Current Capabilities and Future Advancement for Astrophysical Mass Measurements with LEBIT at FRIB

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on behalf of the LEBIT group

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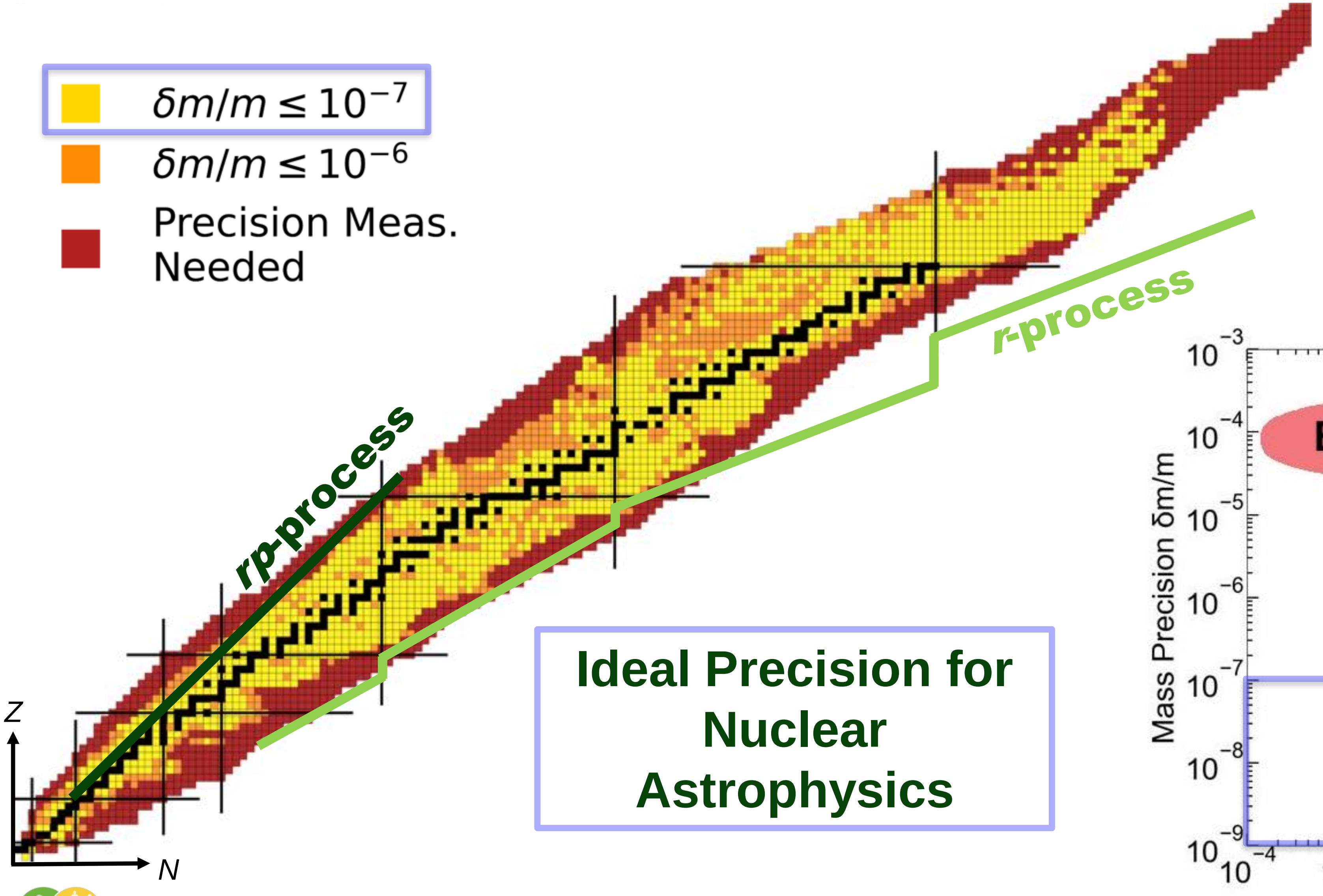
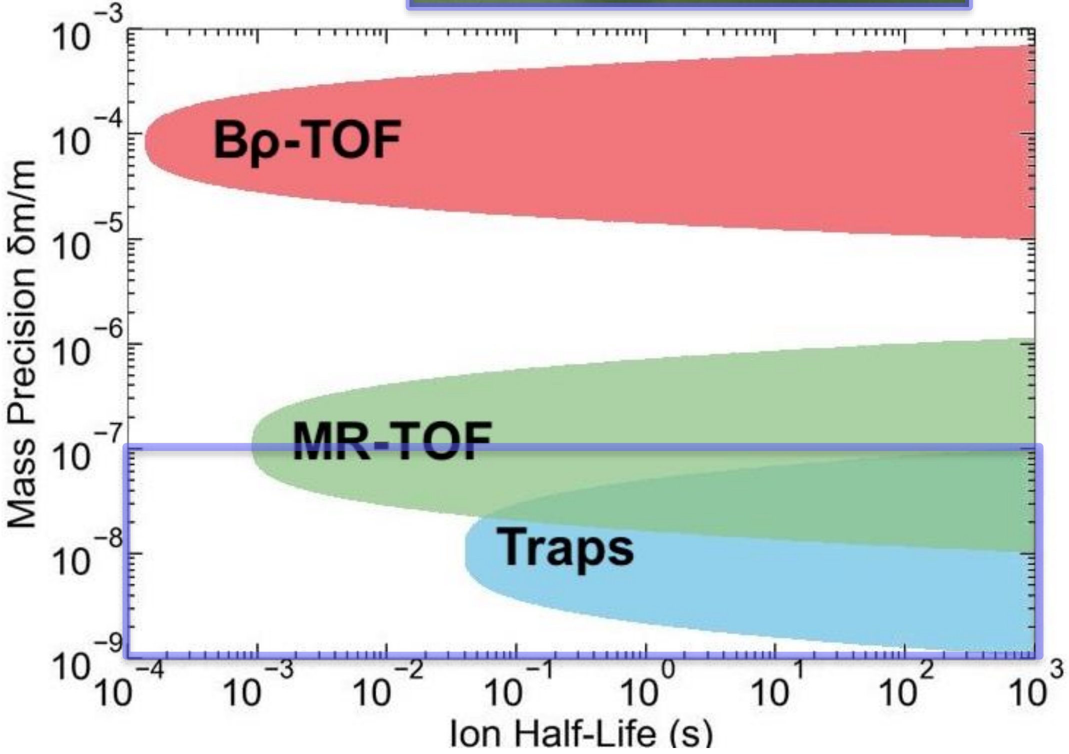
Status of Precise Mass Measurements



Ideal Precision for Nuclear Astrophysics



FRIB

Adapted from: M. Famiano, Int. Journal Mod. Phys. E **28** (2019)
Data from AME2020**:** Huang *et al.*, Chin. Phys. C **45** (2021)

Outline

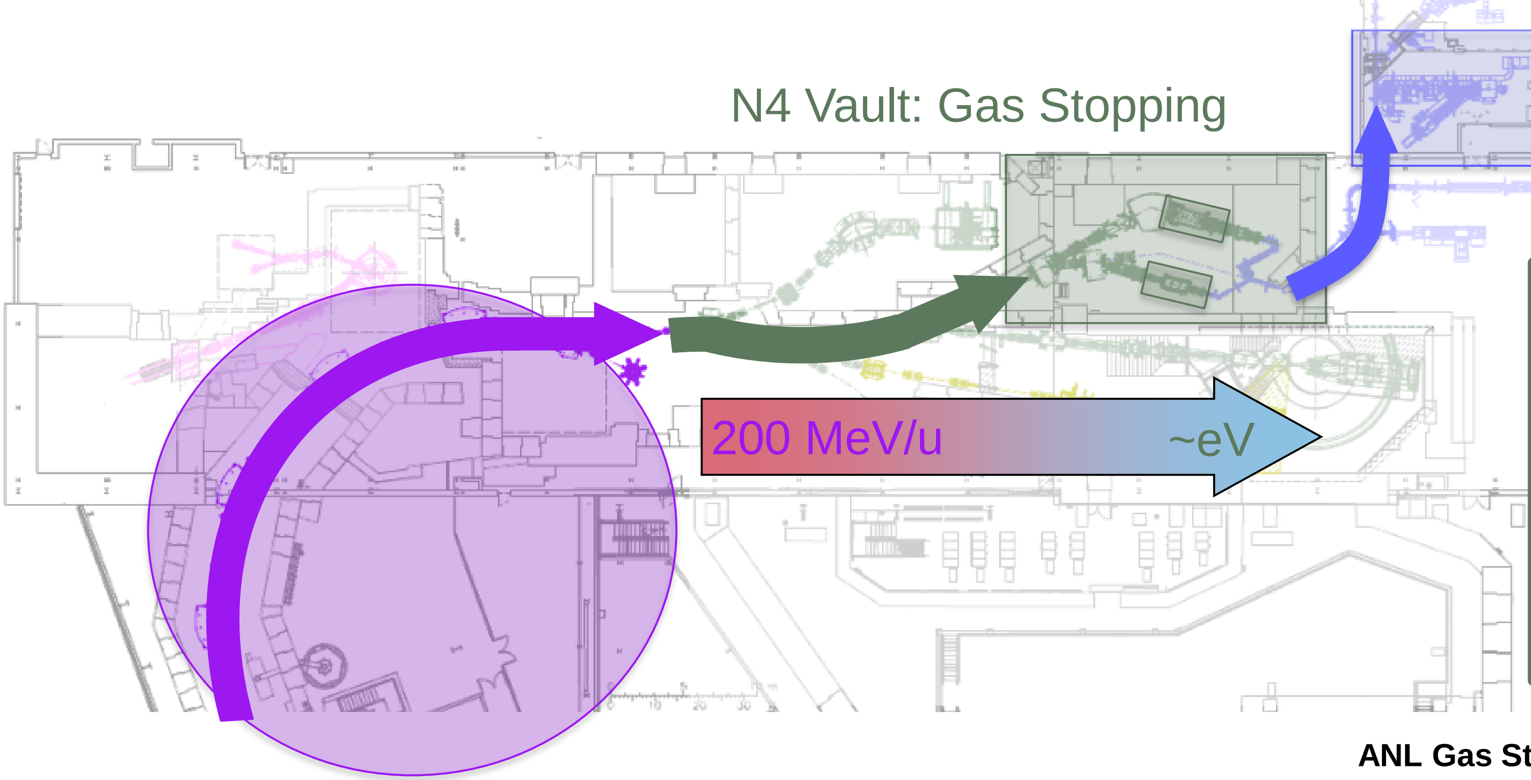
- Performing Mass Measurements at FRIB

- Recent Experimental Efforts

- Advancements to Expand the Reach of LEBIT

Rare Isotopes Must Be Stopped Before Measurement

- FRIB produces beams at high energies
  - Necessary for production
  - Not ideal for ion trapping techniques



Advanced Rare
Isotope Separator (ARIS)

ANL Gas Stopper: C. Sumithrarachchi, *et al.* NIM B **463,** 305 (2020)
ACGS Gas Stopper: K. Lund, *et al.* NIM B **463,** 378-381 (2020)

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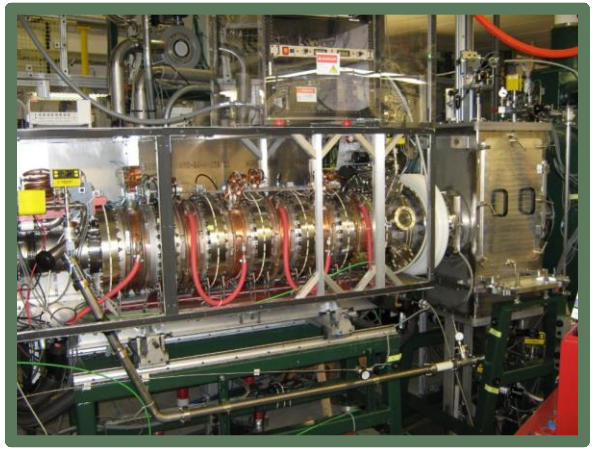
ARIS Separator: M. Hausmann, *et al.* NIM B **317,** 349-353 (2013)

Beam Stopping at FRIB



*ANL Linear Gas Stopper

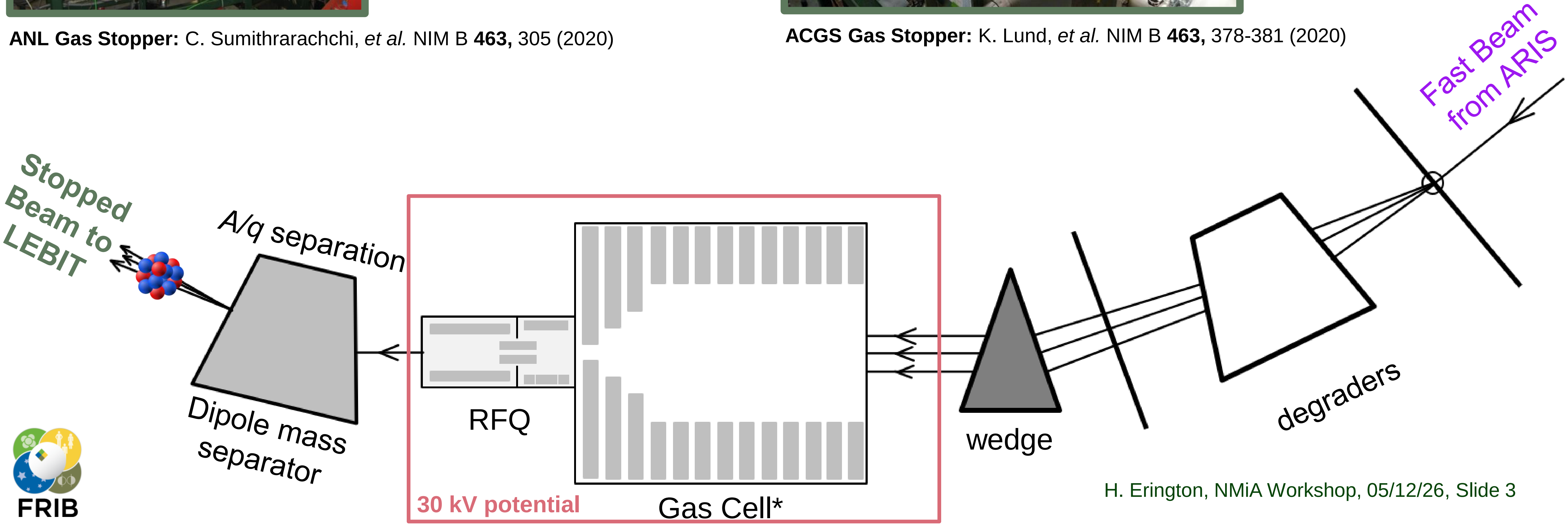
- Reliably in use since 2011
- Filled with ~100 mbar He
- Ions lose energy in collisions
- DC + RF electric fields and gas flow used to transport ions

ANL Gas Stopper: C. Sumithrarachchi, *et al.* NIM B **463,** 305 (2020)

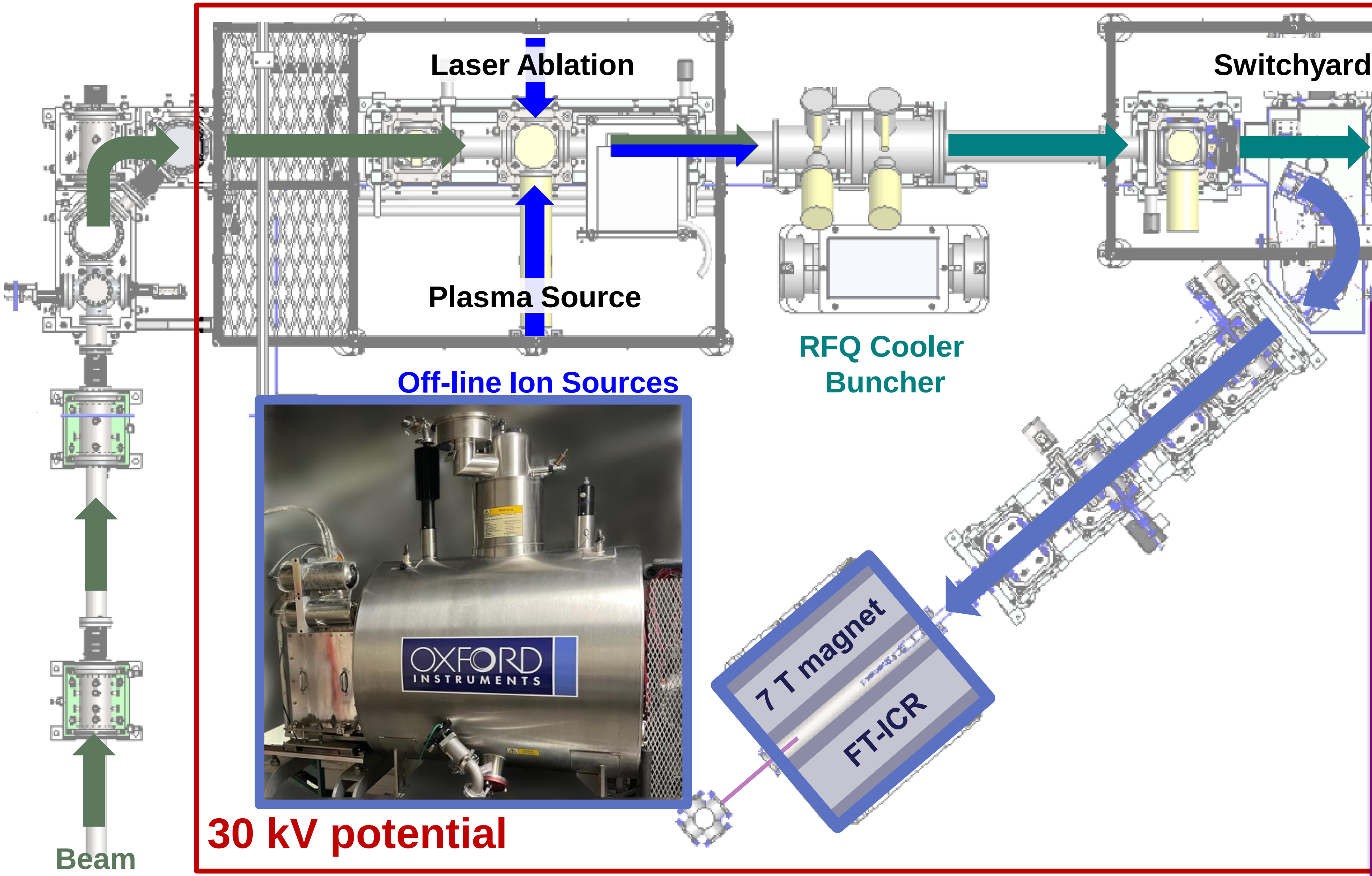
*Advanced Cryogenic Gas Stopper

- Novel geometry for >10x higher beam rate
- Cryogenic (40 K) for higher beam purity
- Ion surfing technique for fast extraction

ACGS Gas Stopper: K. Lund, *et al.* NIM B **463,** 378-381 (2020)



The Low Energy Beam and Ion Trap (LEBIT) Facility



Laser Ablation: C. Izzo *et al.*, NIM B **376**, 60 (2016)

Cooler/Buncher: Schwarz *et al.*, NIM A **816**, 131-141 (2016)

SIPT: A. Hamaker *et al.*, Hyperfine Interact. **240**, 34 (2019)

9.4 T Magnet: R. Ringle *et al.*, Int. J. Mass Spec 349-350 (2013)

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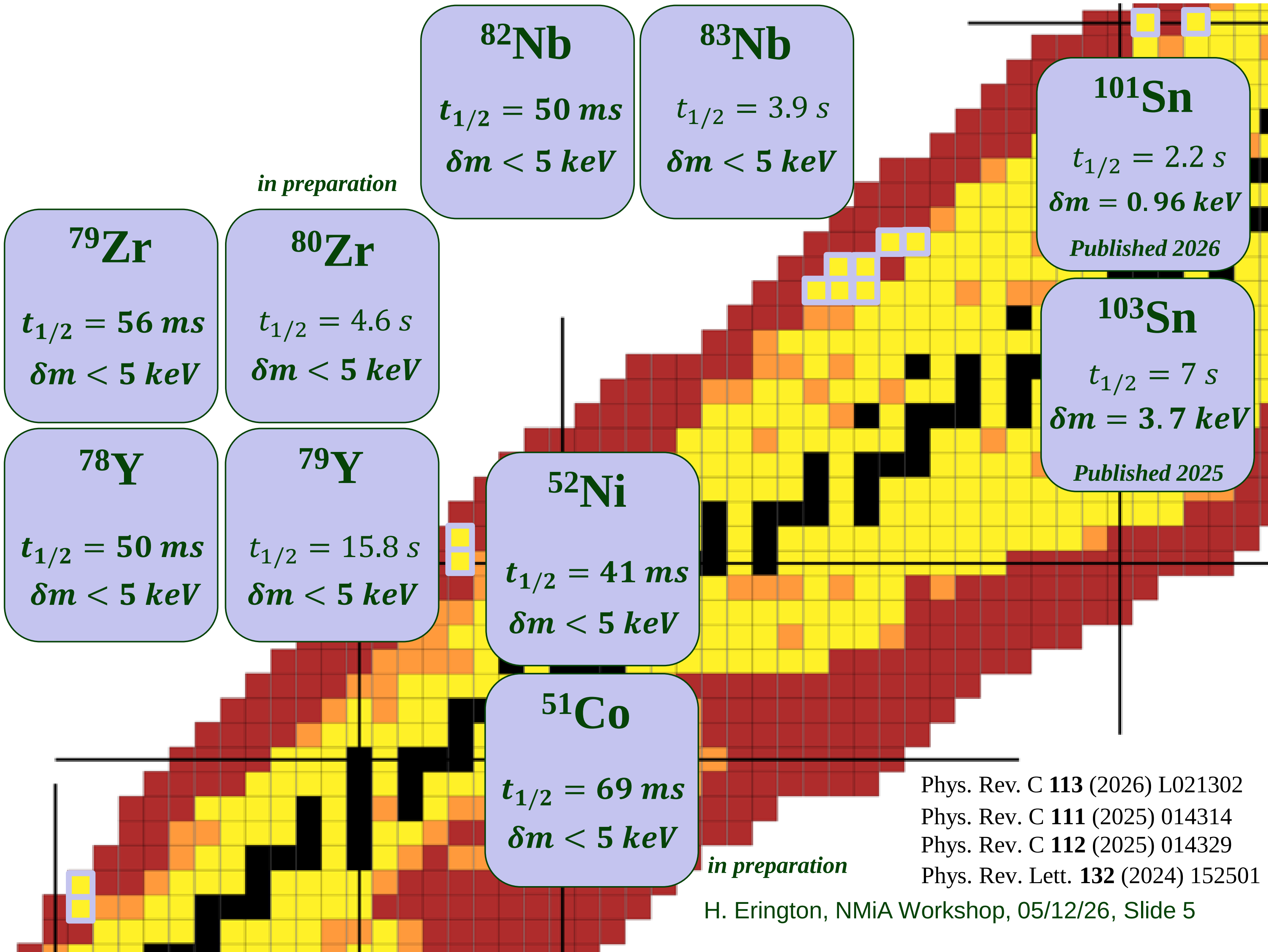
LEBIT Performs Measurements Near the Proton Dripline

- Some isotopes of interest with $t_{1/2} < 100\ ms$
- All isotopes measured to $\delta m/m \leq 10^{-7}$



^{82}Nb
$t_{1/2} = 50\ ms$
$\delta m < 5\ keV$

^{83}Nb
$t_{1/2} = 3.9\ s$
$\delta m < 5\ keV$

^{101}Sn
$t_{1/2} = 2.2\ s$
$\delta m = 0.96\ keV$
Published 2026

^{103}Sn
$t_{1/2} = 7\ s$
$\delta m = 3.7\ keV$
Published 2025

^{79}Zr
$t_{1/2} = 56\ ms$
$\delta m < 5\ keV$

in preparation

^{80}Zr
$t_{1/2} = 4.6\ s$
$\delta m < 5\ keV$

^{77}Y
$t_{1/2} = 57\ ms$
$\delta m < 5\ keV$

^{78}Y
$t_{1/2} = 50\ ms$
$\delta m < 5\ keV$

^{79}Y
$t_{1/2} = 15.8\ s$
$\delta m < 5\ keV$

^{52}Ni
$t_{1/2} = 41\ ms$
$\delta m < 5\ keV$

^{51}Co
$t_{1/2} = 69\ ms$
$\delta m < 5\ keV$

in preparation

^{23}Si
$t_{1/2} = 47\ ms$
$\delta m = 5.8\ keV$
Published 2025

^{22}Al
$t_{1/2} = 88\ ms$
$\delta m = 0.3\ keV$
Published 2024

Phys. Rev. C **113** (2026) L021302
Phys. Rev. C **111** (2025) 014314
Phys. Rev. C **112** (2025) 014329
Phys. Rev. Lett. **132** (2024) 152501

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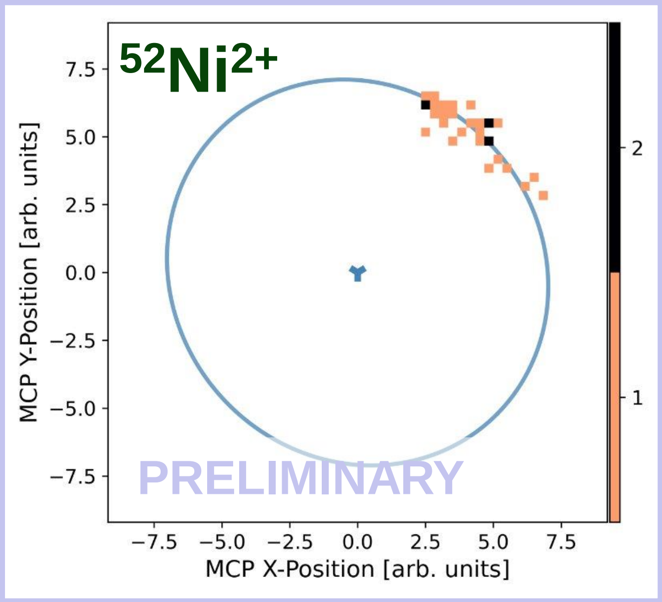
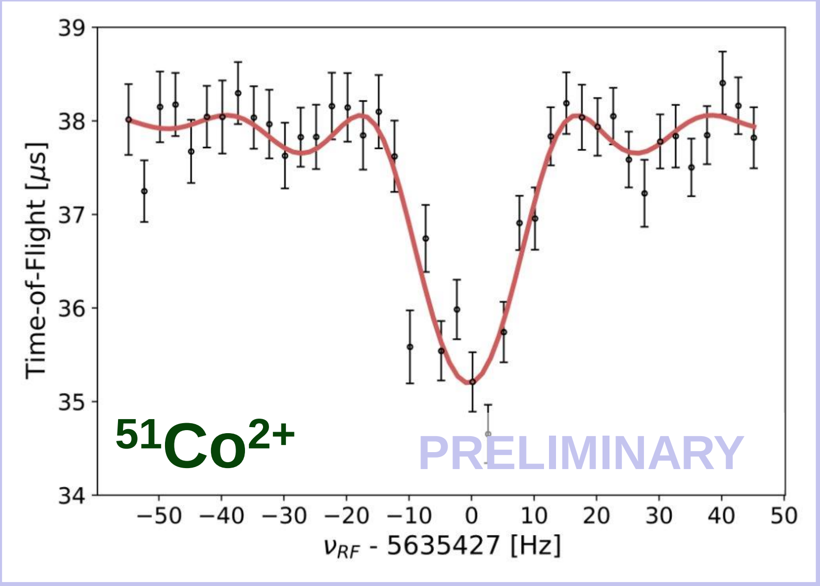
Masses of ^{51}Co and ^{52}Ni Could Impact *rp*-process

- Demonstration of two measurement techniques
  - ^{51}Co measured via Time-of-Flight Ion Cyclotron Resonance (TOF-ICR)[1]
  - ^{52}Ni measured via Phase-Imaging Ion Cyclotron Resonance (PI-ICR)[2]
- ^{51}Co and ^{52}Ni masses impact reaction rates in the *rp*-process[3,4]



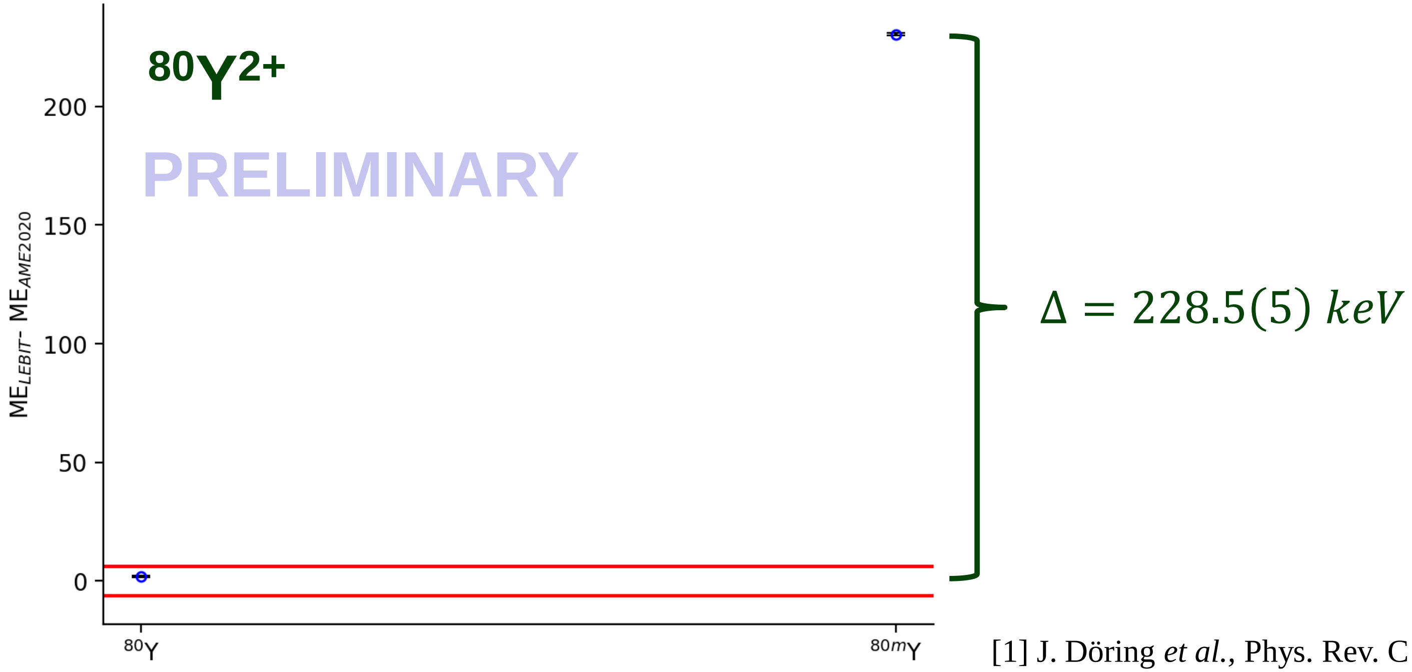


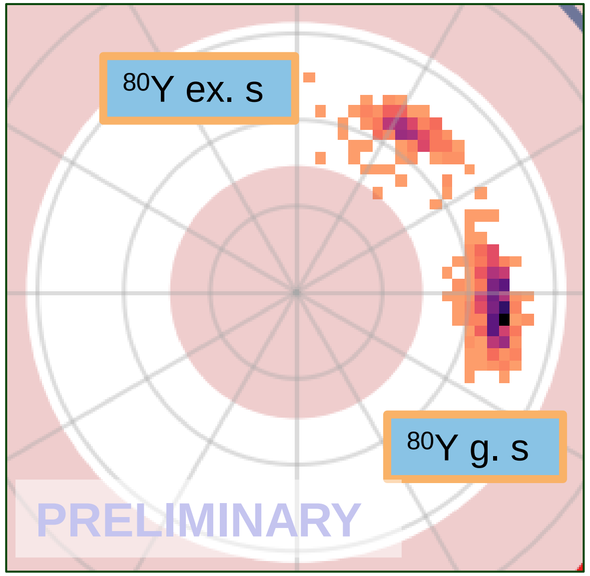
[1] G. Bollen *et al.*, Journal Appl. Phys. **89**, 4355-4374 (1990)
[2] S. Eliseev *et al.*, Phys. Rev. Lett. **110**, 82501 (2013)
[3] L. Zhang *et al.*, Chin. Phys. C **40** 125101 (2016)
[4] D.A. Nesterenko et al., J. Phys. G **44** 065103 (2017)

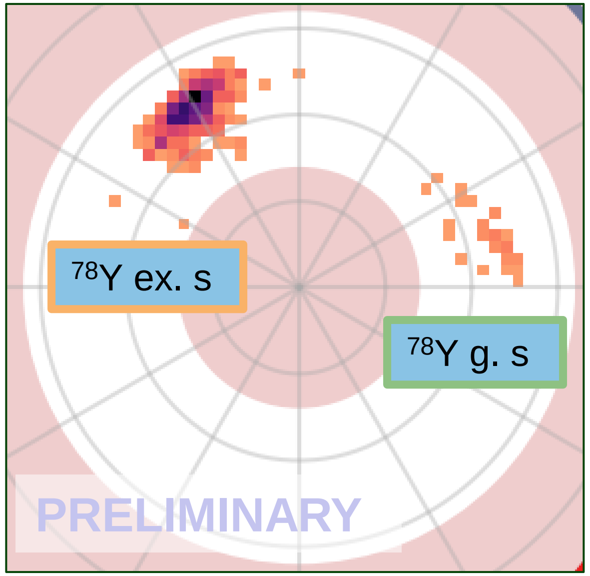
FRIB

First Isomeric Measurement with PI-ICR at LEBIT

- Under certain temperature conditions an isomeric state can act as a distinct species – “astromer”
- Zr, Y, Nb run – measured two isomers in PI-ICR
  - ^{80}Y: $t_{1/2} = 30.1\ s$ (g.s); $t_{1/2} = 4.8\ s$ (isomer)
  - ^{78}Y: $t_{1/2} = 50\ ms$ (g.s); $t_{1/2} = 5.8\ s$ (isomer)
- First demonstration of isomers for LEBIT
  - ^{78}Y, ^{78m}Y: new measurement of ground state
  - ^{80}Y, ^{80m}Y: in agreement with Atomic Mass Evaluation + gamma spec[1]





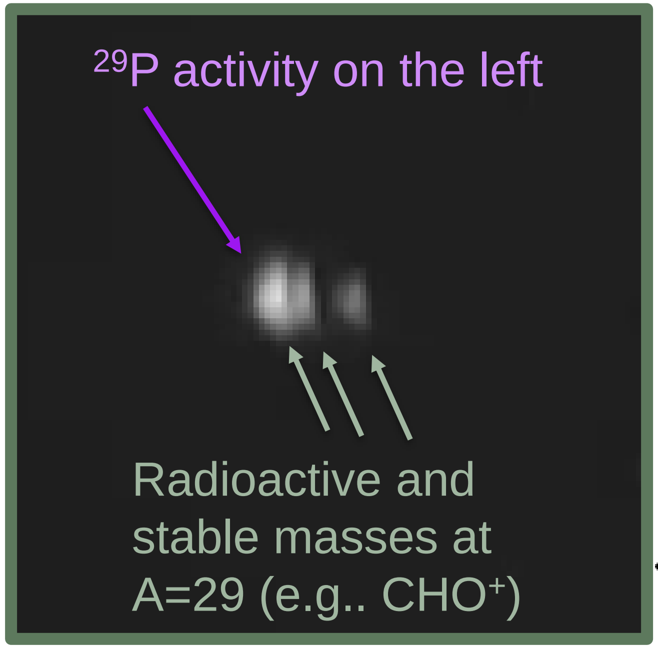


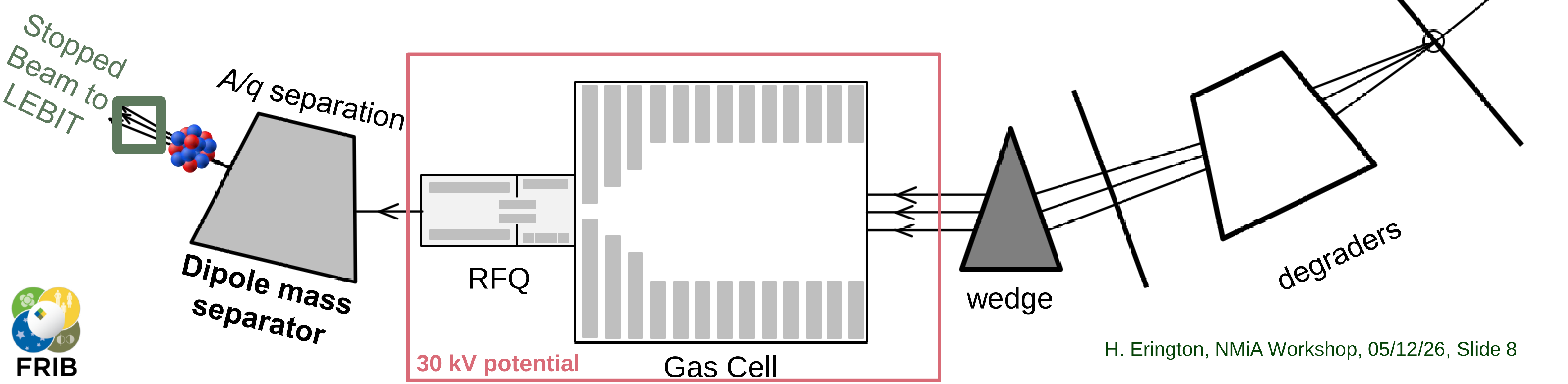
[1] J. Döring *et al.*, Phys. Rev. C **57**, 1159 (1998)

FRIB

Contamination from Gas Stopping is a Challenge

- Every stopped rare isotope generates ~10^6 He^+/e^- pairs
  - Large current of stable beams (~nA) from charge exchange
  - Different charge states (1^+, 2^+)
  - Formation of radioactive molecules
    - » Rare isotopes spread to other mass values
- Resolving power needed to remove contaminants is not always achievable
  - Dipole mass separator: $m/\delta m$ ~ 1500 for cooled beams





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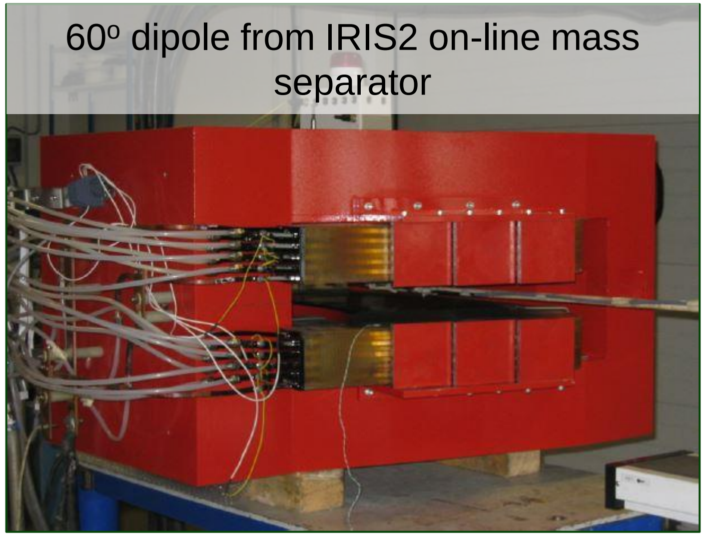
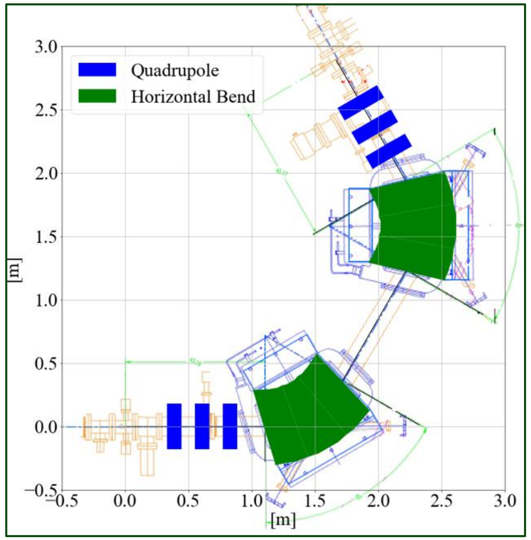
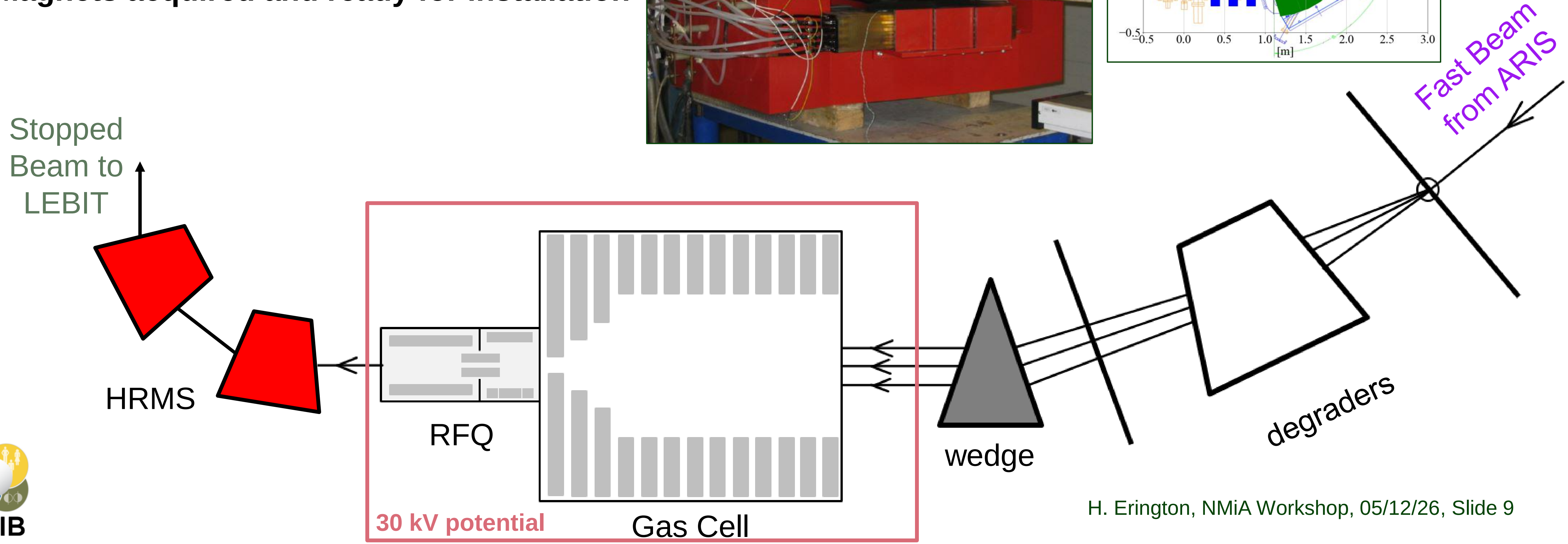
High-Resolution Mass Separator (HRMS) Increases $m/\delta m$

- Increase resolving power to $m/\delta m$ ~ 10k for isobarically pure beams
  - Step towards unambiguous beam delivery
  - Faster beam tuning and beam identification
  - Higher reaccelerated beam rates
  - **Magnets acquired and ready for installation**







FRIB

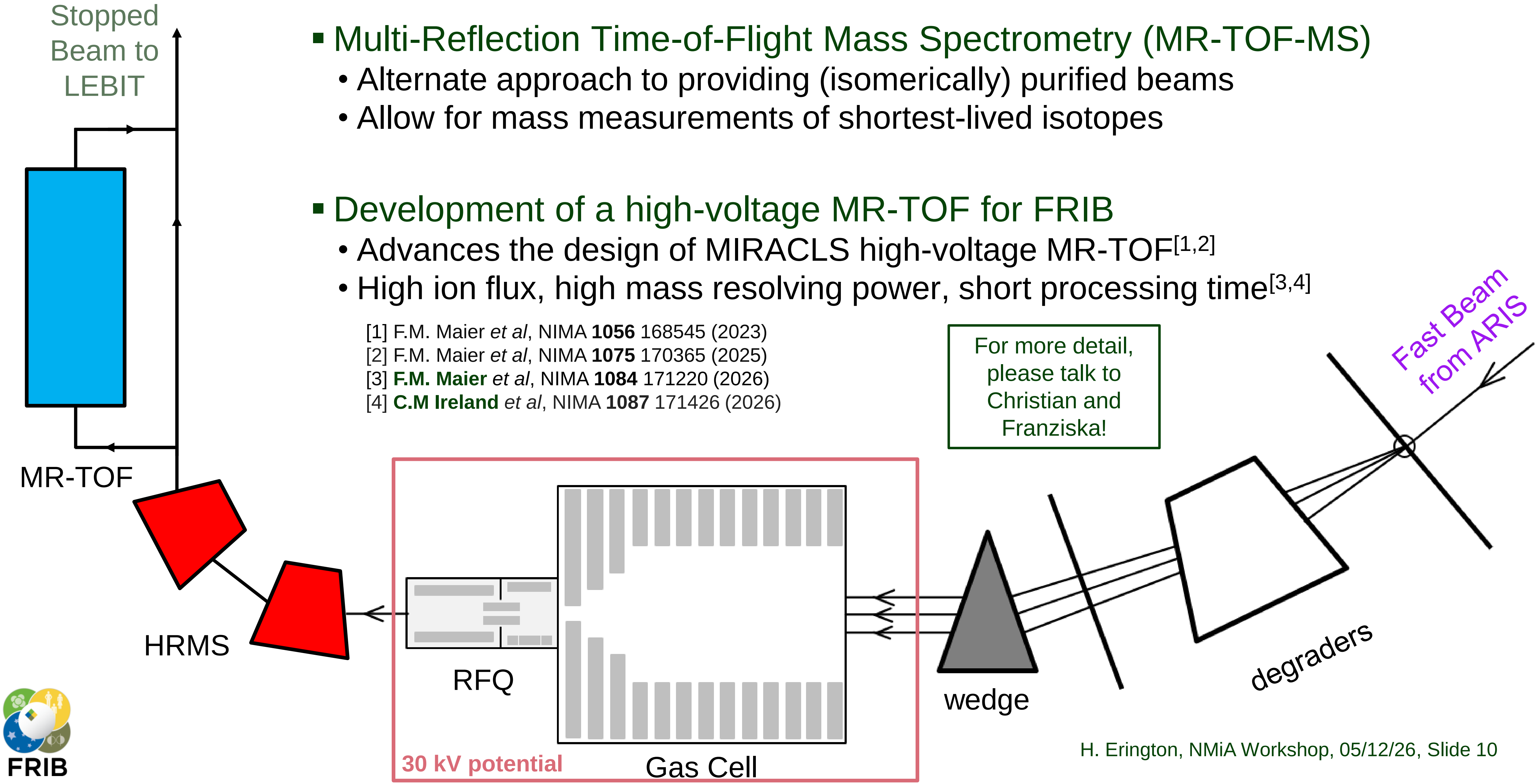
MR-TOF-MS for Mass Separation and Science

- Multi-Reflection Time-of-Flight Mass Spectrometry (MR-TOF-MS)
  - Alternate approach to providing (isomerically) purified beams
  - Allow for mass measurements of shortest-lived isotopes

- Development of a high-voltage MR-TOF for FRIB
  - Advances the design of MIRACLS high-voltage MR-TOF[1,2]
  - High ion flux, high mass resolving power, short processing time[3,4]

[1] F.M. Maier *et al*, NIMA **1056** 168545 (2023)
[2] F.M. Maier *et al*, NIMA **1075** 170365 (2025)
[3] **F.M. Maier** *et al*, NIMA **1084** 171220 (2026)
[4] **C.M Ireland** *et al*, NIMA **1087** 171426 (2026)

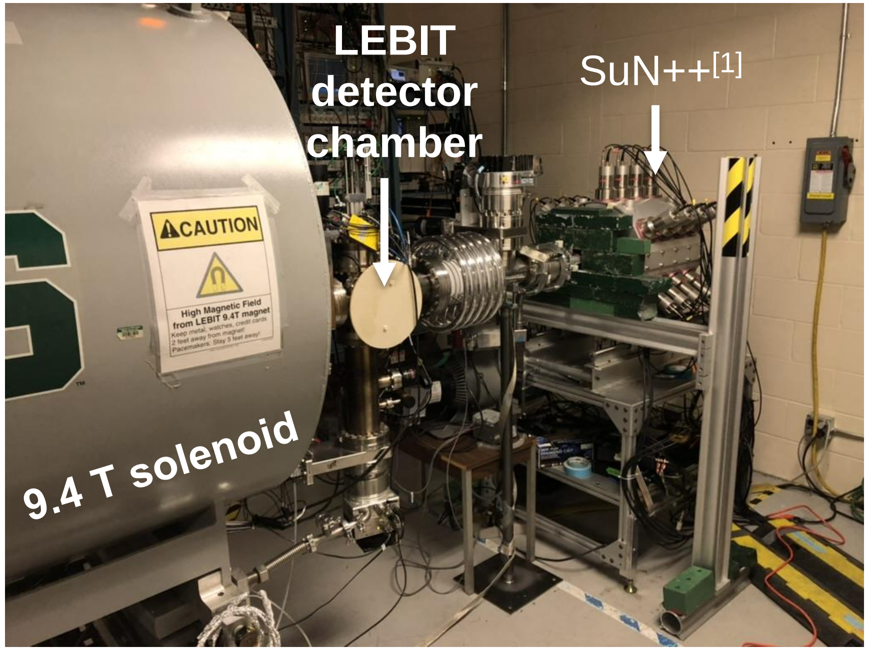
For more detail, please talk to Christian and Franziska!

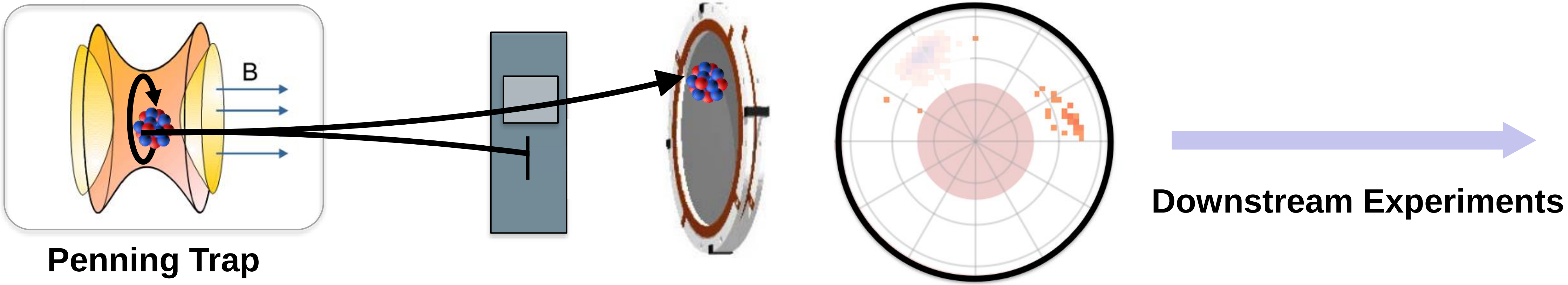


FRIB

PI-ICR Upgrade to Improve Isomeric Beam Purification

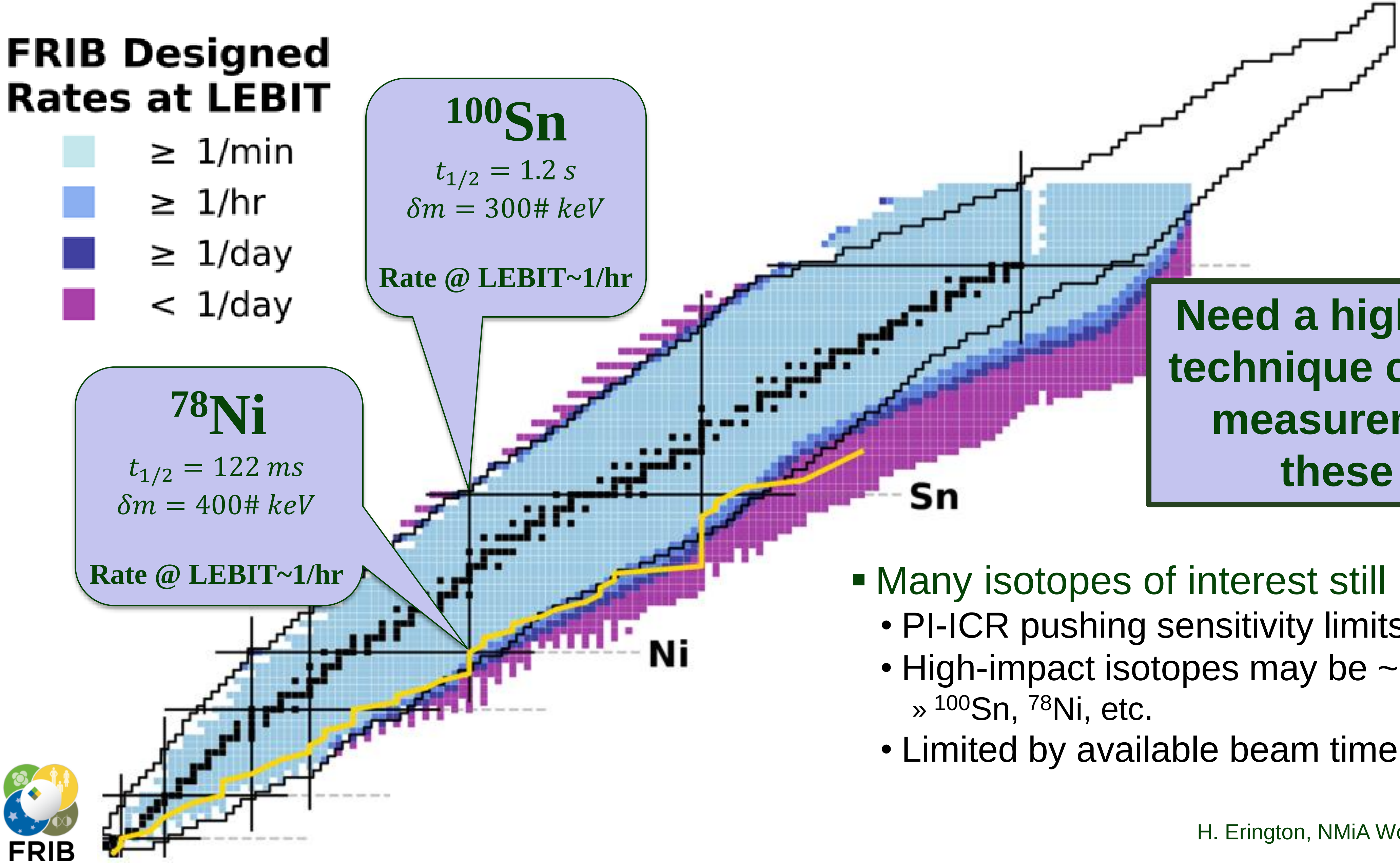
- LEBIT can act as a mass separator ($m/\delta m > 5 \times 10^5$)
- FRIB PAC2: ^{70}Cu with SuN++ ran in 2024[1]
  - Low-lying isomers in ^{70}Cu: **3^- at 101 keV, 1^+ at 242 keV**
  - Separated via TOF-ICR
- New detection system for PI-ICR
- PI-ICR for isomeric beam delivery
  - Adjustable slit system
  - Allow delivery of lowest-lying isomers
- Funded through recently awarded DOE SSAA grant





[1] E.K. Ronning *et al.*, NIMA 170930 (2025)

Future Science Program Requires Ultimate Sensitivity



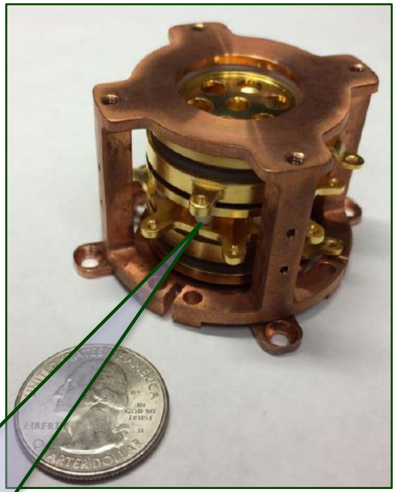
Need a high-precision technique capable of a measurement with these rates!

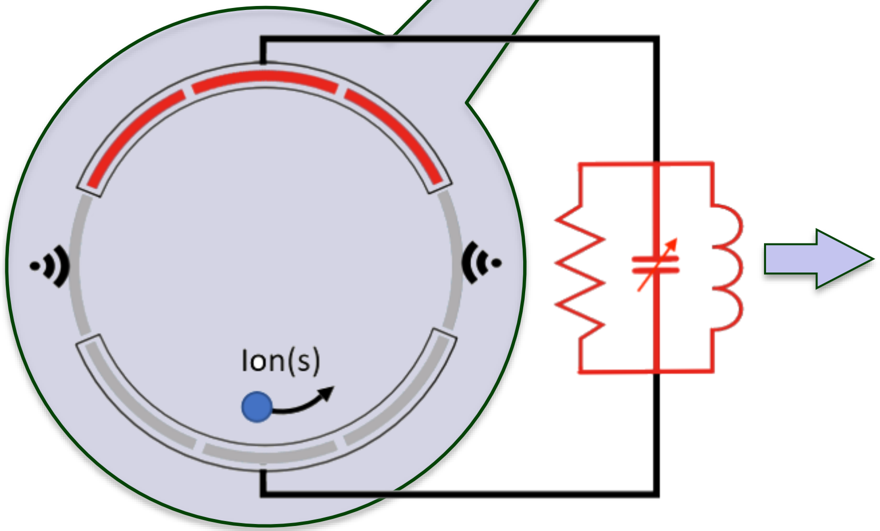
- Many isotopes of interest still inaccessible
  - PI-ICR pushing sensitivity limits
  - High-impact isotopes may be ~1 ion/day
    - ^{100}Sn, ^{78}Ni, etc.
  - Limited by available beam time

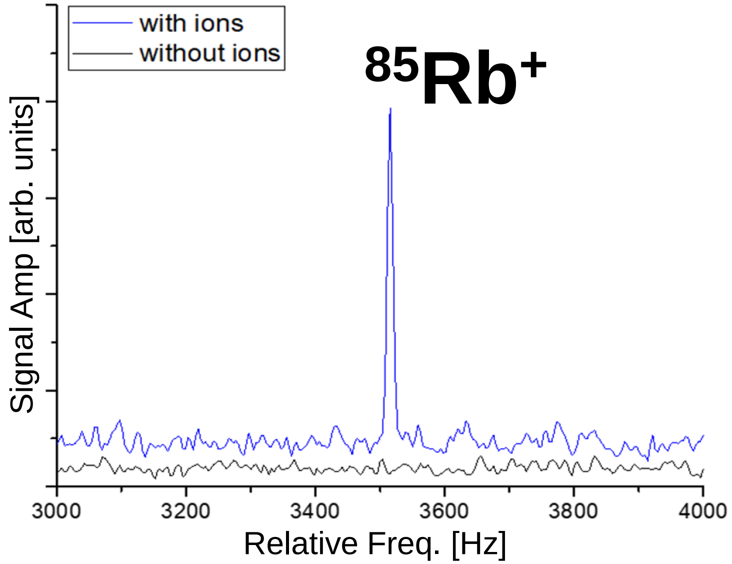
FRIB

SIPT Provides Access to the Most Exotic Nuclei

- Single Ion Penning Trap (SIPT)
  - Fourier Transform Ion Cyclotron Resonance (FT-ICR)
  - Ultimate sensitivity: pickup of the ion image charge
  - Cryogenic (~5 K) to minimize background
- Goal: complete mass measurement from a single ion
  - Offline demonstration complete[1]
  - Validation of single-ion-sensitivity[2]
  - Final development push underway







FRIB

[1] A. Hamaker *et al.*, Hyperfine Interactions **240,** 1-16 (2019)
[2] S. Campbell *et al.*, Atoms **11**, 10 (2023)

Conclusions and Outlook

- FRIB science program is underway
  - Significantly improved access to *rp*- and *r*-process regions
- Improvements to the stopped beam program will provide (isomerically) purified beams
- Technical developments significantly improve experimental reach and precision
  - New/improved detection techniques (PI-ICR, FT-ICR)
  - MR-TOF for beam purification and mass measurements
- LEBIT is well prepared to make optimal use of FRIB beams
  - Nuclear astrophysics, nuclear structure, and fundamental interactions
- **Program Advisory Committee 4 (PAC 4) begins soon!**
  - Open to ideas and collaboration!
  - https://frib.msu.edu/user-facilities/frib/calculator
  - Look for “Stopped beam rate”

RESULTS	
Fast beam rate (FRIB Rate)	2.57e+5 pps
Stopped beam rate	1.24e+4 pps
Reaccelerated beam rate	6.64e+2 pps
FRAGMENT	
A (mass number)	46
Z (atomic number)	17
N (neutron number)	29
Element symbol	Cl
$T_{1/2}$	2.320e-1 sec
BEAM	
AZ beam element	^{48}Ca
Beam energy	242 MeV/u
Target thickness	1933 mg/cm^2

FRIB

Thank You!

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

http://groups.nscl.msu.edu/lebit/

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DE-NA0004252

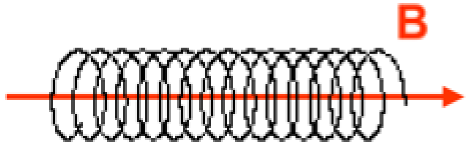
FRIB

Backup

LEBIT Uses Penning Trap Mass Spectrometry

Uniform Magnetic Field + Quadrupolar Electrostatic Field = Penning Trap

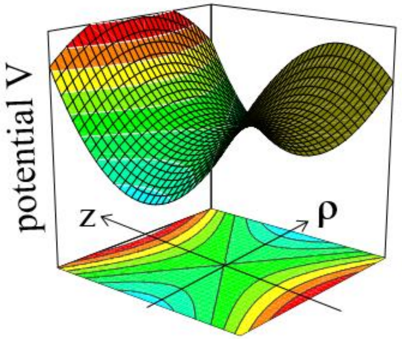
(radial confinement)



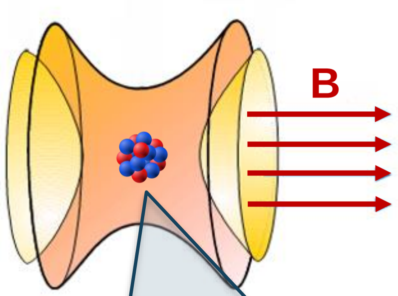
$$\omega_c = \frac{q}{m}B$$

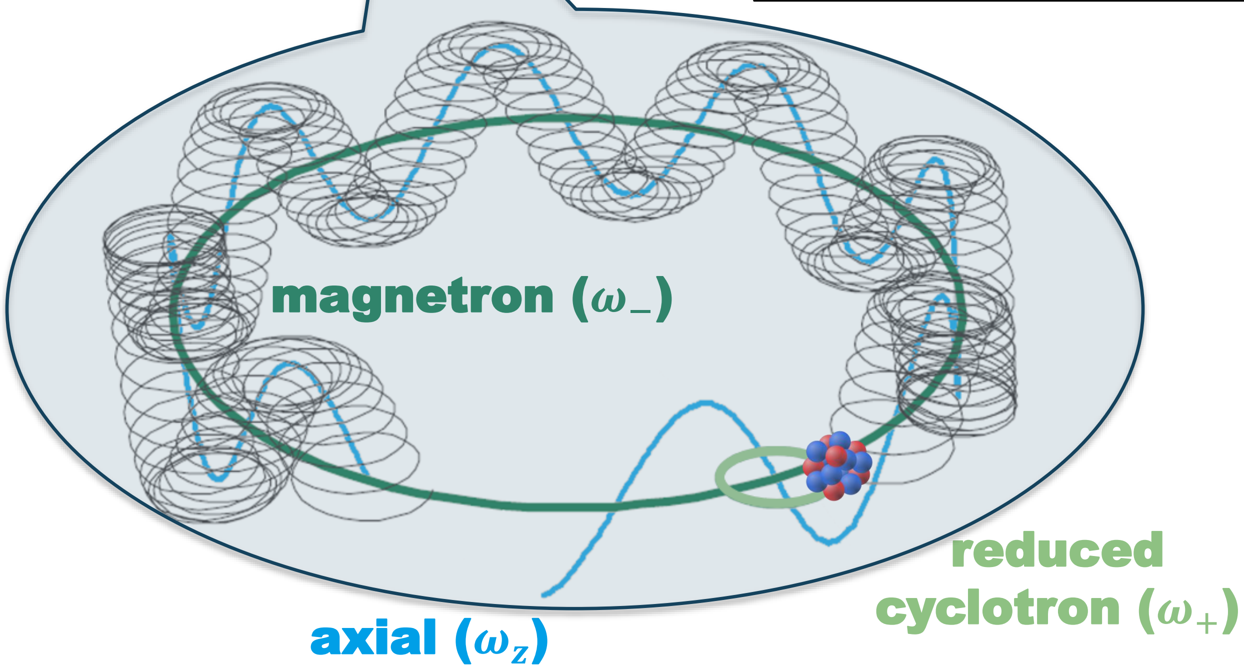
"cyclotron frequency"

(axial confinement)



(3D confinement)





$$m = \frac{q\,B}{\omega_c} \Longleftrightarrow \omega_c \approx \omega_- + \omega_+$$

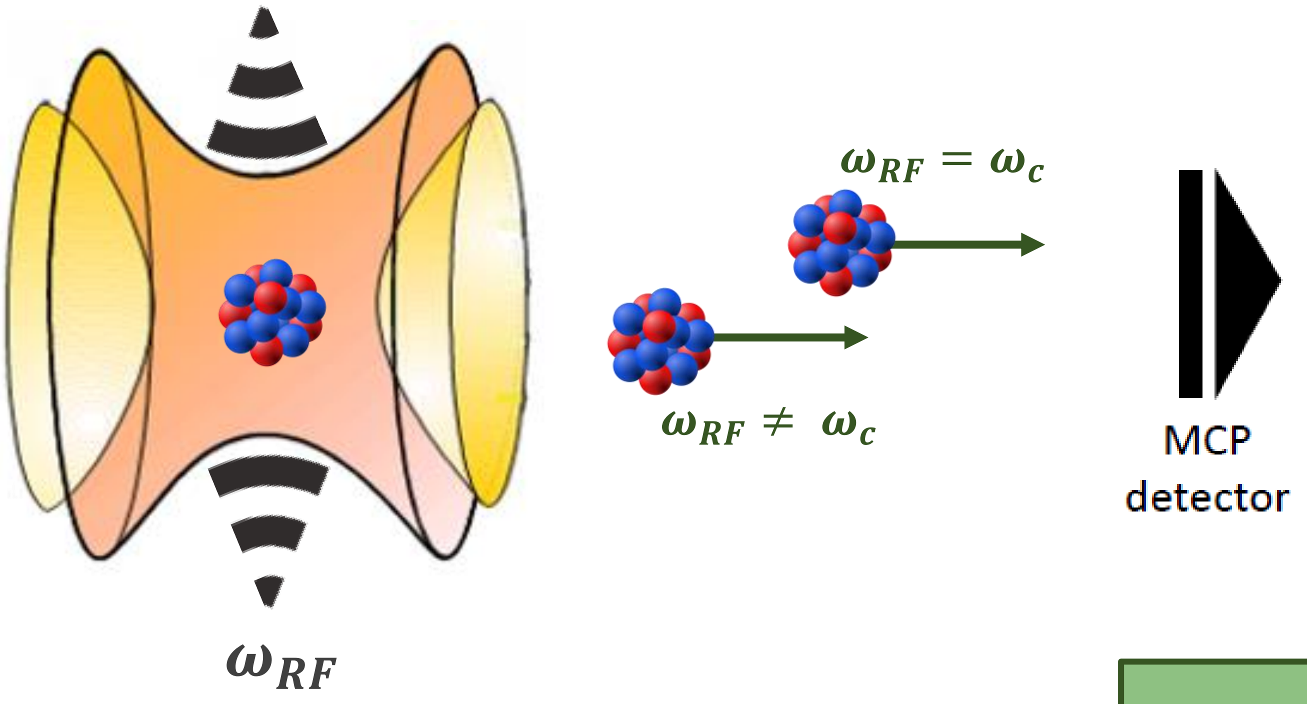
Requirements for mass measurement:

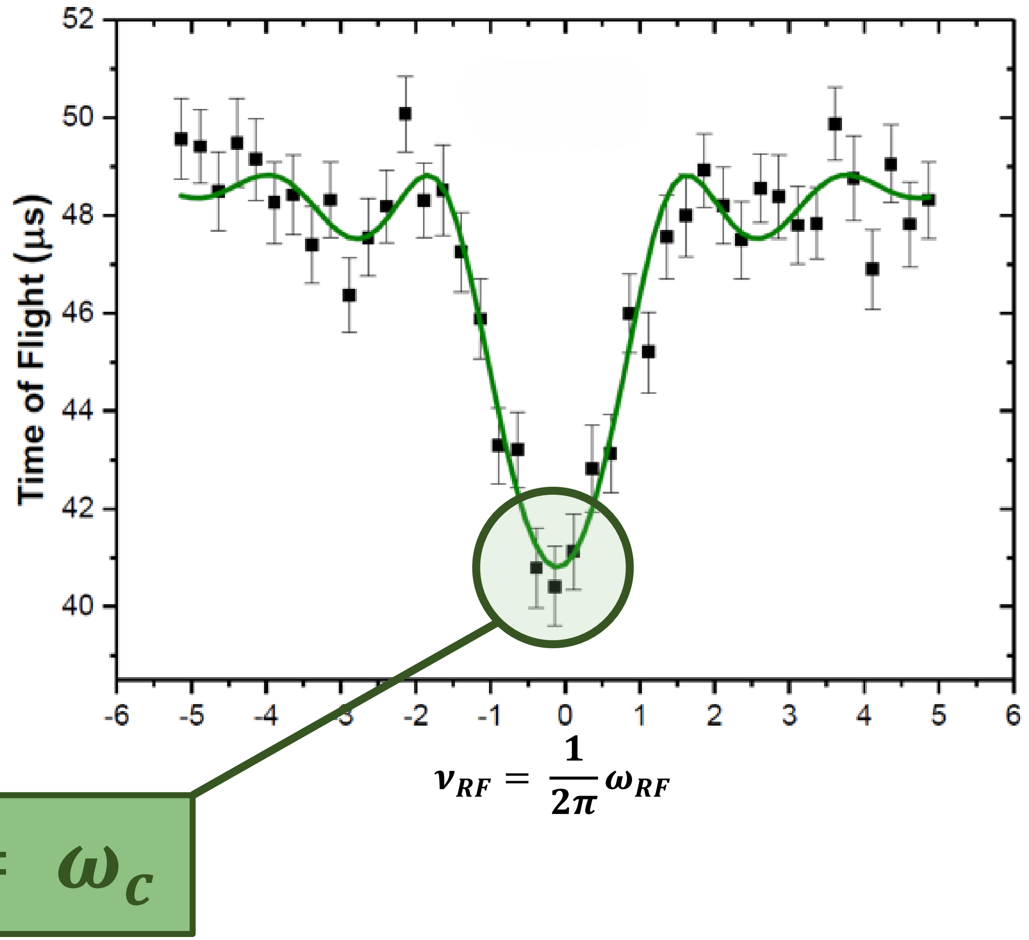
1. Known charge state, q
2. Magnetic field (B) calibrated with measurement of well-known mass
3. Measure ω_c *or* measure ω_+ **and** ω_-

TOF-ICR is a Well-Established and Reliable Method

G. Bollen *et al.*, Journal Appl. Phys. **89**, 4355-4374 (1990)

- Time-of-Flight Ion Cyclotron Resonance (TOF-ICR)
  - Measurement of ω_c
  - Scan of quadrupolar radiofrequency (RF) excitation ω_{RF}

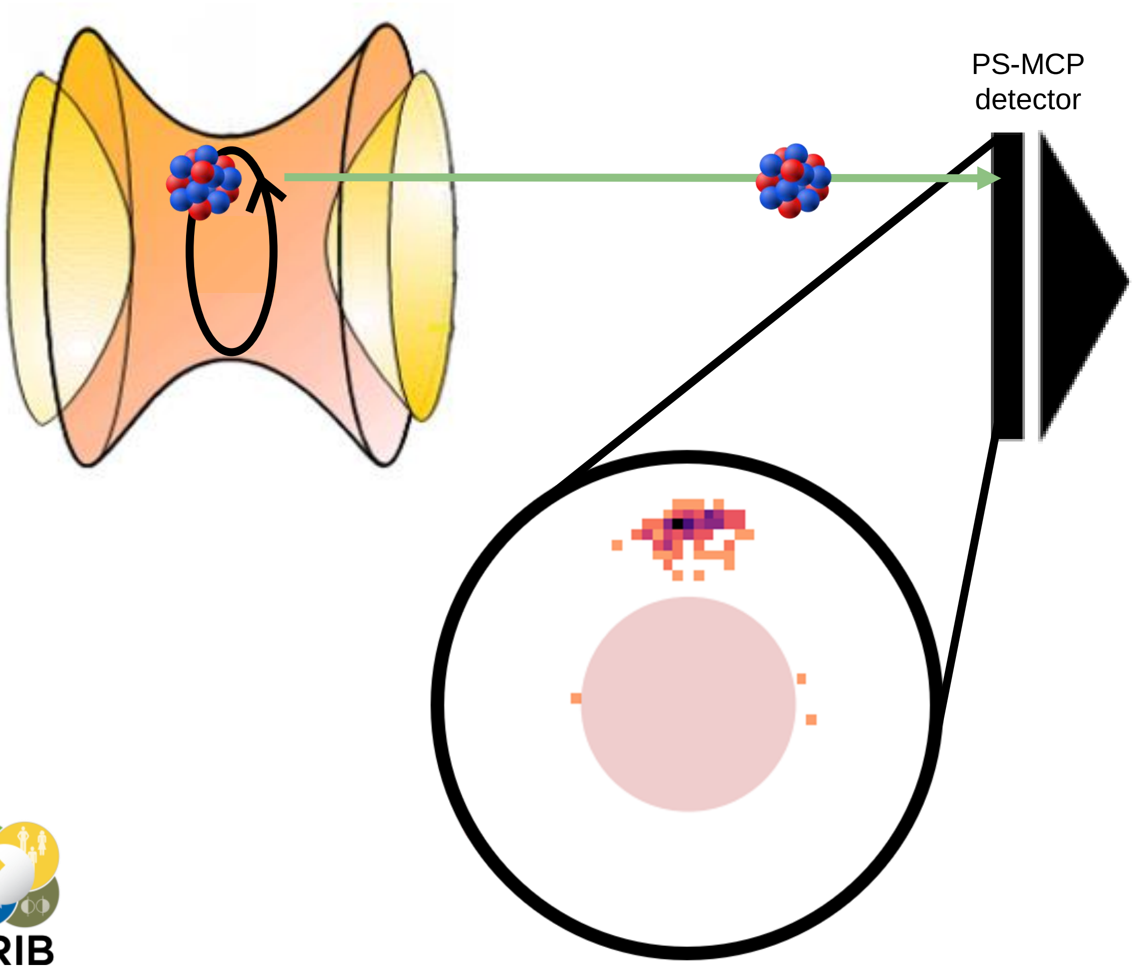




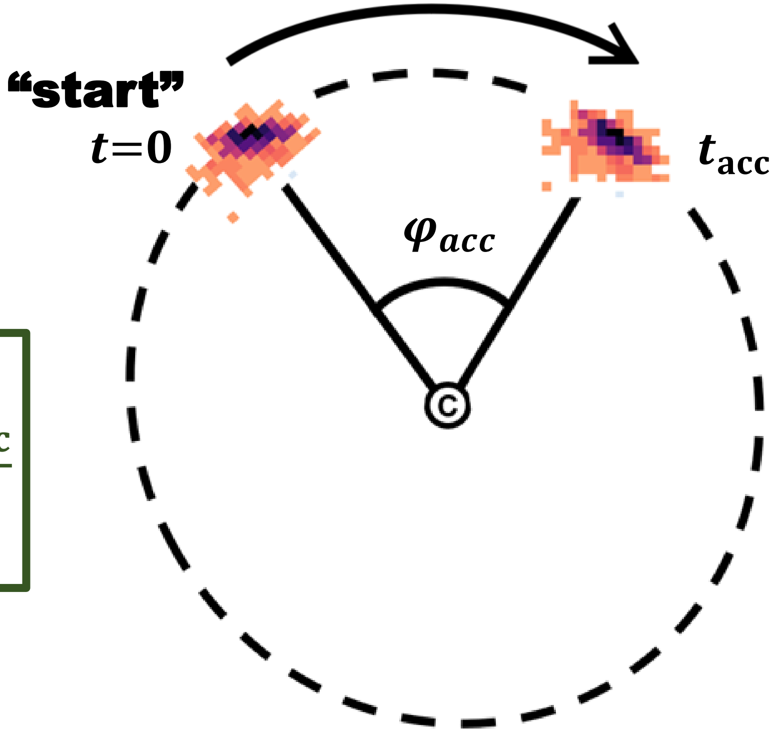
PI-ICR is More Precise and Requires Fewer Ions

S. Eliseev *et al.*, Phys. Rev. Lett. **110**, 82501 (2013)

- Phase-Imaging Ion Cyclotron Resonance (PI-ICR)
  - Measure ω_+ and ω_- independently
  - Allow each motion to accumulate phase (rotate) for set time, t_{acc}



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



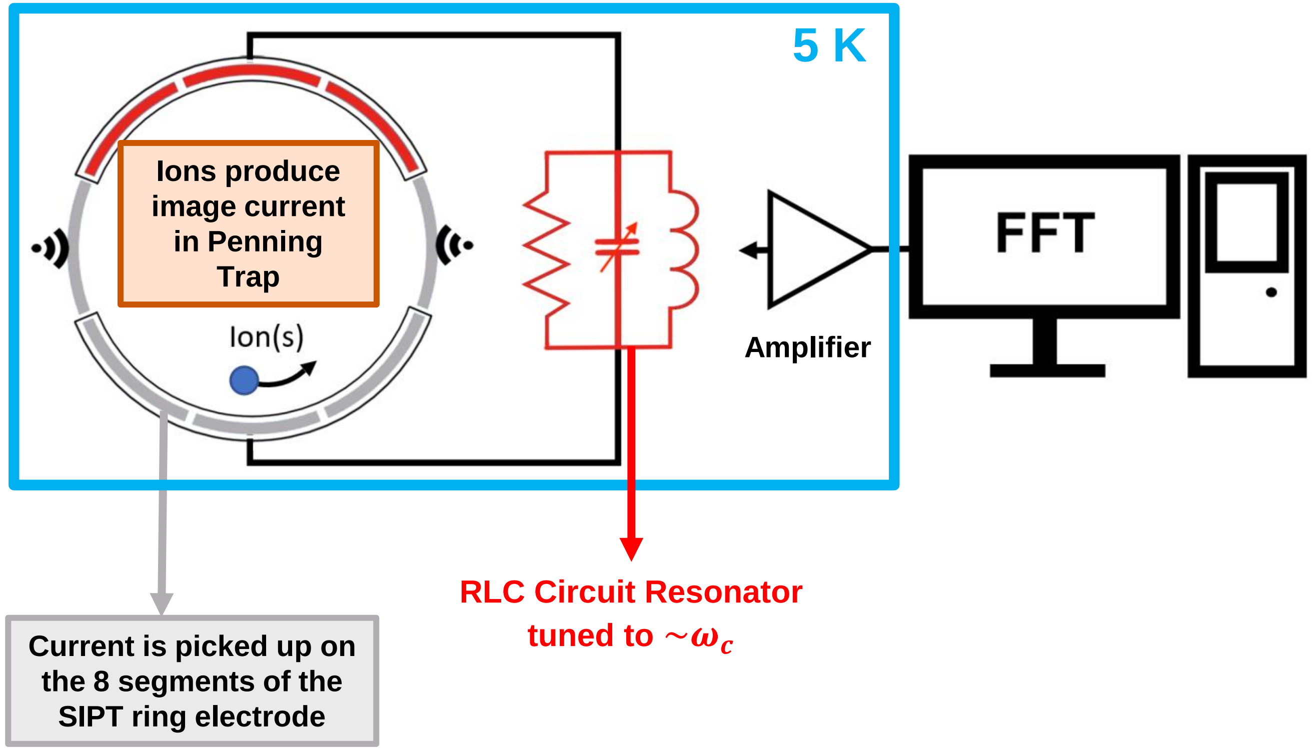
$$\omega_c = \omega_- + \omega_+ = \frac{2\pi N_- + \varphi_{\mathrm{acc},-}}{t_{\mathrm{acc},-}} + \frac{2\pi N_+ + \varphi_{\mathrm{acc},+}}{t_{\mathrm{acc},+}}$$

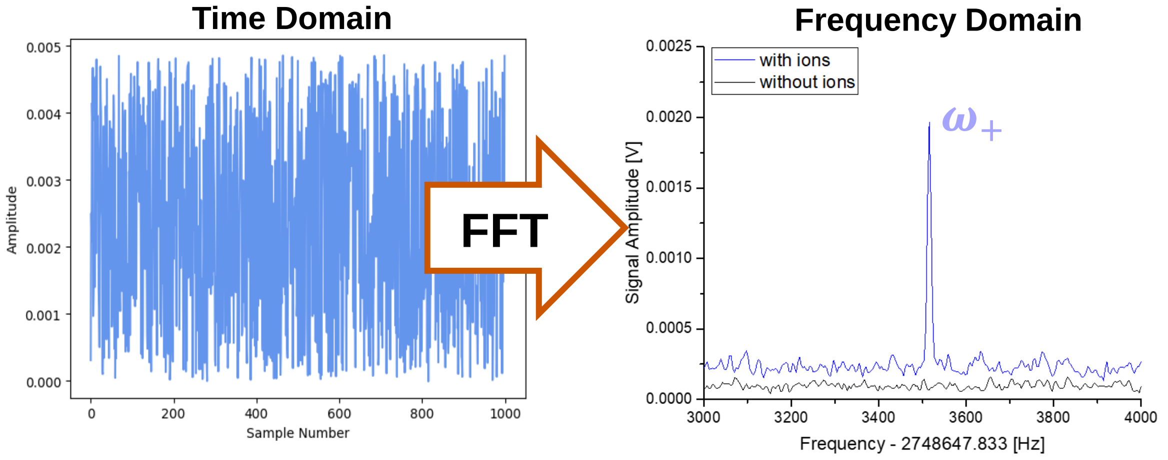
magnetron spot — **reduced cyclotron spot**

FRIB

FT-ICR Enables Precision Measurements with a Single Ion

- Fourier-Transform Ion Cyclotron Resonance
  - Measure ω_c and/or ω_+
  - Ions produce image current that is amplified and FFT performed to produce ω





- Signal to Noise Ratio (SNR) Optimization

$$\mathrm{SNR} \propto Nq\sqrt{\frac{Q}{TC}}$$

N: number of ions in the trap
q: ion charge state
Q: quality factor of resonator, >1000
T: temperature, ~5 K
C: capacitance of the resonator