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Development of a 1-m plasma source for heavy ion beam charge neutralization

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Abstract

Highly ionized plasmas are being employed as a medium for charge neutralizing heavy ion beams in order to focus to a small spot size. Calculations suggest that plasma at a density of 1–100 times the ion beam density and at a length ~0.1–1 m would be suitable for achieving a high level of charge neutralization. A radio frequency (RF) source was constructed at the Princeton Plasma Physics Laboratory (PPPL) in support of the joint Neutralized Transport Experiment (NTX) at the Lawrence Berkeley National Laboratory (LBNL) to study ion beam neutralization. Pulsing the source enabled operation at pressures $\sim 10^{-6}$ Torr with plasma densities of $10^{11}\,\mathrm{cm}^{-3}$. Near 100% ionization was achieved. The plasma was 10 cm in length, but future experiments require a source 1 m long. The RF source does not easily scale to the length. Consequently, large-volume plasma sources based upon ferroelectric ceramics are being considered. These sources have the advantage of being able to increase the length of the plasma and operate at low neutral pressures. The source will utilize the ferroelectric ceramic $BaTiO_3$ to form metal plasma. A 1 m long section of the drift tube inner surface of NTX will be covered with ceramic. A high voltage (~1–5 kV) is applied between the drift tube and the front surface of the ceramic by placing a wire grid on the front surface. Plasma densities of $10^{12}\,\mathrm{cm}^{-3}$ and neutral pressures $\sim 10^{-6}$ Torr are expected. A test stand to produce 20 cm long plasma is being constructed and will be tested before a 1 m long source is developed.

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1. Introduction

HIBALL-II is a possible heavy ion fusion reactor design [1]. The final focusing magnets

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must focus multiple heavy ion beams to a small spot size in the target chamber. This will require a deliberate charge neutralization of the ion beams. This technique can bring substantial benefit to any HIF driver-chamber design. The Neutralized Transport Experiment (NTX) [2] has been configured to investigate the most promising neutralization methods. One charge neutralization concept employs a heavy ion beam propagating through a highly ionized plasma column [3]. The plasma will be created or injected into the drift section between the last magnetic lens and the reactor chamber. The cold plasma ion motion is neglected, and electrons from the cylindrical plasma move into the beam channel, reducing the net positive beam charge over the larger volume of the plasma channel. For NTX, ion beam densities are $\sim 10^8$–$10^9\,\mathrm{cm}^{-3}$. Calculations require the plasma to be in the range of 0.1–2 m in length with an electron density comparable to 1–100 times the beam density. The operating pressure for the plasma needs to be $\sim 10^{-6}$–10^{-5} Torr to prevent neutrals from stripping the beam ions to higher charge states.

2. Previous RF plasma source

The heavy ion beams for fusion will have pulse lengths in the sub-microsecond range. To achieve the low neutral gas pressure and plasma density required for charge neutralization on NTX, the volumetric plasma source was designed to operate in a pulsed mode, where a gas valve and RF power are triggered simultaneously [4]. The idea is to create plasma in the source when the transient gas pressure is $\sim$0.1–0.5 mTorr. With the plasma sound speed 1–2 orders of magnitude larger than that of the neutral gas, the plasma will arrive in the ion beam drift tube before the neutral gas. Since the ion beam pulse duration is $\sim 1\,\mu$s, the conditions required for the charge neutralization can be achieved transiently for the duration of the beam pulse. This can be seen from the source characteristics for a net forward power of $\sim$3.5 kW vs. time in Fig. 1. Before $t = 3.75$ ms, the plasma density is less than the sensitivity of the Langmuir probe ($\sim 10^7\,\mathrm{cm}^{-3}$), and the neutral pressure is below the sensitivity of the dynamic pressure measurement (10^{-6} Torr). At $t = 3.75$ ms the electron density is $10^{11}\,\mathrm{cm}^{-3}$ and simultaneous the neutral pressure is low. The ionization fraction for $t = 3.75$–4 ms is in the range of 50–100%. At later times the power density is not sufficient to sustain the ionization fraction, and the neutral density rises faster than the electron density. During the experiments at LBNL, the pulsed plasma source was effective in charge neutralizing the ion beam. The plasma was approximately 10 cm in length along the NTX drift tube. However, the neutral pressure in NTX would rise due to the plasma source's gas puff and the vacuum system took a few minutes to pump down again. This experience forced the consideration of a different plasma source type for scaling the plasma into a 1-m column with a reduced neutral pressure rise.

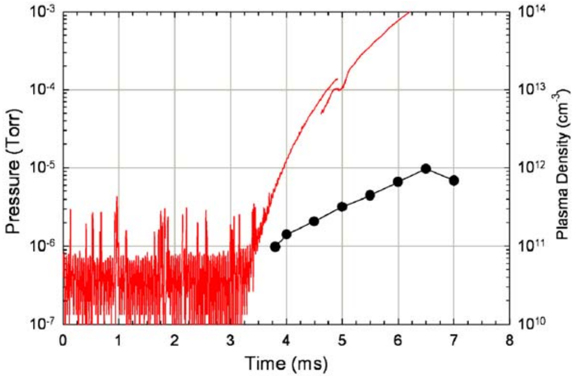

Fig. 1. Time evolution of neutral gas pressure and plasma electron density (solid circles) in the pulsed plasma source.

3. Ferroelectric plasma source

Ferroelectric materials have been intensively examined as high-current density electron emitters [5–7]. They have been projected to serve as large surface area, high-current density cathodes. An electrode mesh-like structure is mounted to the emitting side of the ferroelectric material and the back surface has a metal plate electrode. A 3–15 kV potential is applied to the electrodes depending upon the thickness of the ferroelectric material. For ultra-thin film ferroelectric materials, the applied voltage results in spontaneous polarization reversal on a nanosecond timescale, and a high electric field. Spontaneous polarization reversal yields a noncompensated charge at the surface and a high electron emission across the entire thin film.

For millimeter thick ferroelectrics, the electric fields are too small to produce polarization reversal. However, plasma emission is observed and is simply explained by electron emission from the vacuum micro-gaps between the dielectric surface and the edge of the metal electrode surface. For this configuration, the value of the dielectric constant is the key factor. Commonly used ferroelectric materials have extremely large dielectric constants: $BaTiO_3$ has a dielectric constant in the range of 1000–3000 and $Pb(Zr,Ti)O_3$ has a constant in the range of 3000–6000. Once the threshold voltage is reached plasma is formed over the entire surface of the dielectric. Typical current density yields are $0.5\,A\,cm^{-2}$. Plasma emissions from these dielectrics have been characterized for $BaTiO_3$. There is a sharp fall off in electron density from the dielectric surface as a function of distance. The velocity of the plasma moving away from the dielectric surface is $\sim 1\,cm\,\mu s^{-1}$. In this study 8–16 kV, 0.25 μs pulses were applied to the electrodes. These measurements were completed at a pressure near 10^{-5} Torr. The fact that the plasma is essentially all metal means that neutrals stick to the walls of the vacuum system and does not result in a pressure rise.

The features of this plasma source are exactly what are required for the charge neutralization on NTX. Furthermore, its ability to make the plasma-emitting layer arbitrarily long is important for the 1-m long plasma source. The source will be mounted on the walls of NTX drift tube just past the last focusing quadrupole magnet. The drift tube is approximately 3 in. in diameter. This small tube diameter will allow the density to be $\sim 10^{12}\,cm^{-3}$ on axis. The approach taken is to build a source with cylindrical ferroelectric pieces stacked together to form a 1-m long ferroelectric cylinder. Initially, a 20 cm long ferroelectric source made of 1 in. long and $\frac{1}{4}$ in. thick ferroelectric cylinders was built for evaluation (Fig. 2). The front surface electrode was made of 36, 10 mil. stainless steel wires strung along the length of the cylinder. The wires are mounted at each end of the source with an aluminium ring with 36 set screws. Each ring is mounted in a Delrin insulating sleeve to isolate it from the outer surface of the ferroelectric cylinders. The wires are pulled tight and actually hold the ferroelectric cylinders firmly together. Fig. 2 clearly shows the wires mounted on one of the aluminium rings and the black Delrin insulating sleeve behind the rings. Not shown in the photograph is the copper wire that is wound around the outer surface of the ferroelectric cylinder to provide a good electrical contact. Electrically, the high-voltage pulse is applied to one of the aluminium mounting rings and the copper wire wound a round the outer

Fig. 2. Photograph of the 20 cm ferroelectric plasma source showing the aluminium mounting rings and the stainless steel electrode wires.

surface of the cylinder. All of the stainless steel wires are at the same potential through the aluminium rings.

The power supply for this pulsed source is a standard capacitor bank with a pulse-forming network to match the impedance of the source and maintain the microsecond pulse shape. A schematic of the supply is shown in Fig. 3. As presently configured the pulse-forming network is matched to 4 Ω and has a maximum output of 8 kV and 2 kA. Thyratrons control the discharge of the charging capacitors. The output of the power supply is two 1-ms pulses with an adjustable time delay between the pulses.

4. Future plans

Future plans include testing the 20 cm plasma source. A Langmuir probe will be used to

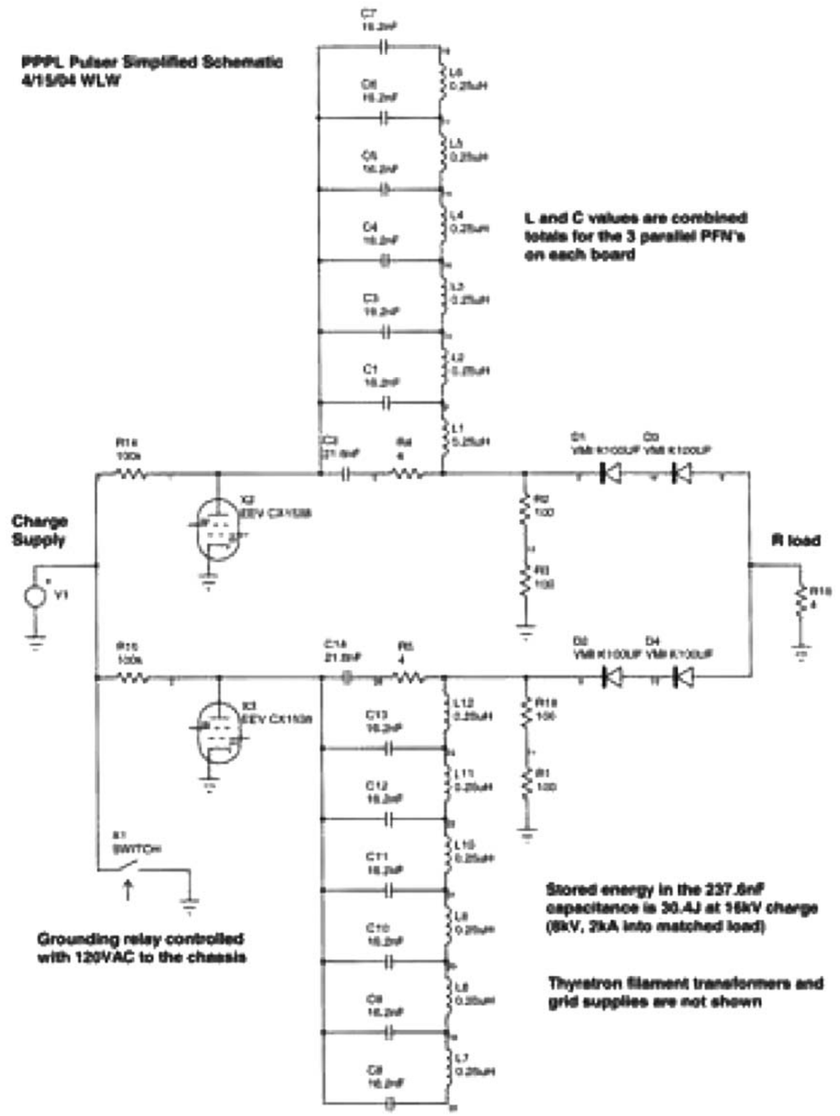

Fig. 3. Schematic of the pulsed power supply.

characterize the plasma. If the density along the source is relatively uniform and $\sim 10^{10}$–$10^{12}\,\mathrm{cm}^{-3}$, the source will be scaled up to 1 m in length and tested before being integrated into the NTX. Future experiments on NTX using the plasma source will include continuation of the charge neutralization experiments and a study of neutralized drift compression.

Acknowledgement

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References

[1] B. Badger, et al., HIBALL-II, An improved conceptual heavy ion beam driven fusion reactor study, KfK-3480, Kernforschungszentrum Karlsruhe Report, 1984.
[2] S. Yu, et al., Bull. Am. Phys. Soc. 46 (2001) 195.
[3] B.G. Logan, D.A. Callahan, Nucl. Instr. and Meth. A 415 (1998) 468.
[4] P.C. Efthimion, et al., Nucl. Instr. and Meth. A 464 (2003) 310.
[5] G. Rosenman, et al., Appl. Phys. Rev. 88 (2000) 6109.
[6] A. Dunaevsky, et al., JAP 95 (2004) 4621.
[7] A. Dunaevsky, et al., JAP 90 (2001) 3689.