FRIB

Status and Further Development of the Single Ion Penning Trap (SIPT) Mass Spectrometer

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MICHIGAN STATE UNIVERSITY

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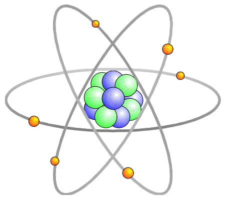
Nuclear Physics and the Importance of Precision Mass Measurements

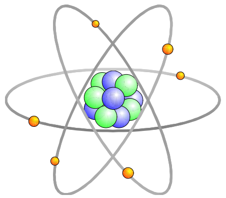


= N • + Z • + Z •

\- binding energy

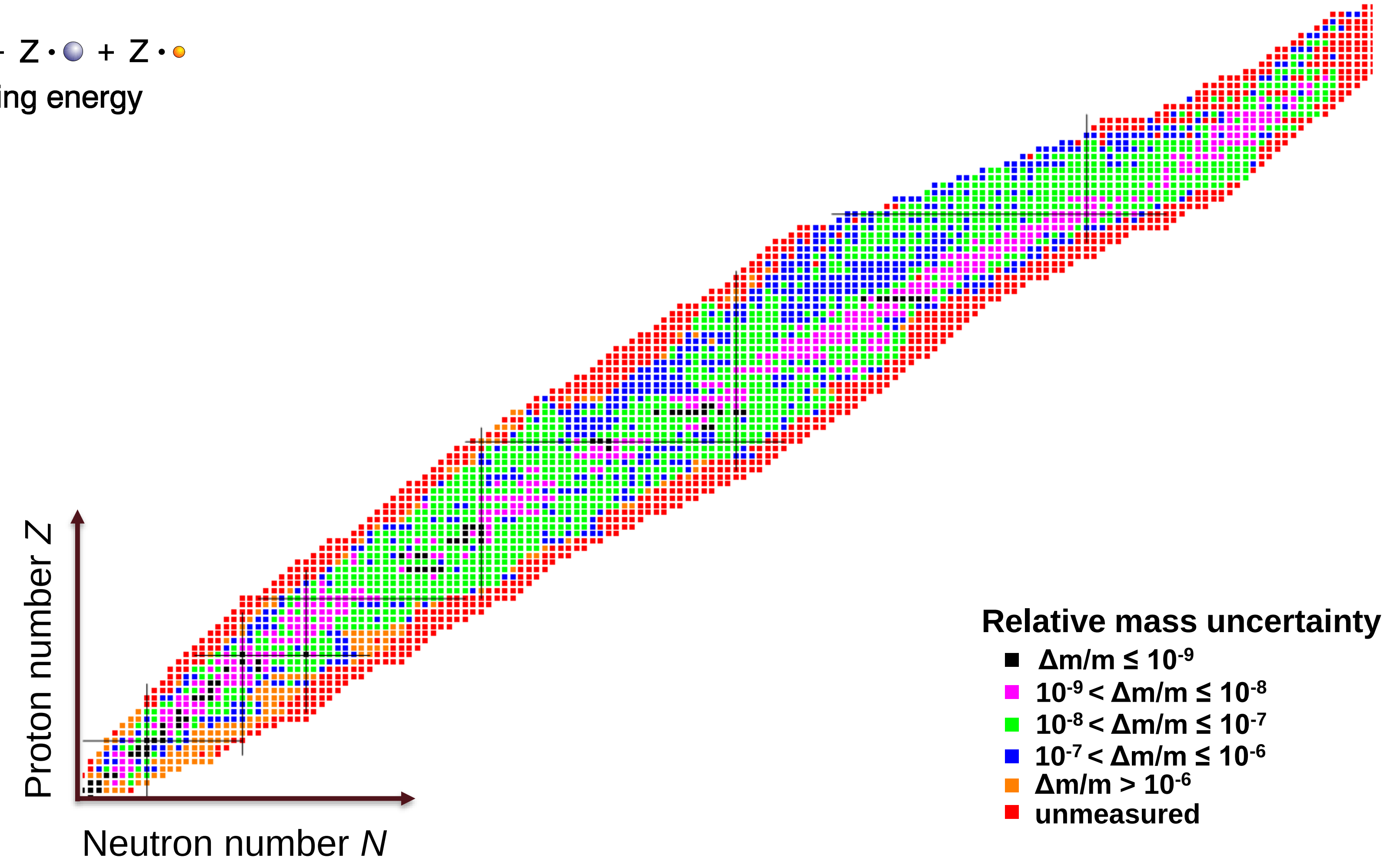
Nuclear Physics and the Importance of Precision Mass Measurements

AME20: Huang et al., Chin. Phys. C 45, 030002 (2021)



= N • (neutron) + Z • (proton) + Z • (electron)

- binding energy



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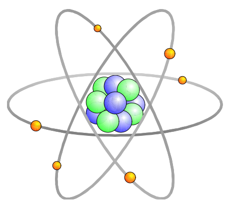

= N • ● + Z • ● + Z • ●
- binding energy

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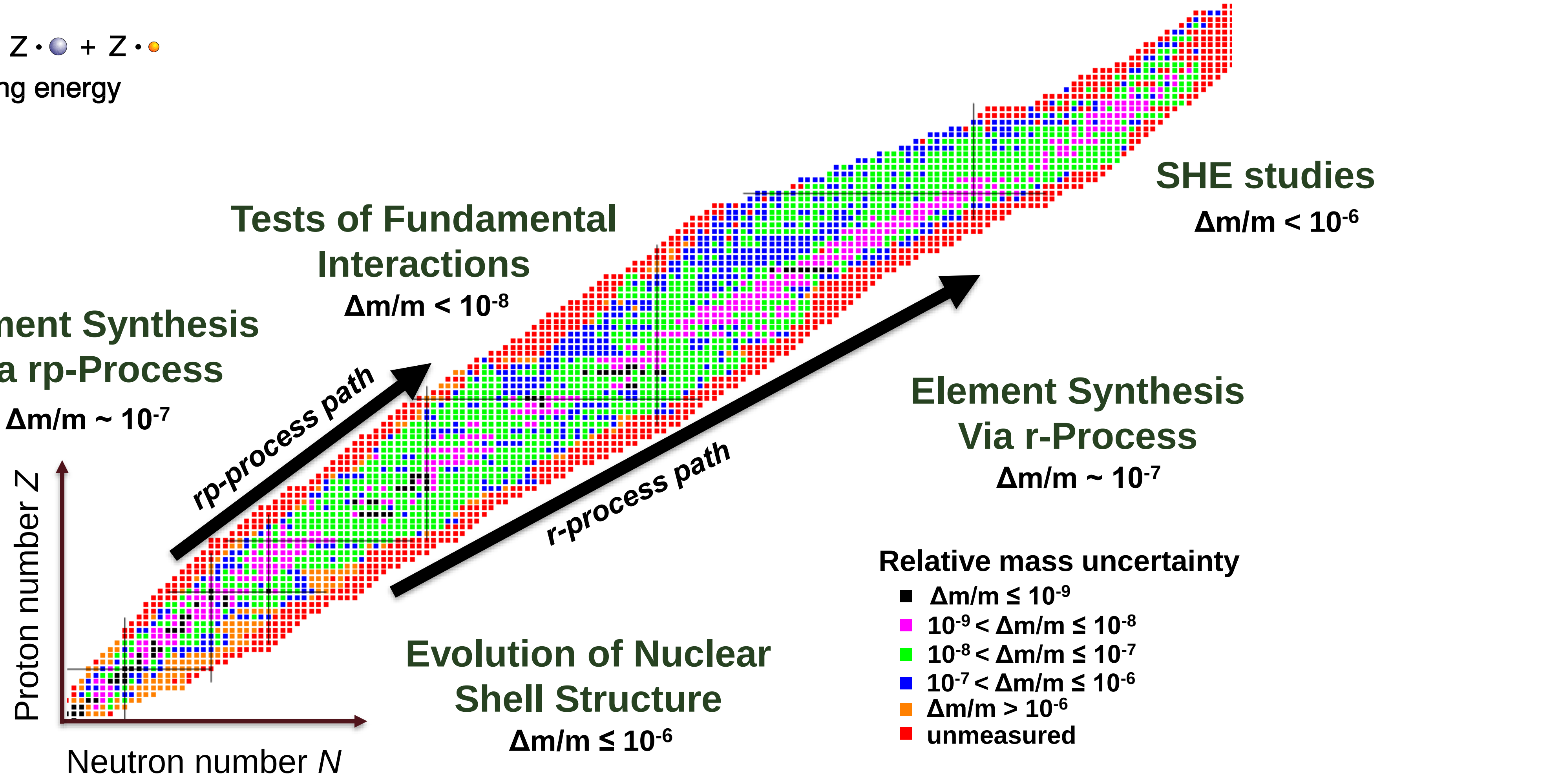

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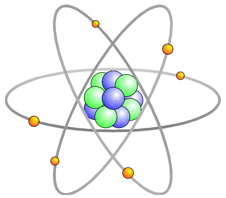

= N • ● + Z • ● + Z • ●

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Penning trap mass spectrometry is the most precise method for mass measurements

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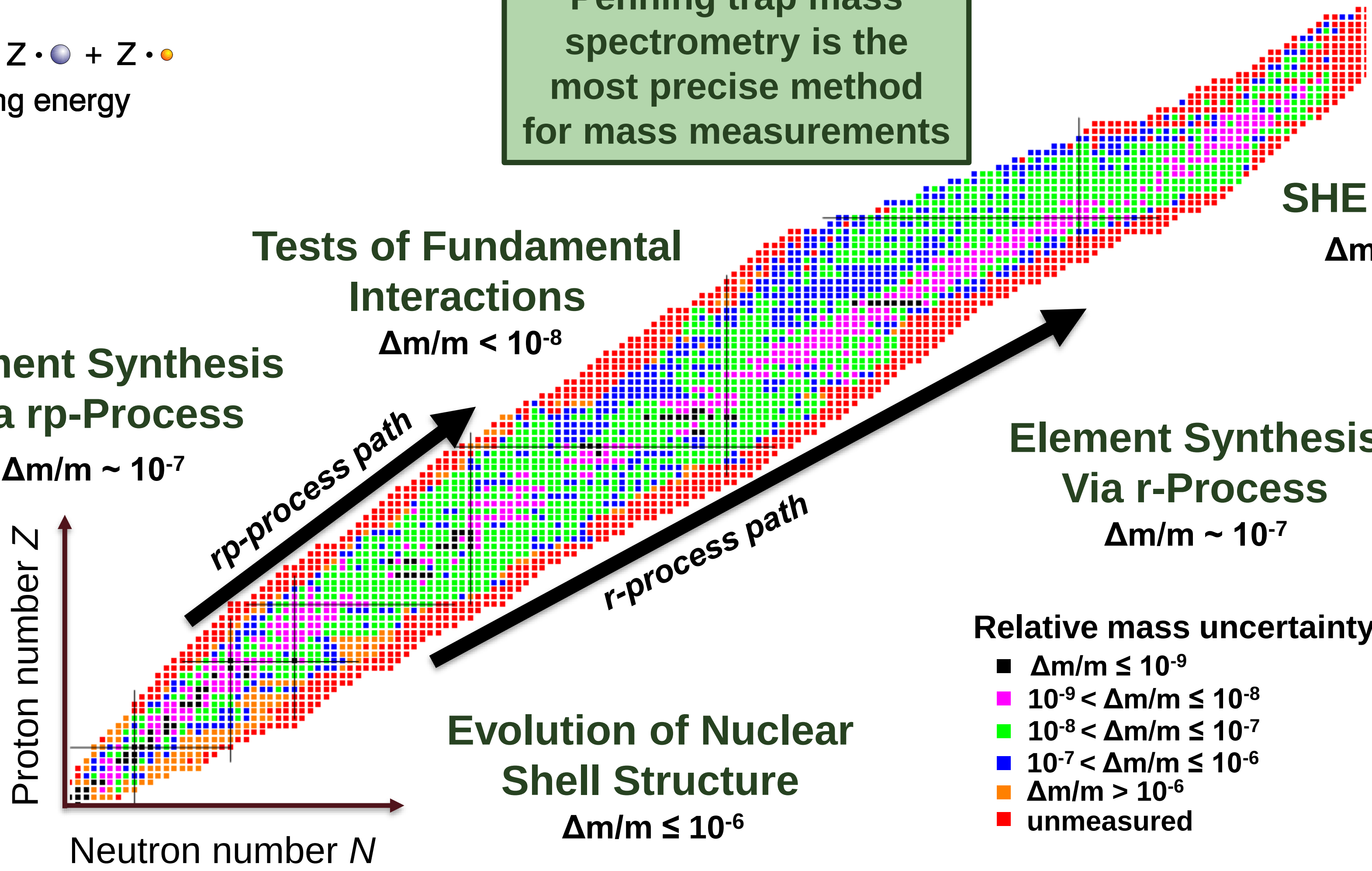


Element Synthesis Via rp-Process
$\Delta m/m \sim 10^{-7}$

Tests of Fundamental Interactions
$\Delta m/m < 10^{-8}$

SHE studies
$\Delta m/m < 10^{-6}$

Element Synthesis Via r-Process
$\Delta m/m \sim 10^{-7}$

Evolution of Nuclear Shell Structure
$\Delta m/m \leq 10^{-6}$

Relative mass uncertainty

- $\Delta m/m \leq 10^{-9}$
- $10^{-9} < \Delta m/m \leq 10^{-8}$
- $10^{-8} < \Delta m/m \leq 10^{-7}$
- $10^{-7} < \Delta m/m \leq 10^{-6}$
- $\Delta m/m > 10^{-6}$
- unmeasured

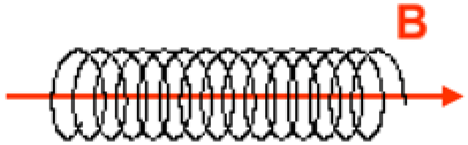
Outline

- Penning Traps & The Low Energy and Beam Ion Trapping (LEBIT) Facility
  - Introduction to Penning Traps
  - LEBIT Facility Overview
  - Current Techniques
- Motivation for the Single Ion Penning Trap
  - Rates at the Facility for Rare Isotope Beams (FRIB)
  - Fourier-Transform Ion Cyclotron Resonance (FT-ICR)
- Single Ion Penning Trap Developments
  - Hardware
  - Software/Analysis Tools
- Summary and Future Work

Performing Precision Mass Measurements with Penning Traps

Uniform Magnetic Field

(radial confinement)



$$\omega_c = \frac{q}{m} B$$

"cyclotron frequency"

Performing Precision Mass Measurements with Penning Traps

Uniform Magnetic Field + Quadrupolar Electrostatic Field

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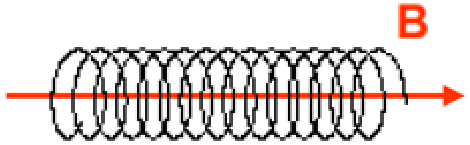

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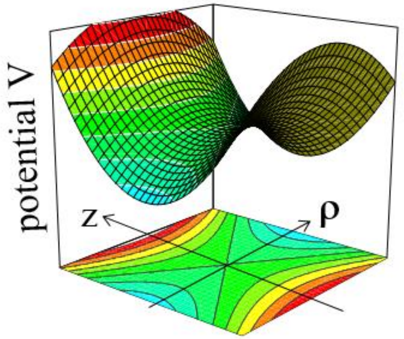
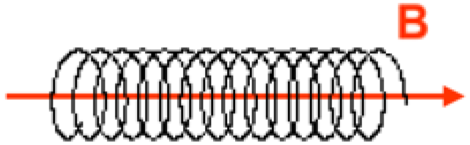


Performing Precision Mass Measurements with Penning Traps

Uniform Magnetic Field + Quadrupolar Electrostatic Field = Penning Trap

(radial confinement) (axial confinement) (3D confinement)



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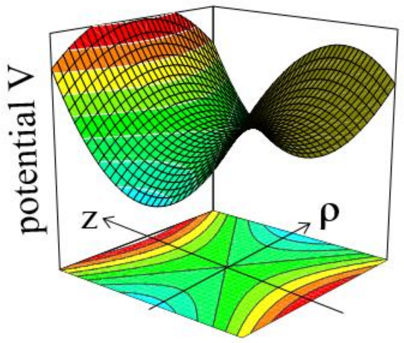

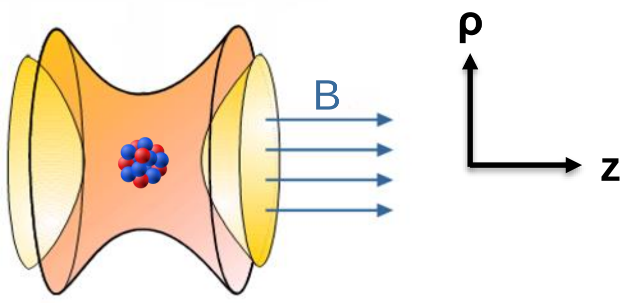

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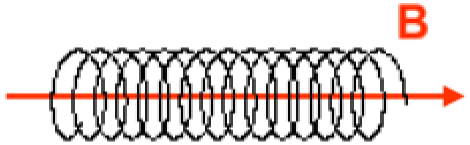

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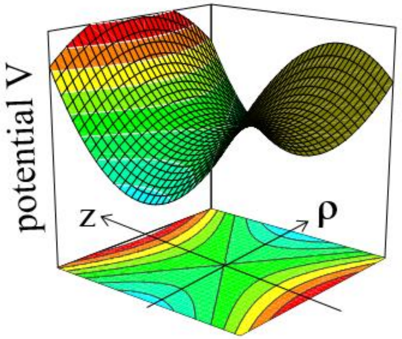

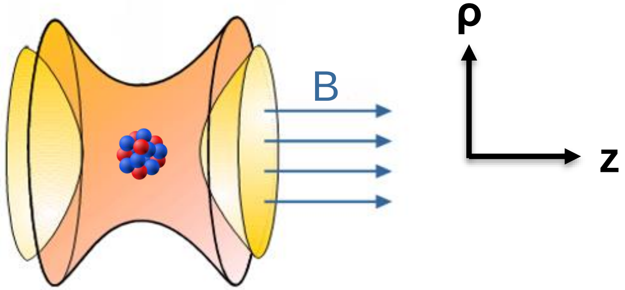

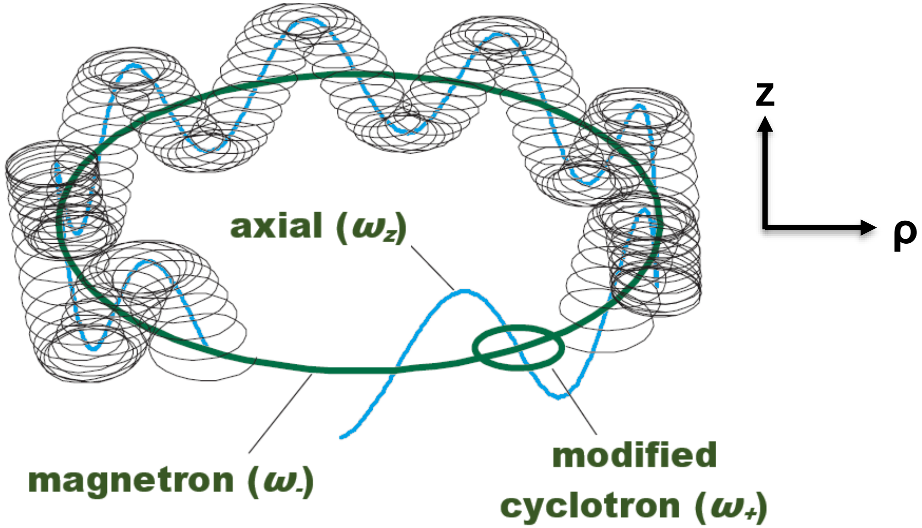

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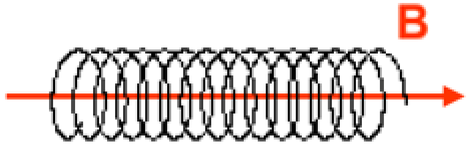

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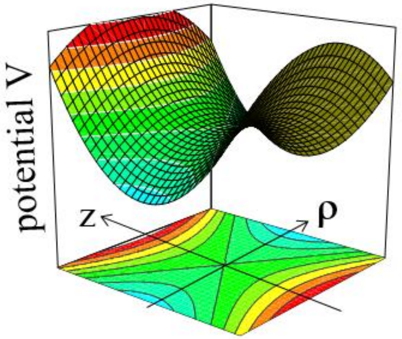
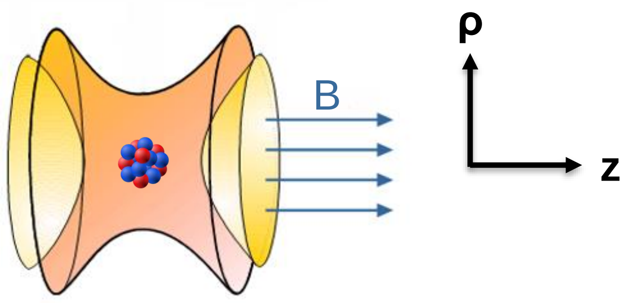
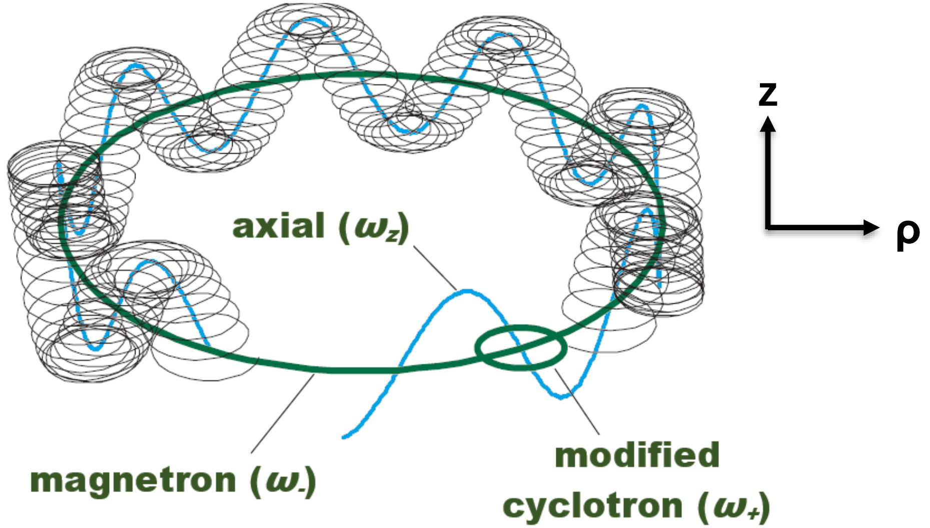




$$\omega_c \approx \omega_- + \omega_+$$



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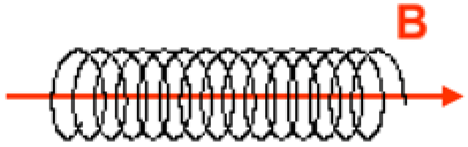

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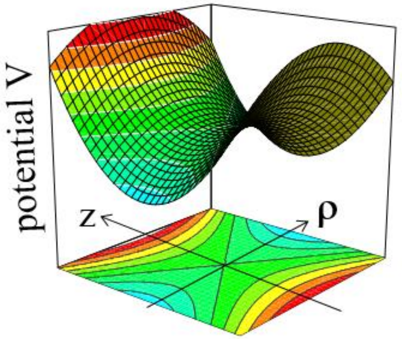
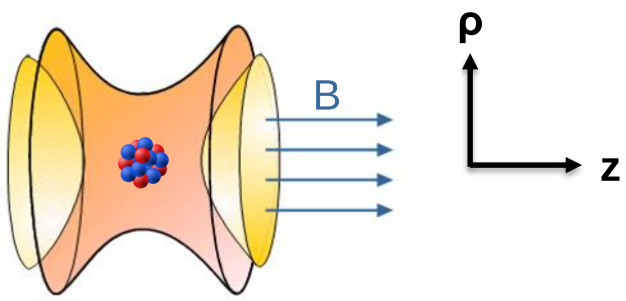
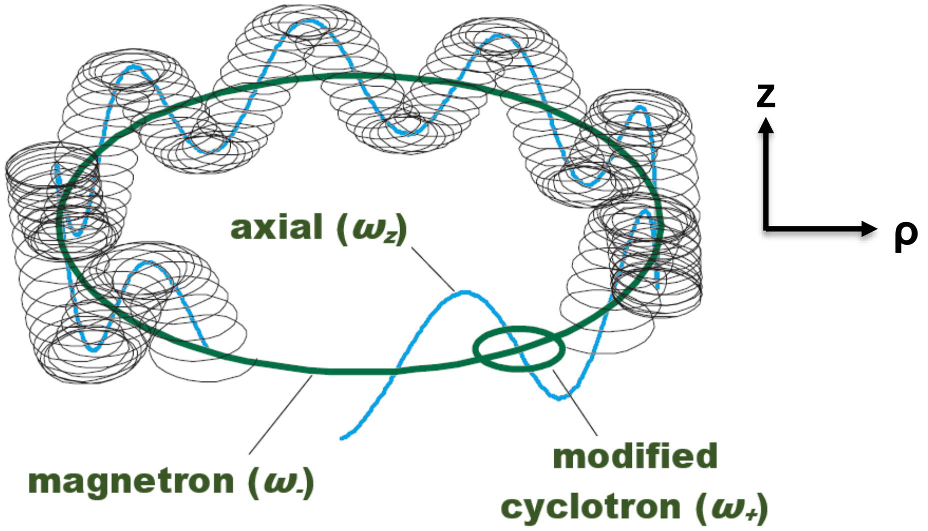




$$m = \frac{q}{\omega_c} B$$

- **Mass Measurement: either measure ω_c OR measure ω_+ and ω_-**
- **Magnetic (B) field calibrated with measurement of well known mass**

$$\omega_c \approx \omega_- + \omega_+$$



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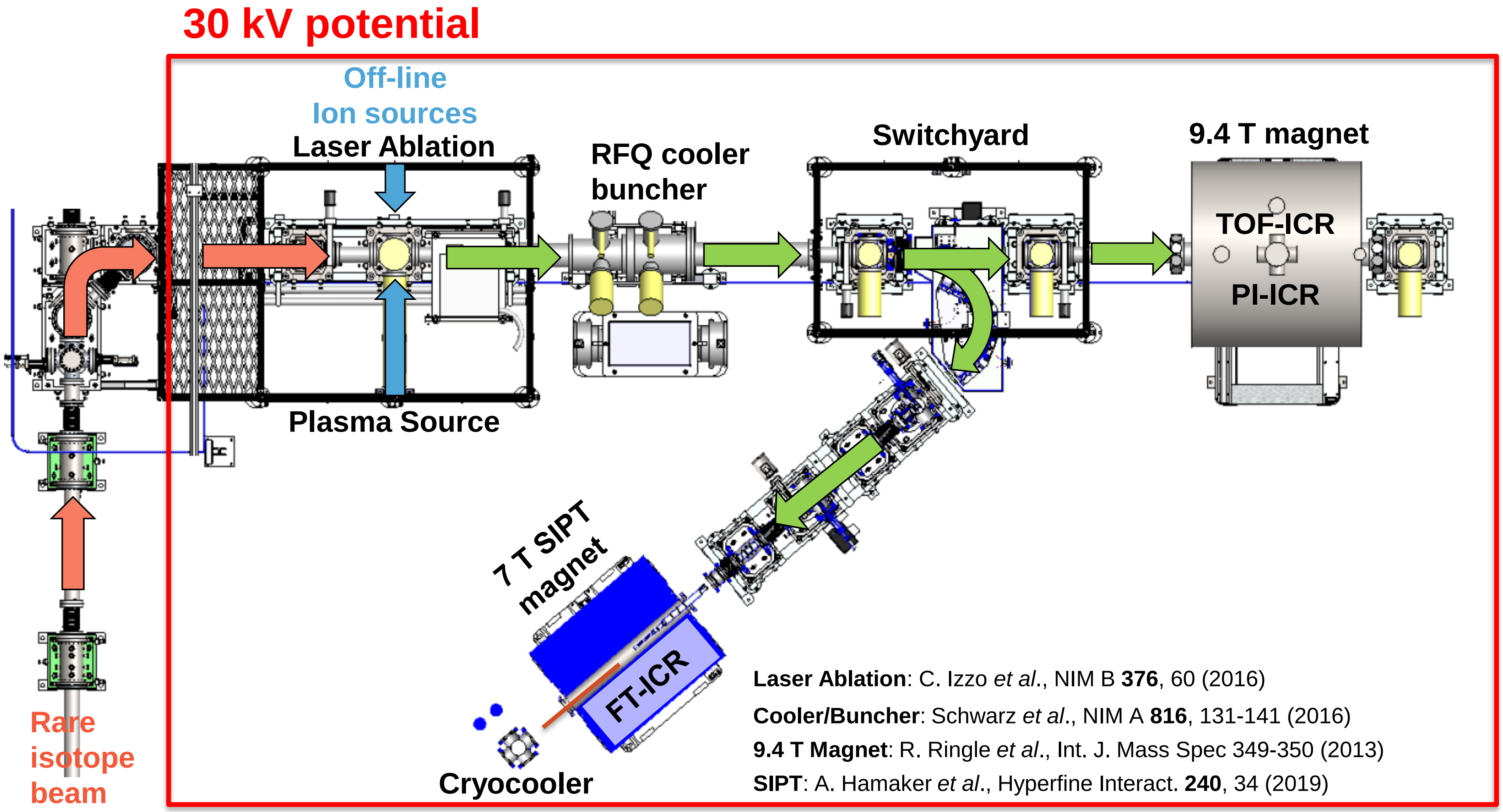

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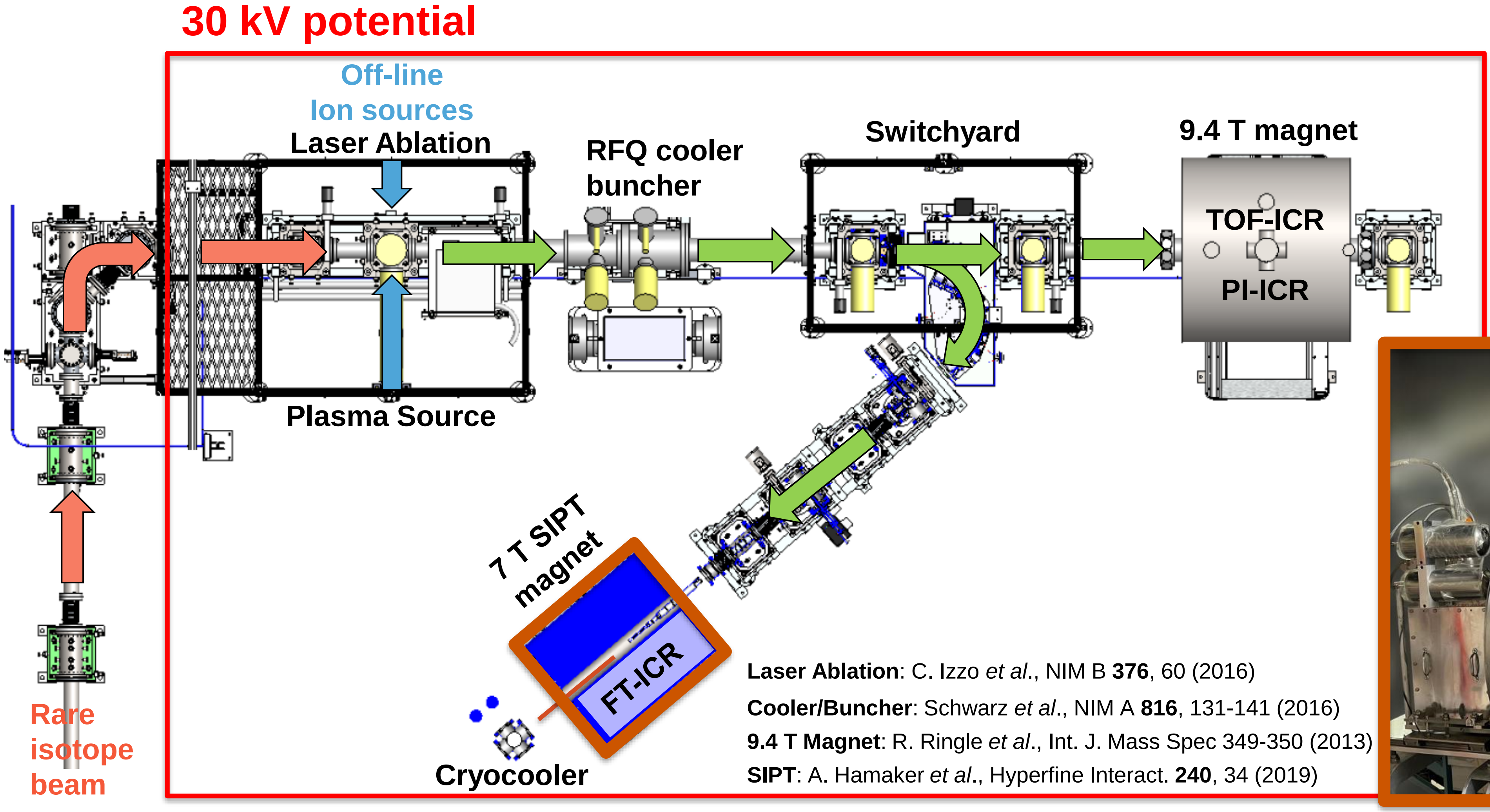

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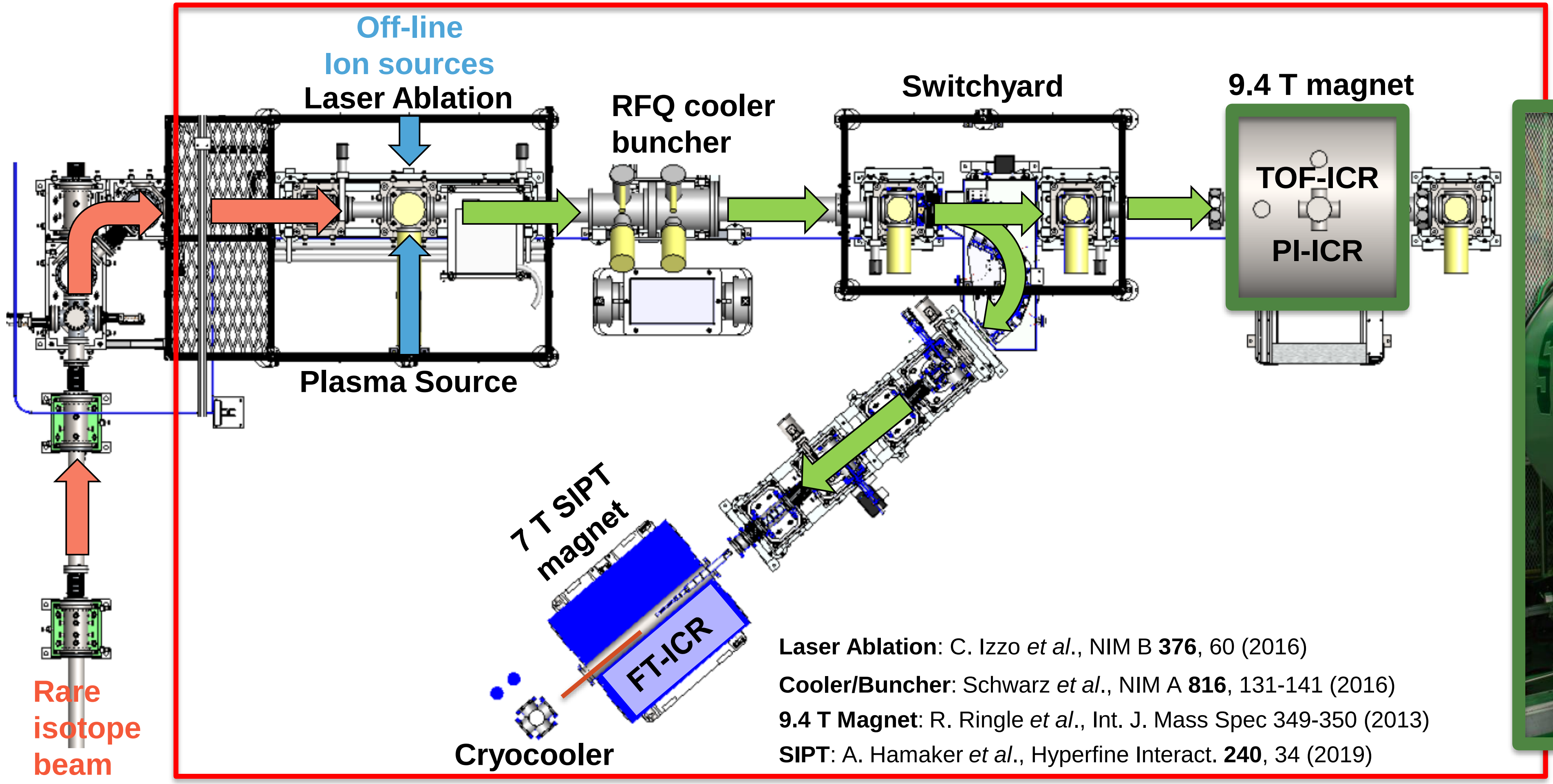

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Current Techniques at LEBIT: TOF-ICR and PI-ICR

- Time-of-Flight Ion Cyclotron Resonance
- Phase-Image Ion Cyclotron Resonance

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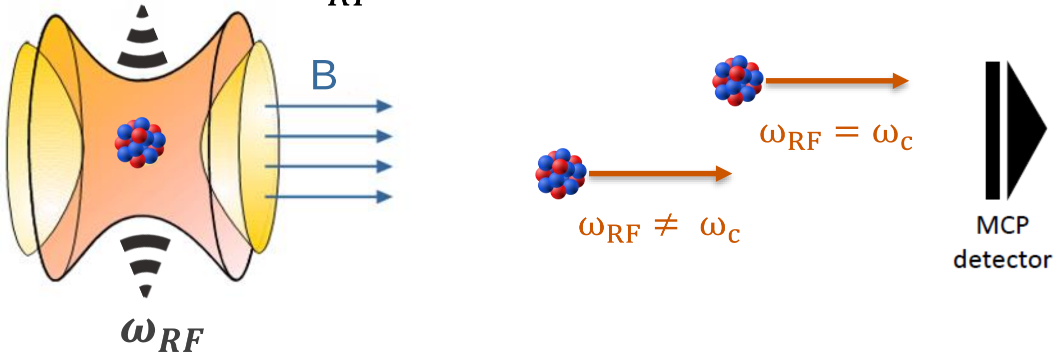

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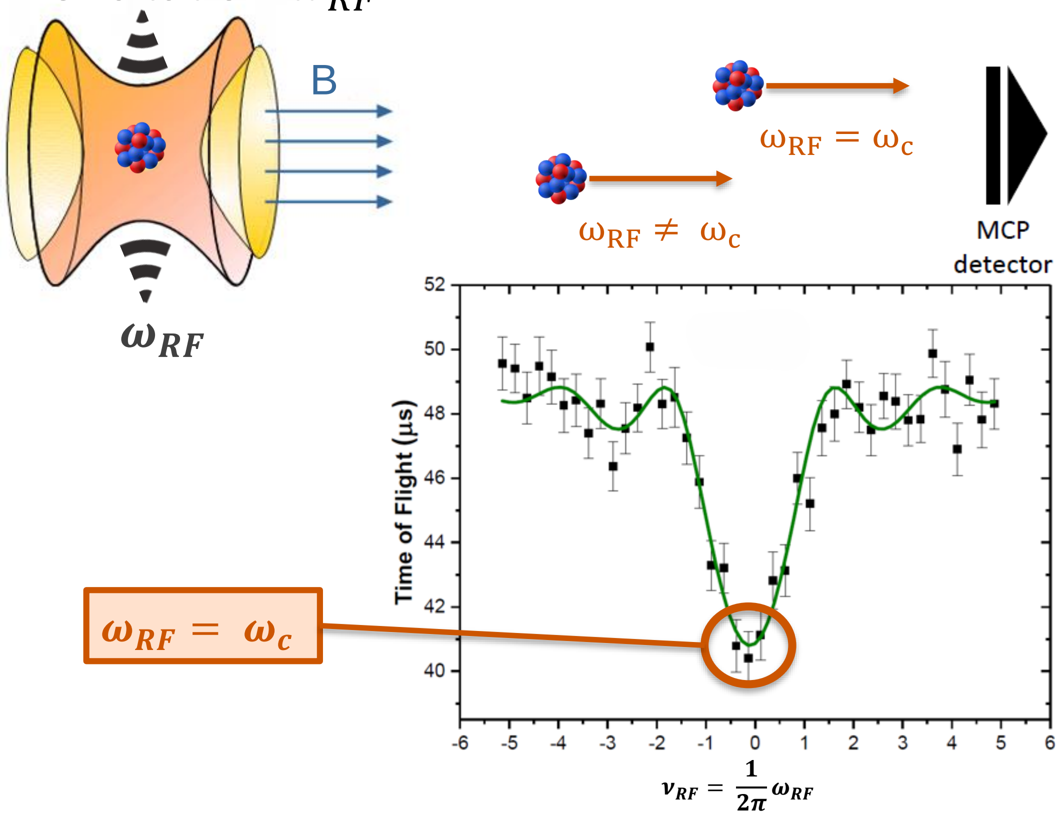

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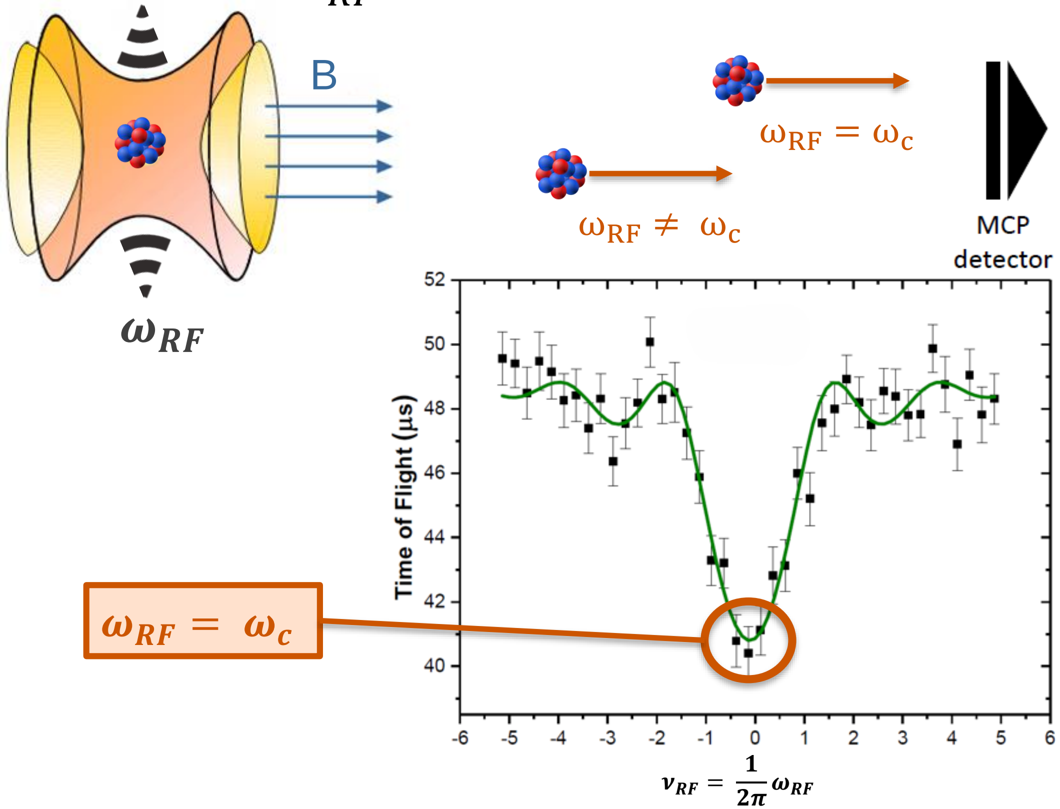

- Phase-Image Ion Cyclotron Resonance
  - Measure ω_+ and ω_- independently

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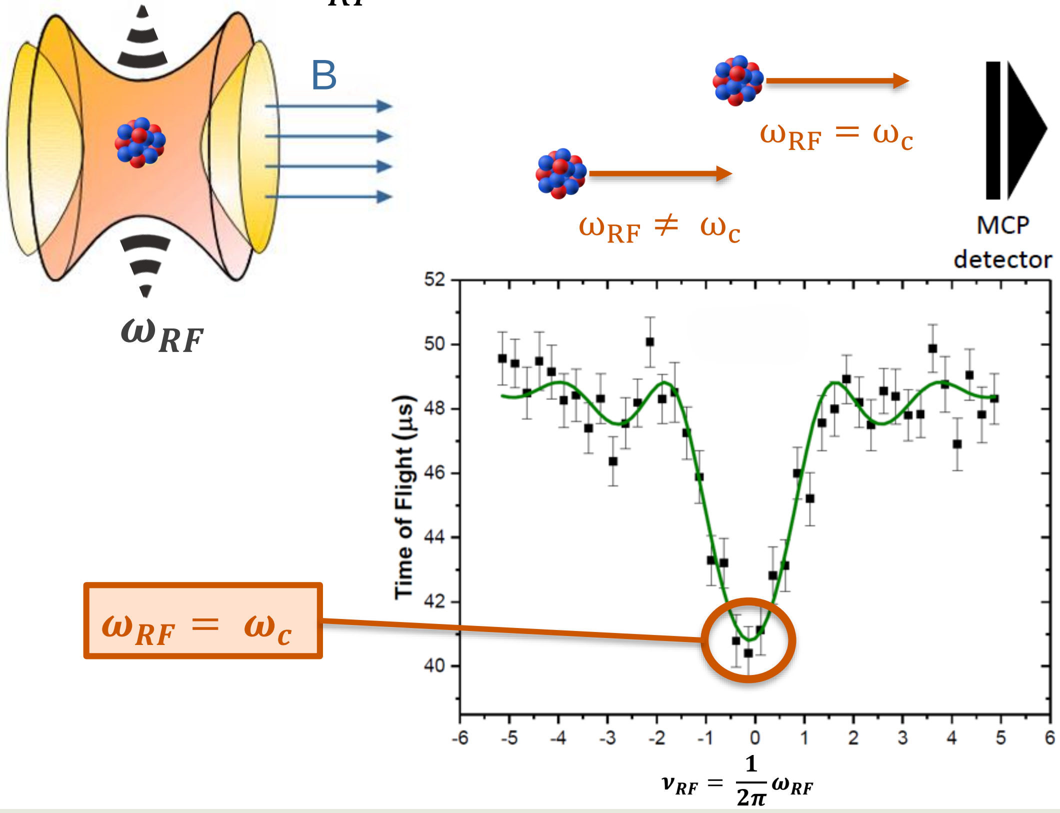

- Phase-Image Ion Cyclotron Resonance
  - Measure ω_+ and ω_- independently
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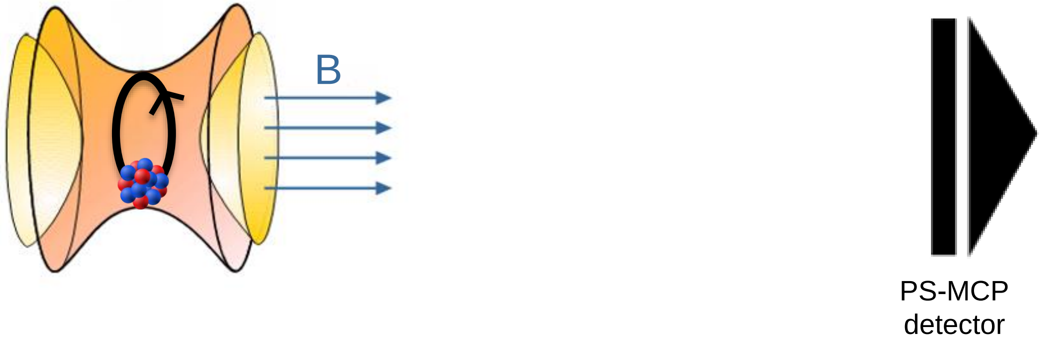

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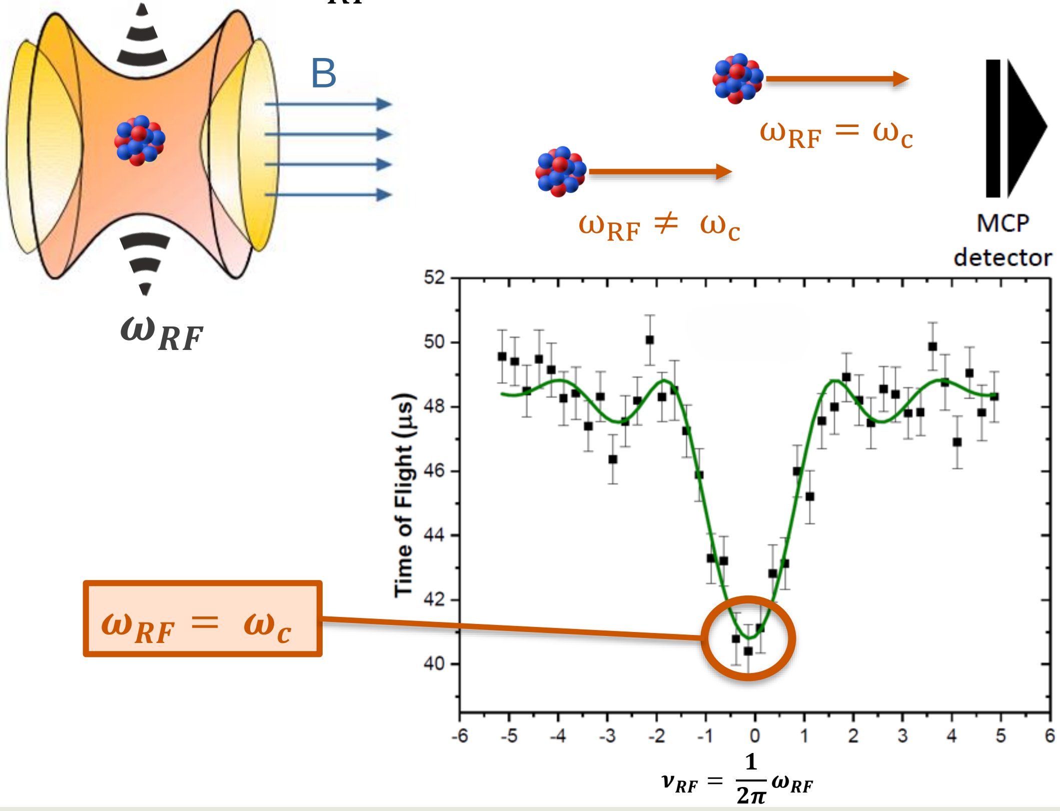

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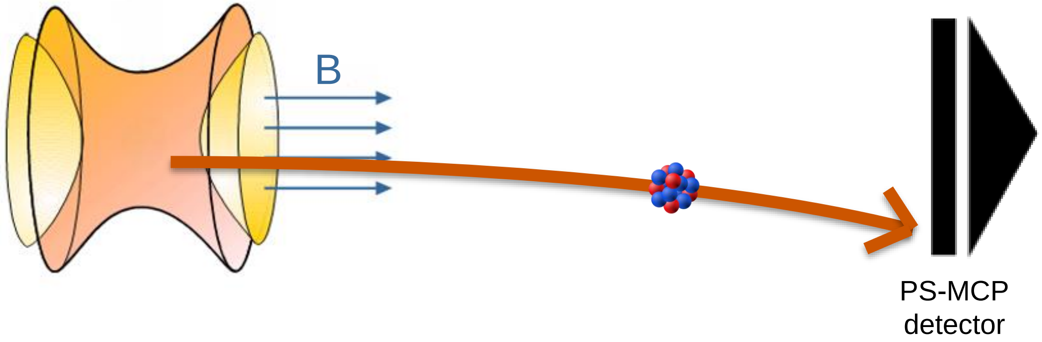

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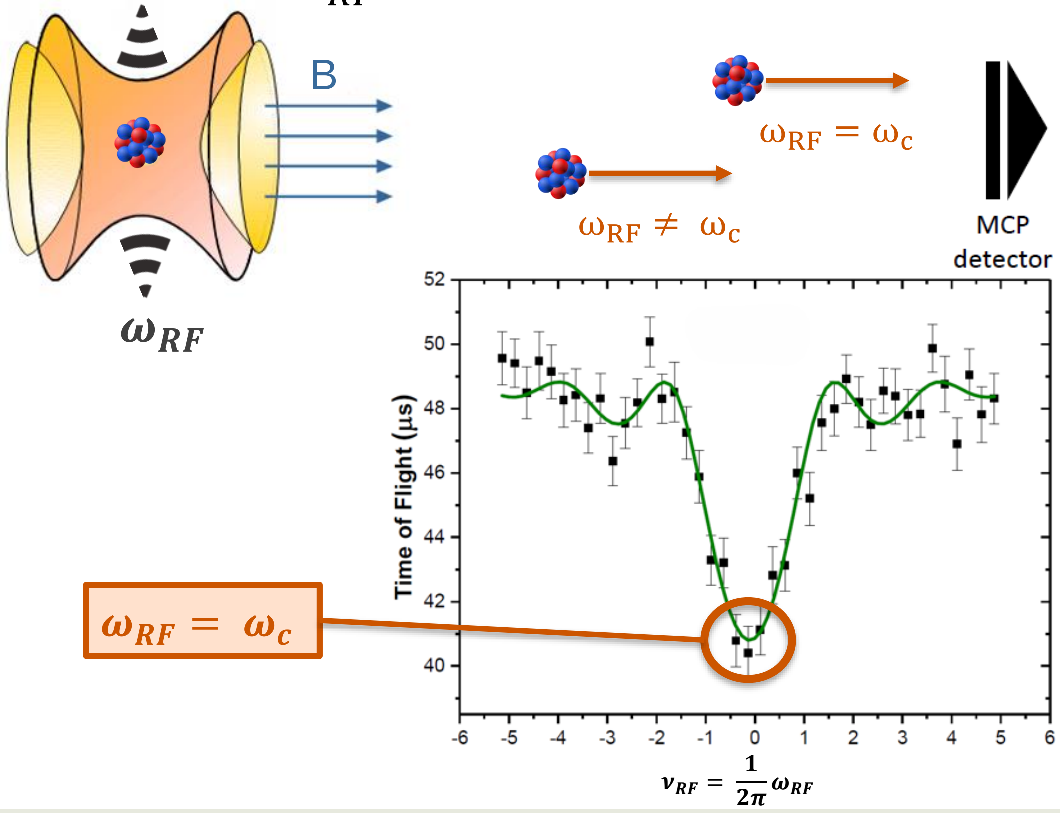

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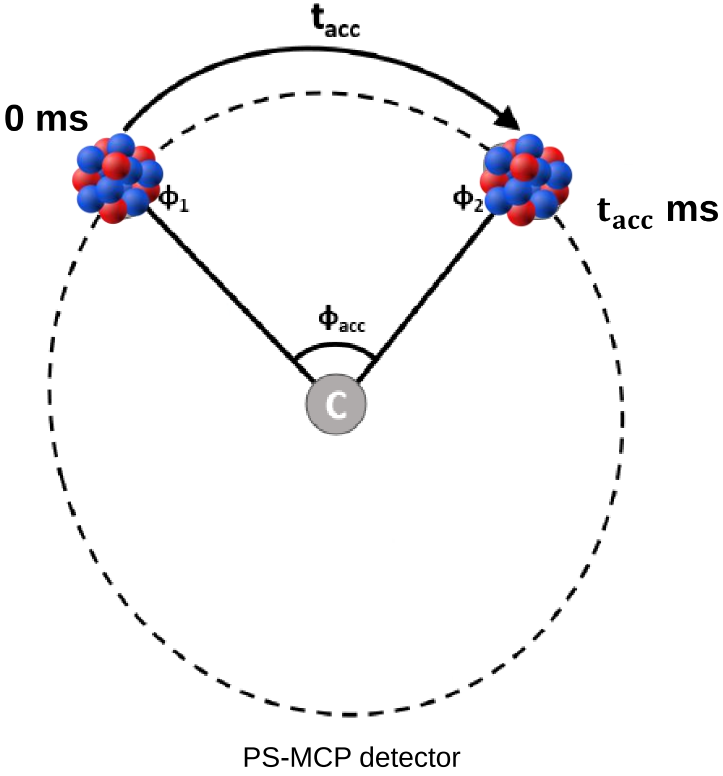

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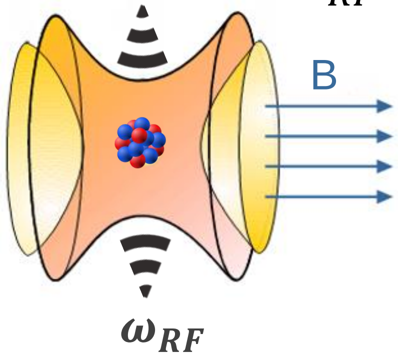

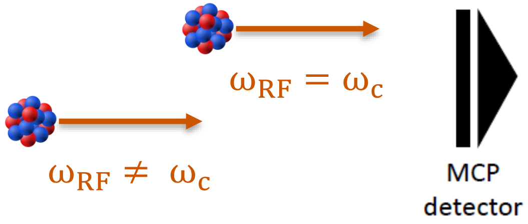

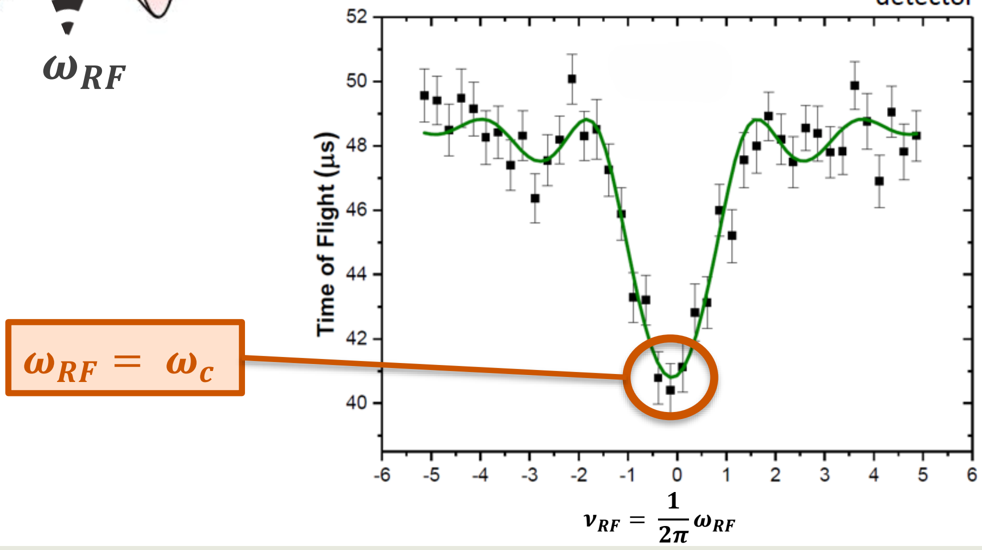

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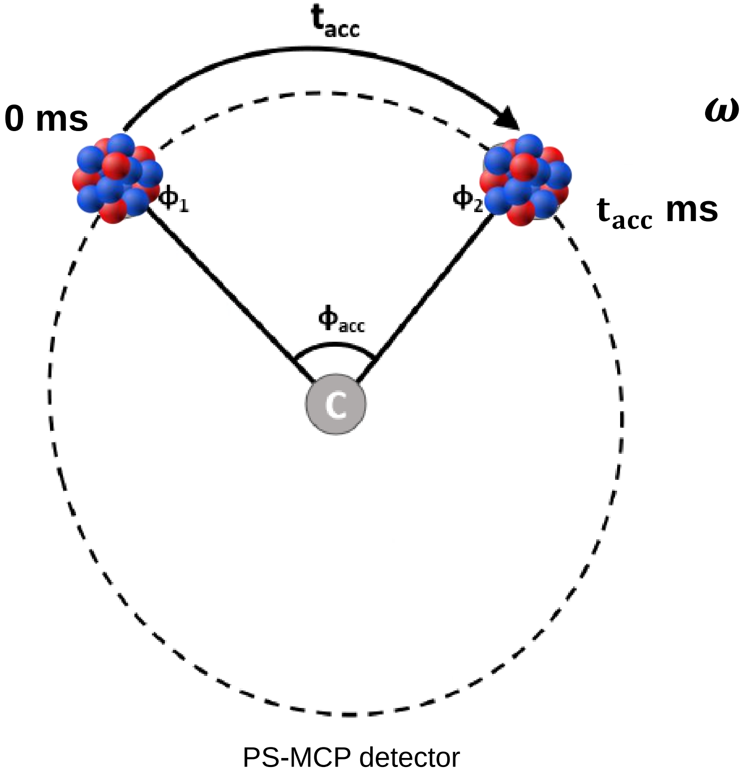

$$\omega = \frac{2\pi N + \varphi_{acc}}{t_{acc}}$$

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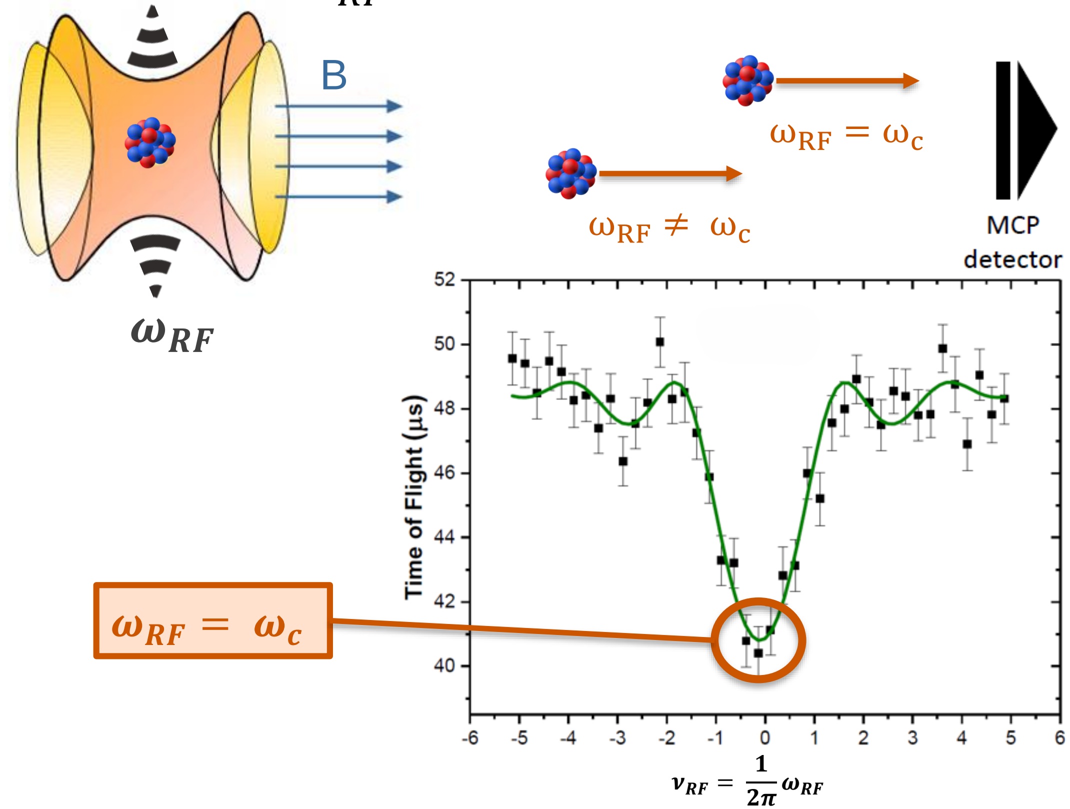

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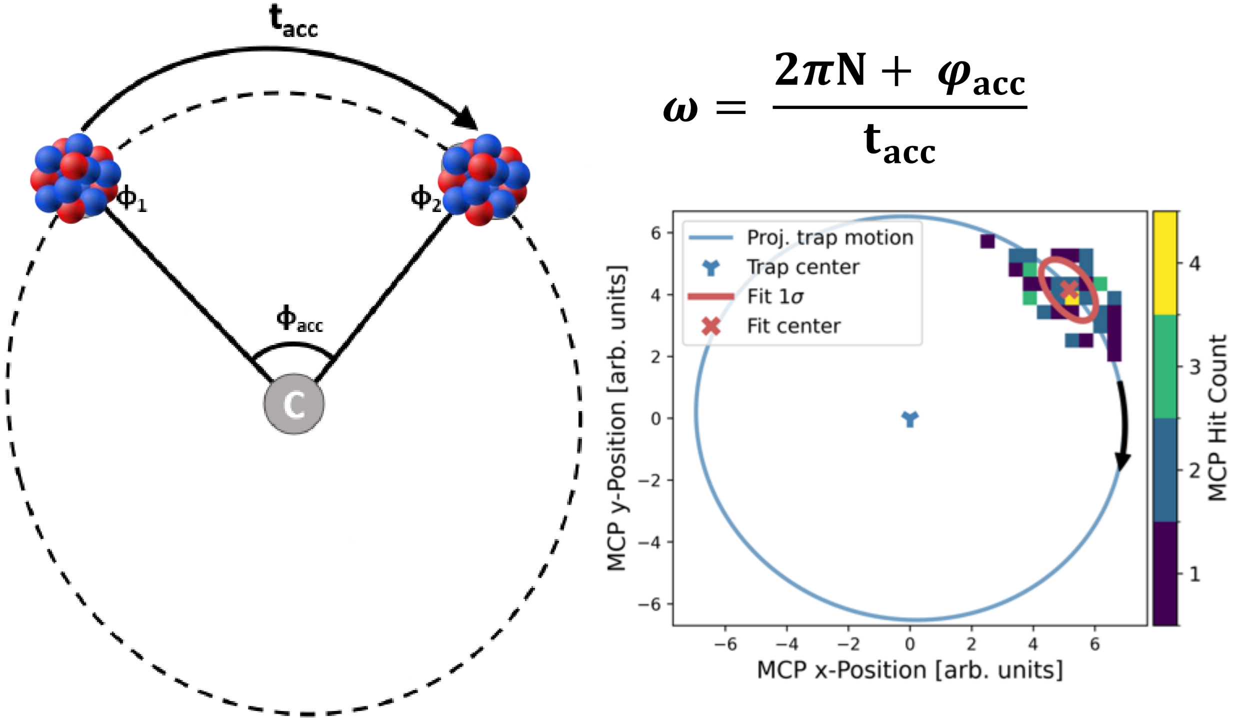

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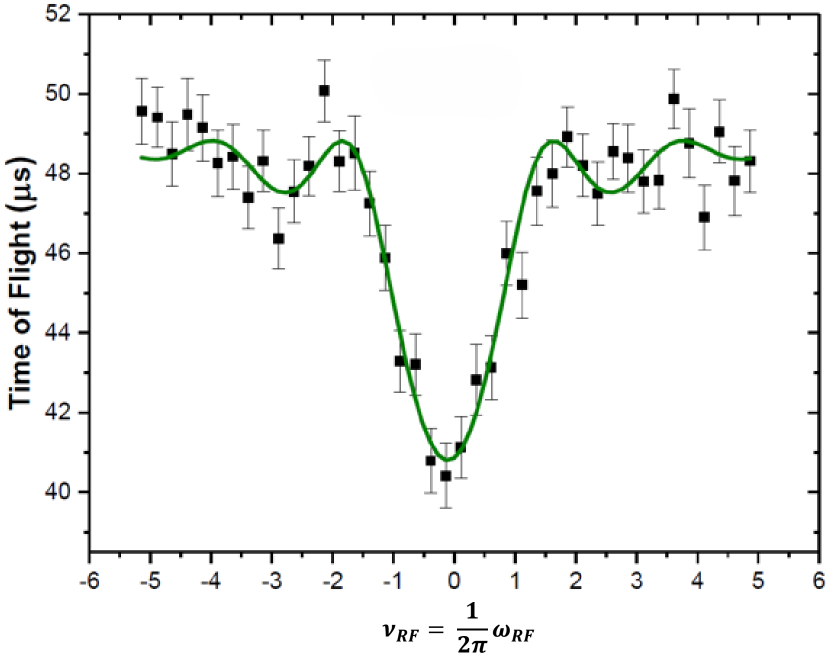

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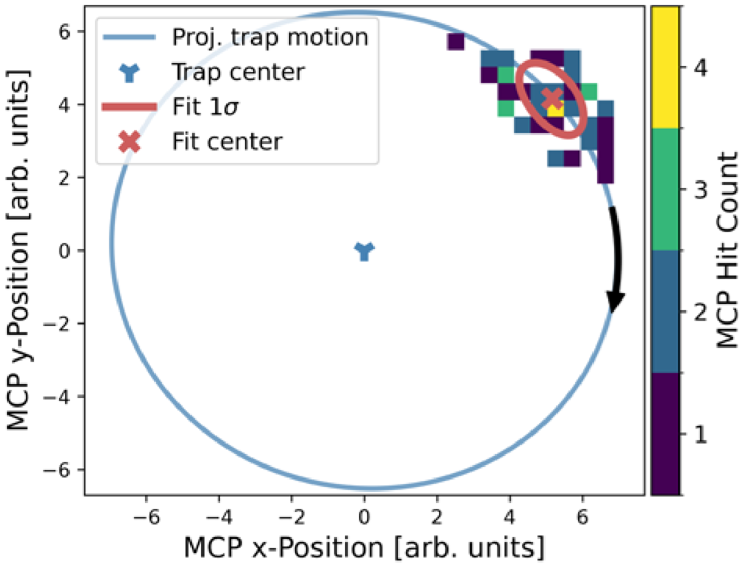

Both of these techniques are destructive → require tens to hundreds of ions

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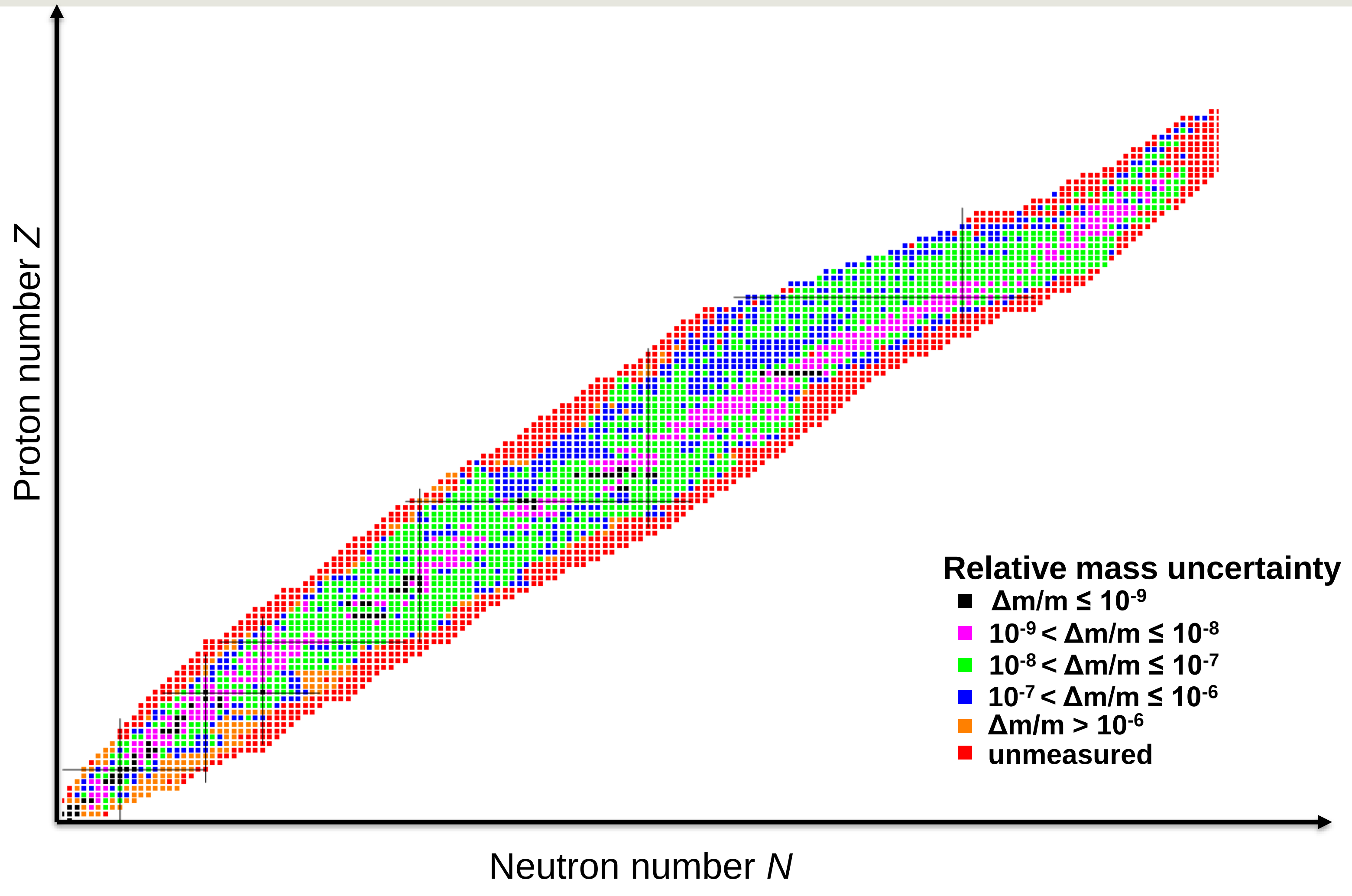

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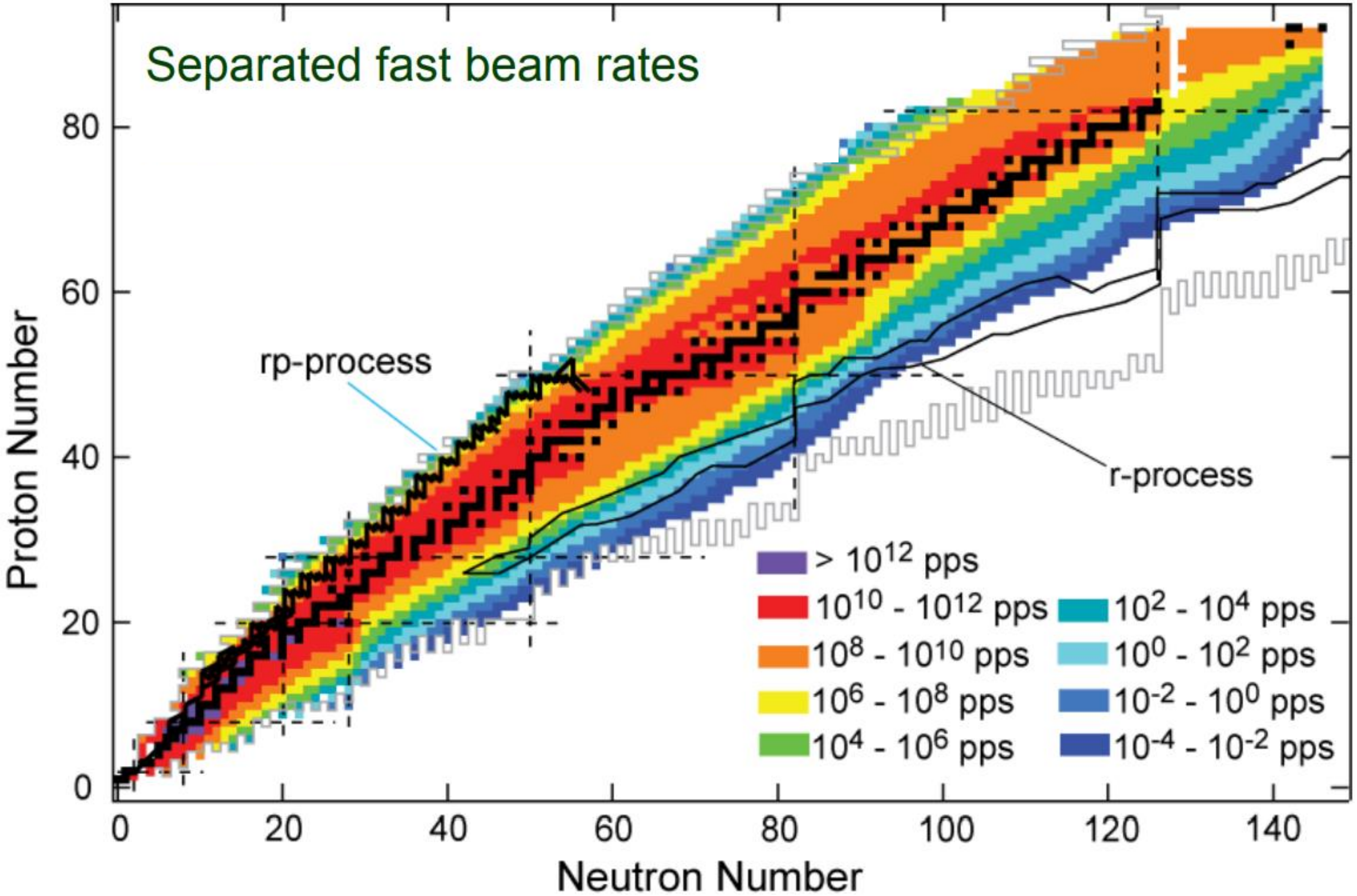
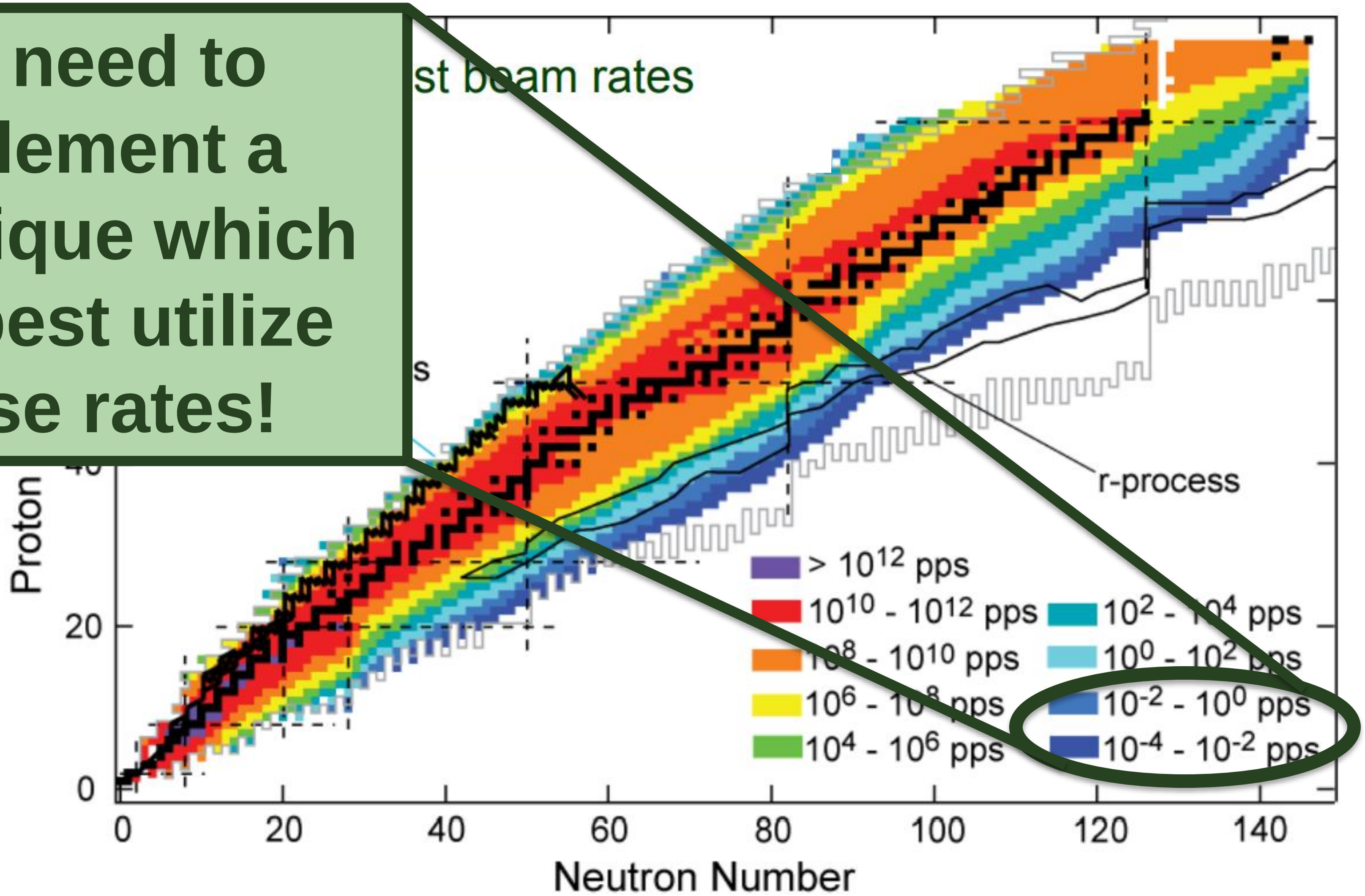


FRIB: Rarer Isotopes at Low Rates

We need to implement a technique which can best utilize these rates!



A Non-Destructive Technique: Narrowband FT-ICR with a Single Ion

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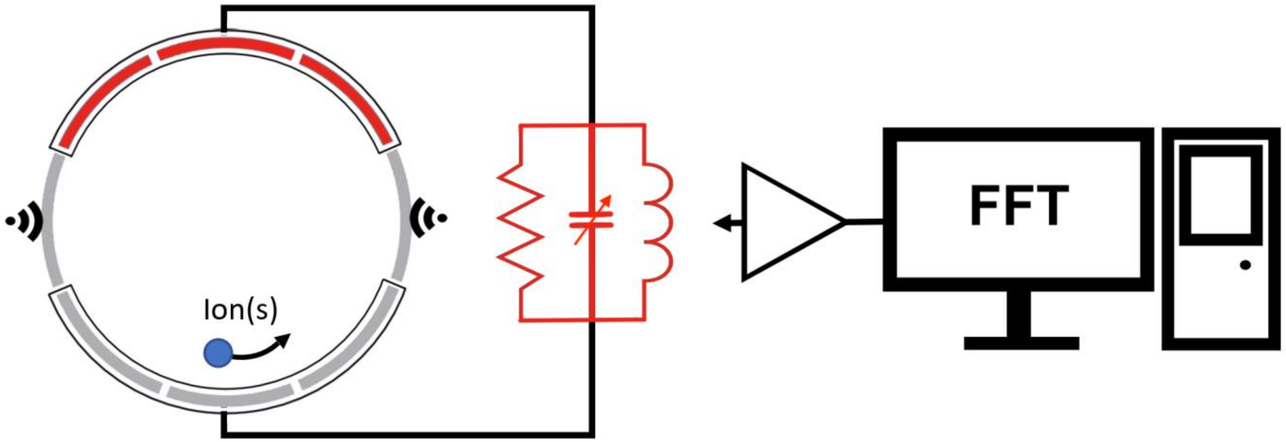

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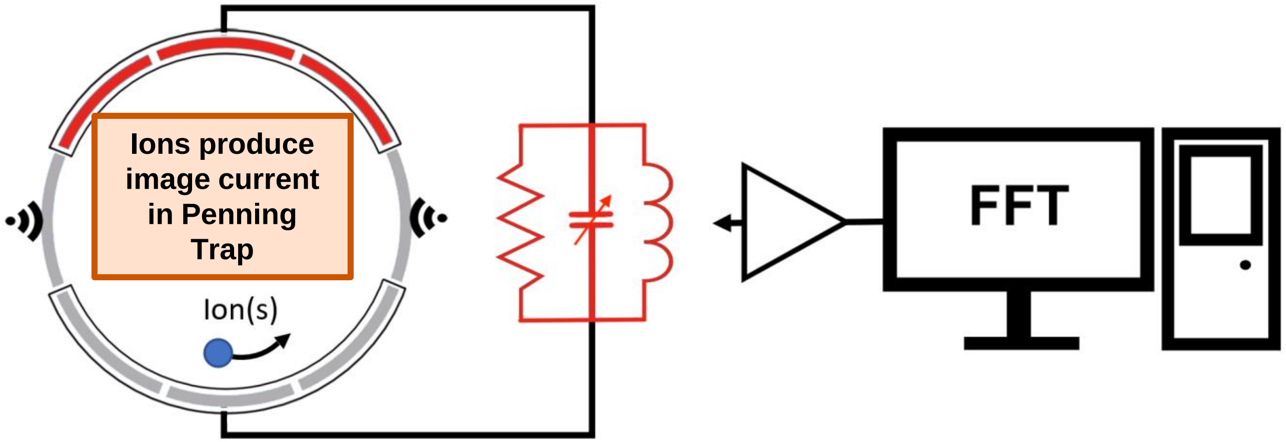

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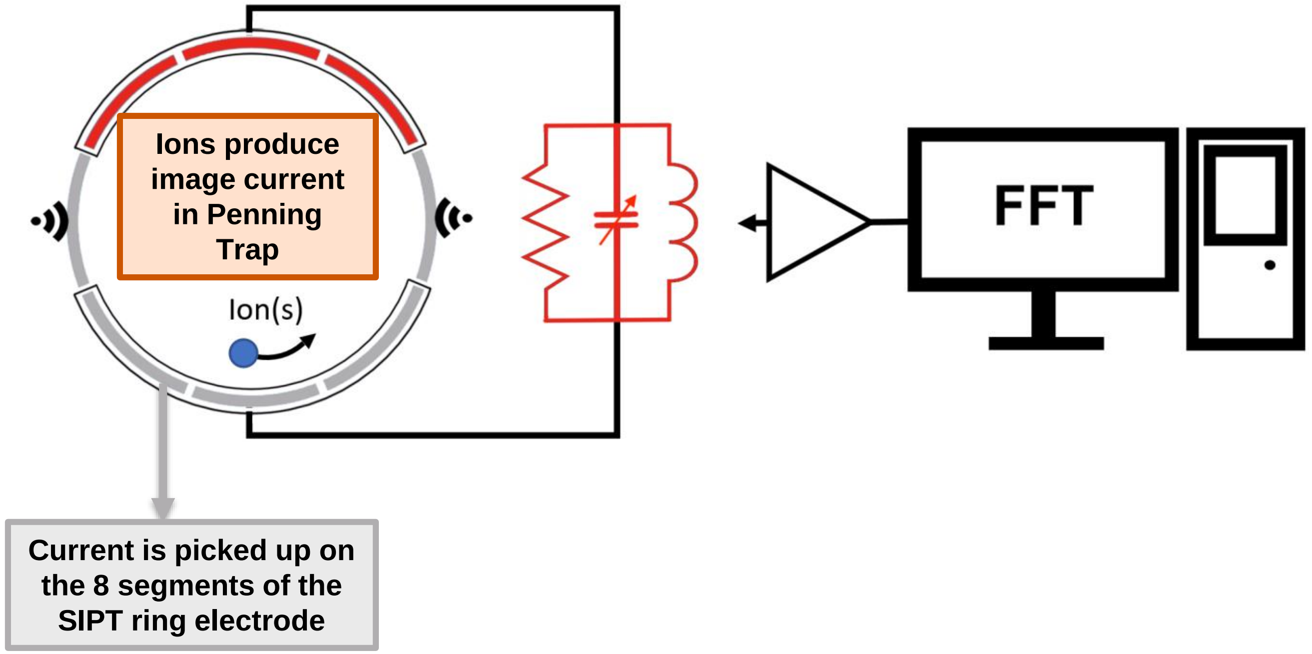

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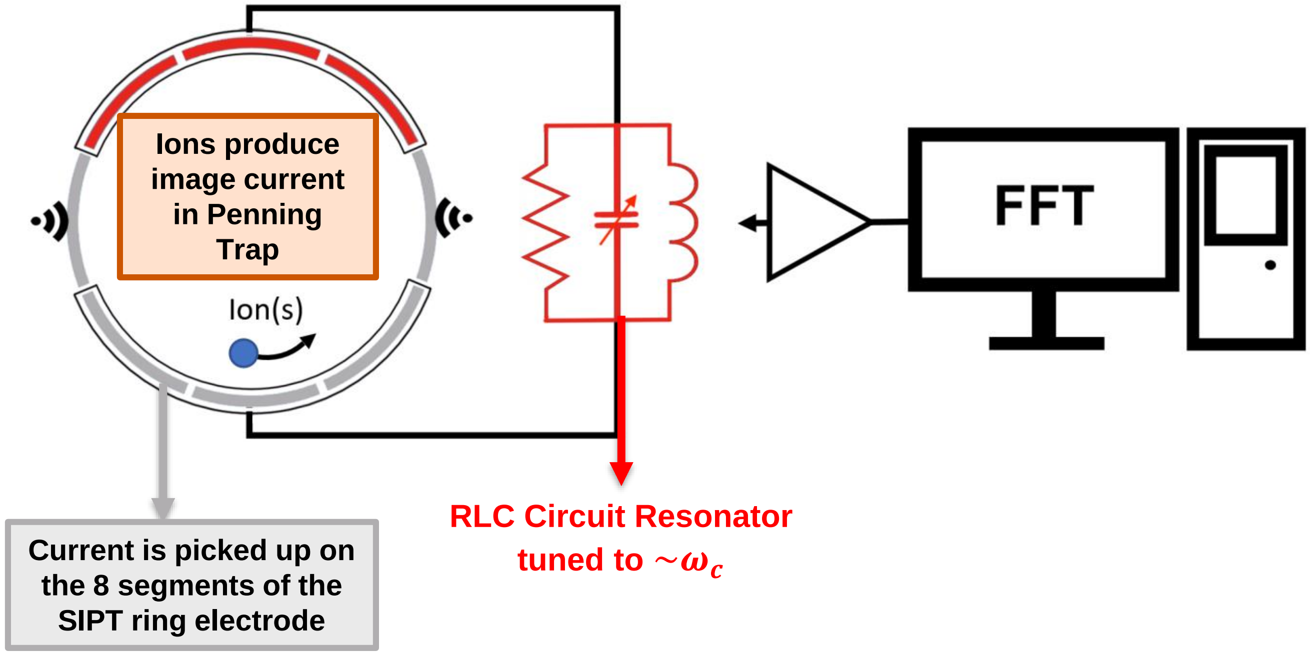

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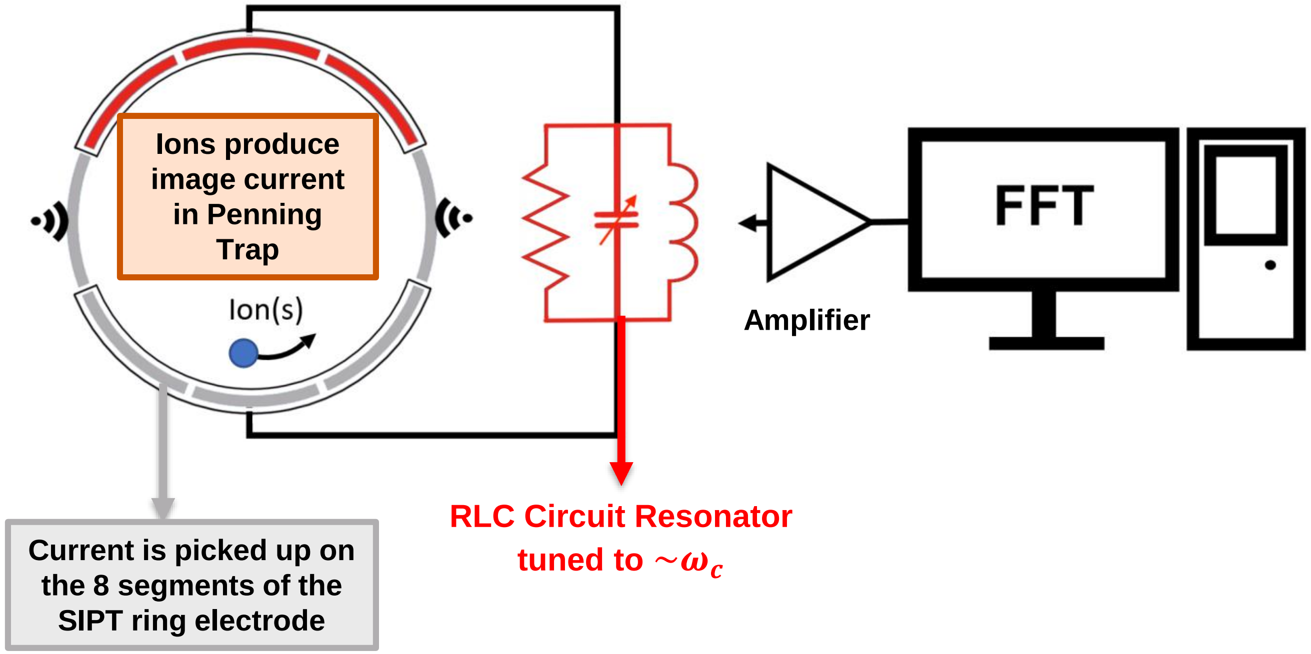

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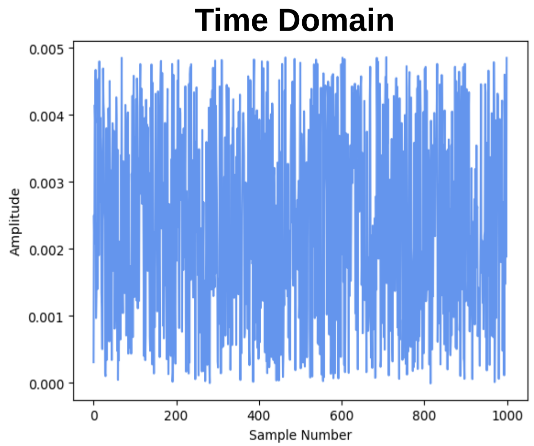

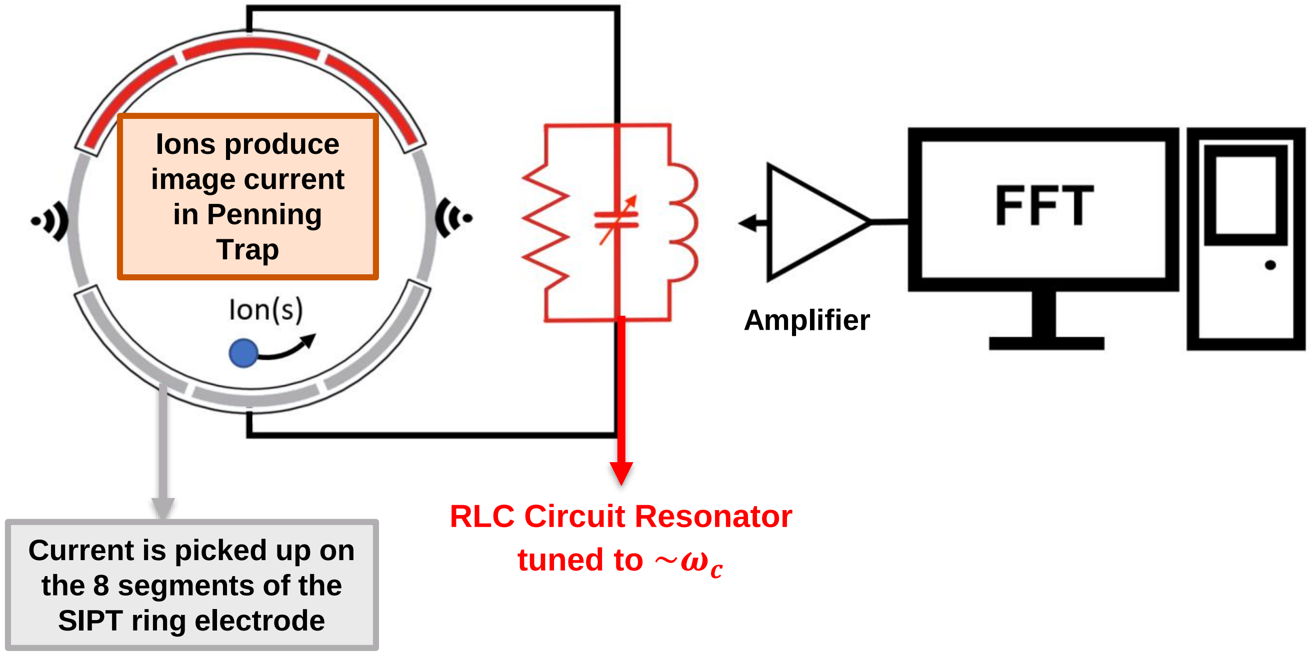

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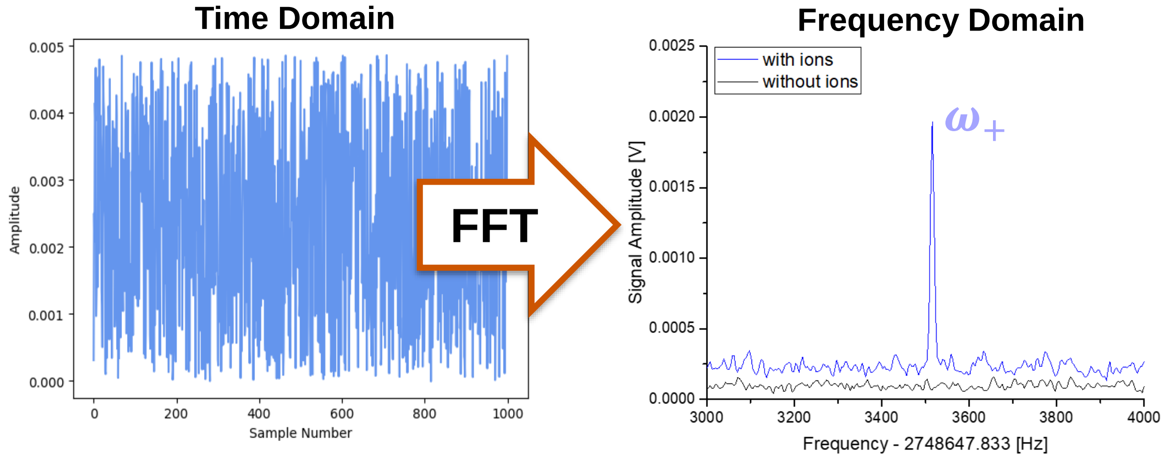

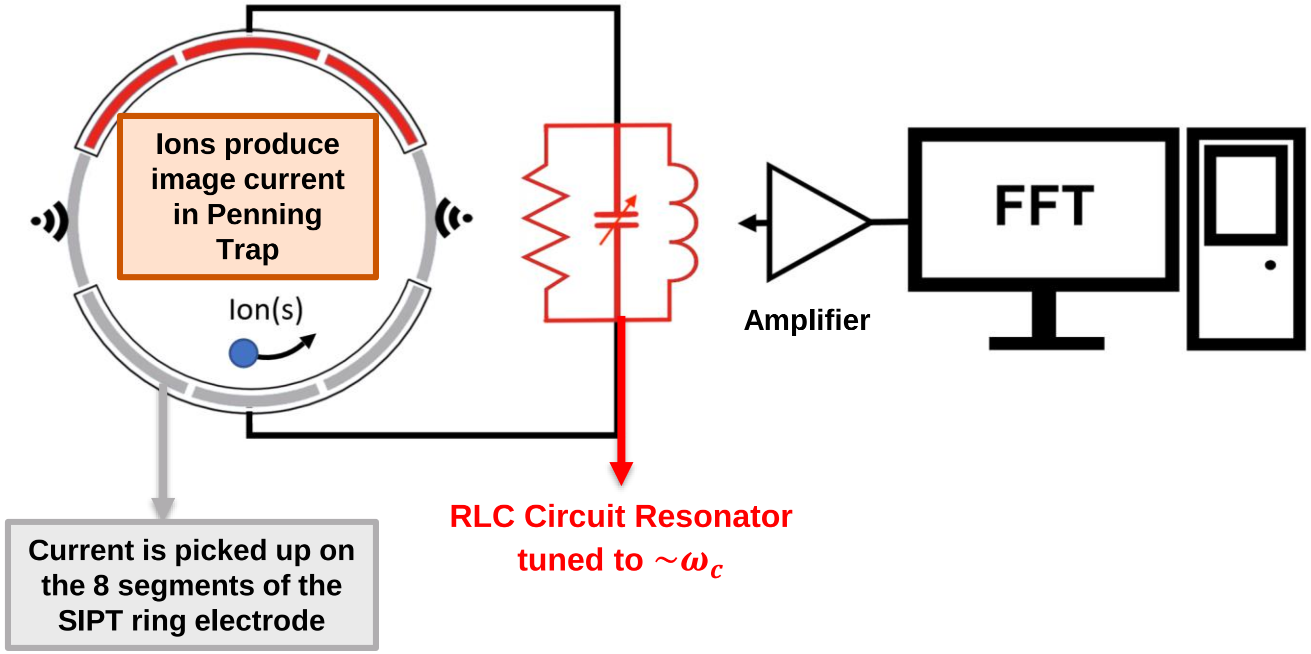

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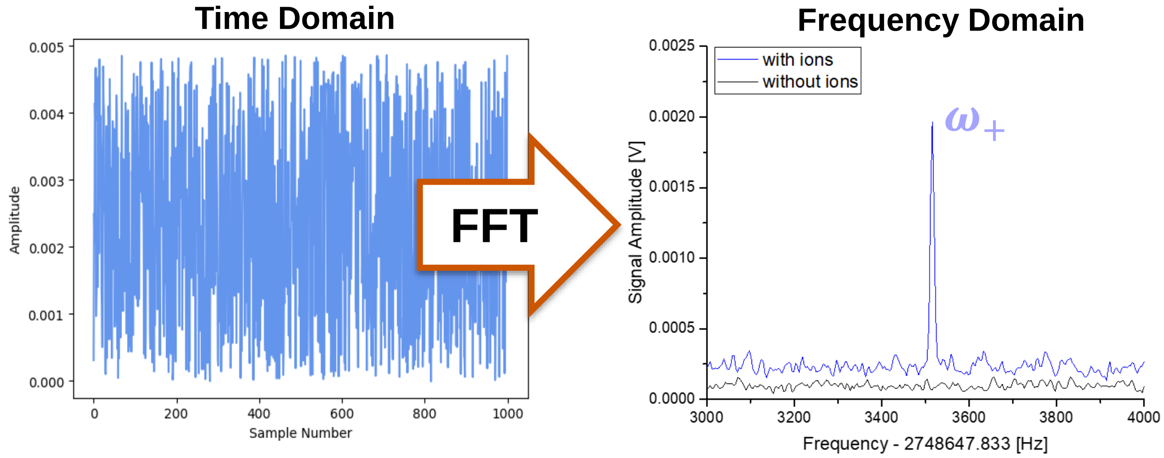

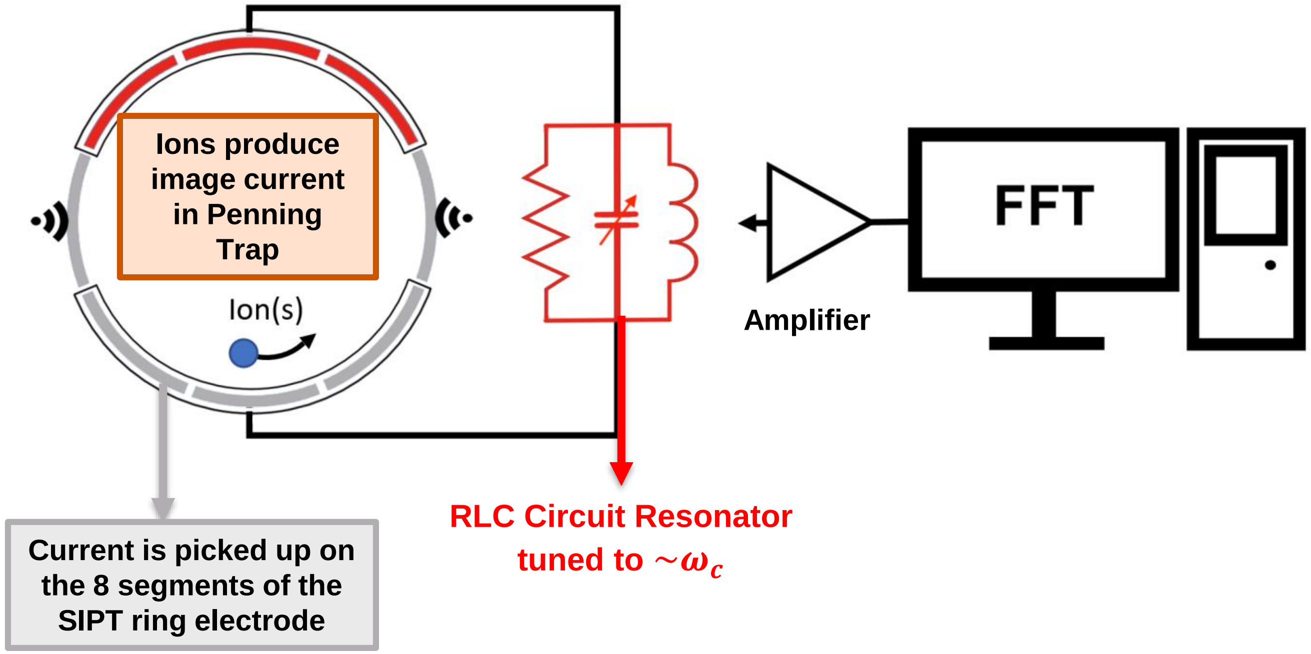

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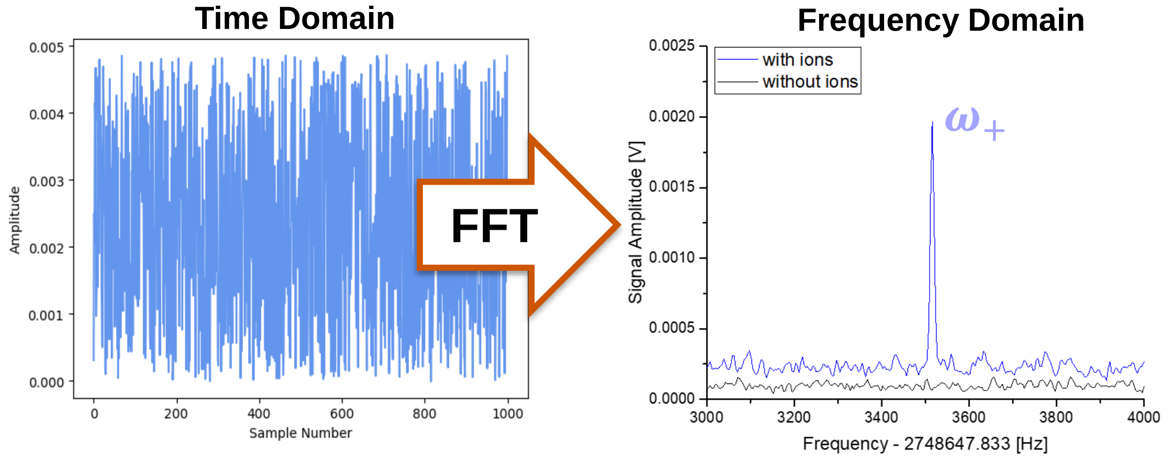

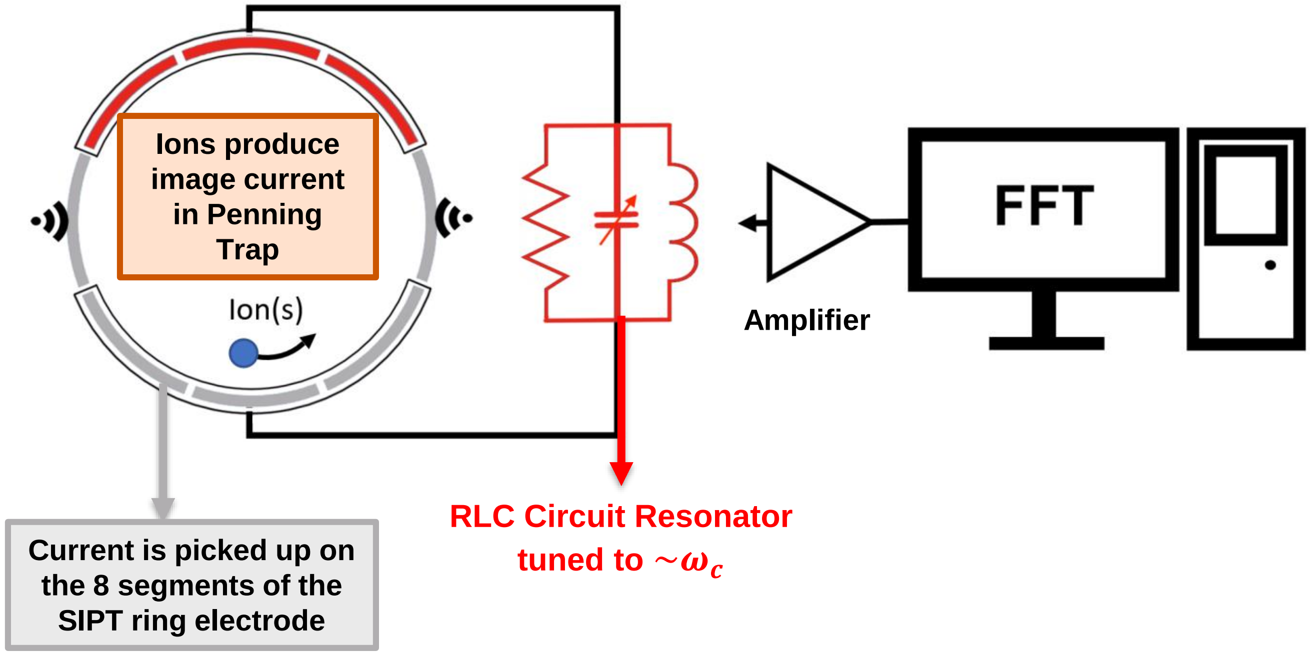

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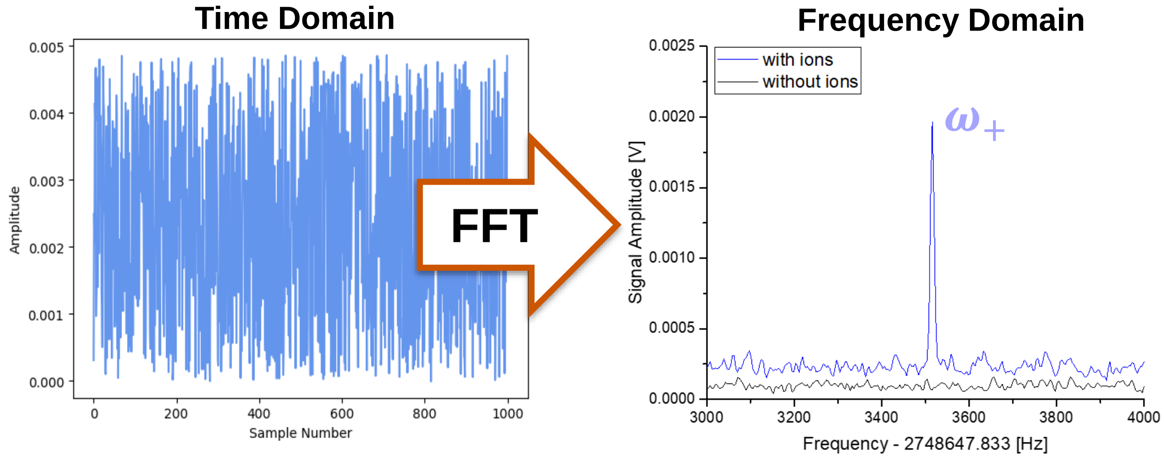

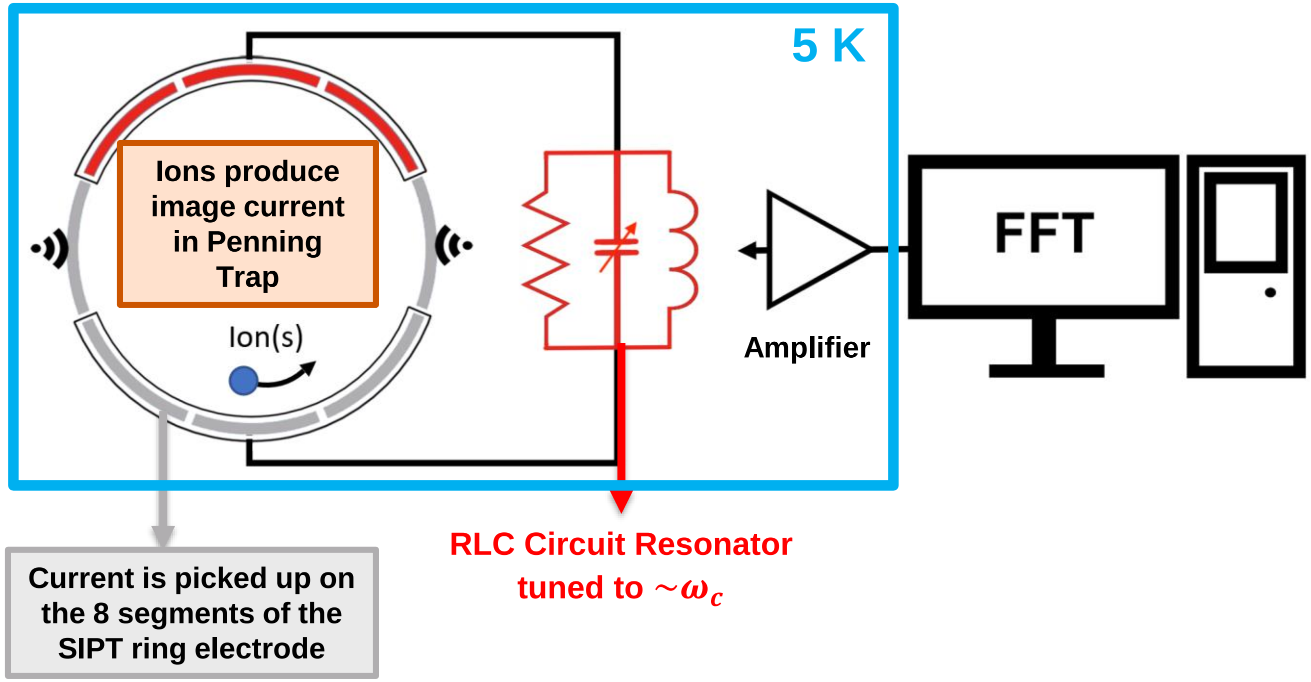

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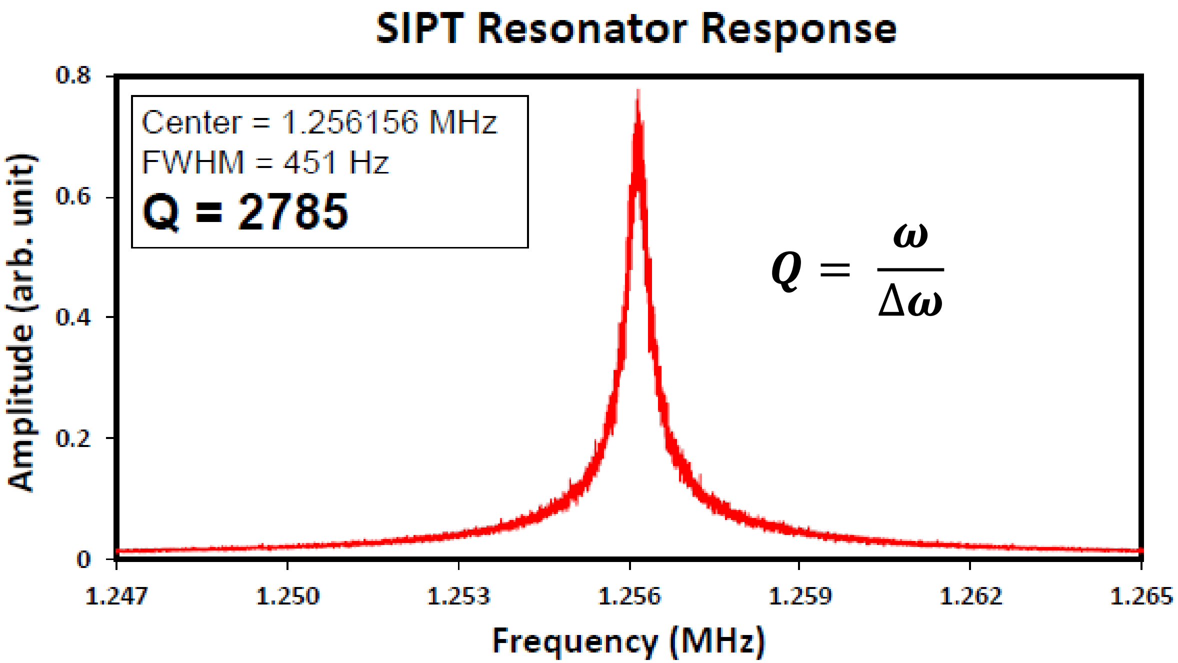

A. Hamaker, Ph.D. dissertation (2021)

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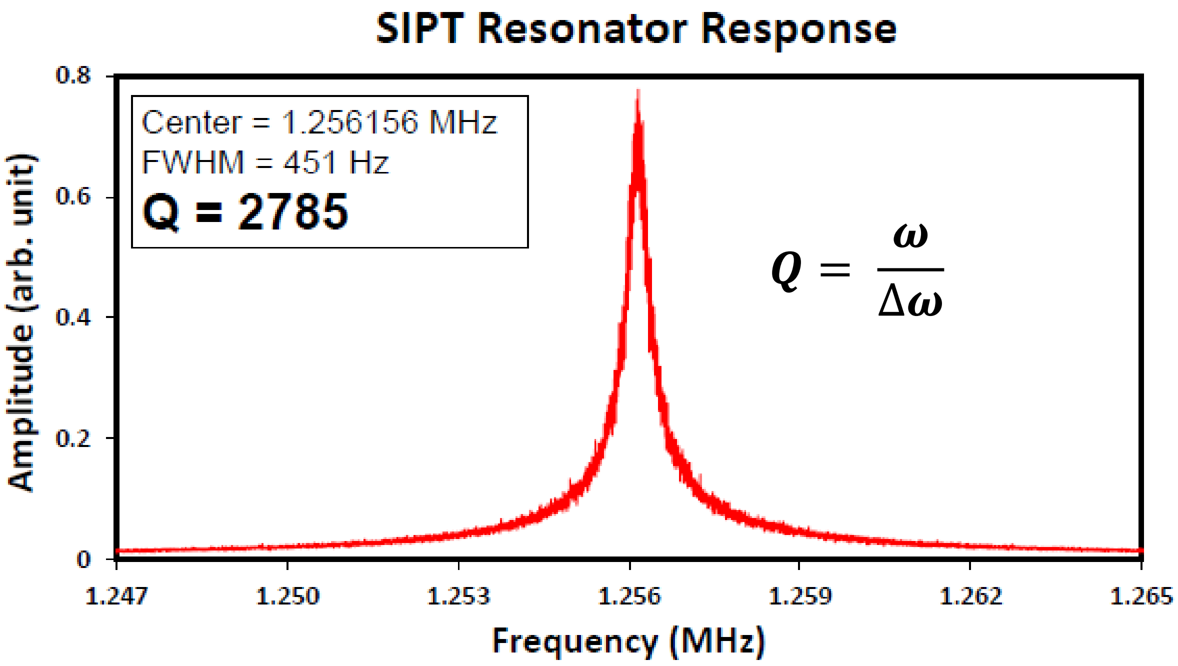

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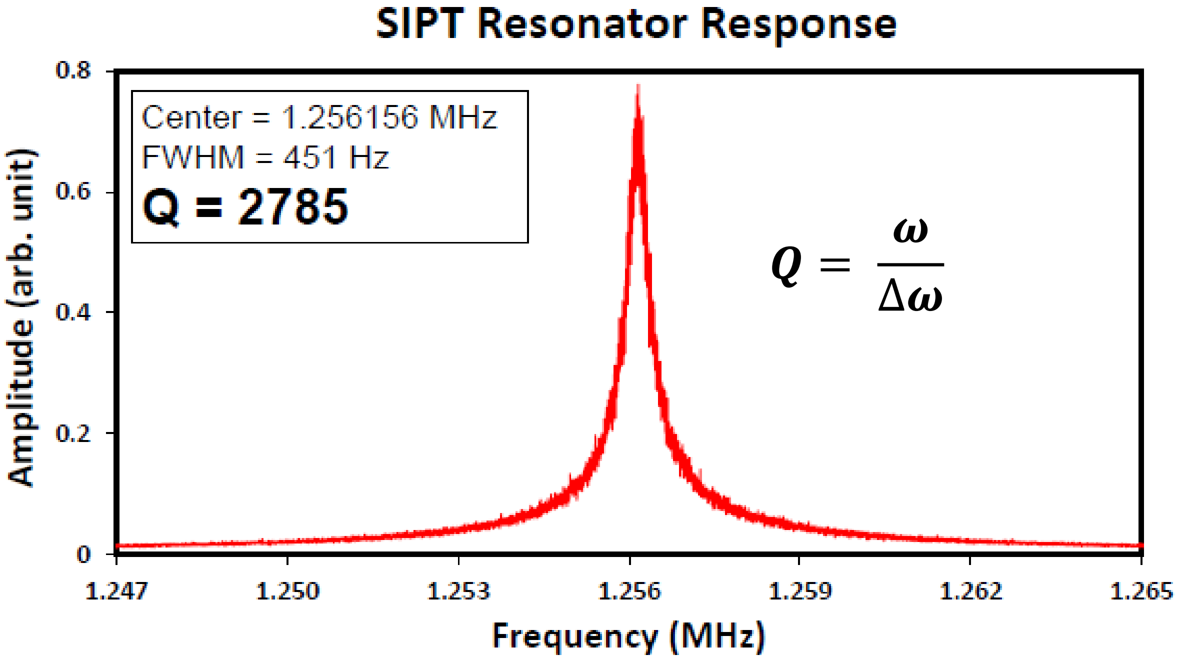

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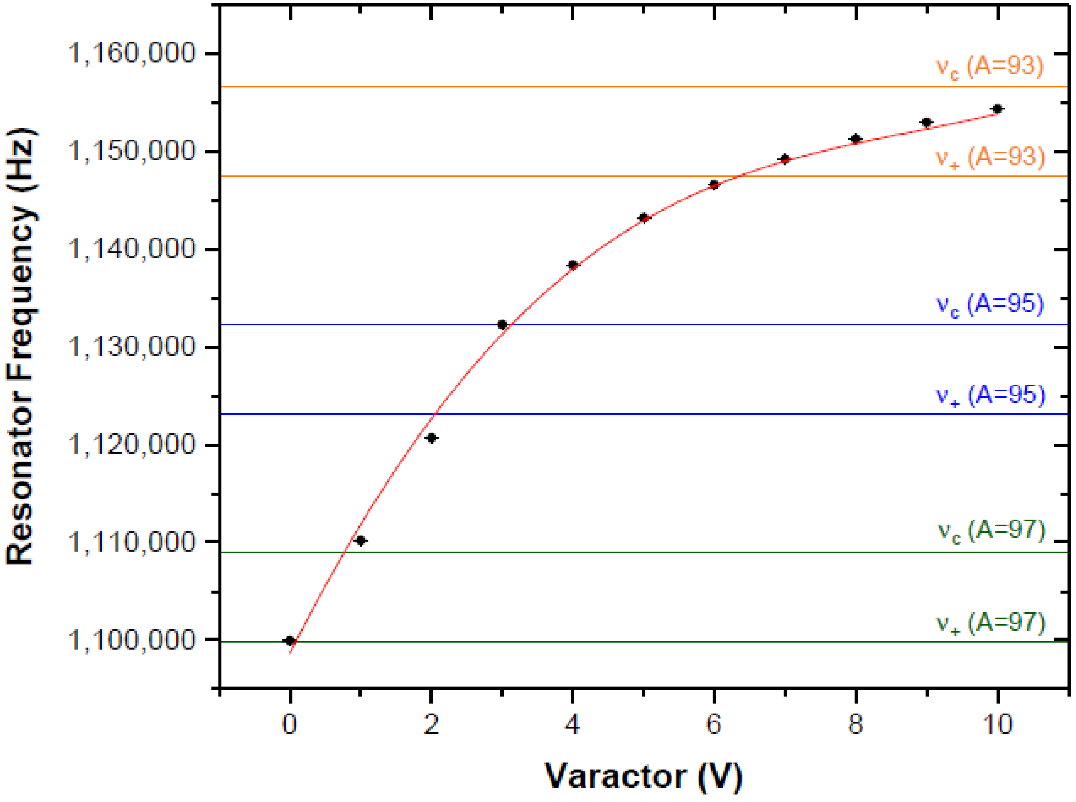

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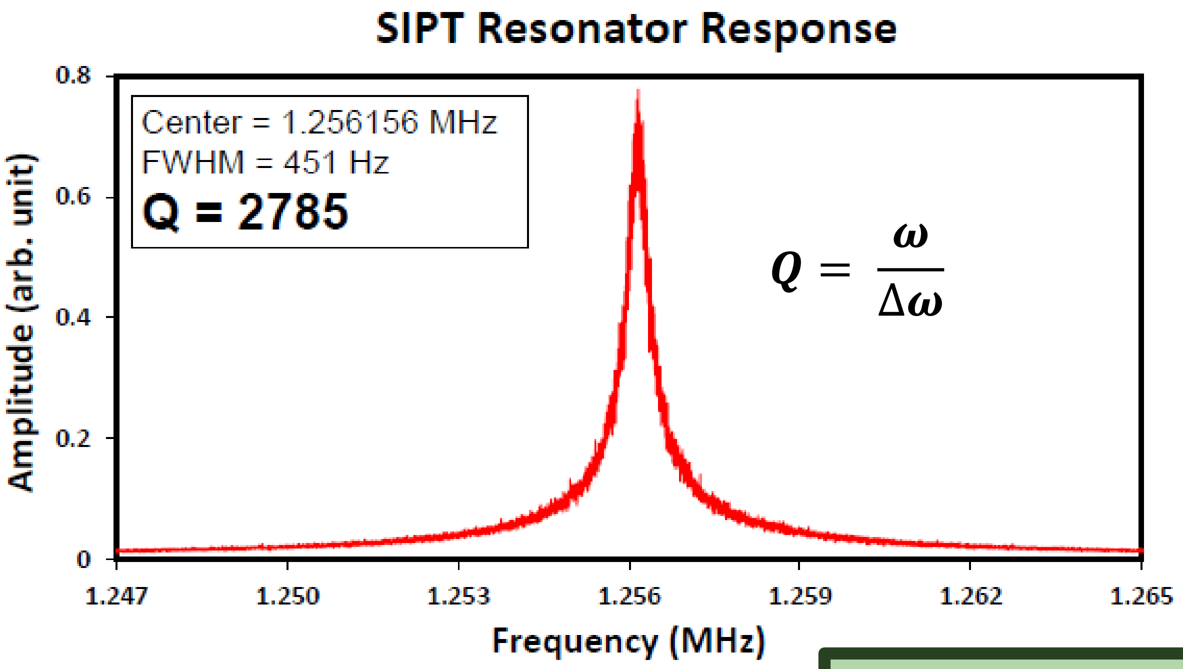

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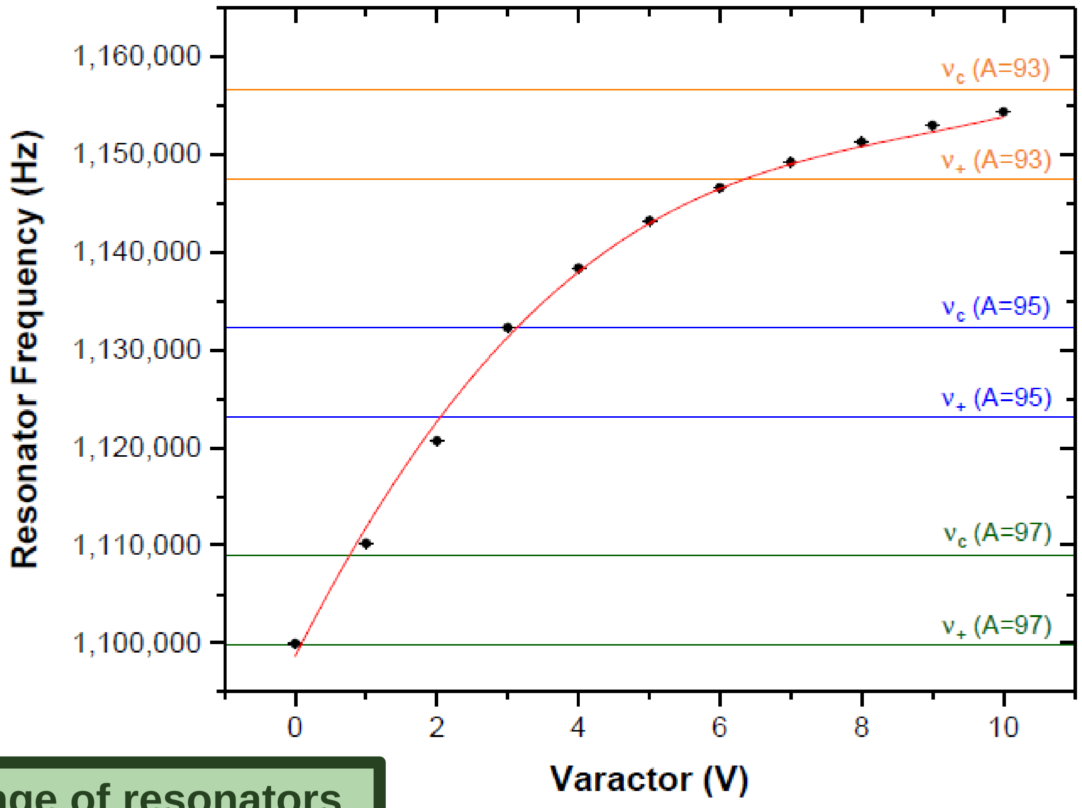

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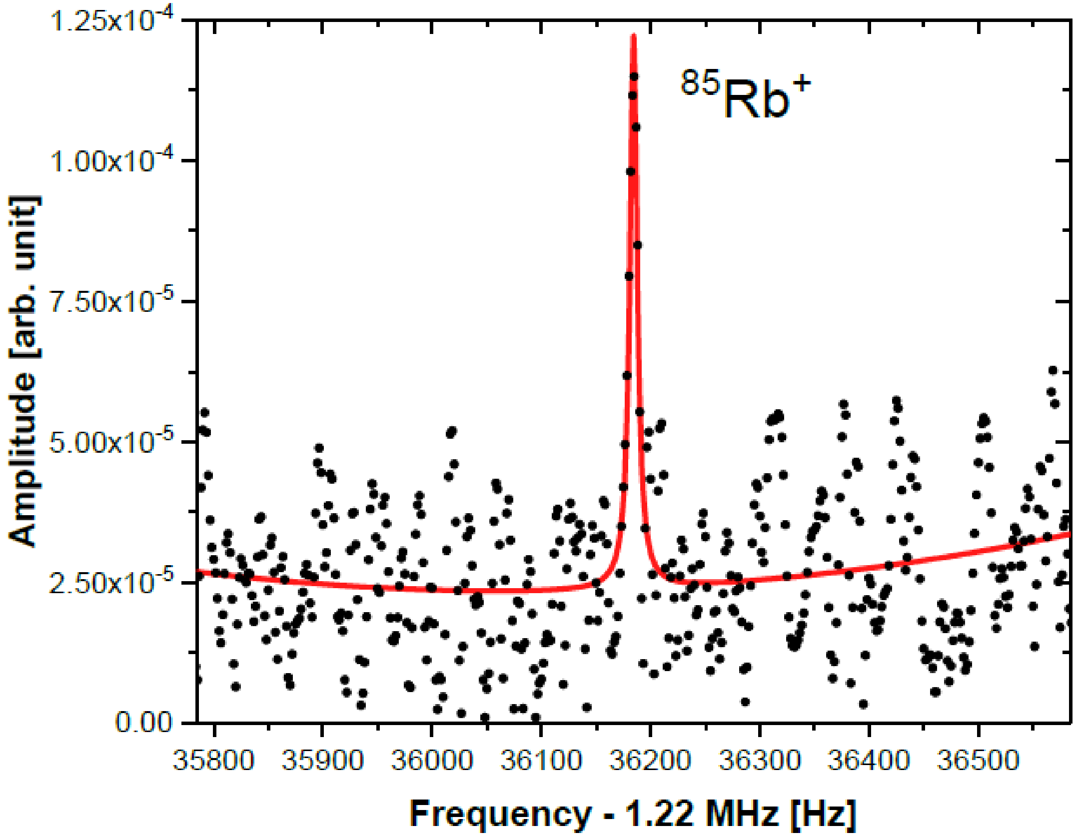
Long Term: build range of resonators for different mass regions

$^{85}Rb^+$ Measured as Test of SIPT

- The ω_+ of $^{85}Rb^+$ measured to test system



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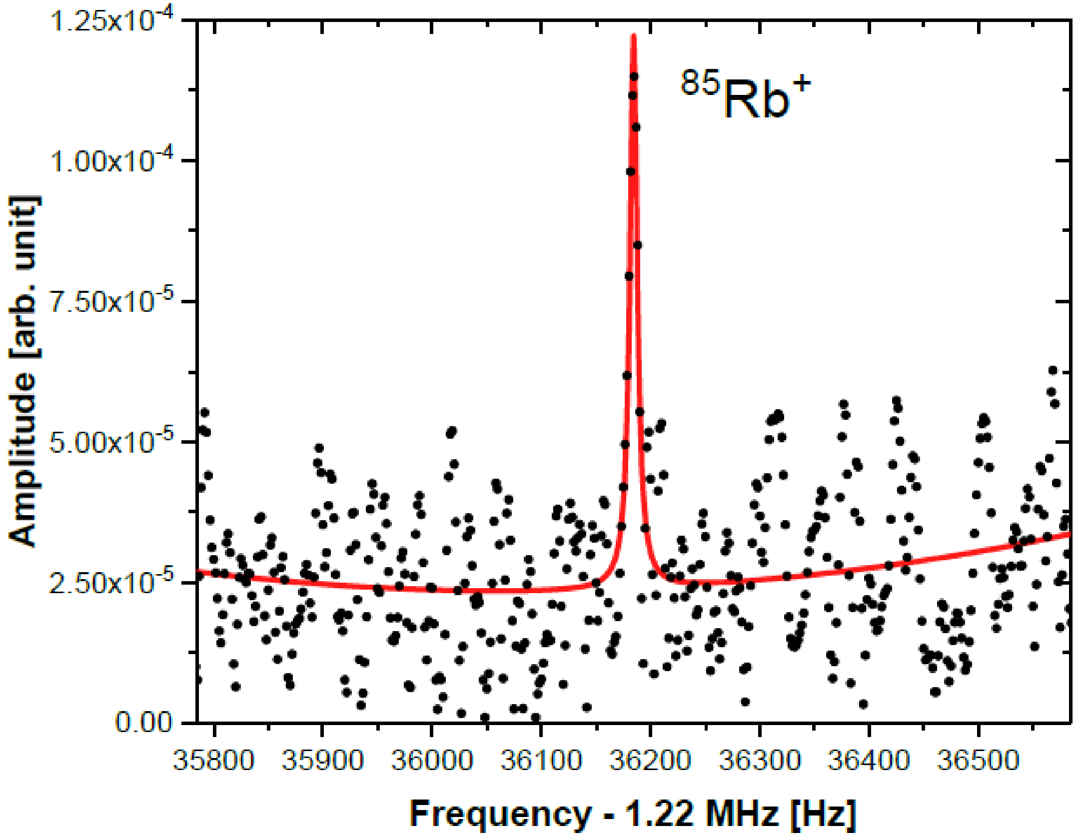

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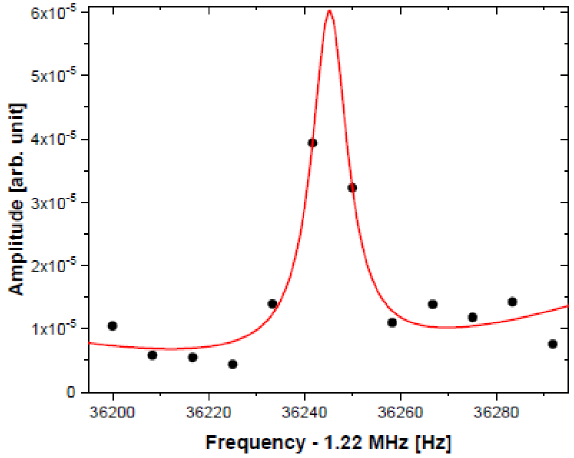

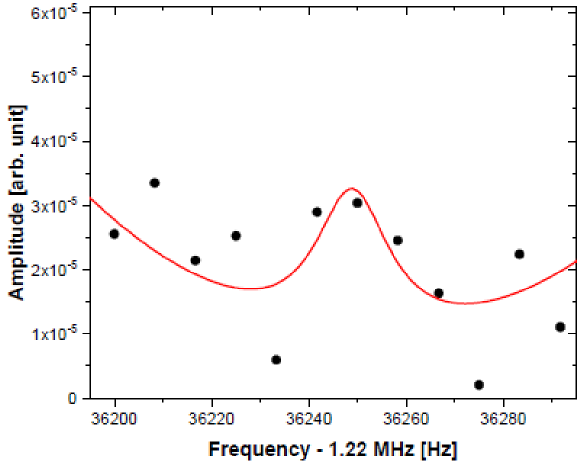

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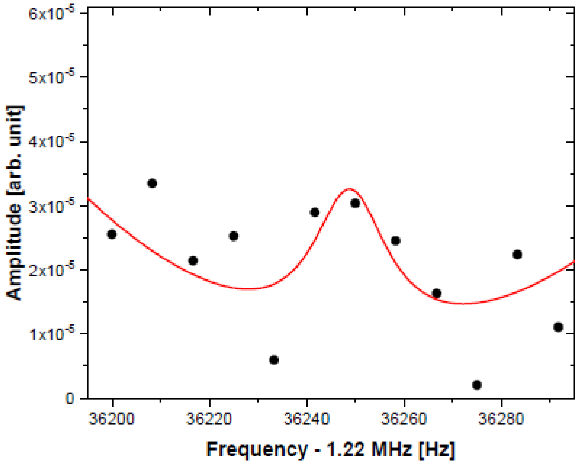

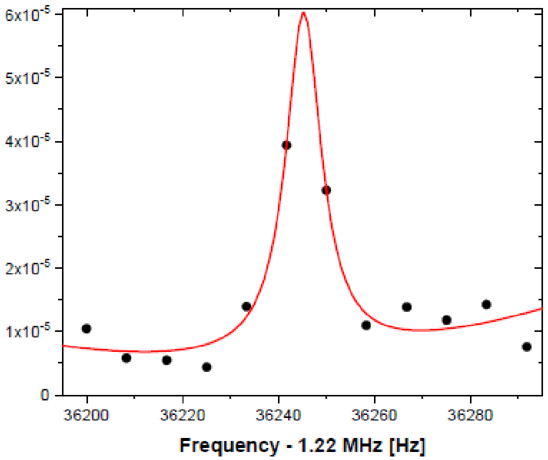

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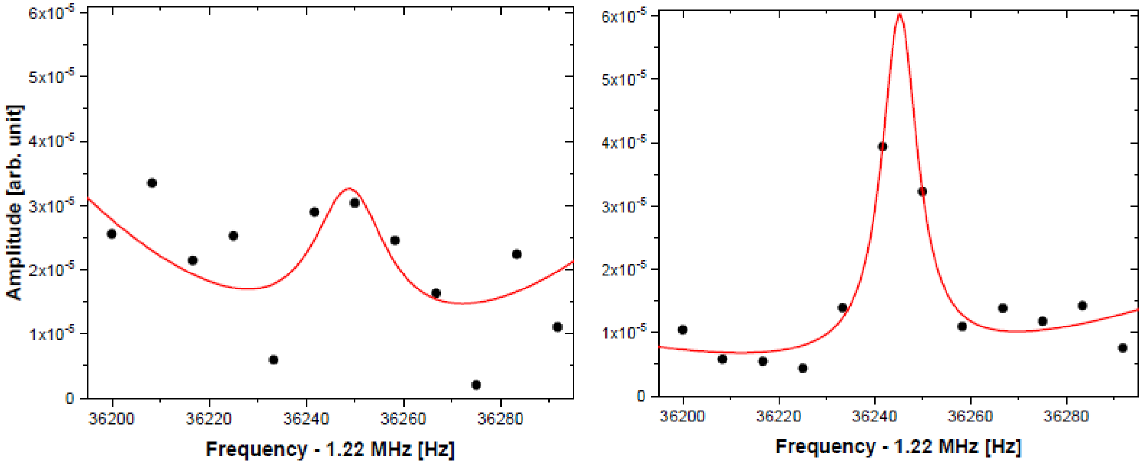

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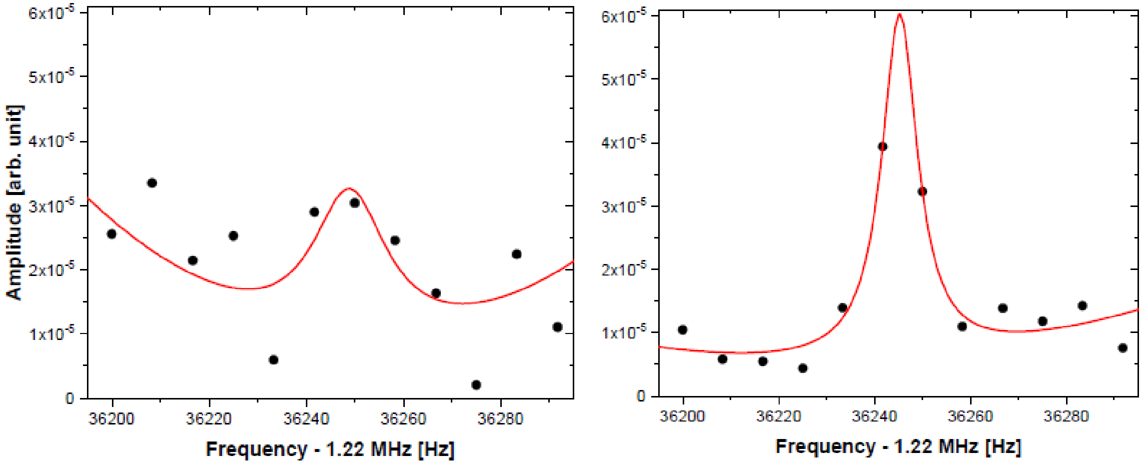

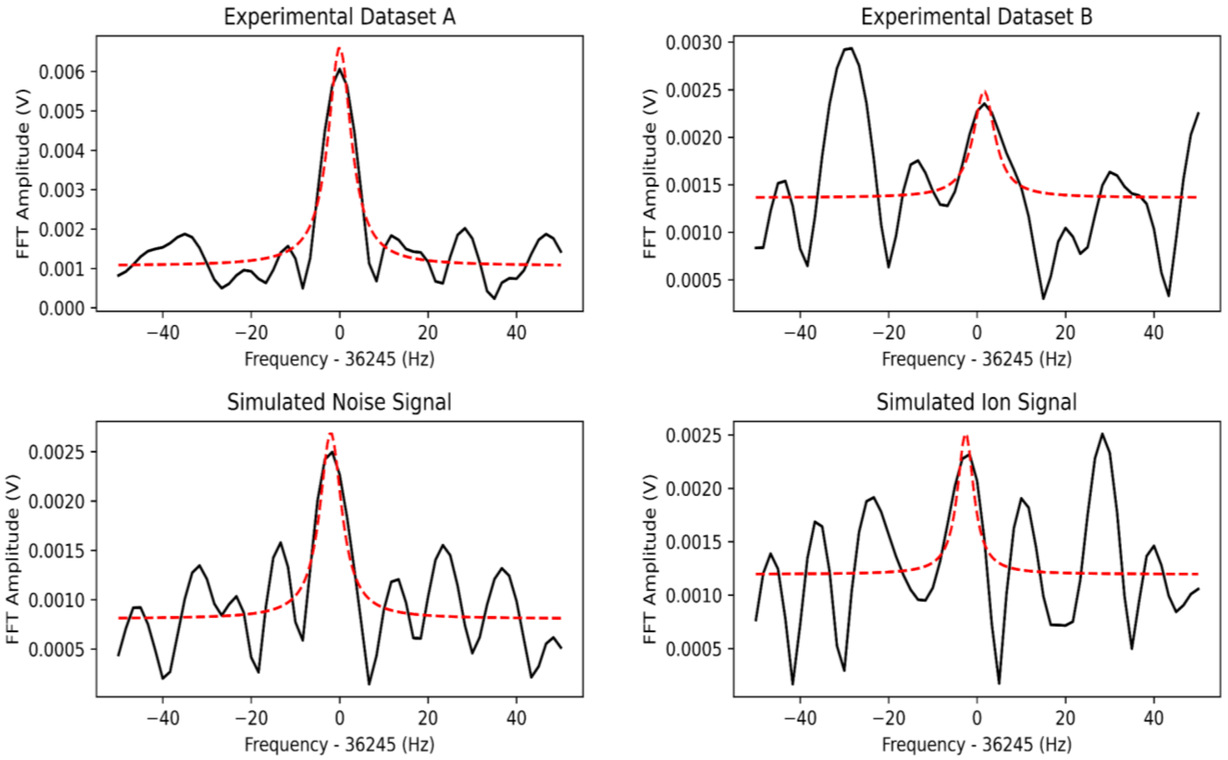

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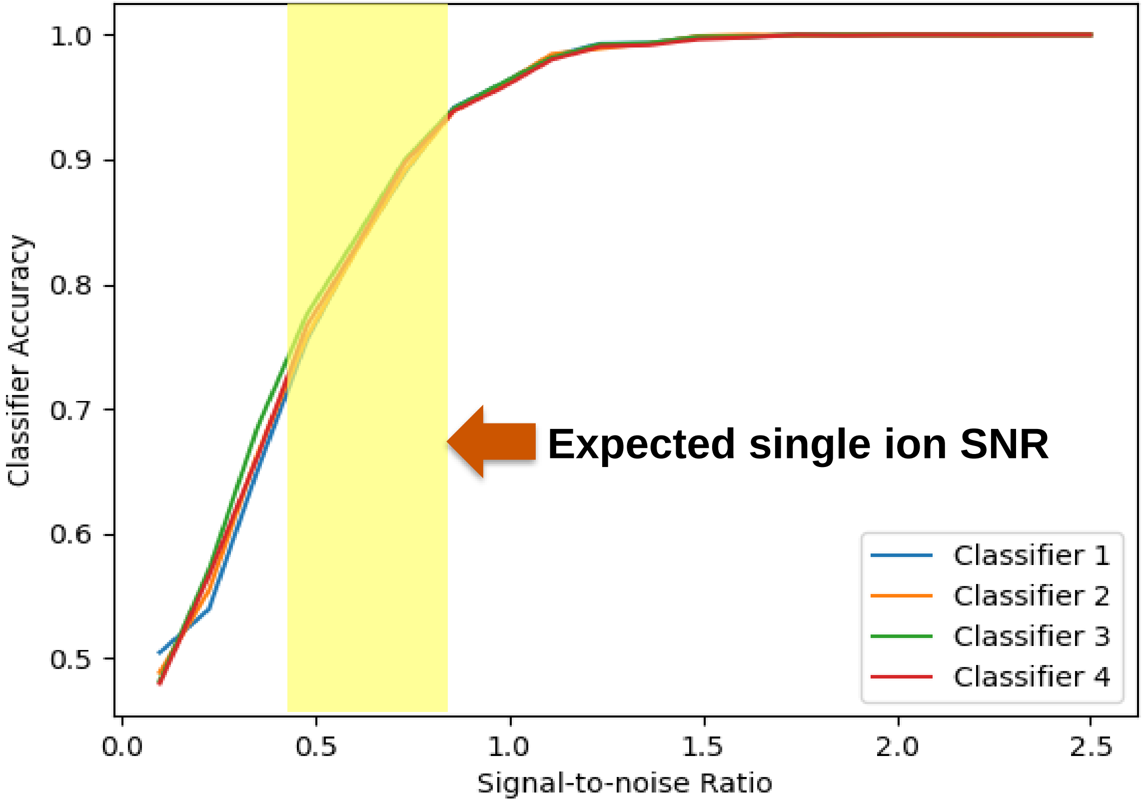

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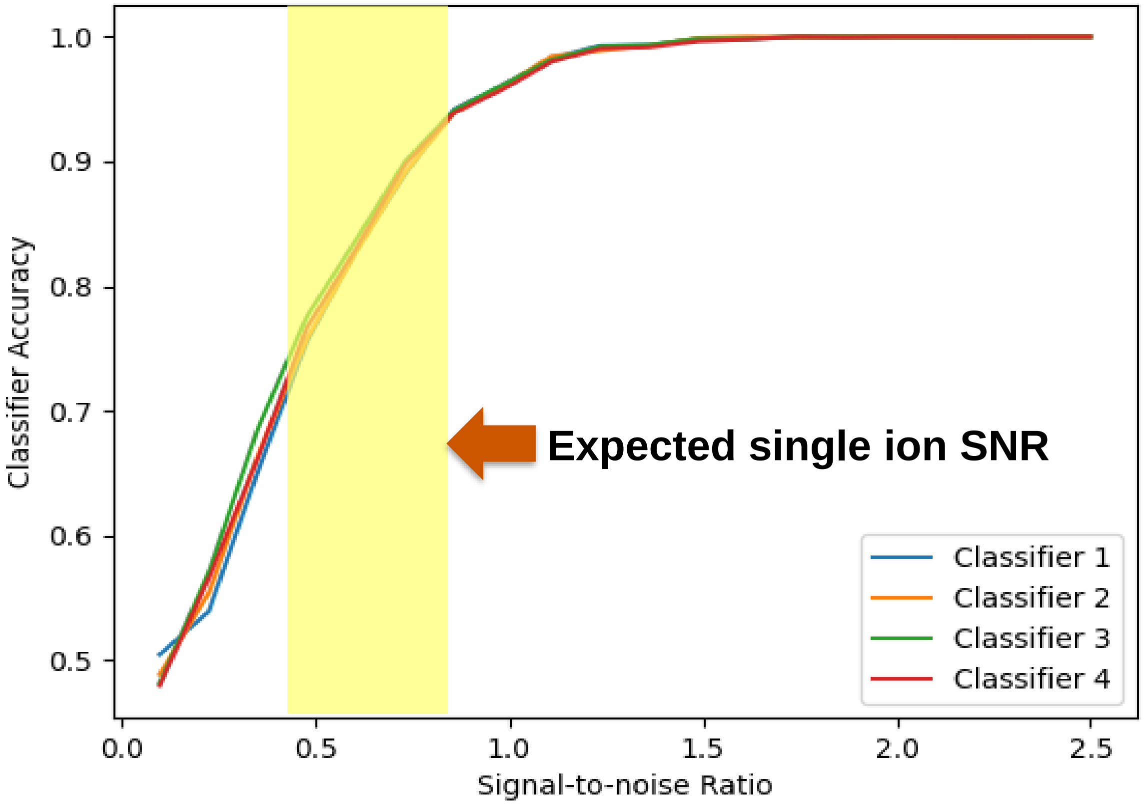

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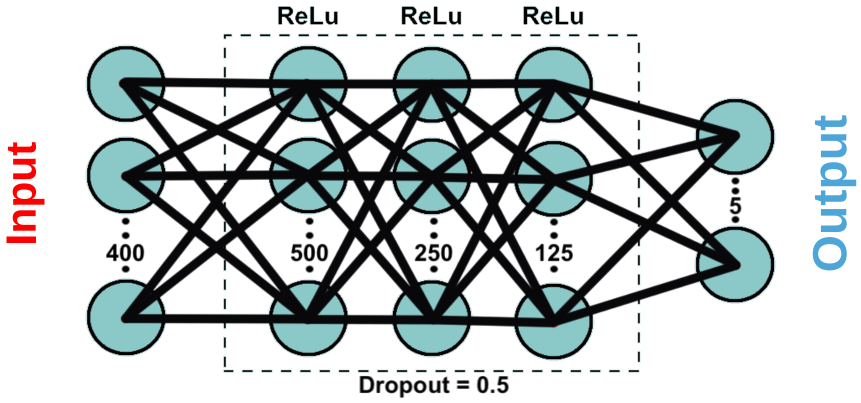
- Single Ion Sensitivity with Deep Learning
  - Output number of ions based on input signal amplitudes (Lorentzian Area)



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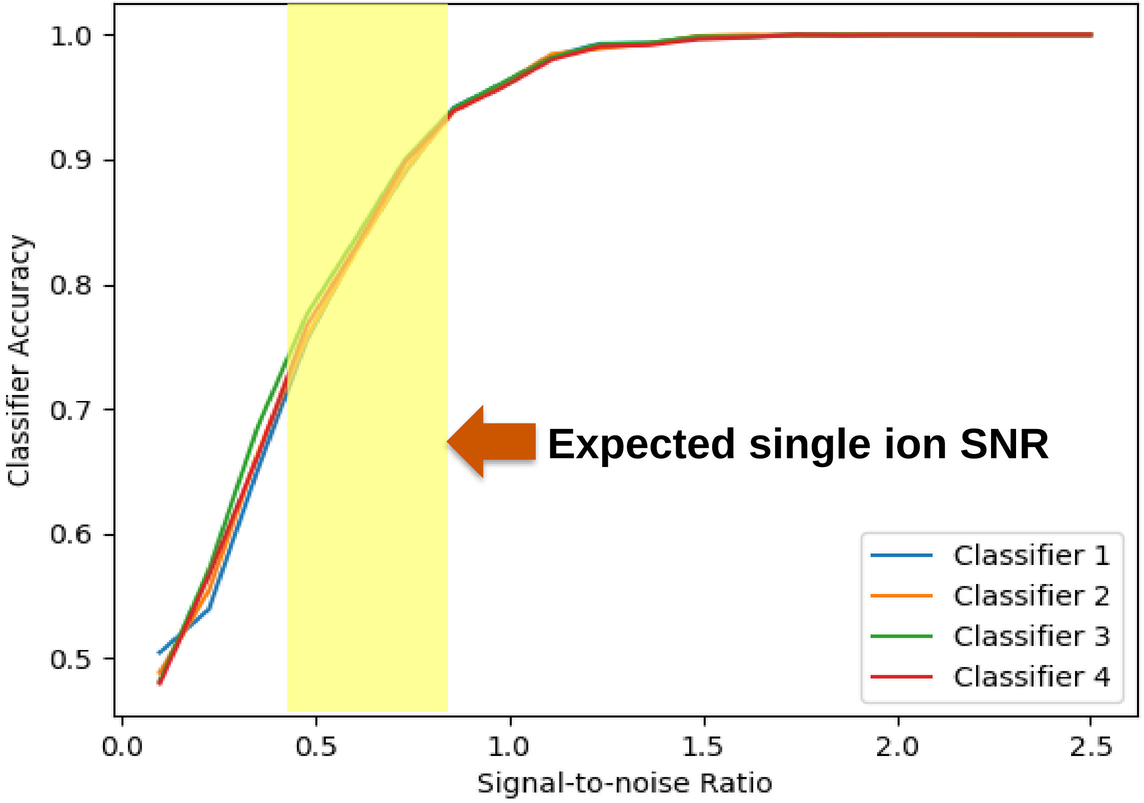

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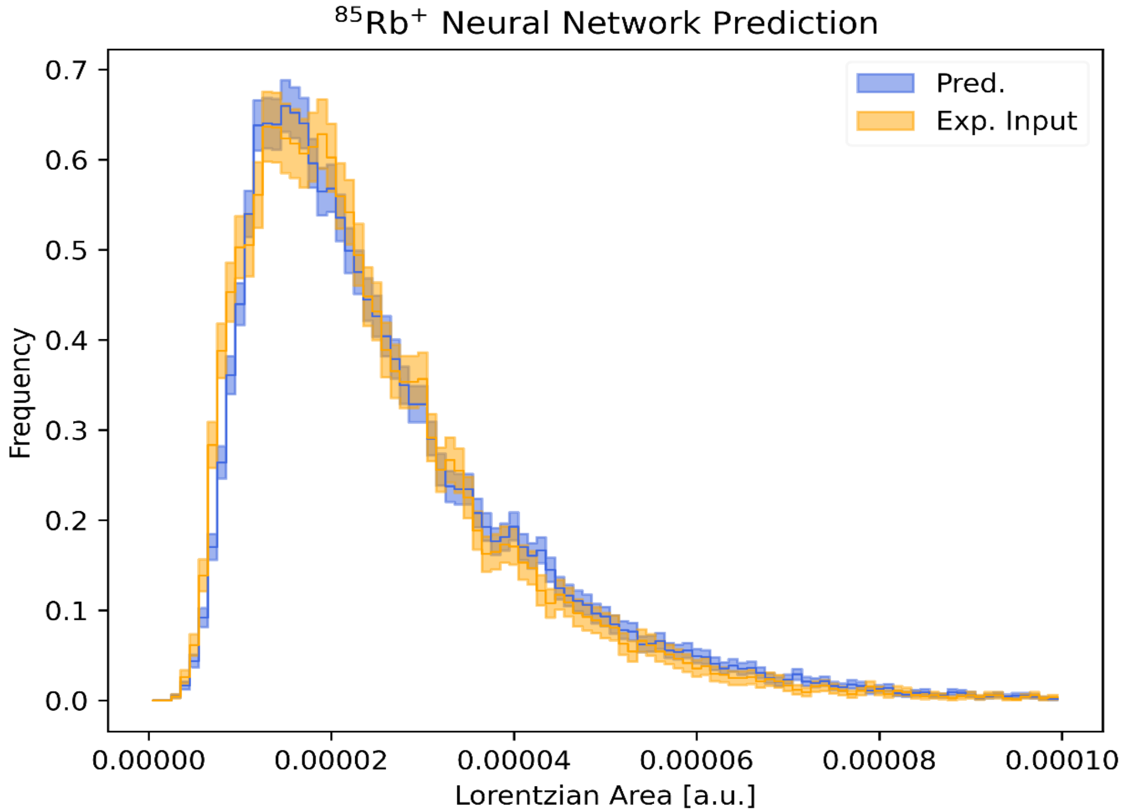

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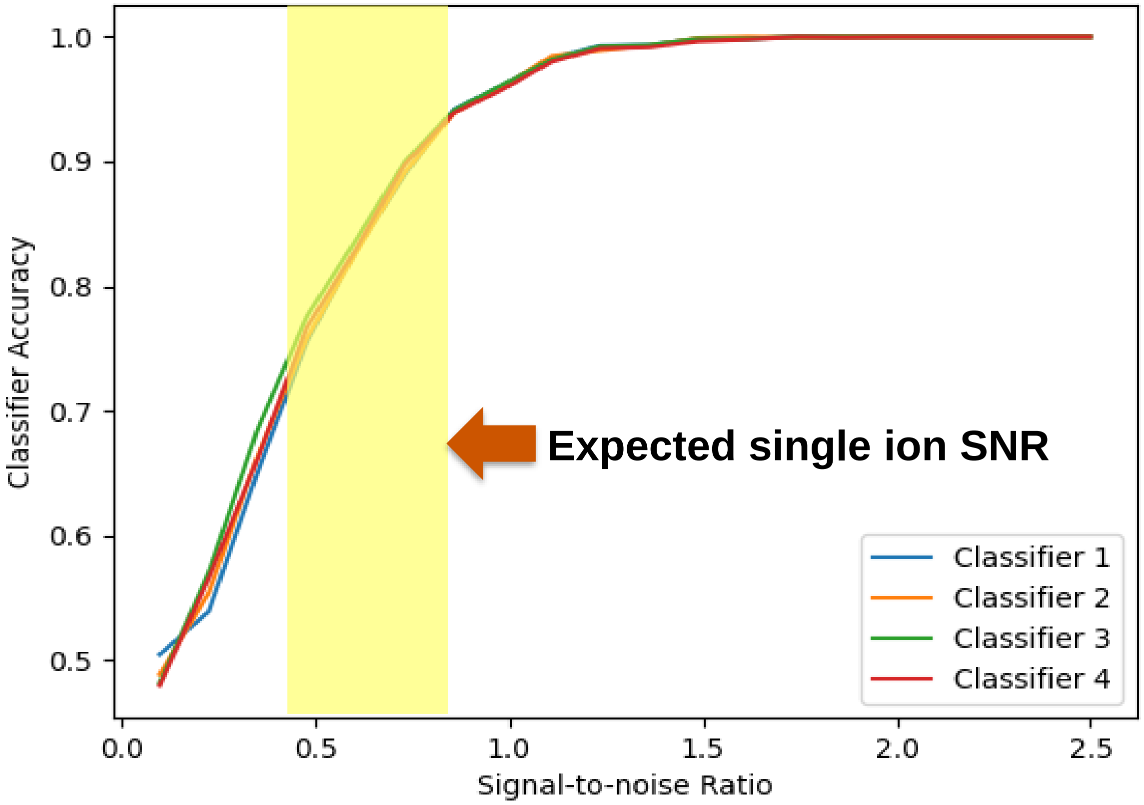

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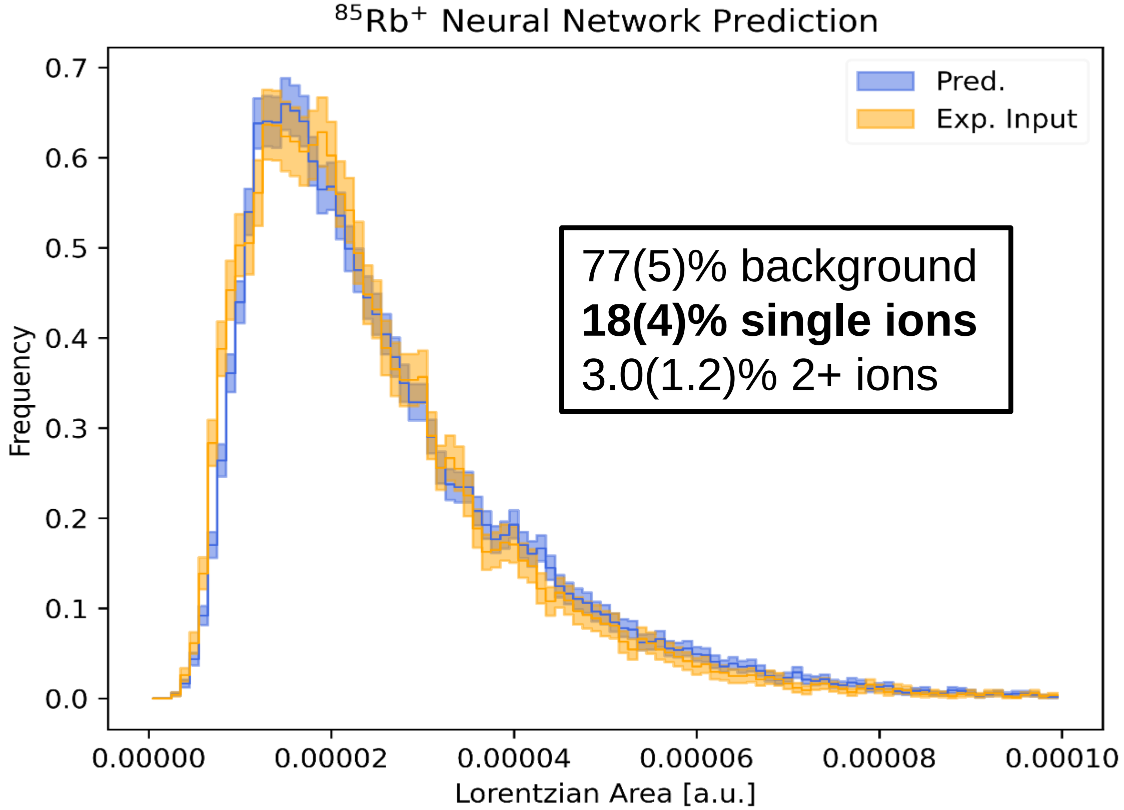

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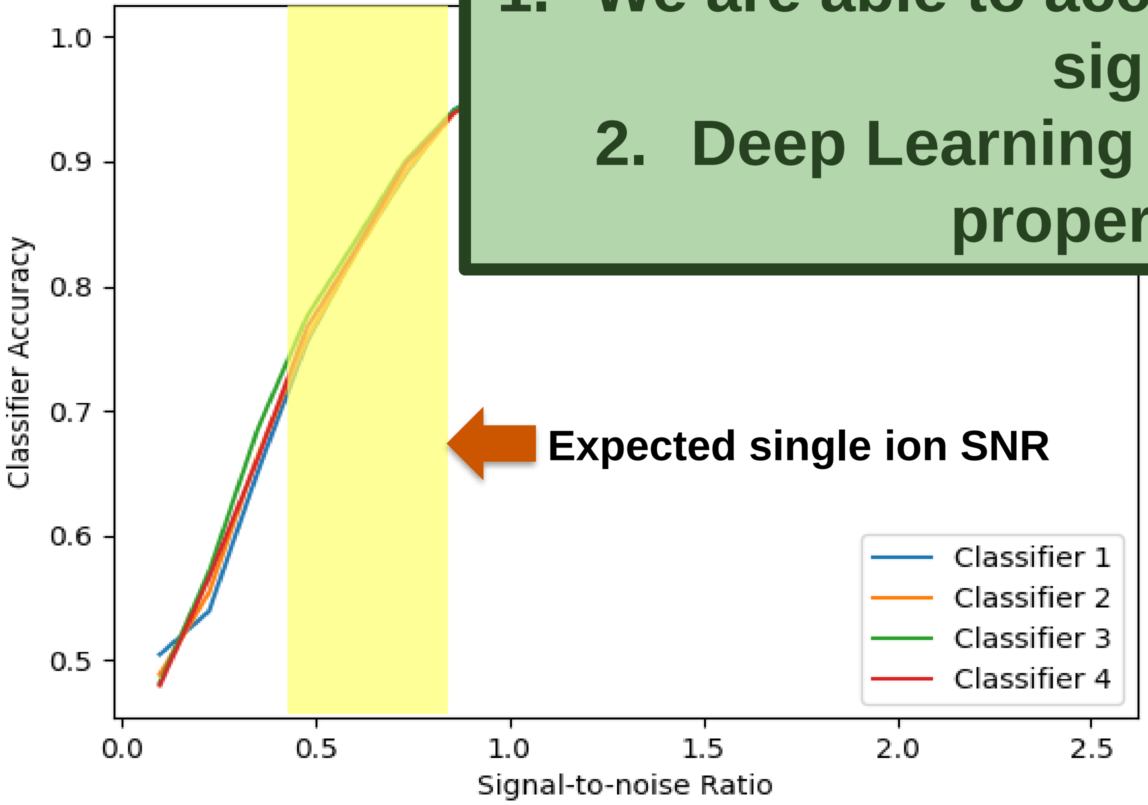
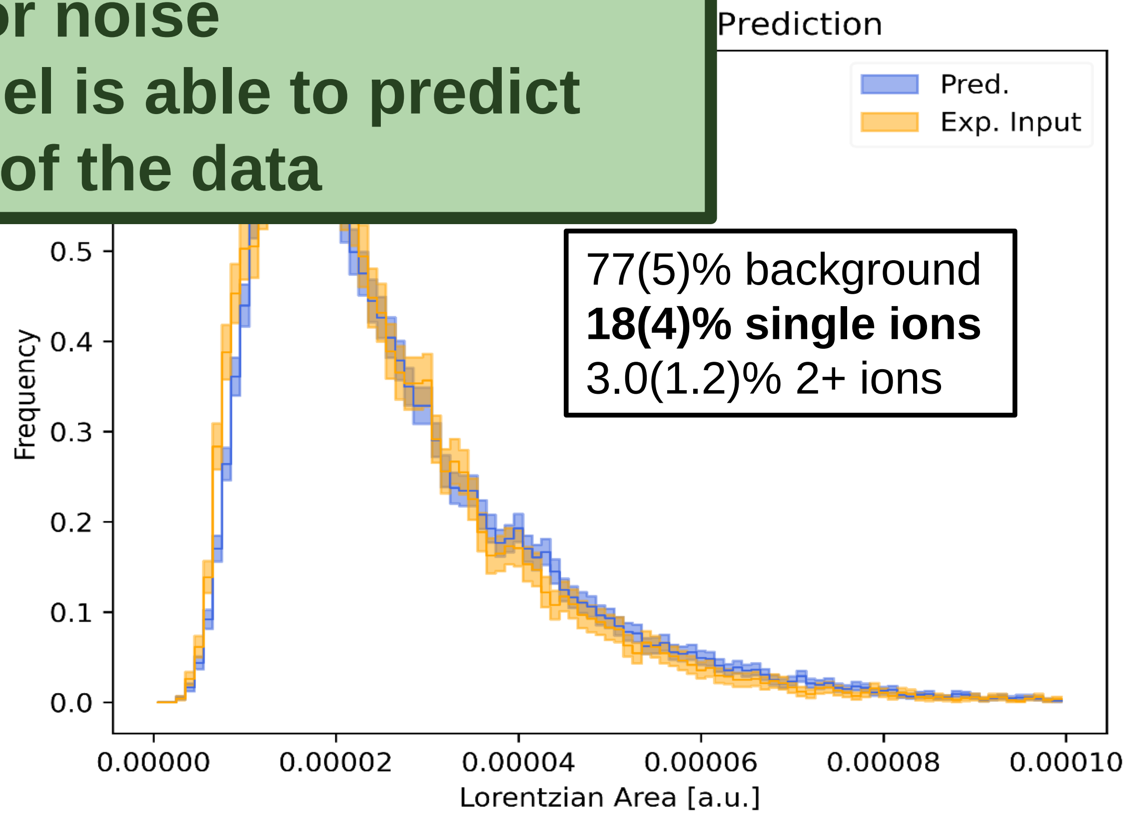


Main Takeaways:
1. **We are able to accurately determine if data is signal or noise**
2. **Deep Learning Model is able to predict properties of the data**



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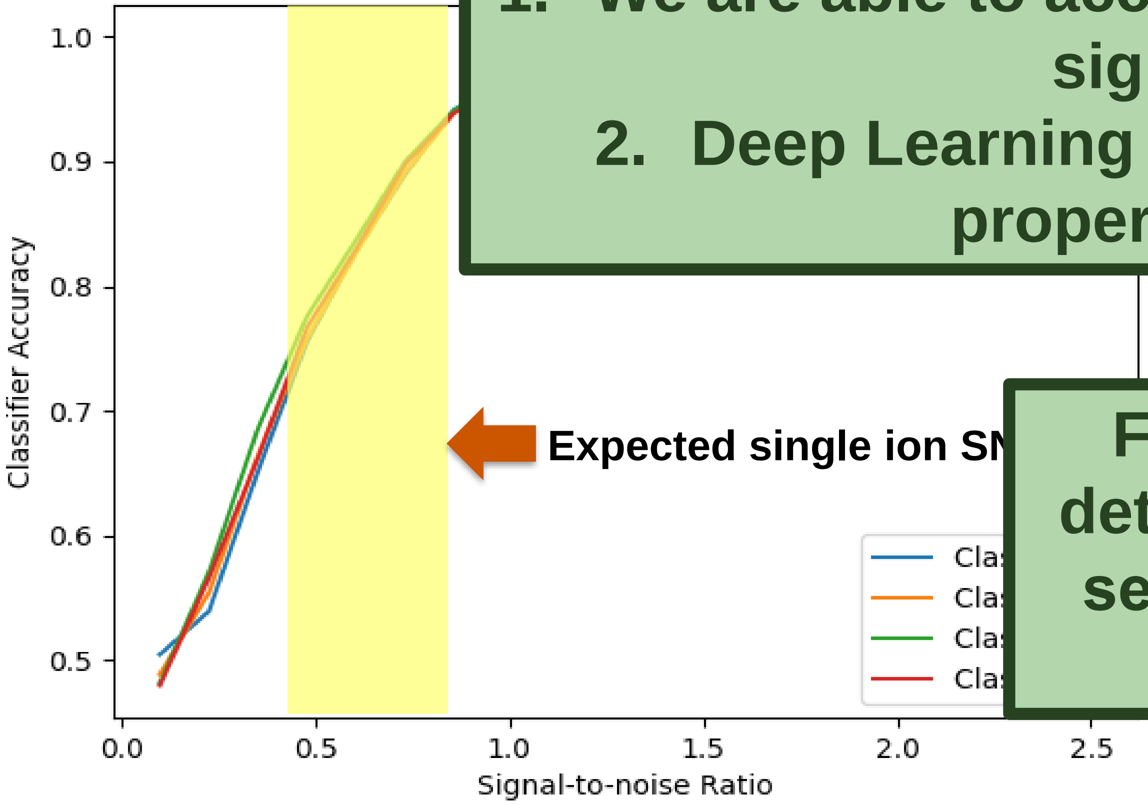

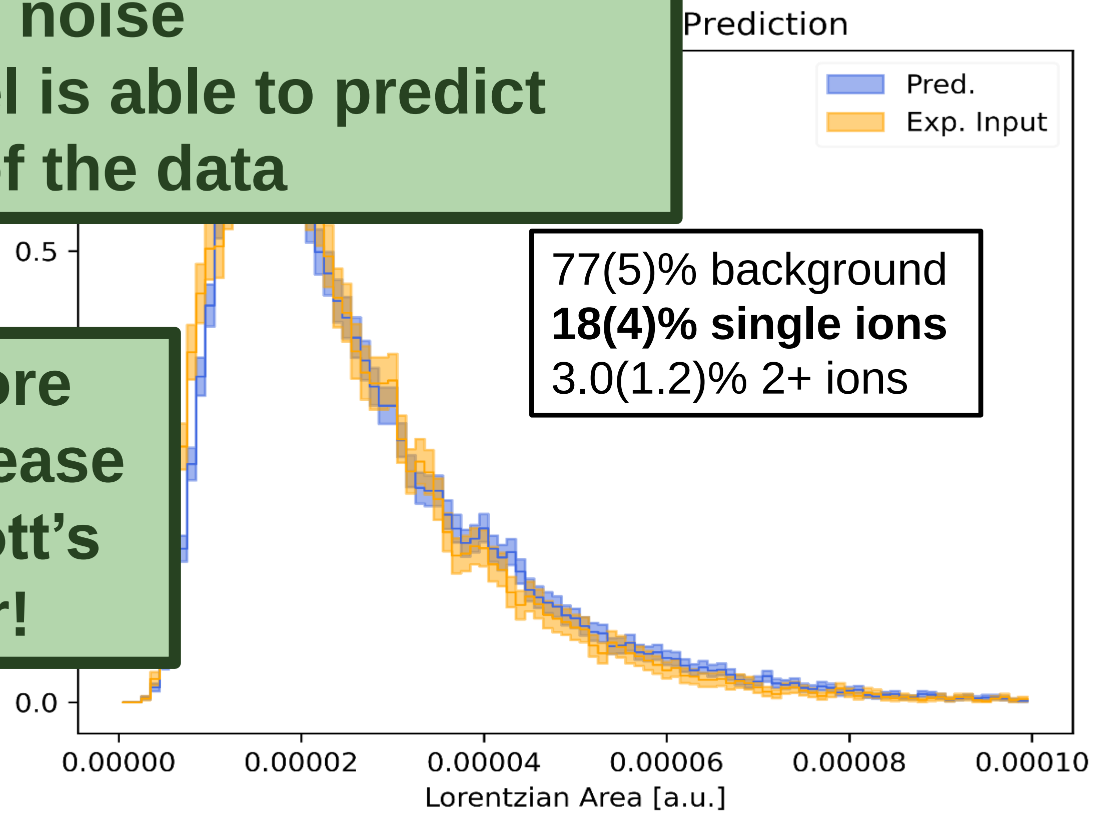

77(5)% background
18(4)% single ions
3.0(1.2)% 2+ ions

For more detail please see Scott's paper!

S. Campbell *et al.*, Atoms **11**, 10 (2023)

Updated Electrode Pickup Scheme Allows for Detection of ω_c

- Detection of ω_c and ω_+ demonstrated with Minitrap[1]
  - FT-ICR magnetometer using H_3O^+ ions

[1]D. L. Lincoln *et al*. Int. J. Mass Spectrom. **379**, 1 (2015)

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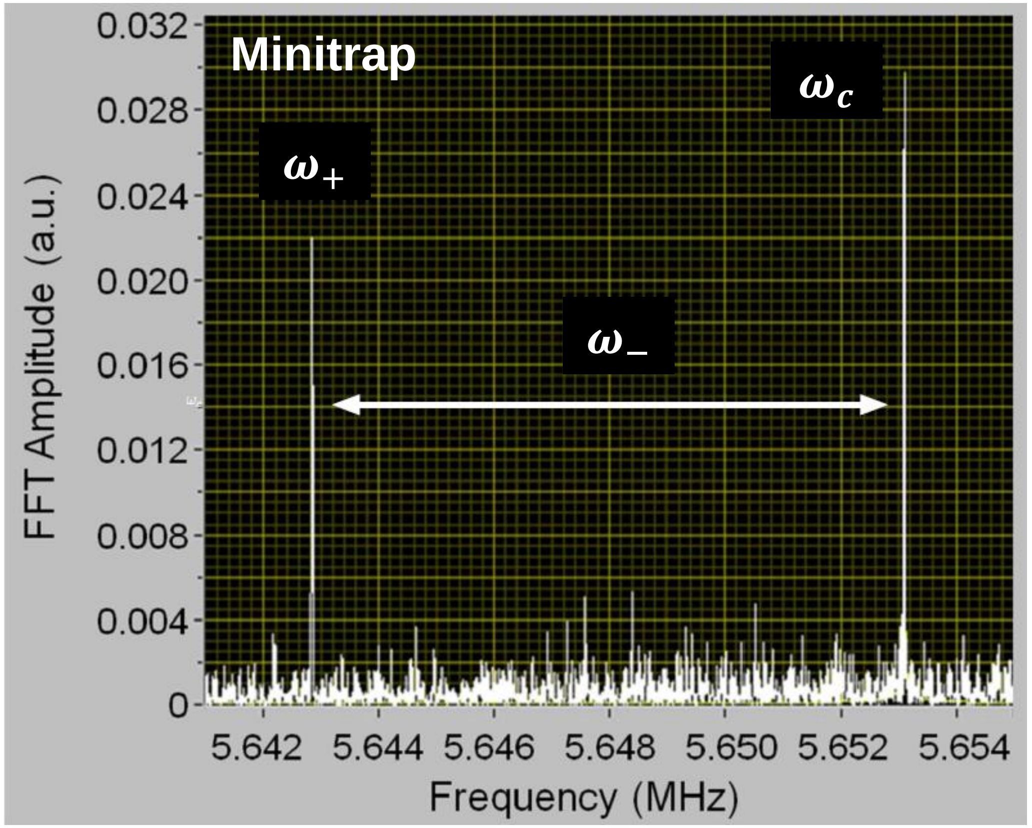

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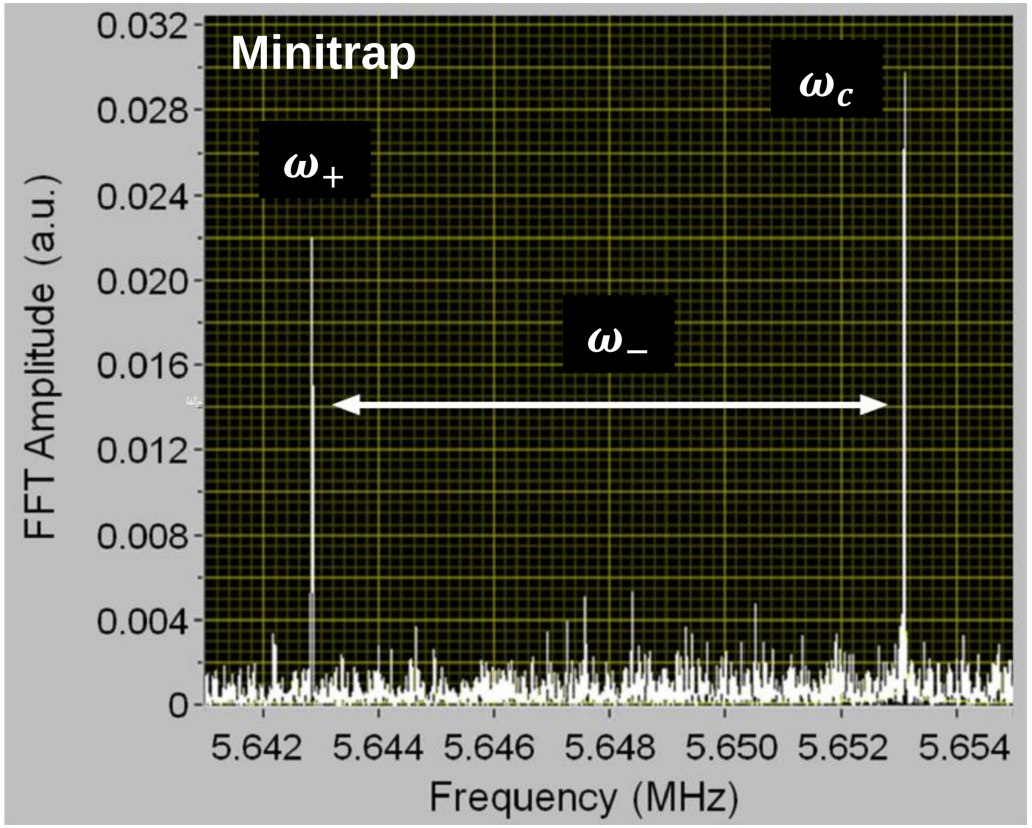

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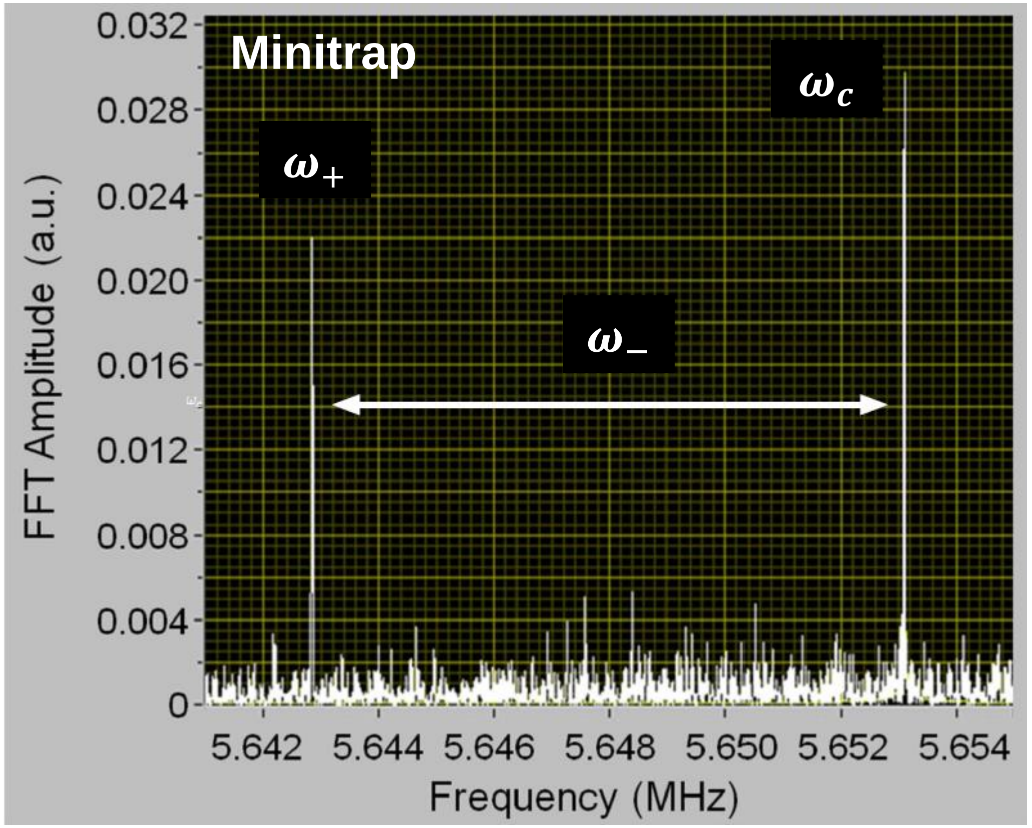

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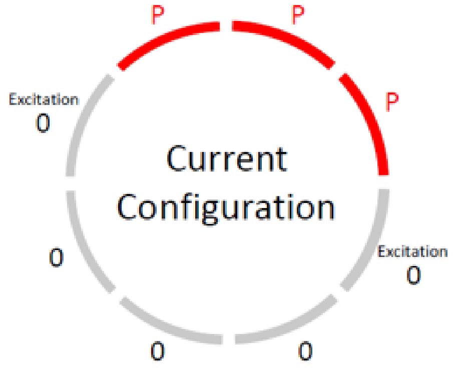

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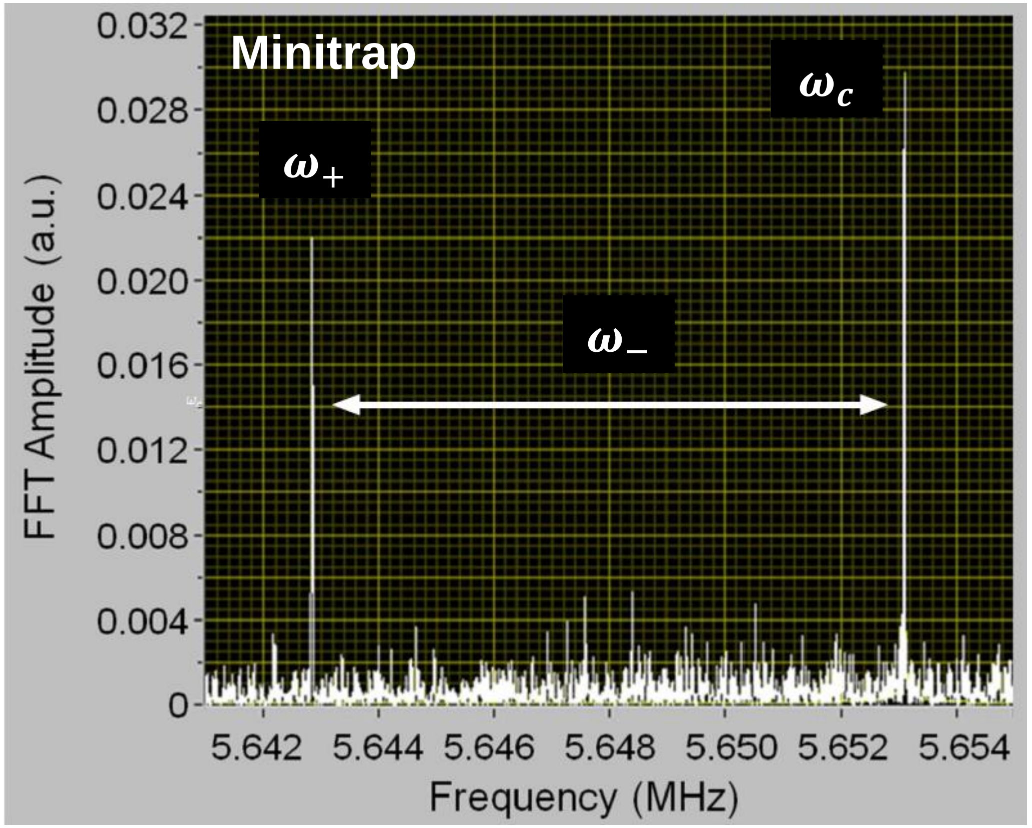

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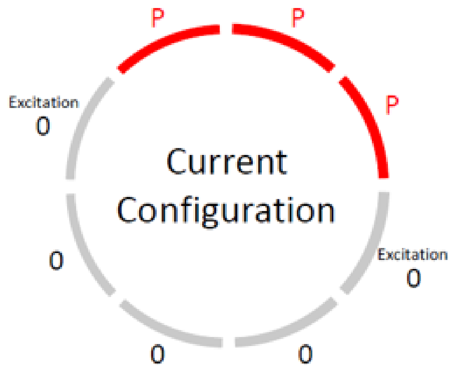

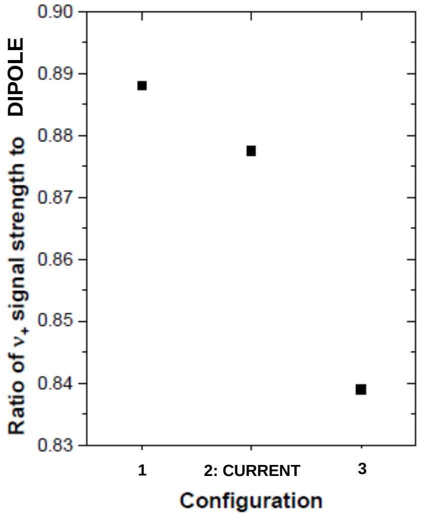

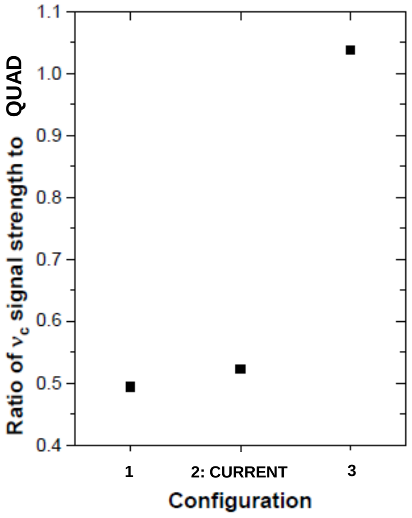

FRIB
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

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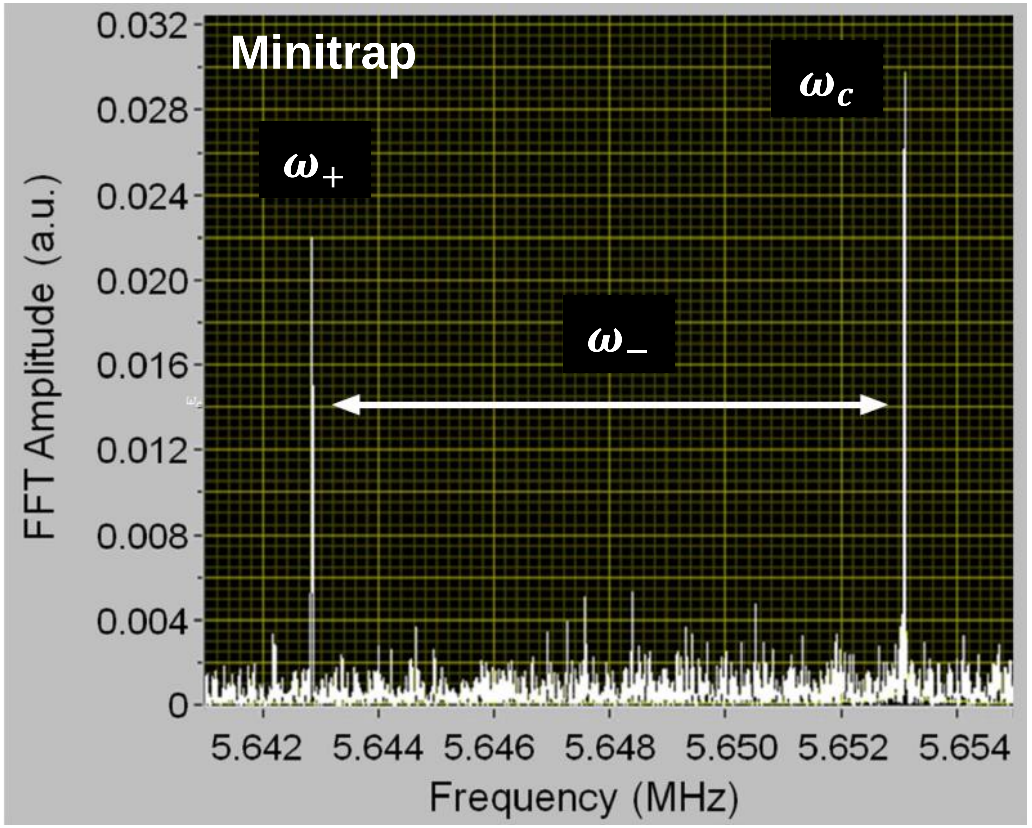

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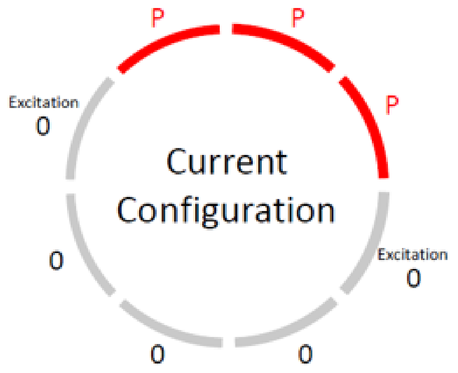

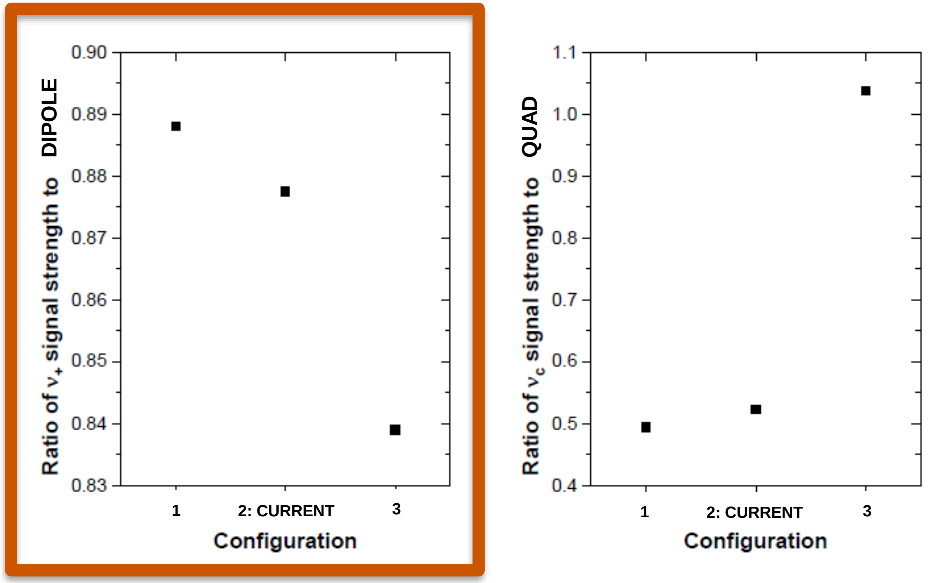

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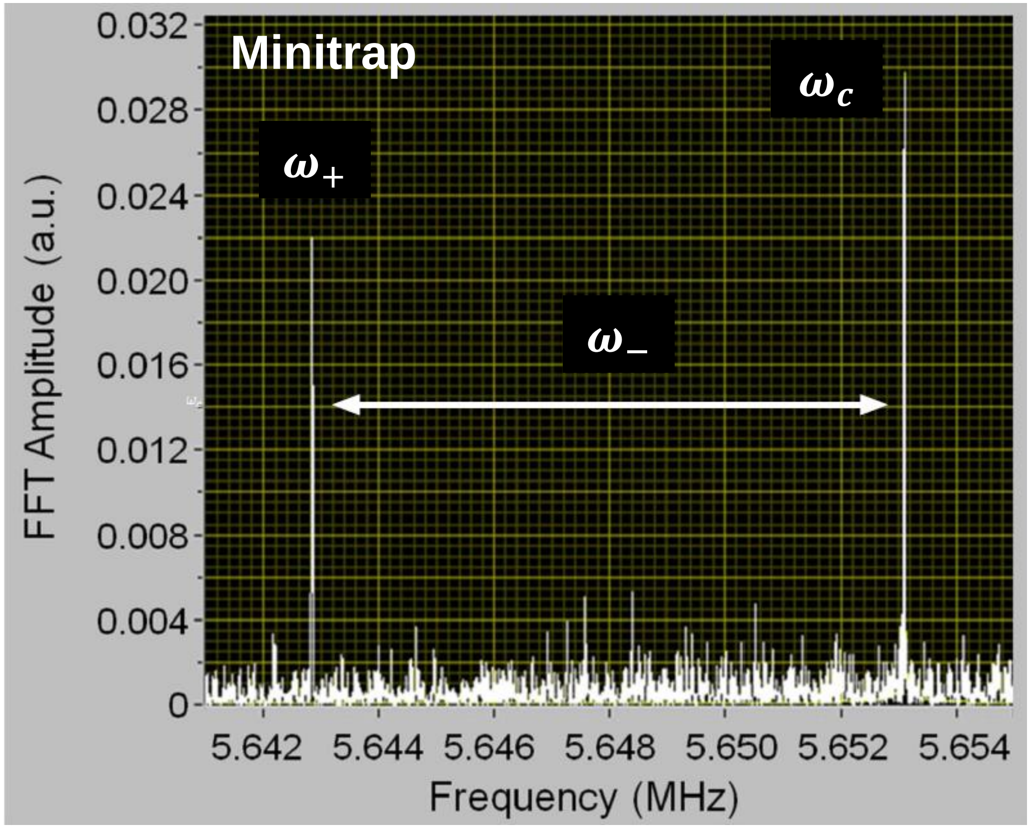

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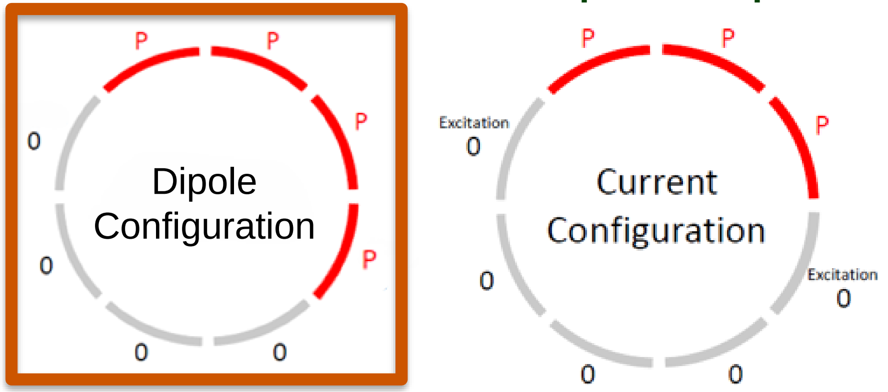

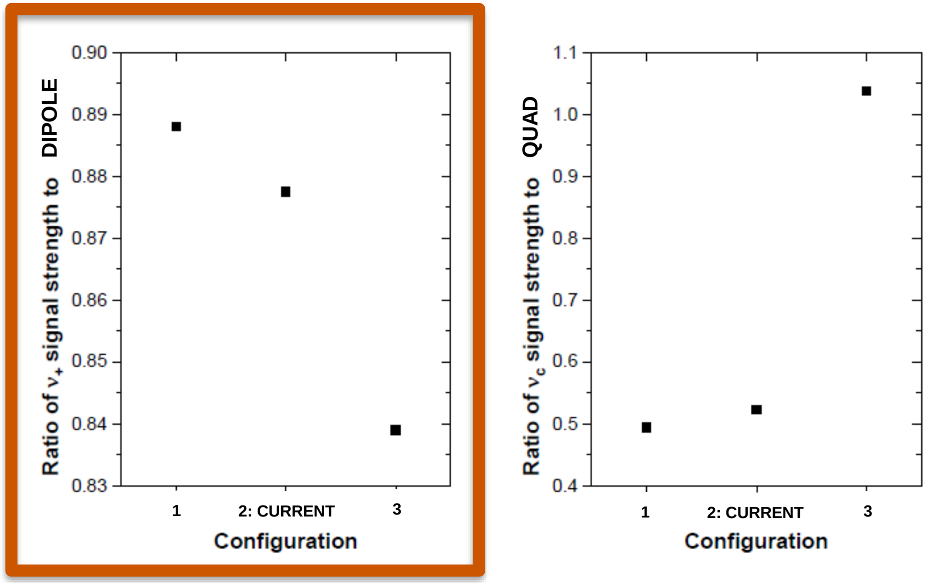

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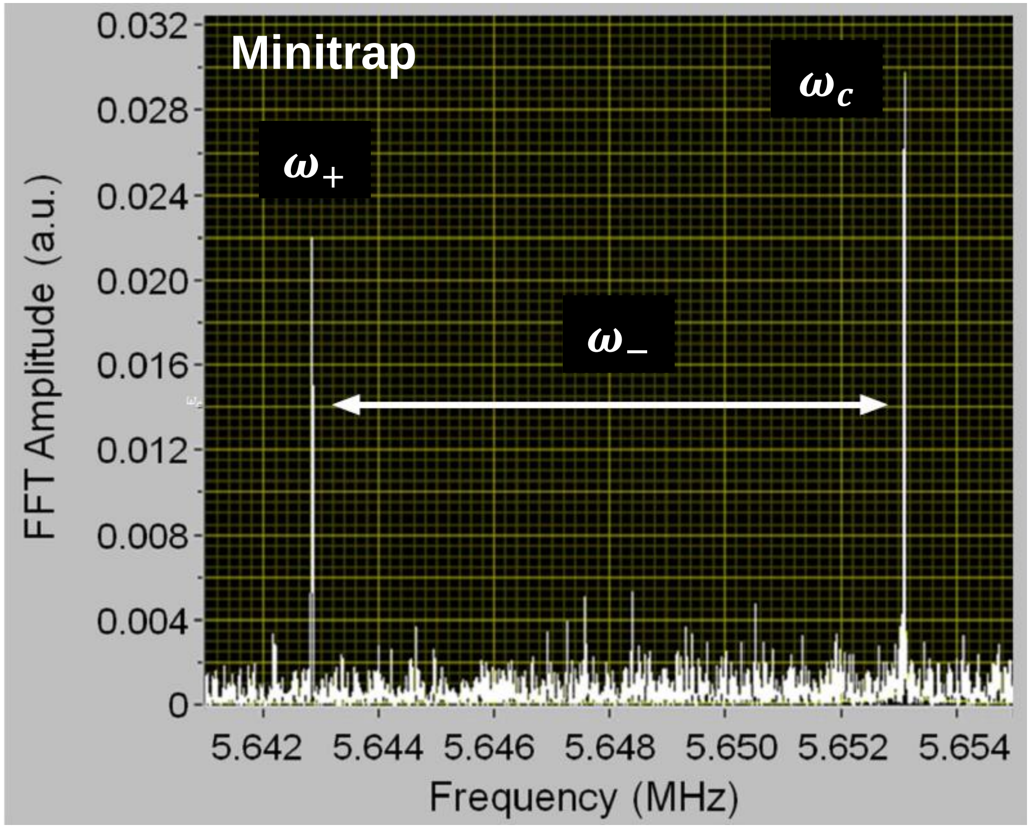

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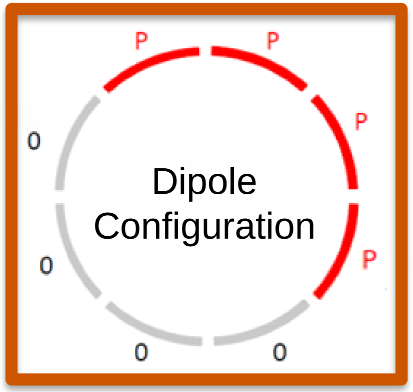

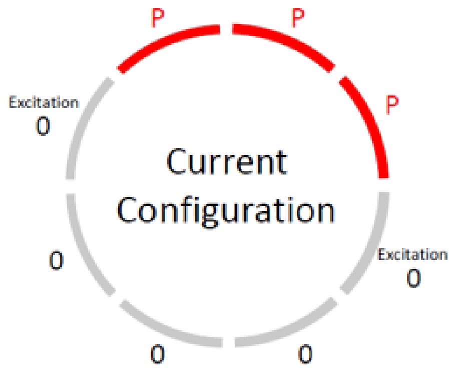

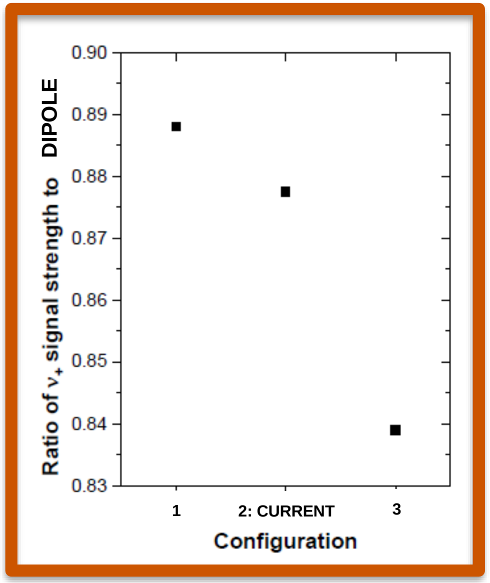

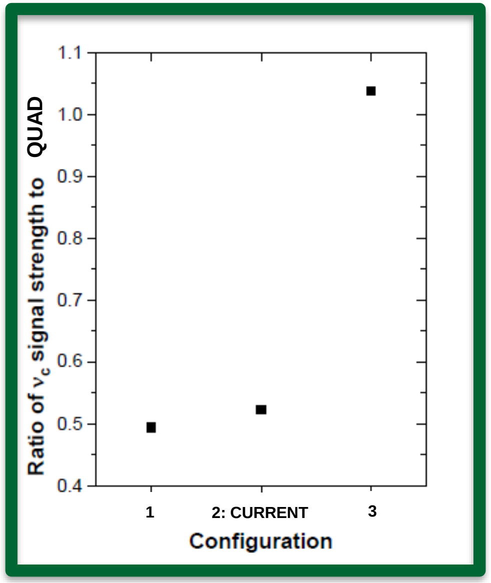

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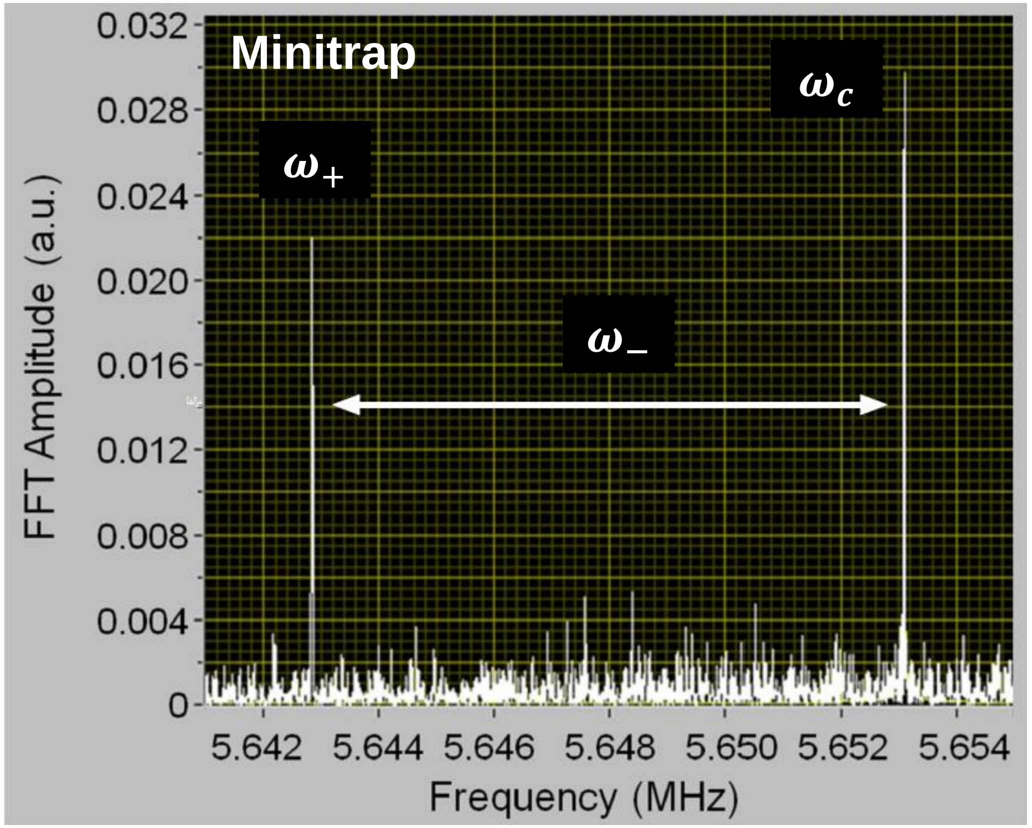

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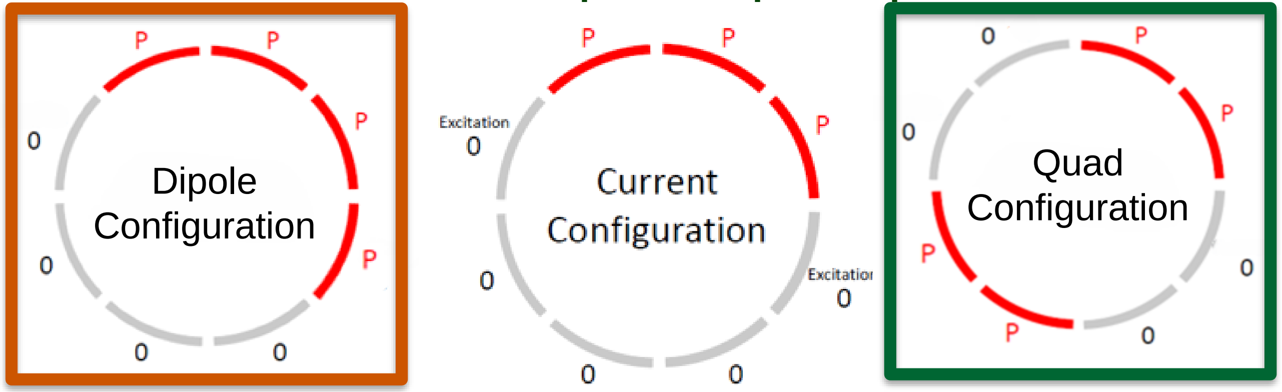

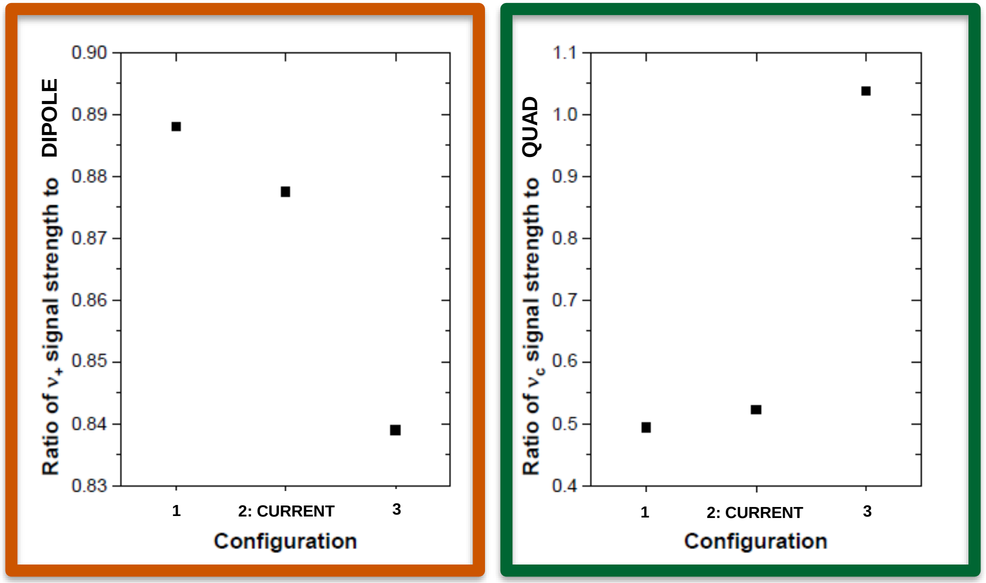

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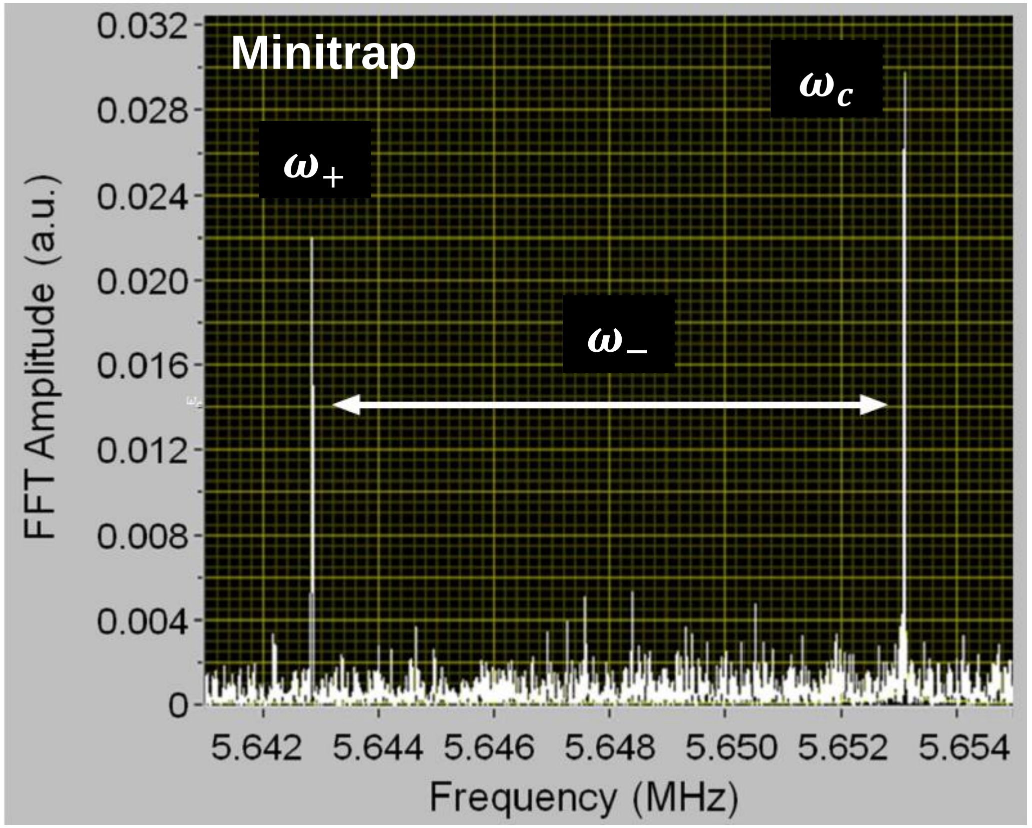

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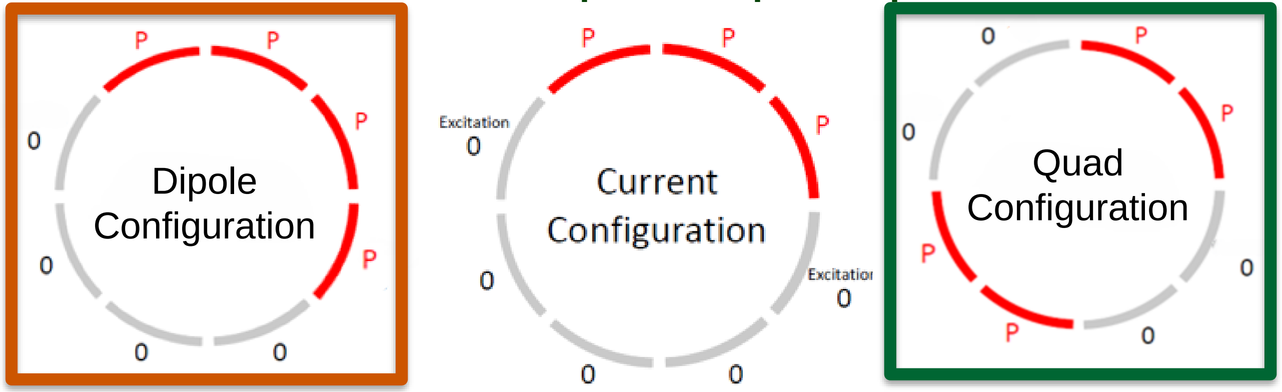

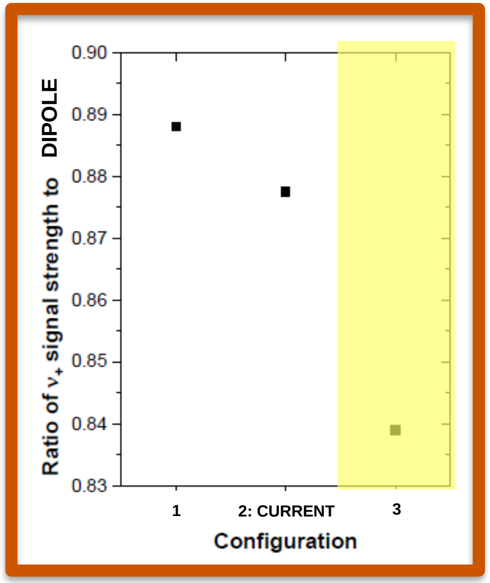

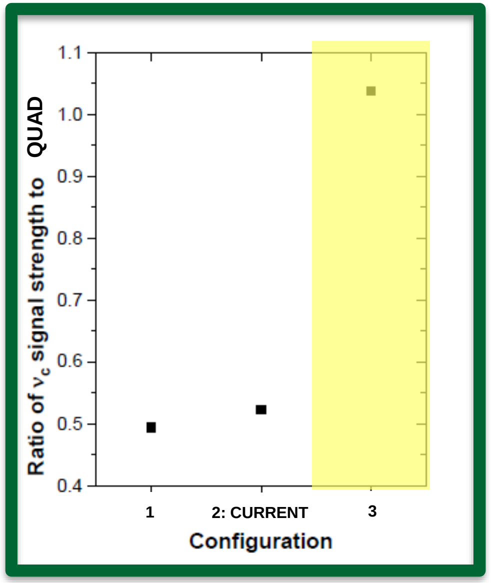

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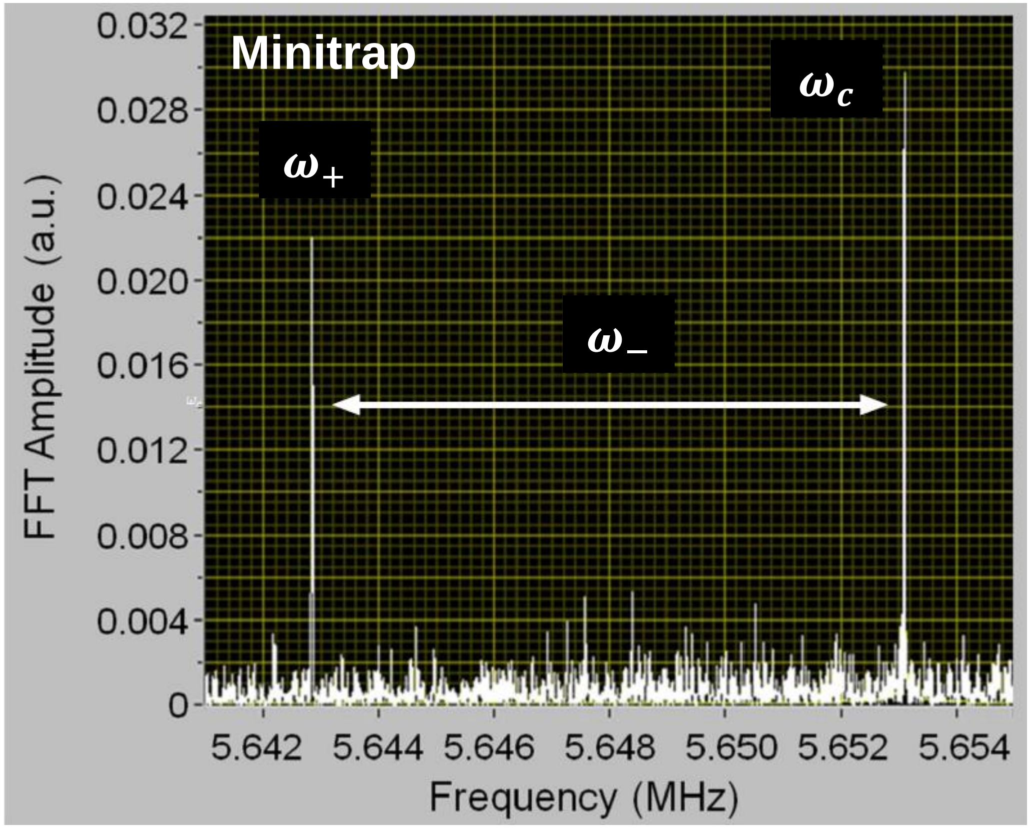

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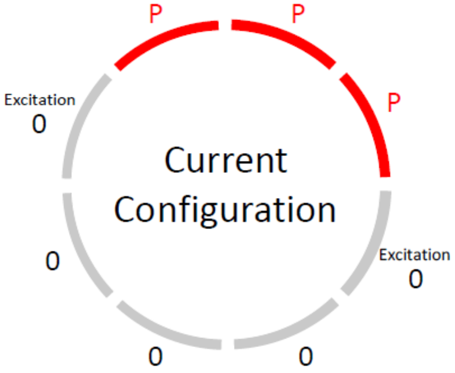

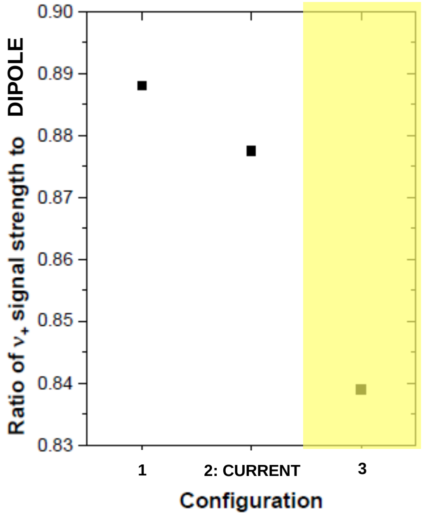

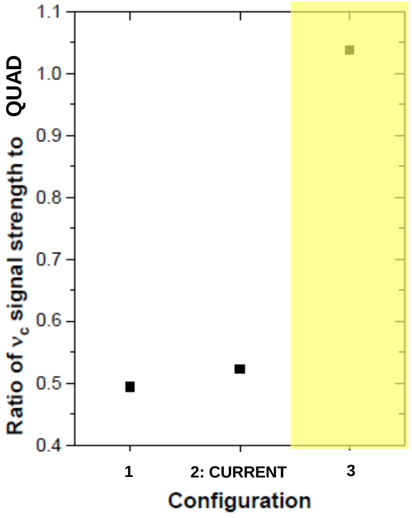

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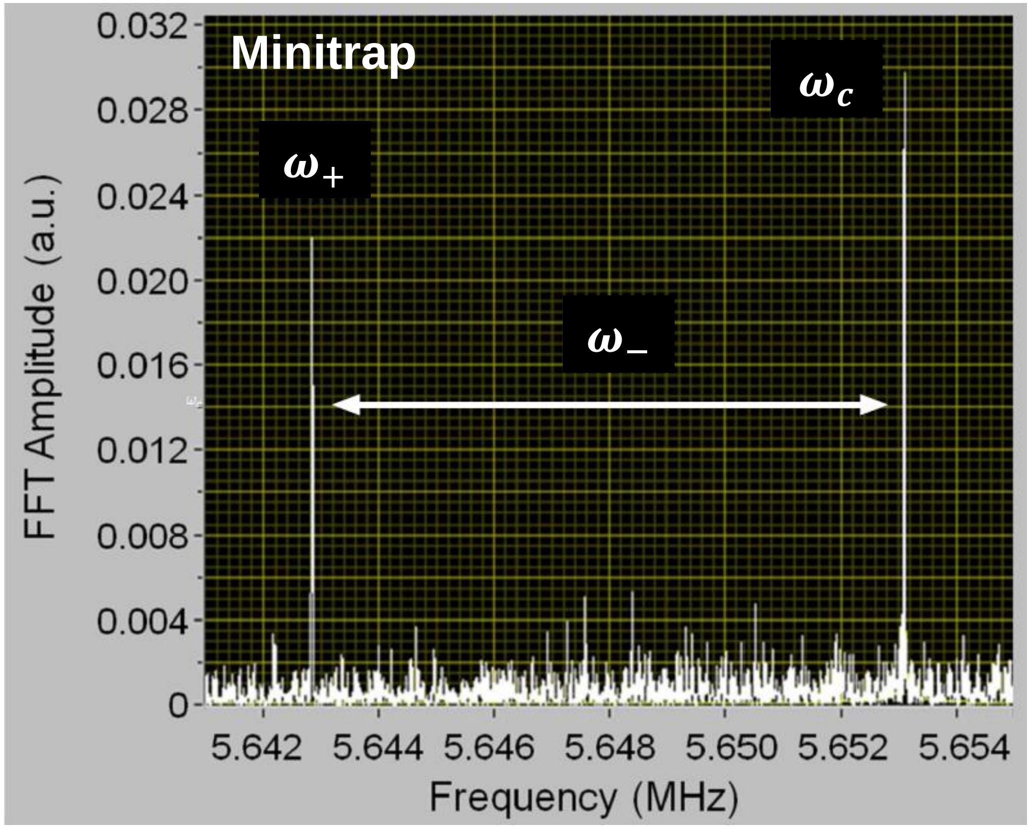

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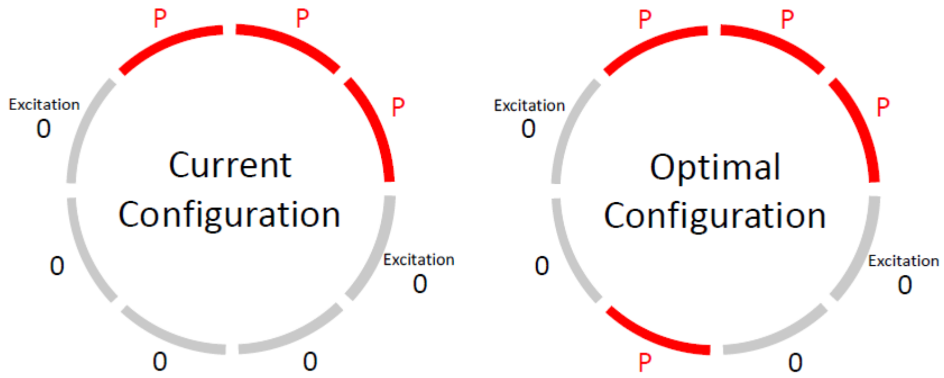

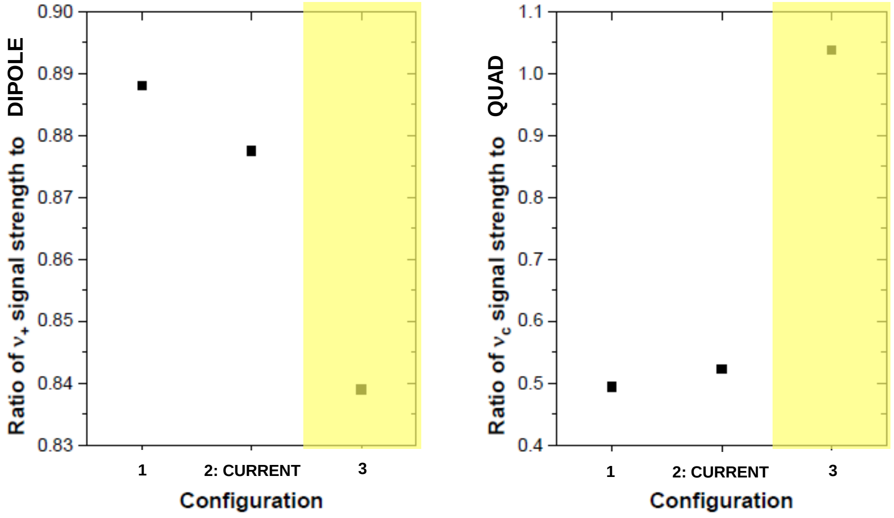

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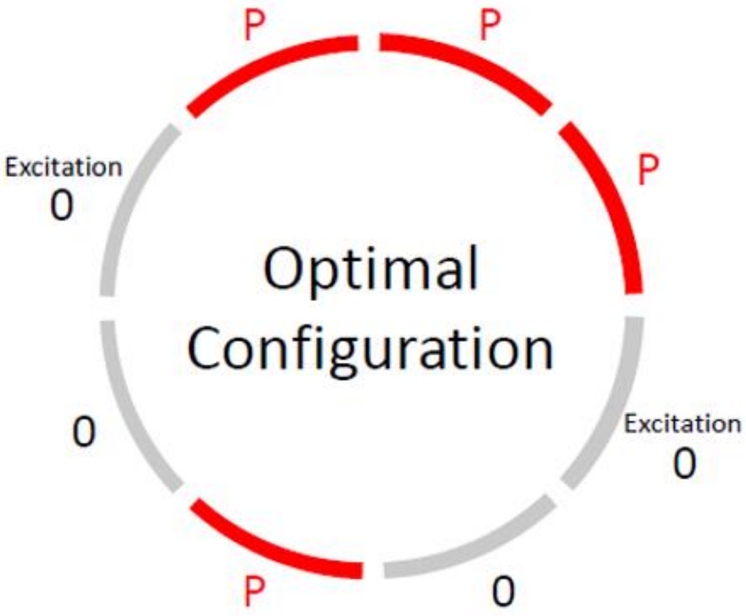

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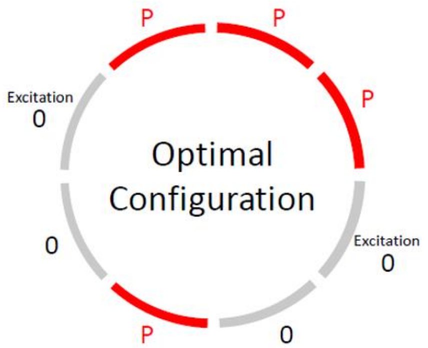

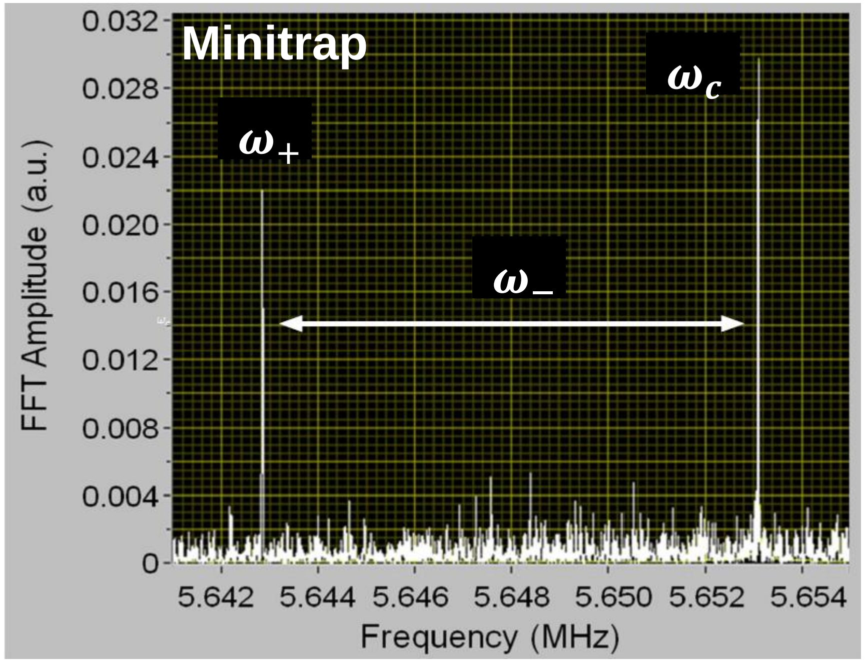

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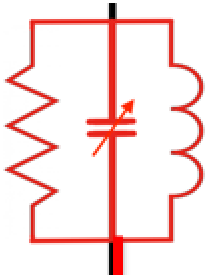

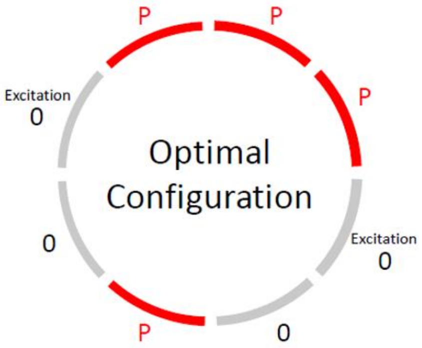

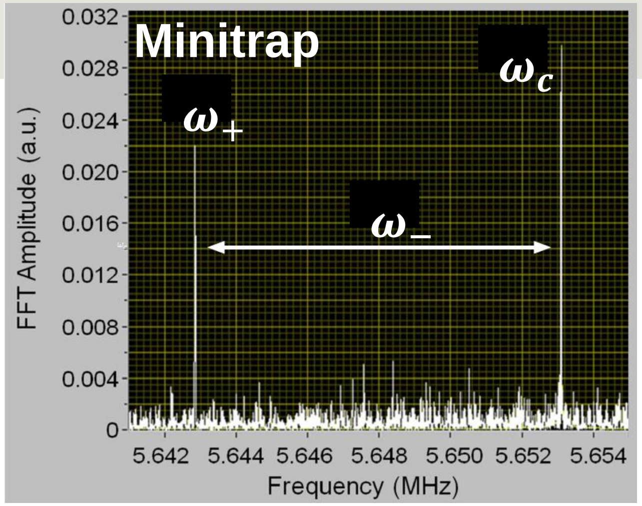

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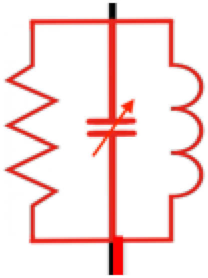

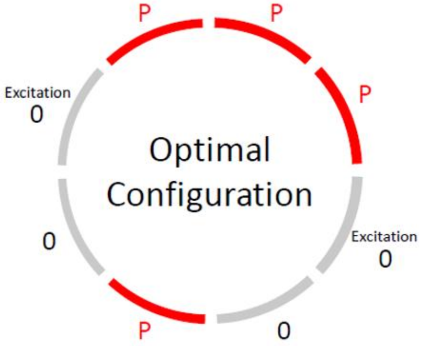

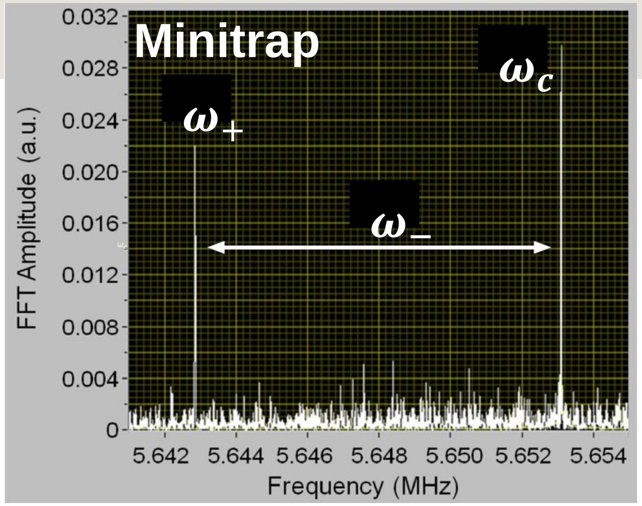

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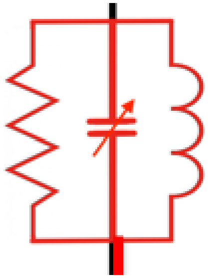

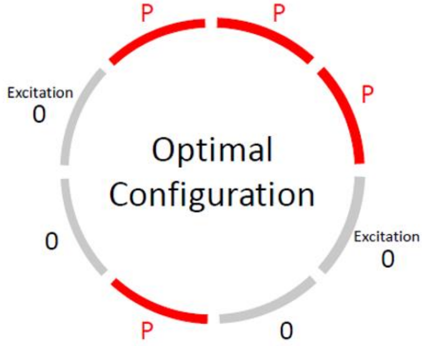

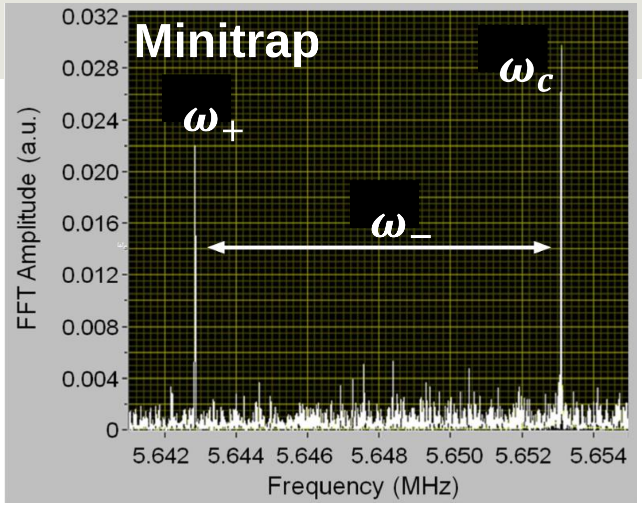

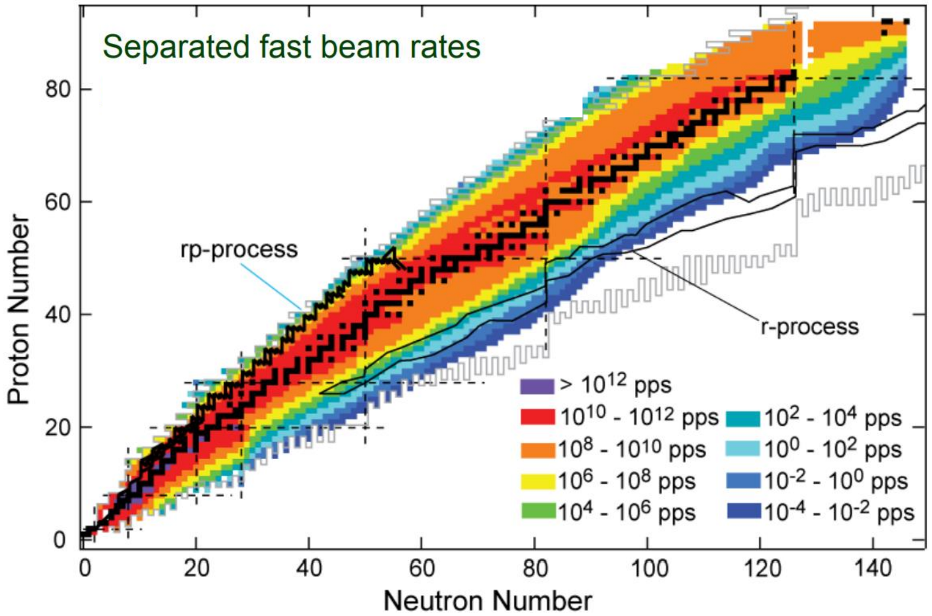

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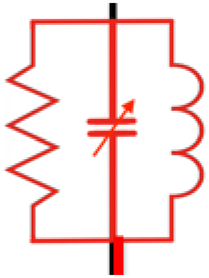

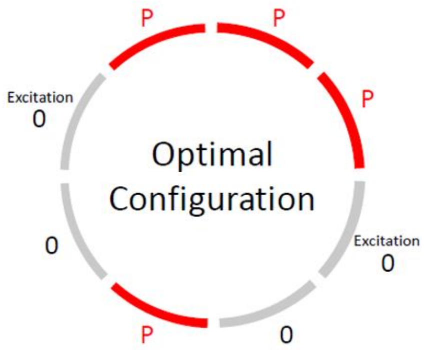

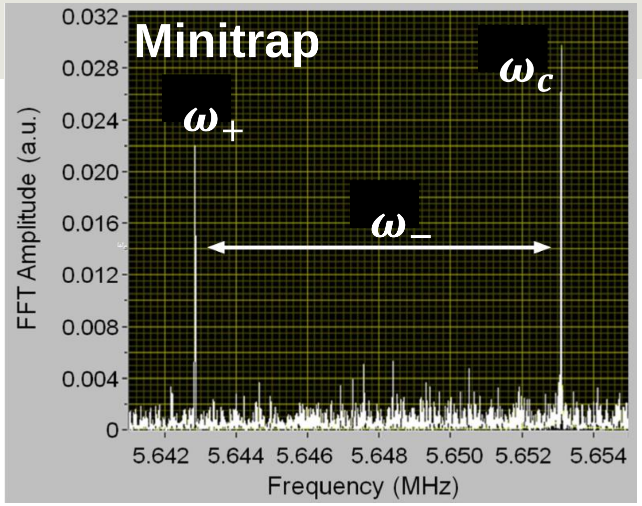

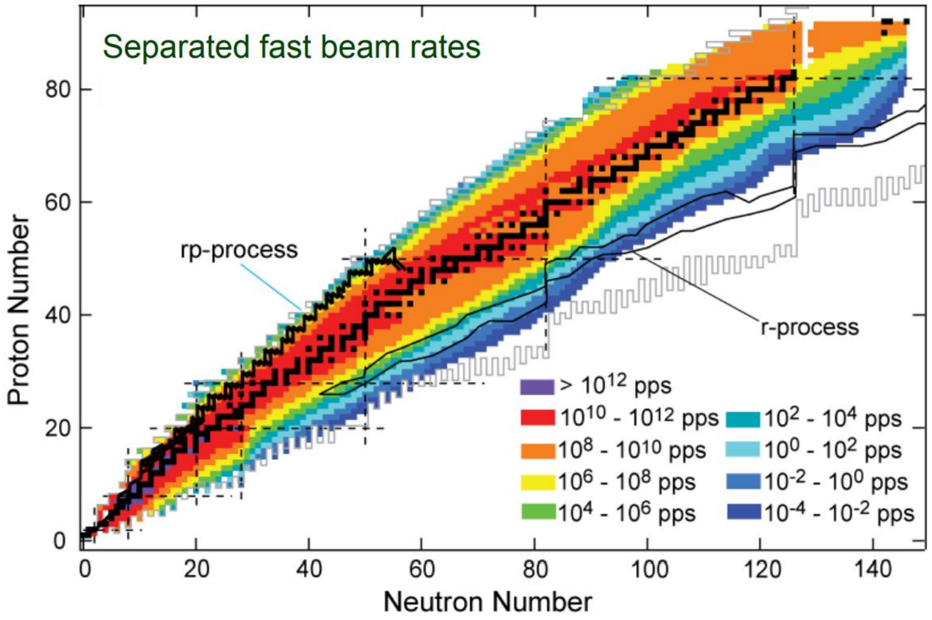

Work will resume on SIPT in late July!

Thank You!

- LEBIT Group
  - G. Bollen, S. Campbell, H. Erington, C. Ireland, F. Maier, R. Ringle

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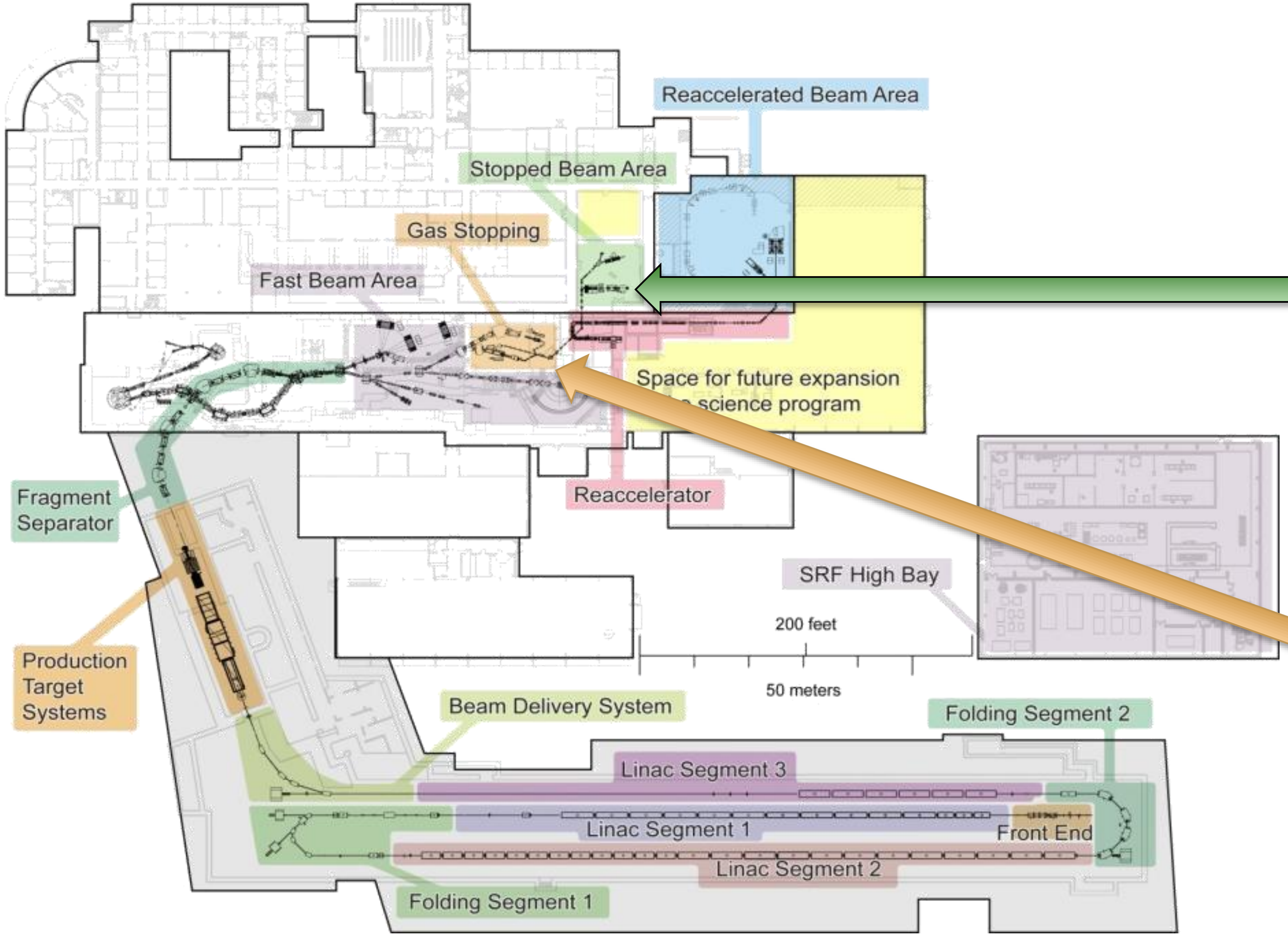
PHY-1913554
PHY-1430152
NSF 2004601

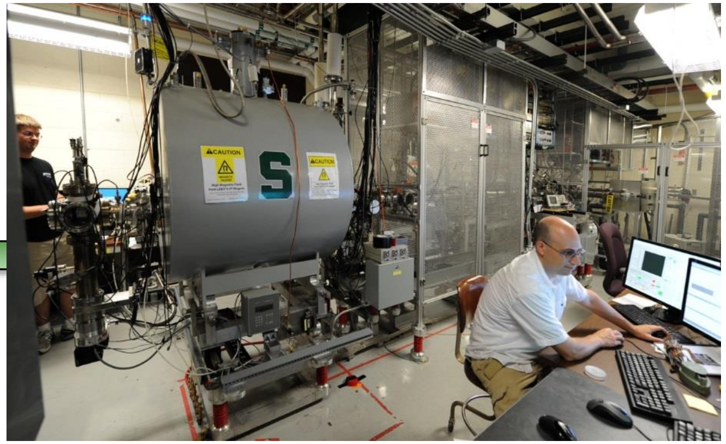
DE-SC0013365
DE-SC0018083

Backup Slides

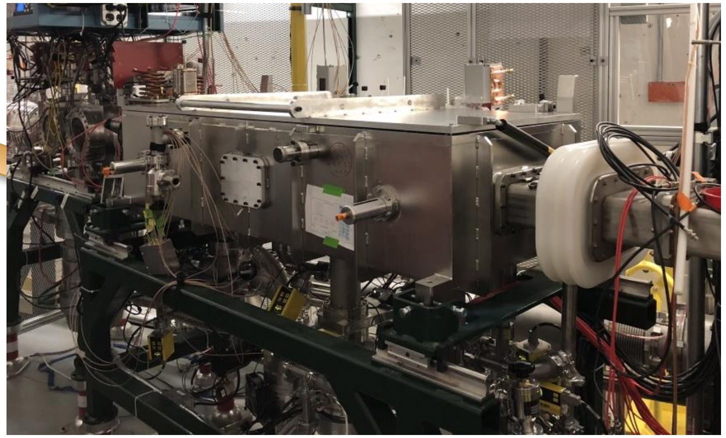
Low Energy “Stopped” Beams from Projectile Fragmentation



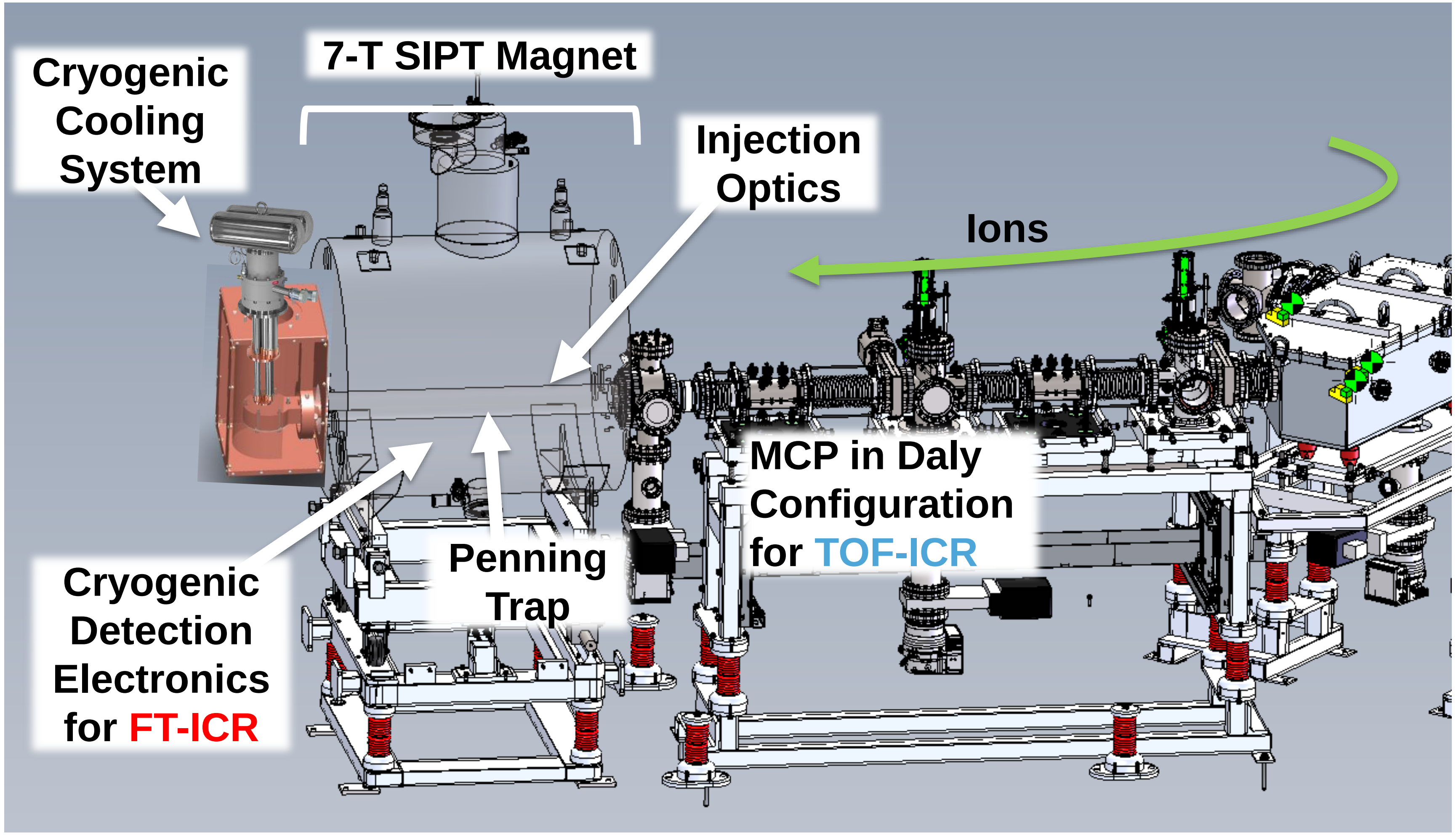
Low Energy Beam Ion Trap (LEBIT) Facility



Advanced Cryogenic Gas Stopper



Major SIPT Components: Overview



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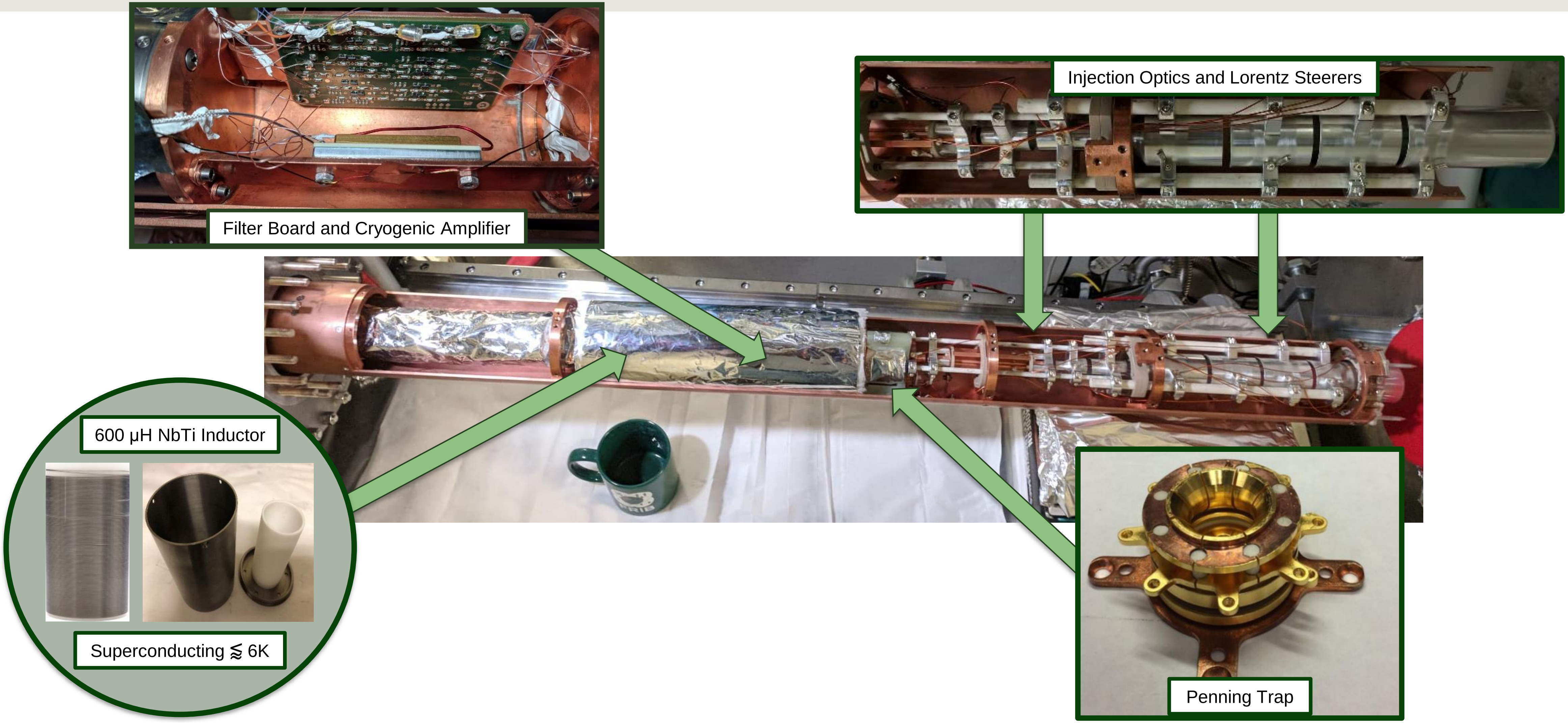
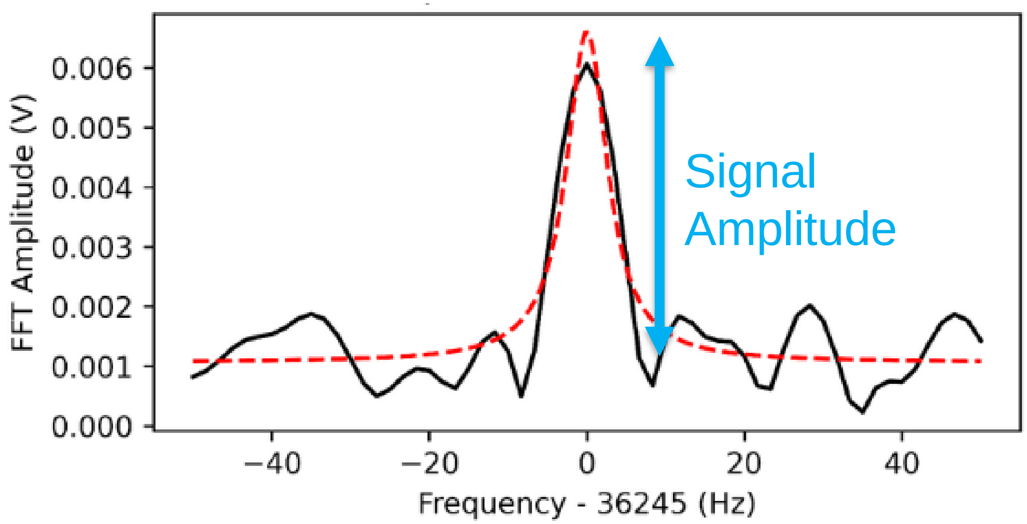


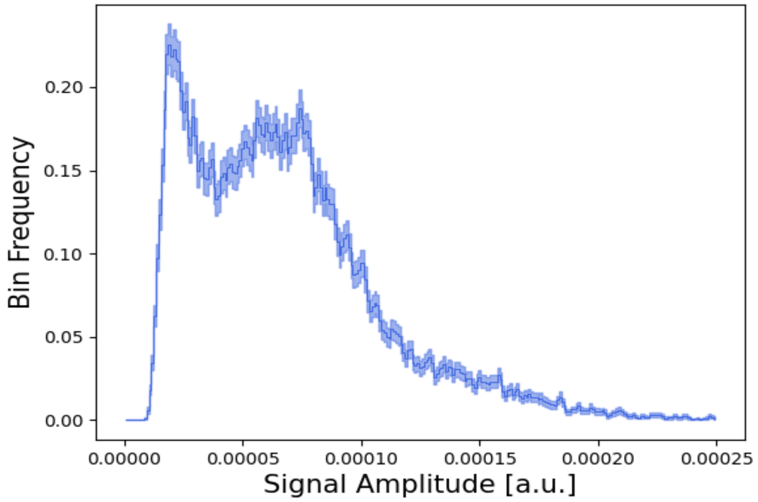
Investigating the Sensitivity Limits of SIPT

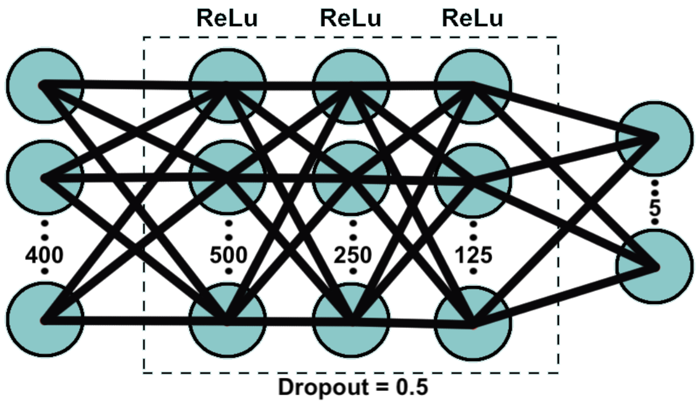
- How do we determine the sensitivity of SIPT?
  - SIPT only useful if single ions are resolvable
  - Single ion signals expected very near noise level
  - No means of knowing ion count going into trap
- Idea: aggregate simulated dataset
  - Better account for statistical variations in each signal
    - » >100k signals per set
  - Use same properties *except* number of ions in trap



Poisson mean:
Ion number dist.

μ_p	0.54
A_{single}	0.53
$\sigma(A_{\text{single}})$	0.00835
V_{offset} (μV)	8.89
ϕ_{max}	4.85





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