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CROSS-FIELD INJECTION OF A CHARGED, POLARIZED,
ION-ELECTRON BEAM

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CROSS-FIELD INJECTION OF A CHARGED, POLARIZED, ION-ELECTRON BEAM

ABSTRACT

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An early idea for fueling a controlled fusion device had been the injection of a polarized mixture of ions and electrons across a magnetic field and into the device. Now, the beam intensity (several kA/cm^2) required for this technique is available from pulsed ion diodes. Remaining feasibility questions involve beam optics and trapping. The most obvious advantage over neutral-beam injection is avoidance of the need to produce high-energy atoms. Therefore, the technique will compete best at ion energies above 100 keV. The method appears feasible for pulsed startup of mirror machines, but not for steady-state injection into a plasma.

INTRODUCTION

An early idea for fueling a controlled fusion device had been the injection of a polarized mixture of ions and electrons *across* a magnetic field and into the device.¹ If the beam particle density is sufficiently high, space-charge separation will occur only within a boundary layer near the surface of the ion-electron beam. As shown in Fig. 1, a transverse electric field will be induced by the space-charge separation such that $\underline{E}$ is equal and opposite to $\underline{v} \times \underline{B}$. Consequently, the main body of the beam will not be magnetically deflected if the beam is sufficiently intense. Only the ions and electrons in the boundary layer will be deflected and lost from the beam.

(a) Beam before entering B field

(b) Beam crossing B field ($\underline{B}$ into paper)

Fig. 1. Propagation of an intense ion-electron beam (from Ref. 1).

Such an injection scheme had several attractive advantages over neutral-beam injections; for example,

- Production of high-energy neutral atoms would not be required, and
- A target plasma would be orders of magnitude easier to produce because, rather than trapping the beam by ionizing the injected neutrals, it would only be necessary to neutralize the E field at the proper time and place.

However, in this injection scheme, each ion in the boundary layer is deflected and lost from the polarized beam in a distance comparable to one gyro-radius. Therefore, the total beam current must be larger than the current required to maintain the boundary layer. Such large currents have only recently become available from pulsed ion diodes.

Lately, we have become interested in high-energy collisionless beams. This situation somewhat differs from that of a collisional plasma injected across a magnetic field.²

THEORETICAL MODEL

The thickness T of the ion boundary layer will adjust itself so that $\underline{E} = \underline{v} \times \underline{B}$ in the main body of the beam; i.e.,

$$\nabla \cdot \underline{E} = nq/\epsilon_0 = j/\epsilon_0 v.$$

In the two-dimensional slab approximation, $\nabla \cdot \underline{E} \sim E/T$. Therefore, $|E| = vB = jT/\epsilon_0 v$.

The current I_b required to maintain the boundary layer is

$$I_b = jT \text{ amperes/metre} = \epsilon_0 v^2 B.$$

For the beam to propagate a distance X across the magnetic field, the ratio $I(\text{total})/I_b$ must be much larger than the ratio X/a (where $a = mv/Bq$ is the ion gyroradius) because this model assumes that each ion in the boundary layer is lost from the beam in a distance comparable to a . This assumption is rather pessimistic; i.e.,

$$I(\text{total})/I_b \gg X/a$$

$$I(\text{total}) \gg (\epsilon_0 v^2 B) X (Bq/mv) = \epsilon_0 (q/m) v B^2 X.$$

For 100-kV D^+ ions, if $B = 1$ tesla and $X = 1$ metre, $I(\text{total}) \gg 1300$ ampere/metre. This requirement is filled by the performance of pulsed diodes. In fact, values of B and X may then be chosen much larger than 1 tesla and 1 metre without violating the above criterion.

This theoretical model applies to propagation of a polarized beam in a vacuum but not through a plasma. Plasma penetration is probably impossible because the plasma would short out the required electric field.

FEASIBILITY

In determining the feasibility of injecting a polarized ion-electron beam, the most obvious questions concern the requirements for beam intensity, for beam optics, and for beam trapping within the magnetic field. Answers to these questions are summarized in Table 1.

Table 1. Summary of feasibility considerations.

Consideration	Comment
Beam intensity	Beams emitted by pulsed diodes have been shown to have adequate intensity (several kA/cm^2). ³
Beam optics	The optical quality of pulsed diode beams is not known. However, because a gas neutralizer is not required, the polarized-beam injector may be located very closely to a large machine such as the MX, and the acceptable beam divergence angle will consequently be several degrees.
Beam trapping within the magnetic field	<p>The polarized beam may be trapped in either of two ways: by using a small target plasma to short out the electric field at the proper time and place; or by choosing an injection path similar to that of Baseball I, for which $\underline{v} \times \underline{B}$ is maximum at the location at which trapping is desired.⁴</p> <p>Steady-state trapping of a charged beam in a collisionless situation is impossible because of the usual Liouville considerations. However, trapping of a pulsed charged beam is possible if the time duration of the induced E field is sufficiently short.</p>

CONCLUSIONS

At the present time, it is easy to find difficulties with all proposed methods for the production of high-energy neutral beams. Thus, the most obvious advantage of polarized-beam injection is that it offers a means of avoiding the production of these atoms. Polarized-beam injection will therefore compete best at energies above 100 keV.

As explained above, steady-state trapping of a polarized beam is probably impossible. Therefore, although the method cannot be used for heating a tokamak plasma, it appears feasible for pulsed startup of a mirror machine because then the electric field required for injection disappears before it becomes a loss mechanism.

REFERENCES

1. A proposal written at Oak Ridge National Laboratory in the 1950's indicates earlier work on polarized-beam injection by a group under R. F. Post and by another group at MIT. I cannot cite formal references for this early work. More recent work has been conducted on propagation of plasmas across magnetic fields, but I think not of directed ion-electron beams.
2. For example, D. A. Baker and J. E. Hammel, "Experimental Studies of the Penetration of a Plasma Stream into a Transverse Magnetic Field," *Phys. Fluids* 8, 713 (1965).
3. For example, D. S. Prono, J. W. Shearer, and R. J. Briggs, *A Pulsed Ion Diode Experiment*, Lawrence Livermore Laboratory Rept. UCRL-77862 (1976); submitted to *Phys. Rev. Lett.*
4. Such an injection path is described by C. K. Hinrichs and J. E. Osher "High-Energy Neutral Injection into a Mirror-Cusp Magnetic Well," *Phys. Fluids* 9, 1522 (1966).

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