Twin-Screw Extruder and Pellet Accelerator Integration Developments for ITER

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Abstract— The ITER pellet injection system consisting of a twin-screw frozen hydrogen isotope extruder, coupled to a combination solenoid actuated pellet cutter and pneumatic pellet accelerator, is under development at the Oak Ridge National Laboratory. A prototype extruder has been built to produce a continuous solid deuterium extrusion and will be integrated with a secondary section, where pellets are cut, chambered, and launched with a single-stage pneumatic accelerator into the plasma through a guide tube. This integrated pellet injection system is designed to provide 5 mm fueling pellets, injected at a rate up to 10 Hz, or 3 mm edge localized mode (ELM) triggering pellets, injected at higher rates up to 20 Hz. The pellet cutter, chamber mechanism, and the solenoid operated pneumatic valve for the accelerator are optimized to provide pellet velocities between 200-300 m/s to ensure high pellet survivability while traversing the inner wall fueling guide tubes, and outer wall ELM pacing guide tubes. This paper outlines the current twin-screw extruder design, pellet accelerator design, and the integration required for both fueling and ELM pacing pellets.

Keywords- ITER fueling; ELM control; twin-screw extruder

I. INTRODUCTION

ITER will require both fueling and ELM mitigation pellets consisting of frozen hydrogen isotopes. The ITER pellet injection system is required to provide a fuel injection rate of ~1500 mm3/s (1800 mbar-L/s) at durations of up to 3000 s [1], of 5mm pellets at 10Hz. Recent experiments on DIII-D suggest ITER may be able to utilize ~3 mm pellets to pace ELMs by injecting them at high frequencies >15Hz [2]. The ITER pellet injection system is comprised of devices to form and accelerate pellets, and is connected to inner wall guide tubes for fueling, and outer wall guide tubes for ELM mitigation [3-5].

The pellets travel from the injector to the plasma through curved guide tubes. As the pellets follow the trajectory of the guide tubes, stress is introduced into the pellet and accumulated stress can cause pellet fracturing. Stress is a function of pellet velocities, angle of impact to the curve, and tightness of the curve radius, as examined in guide tube geometry experiments [6]. The fueling pellet guide tube extends from the pellet injection cask, under the diverter and upwards along the inner wall before curving out through the tiles into the plasma to take advantage of the ExB drift from the high field side for deeper fueling. The ELM mitigation guide tubes extend from the pellet injection cask to through the diverter port and curve up into the plasma on the low field side to slightly penetrate the edge of the plasma and not increase the fueling rate. The guide tube trajectories are shown in Fig. 1. Pellet velocities must be kept below 200-300 m/s for fuel pellets to survive the tight radius bends, and for ELM pacing pellets to penetrate only deep enough to trigger an ELM, but not cause additional fueling of the plasma [2, 6].

High frequency injection rates of 15 Hz have been demonstrated using the DIII-D pellet injector for 10 s with a single batch extruder [7], which suggested increased injection rates should be possible with a similar solenoid driven pellet
cutter, coupled with a fast opening gas propellant valve. Steady state, 5 Hz pellet injection rates have been accomplished with three staged batch extruders as demonstrated on JET with 2.7 mm pellets [8], but a continuous screw extruder is desired because it would not require the careful timing of staging the batch extruders. A single screw extruder operated on JET, has demonstrated the ability to provide pellet injection rates of up to 60 Hz using twin nozzles, coupled with pneumatic accelerators [9], substantiating the viability of providing high frequency pellets by an extruder.

A unique method of using a twin-screw extruder to provide a stream of deuterium ($D_2$) for pellet production is under development at the Oak Ridge National Laboratory [10]. The twin-screw extruder offers advantages over a single screw extruder of positive displacement pumping without relying on wall friction to move the extrusion through the screws, and reduced pulsation at the die, which should provide a more consistent pellet size. The one-fifth ITER scale prototype extruder has been redesigned with reduced gap sizes for increased throughput. Updates in the powertrain, torque handling and measurement, and thermal management have been made. Experiment assembly has begun and tests will be conducted to characterize the quality, duration, and rate of supplied frozen $D_2$.

Simultaneously, the pellet accelerator is under development for future ELM pacing experiments to be tested on DIII-D. A batch extruder has been refurbished and coupled to a redesigned pellet accelerator to provide $> 15$ Hz, 1.4mm pellets. The pellet cutter, chamber, and the solenoid-operated pneumatic valve for the accelerator are optimized to provide pellet velocities between 200-300 m/s. While the twin-screw extruder and pellet accelerator are being developed separately, they will be combined for the ITER prototype with a simple modification to the extruder nozzle.

II. TWIN-SCREW EXTRUDER DESIGN

An estimation of the screw torque required for extrusion was based on a frozen $D_2$ dynamic shear strength model. The model incorporates the shearing of the frozen $D_2$ in one screw against the other screw, to estimate the required torque. The estimated torque ($T$) is a function of the C-chamber (the chamber of one revolution of one screw) shear area ($A_c$), where the C-chamber length calculated from White [11] is $L_c$, the screw diameter is $D$, and the screw helix angle is $\phi$, and the C-chamber width is $w$.

$$L_c = \frac{\pi D}{\cos(\phi)}$$  \hspace{1cm} (1)

$$A_c = L_c w$$  \hspace{1cm} (2)

The force required to shear the frozen $D_2$ ($F_c$), is a product of the $D_2$ dynamic shear strength ($\sigma_{dyn}$) and the C-chamber area for both the inner and outer shear areas.

$$F_c = \sigma_{dyn} 2 A_c$$  \hspace{1cm} (3)

The torque is a product of the force, screw radius ($R$), and number of screw channels ($N_f$), for both screws.

$$T = F_c R N_f$$  \hspace{1cm} (4)

The dynamic shear strength of $\sim 122$ kPa for a 7 rpm rotation rate (extrusion travelling at 0.75 mm/s) was estimated from prior shear experiments [12], resulting in an estimated torque of $\sim 51$ N-m for the 37 mm diameter screws with nine chambers. The torque estimate is conservative because of not accounting for the reduced shear area between the intermeshing screws, but does not include the non-extrusion friction torque of the extruder. The current extruder design is shown in Fig. 2.

A. Extruder Torque Requirements

The twin-screw extruder has been redesigned with increased strength to handle a minimum of 122 N-m of torque, limited by the 22 mm diameter drive shaft. The extruder power requirements demand a high, constant torque source. The powertrain consists of a motor, torque transducer, and slip clutch mounted inline on top of the extruder driveshaft connection. A DC, 186W (4hp), 212:1 gear reduction motor provides a constant minimum torque of 125 N-m throughout the rotation rate range. An AC to DC speed controller allows infinitely variable motor speed from 0-8 rpm. Mounted below
the motor is a 200 N-m peak torque transducer that records the real time torque and rotation rate, as well as the ultimate torque value. Between the torque transducer and the extruder drive shaft is a constant torque slip clutch. The slip clutch provides a safety link that prevents over torque and the resultant breakage of the drive shaft. The slip clutch also provides for an easier extrusion startup.

The extruder is not rotated when the extrusion is first formed to allow a “plug” of ice to form in the nozzle. If the plug is not allowed to form, liquid D_{2} gravity feeds through the extrusion nozzle before it has a chance to solidify. After this plug is formed, the extruder is turned on and the resulting start torque is high due to the high shear strength of cold D_{2}. At startup, the motor is set to a low rotation rate and the slip clutch allows the D_{2} to slowly shear as the screws begin to turn without excessive torque being applied to the driveshaft. Once the screws start to force the extrusion through the die, the viscous heat dissipation (heating caused by shearing of the frozen D_{2}) locally increases the temperature, decreases the D_{2} shear strength, and reduces the required torque for extrusion. The viscous heat generation gradually increases until the screws turn at the same rate as the motor and the clutch stops slipping.

Two custom made heater bands are epoxied around the solidification section to control the freezing temperature. A Lakeshore DRC-91CA temperature controller uses a silicon diode temperature sensor in combination with the two 10 W heaters to maintain a set temperature. The heater power is increased to facilitate lower torque startup by reducing the D_{2} shear strength and then reduced as viscous heat generation increases. Two heaters are also epoxied around the liquefier section to maintain a temperature of ~23 K (above the freezing point) to prevent frozen D_{2} plugging in the liquefier channels.

B. Thermal Connectors
A Cryomech AL330 cryocooler, used to cool the liquefier, is mounted parallel to the extruder with a thermal connection bridging the 178 mm gap. Because the thermal connection is perpendicular to the cryocooler, a flexible thermal connection is required to prevent harmful torque against the coldhead from thermal contraction, and resulting damage. The cryocooler has a cooling capacity of ~40 W at 20 K. The required power to cool the D_{2} gas exiting the precooler at 80 K, to a fully condensed state at 20K with the desired experimental mass flow rate is ~35 W. Thus, the cooling connection between the liquefier and cryocooler has a high conductivity requirement. The desired performance of 40 W conducted across the connection with an allowable temperature drop from 20 K to 23 K was chosen. The thermal connection design that satisfied this specification was two flexible, high conductivity thermal straps, shown in Fig. 3. The thermal straps are made of 0.06 mm thick pure aluminum foil, layered to reach a cross section of 12.7 mm wide by 31.8 mm tall and 178 mm long. The foil layers are mounted at each end in an 1100 series solid aluminum pad, measuring 50.8 mm wide by 50.8 mm tall by 19.1 mm thick. Indium foil is sandwiched between the cryocooler and liquefier connections ensure good thermal contact.

The solidifier section, which is the barrel of the extruder, is connected to the Cryomech GB37 cryocooler through an OFHC thermal bus bar. The cryocooler has ~17 W of cooling capacity at 12 K with no load on the first stage. The required power to cool the incoming liquid D_{2} from ~23 K to the freezing point (18.7 K), freeze the D_{2}, and cool the solid to the extrusion temperature of 12 K, is ~5 W. A low temperature difference was desired in order to reach the lowest possible temperature in the frozen extrusion. The bus bar was designed to conduct 16.7 W with a temperature drop of 0.5 K between the cryocooler and solidifier section. A simple Fourier’s Thermal Law calculation was made to determine the cross sectional dimensions for the required 165 mm bus bar length. The final bus bar measures 25.4 mm high by 101.6 mm wide. The bus bar has a bolted connection around the 76.3 mm hole for the extruder solidifier section.

C. Thermal Isolators
The extruder has been designed to thermally isolate individual cooling sections to prevent excessive heat load on the individual cryocoolers from warmer sections above, and thus increased minimum possible temperatures. Thermal spacers were placed between the solidifier and gear sections, and the liquefier and thermal standoff sections. The spacers were made from a low conductivity polymer. In a similar method to the bus bar analysis, a Fourier’s Thermal Law analysis was performed to determine the spacer dimensions required to minimize the heat leak across the thermal isolators. The spacers are 6.4 mm thick and have a cross sectional area of 0.0106 m² and transfer a maximum of 3.8 W of heat to the next lower cooling section.
D. Extruder Maintenance

The new extruder design allows for easier maintenance and assembly. All extruder sections except for the gas precooler are now mounted coaxially. The extruder is bolted to the bottom of a conflat flange. Maintenance removal requires the disconnection of the precooler gas lines, cryocooler connections, and the extrusion viewport bellows inside the guard vacuum space. On top of the extruder, the slip clutch, torque transducer, and motor must be removed. The conflat can then be unbolted and the extruder subassembly can be hoisted from the guard vacuum chamber.

III. PELLET ACCELERATOR DESIGN

The frozen D₂ stream supplied by the batch extruder to the pellet accelerator for ELM pacing studies is rectangular in cross section with dimensions equal to the pellet length along the axis of the cutter, and double the pellet length normal to the cutter (1.4 mm x 2.8 mm respectively). The cutter uses a solenoid driven cylindrical punch, with a straight opening the same diameter as the pellet for 0.4 mm, and then the opening conically expands 2 degrees so the pellet is only lightly held by friction. The punch transports the pellet to the chamber socket and forms a gas seal as shown in Fig. 4. Between 5 - 10 ms after pellet chambering is complete, the pneumatic valve is pulsed open for ~2 ms, and the open valve allows ~14.5 bar, 293 K, hydrogen gas to accelerate the pellet out of the chamber and through the guide tube. The tube between the pneumatic valve and the pellet chamber is 1.8 mm in diameter, which limits the conductance of the accelerating gas and thus limits pellet velocity.

IV. EXTRUDER AND PELLET ACCELERATOR INTEGRATION

The extruder and pellet accelerator will be integrated for continuous, high frequency pellet injection. The twin-screw extruder nozzle can be machined to replicate the batch extruder nozzle profile as shown in Fig. 5. The twin-screw extruder can then easily be joined to the pellet accelerator.

ACKNOWLEDGMENT

This work was supported by the Oak Ridge National Laboratory managed by UT-Battelle, LLC for the U.S.

REFERENCES