Formation of RF Plasma Transport Channel in External B-Field

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Abstract – The paper describes experiments on formation a plasma channel with imbedded B-field for transporting high power ion beam. The plasma was generated with a 5-turn loop inductive antenna driven by an H-bridge type RF generator. The azimuthal B-field in the channel of 0.5–1.5 kG was formed by a pulsed current from external capacitor bank. Control of the hydrogen gas pressure was provided by an electromagnetic puff valve. The paper describes experimental devices and results on the generated plasma parameters as function of RF frequency, antenna voltage, pulse duration and puff gas pressure. When operating at ~ 1 kG B-field, ambient gas pressure in the range of few-10 mTorr, and 5 kV – antenna voltage at resonant frequency of 150 kHz, the plasma density range was $3 \sim 7 \times 10^{12}$ cm$^{-3}$ with a temperature of a few eV.

Keywords: plasma, RF, ion beam.

1. Introduction

High power dense ion beams (HPIB) are considered to be a promising candidate for heating various plasma configurations by injecting them into the plasma containing chamber along or across B-field [1–2]. The latter approach is based on the collective ExB mode of HPIB propagation, provided fulfillment of certain propagation criteria [3]. To maximize the density of the HPIB it could be initially generated in a large diameter magnetically insulated ion diode with ballistic focusing, followed by a transport through a toroidal B-field lens [4] to transform it from converging geometry to the straight one. But this is not a trivial task due to HPIB high density and respectively $E \times B$ or even- diamagnetic mode of HPIB propagation through such a lens. To neutralize polarization E-field [5] in the HPIB during its propagation through the B-lens we used pulsed hydrogen plasma, generated by RF antenna.

The following paper presents brief description of two experimental setups, main results of experiments and their analysis. In the 2nd part of the paper the brief description of the test bed and RF generator is given, the 3rd part is dedicated to experiments at the test bed; the 4th part gives the brief description of the HPIB generation experiment in the ion diode, and compares the transport efficiency of the beam through the B-lens with and without plasma neutralization, the 5th part concludes the paper.

2. Test bed and RF generator

A test bed was built to measure the efficiency of plasma generation by RF antenna, its parameters and dynamics in the presence of the applied azimuthal magnetic field as functions of the input conditions. Setup schematic is illustrated in Fig. 1, its photo in Fig. 2.

![Fig. 1. Schematic of the test bed](image1.png)

![Fig. 2. Test bed](image2.png)

The test bed consisted of a s-steel tube of 25 cm dia, and 65 cm length, with a centered axial conductor, made of RG-8 cable, stripped of its mesh; capacitor bank C2 with ignitron switch; 5-turns loop RF-antenna, used for inductive coupled plasma formation.
which is more efficient and intensive than capacitive coupled plasma [6], wounded over the glass section of 18 cm dia, connected to the steel tube; axial puff valve, located 30 cm behind the antenna; a RF-power generator, using transformer stepping up and resonant increasing technology [7] to output high voltage and high current to the RF antenna, placed near the antenna. The tube was pumped to $10^{-5}$ Torr before letting gas puff in. The applied azimuthal pulsed B-field in the tube was generated by the current through the RG-8 cable, when discharging 500 µF capacitor bank C2. The voltage on the latter and the current amplitude were up to 3 kV and 17 kA, respectively. A single Langmuir probe with a 10 Ohm termination resistor for measurement, interchangeable with a set of Collimated Faraday Cups (CFC) was placed in the vertical middle plane of the tube at the variable radii 30 cm away from the RF antenna.

RF power generator included a storage capacitor bank E, an IGBT based H-bridge (Q1 ~ Q4); a step-up transformer TR; a resonant tank C1 – RF antenna, as it is shown in Fig 1. Schematic of the RF-generator is given in Fig. 3.

![Fig. 3. Schematic of RF power generator](image)

Primary energy store E had capacitance of 10mf storing 800 J when charged to 400 V, and it could support RF antenna operation up to a few milliseconds with 50% voltage drop. Q1 ~ Q4 are of high pulse current, fast speed IGBT (IRGPS60B120K). Each leg of the H-bridge has 9 IGBTs in parallel to make sure it can provide a few KA pulse current with a few ms duration. Transformer TR has step-up ratio of 1:15, by which the high voltage can be generated on the secondary of the TR while using relatively low voltage on primary. 3 to 5 ferrite cores FT-240-43 were used as the core of TR which works at frequency 100–500 kHz to get small size and high efficiency. The H-bridge, loaded on the TR primary is driven by an RF clock in the way Q1Q4 – Q2Q3 – Q1Q4 – Q2Q3. The secondary of the TR is loaded on the antenna circuit, which includes C1 and the inductance of antenna, resonant with the H-bridge frequency. RS, DS, and CS in Fig. 3 represent the snubber for IGBT to absorb and suppress the high pulse of voltage kickback on c–e of IGBT which may damage the IGBT. In our condition of over 2 KA through IGBT, using $C_s = 0.47$ µf and $R_s = 3$ Ohm can reduce the kickback to lower than 1.5 times of the bank E voltage. Special attention should be taken on correctly selecting an appropriate dead time for H-bridge to avoid short circuit between the legs of the circuit during their switching, i.e. the ON-state of the IGBTs in each half of the bridge must not overlap in time, and respectively, the pause between their switching should be sufficient to provide full transition of IGBT to OFF-state before the second one will turn on. It should not affect operation when driving frequency changes. IRGPS60B120K is a fast response IGBT with a short fall time of only ~ 58 µs, and it can work up to 600 kHz, with ability of switching up to 240 A current in pulse mode. The dead time requirement for the IGBT is longer than 200 ns.

3. Test bed experiment

Up to $10^5$ firings were carried out at the test bed on scaling plasma parameters with varying input conditions: antenna voltage is in the range of 2–8 kV, RF frequency 100–500 kHz; H$_2$ pressure in the puff valve plenum is 10–100 Torr; RG-wire current pulse amplitude is up to 17 kA; and various time delays sequence between valve activation, B-field current, and turn-on of RF power to antenna. Langmuir probe and linear set of Faraday Cups, were placed in the midplane of the vessel at certain distances from the antenna. Both were used to measure the plasma density and velocity of plasma propagation by time of flight method. A 10 Ohm resistor was used as the termination load in the Langmuir probe measurement.

![Fig. 4. Plasma without external B-field. Ch1 – plasma signal from the Langmuir probe, (0.2 A/cm$^2$)/div; Ch3 – RF current on antenna, 1 KA/div; Ch4 – RF voltage on antenna, 2 KV/div; X-axis scale – 50 µs/div )](image)

Time of flight measurements and Langmuir probe data gave for the generated plasma flow temperature ~ 1 eV and calculated density in the range of (1–5) · $10^{12}$ cm$^{-3}$. Application of external B-field delayed formation of the plasma compared with the case w/o it, which increased with B-field amplitude increase. For example, with the usual time delay of 20–40 µs w/o axial external current application of the latter at the level of 7–10 kA resulted in the delay increase to 80–100 µs. It is illustrated in Figs. 4 and 5. Second important result was that the pulsed
azimuthal B-field if applied later than RF plasma generation strongly pushed off the latter from the central part of the volume of the current wire vicinity. The optimal time for turning on the RF corresponded to the maximum of the current pulse amplitude (Fig. 5).

Fig. 5. Plasma in external B-field. (ch1-plasma signal from a langmuir probe, (0.2 A/cm²)/div; ch2-RF current on antenna, 1 KA/div; ch3-current on RG-8 wire, 4 KA/div; ch4-RF voltage on antenna, 2 KV/div; X-axis – 50 µs/div)

4. Experiments on transport of HPIB in magnetized RF-plasma

Based on the test bed results of plasma generation with RF source, we wrapped similar antenna in the post cathode space of the sub-microsecond ion diode (200 kv) over the ion beam channel in the region of the B-lens. The latter was designed to transform the beam from converging geometry with the half angle of 17 ° to the straight one. The schematic of the experiment is given in the Fig. 6. The pulsed current in the lens of ~ 150 µs rise time and up to 15 kA amplitude was provided by the C-bank of 80xz0 µF. The H₂ filling of the lens volume was done by the fast EM puff valve with 1.6 cm³ plenum and rise time of 70 µs located in the apex of the lens. The usual sequence of the operation pulses in each diode firing started with puff-valve firing, followed by RF turning on, toroidal B-field pulse and finally – diode firing with preset time delays. At antenna voltage in the range of 4–5 kV, puff-valve voltage and plenum pressure of 1 kV and 250 Torr respectively, plasma density in the lens varied in the range of few of 10¹² to 10¹⁵ cm⁻³ with temperature of ~ 1 eV. It is approximately 2 orders higher than the beam density. Measurements of the HPIB density by linear set of 3 CFC placed at the distance of 122 cm from the anode (Fig. 6) in various conditions (transport in vacuum, in neutral gas, and in the plasma) showed the improved efficiency in the latter two cases, and enhanced scattering of peripheral layer in the case of transport in neutral gas compared with transport in the plasma.

Figures 7 and 8 present typical ion signals taken from the linear set of 3 CFC. Fig. 7 shows the signals without plasma channel filling of the B-lens, while Fig. 8 shows those with plasma channel. In both Figs. 7 and 8, channels 1–3 are signals from CFCs at radii 0, 3.3 and 6.6 cm from the axis, and channel 4 is the anode voltage during pulse. Compared with Fig. 7, the plasma filled B-lens l was used, the ion current is higher and the transport is better than without plasma channel.

Fig. 6. Schematic of the setup with the ion diode

Fig. 7. Ion beam signals on the target without plasma channel. (ch1 ~ ch3: ion beam signal from faraday cup; ch4: anode voltage)

Fig. 8. Ion beam signal on the target with plasma channel. (ch1 ~ ch3: ion beam signal from faraday cup; ch4: anode voltage)

5. Conclusion

Filling of HPIB transport post-cathode channel by the hydrogen plasma with density of ~ 1–2 orders higher
than the beam density improves its neutralization and respectively efficiency the HPIB of transformation from converging geometry to the straight one.

Magnetic field generated by the electromagnetic lens could help to focus the high power ion beam and guide the beam transport.

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Reference