Alternate Concepts for Generating High Speed DT Pellets for Fueling ITER

R. W. Callis 1), L. R. Baylor 2), P. B. Parks 1), N. B. Alexander 1), C. P. Moeller 1)

1) General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA
2) Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

e-mail contact of main author: callis@fusion.gat.com

Abstract. There is a growing concern that the velocity of the DT-ice pellets being proposed to fuel ITER will not have the velocity to effectively penetrate through the pedestal of the plasma edge, because with velocities of only 300 m/s, high field side launched pellets will only penetrate to $r/a = 0.90$, which may not be adequate for fueling. The likelihood of increasing the pellet velocity is problematic, since the forces on the ice pellet as it goes around bends causes the pellets to disintegrate at velocities above 300 m/s. To achieve deeper penetration, either the pellet needs to have its velocity increased after it has passed the last bend, or the pellet has to be made stronger to survive the increased forces higher velocities create. One method toward higher velocity is to accelerate the DT-ice pellets using microwave power in the last meter of the guide tube after the last bend. A second method to reach higher velocities is to increase the strength of the ice pellets using the technologies developed in the production of the fuel pellets used in Inertial Confinement Fusion. That is to either encapsulate the pellet inside a solid shell of either metal or plastic, or to stiffen the ice by integrating it into a plastic foam sphere. Analysis indicates a plastic shell will increase the strength of a DT Ice pellet by a factor of 100. Bench tests of the microwave pellet acceleration have been performed and are reported below.

Introduction

Various models of the ablation and penetration of the DT-ice pellets being proposed to fuel ITER [1,2], show that the pellets fully ablate somewhere between r/a = to 0.95 and 0.85, but if launched from the high field side of the plasma the grad B drift drives the neutral cloud to depositions in the range of r/a = 0.4 to 0.65. The concern is that if most of the ablation occurs within the pedestal region then the cold gas can trigger an ELM. the fuel will be ejected easier by diffusion losses even if there is no elm, and finally there is no certainty that the grad B drift will take the pellet material out of the pedestal region into the core. A solution to this concern is to have most of the ablation of the fuel pellet occur beyond the pedestal. For ITER, the present pellet-fueling concept has DT-ice pellets traversing through a guide tube to reach the high field side, HFS, launch location. The forces on the ice pellet as it goes around bends causes the pellets to disintegrate at velocities above 300 m/s [2]. Thus deeper penetration cannot be done by just increasing the pellet velocity prior to the insertion into the guide tube. To achieve deeper penetration, either the pellet needs to have its velocity increased after the pellet passes the last bend in the guide tube, or the pellet must be made stronger to survive the increased forces higher velocities create.

Previously Parks and Perkins [3,4] have proposed a novel concept to accelerate DT-ice pellets using microwave power from MW gyrotrons. By absorbing the microwave power in a composite “pusher” medium consisting of a pure deuterium slug seeded with low-Z metallic particles such as Li, Be or C. The pusher is attached to the backside of the pellet, so that a high-pressure “propellant” gas cloud will be developed in the enclosed space between the pellet and the window, which drives the pellet down the straight waveguide/launch tube. This gas boost is created in the last ~1 m straight guide tube section after the last bend. A bench scale experiment was carried to validate the wave absorption model derived in Ref. [3], albeit without significant heating. Our surrogate pusher sample consisted of a solid paraffin slug seeded with 1–2 micron zinc powders. The sample was inserted into a 4 mm diameter section of a cylindrical waveguide, and the losses of a low power (milliwatts) 110 GHz TE_{01} wave after passage through the sample were measured. The absorption coefficients inferred from the measurements were found to be in good agreement with theory predictions [3], and furthermore it was demonstrated that for a constant number of particles in the sample, the power absorption remains constant, also in accord with predictions of theory. The next test is to heat a sample of naphthalene seeded with 1–2 micron nickel powder. For this test, a 500 kW pulse from a 110 GHz gyrotron will be pulsed into a naphthalene slug 4 mm diameter, 25 mm long for 1–2 ms. The pressure and temperature of the generated gas will be measured and compared to theory.

Technologies developed in the production of fuel pellets used in Inertial Confinement Fusion can be applied to increase the strength of the ITER ice pellets. The technologies evaluated can either encapsulate the pellet inside a solid shell of either metal or plastic, or can stiffen the ice by integrating it into a plastic foam sphere, where the foam acts like the strands of fiber-glass used to strengthen resin-based composites. The evaluation shows that surprisingly, the shells or foam spheres only need to be 2% of the volume of the original pellet in order to gain an order of magnitude increase in strength. Analysis indicates a plastic shell will increase the strength of a DT Ice pellet by a factor of 100.

2. Pedestal Penetration Model

Even though high field side fueling of ITER is more effective at fueling, than low field side fueling [5], it is critical to get most of the ice pellet past the pedestal region, because the material ablated from the pellet as it travels through the pedestal can either trigger an ELM or can be swept away to the divertor and does not contribute to plasma fueling. Using the pellet ablation model described in [6] a formula can be derived that relates the mass fraction M_f / M_0 of remaining in a DT cylindrical pellet (with pellet diameter equal to length) after it penetrates through the pedestal to the pellet velocity V_{pell}, namely:

$$V_{pell} = \left[\frac{0.028}{1-\left(M_f / M_0\right)^{5/9}}\right] \Delta_{ped} \left(\frac{T_{ped}}{d}\right)^{5/3} n_{e14}^{1/3} \quad .$$

where d(mm) = initial cylinder pellet diameter, n_{e14} = density (units 10^{14} cm^{-3}), T_{ped} (keV) = temperature at top of pedestal, and Δ_{ped} (cm) = pedestal width. Consider for example a 6 mm pellet injected into ITER from the HFS *mid-plane* launch position, where pedestal parameters expected for high performance ITER plasmas are given by: T_{ped} = 5 keV, n_{e14} = 0.7, and Δ_{ped} = 12 cm [7]. Figure 1 plots the mass fraction of the pellet that penetrates past the pedestal as a function pellet velocity.

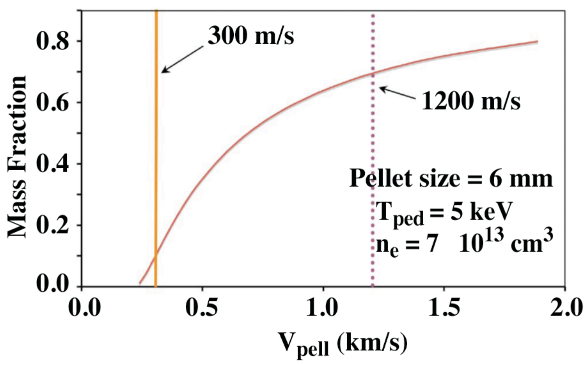

Fig. 1. Plot of the pellet mass fraction that survives past the pedestal in ITER as a function of pellet velocity, for typical ITER parameters of d = 6 mm, T_{ped} = 5 keV, n_{e14} =0.7, and Δ_{ped} = 12 cm.

As can be seen at a pellet velocity of 300 m/s only 10% of the mass survives past the pedestal, but if the velocity is increased by a factor of four to 1.2 km/s, then 70% of the mass survives the transit through the pedestal. By having most of the pellet mass fully ablated beyond the pedestal, deeper fueling realized by means of the grad-B drift of the ablated and ionized pellet material [8,9] becomes more effective. The dependence of pellet velocity on fuel deposition profile, including the grad-B drift effect, will be presented in a subsequent paper.

3. Gyrotron Pellet Accelerator

The basic concept of the Gyrotron Pellet Accelerator (GPA) is that a poor or low microwave absorbing material, such as D ice, can be transformed into a highly efficient microwave absorber by seeding the material with metal dust (~1-2 microns) [3]. The metal dust is heated by magnetic induction, and transfers this absorbed microwave energy to the surrounding host atoms by collisional conduction. By controlling the metal selection, the size of the dust particles, and the concentration of the dust in the medium, the slug of GPA pusher material can be custom tailored to meet the requirements of the specific application, such as ITER. A graphic illustrating the concept of the GPA is shown in Fig. 2. An essential essence of the GPA is that as long as the microwave power is applied to the pusher medium, energy is transferred to the evaporated pusher gas, heating it, and thus creating an increased burst of pressure, even as the gas is expanding because of the increase in volume created by the transit of the DT ice pellet along the launch tube. The optimization of this concept occurs when the absorption of the microwave power on the pusher medium is almost unity for a single pass (even though a reflector placed between the pusher medium and the DT pellet would allow a second pass absorption possibility).

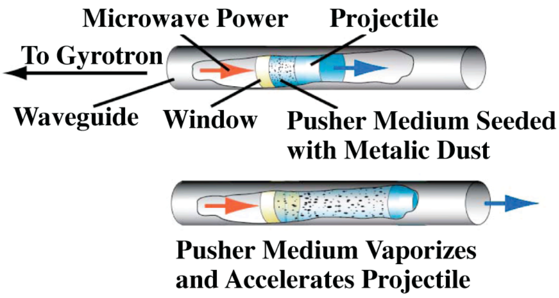

Fig. 2. Illustration of the GPA concept showing microwave power, generated by a gyrotron, entering through a window in a waveguide, heating a pusher medium seeded with metal dust. The absorbed microwave energy vaporizes the pusher medium and accelerates the fuel pellet out of the open end of the waveguide into the plasma chamber.

There are several factors that must be considered when designing a GPA system, pellet diameter, launch tube length, desired pellet exit velocity, and allowable pusher and metal seed materials. This puts a limit on either the volume of the pusher slug, or the density of suspended particles within the pusher matrix. Another limitation is the peak temperature that the metal dust reaches when its microwave energy absorption is balanced by conduction to the pusher gas. If the dust particle temperature gets too high, either the dust particles evaporate and cease to absorb energy, or the particles fuse together making macro clumps, which are also poorer microwave absorbers. By properly selecting the fraction of the pusher medium that is metal dust, the diameter of the dust particles, and the power and frequency of the microwave source, the dust temperature and thus the pusher gas pressure can be optimized.

Owing to the high cost of designing and installing a GPA system on a tokamak, which would require developing a system that could make metal dust-infused D ice in conjunction with a D ice pellet, it was determined that some of the key characteristics should be validated in a more benign laboratory setting using surrogates for the D ice pusher medium. The first test was to demonstrate that as the pusher medium expands as the accelerated pellet travels out of the launch tube, the microwave absorption does not decrease. To test this hypothesis, paraffin wax was used as the pusher medium surrogate and Zn powder (1–2 micron spheres) was used as the microwave absorbing material. Several different mixtures of Zn powder and paraffin were produced (volume fraction of Zn being 0.03, 0.015, 0.010, 0.0075, 0.006, 0.005), a section of a 4 mm waveguide was loaded with each mixture, with the length of the cylinder of the paraffin mixture adjusted so that the total amount of Zn powder was the same in each sample. Tests of these samples proved that the absorption of microwaves was independent of the length of the sample and only dependent on the quantity of absorbing material. Results of these tests are shown in Fig. 3.

The next test is to validate the efficiency of transferring energy from the heated metal dust to the surrounding surrogate pusher medium. This test will use a 4 mm diameter waveguide filled with naphthalene seeded with different concentrations of Nickel powder (1–2 micron). The microwave power will be from a 110 GHz, 1 MW gyrotron operated at a 500 kW level. It is expected that a 1 to 2 ms pulse will evaporate the naphthalene and produce a pressure of 25 atm.

4. Pellet Encapsulation

To determine the benefits of strengthening DT ice pellets using encapsulation techniques developed for the Inertial Fusion Energy program, a set of six types of spherical pellets were compared using ANSYS FEA calculations of a load applied to the edge of the capsules. This gives a relative indication of the survivability of the different types of capsules to the rigors of injection.

The six types of pellets are shown in Fig. 4. They are (A) an all DT sphere (used as the basis for comparison), (B) a polymer foam sphere filled with DT, (C) a polymer foam spherc-al shell filled with DT, both in the foam pores and the interior of the shell, (D) a thinner walled version of the previous case, (E) a solid polymer spherical shell filled with DT, and (F) a solid beryllium spherical shell filled with DT. All capsules had an outer diameter of 5 mm, and their material properties were taken for 6 K. The density and or dimensions of the shell and foams were chosen so that the D or T atoms comprised 95 at. % of the pellet total atom content. The polymer materials were assumed to be fully deuterated, that is only containing C and D atoms. The polymer composition was assumed to be equimolar carbon and deuterium. This is the case for polystyrene (PS), poly-alpha-methyl styrene (PAMS), divinyl benzene (DVB), and close to the case for glow discharge polymer (GDP). Shells (capsules) have been made of all of these materials and other materials as well. A picture of three typical polymer shells is shown in Fig. 5. By choosing shell composition that only consists of material already in ITER (C or Be), and that the shells will ablate first at the very edge of the plasma, that the overall impact on the impurity content of the plasma should be small. The Zeff of the ITER plasma is expected to be in the range of 1.2 to 1.6. If all of the carbon was to be proportionally deposited along with the fuel then the fueling Zeff would be 1.12. However since the shell will ablate at the edge of the plasma it seems unlikely there would be a major affect on Zeff. If carbon is found to be a concern, the shells can be made from Berylium (lower Z), but with a slight decrease in pellet ruggedness (as shown below).

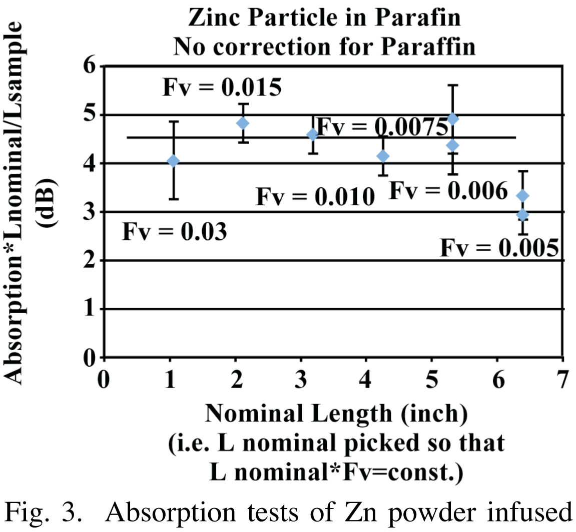

Fig. 3. Absorption tests of Zn powder infused paraffin for volume fractions of 0.03, 0.015, 0.010, 0.0075, 0.006, and 0.005. The lengths of the samples were adjusted to keep the total quantity of Zn powder a constant. The measured adsorption was an approximately constant value of 4.5 dB.

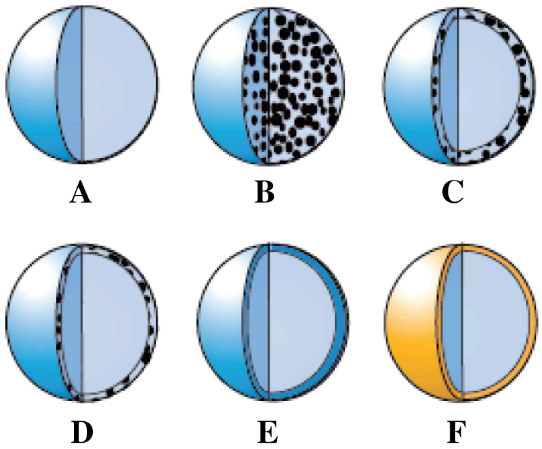

Fig. 4. Pellets analyzed are (A) an all DT sphere, (B) a polymer foam sphere filled with DT, (C) a polymer foam spherical shell filled with DT, filled with DT both in the foam pores and the interior of the shell, (D) a thinner walled version of the previous case, (E) a solid polymer spherical shell filled with DT, (F) and a solid beryllium spherical shell filled with DT.

Fig. 5. Three shells: Left, a 4 mm diameter Poly alpha methyl styrene (PAMS) shell with a wall thickness of ~35 micron; Center, 5 mm diameter Glow Discharge Polymer (GDP) shell with wall thickness of ~20 micron (composition ~CH1.2); Right, a 4 mm diameter Divinyl Benzene (DVB) foam shell with wall thickness of ~260 micron and open cell size of ~1 micron.

The load case used in the FEA analysis is meant to somewhat approximate to a capsule bouncing into a tube/barrel wall, see Fig. 6. When a spherical object has impacted a tube wall on a bounce, it makes contact with the tube along a hemi-circle. To mimic this in a load case, we impose a zero displacement condition along a hemi-circle on the capsule, see Fig. 7. To mimic the sudden stop, an inertial load of 10,000m/s^2 is also imposed on the capsule. This is an arbitrarily picked value since we are comparing the pellets to each other. An inertial load also folds in the effect of the different densities of the pellet types.

Yield strength-to-stress ratios were calculated for the pellets. The stress was taken as either the stress at the south pole of the pellet [point (b), Fig. 7], or the maximum stress found in the YZ plane, Fig. 7. Higher stress is found in the capsules at points (a) and (c), Fig. 7. These are ignored as being artificially high, since in reality at these points the capsule surface would be virtually free to slide down the face of the tube.

The yield strength-to-stress ratios, normalized to pure DT ice, are shown in Fig. 8. All options to pure DT improve (increased) the ratio. From the results, polymer capsules are expected to perform the best, followed by beryllium capsules, foam capsules, and finally polymer foam sphere. The results indicate that there will be an optimum thickness and density to make the foam shell. If the inertial load is proportional to the centrifugal force, then the plastic or foam shells should support a velocity 9 to 10 times higher than presently achievable with DT ice alone. Theoretically, a velocity of 3 km/s should be possible.

The material properties for the DT were taken from Souers [8]. DT density was taken as DT triple point fluid density. The justification for this is that pellets are assumed to be filled as liquid and then cooled without further addition of DT. This means that there will be a small fraction of void (e.g. bubbles) in the solid DT. The DT yield and modulus were taken from D2 properties, also from Souers, at a temperature scaled by triple point temperature ratio [i.e., Yield_DT(T)=Yield_D2(T*Ttriple_D2/Ttriple_DT)].

Since a particular polymer has not been selected, solid polymer properties at 6 K were taken from within the range of values found in the figures of Ref. [10], which gives temperature dependence of properties for several polymers. The polymer density was taken as 1000 kg/m^3, similar to many polymers (e.g., polystyrene is ~1030 kg/m^3).

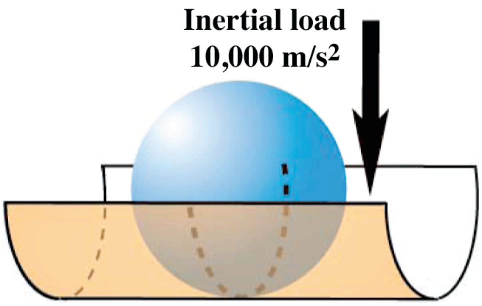

Fig. 6. A spherical pellet will form a line contact when bouncing down a tube or barrel.

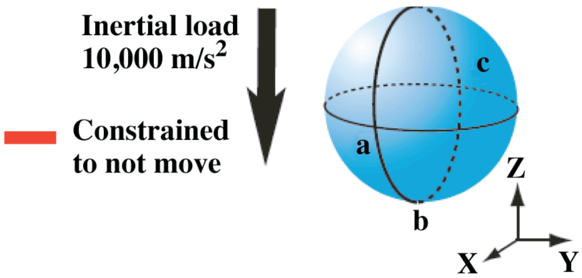

Fig. 7. In FEA analysis the line contact (a,b,c) of the pellet was constrained not to move, and an inertial load of 10,000 m/s^2 was applied to the pellet. The origin of the coordinate system is at the center of the pellet prior to loading.

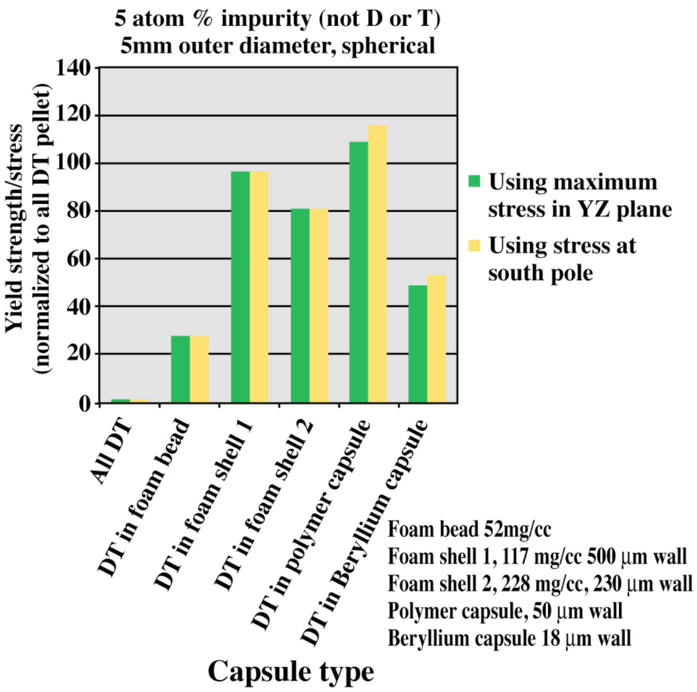

Fig. 8. Adding foam, foam shells, or solid outer shells to DT pellet substantially improve the yield strength-to-stress ratio of the pellet. In the case of solid shells or foam shells, the yield strength is taken as that of the solid shell or foam shell/DT composite.

Polymer foam properties were scaled from solid polymer using density. Yield strength was scaled linearly with density [11]. Elastic modulus was scaled with the square of the density [12]. Poisson's ratio was not changed.

Beryllium properties were taken at room temperature properties. Elastic modulus was taken as given for hot isostatically pressed block [13]. Yield strength was taken from data gathered at LLNL on sputtered deposited beryllium capsules [14]. This is only 65% of the bulk value for hot pressed block, but represents the capabilities in beryllium capsule production approximately three years ago. More recent, improved sputter deposition protocols have not been tested for strength (improvement has been achieving closer to solid density, reduction in leak rate/permeation, oxygen impurity reduction, and more random grain structure). Sputter deposition is the method that is used to make thin walled beryllium shells for ICF targets.

5. Conclusions

Two methods of increasing the velocity of a DT ice pellet for fueling ITER have been identified. One is to use microwave power to heat a pusher gas during the last meter of the inside launch guide tube. Low power bench tests confirmed one essential premise of this concept in that the microwave energy will be absorbed uniformly as the gas expands behind the accelerating ice pellet. The second concept is to reinforce the ice pellets with plastic or metal shells so that they can withstand the large centrifugal forces that higher velocities create as the pellet traverses through the curved guide tube. Velocities as high as 3 km/s are predicted to be achievable. More testing is planned to further validate these concepts. Since the shells are made only from atomic constituents already found in ITER (C or Be), it is expected that the low percentage of impurities introduced by the shells will be acceptable owing to the increased fueling efficiencies that the shelled DT ice pellets have to offer.

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