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# A Two-Coordinate Detector for a Beam of Atomic Hydrogen or Deuterium

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**Abstract**—The profile of an atomic beam in the region where it forms is an important characteristic of a polarized atomic hydrogen (or deuterium) source. A mathematical model for a two-coordinate resistive detector of atomic hydrogen beams is presented. Metering equipment and a technique for measuring an atomic beam profile are described, and the results of our measurements are presented.

The traditional method for measuring the profile of a hydrogen atomic beam is based on the use of a quadrupole mass spectrometer (QMS) in which the atoms pass through the spectrometer and intersect with the internal electron beam [1]. The QMS is deployed on a two-coordinate stage so that it can move in the plane perpendicular to the beam.

The indirect method of determining the beam profile consists in measuring the pressure in a chamber with a compression tube [2]. The direct atomic beam travels over a long tube of small diameter without interacting with its walls (the atoms move parallel to the tube axis). However, the backflow from the vessel is limited by the conductivity of the compression tube. Therefore, the pressure in the vessel is related to the atomic flux and the parameters of the compression tube. If it is possible to move the compression tube in the plane perpendicular to the beam, the beam profile can be measured. A special calibration procedure allows the absolute beam to be measured at the inlet to the compression tube [3].

Both of these well-known methods have been thoroughly investigated in a great number of papers. The main disadvantages of these methods are the Disruption of the beam by the measuring instrument, the mechanical complexity of two-dimensional movement in a vacuum, and the stringent requirements for the vacuum when taking measurements with the QMS.

Our two-coordinate resistive atomic beam detector is able to overcome these difficulties. The operation of the instrument is based on the change in resistance of a thin wire placed in an atomic hydrogen (or deuterium) beam. Atoms of hydrogen recombine into molecules on the wire's surface and heat it; as a result, the temperature of the wire and, hence, its resistance change (Fig. 1). Thus, the resistance of the wire carries information on the beam's intensity. By arranging the wires into a two-dimensional grid, it is possible to reconstruct the atomic beam profile.

It is common knowledge that the sticking coefficient of the atomic hydrogen is rather high [4] and is independent of both the angle of incidence and the atomic velocity (up to $10^4$ m/s). Different research teams have tried to measure the recombination heat by wire resistance on atomic hydrogen sources, but their attempts have so far been unsuccessful, and no results have been

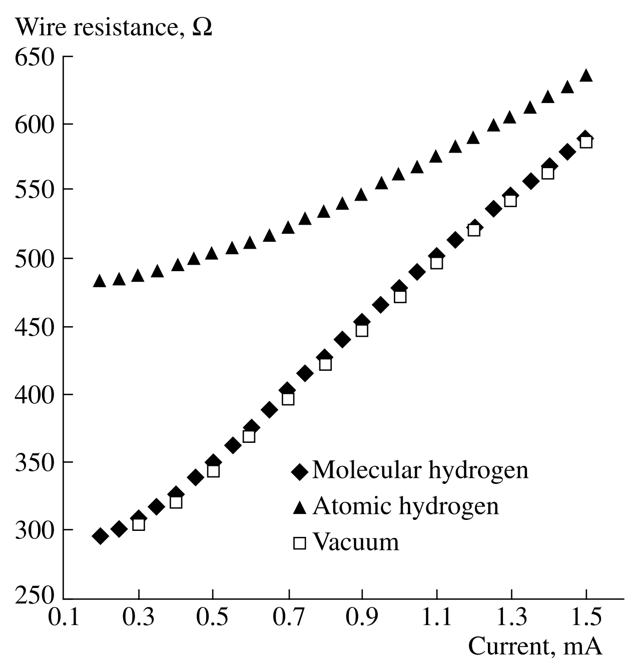


**Fig. 1.** Resistance of a 5-μm-diameter wire as a function of the current in a high vacuum and in beams of molecular $0.5 \times 10^{16}$ molecule/cm$^2$ s) and atomic ($1 \times 10^{16}$ atom/cm$^2$ s) hydrogen.

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published [5]. The main problem is the need to measure the extremely low density of heat liberation. The characteristic intensity of our atomic beam is ~$10^{16}$ atom/(cm$^2$ s). The density of heat liberation for this flux during the surface recombination of atoms is 0.004 W/cm$^2$. Using the mathematical model in [6], we were able to determine the range of suitable wire diameters. The permissible diameter of a wire made of W–Re alloy was 5 ± 2 μm. At the qualitative level, this narrow range is attributable both to the increase in heat removal through the wire that accompanies an increase in wire diameter and to the increase in heat emission that accompanies a decrease in wire diameter. Both of these processes lower the temperature of the wire and, hence, its sensitivity as an atomic beam detector. Wire from Luma Metal (Sweden) [7] was used to manufacture the monitor.

The mathematical model for heating a wire through the recombination of atomic hydrogen at its surface was constructed on the assumption of a homogeneous parallel atomic beam being incident on a wire with a circular cross section and a length significantly greater than its diameter. As a result, we obtained a nonlinear steady-state differential equation of the second order:

$$-\frac{\partial^2 T}{\partial x^2} = \left[\frac{\alpha_\lambda}{1+\alpha_\lambda(T-T_0)}\right]\left[\frac{\partial T}{\partial x}\right]^2 + \frac{\frac{C_s E_{\rm rec} d Q(x, y_{\rm w})}{2} + \frac{I^2[\rho_0 + \rho_0\alpha_\rho(T-T_0)]}{S} - \pi\sigma\varepsilon d(T^4 - T_0^4)}{S(\lambda_0 + \lambda_0\alpha_\lambda(T-T_0))},$$

where $x$ is the coordinate along the wire, $y_{\rm w}$ is the coordinate of the wire, $Q(x, y_{\rm w})$ is the atomic hydrogen beam intensity, $d$ is the diameter of the wire, $C_s$ is the coefficient of the sticking of hydrogen atoms to the surface, $E_{\rm rec}$ is the recombination energy for a pair of atoms, σ is the Boltzmann constant, ε is the reflectance, $T_0$ is the temperature of the vacuum chamber or the temperature of the equilibrium thermal radiation in which the wire is placed, and $I$ is the current through the wire.

The thermal conduction of the wire is

$$\lambda(T) = \lambda_0 + \lambda_0\alpha_\lambda(T - T_0),$$

where $\alpha_\lambda$ is the temperature coefficient of thermal conduction, and $\lambda_0$ is the thermal conduction at temperature $T_0$.

The specific resistance of the wire is defined as

$$\rho(T) = \rho_0 + \rho_0\alpha_\rho(T - T_0),$$

where $\alpha_\rho$ is the temperature coefficient of specific resistance, and $\rho_0$ is the specific resistance at temperature $T_0$.

The boundary conditions for this equation are $T\left(-\frac{L_0}{2}\right) = T\left(\frac{L_0}{2}\right) = T_0$. In this case, the wire resistance is expressed in terms of temperature as follows:

$$R = \frac{1}{S}\int_{-L_0/2}^{L_0/2}\rho(x)dx = \frac{\rho_0}{S}\left[L_0(1-\alpha_\rho T_0) + \int_{-L_0/2}^{L_0/2}T(x)dx\right].$$

In order to discover the qualitative relationships, we found an analytical solution to this equation through the use of simplifying assumptions. This solution can be used with complete confidence for low atomic hydrogen fluxes. On the basis of these analytic expressions, we ascertained the boundaries of the wire parameters. They can also serve as the initial approximation for the numerical solution of the differential equation. In this case, the convergence rate for the numerical solution increases scores of times.

## MEASURING THE ATOMIC HYDROGEN FLUX

There are different methods for numerically solving the nonlinear differential equation for a wire. However, the wire itself is described by a set of parameters; some of these can be measured directly, while others cannot. The directly measurable parameters of a thin (5 μm thick) wire were found to differ widely from the reference data for this material. This is attributable to the substantial effect of the surface layer and the complex composition of the wire (tungsten and rhenium, with a surface layer of gold 0.5 μm thick).

The following parameters are used to describe the wire: temperature coefficient of resistance $\alpha_\rho$, which allows its direct measurement (the resistance of a piece of the wire was measured in a muffle furnace at temperatures as high as 800°C); wire diameter $d$, which can be directly measured with a microscope; thermal conduction λ; and reflectance ε.

The last two parameters do not allow direct measurements. Their values can be obtained from the current dependence of the wire resistance in a high ($10^{-7}$ mbar) vacuum. The values of thermal conduction and reflectance are merely fitted such that the computed resistance agrees with that measured.

The dependence of the wire resistance in a vacuum and in molecular and atomic hydrogen beams is shown in Fig. 1. These measurements confirm the sensitivity of the method when atomic hydrogen is used. The molecular hydrogen beam, which creates similar vac-

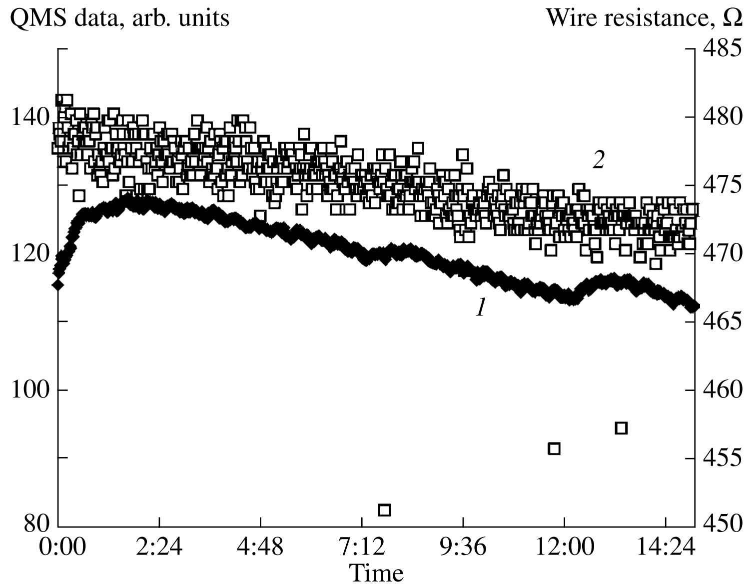


**Fig. 2.** (*1*) Measurement of wire resistance in an atomic hydrogen beam ($1 \times 10^{16}$ atom/cm$^2$ s) and (*2*) simultaneous measurement of the beam using a QMS.

uum conditions for the wire, fails to change the resistance. Note that deterioration of the vacuum conditions can only decrease the resistance (the operating principle of a great many vacuum gauges). The atomic hydrogen causes the resistance of the wire to increase by almost a factor of 2 (at low currents). This effect corresponds to a voltage change of 90–150 mV and can be measured with virtually any voltmeter.

The stability of the parameters over time was monitored as the QMS measurements were being made (Fig. 2). To maintain the reproducibility of the measurements, we developed special technology for cleaning the wire, since its surface condition played a decisive role in our experiments. It turned out that, after annealing the wire in an atomic hydrogen beam at a temperature as high as 900°C, the reproducibility of results was 1% or better. At higher temperatures, the gold evaporated from the wire's surface.

Hence, on the basis of the expression for the wire resistance, one can determine the integral of the intensity of the beam projected onto the wire. A two-coordinate monitor containing two layers of wires (16 × 16) and placed on opposite sides of a steel frame was developed to measure the beam profile [8]. Kapton insulators with copper pads were glued to the frame using araldite (a two-component adhesive that can be used in an ultrahigh vacuum). A gold-plated W–Re wire 5 μm in diameter was soldered and glued to the frame (using proportional chambers technology). A distinctive feature of this technology is the need to work with a thin (5 μm in diameter) wire whose mounting requires a tension of <1.5 g. The design of the monitor satisfies the requirements for devices intended to operate in an ultrahigh vacuum.

A special PC card containing 32 controlled current sources and a 32-channel analog switch was developed for the monitor. After commutation, the wire signals were measured with the help of a digital voltmeter (Keithley, United States). A special CAMAC module based on an Atmel 89S8252 microcontroller was developed with the aim of using the beam monitor on the polarized source in the HERMES experiment at DESY (Hamburg, Germany). The program designed for the microcontroller with the use of the Avocet C51 supports the measuring of the wire resistance and the exchanging of data with the CAMAC controller. The instrument is equipped with a serial RS-232 interface to debug its operating algorithms. After the current is set at the required value in all of the wires (using 32 controlled current sources), the analog signal from the wire passes through a MPC506 switch (Burr-Brown, United States), is amplified, and is digitized by an LTC2410 24-bit analog-to-digital converter (Linear Technology, United States). The use of a high-capacity analog-to-digital converter (ADC) helps to achieve a high accuracy of measurements. An LTC1232 watchdog automatic reset circuit is used to protect the instrument from software failures. The response speed of the instrument is governed by the thermalization time of the wire after it is placed into the atomic hydrogen beam (which is 0.3 s), and by the time required to read out the data from all of the wires (5 s).

The instrument was designed for relative measurements of beam intensity. There exists a certain relationship between spatial resolution and the error of reconstructing the beam intensity, since the entire set of wires participates in the process of calculating the two-dimensional flow pattern. The relative error is composed of a measurement error (0.2%) and the error of

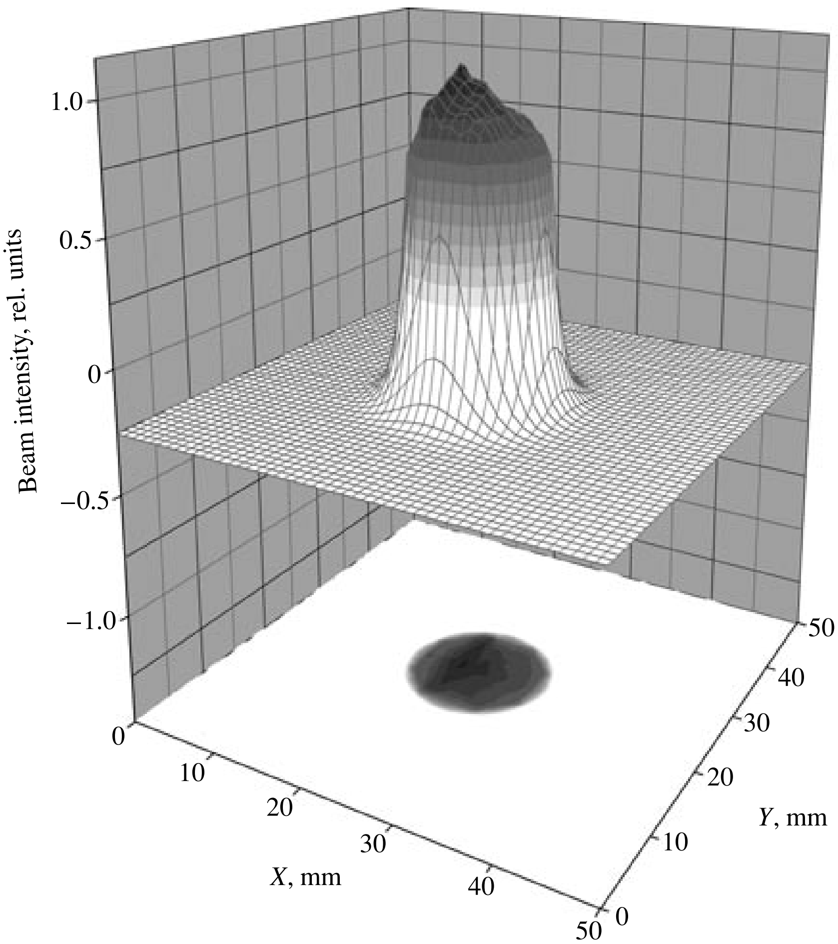


**Fig. 3.** Profile of the atomic hydrogen beam in the second chamber of a polarized source (Jülich, Germany).

the beam intensity reconstruction (4–6% for an instrument containing 32 wires strung with a pitch of 1 mm). The error of absolute beam intensity measurements is considerably higher, since the inaccuracy in determining the coefficient of sticking of atomic hydrogen to the surface is quite great (30–40%) and the dependence of this coefficient on the methods used to apply the coating to and treat the surface of the wire are poorly understood.

## RECONSTRUCTING THE PROFILE OF AN ATOMIC HYDROGEN BEAM

Let $\{R_{a,i}\}_{i=1\dots16}^{a=x,y}$ denote the resistances of the wires in different planes ($x$, $y$) and with different ordinal numbers. The center of the beam can be found easily, which is of great importance in guiding the beam. We define

$$x_0 = \sum_{i=1}^{16} x_i \frac{R_{x,i} - R_{0x,i}}{R_{0x,i}}, \quad y_0 = \sum_{i=1}^{16} y_i \frac{R_{y,i} - R_{0y,i}}{R_{0y,i}},$$

where $\{R_{0a,i}\}_{i=1\dots16}^{a=x,y}$ is the resistance of the respective wire in the absence of an atomic beam.

We cannot eliminate the spread in the wire resistances (it is ~5%); therefore, individual parameters are used for each wire.

The relative beam intensity may be characterized as

$$\Xi = \sum_{a=x,y} \sum_{i=1}^{16} \frac{R_{a,i} - R_{0a,i}}{R_{0a,i}}.$$

The beam size can be estimated by assuming that the beam is cylindrically symmetrical; however, this is not quite so unambiguous and is dependent on the model of the beam [9]. A particular beam model is selected (e.g., a two-dimensional Gaussian distribution) that contains a number of parameters, which must be defined. After specifying the values of these parameters, we calculate the resistances of the wires by searching for a numerical solution to the differential equation [10]. The parameters of the beam model are then varied while minimizing the rms deviation of the theoretical values from the experimental data. Figure 3 presents a reconstructed profile of an atomic hydrogen beam [11].

Our two-dimensional detector for an atomic hydrogen beam has demonstrated both high reliability and stable operation. Above all, it is a convenient instrument for monitoring the intensity and size of a beam in real time without disrupting the beam. A procedure for the manufacture of such detectors and several versions of the data readout electronics have been developed. At present, PC cards and microprocessor-based CAMAC modules are used in the latter.

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