FUELING OF ITER-SCALE FUSION PLASMAS

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ABSTRACT

Fueling system functions for the International Thermonuclear Engineering Reactor (ITER) and similar scale devices are to provide hydrogenic fuel to maintain the plasma density profile for a specified fusion power, to replace the deuterium-tritium (D-T) ions consumed in the fusion reaction, to establish a density gradient for plasma particle (especially helium ash) flow to the edge, and also to supply hydrogenic edge fueling for increased scrape off layer flow for optimum divertor operation. An additional function is to inject impurity gases at lower flow rates for divertor plasma radiative cooling, wall conditioning, and for plasma discharge termination on demand. The burn fraction of ITER is about 1% which is over an order of magnitude lower than values typically assumed in fusion reactor studies. This low burn fraction results in large vacuum pumping and fuel processing systems to handle the larger DT throughput. Gas and pellet fueling efficiency data from past tokamak experiments is reviewed; pellet fueling efficiency is significantly larger than that of gas injection. An overview of the current R&D status of gas and pellet fueling technology is presented.

I. INTRODUCTION

The plasma fueling system design for ITER has evolved over the almost ten year Conceptual and Engineering Design Activities period but the basic requirements have remained essentially the same. From the outset, it was a goal to produce a flexible fueling system that would require minimum change in the progression from ITER to a fusion demonstration (DEMO) plant. In the past, tokamaks have generally used gas puffing for establishing and maintaining the plasma density. With this method, the sources of plasma particles are located at the plasma surface. There is general consensus, however, that gas puffing alone may not be sufficient to fuel the next generation of large, long-pulse fusion devices with thick, dense, scrape-off layers, and that core fueling, where the particle sources are located well inside the plasma edge, will be necessary. The ITER fueling system provides D-T plasma fueling at a steady-state rate (200 Pa-m^3/s) to support a fusion power of up to 1.5 GW for continuous duty with the capability for higher transient fueling rates (500 Pa-m^3/s) for density ramp-up during the plasma start-up phase. A pellet injection system (PIS) is provided for core fueling and a gas injection system (GIS) for edge fueling. The fuel rate to replace the D-T ions consumed by the fusion reaction is quite modest, about 2 Pa-m^3/s for a fusion power of 1.5 GW; the resulting burn fraction is thus only 1% of the steady-state fueling rate. Such low burn fractions result in large vacuum pumping and fuel processing systems with associated tritium inventories and were not anticipated in early[1,2] and even more recent[3] fusion power plant assessments, which had burn fractions in the 10-40 % range. The low burn fraction is only partially due to finite fueling efficiency (see next section). The fueling system[4,5] must also maintain the required plasma density (near the empirical Greenwald density limit), establish a density gradient for plasma particle (especially helium ash) flow to the edge, and also supply hydrogenic edge fueling for increased scrape-off layer flow for optimum divertor operation. Still another function is to inject impurity gases at lower flow rates (25 Pa-m^3/s or less) for divertor plasma radiative cooling, wall conditioning, and for plasma discharge termination on demand.

II. FUELING EFFICIENCY

The fueling efficiency of tokamaks has been studied since the early 1980's. For gas fueling, the determination of fueling efficiency of short pulse tokamaks has been difficult to quantify because of an outgassing source of hydrogenic fuel from the plasma facing components that can be of the same magnitude as the external gas fueling. Pellet fueling, a more recent fueling technology, is easier to quantify in terms of fueling efficiency due to the rapid deposition of the fuel (100's of μs) and its deposition beyond the last closed flux surface, which avoids most atomic physics complications in fuel transport to the plasma. In contemporary tokamaks, fueling provides the required density level for a particular plasma experiment. For ITER and fusion power plants, the fueling system has to provide D-T plasma fueling for pulse lengths in the range of ~1000 s to steady state. There is much incentive to maximize the D-T plasma fueling efficiency due to the

cost and safety implications of a large tritium throughput and the complexity of reprocessing large torus exhaust gas loads[6].

A. Fueling Efficiency of Gas Injection

Fueling efficiency was studied in the early 1980's in ASDEX[7] and PDX[8]. Fueling efficiency is generally defined as the probability that an injected neutral atom (one half a molecule) will cross the last confined flux surface and enter the confined plasma in one attempt. In ASDEX[7], the gas fueling efficiency was close to 100% for limiter discharges at lower density and decreased to about 20% for high density (6 x 10^{19} m^{-3} line average), diverted discharges. A similar pattern was measured on diverted PDX plasmas, where a fueling efficiency of about 50% was noted at lower density (1 x 10^{19} m^{-3} line average), and this was reduced to 10-15% for higher densities (4 x 10^{19} m^{-3} line average). More recently, measurements of gas fueling efficiency have been conducted on Tore Supra[9,10], JET[11,12], TFTR[13], and DIII-D[14]. The Tore Supra experiments were in two distinct operation modes; in the first mode[9], the tokamak was run with an erogidic divertor and very low deuterium gas fueling efficiencies of order 1% were observed. In the second mode[10], Tore Supra was run with edge limiters for long pulses of up to one minute. The plasmas were fueled by strong deuterium gas puffing (~ 0.6 Pa-m^3/s) to sustain a volume average density of ~ 1.8 x 10^{19} m^{-3}, indicating strong pumping by the plasma walls. Long pulse operation of JET[11] produced similar results. In diverted JET discharges with active pumping by a cryopump[12], the fueling efficiency was observed to decrease from ~10% with the pump off to ~2% with the pump on. In TFTR[13], tritium gas puffing fueling efficiencies of about 15% were inferred in low density, limiter plasmas. Finally, in DIII-D actively pumped, diverted discharges, gas fueling efficiencies of ~10% were measured during the density buildup[14] and smaller values (a few percent) during the flattop. Results are summarized in Table 1.

B. Fueling Efficiency of Pellet Injection

Pellet injection[15] provides a means for depositing hydrogenic fuel directly in the confined plasma, with some modest loss of neutral molecules due to ablation in the transit through the plasma scrapeoff layer. Fueling efficiency of pellets was quantified on ASDEX[16,17] in a series of experiments with ohmic heating and neutral beam injection. Fueling efficiency was close to 100% during ohmic heating and decreased to about 30% during neutral beam injection. In JET[18], fueling efficiency was found to be in the range of 20-90% for the three size pellets (2.7, 4, 6 mm) used in this experiment, and was found to improve with pellet penetration. In ASDEX-Upgrade[19], fueling efficiency was found to be in the range of 8-40% for low (magnetic) field side launch of the pellets and was found to a strong function of pellet penetration. For pellet penetration of 10 cm or less the fueling efficiency was low, about 8-10%. It was also found to decrease with auxiliary heating. In DIII-D[20], the fueling efficiency was a weaker function of penetration and auxiliary heating. Results are summarized in Table 1 and Fig. 1. Recent results from ASDEX-Upgrade[21] are also shown in Fig. 1 that compare the penetration and fueling efficiency of pellets launched into the same plasma conditions from the high magnetic field side and low magnetic field side; improvements in pellet penetration and fueling efficiency for high field launch (HFL) are dramatic.

Table 1. Tokamak fueling efficiency

Device	Gas Fueling Efficiency (%)	Pellet Fueling Efficiency (%)	Reference	Remarks
ASDEX	20	30-100	7, 16, 17	high density
PDX	10-15		8	high density
Tore Supra	1	30-100	9,10	ergodic divertor for gas fuelling
JET	2-10	20-90	11, 12, 18	active divertor
TFTR	15		13	low density DT
ASDEX-U		8-50	19, 21	
DIII-D	10	40-100	14, 20	active divertor

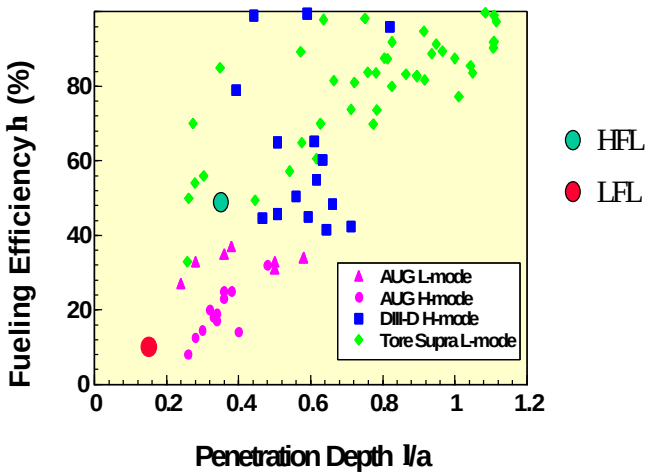

Figure 1. Pellet fueling efficiency for several Experiments. Also shown are recent results from HFL and LFL on ASDEX Upgrade.

III. ITER FUELING SYSTEM OVERVIEW

The ITER fueling system will use a combination of gas puffing and pellet injection to achieve and maintain ignited plasmas. This combination will provide a flexible fueling source with D-T pellets penetrating beyond the separatrix to sustain the ignited fusion plasma and deuterium-rich gas fueling the edge region to meet divertor requirements in a process called isotopic fueling[6]. The isotopic fueling concept was developed for ITER to allow independent control of the plasma deuterium and tritium density profiles which can lead to reduced (by about a factor of two) tritium inventory in plasma facing components. This concept consists of utilizing a tritium-rich pellet source for core fueling and a deuterium-rich gas source for edge fueling. The higher tritium burn fraction allows a significant reduction in tritium gas flows into and out of the vacuum vessel and, for fusion reactors, implies lower required tritium breeding ratios. The fueling system includes a conventional gas puffing system using all-metal electromagnetic dosing valves (five toroidal stations at two poloidal locations-the top of the vessel and at the divertor level) and a pellet injection system using two identical (redundant) centrifuge injectors.

The ITER fueling system design includes a steady state centrifuge pellet injector capable of injecting D-T or tritium pellets deeply into a plasma to achieve high density operation. This type of injector eliminates the need for differential pumping of the pellet injection line and the attendant reprocessing requirements for propellant gas. The PIS comprises two independent injectors, installed in a cask for secondary confinement, which deliver pellets through a common flight tube. The pellets will be injected from the high magnetic field side of the machine through a curved flight tube routed through a divertor port to the inner wall. Only one of the two injectors is active during plasma operations, the second injector being on standby and available for immediate operation, if required, following a failure of the operational unit. This standby injector will also be available for impurity pellet injection (e.g. Ne, Ar) by adjusting the extruder temperature. The hydrogenic feed for the centrifuge injectors is provided by a continuously rotating screw extruder; a Russian Federation prototype system has run for 1-hour pulses using hydrogen feed gas producing ~2 mm extrudant. ITER-scale (10-mm) pure tritium and D-T pellets have been extruded with a piston-type linear extruder and accelerated to about 1 km/s in the Tritium-Proof-of- Principle Phase II (TPOP-II) experiment at the Tritium Systems Test Assembly (TSTA)[22]. Internal pumping of each centrifuge injector is accomplished by an innovative continuous cryopump. The cryopump continuously regenerates with a “snail” regeneration head with a regeneration cycle time of 270 s. The pump has demonstrated a speed of 40,000 litter/s (deuterium) with 0.4 Pa inlet pressure (throughput of 16 Pa-m^3/s). The recent demonstration of improved penetration and fueling efficiency of pellets launched from the high field side on ASDEX-Upgrade[21] has led to adoption of this approach for ITER; R&D is in progress[23] to develop pellet launch and transport systems which can deliver intact pellets to the high (or low) field side via assemblies of curved guidetubes.

IV. FUELING SYSTEM R&D

A. Gas Injection System R&D

Fabrication of a full-scale prototype (see Fig. 2) of the ITER gas fueling system at ORNL (using a single dosing valve and fueling line) was completed in 1996. A variable length injection line (10 mm ID with smooth surface finish) was installed in a facility with a ~0.57 m^3 vacuum tank with attached large roots blower and mechanical pump. Gas pressure and flow diagnostics and the electromagnetic dosing valve were installed and vacuum leak testing was completed. Diagnostics recorded

on the digital scope include pressures P1-P4 and the gas flow rate. Throughput was determined by measuring the pressure increase P4 in the known volume.

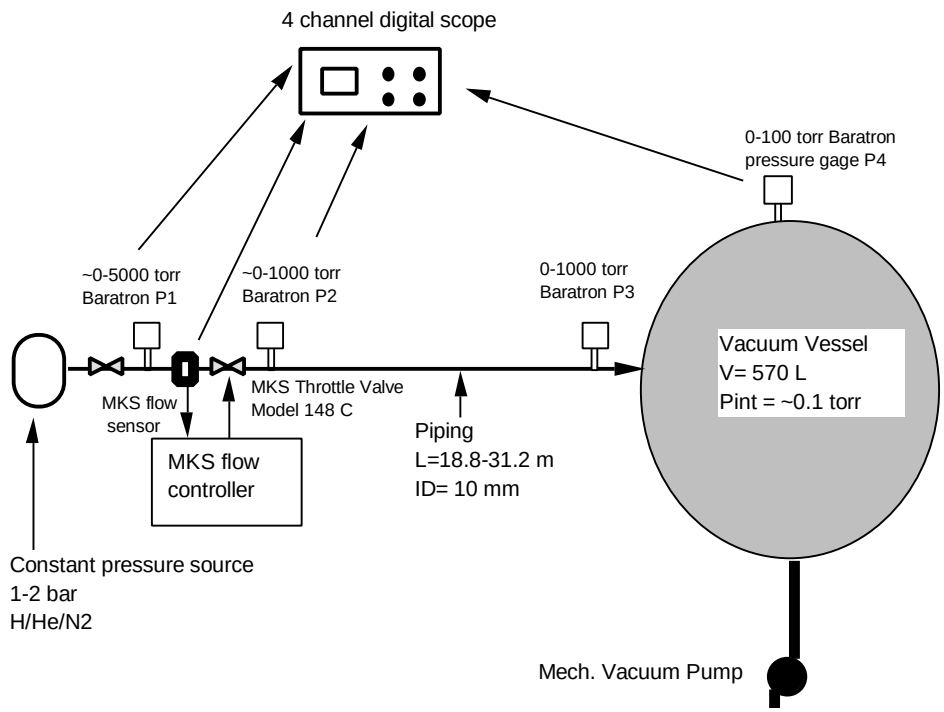

Figure 2. Layout of the GIS Prototype Test Facility.

Testing of this full-scale prototype (using a single MKS electromagnetic dosing valve and 10 mm ID fueling line) was conducted. Data in Fig. 3 below summarize the results and clearly show the effect of line length and gas species on response time (defined as the time to reach 63.2% of the steady-state flow value) for a filling transient.

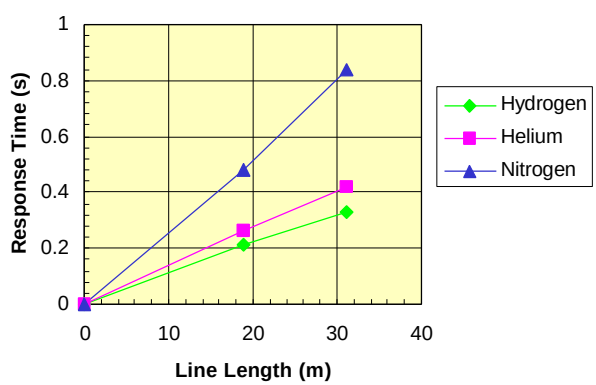

Figure 3. Response time for filling transient.

The difference in the response times of the two line lengths and three gas species is apparent. Also it was found that the response time for a step-down (emptying) transient is generally 10-20% longer than for a step-up (filling) transient. Testing of the full-scale prototype was also conducted for low flow rates for impurity gases. The results in Fig. 4 were obtained in a series of experiments with nitrogen gas (31 m line length, 10 mm line ID, supply pressure 0.13 MPa). The response time was for a filling transient. It can be seen that the response time for flow rates below 25 Pa-m^3/s is in excess of 1 sec. Obviously as the throughput approaches zero, the response time will approach very large values. This issue was further highlighted by modeling of radiating impurity gases in the edge and divertor regions which indicated that response times of 0.1 sec at 1 Pa-m^3/s for impurity gases were needed.

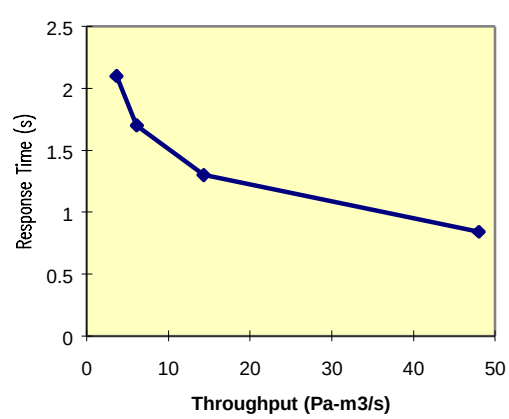

Figure 4. Response time as a function of throughput for nitrogen gas.

Possible methods to decrease the response time of impurity gases include:

- -decrease the line length
- -increase the supply pressure to 0.2 MPa
- -decrease the line inner diameter
- -place the gas dosing valve much closer to vacuum vessel

The first three methods will not result in the desired order of magnitude reduction in the response time. The fourth method, locating the dosing valve 1-2 m from the vessel, will significantly reduce the response time for impurity gases but will require separate gas lines for gaseous impurities and development of a dosing valve that can function in the ITER high radiation environment.

B. Pellet Injection System R&D

There has been much progress in the physics and technology of pellet fueling since this technique was first applied to magnetic fusion experiments about 20 years ago[15]. From first experiments with a single, small hydrogen pellet at 100's of m/s the technology has advanced to pellets of all the hydrogen isotopes in longer pulse length systems, with inventories up to about 1000 pellets and speeds in the km/s range. Table 2 below provides a summary of the status of this technology.

Table 2. Progress in pellet technology 1978-1998

Parameter	**Status 1978**	**Status 1998**
Pellet isotope	hydrogen (H)	H/D/T
Pellet size	1-few mm	0.5-10 mm
Pellet inventory	1-few	1-1200
Pellet feed rate	N/A	0.26 g/s
Pellet speed	100's m/s	1000's m/s
Reliability	unknown	sufficient

Deuterium and tritium pellets up to 10 mm in size (see Fig. 5 below) have been extruded at rates up to 0.26 grams/sec (for short pulses only); this pellet size and feed rate is sufficient for fueling fusion reactors at the gigawatt power level.

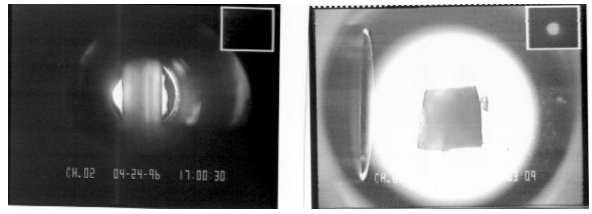

Figure 5. Pure tritium extrusion and pellet.

Pellet speeds up to about 1.2 km/s have been achieved with centrifuge accelerators for small (1 to 2 mm) pellets: and, single-stage light gas guns have accelerated larger pellets (4 to 10 mm) up to speeds in the 1- to 2-km/s range. Two-stage light gas guns operate repetitively with 3-mm pellets at 1 Hz and speeds in the range of 2.5 to 3 km/s. Single 4-mm pellets have been accelerated to speeds above 4 km/s with this technology. This maturing of pellet fueling technology has benefited from a pellet fueling system on virtually every major tokamak and stellerator experiment in the past two decades. Impurity pellet injection systems (typically small lithium or carbon pellets) have been developed for wall conditioning and plasma diagnostics. More recently, there has been interest in repetitive impurity pellets to foster enhanced radiation in the outer plasma and divertor regions and large ("killer") pellets for a controlled, preemptive plasma shutdown in anticipation of a major disruption. These systems typically operate at room temperature or higher cryogenic temperatures, but require similar technology for pellet feed and acceleration as are used on H/D/T pellet fueling systems. The technology to deliver intact pellets at the highest possible speeds around curved surfaces (guide tubes) is under development[23]. This is a complex issue and depends on the pellet speed and temperature (strength) as well as the guide-tube radius of curvature, its diameter relative to the pellet size, and its cross-sectional shape. The speed dependence of penetration for high-field-side or vertical launched pellets is not known, and it may turn out that incremental speed capability from 1–2 km/s to 3–5 km/s (for vertical launch) would be attractive. Predictably, most of the issues in pellet fueling technology are in the areas of extrapolation to reactor-scale fueling which cannot be fully addressed in contemporary, short-pulse confinement experiments. Nearly-continuous pellet feed formation has been demonstrated (~1-hour pulse length) by a new screw extruder concept developed in the Russian Federation to produce 2-mm hydrogen pellets. This needs to be extrapolated to deuterium and tritium feed and larger pellet sizes using this technology or variants such as gear or double-screw extruders. Centrifuges need to be extended to pellet sizes in the 4- to 10-mm range and the allowable speeds quantified. The speed will be limited by

the strength of the frozen hydrogen, which is being investigated in the development of high-field-side pellet launch technology. Engineering issues include reliability for long pulse (100 to 1000s of seconds) fueling systems in the 95 to 99% range, minimization of the hydrogenic (tritium) inventory and closed cycle reprocessing of the pellet erosion and/or propellant gases. Major issues for impurity pellet injection include development of pellet production and feed hardware optimized for the pellet material (i.e. lithium, carbon, nitrogen, argon…) and, for killer pellet injectors, high reliability for a single large pellet or liquid jet on demand.

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