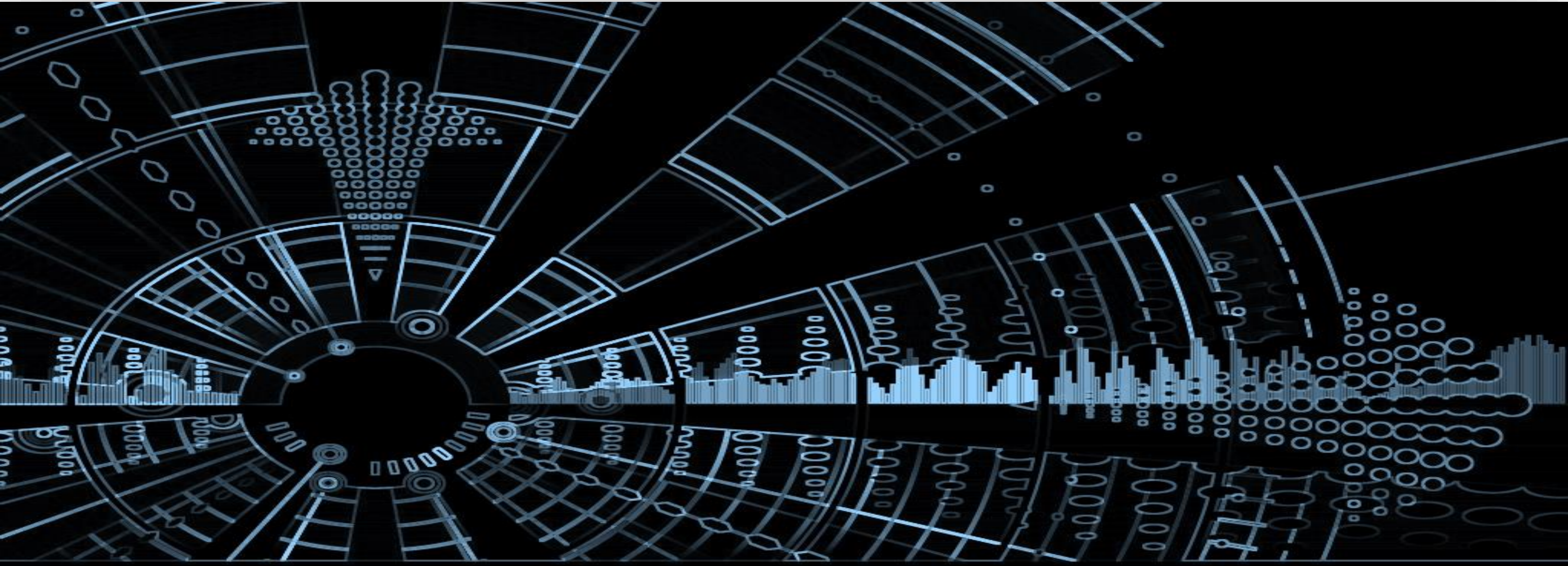
Design and Operation of a Penning Ion Trap Source for the CHIP-TRAP Mass Spectrometer



Madhawa Horana Gamage - 09/20/2021 - ICIS
Supervisor- Dr. Matthew Redshaw
Central Michigan University

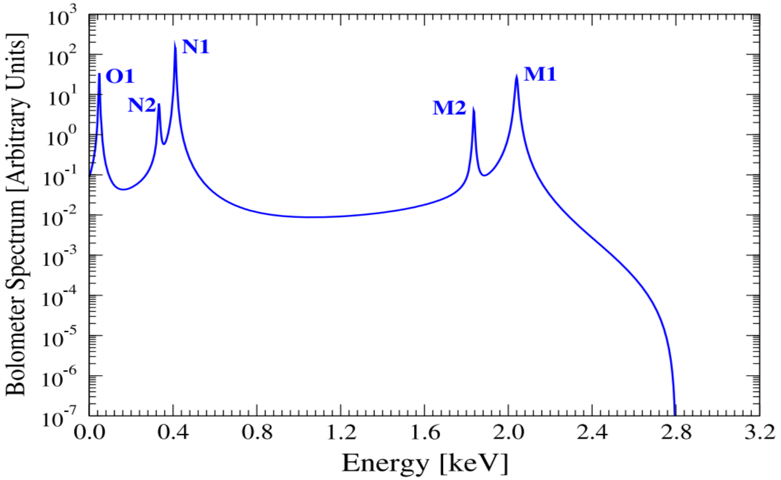
Outline

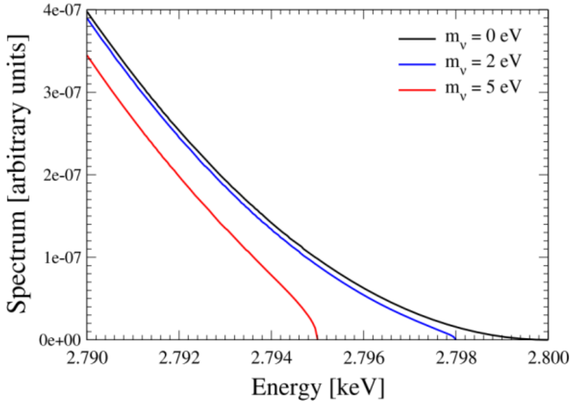
- ***Motivation***
- ***Structure of CHIP-TRAP***
- ***Design of Penning Ion Trap Source(PITS)***
- ***Simulation and Experimental Results***
- ***Calibration of PITS***
- ***Conclusion***

Motivation

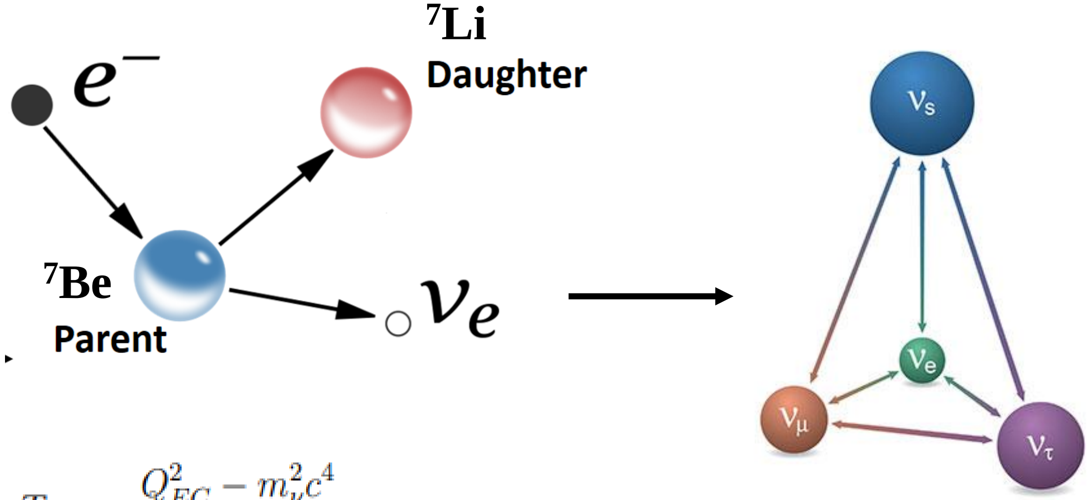
Electron Capture Decay of ^{163}Ho for absolute **Neutrino -mass determination**

$$^{163}\mathrm{Ho} + e^{-} \rightarrow {}^{163}\mathrm{Dy}^{*} + n_{e}$$





Electron Capture Decay of ^{7}Be for **Sterile Neutrino studies via momentum reconstruction (BeEST experiment)**



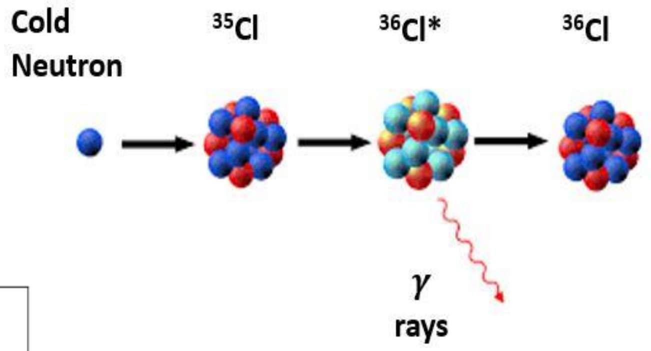
$$T_d = \frac{Q_{EC}^2 - m_\nu^2 c^4}{2\left(Q_{EC} + m_d c^2\right)}$$

$$T_\nu = \frac{\left(m_\nu c^2 - Q_{EC}\right)\left(c^2(m_\nu - 2m_d) - Q_{EC}\right)}{2\left(m_d c^2 + Q_{EC}\right)}$$

Q_{EC} value to ~1 eV

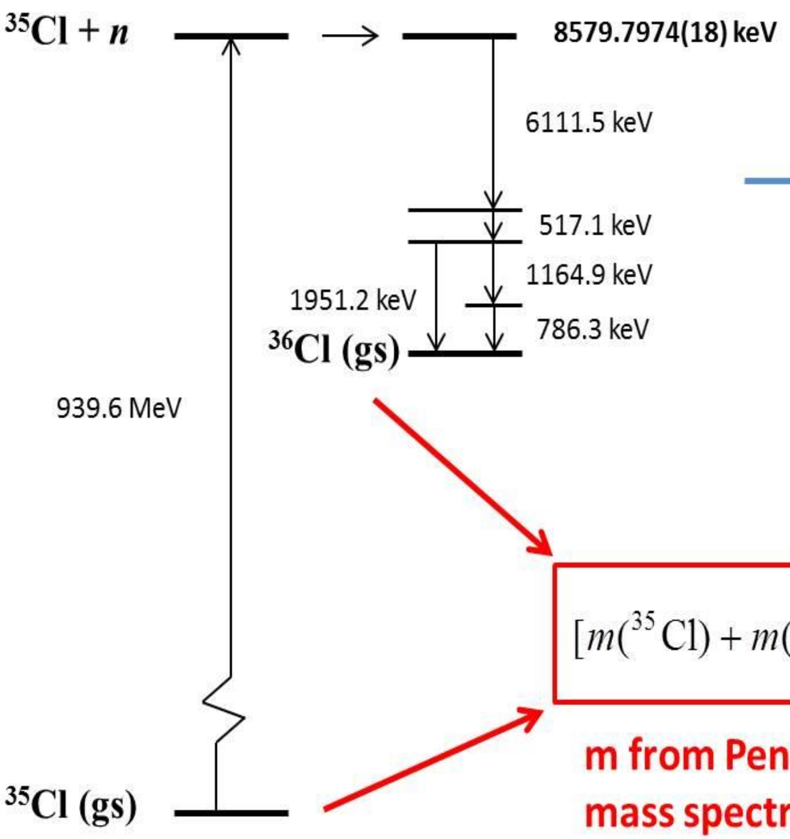
Motivation

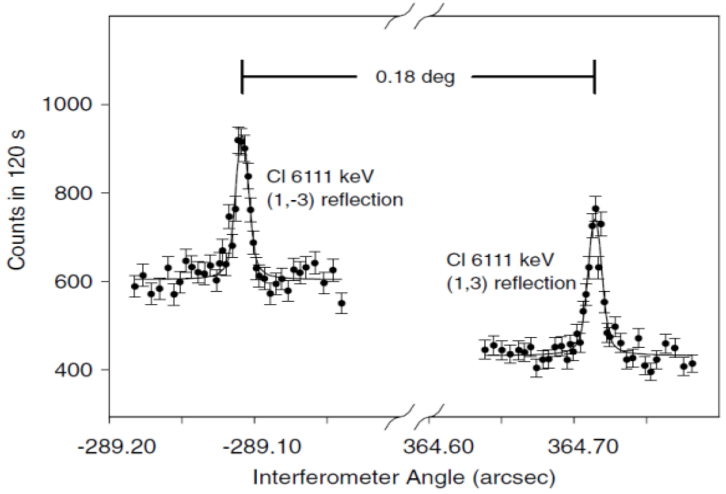
High-precision mass measurements for a test of E = mc^2



Cold neutron capture

$$^{35}\mathrm{Cl} + n \rightarrow {}^{36}\mathrm{Cl} + \gamma' s$$





$$[m(^{35}\mathrm{Cl}) + m(n) - m(^{36}\mathrm{Cl})]\, c^2 = hc\left[\sum \frac{1}{\lambda}\right]$$

m from Penning trap mass spectrometry

E from precise γ-ray spectroscopy

Motivation

High-precision mass measurements for

- Neutrino Physics (^{163}Ho, ^{7}Be)

$$^{163}\text{Ho} + e^{-} \rightarrow {}^{163}\text{Dy}^{*} + n_{e}$$

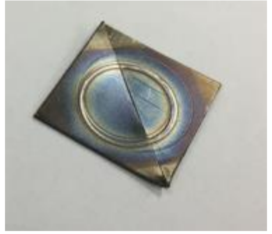
$$^{7}\text{Be} + e^{-} \rightarrow {}^{7}\text{Li} + \nu_{e}$$

- Tests of Special Relativity (^{35,36}Cl) $E = mc^2$

$$^{35}\text{Cl} + n \rightarrow {}^{36}\text{Cl} + \gamma's$$

Versatile ion sources for a range of isotopes

- Laser ablation source for solid materials

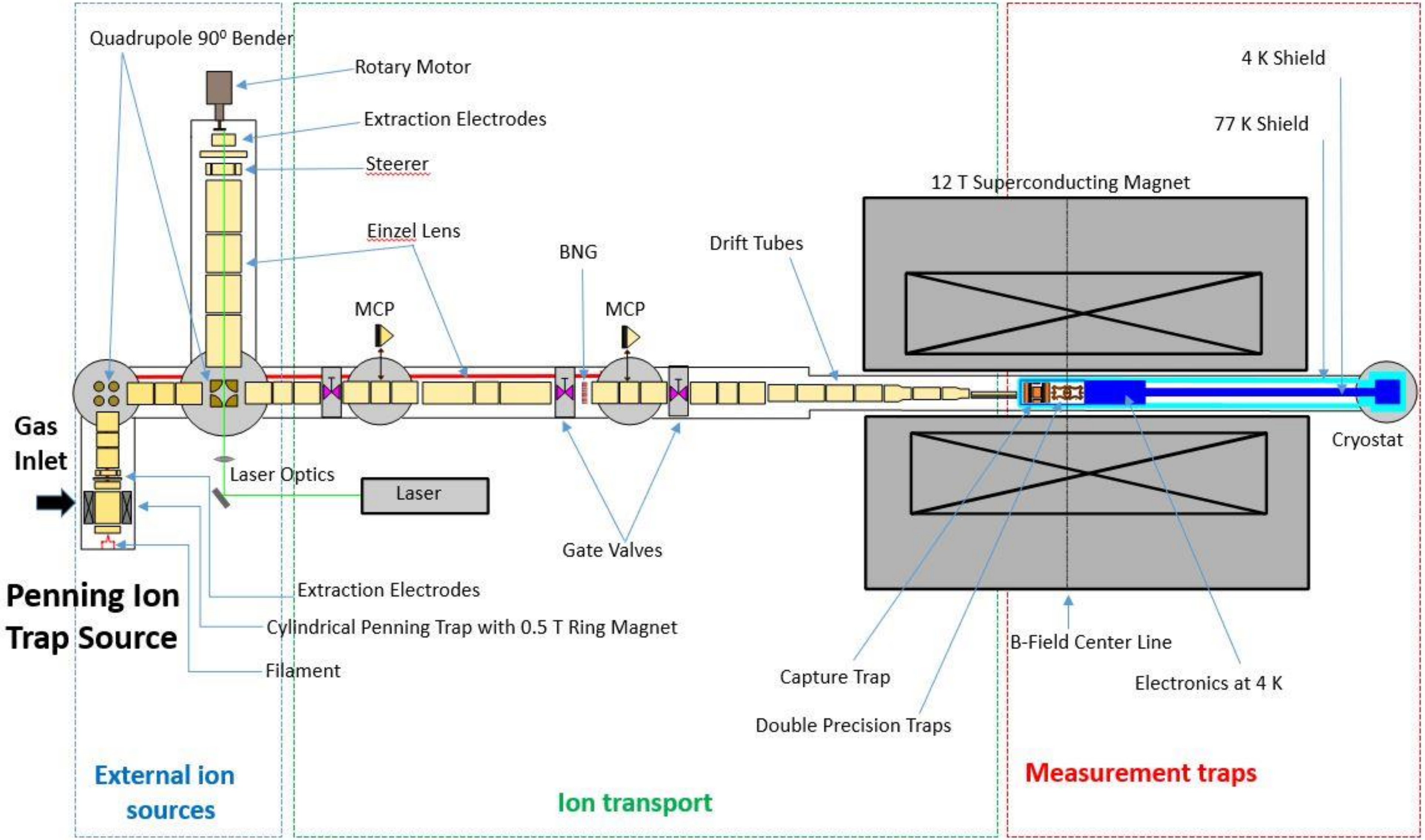


Poster - Precise Measurement of the ^{7}Be and ^{163}Ho Electron Capture Q-value for Neutrino Studies (Ramesh Bhandari – 21st Sep. Tuesday 9AM PDT)

- Electron impact ionization source for gases (^{35,36}Cl)

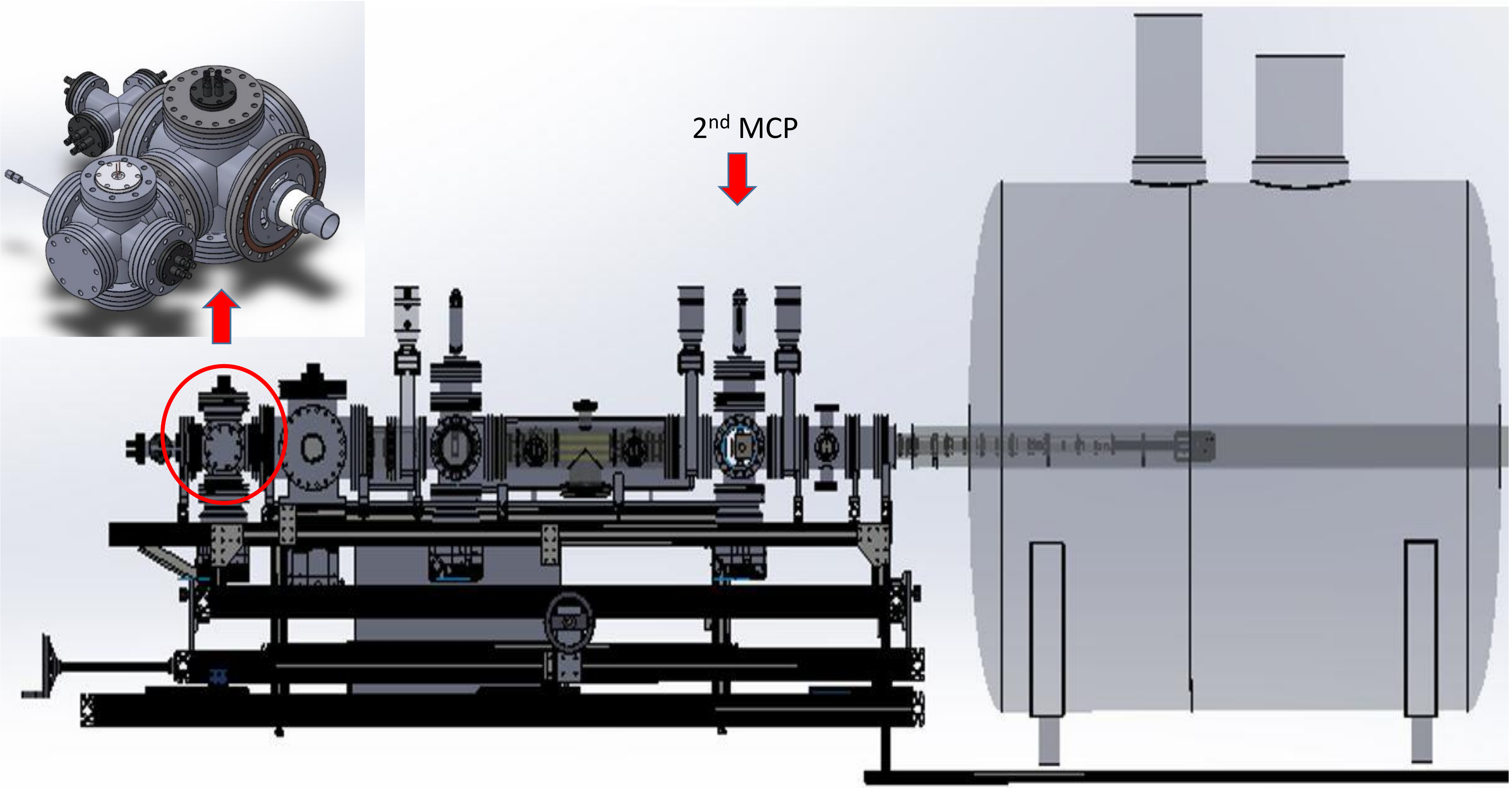
<u>A Penning Ion Trap Source</u>

CHIP-TRAP

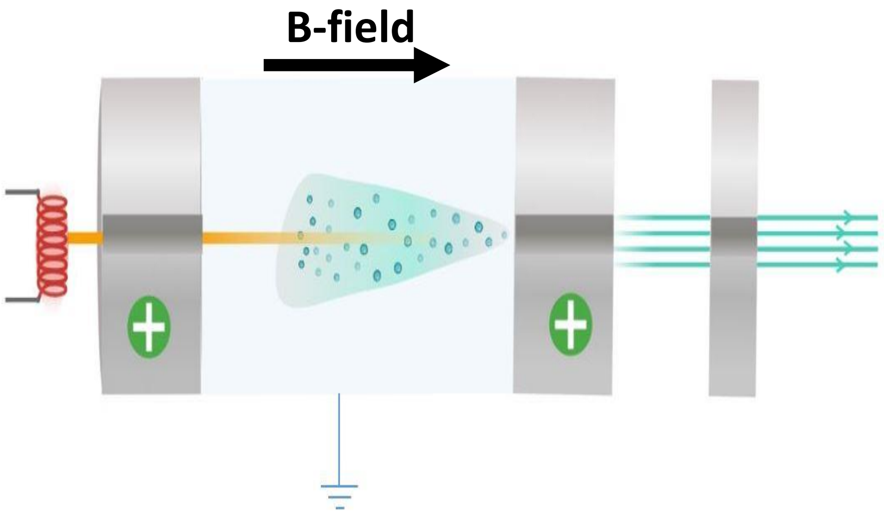


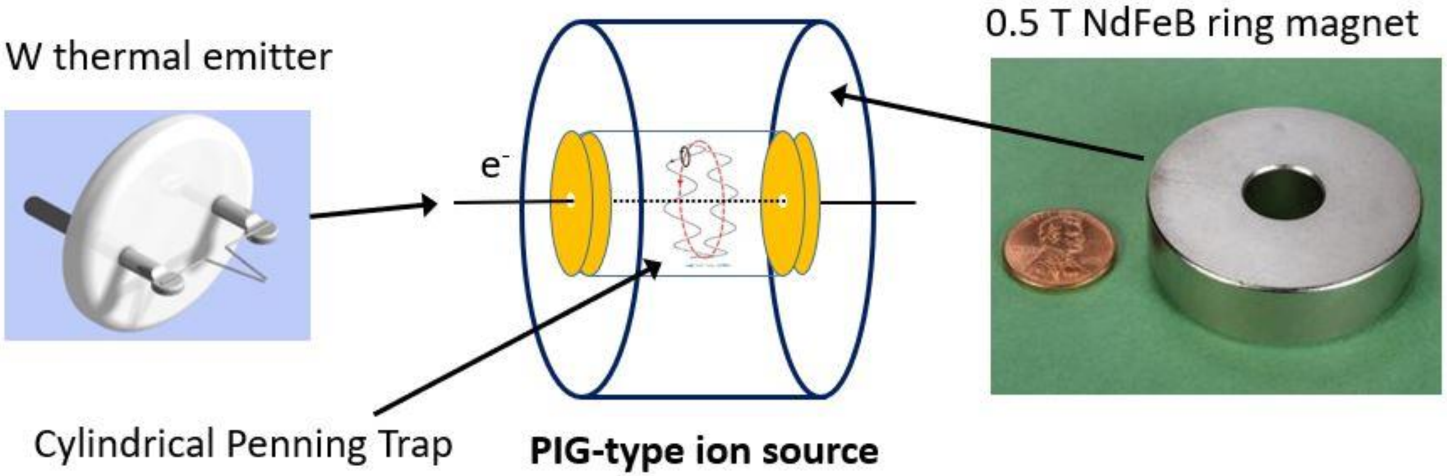
Quadrupole 90⁰ Bender
Rotary Motor
Extraction Electrodes
Steerer
Einzel Lens
BNG
Drift Tubes
12 T Superconducting Magnet
4 K Shield
77 K Shield
MCP
MCP
Gas Inlet
Laser Optics
Laser
Gate Valves
Cryostat
Penning Ion Trap Source
Extraction Electrodes
Cylindrical Penning Trap with 0.5 T Ring Magnet
Filament
Capture Trap
Double Precision Traps
B-Field Center Line
Electronics at 4 K
External ion sources
Ion transport
Measurement traps

CHIP-TRAP



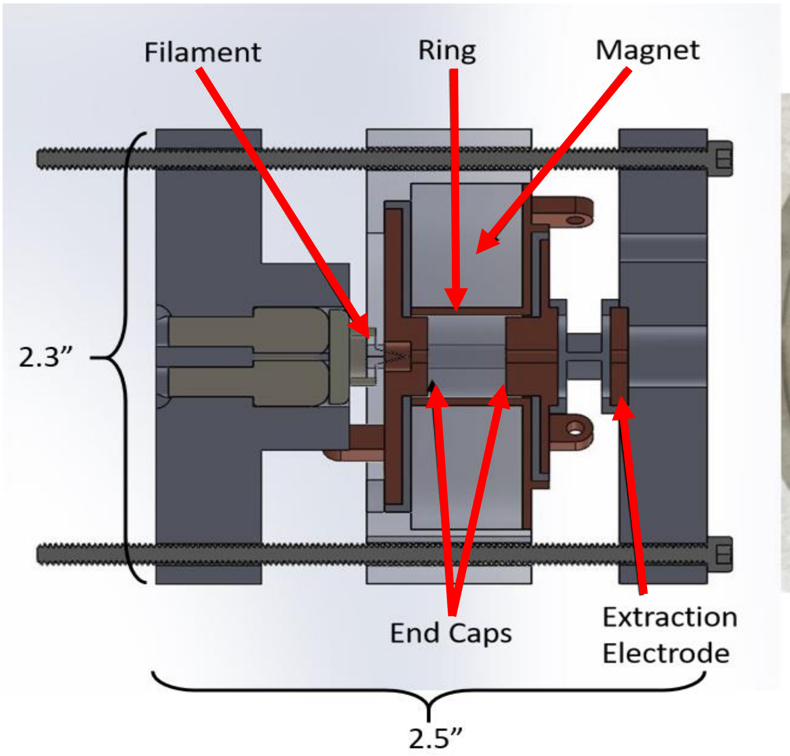
Penning Ion Trap Source (PITS)

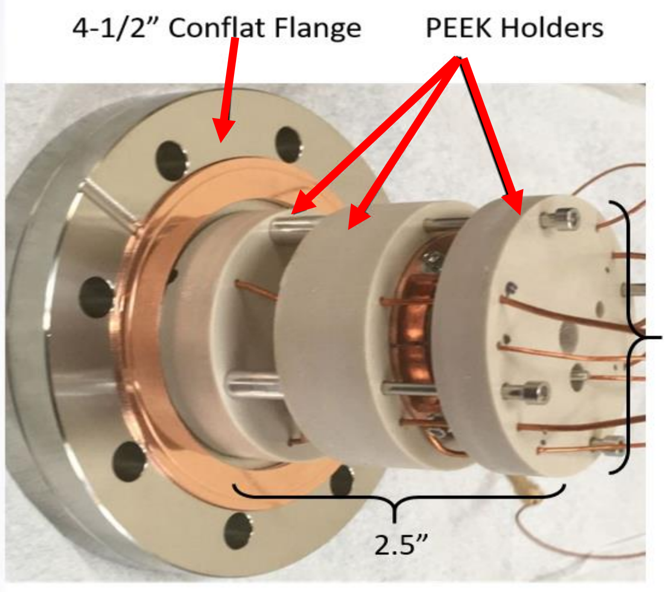


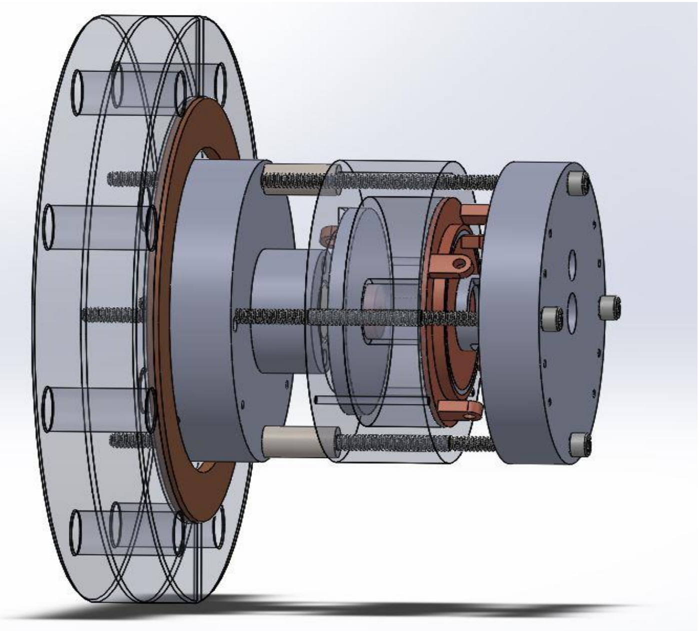


- **PIG-type ion source**
- **Trap ions inside a magnetic and electric field**
- **Trapped ions same behavior as ions in a Penning trap**

Penning Ion Trap Source (PITS)





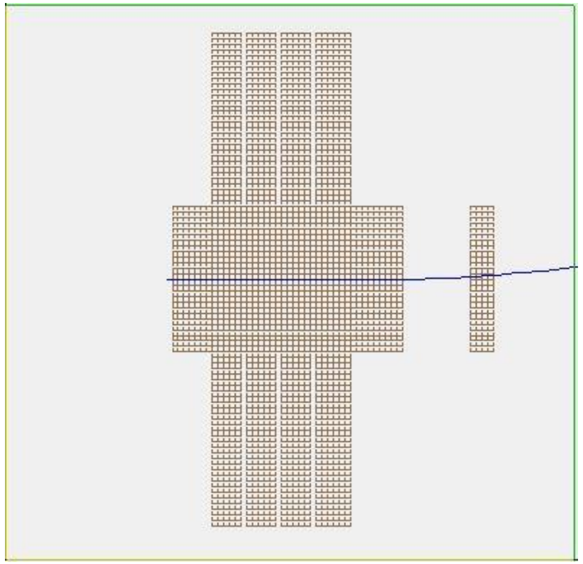


- ➢ **W thermal emitter, cylindrical shape trap, extraction electrodes and gas inlet**
- ➢ **Ions produced by electron impact ionization**
- ➢ **Trap ions in a small volume (0.8 cm^3)**
- ➢ **Extract ions as a bunch**

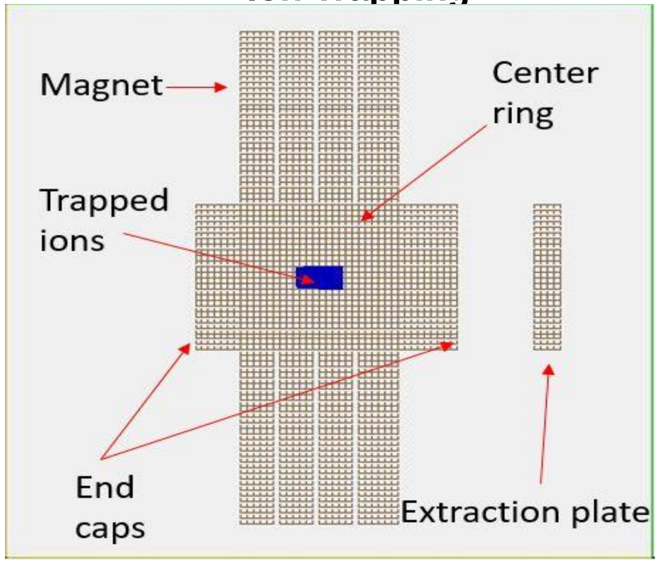
Simulation of PITS

- Electron beam emission
- Ion trapping
- Ion extraction
- Ion transport

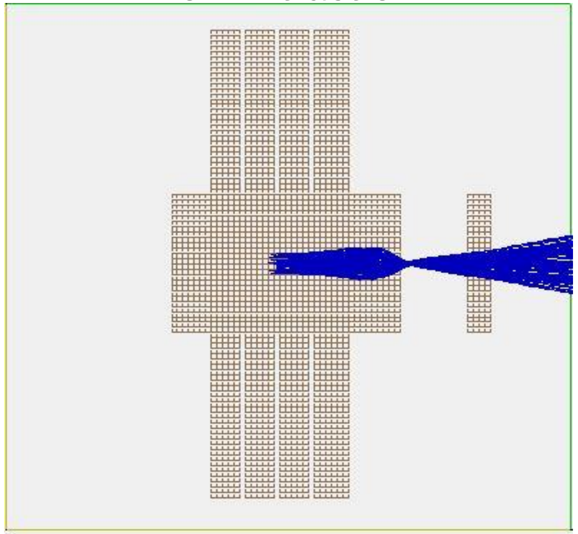
Electron Beam



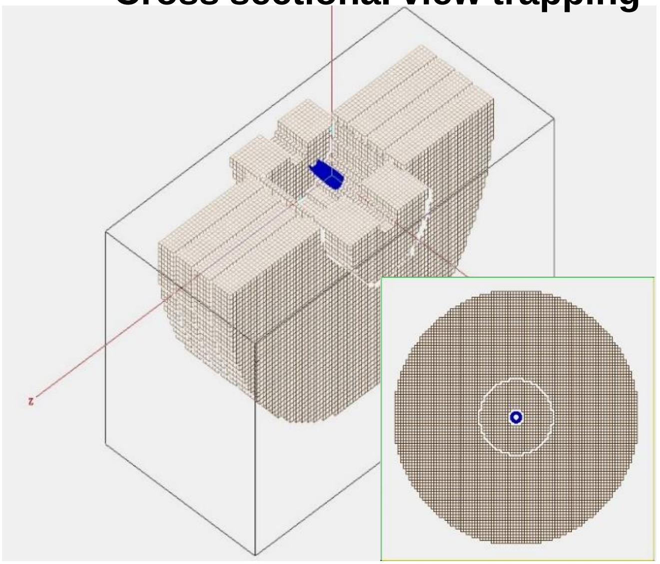
Ion Trapping



Ion Extraction

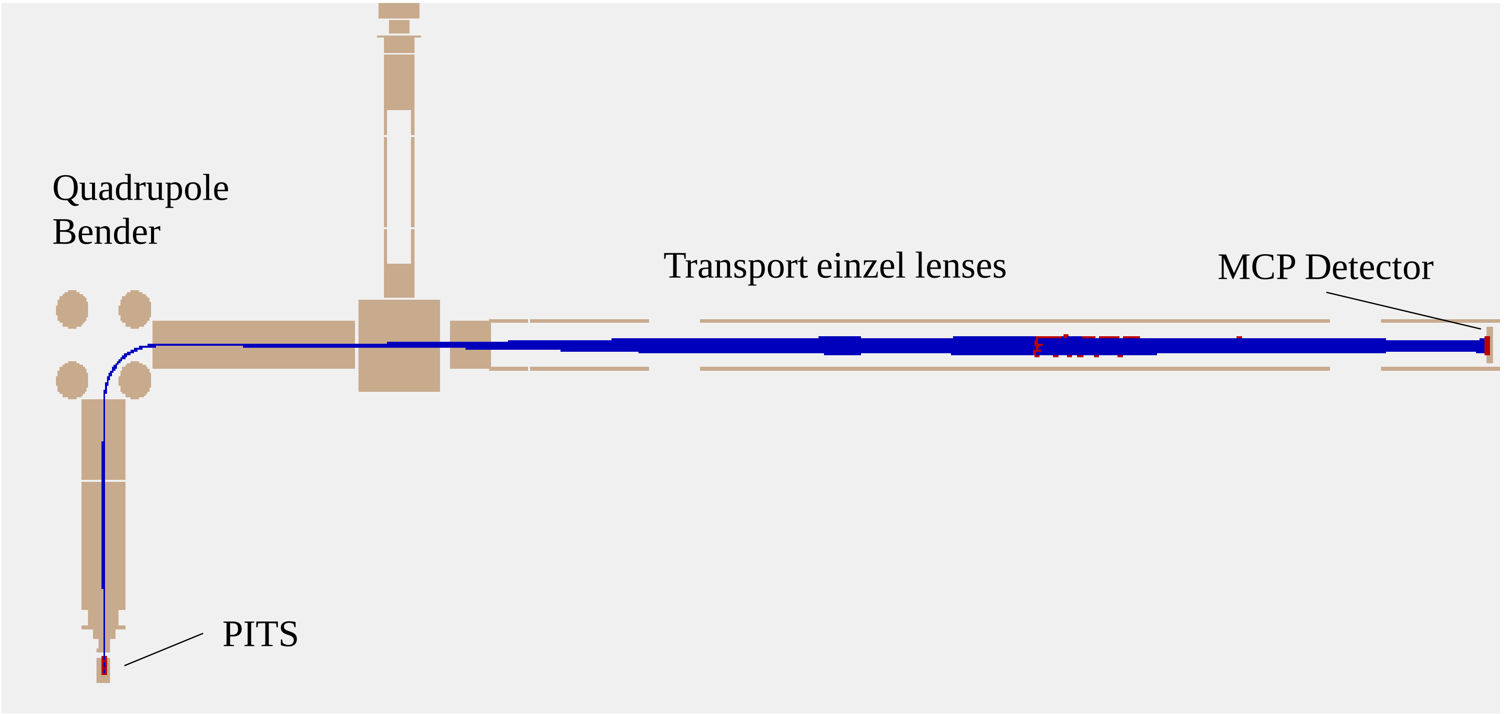


Cross sectional view trapping

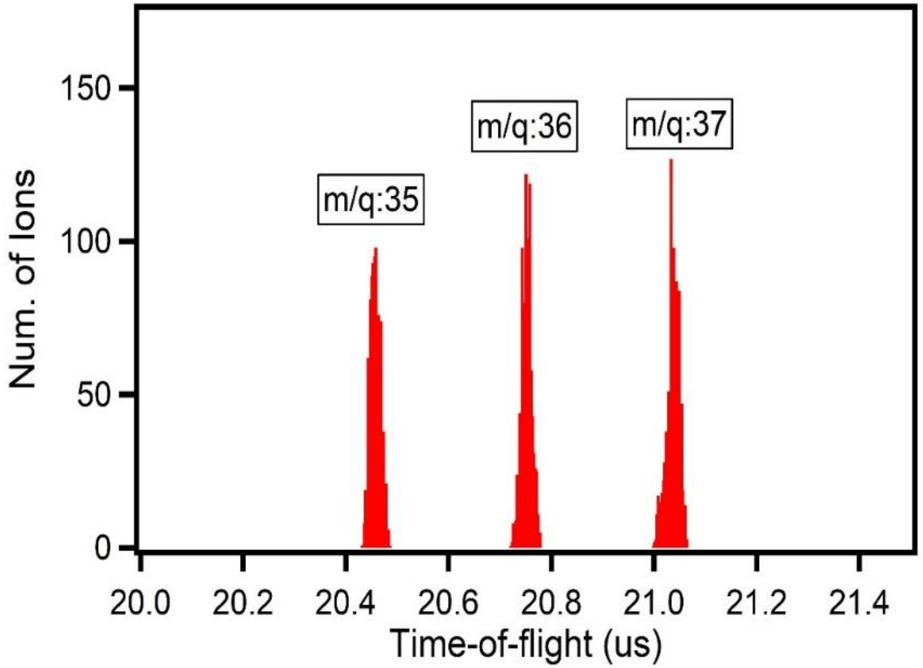


Simulation of PITS

- **Checked the ion transportation via Einzel lens and bender**
- **Separated the Cl isotopes**

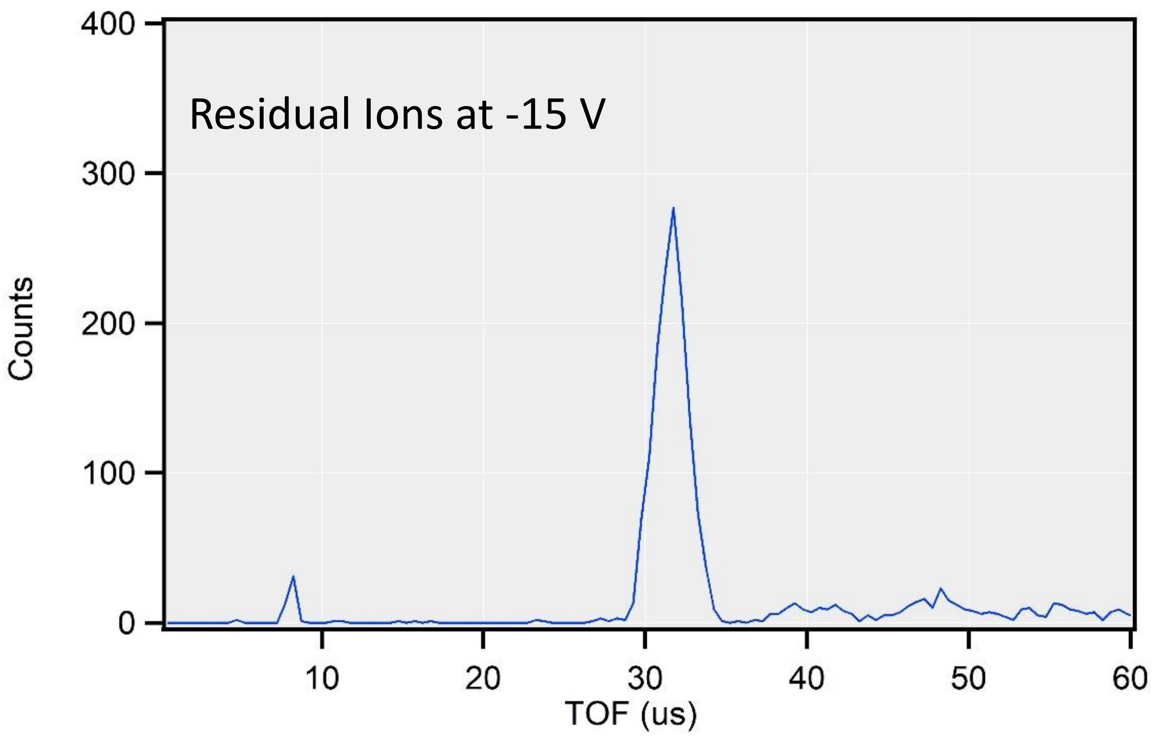


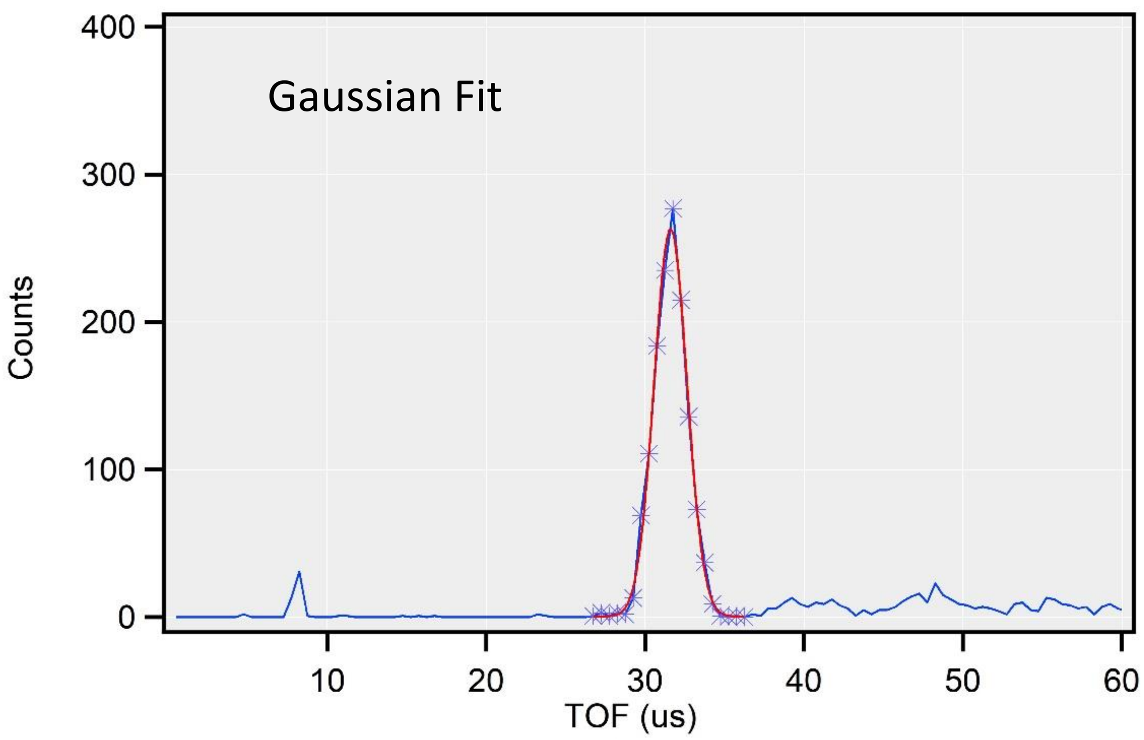
Ion Transport



Cl separation

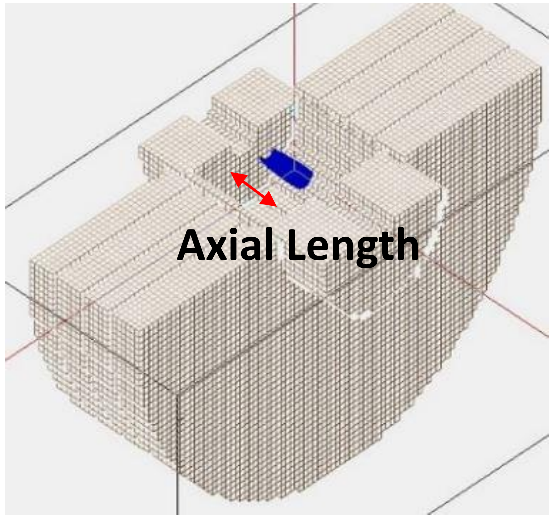
Results: Initial Test

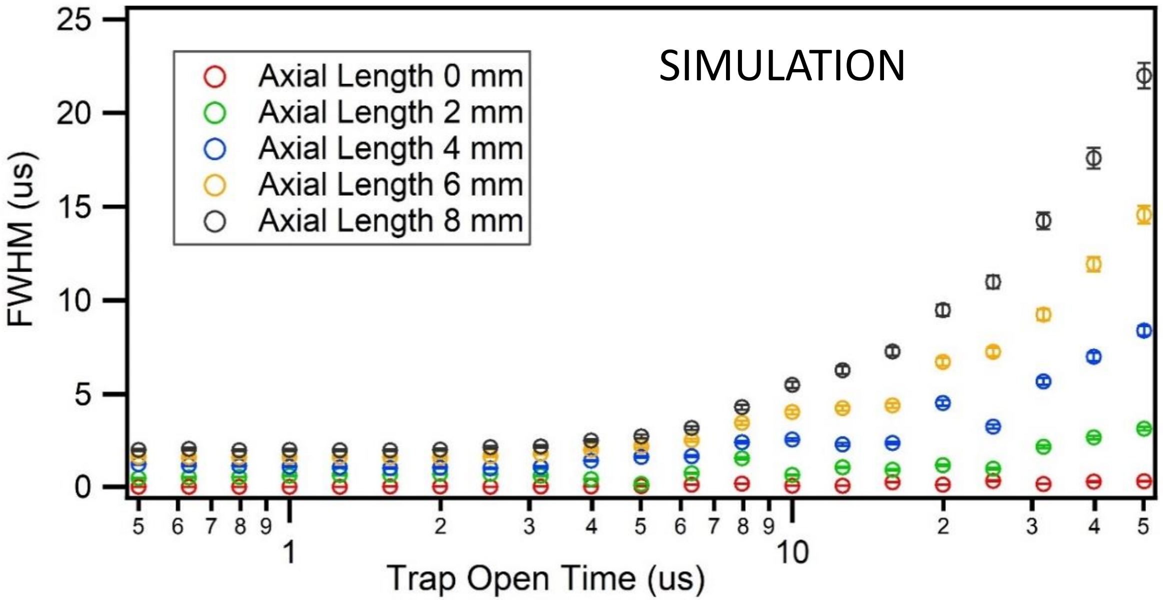


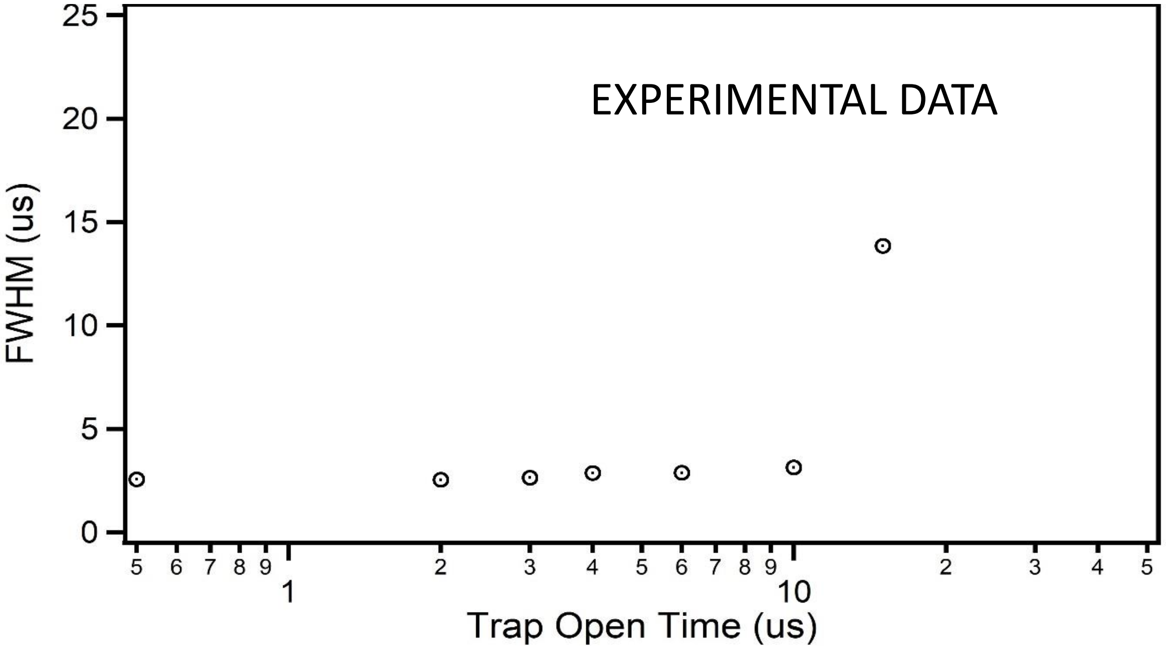


- **Ionization of residual gas in trap**
- **Release ion bunch and detect on MCP**
- **Fit Gaussian profile**
- **FWHM = 2.44 (0.54) us**

Results

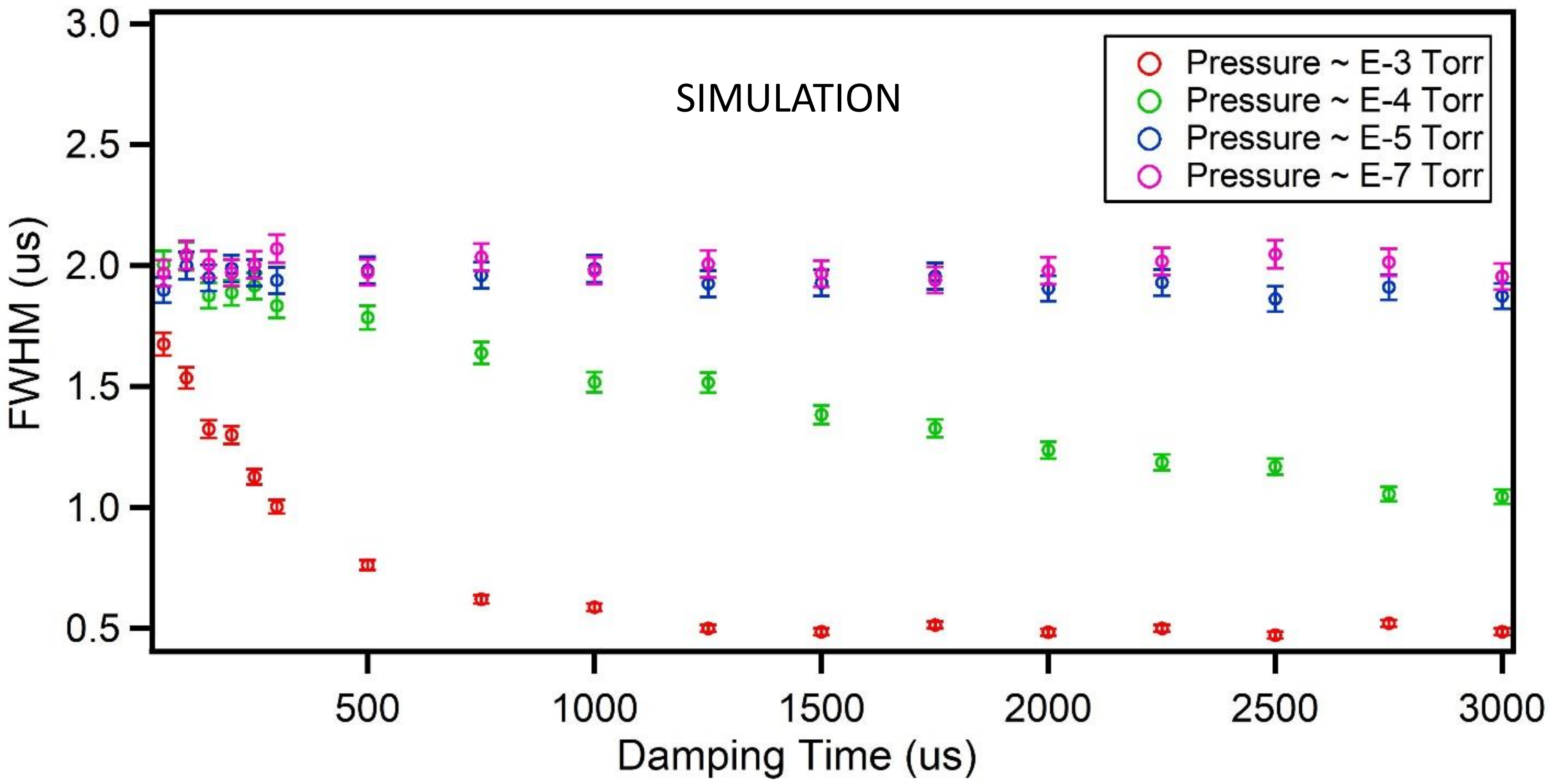






- **Used a 500 ns fast switch for opening trap**
- **Added capacitance to reduce opening time**
- **Agreement of experimental data and simulation**

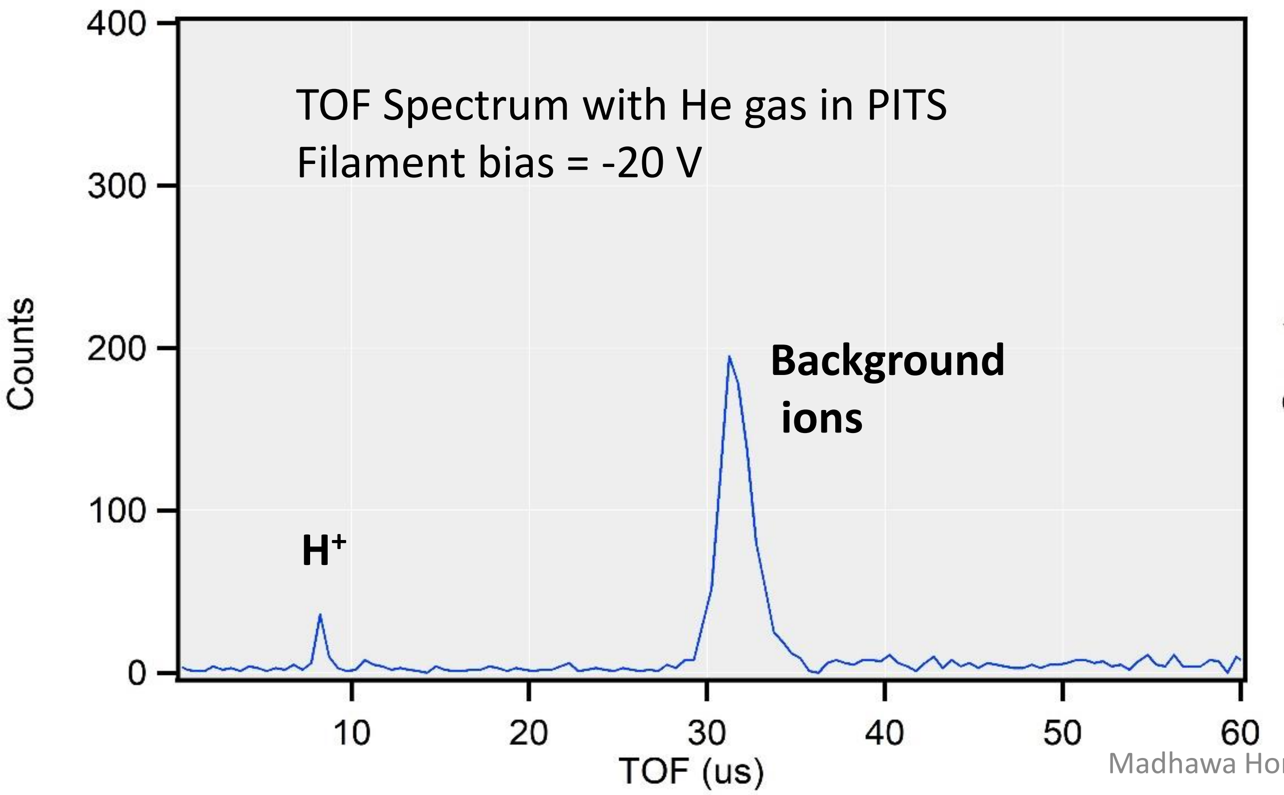
Results

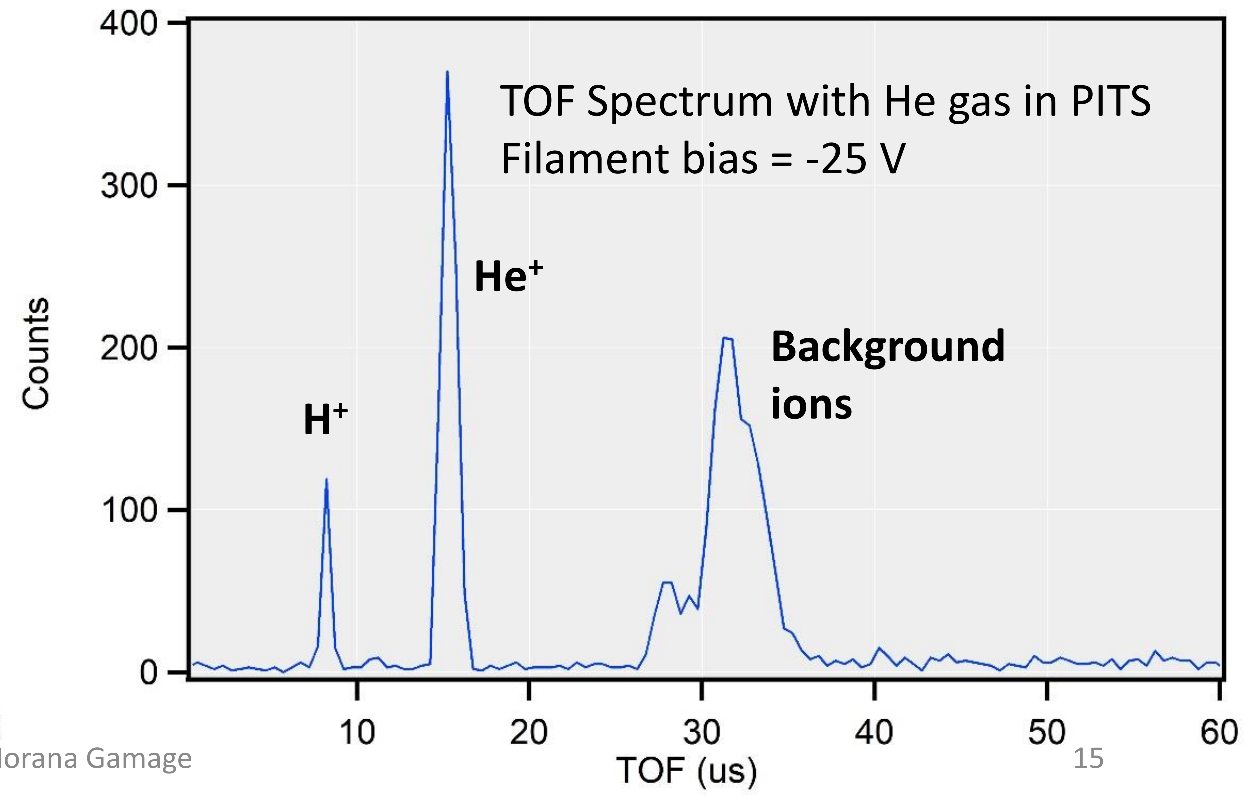


- **Investigated damping effect in the simulation**
- **Experimental investigation with background pressure ~ 10^{-5} – 10^{-6} showed no damping effect**

Results

- **Leaked He gas into PITS**
- **Varied electron beam energy**
- **He ionization energy = 24.6 eV**

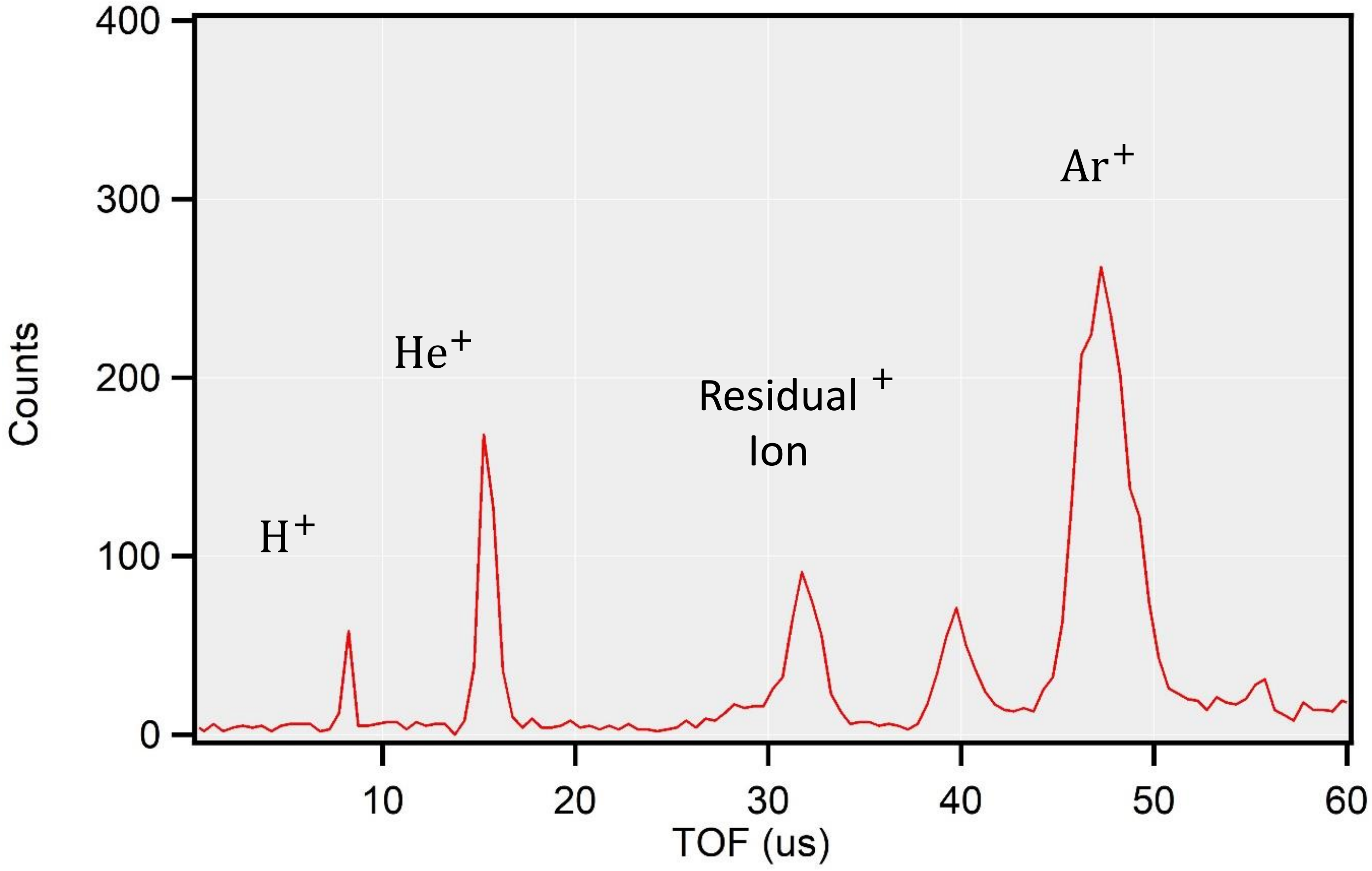




Calibration of PITS

- **Argon gas ionization**
- **Fit Gaussians for each peak**
- **Filament bias voltage -25 V**
- **Vacuum pressure of 5 x 10^{-6} Torr**

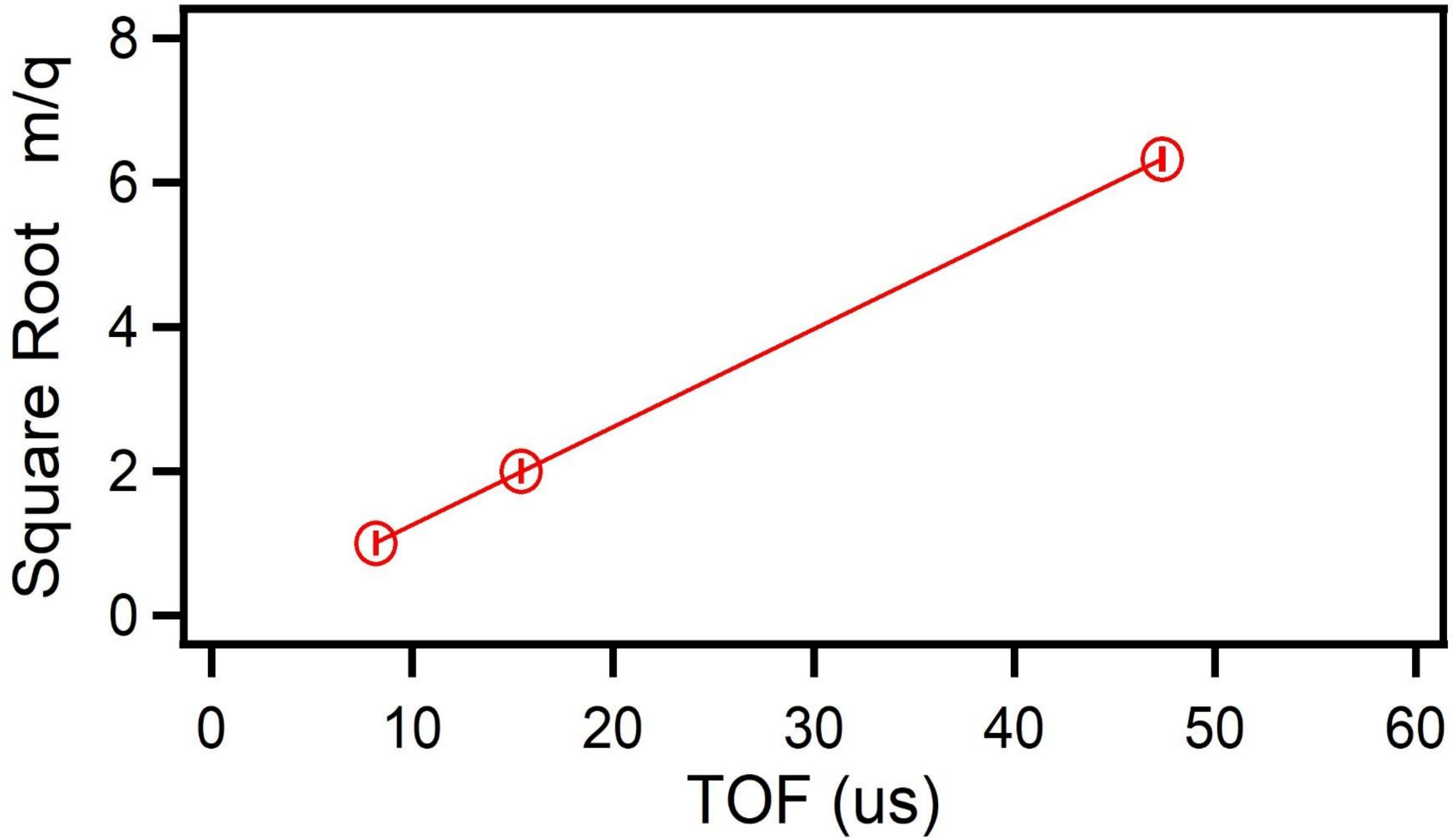
Peak	TOF	FWHM
H	8.17 (0.03)	0.51 (0.21)
He	15.43 (0.02)	0.92 (0.31)
Residual Ions	31.89 (0.05)	1.68 (0.56)
Unknown	39.77 (0.06)	1.84 (0.53)
Ar	47.36 (0.05)	3.11 (0.78)



Results

$$\textbf{TOF} \ \alpha \ \sqrt{\frac{\mathbf{m}}{q}}$$

Ion	Mass (u)	Sqrt(m/q) $(u/e)^{1/2}$	TOF (us)
H^+	1	1	8.17
He^+	4	2	15.43
Ar^+	40	6.32	47.36

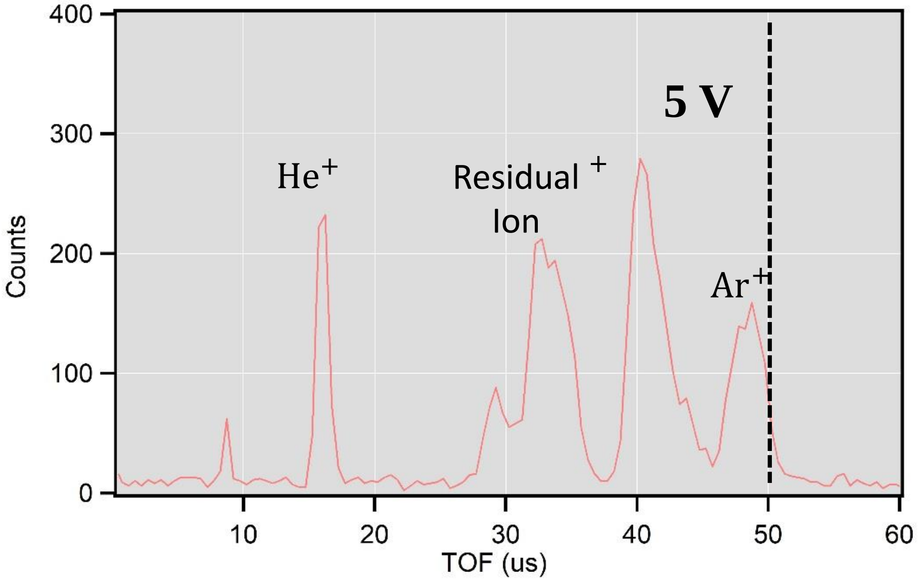


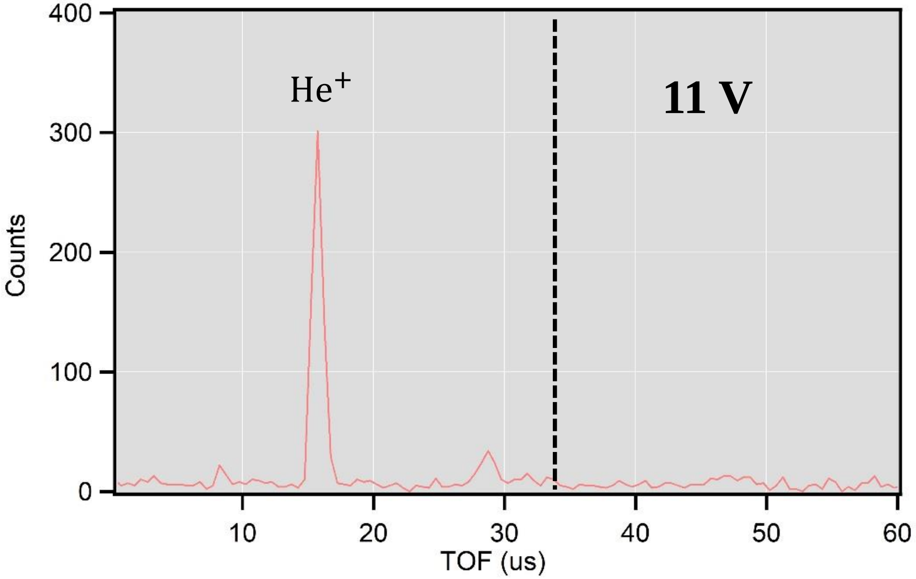
Ion	Calculated Mass (a.m.u)	Error (a.m.u)	Possible candidate
Residual Ions	17.9	1.3	H_2O^+ m = 18 u H_3O^+ m = 19 u

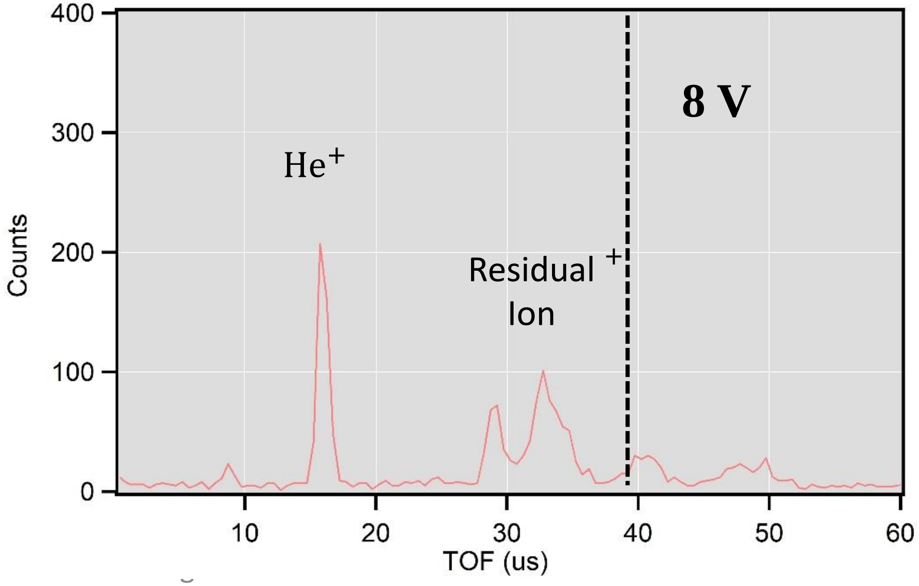
Experimental Results

- **Checked PITS with different end cap voltages**
- **Peaks due to higher mass gases go away when the EC Voltages are increased**

$$\omega_c^{\,2} > \; 2\omega_z^{\,2} \;\longrightarrow\; \left(\frac{qB}{m}\right)^2 > \frac{2qV_0}{md^2}$$







Conclusion

- ***Design, simulation, fabrication and assembly of PITS completed.***
- ***Initial commissioning of PITS begun.***
- ***Agreement between experimental and simulated data observed.***
- ***Calibration of PITS using He and Ar gases underway.***
- ***Future work –calibrate PITS with additional gases; use PITS to create Cl ions.***

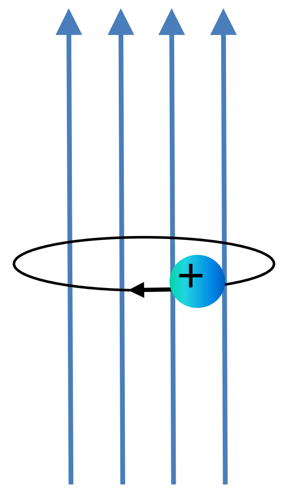
Acknowledgement

- ***Dr. Matthew Redshaw, Nadeesha Gamage, Ramesh Bhandari, Zachary Purcell and Dakota Keblbeck.***
- ***CMU Physics Department***
- ***National Science Foundation (PHY-1607429)***
- ***US Department of Energy (DE-SC0015927)***

Thank You
Questions ?

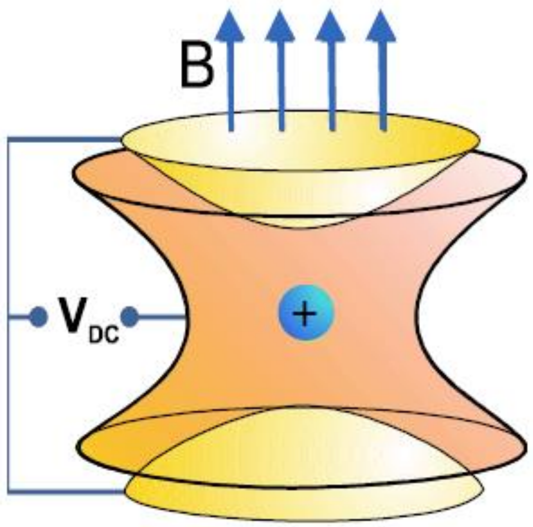
Penning Trap Physics

Uniform B-Field



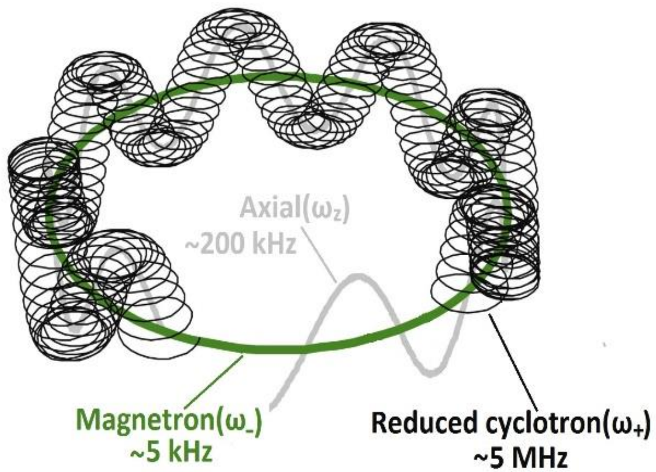
\+

Quadrupole E-Field



=

3 Normal Modes



Measure cyclotron frequency to determine mass

$$\omega_c = \frac{qB}{m}$$

ω_c = cyclotron frequency
m = mass
q = charge
B = magnetic field strength

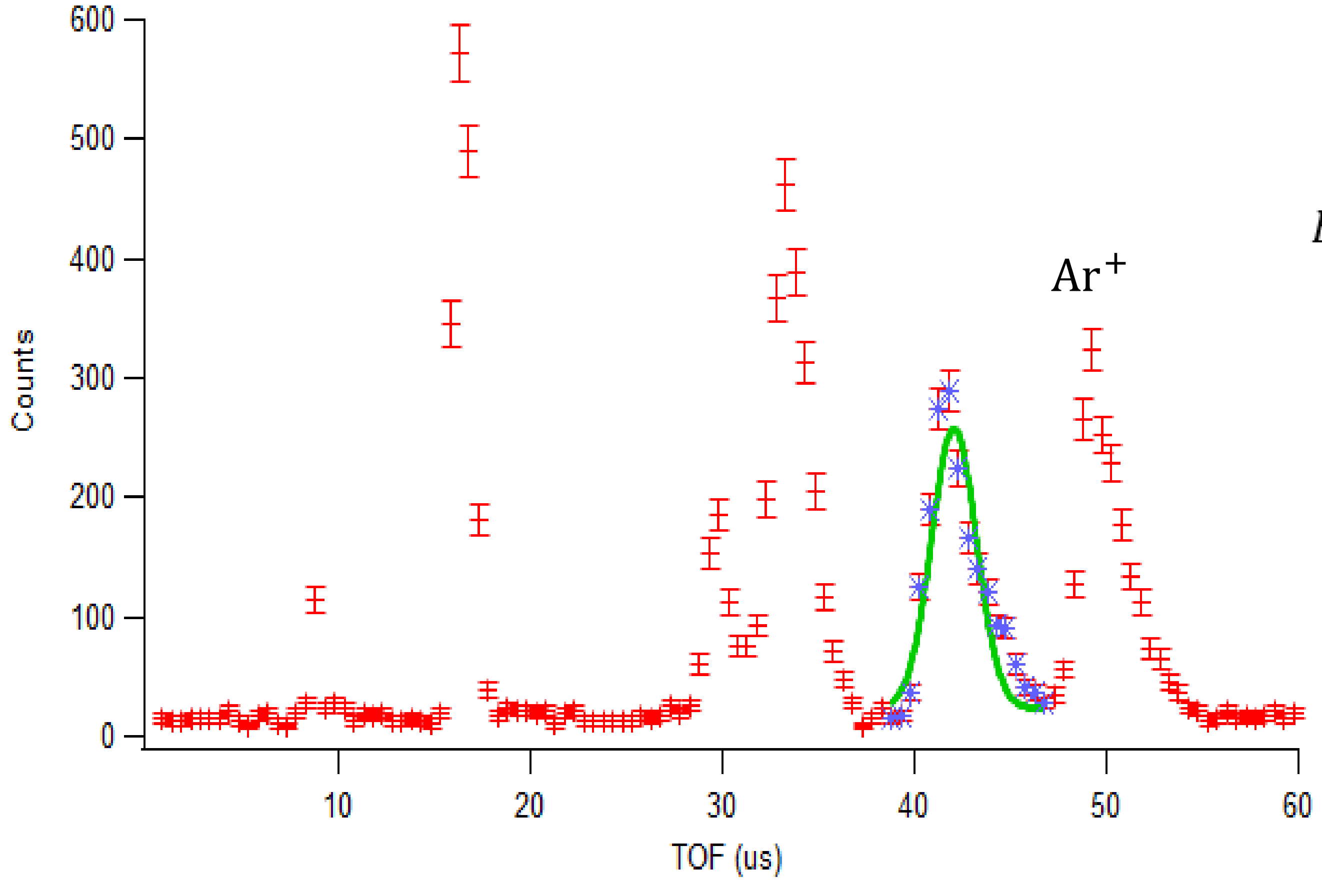
True cyclotron frequency is related to the trap-mode frequencies via

$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

ω_c = Cyclotron frequency
ω_+ = Reduced cyclotron frequency
ω_- = Magnetron frequency
ω_z = Axial frequency

Gaussian Fittings

$$y_0 + A \exp\left\{-\left(\frac{x-x_0}{width}\right)^2\right\}$$



$$\sigma = \frac{\text{width}}{\sqrt{2}}$$

$$FWHM = \frac{2.3548\ .\ \text{width}}{\sqrt{2}}$$

$$Error\ of\ \sigma = \frac{\sigma}{\sqrt{N}}$$

$$Error\ of\ FWHM = \frac{\partial(\text{FWHM})}{\partial\sigma} Error\ of\ \sigma$$

$$Error\ of\ FWHM = \frac{2.3548\ .\ \sigma}{\sqrt{N}}$$

```
V_chisq= 175.189;V_npnts= 17;V_numNaNs= 0;V_numINFs= 0;
V_startRow= 0;V_endRow= 199;
W_sigma={2.74,8.67,0.0401,0.0614}
Coefficient values ± one standard deviation
 y0    =23.535 ± 2.74
 A     =234.33 ± 8.67
 x0    =42.032 ± 0.0401
 width =1.6549 ± 0.0614
```

Calculate mass error

Row	M_Covar[][0]	M_Covar[][1]
	0	1
0	0.00151106	-7.90139e-05
1	-7.90139e-05	4.5751e-06

$$y = f(a, b, x) = a + bx$$

$$\sigma_y{}^2 = \sigma_a{}^2 \left(\frac{\partial y}{\partial a}\right)^2 + \sigma_b{}^2 \left(\frac{\partial y}{\partial b}\right)^2 + 2\sigma_{ab}{}^2 \left(\frac{\partial y}{\partial a}\right)\left(\frac{\partial y}{\partial b}\right) + \sigma_x{}^2 \left(\frac{\partial y}{\partial x}\right)^2$$

$$\sigma_y{}^2 = 1.511e^{-3}(1)^2 + 4.575e^{-6}(x)^2 + 2(-7.901e^{-5})(1)(x) + (0.0256)^2(b)^2$$

$$x = 33.507\,, b = 0.16424$$

$$\sigma_y{}^2 = 1.3645e^{-3}$$

$$\sigma_y = 0.0369$$

EC Voltage	Mass limit	TOF limit
5	41	49.5
8	26	39.0
11	19	33.3