Chapter

Research, Design, and Development Needed to Realise a Neutral Beam Injection System for a Fusion Reactor

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Abstract

The ion temperature in the plasma in a fusion reactor must be sufficiently high that the fusion reaction (probably between D^+ and T^+) will need to be high to ensure that the reaction rate is as high as is required. The plasma will be heated by the energetic alpha particle created in the fusion reaction, but it is widely accepted that additional (externally supplied) heating will also be required to ensure a sustained "burn" and, perhaps, to control the reaction rate. A reactor based on the tokamak confinement system requires a toroidal current to flow in the plasma. Most of that current will be created by the "bootstrap" effect, but an external method of driving current in the poloidal centre of the plasma is needed as the bootstrap current will be low, or zero in that region. Neutral beam injection is an efficient heating mechanism and it has the current drive efficiency required in a reactor. In this chapter the R&D required for an NBI system for a reactor, is considered against the background of the ITER NBI system design as the ITER beam energy and operating environment are reactor relevant. In addition the elements requiring most development are identified.

Keywords: neutral beam injection, negative ion sources, beamline design

1. Basic considerations for a neutral beam injection system on a reactor

A neutral beam system on a fusion reactor will have to meet specifications that are significantly beyond those of any system so far designed. The injectors will be directly connected to the reactor vessel, and therefore they will both form a part of the nuclear confinement barrier and be subjected to high levels of neutron and gamma radiation. Consequently, the injector design must include a radiation barrier around the injectors; the choice of materials that can be used must be acceptable to the vacuum environment, be radiation tolerant, and, where possible, be low-activation materials. In addition, the design will have to satisfy the nuclear regulator, which, typically, limits the engineering design codes that can be used.

It is clear that the main factors that will influence the design of the injectors, and require R&D, are the pulse length, the global efficiency, operation and maintenance in a nuclear environment, and component lifetime. In the following sections of this chapter, each of the aforementioned aspects is discussed more in detail and some suggestions given as to how problems arising from each aspect may be resolved and the parameters of the future injectors achieved. However it is important to understand that although various basic conceptual designs of an injector to be used on a fusion reactor have been considered [1–3], no concept has been chosen, and no serious engineering design of any concept has been carried out. Experience with the design of the neutral beam systems has shown that many aspects of the conceptual design are changed significantly during the engineering design phase. For example:

- The initial design of the neutral beam system on the JET tokamak had one single large ion source, whereas the final design has eight smaller beam sources [4] with the accompanying four residual ion deflection and collection systems and four beamline calorimeters.

- The initial design of the ITER injectors used a vacuum vessel of cylindrical cross section, and all component removal and maintenance were to be carried out through the rear of that vessel [5]. The design being constructed uses a vessel that is rectangular in cross section with a removable lid that allows removal and maintenance of the beamline components from above the injector [6].

It is clear from the above examples that the resolution of problems arising from operation in the fusion reactor environment, for example, maintenance of the injector components, can depend strongly on details of the injector design and that the methods to achieve the required parameters of the injectors may also depend strongly on the details of the design. Therefore the following sections of this chapter do not consider any design in detail, but, against the background of the design of the injectors for ITER, they try to describe the problems that will arise and to suggest ways in which they might be resolved. Also it is important to understand that the components of a neutral beam injector are interdependent and that in the following sections the assumptions made about the design and/or performance of the injector are self-consistent.

2. Issues related to the design of a neutral beam injector operating on a fusion reactor, some possible ways to resolve those issues and suggested R&D

2.1 Global efficiency

The global efficiency of a heating system is simply the ratio of the electrical power required to operate the heating system divided by the power absorbed by the device being heated, the fusing plasma in the case of a fusion reactor, and it is of overriding importance for a fusion reactor. This can easily be understood with an example: suppose that the heating power required to heat the fusing plasma to the temperature required to ensure that the rate of fusion reactions in the plasma is that required to achieve the electrical output from the reactor is 100 MW. Then, if the global efficiency of the heating system were similar to that achieved by the systems operating today, of the order of 25%, about 400 MW of electrical power would be required simply to operate the heating system, that is, the output of a typical power station. There have been several studies aimed at defining an acceptable global efficiency for the heating systems of a fusion reactor, and the typical result is ≈60% or higher [7].

The specification of the neutral beam injectors designed for ITER is the closest of any design to that which would be suitable for use on a fusion reactor.

Thus it is interesting to look at the expected efficiency of the ITER injectors to see where improvements must be made. **Table 1** shows the expected performance of an ITER-like injector plus indications of possible performance changes that could lead to an injector operating on a fusion reactor. Each of the suggested changes is discussed in more detail below.

Before discussing the various items impacting the global efficiency, it is important to understand some of the more important constraints on the design of the injectors.

Firstly, the injectors will need to be commissioned after the first installation on the reactor and then maintained and recommissioned several times during their lifetime. Commissioning or recommissioning of all the injectors involves firing the neutral beam through the beamline components and into a beam dump, usually called a calorimeter. The overall process is that at the start of commissioning, the beam source is operated at low power and beam energy and for short pulse lengths, for example, 5–10 s. That ensures safe operation of the system even if the beam quality, such as the beamlet divergence, is not optimal. Once safe, good operation is achieved at the selected low power, the beam power, energy, and pulse length are gradually increased. This continues until full power and pulse length are achieved, always with the neutral beam being intercepted on the calorimeter. No system has yet been developed which allows commissioning of the high power beam system without a calorimeter. As it is almost certain that a calorimeter is required, it must be designed to withstand the power and power density it will be subjected to, and this has been demonstrated to be a restricting factor in the design of an injector for the ITER heating NB injectors. The calorimeter was one of the most difficult beamline components to be designed, and it can be reasonably considered that the power and power density handling of the ITER calorimeter design is close to the limit of what is technologically possible. Thus the beamline calorimeter sets a limit on the neutral beam power that can be produced by a neutral beam injector of ≈17 MW. In **Table 1**, the changes to be made for an injector to be used in a fusion reactor are such that this limitation is respected.

Table 1 gives a calculation of the global efficiency of an ITER-like heating neutral beam injector (HNB) and of a possible injector for a fusion reactor. Both deliver ≈17 MW of 1 MeV D^0 to the plasma in the device. The calculations in **Table 1** assume that for the injector on a fusion reactor:

I. The ion source and accelerator will be similar to those of the ITER-like injector.

II. The gas flow into the ion source will be 3 times lower than the flow into that of the ITER-like injector.

III. The ion source on the injector on a fusion reactor will be based on solid-state technology with an efficiency of 85%.

A photon neutraliser will be used that has a neutralisation efficiency of 90% and a laser power of 800 kW, with a laser efficiency of 40%. A lower laser efficiency would be acceptable if the required laser power is <800 kW.

2.1.1 Detailed discussion

This section discusses the items of **Table 1** that are considered not to be self-explanatory.

		ITER-like injector (MW)	Reactor injector (MW)
1	RF power to ion source	0.8	0.4
2	Electrical power for the ion source: the AC to RF conversion efficiency for the ITER-like ion source power supplies is ≈50%. The efficiency of the solid-state RF power supplies used for the reactor injectors is assumed to be 85%	1.6	0.5
3	Stripping loss: this is approximately proportional to the gas flow from the source, which is assumed to be reduced by a factor 3 for the reactor injectors	8.0	1.5
4	Back-streaming ion power: this is approximately proportional to the gas flow from the source (see above)	1.0	0.2
5	Electron power exiting the accelerator: this is approximately proportional to the gas flow from the source (see above).	1.0	0.2
6	Total accelerated power	40.0	22.3
7	Total power lost in the accelerator (including back-streaming ions): this is approximately proportional to the gas flow out of the source (see above).	10.0	1.9
8	DC power to accelerator:	50.0	24.1
9	Electrical power to the accelerator: the AC to DC conversion for the accelerator power supplies is assumed to be 87.5% for both injectors	57.1	27.6
10	Beamlet halo: for the beam source of the HNBs, this is assumed to carry 15% of the power of each beamlet, whereas that of the reactor beam source is assumed to be 5%	6.0	1.1
11	Neutral power exiting the neutraliser: neutralisation for the D_2 target is ≈56%; with a photon neutraliser, it is assumed to be 90%	19.0	19.0
12	Neutral power to ITER without re-ionisation loss: the geometric transmission is taken to be the same for both injectors, 95%, for the core of the beamlets	18.1	18.1
13	Re-ionisation loss: in the reactor injector, the total gas influx is reduced by a factor of ≈15; consequently the re-ionisation losses are similarly reduced	0.9	0.06
14	Power injected into ITER:	17.2	18.1
15	Electrical power to the electrostatic residual ion dump: this is reduced because of the considerably higher neutralisation achieved with the photon neutraliser	1.05	0.04
16	Electrical power to the laser: 800 kW of laser power is assumed to be required to inject sufficient photons into the neutraliser, and the laser efficiency is assumed to be 40%	0.0	2.0
17	Electrical power to the active correction and compensation coils: assuming that the AC to DC conversion efficiency for the ACC coil power supply is 95%	1.6	1.1
18	Electrical power for the cryogen supply: 0.5 MW is estimated as the additional power at 4 K in the ITER cryoplant needed for the HNB cryopumps (≈5 MW electrical power). The required pumping speed is reduced in proportion to the gas flow per injector, and the power in the reactor cryoplant is similarly reduced.	5.0	0.2

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	ITER-like injector (MW)	Reactor injector (MW)
19 Electrical power for the water cooling of the beam source and the beamline components: the power needed for the water pumps for the higher efficiency injector is reduced proportionately	0.8	0.1
Total electrical power to the injector	67.2	32
Overall efficiency	26%	57%

Table 1.
Global efficiency of the ITER HNBs and possible injectors for a fusion reactor, based on reduced gas flow into the ion source, improved RF power supplies and a photon neutraliser.

2.1.1.1 RF power to the ion source

The requirement to limit the neutral power to the calorimeter combined with efficiency increases elsewhere in the injector for a fusion reactor leads to a reduction in the accelerated negative ion current of about a factor 2 (see Section 2.1.1.5.), which leads to a similar reduction in the maximum power into the RF source. The reduction in the accelerated negative ion current leads to a more easily realised extracted negative ion current, lower power to the extraction and acceleration grids, lower back-streaming ion power, and lower electron power exiting the accelerator, all of which are very desirable.

2.1.1.2 Electrical power for the ion source

The current design of the RF power supply for the ITER neutral beam injectors uses a high power tetrode oscillator, which results in an efficiency of RF power production of about 50%. More modern RF power supplies which use solid-state technology have a power efficiency of about 85%. The use of such solid-state RF power supplies with an ITER-relevant type of RF-driven ion source has recently been successfully demonstrated at the ELISE facility in IPP, Garching, Germany [8].

2.1.1.3 Stripping loss and back-streaming positive ions

The negative ions extracted from the ion source can, and do, undergo diverse charge changing reactions with the background gas:

$$\underline{D}^- + D_2 \Rightarrow \underline{D}^0 + D_2 + e \tag{1}$$

$$\underline{D}^- + D_2 \Rightarrow \underline{D}^0 + 2D + e \tag{2}$$

$$\underline{D}^- + D_2 \Rightarrow \underline{D}^0 + D_2^+ + 2e \tag{3}$$

$$\underline{D}^- + D_2 \Rightarrow \underline{D}^0 + D + D^+ + 2e \tag{4}$$

$$\underline{D}^- + D_2 \Rightarrow \underline{D}^0 + 2D^+ + 3e \tag{5}$$

$$\underline{D}^- + D_2 \Rightarrow \underline{D}^+ + D_2 + 2e \tag{6}$$

$$\underline{D}^- + D_2 \Rightarrow \underline{D}^+ + 2D + 2e \tag{7}$$

$$\underline{D}^- + D_2 \Rightarrow \underline{D}^+ + D_2^+ + 2e \tag{8}$$

$$\underline{D}^- + D_2 \Rightarrow \underline{D}^+ + D^+ + D + 2e \tag{9}$$

$$\underline{D}^- + D_2 \Rightarrow \underline{D}^+ + 2D^+ + 3e \tag{10}$$

where the underlined species are high-energy particles. Because the above reactions occur inside the accelerator, the produced $\underline{D}^0$ will not have the full acceleration energy, and the precursor $\underline{D}^-$ will not have experienced the full electrostatic optics of the extractor and accelerator, and therefore the $\underline{D}^0$ will in general have a higher divergence than the fully accelerated $\underline{D}^-$. After it is created, the $\underline{D}^+$ will be decelerated, and it will either exit the accelerator with reduced energy, or they will be reflected, and they return to the ion source, and they will impinge on the rear of the ion source.

In addition to the above reactions, the accelerated $\underline{D}^-$ can simply ionise the background gas, that is:

$$\underline{D}^- + D_2 \Rightarrow \underline{D}^- + D_2^+ + e \tag{11}$$

$$D^- + D_2 \Rightarrow \underline{D}^- + D^+ + D + e \tag{12}$$

$$D^- + D_2 \Rightarrow \underline{D}^- + 2D^+ + 2e \tag{13}$$

The D^+ and D_2^+ created in reactions (11)–(13) will be back-accelerated, and they return to the ion source, and they will impinge on the rear of the ion source.

The background gas in the extractor and accelerator of a negative ion-based injector comes overwhelmingly from the ion source, and the background gas density decreases with the distance from the plasma grid. That, combined with the fact that the cross sections of reactions (1)–(13) decrease with the energy of the precursor D^- at energies above ≈10 keV, means that essentially all the D^0 produced by reactions (1)–(5) is not useful for heating a fusion reactor and the precursor D^- is considered as lost in the accelerator. Although the D^+ created by reactions (6)–(10) can be neutralised to produce D^0, that reaction is negligible for D^+ at energies close to that required of the D^0 needed to heat the fusing plasma, so the D^- that undergoes reactions (6)–(10) is also considered to be completely lost. The losses via reactions (1)–(10) are commonly referred to as stripping loss.

In the case of the ITER heating neutral beam injectors, the stripping loss is calculated to be ≈8 MW, and the power in the back-streaming positive ions (mainly from reactions (11)–(13)) is calculated to be ≈1 MW. It is obvious that losing ≈9 MW in an injector that is designed to deliver ≈17 MW to the plasma has a major impact on the global efficiency of the injector, and it must be reduced if the target of 60% global efficiency is to be met. As noted above, most of the background gas in the accelerator comes from the ion source. Hence to achieve a global efficiency of 60%, that gas flow must be reduced. Fortunately, it has been demonstrated with a filamented ion source that extracted current densities higher than those needed in the injectors for a fusion reactor assumed in **Table 1** can be achieved with a filling pressure (the pressure in the in source without source operation) of 0.1 Pa [9], a factor 3 lower than the target value for the ITER injectors. Thus that value is chosen in **Table 1** for the injector of a fusion reactor. It must be noted that any filamented source, including the source type where operation at the low gas flow has been demonstrated, is not considered suitable for use on an injector to be used on a fusion reactor because of the limited lifetime of the filaments (<200 h). Operation at such a low gas flow has not yet been achieved in the type of source to be used on the ITER injectors, an RF-driven source, and significant R&D is needed to develop an RF-driven source that can operate at such low gas flows.

Back-streaming ions are positive ions that are created inside the accelerator, which are then accelerated back to the ion source by the electrical fields in the accelerator. There are three reasons the power in the back-streaming ions must be reduced in an injector on a reactor:

i. Reduction of the back-streaming ion power contributes to increasing the global efficiency of the injectors.

ii. Lifetime of the ion source backplates: the back-streaming ions sputter material from the backplates, and eventually the back-streaming ions will drill through the backplate and, most likely, reach the cooling water channel in the backplate. This problem is avoided in the sources designed for ITER by having a 1-mm-thick molybdenum layer on surface of the backplates receiving the back-streaming ions. Most of the sputtering is due to H_2^+ (from reaction (11)), and the sputtering rate of Mo bombarded by H_2^+ is low compared to other possible materials (copper, nickel, etc.), and it is calculated that a 1-mm-thick layer of Mo will not be eroded away during the foreseen lifetime of ITER [10]. The calculations in [10] predict an erosion depth of ≈0.5 mm during the ITER lifetime, but they assume that D^+ and D_2^+ are the only back-streaming ions. In fact Cs will be present in the extractor, and at a lower density in the accelerator, that Cs will be ionised by the accelerated D^- and back-accelerated into the source. It is calculated that the erosion by Cs^+ could be as important as that of the D_2^+ [11] and that back-streaming Cs^+ will overlap with the back-streaming D_2^+ and add to the erosion by D_2^+. The erosion over the lifetime of the reactor would be about 20 times higher than in the ITER HNBs, which have a duty cycle of 25%. The Mo layer thickness cannot be increased 20-fold to counter that as that would lead to a design of the backplates that cannot withstand the power density from the back-streaming ions.

iii. Reduction of the Cs "consumption": the conversion of D atoms impacting the PG with a low work function surface is the main method of D^- in the ion source. To create the low work function surface Cs is injected into the ion source and deposited on the PG. If Cs injection is stopped, the extracted ion current is found to decrease after some period of operation, which is due to the an increasing PG surface work function, which may be caused by impurities reacting with the Cs on the PG, or coating of the Cs by other material. This is termed "Cs consumption". In order to maintain the D^- production rate and the extracted D^- current constant, it is found necessary to inject Cs into the ion source periodically or even continuously. To avoid the metal sputtered from the backplates that is deposited on the PG, increasing the work function is likely to increase the Cs consumption rate, which is highly undesirable (see Section 4).

It has been suggested that if the plasma grid were made from a low work function material, there would be no need to inject caesium into the source, with the accompanying problems discussed in Section 4. However, as mentioned above, if the PG is coated by several monolayers of metal sputtered from the backplates, the work function will increase leading to a reduction in the negative ion production and hence in the extracted current. The sputtering rate for the ITER beam source is by back-streaming D_2^+ which is calculated to be 5×10^{16} atoms/s, and the rate for the injector on a reactor may be a factor ≈6 lower if the extracted current density is lower (see Section 1.2) by a factor 2 and the gas density in the accelerator is reduced by a factor 3. As a monolayer corresponds to about 10^{17} m^{-2}, so it is obvious that several monolayers of the sputtered material will be deposited on the PG in a time that is short compared to the reactor lifetime.

Potential solutions to the problems discussed above are:

a. Easily replaceable backplates plus a reduction in the back-streaming ion flux. Since the back-streaming D_2^+ is directly proportional to the of D_2 in the extractor and accelerator and that of Cs^+ ion intensity is directly proportional to the density of Cs in the extractor, reducing by a factor 3 the D_2 flow out of the ion source and the Cs density in front of the PG would reduce the sputtering of the ion source backplates enough to avoid the erosion causing a water leak in <1 year of reactor operation, allowing the backplates to be replaced during an annual maintenance period.

b. It should be noted that a factor 3 reduction in the sputtering of the backplates is not sufficient to prevent a non-renewable PG surface deteriorating in a time that is short compared to the lifetime of a reactor.

c. Bending of the D^- after the extraction grid and offsetting the subsequent acceleration grids such that the back-streaming ions, which cause most of the sputtering of the backplates, could be directed onto dumps that are separated from the beam source. The reduction in the sputtering thus achieved should be sufficient to allow the backplates to survive for more than 1 year, but replacement of the backplates must be foreseen.

d. Unfortunately the reduction in the sputtering would not be sufficient to allow a non-renewable low work function PG to maintain its low work function for the lifetime of a reactor. Therefore, the use of a non-renewable low work function PG is not viable.

e. In situ cleaning of the sputtered material off the PG might allow a low work function PG to be used. Of course that would not solve the backplate problem. As a and b above do not solve the problem of the sputtered material "polluting" the PG, it can be concluded that there is little point in carrying out R&D on the creation of a low work function PG unless a technique is developed to remove the sputtered material from the PG in situ.

2.1.1.4 Electrons exiting the accelerator

Some electrons are co-extracted from the ion source, and, as noted in Section 2.1.1.3, electrons are created in the accelerator via reactions (1)–(13). Electrons in the extractor and accelerator will be co-accelerated along with the negative ions until they are deflected onto the extraction grid or one of the accelerator grids, or they exit the accelerator. The power loss in the extractor is given in **Table 1**, line 2, and line 5 gives the power in the electrons exiting the accelerator. That power is deposited on downstream beamline components and the beamline vessel. The reduction in the gas density in the extractor and accelerator, as discussed above, results in a reduction in the exiting electron power by a factor similar to the reduction factor for the back-streaming ions.

2.1.1.5 Total accelerated power

Line 6 of **Table 1** gives the total accelerated D^- power for the injector to be used on a fusion reactor as 22.3 MW compared to 40 MW for a heating neutral beam injector for ITER. The main reason for the reduced accelerated $D-$ power is to keep the power density on the calorimeter similar to that of the ITER injector.

2.1.1.6 Beamlet halo

Early measurements of negative ion beamlet profiles suggested that the optics of the beamlets are not well described by a simple Gaussian divergence, that is,

$$P(\omega) = P_0 * exp\left(-\left\{\frac{\omega^2}{{\omega_0}^2}\right\}\right) \tag{14}$$

where P(ω) is the power density at a radial position that subtends an angle with respect to the beamlet axis of ω and ω_0 is the beamlet divergence. The measured profiles were found to be better fitted by a bi-Gaussian profile. For the ITER design, the latter was chosen, that is,

$$P(\omega) = (1 - f) * P_0 * exp\left(-\left\{\frac{\omega^2}{{\omega_0}^2}\right\}\right) + f * P_0 * exp\left(-\left\{\frac{\omega^2}{{\omega_{0h}}^2}\right\}\right) \tag{15}$$

where f is the fraction of the beamlet power carried by the "halo", which has a divergence of ω_{0h}. For the ITER design, f was assumed to be 15%. It is assumed that R&D from the ITER neutral beam test bed and other negative ion-based systems will allow an improved optics with a halo carrying only 5% of the beamlet power.

3. Pulse length

All neutral beam injection systems that have been designed or built have been conceived for a pulsed mode operation, whereas fusion reactors, and any NBI system to be used on the reactor, are expected to operate continuously for 1 year or more. Continuous operation will require fundamental changes in the design of the injectors, such as:

3.1 Pumping and gas flow

All NBI systems so far designed and/or built require very high pumping speed at the exit of the accelerator and downstream of the residual ion dump in order to minimise beam loss. The former is needed in order to reduce the gas density, and hence the stripping losses, in the accelerator and the latter to reduce the pressure in, and downstream of, the residual ion dump and hence the re-ionisation of the neutral fraction of the beam in that region and in the duct leading to the reactor vessel. That is important as re-ionised particles will be deflected into the walls of the duct by the stray magnetic field from the reactor, reducing the injected power as well as heating the duct walls. The latter is important as removing heat deposited in the duct leads to water-cooled components in the duct, and those may occasionally require maintenance. As those components will become highly active during operation of the reactor, such maintenance will only be possible by remote means, which is inherently complicated and difficult. Reducing the power load means that the components can be designed with a high safety factor, leading to less, perhaps no, maintenance in the lifetime of a reactor.

Cryopumps that "wallpaper" each side of the injector beamline vessel can provide a sufficient pumping speed for D_2, which in the ITER heating injectors is $\approx 3 \times 10^6$ l/s [12]. Gas is not removed from an injector by cryopumps, it is simply frozen on the cryogenically cooled panels of the pumps, and the quantity of D_2 that can be stored on the pumps is limited because of the possible explosion; if the D_2 is released from the pumps, there is sufficient oxygen inside the injector, and a source of ignition is present. Although the risk is low, it is not acceptable, especially in the case of a reactor where the injector is part of the confinement barrier. Consequently, when the gas storage limit is reached, it is necessary to regenerate the pumps, i.e. to release the stored D_2, and pump it away with an external pumping system. As several injectors are likely to be installed on a reactor in order to provide the required total heating and current drive power, continuous provision of the required power can be assured by installing one "excess" injector. Then if the n injectors are installed, $n - 1$ injectors provide the required power, and only $n - 1$ are usually operating. That allows the non-operating injector to be isolated vacuum wise from the reactor and to be regenerated, with each injector being regenerated in turn. That only works if the regeneration time[1] is $\leq\tau/(n - 1)$ hours, where τ is the time for which each injector can operate before regeneration is needed. As an example, assume that the injectors can be regenerated in 1.5 h and that each injector can operate for >3 h before needing to be regenerated. Then with three injectors installed on the reactor, one is regenerated each hour, so that the cryopump of each injector is regenerated after 3 h of operation; all three injectors are regenerated after 4.5 h, and the cycle is then repeated, as shown in **Figure 1**. Having an "extra" injector is expensive, both because of the cost of the injector and the additional cost of operating the extra injector and because it reduces the efficiency of the reactor as the wall space needed for the extra injector cannot be used for generating power.[2]

In the example given above, the injectors would have to operate >3 times longer than permitted for the ITER injectors, so that, all other things being unchanged, the total gas flow into the injectors on the reactor would have to be reduced by a factor 3 compared to the gas flow into the ITER injectors, and that must be achieved without degrading the injector performance or the global injection efficiency.

An alternative to having an extra injector is to instal a higher pumping speed than is required for the efficient operation of the injector and to be able to regenerate the "unnecessary" part of the cryopumps in situ. For example, if the installed pumping speed were twice that required for the efficient operation of the injector, then half the pump could be shut off from the injector, whilst the other half continues to operate; once the first half has been regenerated, that can be opened up to the injector and the second half closed off for regeneration and so on.

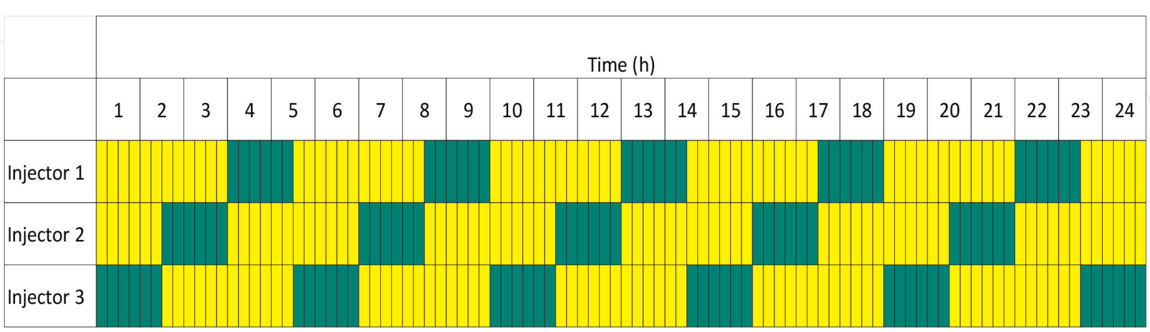

Figure 1.
Schematic of the regeneration cycle for a neutral beam system with three injectors installed, with each injector capable of operating for >3 h before regeneration of the cryopumps being necessary. The yellow areas indicate that the injector is operational and the green ones that it is being regenerated. Two injectors are always operational.

[1] The regeneration time consists of the time to isolate the injector from the fusion device, warming up the cryopumps to the release the gas, pumping down the injector and cooling down the cryopumps, plus the time to recondition the injector.

[2] If a reactor costs 2×10^9 €, and the apertures in the blanket for the injectors take up 1% of the wall space, the cost of not producing power from that fraction of the wall is 2×10^7 €, i.e. 66 M€ per injector.

Unfortunately no system for closing off part of a cryopump sufficiently to allow it to be regenerated whilst the rest of the pump continues operation has yet been developed.

In the above discussion, it is assumed that cryopumps will be used in the NB injectors. It has been suggested that non-evaporable getters (NEGs) could be used instead of cryopumps. NEGs have an advantage that no sudden release of the gas captured by the getters is possible; thus there is no safety hazard associated with the storage of large quantities of D_2 in the getters. If NEGs are to be considered, a viable assembly of NEGs needs to be designed, using NEGs that will not be poisoned by any impurities in the NB injector and, obviously, that the assembly needs to provide the required pumping speed. However the problem of regeneration of the pumps remains as NEGs do not actually pump the D_2 out if the injector, but they trap it within the getter material, and regeneration is needed once the NEGs become saturated with D_2. The possible ways to overcome the lack of pumping during regeneration are, in essence, the same as suggested for cryopumps above. However the regeneration time for NEGs is expected to be several hours, so that with three injectors installed on the reactor, as in the above example with cryopumps, the NEGS would have to operate for 10 h if the regeneration time is 5 h. No design of such a system has yet been done.

Because of the quasi-continuous operation of the injectors, all the gas used for the injectors will be gas recovered from the gas recycled through the reactor "tritium plant". That must include the gas released from the injector cryopumps as that will be contaminated with T_2 that has flowed to the injectors from the reactor. However, the gas flowing into the ion sources must contain only a small fraction of T_2 to make sure that the neutral beams will have a negligible fraction of T^0 as the lower velocity of T^0 would lead to deposition in the plasma of the reactor nearer the outside of the plasma which is undesirable.[3] The requirement to have fairly pure D_2 for the ion source operation impacts directly on the design of the tritium plant, which could lead to substantial cost increase for the tritium plant, and therefore any reduction in that gas flow is highly desirable.

It is to be noted that some of the He produced in the fusion reactions will flow into the neutral beam duct and the injector, adding to the gas density in the duct. That will increase the fraction of the neutral beam that is re-ionised by collisions with the gas in the duct and thus the power to the duct walls. The density of He in the duct and the injector must be kept at a level that the He in the ion source does not compromise its performance and that the He density in the beamline and the neutral beam duct does not significantly enhance re-ionisation losses. An estimate of the density in the ion source and the increase in re-ionisation loss due to the presence of He in the injector and duct is given below:

Assume that a 1 MeV D beam is being injected into the reactor.

If the pumping speed for He in the injectors is zero, the He density in the duct between the injector and the reactor will rise until the flow out of the duct into the reactor is equal to the flow from the reactor into the duct. Assuming that the He temperature in the duct is 100°C (due to collisions with a 100°C duct wall), that the gas flow out of the reactor into the injector duct is $\approx 10^{20}$ atoms/s (a value calculated for the plasma in ITER), and that 10% of the outflow is He (the rest being D and T), the density of He in the duct will be $\approx 2.5 \times 10^{16}$ m^{-3}.

[3] T_2 in the source may also impact on the source performance. Operating in D_2 is known to result in a higher fraction of co-extracted electrons compared to operation in H_2, and it is possible that the electron fraction with T_2 is even higher.

Now the He flow out of the injector into the duct must be equal to the flow into the injector from the duct. Assuming that the He temperature in the injector is 20°C (due to collisions with water-cooled components in the injector), then the gas density in the injector will be $\approx 2.8 \times 10^{16}\ m^{-3}$.

Re-ionisation loss occurs between the entrance to the residual ion dump and the entrance into the reactor. The cross section for re-ionisation of D on He is $\approx 3 \times 10^{-21}\ m^2$. Assume that the length of the duct between the injector and the reactor is 10 m and that the length of the residual ion dump plus that of the beamline calorimeter is 3.5 m. Then the extra re-ionisation loss due to the presence of He in the system is calculated to be ≈0.1%.

If the He temperature in the ion source is 1200 K (the gas temperature in a negative ion source of the type to be used in the ITER injectors has been measured to be 1200 K), then as the He flow into the ion source from the beamline must equal the He flow out of the source, the He density in the ion source will be $\approx 1.6 \times 10^{16}\ m^{-3}$. To put that in perspective, the D_2 density in the ion source should be of the order of $6 \times 10^{18}\ m^{-3}$, that is, the He will represent $<0.25\%$ of the gas particles in the ion source.

In conclusion, the small increase in the re-ionisation loss due to the presence of He in the injector and the duct of ≈0.1% is almost certainly acceptable. The presence of an He density of significantly above $\approx 1.6 \times 10^{16}\ m^{-3}$ has been shown experimentally not to have any significant effect on the source performance [13].

4. Caesium (Cs) "consumption"

It is currently estimated that Cs will need to be injected into each ion source at a rate of ≈20 mg/h in order to reach the required extracted negative ion current. With quasi-continuous operation and that Cs injection rate, >1 kg will have been injected into each source every 6 years. It has been found that most of the injected Cs remains in the ion source and significantly less than 1 kg of Cs is almost certain to cause operational problems. There are three possible ways to overcome this problem:

i. Develop a technique for cleaning Cs from an ion source by remote means, so that cleaning of the source can be done during a reactor maintenance period;

ii. Reduce the required Cs injection rate by about a factor 20 so that Cs accumulation in the source does not become a problem during the reactor lifetime;

iii. Develop an alternative to Cs (see is section 2.1.1.3 above).

5. Operation and maintenance in a nuclear environment

The injectors will be operating in a very hostile nuclear environment, and that will have an impact on many aspects of the NBI system, for example, the activation and transmutation of materials, the requirement to maintain confinement barriers under operational response and accidental scenarios, etc., and the necessity to meet all nuclear safety requirements. A particularly important aspect of operating in a nuclear environment is that all the components in the actual injectors and the injector vessel and the nuclear shielding around the injectors will become activated during operation; that no human intervention for maintenance operations will be possible, so all maintenance must be carried out remotely; and that requirement must be considered at all stages of the design of the injection system.

5.1 Component lifetime

The lifetime of fusion reactors must be very long, and similar to that of a fission reactor, for example, >40 years, and, like fission reactors, they will operate continuously between outages for maintenance, which will occur not more frequently than yearly, and the outage time has to be as short as possible, for example, <1 month, see, for example [14]. The time that the NBI system on a reactor must operate, both in total and between maintenance periods, is orders of magnitude beyond any NBI system designed so far, and that means that many new considerations enter into play, such as the lifetime of components which are subjected to sputtering by the beams and thermal fatigue. It is also evident that as the reactor and the injectors will operate for 1 year or more between maintenance periods, any component that is designed to be replaced routinely must be able to operate for more than 1 year before the replacement becomes necessary.

5.2 Lifetime and fatigue

The injector components should be designed to have a fatigue life that is greater than the life of the fusion reactor, that is, about 40 years with essentially continuous operation. When there is a breakdown in the accelerator, the beam will be re-established in ≈180 ms, which is short compared to the thermal response time of the components, and the components "see" only a small part of a thermal cycle. Therefore fatigue failure will arise from the on-off cycles of the beam, when the components will experience the complete thermal cycle. The number of on-off cycles will probably be dominated by the regeneration cycle of the cryopumps. With a photon neutraliser and a gas flow into the ion source that is reduced by a factor 3, the cryopumps should be regenerated after ≈3 h of operation (see **Figure 2**). As, with continuous operation of the reactor, ≈3000 regenerations will be needed per year, there will be $\approx 1.2 \times 10^5$ cycles in the reactor lifetime, 40 years. The injector will almost certainly require conditioning pulses after a regeneration in order to regain full performance. The low power operation used at the start of the reconditioning does not contribute significantly to fatigue, and about five full power pulses should suffice to complete the conditioning. Thus the injector components will "see" $\approx 6 \times 10^5$ full thermal cycles in the reactor lifetime.

The relatively low extracted current assumed above, together with the reduction in the stripping losses by a factor 3 (due to the reduced source gas outflow), means that the power load to the grids should be easily handled and fatigue should not be a problem. Similarly, the power to the residual ion dump will be quite low because of the high neutralisation expected with a photon neutraliser and designing the residual ion dump to have the required fatigue life not be a problem. The reduced gas flow into the injector will significantly reduce the re-ionisation loss, hence the loads to the panels in the duct leading to the reactor, and fatigue should not be a problem. However, even in the reduced current density design considered in Section 1.2, the beamline calorimeter, which is essential for the commissioning and recommissioning of the beam source, will receive a similar power density to that received by the calorimeter of the heating neutral beams of ITER, and the fatigue life of the optimised design of that component is calculated to be $\approx 7.5 \times 10^4$ cycles, so either a non-negligible improvement of the design is needed or the calorimeter will have to be replaced after about 20 years, i.e. once in the lifetime of the reactor.

It is worth emphasising that, as assumed above, it is reasonable to conclude that the power "seen" by the beamline calorimeter of an injector on a reactor cannot be higher than that "seen" by the calorimeter of the heating injectors of ITER, which precludes increasing the accelerated D^- current density to >100 A/m^2 when a high efficiency neutraliser is used. Another consequence is that any increase in the beam energy would necessitate a decrease in the accelerated current density in order to keep the power to the calorimeter at the acceptable level.

5.3 Space limitations

High-power, high-energy neutral beam injectors are large; for example, the ITER 1 MeV heating injectors are ≈15 m long and ≈4 × 4 m in cross section, and the high voltage bushing through which connects the power, gas, and water cooling to the beam is over 6 m tall and 2.5 m in diameter (see **Figure 2**).

Obviously the injectors will require a large "neutral beam cell" somewhere around the reactor, which must also provide space around the injectors for nuclear and magnetic shielding, and, because the injectors on a reactor will become radioactive, space for the remote handling equipment needed for all maintenance on the injectors. Space around the reactor will also be required for many other types of equipment, and the space for the injectors will inevitably be limited, which will directly influence the design and layout of the injectors and any attachments to the injectors. Some appreciation of the likely space constraints can be gained from the ITER system. The layout of the three heating and one diagnostic neutral beam injectors is shown in **Figure 3**.

5.3.1 Heating power

The three ITER heating neutral injectors will be capable of injecting "only" 50 MW of D^0 into ITER, and significantly higher power may be required on a reactor. If that is realised by adding more injectors, an even larger neutral beam cell will be required. However that might be avoided by increasing the power from each injector, which might be achieved by having a more uniform power density on the calorimeter. In principle, that might be possible as the geometric limitations associated with the gas neutraliser used in the ITER injector would not apply to a photon neutraliser-based system. However that requires detailed considerations of the injector design, and those are not possible with the present state of development of the photon neutraliser.

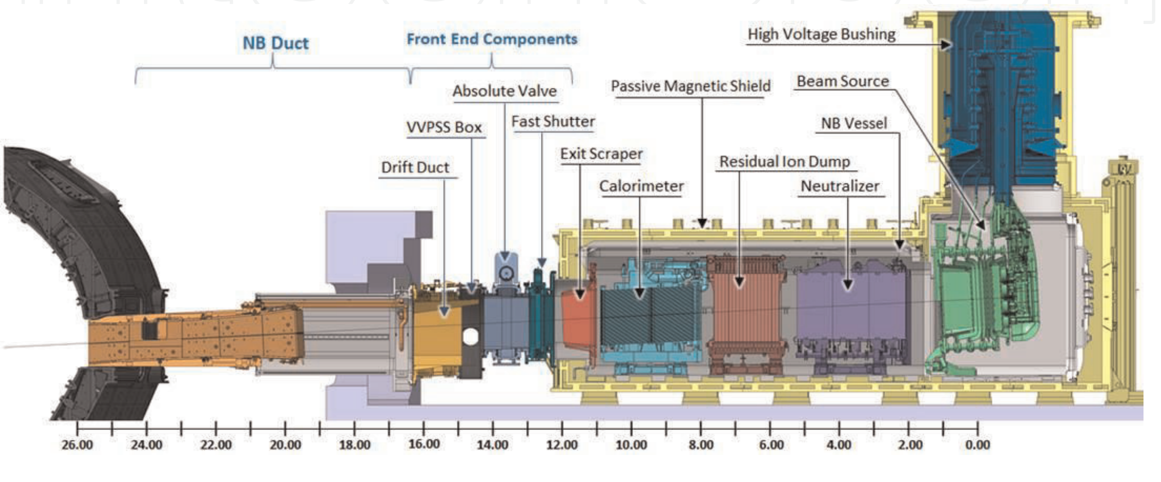

Figure 2.
Computer-generated cut-away view of an ITER HNB beamline. The scale below the beamline shows the distance along the beamline axis in metres from the last grid of the accelerator.

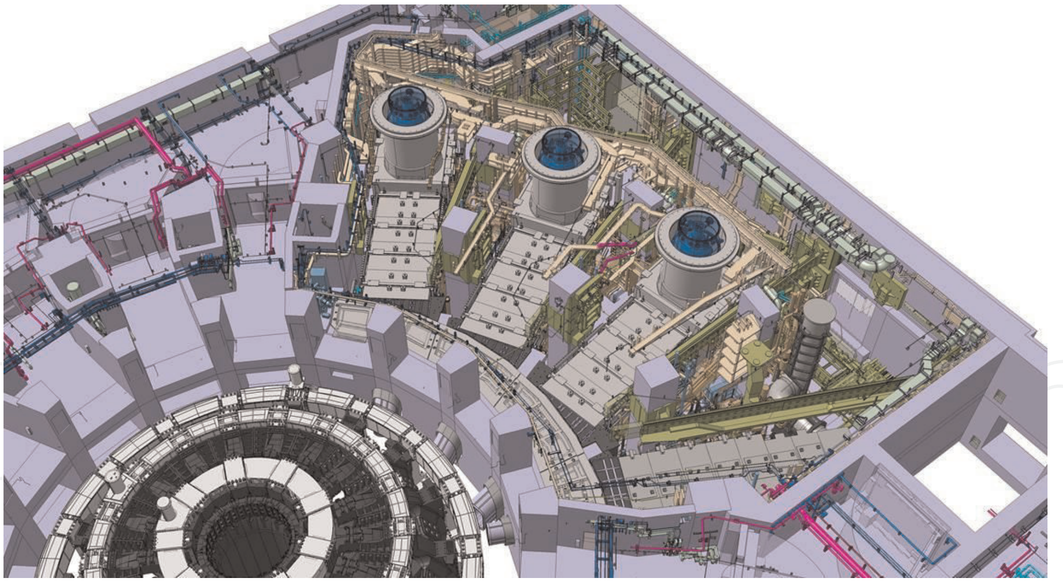

Figure 3.
Computer view of the ITER NB cell with three heating neutral beam injectors and a diagnostic neutral beam injector installed. The three heating neutral beam injectors should be capable of injecting 50 MW into the ITER plasma.

5.4 Operation in a nuclear environment

The injectors at ITER are expected to perform in a harsh nuclear environment which will not be better on a reactor. In the present scheme of things, the injectors are an extension of the vacuum vessel and therefore a part of the nuclear confinement barrier. It is therefore essential that their integrity is assured for all situations including normal and accidental events which can be initiated when the machine operates.

The design and operation of injectors in a nuclear environment need to be considered from various aspects such as the engineering design codes used, the injector materials, their layout, their operational response to normal and accidental scenarios under various load conditions, and maintenance, including remote handling, tooling, and the deployment of remote handling tools. All those have been addressed for the ITER injectors, and the impact on the design has been very significant. Some of the various aspects are discussed below in order to give an idea of the complexity involved in adapting the systems to nuclear environments.

5.4.1 Materials

Operation in a radiation environment impacts the choice of materials used for components, such as to ensure that the essential material characteristics are not modified by irradiation and to reduce the degree of activation and the quantity of activated waste. This impacts on all parts of the injector, including, for example, the choice of vacuum seals, where, essentially, only all metal seals are accepted, the joining techniques for similar and dissimilar materials, etc. The definitions for reactors will be stringent because of the harsh environment and strict safety standards that will be applied. Radiation can damage electronics, components, and sensors, corrupt signals, and make optical fibres and windows become opaque. These effects can appear instantaneously or over a period of time due to an accumulation of, for example, atomic displacements. It is clear that the design of an injector designed to operate on a reactor will have to ensure that all electronics are situated in low radiation areas, as has been done for the ITER design, both to ensure their lifetime is adequate and to allow their maintenance.

5.4.2 Injector layout

Designing a system for the environment of a reactor requires a serious consideration of the layout of the injectors, ensuring good access for the remote handling tooling and adequate shielding in case of the need for man access. Meeting these requirements requires sufficient space, but there is a conflicting requirement, which is to keep the "nuclear island" as small as possible. The latter means that the location of the inventory, the first confinement boundary, is confined to as small an area as possible. The vacuum boundary of the machine, in normal operation, defines the first confinement barrier, and any penetration through the barrier becomes part of the first confinement barrier. To ensure reliability and safety, it is likely that two metal valves will need to be installed, in series, upstream of any penetration of the barrier, as is the case on ITER. In that case, the vacuum boundary of the machine and the second valve, which is the last layer of the primary confinement barrier, defines the nuclear island. To minimise the size of the nuclear island, the valves and windows must be located as close as possible to the machine. This can lead to a complex design which must tolerate high radiation loads, heat loads, neutron fluxes, and electromagnetic loads whilst simultaneously fulfilling the safety function of primary confinement. An example of the impact on the injector design is that this means that any guide tubes for the laser light used for the photon neutraliser will need to incorporate a window in series with a valve close to the injector vessel. That window will have to meet all the requirement of the first confinement barrier and vacuum boundary as well as be able to transmit the laser light quasi-continuously. As some laser power will be absorbed by the window, it is probable that the window will need to be cooled by some type of cooling system. Also the window must be capable of withstanding any over pressure or heat load that might occur during the failure inside the reactor.

5.4.3 Operational response to normal and accidental scenarios

To ensure safe operation of injectors on a reactor, all possible accidental events will have to be analysed under all possible load conditions including those arising from abnormal plasma events such as a "vertical displacement event" (VDE),[4] and under all conditions, i.e. when the system is operating, in stand-by or being maintained. In addition, nuclear analyses will have to be performed to confirm that radiation damage to the materials will be below the level at which the mechanical properties are compromised.

5.4.4 Remote handling

Operation in a nuclear environment limits direct access and hands on maintenance as the injector will become radioactive, and there are then hazards related to exposure to radiation and from inhalation of airborne contamination. The expected level of radioactivity in the ITER NB cell and the defined radiation zoning of the facility lead to the need for remote handling to be in place. Human access is only allowed when the dose rates are kept beneath the allowed limits of <100 μSv/h.

[4] In some magnetic confinement devices loss of control of the plasma position can result in a rapid vertical movement of the plasma, leading to a violent disruption (sudden loss of the plasma), which is known as a vertical displacement event. The consequent release of the energy that was stored in the plasma can lead to very strong, potentially damaging, forces being applied to the machine.

Achieving the compliance with the radiation zoning is carried out by the use of effective shielding in the design of the components and reducing materials which are more activated, i.e. using low cobalt content stainless steel, but achieving a similar situation on a reactor will be difficult.

6. Discussion and summary

6.1 Efficiency increase

A global efficiency of ≈60% or better is required for a neutral beam system on a reactor, which is much higher than any neutral beam system has achieved so far. Meeting that requirement represents a major challenge for neutral beam development. To do so requires both a significant increase in the neutralisation efficiency and a decrease in the losses in the system.

- Increasing the neutralisation efficiency appears most feasible, if difficult, with a photon neutraliser. The only identified alternative is a plasma neutraliser plus energy recovery. However, work so far carried out on this topic has failed, by a wide margin, to produce an adequate D^+ and D_2^+ + electron plasma target[5] nor to demonstrate how to produce a plasma confinement system that allows the transmission of the beam through the neutraliser that does not degrade the beam emittance. Additionally recovering the energy from the D^+ fraction of the beam leaving the neutraliser has severe difficulties and has not been demonstrated [15–17].

- The stripping losses in the extractor and accelerator of the beam sources of the ITER heating injectors are very high (≈30%) and must be reduced. That can only be achieved by reducing the gas flow out of the source into the extractor and accelerator, which would also reduce the back-streaming in power into the ion source and the sputtering from the ion source backplates.

- Solid-state RF power supplies have an efficiency of ≈85% and must be used for injectors on a reactor that use RF-driven ion sources.

6.2 Low work function PG surface

Sputtering from the ion source backplates by the back-streaming ions means that the PG surface will be coated in the sputtered material in a time that is very short compared to the operational time between the reactor maintenance periods. That will result in an increase of the work function and a significant reduction in the extracted ion current. Thus either the PG needs to be replaced or the surface renewed. Replacing the PG is not reasonably possible with the current type of accelerator design. Therefore R&D into low work function PG surfaces should not be prioritised. However the continued use of Cs injection means that:

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[5] In principle other gases could be used in the plasma neutraliser, such as argon (Ar), and it is easier to obtain a higher ionisation degree with Ar [18]. However the potential problems that might occur with Ar such as contamination of the tritium plant and Ar^+ back-streaming into the ion source need to be evaluated, which has not been done.

- The Cs flow into the source must be significantly reduced to avoid excessive Cs accumulation in the source, and ways of in situ cleaning the source of Cs needs to be developed (see Section 1.1.2).

- Preliminary estimates indicate that back-streaming Cs^+ may cause significant sputtering of the ion source backplates, adding to the erosion by back-streaming D_2^+. Therefore the Cs density in the extractor must be reduced via a reduction in the Cs in the in source plasma, and R&D on easily exchangeable ion source backplates may be essential.

6.3 Long pulse operation

Meeting the pumping requirements of the injectors during very long pulse operation is very difficult, even with a substantial reduction of the gas flow into the ion source and no gas into the neutraliser. The only systems that can provide the required pumping speed are cryopumps, and possibly non-evaporable getters (NEGs), and neither of those actually pumps gas out of the injector. Consequently, such pumps require regular regeneration to avoid possible explosions and/or to avoid saturation of the pumps. As no way has yet been developed to allow an injector to continue operation whilst the pumps are regenerated, the only option is to take the injector off-line during the regeneration. That problem could be overcome by having one "excess" injector, so that of the n injectors installed, only $n - 1$ injectors are ever operating, and each injector is regenerated in turn.

6.4 Lifetime and fatigue

Because the beamline component will become activated during the operation of the reactor, any maintenance or exchange of the components will have to be done remotely, and all such operations will be very difficult. That consideration leads to the requirement that all the components must be designed to have an expected life that is longer than that of the reactor, for example, with a fatigue life of >40 years. The calorimeter of the injectors of a reactor will "see" a similar thermal load to that of the calorimeter of the ITER injectors, even though the accelerated current density is reduced by 50% of that expected with the ITER system. The ITER calorimeter design was extremely challenging, and it is unlikely that the design of the calorimeter of the injectors on a reactor will be significantly better. The calorimeter of the ITER injectors has a calculated fatigue life of 7.5×10^4 thermal cycles, and R&D is needed to meet the full fatigue lifetime requirement which could be $\approx 5 \times 10^5$, i.e. 8 times higher.

6.5 Nuclear environment

The injectors on a reactor will have to fit into the available space, and they will have to minimise their impact on the size of the nuclear island. The resulting space constraints will impact on the design and the layout options of the injectors and any attachments to the injectors, and the requirement that all maintenance must be carried out by remote means, with the consequent need for space around the injectors for the remote handling equipment, must be taken into account during the design of the injectors. An obvious conclusion is that in order to be considered for R&D funding, any proposal for R&D should consider the possible implications of the nuclear environment and propose conceptual solutions to those implications.

Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the ITER organisation.

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