Development of a Compact RF Pre-Ionization System for an MHD-Driven Jet Experiment

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Experiment Background

Experiment Applications

Pre-Ionization Project
Vacuum chamber for the MHD-driven jet experiment. The chamber is 2 m long and 1.4 m in diameter.

Cutaway of chamber showing plasma jet.

Holes for gas injection
Anode (r = 25 cm)
Cathode (r = 25 cm)
Magnetic probe
Electrodes for the experiment.
1) External coils create an arched poloidal magnetic field between a central conducting disk (cathode) and surrounding annulus (anode). Neutral gas is puffed into the chamber, then a radial electric field is created by applying a high voltage across the electrodes, breaking down the gas to form current-carrying plasma loops that follow the poloidal field.

2) The current loops expand due to the hoop force, merging along the central axis because their parallel currents attract one another.

3) Driven by the $\mathbf{J} \times \mathbf{B}$ force [toroidal magnetic field gradient], the jet expands away from the electrodes and is collimated. A diffuse envelope completes the current path from the anode to the cathode.

4) The jet goes kink unstable, evolving toward a force-free equilibrium determined by the amount of helicity injected at the electrodes.
Collimated Plasma Jets are Ubiquitous in Astrophysics:

- **Hubble Space Telescope (HST) image of the young stellar object HH 30**
  - Central star
  - Dust blocking visible emission
  - Accretion disk

- **Composite Image of the active galaxy Centaurus A**
  - Supermassive black hole?

- **HST image of bipolar jets in HH 47 creating shocks in the cold interstellar medium.**
  - Jet hitting cold gas cloud

- **2 x 10^{14} m long plasma jet with v = hundreds of km/s**

- **10^{22} m long plasma jet with v \sim 0.5 c**
Until roughly 25 years ago, it was generally assumed that astrophysical jets were driven by purely hydrodynamic forces\textsuperscript{1}. However, such models had difficulty explaining key properties of jets such as their extreme collimation (narrowsness) and oftentimes helical appearance\textsuperscript{2}.

It is now believed that magnetohydrodynamic (MHD) forces are responsible for the formation of most jets. Furthermore, it is likely that similar physics describes the launching of jets from accretion disks of vastly different scales (e.g. protostellar disks vs. active galactic nuclei)\textsuperscript{1}.

Current astrophysical observations lack the resolution to test jet formation models in detail (in particular, measuring the magnetic field strength near stellar accretion disks is rarely possible\textsuperscript{1}). Thus laboratory experiments and numerical simulations can make valuable contributions.

\textsuperscript{1} Bellan, P. M., Phys. Plasmas, 12: 058301, 2005.  
Mechanism for Launching Jets from Accretion Disks

1) A dipole-like (purely poloidal) stellar magnetic field threads an accretion disk, which is rotating at a different rate than the star itself.

2) The differential rotation twists up the magnetic field, creating a toroidal component to the field.

3) Since $B_\phi$ is stronger closer to the disk, there is a magnetic pressure gradient which inflates the poloidal field, ultimately driving an outflow of plasma in the z-direction.

Equivalently: In a frame rotating with the star, a segment of the accretion disk has a velocity $U_\phi$, so the ideal MHD Ohm’s law $\mathbf{E} + \mathbf{U} \times \mathbf{B} = 0$ implies the existence of a radial electric field: $E_r = -U_\phi B_z$. This field drives a current along the poloidal field lines, and the resulting current loops expand due to the hoop force.
Spheromak Formation

Plasmas formed from with the co-axial electrode configuration can evolve toward a force-free state with $\nabla \times \mathbf{B} = \lambda \mathbf{B}$. Integrating this equation over the electrode area gives an equation for the eigenvalue $\lambda$:

$$\lambda_{\text{gun}} = \frac{\mu_0 I_{\text{gun}}}{\psi_{\text{gun}}}$$

Three qualitatively different behaviors are seen depending on the maximum value of $\lambda_{\text{gun}}$:
- Small $\lambda_{\text{gun}} \rightarrow$ straight MHD-driven jet [I]
- Intermediate $\lambda_{\text{gun}} \rightarrow$ kink-unstable MHD-driven jet [II]
- Large $\lambda_{\text{gun}} \rightarrow$ detached plasma with large toroidal field [III]

Case II has been found to be a precursor to spheromak formation, with the kink instability acting as a dynamo mechanism to convert toroidal flux to poloidal flux\(^1\)

Motivation for Pre-Ionization

- Goal: Create lower density, faster jets
  - At present, the plasma density must be high because a high density of neutral gas is required to get plasma breakdown in a DC electric field (Paschen criterion)
  - Jet velocity depends on the plasma density and the $\mathbf{J} \times \mathbf{B}$ forces from the interaction of the $\sim 100$ kA gun current and the $\sim 0.2$ T bias magnetic field.
  - With a high jet density, the jet velocity is constrained to be under $\sim 50$ km/s

- Solution: Puff pre-ionized plasma into the chamber instead of neutral gas to circumvent the Paschen criterion
  - A compact 3 kW RF source has been constructed for the purpose of pre-ionization

- Implications: Making faster jets will allow the experiment to study new physics regimes and have increased relevance to astrophysics

Paschen curve for molecular hydrogen.
The RF pre-ionization system will be located directly behind the high voltage central electrode of the MHD-driven jet experiment, with the entire system floating at high voltage.

**New Experiment Sequence**

1) External coils create an arched poloidal bias field linking the electrodes.

2) The RF source is pulsed and plasma is created in a tube behind the electrodes.

3) Pre-ionized plasma flows into the chamber through a hole in the center of the cathode.

4) The main capacitor bank discharges across the electrodes through the pre-ionized plasma, driving a fast, low-density jet.

Current electrode geometry for the jet experiment. In the modified experiment with pre-ionization, a new cathode with a hole in the center will be installed, and the pre-ionized plasma will flow into the chamber through this hole.
- Compact 13.56 MHz RF source\(^1\) is capable of producing over 3 kW output power in pulsed operation (typically 0.2-1 ms pulses).

- The amplifier is self-contained, powered by conventional AA batteries, which provide the \(\sim 2\) J of energy necessary for each pulse.

- Battery operation allows the RF source to float at 4-6 kV with the MHD-driven jet experiment’s inner electrode.

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\(^1\) Design based on: Choi, G, “Application Note: 13.56 MHz, Class D Push-Pull, 2 kW RF Generator with Microsemi DRF1300 Power MOSFET Hybrid”, 2008.
Transformer Coupled Class D RF Amplifier: Theory of Operation

- Square wave trigger pulses alternately turn power MOSFETs Q1 and Q2 on and off.
- When Q1 is on and Q2 is off, the power supply current $I_p$ flows through the lower half of the transformer’s primary winding to ground.
- When Q2 is on, the currents and voltages reverse polarity.
- Tuned matching network imposes a sinusoidal voltage across the output.
- Class D amplifiers can operate with high efficiency because the product $IV \approx 0$ in the MOSFET switches at nearly all times. Finite switching times, non-zero MOSFET on-state resistance, and transformer losses can lead to less-than-ideal performance.
Impedance Matching

- Maximum power transfer theorem: It is well known that for a source with output impedance $Z_0 = R_0 + iX_0$, maximum power is delivered to a load with impedance $Z_L = Z_0^* = R_0 - iX_0$.

- Adjustment of the load impedance is accomplished by adding tunable capacitors in parallel and in series with the antenna.

- For our class D RF power amplifier, the source impedance comes from non-ideal behavior of the MOSFETs and output transformer, and $Z_0$ is unknown. Output power is maximized empirically by measuring $I$ and $V$ at the RF output while adjusting $C_p$ and $C_s$. Antenna inductance and resistance. $R$ includes radiation resistance from antenna-plasma coupling.

Variable capacitors for matching
Impedance Matching

Precise tuning is achieved by binary arrays of high voltage, low dissipation multilayer ceramic capacitors mounted on a printed circuit board.

- Problem: The plasma has unknown impedance which varies in time, but it is impossible to adjust $C_p$ and $C_s$ on the sub-millisecond RF discharge timescale.

- Solutions we have tried:

  1) Build two separate RF amplifiers and two matching networks. Tune one amplifier to output a high voltage across the unloaded antenna to induce breakdown, then pulse the second amplifier with the matching network tuned to maximize the power delivered to the plasma.
     - This “brute force” approach is feasible because of the low cost and small physical scale of the RF amplifier.

  2) Use a UV flashlamp pulse at the beginning of the discharge to provide seed ionization and facilitate breakdown.
Goal is to Excite Helicon Waves

- Helicon waves belong to the category of whistler waves (right-hand circularly polarized electromagnetic waves in a magnetized plasma), but unlike classical whistlers, they are modes of bound systems.

- Helicons have been shown to be extraordinarily efficient in transferring energy from a power source to a plasma: this property allows for the creation of a high-density plasma ($10^{13}$ cm$^{-3}$) with relatively little input power.

- Collisionless (Landau) damping is suspected to be the energy transfer mechanism$^1$.

- Dispersion relation$^1$:

$$\frac{\omega}{k} \approx \frac{Z_m}{\epsilon \mu_0 a n_0} B_0$$

($Z_m$ is the root of $J_m(Z_m) = 0$, and $a$ is the tube radius)

Nagoya type III antenna$^2$ used to excite helicon waves. A solenoid is placed over the antenna to create a uniform axial magnetic field.

RF Source Behavior

Pulse Generation Stage Output

Left: trigger pulses with the high voltage output stage turned off. Right: trigger pulses with noise pickup from the output stage. Feedback into the pulse generation stage from the high power RF output is a major issue since the physical size of the amplifier is small, but the effects are minimized by using surface mount components.
Left: RF source output voltage waveform with a resistive load. The output is nearly a square wave. Right: Output power into three different loads with a 6:1 turns ratio on the output transformer. With a final stage power supply voltage of 300 V, the source can achieve output powers over 3 kW.
Final Stage Output into Antenna and Matching Network

RF source output voltage (left) and current (right) during a plasma discharge with the matching network tuned to maximize the power delivered to the plasma. The output power in this case is 890 W, and the load impedance is 23 Ω.

Tuning of the matching network capacitors to get the output current and voltage in phase.
Spectroscopic Measurements

Measured Ar II 434.8 nm line emission during a 200 μs RF pulse.

For an argon plasma, most of the strong neutral (Ar I) emission lines are in the red and infrared regions of the spectrum, while the strong ion (Ar II) lines are in the blue and UV. The plasma shown at left is cool and/or weakly ionized, while the plasma shown at right is hotter and/or more ionized.
Left: Time-averaged Ar I 696.5 nm and Ar II 434.8 nm line strengths. Right: Time-averaged 696.5 nm / 434.8 nm line ratio. The argon fill pressure was 10-15 mTorr for all discharges.
Left: Time-averaged Ar I 696.5 nm and Ar II 434.8 nm line strengths. Right: Time-averaged 696.5 nm / 434.8 nm line ratio. The RF source output power was between 840 W and 1065 W for the data points shown (the output power depends on the plasma impedance, which changes at different gas pressures, so maintaining a constant output power for all measurements was not possible).
Preliminary Conclusions

- A compact, battery-powered pulsed 13.56 MHz RF source has been designed to produce a pre-ionized plasma for the Caltech MHD-driven jet experiment.

- Matching of the antenna impedance to the source is accomplished using adjustable arrays of high voltage capacitors mounted on a printed circuit board.

- By adjusting the matching capacitances and the turns ratio on the output transformer, we have been able to deliver up to 1 kW of RF power to the plasma. Further optimization of the impedance matching should allow the power delivered to approach the 3 kW that the RF source can output into a resistive load.

- We have begun using optical emission spectroscopy to measure the ionization fraction, electron temperature, and electron density of the plasma. The Ar II 434.8 nm / Ar I 696.5 nm line intensity ratio rises with increasing RF power output and is highest at low argon gas fill pressures.

- There is no evidence at present for helicon wave propagation; the presence of an axial magnetic field (≤ 200 gauss) does not increase the level of argon line emission.
  - Future work: try different antenna designs, try to increase RF power output