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Sustainment of Spherical Tokamak by Means of Repetitive Injection of Compact Torus Plasma

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Abstract

Sustainment of spherical tokamak (S.T.) has been studied. A compact torus (C.T.) plasma was injected into confinement region by magnetized coaxial gun. For start-up and sustainment of large main spherical tokamak, single pulsed injection of small C.T. is not sufficient in many cases. C.T. plasma injection of high repetition rate is required. For this purpose magnetized coaxial gun was driven with high repetition rate current. The first injected C.T. plasma could start-up S.T. without other help. The repetitive C.T. injection grew and sustained the S.T. plasma. A CCD camera with fast gated image intensifier took a cross sectional view of S.T. during the repetitive C.T. injection.

Keywords:

repetitive CT injection, spherical tokamak, magnetized coaxial gun, sustainment,

1. Introduction

In spherical tokamak (S.T.), current start up, current drive and sustainment are important subjects. Sustainment of a large main S.T. by injection of a small compact torus (C.T.) has been investigated in many laboratories. This method, as compared with the other current drive and particle fueling method, can sustain the main S.T. plasma by itself because the injected C.T. has all plasma components of the main S.T. [1].

In sustainment of S.T., the axis of small C.T. can be aligned with the main S.T. axis and the C.T can be injected along this axis. In case of insufficient sustainment by single injection, C.T. injection of high repetition rate is required [2].

The experiment on repetitive injection of C.T using a magnetized coaxial gun is described in this paper. Using the repetitive current pulse generated by a transformer coupled circuit, a series of spherical tokamak plasmas were generated and injected. The repetitive merging with the spherical tokamak took place in the confinement region.

2. Repetitive C.T. Injection

It is possible that repetitive C.T. injection can sustain helicity, particle and many other components of torus plasma. We tested a simple model of repetitive helicity injection. In the repetitive C.T. injection case, we estimated the helicity from next helicity balance equation [3]

$$\frac{\mathrm{d}\,H_{ST}}{\mathrm{d}t} = -\frac{H_{ST}}{\tau} + f\ 2V_G\,\varphi_G \qquad (1)$$

where H_{ST} is the helicity of the S.T. Input helicity term consists of voltage pulse V_G that is repetitively supplied to the magnetized gun and magnetic flux φ_G threaded electrodes. A function f is time variation included frequency. We can select the proper frequency for an efficient sustainment. Helicity in the confinement region decays with time constant τ. Helicity is determined by

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this balance of the two terms. For simplicity, it is assumed that injected C.T. relaxes instantly.

At the beginning injection term is given. Flux φ_G is constant and gun voltage V_G is repetitive pulse. This gun voltage is shown as rectangular pulse in Fig. 1. The decay time τ is set a constant value comparable to the repetitive period. Helicity balance equation is solved numerically. The resultant helicity is a rising sawtooth pulse and is shown in Fig. 1. In this model the helicity is accumulated and finally sustained repetitively. As a result we can generate S.T. plasma and sustain S.T. by the repetitive C.T. plasma injection.

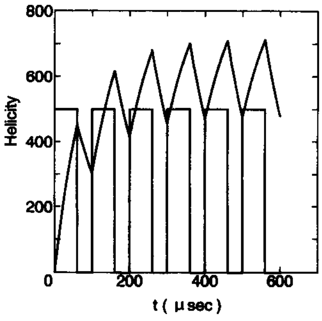

Fig. 1 Helicity injection time history

3. Experimental Devices

The schematic drawing of experimental device was shown in Fig. 2.

The magnetized coaxial gun: ① injects plasmas in high repetition rate into the confinement region. The diameter of inner, outer electrodes and these length are 2 cm, 4 cm and 20 cm respectively. The confinement region consists of toroidal field and vertical field, produced by center rod: ② current and poloidal field coils: ④ respectively. There are partition plates on the both sides of the confinement region: ③. Fast acting valve: ⑤ supplies He gas from this port. A laser path of interferometer (3.39 μm) is shown as: ⑥. A window: ⑦ is 100 mm diameter quartz for camera observation.

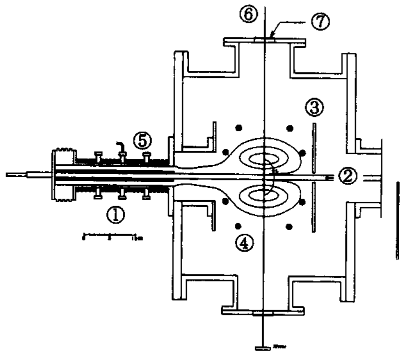

Fig. 2 Experimental devices

One of the methods to generate repetitive current pulses with the same polarity is a discharge circuit coupling the magnetized coaxial gun and the condenser with a transformer. Figure 3(a) illustrates this discharge circuit.

The primary circuit of the transformer is switched on and at the current peak of the circuit, the secondary circuit is switched on. Figure 3(b) shows the current wave form which flows into the magnetized coaxial gun.

The plasma is produced by the first few current pulses and injected into the confinement region.

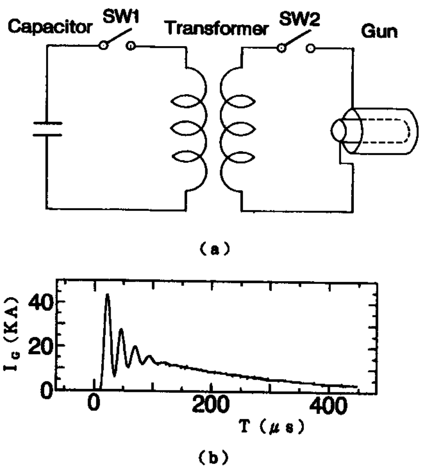

Fig. 3 Discharge circuits and current

4. Experimental Results

Poloidal field profiles measured at mid-plane is shown in Fig. 4. The vertical axis is poloidal field strength and the declined horizontal axis is major radius (the negative side shows 180 degree opposite side). The diagonal axis is time (the origin is shifted –62.5 μsec before the gun start time). As the injection of first plasma, the poloidal field near the center reverse to the outer poloidal field. Toroidal field profiles measured at the mid-plane showed paramagnetic field profiles. We confirmed a S.T. field configuration at the mid-plane. The repetitive increase of magnetic field in the both fields correspond to the repetitive injections of C.T. plasma from the magnetized coaxial gun.

Line integrated densities were measured on the mid-plane by laser interferometer. Average density is shown in Fig. 5 and is 1.5×10^{20} m^{-3}. The repetitive rise

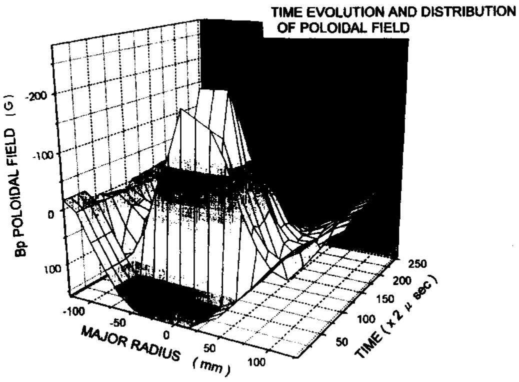

Fig. 4 Poloidal field profiles

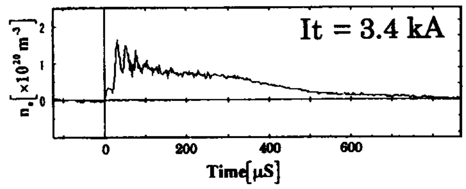

Fig. 5 Average density

of density showed the repetitive C.T. injections. A CCD camera with fast-gated image intensifier set on the side window and took the cross sectional view of S.T. plasma. The camera took the pictures at each 2 μs step. Figure 6 shows 2 μs stepped photographs. The outermost circle is inside wall of the viewing window and the horizontal black line at center is the rod of toroidal field coil. At the left and the right ends, there are part of the vertical field coils and the partition walls. Black circle at center is backside window. In this photograph, C.T. plasma is injected from the left side by the magnetized coaxial gun.

The first five pictures in Fig. 6 (t = 25, 27, 29, 31, 33 μs) are injection phase of first C.T. plasma and show the traveling of luminous front. The plasma front reaches and hits the coil and the end wall. The next four (t = 35, 37, 39, 41 μs) pictures are decaying and reflection phase of the first injected C.T. plasma. The shapes of plasma cross section look like a trumpet shape and differ from the sphere shape.

Following photographs (t = 43, 45, 47, 49 μs) show a spiral structure winded around the center conductor. The spiral structure moves through the dark plasma.

This period corresponds to the second C.T. plasma injection. The spiral structure reaches the end wall and then decays gradually. The cross section of S.T. plasma recovers again trumpet shape and lasts for a long time there after.

5. Summary

We have studied sustainment of S.T. plasma by means of high repetition rate injection of C.T. plasma. The first injected plasma from the magnetized coaxial gun can start up S.T. without other help. The repetitive merging grows the spherical tokamak in external vertical field. Furthermore, the repetitive merging can sustain the spherical tokamak.

Frequency of the current pulse was ~50 kHz. Each current pulse could inject ~5 × 10^{17} particles. Then the particle injection rate was ~2.5 × 10^{22} particle per second. Injected helicity was ~2.4 × 10^{-8} Wb^2 per pulse and the rate was ~1.2 × 10^{-3} Wb^2 per second.

The cross sectional view of S.T. plasma was taken using a CCD camera with fast-gated image intensifier. We observed the start-up phase of S.T. plasma by the first C.T. plasma injection. In the second plasma injection phase, we observed the spiral structure traveling through the dark plasma. We need to control the axial C.T. plasma motion and the optimization of the vertical field configurations.

References

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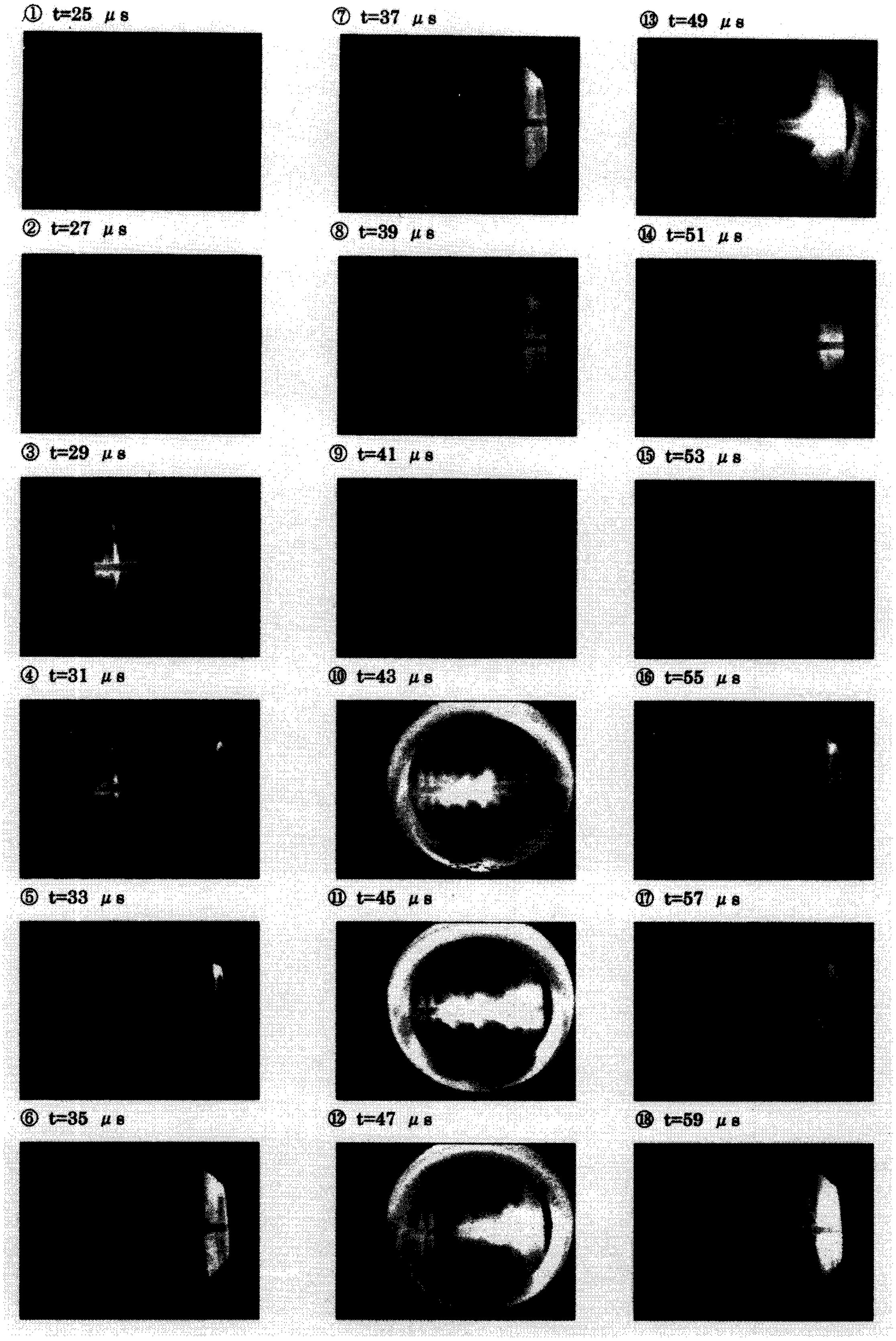
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⑥ t=35 μs
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⑧ t=39 μs
⑨ t=41 μs
⑩ t=43 μs
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