Pellet Fueling of ITER Burning Plasmas*

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\textbf{Abstract—}Pellet injection is the primary technique planned for fueling of ITER burning plasmas. Efficient fueling with D-T is a requirement for achieving high fusion gain and it cannot be achieved with gas fueling alone. 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. Modeling of the fueling deposition from inner wall pellet injection using the Parks ExB drift model indicates that pellets have the capability to fuel well inside the separatrix. Gas fueling calculations show very poor fueling efficiency due to the high density and wide scrape off layer. Isotopically mixed D-T pellets can provide efficient tritium fueling that will minimize tritium wall loading when compared to gas puffing.

\textbf{Keywords—}pellet; fueling; ITER

\section{I. INTRODUCTION}

Pellet injection has been successfully used to fuel present day tokamaks \cite{1} and is the primary fueling technique planned for fueling of ITER burning plasmas \cite{2}. Injection of pellets from the inner wall has been shown on tokamaks to provide efficient fueling and is planned for use on ITER \cite{3,4}. Isotopically mixed D-T pellets can provide efficient tritium fueling that will minimize tritium wall loading when compared to gas puffing. Details of the ITER pellet injection requirements and planned pellet injection system are presented in the following section.

A model for the pellet mass deposition based on ExB drift of the pellet cloud has been developed and used to compare with inner wall pellet injection experimental results from DIII-D \cite{5}. The ExB drift model is used here to predict the pellet fueling effectiveness in ITER burning plasmas. Comparison of inner wall pellet fueling is made with gas fueling calculations in Section III. The scaling of the modeled mass deposition for ITER is discussed from Section IV. Further use of pellets injected from different locations in ITER as an ELM trigger with minimal fueling is discussed in Section IV.

\section{II. ITER PELLET INJECTION}

The fueling requirements for ITER have been specified by the design team and are documented in the ITER technical documentation \cite{2}. The pellet injection system initially is to consist of two pellet injectors, each of which has the capabilities listed in Table 1. Two pellet sizes are specified, a small nominal 3mm size (cylinder of equal length and diameter) to produce small edge perturbations and a medium 5mm size for deeper core fueling. These pellet sizes correspond to density perturbations of 1\% and 7\% respectively for the burning plasma conditions expected in ITER. The size and throughput specifications take into account an expected 10\%-25\% loss of pellet mass due to the acceleration and transport process. Both the throughput and duration requirements are well beyond what has been produced for existing experimental machines and thus further R&D will be required to produce the ITER pellet injection system.

| Plasma Density ($n_{\text{ion}}$) | $0.4 - 1 \times 10^{21}$ m$^{-3}$ |
| Fuel Isotope | $D_2$, $DT$ ($80\%T/20\%D$) |
| 3-5 mm diam => $1.25 - 6 \times 10^{21}$ atoms | $\Delta n/n \approx 1.3\%-6.6\%$ |
| Gas Fueling Rate (Pa-m$^3$/s) | $\text{Up to 400} \times \text{(800 torr-L/s)}$ |
| Pellet Fueling Rate (Pa-m$^3$/s) | $100 \times D_2$, $DT$ ($\approx 800 \text{ torr-L/s}$) |
| Pulse length (s) | $50 \times T_1$ ($\approx 400 \text{ torr-L/s}$) |
| Pulse length (s) | Up to 3000 |

Table 1. ITER pellet fueling requirements.

Operation of ITER at high density near the empirical density limit is necessary to maximize the fusion Q performance \cite{6}. The electron density profile is expected to be fairly flat in ITER as the fueling source is not anticipated to reach the magnetic axis and a modest Ware pinch is expected due to a low loop voltage. A fairly high pedestal electron temperature between 2-4 keV is expected, which will limit the

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1}
\caption{ITER cross section showing the proposed pellet injection trajectories for inner wall fueling and low field side edge perturbations.}
\end{figure}

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penetration depth of injected pellets since the ablation rate is a
strong function of $T_e$. Injection from the inner wall is planned
as shown in Fig. 1. A curved guide tube will be employed to
transport the pellets to the inner wall. Tests on a mockup of
this tube has shown that pellets of the prescribed ITER size
can survive intact up to speeds of 300 m/s [7]. Repetitive
pellet injection though the guide tube will lead to a pressurized
tube due to the pellet erosion and low conductance of the tube.
Pellets traveling through the mockup at 100 torr were found to
still survive intact, but were slowed down about 10% from
their original speed [7].

III. PELLET MODELING

The pellet mass from inner wall injection is observed to be
deposited well beyond the depth reached by the ablating pellet
as determined by duration of the $D_{\alpha}$ light emission and from
new fast camera images. The pellet mass deposition profiles
measured by Thomson scattering have been compared to those
modeled using the numerically solved Pressure Relaxation
Lagrangian (PRL) model [5] coupled to the PELLET ablation
code [8]. In this model the ablation cloud becomes separated
from the pellet and drifts across the field lines due to its
polarization and associated ExB force in the curved toroidal
magnetic field. New features added to the PRL model include
curvature drive from parallel flows, self-consistent plasma
pressure profiles, and magnetic shear induced mass shedding.
With these new effects included, the modeled deposition
profiles are in reasonable agreement with DIII-D experiments
from both inner wall and outside midplane injection [5].

The proposed pellet fueling scenario for ITER has been
modeled using the PRL code with realistic pellet sizes and
speeds. The plasma conditions assumed in the modeling are a
central electron temperature of 20 keV with an edge pedestal
temperature of 4 keV and a pedestal width of 4% of the minor
radius. The modeling shows that inside launched pellets of
3mm and 5mm size with speeds of 300 m/s, that is limited by
the curved guiding tube [7], have the capabilities to fuel well
inside the separatrix as shown in Fig. 2. While not reaching the
plasma center, the inner wall pellets of modest size can be
expected to provide a significant level of fueling [9].

The edge pedestal temperature is expected to affect the
penetration depth of the pellet and also the amount of ExB
mass drift that can be expected. A set of PRL code runs was
done for different pedestal temperatures with everything else
held constant to see how strong the pedestal will affect the
mass deposition. The results of this for 6mm size pellets
injected from the inner wall at 300 m/s is shown in Fig. 3. The
higher pedestal temperature conditions actually promote more
ExB drift and lead to a deeper density perturbation from the
pellet, but more of the pellet mass ends up near the plasma
drive. Thus a high edge pedestal temperature will lead to
stronger edge fueling. Thus very high edge pedestal
temperatures will be a challenge for the pellet to fuel beyond
the region of the plasma affected by edge localized modes
(ELMs).

The expected fueling efficiency for ITER burning plasmas
from gas puffing is much less than 1% [7,8] due to the wide
dense scrape off layer, while that calculated from inner wall
pellet injection approaches 100%. Outside midplane pellet
injection on ITER has also been modeled for ITER and was
found to have significant drift of the pellet mass outside the
separatrix and thus a fueling efficiency less than 10%. However,
such pellets may be useful for triggering ELMs to limit the heat
flux to the divertor [9].

The expected source fueling profile on ITER from gas
fueling has been calculated and shown to have very limited
neutral penetration compared to present day tokamak
experiments [9,10]. This implies that gas puffing and recycling
will have a very limited ability to fuel the ITER core in the
burning plasma scenario. The scrape off layer (SOL) plasma
screens the core plasma from the puffed and recycled neutrals.
It is clear from this result that a core fueling source other than
gas and neutral beam injection, which is limited by the power
level and high neutral energy to a few torr-L/s fueling rate, will
be needed to reach and maintain high density operation and
provide efficient tritium fueling in ITER. The gas puffing in

Fig. 2  Calculated deposition profiles from the PRL code for
ITER 3 and 5 mm pellets injected from the inner wall for 20 keV
central and 4 keV pedestal electron temperatures.

Fig. 3  Calculated deposition profiles from the PRL code for ITER 6
mm pellets injected from the inner wall and outer wall for 20 keV
central and different pedestal electron temperatures.

- $T_{\text{ped}} = 1$ keV
- $T_{\text{ped}} = 2$ keV
- $T_{\text{ped}} = 4$ keV
ITER will therefore predominantly be a tool for controlling the SOL and divertor plasma density rather than controlling the core plasma density.

A comparison of the calculated ITER fueling rates for inner wall pellet injection, low field side (LFS) pellet injection, and gas puffing are shown in Fig. 3. The low field side pellet injection calculation in this case does not include the ExB drift effect which would predict that nearly the entire pellet mass is ejected from the plasma. The pellet fueling rates calculated assume that the maximum pellet repetition rate is used.

IV. SCALING OF PELLET MASS DEPOSITION

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 important parameters that were varied for the set of runs was the magnetic field B, the central electron temperature \( T_{\text{e0}} \), the edge pedestal electron temperature \( T_{\text{eped}} \), the size of the pellet given by equivalent spherical radius \( r_p \), and the edge safety factor value \( q_e \). The central safety factor \( q_0 \) was held constant at 1 and the profile was given by the equation \( q(r) = q_0 + (q_e-q_0) (r/a)^4 \). The drift distance of the pellet mass was determined from the position in the plasma where the calculated density perturbation from the pellet reached 20% of its maximum value.

The results from this analysis yields a drift distance \( D \) that scales as \( B^{-0.15} \times T_{\text{e0}}^{-0.13} \times T_{\text{eped}}^{0.5} \times r_p^{0.76} \times q_e^{-0.15} \). The inverse edge \( q \) and central temperature dependence agrees with that obtained from the DIII-D pellet injection experimental database [11]. The fairly strong edge pedestal scaling is encouraging for a high pedestal temperature, but the pellet penetration will be reduced thus making a larger pellet required in order to get mass into the pedestal where it can drift further inward. Additional data is needed from multiple experiments to compare with the model scaling in order to have more confidence in the predictions from this model.

V. ELM TRIGGERING

Pellets injected into H-mode plasmas have been observed to trigger ELMs in a number of experimental devices and from different injection locations. It was observed on DIII-D that pellets injected from the LFS produced larger ELMs of longer duration [11] presumably from the ability to more easily exceed the ballooning limit by pellet clouds at that location. Thus it is assumed that smaller pellets with shallower penetration can trigger ELMs from the LFS location than from the inner wall.

The triggering of rapid ELMs in order to minimize the ELM size and thus reduce the peak heat load on the divertor has been proposed and tested initially on ASDEX-U [12]. ITER may also use this technique using the LFS trajectory shown in Fig. 1, or a trajectory similar to it. The pellet penetration and deposition from the 3mm pellet size from the LFS is shown in Fig. 3. This figure shows the fueling rate for the LFS pellets assuming all the mass is retained, but with the ExB drift included only a small percentage will be retained by the plasma. Thus it seems likely that small LFS pellets will not significantly fuel the plasma and thus a reduction in plasma thermal confinement from strong edge fueling can be avoided. Much more research needs to be done to understand the ELM triggering mechanism by pellets and its extrapolation to ITER operating conditions.

VI. SUMMARY

Pellet injection into tokamak plasmas from the inner wall has demonstrated deeper fueling than from vertical or outside midplane locations, even at much lower pellet speeds. The difference in fuel deposition has been successfully modeled by taking into account VB and curvature induced ExB drifts of the pellet clouds. When using this model for ITER we show fuel deposition well beyond the scrape off layer for inner wall injected pellets and this scheme looks promising for providing sufficient fueling to operate ITER at high density. ELMs triggered from frequent small injected pellets may prove to be a useful means to limit the ELM magnitude and will be the topic of future investigations.

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