Atomic Hydrogen Beam Characterization Techniques for the Project 8 Experiment

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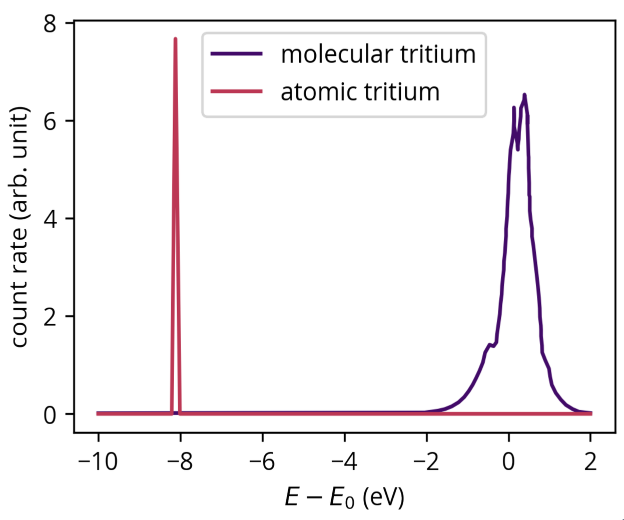
INTRODUCTION

The Project 8 experiment aims to probe the neutrino mass range down to *40 meV/c²* sensitivity by analyzing the tritium beta decay spectrum. Achieving this sensitivity requires injecting atomic tritium into a trap. This necessity stems from the presence of rotational and vibrational exitation states in molecular tritium beta decay (into $^3HeT^+$) which broaden the final spectrum.



Trap Supply Requirements:

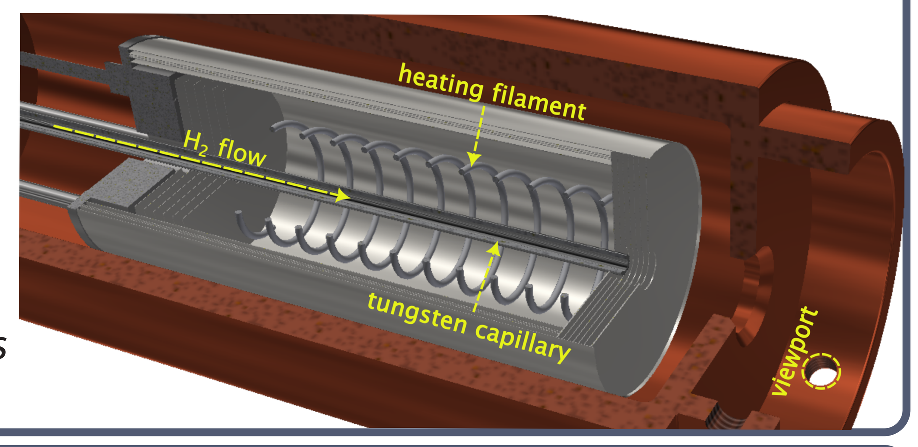
1. Large atomic density: $n(T) \sim 1 \times 10^{17}$ /m³
2. Detector feeding flow: $\sim 10^{17}$ atoms/s
3. Ensemble purity: $n(T_2)/n(T) < 10^{-4}$

ATOM BEAM SOURCE

Due to the natural radioactivity of tritium, current R&D is focused on developing and characterizing an atomic hydrogen source. In Mainz, the Hydrogen Atom Beam Source (HABS) is being tested. Dissociation efficiency of HABS increases with tungsten capillary temperature. An upper limit on the operating temperature exists to protect the device from rapid degradation or failure.

Source Properties:

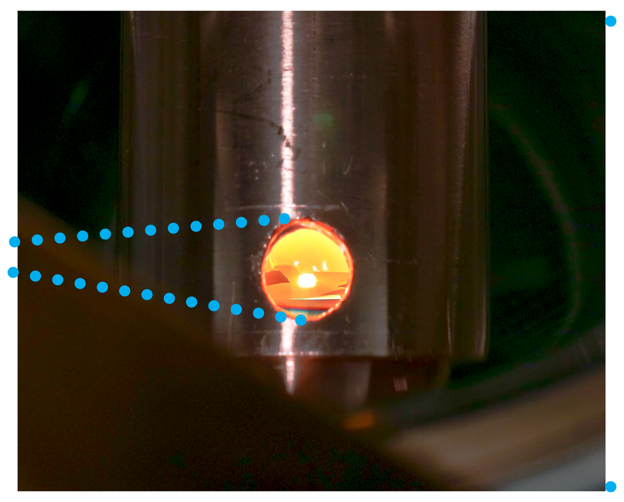
1. Operating Temperature: *≤ 2300 K*
2. Flow range: *0.002 sccm - 20 sccm*
3. Typical total flux of H-atoms: *1 x 10¹⁷ atoms/s*



TEMPERATURE CHARACTERIZATION

Prolonged operation of the HABS at high temperatures results in the aging of the tungsten capillary. This degradation requires progressively higher power inputs to maintain the desired operating temperatures. To accurately monitor and adjust for these changes, and to ensure precise temperature measurements for dissociation data, we employ a near-infrared InGaAs array spectrometer.

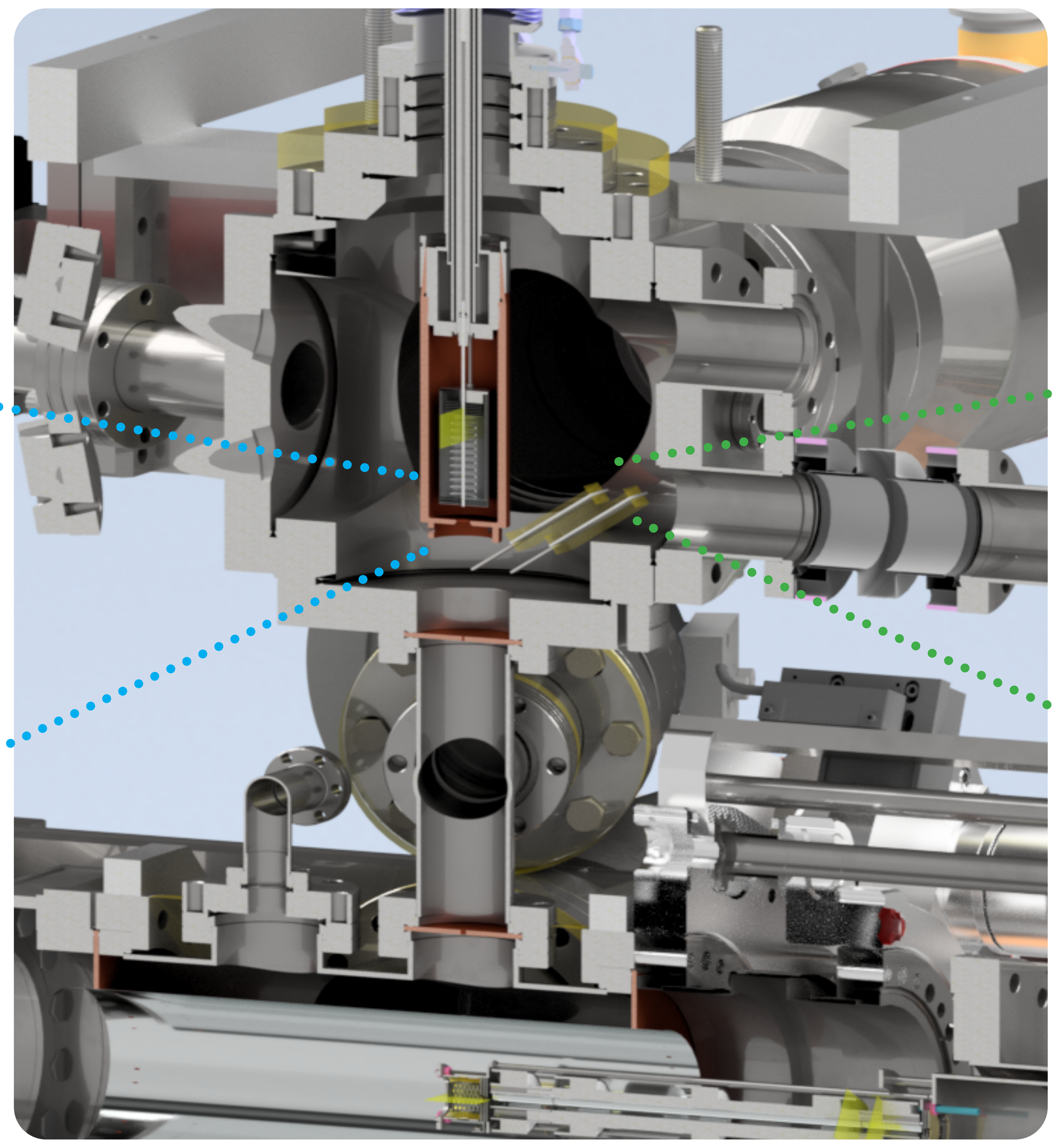
Range: 900 nm - 1700 nm
Resolution: ~4 nm



The surface temperature is determined using Planck's law:

$$L(\lambda, T, \theta, \phi) = \varepsilon(\lambda, T, \theta, \varphi)\, C(\lambda, T)\, \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda k_B T}\right) - 1}$$

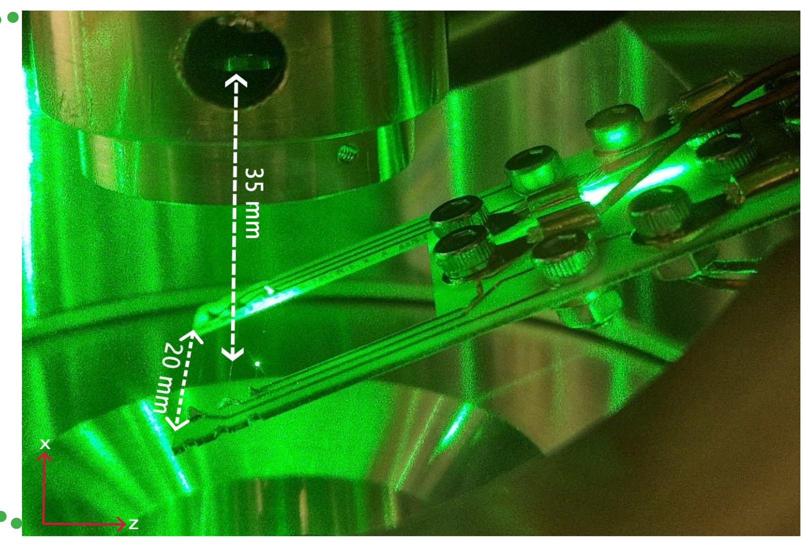
Where ε is tungsten's emissivity dependent on wavelength (λ), temperature (T) and angle of observation (θ, φ) and C(λ, T) is the correction function for the spectral radiation counts (L) from source to detector.



Mainz Atomic Test Stand CAD drawing

BEAM SHAPE CHARACTERIZATION

The wire detector is a calorimetric instrument designed to measure the dissociation fraction of the source and to characterize the atomic beam's shape at the capillary exit. It is comprised of three 5 μm-thick gold-coated tungsten wires mounted on a ceramic board. The board moves along the axis perpendicular to the beam path with the aid of a motorized linear translator.



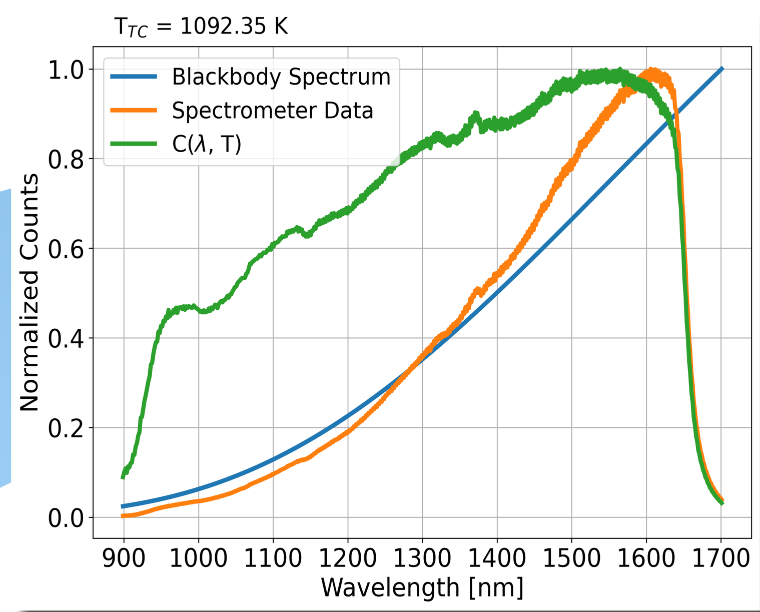
H atoms recombine to H_2 molecules on the wire surface releasing a binding energy of 4.46 eV as heat. An increase in the net heating power (P_{net}) leads to an increase in wire resistance (R):

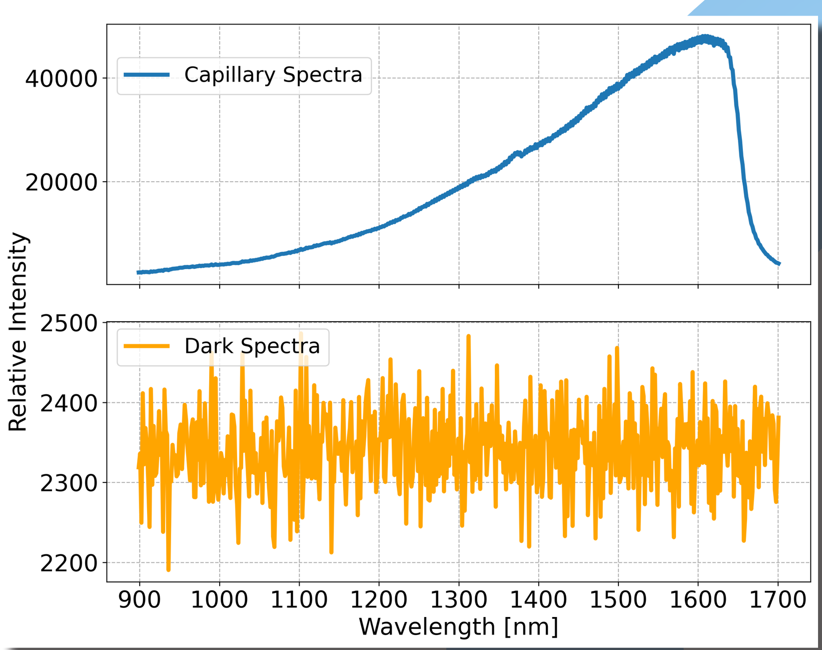
$$P_{net} = \Delta R \, \frac{dP}{dR}$$

where dP/dR is derived from the detector calibration.

ANALYSIS

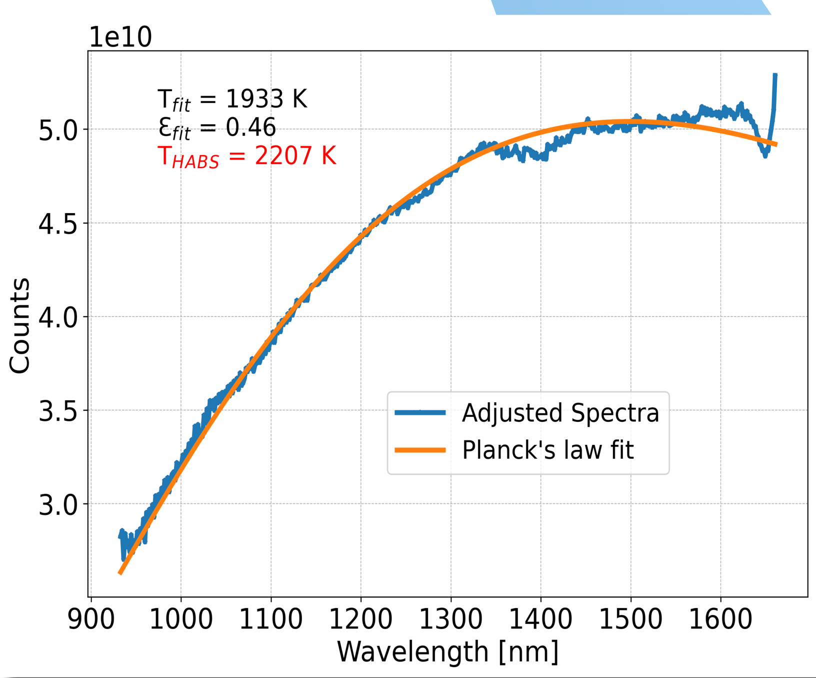
→ Obtain C(λ, T) of the optical system using reference measurements. A blackbody oven was heated to ~ 1100 K and measured simultaneously with the spectrometer and a type K thermocouple (TC).



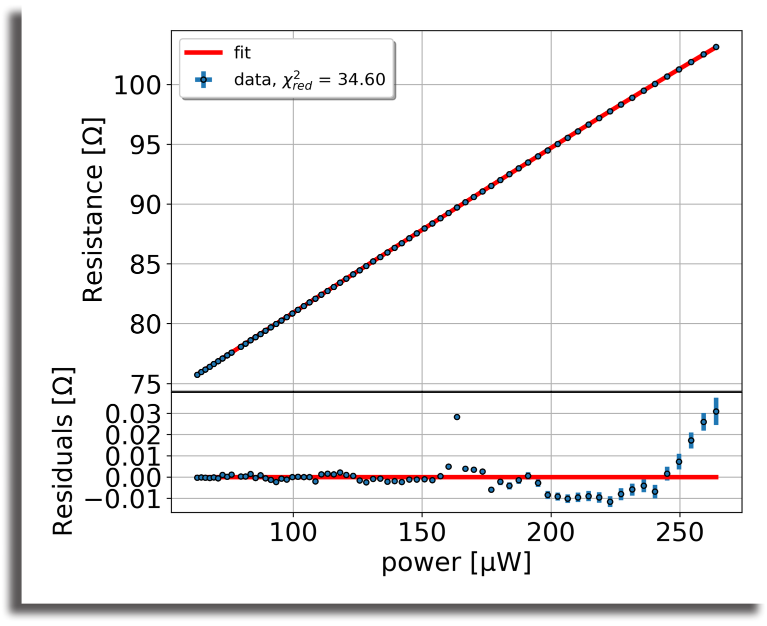


→ Remove background from measured spectra by measuring the dark spectra. This includes dark noise of the electronics.

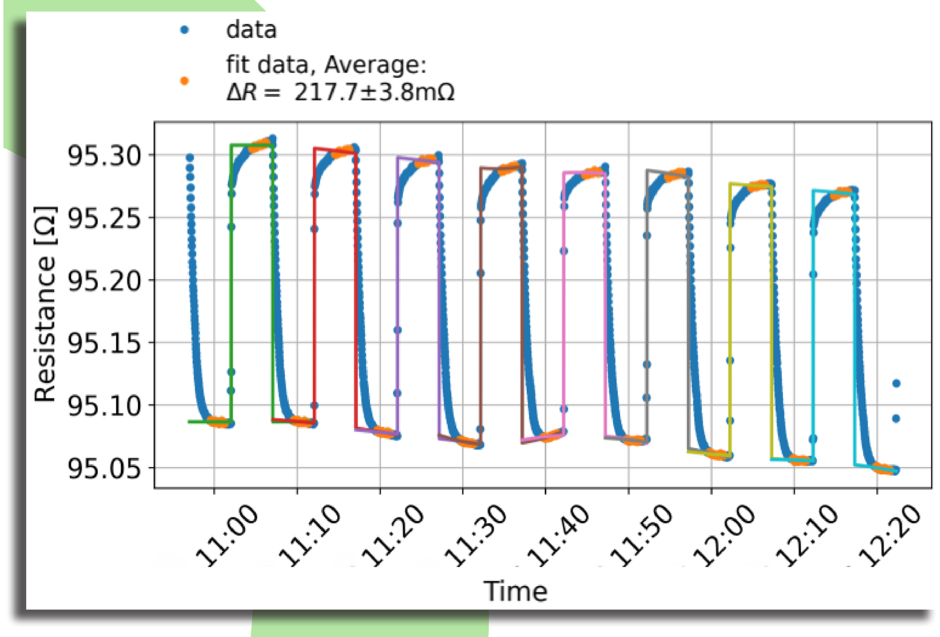
→ Get surface temperature T_{fit} and surface emissivity $\varepsilon_{fit}(T)$ of the HABS capillary. T_{HABS} is the expected temperature of HABS at this operational point.



→ Get dP/dR by supplying the wire with a series of increasing currents from 0.9 mA - 1.6 mA in steps of 0.01 mA.

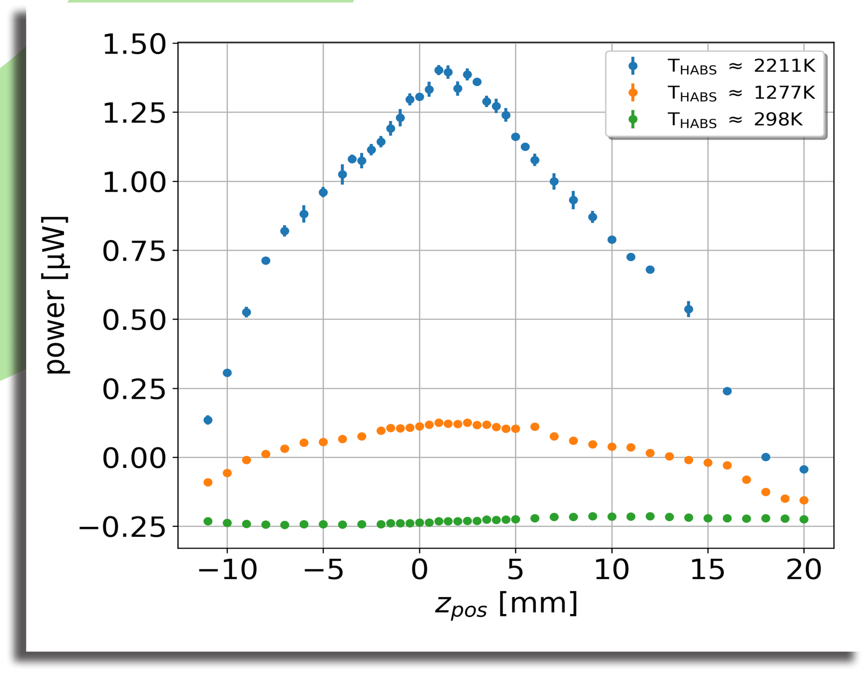


→ Remove background factors by flowing the hydrogen gas in 10 minute intervals.

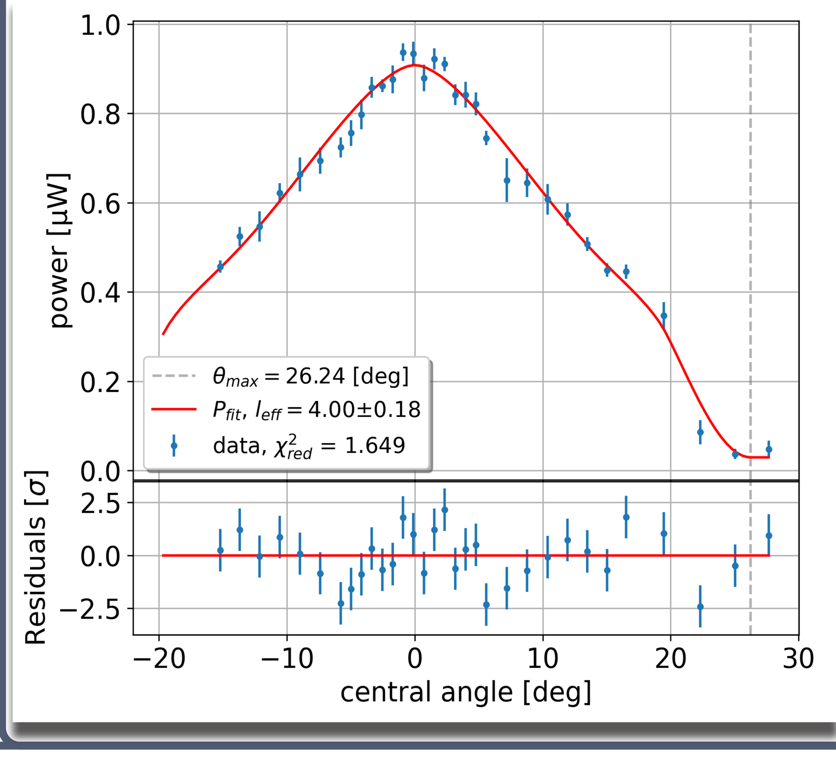


** Measurements for 1 sccm flow and T_{HABS} ~ 2200 K*

→ Measure atom signal accross the beam by translating the detector along the z-axis at different T_{HABS}. Signals at T_{HABS} ~ 298 K correspond to background gas and T_{HABS} ~1277 K corresponds to H_2 signal.



RESULTS



- Atomic hydrogen beam shape is dependent on the capillary temperature.
- The accuracy of the spectrometer's measurement of the capillary temperature is currently limited by uncertainties in the model of $\varepsilon_W(\lambda, T)$.
- To obtain the source's atomic flux, both beam shape and temperature need to be well characterized.

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