Final Progress Report for Ionospheric Dusty Plasma In the Laboratory [Smokey Plasma] DE-FG02-06ER54896 for the period 1 August 2006 – 31 July 2010

"Ionospheric Dusty Plasma in the Laboratory" is a research project with the purpose of finding and reproducing the characteristics of plasma in the polar mesosphere that is unusually cold (down to 140 K) and contains nanometer-sized dust particles. This final progress report summarizes results from four years of effort that include a final year with a no-cost extension.

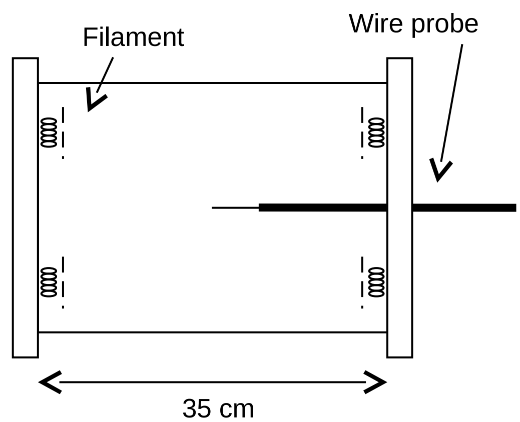
The first two years of the project were aimed at understanding the effect of nanometer-sized dust particles. The third and fourth years concentrated on reproducing in the laboratory the low temperatures of the ionospheric plasma. We recently reported in Physics of Plasmas in 2009 the creation of electron temperatures down to 360 K. The experiment was reconstructed to have a liner cooled by liquid nitrogen in late 2009 and the electron temperature was further reduced to 200 K, also reported in Physics of Plasmas. These are the lowest temperatures (to our knowledge) that have been reported for a steady-state plasma.

The research has resulted in six publications which are summarized in Sec. II below. The most notable experimental results (in publication 6) were the creation of the coldest continuous gas discharge plasma, with electron temperatures down to 200 K and ion temperatures down to 80 K. The most notable theoretical results (publication 3) were that the collection of electrons and ions by nanometer-sized dust particles is significantly enhanced by the inclusion of the induced-dipole force, which increases the rate of electron and ion collection by dust particles.

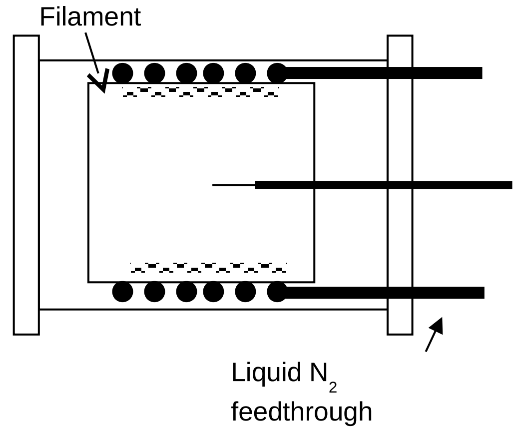
I. Research activity summary

The polar ionosphere is the region with the coldest temperatures on earth. The temperature of the ionosphere near 80 km altitude is in the range 140 – 200 Kelvins. The electrons and ions from photoionization rapidly thermalize with the neutral gas and thus the ion temperature T_i is equal to the electron temperature T_e. In most laboratory plasmas, $T_e >> T_i$ and T_e is of the order of 1 eV or 11,600 K.

The main research project in 2008 was the creation of plasma with an electron temperature of 360 K. Our plasma is now the coldest DC plasma in the literature and may be the only laboratory plasma with $T_e \approx T_i$. Colder plasmas have only been observed in the decay phase of recombining plasmas, which are difficult to diagnose due to the rapidly changing conditions. The very cold plasma was created in the hot-filament discharge device used in much of our earlier research. The device is an aluminum chamber 30 cm in diameter and 35 cm long in which four emissive filaments are used to create plasma by electron impact ionization.



Device in which the 360 K plasma was created.



Device in which the 200 Kplasma was created.

Electron temperatures down to 360 K were created in 2008 by minimizing two sources of heating. First, the primary electrons from the filaments can slow and enter the plasma. By increasing the filament bias voltage to 80 V, the energy of these primary electrons was increased so that after ionizing neutral atoms they are still sufficiently energetic that they are not confined by the plasma potential and instead go to the wall. Second, the wall was coated with colloidal graphite which has a low secondary emission coefficient. We had previously shown that these secondary electrons also caused plasma heating. The lowest temperature obtained with density > 10^8 cm^{-3} was 0.032 eV (371 K) determined by the Langmuir probe characteristic. For this plasma the Debye length is 0.13 mm, the number of electrons in a Debye sphere is 940, and the strong coupling parameter $\Gamma = 0.009$. The electron-electron collision frequency is 9.4 x 10^5 s^{-1} which when multiplied by the average electron speed gives an electron-electron mean free path of 12.5 cm which is comparable to the radius of the vacuum chamber.

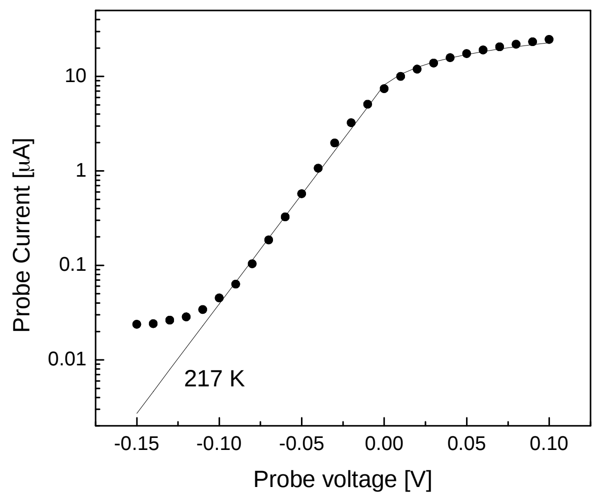
The electron temperature was further lowered in an experiment operated in the no-cost extension period (August, 2009 – July, 2010). The new experiment, shown above, contains an inner liner that is cooled by liquid nitrogen. Liner temperatures down to 140 K were recorded. Following a suggestion by Dr. Arthur Phelps, we changed the working gas to carbon monoxide. This molecule is asymmetric, which results in a dipole moment that gives a larger electron-molecule collision cross section. As a result, the electrons are cooled more effectively by carbon monoxide than by noble gases (no moments) or homonuclear molecules (N_2, O_2, etc.) which have a quadrupole moment but no dipole moment.

The table below shows the electron temperatures recorded with four working gases: CO, N_2, He, and Ar. Data are shown with the walls near room temperature (310 K) and with the walls cooled by liquid nitrogen (140 K). The electron temperatures are as low as 0.021 eV with CO but are no lower than 0.044 eV with the other gases.

TABLE I. Electron temperatures and densities from Langmuir probe data for different gases with wall temperatures 140 K and 310 K.

	310±10 K data		140±10 K data	
Gas	T_e [eV]	n [cm^{-3}]	T_e [eV]	n [cm^{-3}]
CO	0.038	1.79x10^8	0.021	3.98 x 10^8
N_2	0.040	1.55x10^8	0.044	2.54x10^8
He	0.039	0.99x10^8	0.062	1.37x10^8
Ar	0.057	2.95x10^8	0.110	2.79x10^8

The figure at right shows a Langmuir probe trace taken with cooled walls and CO as the working gas. The exponential part of the curve indicates an electron temperature of 217 K or 0.019 eV. This trace is unique in that the entire sweep occupies a voltage range of only 0.25 volts.



Our plasma in the cooled liner is also unusual in that the mean free path for electron-electron collisions and electron-ion collisions (~1.9 cm) is much smaller than the dimensions of the device and smaller than the mean free path for electron-neutral collisions. (The cross section for momentum exchange in electron-CO collisions is about 6 x 10^{-16} cm^2 at 20 meV giving a mean free path of about 30 cm.) For the plasma conditions giving the 217 K electron temperature shown above, λ_D = 4.7 x 10^{-3} cm, λ_L = 7.6 x 10^{-6} cm, λ_D / λ_L = 625, and ln(Λ) = 6.4. Deviation from the standard theory for Coulomb collisions is expected for λ_D/λ_L less than about 3. Electron-ion collision frequencies are more easily measured in continuous plasma than in transient plasma, and our experimental arrangement lends itself to measurement of collision frequencies by the microwave cavity method. The recombination rate is easily measured by removing the filament bias voltage and observing the rate of density decay if recombination losses exceed particle losses to the walls. Hence the hot-filament discharge in cryogenic gas offers a route to investigate Coulomb collisions and recombination in low-temperature plasma that approaches the limit of strong coupling.

A new version of this experiment has been constructed which will allow measurement of the electron-ion collision frequency using a microwave method in which a sweep oscillator is used to find the Q of the cavity containing the plasma.

II. Publications:

1. "Smoky Plasma,"
Scott Robertson, IEEE Trans. on Plasma Science 35(2), pp. 314-322, April 2007. This paper enumerates the physical processes that occur in plasma containing nanometer-sized dust particles and finds the relative magnitudes of gravitational, collisional drag, and electrostatic forces.

2. "Analysis of electron and ion fluxes to the wall of a hot –filament discharge device," X. Wang, S. Knappmiller, S. Robertson and Z. Sternovsky, Physics of Plasmas 14, 043503, April 2007 (9 pages). In order to create a plasma as cold as the ionosphere, it is necessary to understand the energy balance of the plasma. In this experimental work, the flux of electrons and ions to the wall was found using a gridded analyzer placed beyond a slit in the wall. The data was shown to support a theoretical model for electron temperature in which the bulk of the electrons is heated by collisions with secondary electrons from the wall and electrons from ionization of the neutral gas.

3. "Effect of the induced-dipole force on the charging of aerosol particles,"
Scott Robertson and Zoltan Sternovsky, Physics of Plasmas 15, 040702, 2008 (4 pages). This theoretical paper shows that the induced-dipole force is significant for nanometer-sized particles and cannot be ignored in calculating the rate at which small particles are charged by electrons or ions.

4, "A hot filament discharge with very low electron temperature," Ward Handley and Scott Robertson, Physics of Plasmas (Letters) 16, 010702 (2009), This experimental paper shows that electron temperatures down to 360 K can be obtained in the lab if secondary electrons from the wall are suppressed.

5. "Reformulation of Laframboise' Probe Theory in Cylindrical Geometry and the Absence of an Ion Saturation Current," Scott Robertson, IEEE Transaction on Plasma Science 38(4), p. 781-787, April 2010. This numerical work shows that the concept of "ion saturation current" is misleading and should not be used in the interpretation of probe data.

6. "Continuous gas discharge plasma with 200 K electron temperature," S. Dickson and S. Robertson, Physics of Plasmas 17, 033508, (5 pages) 2010. This experimental paper showed that electron temperatures down to 200 K could be obtained in a vacuum chamber with walls cooled by liquid nitrogen and with carbon monoxide as the working gas.

Papers in progress:

A large-volume plasma device with 200K electron temperature, S. Dickson, D. Konecny, and S. Robertson, in preparation. This paper is to contain the first measurement of collision frequency in continuous plasma below room temperature.

A magnetized plasma with very low electron temperature, Devin Konecny, Shannon Dickson, and Scott Robertson, in preparation. The experimental results with cooled plasmas are extended to magnetized plasma.

III. Student training

The research has employed several students at the graduate and undergraduate level. A strong emphasis has been placed on having undergraduates being first-authors or co-authors of refereed publications (see Sec. II above).

1. Ward Handley, an undergraduate physics major, was employed in the laboratory part-time during the semesters and full time in two summers. Ward constructed a UV photoionization apparatus and performed experiments on photoionization. Ward also operated the hot-filament discharge device, developed computer codes for data analysis, and performed experiments to create the coldest DC plasma. His research appeared in 2009 as a Letter in Physics of Plasmas. Ward has pursued a career in teaching at the middle school level and has indicated that he may return to the university.

2. Cody Weber, who worked on the experiment in the construction phase and created the first nanometer particles in plasma, obtained a M.S. in Engineering Physics in 2007 and now works at Electro Magnetic Applications in Denver, Colorado.

3. Shannon Dickson, a senior in Engineering Physics, constructed and operated the cold plasma experiment with the liquid nitrogen cooled wall. Her work, published in Physics of Plasmas in 2010, was also an Honors thesis for which she will be graduated in Spring 2011 summa cum laude, the highest Latin honors.

4. Devin Konecny, a senior in Physics, constructed a magnetized version of the cold plasma experiment and shown that electron temperatures below room temperature can be obtained with a magnetized plasma column. This work is being prepared for publication.

Scott Robertson

Principal Investigator

28 September, 2010.