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Magnetically insulated helium ion diode

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A gas-puff magnetically insulated ion diode is under development as a pulsed source of high-energy alpha particles for magnetic fusion experiments. The diode is patterned after the Cornell gas-puff diode [J. B. Greenly, M. Ueda, G. D. Rondeau, and D. A. Hammer, *J. Appl. Phys.* **63**, 1872 (1988)], but with modifications to accommodate higher voltages (< 1 MeV) and operation in helium. The diode is designed to yield current densities approaching 200 A/cm^2 one meter downstream from the source; in our first test of the new source, a helium beam was obtained.

INTRODUCTION

Although the behavior of alpha particles in a fusion device is a crucial issue, it is difficult to study in existing machines since few devices can produce significant numbers of alphas without polluting the machine with tritium. Intense pulsed ion beams may provide a source of MeV helium ions for testing of alpha particle diagnostics and studies of alpha confinement. In conjunction with edge flux measurements, the short beam pulse (which is essentially a delta function on tokamak timescales) may permit direct measurements of alpha transport. In order for a neutralized helium ion beam to propagate via the $E \times B$ drift² in a typical tokamak magnetic field ($B \approx 2$ T), a current density in excess of 180 A/cm^2 is required. Extrapolation of recent studies³ of beam propagation in plasma suggests that the injected beam will travel collectively through the edge of the background plasma and will stop when the plasma density reaches $O(10^{13}) \text{ cm}^{-3}$.

High current ion sources are well developed. The highest current sources use a magnetically insulated acceleration gap, which insulates the flow of electrons to achieve a significant enhancement in the ion current density above the Child-Langmuir limit.⁴ Spark sources or fast-inductive breakdown coils are typically employed to generate the ions prior to acceleration. Species used in ion beams of this type include H, Li, C, N, Al, Ar, and Ti.^{1,5}

Helium beams have not yet been reported. Helium is expected to be more difficult to use than other gases because it has the largest ionization potential of any element. In this article, we discuss the gas-puff diode we have fabricated for use as an alpha source (Sec. I) and present initial results (Sec. II).

I. EXPERIMENTAL APPARATUS

The overall schematic of the experiment is illustrated in Fig. 1. The ion source is energized by a 500-kV Marx accelerator system, 10 stages of $0.4\text{-}\mu\text{Fd}$ capacitors, $L_{\text{total}} = 1.8 \mu\text{H}$, with a series damping resistance of 1.8Ω . The cathode is located 1.0 cm downstream from the anode and is comprised of two annular coaxial field coils with thin graphite rings facing the anode to protect the field coils from ablation damage; the inner to outer coil turns ratio is 3:1. These coils are energized by a $500\text{-}\mu\text{Fd}$ capacitor typically charged to 3.5 kV to produce a 4.2-kG radial magnetic insulation field that

is uniform across the acceleration gap. Between the coils there is an annular gap of approximately 100 mm i.d. and 150 mm o.d. through which the beam is extracted. Downstream of the acceleration gap the beam is charge and current neutralized by electrons dragged from the surrounding cathode surfaces.

The helium ion source (Fig. 2) is mounted on a tubular anode support post as shown in Fig. 1. The tube serves to shield the ion source power feeds and direct these power cables to the oil-vacuum interface flange. Penetration into oil is achieved through four $\frac{1}{4}$ in. Wilson seal feedthroughs that seal on the polyethylene surface of RG-8 center conductors.

The gas-puff valve is comprised of a five-turn, flat-spiral wound coil and spring-loaded aluminum poppet which injects helium gas radially into the preionization chamber. The valve is driven by a $7.5\text{-}\mu\text{Fd}$ capacitor normally charged to 4 kV. The gas line is typically pressurized to ~ 5 psig; pressures ≥ 8 psig usually cause gas to leak into the chamber. A puff causes the base pressure in the chamber to increase transiently from 5×10^{-5} T to $\approx 10^{-3}$ T.

The preionizer is comprised of eight pins equally spaced around the circumference of the preionization chamber attached to $2.2\text{-}\Omega$ series resistors and inserted into the gas flow upstream of the anode-extractor grid. This circuit is energized by a spark-gap switched $2\text{-}\mu\text{Fd}$, 3.5-kV discharge capacitor delivering 3 kA.

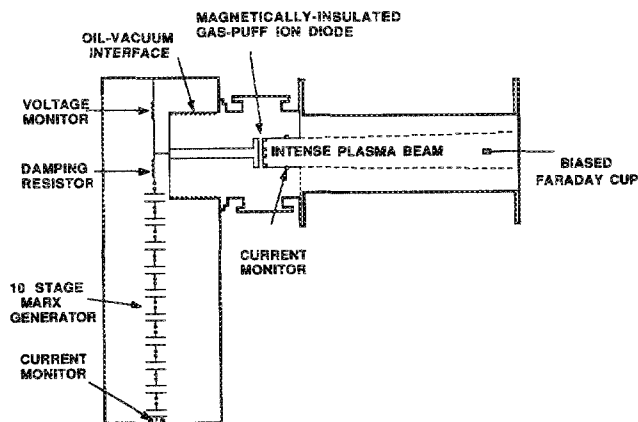


FIG. 1. Schematic diagram of the experiment.

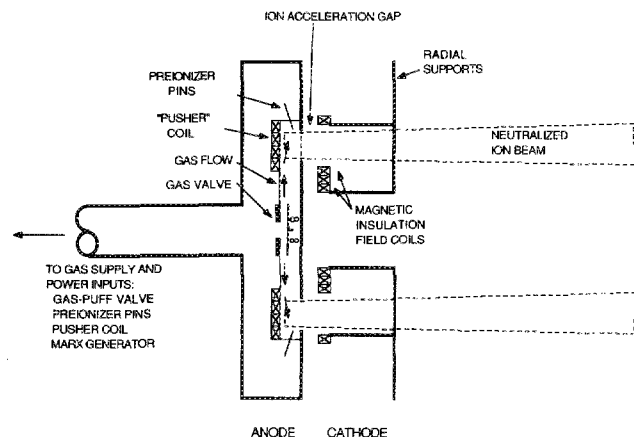


FIG. 2. Schematic diagram of the magnetically insulated gas-puff ion diode.

The B radial "pusher" coil serves to fully ionize the gas, by inducing an azimuthal electric field in the preionized gas, and to compress the plasma, pushing it into the acceleration gap by $J \times B$ forces. Thus, higher density is achieved than would otherwise be provided by Bohm diffusion. The driver for this circuit consists of a spark-gap switched 2.1- μ Fd, 10-kV capacitor bank.

The above three anode-plasma source circuits are located in the oil section of the Marx generator to minimize stray inductance and achieve fast rise time. Each circuit is isolated from ground by long water resistors. The trigger pulses needed to fire these circuits are isolated inductively (0.27 mH) using an iron-core transformer of 50 cm² cross section. Thus, when the Marx generator fires all discharge circuits float to the full anode voltage.

Experimental diagnostics include the Marx voltage and current, biased Faraday cups to measure the ion current density and time-of-flight energy, and a plasma-light monitor to record the light intensity in the accelerator gap.

II. INITIAL RESULTS

In our initial experiments, we have added 0.5% argon gas to the helium gas in the hope that the Penning effect⁶

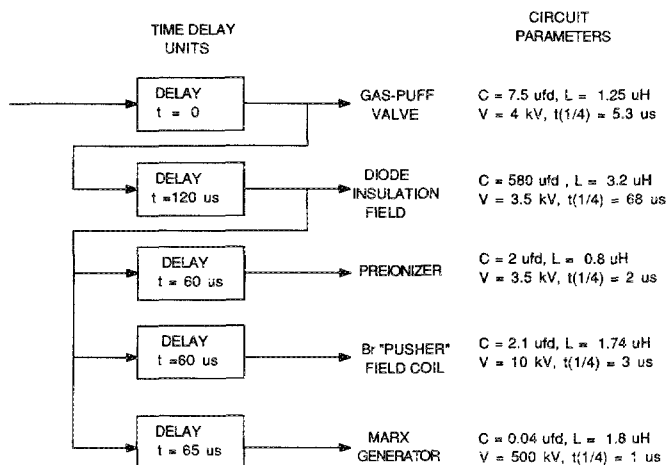


FIG. 3. Timing sequence and circuit parameters.

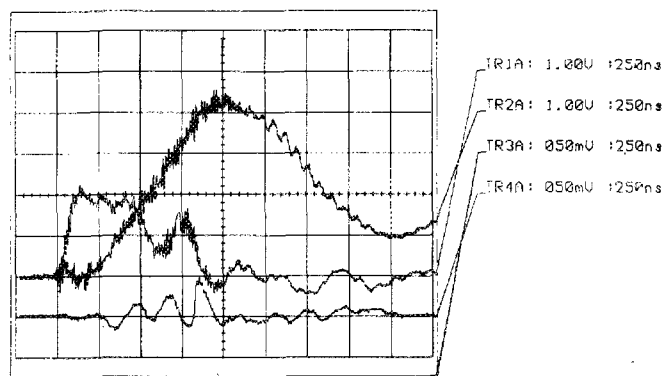


FIG. 4. Marx diode current 15 kA/div (upper trace), Marx output voltage 76 kV/div (middle trace), and ion-current density one A cm⁻²/div (bottom trace).

would facilitate ionization. Breakdown of the helium was monitored using a photodiode. No light was produced by the valve or preionizer circuits alone but was observed when the preionizer was energized > 150 μ s after the gas valve circuit. Dry air was ionized over a wider range of power supply and gas pressure settings than helium. The optimal delay between the valve power supply and the preionizer power supply was only about 20 μ s less for helium than for air, from which we tentatively conclude that the valve takes roughly 120 μ s to fully open. Application of the pusher coil following the preionizer results in a much brighter flash of light; without the preionizer, the pusher coil is ineffective in ionizing the gas. A typical timing sequence is outlined in Fig. 3.

The diode characteristics with the Marx accelerator voltage applied are shown in Fig. 4. In this shot the output voltage is intentionally reduced from the 500-kV maximum supply voltage to minimize the possibility of damage during these initial experiments. The output voltage rises to an initial value of approximately 150 kV as the diode current increases. This V - I characteristic indicates that the diode impedance is decreasing approximately linearly during the pulse. Approximately 0.5 μ s after the start of the pulse a slight increase in the ion current density is noted, followed later in time by two additional pulses. These pulses are correlated with a similar modulation of the accelerator voltage, delayed by the ion-propagation time to the Faraday cup located approximately 50 cm downstream from the anode surface. From the propagation delay for the first ion current peak the ion energy is calculated to be on the order of 100 keV. Subsequent peaks correspond to lower ion energy or higher ion mass. Future measurements will characterize the beam composition and energy with a Thompson parabola. The measured current density is on the order of 1 A/cm², indicating that the diode characteristics require further optimization.

Application of the Marx voltage without first preionizing the gas results in the full open circuit voltage and no measurable ion current density. This mode of operation eventually results in the generator shorting to the chamber walls upstream of the cathode (as verified by no current flow to the cathode shank). Alternatively, preionizing too early

results in rapid shorting of the diode voltage to the cathode as evidenced by no ion current and large cathode shank current.

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⁶Essam Nasser, in *Fundamentals of Gaseous Ionization and Plasma Electronics* (Wiley-Interscience, New York, 1971).