JOINT EUROPEAN TORUS

JET–P(92)65

P-H. Rebut, D. Boucher, C. Gormezano, B.E. Keen, M.L. Watkins
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JET-Joint Undertaking, Culham Science Centre, OX14 3DB, Abingdon, UK

* *See Annex*

Invited Talk to Europhysics Conference on RF Heating and Current Drive of Fusion Devices
(Brussels, Belgium, 7th - 10th July 1992), which will be published in the
Journal of Plasma Physics and Controlled Fusion

A FUSION REACTOR: CONTINUOUS OR SEMI-CONTINUOUS?

P-H. Rebut, D. Boucher, C. Gormezano, B. E. Keen, and M. L. Watkins

JET Joint Undertaking, Abingdon,
Oxon. OX14 3EA, UK

ABSTRACT

Based upon latest results from JET and other tokamaks and upon model projections, the operating conditions of a fusion reactor are predicted. The technical and scientific issues involved in continuous operation of such a reactor using non-inductive current drive are identified. Candidate techniques include injecting beams of high energy neutral particles and radio waves at various frequencies (such as fast, lower hybrid and electron cyclotron waves). The basis for a continuously operating reactor is not apparent and a convincing demonstration would require either a high current drive efficiency (above $10^{20}A/m^2W$) at a density above $\sim10^{20}m^{-3}$; or ignition and adequate impurity control at a density of $5x10^{19}m^{-3}$ with moderate current drive efficiency ($\sim0.5x10^{20}A/m^2W$); or high power operation in a regime with a dominant bootstrap current. Semi-continuous operation with inductive current drive offers the only viable alternative for long pulse reactor operation. This could use either forward current or alternating current operation, provided the central solenoid was sufficiently large. A tokamak reactor operating semi-continuously would be simpler in construction, use re-circulating power more efficiently and would likely be more reliable in operation. It is proposed that the Next Step tokamak be based on inductive semi-continuous operation.

I. INTRODUCTION

Present Fusion Research Programmes are directed ultimately to the construction of a demonstration fusion reactor, which will be a full ignition, high power device. Moderate extrapolation of latest results and considerations of model predictions, taken together with the constraints of present technology, allow the size and performance of a thermonuclear reactor to be largely defined [1]. It will be a large and complex device which must achieve high reliability, a high level of safety and must be economically viable.

This paper identifies the operating conditions of a reactor and assesses candidate techniques for continuous operation with non-inductive current drive.The power requirements of these systems is addressed in addition to the technical and scientific issues involved. As a consequence of these considerations, semi-continuous operation with inductive current drive is proposed as a viable alternative to continuous operation with non-inductive current drive.

A reactor plasma will most likely be characterised by a temperature of ~25keV and a density $>10^{20}m^{-3}$ (Section II). Most critical is the control of impurities and exhaust of helium ash at high power. Ignition must be ensured under conditions compatible with impurity control. A likely solution is with a divertor at high density and present concepts rely on energy removal by neutrals and radiation in the divertor [2]. Any plasma model must therefore include all aspects of plasma behaviour, impurity control and plasma exhaust. One such model - the critical electron temperature gradient model [1,3,4], which is consistent with experimental results from JET and other tokamaks - is discussed in Section III. In Section IV, this model is used to define size, toroidal field, plasma current and operating conditions of the plasma core of a first reactor.

The present status and future prospects of non-inductive current drive for continuous operation of a reactor is reviewed in Section V. The techniques include the injection of beams of high energy neutral particles and radio waves at various frequencies, including fast waves, lower hybrid waves and electron cyclotron waves [5]. The power requirements for external non-inductive current drive are considered, since these affect the economics of a reactor. Although the capital expenditure and power requirements can be reduced by a significant bootstrap current [6], this is shown to be limited for any particular tokamak configuration.

A viable alternative to continuous operation with non-inductive current drive is semi-continuous operation with inductive current drive. Two techniques for semi-continuous operation, namely operation with forward current and with alternating current, are considered in Section VI. The experimental results of preliminary studies of both these techniques on JET [7,8] are reported. A tokamak reactor operating semi-continuously would be simpler in construction and is more likely to be reliable in operation.

II. A TOKAMAK FUSION REACTOR

A reactor is a full ignition, high power device, producing power in the range of 1-2GW (electrical) or 3-6GW (thermal). It would include: superconducting coils; a divertor with high power handling capability and low erosion, which is likely to require high density operation; an exhaust system for impurities and helium "ash"; and a D-T fuelling system, which is an important part of burn control. A hot blanket to breed tritium and exhaust heat will surround the plasma with a first wall that is highly resilient to 14MeV neutrons. Activation and tritium inventory must also be minimised. Low power auxiliary heating will be required for the start-up of the reactor which will operate either continuously with non-inductive current drive or semi-continuously with long pulses (in the range of 1-2 hours).

Above all, a reactor is a large and complex device which must achieve high reliability, a high level of safety and must be economically viable. In particular, the economics of the ancillary systems needed to provide heating and non-inductive current drive must be considered in any assessment of these.systems.

The parameters of a first reactor are defined by technology and physics predictions. The minor radius of the reactor plasma needs to be about twice the thickness of the tritium breeding blanket, which makes it ~3m. A practical aspect ratio of 2.5 to 3 sets the plasma major radius to 8-9m. The elongation of the plasma must be limited to less than 2. Safe operation can be assumed for a cylindrical safety factor greater than 1.6. Plasma physics requirements can be fulfilled by operating at a toroidal field of about 6T. This defines a reactor with a current capability of about 30MA. The total magnetic flux available could be about 1000Wb. The reactor will operate with a D-T mixture, including helium "ash". Impurity control will be achieved by plasma flow in an appropriate divertor configuration. Sawteeth will be beneficial in ejecting helium from the central plasma. The reactor plasma will most likely be characterised by a temperature of about 25keV and a density greater than $10^{20}m^{-3}$. In fact, a Next Step tokamak should be similar to the core of this reactor.

III. A PLASMA MODEL

Any model used to predict the performance of a tokamak reactor must be consistent with experimental data from different devices and with physics constraints. Experimental observations support a model for anomalous transport based on a single phenomenon and MHD limits. This **Critical Electron Temperature Gradient** model [1,3,4] of anomalous heat and particle transport features electrons which determine the degree of confinement degradation; ion anomalous transport with heat diffusivity χ_i linked to electron heat diffusivity χ_e; anomalous particle diffusivities, D, for ions and electrons, proportional to χ; and an anomalous particle "pinch", V, related to the profile of the safety factor, q [4].

Specifically, above a critical threshold, $(\nabla T_e)_c$, in the electron temperature gradient, the transport is anomalous and greater than the underlying neoclassical transport. The electrons are primarily responsible for the anomalous transport, but ion heat and particle transport are also anomalous. The general expressions for the anomalous conductive heat fluxes are:

$$Q_e \equiv -n_e \chi_e \nabla T_e = -n_e \chi_{an,e} (\nabla T_e - (\nabla T_e)_c) H(\nabla q)$$
$$Q_i \equiv -n_i \chi_i \nabla T_i$$
$$\chi_i = 2 \chi_e (T_e/T_i)^{0.5} \times \{Z_i/(1+Z_{eff})^{0.5}\}$$

The anomalous coefficients for particle transport are:

$$D = 0.5\chi$$
$$V = -D (\nabla q)/2q$$

The critical electron temperature gradient model [1,3, 4] specifies possible dependences for $\chi_{an,e}$ and $(\nabla T_e)_c$. To complete the plasma model requires a description of sawteeth, β-limit instabilities and the edge plasma (the separatrix, scrape-off layer and divertor) for which rudimentary models are also included.

The model exhibits the following experimental features: consistency with physics constraints, global scaling laws and statistical analysis; a limitation in the electron temperature; no intrinsic degradation of ion confinement with ion heating power; no dependence of confinement on mass; similar behaviour of particle and heat transport. The model, which has no free parameters, reproduces plasma profiles for a wide variety of discharges in ohmic, L- and H- regimes in various tokamaks. In particular, the simulation of off-axis heating [9] is almost a direct confirmation of a $(\nabla T_e)_c$, while electron heat pulse propagation studies [10] show a diffusivity, $\chi_{HP} \sim \chi_{an,e} > \chi_e$. The existence of the hot-ion mode is consistent with a critical gradient associated with the electron temperature and current ramp experiments are consistent with the effects of magnetic shear modifying the dependence of confinement on poloidal magnetic field. It should be noted that in the plasma interior, the same model applies to the L- and H-regimes and particle and energy confinement improve together. However, at the very edge of an H-mode, a transport barrier forms and the transport might be classical over a short distance (~few cms). In fact, the H-mode may be the 'natural' consequence of the transport model, since $\chi_{an,e}$ depends on shear, and reduces towards zero near the separatrix. Furthermore, MHD activity reduces on making the transition from L $\rightarrow$ H phase. This may imply the stabilisation of some other instability at the edge, where the effect of impurity radiation and neutral influxes on MHD might be

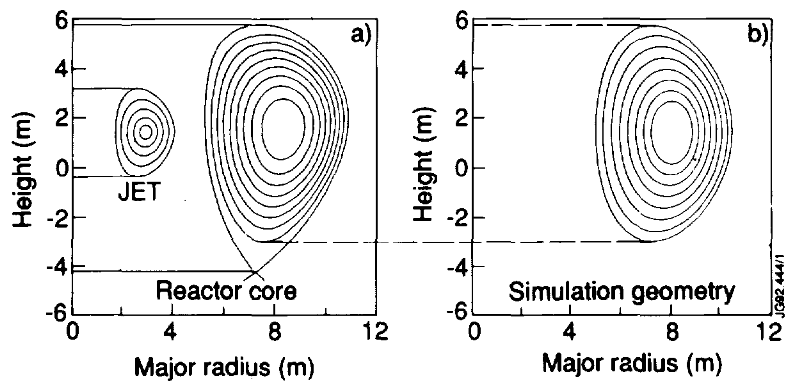


Fig. 1: (a) Typical configurations for JET and a reactor core and (b) the simulation geometry used to solve the full energy and particle transport model.

important in destroying, at least partially, the edge confinement barrier. This instability is apparently easier to suppress in an X-point configuration with high edge magnetic or rotational shear. However, the spontaneous improvement in edge confinement has yet to be modelled.

IV. MODELLING REACTOR PLASMAS

Typical configurations for JET and a **reactor core** are shown in Fig.1(a). The full energy and particle transport model is solved in the simulation geometry (major radius, R=7.75m, horizontal minor radius, a=2.8m, magnetic field at R, B_T=6T, plasma current, I=25MA, and plasma elongation, κ=1.6) in Fig. 1(b). A D-T fuel mixture is assumed and helium ash transport, created during the D-T fusion process, is modelled. 1% of the total recirculation (helium and D-T fuel) is pumped. Impurity control is assumed to limit the beryllium impurity concentration to 5%.

Simulations using the model described in Section III show that the reactor core operates well in L-mode and at high power. Low power operation is possible in a clean plasma, but high helium concentrations (helium "poisoning") precludes such operation. Contrary to the Goldston scaling law [11], which suggests that the fusion triple product, $n\tau_E T_i$ is constant when τ_E degrades as $P^{-1/2}$, the degradation of confinement with the transport model of Section III saturates at high power, P. Thereafter, $n_i\tau_E T_i$ increases with power until the β-limit is reached.

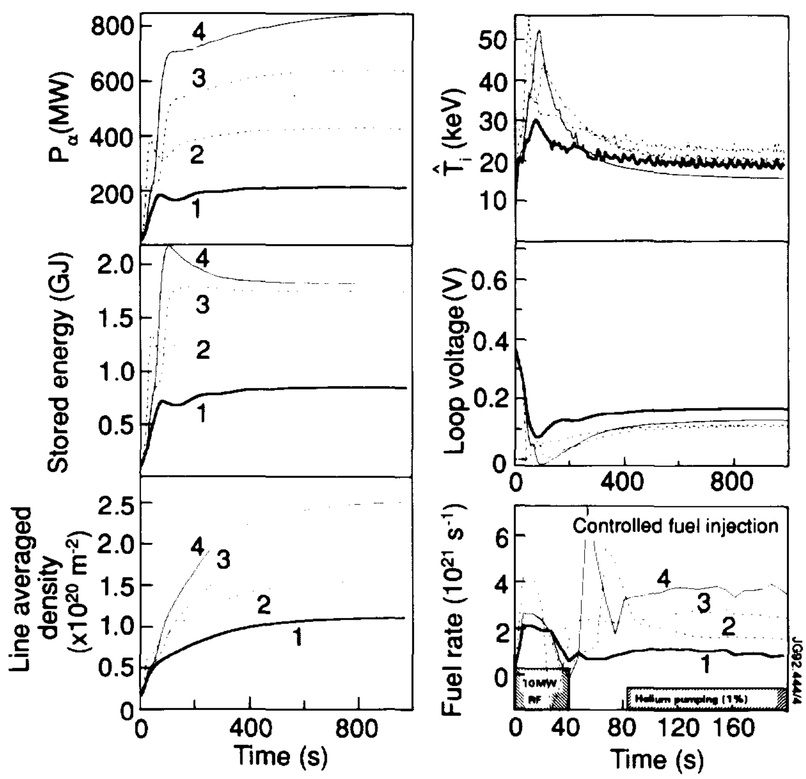


Fig. 2: Simulations of the start-up and burn control of a reactor core operating at various power levels. Shown are temporal evolution of α-power, stored energy, line-averaged density, central ion temperature and loop voltage. The RF heating needed for ignition, fuel injection (controlled by feedback on the power produced) and the helium pumping are also shown.

Table I: Summary of Reactor Core Simulations

Parameter	Case 1	Case 2	Case 3	Case 4
P_α(MW)	216	427	637	850
$T_i(0)$(keV)	19	23	21	16
$<n_e>(10^{19}m^{-3})$	11	16	21	26
τ_E(s)	4.0	3.4	2.8	2.1
I_{boot}(MA)	2.7	4.8	6.6	7.1
n_{He}/n_e (%)	19	24	24	20
V_{loop}(V)	0.15	0.10	0.10	0.11
g_{Troyon}	1.40	2.34	2.86	2.97

In these simulations, ignition is achieved with 10MW ICRH. Burn control at various power levels, is achieved with fuel injection controlled by feedback on the power produced. With these systems, ignition can be maintained for a wide range of powers (Fig. 2) above a minimum α-power, P_α of approximately 0.2GW. The corresponding minimum density of about $10^{20}m^{-3}$ is compatible with impurity control concepts foreseen at present to rely on energy removal by neutrals and radiation in a divertor [2]. Higher power ignition is achieved at higher density and stored energy but, generally, at lower temperature. The confinement time decreases from 4s when P_α=0.2GW to 2s when P_α=0.8GW and the global Troyon factor [12] increases from 1.4 at 0.2GW to 3 at 0.8GW (Table I). In all cases the density profile is slightly peaked (Fig. 3) with edge fuelling being sufficient to fuel the centre. Steady ignition conditions are achieved with a relatively high helium concentration (~20-25%): without sufficiently high transport and adequate pumping, helium poisoning can quench the ignition. In fact, while the H-mode might have short term benefits for approaching ignition, the long term deficiencies due to helium poisoning are evident (see Fig.4).

Ignition is achieved in this reactor core with a total current of up to 25MA. When the plasma pressure, p, is determined by the Goldston scaling law [11], the bootstrap current, $I_{BS} \propto (a/R)^{0.5}\beta_p I$ [6] (where the poloidal beta, $\beta_p \propto pa^2/I^2$) is limited and dependent only on the input power. In fact, $I_{BS} \propto P_\alpha^{0.5}$. For the range of conditions considered, the bootstrap current increases from 2.7MA at 0.2GW to 7.1MA at 0.8GW, and for relatively flat profiles, the bootstrap current tends to occur near the plasma edge. Furthermore, it should be noted that, the loop voltage is similar in all cases (~0.1V), the resistive flux consumption is quite low and a magnetic flux of 360Wb is sufficient for one hour current flat-top. Increasing the radius of the central solenoid of the reactor core by 0.8m would make available a further 360Wb and provide, therefore, an extra hour of steady operation.

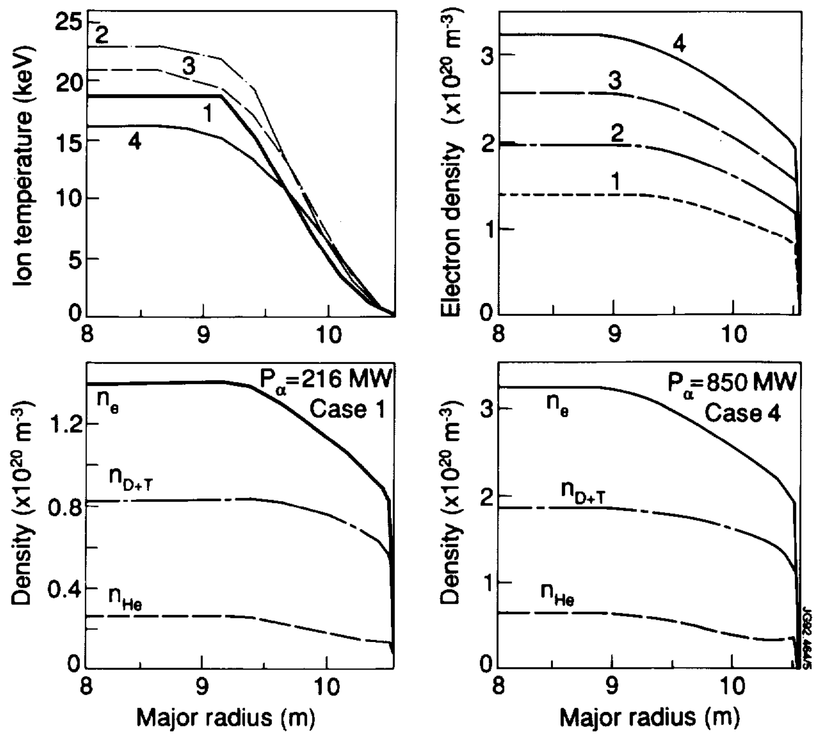


Fig. 3: Steady-state profiles of ion temperature and electron density calculated for a reactor core at various levels of α-power produced. Shown also are the density profiles at nominal α-powers of 0.2GW and 0.8GW.

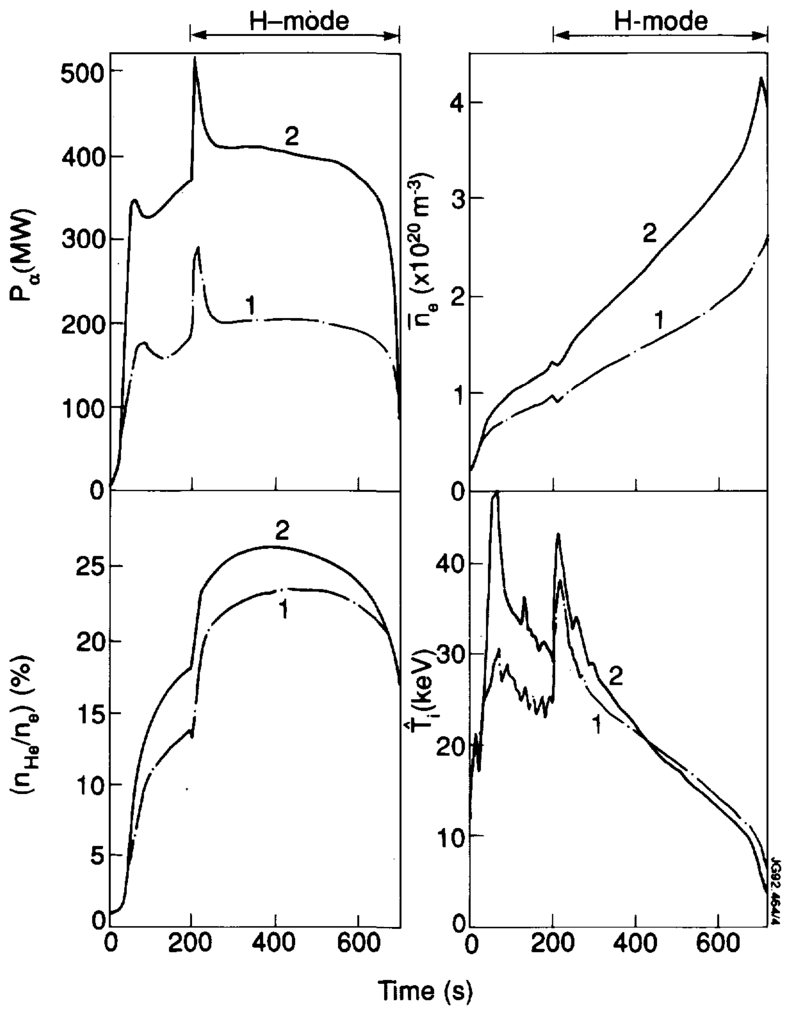


Fig. 4: The long term deficiencies of helium poisoning are shown by modelling the H-mode during the ignited phase of a reactor core. The nominal α-powers are 0.2GW and 0.4GW.

V. NON-INDUCTIVE CURRENT DRIVE

The techniques considered for non-inductive current drive include the injection of beams of high energy neutral particles and radio waves at various frequencies, including fast waves, lower hybrid waves and electron cyclotron waves [5]. The current, I_{CD}, that can be driven non-inductively is usually determined from the efficiency of the current drive technique, defined as $\gamma = I_{CD}R\langle n_e\rangle/P_{CD}$ [in units of A/m^{2}W], where P_{CD} is the power launched into the tokamak and available for current drive. For each technique, the presently demonstrated efficiency, γ_D and the extrapolated efficiency, γ_E (based on extrapolations to an average electron temperature of 20keV in an ITER CDA tokamak [13]) are given. The power requirements for current drive are also considered in relation to the economics of a reactor.

A. Review of techniques

Neutral beam injection is used widely for heating plasmas, particulary to very high ion temperatures at low density. High power neutral beams are readily available. Tens of MWs have been injected into tokamaks at energies up to 140keV. The current drive capability of neutral beam injection has also been demonstrated. The demonstrated efficiency, γ_D is 0.05×10^{20}A/m^{2}W and the extrapolated efficiency, γ_E is 0.5×10^{20}A/m^{2}W. However, neutral beam current drive in reactor plasmas will require the development of beams with energies in the range 1-2MeV. Even then, penetration of the beams to the centre of a reactor plasma is limited to densities less than 10^{20}m^{-3}. Furthermore, such high energy neutral beams are expected to be vulnerable to Alfven instabilities, which have the potential to reduce the efficiency significantly. From a technical stand-point, large access ports into the torus and external structures would be required and these would present difficulties for shielding against neutrons.

Fast waves have not been used so far to drive bulk current non-inductively. However, the hardware needed is the same as that already developed for heating plasmas at the ion cyclotron resonance and this has been readily demonstrated on, for example, JET (up to 22MW in the plasma with frequencies in the range 23-54MHz). While

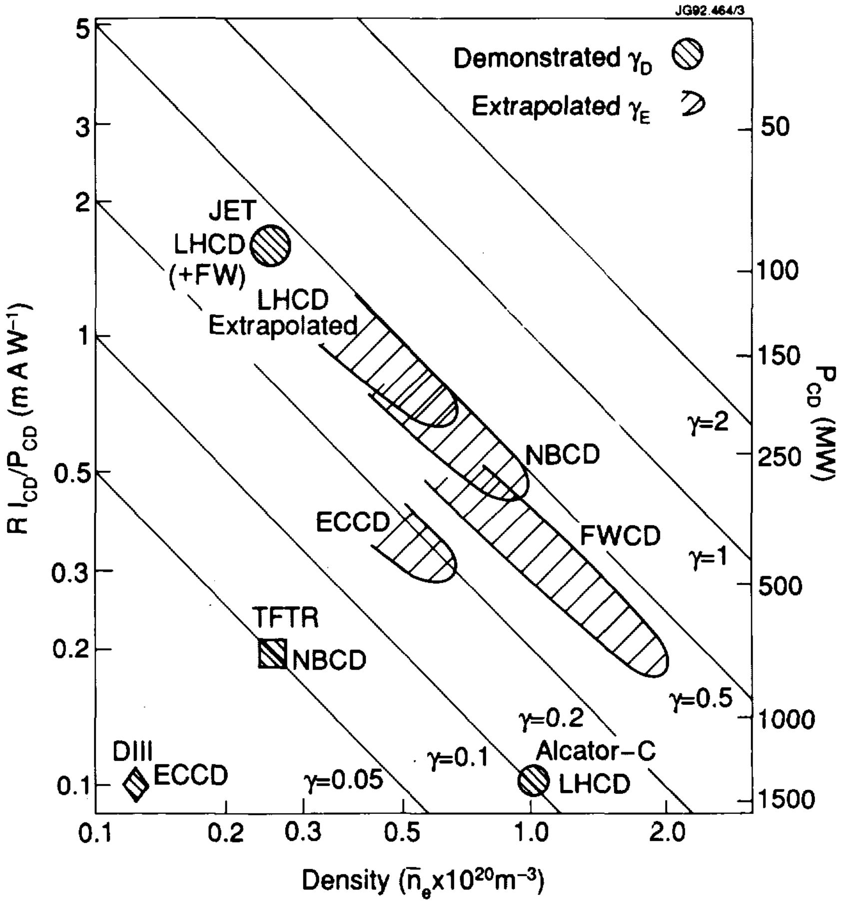


Fig. 5: Current drive efficiencies, demonstrated and extrapolated, for various techniques of non-inductive current drive. Also shown on the right-hand ordinate is the launched power required for 18MA of non-inductive current drive in a tokamak with R=8m.

the database for current drive is inadequate, the technique encompasses a wide range of scenarios which are expected to provide efficient, localised ion and electron heating, independent of electron density. Central current drive and sawtooth control appears possible. Large access ports would not be required and shielding problems would not arise.

Lower hybrid waves with frequencies in the range 2.45-8GHz have been coupled to tokamak plasmas. The highest demonstrated current drive efficiency, γ_D=0.4x10^{20}A/m^{2}W has been achieved with lower hybrid waves, albeit at a relatively low density of 2x10^{19}m^{-3}. The extrapolated efficiency, γ_E is also 0.4x10^{20}A/m^{2}W. The localisation of the wave depends upon density and temperature gradient, and penetration to the centre of the plasma will be very difficult. Therefore, the main use will be profile control, but this will be restricted to the edge at high density. Furthermore, the launcher structure is complex and needs to be located close to the plasma.

Electron cyclotron waves with frequencies in the range 94-140GHz have been injected into tokamak plasmas resulting in efficient and highly localised electron heating. The demonstrated current drive efficiency, γ_D is 0.01x10^{20}A/m^{2}W. This extrapolates to γ_E=0.15x10^{20}A/m^{2}W at 120GHz. Continuous operation will be needed and, so far, pulse lengths are less than 0.5s at the highest frequencies. The main use of electron cyclotron waves is likely to be the control of plasma profiles. Advantages include a simple launching structure and no plasma coupling problems. However, the demonstrated efficiency is low and sources suited to high power, continuous operation need to be developed. In addition, the transmission lines are complex, operation is expected to be limited to fixed frequency and current drive is affected by strong trapped particle effects.

B. Power requirements for continuous operation of a reactor core

The demonstrated efficiency, γ_D, for each of the current drive techniques reviewed is plotted in Fig. 5. Also shown are the lines of constant efficiency, γ, and the extrapolated efficiency, γ_E for each technique. It will be noted that lower hybrid current drive alone has demonstrated an efficiency as high as the extrapolated efficiency, but only at low density. At the higher density required in a reactor core, only fast wave current drive offers potential, but so far this technique has not been demonstrated.

Ignition is achieved in the reactor core studied in Section IV for a total plasma current up to 25MA and the bootstrap current is in the range 3-7MA. Thus, it would be necessary to provide about 15-20MA of non-inductive current drive

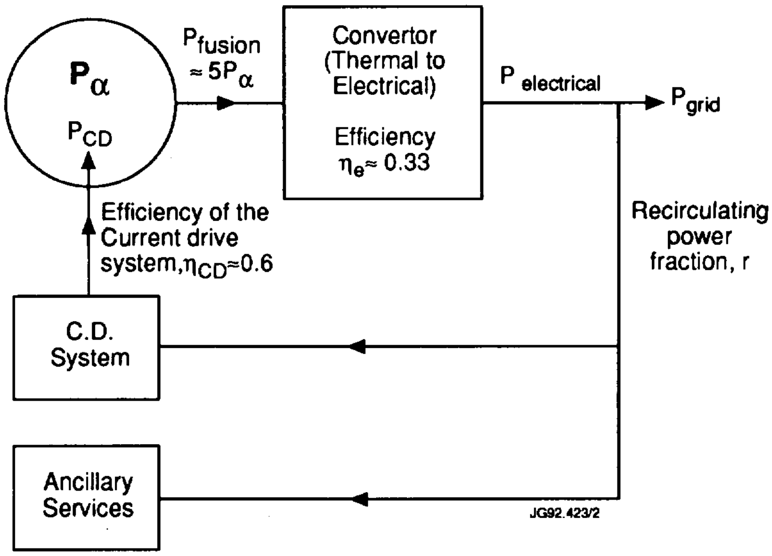


Fig. 6: The power requirements for full non-inductive current drive in a reactor.

for continuous operation. On the right hand ordinate of Fig. 5 is shown the launched power required for 18MA of non-inductive current in such a reactor core. It should be noted that for densities above $10^{20}m^{-3}$ and an efficiency γ=0.5x$10^{20}A/m^2W$, more than 300MW is needed.

The power available from the reactor for current drive is now determined. Consider a reactor which produces a fusion power, $P_{fusion} \approx 5P_\alpha$ (see Fig. 6). The efficiency, η_e, of converting thermal power to electrical power is about 0.33. Most of the electrical power will be supplied to the grid, but a fraction, r - the recirculating power fraction - may be used to power ancillary services, and any systems needed for non-inductive current drive. Given an optimistic efficiency for the current drive system, $\eta_{CD} \approx 0.6$, the launched power, P_{CD}, is approximately given by:

$$P_{CD} = \eta_{CD}\, r\, \eta_e\, P_{fusion} = 0.6 \times 0.33 \times 5\, r\, P_\alpha = r\, P_\alpha$$

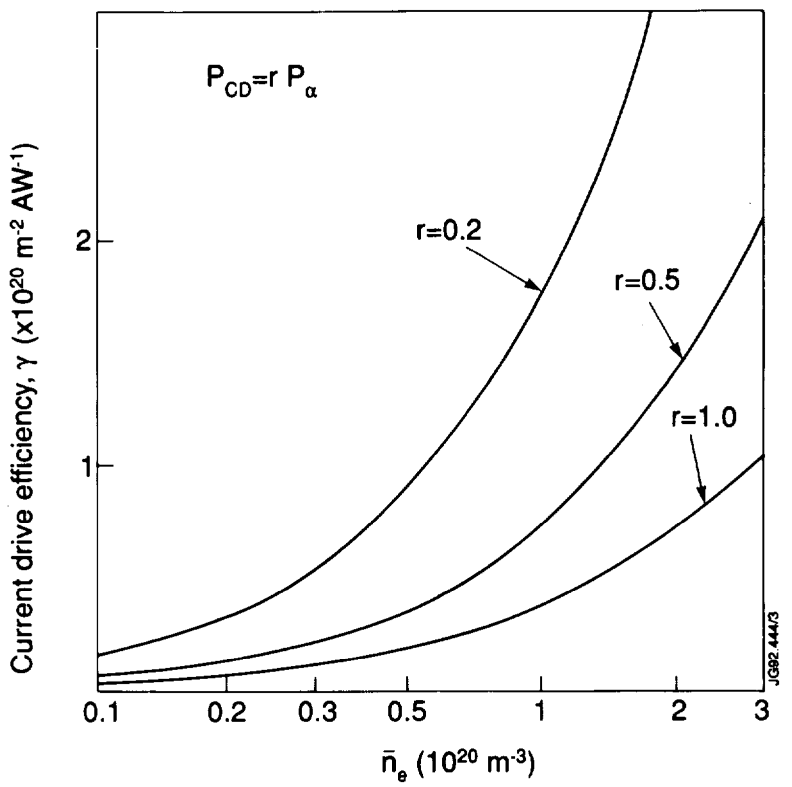


Fig. 7: The current drive efficiency as a function of average electron density for various assumptions about the recirculating power fraction, r.

As an example, consider a reactor producing 1.2GW (electrical) and supplying 0.6GW to the grid, that is, the recirculating power fraction is 0.5. Assuming ancillary services require 0.35GW and that the efficiency of the current drive system is 0.6, the launched power is only 150MW. In a reactor with R=8m, operating at a density of $10^{20}m^{-3}$ and assuming a current drive efficiency of $0.3x10^{20}A/m^2W$, only 6MA could be expected to be driven non-inductively.

Of course, the economics of a reactor will depend very much on the recirculating power fraction, r. For example, r=0.5 would more than double the capital cost for a given net output of electrical power and so, ideally, the recirculating power fraction should be no more than 0.2. In Fig. 7, the current drive efficiency is plotted against average plasma density for different assumptions relating to the recirculating power fraction. It can be seen that $\gamma=2x10^{20}A/m^2W$ is required for reasonable reactor operating conditions (densities above $10^{20}m^{-3}$) and for a reasonable recirculating power fraction (r=0.2).

C. Continuous operation of a reactor core

It is now possible to superimpose the operating domain of the reactor core modelled in Section IV on to Fig. 5. With non-inductive current drive accounting for the difference between the total plasma current of 25MA and the bootstrap current, and with various assumptions on the recirculating power fraction, r, it is seen (Fig. 8(a)) that the most optimistic extrapolations with $\gamma=0.5x10^{20}A/m^2W$ requires all the electrical power produced by the reactor (r=1.0). Even then, only a fast wave system (which has yet to be demonstrated experimentally) could provide central current drive. Otherwise, with the more reasonable assumption of r=0.2, a current drive efficiency of $2x10^{20}A/m^2W$ would be required.

The same model is applied to a high aspect ratio reactor [14] operating at higher magnetic field and lower plasma current (R=7m, a=1.75m, B_T=9T, I=12MA, κ=1.8). In this case, the bootstrap current is a larger fraction of the total current and this would appear to place less stringent demands on the current drive system. Indeed, as seen in Fig.8(b), a recirculating power fraction of 0.5 is compatible with a current drive efficiency of $0.5x10^{20}A/m^2W$, but this must be achieved at even higher densities, above $2x10^{20}m^{-3}$. For a recirculating power fraction of 0.2, a current drive efficiency above $1x10^{20}A/m^2W$ would still be required and at a density above $2x10^{20}m^{-3}$.

D. Conclusions on non-inductive current drive for continuous operation in a reactor

Non-inductive current drive requires the full-time operation of a current drive plant, which must include redundant systems to ensure reliable. continuous operation. Under the conditions foreseen at present for a reactor, a high recirculating power fraction would be needed and this would increase significantly the cost of the reactor. To overcome this disadvantage, the current drive efficiency would need to be significantly greater than presently envisaged; or ignition and impurity control would need to be demonstrated at lower density ($<5x10^{19}m^{-3}$) and higher temperatures; or high power operation in a regime with a dominant bootstrap current would need to be demonstrated. At present, there is no conceptual solution that addresses all these issues consistently.

VI. SEMI-CONTINUOUS OPERATION: INDUCTIVE CURRENT DRIVE

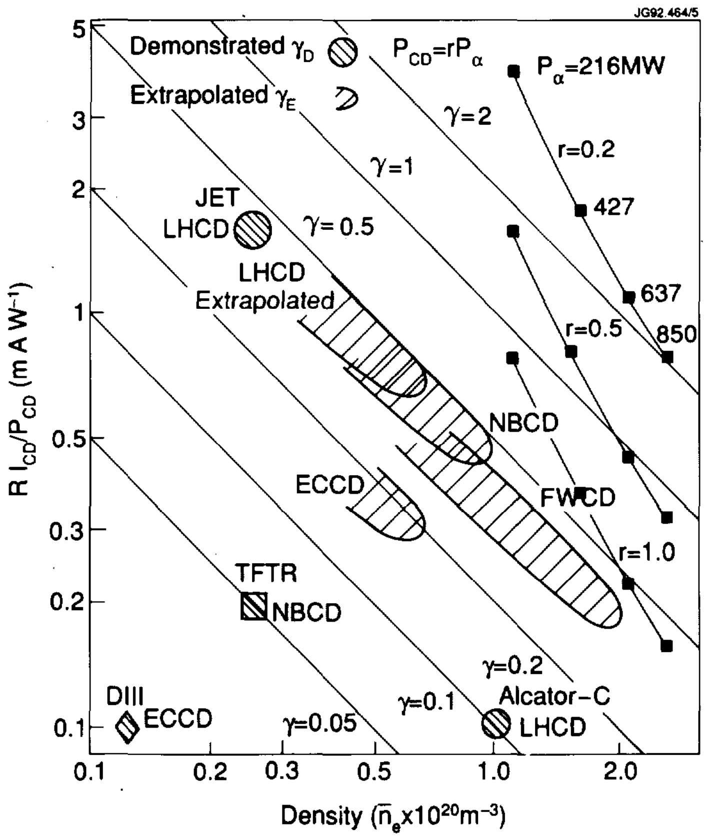
By comparison, there appear to be clear advantages to semi-continuous reactor operation with inductive current drive: the ohmic dissipation in a superconducting central solenoid is very small, the power is used efficiently and the recirculating power is kept to a minimum. The power in the plasma needed to drive 25MA inductively, with a plasma loop voltage of 0.1V, could be 2.5MW, or less. For an efficiency from transformer to plasma of between 0.2 and 0.5, the transformer requires only 5-12.5MW of recirculating power. Furthermore, with semi-continuous operation, systems for additional heating can be optimised for heating to ignition and the reactor really ignites with a fusion amplification factor, Q of about 1000.

A. Techniques for semi-continuous operation

Two techniques are possible for semi-continuous operation, namely operation with forward current and with alternating current. Provided the central solenoid exceeds a minimum size, both techniques can be utilised on the same device and with the same duty cycle. Both techniques have been studied experimentally on JET [7,8].

Forward current and transformer re-charge is the conventional way to operate a tokamak. The magnetic flux consumption comprises the sum of the inductive and resistive flux requirements. In a reactor, with, say, 900Wb available, the burn time can be relatively long (~2 hours and using ~600Wb) to offset the long burn-interruption time needed for re-charging the transformer and ramping the current (~6 minutes, including ~3 minutes for transformer re-charge and ~1 minute each for the rise and decay of the full current and power). An additional power supply could be required for the transformer re-charge.

The magnetic flux consumption for an alternating current technique comprises twice the inductive flux together with the resistive flux. With the same total magnetic flux available for forward current operation, the burn time in a)



b)

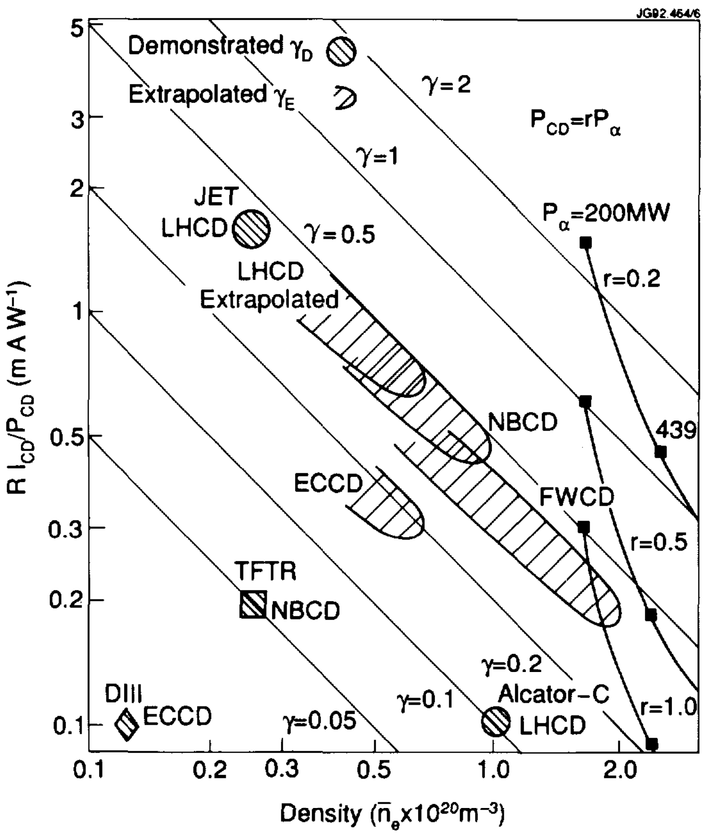


Fig. 8: The operating domain (heavy black lines) for full non-inductive current drive in a tokamak reactor with (a) R=7.75m, a=2.8m, B_T=6T, I=25MA, κ=1.6, and (b) R=7m, a=1.75m, B_T=9T, I=12MA, κ=1.8, for various assumptions about the recirculating power fraction, r.

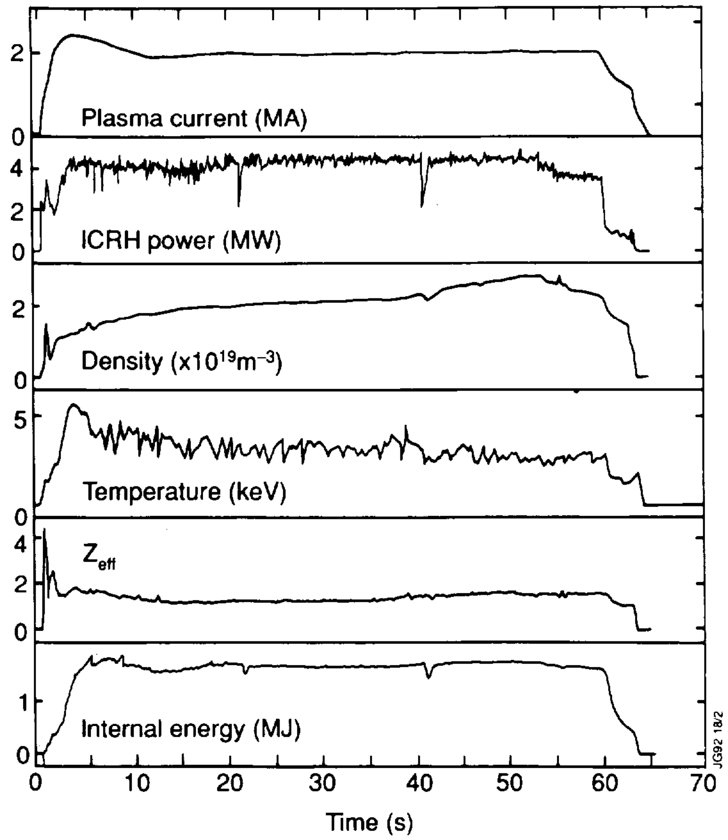


Fig. 9: Time traces for a JET discharge with a one minute current flat-top.

alternating current operation will be shorter (~1 hour and using ~300Wb), but so will the burn interruption time (less than about 3 minutes, including ~1 minute each for the rise and decay of the full current and power). The duty cycle is therefore the same for the two techniques.

B. Experience on JET

Very long pulse operation is essential for a reactor and JET has carried out preliminary studies in certain modes of operation. Fig. 9 shows a discharge in which the current flat-top is maintained for one minute with ion cyclotron heating, and, optionally, lower hybrid heating [7].

Reliable alternating current operation has also been demonstrated on JET at plasma currents up to 2MA [8]. Both plasma cycles shown in Fig. 10 exhibit equivalent parameters. The dwell time can be very short and pump-out of density does not cause a problem. A current ramp rate of about 1MAs^{-1} is acceptable.

C. Conclusions on inductive current drive for semi-continuous operation in a reactor

The same device can be used for either forward current or alternating current operation, provided the central solenoid is sufficiently large. On JET, both forward current operation, with reduced ohmic dissipation and extended flat-top by heating, and alternating current operation at 2MA have been demonstrated. In a reactor, it would be desirable to smooth the power output, especially for burn interruption in forward current operation, and this can be achieved by external storage of thermal energy or by a 10% over-capacity distributed between several devices. Semi-continuous operation with inductive current drive offers, at present, the only viable solution for a long pulse tokamak reactor.

VII. CONCLUSIONS

The operating conditions of the plasma core of a first reactor have been simulated with a model that is consistent with experimental results from JET and other tokamaks. Simulations show that the reactor core operates well in L-mode and at high power. Ignition can be maintained for a wide range of α-powers above a minimum, approximately equal to 0.2GW. The corresponding minimum density is about 10^{20}m^{-3} and is compatible with impurity control concepts foreseen at present. Furthermore, the bootstrap current is limited.

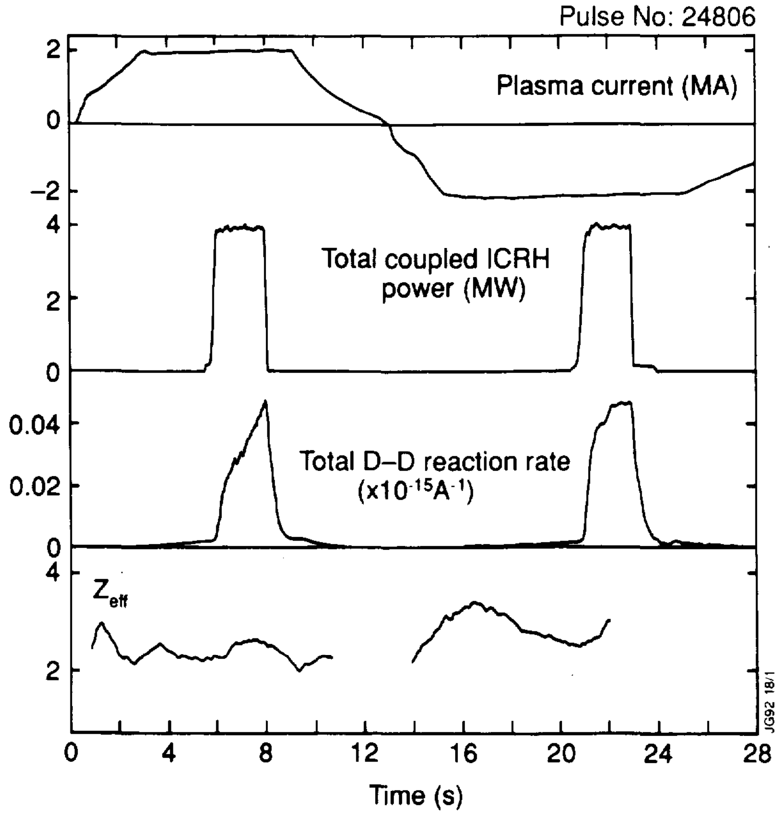


Fig. 10: Time traces for a JET discharge which demonstrated reliable AC operation at 2MA.

At present, the basis for a reactor core that operates continuously is not apparent. Such a continuously operating reactor would require a convincing demonstration of:

(a) a current drive efficiency exceeding 1×10^{20}A/m^{2}W for a density above 10^{20}m^{-3}; or
(b) ignition and adequate impurity control at a density of 5×10^{19}m^{-3} and a current drive efficiency of 0.5×10^{20}A/m^{2}W; or
(c) high power operation in a regime with a dominant bootstrap current.

Semi-continuous operation with inductive current drive offers, at present, the only viable solution for a long pulse tokamak reactor. The same device can be used for either forward current or alternating current operation, provided the central solenoid is sufficiently large. Preliminary experiments on JET have demonstrated the principles of both techniques. Furthermore, a tokamak reactor operating semi-continuously would be simpler in construction, uses recirculating power more efficiently and is likely to be more reliable in operation.

Therefore, the Next Step tokamak must be based on inductive semi-continuous operation.

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Appendix I

THE JET TEAM

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, U.K.

J.M. Adams[1], B. Alper, H. Altmann, A. Andersen[14], P. Andrew, S.Ali-Arshad, W. Bailey, B. Balet, P. Barabaschi, Y. Baranov, P. Barker, R. Barnsley[2], M. Baronian, D.V. Bartlett, A.C. Bell, G. Benali, P. Bertoldi, E. Bertolini, V. Bhatnagar, A.J. Bickley, D. Bond, T. Bonicelli, S.J. Booth, G. Bosia, M. Botman, D. Boucher, P. Boucquey, M. Brandon, P. Breger, H. Brelen, W.J. Brewerton, H. Brinkschulte, T. Brown, M. Brusati, T. Budd, M. Bures, P. Burton, T. Businaro, P. Butcher, H. Buttgereit, C. Caldwell-Nichols, D.J. Campbell, D. Campling, P. Card, G. Celentano, C.D. Challis, A.V.Chankin[23], A. Cherubini, D. Chiron, J. Christiansen, P. Chuilon, R. Claesen, S. Clement, E. Clipsham, J.P. Coad, I.H. Coffey[24], A. Colton, M. Comiskey[4], S. Conroy, M. Cooke, S. Cooper, J.G. Cordey, W. Core, G. Corrigan, S. Corti, A.E. Costley, G. Cottrell, M. Cox[7], P. Crawley, O. Da Costa, N. Davies, S.J. Davies[7], H. de Blank, H. de Esch, L. de Kock, E. Deksnis, N. Deliyanakus, G.B. Denne-Hinnov, G. Deschamps, W.J. Dickson[19], K.J. Dietz, A. Dines, S.L. Dmitrenko, M. Dmitrieva[25], J. Dobbing, N. Dolgetta, S.E. Dorling, P.G. Doyle, D.F. Düchs, H. Duquenoy, A. Edwards, J. Ehrenberg, A. Ekedahl, T. Elevant[11], S.K. Erents[7], L.G. Eriksson, H. Fajemirokun[12], H. Falter, J. Freiling[15], C. Froger, P. Froissard, K. Fullard, M. Gadeberg, A. Galetsas, L. Galbiati, D. Gambier, M. Garribba, P. Gaze, R. Giannella, A. Gibson, R.D. Gill, A. Girard, A. Gondhalekar, D. Goodall[7], C. Gormezano, N.A. Gottardi, C. Gowers, B.J. Green, R. Haange, A. Haigh, C.J. Hancock, P.J. Harbour, N.C. Hawkes[7], N.P. Hawkes[1], P. Haynes[7], J.L. Hemmerich, T. Hender[7], J. Hoekzema, L. Horton, J. How, P.J. Howarth[5], M. Huart, T.P. Hughes[4], M. Huguet, F. Hurd, K. Ida[18], B. Ingram, M. Irving, J. Jacquinot, H. Jaeckel, J.F. Jaeger, G. Janeschitz, Z. Jankowicz[22], O.N. Jarvis, F. Jensen, E.M. Jones, L.P.D.F. Jones, T.T.C. Jones, J-F. Junger, F. Junique, A. Kaye, B.E. Keen, M. Keilhacker, W. Kerner, N.J. Kidd, R. Konig, A. Konstantellos, P. Kupschus, R. Lässer, J.R. Last, B. Laundy, L. Lauro-Taroni, K. Lawson[7], M. Lennholm, J. Lingertat[13], R.N. Litunovski, A. Loarte, R. Lobel, P. Lomas, M. Loughlin, C. Lowry, A.C. Maas[15], B. Macklin, C.F. Maggi[16], G. Magyar, V. Marchese, F. Marcus, J. Mart, D. Martin, E. Martin, R. Martin-Solis[8], P. Massmann, G. Matthews, H. McBryan, G. McCracken[7], P. Meriguet, P. Miele, S.F. Mills, P. Millward, E. Minardi[16], R. Mohanti[17], P.L. Mondino, A. Montvai[3], P. Morgan, H. Morsi, G. Murphy, F. Nave[27], S. Neudatchin[23], G. Newbert, M. Newman, P. Nielsen, P. Noll, W. Obert, D. O'Brien, J. O'Rourke, R. Ostrom, M. Ottaviani, S. Papastergiou, D. Pasini, B. Patel, A. Peacock, N. Peacock[7], R.J.M. Pearce, D. Pearson[12], J.F. Peng[26], R. Pepe de Silva, G. Perinic, C. Perry, M.A. Pick, J. Plancoulaine, J-P. Poffé, R. Pohlchen, F. Porcelli, L. Porte[19], R. Prentice, S. Puppin, S. Putvinskii[23], G. Radford[9], T. Raimondi, M.C. Ramos de Andrade, M. Rapisarda[29], P-H. Rebut, R. Reichle, S. Richards, E. Righi, F. Rimini, A. Rolfe, R.T. Ross, L. Rossi, R. Russ, H.C. Sack, G. Sadler, G. Saibene, J.L. Salanave, G. Sanazzaro, A. Santagiustina, R. Sartori, C. Sborchia, P. Schild, M. Schmid, G. Schmidt[6], H. Schroepf, B. Schunke, S.M. Scott, A. Sibley, R. Simonini, A.C.C. Sips, P. Smeulders, R. Smith, M. Stamp, P. Stangeby[20], D.F. Start, C.A. Steed, D. Stork, P.E. Stott, P. Stubberfield, D. Summers, H. Summers[19], L. Svensson, J.A. Tagle[21], A. Tanga, A. Taroni, C. Terella, A. Tesini, P.R. Thomas, E. Thompson, K. Thomsen, P. Trevalion, B. Tubbing, F. Tibone, H. van der Beken, G. Vlases, M. von Hellermann, T. Wade, C. Walker, D. Ward, M.L. Watkins, M.J. Watson, S. Weber[10], J. Wesson, T.J. Wijnands, J. Wilks, D. Wilson, T. Winkel, R. Wolf, D. Wong, C. Woodward, M. Wykes, I.D. Young, L. Zannelli, A. Zolfaghari[28], G. Zullo, W. Zwingmann.

PERMANENT ADDRESSES

1. UKAEA, Harwell, Didcot, Oxon, UK.
2. University of Leicester, Leicester, UK.
3. Central Research Institute for Physics, Budapest, Hungary.
4. University of Essex, Colchester, UK.
5. University of Birmingham, Birmingham, UK.
6. Princeton Plasma Physics Laboratory, New Jersey, USA.
7. UKAEA Culham Laboratory, Abingdon, Oxon, UK.
8. Universidad Complutense de Madrid, Spain.
9. Institute of Mathematics, University of Oxford, UK.
10. Freien Universität, Berlin, F.R.G.
11. Royal Institute of Technology, Stockholm, Sweden.
12. Imperial College, University of London, UK.
13. Max Planck Institut für Plasmaphysik, Garching, FRG.
14. Risø National Laboratory, Denmark.
15. FOM Instituut voor Plasmafysica, Nieuwegein, The Netherlands.
16. Dipartimento di Fisica, University of Milan, Milano, Italy.
17. North Carolina State University, Raleigh, NC, USA
18. National Institute for Fusion Science, Nagoya, Japan.
19. University of Strathclyde, 107 Rottenrow, Glasgow, UK.
20. Institute for Aerospace Studies, University of Toronto, Ontario, Canada.
21. CIEMAT, Madrid, Spain.
22. Institute for Nuclear Studies, Otwock-Swierk, Poland.
23. Kurchatov Institute of Atomic Energy, Moscow, USSR
24. Queens University, Belfast, UK.
25. Keldysh Institute of Applied Mathematics, Moscow, USSR.
26. Institute of Plasma Physics, Academica Sinica, Hefei, P. R. China.
27. LNETI, Savacem, Portugal.
28. Plasma Fusion Center, M.I.T., Boston, USA.
29. ENEA, Frascati, Italy.

At 1st July, 1992