Contribution to resolution of the proton radius puzzle via measurement of the n = 2 Lamb shift in atomic hydrogen.

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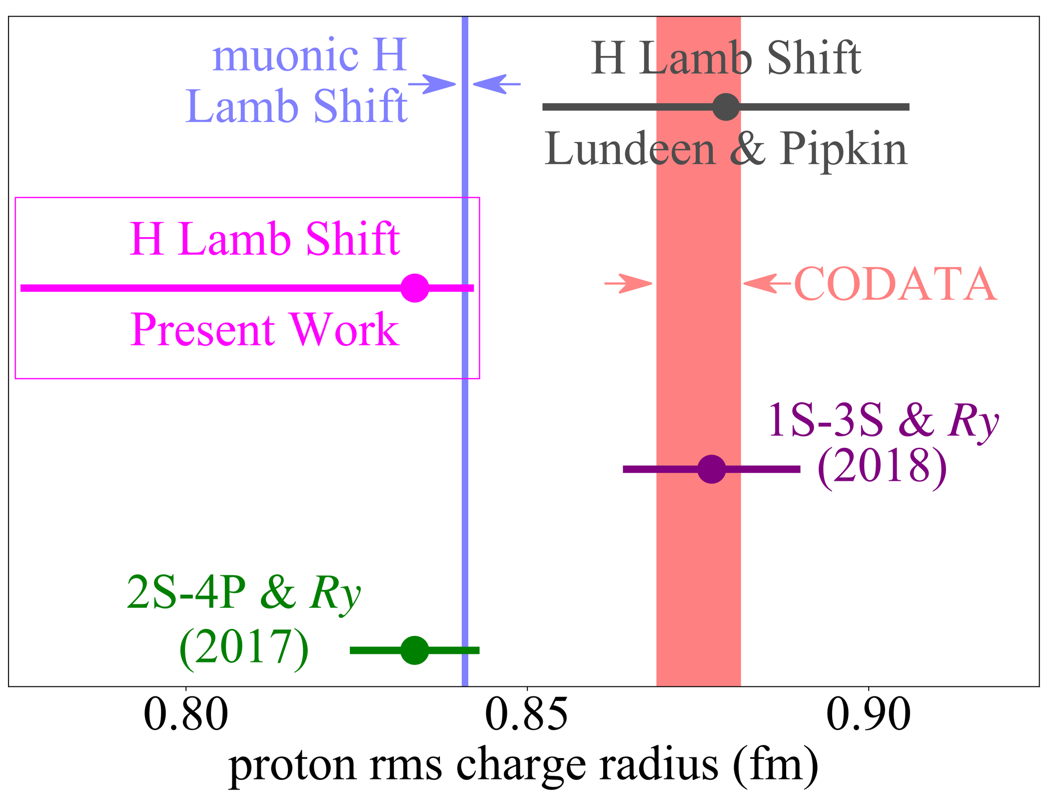
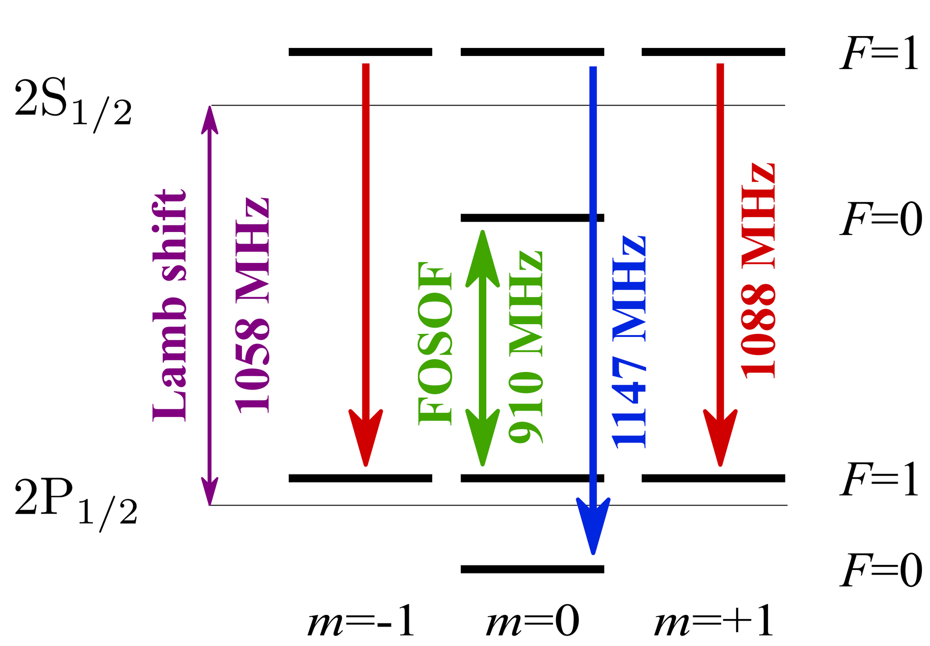
Since 2010 measurements of the n = 2 Lamb shift in muonic hydrogen have resulted in an extracted proton rms charge radius that is different from the accepted 2014 CODATA value by six standard deviations. We perform a measurement of the Lamb shift in atomic hydrogen, most recently measured by Lundeen and Pipkin in 1981. We present our final result of 909.8717 MHz with an uncertainty of +2.9 kHz and -19.3 kHz, from which we extract a proton radius of 0.834 fm (+0.009 fm, -0.058 fm), thereby resolving the proton radius puzzle. Our result shows that a measurement of the proton radius using the n = 2 Lamb shift is independent of whether electrons or muons are used.

PROTON RADIUS PUZZLE

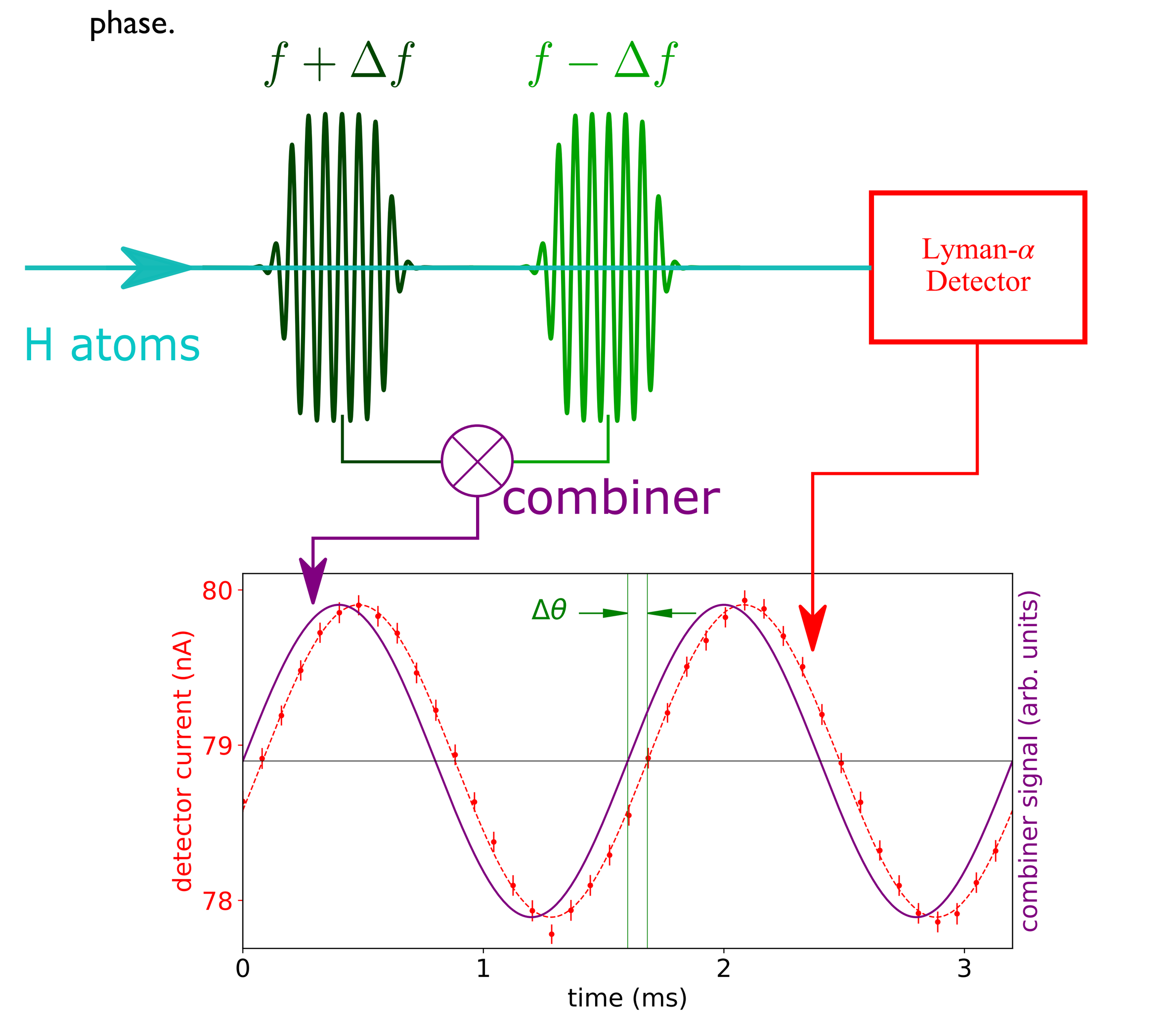


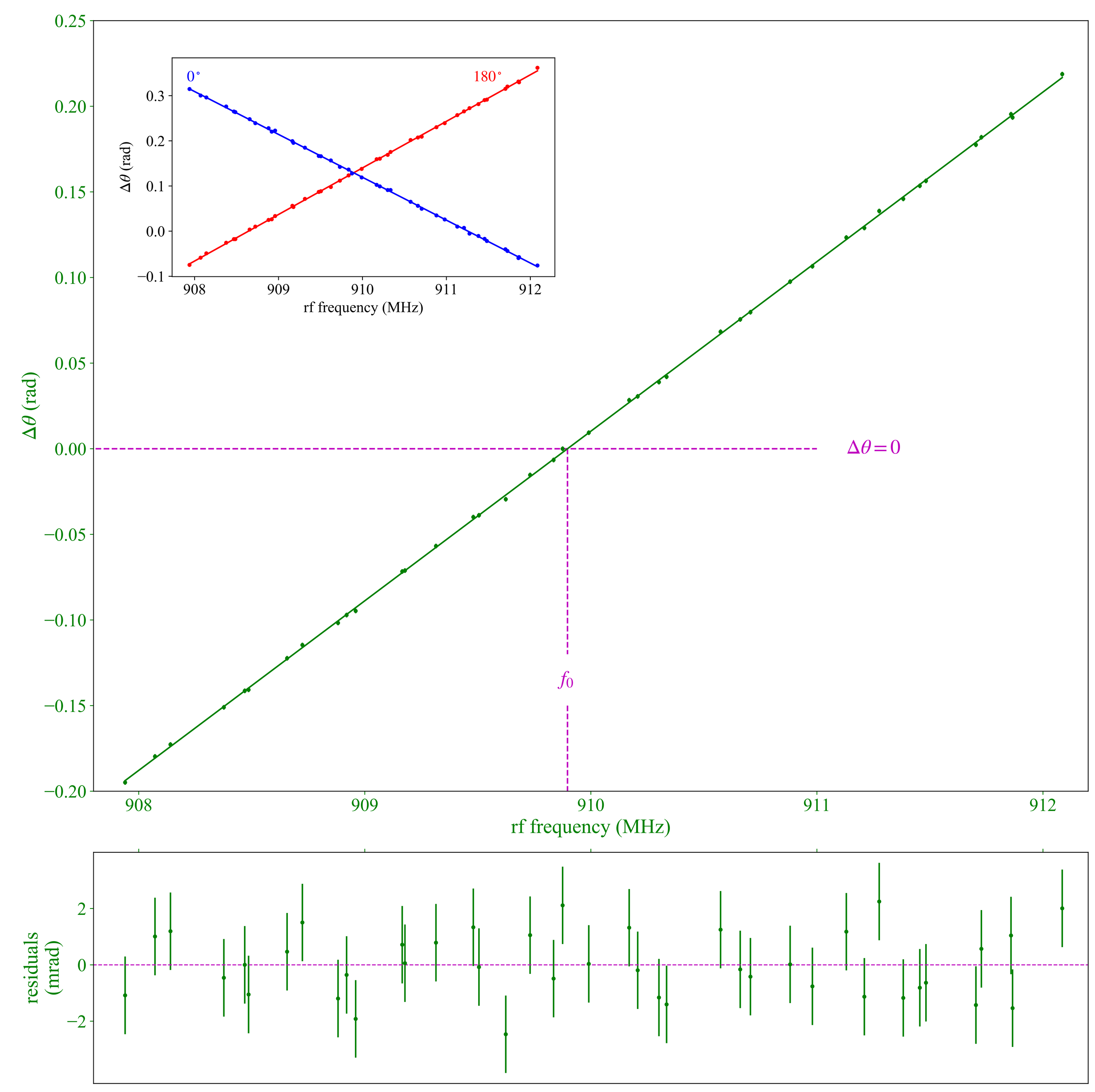
ENERGY LEVEL DIAGRAM

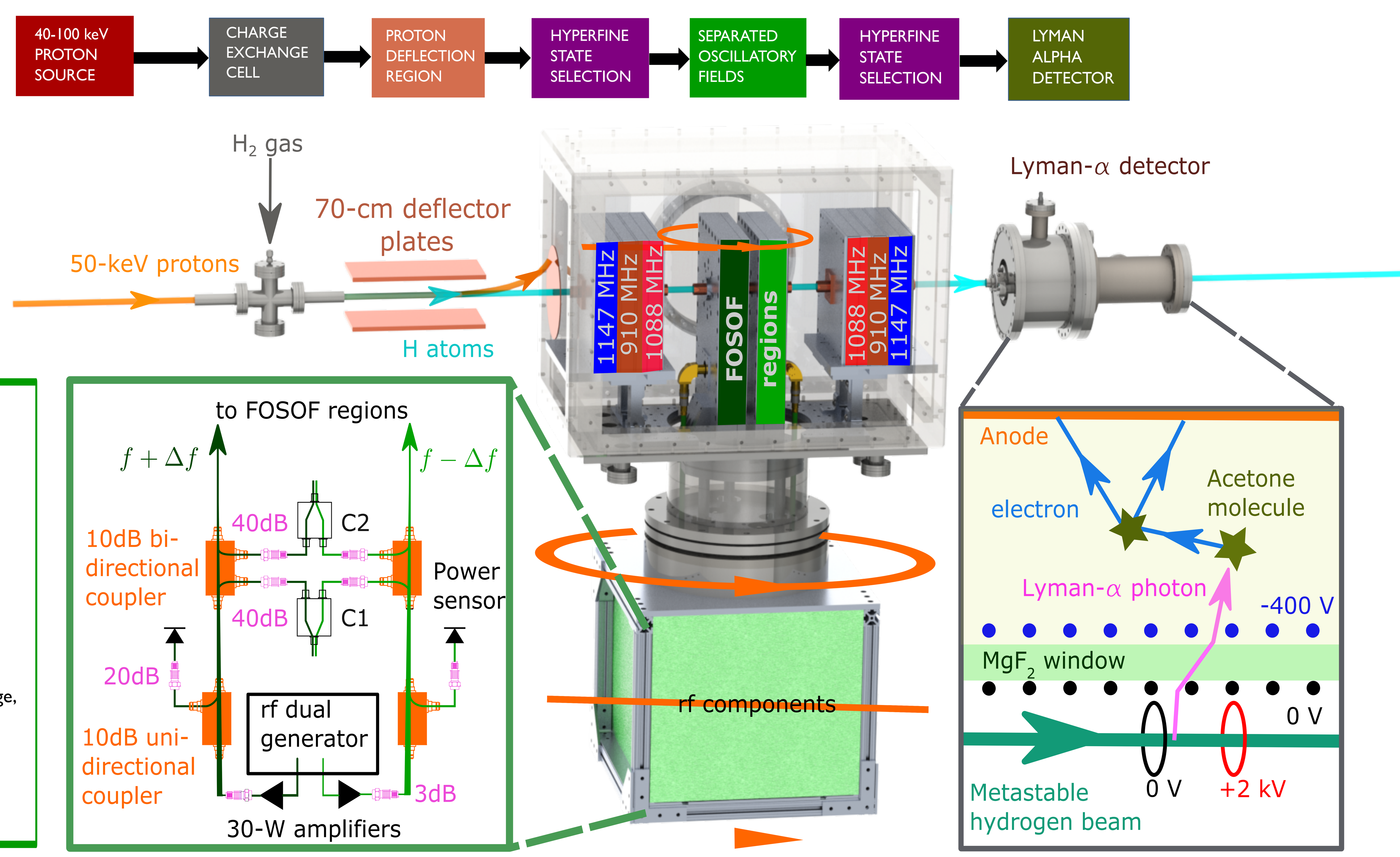


Frequency-offset separated oscillatory fields (FOSOF) technique

- The FOSOF regions are driven at frequencies offset from each other by 625 Hz, resulting in a continuous variation of the relative phase.
- Offset frequency can be chosen in a region of low noise in the spectrum of the detection system to obtain high signal-to-noise ratio (SNR)
- Simple lineshape. Line center extraction is insensitive to lineshape distortions from frequency-dependent microwave system response for low driving powers.
- At the line center, the atomic signal and the reference (beatnote) signal are in phase.







(ROTATABLE) FOSOF MEASUREMENT REGION

- Standing-wave waveguides for FOSOF: constant phase throughout waveguide, no 1st-order Doppler shifts.
- Impedance matching section to efficiently couple power (850-1150 MHz) from coaxial line into standing-wave waveguides.
- Waveguides on rotational stage **can be interchanged under vacuum** to reverse effects of phase offsets.
- Microwave generator & amplifiers mounted directly on air-side of rotary flange, allows reversal of FOSOF regions without any mechanical stress or cable changes.
- TM010 cavities for hyperfine state selection before & after FOSOF region. Enable studies of systematic effects from neighboring resonances.

Systematic studies

- AC Stark and Doppler effects were tested by varying waveguide separation, rf amplitude, and proton accelerating voltage and measuring the resonant frequency. These results are consistent, as shown on Figure (A) and (B).
- Effect due to remaining higher-lying n states was shown to be consistent with zero by varying 2S population, background pressure and proton deflection field.
- Presence of residual DC E field was proven to be consistent with 0 V/cm by applying external transverse B field that transforms to E field in the atoms' reference frame.
- Systematic effects in FOSOF phase measurement can be detected by plotting linecentre vs the inverse of the lineshape slope S.
- Extrapolation of the plot of linecentre vs 1/S, Figure (C), while consistent with the weighted average of all linecentres, reveals a smaller Lamb shift measurement that cannot be ruled out.