DESIGN OF A COMPACT COAXIAL MAGNETIZED PLASMA GUN FOR MAGNETIC BUBBLE EXPANSION EXPERIMENTS

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Abstract

The design of a compact coaxial magnetized plasma gun and its associated hardware systems are discussed in detail. The plasma gun is used for experimental studies of magnetic bubble expansion into a lower pressure background plasma as a laboratory model for extragalactic radio lobe expansion into the interstellar medium. The gun is powered by a 120μF, 10kV ignitron-switched capacitor bank. High-pressure gas is puffed into an annular gap between inner and outer coaxial electrodes. The applied high voltage ionizes the gas and creates a radial current sheet. The ~100kA discharge current generates toroidal flux and poloidal flux is provided by an external bias magnetic field. Axial **J**×**B** force then ejects plasma out of the gun. If the **J**×**B** force exceeds the magnetic tension of the poloidal flux by a sufficient amount then a detached magnetized plasma bubble will be formed. Using a multi-tip Langmuir probe array, a high speed camera and a B-dot probe array, the evolution of this plasma "bubble" as it interacts with pre-existing low pressure background plasma, is studied. In particular, details of the plasma bubble formation system including the main gun cap-bank power system, gas valve control system, bias flux cap-bank power system, and experimental data are provided.

I. INTRODUCTION

Astrophysical radio lobe structures, observed in association with extra-galactic jets as shown in Figure 1, were initially considered a curiosity but now appear to be a fundamental aspect of the evolution of active galaxies. Space-based telescope such as the Hubble Space Telescope and the Spitzer Infrared Space Telescope have provided much higher resolution images than previously achieved and have even provided animated movies showing the expansion process of extra-galactic jet's radio lobe structures.

Outstanding plasma physics issues regarding astrophysical jets and radio lobes include (ⅰ) the nature of radio lobe structures observed in jets, (ⅱ) the processes by which magnetic energy and helicity carried by extra-galactic jets reaches quasi-equilibrium with the surrounding intergalactic medium, and (ⅳ) the role radio lobes play in angular momentum transport between jets, lobes and material impacted by them [1].

Radio lobe phenomena have been studied via direct observation, analytical models, and numerical simulation, none of which are sufficient to resolve all of the non-linear plasma physic issues mentioned above. To help further elucidate the detailed physics, laboratory radio lobe configurations can be created to investigate the important features during the radio lobe expansion process, such as plasma heating and acceleration, angular momentum evolution and transport, and magnetic conversion.

Figure 1. Astrophysical jet with radio lobes structures. Excerpted from [2]

There are several experimental methods which can create laboratory radio lobe structures, including Z-pinch wire arrays, high power pulsed lasers and coaxial plasma guns - which is the method employed in this work.

The first coaxial plasma gun experiment was performed five decades ago by Alfvén [3], Lindberg [4], and Mitild, where plasma generated by a coaxial gun was found to exhibit interesting helical features and flux amplification. Although this experiment shed light on the nonaxisymmetric dynamics of spheromak formation, this early effort was undertaken without the benefit of modern diagnostic techniques. Furthermore, Alfvén, Linberg and Mitlid's device was fired into an insulating container, which was only moderately longer than the gun itself, and thus the plasma in their experiment was not permitted to freely expand without interacting with boundaries.

Following that, the research group in California Institute of Technology (CIT) fired a magnetized coaxial gun into a much larger vacuum chamber successfully [5]. In their case, the size of the chamber effectively removes the plasma-wall interactions. However the background was vacuum rather than plasma.

Several research groups tried to eject plasma bubbles into Tokomaks using a coaxial plasma gun, proposed as a means of tokamak current drive and refueling. In these

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14. ABSTRACT

The design of a compact coaxial magnetized plasma gun and its associated hardware systems are discussed in detail. The plasma gun is used for experimental studies of magnetic bubble expansion into a lower pressure background plasma as a laboratory model for extragalactic radio lobe expansion into the interstellar medium. The gun is powered by a 120ÊF, 10kV ignitron-switched capacitor bank. High-pressure gas is puffed into an annular gap between inner and outer coaxial electrodes. The applied high voltage ionizes the gas and creates a radial current sheet. The ~100kA discharge current generates toroidal flux and poloidal flux is provided by an external bias magnetic field. Axial J~B force then ejects plasma out of the gun. If the J~B force exceeds the magnetic tension of the poloidal flux by a sufficient amount then a detached magnetized plasma bubble will be formed. Using a multi-tip Langmuir probe array, a high speed camera and a B-dot probe array, the evolution of this plasma gbubbleh as it interacts with pre-existing low pressure background plasma, is studied. In particular, details of the plasma bubble formation system including the main gun cap-bank power system, gas valve control system, bias flux cap-bank power system, and experimental data are provided.

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experiments, the bubble is fired into background plasma provide by a tokamak [6] [7]. But the background magnetic field was much stronger than the bubble field itself. This is a fundamentally different situation than the jet/lobe system, where the galaxy is in a surrounding intergalactic medium with a relatively weak magnetic field.

The laboratory experiment described in this paper employs a magnetized coaxial plasma gun which injects a plasma bubble into low density, low temperature background plasma. The magnetic field of the background plasma is adjustable to be weaker or stronger than the bubble's magnetic field to simulate the radio lobe relaxation process in extra-galactic jets. This paper is organized as follows. Section II describes the experimental setup and details of the pulsed power system construction. Section III presents the experimental results and, a summary is given in Section IV.

II. EXPERIMENTAL APPARATUS

Figure 2 shows the experimental setup. The magnetized coaxial gun is mounted on one side wall of the large cylindrical vacuum. The principle of the gun operation is as follows, as operation systems structures shown in Figure 3: First the bias flux capacitor bank discharges, providing bias flux $\Phi_{\mathbf{bias}}$. Next, the gas puff valve injects a large quantity of neutral gas (typically 2~4 μg Argon) into the gap between inner and outer electrodes in a short burst (a few microseconds). The main gun cap-bank then discharges, initiating Paschen breakdown along the bias B-field between electrodes to form the plasma. At the same time, field-aligned current injects toroidal flux into the plasma, and **J**×**B** forces accelerate the plasma out of the gun. Eventually, the bias B-field reconnects as plasma leaves the gun, forming a plasma bubble with closed flux surfaces.

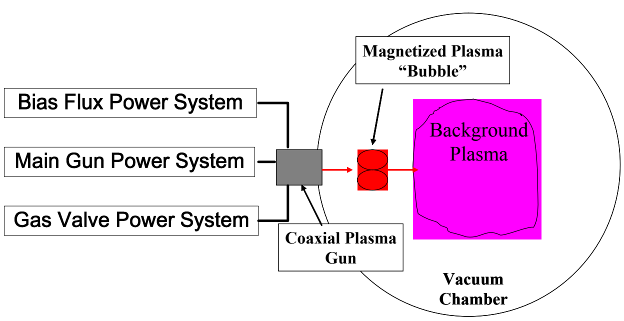


Figure 2. Side view of the coaxial gun, vacuum chamber, background plasma and power systems.

Vacuum is maintained at ~ 10^{-7} Torr base-pressure by two turbo molecular pumps on the main vacuum chamber. The gun is powered by a 120μF ignitron-switched capacitor bank. Bias flux $\Phi_{\mathbf{bias}}$ of up to 3 mWb is produced by a four-layer solenoid coil. All timing trigger signals are provided by Digital Delay Generator (California Avionics Laboratories INC/Model No.IO3CR). The operational sequence of a typical plasma discharge proceeds as follows: A gas puff valve is triggered 17ms after the bias flux cap-bank. The main gun capacitor bank is fired 6ms afterwards and simultaneously oscilloscope and data acquisition system are initiated.

Previous research indicates that the parameter $\boldsymbol{\lambda}_{\mathbf{gun}}$ determines the operating regime. Its functional form, which is defined by equation (1) [8], can be easily derived by integrating $\nabla \times B = \lambda B$ over the inner gun electrode surface:

$$\lambda_{gun} = \mu_0 \frac{I_{gun}}{\Phi_{bias}} \tag{1}$$

where $I_{\mathbf{gun}}$ is the current driven between the inner and outer electrodes after breakdown, $\Phi_{\mathbf{bias}}$ is the bias magnetic flux linking the inner and outer electrodes.

To form plasma bubble with closing surface magnetic flux, $\boldsymbol{\lambda}_{\mathbf{gun}}$ has to reach the threshold value $\boldsymbol{\lambda}_{\mathbf{gun\text{-}critical}}$. When the gun is running at $\boldsymbol{\lambda}_{\mathbf{gun}} \ll \boldsymbol{\lambda}_{\mathbf{gun\text{-}critical}}$, the bias flux dominates the gun current, and the plasma will not detach from the gun. On the other hand, when $\boldsymbol{\lambda}_{\mathbf{gun}} \gg \boldsymbol{\lambda}_{\mathbf{gun\text{-}critical}}$, the gun current dominates, and the bias flux is not enough to form closed magnetic flux surfaces. Therefore, a detached plasma bubble configuration can be produced when the gun operates at $\boldsymbol{\lambda}_{\mathbf{gun}} \sim \boldsymbol{\lambda}_{\mathbf{gun\text{-}critical}}$. Based on the parameters of the gun itself, the critical $\boldsymbol{\lambda}_{\mathbf{gun}}$ value of this gun is ≈ 185.

The parameter $\boldsymbol{\lambda}_{\mathbf{gun}}$ is varied experimentally by adjusting the main capacitor bank and (which control $I_{\mathbf{gun}}$) and the bias coil bank voltage (which control $\Phi_{\mathbf{bias}}$). The capacitance of main gun cap-bank is 120μF which is a typical setting that similar experiments employed before [5]. According to $\lambda_{gun\text{-}critical}$ and main bank capacitance value which indicates I_{gun}, the capacitance of bias flux cap-bank is determined as 60 mF, operated in a range of 250-450V. Furthermore a few microseconds pulse is needed to control the fast gas valve, the gas valve capacitor then set to 50μF, operated in 800V-1kV.

The various components of the experimental setup are described in detail below.

A. The Coaxial Plasma Gun

The compact coaxial magnetized plasma gun is mounted on one side of the main vacuum chamber, as shown in Figure 3. The gun is cylindrical, 10 cm long and 8 cm in diameter. It consists of (1) an inner copper tube (0.89cm wall) with a 2 cm diameter copper disk electrode at the right-most end, (2) a coaxial outer 8 cm diameter copper annulus electrode, and (3) a magnetic field coil that covers the whole cylindrical body of the gun.

The feed-through is mounted on a 8.6cm CF flange. The inner electrode extends 10.2cm from the flange face on the air side and 12.6cm on the vacuum side. The insulator of the inner electrode is an alumina ceramic which can hold off up to 12 kV DC. Thus the inner electrode is electrically floating and is connected to the main gun cap-bank via coaxial cables. The outer electrode is mounted via stainless steel bolts directly to the inner surface of the vacuum chamber and therefore is electrically tied to the chamber ground. A 3 cm diameter annulus vacuum gap separates the inner electrode disk and outer electrode. The bias magnetic coil is discussed in Section II C.

There are four 6.4 mm diameter gas puff feed-lines symmetrically distributed around the gun's cylindrical body to ensure that gas injected into and fill the gap between inner and outer electrodes is fast and localized. Details of gas injection are given in Section II D.

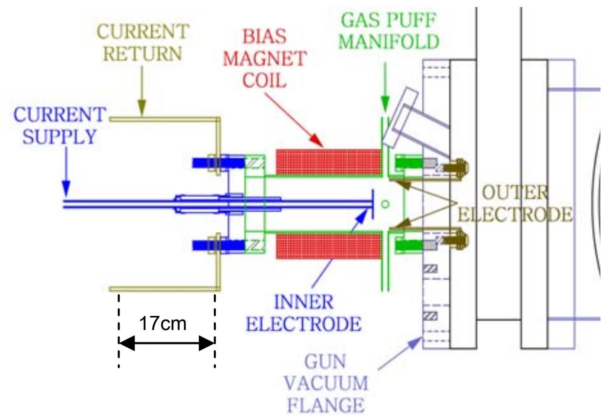


Figure 3. Detailed layout of the coaxial plasma gun

Furthermore the connections between the electrodes and the main bank power system are through eight parallel double-layers, low inductance coaxial cables (0.51uH/m) Belden YK-198 which carry power from the main gun capacitor bank to the gun electrodes with low loss.

B. Main Gun Cap-bank Power System

As mentioned above, the main gun capacitor bank consists of four capacitors. Each capacitor is 30µF/10 kV (Aerovox/PXSOD53) and the total capacitance is 120µF. The bank can be operated from 4 kV up to 9 kV, giving $I_{\mathbf{gun}}$ up to 100 kA. The main gun cap-bank circuit is shown in Figure 4, where SW1, SW2, and SW3 are relay switches. R is a 120Ω resistor to limit the charging current during the charging process and also functions as a dump resistor to discharge the bank. The DC power supply (Glassman High Voltage Inc. /10YDC) can provide up to 10 kV DC charging voltage and 30 mA charging current. The ignitron (Model No. GL-37207A) can handle a peak voltage of 25 kV and a peak current of 300 kA. A Rogowski coil (5 mV/A sensitivity) is placed around the copper bar which connects the ignitron to the double-layer coaxial cables to measure total I_{gun}. An attenuating Tektronix P6015A high voltage probe measures V_{gun}.

Operation is as follows: First SW1 and SW2 close and SW3 opens, and the DC power supply begins charging the main gun cap-bank through the resistor R. When the capacitor bank voltage reaches the required level, SW1 and SW2 open. The ignitron is then trigged and the capacitor bank discharges through the coaxial plasmas gun. After the discharge process is completed, SW3 closes and the capacitor bank is discharged through the resistor R.

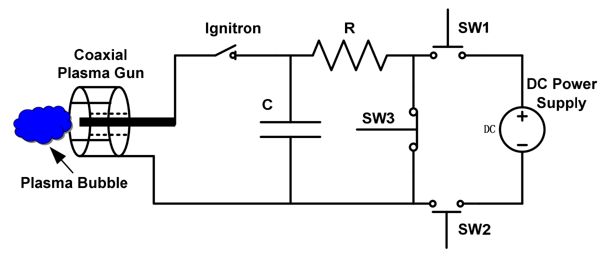


Figure 4. Main gun cap-bank circuit diagram

Routine operation at a bank voltage of 7.5 kV yields a peak plasma current $I_{\mathbf{gun}}$~ 80 kA and gun voltages V_{gun}~1 kV after breakdown. Typical I_{gun} and V_{gun} traces are shown in Figure 5.

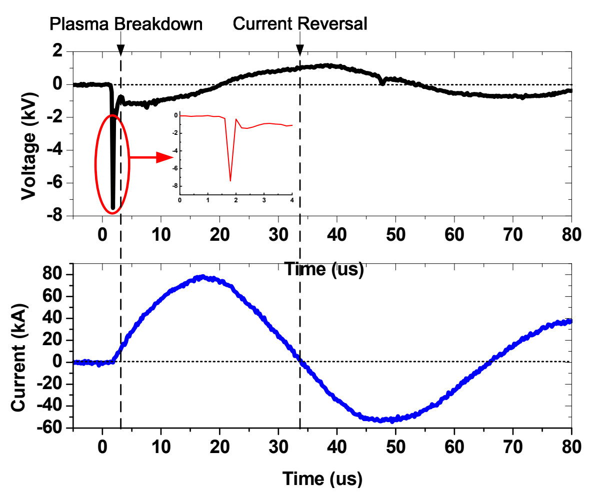


Figure 5. Typical I_{gun} and V_{gun} traces. Initial charge voltage is 7.5 kV. Breakdown occurs at t ≈ 2 µs.

C. Bias Coil and Flux Capacitor Bank Power System

The external bias magnetic field coil covers the main cylindrical body of the plasma gun. The coil consists of 10 layers of 44 turns each layer (440 turns total) of 12 AWG insulated square magnet wire, and has an inductance of 6.25 mH and resistance of 0.5Ω (based on an ohm meter measurement).

The coil magnet wire has Polyester A/I Topcoat insulation, which is rated for 200 C° use and can stand off 4 kV. A layer of fiberglass between the windings and the nipple was also added during fabrication by the manufacturer.

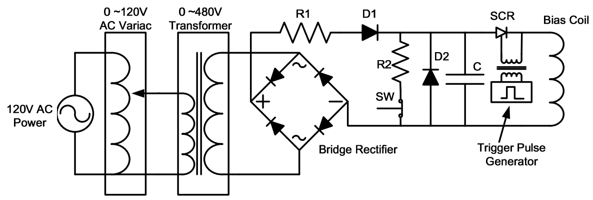


Figure 6. Bias flux cap-bank power system circuit diagram.

The coil is powered by a 60 mF, 450V capacitor bank. The capacitor bank power system circuit diagram is shown in Figure 6, where R1 is a 150Ω current limiting resistor, R2 is a 250Ω dump resistor, D1 and D2 are power electronic diodes, SW is the dump relay and C is the bias flux capacitor bank. The SCR, controlled by a 1 kV Trigger Pulse Generator, is used as the main switch in this system. The bias poloidal magnetic field flux $\Phi_{\mathbf{bias}}$ **(**intercepting the inner gun electrode**),** created by the external coil is typically ~ 0.5 - 1 mWb for bias voltages of 275V - 400V. Figure 7 shows the bias flux evolution with time for different bias voltages.

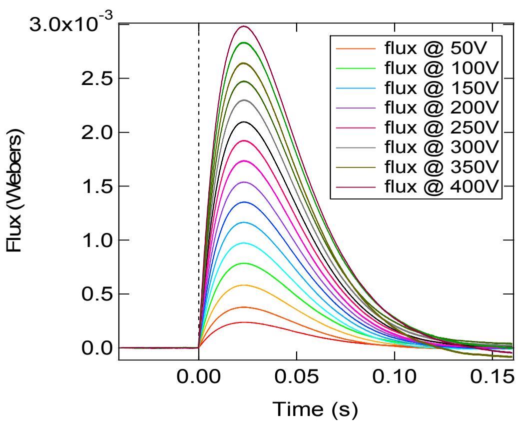


Figure 7. Bias flux evolution at different bias voltage

D. Gas Injection and Gas Valve Power System

Fast gas puffs are necessary in this experiment because a local gas pressure on the order of 100 mTorr is required for successful breakdown [9]. A slow or steady gas fill may result in weakly ionized cold plasma, which is not appropriate for this experiment.

The fast gas valve provides a transient, highly localized cloud of high pressure gas in the gap between the plasma gun electrodes. The gas valve employs a pulsed current in a thin single-turn coil to introduce image current in an adjacent aluminum disk. The pulsed current is generated by the gas valve capacitor. Following this pulsed signal, the disk is repelled from the coil, creating a transient opening for gas flow from the gas feed line into the vacuum chamber. A restoring force on the disk is provided by a combination of a metal spring and the high pressure gas in the gas lines, which is usually operated at ~ 30 - 60 psi. Calibration indicates that each pulse injects 10^{20}-10^{21} argon molecules and the mass is 3.6×10^{-6}g. Optimum timing of the gas valve firing is determined empirically by adjusting the valve firing time to minimize the delay between the main gun capacitor bank trigger and gas breakdown (typically ~ 1 - 2 μs) and to achieve maximize reproducibility. The typical gas valve capacitor discharge voltage is 900V. The gas valve capacitor charging circuit is shown in Figure 8.

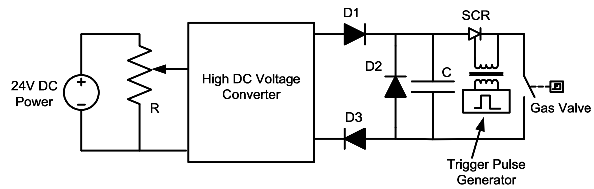


Figure 8. Gas valve capacitor charging circuit diagram

In this circuit, R is a variable resistor with range 0 - 10 kΩ. D1, D2 and D3 are power electronic diodes. C is the pulse capacitor 50 μF/1kV. As for the bias flux capacitor bank, the gas valve power system utilizes an SCR as the main switch, which is controlled by the trigger generator. The commercial high DC voltage converter is an UltroVolt Inc. model number 2C24-P60, with output voltage variable from 0V to 2055V controlled by the input DC voltage.

E. Background Plasma: The HelCat Device

The HelCat (Helicon-Cathode) machine is a basic plasma science device at the University of New Mexico [10]. The cylindrical vacuum chamber is 4m long and 0.5 m in diameter. The chamber has a 25.4cm observation window on the top to provide a good view of the plasma bubble dynamics. The size of the vacuum chamber is large compared to both the coaxial gun source and the plasma bubble so that plasma-wall interactions are avoided, and boundary conditions appropriate for a freely expanding plasma bubble are achieved.

Table 1. Key Parameters of HelCat Cathode and Helicon Plasmas

Params for He	Cathode	Helicon
B (Gauss)	100~2000	100~2000
T_e (eV)	1 ~ 20	1 ~ 10
n_e (m^{-3})	$5\text{x}10^{17}$ ~ $5\text{x}10^{18}$	$5\text{x}10^{18}$ ~ $3\text{x}10^{19}$
v_A / $v_{th,\,e}$	0.1 ~10	0.1 ~ 3
n_n/n_e	1000 ~ <1	1000 ~ <1

where B is operational background magnetic field, Te is electron temperature, n_e is plasma density, V_A is acoustic velocity, Vthe is electron thermal velocity, and n_n is neutral density.

HelCat has two sources that can generate the background plasma: an RF helicon source and a thermionic cathode. The background magnetic field is adjustable from 50 Gauss to 2200 Gauss. Table 1 lists the key parameters of the two plasma sources in helium.

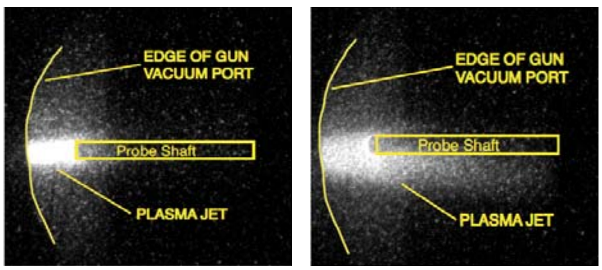
A wide range of parameters such as plasma density, temperature, and background magnetic field can be achieved, which will affect the plasma bubble dynamics, including bubble expansion rate, angular momentum transport, and magnetic energy conversion.

III. EXPERIMENTAL RESULTS

A. Images of Plasma Bubble Expansion

Images were acquired with a charge-coupled device (CCD) camera to verify that plasma is ejected from the gun, as shown in Figure 9 (a) and (b). In these two images, plasma is visible leaving the gun, expanding into the vacuum chamber and impinging on the probe.

The camera was placed on a tripod and viewed radially through a window adjacent to the gun port. A steerable mirror, placed inside the main vacuum chamber, was used to provide a view of the plasma bubble.



(a) (b)

Figure 9. Images showing the plasma bubble detaching from the gun. Image (b) is delayed by 1μs compared to image (a).

B. Multi-tip Langmuir Probe Measurements

For this experiment, a multi-tip Langmuir probe was used to measure ion saturation current (Isat) signals of the plasma bubble. The probe has 10 separate tips with a 5.7mm spacing between tips in a linear array. The tips are cylindrical shape, 2.5 mm long and 0.5 mm in diameter.

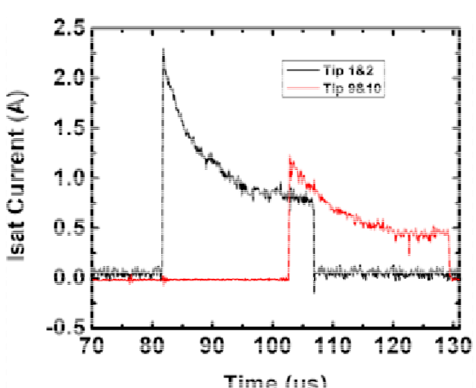


Figure 10. Isat signals from multi-tip Langmuir probe

Based on Isat traces, the plasma density can be estimated. Additionally, the time delay between two Isat traces indicates the propagation speed. Figure 10 exhibits typical Isat signal traces obtained from two separated probe tips.

The plasma produced by the coaxial gun has the following global parameters based on these measurements to date: density n ~ 10^{20} m^{-3}, Te ~ Ti ~ 5-10 eV, propagation speed ~ 0.5 cm/μs (Argon plasma) and ~ 1.5 cm/μs (helium plasma), which corresponds approximately to the ion sound speed of the bubble plasma.

C. Three Dimensional Magnetic Probe Array

Local magnetic field measurements are planned using a radial array of small pickup coils mounted on a stainless steel shaft. The array contains 11 groups of three coils arranged so that all the three components of B field are measured from R=0 to R=17 cm with a 1.4 cm resolution (here R is the radial coordinate of the main vacuum chamber). The coils are commercial chip inductors (Coil Craft/1008CS-472XGBB) and are placed into precision-machined slots of a long thin strip of Delrin, which in turn is covered by a glass tube to prevent metal contact with the plasma. The B-dot probe is mounted to the port opposite the plasma gun port as shown in Figure 11.

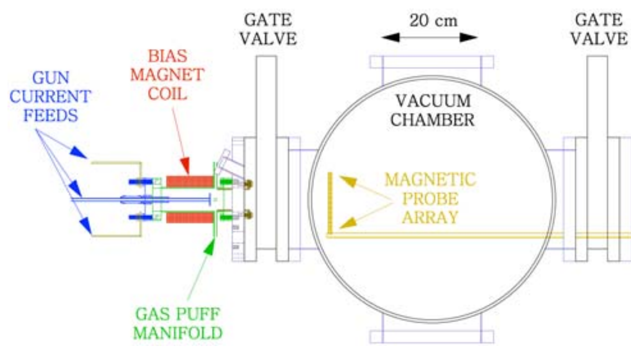


Figure 11. Overview of plasma bubble experiment with coaxial gun on left and magnetic probe on right.

IV. SUMMARY

A coaxial magnetized plasma gun, and associated pulsed power systems, have been designed and constructed in order to investigate the relaxation of a magnetized plasma bubble with closed magnetic surfaces injected into a background plasma. These experiments are designed to simulate the extra-galactic radio lobe relaxation process in the laboratory.

The gun and its associated hardware and power systems have been discussed in detail. The gun has been tested and is currently operational. A CCD camera has been used to verify the injection of a plasma bubble. Bubble plasma density, temperature and propagation speed have been estimated from multi-tip Langmuir probe measurements.

Future work will explore the interaction of the bubble with the background plasma in terms of the evolution of magnetic helicity, magnetic and thermal energy, and azimuthal rotation. Also the experiment will investigate the dependence of flux amplification on gun parameters such as λ_{gun}, as well as background plasma parameters such as the background thermal and magnetic pressure. Furthermore the experiment will address how much magnetic flux conversion occurs during relaxation and how this depends on system parameters. Additional diagnostics (electrostatic Mach probe, visible spectroscopy, interferometry) required for these studies are currently under construction.

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