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Physics of Plasmas

Pellet fueling technology development leading to efficient fueling of ITER burning plasmas *

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Pellet injection is the primary fueling technique planned for core fueling of ITER [ITER Technical Basis 2002 ITER EDA Documentation Series (Vienna: IAEA)] burning plasmas. Efficient core plasma fueling with deuterium and tritium (D-T) is a requirement for achieving high fusion gain and it cannot be achieved with gas fueling. 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 neutral penetration 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. Currently the performance of the ITER inner wall guide tube design is under test with initial results indicating that pellets speeds in excess of 300 m/s will lead to fragmented pellets. The ITER pellet injection technology requirements and remaining development issues are discussed along with a plan to reach the design goal for employment on ITER.

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1. INTRODUCTION

Pellet injection systems using frozen millimeter size pellets composed of the isotopes of hydrogen have been used to explore the fueling of fusion plasmas for nearly 30 years [1]. These systems operate at very low temperatures (~10K) at which hydrogen ice can be formed and sustained. Most injectors use pneumatic (light gas gun) or centrifuge (mechanical) acceleration techniques to achieve pellets speeds of 200-2000 m/s. The pellets are typically transported to the plasma through metal guide tubes that end at the plasma chamber wall. There they transport across the confining magnetic fields and enter the plasma where they ablate and add fuel particles to the plasma.

Pellet injection has demonstrated efficient core plasma fueling in a number of current tokamaks [2] and is the primary fueling technique planned for core fueling of the ITER burning plasma [3]. Efficient core fueling with D-T is a requirement for achieving high fusion gain and it cannot be achieved in ITER with gas fueling alone. Experiments on present day tokamaks have shown that injection of pellets from the inner wall provides efficient fueling [4,5] and is therefore planned to be implemented on ITER. Significant development of pellet fueling technology has occurred in the last 10 years as a result of the ITER R&D process. Ice production for pellet formation in extruders has reached rates of more than 1/2 of the ITER design specification of 1.5 cm^3/s [6] and the formation and acceleration of T_2 and D-T pellets of the required ITER size has been demonstrated in the laboratory.

A significant amount of theoretical and experimental work has been undertaken to gain understanding of the process involved in the fuel deposition from inner wall pellet injection. The basic model that has been developed to explain the process is an ExB radial drift resulting from a polarization of the pellet cloud from ∇B and curvature drifts as first proposed by Rozhansky [7] and further developed by Parks [8]. The application of this model to ITER is presented here and is shown to lead to significant fueling beyond the ITER separatrix with technologically feasible pellet sizes and speeds. In addition to fueling, the use of pellets as an edge localized mode (ELM) trigger has been demonstrated and continues to be investigated as an ELM amelioration technique for ITER.

In this paper we present model predictions of the level of fueling that is expected from the ITER pellet injection system as currently specified, taking into account the pellet size and speed that can realistically be injected from the inner wall. The current state of ITER gas and pellet fueling requirements are presented in Sec. II. In Sec. III of this paper we describe the current state of modeling the ITER gas and pellet fueling scenarios. In Sec. IV we present the technological developments in pellet injection and how they will be applied to ITER. Finally in Sec. V we discuss the expectations for fueling of ITER and the remaining issues to be further investigated.

II. ITER FUELING REQUIREMENTS

The fueling requirements for ITER have been specified and are documented in the ITER technical documentation [3]. 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 nominally 3mm size (cylinder of equal length and diameter) to produce small edge perturbations and a medium 5mm size for deeper core fueling. The sizes specified are nominal and can vary by +/- 20%. The 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.

Operation of ITER at high density near the empirical density limit is necessary to maximize the fusion Q performance [9,10]. 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 penetration depth of injected pellets since the ablation rate is a strong function of T_e [11].

Pellet injection is anticipated to be the primary source of tritium into the plasma. The highest concentration of tritium in a pellet will be ~90%, which is limited by the purification process in the ITER tritium processing system. The injectors are to be able to make pellets with any fraction of tritium up the full 90% level. The tritium concentration will only be changeable on a several minute time scale, although the two injectors can operate with different tritium fractions to allow some variation during the plasma pulse.

ITER will utilize 33 MW of neutral beam injection (NBI) for plasma heating. The NBI system will produce 1 MeV energetic neutrals generated by a negative ion source. This corresponds to a fueling source of ~$2x10^{20}$ atoms/s or ~3 torr-L/s. This compares with a typical NBI power of 10 MW for DIII-D [12] with 80 keV energetic deuterium neutrals for a source rate of ~$8x10^{20}$ atoms/s or ~ 11 torr-L/s. Considering that the ITER plasma volume is 40 times larger , the NBI fueling source will be negligible compared to

present machines such as DIII-D. Using the neutral beam injectors as a tritium fueling source will clearly not be of much utility on ITER.

III. MODELING

The expected source fueling profile on ITER from gas fueling has been calculated using the B2-Eirene code in slab geometry [13]. B2-Eirene contains a coupled two-dimensional fluid model for the electrons and ions (B2) and a two-dimensional Monte Carlo model for atoms and molecules (Eirene). The plasma is assumed to consist of electrons and ions from D, He, and C. All the ions have the same temperature which can be different from the electron temperature. A slab geometry is used in the calculations for DIII-D and ITER with measured scrape off layer (SOL) parameters used for DIII-D and assumed parameters used for ITER [14].

Results of these gas fueling rate calculations are shown in Fig. 1 comparing a DIII-D ELMing H-mode case and the ITER burning plasma scenario for gas flow rates of 100 and 1000 torr-L/s respectively (12 and 120 Pa-m^3/s). The penetration of neutrals in DIII-D is deep enough to produce significant edge fueling and indeed experimentally it is observed that the plasma density can be increased fairly easily with gas puffing [15]. The ITER result is however quite different. The neutral source rate at the separatrix is expected to be over three orders of magnitude lower. This implies that gas puffing and recycling will have very limited ability to fuel the ITER core in the burning plasma scenario. Similar conclusions have been reached in detailed divertor calculations for ITER [16]. It is clear from this result that a core fueling source other than gas and NBI will be needed to reach and maintain high density operation in ITER. The scrape off layer (SOL) plasma screens the core plasmas from the puffed and recycled neutrals. The gas

puff fueling will therefore be a means of controlling the SOL and divertor plasma density rather than controlling the core plasma density.

Pellet injection from the inner wall has been selected as the ITER core fueling source based on successful experimental results on current machines [4,5]. An effort to better understand and predict the pellet fueling deposition process has been underway since the initial inner wall pellet injection results. The mechanism that has been the most successful at explaining the major radius mass drift that occurs with pellet injection in tokamaks is an ExB drift driven by a polarization in the pellet cloud that occurs from ∇B and curvature particle drifts [8,17]. When a pellet enters the plasma, a relatively high-pressure ionized ablation cloud forms near the pellet. Electron heat flux guided by the field lines heats the pellet cloud and drives a primarily axi-symmetric flow. In addition the ablation cloud becomes separated from the pellet and it *E*x*B* drifts across the field lines due to its polarization in the curved toroidal magnetic field. Gas fueling is not expected to benefit from the same mechanism due to the lack of a localized pressure increase and experiments have shown no significant improvement in the inner wall gas fueling efficiency compared to outside gas injection [15].

An extension of the model proposed by Parks [8] has been recently developed that includes curvature drive by parallel flows, plasma profile effects, and shedding from rotational transform of the magnetic field lines [18]. This model has been solved numerically in a code known as pressure relaxation lagrangian (PRL) to solve the coupled drift equations together with the parallel cloudlet dynamics. PRL has been coupled to the pellet ablation code PELLET [19] to get geometry and profile information as well as cloudlet starting parameters. The overall deposition from the pellet is

determined by summing the deposition from 10-20 cloudlets that are launched from evenly spaced pellet locations in the plasma based on the observation of striations in the ablation light from injected pellets [5].

Modeling of the fueling deposition from inner wall pellet injection on DIII-D has been performed using the PRL model. The results give reasonable agreement with both inner wall and outside midplane injection [18]. The same methodology has been applied to ITER using realistic pellet sizes and speeds. A comparison of the fueling profiles from both gas and pellets for DIII-D and ITER are shown in Fig. 2. From this comparison it is clear that the inner wall pellet injection will be crucial to provide a core fueling source for ITER. The modeling also shows that inside launched pellets of 3mm and 5mm size with speeds of 300 m/s have the capabilities to fuel well inside the separatrix as shown in Fig. 3. The results from this model do not project as deep of pellet mass penetration from the drift process as the earlier more simplistic model SMART [20] for the same size pellet and plasma conditions. Nonetheless, the fueling from inner wall pellets of modest size can be expected to provide a significant level of fueling.

The fueling efficiency η, is defined as $\eta = \Delta N_e/N_s$, where ΔN_e is the change in the plasma total electron number and N_s is the particle content from the pellet or gas puff. The expected fueling efficiency for ITER from gas puffing is much less than 1%, while that calculated from inner wall pellet injection approached 100%. Outside midplane pellet injection on ITER has also been modeled and the results are shown in Fig. 3 without including the radial drift effect. It is found with PRL that there is significant drift of the pellet mass to outside the separatrix and thus the outside midplane pellet fueling efficiency is on the order of only 10%.

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The possibility of pellet injection from a pellet injector located inside the central solenoid injecting pellets from the midplane at moderately high speed has been proposed with geometry similar to that shown in Fig. 4 [21]. The potential advantage to an inner bore pellet injector with a straight guide tube to the plasma is that higher velocity pellets can be injected deeper into the plasma. Calculations with PRL for this geometry have been performed assuming a 1 km/s pellet speed that can be obtained in a repetitive fashion from a light gas gun. The results of this injection geometry are compared to slower pellets from an inner wall curved guide tube in Fig. 5. The higher speed pellets do indeed penetrate deeper into the pedestal region; however the peak in the deposition profile from the inward drift is not significantly deeper than for the slower pellet case. The question remains whether the moderately improved fueling depth from this injection concept is worth the many challenging technological difficulties in implementing such a system.

IV. FUELING TECHNOLOGY

The ITER gas fueling system will supply H_2, D_2, T_2, DT, Ar, Ne, and He gas via a gas manifold that extends around the machine. Four gas injectors are planned for the top of the machine and enter at the top outside ports and penetrate the blanket near those ports. Three injectors are planned for the divertor area, nominally near the dome of the divertor. This system will make use of conventional gas handling hardware and will require minimal research and development. The U.S. built and tested a mockup of the ITER gas injection system during the Engineering Design Activities (EDA) and found a time response of nearly 0.2 sec to reach 2/3 of the full gas flow rate in the system [22].

The pellet injection system for ITER has been given functional specifications and a pre-conceptual design that consists of a centrifuge type accelerator with a continuous screw extruder of the type that has been developed by PELIN [23]. An overall block diagram of the pellet injection system specified is shown in Fig. 6. During the EDA period, the pellet injection system was assumed to use multiple batch piston extruders that could produce up to 1.3 cm^3/s of hydrogenic ice. The maximum flow rate from a continuous screw extruder has thus far been ~0.3 cm^3/s and so some development effort will be required to increase this flow rate or possibly use multiple such extruders for each injector.

The centrifuge type pellet accelerator has been under development for more than 30 years [1]. The level of reliability of obtaining full pellets out of the centrifuge rotor has steadily increased and the most recent operational model at the Joint European Torus (JET) [24] employed a stop cylinder built into the centrifuge rotor arm to capture the pellets with high reliability. The ITER centrifuge will likely employ a similar pellet capture rotor design. If the reliability requirement of nearly 100% intact pellets cannot be met with the centrifuge, the option of a light gas gun remains that has been shown to obtain the level of reliability required [23, 25]. The employment of a gas gun on ITER will require the handling of the propellant gas after each pellet, but recent designs have been successful at minimization of the propellant gas to the level to make an ITER light gas gun feasible. Since slow pellets are suitable for ITER inner wall injection, only a modest amount of propellant gas is necessary, thus making the propellant gas handling a very tractable issue. The pellet fueling system for the original ITER design in the early 1990s actually consisted of a moderate speed single stage gun for startup and steady-state burn phase while using a high-speed two-stage gun for achieving ignition [26].

The ITER pellet injection system will be required to produce nearly pure tritium pellets, which will supply the bulk of the tritium injected into the ITER plasmas. Pellet injectors have been operated with tritium as part of the U.S. ITER EDA effort [27]. Extruder experience with T_2 and DT ice, which undergoes tritium beta decay to ^{3}He, showed that relatively high ^{3}He levels of ~1% can be tolerated without problems with ice or pellet integrity. The decay heat in tritium does not prevent pellet formation and the pellets do not rapidly melt. No adverse effects were discovered that would bar the use of tritium in either a centrifuge or pneumatic pellet injector.

Most pellet injectors with high throughput have used liquid helium as a coolant to freeze the hydrogenic supply gases for pellet formation. There are cost and availability issues associated with using liquid helium in a pellet injector. The cost of using liquid helium in laboratory testing can easily reach several thousand dollars per day of operation. When an injector is installed on a plasma device the availability of the liquid helium is often tied to the machine operation schedule thus making off-line testing difficult to schedule. Recently extruders have been tested with closed cycle Gifford McMahon cryocoolers supplying the cooling to reach approximately 10K temperatures. These cryocoolers have the advantage of reliable operation and are relatively small and compact. The disadvantage is a fairly high initial cost of the cryocooler. The extruders for the ITER pellet injector will be designed to employ one or more cryocoolers in order to make testing and operation as independent as possible of liquid helium supplies.

The ITER pellet injectors are to be housed in a cask as shown in Fig. 6, which is a metal box approximately 6.5m x 2.5m x 3.5m tall [3]. The cask will be movable on wheels and rolled into position to the divertor port to connect to the pellet guide tubes

while remaining outside the biological shield. The cask will act as a tritium boundary and thus will require suiting up by personnel to enter the cask for pellet injector maintenance.

During the ITER Conceptual Design Activity (CDA) and EDA the U.S. was responsible for ITER fueling system design and R&D and is in good position to resume this role for the ITER pellet fueling system. Currently the performance of the ITER inner wall guide tube design is under investigation at ORNL. A mockup of the guide tube has been built that allows tests with different pellet sizes and repetition rates. Initial results indicate that pellets in excess of 300 m/s will fracture in the guide tube [28]. At these speeds the pellet mass that is lost in the guide tube by erosion during transport was measured to be up to 10%. Further tests to investigate pellet survival and erosion with high residual pressure in the guide tube, as expected from repetitive operation, is underway.

V. DISCUSSION

ITER will need to operate at high densities for a high fusion yield and inner wall pellet fueling is the only technique currently available to provide that capability. Modeling of the planned ITER fueling scenario looks encouraging for fueling well beyond the pedestal region, even for the relatively slow 300 m/s pellet speeds that have been shown to survive intact in the inner wall guide tube.

From the modeling work presented here it seems unlikely that the pellet mass will directly fuel the magnetic axis. Therefore in order to achieve strongly peaked density profiles a strong inward particle pinch will be required driven by turbulent mechanisms

since the inward Ware pinch will be relatively small due to the low loop voltage expected in ITER.

The smaller size pellets specified for ITER are designed to produce edge perturbations that can trigger edge localized modes (ELMs), which are thought to be a serious issue for survival of the divertor materials. If small ELMs can be triggered at a higher rate than intrinsic ELMs, it may be possible to avoid large catastrophic heat fluxes to the divertor as has been seen recently tested on ASDEX-U [29]. Pellets injected from the tokamak outer wall low field region have been shown to trigger ELMs more readily than inner wall injected pellets, therefore an outer wall guide tube is under consideration for ITER as shown in Fig. 4.

Several issues remain that may affect the ITER operation with pellet fueling. Some of these issues are whether or not pellets will trigger neoclassical tearing modes (NTMs) as the pellet mass drifts across rational surfaces, whether ELMs triggered by pellets can be used to ameliorate ELM destruction of the divertor surfaces, whether alpha particles will have deleterious effects on the ablation of the pellets, and whether any specific diagnostics are needed for determining pellet injection effectiveness.

The pellet injection system for ITER is currently under development. Prototypes of the extruder(s) will be built and tested and also a centrifuge prototype with an integrated pellet capture system will be tested. These protpotypes will likely be available for operational testing on existing tokamak machines to obtain some operational experience. Testing of ELM triggering and amelioration will particularly need to be investigated.

VI. 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. The most detailed theoretical models predict fueling well beyond the pedestal region from pellets injected from the inner wall. Pellets from the inner wall are to be injected through a curved guide tube that will limit their speed to ~300 m/s. Nonetheless, these pellets are predicted to provide fuel penetration beyond the pedestal region even though the pellets themselves will burnout by the time they reach the plasma pedestal. This important result demonstrates a 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.

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REFERENCES

1. S.K. Combs, Rev. Sci. Instrum. **64**, 1679 (1993).

2. S.L. Milora, W. A. Houlberg, L. L. Lengyel, and V. Mertens, Nucl. Fusion **35,** 967 (1995).

3. ITER Technical Basis 2002 ITER EDA Documentation Series (Vienna: IAEA).

4. P.T. Lang, K. Buchl, M. Kaufmann, R. S. Lang, V. Mertens, H. W. Muller, J. Neuhauser, ASDEX Upgrade, and NI Teams, Phys. Rev. Lett. **79**, 1478 (1997).

5. L.R. Baylor, *et al.*, Phys. Plasmas **8** 1878 (2000).

6. S. Combs, A.L. Qualls, C.R. Foust, Rev. Sci. Instrum. **69**, 4012 (1998).

7. V. Rozhansky, I. Veselova, and S. Voskoboynikov, Plasma Phys. Controlled Fusion **37**, 399 (1995).

8. P.B. Parks, W.D. Sessions, L.R. Baylor, Phys. Plasmas **8**, 1968 (2000).

9. ITER Physics Basis, Nucl. Fusion **39,** 2175 (1999).

10. V. Mukhovatov, M. Shimada, *et al*., Plasma Phys. Control. Fusion **45**, A235 (2003).

11. P.B. Parks and R.J. Turnbull, Phys. Fluids **21,** 1735 (1978).

12. J. L. Luxon and L. G. Davis, Fusion Technol. **8**, 441 (1985).

13. D. Reiter, H. Kever, G.H. Wolf, *et al* ., Plasma Phys. Control. Fusion **33**, 1579 (1991).

14. L.W. Owen, R. J. Colchin, R. Maingi, M. E. Fenstermacher, T. N. Carlstrom, R. J. Groebner, J. Nucl. Mater. **290**, 464 (2001).

15. L.R. Baylor, T.C. Jernigan, C.J. Colchin, G.L. Jackson, L.W. Owen, T.W. Petrie, J. Nucl. Mater. **313**, 530 (2003).

16. A.S. Kukushkin and H.D. Pacher, Plasma Phys. Control. Fusion **44**, 931 (2002).

17. V. Rozhansky, I Senichenkov, I Veselova, R Schneider, Plasma Phys. Control. Fusion **46,** 575 (2004).

18. P. B. Parks and L.R. Baylor, submitted to Phys. Rev. Lett.

19. W.A. Houlberg, S.L. Milora, and S.E. Attenberger, Nucl. Fusion **28**, 595 (1988).

20. A.R. Polevoi, M. Shimada, Plasma Phys. Control. Fusion **33**, 1579 (2001).

21. F.W. Perkins, personal communication.

22. M.J. Gouge, K.D.S. Onge, S.L. Milora, P.W. Fisher, S.K. Combs, Fusion Tech. 34 (1998) 435.

23. I. Viniar, *et al*., Symposium on Fusion Technology 2004, to be published in Fus. Eng. Design.

24. M.J. Watson et al., Proceedings of the 18th IEEE/NPSS Symposium on Fusion Engineering, Albuquerque, October 1999 (IEEE Press, Piscataway, NJ, 1999) p. 326.

25. S.K. Combs, T. C. Jernigan, L. R. Baylor, S. L. Milora, C. R. Foust, P. Kupschus, M. Gadeberg, W. Bailey, Rev. Sci. Instrum. **60**, 2697 (1989).

26. M.J. Gouge, et al., Fus. Eng. Design **19**, 53 (1992).

27. P.W. Fisher and M.J. Gouge, Fusion Tech.. **34**, 515 (1998).

28. S. K. Combs, L.R. Baylor, C.R. Foust, D.A. Rasmussen, Symposium on Fusion Technology 2004, to be published in Fus. Eng. Design

29. P.T. Lang *et al.*, Nucl. Fusion **44,** 665 (2004).

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Table I. ITER fueling requirements. n_{GW} is the Greenwald density in 10^{20} m^{-3}, which is defined as the elongation times the average plasma current density in MA/m^2.

PARAMETER	VALUE
Plasma Density <n> (10^{20} m^{-3})	0.5 – 1.2
<n> / n_{GW}	0.4 – 1
Fuel Isotope (Pellet)	D_2, DT, T_2 (90%T/10%D)
Pellet size: 3-5mm diameter cylinder	1.25-6x10^{21} atoms ($\Delta n/n$~1.3-6.6%)
Gas fueling rate (Pa-m^3/s)	Up to 240 (~ 1800 torr-L/s)
Pellet fueling rate (Pa-m^3/s)	100 for D_2, DT (~800 torr-L/s)
	50 for T_2 (~400 torr-L/s)
Plasma duration (s)	Up to 3000

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LIST OF FIGURE CAPTIONS

Fig. 1. Fueling source profiles from gas injection calculated with B2-Eirene for DIII-D ELMing H-mode plasma and ITER steady-state burning plasma scenarios.

Fig. 2. Comparison of pellet fueling and gas fueling source profiles for (a) DIII-D with experimental pellet fueling measurements extrapolated to 3 Hz 2.7mm pellet injection and (b) calculated for ITER using the specified 16 Hz 5mm pellet specification.

Fig. 3. The pellet deposition profile, defined as the change in electron density profile Δn_e, calculated with PRL for ITER with 5mm and 3mm pellet sizes injected from the inner wall guide tube (solid) and from the outside midplane (dashed). The outside injected cases are shown with no radial drift included.

Fig. 4. Cross section of ITER showing the pellet injection locations from the inner wall, the proposed central solenoid injector location, and the proposed low field side location for ELM triggering.

Fig. 5. Deposition profile results from calculations with the PRL code for 5mm pellets injected from the inner bore at 1 km/s and from the inner wall guide tube at 0.3 km/s.

Fig. 6. Block diagram of the proposed pellet injection system for ITER.

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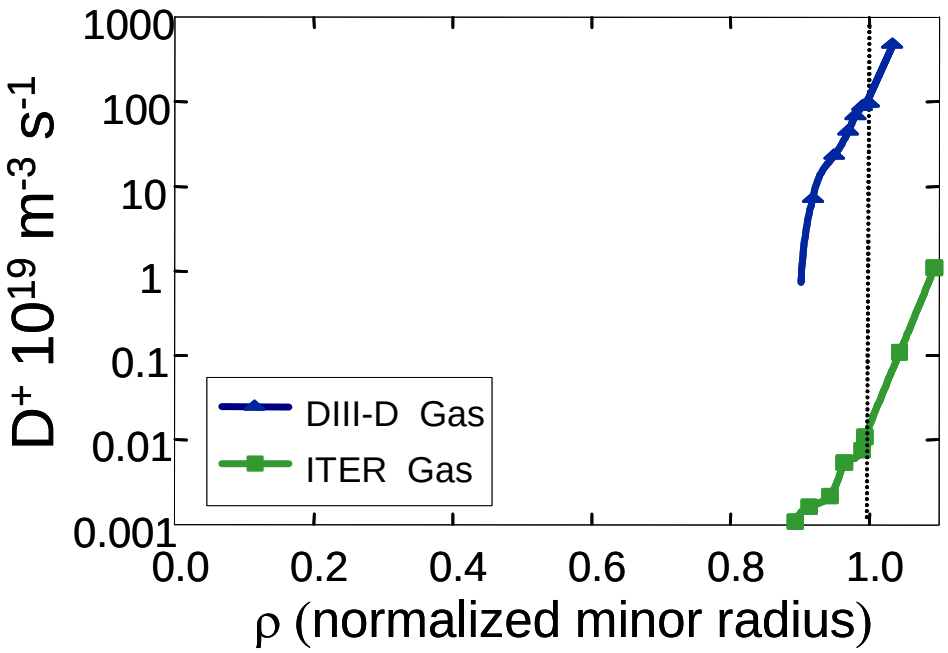
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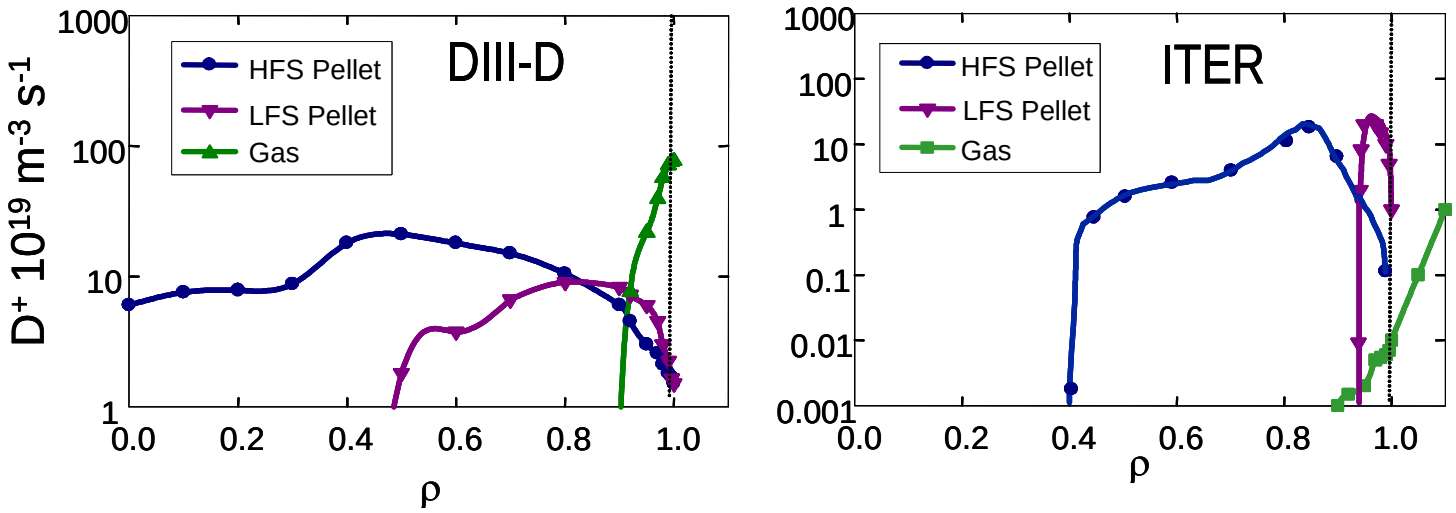
100
10
1
0.1
0.01
0.001
0.0
0.2
0.4
0.6
0.8
1.0
D+ 10^19 m^-3 s^-1
ρ (normalized minor radius)
DIII-D Gas
ITER Gas

Figure 1

18


DIII-D
HFS Pellet
LFS Pellet
Gas
D+ 10^19 m^-3 s^-1
1000
100
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1
0.0
0.2
0.4
0.6
0.8
1.0
ρ
ITER
HFS Pellet
LFS Pellet
Gas
1000
100
10
1
0.1
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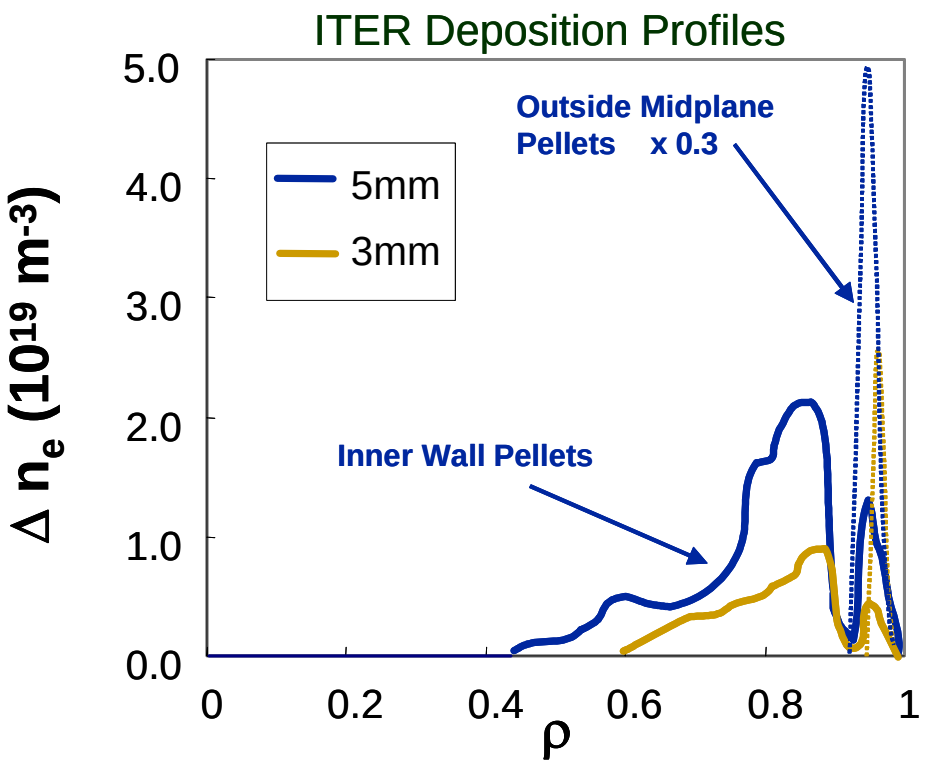
0.001
0.0
0.2
0.4
0.6
0.8
1.0
ρ

Figure 2

19


ITER Deposition Profiles
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4.0
3.0
2.0
1.0
0.0
0
0.2
0.4
0.6
0.8
1
ρ
Δ n_e (10^19 m^-3)
5mm
3mm
Outside Midplane
Pellets x 0.3
Inner Wall Pellets

Figure 3

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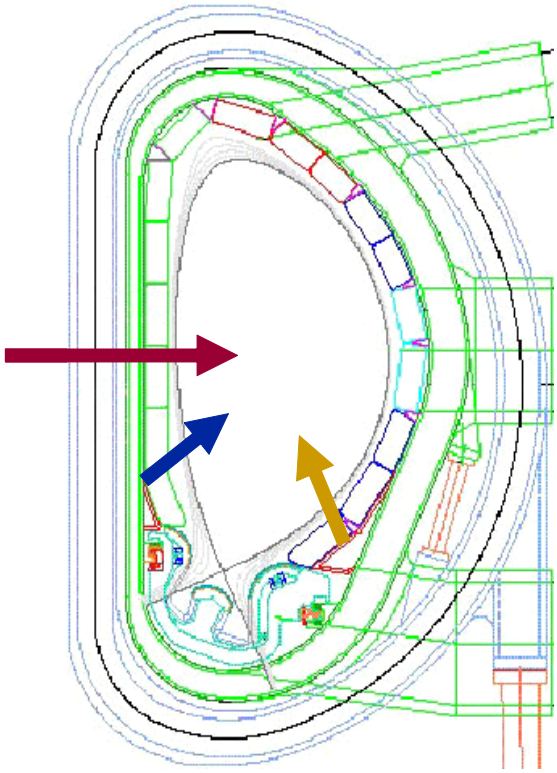

Figure 4

21

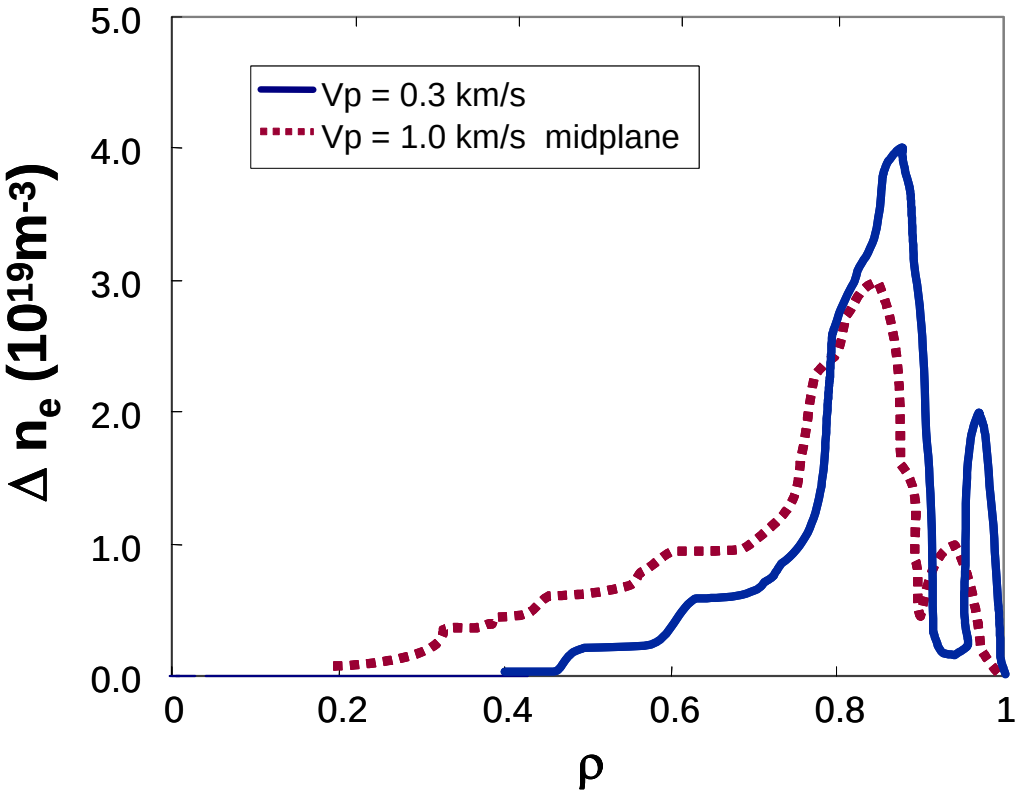
5.0
4.0
3.0
2.0
1.0
0.0
0
0.2
0.4
0.6
0.8
1
ρ
Δ n_e (10^19 m^-3)
Vp = 0.3 km/s
Vp = 1.0 km/s midplane

Figure 5

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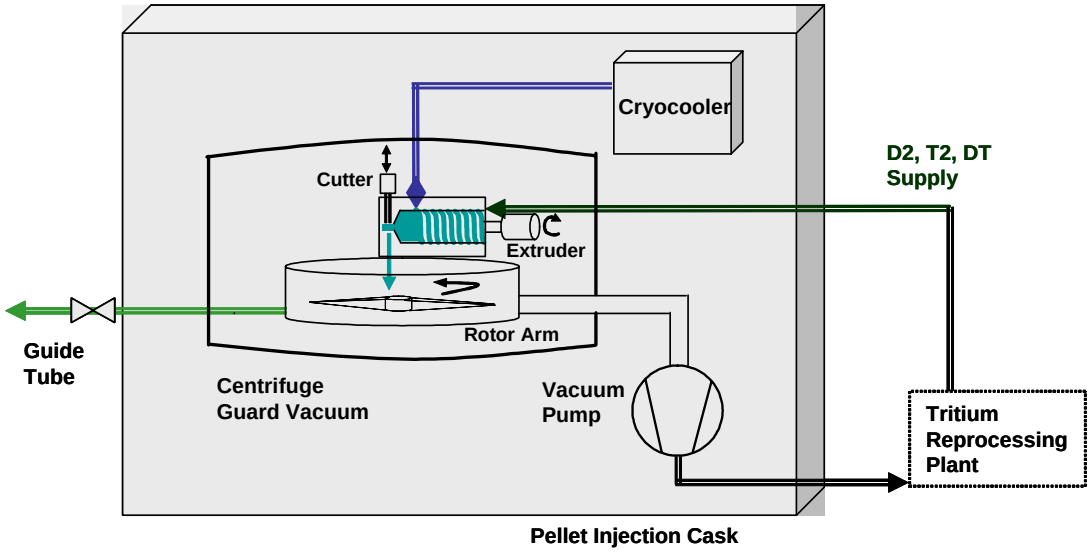
Cryocooler
D2, T2, DT
Supply
Cutter
Extruder
Rotor Arm
Guide
Tube
Centrifuge
Guard Vacuum
Vacuum
Pump
Tritium
Reprocessing
Plant
Pellet Injection Cask

Figure 6

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