Pellet Fueling Technology Development for Efficient Fueling of Burning Plasmas in ITER*

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Abstract. Pellet injection from the inner wall is planned for use on ITER as the primary core fueling system since gas fueling is expected to be highly inefficient in burning plasmas. Tests of the inner wall guide tube have shown that 5mm pellets with up to 300 m/s speeds can survive intact and provide the necessary core fueling rate. Modeling and extrapolation of the inner wall pellet injection experiments from today's smaller tokamaks leads to the prediction that this method will provide efficient core fueling beyond the pedestal region. Using pellets for triggering of frequent small edge localized modes is an attractive additional benefit that the pellet injection system can provide. A description of the ITER pellet injection system capabilities for fueling and ELM triggering are presented and performance expectations are discussed.

1. Introduction

Pellet injection is the primary fueling technique for efficient core plasma fueling of ITER burning plasmas, which is necessary for achieving high fusion gain. Injection of pellets from the inner wall has been shown on present day tokamaks to provide efficient fueling and is planned for use on ITER [1,2,3]. Here we present progress on the development of the pellet technology to provide reliable high throughput inner wall fueling, the validation of physics models for pellet ablatant drift, and apply the results of these studies to ITER burning plasmas.

The ITER fueling system is to consist of the inner wall pellet guide tube and possibly a guide tube for outer wall injection as shown in Fig. 1. The inner wall tube would provide high throughput fueling while the outer wall tube would be used primarily to trigger edge localized modes (ELMs). Gas fueling is to be provided by a set of 4 manifolds of a meter length near the top of the machine and an entrance tube at the dome of the divertor. The gas fueling rate is specified to be up to 400 Pa-m^3/s while the pellet fueling rate is to be up to 100 Pa-m^3/s (50 Pa-m^3/s of T_2). The neutral beam injection system will provide less than 1 Pa-m^3/s of fueling. The pellet injection system is to produce DT pellets with up to 90% tritium content.

2. ITER Fueling System Development

Significant development is needed for the pellet fueling system in order to meet the efficient core fueling and high DT throughput requirements. The first step of this development has been verification that the inner wall pellet injection scheme can provide the necessary fueling.

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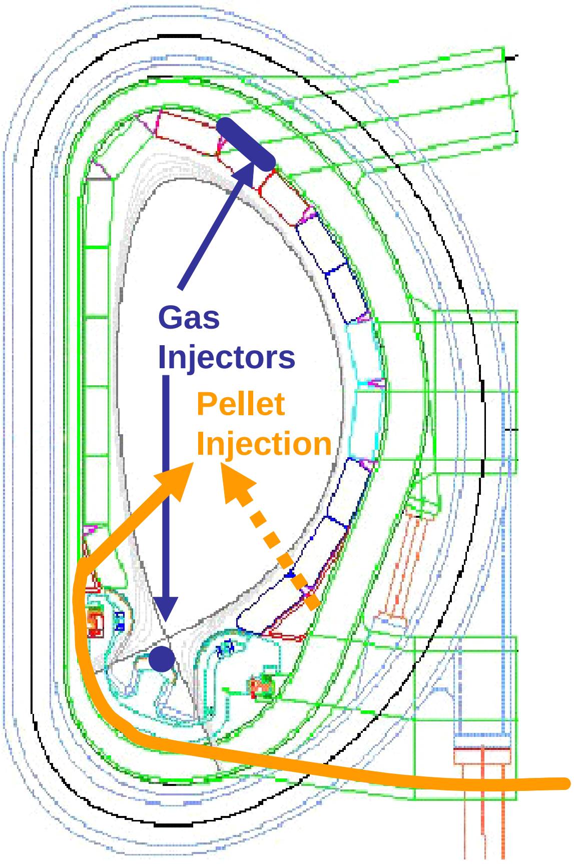

FIG. 1. Cross section of ITER showing the pellet injection and gas injection locations. The dashed pellet trajectory is the proposed low field side location for ELM triggering.

A mockup of the proposed ITER inner wall injection line has been used to study pellet survivability under simulated operating conditions. Tests in a fully evacuated guide tube using 5.3mm cylindrical deuterium pellets formed in a pipe gun pellet injector indicated a speed limit of 300 m/s for intact pellets [4]. Recent tests were performed at both 10 and 100 torr (1300 and 13000 Pa) pressures to simulate the expected environment at high repetition rate (10 Hz) operation [5]. These tests have determined that pellets continue to survive intact up to 300 m/s as shown in Fig. 2. The mass loss in the guide tube was also measured in these experiments using a calibrated set of microwave cavities [6]. Even at the higher guide tube pressures the mass loss of the pellets remains at <20% while the pellet speed decreases by about 10%.

The ITER pellet injection system must be able to supply 0.3 g/s (~1.5 cm^3/s solid DT) to the plasma, which is a significant extrapolation from present devices. Screw type extruders are under development to supply this quantity of solid DT for long durations. A centrifuge is the specified acceleration device; however the

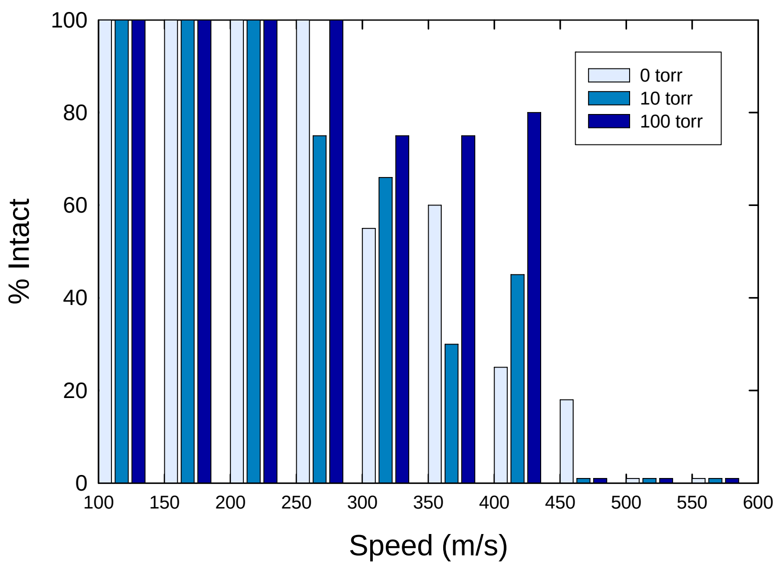

FIG. 2. Guide tube test results showing percent of intact pellets at different speeds for the inner wall guide tube mockup. Tests were performed at 3 different pressures in the guide tube.

anticipated slow pellet speeds make a repeating light gas gun with low propellant gas throughput an attractive option based on the high reliability that has been achieved with such systems [7,8,9]. A design study has been performed to ascertain the feasibility of a gas gun pellet injector system for ITER. The system that was developed in this study is shown in Fig. 3. A screw extruder supplies the DT ice that is cut into pellets and placed in a barrel for acceleration by a low throughput propellant valve. It utilizes a recirculating propellant gas system and a recirculation of the excess extrusion material in order to offload the handling of these gas streams by the tritium plant, which would otherwise require doubling of the capacity of the envisioned plant. These gas streams would be processed by the tritium plant during non-operating periods.

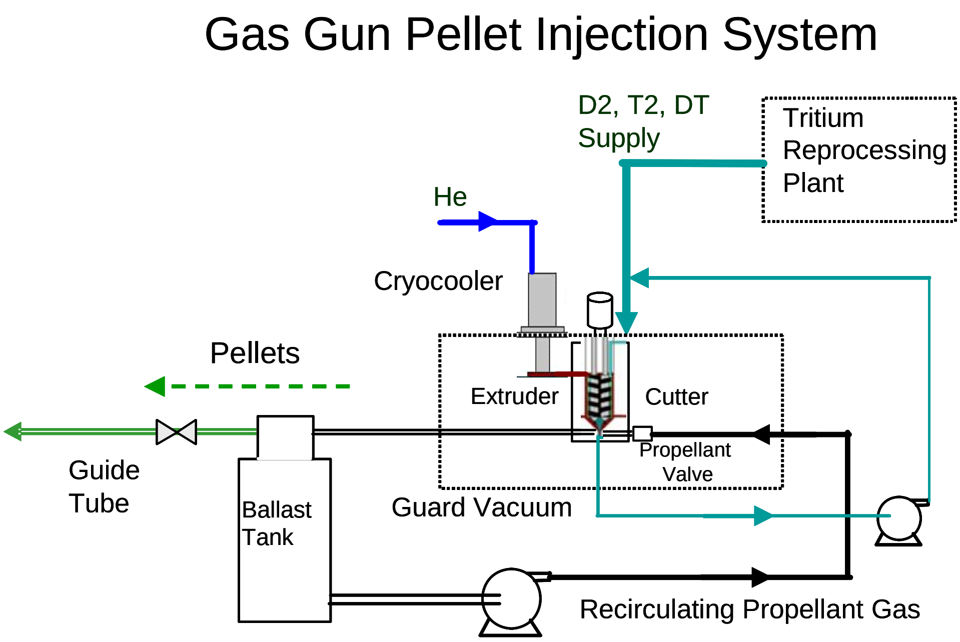

FIG. 3. Block diagram of the proposed gas gun pellet injection system for ITER.

The next step of development for the pellet injection system is the high throughput extruder. Both batch piston and single screw extruders have demonstrated the production of hydrogenic ice streams [10,11]. The ITER requirement for each injector is more than a factor of 5 higher than achieved with a continuous extruder and so a new twin-screw approach is under study that promises to have greater throughput and stability than a single screw. The use of multiple lower throughput extruders is also an option being studied.

3. ITER Fueling System Performance

Experiments have been performed on AUG [1] and DIII-D [2] that show a distinct advantage in deeper fuel penetration when pellets are injected from the inner wall as compared to the outside midplane. This is true despite slow pellet speeds that are necessary for maintaining intact pellets when injected from the inner wall through curved guide tubes. It has been hypothesized that a rapid mass drift occurs in the major radius direction during the time that the ionized pellet cloud expands toroidally along field lines. A regression analysis of the inner wall pellet injection data from DIII-D has shown that the drift distance of the pellet mass has a strong dependence on the pellet size and the pedestal electron temperature and a weak inverse dependence on the edge safety factor [12].

Theoretical analysis of the inner wall pellet injection drift has been undertaken by different authors using different physics models and assumptions. The MHD model by Strauss [13] and refined by Polevoi [14] assumes a very high cloud pressure that results in a poloidal flux shift. This model has indicated a fairly strong edge safety factor dependence on the drift, which has not been observed thus far from the inner wall pellet experiments on DIII-D [12]. E×B polarization drift models have been developed by Rozhansky [15] and Parks [16,17] that are based on the cloud polarization from ∇B and curvature drifts that results in an E×B drift of the cloud in the major radius direction. There are differences between these models in the mechanism for the drifting mass to dissipate and incorporate into the background plasma. More work is ongoing to better understand this aspect of the drift mechanism. Nonetheless, these models have been fairly successful in reproducing the effect seen on AUG and DIII-D respectively.

In this paper we examine the predicted mass deposition for pellets injected from the ITER inner wall using the Parks Pressure Relaxation Lagrangian (PRL) model [17] coupled to the PELLET ablation code [18]. New features added to the PRL model include arbitrary injection angle, curvature drive from parallel flows, and Mach number effect. With these new features included, the modeled deposition profiles are in reasonable agreement with experiment from the inner wall locations on DIII-D [17].

The proposed pellet fueling scenario for ITER has been modeled using the PRL model with realistic pellet sizes and speeds based on the guide tube test results reported above. The inner wall pellets at 16 Hz provide significantly deeper fuel deposition than either outer wall injected pellets or gas fueling as shown in Fig. 4. The low field side pellet case shown in Fig. 4 does not include the E×B drift effect which would cause virtually all of the mass to be ejected from the plasma. The gas fueling source profiles are calculated with a B2-Eirene slab model calculation (solid) [19] and from the SOLPS code with actual ITER geometry and

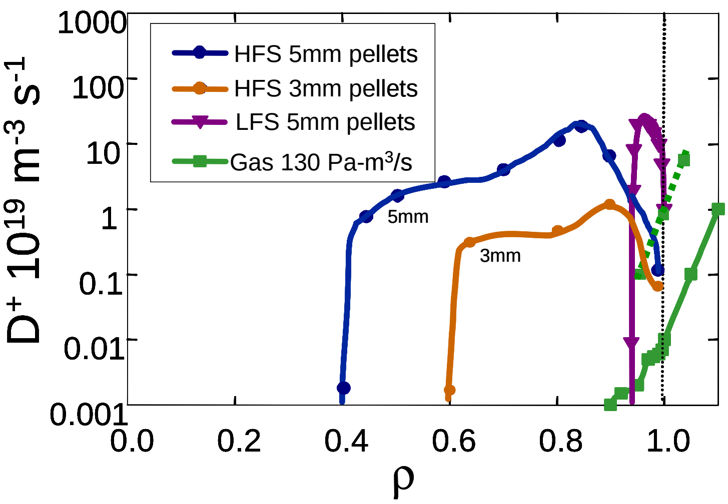

FIG. 4. Comparison of pellet fueling and gas fueling source profiles for ITER using the specified 16 Hz 5-mm pellets and 130 Pa-m^3/s (1000 torr-L/s) of gas. The dashed gas curve is calculated from the SOLPS code in actual ITER geometry. The solid gas curve is from a B2-Eirene slab calculation.

fueling locations (dashed) [20]. The SOLPS calculation yields more than a factor of 10 higher gas fueling profile, nonetheless, the fueling source is very shallow and has a fueling efficiency much lower than seen on current day smaller tokamaks. The pellet modeling shows that inside launched cylindrical DT pellets of 3mm and 5mm size with speeds of 300 m/s (limited by the curved guide tube) have the capability to fuel well inside the separatrix as shown in Fig. 4. While not reaching the plasma center, the inner wall injected pellets of modest size can be expected to provide a significant level of fueling beyond the expected edge localized mode (ELM) affected layer. The fueling efficiency is predicted to be nearly 100%, which will help minimize the tritium retention of the first wall that would likely occur from tritium gas fueling.

The scaling of the pellet mass drift distance in ITER from the PRL model has been determined using a regression analysis on a set of ITER pellet injection cases with varied parameters. The drift distance D scales as $B^{-0.15} * T_{e0}^{-0.13} * T_{eped}^{0.5} * r_p^{0.76} * q_a^{-0.15}$ where B is the magnetic field, T_{e0} is the central electron temperature, T_{eped} is the pedestal temperature, r_p is pellet equivalent spherical radius, and q_a is the edge q. The inverse edge q, pellet size, and pedestal temperature dependence is similar to that obtained from the DIII-D experimental database regression analysis [12].

4. Pellet ELM Triggering

Pellets injected into present day tokomaks from all injection locations have been found to trigger ELMs in H-mode plasmas presumably due to localized pressure gradient excursions beyond ballooning mode stability. The ELMs triggered from outside midplane injection have been found to be much stronger and longer lasting that those from the inner wall injected pellets. The use of pellets as an ELM trigger continues to be investigated as an ELM mitigation technique on present day tokamaks [21]. The pellet injection technology being developed for ITER fueling will have the flexibility to be employed also as an ELM mitigation system if needed.

The pellet injectors planned for ITER will have the capability to inject small 3mm size cylindrical pellets at fairly high repetition rates. These smaller pellets may make the triggering of frequent small ELMs a possibility as was demonstrated on ASDEX-U [21]. It may also be possible to utilize even smaller sized pellets if the 3mm size provides too many particles and adversely affects confinement. A pellet guide tube that aims pellets from the top of the divertor port to the magnetic axis (as shown in Fig. 1) has been proposed primarily for triggering ELMs with the small pellets. Calculations of the pellet penetration depth and deposition without considering the E×B drift mentioned in section 3 have been made with the PELLET code using the neutral gas shielding model [22]. The results of these calculations are shown in Fig. 5 where the density perturbations from different size pellets all injected at 300 m/s from the low field side location are shown overlaid with the assumed electron temperature profile before injection. In these calculations the mass drift is not included in order to show how deep the pellet is expected to reach. In all of these cases the predicted E×B mass drift is so strong that virtually the entire pellet mass is expected to drift rapidly outside of the plasma boundary. For the larger size pellets the perturbation is likely to reach the top of the temperature pedestal, which in this case is assumed to be at 4 keV. This is believed to be sufficient to trigger an ELM based on the results from ASDEX-U. More definitive tests to replicate this scenario scaled to the smaller machine sizes are needed. Future tests with small pellets injected into the low field side of the plasma will be undertaken in the next year on multiple existing machines in order to further investigate this possibility for ITER.

The mechanism for triggering ELMs by pellets has been hypothesized to occur from a localized pressure gradient excursion of the pellet cloud pressure over the peeling-ballooning mode stability limit. The local pressure excursion for pellets in DIII-D has been calculated with the PRL code to be in excess of 6 times the background plasma pressure at a normalized radius of 0.95. Using the same calculation method for the ITER low field side pellet injection scenario we obtain a pressure excursion of over 15 times the background pressure for 3mm size pellets injected at 300 m/s. A much smaller pellet less than 2mm size can produce a pressure excursion above the value calculated for DIII-D, therefore it may be possible to relax the pellet size requirement for inducing ELMs with LFS pellets. Future experiments on DIII-D will examine the use of much smaller pellets at low speeds for triggering ELMs and this should produce useful data for sizing the ITER pellets.

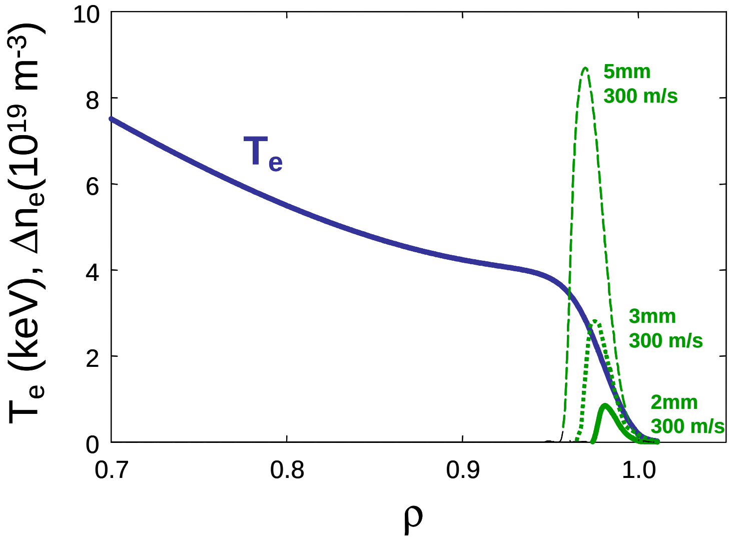

FIG. 5. Electron temperature profile in the outer 1/3 of the ITER plasma overlaid with calculated pellet mass perturbations from different size and speed pellets injected from the proposed outer wall injection line.

5. Discussion

The pellet injection system specified for ITER will have the capability to fuel with tritium rich pellets from the inner wall at a sufficient rate to maintain high density in a burning plasma. Gas fueling will likely not provide very efficient core fueling and will be utilized primarily to maintain optimal divertor conditions and help to sweep impurities into the divertor. The technology to achieve the needed reliable high throughput pellets is still under development, but is anticipated to be available well within the needed ITER time scale. A gas gun accelerator approach is under study and is believed to have a reliability advantage over the currently specified centrifuge accelerator. The propellant gas from a gas gun system can be recycled without too much complication, thus making this an attractive system for ITER without imposing undesirable loads on the tritium plant.

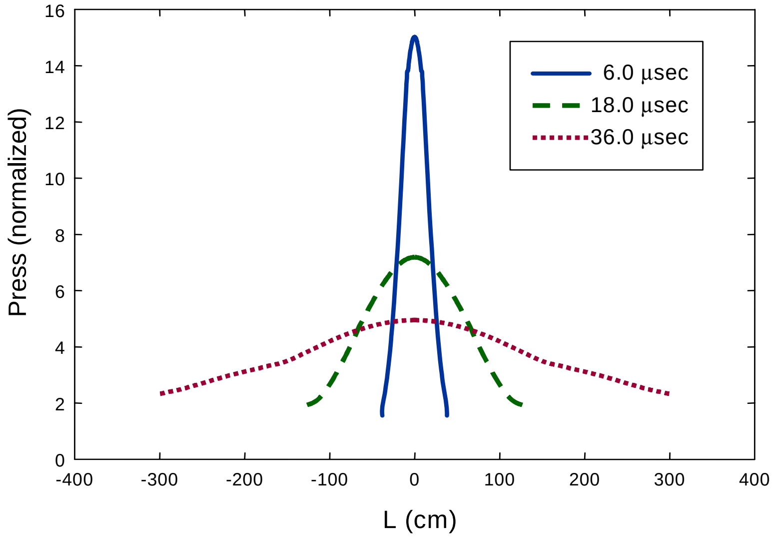

FIG. 6. Pellet cloud pressure along magnetic field line normalized to the background plasma pressure at the start location of the cloudlet drift. The profile is shown for different times after the cloudlet is detached from the pellet and starting to drift. 0 on the X axis is the pellet location.

Pellets injected into present day tokomaks from all injection locations have been found to trigger ELMs in H-mode plasmas presumably due to localized pressure gradient excursions beyond ballooning-peeling mode stability. Pellets injected from the outer wall low field side region have been shown to trigger larger ELMs than the same size inner wall injected pellets; therefore an outer wall guide tube is under consideration for ITER. The use of pellets as an ELM trigger continues to be investigated as an ELM mitigation technique on present day tokamaks and future experiments with low field size injection of small pellets will yield valuable information on this option for ITER. The pellet injection technology being developed for ITER will have the flexibility to be employed as an ELM mitigation system if needed. Small pellets injected at 10Hz from the low field side injection line may be sufficient to maintain an ELM frequency of 10 Hz and thus keeping the size of the ELMs much lower than they would become at a much lower natural ELM frequency.

6. Summary and Conclusions

In conclusion, ITER will require a reliable fueling system to meet its operational goals and pellet injection is the key element of that system. Gas fueling will not provide sufficient neutral penetration in the hot dense plasma to be effective at introducing the level of DT into the plasma that is needed to operate at high density and produce optimal divertor conditions. The most detailed theoretical models predict fueling beyond the pedestal region from pellets injected from the inner wall. Further theoretical work is needed to better understand how the drifting pellet mass is incorporated into the background plasma.

Pellets injected from the inner wall in ITER through a curved guide tube will have their speed limited to ~300 m/s. Nonetheless, these pellets are predicted to provide fuel penetration beyond the pedestal region even though the pellets themselves are predicted to be fully ablated by the time they reach the burning plasma temperature pedestal. This important result demonstrates a potentially feasible fueling scenario for ITER that did not exist just 10 years ago. Strong peaking of the density profile shape is not likely to be provided by this scenario unless a significant inward particle pinch exists in the ITER plasmas. If strong density peaking is needed by the fueling source directly then deeper penetrating fueling technology will need to be developed.

Acknowledgements

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