TRITIUM ASPECTS OF FUELING AND EXHAUST PUMPING IN MAGNETIC FUSION ENERGY

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Magnetically confined fusion plasmas generate energy from deuterium-tritium (DT) fusion reactions that produce energetic 3.5 MeV alpha particles and 14 MeV neutrons. Since the DT fusion reaction rate is a strong function of plasma density, an efficient fueling source is needed to maintain high plasma density in such systems. Energetic ions in fusion plasmas are able to escape the confining magnetic fields at a much higher rate than the fusion reactions occur, thus dictating the fueling rate needed. These lost ions become neutralized and need to be pumped away as exhaust gas to be reinjected into the plasma as fuel atoms.

The technology to fuel and pump fusion plasmas has to be inherently compatible with the tritium fuel. An ideal holistic solution would couple the pumping and fueling such that the pump exhaust is directly fed back into pellet formation without including impurity gases. This would greatly reduce the processing needs for the exhaust. Concepts to accomplish this are discussed along with the fueling and pumping needs for a DT fusion reactor.

I. INTRODUCTION

The fueling of a fusion reactor is much more complicated than conventional power producing sources for a number of reasons. Since the fusion cross section is the highest for deuterium-tritium reactions, the fuel will need to have a high fraction of the tritium radioactive isotope of hydrogen that does not occur in nature. The fuel burn fraction in fusion relevant plasmas, which is the fraction of fuel in the plasma that fuses before it is lost as neutral particles, is anticipated to be low which precipitates the need for a significant fueling and exhaust flow rate and recirculation of the unburned fuel back into the burning plasma.

The conventional approach to the fusion fuel cycle that is being implemented on ITER is to subdivide the fuel cycle into several separate tasks; the torus vacuum pumps, a secondary vacuum system to regenerate the primary pumps, a helium-D-T separation system, an isotope separation system, a pellet fabrication apparatus, and a pellet injection system. The D-T fuel passes sequentially from one subsystem to the next and continually recirculates. In this paper we discuss a more holistic approach to the traditional fuel cycle that is potentially more attractive for a burning plasma device that operates in steady-state for very long times well in excess of what is planned for ITER. A simplified diagram of the fusion fuel cycle is shown in Fig. 1.

Fuel injection into a burning fusion plasma is technically challenging as it requires the injection of cryogenically cooled solid fuel pellets in order to penetrate into the plasma. Exhaust pumping technology is not yet suitably developed for steady-state operation in the fusion environment. Compatibility of the fuel cycle systems with the mitigation of transient events in the plasma, such as disruptions, may also be necessary. In the sections below we discuss the tritium aspects of the fuel injection, the exhaust pumping, pellet formation and some aspects of tritium produced near the plasma. The tritium reprocessing system technology has been covered by many other authors. Its incorporation into the fusion system needs careful integration with the entire fuel cycle.

II. FUELING

The fueling system must provide the hydrogenic fuel to maintain the plasma density by replacing the D-T ions consumed in the fusion reactions and that escape the confining magnetic fields. It must also control the isotope mix for a specified fusion power,

$$P_{DT} = E_{DT}\,\gamma\,(1-\gamma)\,n_i^2\,\langle\sigma v\rangle_{DT}\,, \qquad (1)$$

where $\gamma = n_T/(n_D + n_T)$, n is the ion density, E_{DT} is the energy released per reaction, and $\langle\sigma v\rangle$ is the reaction rate parameter. In the range of plasma temperatures now achievable in magnetic confinement devices, the reaction rate has a temperature dependence of $T^{2/3}$ [1], therefore the fusion power output from such devices scales as:

$$P_{DT} \sim \gamma (1 - \gamma) n_i^2 T_i^{2/3} \qquad (2)$$

Thus it is highly advantageous to operate at the highest plasma density possible. For a given density and ion temperature, assuming there is no isotope dependence on these or significant isotopic particle transport differences in the plasma, the power scaling with isotopic fraction γ is shown in Fig 2. The fusion output power only varies ~10% as long as the tritium fraction is with the range of 35-65% and therefore the isotopic mix does not have to be controlled very precisely to achieve high power.

Neutral hydrogenic atoms that result from ions backscattering from the vessel surfaces or desorbed neutrals from the surface enter the plasma and are known as recycled fuel particles. The recycling of neutrals is expected to be very low in a reactor, the recycling rate R ~ 0, because high density operation makes neutrals largely opaque to entering the plasma before being ionized.

Fueling efficiency of gas injected into the vacuum chamber is expected to be very low for the same reason that recycling is nearly 0. Thus solid pellets of fuel are needed to inject the fuel atoms into the confined plasma. Pellet fueling efficiency, η_f, can be nearly 1 in current small tokamaks using inner wall injection[2], but is not clear how efficient it will be in a large burning plasma. The tritium burn fraction in the plasma is the ratio of helium production to tritium input $f_B = \Gamma_a/\Gamma_T$. From plasma physics considerations of burning plasma particle transport and the fusion reaction rate, a recent study by Jackson et al.[3] has shown that with R=0 and $\eta_f = 1$, f_B

is anticipated to be ~2%. Therefore significant recirculation of the fuel will be required to maintain the burning plasma.

Injectors that produce solid cryogenic pellets of DT mixtures have been developed that can operate with the tritium self-heating and accelerate the pellets using light gas guns or centrifuges. This technology has reached a maturity level to be implemented on the ITER burning plasma experiment[4]. Some further development of this technology to produce reliable and efficient steady-state fueling for a reactor will be required. Multiple injectors with different isotopic mixes can be employed with varying pellet sizes, speeds and injection locations. The fueling injection lines need to be incorporated into the reactor design from conception in order to provide optimal injection locations.

III. EXHAUST PUMPING

A fusion reactor will require reliable steady-state pumping that can be controlled and maintained in a nuclear fusion environment. It is likely that the required pumping speeds and throughputs will be comparable to ITER, but with a much higher duty factor. The exhaust pumping must maintain low divertor neutral pressure (~10 Pa) while removing helium ash that will be generated by the fusion burn. The pumping must be carefully designed in concert with the divertor to assure suitable conductance to provide the needed pumping. The predominantly DT exhaust gas from the reaction chamber contains species in addition to the fuel, e.g. 1-3% helium ash produced in the fusion reactions[3], trace levels of hydrocarbons and water, and < 5% other impurity gases possibly injected to maintain edge plasma conditions. These also have to be efficiently exhausted by the reactor pumping system. The pumping technology for continuously exhausting tritium containing exhaust gases from a fusion reactor is not currently as well developed as the fueling capability.

The primary pumps for ITER are large cryo-sorption pumps that are periodically regenerated when their inventory reaches a limit set by inventory and deflagration limits. The ITER torus cryopumps need to regenerate at 100K in order to release at least 90% of the hydrogenic isotopes. This requires a large mass to be warmed and cooled back down very quickly for cyclical operation. To regenerate, the inlet valves to the pump are closed to isolate the pump from the vessel and the pump is allowed to warm up to sublimate the cryosorbed gases, which are then pumped out by a tritium compatible roughing pump system[5]. A fundamental limitation with this type of design is that in order to maintain the tritium contained in the pumps to a low level, they must be regenerated very frequently, which also requires that they be regenerated rapidly. This design requires many redundant pumps with a large supercritical helium consumption to accommodate the frequent thermal cycling of the pumps, frequent valve cycling, and a large roughing pump system. This system has adequate pumping capability, but the frequent regeneration requires a close coupled valve that must operate in the fusion environment.

Concepts of continuous tritium compatible pumping schemes exist[6], but all of these concepts need significant further development. Two of the more promising concepts that have been prototyped or are undergoing prototype testing are a continuously regenerating cryopump[7] and mercury diffusion pumps[8].

The use of mercury in diffusion pumps and liquid ring pumps for fusion application has been suggested by Karlsruhe Institute of Technology (KIT)[8] and is now being tested. Mercury has been used as a pumping fluid for long time even before the molecular diffusion pump was invented by Gaede in 1913[9]. Mercury's toxic properties have led to the elimination of mercury containing systems and devices where suitable replacements can be found, generally replaced by low pressure distilled oils. Its melting point is -39^{o}C and it boils at 360^{o}C and thus requires a cold trap to prevent vapor from back streaming into the pumping volume. It will however oxidize so exposure to air and other oxidants must be minimized. On the positive side, mercury is compatible with ceramics and stainless steel and does not appreciably activate during neutron exposure.

The exhaust from a mercury based pumping scheme will need separation of impurities and helium from the hydrogenic species. Any mercury vapor exhausted to downstream tritium exhaust processing systems (shown in Fig 1) would potentially poison catalysts and present major operational difficulties. Great care has to be taken with the use of mercury in the fuel cycle.

The continuous cryopump developed by Foster[7] uses a cold inlet duct to compress helium and improve conductance into the pump. An impurity cryogenic trap is used to cryosorb impurities before they can enter the main pumping area. This can be regenerated during any dwell times of the machine or periodically during operation. The plot in Fig. 3 shows that a 20K trap can effectively remove all of the impurity condensing species expected except for neon. The pump employs a mechanical scraper known as a snail to continuously scrape the main cylindrical pumping volume that is cooled with liquid helium. The scraped hydrogenic material is vaporized by resistive heaters to produce low temperature ~30K gas that can be sent for further processing. A prototype of this pump technology was tested and was found to work well for compressing helium in the input stream and met expectations for deuterium pumping speed[9]. The pump was never tested with tritium due to the shutdown of the Tritium System Test Assembly, but was designed to be tritium compatible. The rotating scraper drive system of the snail pump was the weakest link in the prototype pump and will require further engineering development to achieve the reliability needed.

IV. PELLET FORMATION

A more holistic approach to the fuel cycle design would be to feed the fueling system directly from the pumping system exhaust without going through tritium plant reprocessing. A concept for a low tritium inventory fuel cycle was promoted by Foster[10] to use the cold exhaust DT gas from the snail pump to form new pellets that could be fed into a centrifuge type pellet accelerator. A pellet pump was developed and tested to form pellets from the gas that could be released when needed. One difficulty that was encountered with this scheme was the tendency for pellets to stick together when they fall into a hopper to load the centrifuge. A potentially more effective way to use the DT exhaust of the snail is to feed it into a pellet forming continuous extruder that produces a ribbon of solid DT from which pellets are cut on demand for injection into the plasma[11]. An alternative scheme proposed by KIT uses super permeable metal membranes[12] to separate the hydrogen isotopes for feeding into the pellet system as warm gas.

The use of extruders to form pellets has been under development for many years and is effective at producing the needed flow rates to cut pellets on demand. Cutting pellets from extrusions does result in unused material that can be as much as the pellet injection flow rate. Therefore a fuel recirculation loop is being developed[11] to feed the excess extrusion back into the extruder without the enthalpy change by warming up to room temperature and processing of the gas in the tritium plant. The 30K exhaust gas from the snail pump is ideal to feed into this recirculation loop of a pellet injector. A schematic of a continuous cryopump directly coupled to a pellet injector through the fuel recirculation loop is shown in Fig. 4. Helium removal is achieved by allowing it to pass through the snail pump and be pumped by conventional vacuum pumps similar to the scheme ITER will use to remove helium in the roughing system cryopumps[5].

Potential issues with such a coupled fueling and pumping scheme are that the isotopic mix of the exhaust gas is not necessarily what is desired for feeding into the pellet making system if a lot of deuterium gas is introduced into the reactor to maintain divertor conditions. This can possibly be compensated by mixing with fuel gas that feeds the extruder in parallel. Another aspect is the impurity gas injected into the plasma device for optimizing divertor radiation conditions. Neon is a likely candidate and its triple point temperature of 24.5K is close enough to that of tritium that the impurity trap in front of the snail pump would possibly not remove all the neon before it ends up in the snail pump. Further removal of neon downstream of the snail pump may be required if the levels are too great. Keeping accurate inventory of tritium in the different parts of such a system will require careful design integration and measurement.

V. TRITIUM RECOVERY AND INSERTION

In order for the DT fusion reactor to be able to operate continuously there must be as much tritium produced by breeding blankets containing lithium as is consumed in the reactor. For 1 GW electrical (3 GW thermal) power production from a reactor, the amount of tritium burned in fusion reactions per day is on the order of 0.5 kg. This will require a significant fraction of the first wall be dedicated for breeding to produce tritium that can be processed[13] and inserted it into the fuel cycle, possibly directly into the pellet formation loop.

Another area where tritium may need to be recovered and inserted into the fuel cycle is from liquid metal walls. These are being proposed as a reactor first wall to handle the high heat fluxes. The tritium retention by a flowing lithium wall will require removal to maintain low inventory. Lithium as a first wall coating has resulted in very low recycling and confinement improvements[14]. Improved performance of a reactor plasma could lead to a higher tritium burn fraction than currently anticipated and thus warrants further research and development of liquid lithium plasma facing components (PFCs) and efficient schemes for tritium removal and re-insertion into the fuel cycle.

VI. SUMMARY

A holistic approach is needed to develop an optimized fuel cycle design for a DT fusion reactor system. Continuous pumping systems are needed for long pulse reactors that can exhaust directly to the fuel injectors for a more efficient tritium handling system. Pumping technology options exist that need further development and close collaboration with divertor designs. Tritium removal from breeding systems and liquid metal PFCs are also required for a viable fusion fuel cycle. Significant additional research and development is needed in the fusion fuel cycle to make fusion viable even for a fusion nuclear test facility.

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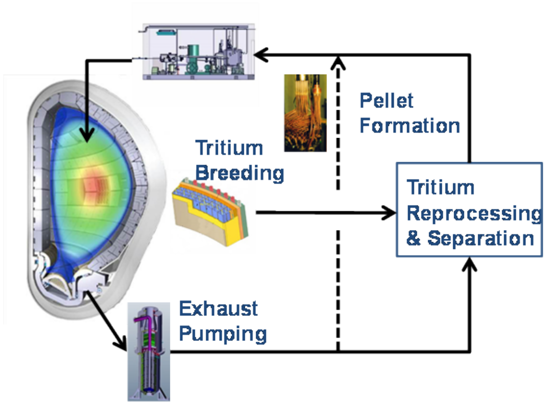

Fig. 1. Simplified fuel cycle schematic for a burning plasma fusion device showing a direct exhaust to pellet formation link (dashed) that circumvents reprocessing and separation.

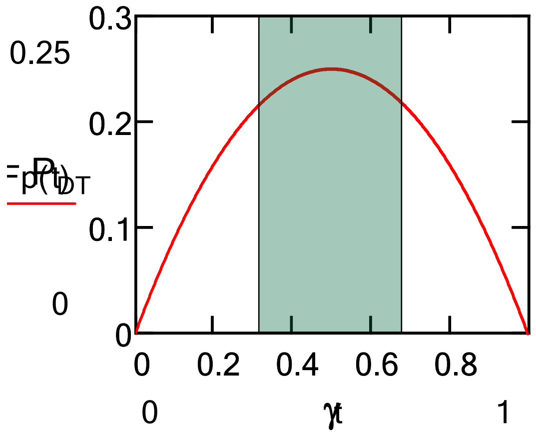

Fig. 2. Normalized fusion power output as a function of tritium isotopic fraction.

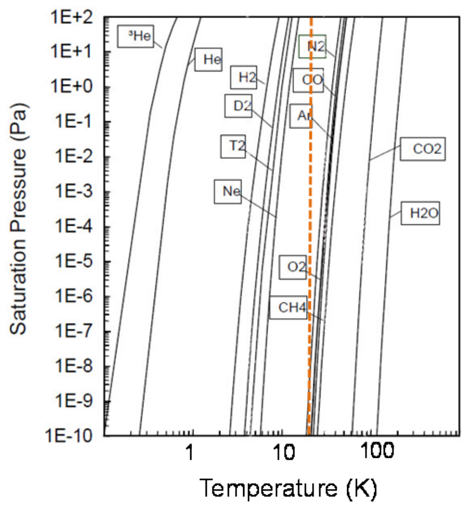

Fig. 3 Saturation pressures of fusion exhaust products as a function of temperature. An impurity trap temperature of 20K is shown in the dashed line.

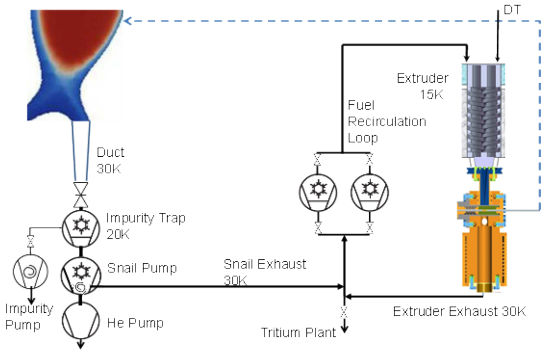

Fig. 4 Flow diagram of continuous cryopump system coupled with pellet injector recirculation loop.