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PELLET FUELING DEVELOPMENT AT OAK RIDGE NATIONAL LABORATORY*

C. A. Foster, S. L. Milora, D. D. Schuresko, S. K. Combs, and R. V. Lunsford
Oak Ridge, National Laboratory, P.O. Box Y,
Oak Ridge, Tennessee 37830 (U.S.A.)

Injecting high speed frozen pellets of D_2,T_2 has been proposed as a means of continuously fueling a tokamak reactor /1,2/. Pellets, being neutral, can penetrate across the confining magnetic fields. Furthermore, they can penetrate the plasma, since the ablation cloud surrounding the surface shields the pellet from the intense energy flux of the plasma. Several experiments /3-7/ have been conducted to inject frozen pellets into tokamaks. A neutral shielding ablation theory /8-11/ has been developed to explain the results of these experiments and has been used to simulate pellet fueling of the Fusion Engineering Device (FED) reactor study plasma /12/. Deuterium and tritium pellets 4 mm in diameter, injected at a speed of 2 km/s and a rate of 20 pellets/s, are shown to directly fuel 60% of the plasma volume, as opposed to 5% for gas injection.

A pellet injector development program /13/ has been under way at the Oak Ridge National Laboratory (ORNL) since 1976 with the goals of developing D_2,T_2 pellet fuel injectors capable of reliable repetitive fueling of reactors and of continued experimentation on contemporary plasma devices. The development has focused primarily on two types of injectors that show promise. One of these injectors is the centrifuge-type injector, which accelerates pellets in a high speed rotating track. The other is the gas or pneumatic gun, which accelerates pellets in a gun barrel using compressed helium or H_2 gas.

1. THE CENTRIFUGE INJECTOR

Cryogenic liquids or solids will float with very low friction when placed on a room temperature surface. When a frozen pellet is injected into a track or tube which originates near the center of a rotating wheel and exits in the forward tangential direction, the pellet is accelerated to twice the peripheral speed of the wheel. This is simply a result of conservation of energy and momentum. Furthermore, it can be shown that during the residence of the pellet, the wheel rotates through an angle that is a function only of the geometry of the track and is independent of both the mass of the pellet and the frequency of the wheel.

The concept of centrifuge acceleration was demonstrated in 1978 with a device having a 30-cm-diam stainless steel rotor which accelerated 0.8-mm-diam frozen D_2 pellets at a rate of 150/s to a speed of 300 m/s (double the peripheral speed of the rotor). Subsequently, a larger device designed to accelerate pellets to 2 km/s has been constructed and is now being

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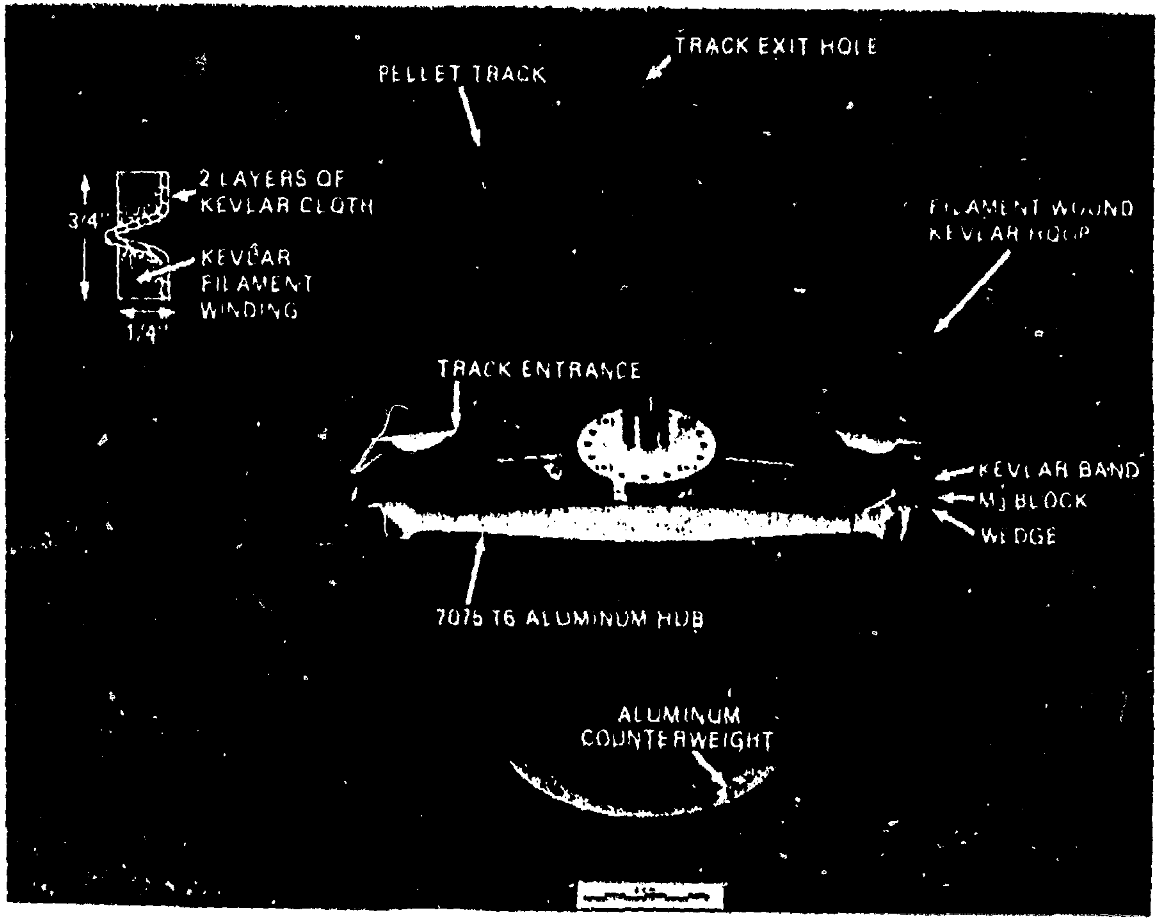

Fig. 1. The centrifugal hoop accelerator.

tested. A 1-m-diam hoop-rotor in the shape of a centrifugal catenary, shown in fig. 1, was fabricated from KEVLAR-49/epoxy by the filament winding technique. The catenary shape assures that the KEVLAR filaments experience only tensile forces. This rotor has a track molded into the inside of the hoop that guides the pellets and allows them to escape near the apogee through a hole. The hoop is secured to a 7075T6 aluminum hub that also contains the beginning of the pellet track. This accelerator has been spin tested to its design peripheral speed of 1 km/s at 20,000 rpm. At this speed the peak design stress in the KEVLAR composite is 930 MPa (135 ksi), which is 60% of the ultimate, a reasonable value for long, reliable operation.

The demonstration centrifuge device was fed by directly extruding a filament of D_2 into the razor-edge entrance of the accelerating tube. The extrusion rate was adjusted so that a right cylindrical pellet of D_2 was sheared off on each revolution of the rotor. The present centrifuge has a more sophisticated and versatile indirect feed mechanism that injects a pellet into the entrance of the accelerator track. This method enables the pellet production rate to be independent of the rotational speed of the accelerator. For larger pellets, lower production rates of the order of 10-50/s are desirable. Two indirect feed mechanisms were tested. The first was a knife mounted on a chopper wheel, which was driven in a subsynchronous phase-locked loop relative to the accelerator. The second, more successful system is an electromagnetic razor knife punch, which slices a pellet from an extruding filament and injects it at a speed of 3 m/s into the accelerator. This mechanism can produce and inject pellets at given intervals up to 50/s. The D_2 extruder used to feed the punch is similar in design to the one used in the demonstration device and the advanced pneumatic gun shown in fig. 2. A solid 4-cm^3 billet of D_2 is formed in a cylinder. The billet is extruded through a nozzle by a piston driven by a screw press. The extrusion lasts for approximately 60 s for 1.4-mm-diam D_2 pellets at 40 pellets/s. At the end of the stroke, the piston retracts, opening ports that refill the cylinder with liquid D_2 from a reservoir. The billet and nozzle are cooled to 14.6 K, using liquid helium as a refrigerant, and the liquid deuterium reservoir is maintained at 19 K. The temperature of the solid D_2 is closely controlled, since the extrusion pressure is highly temperature-dependent and flow instabilities occur at high extrusion rates and low temperatures.

Initial tests of the pellet feed mechanisms coupled with the accelerator have been performed. The pellets are viewed in stop action as they enter the accelerator by using a strobe lamp and television camera and recorder. The pellets leaving the accelerator are detected by monitoring their impact on a band encircling the spin tank. By recording the time of impact relative to the position of the accelerator, the residence angle of the pellets has been determined to be 150° ± 4°, which is the value predicted from frictionless theory. Modifications of the injector to align the pellets into the exit port are now under way. Future testing will center on reliable operation at 1 km/s through a guide tube transport system before attempting 2-km/s operation. Once reliable 1-km/s operation is demonstrated, continuous pellet fueling experiments will be performed on the PDX device at Princeton Plasma Physics Laboratory (PPPL).

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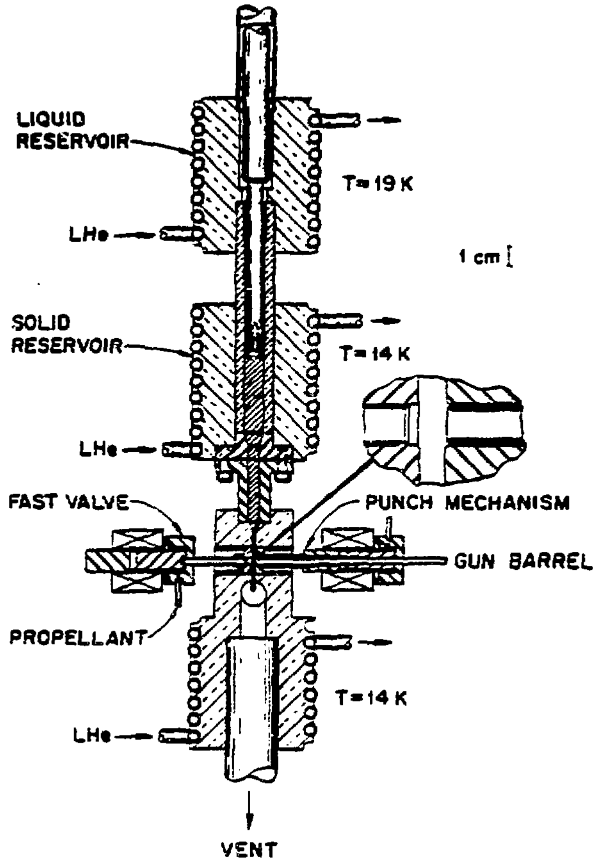

Fig. 2. Repeating pneumatic gun.

2. THE PNEUMATIC PELLET INJECTORS

A dramatic demonstration of the pneumatic gun acceleration technique was performed on the ISX-A tokamak /4/ at ORNL in 1977. Single 0.6-mm H_2 pellets were injected into ISX at 300 m/s, resulting in a 30% increase in the plasma density. Since this experiment, the single-shot injector has been upgraded in experiments on ISX-B /5/ and PDX /6/ with pellets 1.1 to 1.4 mm in diameter at 1 km/s giving density increases of several hundred percent. This gun is now being used to test pneumatic gun theory and the use of guide tubes, with the result of pellet speeds up to 1.3 km/s at 5515-kPa (800-psi) gas pressure. Tests of quartz, Teflon, and stainless steel guide tubes up to 5 m long result in more reliable gun operation and ease gas handling problems.

A four-shot version of the single-shot gun, shown in fig. 3, has also been tested and a four-pellet experiment performed on PDX. The four-shot device loads four pellets into separate guns housed in a single cryostat. The pellets can be independently fired, each having its own propellant valve. Additional four-shot injectors are being fabricated for experiments on Alcator-C at the Massachusetts Institute of Technology (MIT) and ISX-B at ORNL.

A facility has been built to test repeating pneumatic gun concepts. In this device, shown in fig. 2, the screw press extruder developed in the centrifuge program is used to extrude a ribbon of D_2 between a fast valve and a 2-mm-ID gun barrel. An electromagnetically driven concentric punch chambers the 2-mm pellet. The punch and valve units have been tested to over 30 pulses/s. A low conductance guide tube system will be used for the helium gas propellant, allowing the pellets to be injected into high vacuum.

The ORNL pellet program is therefore rapidly approaching reactor pellet injector parameters with both the centrifuge and the pneumatic gun concepts.

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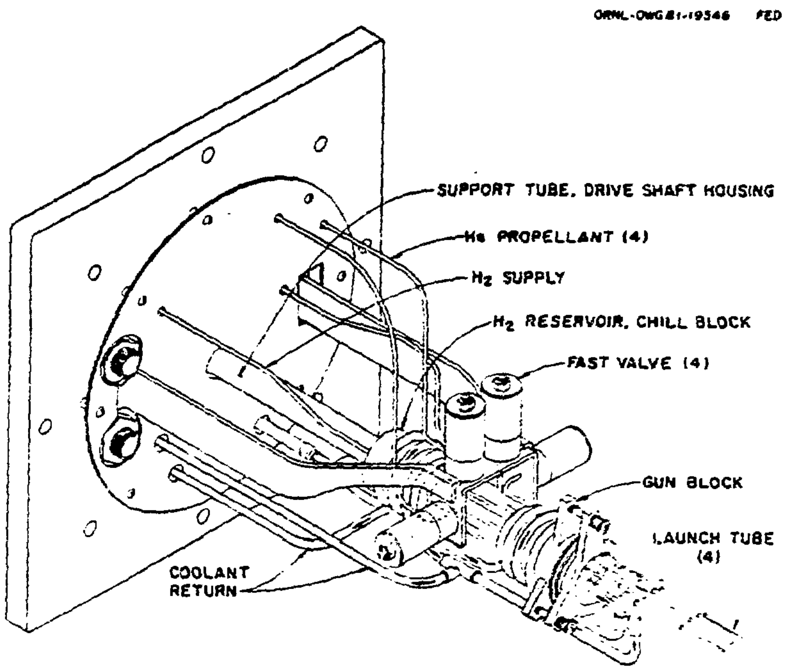

Fig. 3. 4-shot pneumatic gun.