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M. Takeshi Nakata, Grant W. Hart, and Bryan G. Peterson

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Using the Plasma Noise Spectrum to Measure the Parallel Temperature in a Nonneutral Plasma

M. Takeshi Nakata, Grant W. Hart, Bryan G. Peterson

Department of Physics and Astronomy
Brigham Young University
Provo, UT 84602 USA

Abstract. A simple, non-destructive diagnostic for the temperature of a non-neutral plasma is desirable as plasma lifetimes increase and the confined species become more exotic. If the confinement system includes an isolated wall sector, the motion of the charges beneath that sector will result in a noise signal that can be directly related to the velocity distribution of the confined particles. Care must be taken to differentiate the resulting plasma signal from the instrumental noise spectrum and the strong signals from plasma oscillation modes. The theoretical basis of the relationship between the noise spectrum and the temperature as well as experimental results are presented.

INTRODUCTION

A simple, non-destructive parallel temperature diagnostic is desirable as plasma lifetimes increases and the confined species become more exotic. Thus, we have develop a way to use the plasma noise spectrum from a isolated wall sector to measure the parallel temperature of the plasma.

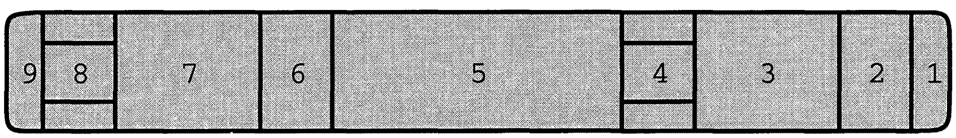

FIGURE 1. Schematic of our Malmberg-Penning Trap with ring numbers

To measure the plasma noise spectrum of a plasma, we use an isolated wall sector commonly find in a Malmberg-Penning Trap. Fig. 1 illustrates how our Malmberg-Penning Trap is configured. In this trap, Rings 1 and 9 are used to confine our electron plasma. This trap operates in the normal fill-prepare-experiment-dump cycle.

Typical parameters for this trap are the electron density $n \sim 10^7 cm^{-3}$, confining potential of $\phi_c \sim -150$ V, an axial magnetic field of $B_z \sim 700$ G, an electron thermal energy of $kT \sim 1$ eV, and an average axial transit time of about $\sim 1.5 \mu s$. [1]

Our noise spectrum diagnostic basically consists of a wall sector in this trap, a charge sensitive pre-amp, and a spectrum analyzer.

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NOISE SPECTRUM THEORY

The basis of this diagnostic is that the motion of the charges beneath the wall sector induces a noise signal that is directly related to the velocity distribution of the confined particles.

To better understand this signal, we developed a simulation to study the plasma noise spectrum. This simulation calculates the induced charge on a wall sector by the particles using the solution for a cylindrical green function. We also assumed in our simulation that these particles were not interacting with each other and that we had hard walls as the confining potentials.

To better understand this signal, we began by looking at what one electron does under a wall sector. As an electron passes underneath the wall sector, it induces a charge in that sector, as a function of time. This signal is measured as a pulse in our detector.

The amplitude of the pulse is related to the charge that is induced on the wall sector by the electron. This amplitude does not change with velocity.

In contrast, the width of this pulse is a function of velocity of the electron under the wall sector. As the velocity of the electron under the sector increases, the width of the pulse decreases.

By Fourier transforming this signal, we find that the frequency spectrum is also a function of velocity of the electron. As the velocity of the electron increases, it lowers the transit time of the electron under the wall sector, which translates to higher frequencies in the corresponding spectrum.

For a collection of electrons in our plasma, the revelant velocity is the thermal velocity of the electrons, which is related to the temperature of the plasma in the direction parallel to the confining magnetic field.

$$v_{th} = \sqrt{\frac{2k_B T}{m_e}} \propto l_{ring} f$$

Thus, the frequency is proportional to the square root of the parallel temperature $\sqrt{T_{\parallel}}$.

Fig. 2 illustrates how the plasma noise spectrum varies with the temperature. As temperature increases, the width of the spectrum correspondingly increases. This also show how our most temperature sensitive region is between 1 to 3 MHz when we use ring 5 as an detector .

The amplitude of this spectrum is also influenced by both the parallel temperature and number of particles in the plasma. As the parallel temperature increases, the amplitude at $f = 0$ Hz goes as $\sim T^{-\frac{1}{4}}$. As the number of particles increases, the amplitude increases as $\sqrt{N}$.

The $\sqrt{N}$ scaling demonstrates how each electron contributes in an incoherent manner to the induced charge. In consequence, while the time domain signal is incoherent, the frequency domain signal adds up as $\sqrt{N}$.

This signal is just the shot noise of the plasma current passing beneath the wall sector. It is the fluctuations on top of the overall charge signal in the time domain. Thus, by examining the frequency spectrum of this signal, one can determine the parallel velocity distribution and therefore the parallel temperature of the electron plasma. Typical times

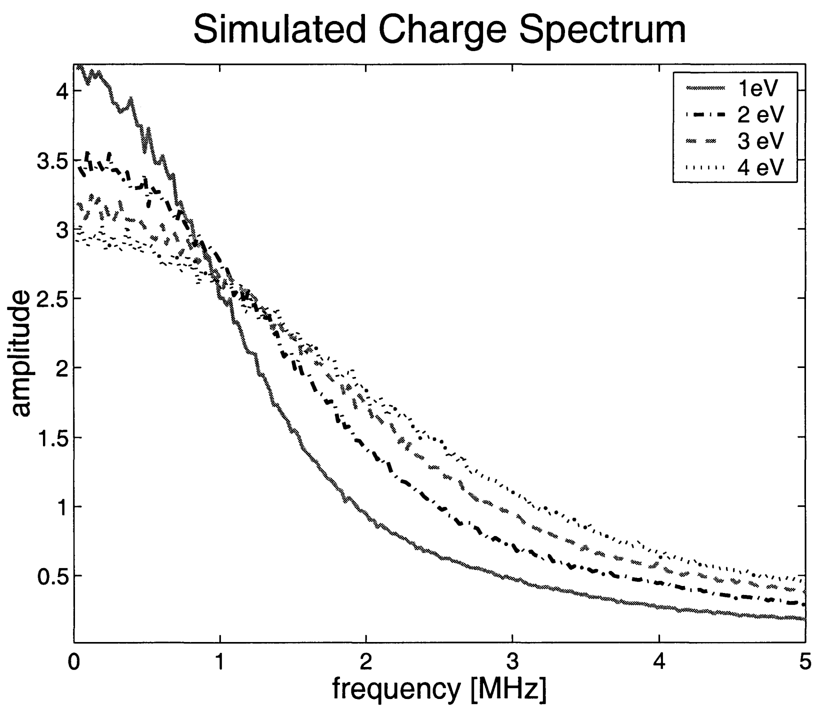

FIGURE 2. Simulated Spectrum for a plasma passing through 20cm ring. Amplitudes has been normalized.

for an electron in a 1 eV plasma under a ring of 20 cm is $\sim 0.5\mu s$ which implies a typical frequency of $\sim$2 MHz.

NOISE TEMPERATURE DIAGNOSTIC

Acquisition of the Spectrum

In our experiment, we used an isolated wall sector on this trap to measure the noise spectrum of the plasma. We used the center wall sector on our trap (Ring 5 in Fig. 1) because it is insensitive to the $n_z = 1$ normal mode which usually is found in our temperature sensitive range of 1 to 3 MHz for our plasma parameters.

This signal is first amplified by an Amp Tek A250 charge sensitive amplifier. This amplifier is AC coupled and configured to produce a signal proportional to the charge on the wall sector. We are careful not to saturate this amplifier by using an optically coupled JFET transistor to ground the input when the plasma is filled and dumped.

Since our plasma noise spectrum is a broad spectrum and is small compared to other electromagnetic oscillations found in the environment, a swept spectrum analyzer was chosen to be used in the acquisition of our noise spectrum. To obtain the plasma noise spectrum, we acquire both the spectrum with plasma and the spectrum without plasma under the wall sector and subtract the two.

The spectrum analyzer is limited by its sweep time. Our plasma evolves during the sweep time of about 20 ms. To get better time resolution we set our spectrum analyzer to zero span to acquire our noise spectrum. At this setting, the spectrum analyzer looks at one frequency and records the amplitude as a function of time. In effect, this gives us the best frequency resolution possible for a given amount of sweeping time.

However, one of the drawbacks to this method is that we need to take a new shot (plasma) for each frequency. We also average 5 traces to account for shot-to-shot variability. In consequence of using this method, our acquisition of the spectrum becomes a long process and not a short process as we had hoped for.

Postprocessing

Using this method, we can obtain how the plasma noise spectrum evolves with time. Thus, our data set is of time, frequency, and amplitude. Of course in postprocessing this data, we take one spectrum for one time.

Our first step in this postprocessing is to subtract the spectrum with plasma from the spectrum without plasma. Next, we take into account the frequency response of the charge sensitive amplifier by normalizing our spectrum from the measured frequency response.

Finally, we fit our data to our simulated spectrum. To do this, we first eliminate frequency bands which have the mode frequencies and then use a nonlinear least squares algorithm to fit to the simulation. In this algorithm, the amplitude and the width of the simulated spectrum is used as adjustable parameters to fit to the data spectrum.

In the end, we use the standard evaporation method [2] by slowly dumping ($\sim$1 ms) the plasma to find how the temperature of the plasma changes with time for comparison to the noise temperature technique.

RESULTS

Fig. 3 illustrates some typical data from our spectrum analyzer. This data was taken with the peaks of the mode frequencies truncated. This figure demonstrates that there is a plasma noise spectrum that is similar to our simulation. The 'x' data points is the spectrum that was use to fit to our simulated curve, the solid dark gray line. We eliminated the shaded frequencies band from the raw spectrum, the dash line curve to obtain this spectrum.

In Fig. 4, both fitting parameters are plotted as a function of time. These parameters are the amplitude^2 and temperature of the spectrum.

The amplitude^2 plot shows how fitting amplitude A is proportional to square-root of number of particles $\sqrt{N}$ as we expected from our simulation. The normalized number of

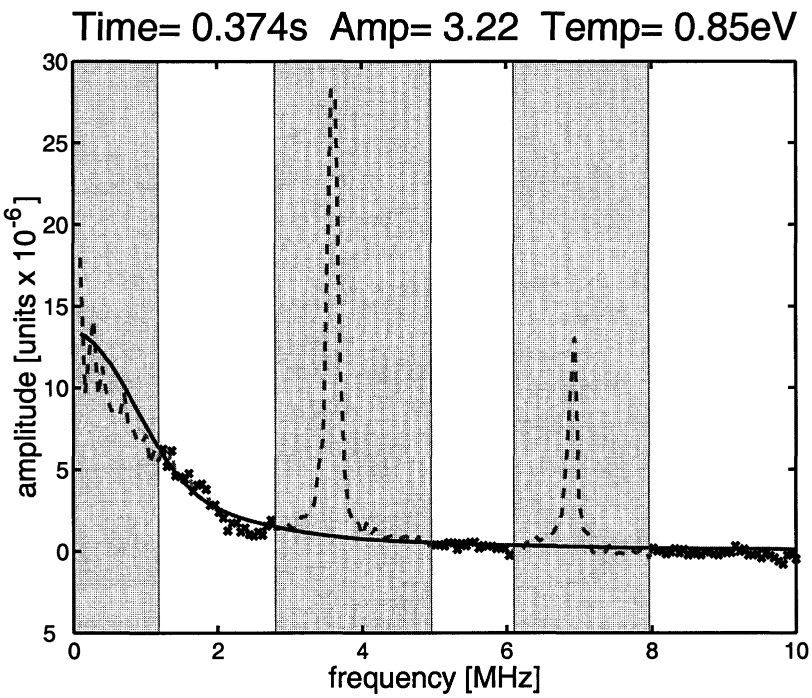

FIGURE 3. 5 Oct 2000, #1 - Relative Amplitude vs. Frequency

particles is normalized in the following way:

$$A^2 \times \frac{<\overline{N}>}{<\overline{A}^2>}$$

where A is the fitting amplitude and N is the number of particles. The number of particles N is calculated from by integrating radial density profiles.

The temperature plot illustrates that the noise spectrum method does generally follow the evaporation method until later times past 0.40 s. After 0.40 s, the evaporation method deviates from the noise spectrum method. This illustrates how the evaporation method is sensitive the central temperature of the plasma and the noise spectrum is sensitive to the radially averaged temperature of the plasma. After 0.40 s, plasma expansion heats the outer regions of the plasma.

Another thing to notice from these plots is the fact that both of these parameters correlate to each other. As the amplitude^2 is farther away from the normalized number of particles N like around 0.28 s, the noise diagnostic method is farther away from the evaporation method.

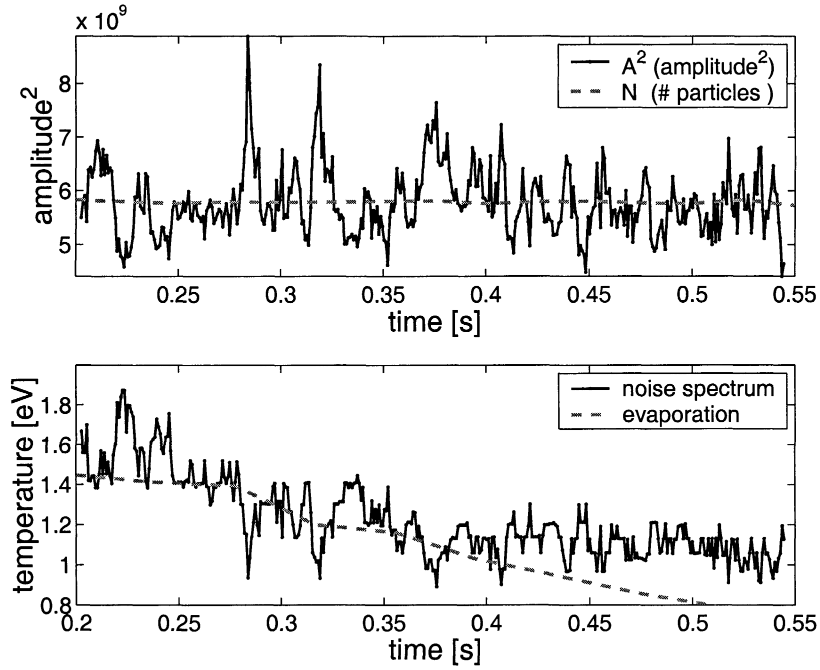

FIGURE 4. 5 Oct 2000, #1 - Fitting Parameters

CONCLUSION

In conclusion, we found out that the plasma noise spectrum can be used as a temperature diagnostic as long as we have a good signal to noise ratio and are clear from plasma modes in the 1 to 3 MHz range. We find that this method is not as practical as we had hope for because plasma modes usually dominate in that range where our sensitivity to temperature is most significant. It also takes some time to obtain this measurement. However, we did find that we can get the radially averaged temperature of a nonneutral plasma by the using plasma noise spectrum.

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