Conceptual Design of a Pellet Injector for the ST40

INFUSE 2021-2022

A SUMMARY REPORT SUBMITTED TO THE US DEPARTMENT OF ENERGY IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS OUTLINED IN THE
CRADA No. NFE-21-08743

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Executive Summary of INFUSE CRADA work:

The Cooperative Research and Development Agreement (CRADA) between Oak Ridge National Laboratory (ORNL) and Tokamak Energy Inc. (TE) focused on a design study of a pellet injection system that would enable the investigation of fueling ST plasmas to demonstrate high density operation and to eventually be used in future devices to inject DT pellets. This design study was based on a previous injector design to result in an optimized design for 4 pellets. This study determined the optimum pellet sizes based on projected ST40 plasma parameters and has the ability to be used for tritium pellet compatibility in future devices. The project has resulted in a 3D CAD model of the pellet injection system and component definition for the injection line, gas handling, and a pellet mass and speed diagnostic. A guide tube selector switch is incorporated into the injection line design to be able to select either low field side midplane or upper high field side injection of the pellets.

1. Background

Pellet fueling is an important step on the path to providing a fusion energy output demonstration in the ST40 spherical tokamak concept and beyond. Gas fueling of a spherical tokamak (ST) is possible but will lead to excessive recycling in the divertor, rendering control of divertor detachment difficult and will also lead to significant tritium retention in the walls when deuterium-tritium (DT) fuel is used. The significantly more efficient fueling from cryogenic pellets can be used to carefully tailor the density profiles in the ST and can also be used to adjust the DT ratio to optimize fusion reactivity. The use of pellets to fuel the plasma will also minimize the recycling of tritium that will be beneficial in minimizing the resulting inventory in the machine plasma facing components, reducing the safety case burdens.

There is a long history of pellet injection technology development [1] which has been applied to numerous magnetic fusion experimental fueling demonstrations as well as for edge localized mode (ELM) and disruption mitigation. For the application of pellet fueling on ST40, a previous design of a flexible pipe-gun type injector named pellet injector in a suitcase is to be used as it has already been proven on several fusion devices and can be built and integrated into ST40 for relatively modest cost. The application of this system for Tokamak Energy would require some changes to make it DT compatible and provide the necessary isolation of tritium containing components, to enable use on future research programs. The implementation of the injector for tritium use is of research interest as such an injector has yet to be deployed for use for a DT fusion demonstration. Basic research on DT pellet formation was performed many years ago [2] and it has yet to have been put to practical use.

2. Statement of Objectives

The following are the technical objectives set out in the CRADA No. NFE-21-08743- for collaboration between ORNL and Tokamak Energy Inc on pellet injection for ST40:

Objective 1 - Determination of pellet sizes to be used

An analysis will be conducted to determine the minimum and maximum pellet sizes and speeds that would be suitable for injection into ST40 plasmas. Existing neutral gas shielding codes will be utilized along with measured and future anticipated ST40 plasma parameters of electron temperature, density, plasma radius, and magnetic field. Injection geometry into ST40 will be defined and pellet speeds that can survive in that geometry will be used in the modeling.

Objective 2 - 3D CAD model and component definition

A design based on an existing design for a 3-barrel pipe gun pellet injector with all metal seals suitable for use with tritium will be updated to 4 barrels and incorporate the barrel sizes determined in Objective 1. The envelop and interface requirements that the injector must meet to be incorporated onto ST40 will be defined. A 3D CAD model of the injector will be developed that meets the defined envelop and interfaces. Components that interface to the injector such as the cryocooler, propellant valves, gas manifold, vacuum pumps, and injection line diagnostics will be defined.

3. Technical work performed

3.1. Modelling of pellet ablation into ST40

1. Injection trajectory definition and plasma parameters

The ST40 spherical tokamak has the basic geometry parameters of R0=0.4-0.6m, R0/a=1.6-1.8, k=2, with a plasma current up to 2 MA and 3T toroidal magnetic field. A high field side vertical injection geometry was proposed to investigate pellet penetration depth for different size pellets in high performance ST40 plasmas. The injection geometry aims from the top of ST40 to cross the midplane inboard of the plasma center to take advantage of an inward gradB drift as shown below in Fig. 1. The internal guide tube inside of ST40 vacuum vessel would have an approximately 30-degree bend and a bend radius of over 1 m. Such a geometry can withstand pellet speeds in excess of 300 m/s from previous studies of D2 pellet survival [4]. External guide tubes would add additional curves to interface with the injector and those have not been studied yet for pellet survivability but are thought to be able to have more generous radii and so are thought not to present significant issues.

The plasma kinetic parameters assumed for this study were central electron temperatures of 1.0, 2.0, and 5.0 keV with an assumed electron density of 1.0×10^{20} m^{-3}. The temperature profile was assumed to be fairly linear with minor radius while the density profile was considerably flatter.

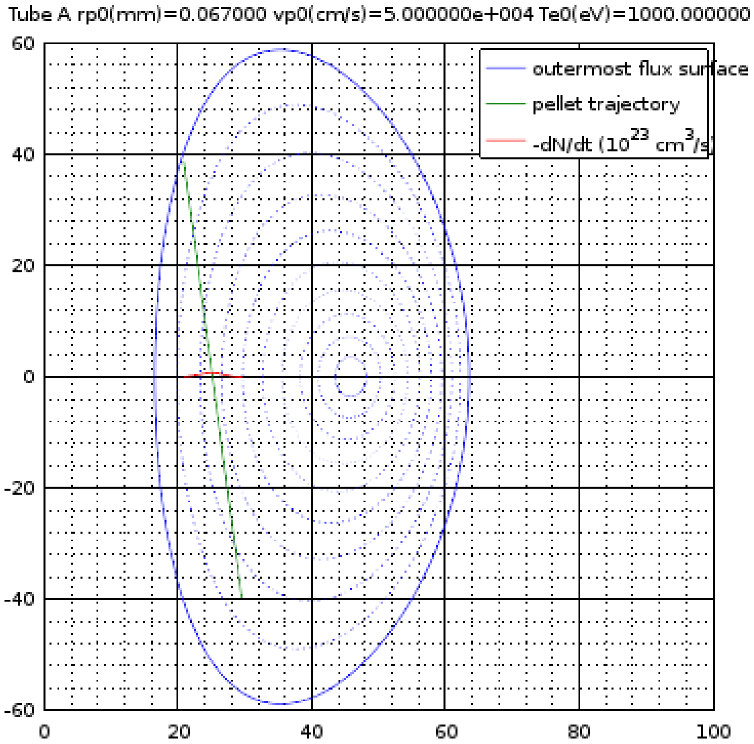

Fig. 1 ST40 flux surface geometry and vertical proposed high field side injection line trajectory used in the ablation penetration calculations.

2. Neutral gas shielding modeling and pellet size determination

Ablation calculations were performed for different size deuterium pellets at speeds of both 200 and 500 m/s along this injection path for plasmas with a central electron temperature of 1.0, 2.0 , and 5.0 keV. The pellet sizes of cylinders with the diameter equal to the length and their volume in mm^3 that are under consideration for use on ST40 are listed below in Table 1. These calculations use the neutral gas shielding model [4] to determine penetration depth without consideration of the gradB drift that will help deposit the fuel even deeper than the ablation model predicts. The pellet sizes investigated were 1.2, 1.5, and 2.0-mm diameter cylinders of length equal to the diameter. The results of these calculations indicate that the maximum ablation rate would occur at a minor radius of 0.9 to as deep as 0.74 for the lowest temperature plasma case. The benefit of the gradB drift would therefore be necessary to obtain deep fueling with this range of pellet sizes and speeds.

Pellet Diameter (mm)	Pellet Volume (mm^3)	Number Atoms
1.2	1.35	0.82×10^{20}
1.5	2.65	1.6×10^{20}
2	6.28	3.8×10^{20}

Table 1. Pellet sizes considered for ST40

3.2. Pellet injector design and component definition

The design of the pellet injector for ST40 started from previous multi-barrel pellet injector designs at ORNL known as a pellet injector in a suitcase [6] and the shattered pellet injector (SPI) used on JET [7] that extended the technology to be an all-metal sealed design. Important features from both of these designs were combined into a unique design to meet the requirements for ST40 of four independent pellets with an all-metal sealed design that can be used with DT pellets in future devices. The design uses an injection line that combines the pellets into a single guide tube much as in the JET SPI design. The single guide tube incorporates a microwave cavity to measure the pellet mass and speed as well as a guide tube switch as was developed for pellet injection on DIII-D. This switch will allow the pellets to be routed either to the outside midplane for low field side injection or to a curved tube that the enters the top of the ST40 vessel for vertical high field injection as mentioned above and shown in Fig. 1. The injector will use the custom solenoid operated propellant valves that ORNL has used successfully for decades to inject pellets with similar gas guns [8].

The guard vacuum chamber that surrounds the injector to provide thermal insulation has been selected to be a welded chamber that has large 10-inch conflat flanges on the front, top, and sides to connect the barrels, cryocooler, and electrical connections respectively. These large size flanges also make maintenance inside the injector easier and facilitate changing barrels to different sizes. Fig. 2 shows this chamber with the barrels inserted and cryocooler installed on the top plate of the box.

The injector is cooled by a Sumitomo RDK-415 Gifford McMahan closed cycle helium cryocooler as has been used successfully on the KSTAR SPIs [7]. A version of the cryocooler with a conflat seal on the guard vacuum chamber would be used to maintain the all-metal seal design philosophy for the injector. This cryocooler can easily handle the cooling requirements for four pellets of this size and can achieve a low temperature of ~ 8 K in this design configuration. The first stage of the cryocooler will attach to a thermal shield to provide further insulation from the radiation heat load on the barrel coldzones. The guard vacuum chamber must be pumped to approximately a 10^{-2} mbar pressure level in order to obtain good thermal performance from the cryocooler. Once the cryocooler is cold the copper attached to the coldhead will cryopump the chamber to much lower vacuum levels typically below 10^{-6} mbar. A small turbo pump can also be applied to the vacuum chamber for verification of leak tightness when the cryocooler is not operating.

The fuel gas and propellant gas will be fed to the injector through a gas manifold panel that contains valves, flow controllers, and pressure sensors used to make the pellets and fire them. This manifold is designed with all Swagelok VCR metal sealed components. This manifold panel would be mounted on the side of the stand that supports the injector that is shown in Fig. 3.

The injector system is envisioned to be controlled by a commercially available programmable logic controller and a Windows PC that provides a graphical human machine interface to operate the injector and collect data for providing a trend record of the injector performance. This control system would mimic the design used for the KSTAR SPI systems and utilize similar PLC software. The firing of pellets is controlled by the overall ST40 timing control system. A trigger pulse is needed to fire each propellant valve to launch the pellets. Once formed the pellets can be fired whenever the ST40 desires. A valve will be supplied as a target plate to be able to fire pellets offline when ST40 plasma is not operating.

The injector and its injection line would be mounted to a plate that would then be placed on top of a stand shown in Fig. 3 that could be made of extruded aluminum tubing using off the shelf hardware. The stand would hold the gas manifold plate and support the vacuum lines and pumps underneath the stand.

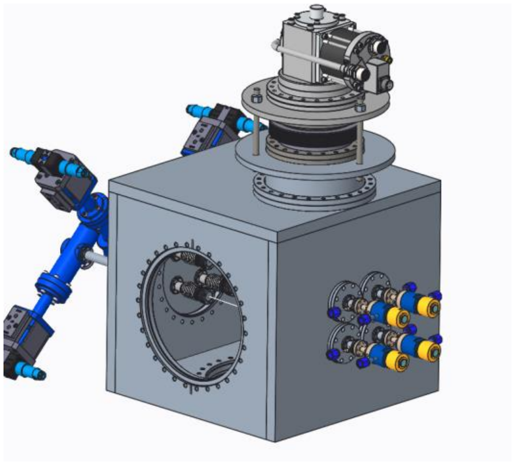

Fig. 2 3D CAD model of the concept injector design showing the guard vacuum chamber with 10-inch conflat flanges and cryocooler connection on the top of the chamber. Barrel gate valves are shown to the left in the ends of the barrels.

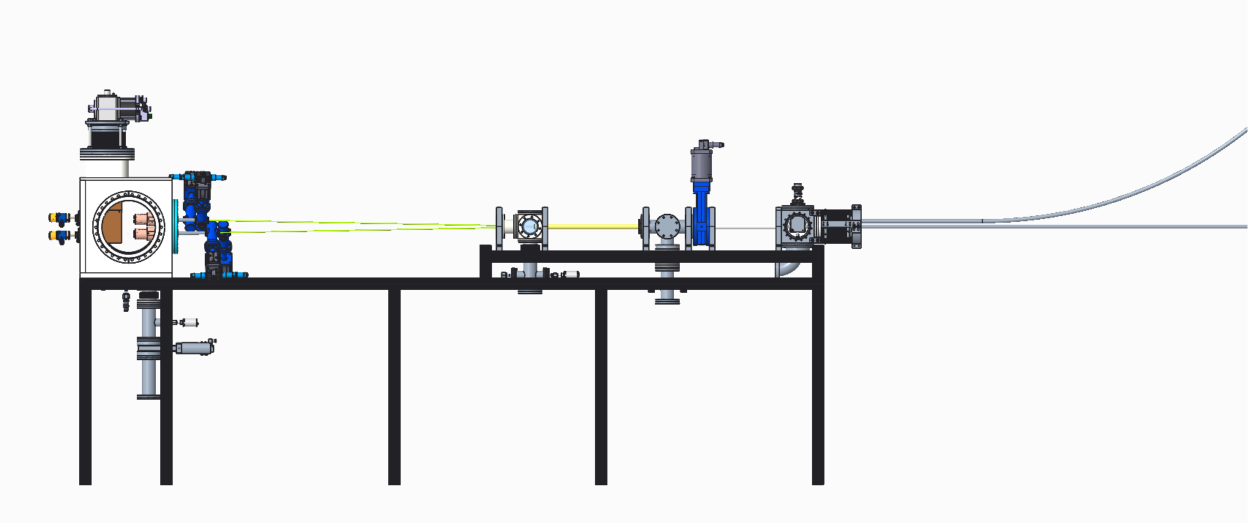

Fig. 3. CAD elevation view of the overall pellet injection system on a stand showing the injector guard vacuum chamber on the left and the injection line with a microwave cavity and guide tube selector at the right. External guide tubes are shown for midplane low field side injection and vertical high field side injection.

4. Potential applications and technology transfer

The completed work has identified a suitable design configuration of a pellet injector for ST40 to be implemented to obtain high density plasmas in the core of the device. The result from this collaboration provides an exciting opportunity to experimentally validate theoretical predictions with a proof-of-concept pellet fueling system and, potentially, the future use of this system in DT plasmas as an ST fusion demonstration. This would bring a substantial mitigation of technical and financial risk for the TE company.

List of presentations, diagnostic development, publications:

1. Publications are expected from this work on both the pellet injector design and performance and on the future ST40 plasma performance with pellet injection.

5. Benefits of the collaboration to DOE's mission

High-level motivation and capabilities of the pellet injector conceptual design are to provide a future path for obtaining high density ST plasmas that are needed to optimize and accelerate the ST fusion concept. The project also strengthens the collaboration between TE and ORNL, benefiting both parties by cross-fertilization of ideas and opening the doors for further cooperation in fruitful public-private partnerships.

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