Comparison of Gridded Energy Analyzer and Laser Induced Fluorescence Measurements of a Two-Component Ion Distribution

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Abstract

One of the challenges in interpreting energy analyzer measurements of ion populations is the removal of the effects of the potential step between the plasma and the probe. We present on-axis distribution (bunch) measurements obtained with a cold and relativistic field energy analyzer (RFEA) and ion measurements obtained with laser-induced fluorescence (LIF) for an expanding helium plasmas. When the RFEA measurements are corrected for acceleration due to the electric potential difference across the plasma sheath, we find that the RFEA measurements indicate a smaller background ion beam density and a much larger parallel ion temperature than the LIF. The energy of the ion beam is the same in both measurements. These results suggest that ion heating occurs during the transit of the background ions through the sheath and the LIF cannot detect the fraction of the ion beam whose temperature has been elevated by collisions.

RFEA Theory and Analysis

The principle operation of a retarding field analyzer is to select or reject either positive ions or negative electrons from the plasma using electrostatic fields. These fields are created by applying variable voltages between parallel plates. To compensate for the retarding fields on collector A flat plate and measured as a current. An expression that describes the retarding field is increased current decreases until all of the particles are rejected. The derivative of the retarding potential (also called the accelerating voltage) is usually determined from the particle energy distribution and used by the voltage difference between the front grid of the RFEA and the plasma, i.e., the plasma potential. This expression is not entirely correct as both drifts of particles lead to an increased width of the distribution as measured in energy space. For a drifting Maxwellian ion population, the measured current as a function of retarding voltage, I, is given by

\[ I(V) = \frac{n_e}{2m_e} \left( \frac{2m_e}{e} \right)^{1/2} \left( \frac{1}{\varepsilon_0} \right)^{3/2} \left( \frac{k_B T_e}{m_e} \right)^{1/2} \left( \frac{\left(\frac{k_B T_e}{m_e}\right)/e - V}{\left(\frac{k_B T_e}{m_e}\right)/e} \right)^{3/2} \]

where \( n_e \) is the beam density, \( E_b \) is the beam drift energy, and \( T_{e,0} \) is the beam temperature.

Comparison of Derivative and Fitting Methods to Obtain IEDF/IVDF

The derivative of the expression, often described as the ‘energy distribution function’ when applied to experimental measurements is given by

\[ \frac{dI(V)}{dV} = -\frac{n_e}{4\pi^2 m_e} \left( \frac{2m_e}{e} \right)^{1/2} \left( \frac{1}{\varepsilon_0} \right)^{3/2} \left( \frac{k_B T_e}{m_e} \right)^{1/2} \left( \frac{\left(\frac{k_B T_e}{m_e}\right)/e - V}{\left(\frac{k_B T_e}{m_e}\right)/e} \right)^{3/2} \]

Note that the distribution width depends strongly on the beam energy and does not represent the true temperature of the ion distribution.

Experimental Geometry

Stable Double Layer Occurs at Higher RF Frequencies

The measured collector current is well fit by a two-population pair of Maxwellian distributions, as described by the expression above. The fit yields a plasma potential of 0.5 V and a total ion energy (after accelerated through the plasma) of 6.3 eV. The two populations are nearly equal in magnitude and have very low ion temperature.

The total ion distribution (shown in green) matches the measured collector current very well. The relative amplitudes of the two populations given by the fit result is quite different than what was indicated by the simplistic derivative method.

Comparison of RFEA IVDF and LIF IVDF Measurements

Both the ‘derivative’ and ‘beam-fitting’ analysis methods show above ion key aspects of the RFEA measurement process. First, the acceleration of a drifting Maxwellian population is spatially uniform across the drift (as shown in front of the plasma). Second, the ion temperature is higher than what would be calculated by the observed drift velocity in the plasma. The expression below describes the expected current for two-drifting Maxwellian populations (a ‘plasma’ and a ‘beam’) that have been accelerated into the RFEA by the plasma potential between the RFEA and the plasma. Note that only the half of the plasma that best fits the data is shown in the RFEA.

The best fit of the above expression to the RFEA measurement is shown in the top figure at the right. The two-ion populations that are obtained have high ion temperatures (as indicated by the fit) in contrast to LIF measurements obtained at a similar axial location in USA. Note how the analysis method dramatically reduces the amplitude of the ion population. A result of greatly accounting for the greater impact on measured current as an ion beam. The higher temperature background population obtained from the RFEA measurements suggests that the ions are heated in the RFEA as they fall into the RFEA probe.

Summary:

- For all plasma cases shown to produce an ion beam in laser-induced fluorescence (LIF) measurements, RFEA measurements confirm the presence of an ion beam population in the expansion region of HELIX.
- Conventional RFEA theory and analysis has been modified to include the effects of the additional accelerations in the RFEA probe sheath of a drifting Maxwellian population. The new model accounts for the velocity-space ‘compensation’ and results from acceleration in the sheath and the reflection of only half of the background, mostly stationary, ion plasma.
- One surprising result was the observation that the double layer is more stable and produces "cleaner" ion beams when the source is operated at higher RF driving frequencies.

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