A More Precise Atomic Mass of ^{4}He

Ongoing Reduction of Uncertainties
for the University of Washington
Penning Trap Mass Spectrometer
(UW-PTMS)

DAMOP 2004 Oral Session

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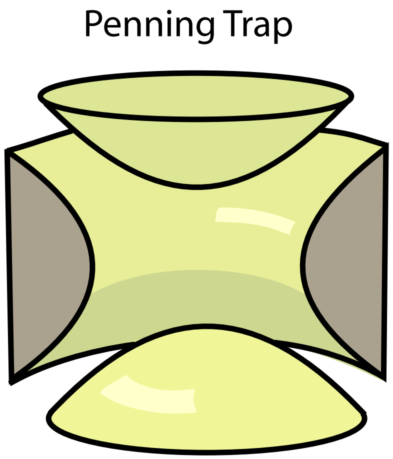
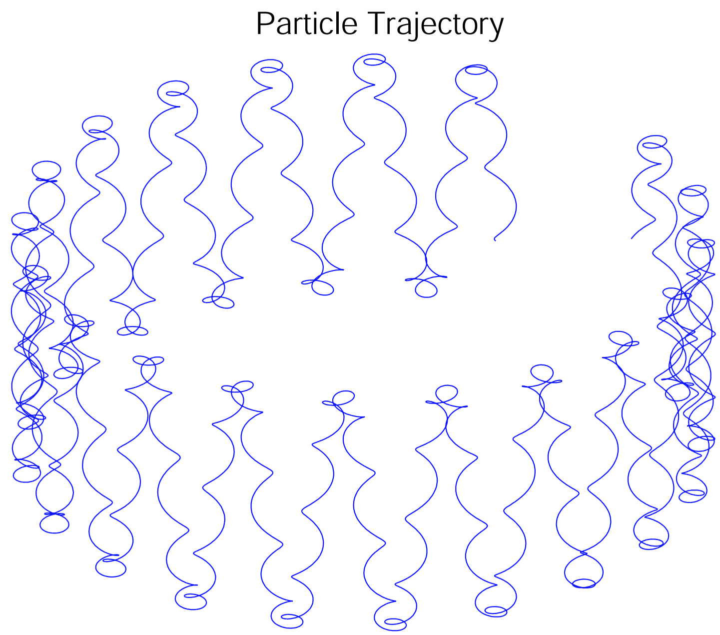
Our Measurements of $M(^4\text{He})$

- Motivation:
  - ^{4}He can be used as a reference ion.
  - The α-particle's mass is considered a fundamental constant.
- Results: (16 ppt precision)
  - $\text{M}(^4\text{He}) = 4,002,603,254.153(64)$ nu
  - $\text{M}_\alpha = 4,001,506,179.147(64)$ nu
  - This agrees with the two most accurate previous measurements at the 2σ level, but should be ~ 20 times more accurate.

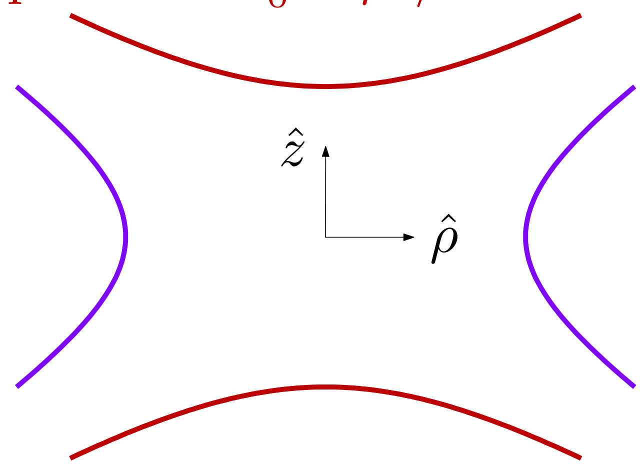
Outline of Talk





1. Introduction to our Penning traps
2. Recent improvements to the apparatus
3. Our new measurements of $M(^4\mathrm{He})$
4. Work in progress

Introduction to our Penning Traps



- Particle Dynamics—Confinement
  - Magnetic and electric fields:
    - Hyperbolic electrodes give harmonic oscillator potential.
      - $d^2 \equiv \frac{1}{2}(z_0^2 + \rho_0^2/2)$ (Trap length scale)
      - $d = 2.11\,\mathrm{mm}$
      - $V \approx V_0 \frac{z^2 - \rho^2/2}{2d^2}$ (Electrostatic potential)
      - $V_0 \sim 50\,\mathrm{V}$
    - Superconducting solenoid gives uniform B-field
      - $\mathbf{B} \approx (6.0\,\mathrm{T})\,\hat{\mathbf{z}}$

Introduction to our Penning Traps

- Ion mass ratio measurements are based on the equation:

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

- Ion-cyclotron excitation causes a shift in the ion's axial frequency:

$$\frac{\delta\omega_z}{\omega_z} = \left[\frac{B_2}{m\omega_z^2 B_0} - \frac{1}{2mc^2} - \frac{3C_4}{qV_0}\left(\frac{\omega_z}{\omega_c'}\right)^2\right] E_c$$

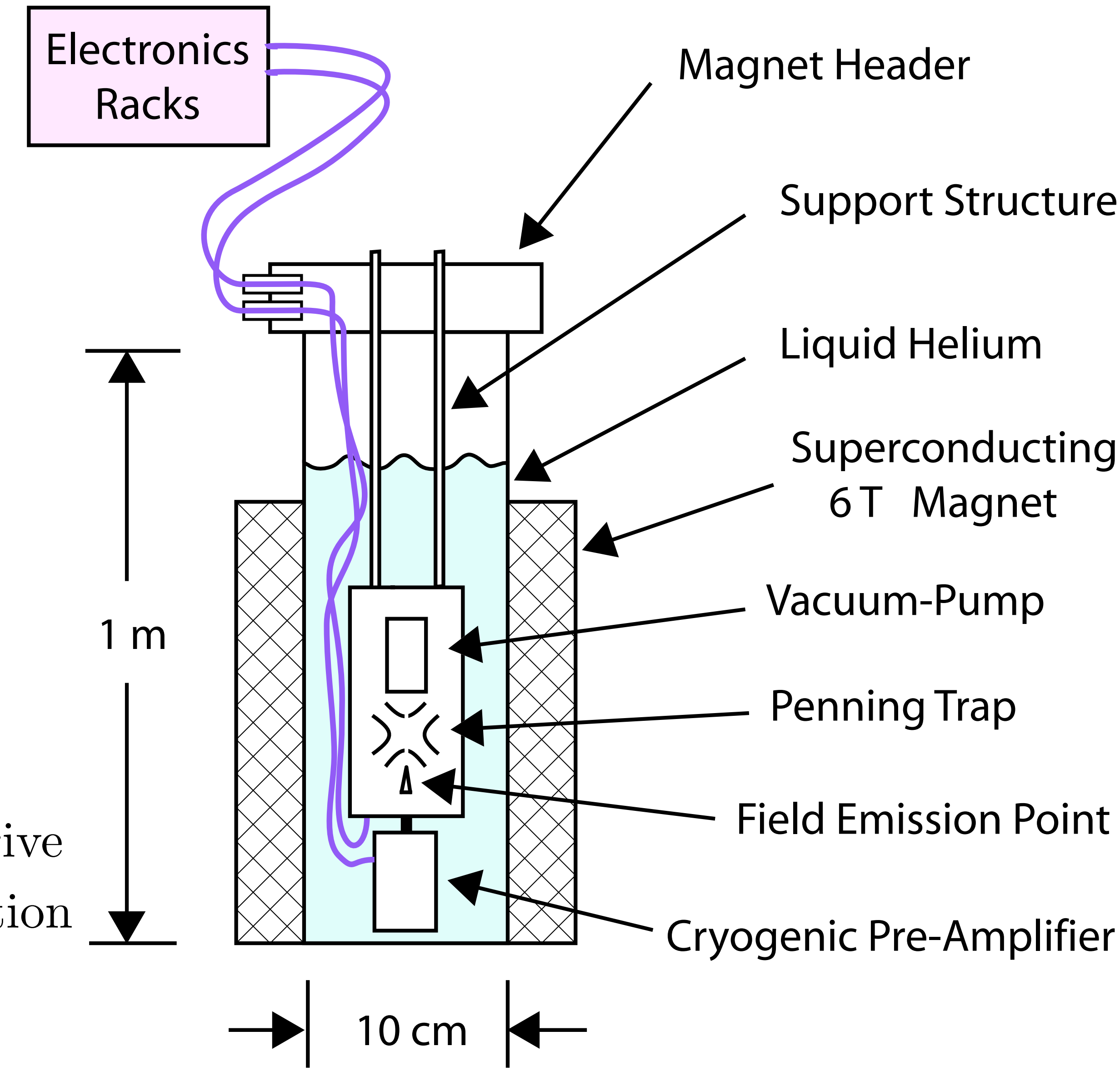
or, $\frac{\delta\omega_z}{\omega_z} = \Big[$ (quadrupole B-field term)
+ (special relativity term)
+ (anharmonic E-field term) $\Big]$ (cyc. energy)

(This is how we detect the cyclotron resonance.)

Introduction to the Apparatus

Penning Trap Mass Spectrometer

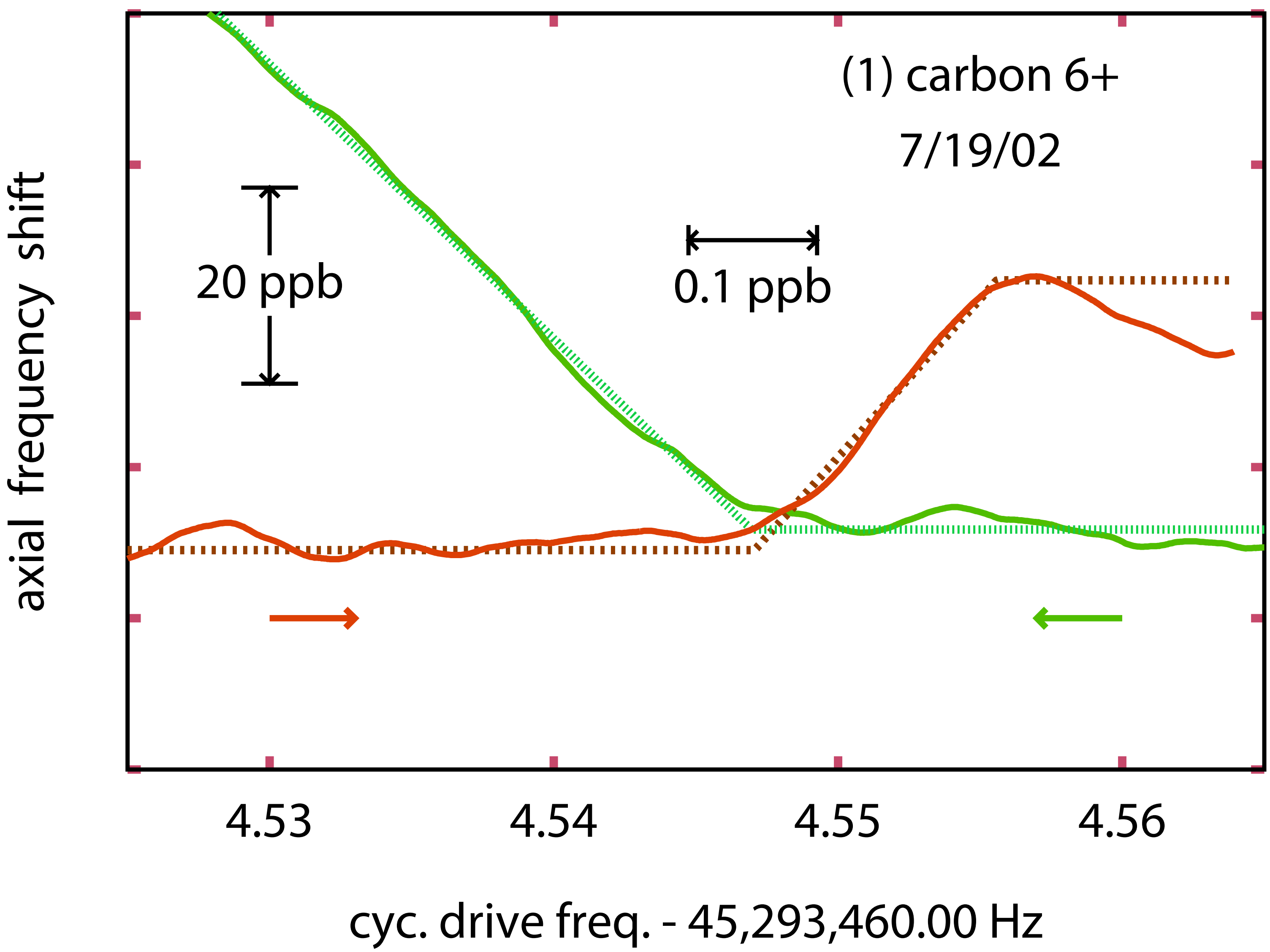
- Penning trap in vacuum at $T = 4\text{K}$
- Neutral gas desorbed from cryogenic surfaces
- Field emission point for ionization
- Ultra-stable magnet/cryostat system
- Electronic circuits for drive and detection of ion motion



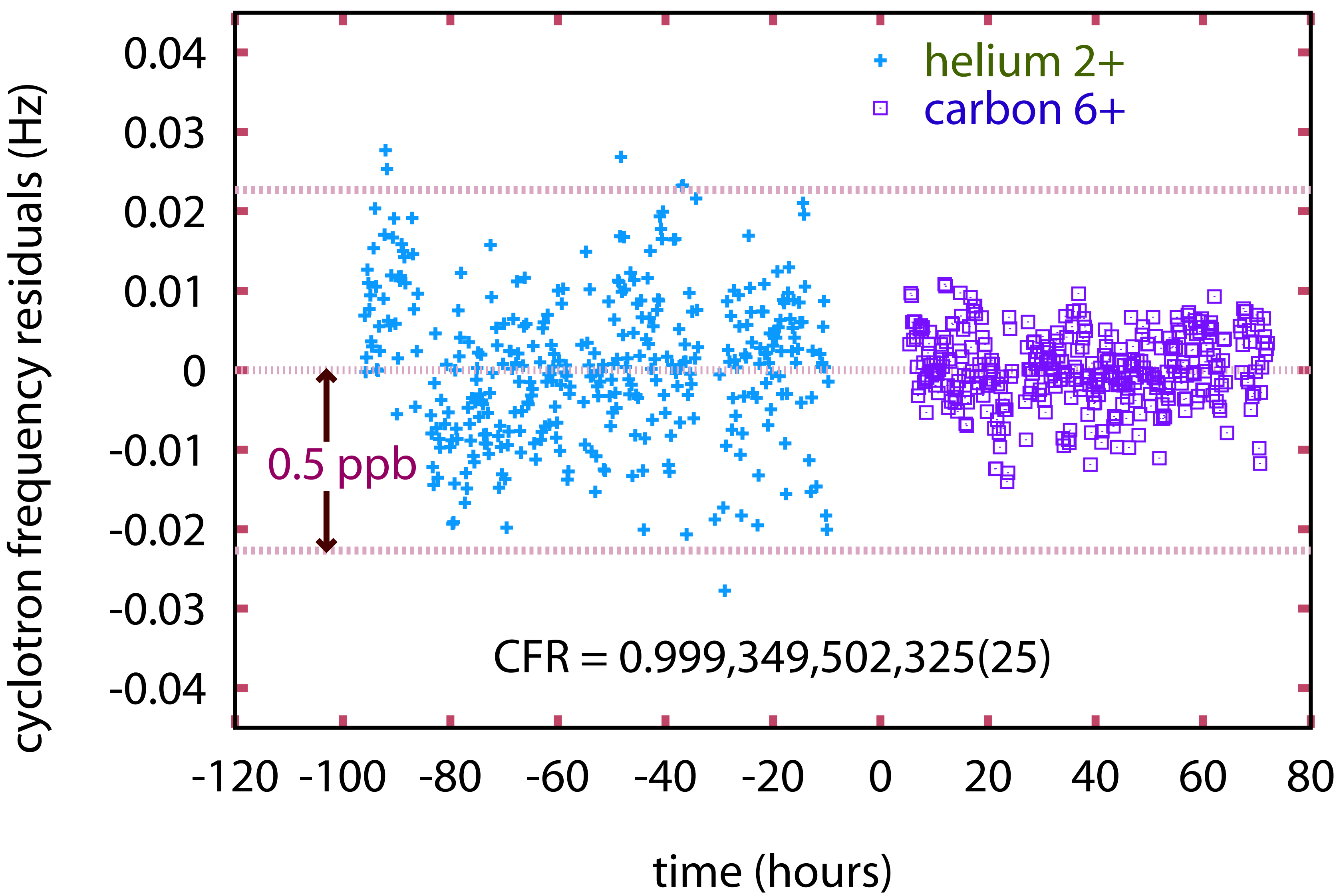
Recent Improvements to the Apparatus

- New frequency standard:
  A GPS-disciplined rubidium standard has replaced our free-running quartz crystal.
- We have improved procedures for eliminating contamination ions.
- The superconducting magnet's stability is improving with time.
- Sources of uncertainty are becoming better understood.

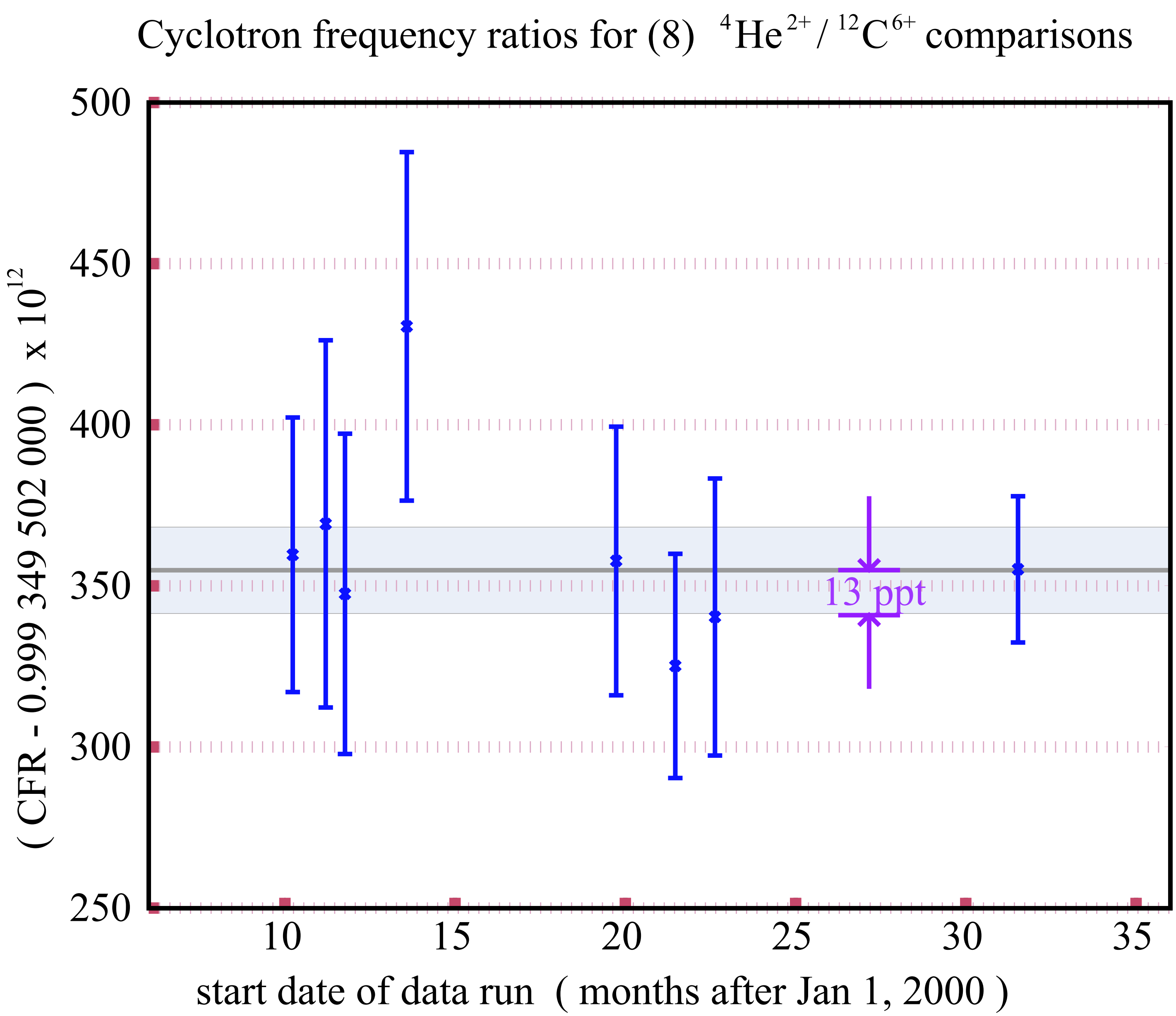
Our Measurements of $M(^4\mathrm{He})$



Our Measurements of $M(^4\mathbf{He})$



Our Measurements of $M(^4\mathrm{He})$

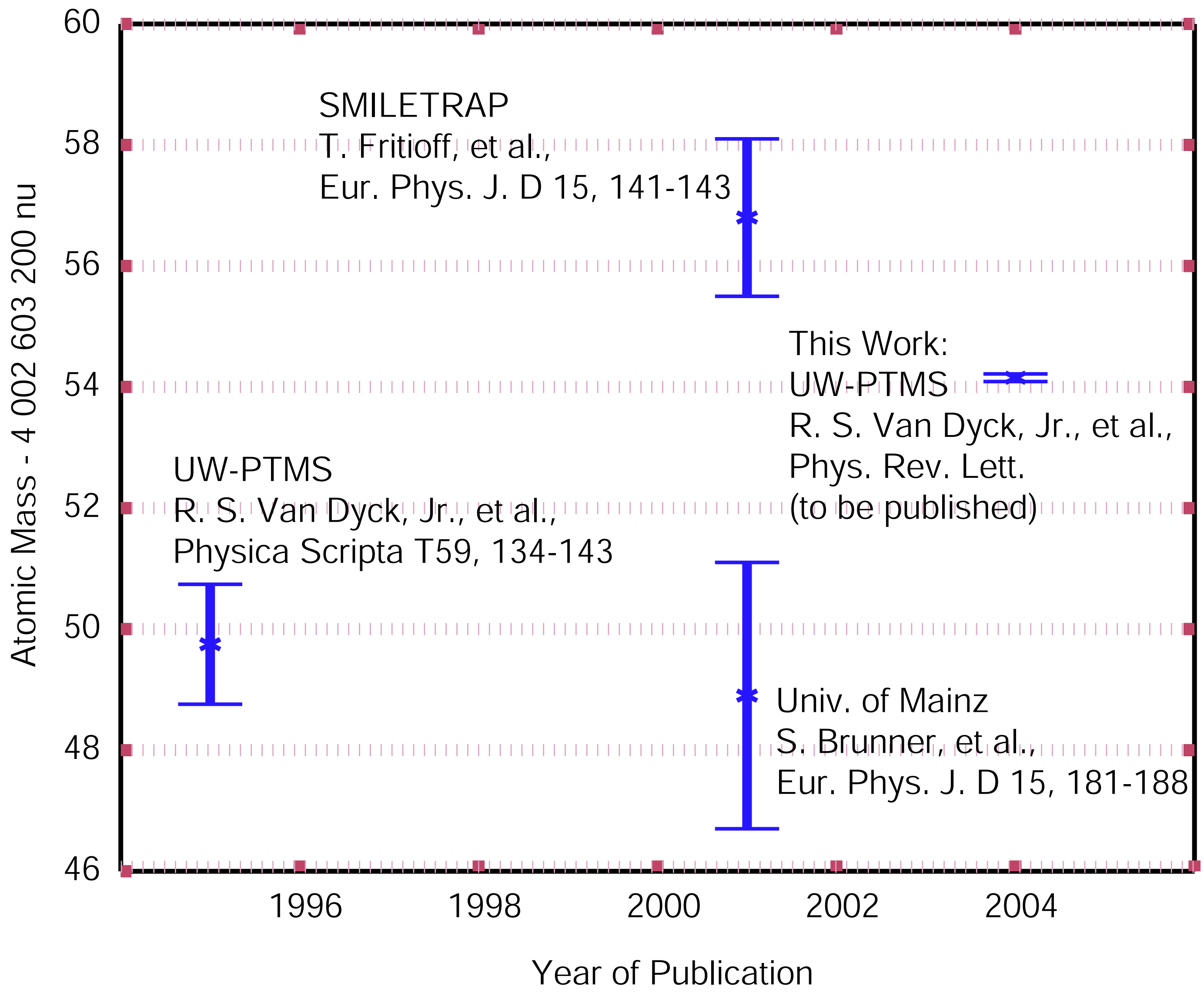


Our Measurements of $M(^4\text{He})$

Error Budget

- An uncertainty of $13.4\,\text{ppt}$ (1σ) could be reduced through repeated measurements:
  - This gives the conservative $\chi^2 = 0.41$, when all data is included.
  - The scatter of points within each data-run contributes $10.3\,\text{ppt}$.
  - Uncertainties on corrections for systematic shifts contributes the other $8.3\,\text{ppt}$.
- Uncertainty from the image-charge shift correction is $9\,\text{ppt}$. (This correction comes from a separate measurement.)
- Adding the missing electron masses and their binding energies introduced negligible uncertainty.
- Thus $16\,\text{ppt}$ is the stated accuracy of the measurement.

Recent Measurements of $M(^4\mathbf{He})$



Conclusion

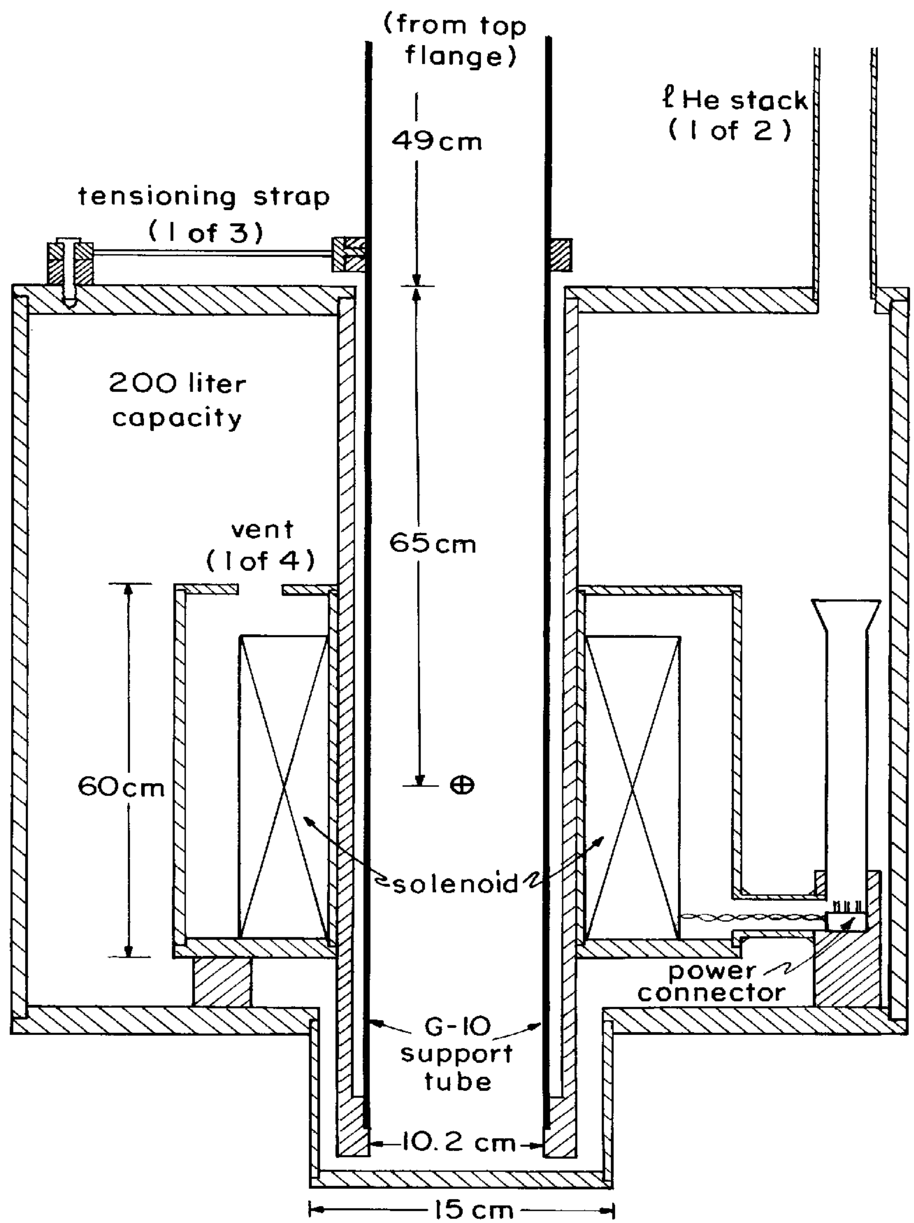
Work on light ions continues:

- ^{2}H atomic mass data awaits analysis
- ^{3}He atomic mass data-taking in progress
- New apparatus under construction for ^{3}H atomic mass measurement
  - External ion source
  - Double Penning trap

Superconducting Magnet and Cryostat

- Active and passive shielding reduces the ambient magnetic field noise by a factor of 10^4

- Overall temporal B-field stability is currently ~ 1 part in 10^{12} per hour.



Electronics Overview: Drive and Detection

Ion Cyclotron Excitation is Detected bacause it Shifts to the Ion's Axial Frequency