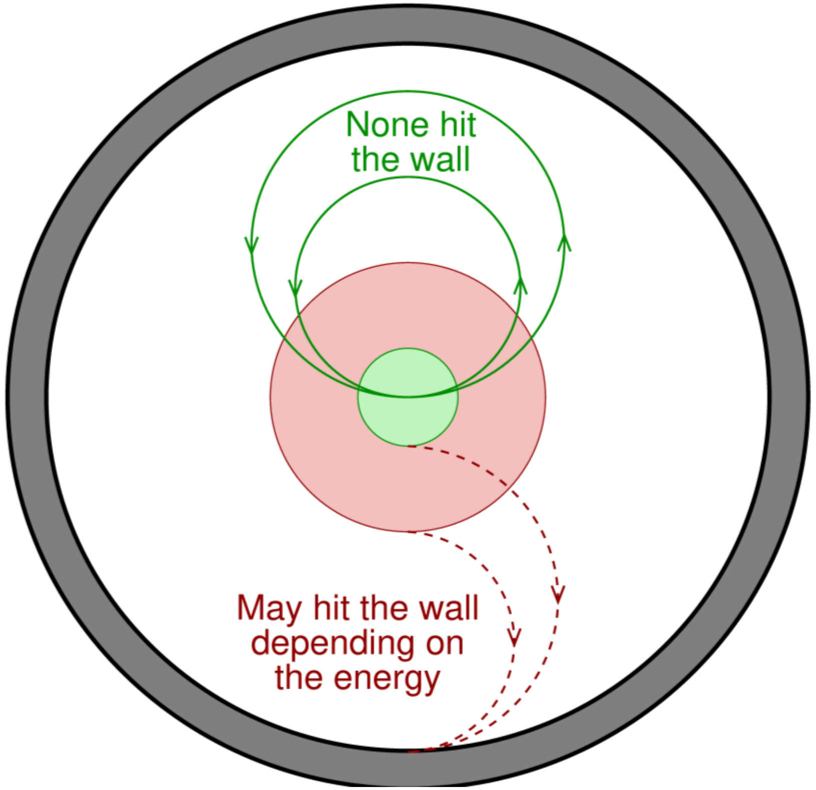

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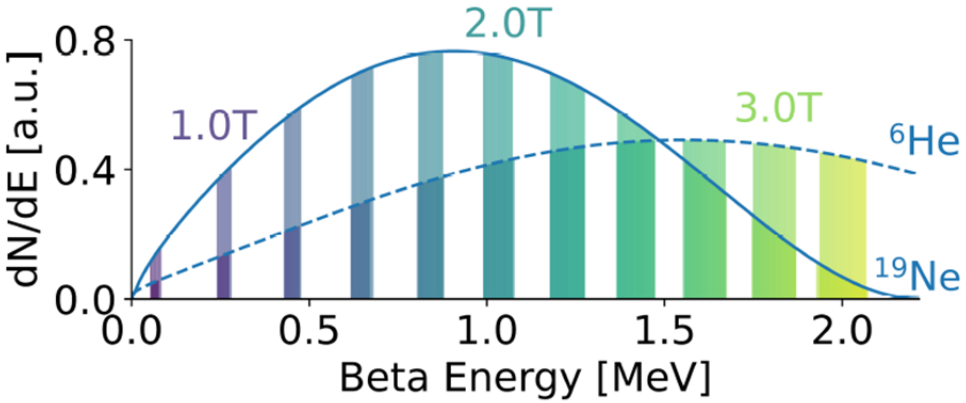

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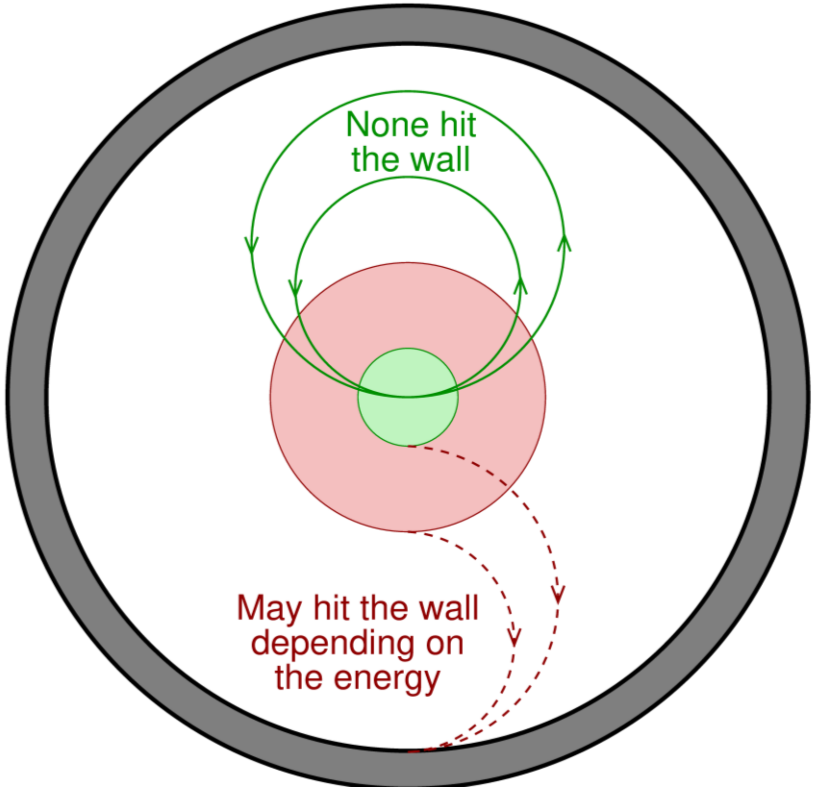
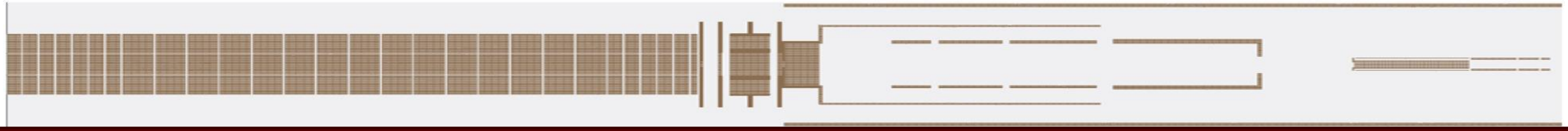


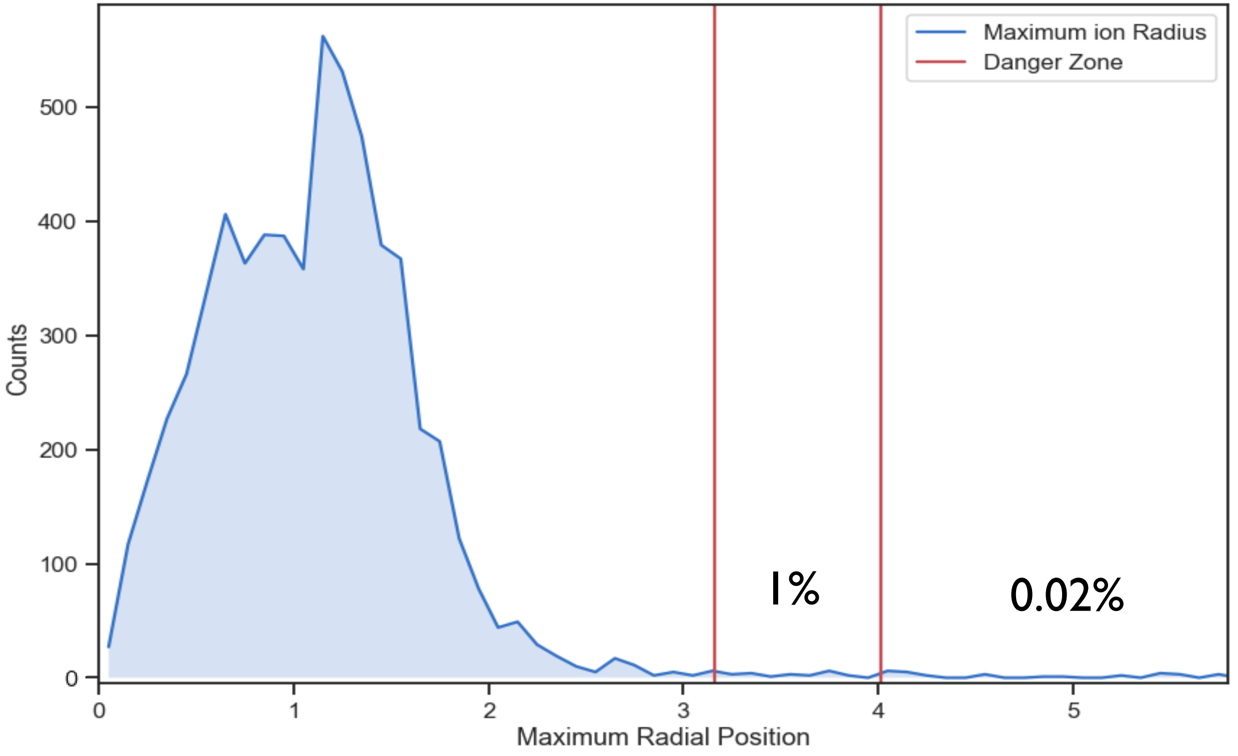
- Radial confinement of ions with ion trap

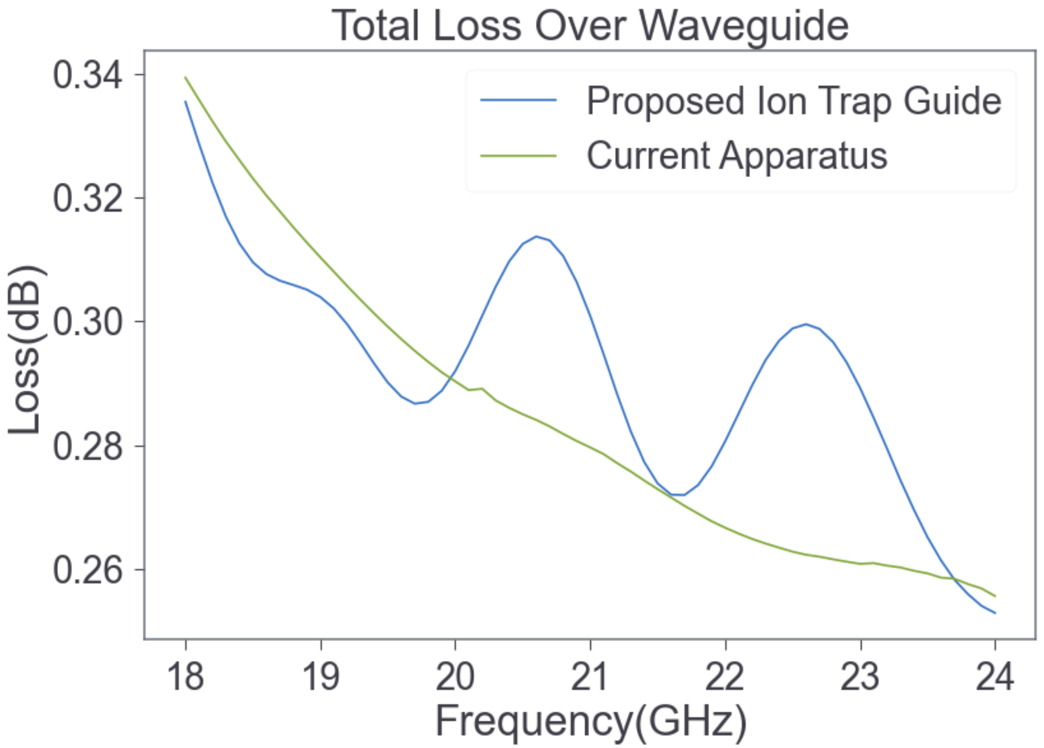
Ionizer and filter → Radio Frequency Quadrupole Cooler/Buncher → Transmission Optics → Penning Trap Waveguide

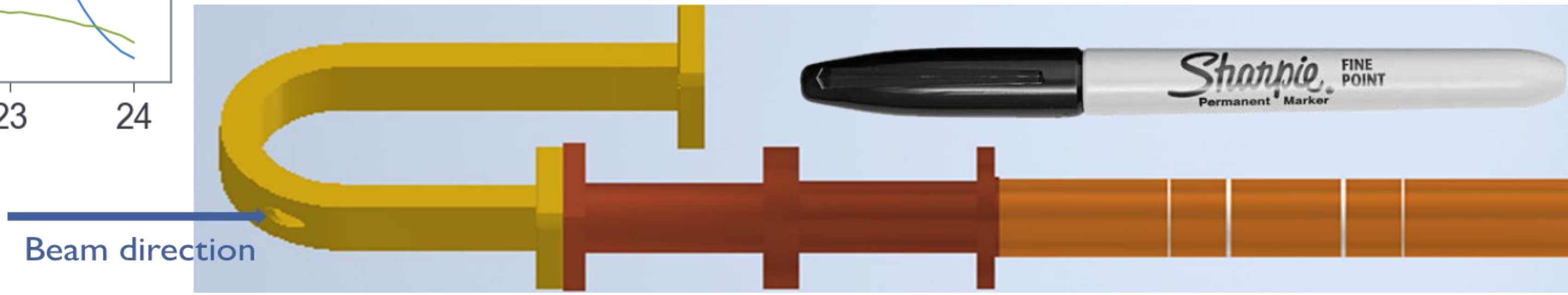


PENNING TRAP WAVEGUIDE

1. Can we constrain the particles and reduce wall effects?
2. Can it propagate our frequencies without major losses?
   - Power ~15 fW

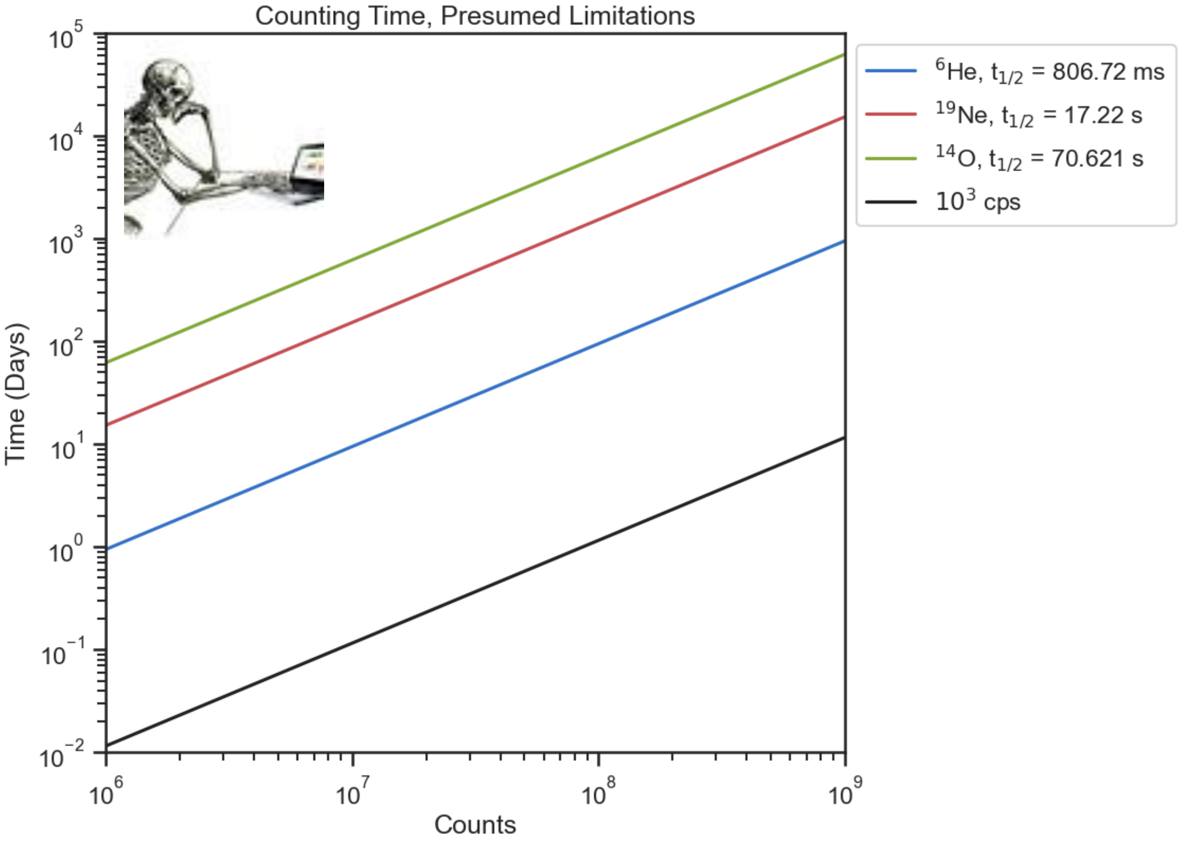






COUNT RATE

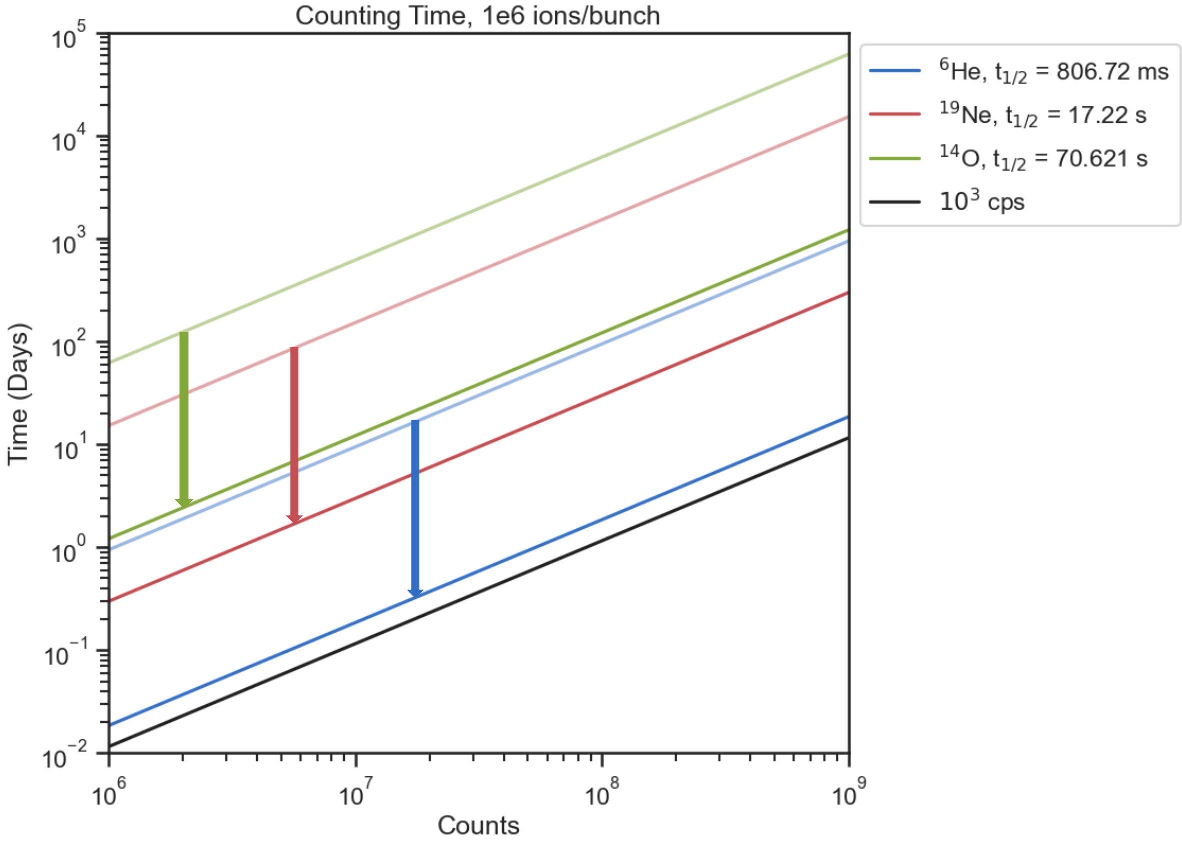
- With the presumed limitation of 10^4 particles per bunch statistics are an issue!



Cause of Loss	Effect
RFQ Efficiency (continuous mode)	83% efficiency
Beamline & Trap Injection	66% efficiency
Trapped Betas	3% efficiency
Events observed within frequency window	10% efficiency

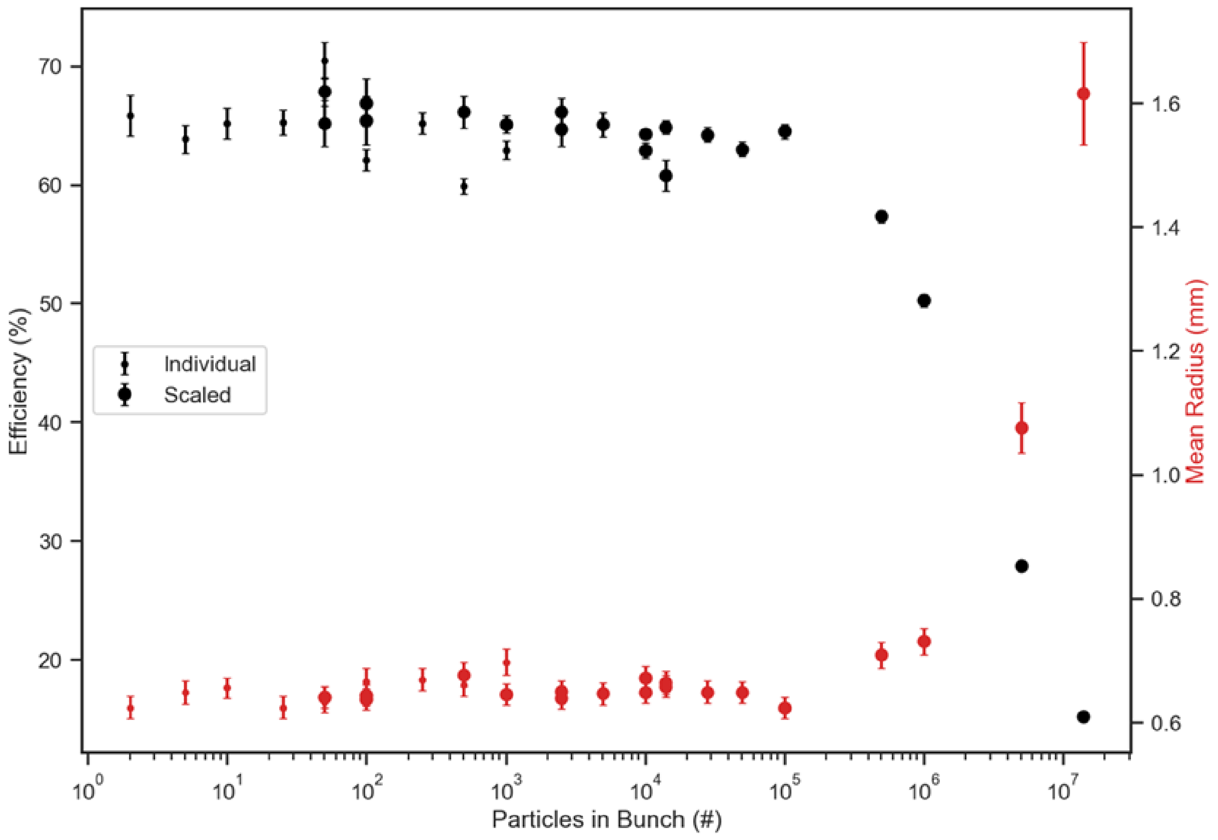
COUNT RATE

- ➢ With the presumed limitation of 10^4 particles per bunch statistics are an issue!



- ➢ Bunches as large as 10^6 particles possible!

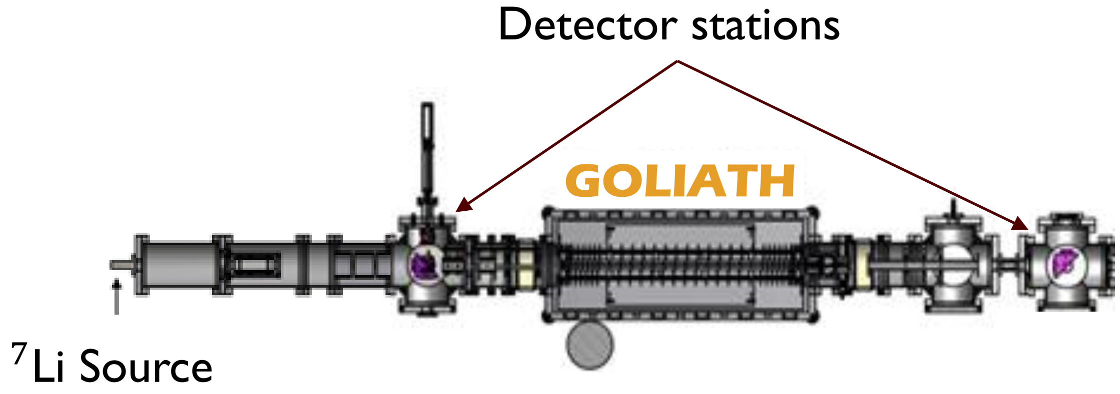
Cause of Loss	Effect
RFQ Efficiency (continuous mode)	83% efficiency
Beamline & Trap Injection	66% efficiency
Trapped Betas	3% efficiency
Events observed within frequency window	10% efficiency

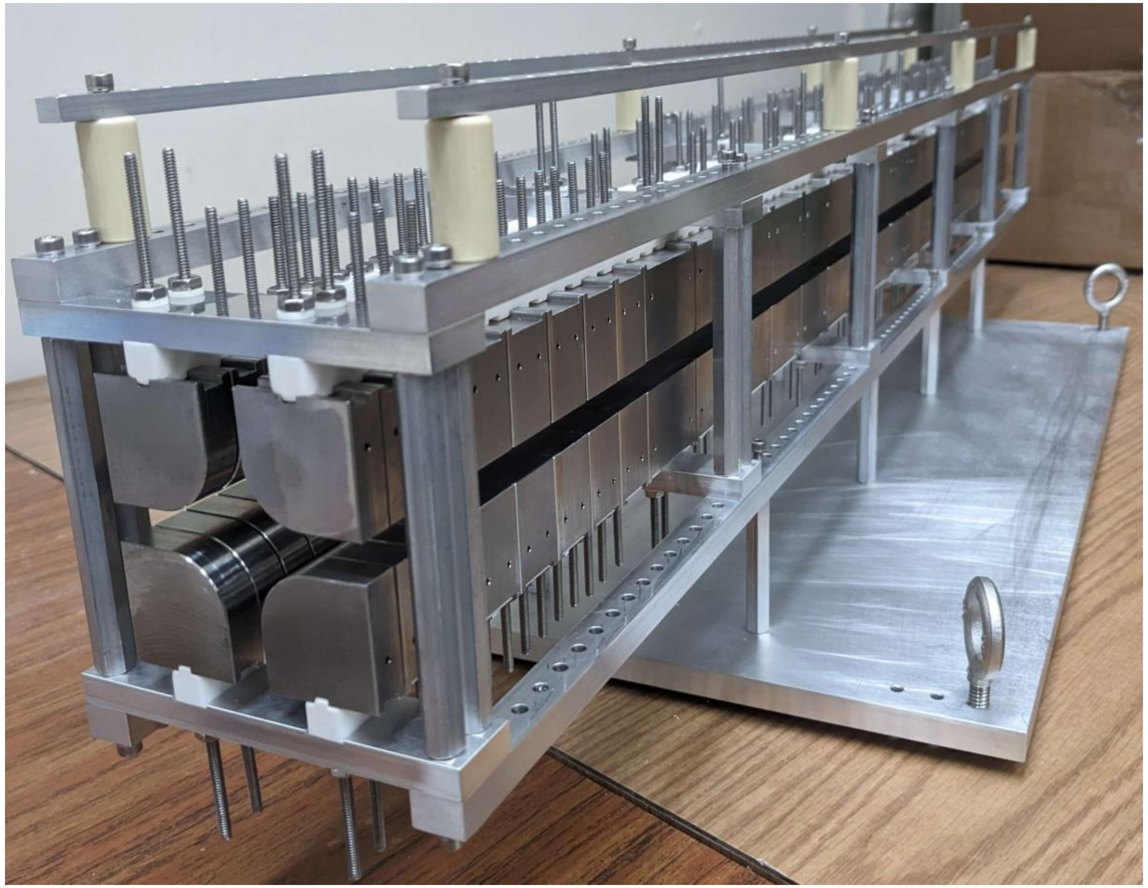


GOLIATH

Gas **O**perated **L**arge **I**on-bunch **A**tomic **T**rap for **H**e6-CRES

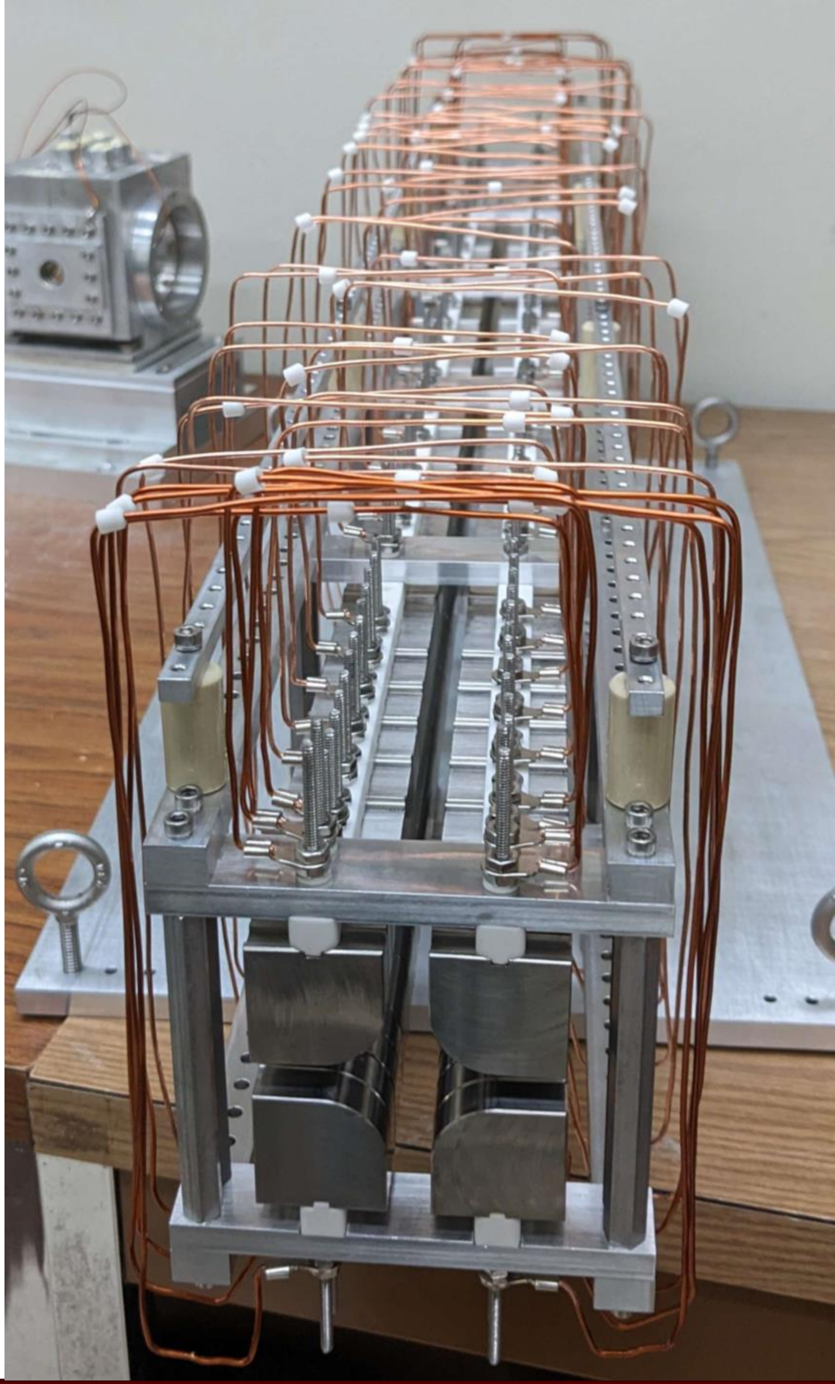
- To utilize H_2 buffer gas to cool He beam
- Simulated Resulting Bunch Characteristics
  - Time spread: $\Delta t \sim 0.57\ \mu s$
  - Energy spread: $\Delta E \sim 3.5$ eV
  - Emittance: $\varepsilon_{rms} \sim 0.9\ \pi$ mm mrad @ 60 keV
  - Transmission Rate (Within RFQ): 83%





SUMMARY AND CONCLUSION

- Ion trap addition
  - Reduces wall effects caused by gaseous sources
  - Opens CRES technique to a broader range of isotopes
- **GOLIATH**
  - Will utilize non-standard H_2 buffer gas
  - Planned 50x standard throughput
- Tests to be conducted soon at Texas A&M!
  - Results will be used to finalize design of Penning trap & beamline
- After testing will be moved to the University of Washington for implementation



^{6}He-CRES

UNIVERSITY OF WASHINGTON 1861

N. Buzinsky, W. Byron,
W. Degraw, B. Dodson,
A. Garcia, T. Goodson,
B. Graner, H. Harrington,
K.S.Shaw, P. Kolbeck,
E. Novitski, R.G.H. Robertson,
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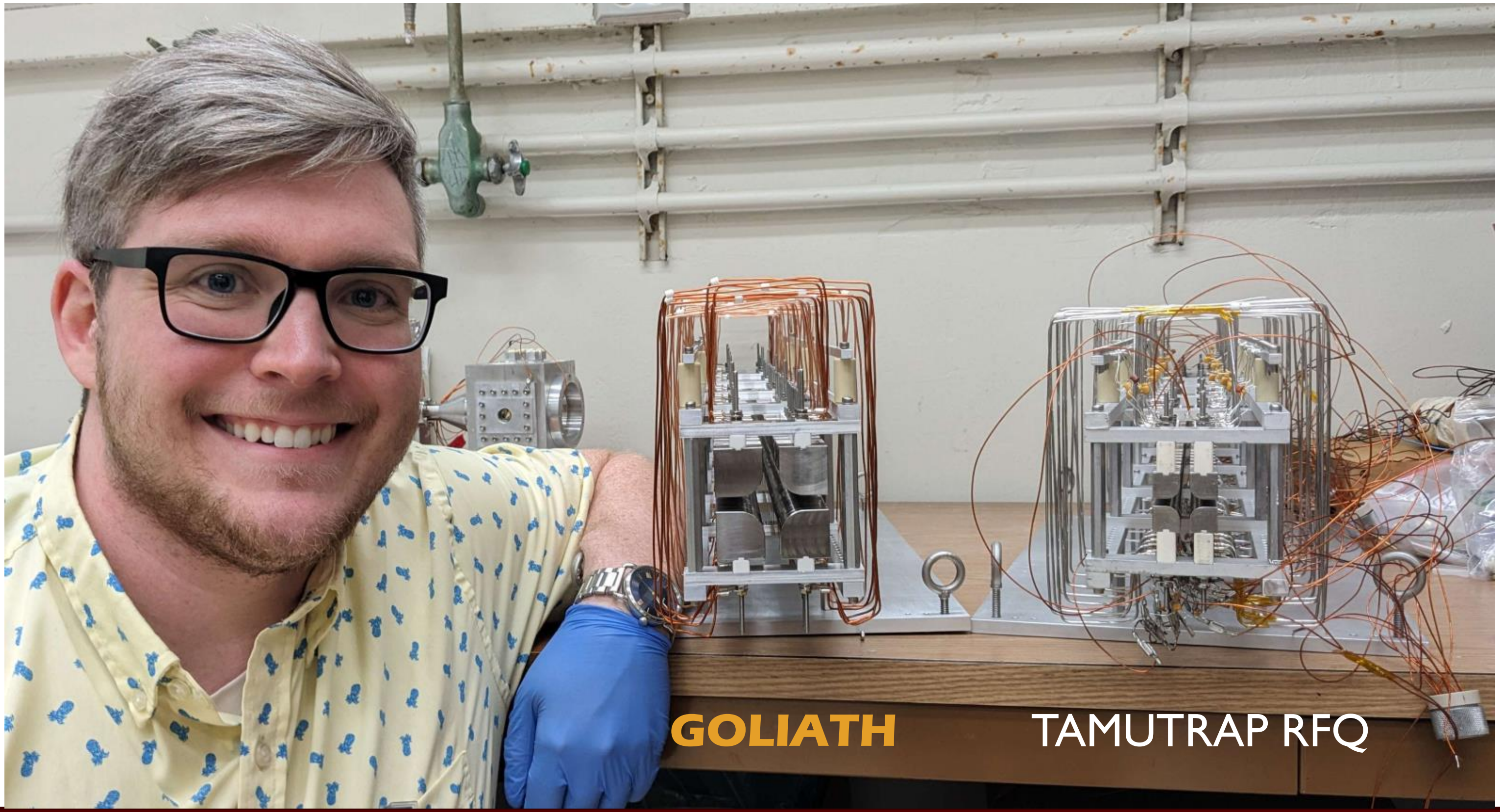
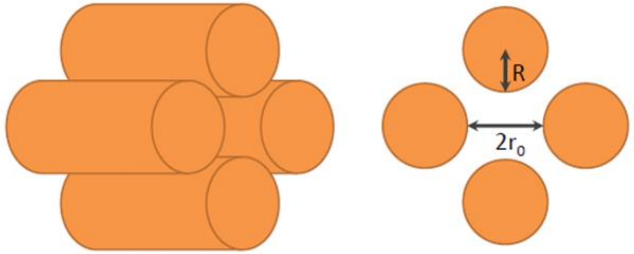
THANK YOU

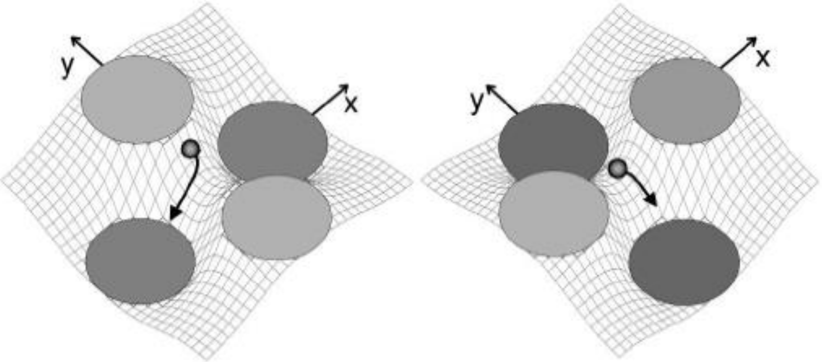
Questions?



BACKUPS



Radio frequency quadrupole trap (RFQ)

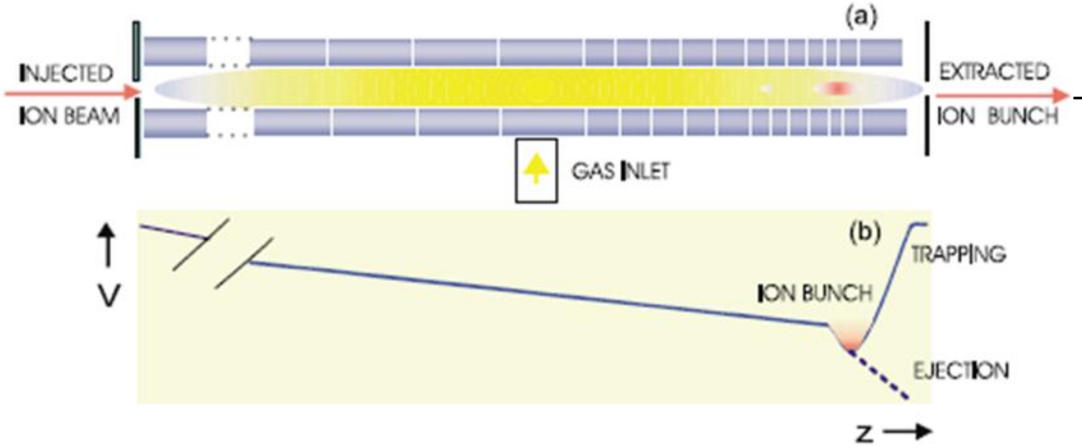


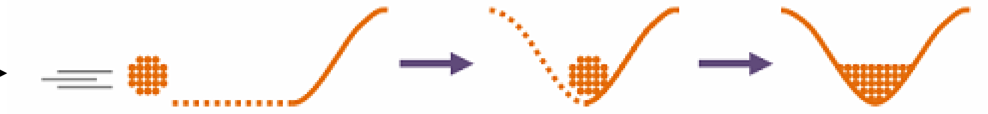
The Mathieu stability parameter q must be constrained between 0.4 < q < 0.7 from for the highest probability of retaining an ion of mass M

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

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



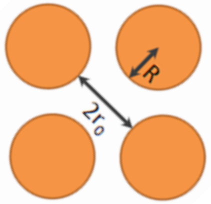


GOLIATH

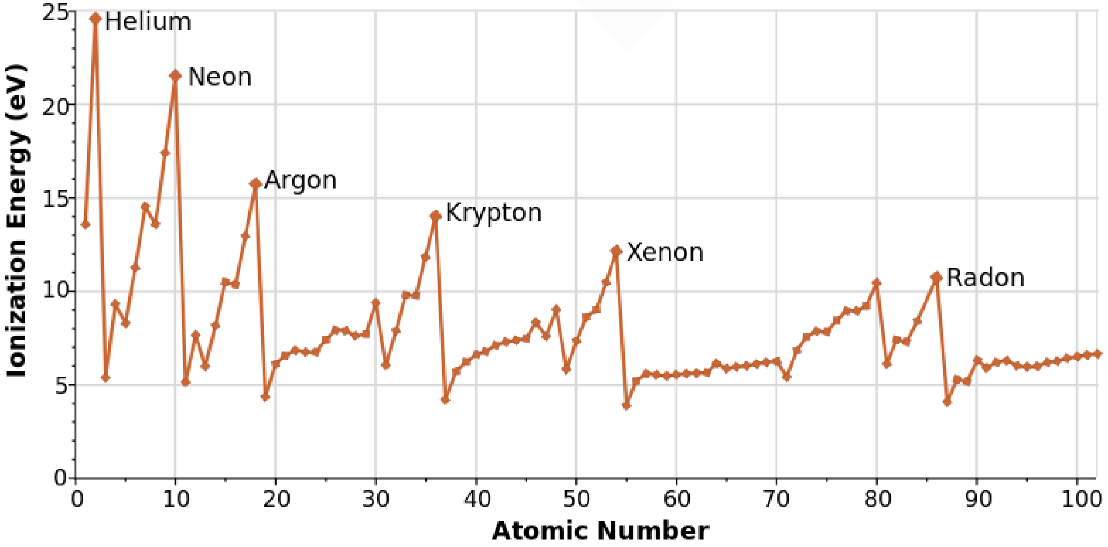
Gas Operated Large Ion-bunch Atomic Trap for He6-CRES

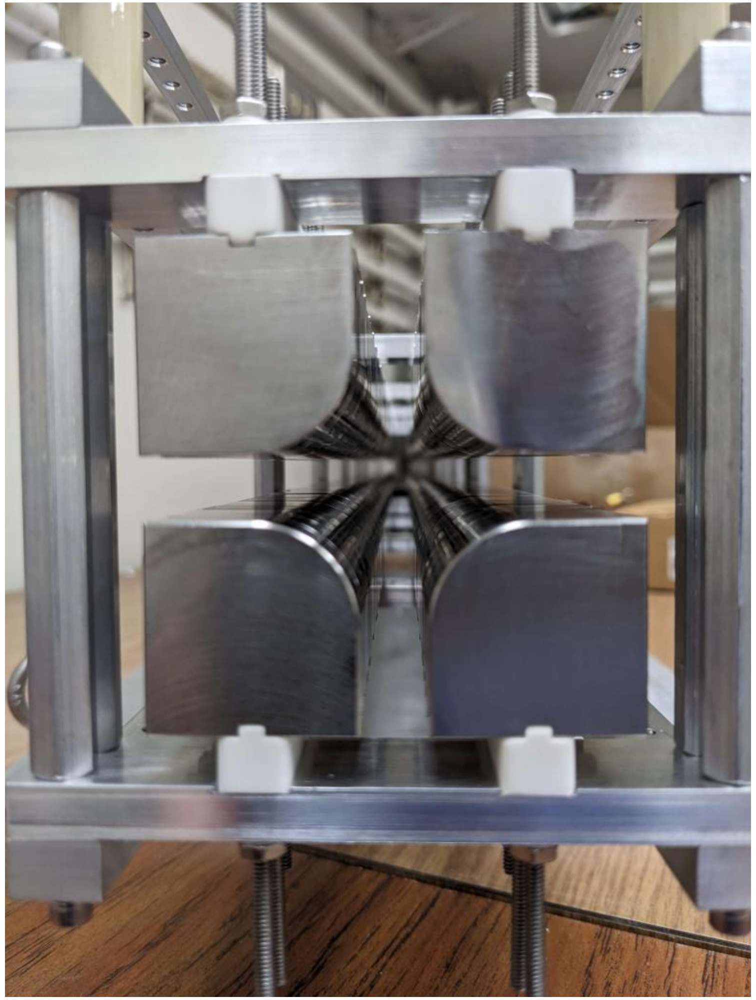
Design Specifications

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

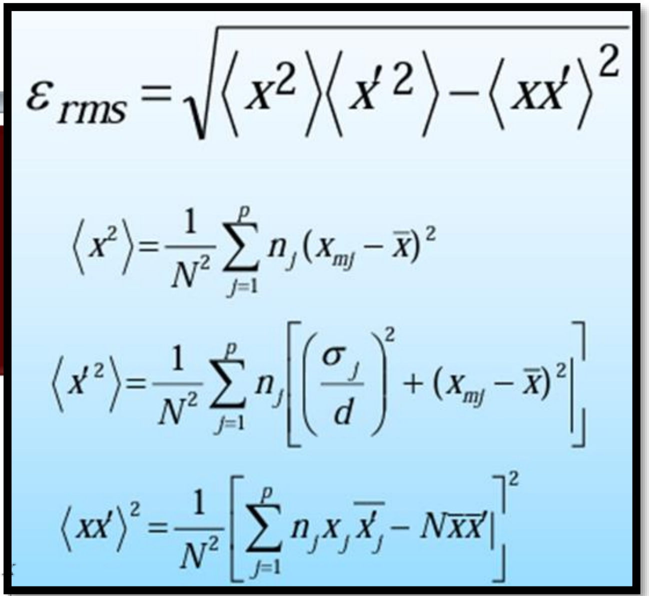


H_2 to be used in place of usual ^{4}He to avoid charge exchange with ^{6}He





EMITTANCE ∝ TRAP RADIUS



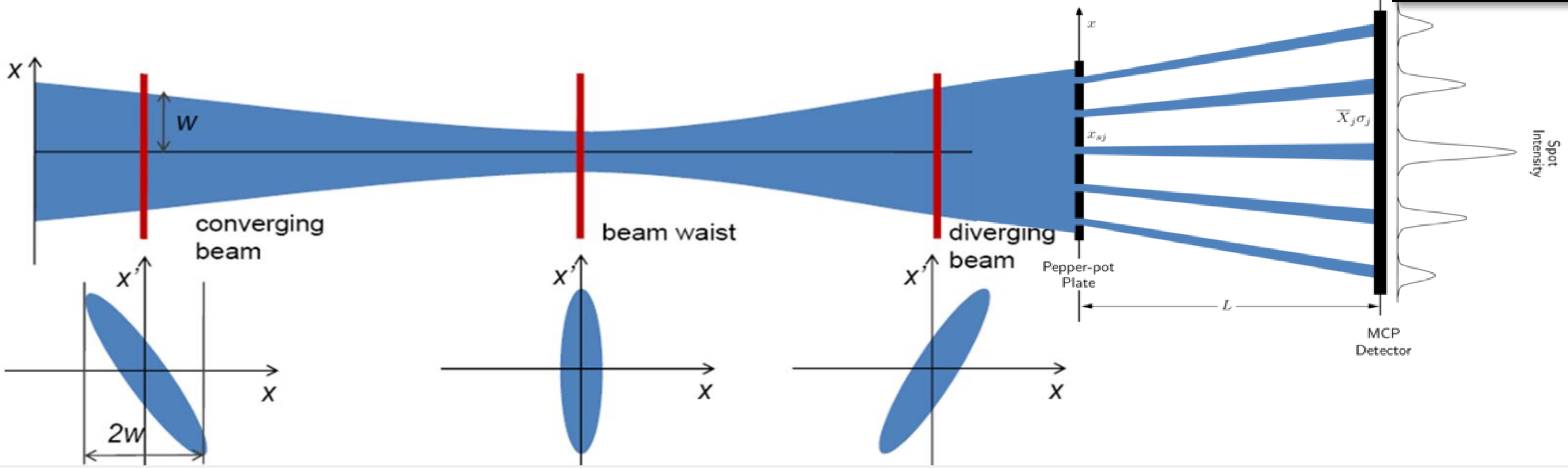
$$\varepsilon_{rms} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

$$\langle x^2\rangle = \frac{1}{N^2}\sum_{j=1}^{p} n_j (x_{mj}-\bar{x})^2$$

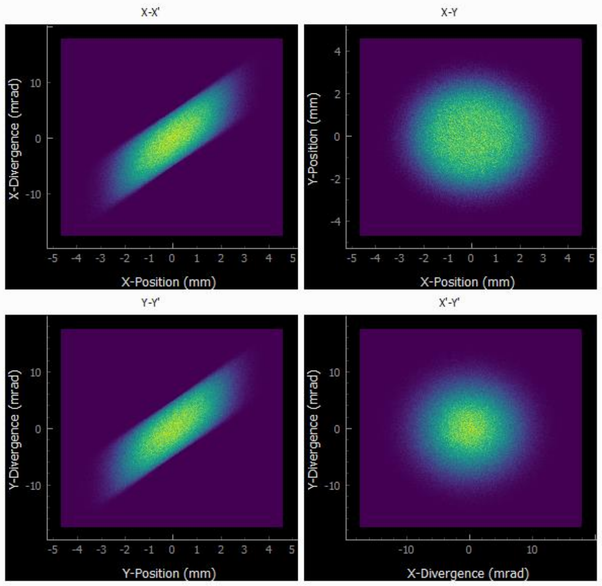
$$\langle x'^2\rangle = \frac{1}{N^2}\sum_{j=1}^{p} n_j\left[\left(\frac{\sigma_j}{d}\right)^2 + (x_{mj}-\bar{x})^2\right]$$

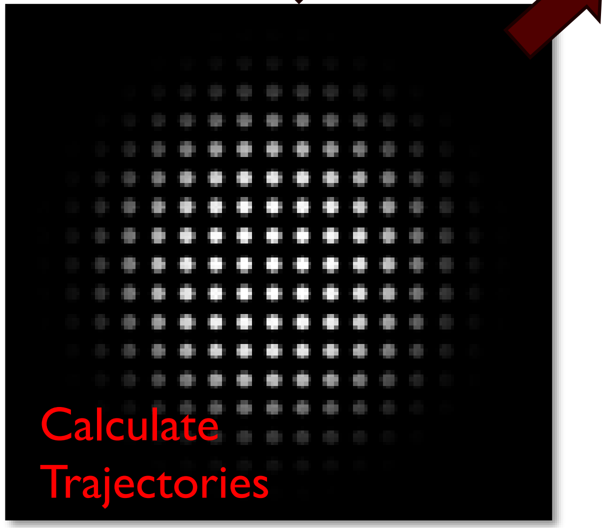
$$\langle xx'\rangle^2 = \frac{1}{N^2}\left[\sum_{j=1}^{p} n_j x_j \bar{x}'_j - N\bar{x}\bar{x}'\right]^2$$

- Liouville's theorem states that the area of the phase-space distribution is constant with time



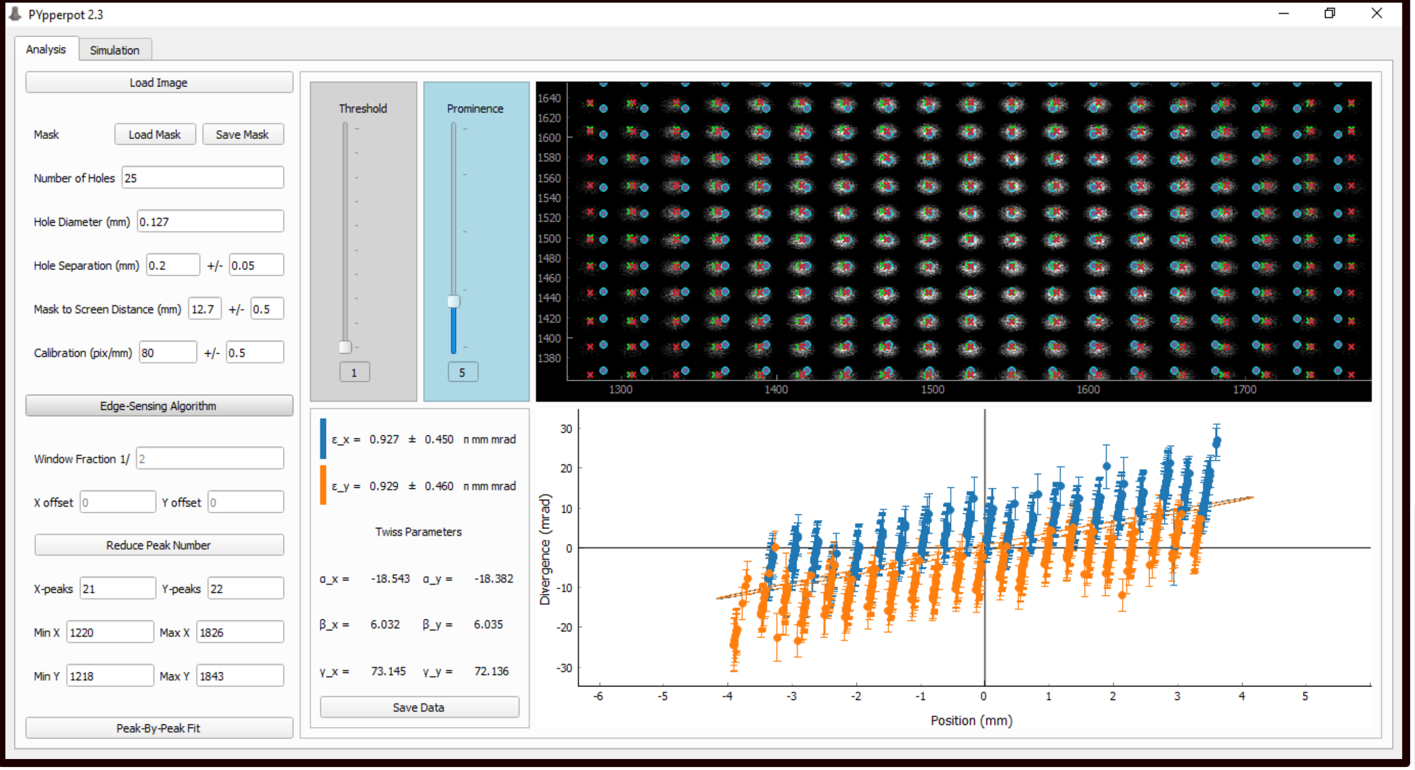
Generate Beam





Calculate Trajectories

Pypperpot Analysis Software



Mask

Number of Holes 25

Hole Diameter (mm) 0.127

Hole Separation (mm) 0.2 +/- 0.05

Mask to Screen Distance (mm) 12.7 +/- 0.5

Calibration (pix/mm) 80 +/- 0.5

Window Fraction 1/ 2

X offset 0 Y offset 0

X-peaks 21 Y-peaks 22

Min X 1220 Max X 1826

Min Y 1218 Max Y 1843

Threshold 1

Prominence 5

ε_x = 0.927 ± 0.450 π mm mrad

ε_y = 0.929 ± 0.460 π mm mrad

Twiss Parameters

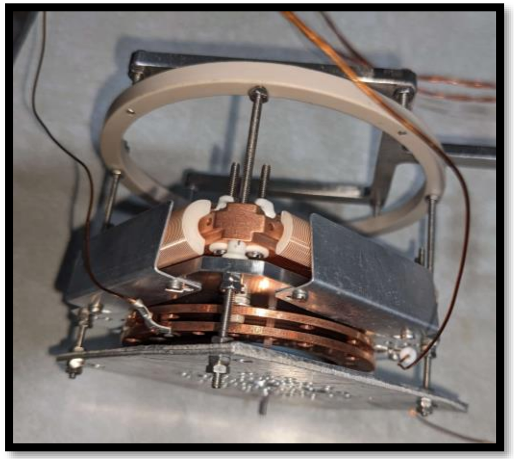
α_x = -18.543 α_y = -18.382

β_x = 6.032 β_y = 6.035

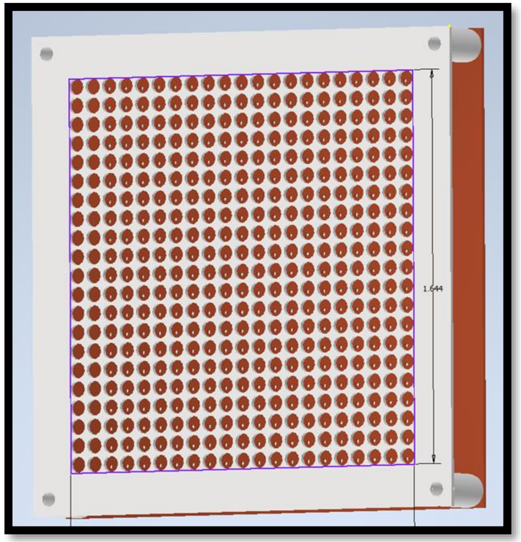
γ_x = 73.145 γ_y = 72.136

Visualize Phase-Space

Apply First Mask Design

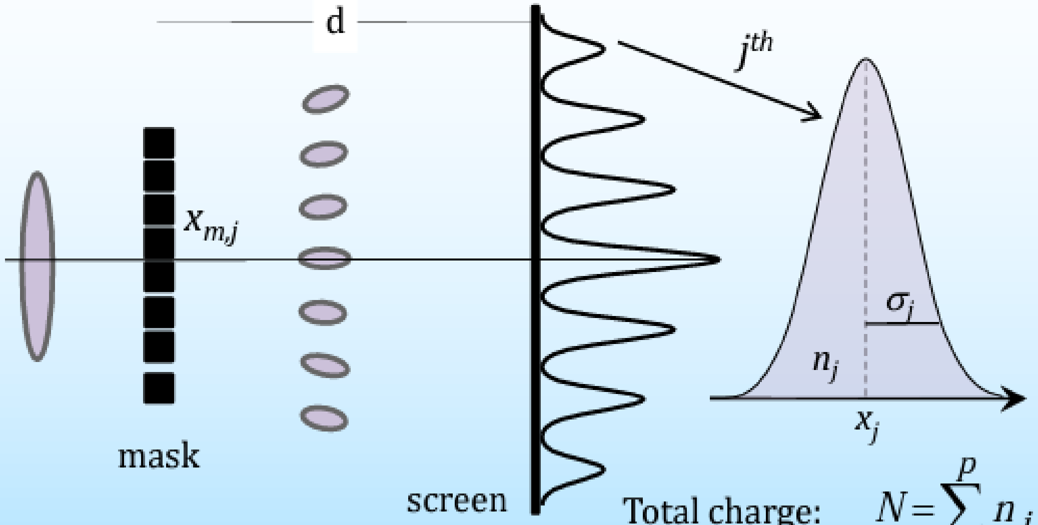


Finish First Mask Design



Pepperpot/slits emittance measurement

More at the end of this presentation



Total charge: $N = \sum_j^p n_j$

$$\varepsilon_{rms} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

$$\langle x^2 \rangle = \frac{1}{N^2} \sum_{j=1}^{p} n_j (x_{mj} - \bar{x})^2$$

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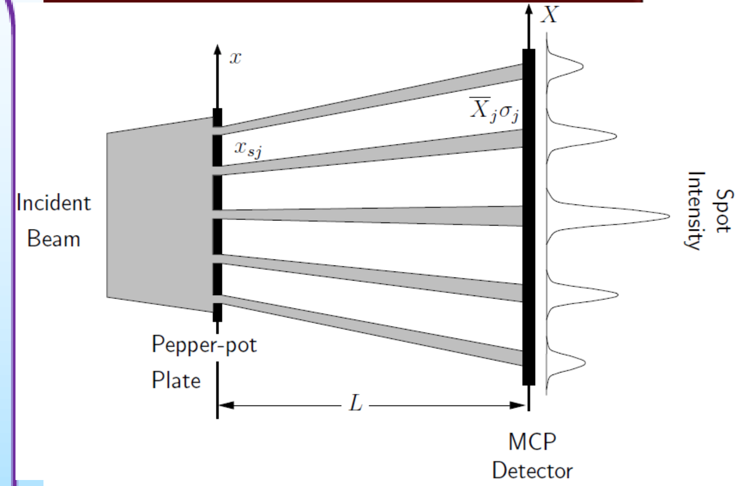
$$\langle xx' \rangle^2 = \frac{1}{N^2} \left[\sum_{j=1}^{p} n_j x_j \overline{x'_j} - N \overline{x}\overline{x'} \right]^2$$



In all beamlets:

Mean position:

$$\bar{x} = 1/N \sum_j^p n_j x_{m,j} = \langle x \rangle$$

Mean divergence:

$$\bar{x}' = 1/N \sum_j^p n_j \bar{x}'_j = \langle x' \rangle$$

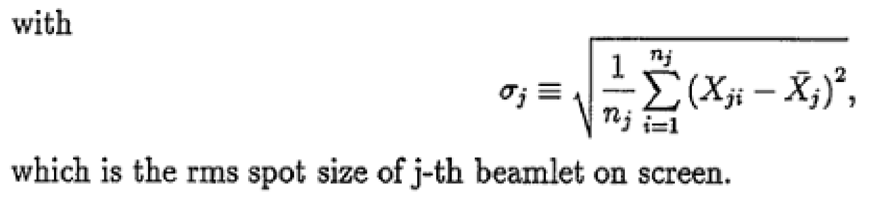
In j^{th} beamlet:

Mean divergence:

$$\bar{x}'_j = 1/n_j \Sigma x'_{ij}$$

rms divergence:

$$\boxed{\sigma_{j,x'} = \frac{\sigma_j}{d}}$$



with

$$\sigma_j \equiv \sqrt{\frac{1}{n_j} \sum_{i=1}^{n_j} (X_{ji} - \bar{X}_j)^2},$$

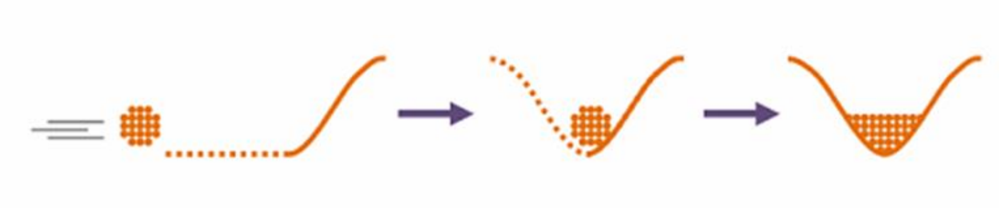
which is the rms spot size of j-th beamlet on screen.

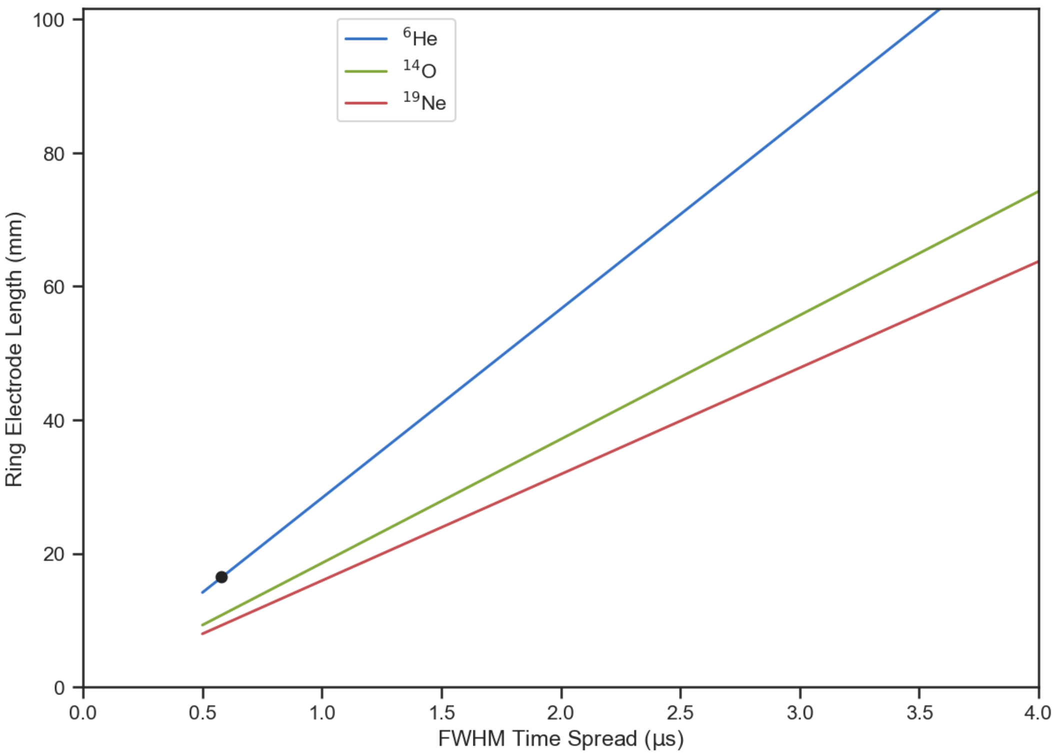
p = number of slits, $x_{m,j}$ = j-th slit position, N = all particles behind the slits

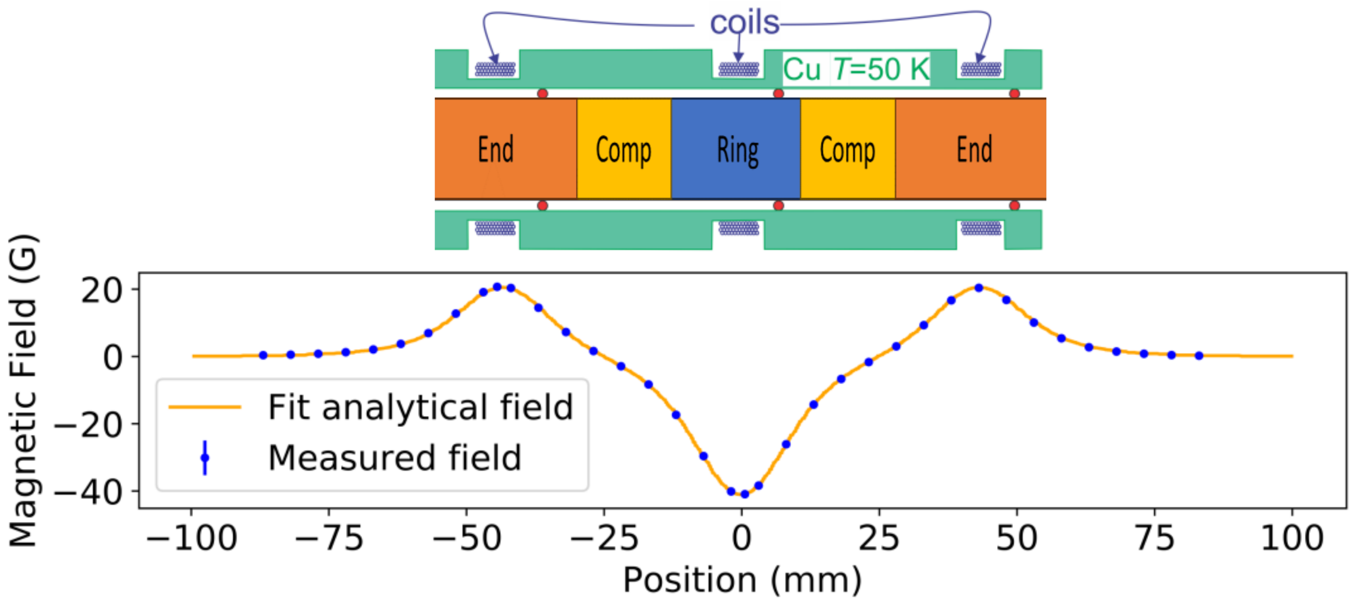
n_j = number of particles passing through slit (weight of spot intensity)

TIME SPREAD ∝ RING ELECTRODE LENGTH

- The ring electrode length along with the radius are integral to effective trapping

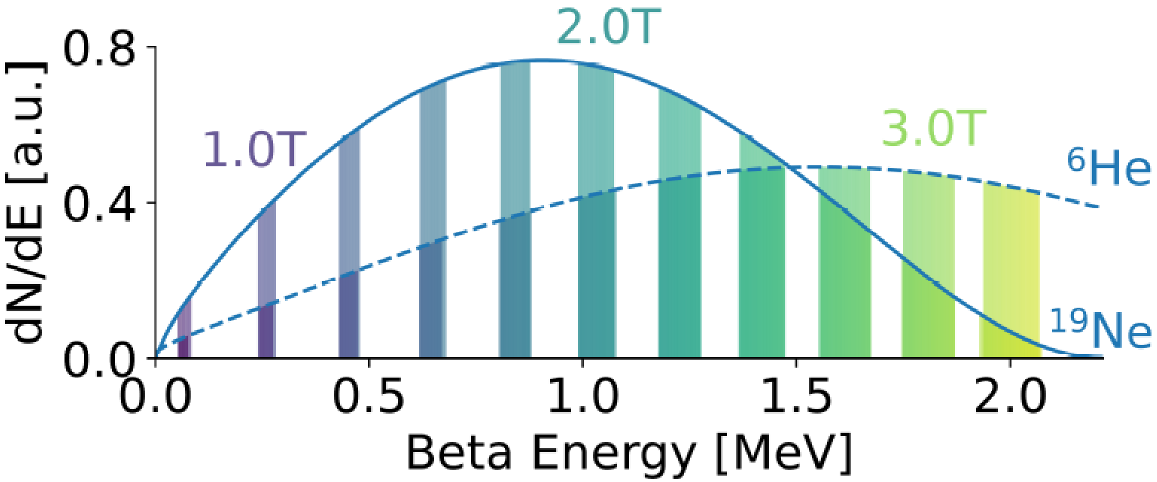


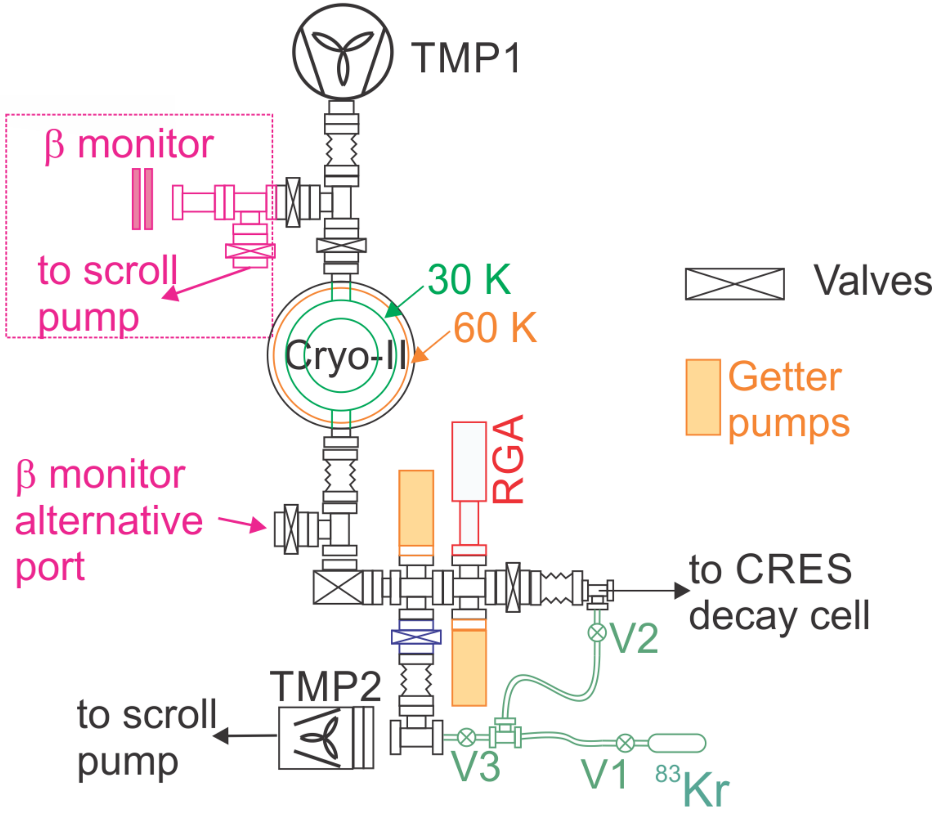




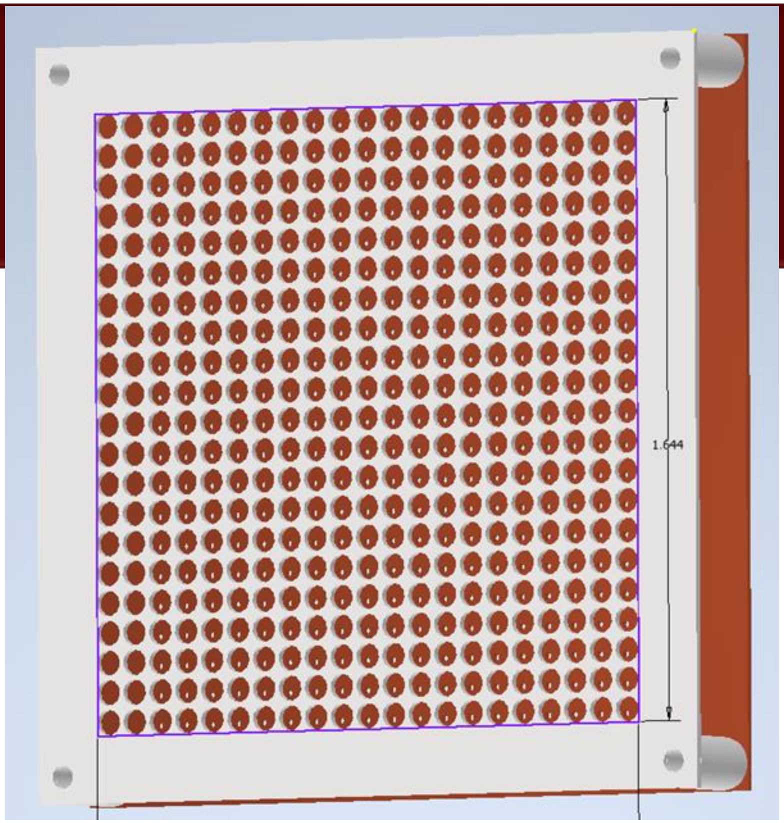
IMPORTANCE OF NORMALIZATION

- Because we are looking at slices of the beta spectrum, it is extremely important to have a normalization to our source rate
- TAMU actively engaged in development and characterization of β monitors

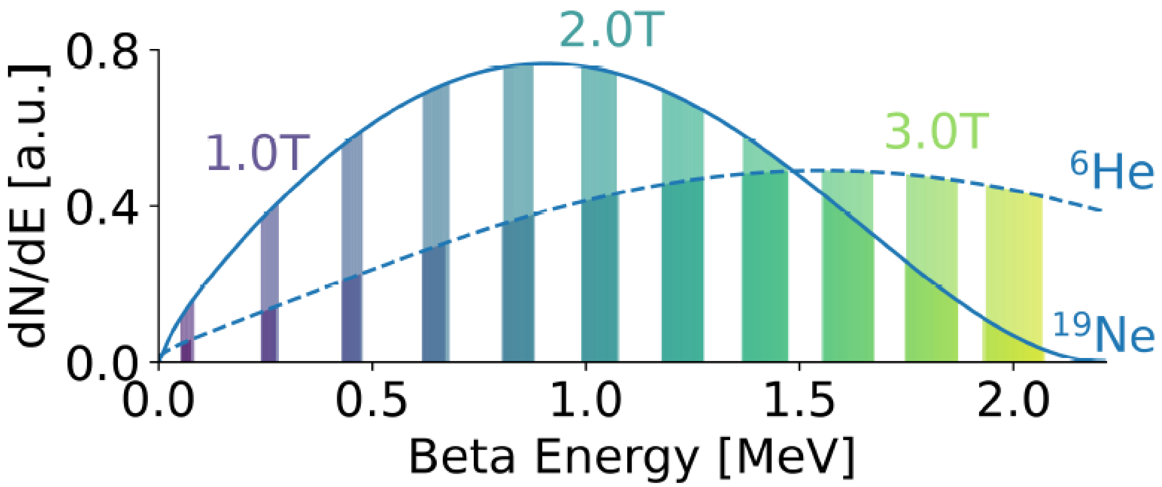


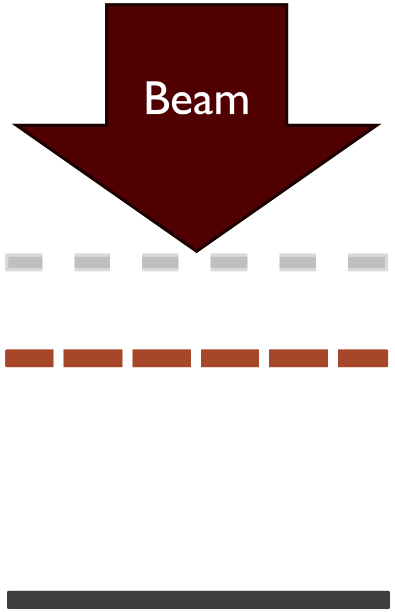


NORMALIZATION



- Repeatability is paramount to normalization
- Need to make sure that we are receiving both the rate and emittance we need



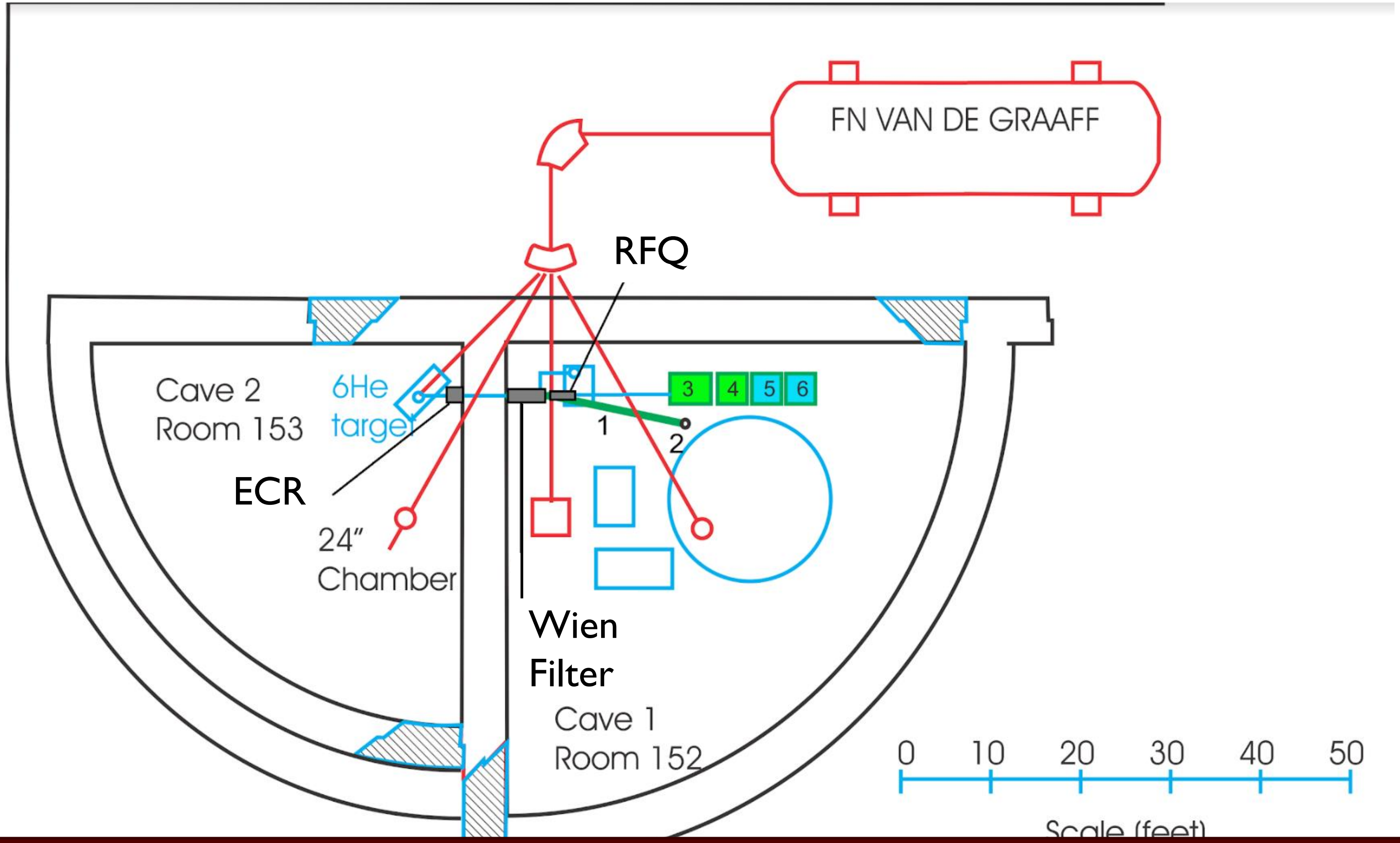


Electron Suppression Mask (64% open)

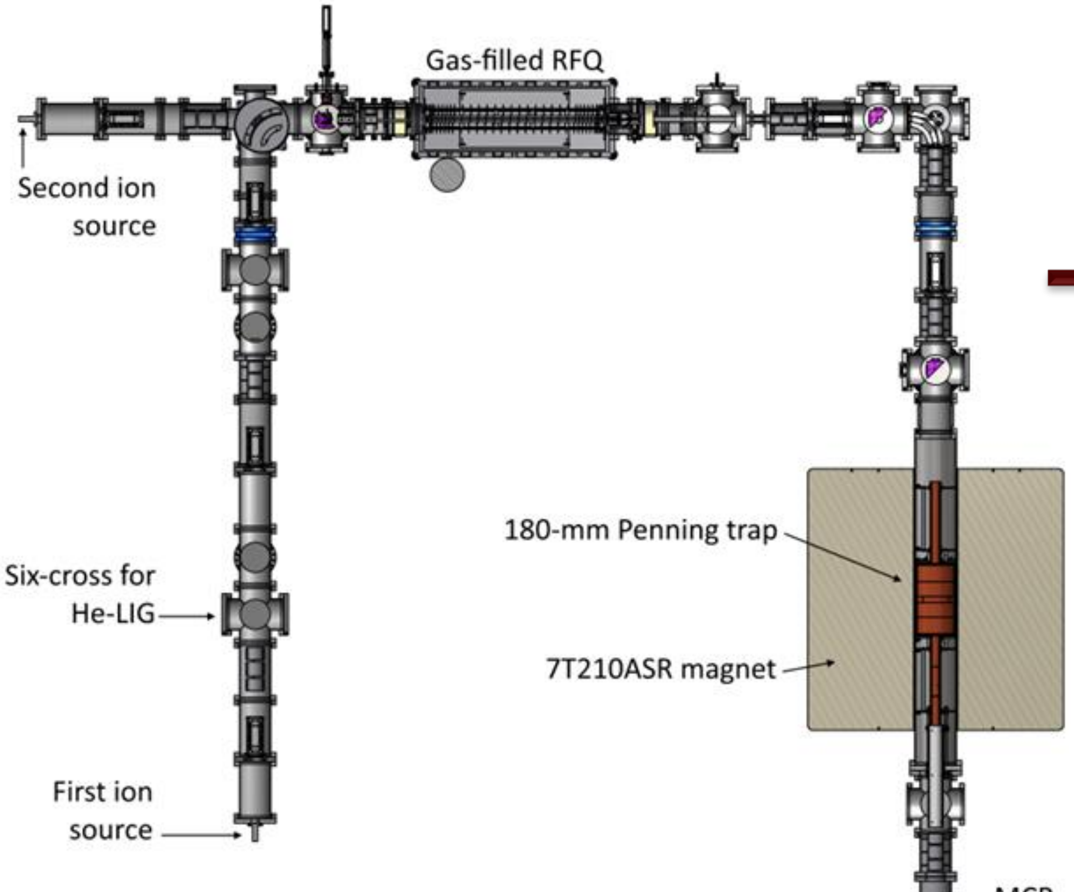
Faraday Mask (2%) open

MCP

ION TRAP ADDITION



CHANGES AT TAMUTRAP



Texas A&M University Penning Trap Facility (TAMUTRAP)