Journal of the Korean Nuclear Society
Volume 12, *Number* 3, *Septemer*, 1980

《**Original**》

Study on a Coaxial Plasma Gun (Ⅲ)*

Hae iLL BAK, Sang Ryul In, Kie Hyung Chung and Un Chul Lee

Nuclear Engineering Department, Seoul National University

(Received August 19, 1980)

Abstract

A Mather type plasms gun is operated at below 1 torr with a energy storage system (4KJ, 16.5KV, 35nH) to study the conditions of the efficient plasma focus. When the D_2 gas filling pressure is 0.18 torr and the stored energy is 3.8KJ, the discharge current of max. 180KA is obtained and the average axial velocity of the plasma is about 7cm/μs. This is lower than the calculated velocity with above conditions by the snow-plow model. The discrepancy is due to the currents flowing over the insulator surface. The plasma focus occurs at low pressure compared with the results obtained by Bruzzone. The reasons are such that the plasma gun employed in this experiment is large for the stored energy and the concentration of the residual gas is comparatively high.

It is confirmed by a Long counter that the neutrons are generated from the dense plasma focus.

요　　약

4KJ의 에너지 뱅크(16.5KV, 35nH)를 사용하여 Mather형의 플라즈마총을 1 torr이하의 낮은 기체압력에서 동작시키면서 플라즈마의 효율적인 집속조건을 구하였다.

중수소기체의 충전압력이 0.18torr, 저장에너지가 3.8KJ일때 방전전류의 최고치는 180KA이었고 플라즈마의 축방향 평균속도는 약 7cm/μs이었다. 이것은 snowplow모델에 의해 계산된 속도보다 작은 값인데 이는 절연재 표면을 통한 전류의 손실에 기인하는 것으로 생각된다. H. Bruzzone의 플라즈마 집속장치(1KJ, 16KV, 4.2μs)에 비해 본 실험에서는 기체압력이 낮은 영역에서 플라즈마 집속이 일어났다. 이는 이 실험에서 사용한 플라즈마총의 크기가 저장에너지에 비해 크고 또 잔여 기체의 함량이 비교적 높기 때문이다. 집속된 플라즈마로 부터 방출되는 중성자는 Long counter를 사용해서 계측했다.

Ⅰ. Introduction

The plasma focus device is characterized by the fact that it is able to compress and heat the plasma up to 10KeV and 10^{19}/cm^3 within 100 ns short enough for the highly compressed plasma not to be destroyed by instability. In the operation of the plasma focus device three stages are required; the plasma generation, the acceleration, and the plasma focus. At the focusing stage the preheated plasma is compressed instantly by the magnetic pressure which is inductively storaged to the maximum value. Thereby the plasma focus device is more effective for the compression of the plasma than the traditional devices such as the θ-pinch or the

* This is the 3rd paper on the coaxial plasma gun studies. Refer to the articles (Ⅰ); Eng. Report, 10 (1), 1978, and (Ⅱ); Eng. Rep., 11 (2), 1979.

Z-pinch which begin to compress at the plasma generation which the magnetic pressure is not sufficient for the intense and stable compression[1]. To obtain the intense focus of the plasma it is necessary to maximize the storaged magnetic pressure or the discharge current for the stored energy of the capacitor bank. It is important to maximize the discharge current at the beginning of the focusing stage, so the storaged energy of the capacitor bank, the capacitance, and the inductance of the circuit have to be matched with the length of the center electrode of the plasma gun and the gas filling pressure. The plasma focus device enables to visualize the nuclear fusion reaction and to produce the neutrons from the focused plasma when D_2 gas is used. In this experiment the low inductance energy storage system composed of the capacitor bank, the spark gaps, and the transmission lines was constructed and a Mather type plasma gun was manufactured. Then the characteristics of each component of the plasma focus device were determined through the impedance matching considerations with H_2 gas. And the creation of the neutron from the D-D reastions in the dense plasma focus was confirmed with D_2 gas by a Long counter. In the section Ⅱ the components of the apparatus utilized for this experiment and the impedance matching problems will be described. In the section Ⅲ the experimental results are illustrated. Some conclusions occupy the section Ⅳ.

Ⅱ. Apparatus

The plasma focus device consists of a energy storage system and a plasma gun. The photographic overview of the plama focus device is shown in photo. 1.

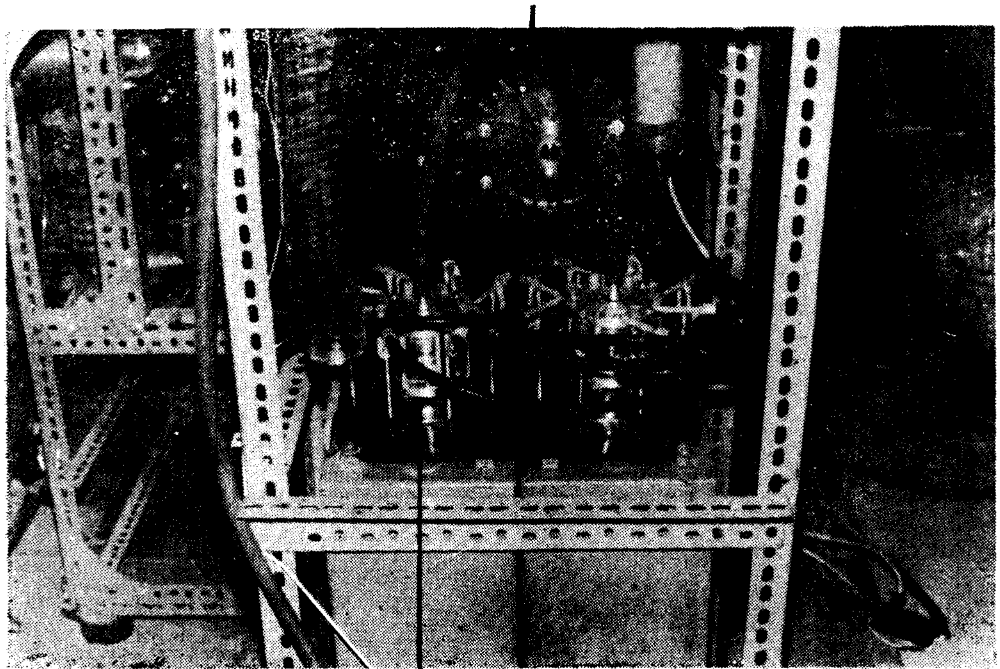

Photo. 1. Overview of the Plasma Focus Device

1. **Energy Storage System** (capacitor bank, spark gaps, transmission lines)

When the charging voltage of the capacitor is V, the capacitance is C, and the inductance of the circuit is L, the maximum of the discharge current I_p is approximately expressed as $I_p=0.8V\frac{C}{L}$. In order to maximize the discharge current increasing the charging voltage is inevitable. But for the capacitance and the inductance it is difficult to determine to what extent those are increased or decreased in the impedance matching aspect. Of course the increase of the capacitance and the decrease of the inductance bring out the rise of the maximum discharge current. It is however more complicated to accord the time of the maximum discharge current exactly with the end of the plasma accelerating stage.

If the inductance of the circuit is decreased extremely, the discharge current rapidly oscillates and damps down, and there is not enough time for the magnetic pressure to be stored sufficiently for the focus of the plasma. The increase of the capacitance causes the technical problem such as the guarantee of the coincidency in the operations of the switches and the capacitors. In this experiment two capacitors of 15μF and 20KV with two field distorion spark gaps[2)~4)] are employed in parallel. The transmission lines are composed of 16×1.25m RG 8A/U coaxial lines. The overall inductance of the system is about 35nH. In the figure 1 the triggering circuit for the field distortion spark gas is shown. The insulating cylinder of the spark gap is made of the acril cylinder of 16mm thickness. The electrodes are made of aluminium covered with stainless steel to prevent the electrodes from the severe damage by the discharge arc. The center ring electrode has a knife edge along the inner circumference. The vertical gap spacing between the main electrodes is 6mm. To assure the switching simultaneity of two spark gaps the electrodes are fabricated within the accuracy of 0.05mm and the spark gaps are set up within the accuracy of 0.2mm. To generate the triggering pulses simultaneously two Blumlein circuits[3)] which have the triple structure with three copper plates and three insulating plates are constructed. The rise time and the pulse height of the triggering voltage pulse are 10 ns and 9KV. Because of the low charging voltage operation of the device the polarity of the central ring electrode has to be reversed to close the spark gaps with stability upon the influence of a triggering voltage pulse in contrast with the high voltage operation. Each ground electrode of the spark gaps is connected to the plasma gun by eight coaxial cables. The other electrodes are connected directly to the high voltage section of the capacitors. The ground sheaths of the coaxial lines are connected to the brass rods standing around the spark gaps.

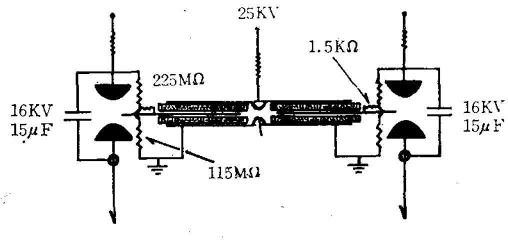

Fig. 1. Triggering Circuit of the Spark Gaps

2. **Plasma Gun**

The characteristics of the Mather type plasma gun are mostly decided by the ratio of the diameters of the outer electrode and the center electrode, and the length of the center electrode. As the former is a and the latter is l, the inductance per unit length of the plasma gun L_i is given by $2 \ln a$ nH/cm, and the input power into the kinetic energy of the plasma $\dot{K}$ is represented as follows, $\dot{K}=\frac{i^2}{2}\frac{dL_iZ}{dt}\cong\frac{i^2}{2}L_iv$ (where Z is the axial position of the plasma and v is the velocity of the current sheet). As long as the discharge current is increased, the acceleration of the plasma is also increased until the end of the accelerating stage. The average velocity $\bar{v}$ of the plasma in the accelerating stage is proportional to the root of the stored energy of the capacitor bank, and inversely proportional to the root of the gas filling pressure, that is, $\bar{v}\sim\sqrt{\frac{E}{\rho}}\sim\frac{I_p}{\sqrt{\rho}}$, where E is the stored energy of the capacitor bank, ρ is the density of the filling gas, and the relation $E=\frac{1}{2}CV^2\sim I_p{}^2$ is used in the last step. The time to reach the maximum discharge current t_p is in proportion to $\sqrt{LC}$, and the travel time of the plasma in the plasma gun t_g is $\frac{l}{\bar{v}}$. In the case that t_p and t_g nearly accord, the scaling law such as $\frac{V}{\sqrt{\rho l}}\sim$constant is obtained for the condition of the plasma focus. With above mentioned scaling law it is well recognized that the increase of the charging voltage, and the decrease of the gas filling pressure and the length of the center electrode equivalently influence on the plasma focus. The inductance of the plasma gun is gradually increased at the accelerating stage. Then the rate of the change of the discharge current becomes lower and the wave form of the discharge current is deviated from the sine wave. When the plasma gun is operated with the condition of the plasma focus, the change in the discharge current wave due to the variation of the inductance is negligible compared with the rapid drop in the discharge current wave due to the sudden increase of the plasma resistance. Because the plasma focus at the front of the center electrode causes the increase of the resistance and the inductance, there are great changes of the discharge current and the voltage of the center electrode. The diameters of the outer electrode and the center electrode of the plasma gun shown in the figure 2 are 46mm and 21mm respectively. The inductance of the plasma gun per unit length is 1.67nH/cm. Between the outer and the inner electrodes teflon cylinder is inserted to induce the inverse pinch which lead the surface of the discharge to be shaped in the form of an umbrella, that is essential for the stable acceleration of the plasma[1]. The insulating section of 30mm length increases intrinsically the inductance of the plasma gun by about 5nH. The coaxial lines from the spark gaps are connected into the current collecting disk which is attached to the center electrode. The maximum inductance of the plasma gun including the conducting lines is about 30nH. Usually the ratio of the inductance of the plasma gun itself to that of the external circuit is controlled to be slightly greater than or nearly unity. The central electrode is made to slide through the teflon cylinder to vary the effective length of the plasma gun, but it is time consuming to actually change the length because of the conducting lines which have to be disconnected in order to attach a spacer into the center electrode. Therefore in this experiment through the change of the gas filling pressure the condition of the plasma focus were examined. The gas filling pressure is maintained from 0.05 torr to 1 torr with a variable leak valve which allows the gas to flow infinitesimally into the plasma gun evacuated by the vacuum pumps.

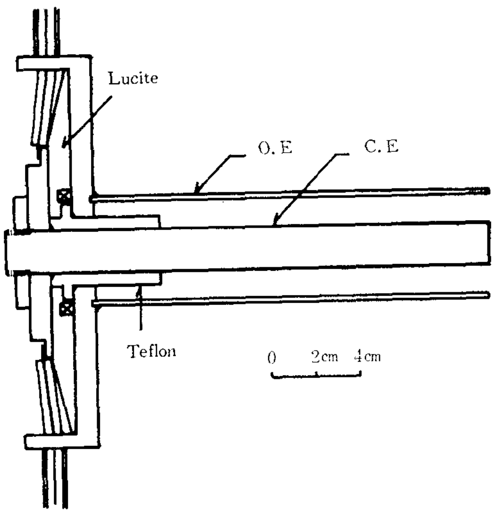

Fig. 2. Schematic Diagram of the Plasma Gun

III. Experimental results and discussion

1. Measurements of the Current and the Voltage

The discharge current is measured by the Rogowski coil located at just below the current collecting disk. The voltage signal from the Rogowski coil is transmitted to a Tektronix 485 oscilloscope via. a integrating circuit of 20μs time constant. The conversion factor of the amplitude of the oscillogram into the discharge current is 5.2kA/V. The voltage of the center electrode is measured with a Tektronix P6015 high voltage probe (response time; 7ns). The voltage drop through the plasma is measured by a tungsten wire inserted between the electrodes of the plasma gun.

In photo. 2 several oscillographs of the discharge current and the voltage are shown. When the plasma focus occurs the oscillograms show the distinct features which may not appear without the plasma focus. The discharge current does not critically damp, but still oscillates with reduced amplitude by the energy loss in the focused plasma. The oscillating period T is obtained from a oscillogram and the inductance L is given by the relation $L=\frac{T^2}{4\pi^2C}=0.84\,\mathrm{nH}/\mu\mathrm{s}^2$. The overall inductance of the circuit is about 65 nH. For the average velocity of the plasma and the travel time t_g is varied with the charging voltage and the gas filling pressure, while the time of the maximum current t_p remains nearly constant, the plasma focus may start before of after the maximum of the current. In such cases the efficient plasma focus can be obtained by controlling the charging voltage and the gas filling pressure to the proper values. The probability of the plasma focus is about 1 to 10 for 300 shots. This low probability is mainly due to the unstable operations of the spark gaps. Whenever the main discharges occur the central ring electrodes become slightly twisted by the thermal pressure and the resistance between the center ring electrode and the high voltage electrode is gradually reduced by the attachment of the carbide to the cylinder wall, which causes that the potential of the center ring electrode is raised too high to be changed in polarity by a triggering pulse. Then the simultaneous switching of two spark gaps are not guaranteed. That is confirmed by the fact that the plasma foci take place with stability just after the maintenance of the spark gap, but the unstable switching operations appear at once. The study on the methods to improve the characteristics of the spark gaps is completed and a new spark gap is designed, which will be reported later. Although it is confirmed that the rise of the charging voltage and the diminution of the gas filling pressure make the velocity of the plasma increased and make the plasma focus starting time shorter, and vice versa, the quantitative results have not been obtained because of the lack of the experimental data.

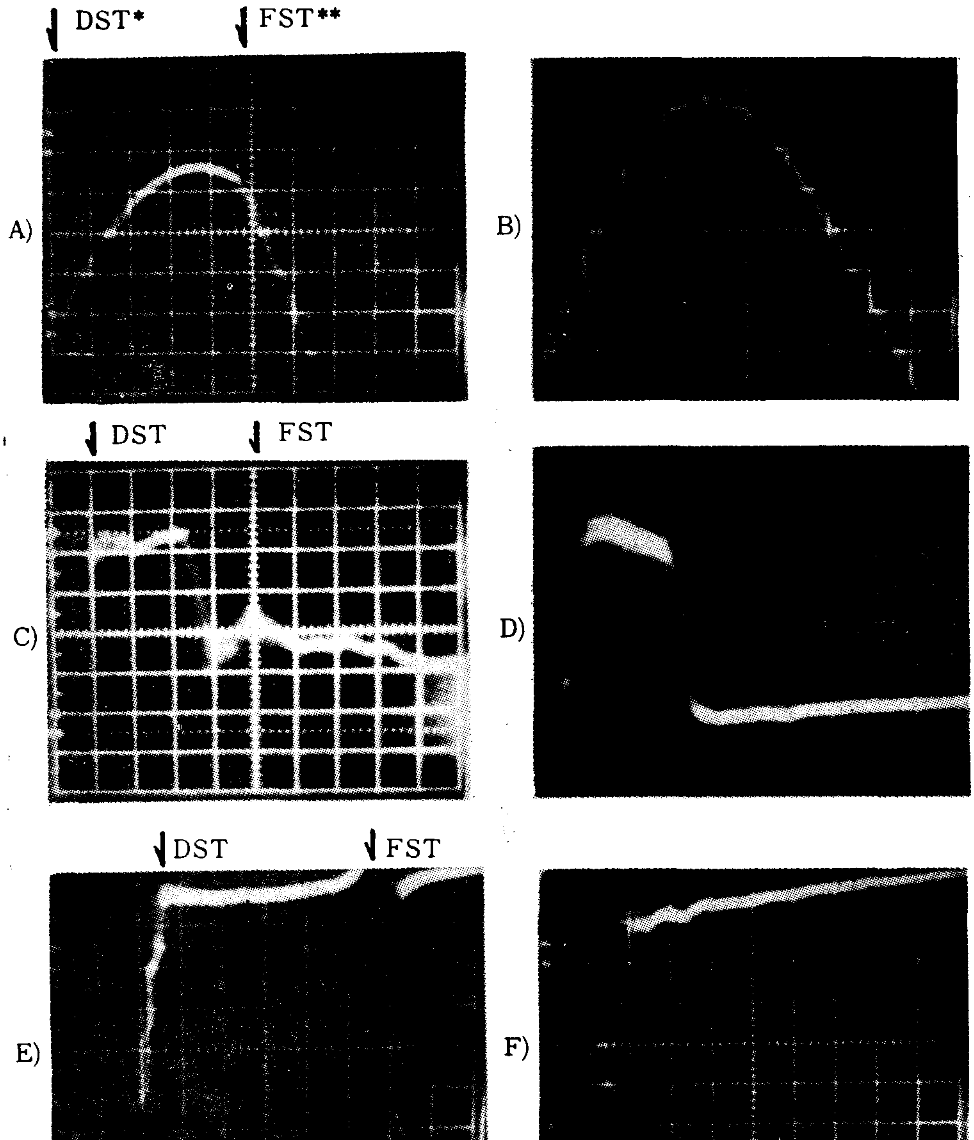

Photo. 2. Typical Current and Voltage Oscillograms

A) Discharge current, 26kA/Div., 0.5us/Div., P_{D2} ; 0.15torr, $V_{app.}$; 14kV
B) Discharge current, 26kA/Div., 0.5us/Div., P_{D2} ; 0.5torr, $V_{app.}$; 16kV
C), D) Voltage of C.E, 4.6kV/Div., 0.5us/Div., P_{D2} ; 0.2torr, V_{app} ; 16kV
E), F) Voltage drop of the plasma, 50V/Div., 0.5us/Div, P_{D2} 0.1torr, $V_{app.}$ 15kV
A), C), E); with a plasma focus B), D), F); without a plasma focus
*** DST; discharge starting time**
**** FST; focus starting time**

When all other conditions are maintained, comparing the case of using H_2 gas with the case of using D_2 gas, the maxima of the discharge currnt and the wave forms do not show any dominant differences, but the focus starting time of the D_2 plasma is longer by about 1.4 times than that of the H_2 plasma. When D_2 gas filling pressure is 0.18 torr, the focus starting time is about 2μs, and consequently the average axial velocity of the plasma is about 7cm/μs. By the snowplow model the axial velocity of the plasma v is represented as follows[5),6)],

$$v=\frac{VC}{T}\left\{\frac{\mu_0 \ln\left(\frac{r_0}{r_i}\right)}{\eta\rho(r_0^2-r_i^2)}\right\}^{\frac{1}{2}} \text{ in MKS,}$$

where μ_0 is the permeability, r_0 is the radius of the outer electrode, r_i is the radius of the inner electrode, η is a constant related to the sweeping efficiency, and the term $(r^2_0-r^2_i)$ corresponds to the mechanical load of the plasma gun itself. When the charging voltage is 16kV, the D_2 gas filling pressure is 0.18 torr, and η is 0.64, the velocity calculated by the snowplow model is 12cm/μs. It is larger than the experimental result at the same condition. The discrepancy can be explained in terms of the currents flowing over the insulator sulface. H. Bruzzone reported that the stable plasma foci may be obtained at the stored energy of about 1KJ and the D_2 gas filling pressure of 1~2 torr. In our experiment at the pressure of above 1 torr the occurrence of the plasma focus is limited. The reasons are such that firstly the mechanical load and the length of the plasma gun is large for the stored energy, secondly the efficiency of the energy transfer into the D_2 plasma is low because of the comparatively high concentration of the residual heavy elements in the gas. By reducing the length and/or the mechanical load of the plasma gun, the pressure of the plasma focus will be extended to a few torr. To a few torr the maximum of the discharge current and the probability of the plasma focus are increased with the rise of the gas filling presure.

2. Detection of the Neutrons

The energy of the neutron produced from the D-D reaction is about 2.45 MeV, and the number of neutrons per discharge pulse of the plasma focus device is represented as $3.56\times10^6\ E^{2.1}$ (where the unit of E is KJ)[4)]. The width of the neutron pulse is about 100ns, which is comparable with the time of radial compression at the focusing stage. In our experiment a Long counter was used to detect the fast neutrons from the focused plasma. With the Long counter the thermalized neutrons are detected by a BF_3 detector covered with paraffin which moderates and thermalize the incident fast neutrons. Because the time constant of the BF_3 detector and its preamplifier is 5.3μs, this detecting system is not useful to count accurately the neutron flux for 100ns, but it enables to decide the existence of the fast neutron with its high detecting efficiency. The signal from the preamplifier is reamplified with a spectroscopy amplifier. The pulse from the spectroscopy amplifier is shown in photo. 3. Both photographs show the severe noise. The first~100MHz noise is originated from the triggering pulse, while the second large ~MHz noise is due to the main discharge. It is regarded by the following aspects that a neutron pulse is appeared from the amplifier as the characteristic signal. Firstly the appearing time of the signal is agreed with the focus starting time. Secondly the frequency of the noise is greater than that of the neutron pulse, and thirdly any noise

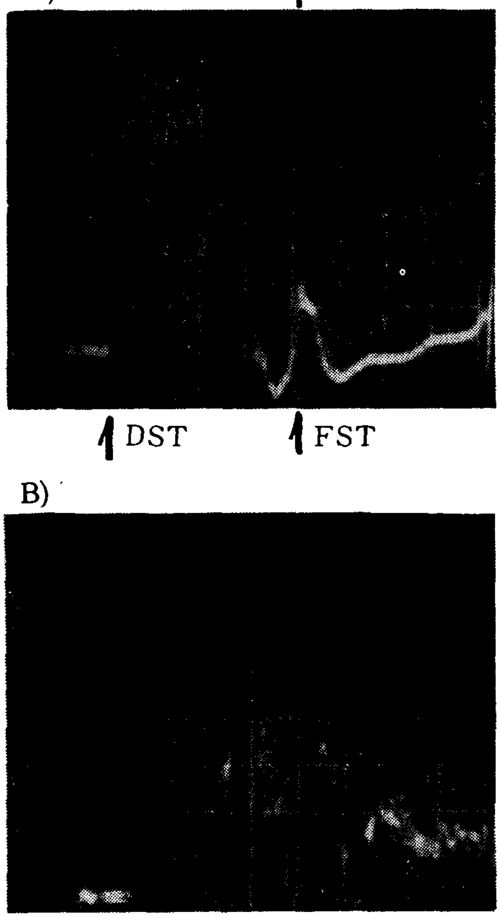

Photo. 3. Neutron Pulse Oscillogram
Sweep speed; 0.5us/Div., P_{D2}; 0.18torr, $V_{app.}$; 16.5kV A) ;with a plasma focus B) ;without a plasma focus

picked up can not produce the characteristic signal which is only resulted from the incidence of the neutron into the detector. Now the fast neutron detectors are under preparation, which enable to count accurately the neutron flux and measure the neutron spectrum. The results of the work will be reported later.

Ⅳ. Conclusion

Even at low stored energy the plasma focus can be efficiently achieved by decreasing the inductance of the circuit and controlling the load of the plasma gun. At the charging voltage of 16kV the maximum of the discharge current is 180kA and the average axial velocity is 7cm/μs. It is smaller than the calculated velocity by the snowplow model. The difference is due to the current loss through the insulator surface and to the local arc. To switch two spark gaps simultaneously, the structure of the spark gaps should be firm enougn to hold the mechanical and thermal stress due to the powerful discharges. It is desirable for the stable triggering to operate the spark gaps at high voltage as possible. It is also necessary for the simultaneos switching to increase the triggering voltage. To do this the insulator of the high breakdown strength and the high permitivity must be used in the Blumlein circuit. For the accurate measurement of the neutron, the shielding of the signal lines from the discharge noise must be reinforced by the triaxial structure with the copper tubes. The neutron emission from the focused plasma is detected by a Long counter with D_2 gas at the proper conditions.

References

1. H. Rapp, Rep. No. IPF-74-1, Institute for Plasma Research, Stuttgart (1974)
2. J.L. Brewster et al., PEP 4-1, Note 8, Air Force Weapons Laboratory (1974)
3. R. Toschi, "Technological and Engineering Problems of Fusion Reactor," V. II, 442, USAEC (1974)
4. 横山昌弘 外, 核融合研究, **35**(6), 428 (1976)
5. T. Butler et al., *Phys. Fluids*, **12**, 1904 (1969)
6. H. Bruzzone, "Energy Storage, Compression, and Switching," 255, Plenum Press (1976)