Optical measurement of the ion temperature in a barium $Q$ plasma


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The ion temperature in a single-ended barium $Q$ machine has been determined optically, with and without current drawn through the machine. Ion temperatures which were consistent or slightly higher than the hot-plate temperature of 0.25 eV rose to 5-7 eV when an electron drift was initiated. The ion temperature rose to 1 eV if an ion current was drawn along the column. These phenomena are independent of magnetic field.

In this letter, we report a measurement of the ion temperature in a barium plasma$^{1-3}$ and find some unexpectedly high ion temperatures generated by electron currents through the plasma. The use of optical diagnostics in a plasma is currently of great interest,$^{4,5}$ in part because properties can be measured without perturbing the plasma. Optical diagnostics could be useful in exploring characteristics of various devices such as thermionic converters. The central difficulty in such measurements is the low plasma luminosity which must be collected and processed in the presence of intense background light from the hot plates.

A schematic of the apparatus is shown in Fig. 1. The plasma chamber is a single-ended $Q$ machine with magnetic confining coils. The plasma was generated by spraying barium onto a rhenium hot plate$^4$ (chosen because of its high work function), operating at 3000 $^\circ$K. Plasma density and profiles were determined by measuring ion saturation current to Langmuir probes.$^7,9$ The plasma column was about 2 cm in diameter and 80 cm long. Light was collected through a 1 $\times$ 2-in. port with an effective $f/8.7$ aperture, with a compound lens, and focused on a collimating pinhole of 0.8-mm diameter. For phase-sensitive detection, a chopper of 660-Hz frequency was placed near the pinhole. The barium line of interest was selected by a bandpass interference filter centered at 4554 $\AA$ of 25-$\AA$ width, placed in the light path. A compound collimating lens was placed in front of, and a focusing lens after, the pressure-scanned Fabry-Perot interferometer.$^9$ The Fabry-Perot consisted of a pressure chamber and two flat $\lambda/100$ plates of 2-in. diameter with 0.5-cm Invar spacers loaded with fine-tuning spring adjustments. The
dielectric coatings were 94% reflective at 4554 Å and were selected to give a high transmission and a finesse of about 30. An FW-150 startracker photomultiplier with an internal 0.1-in. aperture was used. The focal length of the focusing lens was chosen so that the diameter of the first fringe of the Fabry-Perot matched the 0.1-in. aperture (this was done by taking Polaroid pictures of the fringe pattern with the barium reference lamp as a source). Adjustment of the position of the central fringe on the phototube was achieved by lateral and vertical motion of the focusing lens mounted on a microscope stage.

The ion temperature was determined by measuring the Doppler broadening of the barium ion D_2 line at 4554.03 Å. The D_2 line arises from the 6^2P_3/2-6^2S_1/2 transition, which is Zeeman split by the confining magnetic field into two π lines and four σ lines. The σ lines were eliminated by a Polaroid filter in front of the phototube. Because of the high ion temperature, the splitting of the π lines, given by Δλ = 3.23 × 10^{-9} B (Δλ in Å, B in G), was not resolved in the 2- to 7-KG field. A correction for the π-line splitting was made by simple incoherent addition of the two displaced Gaussians. No correction for Stark and pressure broadening was necessary at the plasma densities, <3×10^{10} cm^{-3}, used.

Correction for instrumental distortion was made by calibrating the transmission function of the Fabry-Perot using a single-mode argon ion laser at 4880 Å, locked in a single mode with the use of an etalon. The beam was split, some entering a Tropel confocal Fabry-Perot interferometer with a free spectral range (FSR) of 0.06 Å and a finesse of 30. This interferometer was piezoelectrically swept at 2×10^4 sec/FSR, and its detector output was monitored on an oscilloscope to ensure that the etalon did not become misaligned. The measured transmission function was a Voigt function, closely approximated by Lorentzian within the experimental error. The Lorentzian fullwidth at half-maximum was 0.0126 Å. The result of a convolution of the Lorentzian transmission function and the Gaussian Doppler-broadened spectral line is a Voigt function. Tables by van de Hulst and Reesnick were used for deconvolution.

These first measurements were taken with the confocal Fabry-Perot mentioned above. The original mirror coating yielded a finesse of 40; the mirrors were subsequently recoated at a lower reflectivity (F=30) to increase the transmission. The small mirrors and geometry of this instrument limited its light-collection capabilities so that no data could be taken when current was not drawn along the plasma column. With voltages in excess of 100 V along the column, data could be taken. The instrumental output was always dc; this implied that the ion temperature was in excess of 2 V and led us to construct a flat-plate Fabry-Perot with a larger FSR.

Throughout the course of the measurements, a Ba-Ne hollow cathode lamp (with a known linewidth of 0.02 Å) which could be focused into the center of the plasma column was employed. It was periodically turned on and its line plotted to ensure that the system was in alignment and to locate the system base line. The base line could also be measured by turning off the plasma and measuring background light from the hot plate. The electrical detection system was quite stable and did not drift.

Error bars were determined by plotting a spectral line from several to 10 times for fixed plasma conditions. The standard deviation was determined from the temperatures calculated and also by superposition of the data.

Figure 2 shows the ion temperature as a function of voltage across the plasma column. The hot plate and chamber walls were at ground potential, and the collector disk was biased positive or negative. The magnetic confining field was 2888 G, the background pressure was 7×10^{-8} Torr, the plasma density was 1.3×10^{10} cm^{-3}, and the hot-plate temperature was 2900 K. The numbers near the data points indicate the current collected in mA, where positive current indicates electron current. With zero current, the ion temperature was measured to be \frac{3}{2} + \frac{1}{4} eV, consistent with a hot-plate temperature of \frac{1}{4} eV, as might be expected. When electron current was drawn, the ion temperature increased to more than 7 eV and then dropped slightly. This was the highest temperature recorded, and more usually we

FIG. 2. Ion temperature in eV as a function of collector-disk bias. Collected current is designated near several data points; negative values indicate ion collection.

FIG. 3. Ion temperature in eV as a function of collector-disk bias for three magnetic fields. Dots indicate B = 2888 G; dashed line, B = 4620 G; and solid line, B = 3764 G.
found 5- or 6-eV temperatures. At a bias voltage of approximately +150 V, the plasma became turbulent with the electron temperature going through a maximum (0.5 eV). With negative bias drawing ion currents, the ion temperature increased only slightly to about 1.5 eV.

Since the ion temperature was elevated only in the case of electron drift through the machine, we suspect a two-stream instability to be the heating mechanism. Waves in the center of the column at frequencies above typical drift-wave values were observed (this will be discussed in a forthcoming paper). The Buneman instability, triggered when the electron drift velocity is greater than 0.926V_{th} for Ba, has a large growth rate and grows in proportion to the electron plasma frequency. This instability cannot heat the ions for small ion drifts (ion collection) or no relative drift.

To investigate the effect of neutral collisions, xenon gas at a pressure of 3×10^{-4} Torr was added to the barium plasma. The dashed curve in Fig. 2 shows the barium ion temperature to be lowered, which is consistent with cooling due to elastic collisions.

An attempt was made to investigate a possible magnetic field dependence of the ion temperature. In Fig. 3, we show the results at three magnetic fields (2888, 3754, and 4620 G), as a function of bias voltage. The hot-plate temperature was 2900 K, and the plasma density was approximately 2.5×10^{10} cm^{-3} (this is somewhat magnetic field dependent). No systematic variation with magnetic field was observed, and we conclude that the ion temperature is independent of magnetic field, within the experimental error and the limited regime of fields investigated.

This is the first instance in which large ion temperatures are reported in a single-ended barium Q machine with drifting electrons. The diagnostics and experimental conditions are ideal for the study of anomalous plasma resistivity due to wave-particle interactions.

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**Subnanosecond pyroelectric detector**

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We have designed and tested a 500-ps rise-time pyroelectric detector. The responsivity is great enough to drive a Tektronix 519 oscilloscope when amplified with a 1.0-GHz bandwidth amplifier. To obtain this spectral response, we have developed a thermally fast-absorbing black which has approximately 50% absorption from 0.3 μm to greater than 50 μm, and transfers 90% of the absorbed energy to the pyroelectric crystal in 400 ps. The maximum detector output voltage prior to amplification is 2.2 V, limited by the absorbing black's burn intensity.

With the increasing use of mode-locked CO₂ lasers at 10.6-μm radiation, there is a need for a detector which can resolve the signal pulse shape. Since pyroelectric detectors have a potential frequency response of greater than 1010 Hz, actually limited only by the amplifier and oscilloscope bandwidth, they can make a significant contribution to the solution of this detection problem. Recently, Abrams and Wood used a pyroelectric detector to observe mode-locked TEA CO₂ pulses with a 2-nsec pulse width.

We have designed and tested a room-temperature LiTaO₃ pyroelectric detector matched to a 50-Ω input-impedance 1.0-GHz-bandwidth amplifier. The detector RC response time is 300 pcs, and the amplifier output is adequate to drive a Tektronix 519 fast-rise-time oscilloscope. Figure 1(a) shows 519 oscilloscope traces of a silicon diode and pyroelectric detector monitoring the output of a Q-switched mode-locked Nd:YAG laser at 1.06 μm. The top trace is the output of an HPA 4203 silicon photodiode applied directly to the 519 input. The pyroelectric detector output in the bottom trace is followed by an Avantek 1000T amplifier with 25-dB gain and 100- to 1000-MHz bandwidth. The pyroelectric signal is the pulse slightly delayed behind the diode pulse and is followed by reflections in the amplifier which appear at the leading edge of the diode pulse. Figure 1(a) shows that the pyroelectric signal is faster than the photodiode and has an approximately 500-ps 10–90% rise time. The measured responsivity in the lower trace of Fig. 1(a) is about 25% of the calculated value, with large uncertainties in the power of the laser pulse. Figure 1(b) shows the output of the pyroelectric detector monitoring a mode-locked TEA CO₂ laser at 10.6-μm