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The DITE tokamak experiment

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The expectation of power from fusion reactions currently involves magnetic containment of hot plasma in the tokamak toroidal configuration, and plasma heating by injection of energetic neutral atoms. Isolation of the plasma from the walls, to maintain the required purity, and exhaust of the spent fuel both involve the use of a divertor. This removes plasma from the boundary layer into a separate chamber. We report tests of these concepts in the Divertor Injection Tokamak Experiment (DITE) at Culham Laboratory. We also present the first measurements in a tokamak of the neutral-beam driven current. This demonstrates the principle of a continuously operating tokamak, with possible advantages for a reactor.

1. Introduction

The realization of fusion power requires the achievement of hot, pure, well contained plasma. The DITE experimental programme (Paul 1979) at Culham Laboratory addresses all three problems; **D**ivertor for purity control, **I**njection for heating and **T**okamak **E**xperiment for containment. The medium sized toroidal device (Paul *et al.* 1976) has major radius $R = 1.17$ m and minor radius to the limiting metal aperture $r_L = 0.26$ m. The magnetic containment is provided by the helical field formed by the dominant quasi-steady toroidal magnetic field, $B_\phi \leqslant 2.8$ T, and the poloidal field from the toroidal plasma current, $I_p \leqslant 280$ kA. The latter is induced by a transformer for a pulse of several hundred milliseconds. The arrangement of the device is shown in figure 1.

The structure of the helical field is described by the radially varying safety factor $q(r)$ which is the number of major rotations per minor rotation of a field line. It is called the safety factor because tokamaks become more difficult to operate as $q(r_L)$ decreases below about four.

Equilibrium of the plasma ring against magnetic and pressure driven major radial expansion is achieved by the $I_p B_Z$-force produced by applying a field (B_Z) out of the plane of the torus. The field is feedback controlled from plasma position sensors.

The unique bundle divertor is only a prototype, limited by mechanical constraints to operation at $B_\phi \leqslant 1.0$ T and $I_p \leqslant 60$ kA. The neutral injection heating system delivers power to the plasma, $P_I \leqslant 1.2$ MW, exceeding the ohmic power from the plasma current, $P_\Omega \approx 0.3$ MW, but only for a pulse duration of 100 ms. The principles of these two systems will be demonstrated later but their disposition around the torus, and the array of measurement systems is shown in figure 2.

The plasma parameters achieved in DITE, not necessarily at the same time, are as follows: electron temperature $T_e \leqslant 1.6$ keV; ion temperature $T_i \leqslant 1.0$ keV; electron number density $n_e \leqslant 10^{20}$ m^{-3}; and energy replacement (containment) time $\tau_E \leqslant 30$ ms.

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The experiments described here explore the principles involved in extrapolating to future generations of devices, such as JET, Intor and reactors in which fusion reactions will take over as the dominant powei input.

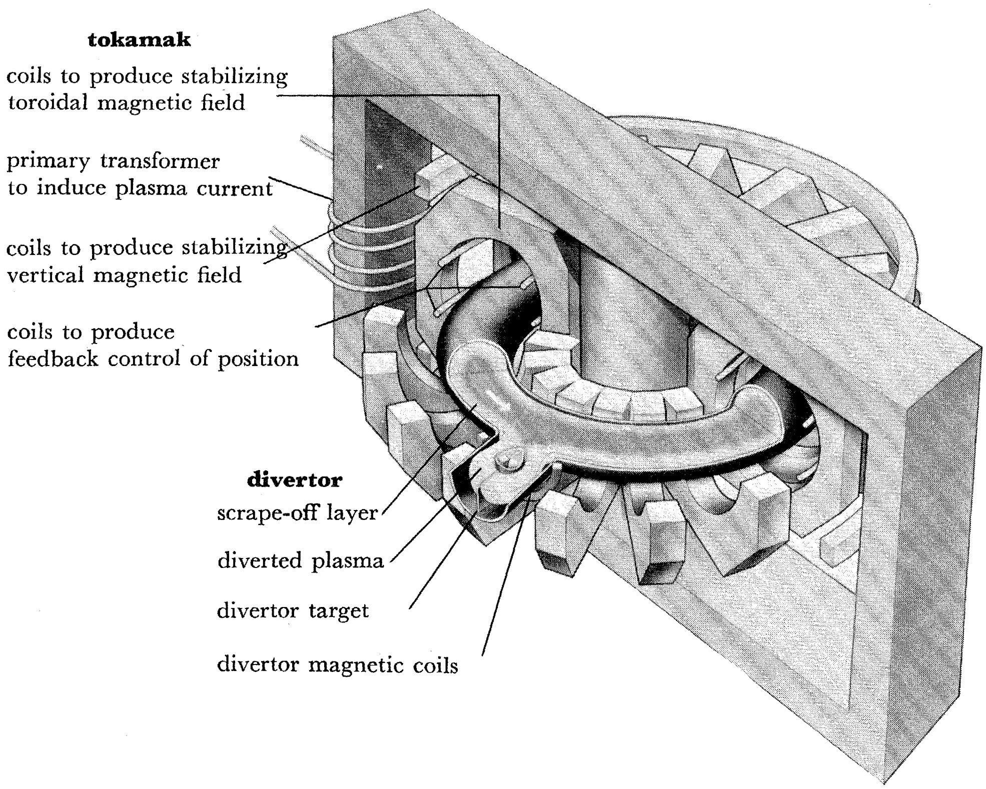

FIGURE 1. Cut-away schematic diagram of the DITE tokamak with the divertor in operation.

2. Plasma containment

In the idealized theory of magnetic containment, the helical field forms a set of nested magnetic surfaces. The orbits, drifts and collisions of plasma particles in this field are described by kinetic equations forming the neoclassical theory of toroidal containment (Rosenbluth *et al.* 1972). This theory involves the trapping of particles with low collision frequency (collisionless), between the magnetic mirrors formed by the high field on the inside of the torus. This kinetic theory is used to derive transport coefficients, which are then used in fluid transport codes to interpret measurements and to predict performance.

As we shall see, often there is no correspondence between containment theory and experiment. Plasma instabilities, particularly the resistive fluid m.h.d. types described by Robinson (this symposium), play a major role.

These instabilities are mainly associated with rational values of $q(r)$, where modes with azimuthal mode number $m = q$ occur. They break the nested surfaces and depending on their nonlinear growth either saturate, forming magnetic islands, or violently expel plasma in what is called a disruption. The growth depends on $q(r)$, which is determined by the current density profile. This is in turn determined by the electron temperature profile, $T_e(r)$.

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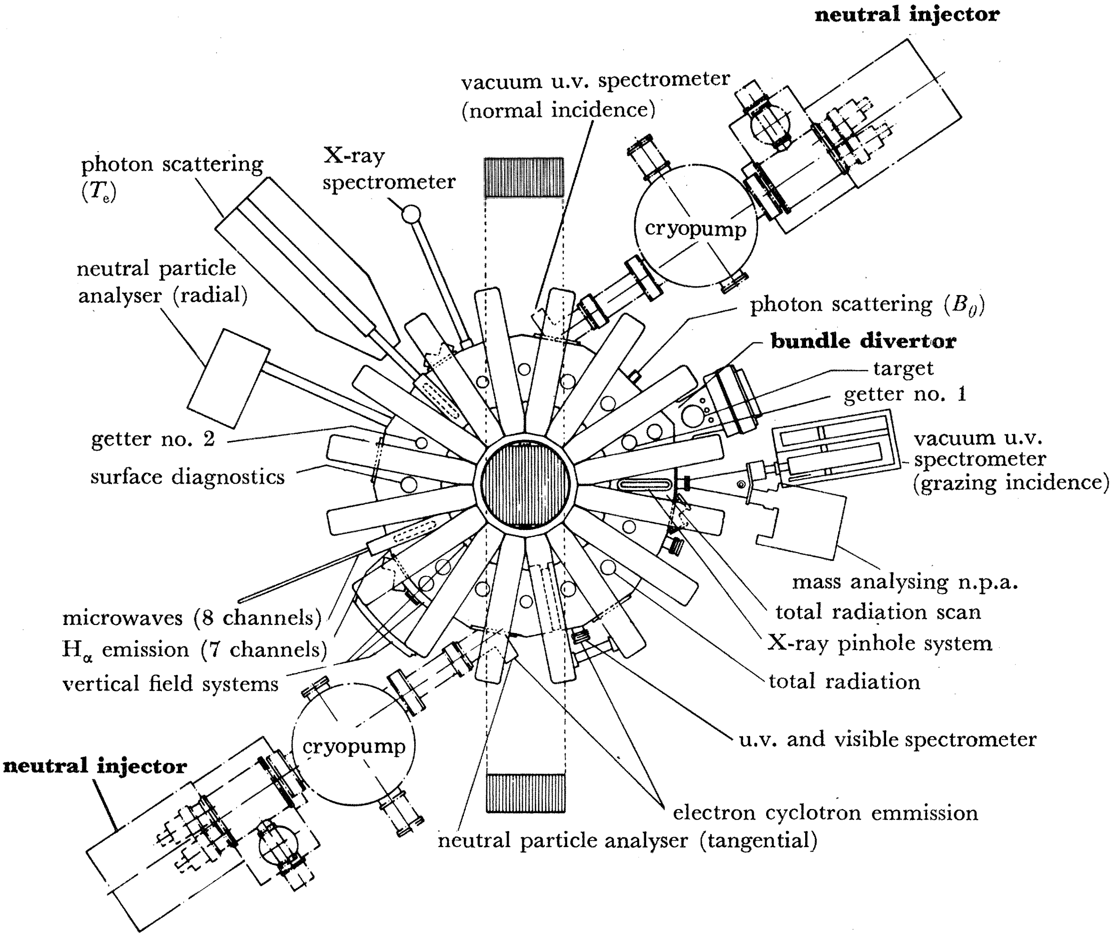

FIGURE 2. Plan view schematic diagram of DITE tokamak showing divertor, injectors and measurement systems.

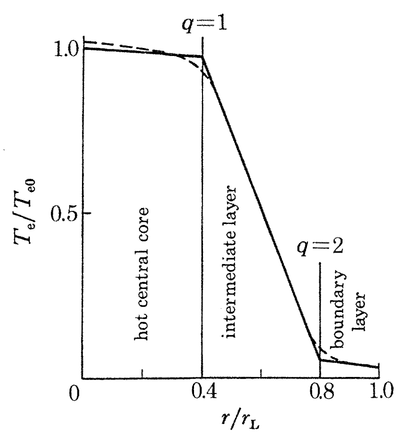

FIGURE 3. Schematic diagram of T_e (r).

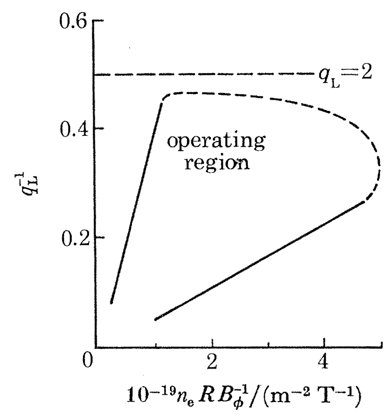

FIGURE 4. Schematic diagram of operating region.

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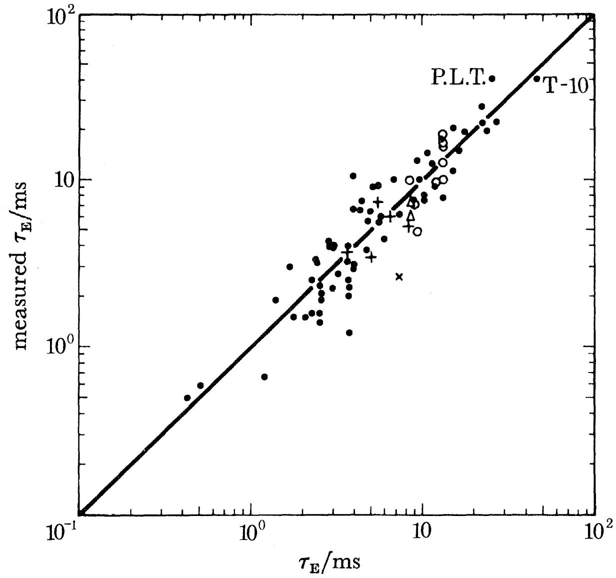
The m.h.d. stability is affected, through $T_e(r)$, by plasma cooling caused by impurity and gas feed. Also, the m.h.d. activity itself tends, in the absence of disruption, towards marginal stability. The schematic profile of $T_e(r)$ in figure 3 shows how most of the containment occurs between $q = 1$ and $q = 2$. Inside $q = 1$, m.h.d. activity with $m = 0$ and $m = 1$ flattens the profile, while outside $q = 2$ is a cold boundary layer.



($\tau_E = 2.7\ n_e^{0.61}\ a^{1.57} B^{0.88} A_i^{0.65}$)

Figure 5. Empirical global scaling. ——, Fit to experimental points (●) with a correlation function of 0.92, from Hugill & Sheffield (1978). DITE data is given for high n, gettered, (○), low-Z impurities (△), high-Z impurities (+) and for a hollow profile (×). Recent data from the two large experiments P.L.T. and T-10 are also included.

The violent m.h.d. disruptions limit the operating range of current ($I_p \propto q^{-1}$) and density, as shown schematically in figure 4. Experiments on DITE have extended both these limits. Careful control of $T_e(r)$ has allowed operation with the safety factor reduced from $q(r_L) \approx 4$ to $q(r_L) = 2.2$. Also, improved cleanliness has increased the density limit by a factor of two. A further increase is obtained by the application of injection heating. This latter extension appears essential for the next generation of tokamaks.

Within the foregoing operating region, the containment can be measured by dividing the energy content of the plasma by the power input, to obtain a global energy containment time (τ_E). Experimental values normally bear no relation to and are far below neoclassical values. However, there is a remarkably consistent empirical scaling of τ_E with plasma parameters for widely differing devices and condition. This is shown in figure 5 from Hugill & Sheffield (1978), with DITE data added. This and other empirical scaling laws are not understood and do not conform to the dimensional scaling required by Connor & Taylor (1977) for plasma phenomena. However, they are used, for lack of anything better, for estimating the performance of future tokamaks.

More detailed measurements of radial profiles, such as in figure 6, allow the derivation of local electron and ion energy fluxes, and transport coefficients. Normally on DITE, the electron energy losses are up to two orders of magnitude above neo-classical expectation, while the ion energy losses are up to one order of magnitude above neo-classical expectation. Recently,

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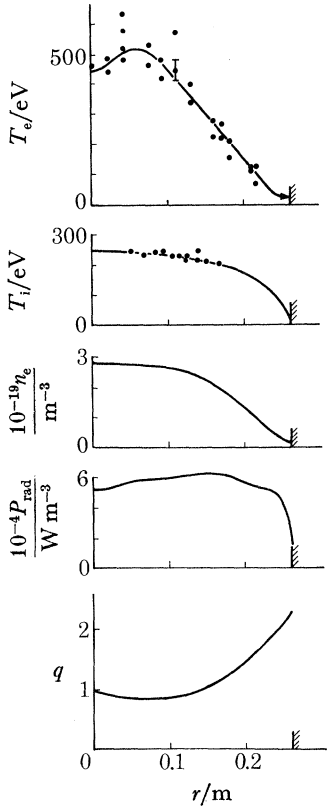

FIGURE 6. Radial profiles of plasma parameters.

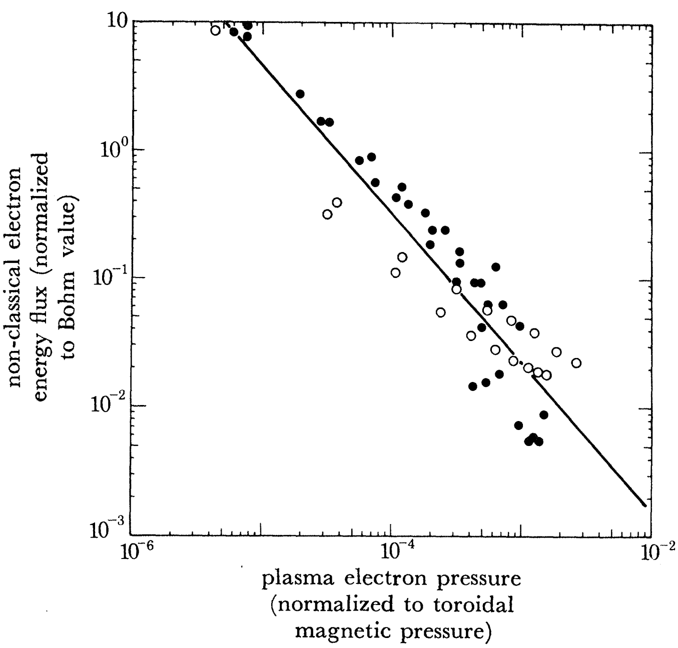

FIGURE 7. Scaling of non-classical heat flux for DITE (●) and other experiments (○). Correlation function 0.94.

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measurements on DITE have shown that the non-classical part of the electron energy flux scales reasonably well with a dimensionless plasma parameter, as shown in figure 7. Some plasma instabilities which might be responsible for these losses are discussed by Riviere (this symposium).

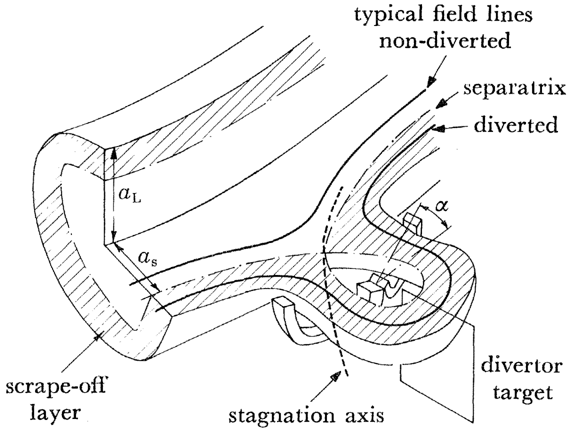

FIGURE 8. Cut-away schematic diagram of bundle divertor.

3. PURITY CONTROL

Impurities radiate power, and for fusion reactor operation, the purity level must be below about 2% for light (for example, O) and about 0.1% for heavy impurities (for example, Fe). These impurities arise from plasma–surface interactions within the vacuum vessel, as discussed by McCracken & Stott (1979).

DITE has a unique facility for the control of impurities in the bundle divertor which was first proposed by Colvin *et al.* (1972). A bundle of the outer toroidal field lines is displaced out of the torus by a local pair of coils, passing through a pair of vacuum tubes into a separate target chamber as shown in figures 1 and 8. While the bundle is localized in minor azimuth, the helical field connects it to an annular scrape-off layer.

Plasma and power transported from the hot core arrive in the scrape-off layer, and a proportion of it, given by the exhaust efficiency (ξ_E), is diverted along the bundle onto the target plate. This 'unloads' some of the plasma–surface interaction from the torus, transferring it to the target plate. Impurities evolved from this plate can be pumped away without much chance of returning to the torus.

In addition, impurities evolved within the torus will be ionized in the scrape-off layer. A proportion of such impurities, given by the screening efficiency, (ξ_s), will be diverted into the target chamber, thus screening the hot core.

The magnetic topology of the double torus is such that magnetic surfaces cannot form, and some field lines escape (Taylor 1974). This effect is now considered to be negligible. The field asymmetries create two new classes of trapped particles which may be important at high temperature. One is caused by the mirror effect of the divertor coils in the scrape-off layer (Stott *et al.* 1978) and the other by the local perturbation of the field in the central plasma (R. H. Fowler *et al.* 1979).

The prototype bundle divertor on DITE has demonstrated all the beneficial effects (unload, exhaust ($\xi_E \approx 0.3$) and screening ($\xi_s \approx 0.4$), as illustrated in figure 9) without any

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of the deleterious effects of topology. Under certain circumstances the radiated power has been reduced by a factor of five, and heavy metal (Fe, Mo) impurity concentrations reduced by a factor of up to ten (for example, Fe ≈ 0.1 %, see Peacock *et al.* 1979). A new divertor, capable of operating at $B_\phi = 2.8$ T, will be brought into operation in 1981. The modular nature of this divertor, shown in figure 1, makes it attractive for a reactor.

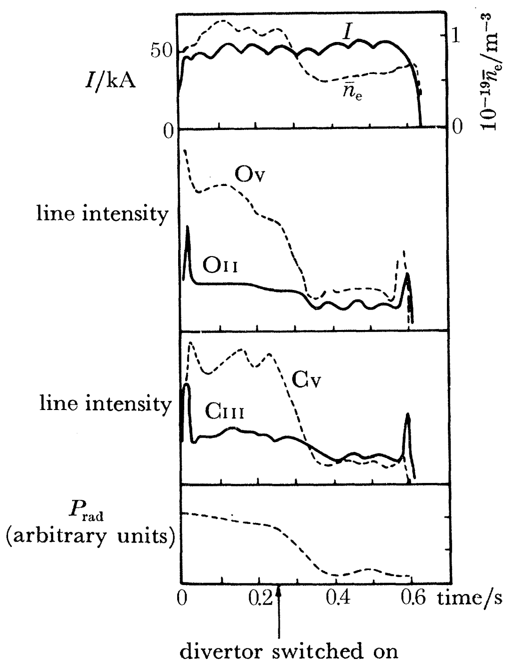

FIGURE 9. Effect of mid-pulse operation of the divertor in exhausting plasma (fall in n_e), screening the inner plasma (Ov and Cv) from the wall influx (OII and CIII) and reducing radiated power (P_{rad}).

4. Neutral beam heating

Ohmic heating by the plasma current becomes less effective at high temperatures, as it is proportional to $T_e^{-\frac{3}{2}}$, and another heating process is required. Currently, the most highly developed form of additional heating is provided by powerful beams of neutral hydrogen atoms (neutral injection). These beams are produced by multi-aperture ion sources and hydrogen gas neutralizers. Gas from the neutralizer is prevented from entering the torus by a liquid He cryopump in the tangential beam lines as shown in figures 2 and 10. On DITE, four-ion sources, operating at up to 30 kV, deliver neutralized hydrogen beams down two beam lines (figure 2) with a total power to the plasma of up to 1.2 MW (Hemsworth *et al.* 1979).

The injected atoms are ionized, mainly by charge exchange, and then trapped in the plasma by the magnetic fields. The deposition of these fast hydrogen ions as a function of radius is computed from the measured plasma parameters. The fast ions circulate around the torus many times transferring energy first to the electrons and then to the ions as they slow down. This transfer of energy is computed as a function of radius by using a Fokker–Planck kinetic model and measured plasma parameters. The energy spectrum of the circulating ions is measured by energy analysis of the fast neutrals produced by charge exchange on the thermal neutrals in the plasma. The agreement of experiment and theory in figure 11, together with further data

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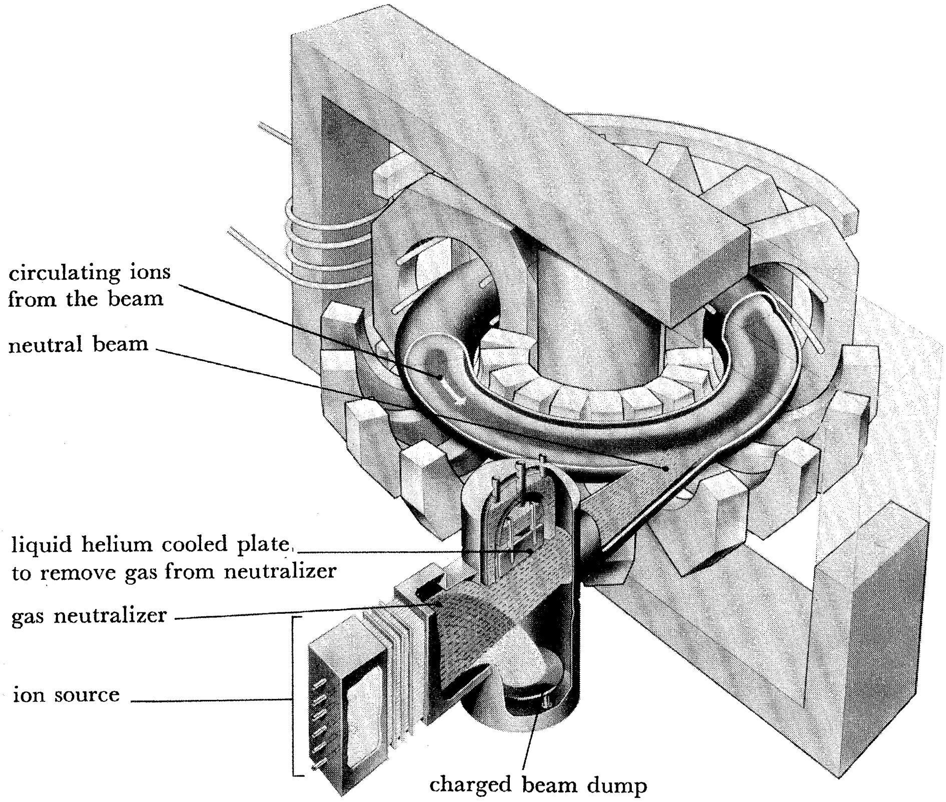

FIGURE 10. Cut-away schematic diagram of injection system on DITE.

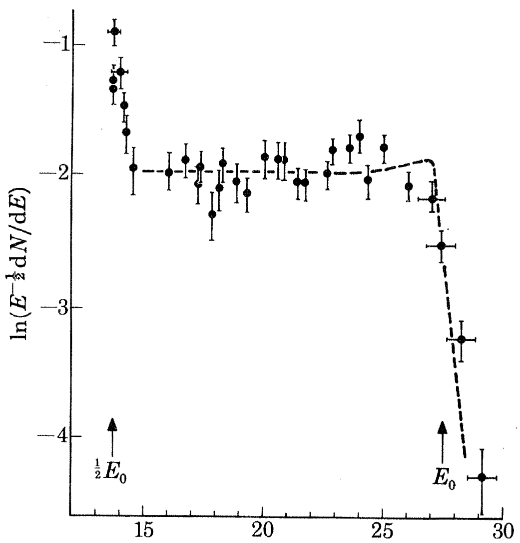

FIGURE 11. Comparison of experimental (●) and theoretical (---) energy spectra of circulating fast ions of initial energy E_0.

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in §5, confirms the foregoing computations. This subject is discussed by Sweetman *et al.* (this symposium).

The energy transfer to the plasma is as expected from theory but the amount of heating depends on the losses which are not well understood. On DITE, neutral injection increases the ion temperature by a factor of three, up to 1 keV (collisionless), and the electron temperature by a factor of two, under different conditions. This method of heating has achieved the record tokamak ion temperature of 6.5 keV in the more powerful P.L.T. device (Eubank *et al.* 1979). The injected power into DITE will be raised to 2.4 MW for 130 ms, for use with the new divertor, in 1981.

5. Beam driven current

The circulating fast ions produced by injection form a current (I_f), but collisonal momentum transfer to the plasma electrons generates an opposing electron current (I_e). The net current ($I_d = I_f - I_e$) is driven by the beam and not by the transformer. Consequently, it can in principle permit continuous operation of a tokamak. The reactor potential of this idea, first proposed by Ohkawa (1970), requires further investigation. This beam driven current was first observed in the otherwise currentless low temperature plasma of the Culham Levitron device (Start *et al.* 1978). Recently, on DITE, this current has been identified for the first time in a tokamak (Clark *et al.* 1980).

The balance of momentum transfer from the fast ions to the electrons and the electrons to the thermal ions gives the relation

$$I_d = I_f - I_e = I_f(1 - Z_f/Z_{eff}),$$

where Z_f is the fast ion charge and Z_{eff} is the effective ionic charge of the plasma.

The fast ion current is obtained from deposition and Fokker–Planck calculations as in §4. The validity of the calculations for these experiments is checked by measuring the centripetal force required to maintain the circulating fast ions in major radial equilibrium. This force is provided by an increase in the B_Z field which maintains the plasma current ring in equilibrium. However, during injection, changes in plasma parameters also affect this equilibrium and these have to be taken into account through other measurements, in particular plasma diamagnetism. In this way the contribution of the fast ions to the change in B_Z is obtained. Good agreement between these measurements and the calculations give confidence in the calculated fast ion current.

The Fokker–Planck calculations have been extended by Cordey *et al.* (1979) to include the back electron current and hence to calculate the resulting beam driven current. The effects of trapped electrons, plasma rotation, and the neoclassical current are negligible (less than 10%) in the experiments on DITE.

During injection, the transfer from transformer to beam driven current and changes in $T_e(r)$ lead to field diffusion. Consequently the kinetic equation for the beam driven current is solved together with Maxwell's equations and Ohm's law.

On DITE, the transformer circuit maintains the current constant. Consequently the beam driven current manifests itself as a change in the loop voltage from the transformer, V_l (figure 12). When the beam and the plasma current are in the same direction (co-injection), some of the transformer-induced current is replaced by beam driven current and the required V_l drops. For counter-injection, V_l has to increase to cancel I_d.

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However, V_l can also be affected by changes in plasma resistance and inductance resulting from the effect of injection on $T_e(r)$ and Z_{eff}. These parameters are measured and from them the loop voltage required for the transformer to drive the current is calculated as described above, but omitting I_d. The resulting $V_l(t)$ shown in figure 11 (curve A) shows almost no change, compared with the large drop observed experimentally (curve B). Inclusion of the beam driven current in the calculations (curve C) shows good agreement with experiment.

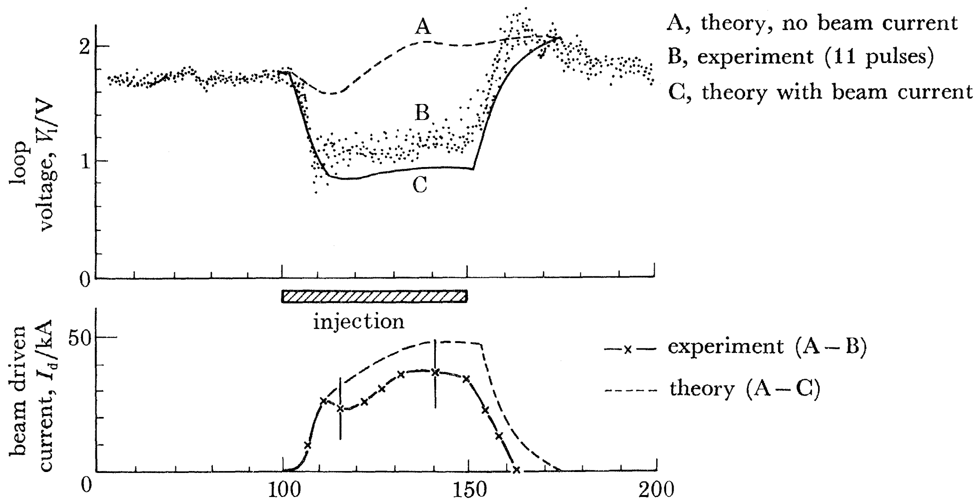

FIGURE 12. Comparison of experimental and calculated drop in loop voltage on injection, and derived beam driven current.

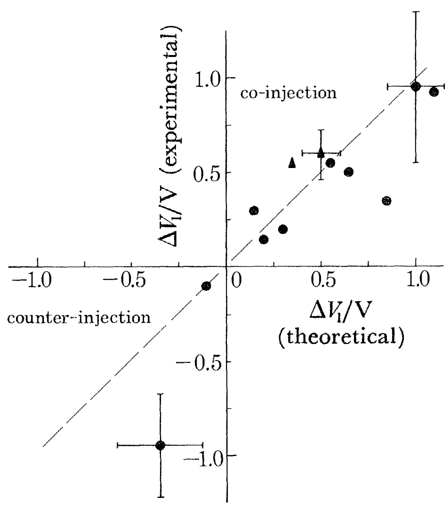

FIGURE 13. Comparison of experimental and theoretical change in loop voltage caused by the beam driven current for helium (●) and deuterium (▲).

The experimental change in loop voltage (ΔV_l) produced by the beam driven current is the difference between curves A and B of figure 12, while the theoretical ΔV_l is the difference between curves A and C. As there is almost no change in the profiles $T_e(r)$, the beam driven ΔV_l can be converted to I_d. The resulting $I_d \leqslant 38$ kA (figure 12) constitutes almost half of the total current (80 kA).

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Experimental and theoretical values of ΔV_1 are compared in figure 13 for a range of densities (3×10^{19} to 8×10^{19} m^{-3}), Z_{eff} (1.8–4) and currents (80–160 kA) including counter-injection. This demonstrates agreement between theory and experiment and hence the existence of the beam driven current in DITE.

6. Conclusions

The DITE programme has demonstrated the principles addressed in its objectives. The prototype divertor performs its expected functions and the neutral beam interaction with the plasma, including the beam driven current, agrees well with theory. Although the empirical scaling of energy losses is favourable for a reactor, it is unfortunate that the basic mechanism of energy loss is still not understood. There is some comfort in the thought that the steam engine was doing useful work before the laws of thermodynamics were understood.

With the next generation of devices, fusion research will, it is hoped, move from empirical extrapolation to interpolation and thereby further increase the credibility of fusion power.

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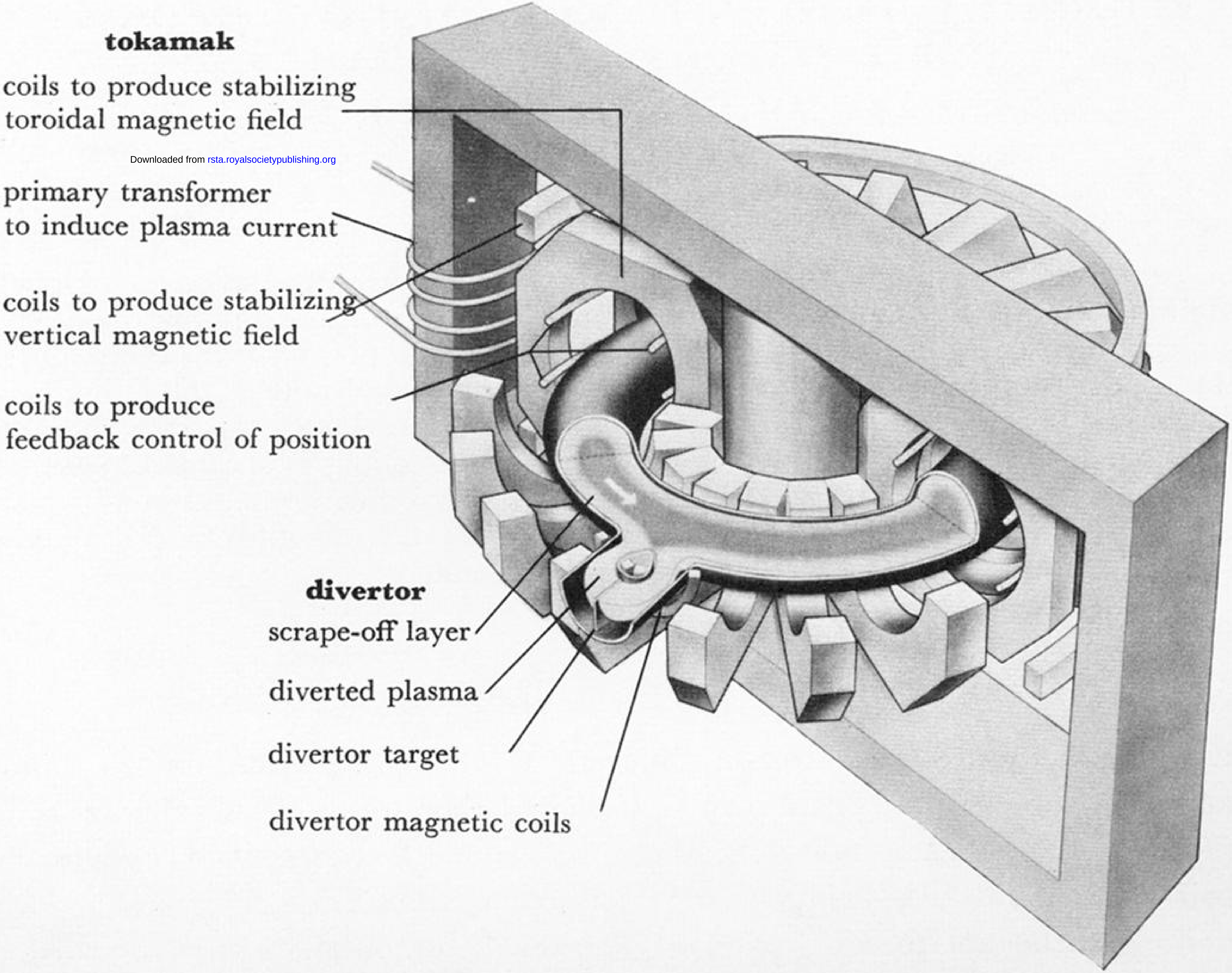

FIGURE 1. Cut-away schematic diagram of the DITE tokamak with the divertor in operation.

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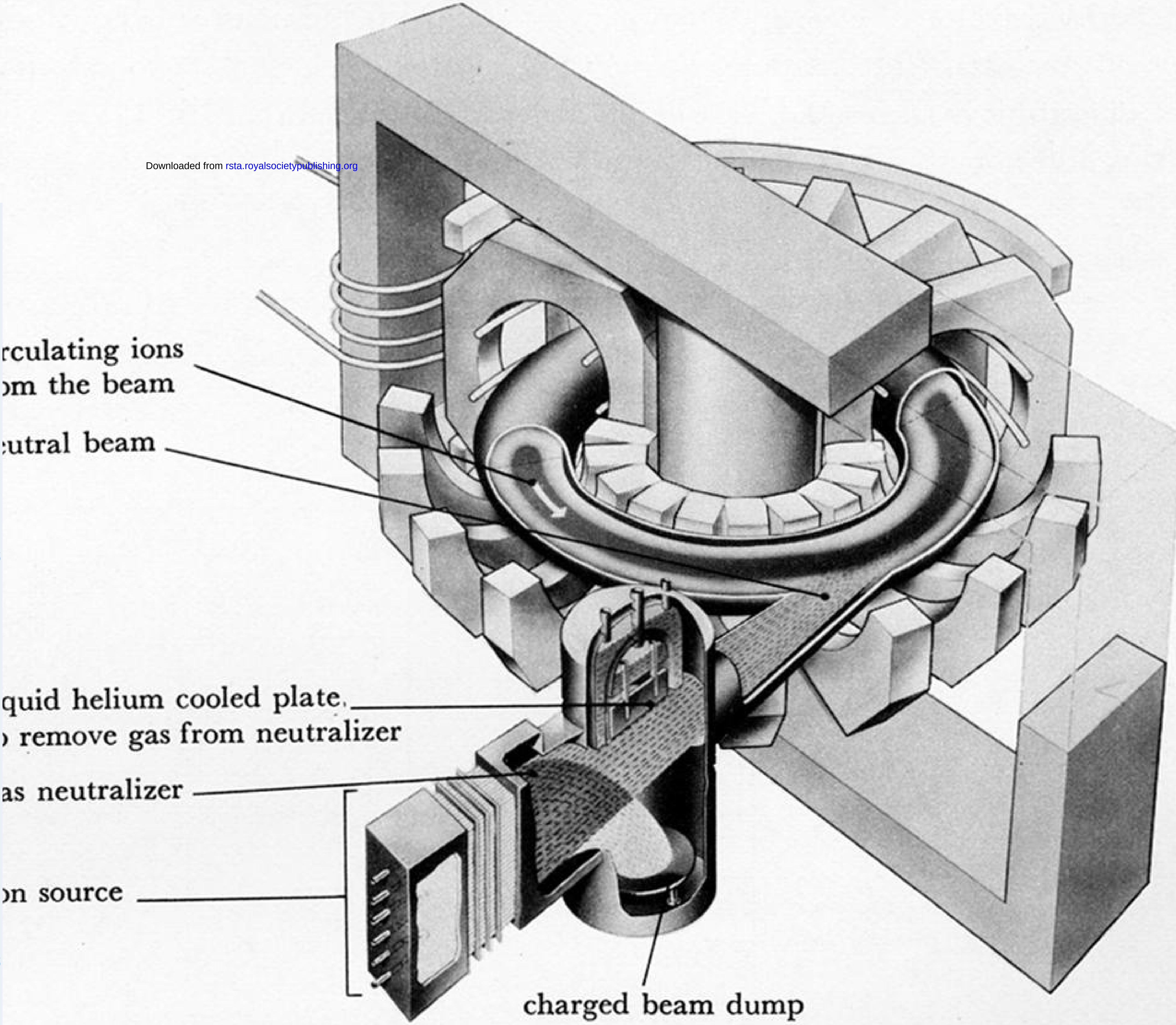

FIGURE 10. Cut-away schematic diagram of injection system on DITE.

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