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Long pulse neutral beam injection

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Abstract
Long pulse operation has an important impact on the design and utilization of a neutral beam injection system. This paper, first describes briefly the injectors designed for ITER FEAT as they are the first to be designed for long pulse operation under conditions approaching those that will be experienced in future machines. The important consequences of long pulse operation on the injector design will be then discussed, and finally some suggestions will be made for future, continuously operating systems.

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1. NBI Systems considered

Before considering the problem of long pulse neutral beam injectors it is necessary to define exactly what is meant by long pulse and what type of injectors are being considered.

1.1. Long pulse injectors—what this implies

Present day fusion devices all have energy confinement times less than 10 s, and, except for a few special cases, all operate for pulses of <30 s [1], whereas future experimental devices, such as ITER will operate for long pulses, 500–3600 s, and it is planned to operate fusion reactors continuously [2, 3]. Also most such devices will use D^+/T^+ plasma, and the injectors will experience significant neutron and gamma radiation. This paper will concentrate on future systems, so 'long pulse' is taken to mean $\geqslant$500 s to continuous operation in a hostile radiation environment.

1.2. Injector type and beam species

The future machines considered, whether experimental devices or reactors based on the Tokamak scheme, will be large, with rather dense, D^+/T^+, plasmas, which means that the neutral beam injectors will need to produce very high energy beams in order to penetrate and drive current in the plasma, typically $\geqslant$1 MeV, and the beams will need to be D° to avoid 'polluting' the plasma with H° [4, 5]. Nearly, all operating neutral beam systems are based on the neutralization of positive ions. However, as the efficiency of this process becomes extremely small at the required energies, whereas that of negative ions

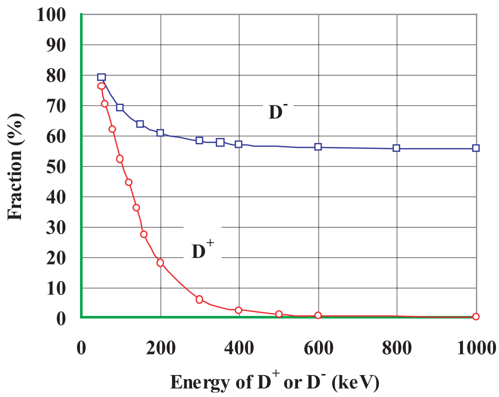

Figure 1. Neutralization of D^+ and D^- on D_2 as a function of energy of the ions.

remains high [6, 7] (see figure 1), injectors for future machines will be based on the neutralization of accelerated negative ions, D^- [2]. Thus, it will be assumed that the injected species will be D° from negative ion (D^-) based injectors.

2. The neutral injector and the required sub systems

In order to appreciate the problems created by long pulse injection it is necessary to understand the basic design of such an injector. The ITER injectors [8] are the first injectors designed to the criteria outlined in section 1, so the design of those injectors is described briefly here. In addition to the injectors themselves, a neutral beam system includes several important subsystems, the design of which can be significantly influenced by the need for long pulse operation, and this can

[1] An exception amongst the larger devices is the Tore Supra tokamak at the DRFC, CEA Cadarache which plans to have 1000 s pulses [1]. However, there is no neutral beam heating system on Tore Supra, and, although it is planned that there will be a diagnostic neutral beam injector which will operate throughout the 1000 s pulse, it will operate in a repetitive pulsed mode.

[2] Although in principal the injection of T° would also be acceptable, this is not presently considered because of the technical difficulties associated with T_2 handling, and with the development of the T^- ion source.

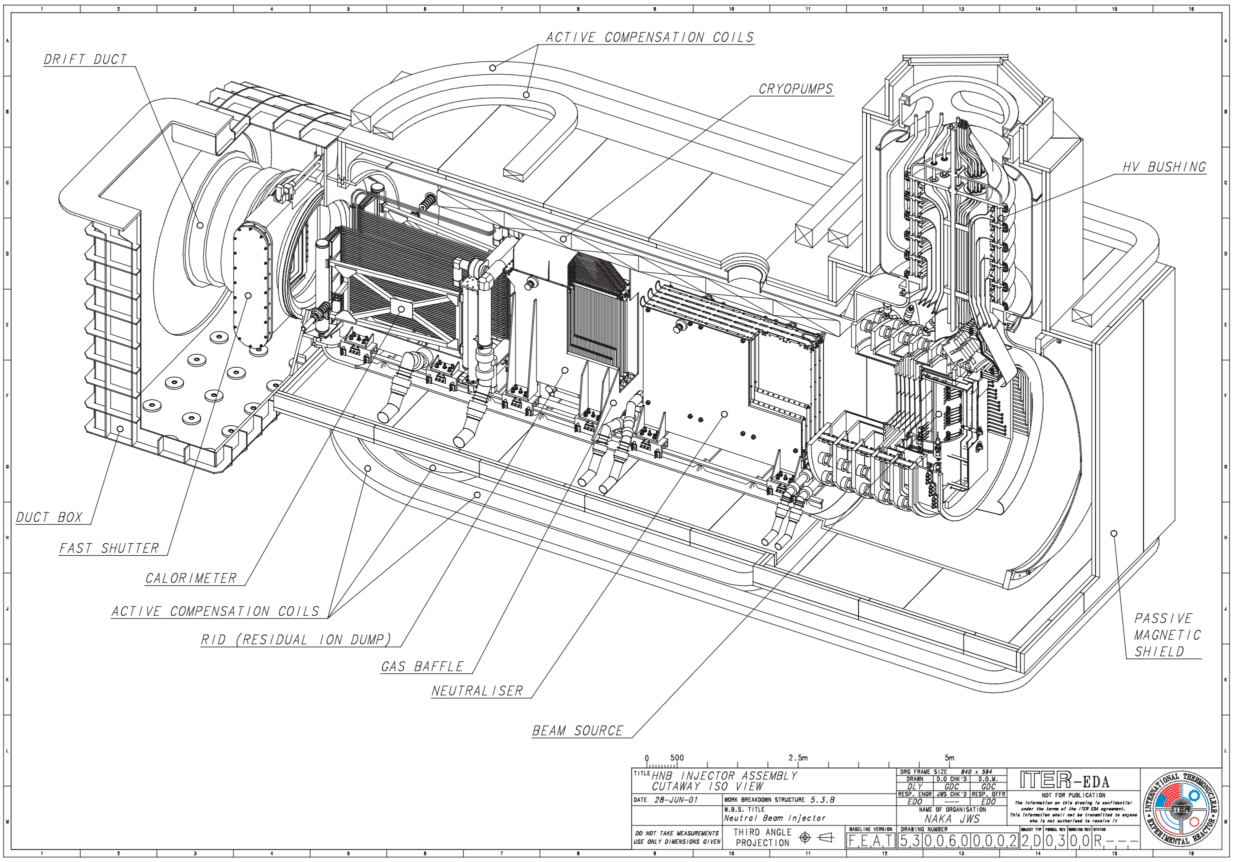

Figure 2. Cut-away three-dimensional schematic of the ITER FEAT injector showing the main injector components.

then have an important influence on the design of the injectors. Therefore the required subsystems are also briefly discussed below.

2.1. The ITER FEAT neutral beam injectors

The main specification of an ITER FEAT injector, a schematic of which is shown in figure 2, is:

Beam species	D°
Accelerated species	D^-
Accelerated current	40 A
Beam energy	1 MeV
Pulse length	500 s, with the possibility of 3600 s
Neutralizer	D_2 gas cell
Neutral power to ITER	17 MW
Overall efficiency	40%

The negative ions (D^-) are first created in a multi-cusp filamented arc discharge source, then extracted and accelerated electrostatically to 1 MeV. The negative ions then pass through a gas (D_2) cell (the neutralizer) where they are partially neutralized by collisions with the D_2. The most important reactions occurring in the neutralizer are:

$$\underline{D}^- + D_2 \Rightarrow \underline{D}^0 + D_2 + e$$

$$\underline{D}^0 + D_2 \Rightarrow \underline{D}^+ + D_2 + e$$

$$\underline{D}^+ + D_2 \Rightarrow \underline{D}^0 + D_2^+$$

where the underlined species have an energy of 1 MeV. The result is that the incoming D^- beam is converted to a mixed beam of D^-, D^+ and D^0. The ratio between these varies as a function of the D_2 target thickness as shown in figure 3.

It can be seen from figure 3 that at the optimum target thickness the beam exiting the neutralizer will consist of $\approx$60% D^0, $\approx$20% D^-, and $\approx$20% D^+. The charged fractions of the beam are deflected electrostatically and collected on cooled surfaces in the residual ion dump (RID), whilst the neutral beam continues to the tokamak.

A novel feature of the ITER injectors is the subdivision of the neutralizer and RID to form 4 vertical channels. The neutralizer is subdivided to reduce its gas conductance whilst keeping its length reasonably short. Furthermore, the gas is introduced midway along each of the channels in order to minimize the gas flow required to obtain the optimum target for neutralization.

The opposing plates of each RID channel are polarized to produce an electric field that deflects the negative and positive charged fractions in opposite directions. The RID is subdivided to reduce the required angular deflection of the charged species, thus reducing the required deflecting electric field. Additionally, as all eight surfaces of the RID channels collect the deflected beams, the power from the beam is spread over a large area. Nevertheless, the peak power density on the RID surfaces is calculated to be $\approx$6 MW m^{-2}.

A 'beamline calorimeter' can be positioned either to intercept the beam downstream of the RID, allowing 'offline'

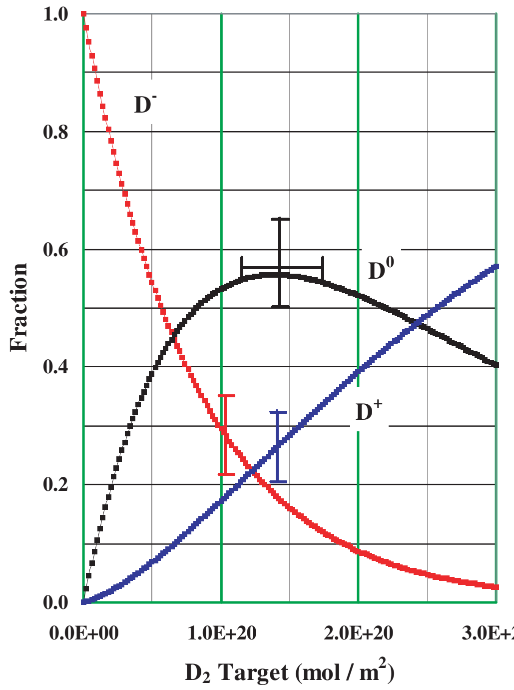

Figure 3. Variation of the species from a D^- beam as a function of the D_2 target thickness.

commissioning of the injector, or retracted to allow the neutral beam to continue into the tokamak plasma.

3. The major subsystems

A neutral beam system consists not only of the injectors, but also of many subsystems, the major ones being:

(i) The cooling system.
(ii) The pumping system.
(iii) The maintenance system.
(iv) Magnetic shield and magnetic field compensation coils.
(v) The electrical power supplies.
(vi) The control and data acquisition system.
(vii) The tritium and radiation confinement system(s).
(viii) Beamline diagnostics.

Although there are some problems related to long pulse or continuous operation with subsystems (iv)–(viii), they do not significantly impact on the long pulse aspect of the injector design, so they are not further discussed here.

4. The impact of long pulse operation

4.1. The cooling system

Although this system is not immediately seen as the most important part of the injection system, with long pulse operation it has a significant impact on the design of the injectors.

It is recalled here that because the neutralization efficiency is ≈60% and there are also other losses in the beamline, a high power is dumped within the injector and has to be removed by the cooling system. On ITER FEAT the power dumped into the injector will be ≈27 MW.

Now the injectors in use today typically operate for short pulses, <10 s, with relatively long intervals between pulses, >3 min. This means that the average power load to be removed by the cooling system is low, typically $\leqslant 5\%$ of the power absorbed inside the injector during the pulse. For the long pulse systems discussed here, since the thermal time constants of most of the injector system components will be shorter than the pulse length, the cooling system must remove the deposited power continuously. If the same conditions were to be demanded as enjoyed with today's injectors, i.e. the temperature of the water into the injector of about 20˚C, and at the outlet of 40˚C, the cooling system becomes excessively large. Thus, it becomes very important that the efficiency of the cooling system is high. This means that the temperature difference between the inlet and the outlet on the primary side (i.e. to and from the injector) has to be maximized, and that the temperature into the injector should be well above that of the secondary side.

The consequence of the high inlet temperature and the high temperature increase for the different components of the ITER injectors are:

(a) Beamline components. The beamline components can accept a high inlet temperature (75˚C), but careful design is required to ensure that a high temperature rise (to 110˚C) is obtained whilst maintaining the required heat removal capacity, particularly with the high heat flux elements of the RID and beamline calorimeter. This is difficult because slight variations must be anticipated in, for example, the magnetic field inside the injector, the density of the gas in the neutralizer, or the voltages on the accelerator or RID, all of which can cause variations in the power deposition profile on those components. (The ITER FEAT design also caters for possible variations in beam divergence and alignment, as these are not yet accurately known.) In the ITER FEAT injectors the high heat flux elements are 25 mm wide rectangular cross section swirl tubes, which are arranged in flat arrays to make up the panels of the RID and the calorimeter. A schematic of a single RID panel is shown as figure 4. By making the cooling water pass through two such elements, see figure 4, chosen such that one has a high heat load and the other a low heat load, the flow and required temperature increase can be achieved whilst allowing for variations in the power deposition profile. This is because the changes judged possible give rise to either a change in position of the profile, or a change in the shape of the profile. The result is that if the power to the element receiving the higher load increases, the power to the second element decreases or vise-versa.

(b) Accelerator. The apertures in the various extraction and acceleration grids need to be precisely aligned in order to obtain the required beam optics. Since each aperture forms an electrostatic lens, offsetting the apertures in one grid with respect to other grids results in a steering of the beamlets, a feature which is used to 'focus' the beams. It is necessary to avoid unwanted offsets due to thermal expansion of the grids (or their support structure) creating excess beam misalignment. The problem can be offset in, for example, the extraction grid, which is 0.5 mm and the displacement due to thermal expansion. The grid is 850 mm wide, so a temperature increase of 40˚C causes the grid to expand by 0.85 mm. However, as all the grids will expand in a similar way (but by

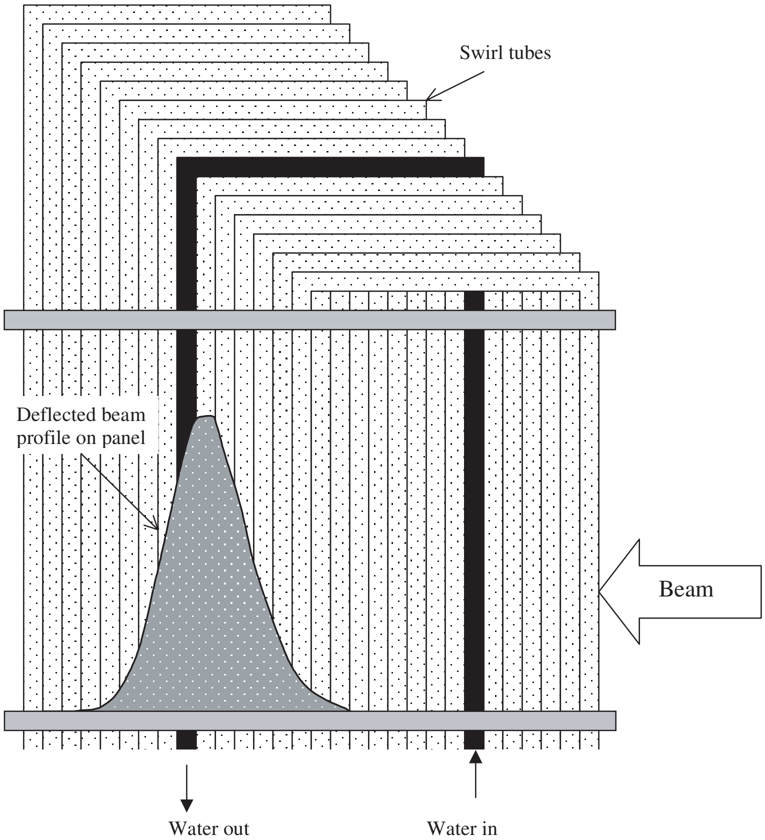

Figure 4. Schematic of a RID panel indicating the water flow pattern for one of the high heat flux elements.

different amounts), the differential motion will be small and a temperature rise of 40˚C is judged acceptable. To achieve this, the water needs to be chilled. The design inlet and outlet temperatures are 55˚C and 95˚C, respectively.

(c) Ion source. An exception has to be made for the ion source. Caesium is introduced into the ion source to improve the efficiency of generation of the negative ions (see section 4.3.1.3). It has been shown experimentally that if the cooling water temperature is increased from 20˚C to 40˚C, the Cs consumption rate doubles. To keep the Cs consumption acceptable, the cooling water from the heat exchanger to the source will be chilled to have an inlet temperature of 20˚C and the cooling designed such that the temperature rise will be 20˚C.

In addition to the high coolant temperature, the coolant velocity has to be kept below about 6 $\mathrm{m\,s^{-1}}$ in order to reduce erosion. This is important as the injector components will be radioactive during operation and any erosion or corrosion will result in the transport of radioactive materials to the cooling plant.

4.2. The pumping system

High speed pumping is an essential feature of all existing neutral beam systems and the ITER injectors. Pumping is necessary to reduce the pressure in the beamline outside, and downstream of, the neutralizer in order to minimize reactions between fast particles and the background gas. A high pumping speed is required as it is necessary to feed gas at a relatively high rate into the ion source and the neutralizer ($\approx$2 and 15 $\mathrm{Pa\,m^3\,s^{-1}}$, respectively, for an ITER FEAT injector), and the pressure in the injector needs to be $\approx 5 \times 10^{-3}$ Pa (or less), so that the pumping speed needs to be $\approx 3 \times 10^3\ \mathrm{m^3\,s^{-1}}$. In present day injectors this is usually achieved by liquid helium (LHe) cooled cryopumps located inside the injector vacuum vessel, which maximizes the pumping speed and minimizes the injector space envelope. The same solution is proposed for the ITER FEAT injectors.

The use of cryopumps has two consequences: first the gas is trapped or frozen on the cryopumps, and it could potentially be released. Second there is a maximum quantity of gas that can be pumped.

Gas is released from cryopumps when they are warmed up, either in a controlled or uncontrolled way. The former is carried out routinely and is termed regeneration as the pumps are returned to their initial condition thereafter. Uncontrolled warm up (or uncontrolled regeneration) occurs when the heat load to the pumps becomes too high. This can be due to the pressure in the injector increasing to the level that conduction through the gas from the warm surfaces of the injector to the cold surfaces of the cryopump becomes significant, typically $>10^{-2}$ Pa, or through a drop in the supply of cryogens to the pumps. High pressure would occur either because of a leak in the system or because of diminished pumping speed with a constant gas input. The former is a fault condition and not discussed further here. The latter occurs either because (a) cryosorption pumps are used and the sorption material is saturated or (b) cryocondensation pumps are used and a sufficiently thick deuterium ice has built up on the LHe temperature surface such that the temperature gradient is so high that D_2 is no longer condensed on the surface. These situations are avoided by carrying out routine regenerations of the pumps, which are necessary to avoid other potential problems, as outlined below. This situation is satisfactory for the type of long pulse operation proposed for ITER FEAT as the cryopumps can be regenerated between pulses, and the regeneration has no influence on the ITER FEAT operations.

Minimizing the potentially releasable gas load on the cryopumps via regular regenerations is necessary to avoid problems that could arise during a regeneration, planned or otherwise. Scenarios have been considered that lead to the presence of oxygen in sufficient quantities that an explosive mixture is formed when the D_2 is released from the pumps during regeneration. For this reason, regular regeneration of the ITER injector cryopumps is planned. (The scenarios considered are small air leaks over a long period, large air leaks causing regeneration, and a water leak in the tokamak leading to oxygen formation via the reaction between the water and the hot carbon.)

Because of the need for frequent, fast (inter-pulse), regeneration, the cryopumps need to be designed with the minimum of LHe inside the pumps. It is worth noting that since LHe is a good absorber of gamma radiation, this is also highly desirable in order to minimize the heat load to the LHe.

4.2.1. A pumping system for continuous operation. Obviously for a continuously operating injector, continuously operating pumps are also needed. Three techniques to achieve this with cryopumps have been suggested:

(i) *Extra injector.* If one extra injector is installed, then one of the injectors can be 'off' and regenerating whilst the others are operational. Once that injector is regenerated, then it can restart operation, and another can be switched off and regenerated and so on. With this solution it is necessary to ensure that, if N injectors are installed, the injectors can operate for the time taken to regenerate $N - 1$ injectors. This solution has the disadvantage that an extra injector and the associated subsystems has to be installed, which is expensive and it occupies a tokamak port. Advantages of this solution is that it requires no development, and it supplies some redundancy, although that would be time limited. For example, if one injector is taken out of service, the 'spare' could be brought on-line, and system operation continued, until regeneration of one of the injectors becomes necessary. This could allow either minor faults to be corrected, or a programmed shut down of the machine.

(ii) *Appendage cryopumps.* If, instead of large internally mounted pumps, several smaller, so called 'appendage pumps' attached to the injector vessel are used, then a valve can be interposed between each appendage pump and the injector. This then allows the regeneration of one or more pumps to be carried out whilst the injector is operating by isolating the regenerating pump(s) with the valve(s). This is shown schematically in figure 5(a). Here, it is to be noted that the diameter of these appendage pumps will be large in order to

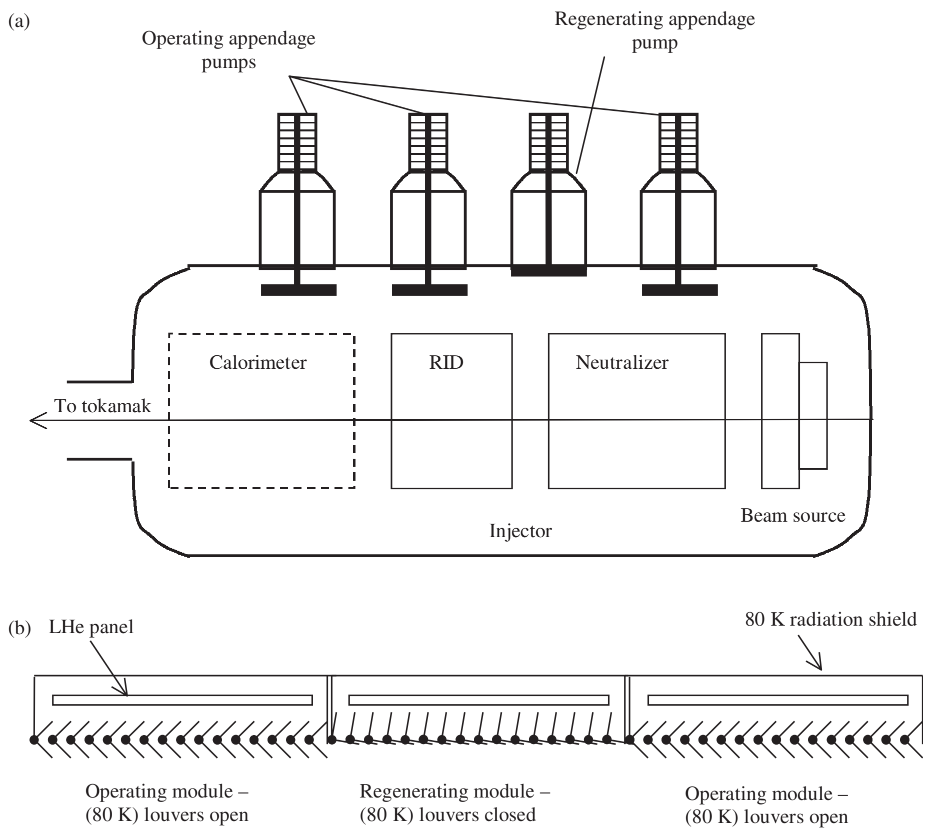

Figure 5. (a) Sketch of an injector with appendage pumps. (b) Sketch of variable louver cryopump concept.

have a high pumping speed (typically $\geqslant$1.5 m diameter), and all the valves need to be metal in order to survive the hostile radiation environment of a reactor. However, the valves can be relatively 'leaky' in that it is only required that the leak rate across the seal is small compared to the gas flow into the injector. Such a pump, including the valve, has been designed and is operation on the lower hybrid launcher at JET [9].

The obvious disadvantage of such pumps is that they protrude out from the injector, increasing the injector space envelope. This is a major disadvantage as the injectors need to be surrounded by radiation shields and to have a magnetic field reduction system (MFRS). The former is needed to minimize the activation of the components outside the main injector envelope. The latter is necessary to reduce the magnetic field inside the injectors to avoid the deflection of fast D^- and D^+ in the neutralizer and RID. The MFRS on ITER FEAT includes a magnetic shield, which also acts as a radiation shield, made of 150 mm thick iron that surrounds the injector, and a set of compensation coils (see figure 6). The extended space envelope that would result from the use of appendage pumps increases the size and complexity of the required iron shield and the compensation coils, and increases the difficulty of achieving the required low field inside the injector.

(iii) *Variable geometry louvers.* Typically, the radiation shield of the cryopumps is a chevron structure cooled to <80 K by cold gaseous helium or liquid nitrogen. These chevrons cover the entire surface of the pumps facing the injector components. If the pumps are made modular with the louvers on the radiation shield able to be closed, as shown in figure 5(*b*), then one or more modules could be regenerated whilst the rest continue to pump the operating injector. As with the appendage pump solution, the leak rate through the louvers needs to be small only when compared with the gas input to the injector. The obvious disadvantage of such pumps is the number of moving parts in vacuum, and the resulting necessary maintenance.

Of the three solutions mentioned before, the extra injector option requires no development and offers some advantages, but it is expensive. The appendage pump system offers easier maintenance than the variable louver option as the pumps are readily accessible, although the latter produces a more compact injector.

The problem would be considerably eased if the gas input to the injector were reduced. A reduction in gas flow to the level that mechanical pumping can be used is perhaps foreseeable, but extremely ambitious as it would require the development of an ion source operating with very low gas flow (i.e. high gas efficiency) and, most likely, the use of a laser neutralizer. The laser neutralizer uses the photo-detachment of the loosely bound (0.75 eV) electron from the D^-. In this case, the neutralizer has to have very high reflectivity walls to ensure efficient usage of the injected photons, and the development of a high efficiency laser [10].

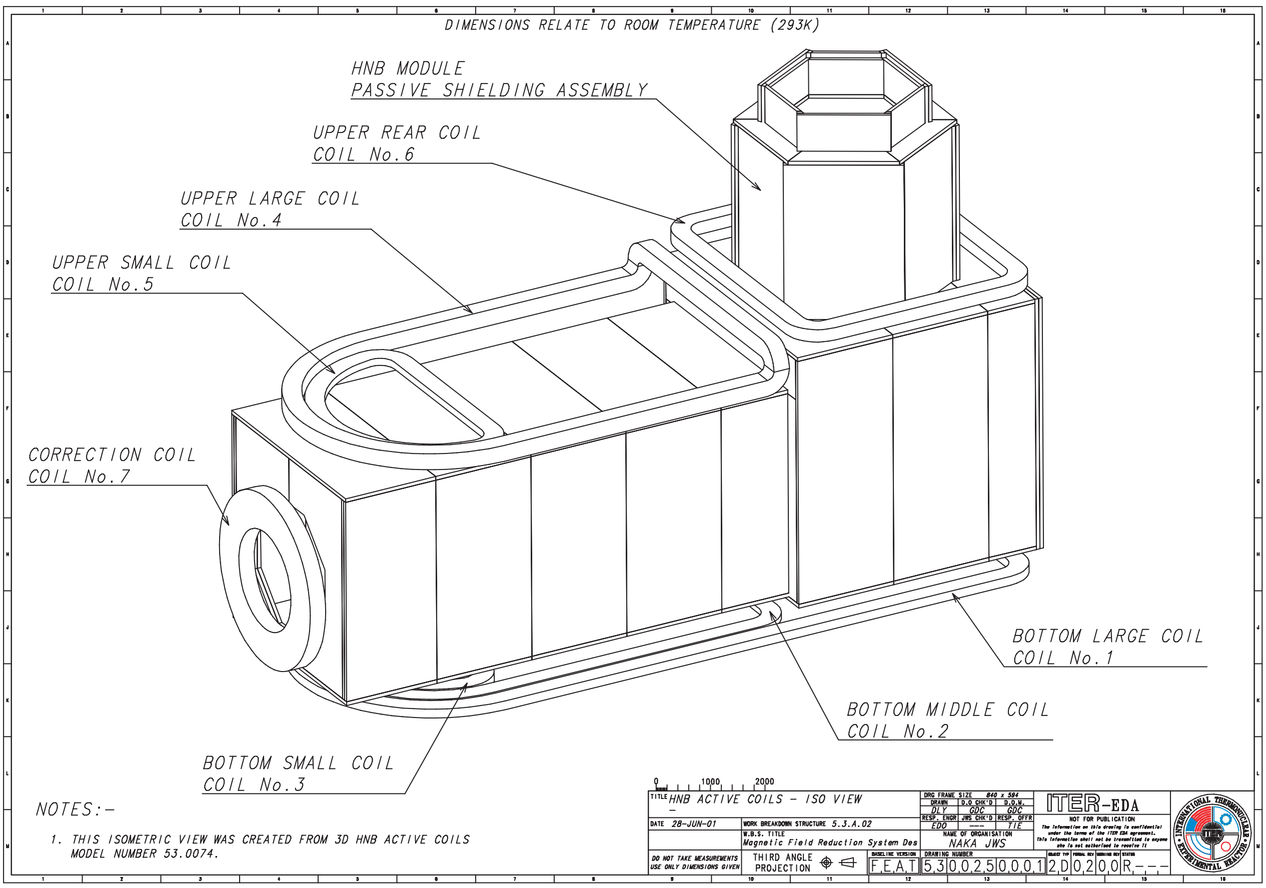

Figure 6. The ITER NBI MFRS.

The use of a plasma neutralizer could reduce the flow to the level that only a few appendage pumps would be necessary, which would be a rather attractive solution. (Should the gas efficiency be very high, this could be an alternative to the laser neutralizer discussed above.) Plasma neutralizer development is being carried out at JAERI, Japan and the Kurchatov Institute in Moscow, Russia [11–13] with the aim to improve the overall efficiency of the injector. The Kurchatov work has shown that a plasma neutralizer operating with deuterium will probably require the gas flow into the ITER injector to be ≈20% of that required with the simple gas neutralizer, and that if argon were used instead, the flow would be reduced by a factor 20. Assuming the more conservative case of the deuterium plasma neutralizer, the required pumping speed for an ITER injector falls to about 600 $m^3 s^{-1}$, which could be provided by several appendage pumps.

4.3. The maintenance system—component lifetime

As is mentioned in section 1, long pulse injectors will operate in hostile radiation environments, they will therefore become highly radioactive, which means that all maintenance has to be carried out remotely.

The following reasons have been identified for maintenance during the lifetime of ITER FEAT:

- The replacement of the filaments in the ion source.
- Replenishment of the caesium needed for the ion source operation.
- Cleaning caesium from the accelerator and ion source.
- Replacement of the seal of the shutter between the injector and the tokamak.

Although viable schemes for carrying out these operations have been identified and the necessary equipment designed, the operations are not simple, requiring, for example, the remote cutting and welding of the end flange of the injector, whilst ensuring the containment of all contaminated[3] or activated substances.

On ITER FEAT, all the other components of the injector (RID, calorimeter etc) are expected to survive without maintenance. This will not be the case with a reactor. The need for maintenance is discussed (briefly) below for each injector component.

4.3.1. The ion source. The ion source chosen for the ITER injectors is the caesium seeded, filamented, arc discharge source and there is ongoing R&D to study the performance of such sources, including the operation for pulses of 1000 s [14, 15]. The first acceleration of D^- (and H^-) for 1000 s were obtained with an ITER model source under the anticipated conditions (plasma grid temperature, arc power arc filling pressure) in 2001 [15] (see figure 7). Unfortunately, the accelerated D^- density was only 40% of that expected, for reasons yet to be found, but it is possible that they are connected to long pulse operation. The R&D is continuing with the aim to demonstrate that long pulses can be obtained at the current density levels required for ITER.

[3] Components will be contaminated by T_2, tokamak dust or activated corrosion/erosion products.

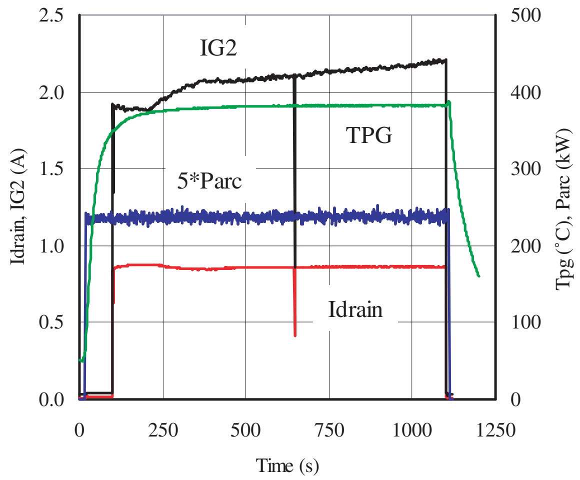

Figure 7. The 1000 s D^- beam extracted from the ITER model source with the expected ITER like parameters, i.e. an arc power of 47 kW, a source filling pressure of 0.3 Pa, >600 mg of Cs in the source, and the plasma grid at ≈350˚C throughout the pulse. The extraction voltage was 6.5 kV and the acceleration voltage 25 kV. The calorimetrically determined current density was 80 A m^{-2}. Here IG2 is the current to the extraction grid, TPG is the temperature of the plasma grid, Idrain is the accelerated current and Parc is the discharge power.

The cathodes used in the arc discharge sources are directly heated tungsten filaments, which have a finite lifetime due to evaporation of the tungsten. As on present day sources, on ITER caesium will be supplied from a small oven mounted directly onto the rear of the ion source. This needs to be refilled when all the Cs has been bled into the ion source. The 10 g of Cs in each of the two ovens of the ITER source [16] is calculated to be sufficient that frequency of refilling of the Cs oven is lower than the filament replacement frequency, and the two operations will be carried out at the same time. (There is a 'spare' oven installed, and the 'used' oven will be replaced before it is empty.)

4.3.1.1. Cathodes. Directly heated pure tungsten filaments have proven to be the most reliable form of cathode in the arc discharge sources used on neutral beam injectors. The lifetime of the filaments due to evaporation at the expected operating temperature in the ITER negative ion source is calculated to be about 200 h, so the filaments of the ITER sources will need to be changed once or twice a year. Clearly, this is not an acceptable situation for continuously operated sources, and R&D is planned to develop long life cathodes. Two approaches have been suggested. First, directly heated thoriated tungsten filaments. Such filaments operate several hundred degrees lower in temperature than pure tungsten for the same emitted electron current density. This means that their evaporation lifetime would be many times more than that of pure tungsten [17]. Tests are needed to establish that these filaments work as expected inside a negative ion source where their surface is bombarded by energetic D^+ and Cs^+. Second, alternative, massive, indirectly heated, cathodes have previously been developed for positive ion sources [18] that could, in principle, be adapted to be used in the negative ion source.

4.3.1.2. RF driven sources. Various types of RF driven sources have been developed for positive ion sources, but

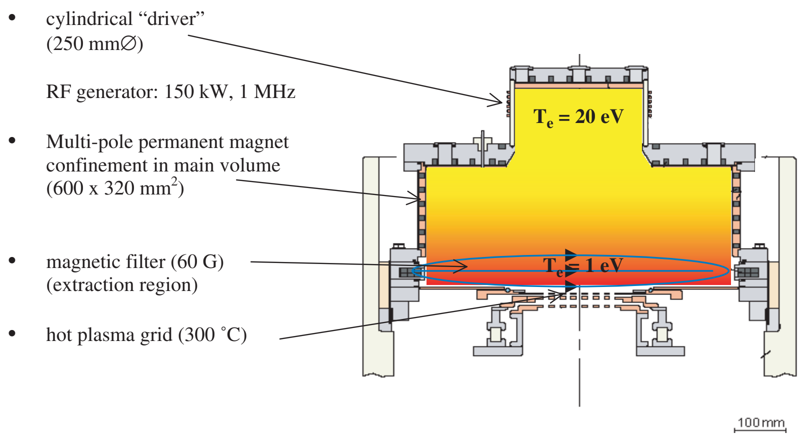

Figure 8. The mark 6 RF driven negative ion source.

only one type has been developed with the characteristics needed for a positive ion based injectors: the inductively driven RF source, developed at IPP Garching, versions of which are used on the ASDEX Upgrade and Wendelstein 7AS neutral beam injectors [19]. The development of a negative ion version of these sources is currently underway at IPP Garching in Germany. The latest version [20, 21] (see figure 8) has an RF coil around a ceramic cylinder connected to the rear of a rectangular chamber. RF power applied to the coil initiates, and inductively couples to, a plasma inside the ceramic cylinder, which then expands into the rectangular chamber. Arrays of permanent magnets on the outside of the rectangular chamber and on the rear of the cylinder improve the plasma confinement. The plasma grid is located on the wall opposite the ceramic cylinder, on the far side of the rectangular box. Permanent magnets placed either side of the chamber form a magnetic filter in front of the grid (as in the arc discharge negative ion sources). A copper Faraday shield can be installed inside the ceramic cylinder to protect the ceramic from sputtering by the plasma. It is found that the addition of argon to the hydrogen plasma significantly enhances the H^- yield (the 'argon effect') and further enhancement is obtained by adding caesium. This source has yielded 150 A m^{-2} of H^- at a source filling pressure of 0.7 Pa.

Although a substantial improvement is required, particularly a reduction of the source operating pressure, this source shows a lot of promise, in particular:

- As there are no filaments, there is no filament lifetime problem, hence the 'regular' maintenance of the ion source would be reduced to the replenishment of the Cs.
- It is possible that a deeper understanding, and enhancement, of the 'argon effect' could lead to operation without any caesium.

4.3.1.3. Caesium. The addition of caesium to an arc discharge ion source is found to significantly enhance, by more than a factor 4, the negative ion production [14, 22, 23]. (A smaller enhancement is found with the RF source mentioned above.) However the effect disappears after a certain time, i.e. the Cs is 'consumed'. This is believed to be due simply to the loss of Cs neutrals from the source. The Cs should be ≈98% ionized, and Cs^+ is inhibited from leaving the source by the (negative ion) extraction potential. However, the 2% Cs that is not ionized can simply flow out of the source via the apertures in the plasma grid.

The Cs consumption rate is small (it is calculated to be <1.6 μg per second of operation of the ITER source), and a negligible amount of Cs will reach the tokamak [16]. However, the Cs accumulates in the system, mainly in the accelerator. With the short pulse systems presently in use this has never caused any problems. However, over very long periods of beam operation it must be expected that problems will arise, e.g. from Cs accumulation on the insulators of the accelerator, and Cs removal must be anticipated. For the ITER FEAT system, *in situ* Cs removal schemes have been developed (water wash and laser ablation), but the frequency at which this will be necessary is as yet unknown, although it is certainly much lower than the filament replacement frequency.

On present day systems the Cs is supplied from a small oven connected directly to the ion source, which contains a fixed, small, quantity of Cs. The same solution is proposed for ITER, where the oven will contain 10 g of Cs, sufficient for 6000 shots of 1000 s duration, after which the Cs in the oven will need to be replaced. On ITER it is planned to refill the oven at the same time as the filaments are replaced, so this will involve little extra effort. The same procedure could be adapted on injectors requiring regular maintenance. However, if the filament lifetime problem is removed, e.g. by the use of a filament-less source such as the RF source discussed above, then the Cs replenishment and/or the Cs clean up would be the only reason for regular maintenance of the injector (other than component failure or replacement due to fatigue—see below). The problem of a long term supply of Cs, i.e. not using a limited quantity in a local oven, is a technical problem that can, in principle, be overcome by having a remote Cs supply. Thus, it is important for future injectors that the frequency of Cs clean up be determined, or the use of Cs avoided. The discovery of the 'argon effect' with the RF source (see 4.3.1.2) may open up the possibility of Cs free operation.

4.4. Fatigue

The components in the injector will experience abrupt 100% power variations at the start and end of each pulse (0 to full power or the reverse, in ≈100 ms) and during accelerator breakdowns. The accelerators used in all neutral beam systems experience 'breakdowns', i.e. instantaneous short circuits between grids in the extractor, pre-accelerator or the accelerator. Like present day systems, the ITER injector power supplies are designed to switch off all power to the accelerator for a short period when a breakdown is detected, then to reapply the power. The time between detection and reapplication of the accelerator voltages will be between 130 and 180 ms, so, if the reapplication is successful, this 'off period' will be almost invisible to the ITER plasma. However, the thermal response of the high heat flux components is such that they experience a partial fatigue cycle in this time. Of course a full fatigue cycle is experienced at the start and end of each pulse. Now the frequency of accelerator breakdowns has been estimated by extrapolation from experience with present day systems (negative and positive ion based) as 1 per 50 s during operation, and an average of 1 per 5 s during commissioning. At first sight these figures may appear low when compared to the breakdown frequency experienced with present day positive ion based injectors. However, negative ion injectors operate at a much lower perveance[4], and it is generally found that operating at low perveance substantially reduces the breakdown frequency. It is encouraging to note that during the 1000 s pulse shown as figure 7, there was only one breakdown.

The total number of full, on/off, cycles and breakdown induced cycles foreseen for ITER FEAT is 4×10^4 and 4.5×10^5.

Because of the high number of fatigue cycles, fatigue failure must be considered for the injector components, and there is a clear difference between long pulse and continuous operation. For the ITER FEAT, long pulse system, the injector components are designed to survive throughout the lifetime of ITER FEAT. With continuous operation as in a reactor, it will probably be necessary to foresee component replacement as a regular event unless the breakdown frequency can be reduced significantly. Experience with the JET injectors, indicates that the most obvious way to ease the remote maintenance difficulties is to allow for vertical access with a crane, which is likely to have a significant impact on the design of the reactor.

4.5. Sputtering

The incident particle density on the RID is such that erosion of these components by sputtering may have to be considered. Unfortunately, there is little data on the sputtering of copper by deuterium at the energies and angles of incidence that will be experienced by the injector components. A first approximation can be obtained by assuming that the sputter yield (γ) is $\approx$4 times higher at low angles of incidence [24] and extrapolating (assuming $\gamma \propto 1/\text{energy}$ from the measured yields for moderate energy hydrogen [25–27] (<40 keV). (The sputter yield of 40 keV H^0 at normal incidence on a rough copper surface is $\approx 2 \times 10^{-3}$ [24], at an angle of $\approx 12^\circ$ with respect to the surface is $\approx 9 \times 10^{-3}$ [24]. Similar results are found with a smooth copper surface [27].) The yield at 1 MeV for D^0 is calculated to be $\approx 7 \times 10^{-3}$. Taking the surface power density as 6 MW m^{-2}, the surface erosion rate is then calculated as $\approx 3.2 \times 10^{-9}$ mm s^{-1}. Assuming that the erosion of the surface by 0.5 mm is acceptable, the lifetime against erosion is then $\approx$7.5 years of continuous operation. Although this is a very rough calculation, one can conclude that sputtering is not a serious problem for ITER, but it could be for a continuously operating system. It is worth noting here that copper sputtered from one RID plate may be re-deposited on the opposing plate, further reducing the actual erosion rate.

Sputtering from the calorimeter will be higher than that from an RID plate as the power density is higher, but again there will be re-deposition on the opposing calorimeter plate. However, this is not likely to be a problem even for a continuously operating system as the calorimeter is only used for the relatively short commissioning and recommissioning periods.

4.6. Thermal equilibrium considerations

It is clear that in continuous operation all the components will reach thermal equilibrium, although this is not necessarily true for 'short' long pulses, e.g. 500 s operation, as some components in the subsystem can have very long thermal time constants (>1000 s), such as the transformers of the power supplies.

Any beamline component that receives power will heat up until thermal equilibrium is achieved. As the components of a neutral injector are all under vacuum, there is no convective cooling, and any conduction cooling will be poor unless the connection to a cooled component is very good, i.e. via a brazed or welded connection. If the most significant cooling is via radiation, then even very low heat loads will lead to high temperatures, e.g. to radiate 10 W cm^{-2} from a black surface requires a surface temperature of $\approx 850^\circ$C; the power density at the centre of an ITER neutral beam at the beamline calorimeter is about 10^4 W cm^{-2}. Thus, great care must be taken to ensure that all components that receive even small heat loads are sufficiently cooled (see 'devious' particles below).

4.6.1. Devious particles. A class of particles, dubbed 'devious', inhabit all neutral beam injectors. These are particles that do not constitute a part of the normal beams, but they carry power, and must be collected on adequately cooled surfaces. The situation as regards the devious particles identified in the case of the ITER FEAT injectors is discussed here in order to illustrate the care that must be taken in designing long pulse injectors where even small power loads must be absorbed on cooled surfaces (see section 4.5). The devious particles in an ITER FEAT injector are:

(i) High divergence particles due to aberrations in the extractor and/or accelerator.
(ii) High divergence D^0 created by stripping in the extractor and accelerator.
(iii) Accelerated electrons from either stripping or secondary emission in the accelerator or extracted and 'leaking' from the extractor into the accelerator.
(iv) Back streaming positive ions created by ionization and charge exchange in the accelerator.
(v) Full energy neutrals created inside the RID by neutralization of the D^- and D^+ exiting the neutralizer
(vi) Ions or electrons extracted from the neutralizer by the electric field from the RID.

[4] The perveance is defined as $I/V^{3/2}$, where I and V are the accelerated current and the acceleration voltage.

(vii) D^+ created by re-ionization of the D^0 beam exiting the neutralizer.
(viii) Secondary electrons created in the RID by the deflected positive ions hitting the RID plates.

The most important categories of devious particles are (iii) the electrons from the accelerator ($\approx$3 MW), (vii) the re-ionized D^0 ($\approx$0.8 MW), and (viii) the secondary electrons generated in the RID ($\approx$1.2 MW).

In the ITER FEAT injectors types (i)–(iii) will fall either on the acceleration grids or the neutralizer, which are all cooled, and the back streaming ions will impinge on the (cooled) ion source body. It is necessary to carry out calculations to estimate the powers in these particles and assure that adequate cooling is installed.

The power and trajectories of all the re-ionized D^0 have been carefully considered for the ITER FEAT injector. Approximately 50% are created in the RID, and the rest between the RID exit and the tokamak plasma. Those created in the RID are deflected by the electric field, and most are lost on the walls of the RID. A few of these strike the calorimeter (in its open position), or the beam scraper located at the exit of the injector. D^0 re-ionized downstream of the RID are deflected into the walls of the duct between the injector and the tokamak by the stray magnetic field from ITER. A cooled liner is installed in the duct to remove the associated power. It is well-known that the dumped, re-ionized, particles desorb gas from the duct wall, which leads to enhanced re-ionization and, in some circumstances, to 'beam blocking'. This phenomenon has been carefully evaluated for the ITER FEAT situation and it has been shown not to be significant.

The secondary electrons created in the RID are accelerated from the negative (positive ion collecting) plates across to the positive plates. The RID cooling is designed to cater for the extra power from these electrons. Here, it is necessary to mention that the secondary electrons experience not only the electric field of the RID, but also the stray magnetic field from the tokamak. Their rather complex motion in the combined field has been calculated, and they are all eventually lost on the cooled RID plates. In spite of the long path length of some of the secondary electrons, no 'magnetron' type discharge should occur due to the low pressure in the RID.

5. Summary and conclusions

Long pulse operation of future neutral beam injectors in the foreseen hostile radiation environment presents many challenges. Although further R&D is required, the successful design of the injectors for ITER FEAT has shown that the realization of injectors producing high power, high energy beams for 1000 s pulses with a reasonable efficiency is feasible. The development of continuously operating injectors such as might be required on a fusion reactor presents even more challenges and requires yet more R&D.

Key maintenance issues that have been identified are the cathodes of the ion source, the caesium accumulation in the accelerator and fatigue failure of the beamline components. The successful development of long life cathodes would ease the problem of filament replacement, and the successful development of the RF driven negative ion source would remove this necessity completely. It is also possible that an understanding of the 'argon effect', i.e. the enhancement in negative ion yield seen in the RF source when argon is added to the plasma, could remove the need to add caesium to the ion source. Although substantial improvements in the performance of the RF source are required to achieve these goals, it is clear that this development is to be strongly encouraged.

The very rough calculations given here show that sputtering may also lead to maintenance after some years of operation. However, there is little data available and R&D is required to determine the sputtering yield at the deuterium energies of interest, and at small angles of incidence.

The difficulties of continuously operating pumps can be considerably eased if the gas flow into the injector is substantially reduced. The successful development of plasma neutralizer would have the twin benefits of increasing the injector efficiency (to $>$50%) due to the increase in neutralization from $\approx$60% to $\approx$80%, and substantially reducing the gas input to the neutralizer, by up to a factor 20 if argon can be used as the neutralizer gas. As with the RF source, substantial development is required to reach these goals.

The use of a plasma neutralizer would also reduce the charged fractions in the beam leaving the neutralizer, and hence reduce the power load to the RID. This should lead to smaller temperature changes on the high heat flux elements, and hence an increased fatigue life of that component. The other component that is likely to have a limited fatigue life is the calorimeter. However, with a continuously operating injector, by definition the calorimeter would be little used once the system is operational, and its fatigue life is probably not critical.

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