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Title: The advanced concept thruster: A new high efficiency approach to flowing plasma technology

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Form 836 (8/00)

FY02 LDRD/ER Proposal Title:

The Advanced Concept Thruster: A New High-Efficiency Approach to Flowing Plasma Technology

Technical Category: ES

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Co-Investigators:
Zhehui Wang and Louis Schrank (P-24)

Funding Request by Fiscal Year ($K): 170 for three years

Abstract:
To be written later

Work Proposed and Expected Results

Our fundamental goal is to build and demonstrate an advanced concept thruster and prove its performance and behavior for future applications. Our plan would be to:

- FY02: Revamp present facility, build plasma accelerator and power supply, and initiate tests.
- FY03: Determine current and voltage characteristics, flow density and energy. This would use standard electrical diagnostics and simple probes. Vary and optimize design.
- FY04: Change plasma parameters (by changing working gas and voltage of operation) and explore ionization and resistivity behavior of accelerator.

From this work we would have a working, well-understood prototype electrostatic plasma accelerator not constrained by Child-Langmuir limits on ion flow because of charge separation. This would allow us to propose optimized designs for applications in electric propulsion, applied plasma technologies, and basic research in magnetized plasma flow.

1) The Advanced Concept Thruster: What It Is

The intense energy density of a flowing plasma has been applied to many uses. Los Alamos National Laboratory has been working for over 40 years on research in plasma acceleration, including invention of "Marshall Guns[1]" and developments in opening switches and power flow channels. This effort includes use of such facilities as the CTX ("coaxial thruster experiment") program that developed magnetic nozzles for electric propulsion for NASA[2] and for applied plasma technologies for 3M[3], and past and current research in magnetic helicity injection[4] for magnetic fusion configurations. All these applications have generally been modeled as "ideal" magnetodynamic flows where electromagnetic forces (driven by **JxB** forces of current in the circuit) push both the electrons and ions together in the same direction at Alfvén speeds.

In reality, the Hall effect (where **JxB** forces of the opposite sign separate the ions and electrons) is important, and resulting electrostatic forces are significant in determining the flow. Charge separation develops along the direction of the acceleration. We have recently invented and applied for a U.S. patent[5] for using curved electrodes in a coaxial geometry, where the shape determines the axial distribution of the radial current density, allows straight axial streamlines to intersect both electrodes and hence see an electrostatic acceleration. The outer downstream electrode is made into a mesh to allow the accelerated plasma to exhaust. The charge separation due to the Hall effect just balances the electrostatic forces, creating plasma acceleration with theoretically more favorable scaling (ion thrust exceeding Child-Langmuir limits by an order-of-magnitude or more).

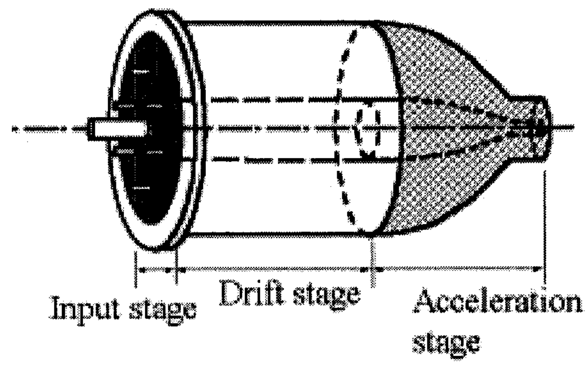

Figure 1: The converging front-end version of the Advanced Concept Thruster, from the Patent application.

While we have applied for a patent on the idea without a working model based on theoretical understanding[6], several key technical issues need to be addressed with a working system:

- Are the estimated device parameters for voltage, current, and density correct?
- Does the particle flux scale favorably with system power?
- Is the velocity of the flow and its radial profile in agreement with expectations?

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[1] J. Marshall, Plasma Phys. Controll Fusion **2**, 449 (1966)
[2] J. T. Scheuer, K. F. Schoenberg, R. A. Gerwin, R. P. Hoyt, I. Henins, D. C. Black, R. M. Mayo, R. W. Moses *IEEE Trans. Plasma Sci.* **22**, 1015 (1994)
[3] K. F. Schoenberg, R. A. Gerwin, R. W. Moses, Jr., J. T. Scheuer, and H. P. Wagner, *Phys. Plasmas* **5**, 2090 (1998).
[4] Cris W. Barnes, T. R. Jarboe, G. J. Marklin, S. O. Knox and I. Henins, *Phys. Fluids* **B2**, 1871 (1990)
[5] Zhehui Wang and Cris W. Barnes, USPTO Application S-91787 September 8, 2000
[6] Z. Wang and Cris W. Barnes, "On electrostatic acceleration of plasmas with the Hall effect using electrode shaping", submitted to *Phys. Plasmas* (2001). This manuscript was completed in early 2000, but we were advised to await international patent processing before submission.

- Can the obvious engineering drawback of a mesh at the output that must be cooled in steady-state be effectively dealt with?

2) Scientific and Technical Impact of this Project

An electrostatic accelerator not constrained by Child-Langmuir limits on the ion flow because the electrons are naturally used by the Hall effect to neutralize the space charge has many possible uses.

Electric Propulsion

"Engineers have known that the much higher exhaust velocities that are possible with electric propulsion are needed to make spaceflight less expensive and some deep-space missions even feasible."[7] Present "electrostatic propulsion" uses ion propulsion with a downstream grid accelerating ions from a source. These devices are currently in use for station keeping and on at least one deep-space probe. But the charge buildup seriously limits the thrust. The way around space-charge limitation is through plasma thrusters, the most developed of which are "Hall-effect thrusters"[8] which use magnetic fields to trap electrons while allowing electrostatically accelerated ions to escape. For even more powerful thrust, magnetoplasmadynamic (MPD) thrusters or "arcjets" have been proposed. These are the closest relative to our idea. The Advance Concept Thruster would have the advantages of better scaling at lower powers, and no ejected magnetic fields (electrostatic operation). Studies with its curved electrode surfaces are related to the need for "nozzles" in gas or plasma dynamic accelerators.

Applied Plasma Technologies

Coaxial plasma sources can serve as a cheap, efficient source of high energy density ions in the 100-1000V energy range for surface modification and treatment. The absence of magnetic fields with favorable power characteristics could make our device a good candidate for certain industrial applications.

Magnetized Plasma Flow

Such a source of flowing plasma without embedded magnetic field has a number of possible applications in basic research of plasmas. It could be used on plasma dynamo experiments, laboratory astrophysics simulations, or innovative fusion concepts that require velocity shear for improved confinement.

In general, the Advance Concept Thruster builds on a very long LANL history in the area of coaxial plasma sources, and advances our understanding of magnetohydrodynamics that should impact a variety of applications.

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[7] From "Plasma Propulsion in Space," by Eric J. Lerner in *The Industrial Physicist,* **6**:5, pg. 16 (October 2000).

[8] While the name "Hall-effect thruster" sounds very similar to our idea, the concepts are very different. The electrons are injected from an external cathode to neutralize the ion flow.

3) Background and Technical Description

With the inclusion of resistivity, the MHD equations in steady-state (where local time derivatives are negligible) with the Hall effect apply to this problem. We consider axisymmetric systems (in a coaxial geometry) that are "self-field "accelerators only (rather than deal with applied field systems that create magnetic nozzles). In resistive MHD with the Hall effect, if and only if when the electric current and the plasma flow are orthogonal ($\mathbf{J} \cdot \mathbf{U} = 0$), then there is a conserved quantity, in the form

$$U^2/2 + w + e\Phi/M = \text{const} \qquad (1)$$

along the flow, where **U** is the flow velocity, **Φ** is the electric potential, w is the enthalpy, and M is the ion mass. New solutions show that in coaxial geometry the Hall effect along the axial plasma flow can be balanced by proper shaping of conducting electrodes, with acceleration then caused by electrostatic potential drop along the streamlines of the flow. The Hall effect separation of ion and electron flow then just cancels the electrostatic charge separation. Assuming particle ionization increases with energy density in the system, the resulting particle flow rates (Γ_p) scales with accelerator bias (V_{bias}) as $\Gamma_p \propto V_{bias}^2$, exceeding the Child-Langmuir limits, which predicts a particle rate that is proportional to the bias voltage to the *3/2th* power, that is, $\Gamma_p \propto V_{bias}^{3/2}$. This enhanced particle flux achievable indicates that the proposed plasma thruster is *fundamentally different* from a *traditional* ion thruster or neutral-beam-injector type system, because it is *not* space-charge limited in the current. In particular, at low voltages this electrostatic acceleration can result in very favorable magnitude of particle current driven.

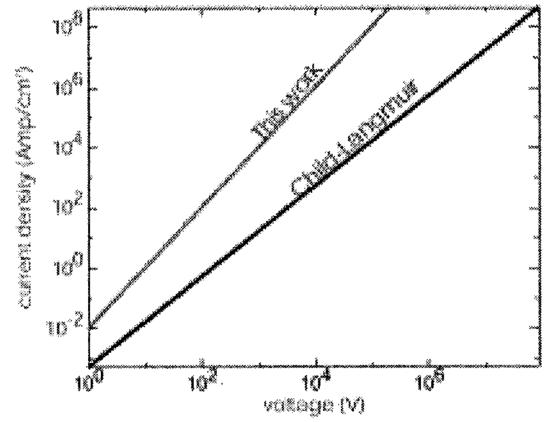

Figure 2: Predicted current density vs applied voltage in an Advanced Concept Thruster

Previous workers have proposed using segmented electrodes[9] to overcome the charge separation from the Hall effect. Alternatively, we have discovered that the electrode can be shaped in such a way that axial acceleration can occur with different streamlines intersecting the electrode all at the same potential, but with potential drops along the streamlines of the accelerating plasma. This results in a changing radius of the electrode and is hence related to the need for a "nozzle "in the acceleration process; however, our derivation using the Hall effect and resistivity added to the usual MHD equations shows the acceleration is from electrostatic forces applied on the plasma.

The solution requires a converging channel shape (for central anode; for central cathode the channel diverges in shape); to allow the axial flow to escape, one electrode would actually be made as a mesh. There is a resulting radial dependence of the exit axial ion energy. These new electrode configurations can be regarded as a hybrid of the electrostatic and

[9] A. I. Morozov, *Soviet J. Plasma. Phys.* **16**, 69 (1990); A. D. Gallimore, R. M. Myers, A. J. Kelly, and R. G. Jahn, *J. Propul. Pwr.* **10**, 262 (1994).

electromagnetic plasma accelerators, which eliminate the charge separation problem along the direction of acceleration.

The Bernoulli's law (Eq. (1) above) in the case with the Hall effect and resistivity can be compared to the usual ideal MHD case without the Hall effect. If we ignore resistivity and the Hall effect then dotting the velocity into Ohm's Law results in $\mathbf{U}\bullet\nabla\Phi=0$ and the streamlines must be equi-potential surfaces. The $\mathbf{U}\bullet(\mathbf{J}\times\mathbf{B})$ term from the force balance equation can be expanded using Ampere 's Law to result in the form

$$U^2/2 + w + I^2/(\mu_0 \rho r^2) = \text{const},$$

where we see how the electromagnetic energy is converted into velocity. We are considering something different and new, where we use the Hall term in the axial Ohm's Law to allow charge separation along the flow (driven by the radial current density) and to allow a potential drop along the streamline which provides electrostatic acceleration of the flow.

The Hall MHD equations can be solved to determine the shape of the electrodes for a given axial current density distribution. Figure 3 shows equipotential surfaces and velocity contours for a typical cases. In the converging (central anode) case the outer electrode is a mesh; in the diverging (central cathode) case the inner electrode is the mesh. In both cases, since the flow streamlines (horizontal) intersect the final electrode at different velocities, the velocity profile is hollow and radially varying.

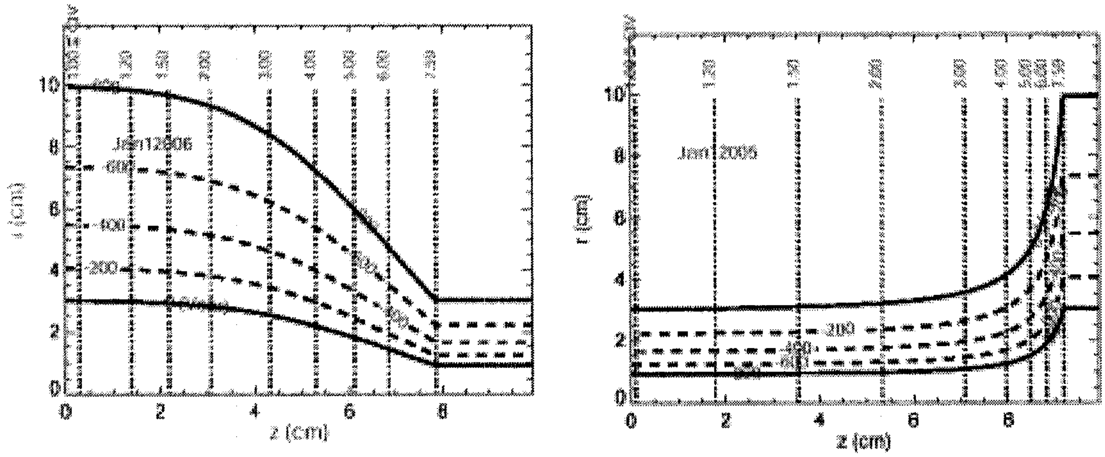

Figure 3: Equipotential surfaces (dashed lines) and velocity contours (vertical dotted lines) of converging (central anode) or diverging (central cathode) accelerators.

4) Experimental approaches, research objectives and goals

Our fundamental goal is to build and demonstrate an advanced concept thruster and prove its performance and behavior for future applications. A proposed prototype is the following. The experiment will use hydrogen as propellant, although other inert gas will also be considered to compare the effect of the atomic mass. The three stage thruster is shown in Fig. 1. It is consists of input stage, drift stage and the acceleration stage. For each stage, both the inner and the outer electrode are made of copper. In the input stage, the insulating annulus, which separates the inner electrode at the symmetry axis and the outer electrode and also supports the gas input ports, is made of boron nitrides. The number of gas input ports is 6, evenly distributed at a radius of 5 cm. The gas input holes are 0.3 cm in diameter. The inner electrod in the input stage is of radius 3 cm. In the drift stage, the radius of the inner electrode is 2.2 cm, the outer electrode has a radius of 22 cm, the annulus width is 19.8 cm. The radial dimension of the outer electrode should match the dimensions in the input stage. Thickness of outer electrode in the drift stage can be around 1 to 2 cm. The axial dimension of the drift stage is 20 to 40 cm. The outer electrode in the acceleration stage is made of tungsten coated copper meshes. The mesh axial dimension can be 15 to 30 cm. The mesh wire can be as thick as 0.5 cm in diameter. The hole of the mesh should be about 5 cm in diameter. The tapered inner electrode in the acceleration stage should match the length of the mesh. The end of the inner electrode has a radius of 0.5 cm or so. The exit annulus in the acceleration stage has an outer radius of 2.2 cm to be compatible with the mesh. Expected electrical input is 3.3 kA DC current, and voltage of 112 V. And around 20% of the electrical current variations (both higher and lower currents than 3.3 kA) are permissible. Such variations in electrical current would correspond to a 20% variation in voltage difference between the inner and outer electrode. The particle flux from such a system can be as high as 1.5×10^{22} hydrogen atoms per second. And the corresponding particle thrust is as high as 1.4 N. Similar dimension accelerators can also be constructed for the diverging configuration, FIG. 3. This type of plasma accelerator has applications in high power interplanetary space travel. These power supplies from pulsed-power capacitor banks are straightforward to apply; the key issues are the impedance and performance of the plasma accelerator itself.

We will need to build:

- The electrodes with mesh section;
- Gas puff valves for introduction of the working gas (hydrogen or noble gases like argon);
- Power supplies and switching for the electric circuit;
- Some preionization may be required in the upstream section of the accelerator, such as from a standard 13.2 MHz rf source.

We also have some scientific issues this project would allow us to study. The initial conditions of the flow in the plasma accelerator are assumed to be set by the Alfvén Critical Ionization Velocity[10] in the upstream end, and this needs to be confirmed. The 'displacement factor' or the 'Morozov Hall parameter' (the ratio of electric to mass current) relates to the ionization physics in all such systems. It reflects how much energy is required for each ion-electron pair creation in the coaxial channel. This ionization physics is vital to the operation of all plasma flow channels. We believe the role and interplay of the plasma resistivity (which previously has been ignored in such systems but which determines the boundary conditions of the ideal MHD flow) and the Hall effect have not been previously understood; for example, there has been the long-standing result that computations with Hall effect but not resistivity are not stable[11], a result we now understand and in fact use in our invention[6].

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[10] H. Alfvén, *Rev. Mod. Phys.* **32**, 710 (1960). N. Brenning, *Space Sci. Rev.* **59**, 209 (1992).

[11] K. Brushlinskii, A. I. Morozov, in *Review of Plasma Physics* **Vol .8**, 105, Consultant Bureau, (New York, 1980).

4) Participants and Plans

The Principal Investigator for this project will be Cris W. Barnes. While presently primarily involved in the ICF and Radiation Physics program, Cris has a long background in coaxial plasma sources for fusion and space propulsion, and currently is involved in magnetized plasma flow studies associated with the Livermore SSPX spheromak experiment. Co-investigators include Zhehui "Jeff" Wang, who is the principal participant in LANL's collaborative work with Livermore on SSPX, and Lou Schrank, electrical engineer and designer of advanced power supply systems for a number of high-powered fusion technology systems. (See the attached CVs for more details.)

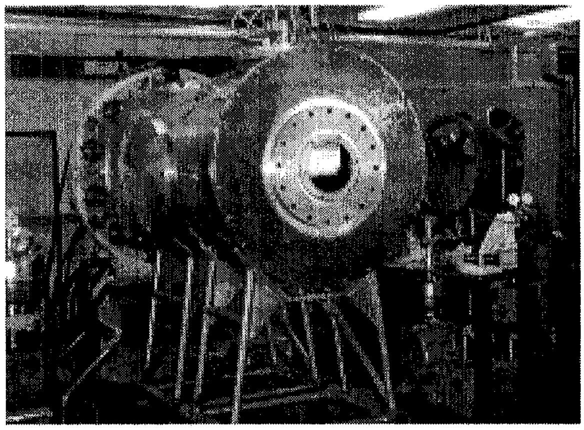

Figure 4: The existing Small-Magnetized-Plasma-Gun experimental facility is ideal for the proposed project.

The schedule for work is:

- FY02: Revamp present facility, build plasma accelerator and power supply, and initiate tests.
- FY03: Determine current and voltage characteristics, flow density and energy. This would use standard electrical diagnostics and simple probes. Vary and optimize design.
- FY04: Change plasma parameters (by changing working gas and voltage of 4operation) and explore ionization and resistivity behavior of accelerator.

To perform this work we need funding for Barnes (15%), Wang (15%), and Schrank (15%) or 0.45 staff FTE ($90k). Added to this is support for a technician (0.35 FTE or $40k) and $40k of M&S for hardware for a cost of $170k.

We would use the present the Small-Magnetized-Plasma-Gun facility at TA-35 in TSL-86 previously built for applied plasma technology development. Use of the pre-existing facility for the electric thruster operation provides vacuum systems, electric power delivery systems, some plasma diagnosis systems, a data acquisition system, and the necessary environmental, safety, and health infrastructure. Our primary work will be to build the new electrode configuration and provide needed performance diagnostics. This work would provide a working prototype for our patent, and would support future proposals for outside funding from NASA, the Office of Fusion Energy Science in DOE, and possible industrial applications.