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FUELING BY COAXIAL PLASMA GUNS*

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Coaxial Guns

Many kinds of plasma guns have been investigated by various workers and a number of them might be suitable for fueling thermonuclear reactors. I shall limit my attention here however to pulsed coaxial guns, because of their simplicity of construction, high performance, and high efficiency.^{1,2}

A coaxial gun consists essentially of two circularly symmetric metal electrodes separated at the breech by an insulator-vacuum seal, and open at the muzzle for the emergence of plasma. The plasma is derived from a puff of gas admitted by a fast valve. This makes it possible for the space beyond the muzzle to remain evacuated except for the plasma admitted by the gun. A high-voltage, high-current power supply such as a capacitor bank or an inductive energy store is connected across the electrodes at the breech. This is switched on, usually with some predetermined delay after gas admission, and produces a radial discharge through the gas between the electrodes. The B_0 magnetic field associated with the radial current produces a $j \times B$ force on the discharge, tending to drive it away from the breech and out through the muzzle. The actual processes involved are exceedingly complicated, involving ionization phenomena, electrode effects, finite gyroradius orbits of the ions, space charge electric fields and strong differences in currents carried by ions and electrons, described reasonably well as a Hall effect. The performance of a gun depends strongly on its parameters, which might be described by position in a multidimensional space with coordinates describing dimensions, electrode shapes, magnitude and polarity of supply voltage, position of gas inlet, amount of gas admitted, delay after gas admission, insulator design, etc. Optimization of performance is difficult because of the many parameters, and in practice is usually done by maximizing some single criterion of performance, e.g., neutron yield or plasma velocity. The result is a wide variety of designs and performance characteristics.

Performance of appropriately optimized designs is characterized by high efficiency (>50%), high plasma purity, and large plasma energy with state-of-the-art power supplies. The acceleration of the plasma appears in all cases to be expansion of magnetized and moderately heated plasma out through the muzzle, driven by its own internal pressure, kinetic and magnetic. Nearly all coaxial guns are operated with negative center electrode. This is because of better collimation of the emerging plasma with negative polarity. The reason is that, with Hall effect, the current streamlines are tipped backward at the cathode, producing an inward pinching force component along with the axial force responsible for acceleration through the muzzle. The B_0 field is mixed with the plasma during the ionization process. The embedded field is convected out through the muzzle with the plasma, and thus the plasma must carry an extension of the cathode current. This produces a radial pinching force, helping to collimate the plasma beyond the gun muzzle. Electrical resistivity in the emergent plasma leads to magnetic flux annihilation on the axis, and a tendency for plasma to accumulate

there as it follows the flux. This is particularly important with high Z plasmas because of electron temperature clamping by line radiation.

Plasma guns have been operated at total emergent plasma energies of 300 kJ and more. There seems to be no serious obstacle to their energies being extended to several megajoules.

Coaxial guns are divided into two types, "snowplow" and "deflagration" guns. In the snowplow gun (Figs. 1, 2) a magnetic piston progresses along the interelectrode space, ionizing the gas, mixing it with field, and pushing it aside to rest against the outer electrode. The embedded magnetic field serves to reduce heat loss to the electrodes, and its pressure subsequently drives the plasma out through the muzzle. The magnetic piston also carries a plasma (more tenuous than the plasma pushed aside and left behind). The snowplow gun is characterized by a wide spread of plasma velocities and densities. Frequently it appears in two distinct "plasmoids", a fast one followed by a slow one. The deflagration gun appears in two distinct types.^{3,4} One is the familiar M.P.D. accelerator, and its relatives, operated dc or quasi dc at a few thousand amperes and a few hundred volts. The other is a pulsed variety (Fig. 3).^{5,6} In either case a more or less stationary discharge is formed with plasma ionized, magnetized and driven out through the muzzle continuously. The deflagration gun has been the less thoroughly studied till now. In some embodiments it appears to have superior focussing properties, and to the extent it is steady-state it would appear to produce a stream of plasma with steady characteristics, velocity and density.

The plasma from coaxial guns of the snowplow-type (the ones which have been most investigated) is surprisingly free of contamination by electrode materials (usually Cu). This is due to happy accidents in the mechanisms of current transfer between plasma and electrodes. For example the initial ionizing snowplow appears to derive most of its cathode current from the collection of low-energy ions. This produces little heat at the cathode and leaves there a dense layer of neutrals, which can be ionized later during the plasma expansion acceleration phase to provide electron current without the need of thermionic emission or potential sheaths. The situation in deflagration guns is not clear, although M.P.D. devices, which share some of the characteristics of the class, appear usually to depend on thermionic emission from a hot cathode, and in some cases have shown strong potential sheaths at the anode.⁷ There may be substantial differences between pulsed and dc or quasi dc operation.

Injection into Containment Fields

Injection of gun plasma into containment fields involves phenomena at least as complicated as those in the gun. The plasma can be injected into open geometries (straight solenoid or mirror machine). In these cases it is convenient to inject parallel to the field lines. It can also be injected into closed geometries (toroidal devices such as tokamaks or absolute minimum fields as in canted-cusp toroidal

multipoles). The plasma can be injected into a device which already has a plasma in it, or into a vacuum field. The plasma can have large enough ion energy to provide a trapped plasma at thermonuclear temperatures or it can provide plasma at reduced temperatures suitable for refueling an ignited thermonuclear reactor or to provide a pre-plasma for heating by compression or other process. Injection can be high-beta or low-beta depending on whether the injected plasma substantially excludes magnetic field after injection or not. We have here four pairs of alternatives which can be combined to give sixteen different combinations. The phenomena encountered in the different combinations are generally quite different from each other, and few of them have been adequately investigated experimentally. For this reason I shall mostly limit my discussion to cross-field injection and shall concentrate on the case of injection into systems already containing plasma, the general case for a tokamak.

A number of experiments have been performed in which coaxial gun plasma is injected across a magnetic field at right angles to the direction of the field.^{7,8,9,10} At moderate magnetic field strengths, the fast plasma enters the field almost as though it weren't there, and proceeds across the field at its original speed, still collimated into a narrow jet. The plasma is thoroughly permeated by the magnetic field in a low-beta manner, there appearing to be no reduction of field strength inside the plasma. This implies that the plasma was initially at a low temperature, although it has a large streaming energy density, and that it is not heated appreciably upon entering the field. The plasma is observed to contain a transverse electric field commensurate with its velocity and the strength of the magnetic field ($\vec{E} = \vec{v} \times \vec{B}$). The propagation of the plasma across the field appears to be reasonably explainable in terms of polarization charges on its transverse surfaces. Plasma between the charges finds itself in a uniform transverse electric field and thus drifts at speed E/B . A tenuous plasma spreads outward along the field lines passing through the plasma, providing electrical contact between the plasma and whatever lies on the same field lines. This allows potential probing outside of the energetic plasma stream. It is also possible, because of this, to bring the plasma to a stop by discharging its polarization field through a metal plate or through another plasma, moving across the field in the opposite direction and therefore with opposite electric polarization. Substantial currents flow along the field lines and across the plasma. The $\vec{j} \times \vec{B}$ force of this current then stops the plasma.

While the propagation of the magnetized plasma across the field can be rationalized, its entry into the field is not well understood. The question is how are the field and the plasma thoroughly mixed without heating the plasma? We might say that the mechanism is unimportant and that we care only that it does enter the field. The difficulty here is that under some conditions it does not enter the field, and that these are conditions of some practical interest.

We are concerned with the entry of a long stream of plasma into a transverse magnetic field and we know that, once the stream is well inside, it is thoroughly permeated by the field. We can imagine that the ions, because of their larger mass, can penetrate the field farther than the electrons, produce a positive space charge and an electric potential, the gradient of which gives the electric field required for the cross-field drift. Somehow the electric field of this space charge then manages to drag the electrons in to produce quasi-neutrality. The potential of the ion

space charge, according to this picture, would be limited by the ion kinetic energy in the plasma stream and this would put a limit on the width of the stream given by $w < Mv/2Be$. Further complications are introduced by the loss of ion kinetic energy to be expected when the ions penetrate to the high positive potential produced by their own space charge. In addition the electrons would be expected to gain energy in falling into the positive potential, and this would certainly heat them and produce diamagnetism. Observations show that the diamagnetism is minimal, not over 10% beta, and that no appreciable slowing of the ions occurs. The injection process may involve some kind of clumping of the entering plasma so that ions and electrons enter the positive potential attached to one another so that the gain and loss of energy are minimal.

There is experimental evidence that the presence of a background plasma in the magnetic field interferes with the entry mechanism and prevents low-beta injection. This was discovered during a two-gun injection experiment, where the electric field of each plasma stream was used to depolarize and stop an oppositely directed stream.⁹ If one of the guns was fired about one millisecond early, the other gun plasma did not enter the field. The phenomenon was not thoroughly investigated because of the shortness of time, so it is not known whether a change of parameters, e.g., a reduction of field strength, would have allowed the second plasma stream to enter. It is not known whether the cause is interference with the field-plasma mixing process or whether it is line-tying after mixing.

Injection into Reactors

Where does all this leave us with regard to injection into the ambient plasma of an operating reactor? It appears that if line-tying has anything to do with the prevention of low-beta injection by a background plasma, the effect should be even stronger under reactor conditions. This is because at reactor temperatures the effective magnetic Reynolds number should be very large, $R_m = 2\pi w/a \sigma v \gg 1$ where w is the width of the plasma stream, a is the minor radius of the plasma, σ is the conductivity (emu), and v is the velocity. This is equivalent to saying that, on the timescale of plasma flow into the field, the magnetic lines of force are well frozen into the plasma. Qualitatively this implies that field lines in the injected plasma are trailed behind it inward into the containment field, slowing it down by their tension and then perhaps pulling it outward again, provided they are anchored at the outside. It should be emphasized that this qualitative picture tends to break down at its very complexity, so that theoretical predictions supported by experiment are on shaky ground. However, it appears that we should first consider high-beta injection.

In high-beta injection, with reference to Fig. 6, we might expect the plasma stream to impact against the field in a more or less cylindrical form. We assume that the stagnation pressure (nm^2) is larger than the field pressure. Thus the plasma punches a hole in the field and enters as though it were a conducting metal cylinder. In impacting against the field, the ion temperature of the plasma is raised (Fig. 7). Once inside, the transverse kinetic pressure of the plasma holds back the surrounding magnetic field. There is no equilibrium in this configuration because the pushing aside of the field raises its pressure on the transverse boundaries and lowers it near the plasma in the direction of the field. The plasma thus is compressed transversely and

expands along the field. The result is that the original cylindrical shape of the plasma is transformed into a spatulate shape, twisted like a corkscrew in a sheared field as in a tokamak. The plasma does not really have a thin current sheet separating a field-free region from the containing field. Normally we find a current sheath of the order of an ion-gyro radius thick. A thin sheath implies electric fields to transfer to the ions the $\mathbf{j} \times \mathbf{B}$ forces on the electrons. As the cylinder is flattened between the field lines, it eventually becomes so thin that it is all sheath. It has magnetic field soaked into it through its whole thickness. The plasma in the sheath on the surface of the stream is at all times line-tied to the ambient plasma in the field, and tends to drag it along. This slows down the sheath plasma and leaves it behind to flow out along the field lines and mix with the ambient plasma. It is likely to slow down the whole stream because of interchange of ions between sheath and the body of the stream.

Thus we expect that, on some scale, gun plasma with sufficiently high stagnation pressure should enter the containment region of a reactor and mix with the ambient plasma. A denser, faster, larger diameter stream should penetrate farther. The subject is too complicated for reliable predictions to be made. Some relatively simple experimentation would illuminate the subject considerably. It is regrettable that the experiments of Hammel and Kewish were terminated before attaining more data.

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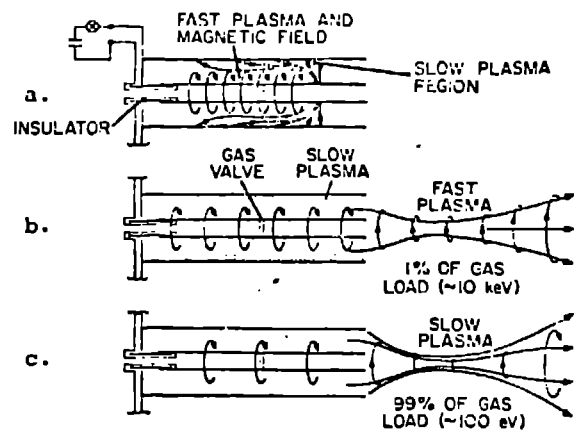


Fig. 1. Coaxial Gun, Snowplow Type.
a. Magnetic piston moves along barrel, dense magnetized plasma pushed aside, tenuous plasma in piston.
b. Piston with "fast plasma" emerges from muzzle.
c. Dense magnetized plasma emerges to produce "slow plasma".

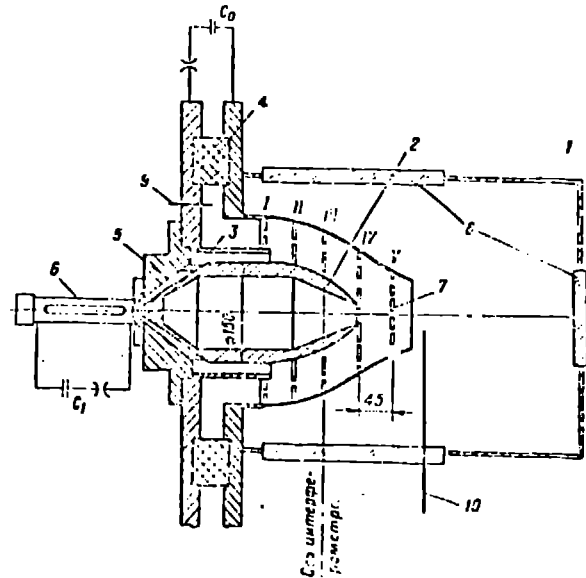


Fig. 2. Coaxial Gun at Kurchatov Institute. Typical of reference (2). Inner electrode diameter 15 cm. Slots are for interferometric observation.

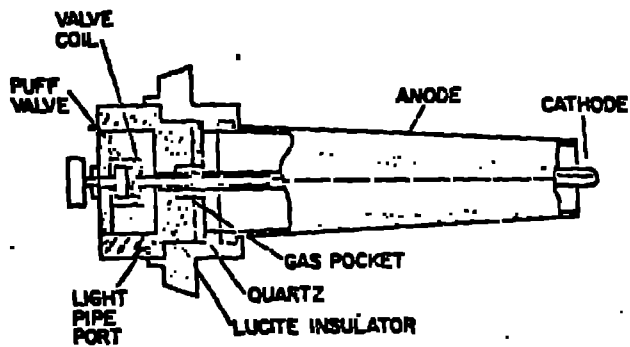


Fig. 3. Deflagration Gun of D. Y. Cheng Gun - 30 cm long.

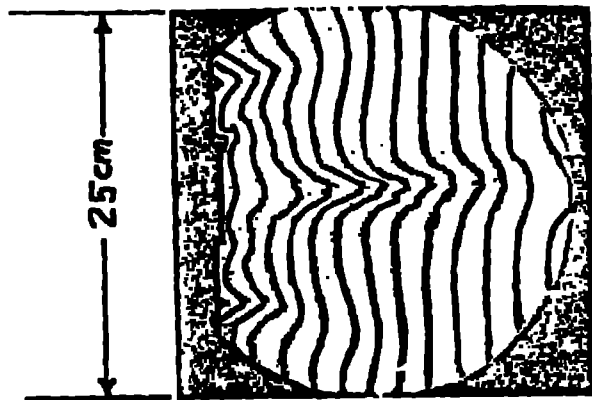


Fig. 4. Ruby Laser Holographic Interferogram (retouched) One fringe - $3 \times 10^{17}/\text{cm}^3$; Plasma speed - 2×10^7 cm/sec; Central density - $10^{17}/\text{cm}^3$; Deuterium.

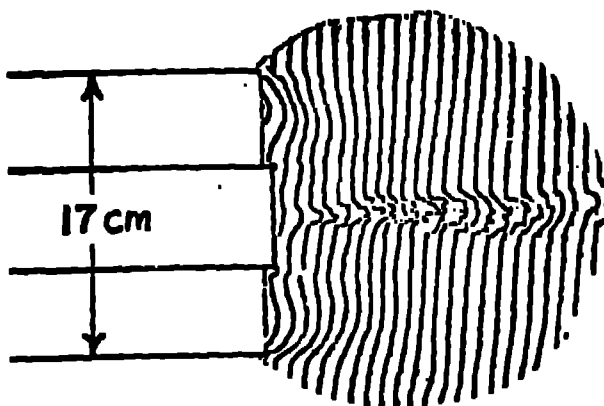


Fig. 5. Holographic Interferogram of Ne Gun Plasma (retouched). Dense condensation on axis is due to resistive flux annihilation.

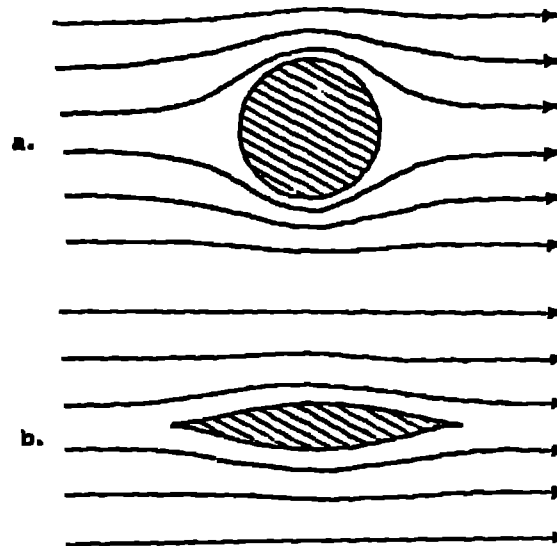


Fig. 6. High-Beta Injection
a. Plasma on first encountering field
b. Plasma after deformation by field

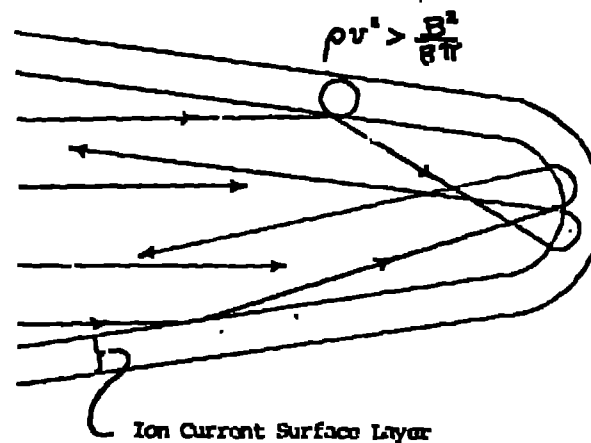


Fig. 7. High-Beta Collisionless Injection.