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NEUTRAL BEAMS

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Abstract

The development of low frequency (1 - 2 MHz) RF plasma generators for high power neutral beam applications is summarized. Immersed couplers from one to three turns were used. Acceptable plasma profiles, $\pm 15\%$ max/min, were obtained in a variety of field-free, magnetic bucket and magnetic filter-bucket sources, with 10 x 10 cm or 10 x 40 cm extraction areas. Hydrogen beam properties were measured with a 7 x 10 cm accelerator operated at 80 kV. Atomic fraction and power efficiency were at least as high as with arc plasmas in similar chambers. The potential advantages of an rf plasma source are: ease of operation; reliability; and extended service lifetime.

Introduction

Neutral beam injection remains the principal means of heating large fusion plasmas to reaction temperatures.^{1,2} Traditionally, a variety of arc plasma generators has been used for fusion applications, which must meet increasingly stringent requirements for beam performance and reliability. The potential advantages of an rf plasma source are: ease of operation; reliability; and extended service lifetime. Although rf plasma generators had been used previously for small ion accelerators,^{3,4} fusion applications require large size systems, with high power densities. RF systems with external antennas, in which the vacuum wall is used as an insulator, do not scale to sizes of interest for fusion applications.

An immersed coupler had previously demonstrated acceptable plasma production,³ but its ability to survive back-streaming electron power from the accelerator was questionable. In these tests, the feasibility of rf plasma generators for large scale fusion accelerators was demonstrated with an immersed coupler and a long pulse LBL accelerator. The plasma generator is expected to efficiently couple 100 - 200 kW into a box $\approx 20 \times 50 \times 60$ cm, and must tolerate the back electron power from a large, long pulse accelerator, ≈ 1 kW/cm². Plasma requirements are: hydrogen or deuterium current density up to 300 mA/cm²; uniformity, 15% max/min over the extraction area (up to 12 cm x 48 cm); atomic fraction, 80%; and low impurity fraction (0.2%).

The rf couplers used here were made from quarter inch copper tubing (one or two turns) covered with a glass cloth insulator. The couplers were fit as close as possible to the extraction area, for best efficiency, but slightly larger, to avoid the full backstreaming electron power density. The couplers were positioned near the center of the plasma volume, without optimization.

An acceptable 10 x 10 cm plasma profile was first obtained in a axial line cusp magnetic bucket, with chamber dimensions 24 x 24 x 24 cm. This chamber had previously been used for arc development.⁵ For convenience, all plasma generator dimensions will be referred to here in terms of the extractable area, regardless of chamber dimension. The same 10 x 10 cm generator was later mated to a 7 x 10 cm accelerator and run at 80 kV for 1.2 seconds. A similar antenna was then inserted into a 10 x 10 filter-bucket chamber,^{6,7} and again run at 80 kV. In both cases, the beam species and divergence were at least as good as with an arc. Acceptable plasma profiles were later demonstrated in 10 x 40 cm size plasma chambers, with field-free, axial magnetic cusp, and hoop cusp geometries.

I. 10 x 10 cm Plasma Generator

In previous tests, a prototype rf plasma generator with immersed coupler had demonstrated ion current densities of 250 mA/cm^2 (hydrogen or deuterium). Couplers were made of copper tubing, with one to three turns, and a glass or quartz cloth insulator. During initial operation, the cloth was found to out-gas and fuse into a good plasma insulator. From button probe measurements, no evidence of significant rf modulation of the ion current density was found. The plasma was also successfully "notched", i.e., the plasma density was dropped to zero, and then brought back to its previous level with a 200 μsec rise time. Plasma notching is required to maintain perveance match during beam turn-on. The next step was to demonstrate an acceptable profile in a chamber which could be used with an existing accelerator.

A 10 x 10 cm arc chamber was adapted for rf at TRW by replacing the filament backplate, with rf feedthrus, rf coupler, and a small starter filament. This chamber was an axial line cusp magnetic bucket which had a large data base from arc development.⁵ Couplers were made from standard OFHC, 6.2 mm diameter, hard drawn copper tubing. The one used for beam was two turns, ≈ 15 cm square, fit as closely as possible to the extraction area. The coupler was supported from parallel leads mounted in O-rings and boron nitride rings that came through two of the existing filament feedthru holes. A starter filament was mounted using two other filament feedthrus. Both the coupler feeds and the starter filament were mounted outside of the direct path of backstreaming electrons. The setup is illustrated in Figure 1. A picture of a two turn antenna is shown in Figure 2.

A class C oscillator-amplifier, nominally 30 kW cw, was also designed and built at TRW. A block diagram of the supply is shown in Figure 3. The drive was

a sine wave oscillator, which was preamplified by a 10 W, wide band amplifier, then by a 1 kW grounded grid class B amplifier.

The antenna matching network was a tunable, resonant parallel LC circuit mounted on the plasma source. The matching network, coupler and plasma formed a matched 50 ohm load. Both the resonant coils and the coupler were water cooled. The matching network was fully enclosed to minimize rf leakage. The rf leads from the amplifier to the transformer were co-axial, and the filament leads were parallel transmission lines. Operationally, the power supply was set at a given level, then the matching network was adjusted for optimum plasma coupling at the desired current density. Optimum coupling was achieved by adjusting the oscillator frequency and the matching network to give the maximum power transfer into the plasma.

The maximum coupled power was ultimately determined by insulator breakdown. Except during initial conditioning, breakdown of the glass cloth insulator could not be reached with this power supply. However, a plasma spray alumina coating did breakdown. During subsequent tests at LBL, the breakdown voltage of the glass cloth was found to be 1.2 kV. An enamel coating was later developed which held up to 5 kV in the presence of plasma.⁸ The enamel also had a higher melting temperature.

An array of 12 separately biased button probes, 1.27 cm^2 , was mounted approximately at the extraction plane. The probes were used to measure the plasma profile (i.e., saturated ion current density) and to correlate power supply settings with probe level. A 15% profile (max/min) was achieved relatively quickly. This is as good as had been obtained with an arc in the same chamber. The power supply, source chamber, and matching network were then shipped to LBL for beam testing.

II. 80 kV Beam Operation

At LBL the 10 x 10 cm plasma chamber, rf supply, and matching network were mated to the 10 x 10 cm prototype Long Pulse Accelerator (LPA), mounted on Test Stand IIIA. Due to the small size of the neutralizer, the LPA had been masked to 7 x 10 cm during previous testing. The rf power was coupled to the antenna matching circuit by a two turn, 1:1 ferrite core high voltage isolation transformer. The matching network was mounted on the back of the plasma generator at high voltage.

The 7 x 10 LPA had been used for long pulse beam development for several years. Perveance, beam divergence, and beam composition with arc plasmas in similar chambers were well known. Divergence was routinely measured with an Inertial calorimeter, 8.8 m from the exit of the accelerator. Beam species and divergence were routinely measured by Doppler shifted beam spectroscopy, the Optical Multichannel Analyzer (OMA).⁹

A standard, 0.1 cm² Langmuir plasma probe was mounted in the plasma generator, with the tip near the edge of the accelerator. The chamber wall floated electrically, and the probe was biased at -40 V with respect to common (positive accel), to read ion saturation current. Unfortunately, the Langmuir probe signals were ambiguous, with nearly 50% modulation. The question was whether the probe modulation was ion density fluctuation, or rf pickup.

Prior to beam operation, the plasma density was run up to the full capability of the power supply for six seconds, without damage to the source or power supply. Based on later correlation of beam and Langmuir probe data, this corresponded to 210 mA/cm² (higher current density could be achieved on short pulses). A peak plasma density ≥ 0.5 A/cm² was achieved accidentally during notching tests, and damaged the power supply. Only hydrogen was used for the

rf beam test, to avoid the radiation shielding required with deuterium.

Measurement of the power efficiency of the rf plasma generator at 80 kV proved difficult. The Langmuir probe readings during beam differed from readings on the same probe during plasma-only operation taken at the same power supply settings. Coupled rf power, as measured by a high frequency power meter was unreliable due to the presence of high frequency parasitic currents. Based on rf power measured into the isolation transformer, the general conclusion is that the power efficiency of the rf plasma source was comparable to a similar arc (≈ 0.6 A of beam per kW of power).

The choice of an oscillator-amplifier (e.g., instead of a power oscillator) made load matching difficult, since the load impedance changed with the plasma level, but notching for beam turn-on was relatively easy. The output of the frequency generator was notched by feeding the output of an RC circuit into the amplitude modulation input of the oscillator. The advantage is that low power circuit elements could be used.

The possibility of rf modulation of the ion current density was checked with short beam pulses, to avoid damage to the accelerator. For initial beam tries, it was convenient to leave the power supply at an arbitrary level. Starting at 35 kV, the accelerator voltage was raised until a pervenace match was found, at 70 kV (the accelerator was gapped for 120 kV). However, 30% modulation at the fundamental frequency (≈ 1.5 MHz) was observed on the signal from the gradient grid current monitor (normally a Hall probe, but, in this case, a resistive divider). This modulation could have been due to either the beam, or rf pickup. The final check for ion modulation was done by looking at the signal on a plate located behind an aperture in the beam target. The beam was restricted to 1 msec at 70 kV, and no ion separation magnet was used. The plate was shunted to ground with a 50 Ω resistor. High frequency

oscillations (≥ 10 MHz) observed on the plate were attributed to electrical pickup, but no modulation at the fundamental was detected.

The beam was then run up to 80 kV, with the pulse limited to 1 second. "Tunes" were taken at 60, 70, and 80 kV, by varying the accelerator current at fixed voltage. The optimum perveance, which is species and profile dependent, was similar to the arc, 0.25 μ pervs. The beam divergence at optimum was similar for both the arc and rf plasmas, $\approx 0.7^\circ \times 1.1^\circ$ (total beam, 1/e half angle). Divergence was measured with both the calorimeter and the OMA.

OMA species fractions from optimums at 60, 70, and 80 kV are plotted as a function of plasma current density in Figure 4, for both arc and rf plasmas. Plotting species vs current density allows easy comparison with data from other plasma generators and accelerators. The rf plasma had a higher atomic fraction than the arc plasma in the same bucket chamber.

Beam current and voltage are related to the optimum perveance by

$$(P)_{\text{optimum}} = I / V,$$

where, I is in amperes and V is in volts. In practice, the optimum perveance is checked with an occasional tune, and the beam voltage and current are independently measured on every shot. The inferred plasma current density is related to the beam current by the accelerator aperture and transparency,

$$j = I / AT,$$

where the area of the accelerator, A, is 70 cm² and the transparency, T, is about 0.6.

The general goal of the beam test was to demonstrate compatibility of the rf plasma with long pulse beam operation. The accelerator is an actively cooled design, which had previously been operated up to 28 seconds at 80 kV. The magnetic bucket chamber was only indirectly cooled, by 1/4 inch external water lines soldered to the outside of the copper walls. The rf coupler also had limited water cooling. The pulse length was stretched out with the expectation that either the coupler or the bucket would fail due to inadequate cooling. The coupler insulator, which had survived numerous 2 second shots at 70 kV, melted after 1.2 seconds at 80 kV, 5.5A. Inspection afterwards revealed local melting, probably due to back-streaming electrons reflected from the back plate magnets. The consensus was that a larger diameter coupler, with more cooling and a higher temperature insulator⁸ would be capable of cw beam operation.

Since the rf bucket test had been completed ahead of schedule, the same backplate was tried in a 10 x 10 cm filter-bucket.⁷ The magnetic filter concept is to restrict the energetic primary electrons to a local volume, with a drift region to the accelerator in which molecular ions are dissociated by low energy electrons. In this case, a set of magnetic cusps, made of permanent magnets in copper rods, had been inserted between the filaments and the accelerator, in an identical axial cusp chamber. The magnetic filter was developed to produce a 90% atomic fraction, and has also been successful as a volume negative ion source.¹⁰

The 10 x 10 filter-bucket was converted from an arc to rf simply by replacing the filament backplate with the rf backplate used previously. Due to time limitations, no profile data were taken, but the filter-bucket beam divergence was comparable for both arc and rf. OMA hydrogen atomic fraction for the rf and arc filter-bucket plasmas are also included in Figure 4.

III. 10 x 40 cm Plasma Generator

Following the successful 10 x 10 beam tests, acceptable plasma profiles ($\pm 15\%$ max/ min) were obtained over 10 x 40 cm extraction areas with immersed rf coils in field-free, axial cusp, and hoop cusp geometries. Because of the problem with back-streaming electrons in the beam tests, all of the chambers had field-free backplates. The couplers were at least 13.5 x 45 cm. The same rf supply was used, modified to produce 100 kW of output power for 1 second.

Ion current density profiles were measured by an array of twenty 1.27 cm² disc probes, mounted at the extraction plane and biased to collect ion saturation current. Acceptable profiles could be obtained over a wide range of operating pressures, from 1 to 20 mTorr, with some variation in the required power and rf impedance. For all chambers, deuterium was slightly more efficient, with better profiles, than hydrogen.

Conclusions

Uniform plasma densities were obtained over 10×10 cm and 10×40 cm areas using immersed rf couplers, operating at 1 - 2 MHz. The couplers were made from copper tubing, with a glass sleeve insulator. The number of turns, from one to three, was determined by plasma profile and coupling efficiency in a particular chamber. Ion current densities up to 250 mA/cm^2 , with plasma profiles $\leq 15\%$ max/min, were obtained with hydrogen and deuterium. Source pressure was comparable to an arc operated in similar chambers, ≈ 10 mTorr.

Beam tests were carried out using a 7×10 cm, long pulse accelerator mated to a 10×10 cm axial magnetic bucket, and a magnetic filter-bucket. A two-turn rf coupler was mounted in a 10×10 cm axial magnetic bucket, and a similar magnetic filter-bucket chamber. The rf plasmas were easier to operate and notch than arcs. Beam divergence was comparable to that obtained with arcs in the same chambers. The beam atomic fraction, measured with the OMA spectral diagnostic, was slightly higher for the rf sources. Local melting, due to back-streaming electrons, caused insulator failure after 1.2 seconds at 80 kV. Long pulse rf beam operation should be achievable with a slightly larger coupler diameter and a higher temperature insulator.

Based on these results, rf plasma generators with internal couplers appear to offer superior operability and reliability than arcs for large scale fusion plasma generators. Since present users of positive ion based neutral beams have already invested in arc and filament power supplies, the most likely application for rf is cw volume generation of negative ions.

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Figure Captions

FIG. 1. A layout of the rf bucket chamber, viewed from the accelerator.

FIG. 2. Picture of a two-turn rf coupler of the type used in the 10 x 10 cm chambers.

FIG. 3. Block diagram of the rf power supply.

FIG. 4. OMA atomic fraction is plotted vs ion current density for rf and arc plasmas in the bucket and filter-bucket chambers. The beam was hydrogen, from 60 to 80 kV.

XBL 8410-4148

Fig. 1

CBB 820-10616

Fig. 2

XBL 8410-4103

Fig. 3

Full Energy Hydrogen (OMA), %

Fig. 4

XBL 8410-4102

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