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A FUEL PELLET INJECTOR FOR THE MICROWAVE TOKAMAK EXPERIMENT (MTX),

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Unlike other fueling systems for magnetically confined fusion plasmas, a pellet injector can deliver many fuel gas particles to the core of the plasma, enhancing plasma confinement. We installed a new pellet injector on the MTX (formerly Alcator-C) to provide a plasma with a high core density for experiments both with and without ultrahigh-power microwave heating. Its four-barrel pellet generator is the first to be designed and built at LLNL. Based on "pipe-gun" technology originated at Oak Ridge National Laboratory (ORNL), it incorporates our structural and thermal engineering innovations and a unique control system. The pellet transport, differential vacuum-pumping stages, and fast-opening propellant valves are reused parts of the Impurity Study EXperiment (ISX) pellet injector built by ORNL. We tailored designs of all other systems and components to the MTX.

Our injector launches pellets of frozen hydrogen or deuterium into the MTX, either singly or in timed bursts of up to four pellets at velocities of up to 1000 m/s. Pellet diameters range from 1.02 to 2.08 mm. A diagnostic stage measures pellet velocities and allows us to photograph the pellets in flight. We are striving to improve the injector's performance, but its operation is already very consistent and reliable.

INTRODUCTION

In building the pellet injector for the MTX, we wanted to achieve the performance characteristics and provide the features shown in Table 1. An existing pellet injector, built by the ORNL Plasma Fueling Program and last used at the Texas EXperimental Tokamak (TEXT), became available and was transported to LLNL.

MASTER

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On the advice of Milora, Gouge, et al.[1] of ORNL, we adopted the "pipe gun" design concept (Fig. 1). We also installed a new control system and pellet diagnostic station. We left the pellet guide section between the pellet generator and the tokamak essentially intact and refurbished the main structural platform. We elevated the entire injector assembly on columns and positioned it to launch pellets into a side port and along a major radius of the MTX, with the electronics racks underneath. Figure 2 shows the finished injector installed on the MTX. Design and construction were done in 12 months and cost approximately $500K, divided about equally between new hardware and labor.

THE PELLET GENERATOR

A pellet generator makes fuel pellets and launches (fires) them at speeds from 0.5 to about 1.5 km/s. In any gun-type pellet generator for magnetic-confinement plasma fueling, fuel gas (either hydrogen or deuterium for MTX) is frozen to make an individual pellet. The pellet is then accelerated through a tube (the barrel) by a sudden burst of high-pressure gas. Several gun types have been used,[2,3,4,5,6] but we selected the pipe gun because of its established reliability and because it is easy and inexpensive to build, maintain, and change.

Figure 2 shows a schematic of the MTX pipe gun, which is virtually generic. In any pipe gun, fuel gas is cryocondensed and frozen in a short cold zone in the tube from which the resulting pellet will be launched. The cold zone is established by intimate thermal contact with a liquid-helium-cooled copper cold block. The contact length determines the pellet's nominal length. The cold zone divides the tube into a "chamber" upstream and a "barrel" downstream. Sleeves are brazed to the tube upstream and downstream of the cold zone. They are thermally connected to the cold block. Electrically heating the sleeves establishes thermal gradients on both sides of the pellet, shaping the boundaries of the cold zone and thus adjusting the pellet length. The thermal gradient sleeves also help

ensure that the pellet does not stick to the inside surface of the barrel when the gun is fired.

In the MTX pipe gun (Fig. 3), the cold zone is established by a copper ferrule brazed onto each of gun's four barrels. All of the ferrules have the same outside diameter and length, but they are individually undercut to provide the selected nominal pellet length for each barrel. The ferrules are wrapped with indium foil to ensure thermal continuity and are clamped into a common cold block. Our pellet generator can thus simultaneously provide pellets of different sizes, and we can change the sizes by installing new barrels, made of commercially available stainless-steel tubing. Temperatures of the cold block and of the thermal gradient sleeves for each barrel are controlled by Lakeshore Cryotronics Model 805 and Model DRC-80C controllers that supply current to heating resistors mounted on each component. Lakeshore Model DT-470 silicon diode sensors provide temperature feedback to the controllers.

The pellet generator components are mounted on a bulkhead plate that is fixed to the injector's main frame, (Fig. 4). The location and angle of the plate can be adjusted and then locked. Fuel gas, propellant gas, electrical firing pulses to the propellant valves, heating current, and thermocouple signals all pass through this plate in appropriate feedthroughs. Ferrules brazed to the muzzles of the gun barrels fit finely machined holes in this plate, aiming the barrels simultaneously when the bulkhead plate is aligned.

The pellet generator is enclosed in a vacuum chamber that provides additional thermal isolation for the cold block. The chamber, with its high-vacuum pump attached, is rolled up over the pellet generator and bolted to the bulkhead plate with an O-ring vacuum seal. Rolling it back exposes all parts of the pellet generator for maintenance or modification.

Additional thermal isolation is provided by a heat shield that surrounds the pellet generator. Helium boil-off gas from the cold block passes through approximately 10 ft of 0.25-in.-diameter copper tubing that is brazed to the electropolished stainless-steel heat shield. The shield separates into halves for access to the cold block. Finally, the copper cold block is gold plated to preserve its low surface emissivity. Liquid helium coolant supplied from a portable 500-l dewar is used at a rate of about 20 l/hr, whether cooling the cold block, holding it at temperature, or making and firing pellets.

Previously, the cold block was supported on a stainless-steel stem attached to the warm wall of the vacuum chamber, with an intermediate liquid-helium-cooled block intercepting the resulting heat load. We replaced the metal support with a trusslike framework made of fiberglass-epoxy laminate manufactured to National Electrical Manufacturers' Association (NEMA) standard G-10. No intermediate cold block is used. The laminate is about as strong and as stiff as aluminum, but at 0.08 W/m-°C, its thermal conductivity is only about 25% that of the metal it replaces. Therefore, it provides firm support and adequate thermal isolation for the cold block while simplifying the ancillary mechanical systems.

The same framework extends beyond the cold block to support the four fast propellant gas valves, which open directly into each gun chamber. We reused the original Skinner Valve Company Type B-2 miniature solenoid valves, which were extensively modified by ORNL for this application. Each valve is supplied from a separate gas-pressure regulator and is opened by a 450-V pulse from a solenoid-driver power supply. The mechanical design leaves space to retrofit the faster-opening, but larger, propellant valves that have since been developed at ORNL.[7]

Because we use a common cold block, support frame, and bulkhead plate, all gun barrels and chambers must be the same length, although barrel diameters and pellet masses can be changed. Using the existing vacuum chamber limited

the overall length of the gun tubes. We limited input pressure to the fast propellant gas valves to 1200 psig to avoid administrative complications, and because the valves will not open at pressures above about 900 psig. On the MTX, we have used only helium propellant gas, but we could use hydrogen if we prepare additional pressure and fire safety documentation.

Our final design constraint was to retain the original spacing between barrels, allowing us to use the pellet guide section without modification. Therefore, the largest pellet for which this pellet generator can be retrofitted is 3.75 mm diameter. The largest pellet that can be accommodated without changing the present cold block is 3.00 mm diameter.

CONTROLS

We created a new control system that allows us to initiate the firing sequence either locally (at the pellet injector) or remotely (from the MTX control room), but the pellet-making cycle is always controlled locally. We can also operate individual system components at will and can locally select setup parameters, such as which barrels to fire under automatic control, the time intervals between individual barrel firings, and whether to admit fuel gas for making pellets from the chambers, the barrels, or both. Only minimal injector status information is transmitted to the MTX control room, and no parameter changes can presently be made there.

A local Hewlett-Packard 340C+ computer is interfaced through Computer Automated Measurement and Control (CAMAC) modules to the valves controlling the partitioning of the pellet guide section and the fuel gas, propellant gas, and vacuum systems. The computer runs a graphics-oriented software system named TACL (Thaumaturgic Automated Control Logic).[8] Using TACL's Logic Editor, we entered the pellet injector's control logic in schematic form. Then we used its Display Editor to create multicolored control screens that pictorialize the entire

injector. On these screens, the operators then use a trackball and on-screen cursor to control the pellet injector. The control screens inform the operator of hardware status and of the setup parameters for automatic operation. These can all be changed with the trackball and cursor. TACL monitors and operates safety interlocks in the background. Fuel gas is supplied at constant pressure that is maintained by standard MKS Baratrons and an MKS Model 254A pressure/flow controller. All other hardware controls are manual. Pressures in the propellant and vacuum systems are displayed on stand-alone mechanical or electronic gauges, and set-point signals are sent to the computer as interlock inputs. The turbomolecular vacuum-pump controllers with fail-safe valve default positions effect an orderly vacuum system shutdown if power fails.

Although TACL allows single-step loading and firing by actuating individual components on-screen, these operational sequences are usually controlled automatically and can be initiated either locally or remotely. The local computer always runs the preset time sequences during pellet freezing and pumpout and operates hardware components at intervals as short as 1 s. The high-resolution timing needed to operate the pellet-firing sequence is provided by two CAMAC modules: a Kinetic Systems KS3655 timing generator with 10-μs resolution and an LLNL-built local sequence controller. The timing generator produces trigger pulses that pass through the sequence controller, which triggers the selected propellant valves at the set time intervals. For local automatic pellet firing, the computer triggers the sequence controller. For remote firing synchronized with a plasma discharge, the MTX pre-sequencer inititates the automatic pellet-making sequences. Then the MTX fast sequencer provides the firing trigger signal to the injector's sequence controller. A holding interval of up to 10 min is allowed between pellet-making and firing.

PELLET DIAGNOSTICS

Pellet Velocity. Pellet velocity is measured for each barrel by a pair of optical timing traps spaced 150 mm apart along the direction of pellet flight. A single timing trap consists of a miniature incandescent lamp on one side of the pellet path and a photodiode array on the other. The four barrels thus have eight timing traps. The continuously illuminated photodiodes respond to passage of a pellet shadow with a momentary reduction in photocurrent. These traps are packaged in a monolithic velocity station located downstream of the pellet guide section. Since the pellets tumble and touch the tubes in the guide section, their true velocities are most accurately measured beyond it.

Lamp current and electrical signals pass through appropriate vacuum-tight electrical feedthroughs. Photodiode signals pass through a set of conditioning amplifiers and then through our discriminators. From these Nuclear Instrument Module Systems (NIMS) modules they pass to BiRa time interval meters located in a CAMAC crate. The resulting time intervals are available to the MTX VAX data-acquisition system via a serial highway at the CAMAC crate.

Pellet Integrity. A camera photographs the pellets as they fly past the 150-mm-wide space between the timing traps. Pulsed backlighting is provided by a fiber-optic-coupled flashlamp. The signal from the first trap triggers a microchannel-plate image intensifier, which acts as an ultra[illegible] camera shutter. It provides an 18-mm-diameter image either on film or on an electronic imager for storage and future image processing.

Off-Line Pellet Confirmation. A shock transducer station is positioned downstream from the velocity station. The transducer is mounted in the carriage of a vacuum gate valve whose vacuum sealing capability has been disabled. The valve thus functions as a low-cost carrier that places the transducer either in the pellets' path for off-line operation or out of their path for delivery to the

tokamak. The transducer is a much-used diagnostic that verifies pellet firing, gives a good subjective impression of pellet mass and integrity, confirms the velocities reported from the velocity station, and allows us to measure the time intervals between pellets.

Pellet Ablation. Two photodiodes with H^{α} filters are mounted on the top port of the MTX. As the pellets pass across the plasma, they measure the H^{α} light that is emitted. The time histories of their signals, together with known pellet speeds, reveal how far a pellet penetrates the plasma before it is completely ablated. Other tokamak diagnostics confirm and corroborate: two fast x-ray detectors show a drop in signal, the fast visible bremsstrahlung detector shows signal increases, the fast electron-cyclotron emission diagnostic follows the rapid electron temperature decrease resulting from fuel pellet injection, and the fast far-infrared interferometer confirms the accompanying increase in electron density. Figure 5 shows output for the same pellet from the pellet velocity station and from the pellet camera. Shown in Figure 6 are the outputs from the Pellet Ablation diagnostic and several plasma diagnostics during pellet operation of the MTX.

REAL VS PREDICTED PERFORMANCE

More sophisticated analyses are available today, but the work by Seigel[9] presents the many interrelated parameters that govern gas-gun performance in a convenient graphic format. Using Seigel's work, we extracted many predictive iterations and rapidly found the gun geometry to meet our needs and fit the existing space constraints. The many geometric limitations allowed us to optimize gun geometry for only one of the three pellet sizes; the others are compromises. We expected to reach 1000 m/sec for pellets up to about 1.0 mm diameter and to provide lower but still useful velocities for larger pellets. Table 2 lists these geometry selections, predicted pellet velocities, and actual velocities. Velocities

for pellets of about 1.0 mm diameter are 10% to 25% lower than predicted, while pellets of about 2.0 mm diameter are almost exactly as fast as predicted. Predictions based on Seigel's work account for a pressure drop and reflected rarefaction waves as the pellet accelerates along the barrel, but they do not account for sliding friction (probably a very small effect because a fuel pellet rides on a film of gas) or for the pellet's occasional tendency to momentarily stick to the barrel wall before accelerating. Indeed, we believe this sticking is the primary source of uncertainty in launch timing, especially for small pellets since their ratio of circumferential surface area to end surface area is greater than for a large one.

OPERATIONAL EXPERIENCE ON THE MTX

We have worked only with helium propellant and deuterium pellets, although hydrogen is still an option for both. We found that this injector runs best with the parameter settings in Table 3.

Deuterium from industrial gas suppliers is only 99.5 to 99.7% pure, the remainder being mostly H_2O, D_2O, and HDO. Pellets made of this gas often stick in the barrels, refusing to move even at maximum propellant pressure. We suppose that when fuel gas is introduced into the cold zones, the contaminants condense first, effectively roughening the barrel surfaces and mechanically restraining the pellets. To purify commercial deuterium, we pass it through an extended molecular seive at 77 K. When impurity levels are thus reduced to a few tens of parts per million, we greatly improve the probability of successful firing.

In operation, the cold block is initially cooled to about 5 K with a flow of liquid helium. Then it is heated and held at about 12 K. We do not precool with liquid nitrogen. At low flow, there is a temperature oscillation from about 7 K to 20 K within about a 30-s period. We believe this is caused by liquid helium surging through the cold block. When we increase pressure in the supply dewar,

the flow rate increases until temperature stability within ± 0.5 K is achieved. Surge suppression thus governs our liquid helium consumption rate at present. We expect to reduce it substantially in the future.

Heat flow along the chambers to the cold block froze the elastomer seals in the propellant valves so that they leaked when closed. Our solution was to retrofit heating resistors to each valve body. A Type "E" thermocouple on one of the valves feeds back to the Omega Model 9000 controller that powers all of the resistors. The 2 to 3-W/valve heat load does not noticeably affect liquid helium consumption.

SUMMARY

We have described reliable operation of the four-barrel MTX fuel pellet injector. The system could be improved by installing the higher-performance ORNL fast propellant valves and by installing a variable throttle valve in the liquid helium coolant exhaust to help reduce surging in the cold block.

We are currently running the pellet injector together with MTX plasma operations. Peaked electron density profiles have been shown to have enhanced energy confinement. Therefore, during upcoming MTX electron-cyclotron resonance heating experiments with both a gyrotron (500-1000 kW) and a free-electron laser (1-2 GW peak), we will operate the pellet injector so that the peak electron density is less than the 140-GHz microwave cutoff density of about 2×10^{14} cm^{-3}.

ACKNOWLEDGMENTS

We thank S. L. Milora, M. L. Gouge, and P. Fisher of the Plasma Fueling Program at Oak Ridge National Laboratory for helping to make the pellet injector available to us and for valuable advice and design reviews. We especially thank P. Fisher for traveling to Livermore to assist with startup. Thanks also to D. L. Behne, F. M. Bowman, M. L. Delong, R. W. Geer, and E. D. Valenzuela of LLNL, who

assembled the injector and now operate it. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

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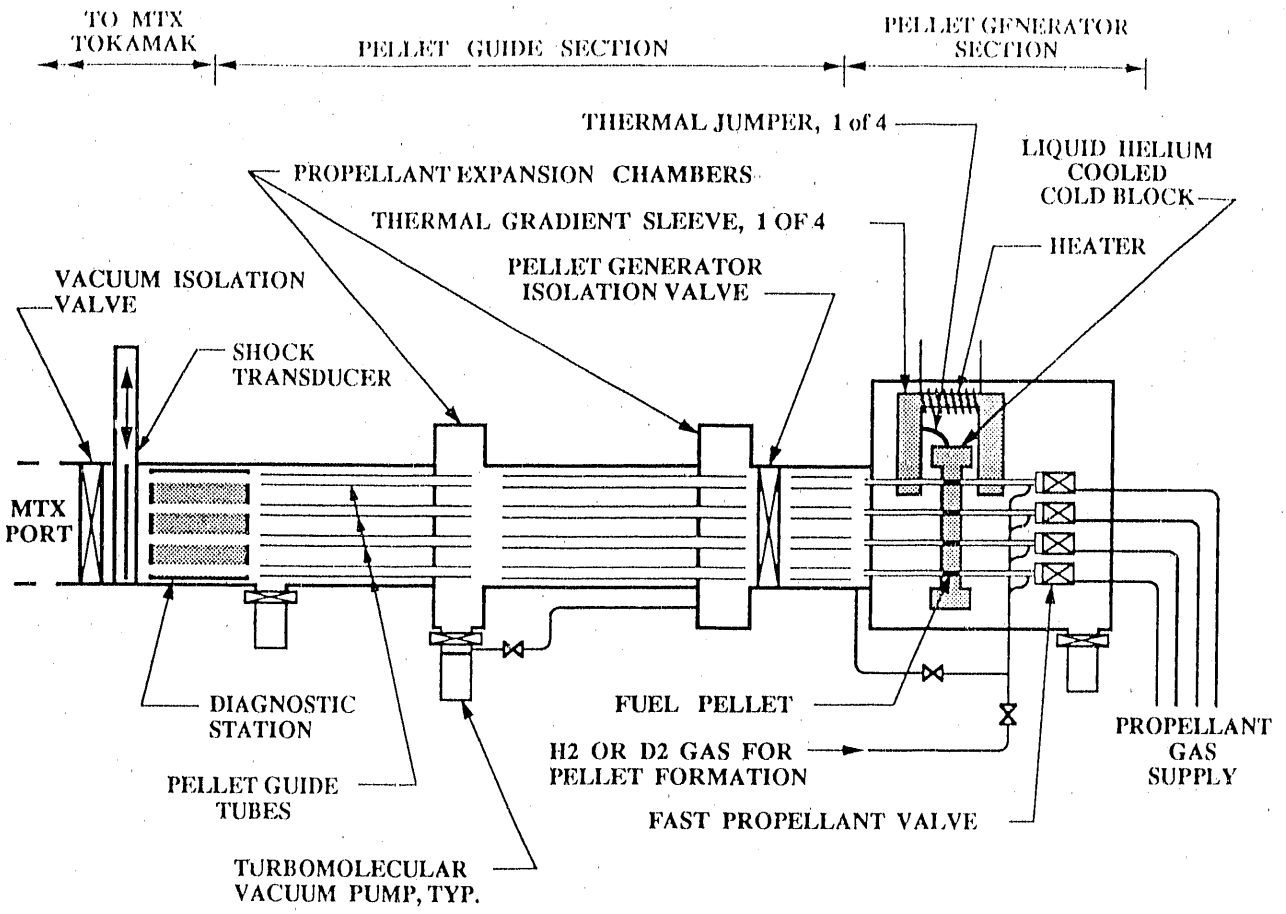

FIG. 1. Schematic diagram of a pellet injector with Pipe Gun pellet generator

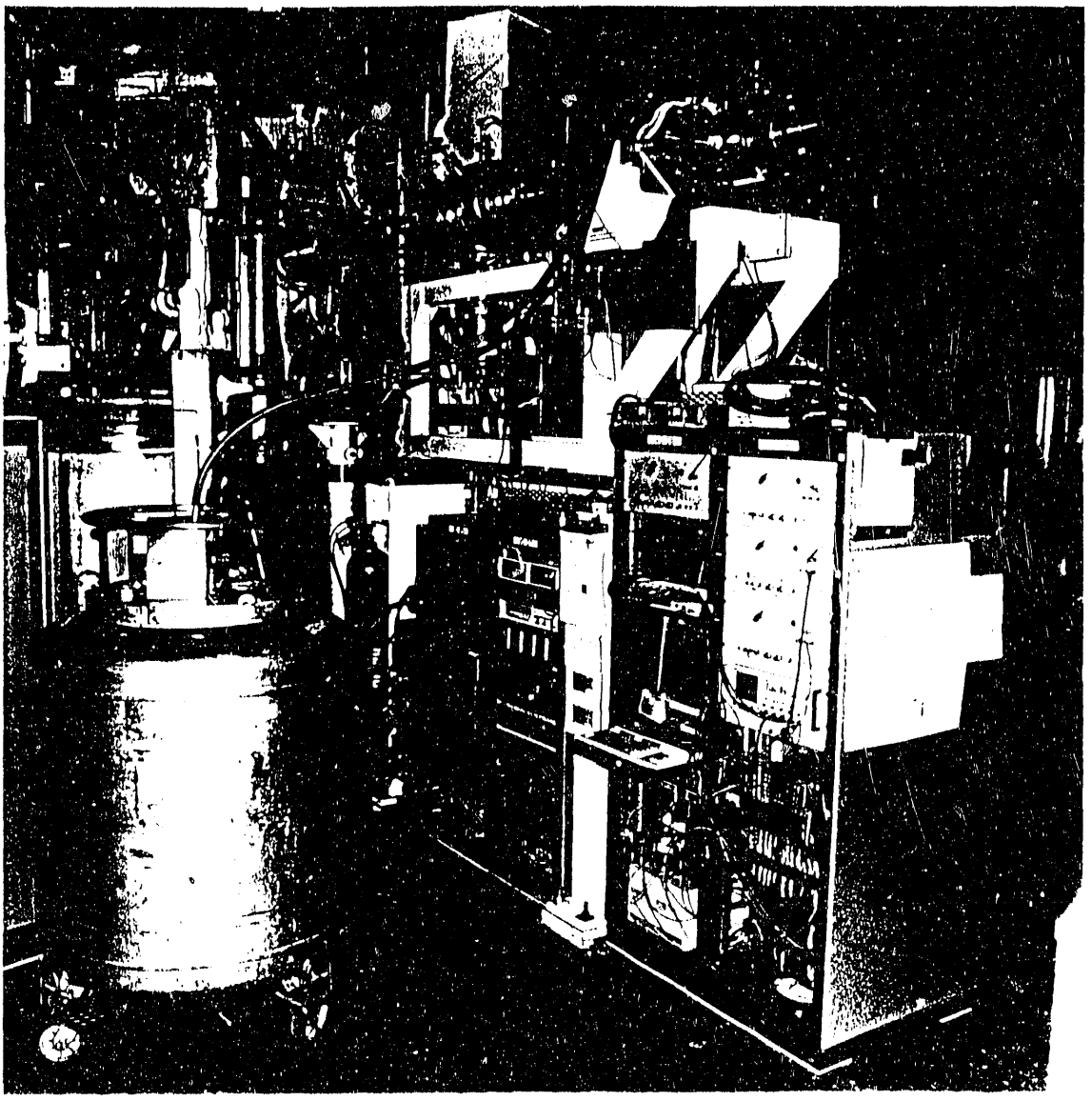

FIG. 2. The pellet injector installed on the MFTX. The white main frame is elevated on columns with electronics racks below. The pellet generator is inside the small vacuum vessel atop the main frame at upper right. Pellets move to the left though the pellet guide section which ends at the MFTX side port (the velocity diagnostic station has been removed in this photograph). The [illegible] is [illegible] the left.

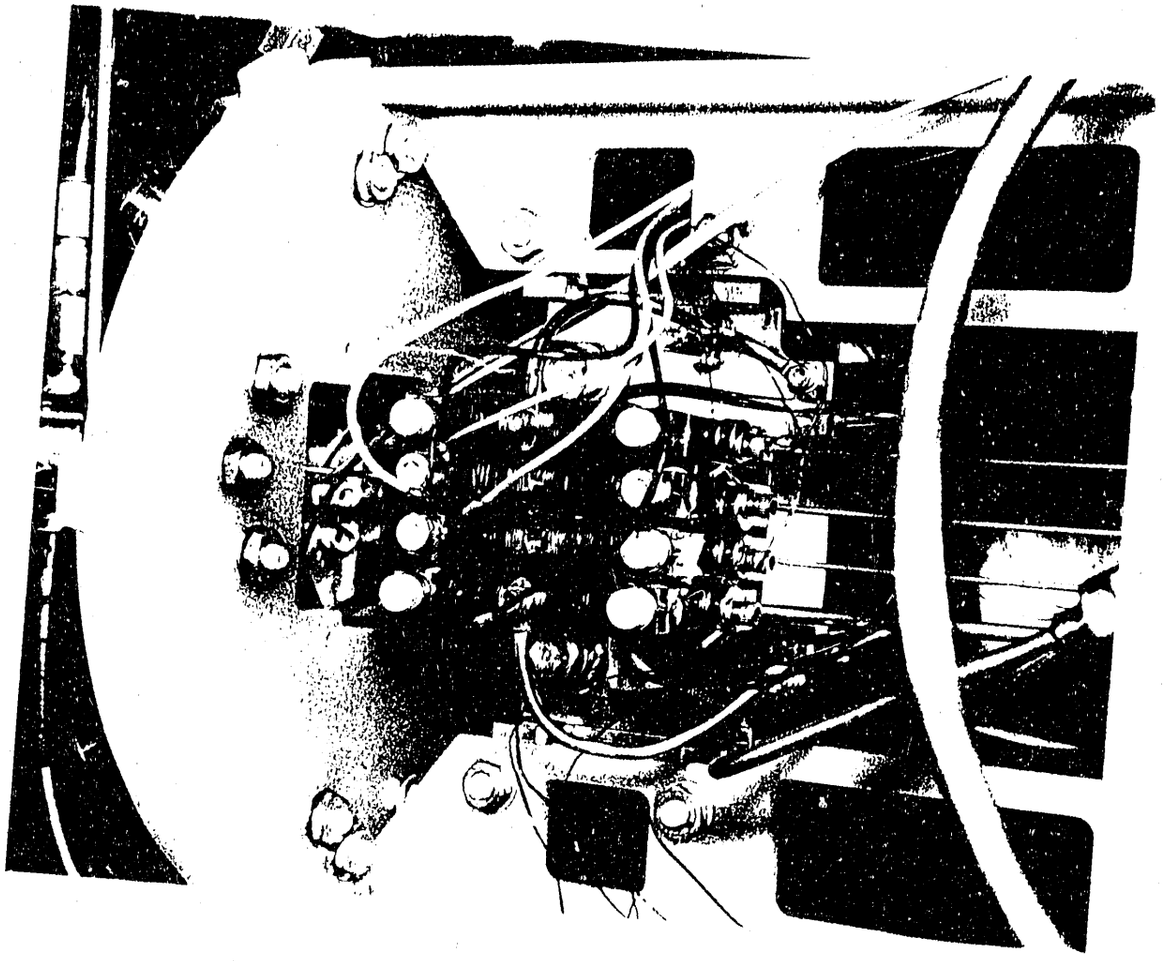

FIG. 3. The cold block mounted in the G-10 framework. The barrels emerge to the right from the thermal gradient sleeves. Heating resistor wire is wrapped around copper heater bars bolted to each pair of thermal gradient sleeves. Copper thermal jumper wires extend from each heater bar to the cold block. The cold-zone ferrules are clamped in the cold block between thermal gradient sleeves and behind the heater bars. Temperature sensors can be seen near the barrels. The fast propellant valves are behind the plate to the left and half of the heat shield is visible behind the cold block.

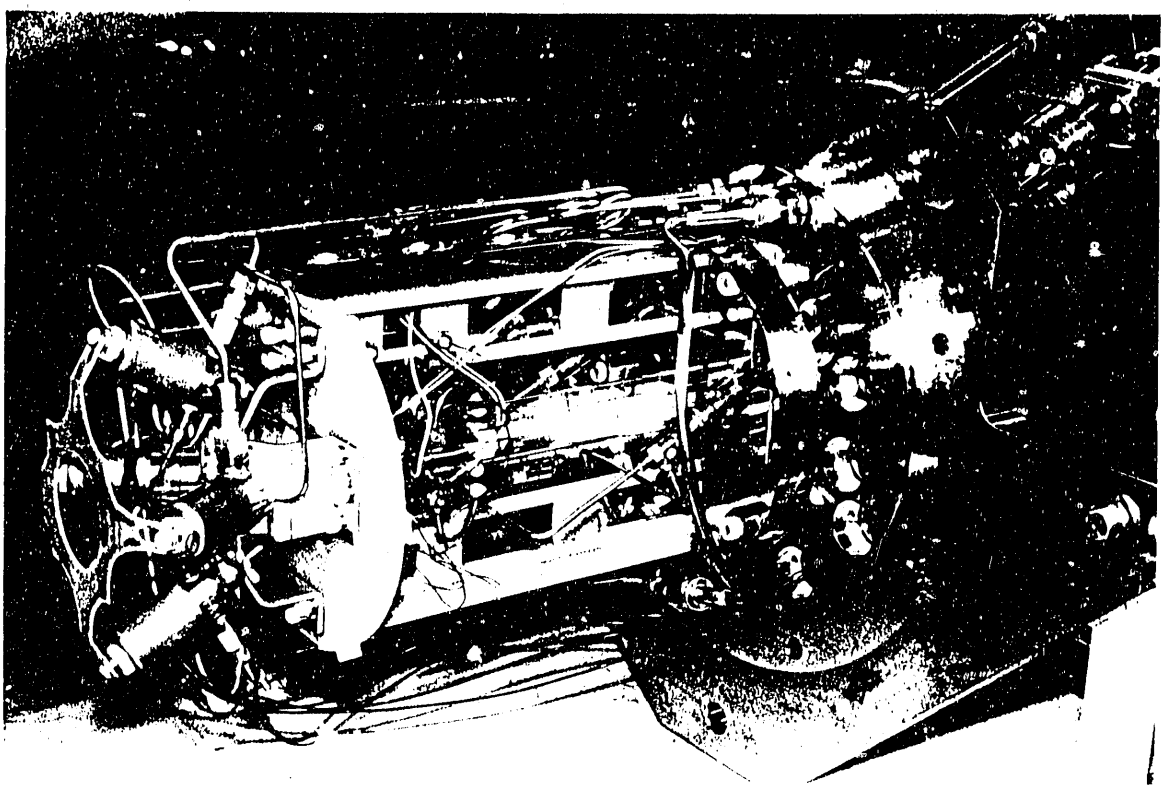

FIG. 4 The entire pellet generator subassembly is supported and aligned by the bulkhead plate shown. All feedthroughs pass through this plate. Half of the heat shield has been removed to show the G-10 framework, cold block, and barrels. The fast propellant valves are mounted at the left. The entire subassembly is enclosed inside a vacuum chamber that rolls away to the left.

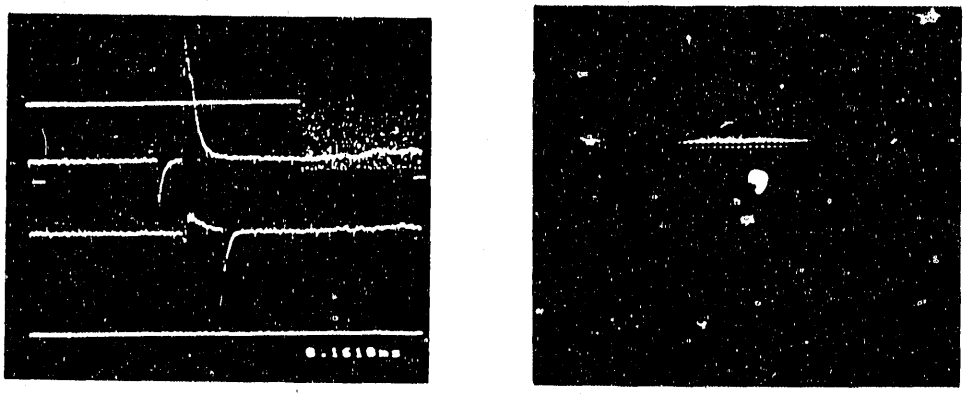

FIG. 5. In the oscillograph (left), the negative (downward) deflections on the second and third traces record the output of the first and second velocity traps, respectively, for this 2.0 mm dia. × 2.3 mm deuterium pellet (right). The large positive deflection on the second trace is electrical noise from the flashlamp illuminating the pellet photograph. The top trace records the output of the shock transducer. The 0.1610-ms time between the velocity trap signals corresponds to a pellet velocity of 930 m/s over the velocity station's 150-mm baseline. The pellet is moving from left to right, and the dots above it are 0.5 mm apart.

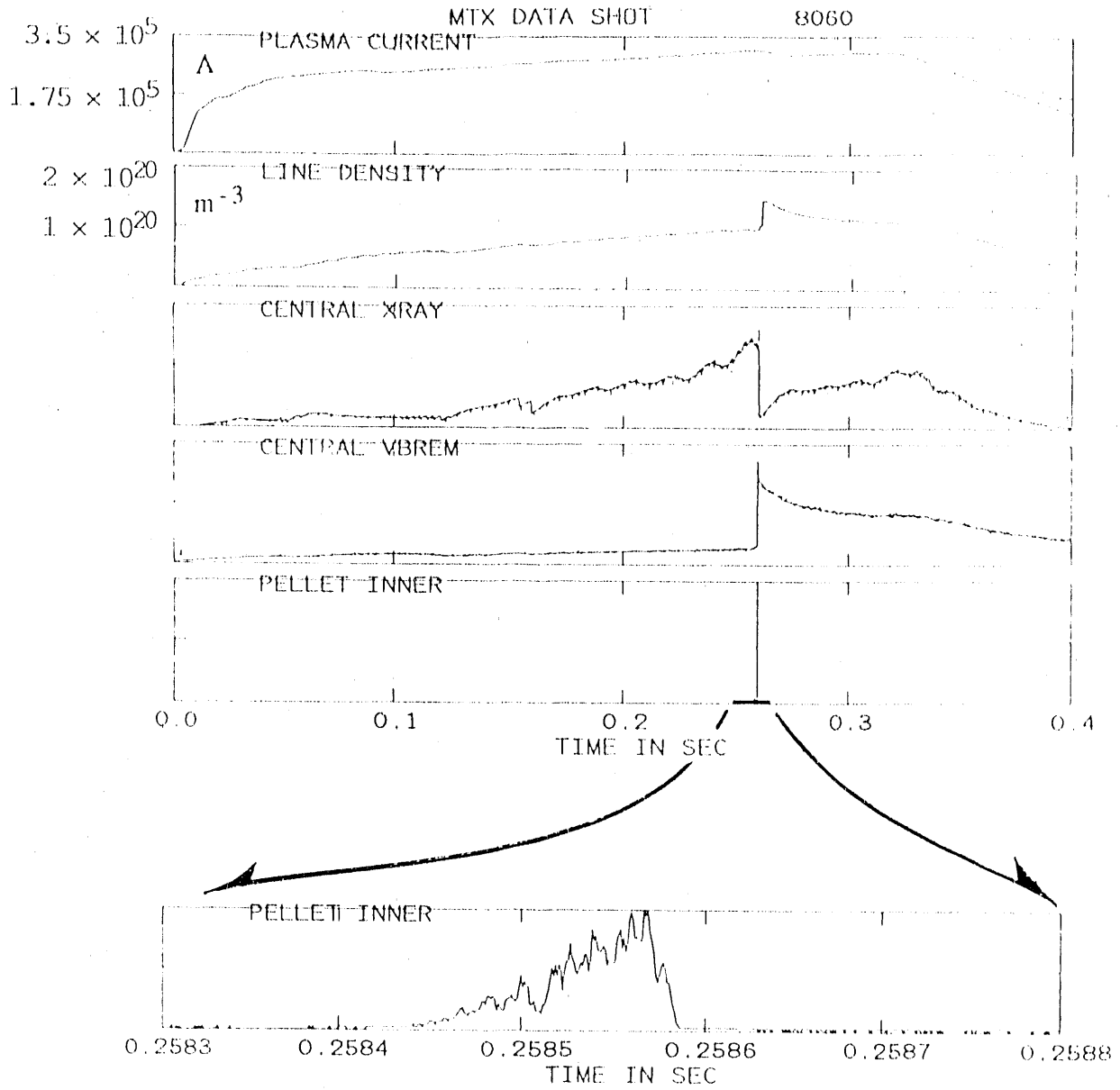

FIG. 6 Plasma diagnostic outputs during MTX pellet operation. The pellet was injected at about 250 ms. A large increase is shown on the central-chord line density from the far-infrared interferometer, with a corresponding increase in the central visible bremsstrahlung. The plasma electron temperature drops and then recovers, shown by the central soft x ray. The pellet ablation diagnostic is shown at the bottom and is repeated on an expanded scale. It is estimated from this trace and the pellet velocity that the pellet is fully ablated before it reaches the plasma axis.

Pellets:	Either hydrogen or deuterium Injection in bursts of from 1 to 4 pellets: 2 pellets at 0.75 mm dia. by 1.50 mm long 1 pellet at 1.00 mm dia. by 2.00 mm long 1 pellet at 1.55 mm dia. by 2.33 mm long Retrofittable to provide other sizes Maximum velocity 1,000 m/sec for all sizes Time interval between pellets of 1 to 100 ms +/- 100 μs Time interval between bursts of 5 minutes, max.
Propellant:	Either pressurized helium or hydrogen
Controls:	Manual pellet making and firing at the injector Automatic pellet making and firing at the injector Automatic pellet making at the injector with firing from the MTX control room
Diagnostics:	Pellet velocity measurement Pellet integrity check (photography) Pellet impact sensor for off-line operation Pellet ablation sensor on the tokamak
Reliability:	95% for single-pellet shots 80% for multiple-pellet bursts

TABLE 1. Desired features and design performance targets for the MTX Fuel Pellet Injector.

Pellet Material	Deuterium	Deuterium	Deuterium
Pellet Diameter, mm	1.12	1.02	2.08
Pellet Length, mm	2.0	1.5	2.4
Propellant	Helium	Helium	Helium
Propellant Supply Pressure, psig	900	900	900
Estimated Chamber Pressure, psig	600	600	600
Chamber Length	102	102	102
Barrel Length	251	251	249
Predicted Pellet Velocity, m/s	1,040	1,135	970
Actual Pellets Velocities, m/s	770 to 960	Not Meas.	920 to 980

TABLE 2. Pellet Generator geometry and predicted vs. actual pellet velocities

Barrel	1	2 & 3	4
Pellet size, dia. X length, mm (ref)	1.12 X 2.0	1.02 X 1.5	2.08 X 2.3
Cooldown time before operation	- - - - - - - - - - 1 hour - - - - - - - - -		
Deuterium fuel gas supplied to . . .	- - - - - - - - Chambers only - - - - - - -		
Deuterium pressure for pellet making	- - - - - - Constant 17 Torr - - - - - -		
Pellet freezing time	90 s	90 s	90 s
Cold block temperature	- - - - - - - - - - 12 K - - - - - - - - - -		
Thermal gradient sleeve temp.	110 K	110 K	130 K
Liquid helium dewar pressure	- - - - - - - - - - 5 psig - - - - - - - - -		
Propellant gas	- - - - Helium at 200 to 900 psig - - -		
Fast propellant valve solenoid volts	450 V	450 V	450 V
Fast propellant valve open time	15 ms	15 ms	15 ms

TABLE 3. Pellet Injector optimum operating parameters

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