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The Impedance and Energy Efficiency of a Coaxial Magnetized Plasma Source used for Spheromak Formation and Sustainment

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Electrostatic (dc) helicity injection has previously been shown to successfully sustain the magnetic fields of spheromaks and tokamaks. The magnitude of the injected magnetic helicity balances (within experimental error) the flux lost by resistive decay of the toroidal equilibrium. The problem of optimizing this current drive scheme hence involves maximizing the injected helicity (the voltage-connecting-flux product) while minimizing the current (which multiplied by the voltage represents the energy input and also possible damage to the electrodes).

The impedance (voltage-to-current ratio) and energy efficiency of a dc helicity injection experiment are studied on the CTX spheromak. Over several years changes were made in the physical geometry of the coaxial magnetized plasma source as well as changes in the external electrical circuit. The source could be operated over a wide range of external charging voltage (and hence current), applied axial flux, and source gas flow rate. A database of resulting voltage, helicity injection, efficiency, electron density, and rotation has been created. These experimental results are compared to an ideal magnetohydrodynamic theory of magnetic flux flow. The theory is parameterized by the dimensionless Hall parameter, the ratio of electric to mass current. For a constant Hall parameter the theory explains why the voltage depends quadratically on the current at constant flux. The theory also explains the approximately linear dependence of the impedance-to-current ratio on the current-to-flux ratio of the source. The current-to-flux ratio itself (the energy per unit-helicity of the source) is bounded below by considerations of force balance. While the rotation of the flow is not understood, the density of the sustained spheromak is shown to be related to the mass flow in the source, supporting the constant Hall parameter assumption. The overall efficiency of sustainment through dc helicity injection is limited by the usual ohmic resistive decay, by the force-balance limits on the current-to-flux ratio, by the losses of the external electrical circuit, and by the fundamental limitations on the achievable impedance of flux flow in a magnetized plasma. Even so, ratios of spheromak magnetic energy to capacitor bank energy of over 17% have been achieved on CTX. Ignoring external circuit losses the efficiency of electrostatic helicity injection for converting energy received by the coaxial source to the energy of the spheromak magnetic field has exceeded 70%.

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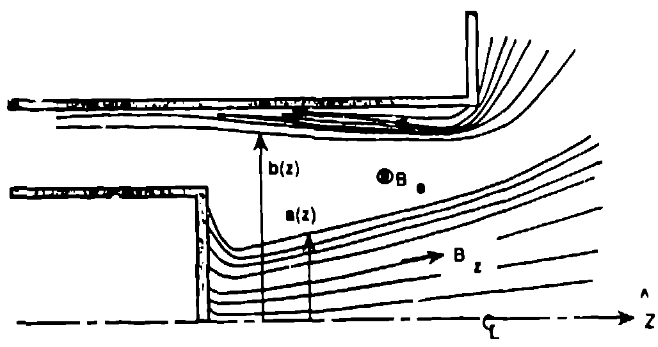

Figure 1: Diagram showing the geometry of the simple coaxial channel flow model. A region of azimuthal field B_θ where the axial flow occurs is bounded by regions of axial field B_z, with separatrices of radius $a(z)$ and $b(z)$. Diagram showing the geometry of the simple coaxial channel flow model. A region of azimuthal field B_θ where the axial flow occurs is bounded by regions of axial field B_z, with separatrices of radius $a(z)$ and $b(z)$.

Introduction The key to high-field steady state sustainment of spheromaks by dc helicity injection[1] is to maximize the magnetic helicity injection rate $\dot{K} = 2V\Phi_g$ while minimizing adverse effects due to the current I. (V is the volt age between electrodes which are connected by a magnetic flux Φ_g.) However, in the presence of a magnetized plasma an arbitrary voltage cannot be applied at the electrodes. The flux flowing away from its source is limited by the Alfvén speed of the plasma. The result is that the voltage of the source (the rate of change of flux) is not the charge voltage on the external capacitor bank, but has a very strong dependence on the current of the system[2]. The magnitudes of the magnetic fields of spheromaks[3], reversed-field pinches (RFPs)[4], and tokamaks[5] have been shown to be determined by the balance between the injected magnetic helicity and resistive dissipation. The energy-per-unit-helicity efficiency of the sustainment[3] can be raised by increasing the connecting flux, but such an increase in flux impedes the fluid flow and lowers the electrical impedance (voltage/current ratio).

The problem of maximizing the impedance and efficiency is important for any scheme for sustainment by helicity injection, including spheromaks, RFPs, or tokamaks. Understanding the physical constraints on the flow of flux in a magnetized plasma, and its relation to mass flow, is also important to understanding the physics of "relaxation" phenomena[6]. The observed relationship of mass flow to current is critical in determining the density of the sustained spheromak, which affects its transport properties[7].

Ideal MHD theory of the flow The problem of sustainment by helicity injection can be treated as a "steady-state" problem, where local time derivatives are negligible ($\partial/\partial t \to 0$). Single-fluid MHD equations with an ideal Ohm's Law are used to explain the observations. The basic equations include conservation of mass and flux, Ohm's Law, and force balance.[8]

The ideal Ohm's Law may be violated due to the presence of a Hall current. The important parameter is[2, 9]

$$\Xi = \frac{I_\mu}{I_{\dot{m}}} = \frac{I_\mu}{e\dot{m}/M} \qquad (1)$$

where $I_{\dot{m}}$ is the flow rate of a material with atomic mass M expressed in units of the current. The Hall parameter Ξ is also called the "replacement factor" since it tells us how many times the electrons that neutralize the space charge of the ions that traverse the accelerator channel are replaced.[2] If $\Xi = 0$ then the electrons and ions move identically together, and there is no current flow at all. As Ξ increases the current carried by the electrons exceeds that carried by the massive ions, resulting in a net current. In the limit where the ions are stationary and the electrons carry all the current the Hall parameter becomes infinite. If $\Xi \ll 1$ then the Hall terms can be ignored. In the CTX case, Ξ ranges between about 0.03 and 0.16.

We consider the flow in a geometry such as Figure 1. The magnetizing axial flux, created by a solenoid inside the inner electrode, emerges from the front region of the inner electrode and returns through the outer electrode of the Marshall gun. Above the lower current sheet [at $a(z)$] there will be plasma flow, electric field, and radial current density. Below $a(z)$ the axial flux (with no flow along it or azimuthal flux in it) will be compressed until radial force balance is satisfied. Only some fraction of the axial flux may be trapped in the axial flow region, and above the upper current sheet [at $b(z)$] is another region of axial flux (of the opposite sign) that is compressed against the entrance region wall. The axial flow channel expands radially against both regions of axial flux until radial force balance is achieved. Our simple model assumes there is no axial flux embedded in the region of axial flow. This approximation is essentially that the effect of the rotational force $E_r B_z$ is small compared to the axial force $E_r B_\theta$.

The force balance along the flow (Bernoulli's equation) determines an energy constant of the motion. Differentiating along the flow leads to the Huginoit equation which determines the acceleration. The acceleration can only take place when the geometry of the channel changes, or at a choke point where the velocity equals the

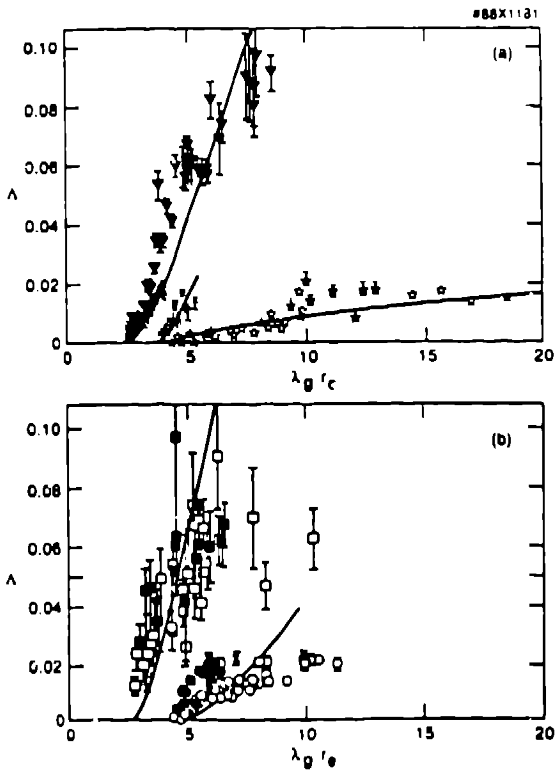

Figure 2: Gun parameter Λ versus $\lambda_g r_e$ for several different conditions.

Alfvén speed. Since the flow accelerates throughout the nozzle, the axial velocity is thus determined at the throat. The geometric shape of the nozzle is determined from radial force balance between the axial and azimuthal magnetic fields. This analysis leads to the following expression for the gun voltage

$$V_g = \frac{e\mu_0^2}{4\pi^2 M} I_g^2 \,\Xi F(x) \qquad (2)$$

where $x = \lambda_g r_e$, $\lambda_g = \mu_0 I_g/\Phi_g$, and $F(x)$ depends on λ_g/λ_{th}.[8] If there is too much axial flux in the gun, the tension in the axial field can exceed the pressure in the toroidal field and the toroidal flux will not be able to emerge from the gun.

The three powers of current in the voltage scaling Eq. (2) can be understood as follows: One power is due to the source current determining directly the toroidal flux magnitude for fixed λ_g. One power comes from the proportional increase in the Alfvén speed with the increase in magnetic field. The final power of current comes from the necessity of constant mass flow through the source due to the continuity equation. This results in a rarefaction of the density as the velocity of the flow increases since the velocity goes through the Alfvén speed at the nozzle. Thus at constant mass input the density drops as the velocity increases, further increasing the voltage and adding the final power of current to the voltage. The actual experiment only shows 2 powers of current in the voltage scaling. This is because the amount of mass flow in the experiment generally increases proportionately with the current (the Hall parameter is a constant), and thus one power of the current is canceled by the increase in density.

Experimental results The gun parameter

$$\Lambda \equiv \frac{V_g}{I_g^2}\frac{4\pi^2 M}{e\mu_0^2} = 2.6 \times 10^5 \frac{M}{m_p}\frac{V_g}{I_g^2}$$

can be plotted versus λ_g and compared to $\Xi F(\lambda_g r_e)$ from Eq. (2) (Fig. 2). The comparison with theory is a two parameter fit: first the value of $\lambda_g = \lambda_{th}$ where the voltage limits to zero is found, and then second the Hall parameter Ξ is adjusted to match the magnitude of the impedance/current ratio of the gun parameter Λ. The scaling of voltage with the square of the gun current has removed a large variation in the data, and the theory also predicts the approximate linear increase of V_g/I_g^2 with increasing I_g/Φ_g. When these large variations are removed, the simplified theory does not have the remaining curvature of the experimental data quite right, and the theory tends to underestimate Λ at small λ_g and overestimate Λ at large λ_g.

Using the two parameters λ_{th} and Ξ determined from the data combined with the value of the external circuit impedance, the voltage and current can be uniquely determined given the charging voltage on the main bank and the applied magnetizing flux. Figures 3(a) and (b) show plots of the observed current and voltage versus flux, with the predicted values from the

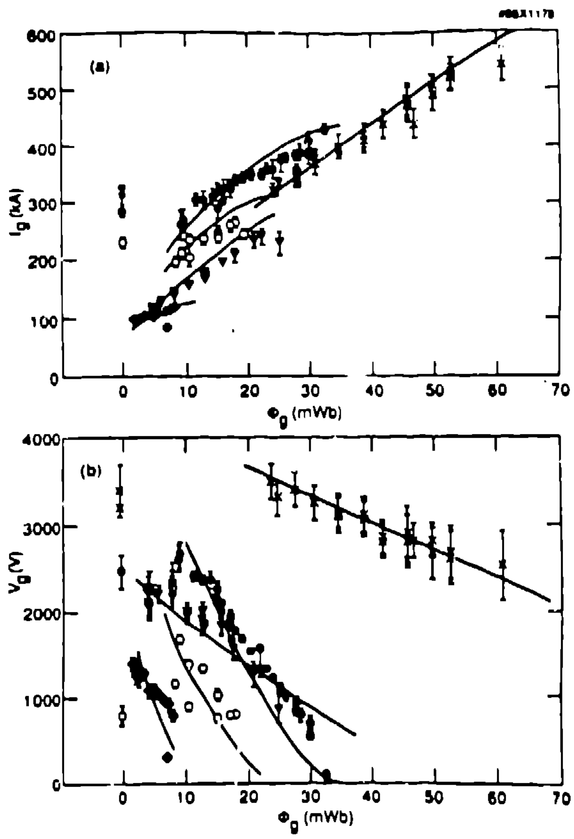

Figure 3: Gun current and voltage versus gun flux, compared to the analytic theory with the two adjustable parameters λ_{th} and Ξ. Each symbol represents a given geometry and circuit type, with the main bank voltage held constant. (a) Gun current. (b) Gun voltage.

gun law fit through the data. When plotted this way one can clearly see the huge differences in the observed voltages and currents at similar connecting flux but for different main bank voltages and circuit types.

Curves may be calculated of the current, voltage, impedance, helicity injection rate, and efficiency versus Φ_g for different main bank voltages for a given circuit. Figure 4 illustrates such a set of calculations. The efficiency η and the helicity injection rate both have maxima versus magnetizing flux, but not at exactly the same value. The maxima occurs because at low flux very little helicity is injected by the low connecting flux, and at high flux very little helicity is injected by the low voltage.

The magnitude of the density in the spheromak during sustainment depends on the gun current. Figure 5 shows how the spheromak density remains approximately proportional to the gun current, despite a significant increase in the magnitude of the "confining" magnetic fields of the spheromak[7]. Usually the amount of gas generated in the source is undetermined and $\dot{m}$ is a free parameter of the operation. In one case [Mode 1984b(5)] a "slow" gas valve was installed on the source which continually fed 10^4 torr-liter sec^{-1} of gas for many milliseconds. Figure 6(a) illustrates the changing proportionality of the spheromak density-to-current ratio as more gas was added to the source. Fig. 6(b) shows how normalizing the gun parameter Λ by the n_t/I_g proportional-estimate of $\dot{m}$ reasonably brings the voltage data together, that is, the drop in voltage as the gas is added is in theoretical agreement with the increase in $\dot{m}$.

Discussion and conclusions In the CTX helicity injection experiment we operated with a wide range of electrode dimensions, external electrical circuits, charging voltages and magnetizing fluxes. The resulting source voltages and helicity injection rates can now be understood for our coaxial source by a simple MHD theory. Previous work on coaxial accelerators had predicted and found that the voltage depended on the square of the current, assuming the the ratio of electrical-to-mass current (the Hall parameter Ξ) remained constant. We have confirmed this result, and further observed the proportional dependence of the spheromak density on source current as expected for constant Ξ. The measurements of the density and gas flow rates are within factors of 2 or 3 from expectations based on the fitted value of Ξ. We also learned that the geometry of the injection should be designed to reduce the value of λ_{th} to as close to the value of the equilibrium to be driven as possible.

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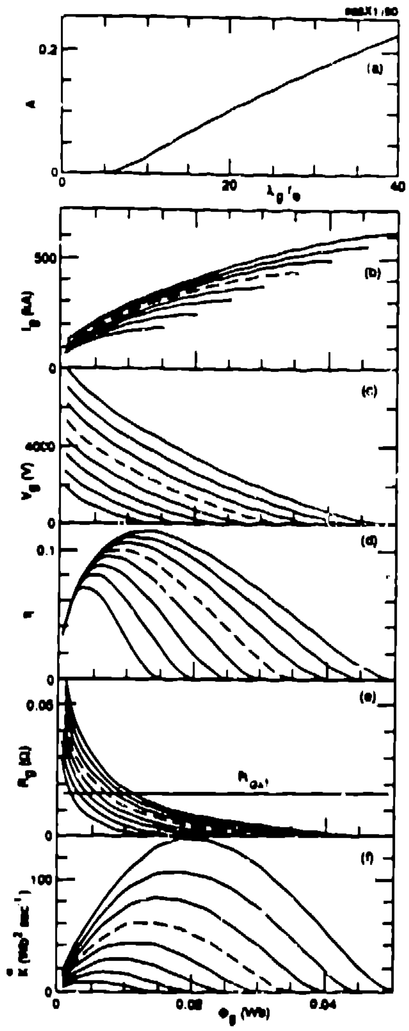

Figure 4: Gun performance versus axial flux, using the analytic theory fit to the data. Using the theory shown in (a) with R_{ext} = 16 mΩ, λ_{th} = 15.4 m^{-1} and Ξ = 0.05, the (b) current, (c) voltage, (d) efficiency η, (e) impedance, and (f) helicity injection rate are all plotted versus gun flux for main bank charge voltages from 3 to 10 kV. The curves at 7 kV are dashed.

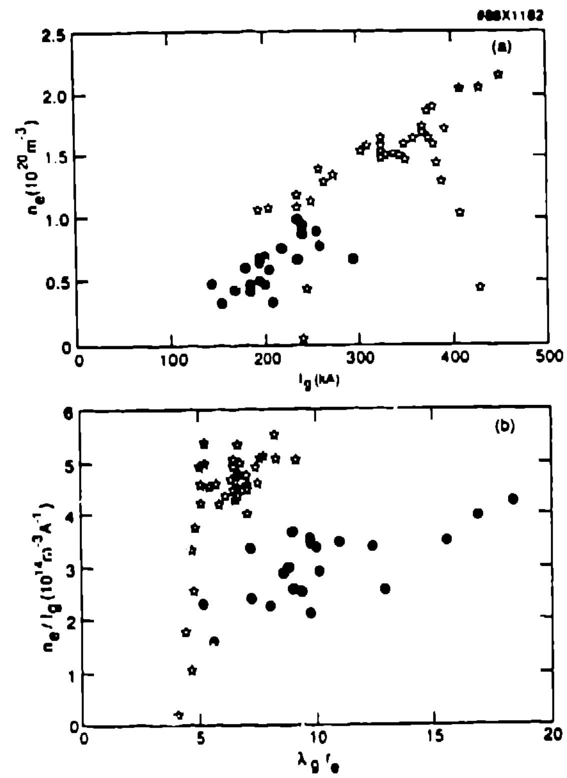

Figure 5: Spheromak volume-average density dependence on source parameters. (a) Density versus source current for two different operating modes. (b) Density divided by current versus λ_g, showing the near constancy of the spheromak density on the source current except near the helicity injection threshold when the density drops.

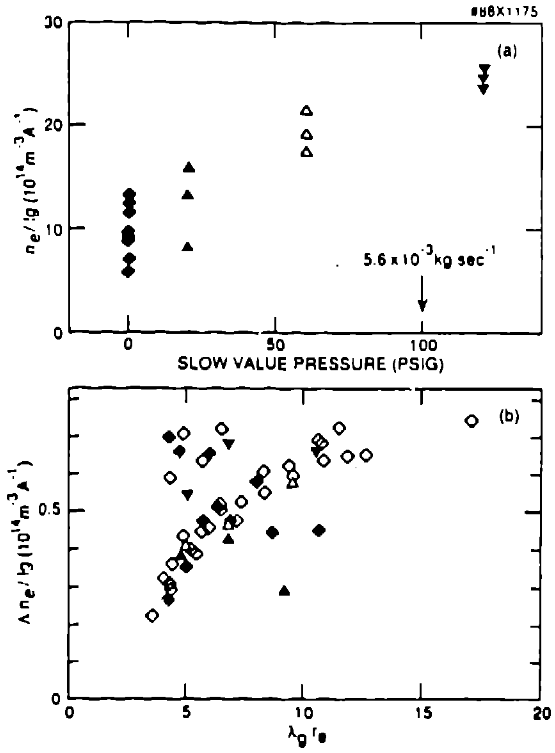

Figure 6: Effect of external changes to gas flow rate. (a) Density divided by current for Mode 1984b(5), versus the amount of pressure in the slow gas valve (in PSIG). The finite y-intercept defines the amount of $\dot{m}$ for the usual uncontrolled case. (b) Gun Parameter Λ normalized by the current-to-density ratio versus $\lambda_g r_e$ for the different discharges with the slow valve. The symbols are the same as (a), with added data from this same mode but with no slow valve and a constant value of n_e/I_g $10 \times 10^{14} m^{-3} A^{-1}$ assumed also shown (◇).