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Proton-Beam Transport through Wall-Confined Plasma Channel in the Nagaoka ETIGO-I

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Transport of an intense pulsed proton beam has been studied experimentally through a wall-confined plasma channel (1-m long) in the Nagaoka ETIGO-I. A proton beam with an energy of 800-keV is injected into the channel. The transport efficiency increases with increasing channel current or decreasing channel pressure, being in good agreement with the existing theories. Changing the timing between channel current and beam injection, we have found that there exists a good timing for the beam injection. In some cases, the beam ceases to be transported probably due to some plasma instabilities.

Recently, considerable attention has been given in the literature to inertial-confinement fusion (ICF) by an intense pulsed light-ion beam (LIB).[1] Concerning the transport[1,2] of the LIB, several ideas have been proposed and tested to form z-discharge plasma channels such as by an exploding wire,[3–6] a wall-confined discharge,[7] or a laser-guided discharge.[3,8] As reported elsewhere, we have shown some data of the LIB transport through a plasma channel (50-cm long) produced by an exploding wire.[5,6] In this paper, we wish to present experimental data obtained in a wall-confined plasma channel (1-m long).[9]

The experiments were carried out in the Nagaoka ETIGO-I,[5,6,10–13] 15-kJ-LIB generator at Tech. Univ. of Nagaoka. It consists of a Marx generator (43-kJ of stored energy), a pulse-forming line (PFL) of $5\,\Omega$, and an ion diode. The diode utilized here is a spherically-shaped, magnetically-insulated diode (MID) to achieve a geometric focusing[12,13] of the LIB. Figure 1 shows the outline of the LIB-transport experiment. We have chosen the gap length between anode (polyethylene) and cathode as $d=10$ mm. The diode voltage (V_d) and current (I_d) are typically ~ 900 kV and ~ 60 kA, respectively. The beam-pulse width is ~ 80 nsec (FWHM). We have operated the MID at $B/B_c \sim 2.7$, where B and B_c are the transverse magnetic field strength and the critical magnetic field strength above which an electron flow is insulated, respectively. The diameter of the flash-board anode is 110 mm, where ~ 1100 knock pins (copper) are buried. The radii of curvatures of anode and cathode are 180 mm and 170 mm, respectively. Around the geometric focusing point, we have obtained the maximum ion-current density (J_i) of ~ 6 kA/cm^2. A plastic foil (2 μm) separates the diode region ($p_d \sim 10^{-4}$ Torr) and the channel region ($p_{ch}=0.1$–10 Torr (air)). The energy loss due to this foil is estimated to be ~ 100 keV at 900-keV beam of protons. The z-discharge is fired by a 3.4-kJ fast condenser bank (60-kV, 1.9-μF). The channel current rises up to ~ 45 kA within $t \sim 1.7$ μsec, where t is the time after the closure of the channel switch. Theoretically, the channel current required for the perfect confinement of the proton beam can be written by[2]

$$I_{ch}(A)=\frac{0.1v_0(1-\cos\theta_m)}{1-(a/R)^2}, \tag{1}$$

where v_0 is the beam velocity (m/sec), θ_m is the maximum injection angle (radian), a is the maximum injection radius, and R is the channel radius. We estimate $I_{ch} \sim 90$ kA by using the following experimental parameters; $a/R=3/5$, $\theta_m \sim 0.31$ radian, and E (energy of the proton beam) ~ 800 keV.

By use of a small sized magnetic probe, we have measured the spatial and temporal evolution of the B_θ field produced by the channel current. The profile of magnetic field B_θ is shown in Fig. 2. As seen in Fig. 2, the B_θ field increases with increasing channel radius. At $r \sim 5$ mm, B_θ begins to increase rapidly, clearly indicating the presence of a current sheet. The sheet current is seen to be compressed toward the central part from $t=1$ μsec to 1.5 μsec.

Based upon the preliminary data described above, we then inject the focused proton beam[12,13] into the preformed wall-confined z-discharge plasma channel to study the transport efficiency[9] in a parameter space. Figure 3 shows the typical result, where the transport efficiency of the beam energy (○) measured by a calorimetric method and that of the particle number (▲) measured by a nuclear activation technique[14,15] (^{12}C(p, γ)^{13}N(β^+)^{13}C) are plotted as a function of channel current. The energy (or particle number) transport efficiencies are defined by the ratio of the beam energy (or particle number) at the channel outlet to that at the inlet. The diameters of both the copper plate (for a calorimeter) and the carbon target (for an activator)

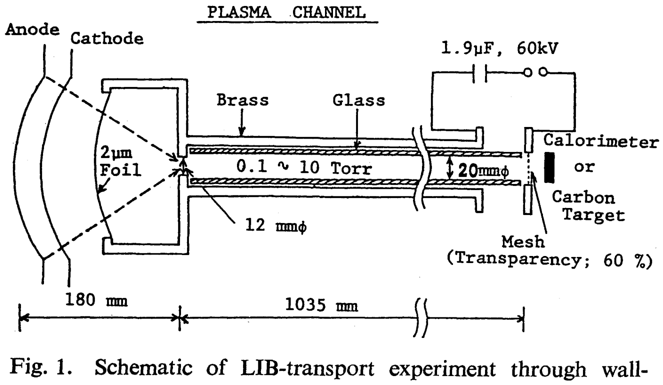

Fig. 1. Schematic of LIB-transport experiment through wall-confined plasma channel.

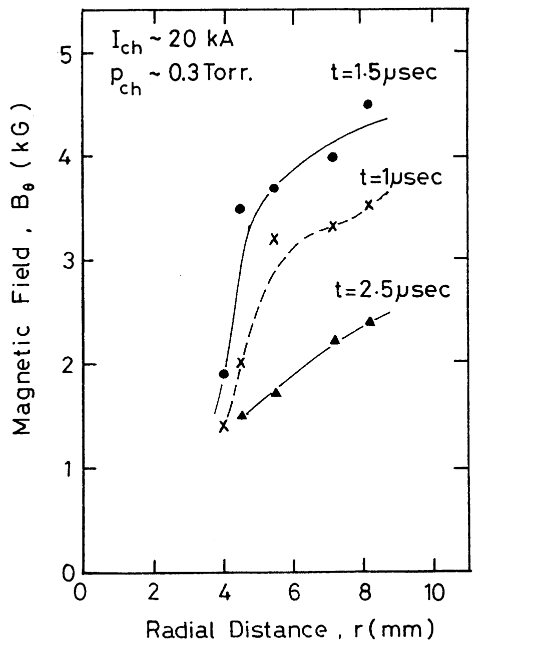

Fig. 2. Radial distribution of B_θ field strength measured by a magnetic probe, where a 2-kJ condenser bank (50-kV, 1.6-μF) has been utilized.

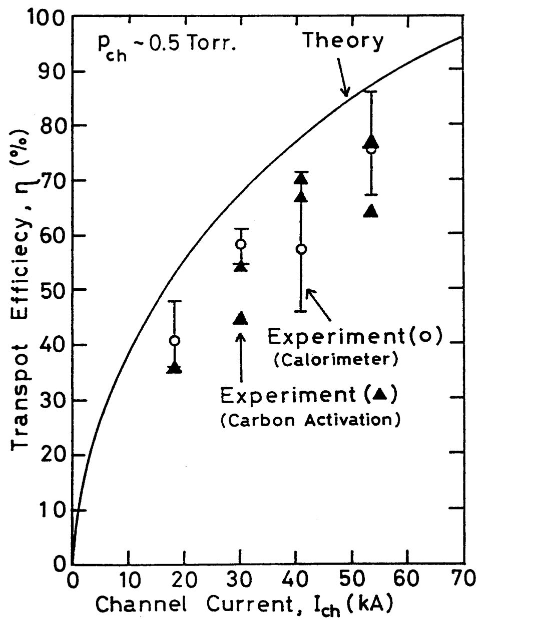

Fig. 3. Transport efficiency (beam energy and proton number measured by calorimeter and carbon activation technique, respectively) as a function of channel current. The solid line represents the theoretical value estimated by eq. (1).

are 33 mm. The effective areas of these targets are 8.55 cm^2. The proton beam has been injected into the plasma channel at $t \sim 1.3$ μsec, a little before the peak of the channel current. The solid line in Fig. 3 represents the theoretical estimate calculated by eq. (1). As seen in Fig. 3, the transport efficiencies are found to increase with increasing channel current, there being considerable agreement between the experiment and the theory. At $I_{ch} \sim 53$ kA, we have obtained the maximum transport efficiency of more than $\sim 80\%$.

Figure 4 shows the transport efficiency vs channel pressure at $I_{ch} \sim 40$ kA. As seen from Fig. 4, the transport

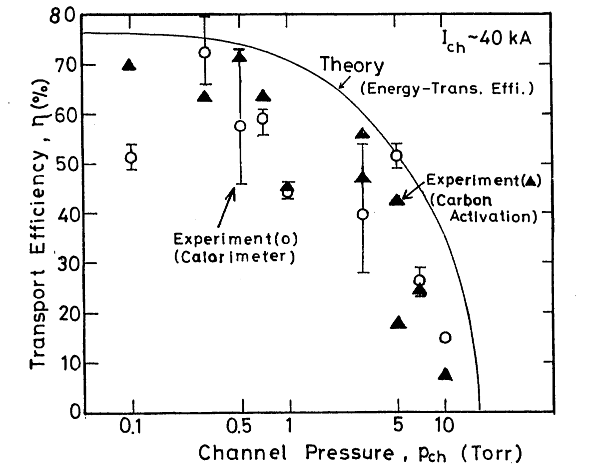

Fig. 4. Transport efficiency vs channel pressure, where the solid line represents the theoretical value of the energy transport efficiency calculated by Bethe-Bloch equation.

efficiencies of both the energy and the particle number tend to decrease rapidly at $p_{ch} \sim 1$ Torr. It is probably caused by the energy loss due to Coulomb scattering between proton beam and bound electrons (or partly free electrons) in the plasma channel. The energy loss due to the Coulomb scattering has been theoretically calculated by Bethe-Bloch equation.[16] In Fig. 4, we have also plotted the theoretical value of the energy transport efficiency obtained by the assumption that a 800-keV of proton beam was transported in a singly-charged, fully-ionized plasma channel of 1-m long. In the above estimate, we have utilized the experimental observation that the channel resistance (R_{ch}) is $\sim 0.3\ \Omega$ at $p_{ch} \sim 0.3$ Torr. Using the Spitzer resistivity, we have calculated the electron temperature (T_e) to be ~ 3 eV for a singly-charged state of air. As seen from Fig. 4, a reasonable agreement is obtained between the experimental and the theoretical data. Theoretically, the beam energy that has passed through the channel of 1-m long should reduce to less than 500 keV at $p_{ch} > 5$ Torr, hence being impossible to be counted by the nuclear activation technique. Actually, however, the experimental measurement was made possible until

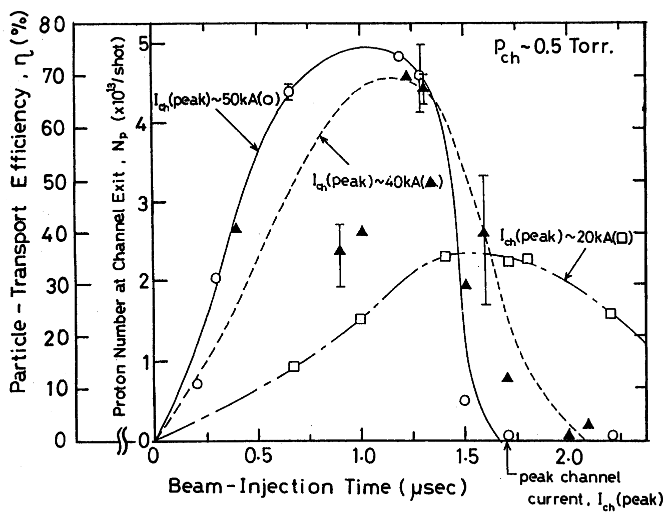

Fig. 5. Particle-transport efficiency plotted against beam-injection time after the closure of the channel switch, where the channel current is a parameter.

$p_{ch} \sim 10$ Torr. This appears to be due to the fact that the plasma density in the central part of the channel plasma will decrease with the increasing plasma temperature.

Finally, we have studied the transport efficiency by changing the timing of the beam injection after the closure of the channel switch. Figure 5 shows the particle-transport efficiency again measured by the nuclear activation technique plotted vs beam-injection time, where the channel current attains the peak value at $t \sim 1.7$ μsec. At I_{ch} (peak) ~ 20 kA, the beam is able to be transported in the channel after the peak of the channel current ($t > 1.7$ μsec). At I_{ch} (peak)>40 kA, however, it is noted that the beam *cannot* be transported after the current peak. This presence of the channel-parameter region for the LIB non-transport seems to be associated with the appearance of some plasma instabilities (*e.g.*, sausage instability[17]) in the plasma channel. The non-transport region has also been clarified in another parameter space.[9]

Detailed studies on the channel instabilities are being carried out, and will be discussed elsewhere.

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