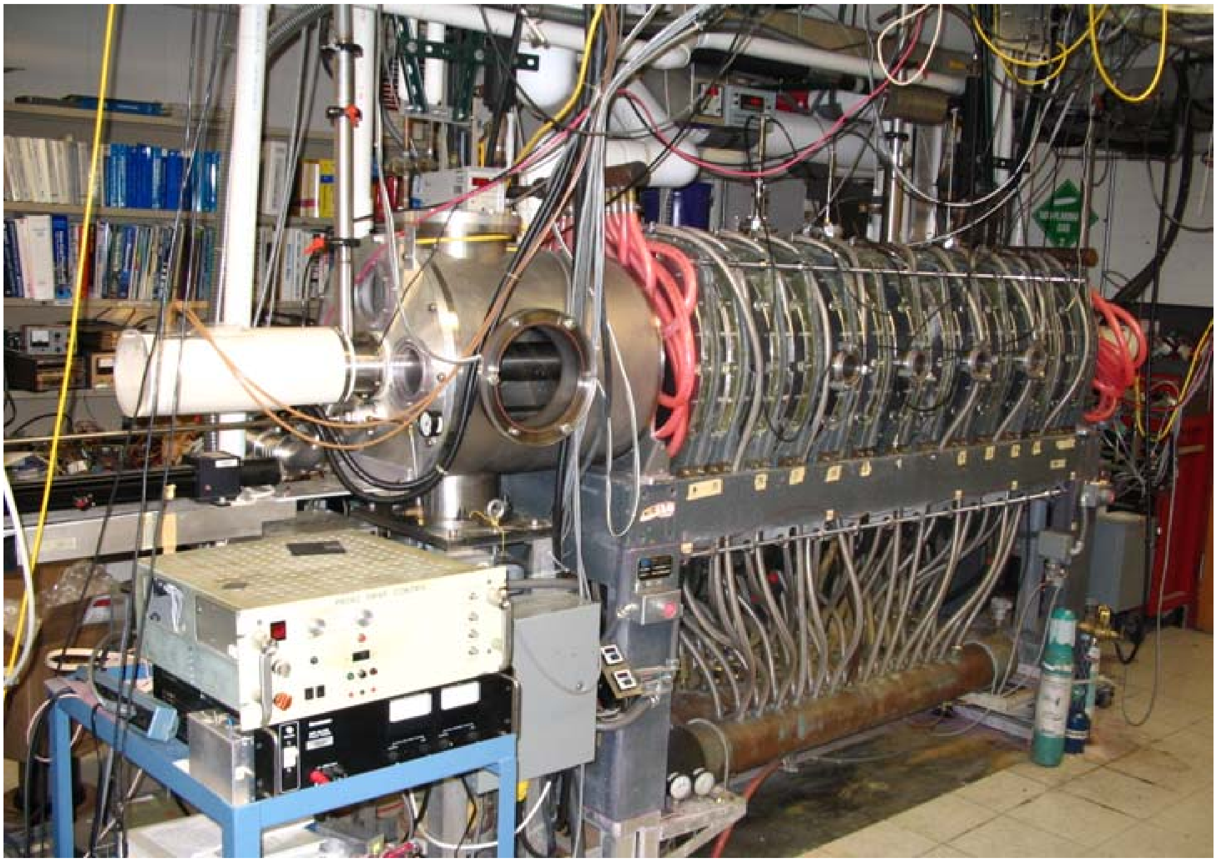
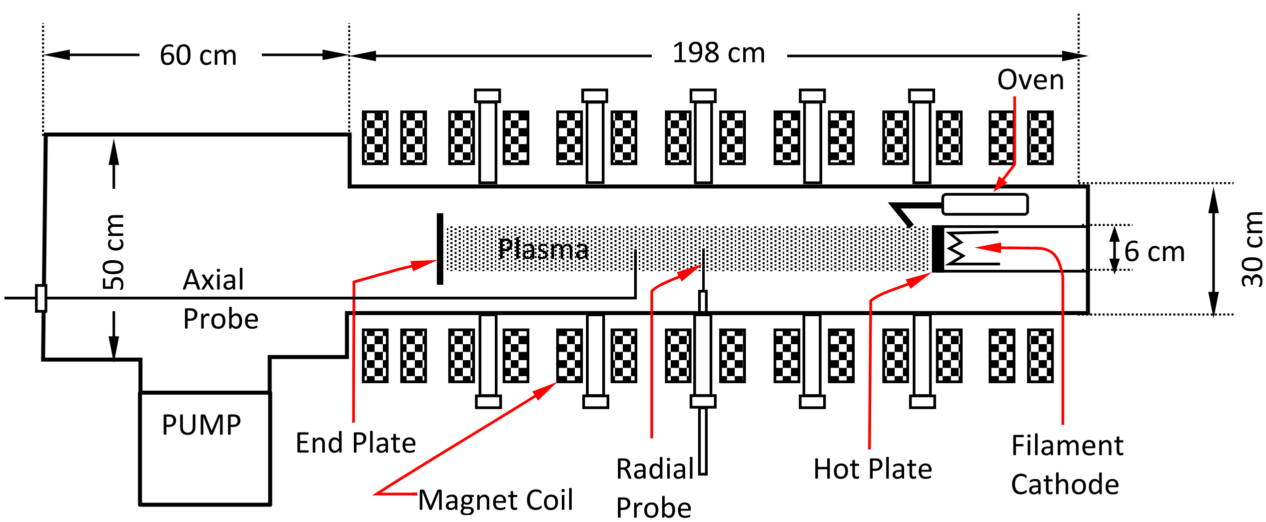
The Q - Machine





THE Q-MACHINE

1. GENERAL CHARACTERISTICS OF A Q-MACHINE

A Q-machine is a device for producing a magnetized plasma. The “Q” in Q-machine stands for “quiescent” because the plasma that is created has a relatively low level of intrinsic electrical noise. This makes the Q –machine an ideal device in which to study plasma waves. The Q-machine produces a cylindrical plasma column that is confined radially by a strong axial magnetic field typically up to a few kilogauss. The plasma is terminated on an end plate that is electrically floating. Both the ions and the electrons in the plasma are magnetized which means that the radius of the plasma column is much larger than the gyroradii of the electrons and the ions. The Q-machine produces a relatively “cold” plasma, with nearly equal temperatures of the ions and electrons at 0.2 eV (~ 2300 K). Since the ion mass is much larger than the electron mass, the gyroradius of the ions is much larger than the gyroradius of the electrons, but still much smaller than the radius of the plasma column. The plasma is “quasineutral” meaning that the electron and ion densities are very nearly equal. This is a general property of all plasmas – electrical neutrality. The plasma density depends on operating conditions, but is typically in the range of 10^{13} to 10^{16} per cubic meter. Because the plasma densities are relatively low, collisions between the charged particles are rare, and we say that the plasma is “collisionless”. The plasma is also nearly fully ionized meaning that the density of neutral atoms in the plasma is very low. Thus collisions between the ions and atoms are also very rare.

2. SURFACE IONIZATION

The plasma in a Q-machine is produced by a process known as surface ionization. Surface ionization occurs when an atom with a very low ionization potential, such as K, Cs, or Ba comes into contact with a metal having a high work function, such as W, Ta, Mo, or Re. When such an atom is in contact with one of these metals, it is energetically favorable for the outer electron in the atom to be captured by the metal, thus forming a positive ion. The process is dependent on the temperature of the metal surface, and the ionization probability increases with temperature. A typical combination of atom/metal is Cs on W or Ta. When the metal is sufficiently hot, thermionic electrons are also emitted and so both positive ions and electrons emerge from the surface, thus forming a plasma. The atoms are forms in an atomic beam oven. Either a pure form of one of the alkali atoms is used or a combination of chemicals that upon reaction releases the alkali atom. A typical combination used is cesium chloride and calcium. When this mixture is heated to 300 - 400 C, a chemical reaction occurs:

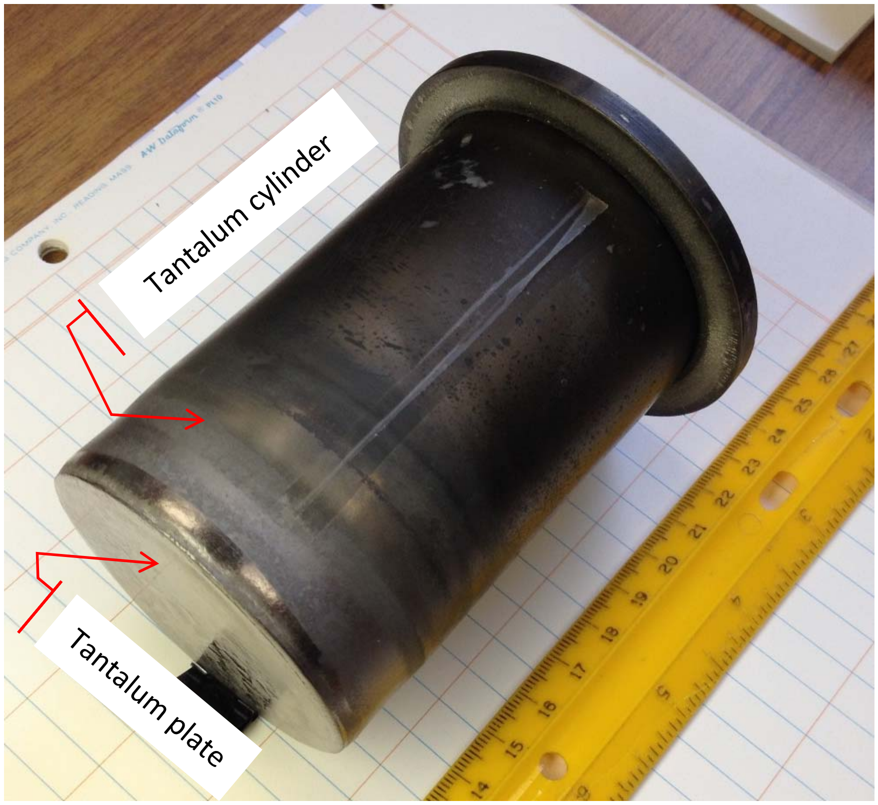
$$CsCl + Ca \rightarrow Cs + CaCl$$

producing a beam of Cs atoms which is directed onto the hot metal using a nozzle. Because the atoms are in good thermal contact with the heated metal plate (called the "hot plate") the emerging ions as well as the electrons acquire a temperature very nearly equal to the temperature of the hot plate, approximately 0.2 eV. The walls of the vacuum chamber are kept at a low temperature (- 15 C) so that any non-ionized cesium vapor is condensed on its inner surface. The ion emerging from the hot plate is singly-ionized.

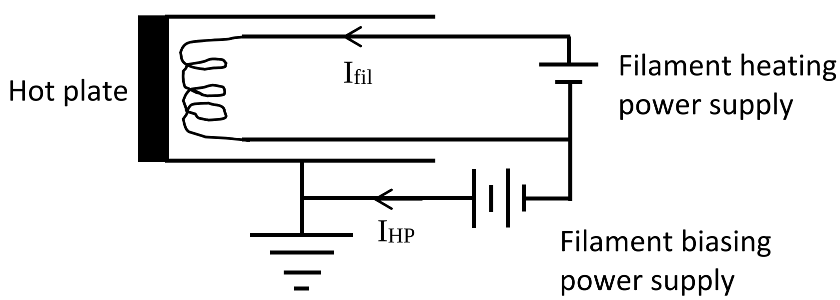
2. DETAILS OF THE Q-MACHINE CONSTRUCTION

The main component of the Q machine is a vacuum vessel, typically of stainless steel, and pumped out to a base pressure of $< 10^{-6}$ Torr. The outer walls are surrounded by coils through which a cryogenic fluid is pumped (typically ethylene glycol) to cool the chamber. The vacuum vessel is contained in a set of magnet coils (solenoid) for producing the axial magnetic field. A DC current is passed through the coils to produce the B field. The relatively high rate of heat dissipation in the coils requires that they be cooled, typically using water.

The hot plate used in the Iowa Q machine is a circular piece of Ta 6 cm in diameter, and roughly 5 mm thick. This plate is welded onto a Ta cylinder roughly 10 cm in height. A photo of the hot plate and cylinder is shown below. The hot plate is heated from behind by electron bombardment. A tantalum spiral filament is located on the inside of the cup a few mm from the back side of the Ta plate. The filament is heated by a direct current so that it emits electrons thermionically. The filament is biased at a voltage of



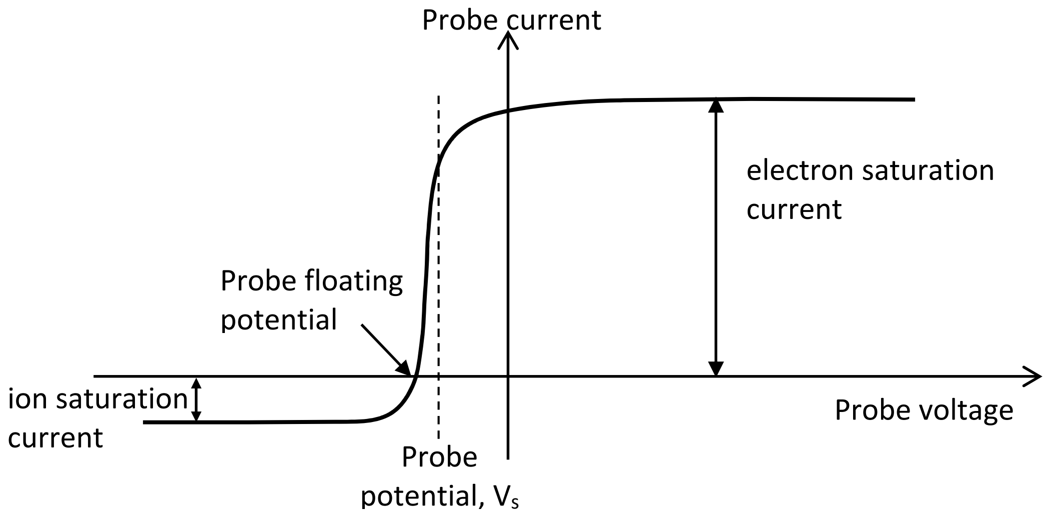
–2 kV so that the thermionic electrons are emitted and bombard the back of the plate which is grounded. The electrical schematic is shown below.



3. PLASMA DIAGNOSTICS

A Langmuir probe is used to measure the plasma density, the electron temperature, and the plasma potential. The probe consists of a bare small (2-4 mm) diameter tantalum disk welded onto the end of a wire and inserted into the plasma. The probe can be biased electrically to collect either ions or electrons. In practice, the probe bias is swept from roughly –10 V to + 10 V, and the current collected is recorded to produce an I-V characteristic. The I-V characteristic is analyzed to obtain the relevant plasma parameters. The probe, or multiple probes, can be moved radially and axially to obtain profiles of the plasma parameters.

A typical Langmuir probe I-V characteristic for a Q machine plasma is shown below. (This is only a schematic I-V plot, so it is not drawn to scale.)The bias voltage applied to the probe is on the x-axis and the current collected by the probe is on the y –axis. The electron current to the probe is taken as the positive current and the ion current as the negative current. The walls of the



device and the hot plate are at ground potential and the plasma is at a potential relative to ground called the "plasma or space potential", V_s. The plasma potential usually varies with position in the plasma. The current collected by a probe depends on its bias relative to the local plasma potential. When the probe is biased at a large negative value relative to V_s, it collects the positive ion current. When the probe is biased at a large positive voltage relative to V_S it collects electrons. When the probe is biased above the space potential it essentially collects all the electrons that randomly fall on it – this is called the electron saturation current. Likewise, when the probe is negative with respect to the space potential, it collects all the random ion current – this is called the ion saturation current. Since the current collected depends on the plasma density, a measure of the ion saturation current can be used to estimate the plasma density. Since the ion and electron temperatures in a Q-machine plasma are equal, and since the ion mass is >> electron mass, the random thermal speed of the electrons is much greater than the thermal speed of the ions, so the ion saturation current is much less that the electron saturation current, as indicated in the I-V plot above. Both the electrons and ions have approximate Maxwellian velocity distributions in the plasma. When the probe bias is near or somewhat negative relative to the space potential, some of the electrons (the slower ones) will be repelled by the probe and thus the current begins to decrease. The probe voltage range over which the electron current decreases depends on the electron temperature, and analysis of this region can be used to estimate the electron temperature. As the probe bias is made more and more negative relative to the space potential, both electrons and ions will be collected by the probe and the voltage at which the electron and ion currents are equal (zero total current) is called the probe floating potential. The floating potential is the potential of an unbiased (floating) probe. If the electron temperature is not too high (this is true for the Q machine, where $T_e \approx 0.2$ eV), the floating potential of the probe is very close to the actual space potential and the floating potential, which is easy to measure, is taken as a very good approximation to the space potential.

The forgoing discussion of the probe I-V characteristic is generally applied only to a plasma that is not confined by a magnetic field. When there is no magnetic field, the electrons and ions are relatively free to move around the plasma in random directions, and so we assume that the currents collected by a probe are due to the random (isotropic) thermal motions. However, when a magnetic field is present, the electron and ion motions are restricted to a gyromotion around the field lines, and this significantly affects how electrons and ions are collected by a probe. This is particularly true for the electrons, since the electron gyroradius is much smaller than the ion gyroradius.

4. PLASMA PARAMETERS

A schematic plot of the radial profiles of the plasma density and probe floating potential (approximately the space potential) is shown below. The plasma density (upper plot) peaks on the axis (r = 0) of the column and falls off with radial distance from the center. Although the plasma is created on the hot plate, it diffuses outward, so there is always some plasma outside the region that maps to the hot plate. The radial profile of the plasma potential is shown in the lower plot. In the region of the hot plate the potential is negative (~ -2 to -3 V). This is the situation when the Q-machine is operated under electron-rich conditions. In the electron-rich condition, the thermionic emission of electrons from the hot plate slightly exceed the production of the positive ions, so that the potential in this region is negative. In the central region, the potential is relatively flat, indicating that there is very little radial electric field in the plasma. However, substantial radial electric fields are present near the edges of the plasma column.