Alpha: Articulated Large-area Plasma Helicon Array

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Abstract. Construction of the Articulated Large-area Plasma Helicon Array is complete, and initial testing of the multi-helicon source reported. The 4 m long, 50 cm diameter facility is designed to study Alfvén waves and magnetic reconnection in a high-density, current-free plasma. Details of the facility and initial plasma parameters are reported.

INTRODUCTION

Controlled, basic laboratory plasma physics studies are indispensable in testing theoretical predictions and confirming the essential dynamics of more complicated plasma systems. One particular area of strong experiment/theory interaction is between observational space plasma research, theoretical modeling and simulation, and focused laboratory experiments. Several plasma experiments have been designed, motivated by space plasma issues (see e.g. references[1,2]). One area where laboratory studies should prove extremely useful is in understanding magnetic reconnection and the role of Alfvén waves. Theoretical models and simulations indicate that during magnetic reconnection Alfvén waves are excited[3]. Satellite observations have seen evidence of magnetic reconnection at Earth's magnetopause and in the magnetotail[4], while separate observations have identified Alfvén waves in both the magnetosphere and the auroral zone[5]. In this paper we report completion of a laboratory facility, *Alpha* (Articulated Large-area Plasma Helicon Array), designed to explore this link between magnetic reconnection and the excitation of Alfvén waves. In contrast to satellite observations, laboratory experiments allow simultaneous measurement of both macro- and microscale phenomena, permitting detailed study of reconnection and subsequent Alfvén wave generation under controlled, reproducible conditions.

The design of *Alpha* was motivated by several considerations with regards to the intended studies. The cross sectional area needs to be large enough to insure that ions are magnetized and to allow formation of the alfvénic shock structure created during a reconnection event. The experiment also needs to be dense enough and long enough to accommodate several Alfvén waves along its length. This criterion is less trivial to satisfy. Defining a nominal Alfvén wavelength as v_A / ω_{ci}, the wavelength scales as $\lambda_A \propto \sqrt{m_i / n}$, where m_i is the ion mass, and n is the density. One experimental approach is to build a very large device, as with the LAPD, a 20 m long facility[2]. The alternative solution is to create a high-density plasma. High-density Alfvén wave studies have been done on both linear and toroidal fusion devices. However, previous linear devices invariably had a large neutral fraction[6], increasing the damping and significantly influencing the wave dynamics. Though fusion devices can achieve a low neutral fraction, very high temperatures are required, and they are hence difficult to diagnose. Moreover, in all these studies the plasma ionization mechanism is an axial current, which can significantly influence the wave dynamics.

The *Alpha* facility addresses many of these limitations by creating the plasma using helicon wave sources. Helicons have been shown to be highly efficient at generating completely ionized plasmas, allowing one to obtain very dense (~10^{20} m^{-3}), albeit cold (<10 eV), plasmas[7-9]. The advantages of this approach are many. The high density relaxes the requirements on the machine length. There is a very low neutral fraction and the plasma is inherently current-free. Moreover, the discharge is steady state, though pulsed mode is possible. One major limitation is the cross–sectional area of the source, which is typically 10-100 cm^2. We address this issue using multiple sources to create an articulated large-area helicon source.

To aid in designing *Alpha* we initiated studies of Alfvén wave propagation in a helicon plasma on the Auburn Linear Experiment for Space Plasma Investigations (ALESPI)[10]. ALESPI was a prototype for *Alpha* using only a single helicon source, but with essentially the same discharge parameters. Shear Alfvén waves are produced in this discharge by means of an inductive coil positioned to oscillate the magnetic field perpendicular to the background field lines. The waves are detected by means of a second inductive coil positioned down the plasma column. Initial investigations demonstrated the propagation of shear Alfvén waves within the plasma through the localization of the oscillations along the magnetic field lines and the expected phase velocity of the waves. Continued work on ALESPI has demonstrated modification of the dispersion relation with increasing neutral fraction[11]. Experimental results agree well with theoretical predictions, and may be important in the dynamics of Earth's upper ionosphere and wave propagation in the solar photosphere.

ALPHA MACHINE DESIGN

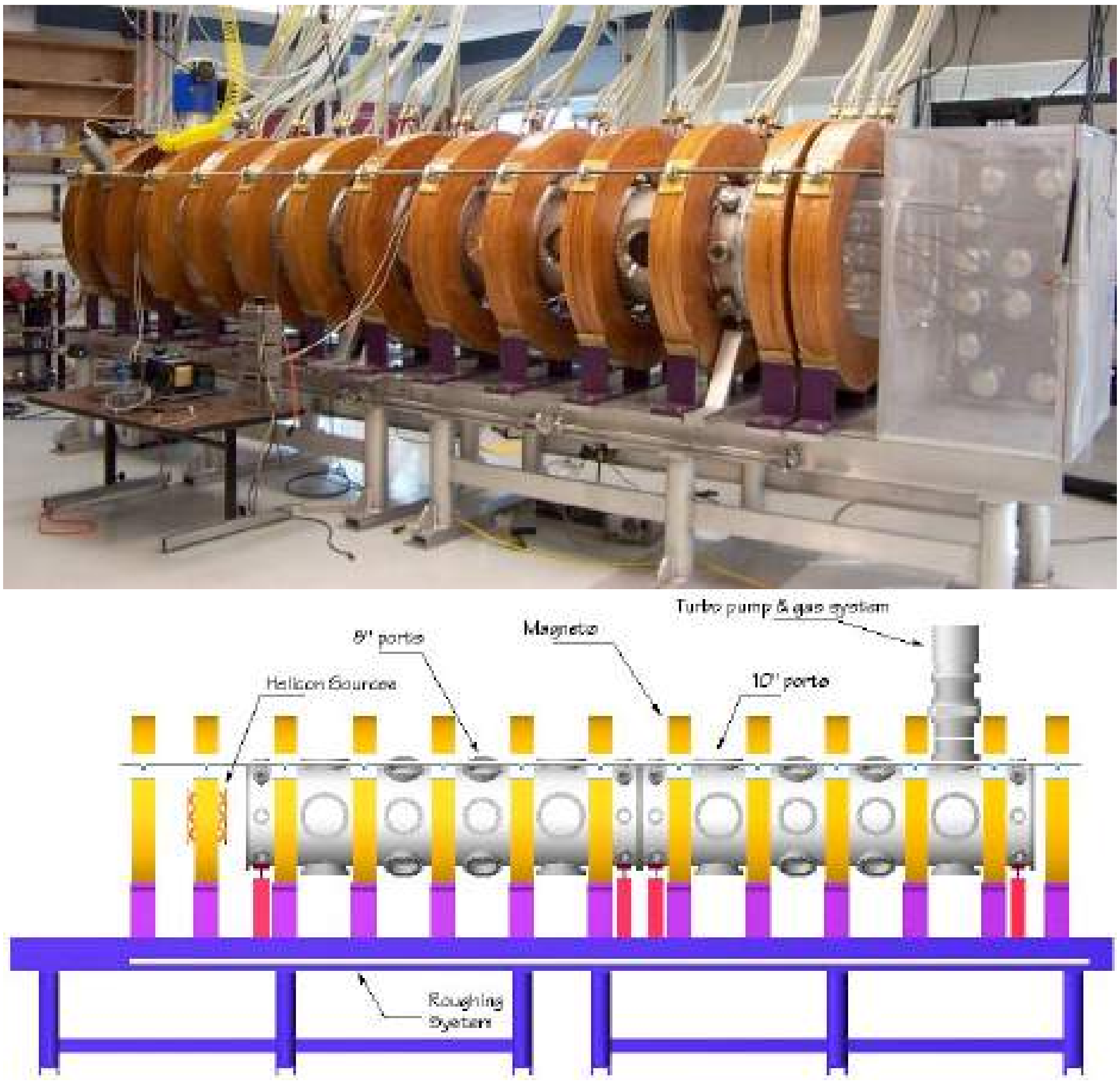

FIGURE 1. The *Alpha* device. Top: photo of completed device. Bottom: sketch showing major components.

Vacuum System: The vacuum chamber was designed to allow maximum diagnostic access to the plasma. The chamber consists of two two-meter stainless steel sections, with a diameter of 50 cm. Each section has eight 10" conflat ports, twelve 8" ports and fourteen 3.75" ports (see Figure 1). The location of the ports takes maximum advantage of the spacing of the magnets for optimal plasma diagnosis. The two chamber sections are joined with a standard ISO 500 o-ring gasket. The two end plates are similarly attached.

The vacuum chamber, magnets and roughing system are attached to an aluminum I-beam support structure. The cradles supporting the chamber are designed to allow *xyz* positioning, where *z* runs along the chamber axis, as well as rotational alignment about the chamber axis. The magnets can be positioned along the I-beams and adjusted in *xz*.

The vacuum system consists of a 1000 L/s turbo-molecular drag pump located at the end of the chamber furthest from the helicon sources, mounted to one of the 10" conflat ports. The pump is shielded from the magnetic field with 1/16" cold rolled steel cylinder surrounding the pump housing which ducts ~90% of the field around the pump. A rotary vane pump backs both the turbo pump and a roughing system running along the support structure on both sides of the chamber. The turbo pump is isolated from the vacuum chamber with 10" pneumatic gate valve and interlock system. Vacuum measurement is with standard and extended range pirani gauges and a hot cathode ion gauge. The ion gauge is situated one meter above the chamber to reduce magnetic field stress on the filament. The base pressure is maintained at $3x10^{-5}$Pa (~$2x10^{-7}$ torr).

The gas feed system can be operated in one of two modes, constant flow or constant pressure. A regulating needle valve can be adjusted to maintain a steady gas flow into the vacuum chamber. However, especially during pulsed operation, the fill pressure may vary during the plasma discharge. To compensate for this a self-regulated gas system is installed. Gas is still bled in through the needle valve. However, the main gate valve to the turbo is closed, and a servo-controlled butterfly valve regulates the gas flow through a bypass section of tubing. A pressure sensor maintains a constant fill pressure via a feedback loop to the butterfly valve. Constant fill pressures ranging from 0.1 to 15 Pa (2 – 100 mtorr) can be maintained during the helicon discharge.

Magnet System: The magnet system was designed to allow maximum diagnostic access while minimizing magnetic field ripple along the axis of the chamber. The design specifications call for less than 1% magnetic field ripple on axis. The system consists of 11 planar coils placed at 40 cm intervals along the chamber, and two end coils at 32 cm spacing. The nominal diameter of the coils is 82 cm. Each coil consists of 10 pancake layers of 14 turns each for a total of 140 turns per coil. Square cross-section copper tubing, 1 cm on a side, with a 1/4” diameter hole for water cooling was used for the magnet windings.

The magnets were constructed in house. A single 74 m strand of copper tubing was used for each pair of layers. Winding was done onto a cylindrical template affixed to a rotating platform (see Figure 2). A crossover bend was made at the midpoint of the tubing using a jog press, a specially developed tool based on a design by Fred Skiff at the University of Iowa. The strand was clamped to the template at the midpoint and the “excess” half of the strand was placed on the rotating platform. The section of bare copper to be wound was placed on a second rotating platform. The bottom layer was wound outward from the kink at the midpoint, then the top layer was wound from the remaining copper. Turn to turn insulation is provided by fiberglass tape which was wrapped onto the bare copper during the winding process. The entire process was mechanized so that a one person could wind the layer alone. During the winding, bare copper was pulled through a straightener (courtesy of the HSX stellarator group) to remove twists in strand; the straigtener also provided tension for winding onto the template. The copper then passed through an in-house developed planetary tape winding machine that automatically wrapped the fiberglass tape around the copper. The speed of the winding platform was adjusted so that the tape was wrapped in a half-lap configuration. During the process the operator used both rubber mallets and a “twisting tool” to align the copper as it wound onto the template and insure that the copper lay flat. For the 13th magnet winding of each layer took about 3 hours.

All five double-layers were wound on to the same template. Successive double layers were wound with opposite helicity to minimize the field error due to the crossovers. Once all layers were wound, the completed magnet was removed from the template. Electrical and cooling connections were brazed on. The outside ends of the tubing are electrically connected in series, but the water connections are in parallel so that each double layer has a separate cooling connection. The magnet support base and side “ears” were attached at this point.

The entire magnet was then wrapped in a layer of fiberglass tape, and then wrapped in plastic “release” tape. It was then placed on a form for epoxying. During the epoxy process the magnet was put under vacuum. The liquid epoxy was poured into the form and allowed to settle, then the magnet was then brought up to atmospheric pressure. This process insures that the epoxy is forced into the voids in the fiberglass between coil turns. The magnet was heated to 80°C speed curing, which typically took two days. Once the magnet was cured, epoxy flashing was chipped away, facilitated by the release tape.

Power to the magnets is provided by a 180 kW DC power supply, giving a maximum field on axis of 0.22 T. The power supply is specified to less than 1% AC ripple into the magnet inductive load. A closed loop water system is

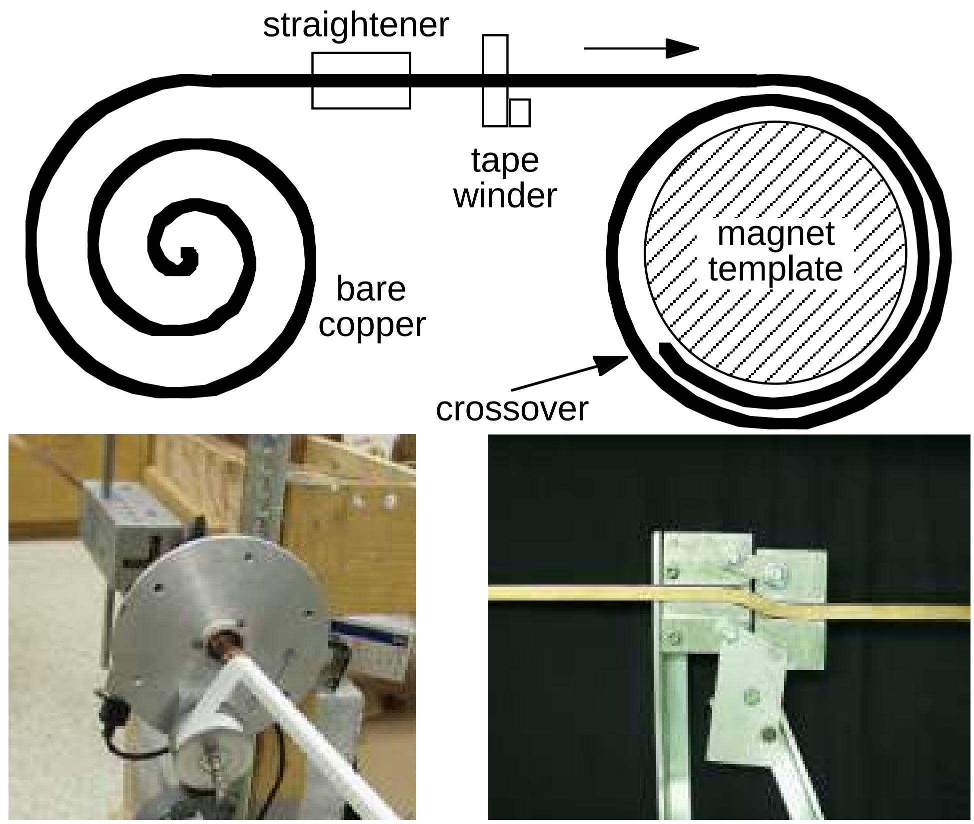

FIGURE 2. Top: Sketch of the magnet winding setup during winding of the second layer of a double pancake. Bare copper is fed through the straightener and tape winding machine, then wrapped around the template. The crossover to the layer below is indicated. Bottom left: Close-up tape winding machine. Right: Jog press used to make crossover bends.

used the cool the magnets which connects to the building chilled water supply at 16°C through a heat exchanger. The 100 L/min flow rate is adequate to maintain the magnets at room temperature indefinitely when operating at 0.22 T.

The vacuum magnetic field was measured for comparison with specifications. A hall probe was affixed to a servomotor-driven threaded rod running along the chamber axis. All three components of the magnetic field were measured over a 30 cm by 30 cm cross-sectional grid along the chamber axis. Figure 3 depicts the measured magnetic field along the machine axis compared to the design specifications. The stipulation for less than 1% ripple on axis is met. Detailed measurements of the field in all three directions indicate a uniformity of better than 3% across the chamber cross-section and a maximum deviation of no more than 5%. We believe most of the this error is due to small alignment errors in the hall probe, which results in very large measurement error due to the enormous difference between the axial and perpendicular fields.

Helicon Sources and RF System: Helicon sources were originally used in plasma processing[8,9], but have now found their way into laboratory research of both fusion[12] and space plasmas[13]. Extensive studies have been done characterizing their ionizing capabilities over a wide range of plasma parameters and background magnetic field strengths[14,15].

Helicon waves (bounded whistler waves) lie on the fast branch of the cold plasma dispersion relation, propagating in the frequency range $\omega_{ci} << \omega << \omega_{ce}$. They are right-hand circularly polarized electro-magnetic waves propagating along the magnetic field. In cylindrical geometry, for wave propagation along the magnetic field, the solution to the eigenmode equations is an *m*th order Bessel function of the first kind,

$$m\beta J_m(wa) = -kaJ'_m(wa) \tag{1}$$

where

$$\beta = \frac{\omega}{k}\frac{n_e e \mu_0}{B_0} \quad \text{and} \quad w^2 = \beta^2 - k^2, \tag{2}$$

with *a* the radius of the cylinder. For *w*>>*k*, the lowest Bessel root for the *m* =1 mode yields [8]

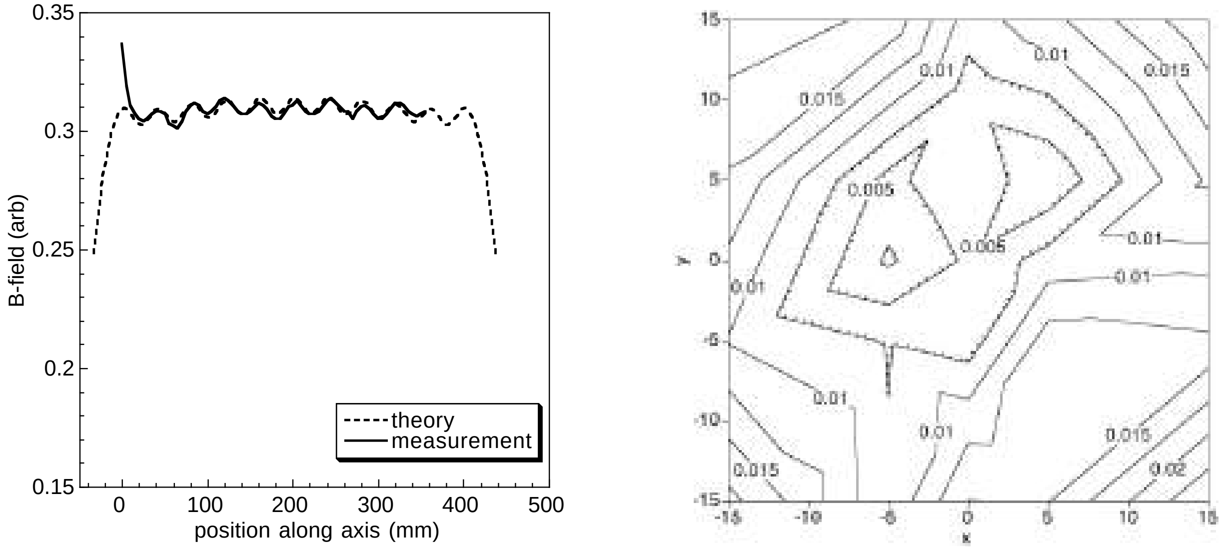

FIGURE 3. Left: Measured magnetic field along the chamber axis compared with design specifications. Right: Contour plot of mod(B) perpendicular to the axis.

$$\frac{\omega}{k} = \frac{3.83}{ae\mu_0}\frac{B_0}{n_e}. \qquad (3)$$

For a given magnetic field B_0, excitation frequency ω, and wavenumber k fixed by the antenna length, this relation determines the density achievable in the plasma. For a small diameter antenna, high density ($n_e > 10^{20}$ m^{-3}) uniform plasmas have been demonstrated[8,9]. A significant additional advantage is that only modest power is required to sustain the discharge. Densities of the order of 10^{19} m^{-3} are routinely reported for modest sized discharges with a few hundred watts of power[8,15].

In the context of *Alpha* the density predicted by Eq. (3) is problematic. Solving for the density, we see that it is inversely proportional to the radius of the plasma column. Further, satisfying $3.83/a >> k$ requires very long wavelength modes, necessitating a long vacuum chamber and antenna. Choosing a = 0.2 m, B_0 = 0.1 T, and f = 10 MHz, fulfillment of $w >> k$ requires at a minimum λ > 1 m, resulting in $n_e \sim 10^{18}$ m^{-3}. Hence, for large-area experiments helicon sources do not seem particularly advantageous.

We have overcome this difficulty through the use of a "Gatling gun" approach. A system of seven 13 cm diameter, hexagonally packed individual helicon antennae act as a single source to create a 40 cm diameter plasma on *Alpha* (see Figure 4). The sources consist of m=1 helical half-twist copper antennas surrounding 13 cm diameter Pyrex tubes 40 cm long. We found length of the tube has a significant effect on the discharge, which shorter tubes requiring more power to initiate and sustain the discharge. The sources are separated by 14.25 cm center to center. The glass tubes are closed at one end and mounted to the end flange of the vacuum chamber using an o-ring compression fitting. Rotational alignment of the array coincides with the orientation of the 8" ports. The antenna leads are connected though a UHF type connector to semi-rigid Heliax coaxial cable, which connects to the RF matching network.

In previous work by Chen, *et al.*[16] a single RF amplifier and matching network were used to initiate a helicon discharge in a similar multi-source array. However, preliminary studies on *Alpha* with two and three sources established that a single RF amplifier would not work in our situation. We hypothesize that this is due to the difference in magnetic field configuration, and is a focus of ongoing studies. Thus, we instead use seven independent RF amplifiers and matching networks driven by a single RF signal source.

The helicon wave is a right-handed wave (whistler) near the lower hybrid frequency. Thus, for most laboratory situations, B~ 0.1 T, helicon plasmas can generated using radio frequencies in the standard ham radio band, 1.8 to 30 MHz. A signal generator drives seven solid-state preamplifiers with a nominal gain of 55 dB and a maximum output power of 300 W each. The preamplifiers have individually adjustable gain, allowing one to balance the power into each antenna. The preamplifiers drive in turn seven Henry Radio 8K Ultra tube amplifiers with a nominal gain of 20 dB. These are capable of 2.5 kW continuous and 5 kW pulsed (~ 5s cycle time) output. The output power is fed to the matching networks (Figure 4).

The helicon sources are connected to the amplifier in a pi configuration with the antenna acting as the inductor. Both the load and tuning capacitors are vacuum variable capacitors adjustable between 40 and 2500 pF. These are mounted to an aluminum plate comprising one side of the faraday cage enclosing the helicon sources, mounted to the *Alpha* support structure. Currently, the matching networks are independent. However, there is significant coupling between the antennas due to their mutual inductance. Preliminary analysis indicates that this can be compensated for by installing trim inductors between the matching network capacitors of adjacent helicon sources.

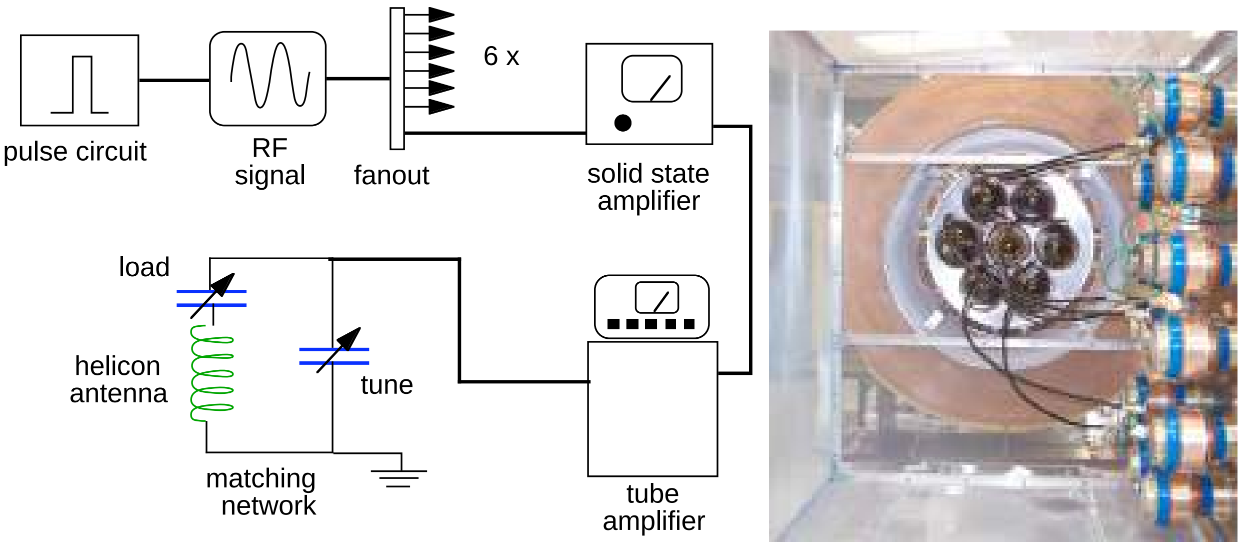

FIGURE 4. Left: Schematic of RF system. Right: End view of *Alpha* showing the seven helicon sources inside the faraday cage. To the right are the matching network capacitors.

PLASMA PARAMETERS

Both single and multiple source operation in *Alpha* has been demonstrated. Argon and helium helicon discharges are practicable in both steady state and pulsed plasma mode. Peak densities in excess of 3×10^{19} m^{-3} have been obtained in argon with 1 kW of input power in a single source, and a peak density of 1×10^{19} m^{-3} in helium with 1.5 kW of input power.

Temperature and density profiles during multi-source operation are depicted in Figure 5. Data were obtained in pulsed mode, with a 1 s discharge and 3 s repetition rate. A 3 mtorr fill pressure in argon was used with a background magnetic field of 0.08 T and 1 kW of input power. The profile was obtained with a Langmuir probe located at one of the 8” ports 90 cm from the chamber end near the sources. Clearly distinguishable are the individual sources in the density trace, though the temperature trace is more uniform. We had anticipated, based on previous studies of multi-helicon sources, that a more uniform density trace would be obtained this far from the sources[16]. We believe the persistent demarcation of the individual sources is due to the stronger axial field configuration of *Alpha*. That notwithstanding, we can obtain the desired high-density characteristics with multiple helicon sources. More recent measurements indicate that we can adjust the density profile by modifying the magnetic field near the sources. These results, including more extensive studies of the plasma discharge as well as a more detailed discussion of the plasma sources, will be reported in a future paper.

In conclusion, construction of the *Alpha* facility is complete and multiple helicon source operation had been demonstrated. Studies in the near future will focus on obtaining a more uniform density and temperature profile and in characterizing the plasma parameters over a range for frequency, magnetic field, input power and fill pressure. We have reported work on Alfvén wave measurements in helicon plasmas elsewhere[10]. Similar studies on *Alpha* will begin in the near future.

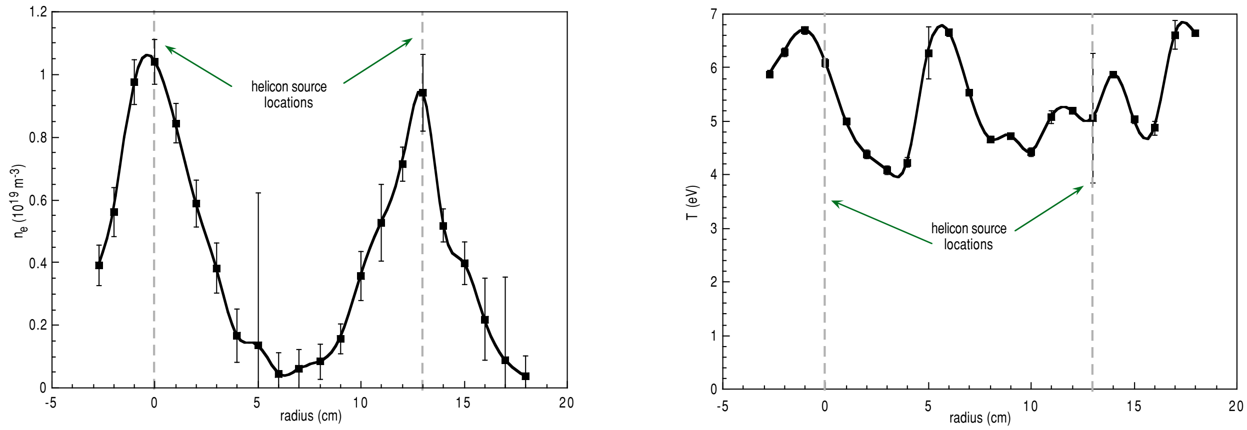

FIGURE 5. Density and Temperature profiles for multi-source operation in *Alpha*.

ACKNOWLEDGMENTS

The author would like to thank the many people involved in the construction of *Alpha*, including Chris Leach, David Jackson, Kristie Lynn, Tony Casey, Summer Spores, Joe Allen, Maggie Stauffer, Kyle Campbell, Adam Searl, Sara Hawkes, and especially Jeremy Hanna.

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