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Pneumatic Hydrogen Pellet Injection System for the ISX Tokamak

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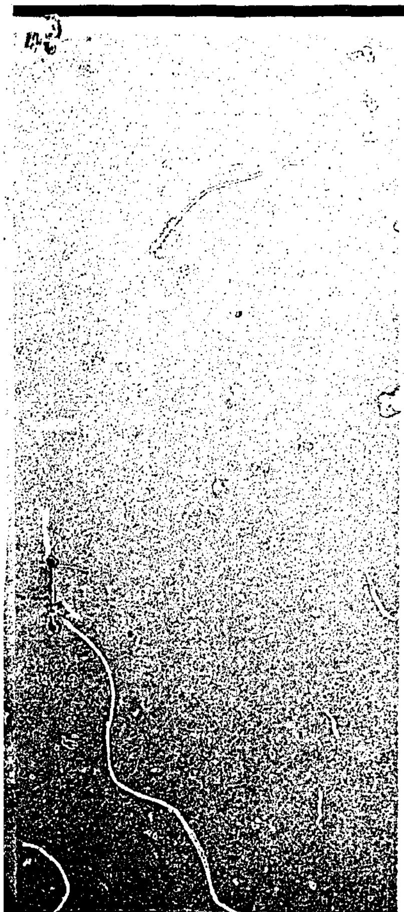
C. A. Foster



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FUSION ENERGY DIVISION

PNEUMATIC HYDROGEN PELLET INJECTION SYSTEM FOR THE ISX TOKAMAK

S. L. Milora
C. A. Foster

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ABSTRACT

We describe the design and operation of the solid hydrogen pellet injection system used in plasma refueling experiments on the ISX tokamak. The gun-type injector operates on the principle of gas dynamic acceleration of cryogenic pellets confined laterally in a tube. The device is cooled by flowing liquid helium refrigerant, and pellets are formed in situ. Room temperature helium gas at moderate pressure is used as the propellant

The prototype device injected single hydrogen pellets into the tokamak discharge at a nominal 330 m/s. The tokamak plasma fuel content was observed to increase by $0.5\text{-}1.2 \times 10^{19}$ particles subsequent to pellet injection. A simple modification to the existing design has extended the performance to 1000 m/s. At higher propellant operating pressures (28 bar), the muzzle velocity is 20% less than predicted by an idealized constant area expansion process.

INTRODUCTION

Fusion power reactors based on the tokamak concept will require an active mechanism for replenishing the spent fuel. Present tokamak confinement devices rely on gas puffing at the plasma edge and particle recycle from the vacuum vessel walls and from the plasma limiters to maintain the plasma density over several particle confinement times. As an alternative to gas puffing, injection of solid hydrogen isotope pellets at high speed has been proposed as a method of carrying fuel more deeply into the hot central core of the plasma. Estimates of the pellet size and velocities required for deep penetration into the plasma generally range from 1 mm and 1000 m/s for present tokamak plasmas to 5 mm and 5000 m/s for conditions likely to be typical of power reactors.[1]

In the first demonstration of pellet injection into a tokamak plasma,[2] spherical pellets of 0.070-mm and 0.21-mm diam were injected into the Oak Ridge Tokamak at speeds of 100 m/s using the liquid droplet generator described by Foster et al.[3] In a different experiment, large, freely falling pellets produced by an extrusion-type pellet source were dropped into the Pulsator tokamak prior to initiation of the plasma discharge.[4] In this paper, we describe the design and performance of a newly developed gun-type injector that has been used in recent hydrogen pellet refueling experiments on the Impurity Study Tokamak (ISX-A).[5] The prototype device was capable of injecting a single pellet during the tokamak discharge at a speed of ∿330 m/s, resulting in a nominal 30% increase in the plasma particle content. The simple modifications described in this paper have extended the performance to 1000 m/s, and further improvements may be possible.

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I. PRINCIPLE OF OPERATION

The gun-type injector described below operates on the principle that a projectile confined laterally in a tube will experience an acceleration when subjected to an applied pressure imbalance. When the fluid that supplies the driving force is a compressible gas, the projectile can be accelerated to high speeds as the internal energy of the gas is converted in the expansion process to kinetic energy of the projectile.

By invoking simplifying assumptions, the performance of such a device can be readily estimated. Neglecting nonideal effects such as friction at the projectile-tube interface, heat transfer from the propellant to the tube wall, viscosity, and gas leakage, the projectile velocity $U(t)$ at time t after sudden application of the gas pressure P_0 is given (for a constant area tube) by[6]

$$U(t) = \frac{2C_0}{\gamma - 1} \left\{ 1 - \left[1 + \frac{(\gamma + 1)\, A_p}{2M\, C_0} P_0\, t \right]^{-(\gamma-1)/(\gamma+1)} \right\} , \qquad (1)$$

where C_0 is the speed of sound of the propellant, γ is the ratio of specific heats, M is the projectile mass, and A_p is the projectile base area (equal to the cross-sectional area of the tube). The behavior of the pressure $P(t)$ at the projectile base will decrease in time according to

$$P(t)/P_0 = \left[1 - \frac{\gamma - 1}{2} \frac{U(t)}{C_0} \right]^{2\gamma/\gamma-1} . \qquad (2)$$

It follows from Eqs. (1) and (2) that the ultimate attainable speed for an expansion to zero pressure is

$$U_{max} = \frac{2C_o}{\gamma - 1} . \qquad (3)$$

For ideal gas conditions, $C_o = \sqrt{\gamma RT/m}$ where R is the universal gas constant, T is the temperature, and m is the propellant molecular weight. This result obviously favors light gases (such as hydrogen or helium) at elevated temperatures. At room temperature, hydrogen ($\gamma = 7/5$) exhibits an ultimate speed of 6500 m/s compared with 3000 m/s for helium ($\gamma = 5/3$). In practice, these limits are never attained because, as the projectile accelerates, the pressure steadily decreases and is eventually balanced by the increasing retarding effects of friction. The presence of friction and other nonidealities suggests an optimum gun barrel length and hence velocity for given projectile/propellant conditions.

Equation (1) can be recast into a form that gives the net acceleration path length L as a function of muzzle velocity U_m. In terms of the characteristic time $\tau = [(\gamma - 1)\, U_{max}\, M]/[(\gamma + 1)\, A_p\, P_o]$, we can write

$$L(U_m) = \int_0^{t_m} U(t)dt = \tau U_{max} \int_0^{t_m/\tau} \left[1 - \left(1 + \frac{t}{\tau}\right)^{-(\gamma-1)/(\gamma+1)} \right] \frac{dt}{\tau} , \qquad (4)$$

where

$$t_m/\tau = \left(1 - \frac{U_m}{U_{max}}\right)^{-(\gamma+1)/(\gamma-1)} - 1 .$$

This result implies that high velocities can be attained in relatively short acceleration paths at moderate working pressures when using low inertia projectiles. For 1-mm solid hydrogen pellets (mass density = 86 kg/m^3), a characteristic time of 65 μs results for room temperature helium propellant at P_o = 10 bar. The solution to Eqs. (1)-(4) for these conditions suggests that velocities in the vicinity of 500 m/s would result with a gun barrel length on the order of a few centimeters. This illustrates the merits of hydrogen as the projectile material. Its low density allows high performance at moderate working pressures which are easily obtainable without having to resort to the use of explosives.

As noted in Section V, we have obtained velocities in the range 300 m/s to 1000 m/s with gun barrel lengths of 3.2 and 16 cm, respectively. The higher performance occurs at $\sim$28-bar working pressure and is in reasonable agreement with the value predicted by this simple model. This result implies that the degrading effects of friction might not be a major impediment to attainment of higher velocities.

II. INJECTOR DESIGN DETAILS

Essential design elements of the injector are illustrated in Figs. 1 through 3. A miniature stainless steel gun barrel insert (two were studied: 0.082-cm bore x 3.18-cm long and 0.1-cm bore x 16-cm long) is fixed within the barrel housing made of OFHC copper. A disc-shaped stainless steel pellet carrier is situated between the barrel housing and the OFHC copper main housing. The carrier has two 1-mm-diam holes drilled opposite each other extending through the face of the disc within which pellets are located. The pellet carrier, which is free to rotate between two brass washers, serves the dual purpose of (1) forming a frozen hydrogen plug in the condensate well located in the lower half of the main housing and (2) transporting it to a position in line with the gun barrel located directly above. The gun assembly is convectively force-cooled by liquid helium flowing through 0.635-cm-OD cooling lines brazed to the barrel housing and the copper heat exchanger appendage of the main housing. Liquid helium coolant is transferred to the system from a pressurized storage dewar through a bayonet coupling transfer tube.

The liquid helium flow causes hydrogen gas to condense in the interior of the mechanism, filling the condensate well and the lower cylindrical void in the pellet carrier with liquid. When this volume is saturated with liquid, further cooling produces a frozen plug of hydrogen in the bottom hole of the pellet carrier. The pellet carrier is rotated 180° to transport the plug to the position in line with the gun barrel. The pellet is propelled from the mechanism by pressurized helium gas admitted to the chamber behind the pellet carrier by a fast opening magnetic valve (Skinner model V5H26260, 0.318-cm orifice). The valve is opened momentarily by discharging a 5-μF capacitor initially charged to 300 V into the valve solenoid. This arrangement ensures that the valve will open against the higher working pressures. The electronic triggering unit shown in Fig. 4 includes a variable time delay crow bar circuit to de-energize the capacitor and minimize the time that the valve remains open. The valve is maintained at or near room temperature by heat sinking to the device vacuum chamber wall. Heat leakage from the valve to the main housing is minimized by using thin wall (0.318-cm OD x 0.267-cm ID) connecting stainless steel tubing. At working pressures on the order of 10 bar, a gas load of ∿10 Torr-ℓ results from a single valve pulse. This gas is effectively prevented from entering the tokamak by the low-conductance, gas delay system described in Section III.

Vacuum thermal insulation is maintained around the exterior surfaces of the mechanism. A mechanical vacuum pump is used to evacuate the vacuum enclosure to $\sim 10^{-2}$ Torr before cooldown. During operation, the cold surfaces of the coolant lines pump the interior of the chamber by cryocondensation, and the mechanical pump is valved off. Hydrogen leakage into the vacuum enclosure is prevented by silver solder joints at all mating surfaces. To facilitate disassembly, an indium seal is provided between the flange surfaces of the main and barrel housings.

The pellet carrier is connected to an externally located air-driven rotary actuator by a shaft fabricated from 0.953-cm OD x 0.810-cm ID stainless steel tubing. This is of sufficient strength to withstand the starting torque ($\sim$130 in.-lb) used to free the pellet carrier when the mechanism is saturated with hydrogen ice. The drive shaft is housed within a 1.27-cm OD x 1.22-cm ID stainless steel sleeve that supports the gun assembly. An external quick-connect O-ring fitting prevents air from entering the annulus between the drive shaft and this support tube. This annulus serves as a passageway for hydrogen gas admitted to the gun mechanism.

Three adjustable tensioned stainless steel struts pictured in Fig. 3 support the gun mechanism inside its vacuum housing and prevent twisting motion and damage to the support tube during rotation of the pellet carrier. These are constructed of thin wall tubing to minimize heat leakage to the gun assembly. The struts extend through quick-connect O-ring fittings on the vacuum chamber wall to facilitate positioning and alignment of the device from outside the vacuum enclosure.

The exterior temperature of the main housing is monitored with a single Chromel/gold 0.07% atomic iron thermocouple located near the condensate well. Digital temperature readout is accomplished with a Scientific Instruments model 3700 temperature indicator/controller. When used in conjunction with a 25-W cartridge heater incorporated into the heat exchanger appendage of the main housing, this arrangement permits coarse temperature regulation. During normal operation as described in Section IV, temperature regulation is unnecessary.

The choice of OFHC copper as the material of construction for the housing subassemblies ensures that nearly isothermal conditions will exist throughout the mechanism. To lessen the likelihood of hydrogen freezing within the gun barrel insert, it is thermally insulated from the barrel housing by a thick (0.318-cm OD) stainless steel sleeve. Freezing of liquid hydrogen occurs preferentially within the condensate well due to the high thermal conductivity of copper relative to stainless steel at liquid helium temperatures.

III. PELLET INJECTION LINE

The primary function of the pellet injection line is to isolate the tokamak vacuum vessel from the pressurized environment of the pellet injector. This is accomplished by using the staged gas delay line (shown in Fig. 5) which consists of a 92-cm length of 23-cm-diam stainless steel pipe partitioned into eight separate chambers. Small clearance holes drilled through the center of each partition allow the pellet to pass through the volumetric pumping stages and enter a short section of 3.8-cm-diam tubing connecting to the tokamak. The throughput of helium propellant is retarded and minimized during the tokamak discharge (∿200 ms) by the large effective time constant of the system of small area apertures and large capacity chambers.

In addition, a fast magnetic gate valve (Veeco model SV 62S-AC, 1.9-cm aperture) situated between the fourth and fifth chambers closes behind the pellet, trapping most of the gas in the first four compartments where it can be removed between tokamak discharges by a mechanical pump. This prevents large amounts of gas from entering the high vacuum final stage of the system. A 20-cm oil diffusion pump removes any propellant gas that is admitted during the time interval that the gate valve is open. Pressure excursions in the final stage are limited to $\sim 10^{-5}$ Torr by this arrangement.

The magnetic gate valve cycle time (close-open-close) can be varied from 50 to 200 ms with a 160-μF capacitive discharge circuit similar in design to that used to actuate the gas propellant valve. During normal operation, the gate valve circuit is triggered before the injector fires. The length of time that the valve remains fully open is sufficient to accommodate the 7-ms delay that exists between triggering of the gas pulse valve and emergence of the pellet from the injector.

IV. OPERATING PROCEDURE

The injector may be operated while mounted on the pellet injection line or any vacuum chamber equipped with a mechanical vacuum pump. When operating the device with the pellet injection line, the following procedure was found to produce pellets reliably. With the magnetic gate valve closed and the system under vacuum, liquid helium is transferred from the pressurized storage dewar by venting the coolant exhaust line through a liquid nitrogen service solenoid valve. No adjustment of the liquid helium flow rate is required, and optimum operation results when the storage dewar is pressurized above 118 kPa (2.5 psig). When the temperature of the main housing has stabilized (∿4.3 K), the hydrogen feed valve is opened, and room temperature gas is allowed to enter the evacuated mechanism at a rate of ∿60 Torr-ℓ/s. The low flow rate is necessary to prevent excessive heat loads and concomitant temperature excursions. The gas throughput is set by a metering valve located downstream from the gas pressure regulator (set just above atmospheric pressure) and the hydrogen feed valve. This arrangement ensures that only low pressure gas will enter the device initially. At low pressures, the gas freezes on contact with the walls of the mechanism, forming a gas-tight seal between the pellet carrier disc and the two retaining brass washers. This effectively prevents hydrogen gas from escaping through the gun barrel into the pellet injection line. When the pressure rises above the triple point (54 Torr), the gas condenses in the condensate well and liquid is forced into the lower hole in the pellet carrier disc. The pressure equilibrates to the value set at the supply in ∿10 s, indicating that the condensate well is full. The hydrogen feed valve is closed and ∿20 s is allowed to lapse while the liquid freezes.

Operation of the rotary actuator applies a torque to the pellet carrier, and the resulting shearing action at the interface of the pellet carrier disc and the inside brass washer breaks the hydrogen cylinder in the condensate well. The resulting hydrogen plug left inside the 1-mm cylindrical void in the pellet carrier is then transported to the vertical firing position, and operation of the helium propellant valve discharges the pellet from the mechanism.

To repeat the cycle, the hydrogen remaining in the mechanism and the helium gas in the pellet injection line are exhausted through the mechanical vacuum pump, the pellet carrier is returned to its original position, and the procedure described above is repeated. The cycle can be completed in less than 2 min.

V. RESULTS

Accurate velocity measurements were made with the pellet injector in operation on the ISX-A tokamak (with the 3.2-cm gun barrel). The experimental arrangement is shown schematically in Fig. 6. Two photodiodes (0.03-cm^2 active area) were used to measure the time of flight in the pellet injection line and the drift tube assembly. The interaction between the pellet and the plasma resulted in a sharp burst of light that was easily distinguished from the background radiation level by the plasma view photodiode situated in the drift tube. Velocities as high as 380 m/s were measured, but a value of 330 ± 20 m/s was typical during the experimental sequence.

Time-of-flight velocity measurements were made with the 16-cm barrel by replacing the gate valve on the pellet injection line with a dynamic microphone (standard telephone ear piece). The impact of the pellet on the microphone diaphragm creates a 1-kHz oscillation with a sharp leading edge. A signal level of $\sim$5 V is typical at the higher velocities. Pellet velocities in excess of 1000 m/s were observed at working pressures approaching 30 bar.

The muzzle velocities measured with both gun barrels are plotted in Fig. 7 as a function of the parameter L/τ where L is the gun barrel length and τ is the characteristic time defined in Section I for the propellant/projectile combination. The results were obtained by varying the propellant working pressure P_0 up to a maximum of 28.6 bar. Higher pressures were not explored because of the possibility of damaging the stainless steel bellows in the main housing assembly.

For high values of L/τ, the performance is in relatively good agreement with the simplified model presented in Section I. At lower pressures, a 50% discrepancy is typical, and this is very likely due to the increased importance of kinetic and perhaps static friction in this operating range.

The angular dispersion in pellet trajectory is well within the 0.64° limit imposed by the aperture sizes in the pellet injection line. When the injector is properly aligned, over 90% of the pellets produced pass through the restrictions. Alignment is performed optically by sighting through the series of apertures and centering the gun barrel in the field of view.

The shadowgraphs of Fig. 8 give an indication of pellet size and shape when operating with both gun barrels. The photographs were taken through a microscope by backlighting the pellet with a spark lamp (Xenon Corporation model 437 A Nanopulser). The two-dimensional information of the shadowgraphs suggests that pellets are cylinders in various orientations. The physical dimensions are close to the expected values as determined by the thickness of the pellet carrier disc (1 mm) and the gun barrel bore (0.82 mm and 1.0 mm). There is no evidence of pellet fragmentation even at operating pressures that are many times greater than the published values for the tensile strength of hydrogen ice.[7]

VI. CONCLUSIONS

We have described a device that is simple in design and operation, having advanced performance capabilities (pellet mass and velocity) that are within the range of values required by present tokamak confinement devices. The ease with which pellet velocity and size can be varied makes the apparatus a useful tool for pellet ablation studies and plasma refueling experiments. Its compact size and simplicity of design suggest several possible configurations that would perform suitably as continuous fueling devices for the present generation of short pulse length tokamaks.

The performance limitations for this device have not been determined, and we have not fully explored the range of operating parameters and device configurations. Higher velocities should result from operation at increased working pressures (if pellet structural integrity is preserved) and optimization of gun parameters such as barrel length and diameter and projectile shape. According to the simple model of Section I, the use of hydrogen gas as a propellant should similarly result in substantial performance improvements.

ACKNOWLEDGMENTS

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FIGURE LEGENDS

FIG. 1. Schematic of pellet injector. Pellets exit the device through the tube at right.

FIG. 2. Detail of main housing/barrel housing subassembly featuring 3.2-cm barrel. Heat transfer surfaces are not shown. The discharge tube extends through the front flange via a quick-connect O-ring fitting. Maximum pellet size is determined by the thickness of the pellet carrier disc and the ID of the barrel. The hole at the top of the pellet carrier is for clearing the barrel.

FIG. 3. Photograph of assembled pellet injector with front flange removed. The discharge tube is shown in the center.

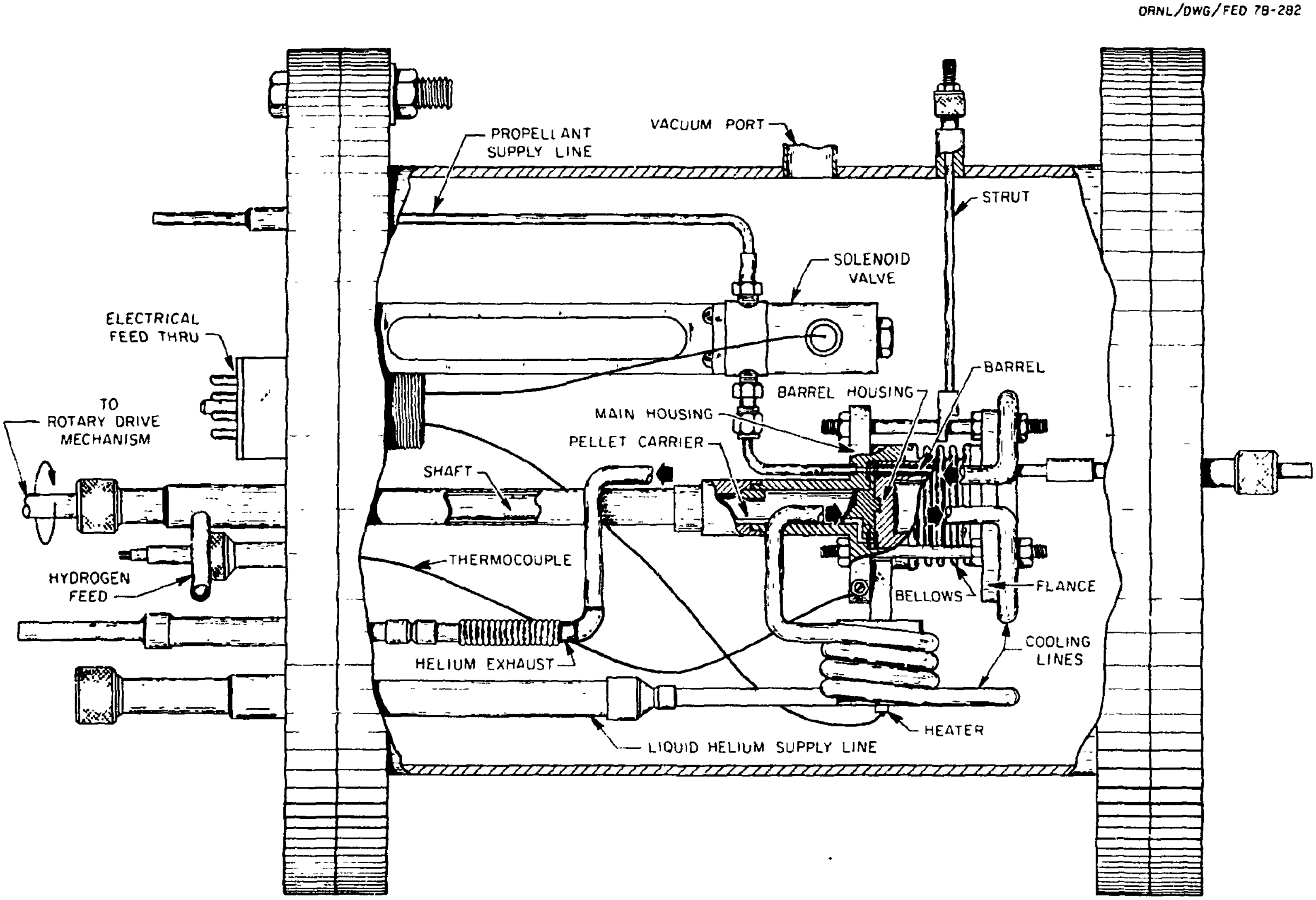
FIG. 4. Capacitive discharge circuitry for energizing propellant valve (5-μF capacitor) and injection line gate valve (160-μF capacitor). Capacitors are charged to 300 Vdc with an external power supply. The variable time-delay crow bar circuit de-energizes the capacitor and valve solenoid after the energizing SCR fires, thus enabling rapid closing. The circuit can be triggered manually, with an external switch, or with a positive going pulse (>2 V, ~ 5 mA).

FIG. 5. Schematic of pellet injection line. Small aperture restrictions constitute a maximum acceptance angle of 0.64°.

FIG. 6. Schematic of pellet injection experiment on ISX-A tokamak. Filament of 15-W lamp is focused on the photodiode at the entrance to the injection line. Drawing is not to scale.

FIG. 7. Dependence of muzzle velocity on the parameter L/τ for 3.2-cm and 16-cm barrels using pressurized helium propellant at room temperature ($C_0 = 1000$ m/s, $\gamma = 5/3$). The data are compared with the theoretical scaling law of Section I.

FIG. 8. Shadowgraphs of pellets in flight. The trajectory is from left to right. (a) 3.2-cm barrel, 0.82-mm bore, 350 m/s. (b) 16-cm barrel, 1.0-mm bore, 780 m/s. (c) 16-cm barrel, 1.0-mm bore, 620 m/s.


ORNL/DWG/FED 78-282
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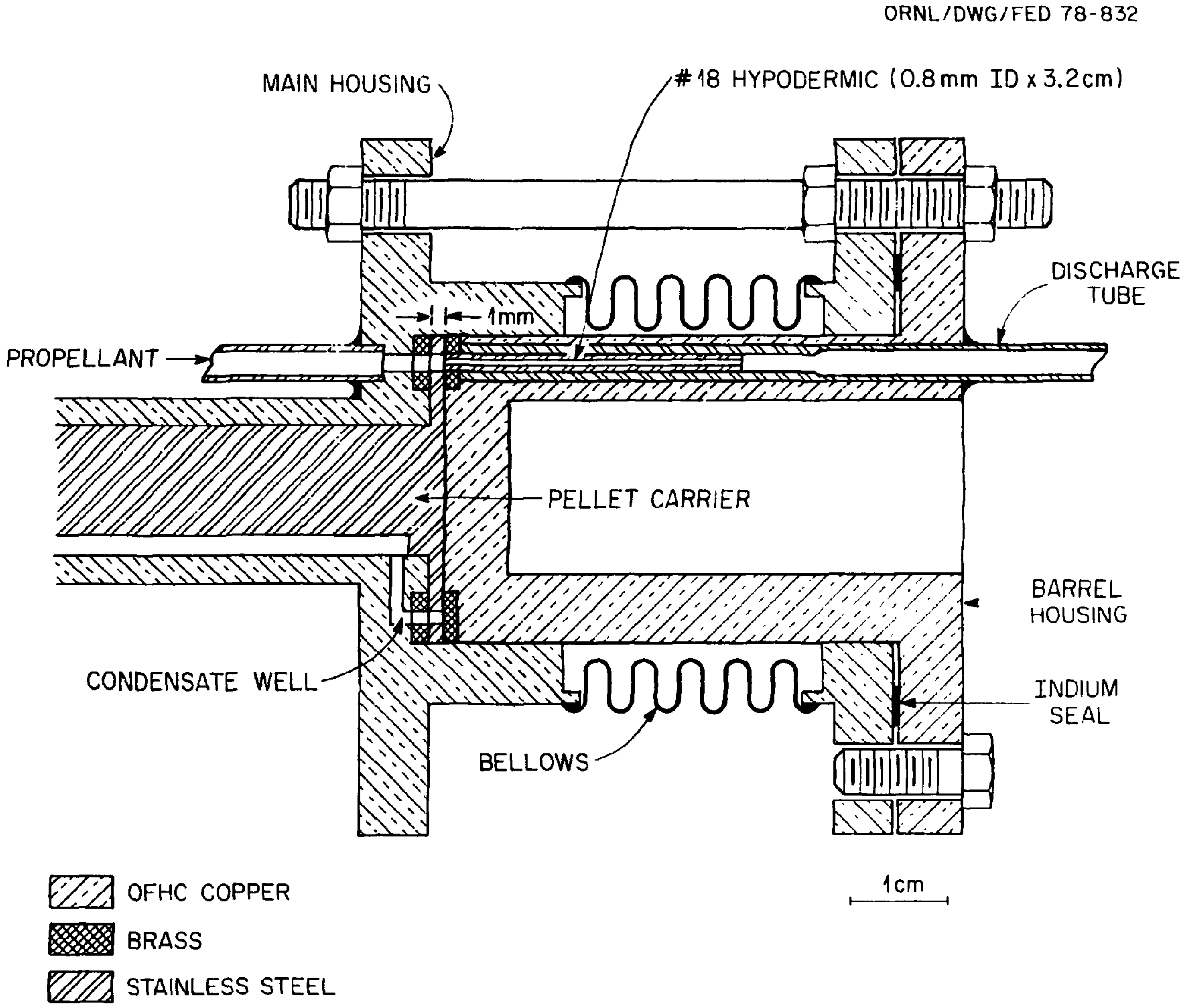
LIQUID HELIUM SUPPLY LINE

Figure 1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PELLET CARRIER
BARREL HOUSING
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▩ BRASS
▨ STAINLESS STEEL
1cm

Figure 2

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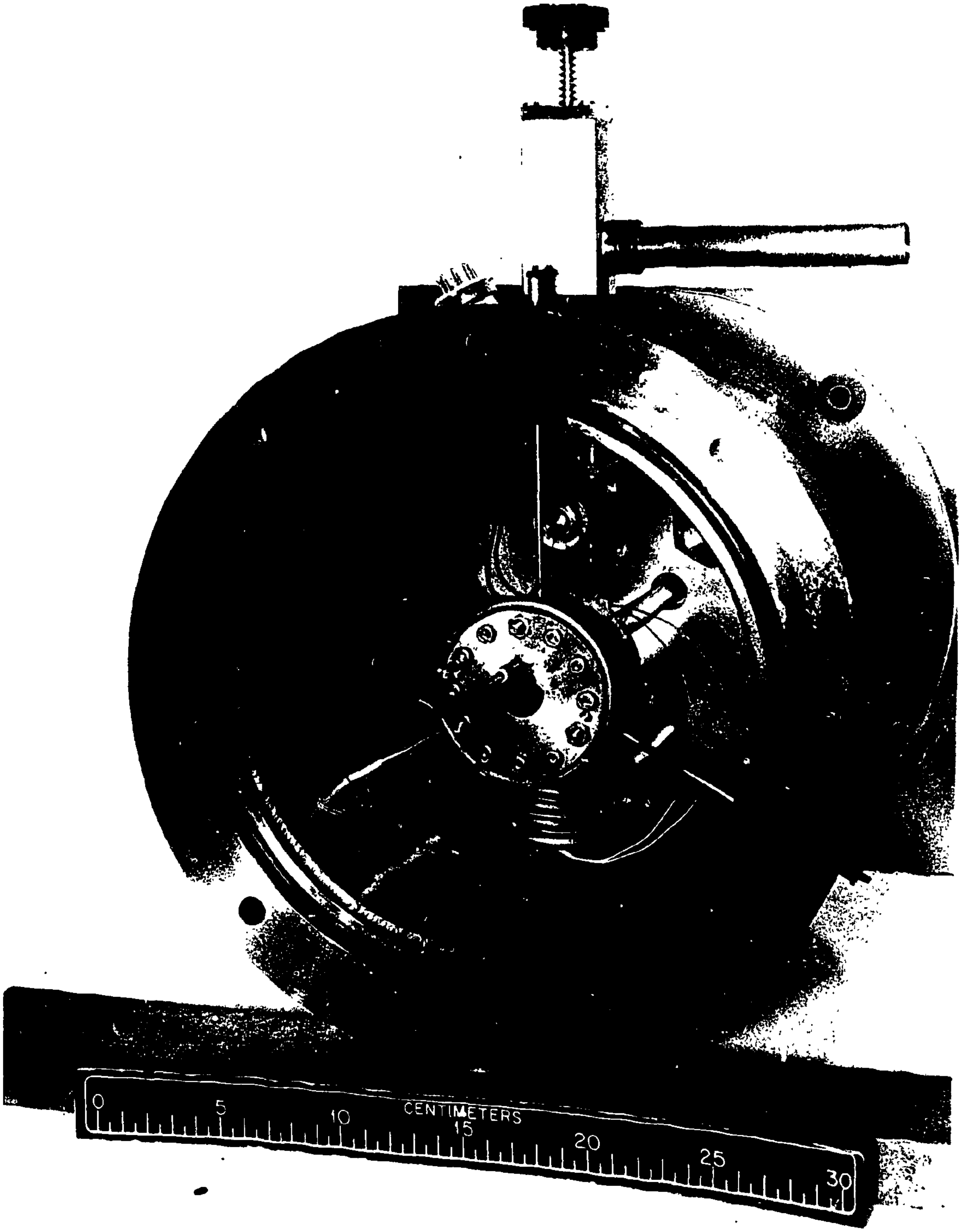

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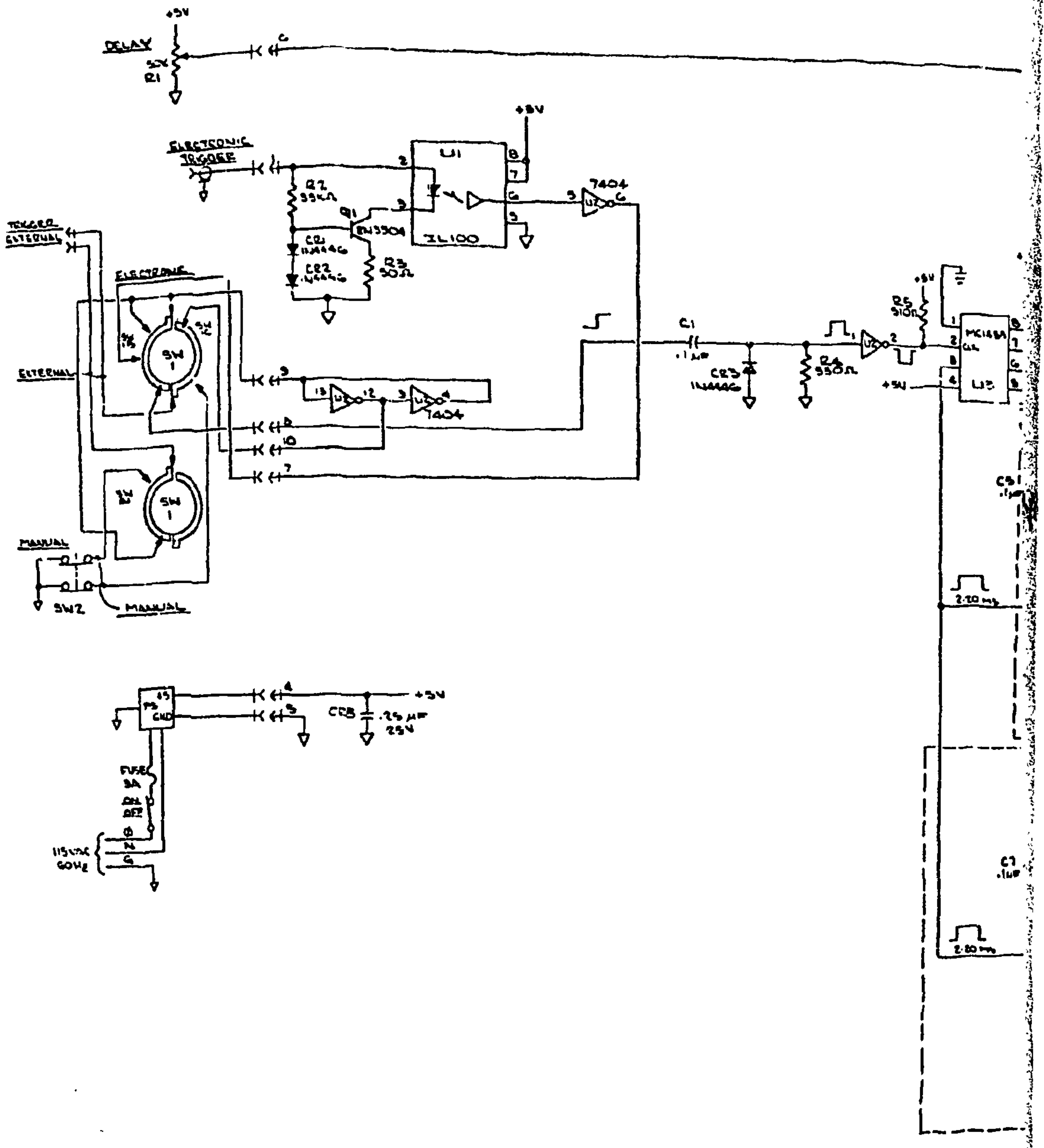
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2
3
8
7
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TRIGGER EXTERNAL
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PS
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N
G
115VAC 60Hz

Figure

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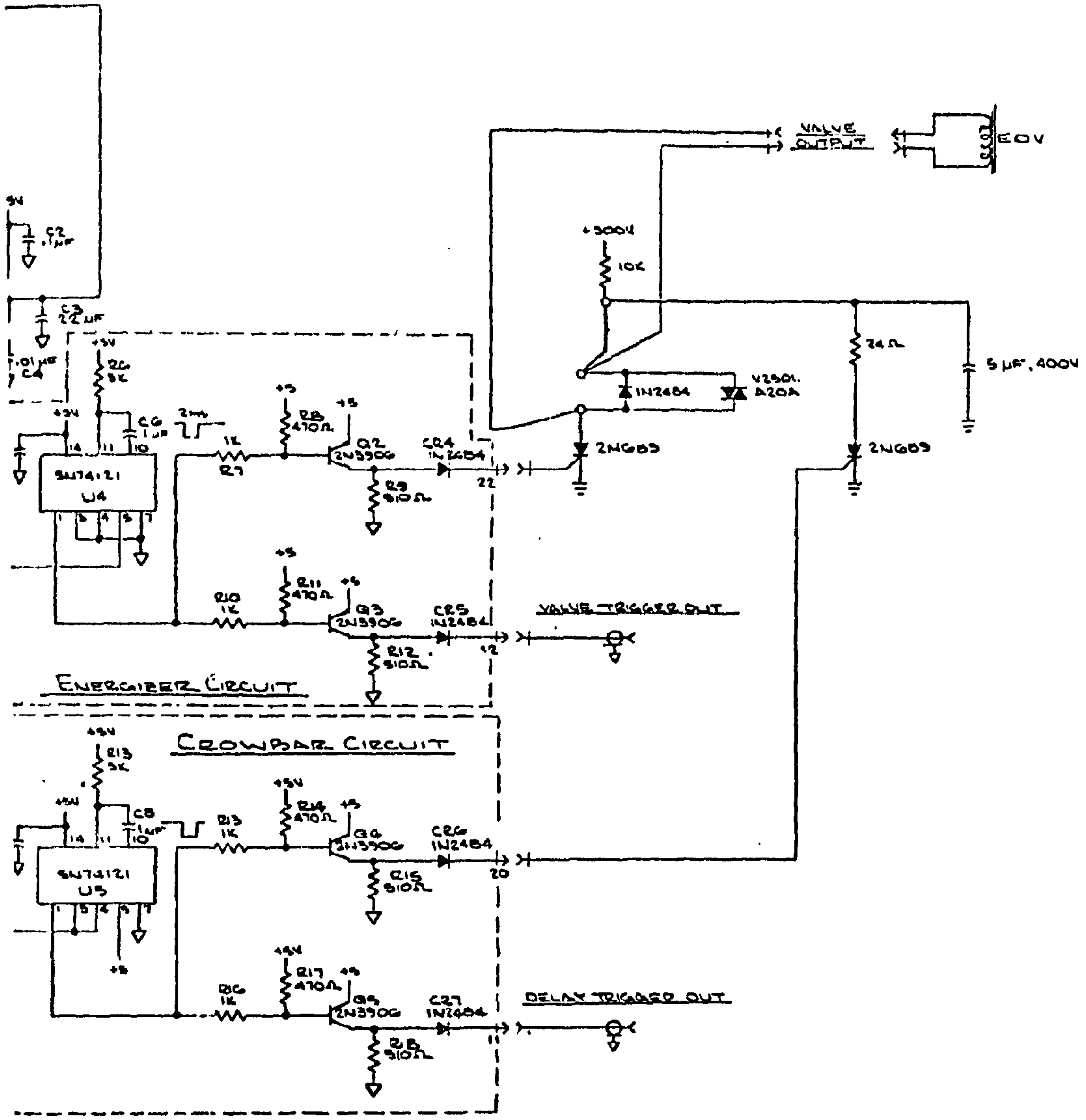
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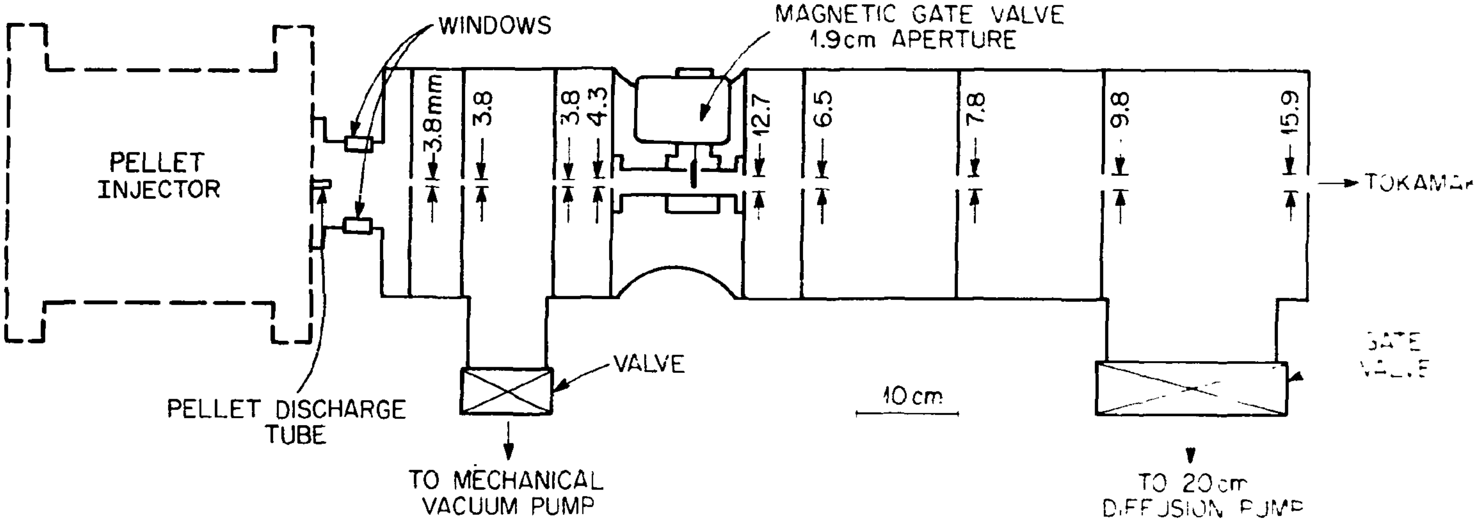
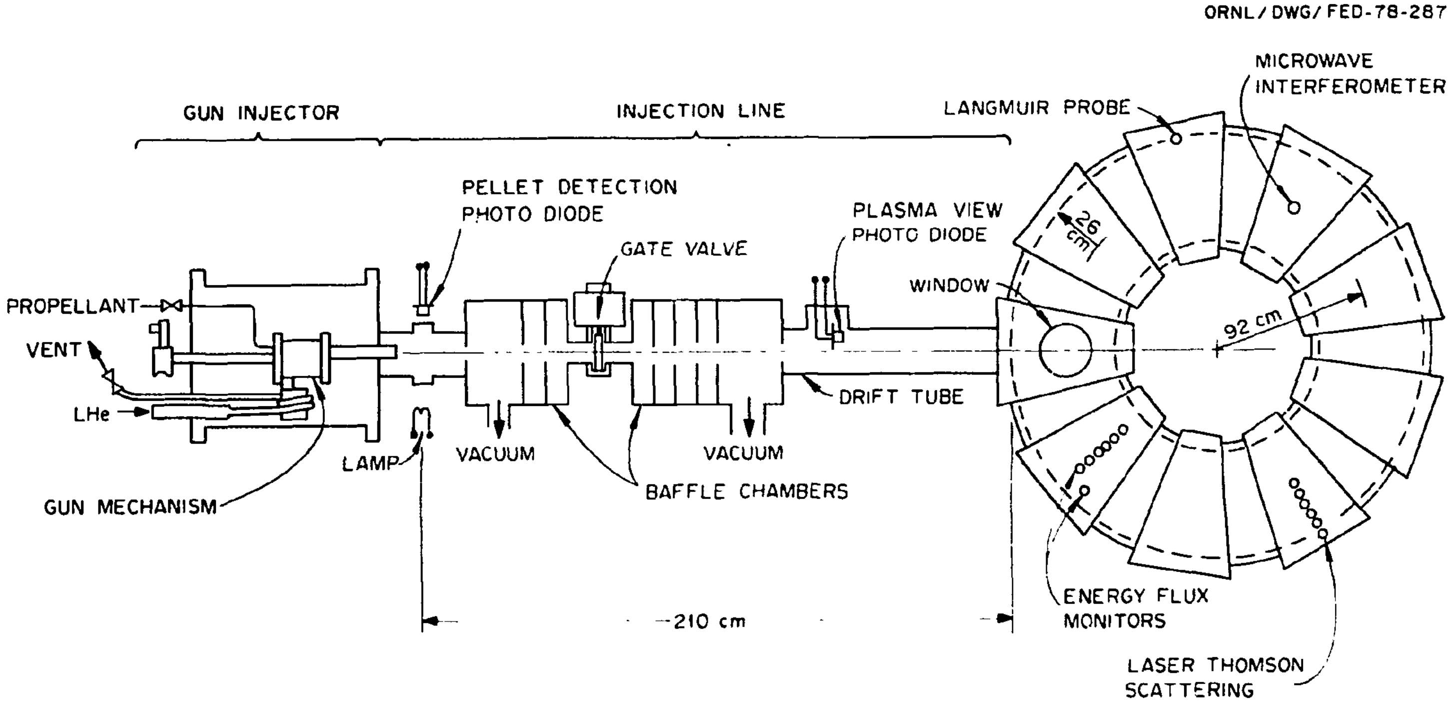


Figure 5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WINDOW
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LAMP
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Figure 6

ORNL/DWG/FED 78-899

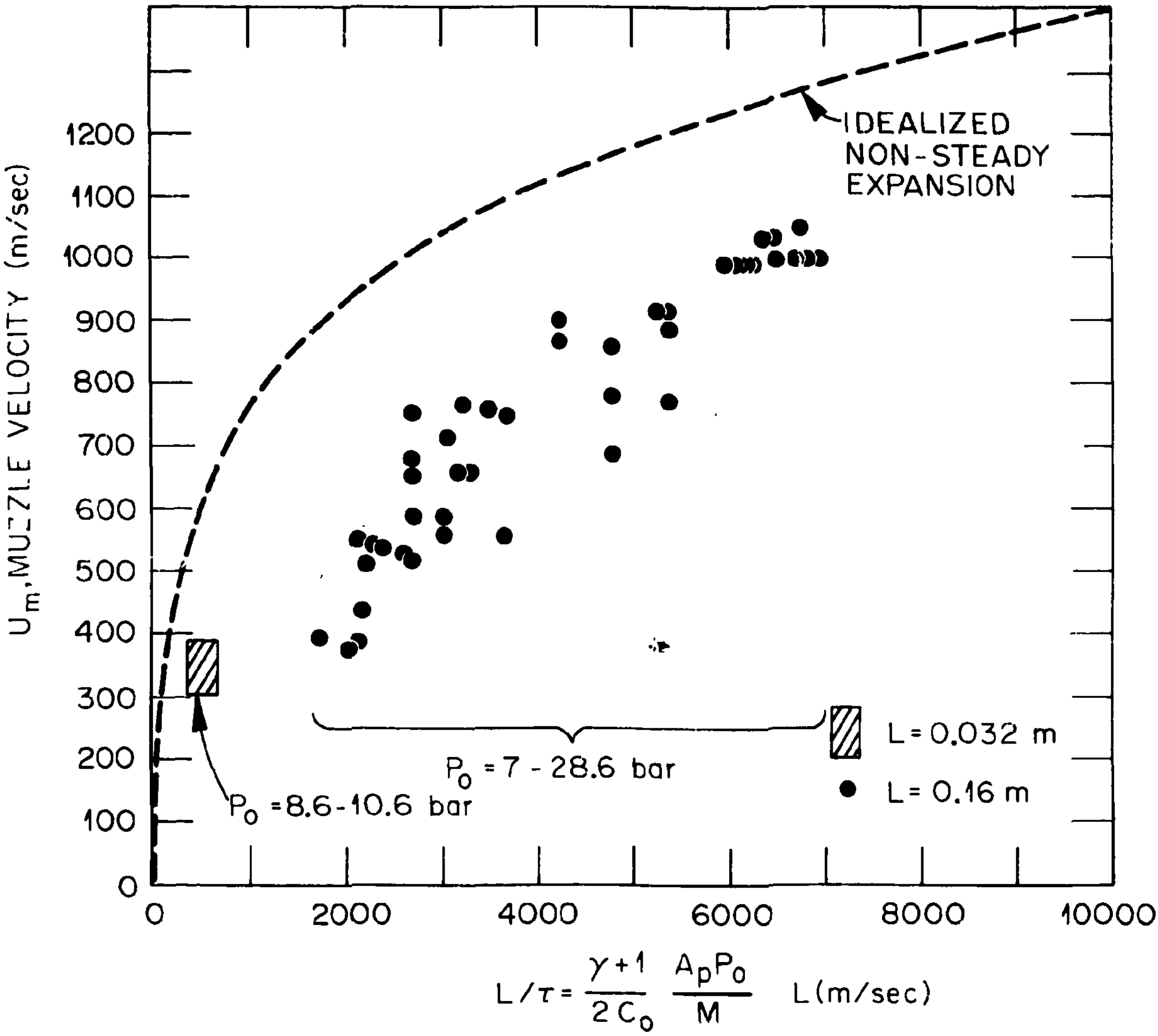

Figure 7

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