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History of the approach to ignition

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THE ROYAL SOCIETY

History of the approach to ignition

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The origin of the energy of the stars as being due to the fusion of light nuclei was identified by Edington in 1920. In the late 1940s, work started, aimed at creating suitable conditions in the laboratory to develop a major new energy source for the world. The two radically different approaches depend either on the inertia of a small dense hot pellet or on the use of magnetic fields to control and contain the motion of charged particles. This paper concentrates largely on the latter 'magnetic confinement' history leaving 'inertial confinement' to other contributors. Early work saw the invention of a wide variety of magnetic-field geometries for the confinement of hot ionized gases (plasmas). By a process of natural selection, this has been almost entirely reduced to so-called 'closed toroidal systems', such as the stellarator, tokamak and reversed-field pinch. Effort has been concentrated on the tokamak, culminating in the present position where 'breakeven' has been achieved in large machines. An improvement by a further factor of five to ten in the key triple-product parameter ($n\tau T$) is needed to reach the ignition point where the reaction becomes self-sustaining. New machines designed to achieve this, and in one case (International Thermonuclear Experimental Reactor) to demonstrate the technical feasibility of an ultimate power-generating system, are under consideration. A course of action in this direction is recommended.

Keywords: plasma; fusion; tokamak; ignition; energy; fusion power

1. Background and early history

In 1920, Eddington put together the results of Einstein, showing the equivalence of mass and energy, with the measurements of isotopic masses by Aston (Eddington 1920). These showed that energy could be released by the fusion of light nuclei (figure 1). Eddington proposed that such fusion processes were the source of heat 'which the Sun and stars are continually squandering'. He referred to 'our dream of controlling this latent power for the well-being of the human race—or for its suicide'. He also remarked, memorably, 'what is possible in the Cavendish Laboratory may not be too difficult in the Sun'. Hence our search to find ways in which fusion energy can be released in a controlled, economic and safe way to satisfy the energy needs of the world. In fact we hope to do in the laboratory what is done in the Sun. Two further key contributions were the discovery of the isotopes of hydrogen: deuterium by Urey *et al*. (1932); and tritium by Oliphant *et al*. (1934). As an aside, we note that the Cambridge group objected to the name 'deuterium' proposed by the US group and put forward erudite arguments in favour of 'diplogen'. The Americans won.

The fusion reactions which will most concern us are

$$\left.\begin{aligned} D + D &\rightarrow {}^3He + n + 3.27\,MeV, \\ D + D &\rightarrow {}^3T + p + 4.03\,MeV, \end{aligned}\right\} \tag{1.1}$$

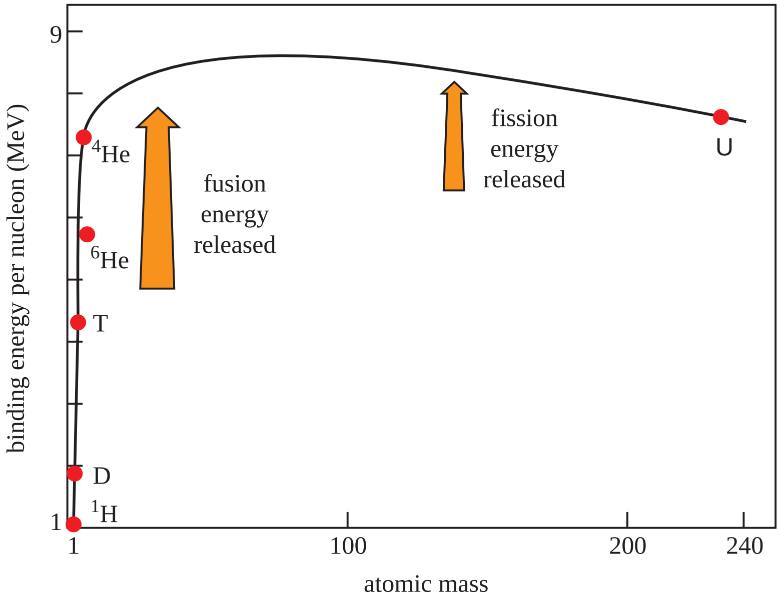

Figure 1. Binding energy curve.

$$D + T \rightarrow {}^4He + n + 17.6\ MeV. \qquad (1.2)$$

The two branches of the D–D reaction occur with equal probability. The D–T cross-section is approximately 100 times that for D–D in the relevant energy range, 10–200 keV; consequently, the plasma conditions required are greatly reduced. Attention is therefore concentrated on D–T systems in the short term, i.e. the next 50 years. Since tritium has a half-life of *ca.* 12 years, it must be bred by using the emitted 14 MeV neutrons absorbed in a blanket containing lithium.

The achievement of a significant power output requires a hot gas with temperatures in the range 5–20 keV ($1\ keV = 10^7$ K). Such a gas is fully ionized and very close to charge neutral with equal numbers of electrons and ions. Up to 1945, the body of knowledge about such 'plasmas' came either from laboratory experiments on gas discharges or from theoretical work related to astrophysics.

The problem is to heat a volume of gas to the required temperatures and hold it in pressure equilibrium long enough to release more thermonuclear energy than is used in its formation. In the Sun, the core temperature is 1.5×10^7 K and the density *ca.* 100 g cm^{-3}. The resulting pressure of 10^{11} atm is held in equilibrium by gravitational forces. Such forces are far too weak to be used with terrestrial plasmas. Instead, magnetic fields can be used, since these restrict particle motion perpendicular to the field. Motion along the field lines is unrestricted, a variety of solutions to deal with this problem will be discussed below.

An alternative to magnetic confinement is to heat a small very high density plasma to thermonuclear temperatures, such that sufficient energy is released before it flies apart. This 'inertial confinement' is the major competitor to 'magnetic confinement' in the quest for fusion power. Such an inertial confinement scheme envisages a series of these microexplosions in an eventual power-producing reactor.

2. Early work on magnetic confinement

Discussion of the possibilities of controlled thermonuclear reactions in the laboratory began in the early 1940s, and by the late '40s and early '50s proposals for specific magnetic geometries were being made. Hydrogen bombs were exploded by the main weapon states, giving dramatic proof of the energy released by fusion. Fusion programmes in the USA, USSR and UK were carried out in secrecy until 1958. It was thought that the copious neutron emission from a successful thermonuclear system might be a cheap source of fissile material for use in weapons. All three programmes received varying degrees of encouragement from the announcement in 1951 by the Argentine leader Juan Perón, that the successful controlled release of fusion energy had been achieved in a laboratory he had set up for the physicist Ronald Richter. The claim proved to be false, but it could be said to have had an overall positive effect on the field. It was the forerunner of several 'claim problems' in this subject, culminating, in recent years, with the cold fusion controversy.

In 1957, Lawson published a long-overdue analysis of the conditions required to generate useful power from fusion reactions (Lawson 1957). A volume of plasma, with particle density n, is heated instantaneously to a temperature T, held there for a time τ and then disassembled. The ratio R between the energy released to energy supplied is then

$$R = \frac{\tau P_{\mathrm{N}}}{\tau P_{\mathrm{B}} + 3nT} = \frac{P_{\mathrm{N}}/3n^2T}{(P_{\mathrm{B}}/3n^2T) + 1/(n\tau)}, \tag{2.1}$$

the radiated power P_{B} and the fusion power P_{N} are both proportional to n^2, so R is only a function of T and $n\tau$. Taking the efficiency, η, of conversion of heat to electrical power, the condition for more electrical power out than in is

$$\eta(R+1) > 1, \tag{2.2}$$

with $\eta = \frac{1}{3}$, $R > 2$. For the D–T reactions, this leads to the two 'Lawson' requirements for net power production:

$$n\tau > 10^{14}\ \mathrm{cm}^{-3}\ \mathrm{s}, \qquad T > 2 \times 10^8\ \mathrm{K}. \tag{2.3}$$

For a steady-state system, the pulse time, τ, is effectively replaced by the energy confinement time τ_{e}, defined as

$$\tau_{\mathrm{e}} = 3nT/P_{\mathrm{L}}, \tag{2.4}$$

where P_{L} is the power lost from unit volume by radiation, conduction and convection.

3. Ignition

For steady-state magnetically confined plasmas, the definition of ignition is simple. It is that condition when the power deposited in the plasma by charged reaction products is equal to that lost from the plasma. It is analogous to lighting a fire: once ignited, the plasma does not need any additional heating input to maintain its temperature. The condition for ignition is, thus,

$$\tfrac{1}{4} n^2 \overline{\sigma v} W_{\mathrm{ch}} \geqslant \frac{3nT}{\tau_{\mathrm{e}}}, \tag{3.1}$$

where a 50:50 mixture of D–T leads to the factor $\frac{1}{4}$ in the binary collision rate, $\overline{\sigma v}$ is the D–T fusion cross-section velocity product averaged for a Maxwellian velocity distribution at the temperature T. W_{ch} is the energy release in confined charged particles, 3.5 MeV α-particles in the case of the D–T reaction.

From (3.1) we find the condition

$$n\tau_{\mathrm{e}} \geqslant \frac{12T}{\overline{\sigma v}W_{\mathrm{ch}}}. \tag{3.2}$$

For D–T, the $\overline{\sigma v}$ product is approximately

$$\sigma v = 10^{-24}T^2 \ \mathrm{m^3\ s^{-1}}, \tag{3.3}$$

with T in keV and in the range $7 < T < 20$ keV, substitution into (3.2) then gives a condition for ignition on the triple product

$$n\tau_{\mathrm{e}}T > 3.4 \times 10^{21} \ \mathrm{m^{-3}\ s\ keV}. \tag{3.4}$$

More accurately, we can use the full variation of $\overline{\sigma v}$ with T and calculate ignition curves of the required $(n\tau_{\mathrm{e}}T)$ as a function of T. Such curves will be used later to exhibit the progress towards ignition of various experiments. Corrections are also required to take account of radial pressure profiles and of the presence of impurities (Bickerton 1989).

During the approach to ignition, the parameter Q is a useful measure of progress, where

$$Q = P_{\mathrm{fusion}}/P_{\mathrm{heat}}, \tag{3.5}$$

where P_{fusion} is the total power output in both neutrons and α-particles while P_{heat} is the externally supplied power required to maintain the plasma in steady state. Ignition corresponds to $Q = \infty$, while $Q = 1$ is defined as breakeven. As for ignition, curves can be plotted in the $n\tau T$ versus T space for various Q values.

Once ignited, a notional magnetic-confinement fusion reactor can be maintained in steady state provided that the following conditions are met.

(a) High-energy α-particles are contained for long enough to give most of their energy to the plasma. Since energy transfer is primarily to the electrons, the electron temperature will exceed that of the ions in a steady state.

(b) Thermalized fusion products are removed from the plasma core to avoid excess fuel dilution.

(c) Fresh fuel, in our case D and T, is supplied to the central core at a suitable rate to maintain a steady state.

(d) The confining magnetic fields are held steady. This will require some power to maintain the refrigeration of superconducting coils as well as arrangements to maintain any externally driven plasma currents needed to provide part of the confining magnetic field.

Note that since the power output of such a system is proportional to the losses, it is normally envisaged that plasma conditions will be moved from some initial low-loss ignited state to one with higher losses and, hence, higher output. Figure 2 shows the main features of such a notional fusion reactor. Electricity generation is through a

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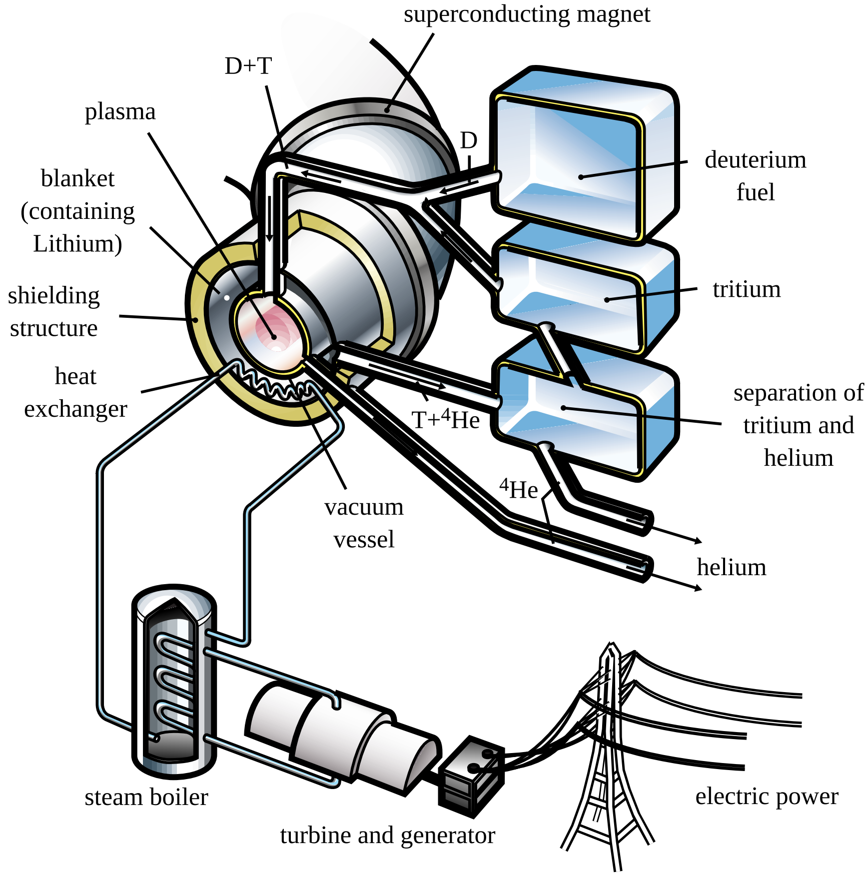

Figure 2. Notional fusion reactor.

conventional steam cycle. Schemes for direct conversion of charged-particle energy into electricity are, at first sight, attractive and more elegant. However for the D–T reaction, only 20% of the fusion power is in the form of charged particles. In addition, direct conversion normally requires that the plasma is taken around some form of Carnot cycle. The resulting combination of time-periods of low output between full power phases more than offsets the undoubted gain in thermal efficiency.

Note that the blanket surrounding the plasma that converts the flux of 14 MeV neutrons into heat, shields the superconducting coils and breeds tritium, has a thickness in the range 1.5–2 m. This sets the scale of the reactor core and is consistent with the expected confinement performance of tokamaks and stellarators (Bickerton 1989).

Ignition for inertial confinement describes the state in which conditions are reached such that a thermonuclear burn wave propagates outwards from the hot core. The pellet gain G is a more useful performance measure, where

$$G = \frac{\text{nuclear energy output from micro-explosion}}{\text{energy input to heat pellet}}. \tag{3.6}$$

A promising scheme for inertial confinement is one in which only a small central volume in a sphere of high density D–T is heated to thermonuclear temperatures.

Under suitable conditions the α-particles then drive a thermonuclear reaction wave through the surrounding, initially cool, volume of gas (Chu 1972). In such a case, very high values of G (greater than 100), are theoretically possible. Progress in this field will be described in other papers in this issue.

4. Natural selection

A plasma with an isotropic pressure p must be in equilibrium with the magnetic field B, such that

$$\bar{\jmath} \wedge \bar{B} = \operatorname{grad} p. \tag{4.1}$$

In the late 1950s, a wide variety of field configurations was tried, some only contained plasma with anisotropic pressure, notably the mirror machine in which $p_\perp > p_\parallel$, $\perp$ and $\parallel$ referring to the magnetic field. The observed Van Allen belts of trapped charged particles in the magnetic field of the Earth (Parks 1991), constitute a proof of this mirror concept, in which particles are reflected from regions of stronger magnetic field. Confinement is, however, limited to the characteristic time for collisional equilibration between $p_\perp$ and $p_\parallel$. At temperatures of thermonuclear interest, this time is marginally too short for an acceptable fusion reactor. By a process of natural selection, many of the early magnetic confinement proposals have now been largely abandoned. Attention is now focused on closed systems, which can, in principle, contain plasmas with isotropic pressure. Because of the properties of magnetic fields, such systems are, necessarily, topologically toroidal.

5. Neutron paranoia

A leading pioneer of fusion research in the UK was the Australian physicist Peter Thonemann. The climax of his efforts was the construction, in secret, at Harwell of ZETA ('zero energy thermonuclear assembly'). ZETA was an ambitiously large toroidal pinch for the time, with a major radius of 1.5 m, minor radius 0.5 m, a toroidal magnetic field of up to 400 gauss and, initially, a plasma current of 200 kA for a few milliseconds. In a highly publicized declassification, the impression was given that the 10^6 neutrons per pulse observed in deuterium were of thermonuclear origin, even though the published paper specifically said that a thermonuclear origin had not been identified (Thonemann *et al*. 1958). Six months later it was shown by cloud-chamber measurements that the observed neutron spectra were inconsistent with a thermonuclear origin (Rose *et al*. 1958), but rather corresponded to the production of accelerated deuterons with energy *ca.* 17 keV. This triggered a period of more than a decade of paranoia concerning the origin of neutrons from various plasma devices. Truly thermonuclear neutrons were noble and the development of diagnostics to prove nobility received a suitable boost.

ZETA continued to operate for 10 years up to 1968 and was highly successful and useful in

(i) discovering the phenomenon of magnetic relaxation, in which the plasma uses internal dynamo mechanisms to adopt a stable magnetic configuration (the so-called 'reverse field pinch' in modern jargon);

(ii) inspiring the development (Taylor 1974) of magnetic relaxation theory, now of widespread application in astrophysics (Kusano *et al*. 1995) and in geophysics (Kumar & Rust 1996);

(iii) providing an early stimulus for the development of techniques for measuring plasma parameters;

(iv) the successful spectroscopy of highly stripped ions relevant to solar physics; and

(v) the training of physicists, engineers and, to a lesser extent, theoreticians to work together in this field and to recognize the importance of public relations.

6. Bohm diffusion paranoia

Meanwhile, in the USA the astrophysicist Lyman Spitzer Jr had conceived a unique system for magnetic confinement (Spitzer 1958). He called it the stellarator. It was basically a toroidal system with a strong magnetic field parallel to the minor axis. He showed how by either geometric distortion of the toroid or winding helical multipolar coils on the surface of a planar toroid, vacuum magnetic fields could be produced entirely by currents in external windings with the properties needed to confine plasma. Spitzer led a large experimental and theoretical effort at Princeton, in the course of which ever larger and more powerful stellarators were built. The loss rate of particles from these machines far exceeded expectations, and was shown in a series of careful experiments (Stodiek *et al*. 1962) to correspond to the diffusion coefficient

$$D = \frac{ckT}{16eB}\ \mathrm{cm}^2\ \mathrm{s}^{-1} \tag{6.1}$$

(where T is in absolute units and k is Boltzmann's constant). This expression had been proposed by Bohm in connection with the operation of wartime ion sources for isotope separation. No theoretical justification was given by Bohm. Theoreticians were able to show later that this scaling results from maximizing the losses due to fluctuating electric fields perpendicular to the magnetic field. Such fluctuations would originate in the vast sea of instabilities discovered by theoreticians studying confined plasmas. If the Bohm loss rate was unavoidable, a reasonable sized fusion reactor would be impossible. Experiments on Princeton stellarators continued to show this loss rate, leading to disbelief when any claim of 'better than Bohm' was made. This paranoia was also positive in leading to extensive measurements before any such confinement claims could be made.

7. Back-to-basics period

These early magnetic confinement experiments all showed losses much greater than expected on the basis of inter-particle collisions only. The Russian physicist Artsimovich memorably said in 1961, 'Initial belief that the doors to the desired region would open smoothly at the first powerful pressure exerted by the creative energy of physicists has proved as unfounded as the sinner's hope of entering Paradise without passing through Purgatory. We do not know how long we will be in Purgatory.' There followed a period in which the cry 'back to basics' was heard. Magnetized plasma was

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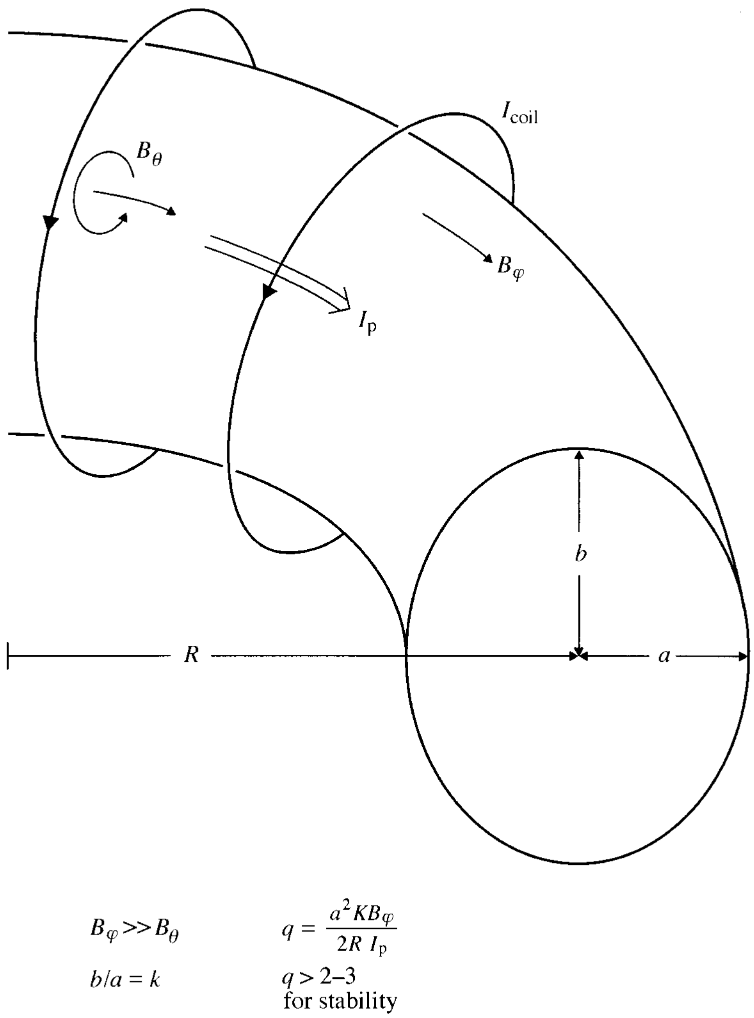

Figure 3. Tokamak schematic.

clearly a complex medium to deal with and, consequently, many specially designed experiments were now performed to study its basic properties. Every type of small amplitude wave in a magnetized plasma was studied and its properties compared with theory. Careful experiments showed the reality of esoteric plasma properties such as Landau damping and echo phenomena. With hindsight, we can see that in properly designed experiments the linear properties of plasma were found to be in excellent agreement with theory. This work gave plasma physics a sound and proven basis. It was also popular in political circles since, in general, it was much cheaper than the building of large confinement apparatus.

8. Tokamak fever

Meanwhile, in the Soviet Union under the leadership of Academician L. A. Artsimovich, the tokamak system was being developed (Artsimovich 1972). Similar in

Table 1. *Representative tokamaks*

device	year	location	major radius (m)	minor radius (m)	field (T)	current (MA)
T-3	1962	Moscow Russia	1.0	0.12	2.5	0.06
TFR	1973	Paris France	1.0	0.20	6.0	0.41
T-10	1975	Moscow Russia	1.5	0.37	4.5	0.68
PLT	1975	Princeton USA	1.3	0.4	3.5	0.72
Alcator C	1979	MIT USA	0.64	0.17	12.0	0.90
TFTR	1982	Princeton USA	2.52	0.87	5.5	2.7
JET	1983	Culham UK	3.0	1.25	3.5	7.0
JT-60	1985	Naka Japan	3.0	0.95	4.5	2.3
DIIID	1986	San Diego USA	1.67	0.67	2.1	*ca.* 1.0
Tore-Supra	1988	Cadarache France	2.37	0.8	4.5	2.0

many ways to the ZETA-type toroidal pinch, the major difference was a very strong toroidal magnetic field. Figure 3 is a schematic showing the basic tokamak features. The stabilizing toroidal field is characterized by the safety factor q, where

$$q = \frac{a}{R}\frac{B_\phi}{B_\theta} = \frac{a^2 B_\phi}{2RI_\mathrm{p}}, \tag{8.1}$$

where q at the plasma boundary must exceed 2–3 to provide the required stability. Here B_ϕ is the toroidal field, produced by external coils, B_θ is the poloidal self-field of the plasma current I_p, a and R are the minor and major radii of the toroid. Early work was hampered by the lack of diagnostics and the difficulty of access to the plasma through the substantial toroidal field coils and the thick-walled tori used. In 1969, laser-scattering experiments carried out on the T-3 machine showed relatively high electron temperature, and, more importantly, a clear break-out from the infamous Bohm diffusion (Peacock *et al*. 1969).

Consequently, since 1970 the major magnetic fusion effort in the world has been concentrated on the tokamak system. Progress in both performance and physics understanding has been steady and the most recent machines now produce conditions almost equal to those required for a tokamak fusion reactor. Table 1 shows the parameters of a few representative tokamaks built and operated over the past 30 years. Experimentally, the confinement time in these tokamaks, although much better than Bohm, is still sometimes orders of magnitude smaller than that predicted by theory, which takes into account the toroidal geometry but which includes only collisional processes (Hinton & Hazeltine 1976). This is not surprising when the wide range of linear instabilities theoretically predicted for such confined plasmas (Wesson 1997) is taken into account. The nonlinear consequences of such instabilities are much harder to predict. By regression analysis of the existing database, Goldston (1984) produced an empirical relation for τ_E,

$$\tau_E = 3.7 \times 10^{-2} I P^{-1/2} R^{1.75} a^{-0.37} K^{1/2}, \tag{8.2}$$

where τ_E is the confinement time in seconds, I the plasma current (MA), P the input power (MW), R and a the major and minor radii (m) and K the elongation of the plasma cross-section. This expression fits remarkably well with the performance of much larger tokamaks brought into operation since 1984. Several modes of operation have been discovered that give improvements by factors of 2 to 3 over this basic scaling. These are variously known as H (for high), VH (very high), etc., modes (Wesson 1997). The H-mode depends on using a poloidal divertor rather than a limiter to bound the plasma and, in addition, exceeding a heating-power threshold. With a reasonable allowance for the dilution of the plasma by helium, and with a typical set of reactor parameters $R = 10$ m and $a = 3$ m, the required plasma current for ignition is

$$I \approx 32/\gamma_g \text{ MA}, \tag{8.3}$$

where γ_g is the factor by which the confinement time exceeds that given by the Goldston formula.

The performance of tokamaks is shown on the $\langle n\tau_E T_i \rangle$ versus T_i diagram (see figure 4). Curves show the boundaries for breakeven and for ignition. These curves have been calculated for strictly steady-state plasma. The experimental points are all for transient plasmas leading in some cases to over estimation of the experimental Q by a factor less than three. The large tokamaks JET and TFTR have been run in deuterium–tritium mixtures and have shown α-particle heating effects on the electron temperature (Thomas *et al*. 1998; Taylor *et al*. 1996). In the case of JET, the α-power reached 10% of the input power. Clearly, these tokamaks and the Japanese JT-60 in deuterium are close to breakeven and only factors of order 10 away from ignition, in the parameter $\langle n\tau_E T_i \rangle$.

These advances have been made by technical and scientific progress in the fields of plasma heating, plasma diagnostics and machine building. On the plasma heating front, there are now well-developed techniques for putting 10s of megawatts into the plasma with resonant radiofrequency (RF) waves launched from the boundary or with powerful neutral particle beams. These heating schemes are well understood theoretically and can be extrapolated to reactor conditions with confidence. A major challenge has been to measure plasma quantities such as n, T_e, T_i, E and B inside the discharge. Conditions are such that no material probes can be used. Instead, parameters must be deduced from radiation and particles leaving the plasma and by the use of probing beams of particles or laser light. Table 2 lists the main diagnostics now used routinely on these machines. There are still difficulties in measuring fluctuating electric and magnetic fields in the plasma core. This means that no definitive connection has yet been established between theories of plasma instabilities and the observed radial transport of energy and particles.

In all tokamaks, the essential toroidal plasma current is driven by transformer action and is, therefore, pulsed. A reactor would benefit greatly if it could be run in steady state. Fortunately, there is an effect of collisional transport theory that

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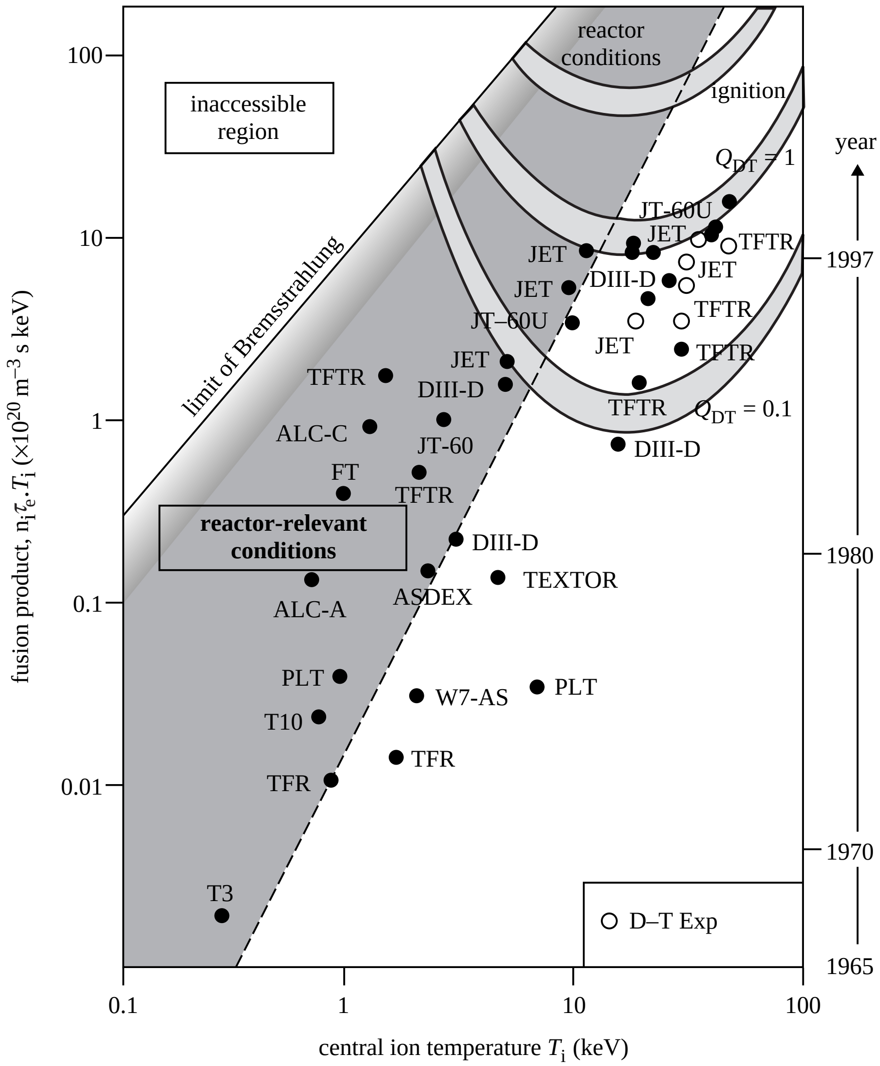

Figure 4. $\langle n\tau_e T_i\rangle$ versus T_i.

means that some part of the toroidal current, the bootstrap current, is effectively driven by the radial plasma pressure gradient. This is one case where the theoretical predictions have been followed later by experimental proof. The result is that in a suitably designed tokamak reactor, only a fraction of the current has to be somehow driven by other methods. Current drive by RF waves and by suitable injected beams has been clearly demonstrated experimentally. This current drive needs to have high efficiency in order to keep down the circulating power in a reactor. Table 3 lists the key parameters required for a reactor and the experimental achievements to date. Except for the triple confinement product, it is clear that each of the key parameters has been achieved separately in one machine or another. The table also highlights the importance of international collaboration and of having several multi-megampere machines. The values quoted for a reactor are uncertain, depending on plasma trans-

Table 2. *Plasma diagnostics*

electron temperature	(i) Thomson scattering of laser light (ii) electron cyclotron emission
ion temperature	(i) charge exchange neutral atoms (ii) impurity line broadening (iii) neutron yield and spectrum
plasma density	(i) interferometry (ii) Thomson scattering (iii) reflectometry
plasma impurity content	spectroscopy (visible, UV, soft X-rays)
radiated power	bolometer arrays
plasma current, position, shape	external magnetic field detection coils
loop voltage	external coils
internal magnetic field	motional Stark effect

Table 3. *Key parameters*

(Note that only the $(nT_i\tau_e)$ parameter is needed to reach the quoted value for ignition. The other parameters are required to achieve a satisfactory power density and to minimize the circulating power in a fusion reactor.)

	presently achieved	required for a reactor
I (MA)	7 (JET, EC)	10–30
β (%)	12 (DIIID, USA)	greater than 5
$(nT_i\tau_E)$ (m^{-3} keV s)	10^{21} (JET, EC) (JT-60U, Japan) (TFTR, USA)	*ca.* 7×10^{21}
current-drive efficiency ($A\ m^{-2}\ W^{-1}$)	4×10^{19} (JET, EC)	*ca.* 6×10^{20}
T_i (keV)	45 (JT-60U, Japan)	*ca.* 20
superconducting coils	T-15 (Russia) Tore-Supra (France)	required
D–T operation	TFTR (USA) JET (EC)	50:50 mixture

port and the achieved β ($\beta = 2nT/(B^2/8\pi)$ is the ratio of plasma to magnetic pressure). The current-drive efficiency quoted for a reactor is that needed to drive the entire plasma current taking only 10% of the station output. It is unlikely that the current-drive efficiency can be increased to the quoted value, but the bootstrap effect can make a large contribution if transport and stability effects allow operation at the lower end of the plasma current range.

The tokamak does have one major problem that may prove decisive in the long term. This is the so-called disruptive instability in which there is a sudden loss of plasma energy to the wall accompanied by rapid collapse of the current. This is thought to be due to the opening of the magnetic surfaces predicted to occur when two or more incommensurate hydromagnetic instabilities grow and interact. The

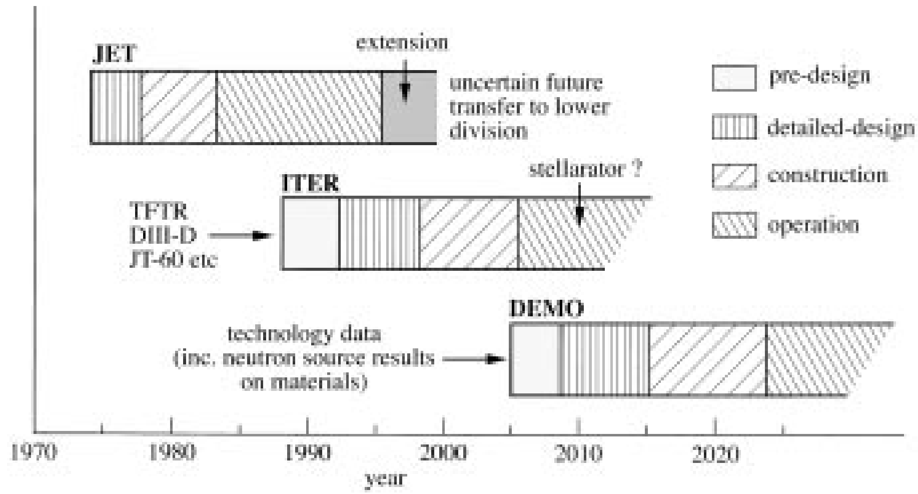

Figure 5. Route to a fusion reactor.

disruption is very dangerous because of the high heat loads and large electromagnetic forces on the vacuum vessel and supporting structure. It can be largely avoided by operating in a safe region of parameter space defined by the plasma current and particle density. However, the achievement of high performance tends to require operation of the tokamak perilously close to these disruption limits.

9. Stellarator substitute

Stellarator research has emigrated from its birthplace in Princeton (USA) to Germany and Japan. Operating stellarators have physical sizes and technical parameters of tokamaks of 20 years ago. The stellarator has the major advantage of not having the disruptive instability, not requiring current drive and being relatively easy to operate in steady state since the confining magnetic fields are produced entirely in external coils. The price is technical complexity but the system may eventually usurp the tokamak. The confinement performance of stellarators is remarkably similar to that of comparable tokamaks (Stroth 1998).

In World Cup soccer parlance the stellarator is on the substitute's bench and may be called upon by the coach if the tokamak team runs into difficulties. The triple product achievement of the German Wendelstein VII A S machine is shown in figure 4. New larger stellarators are being brought into operation in both Germany and Japan. Thus the substitutes are warming up on the line.

10. The future

The route to a fusion reactor as envisaged in 1993 is shown in figure 5. Clearly, the next major step in magnetic confinement research should be the demonstration of an ignited plasma. An international collaboration between the four blocs, Russia, Japan, Europe and the USA, was established to prepare the engineering and physics design of a machine with the following aims.

(i) To demonstrate controlled ignition for times of order 1000 s.

Table 4. *Parameters of proposed ignition tokamaks*

	Ignitor	ITER
major radius R_0 (m)	1.32	8.14
minor radius a (m)	0.47	2.8
elongation	1.8	1.6
magnetic field at R_0 (T)	13.0	5.7
plasma current (MA)	12.0	21.0
plasma volume (m^3)	10.0	2000
auxiliary heating (MW)	18	100
fusion power (MW)	100	1500
pulse length (s)	4.0	1000
safety factor q	3.3	3.0

(ii) To demonstrate technologies essential for a reactor.

(iii) To perform integrated testing of high heat flux and nuclear components.

The International Thermonuclear Experimental Reactor (ITER) is the result of this work and the main parameters are listed in table 4. This machine is physically very large and expensive. A decision on whether and where to build it is likely to be delayed for several years after the date shown in figure 5. Delays that have already occurred mean that the earliest conceivable date for the first plasma in ITER is around 2010.

Another proposal (Ignitor), developed over many years by Professor Bruno Coppi, is aimed at simply demonstrating an ignited plasma (Coppi 1994). This is a physically small, high-field tokamak employing cryogenic copper coils. The engineering design of Ignitor is very well advanced, with prototype tests of critical parts already successfully carried out in Italy. The main parameters of Ignitor and ITER are set out in table 4.

The costs of these projects are sensitive matters depending on siting, etc.; ITER is probably of the order of $10 billion and Ignitor $1 billion. In view of the importance of the long-term energy problem, it is clear that both projects should proceed with all possible speed. The higher cost and four-bloc involvement in ITER is bound to result in agonizingly slow decision making. However, Ignitor could be authorized quickly, preferably by the European Union, and preferably using the JET site. This would give continued use of the JET site infrastructure including tritium-handling facilities, power supplies, laboratories, etc.

The JET project itself has been extended to the end of 1999 with valuable experiments still to be done on deuterium–tritium discharges. After 1999 the fate of the apparatus is unclear. It will remain the most powerful machine in the world for some years, and ways must be found in which to use it effectively.

On the stellarator front, the situation is better with a new large machine, Wendelstein VII X, being built in Germany.

In the field of inertial confinement the situation is a great deal better. The National Ignition Facility is being built at Livermore, USA. The 1.8 MJ, 500 TW glass laser giving final output at 0.35 μm should enable the ignition of pellets to be demonstrated. Note that this *ca.* $1 billion project is funded primarily for reasons of national security. It will enable nuclear-weapon simulation to be carried out without the now banned underground tests.

On the magnetic fusion front, we need to be inspired by Orville Wright, who said in 1899, 'If you are looking for perfect safety you will do well to sit on a (solid) fence and watch the birds, but if you really wish to learn you must mount a machine and become acquainted with its tricks by actual trial.' We are faced with a crisis of will. After the enormous success of deuterium–tritium experiments in TFTR and JET taking us to the threshold of an ignited plasma, we must now maintain momentum and pursue the task with all speed. The cost is minuscule compared with turnover in the energy field, while progress in exploring a major new energy source is central to the long-term well-being of society.

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Discussion

R. S. Pease (*West Ilsley, Newbury, UK*). Dr Bickerton's abstract in the meeting programme stated: 'We now know how to achieve an ignited plasma confined by magnetic fields'. Could he elaborate on this important statement?

R. J. Bickerton. Heating of plasma is well understood, both theoretically and experimentally. So it can be extrapolated to ignition with confidence. On the question of confinement, we have less than a decade to go in the triple fusion product. In the past 30 years, we have progressed over many decades and established empirical scaling laws. So these can be relied upon for this small step.

R. Hawryluk (*Princeton Plasma Physics Laboratory, USA*). In the inertial fusion energy (IFE) confinement concept, spark ignition in the core can be achieved at overall gains of much less than 100. Please comment on the relationship of 'ignition' and gain in IFE.

During the past six months, LHD in Japan has come online and will provide data at an intermediate size.

R. J. Bickerton. Inertial confinement fusion requires a gain large enough to compensate for the driver efficiency, the cooling efficiency and the efficiency of conversion of heat to electricity. I estimate that a gain of about 100 is the equivalent target to that of ignition in magnetic confinement fusion.

Yes, LHD will provide valuable data on the stellarator substitute.

J. E. Allen (*Department of Engineering, University of Oxford, UK*). In order to produce a fusion reactor, is ignition absolutely necessary, or only highly desirable?

R. J. Bickerton. Ignition is not absolutely necessary for a fusion reactor, but it is highly desirable in order to minimize the recirculating power fraction.

K. Lackner (*Tokamak Physics Division, Garching, Germany*). Dr Bickerton has suggested the construction, as a next step, of the Ignitor device. I think it is important to raise some of the points that speak against this proposal. First, all copper-coil, high-field devices could study the dynamics of the thermonuclear burn essentially only on the energy confinement timescale (albeit at $Q \to \infty$). With the now emerging emphasis on steady-state, high-bootstrap-fraction operation, the most important issue regarding thermonuclear burn, however, is the dynamics on the timescale of current profile diffusion, including the sensitive response of confinement barriers to it. These aspects require for their conclusive study a few skin times, as they are linked to the adjustment of the current profile. Second, the Ignitor, in particular, would operate rather far away from reactor-typical values of ν^*, ρ^*, β^* in a similar regime to JET (note that the $nT\tau$ value, for identical values of ν^*, ρ^*, β^*, scales like $R^{-5/4}$ with major radius, and would hence be a factor of about three larger in Ignitor than in an otherwise equivalent JET discharge). Hence, the physics that could be learnt from it, in case it fails its thermonuclear aim, would not be novel, and moreover covered already by an experiment with much better diagnostic access. Considering that Ignitor would not have a divertor, its chances for H-mode access and ignition have also to be viewed considerably more sceptically than for ITER.

R. J. Bickerton. Ignitor does operate with different values of collisionality, beta and normalized gyro radius to those for ITER. The difference is small, typically a factor of 2. Since the operating temperature is more or less fixed by reactivity considerations, the remaining variables of density, size and field strength are precisely fixed if three dimensionless parameters are fixed. In other words, the only 'similar' discharge to ITER is ITER.

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With regard to the H-mode, Ignitor plasma is more elongated than that in ITER (1.85 versus 1.55) so there would seem to be ample opportunity for separatrix operation and hence the possibility of doing it quickly. Operated at a lower field (*ca.* 8 T), it can also be used to study advanced tokamak questions, such as high normalized beta, high bootstrap fraction and operation at the Greenwald density limit. It cannot look at phenomena on timescales longer than the skin time.

D. C. Robinson (*UKAEA Fusion, Culham Science Centre, Abingdon, UK*). Dr Bickerton indicated that direct conversion is not much use. Would he like to expand upon that comment?

There has been significant progress in the approach to ignition on existing facilities, with Q equivalent values now greater than 1 (recent results from JT-60U) and plasmas in D–T with fusion power densities in the core greater than the heating power. What scope is there for approaching ignition on existing facilities?

R. J. Bickerton. The first point is that only 20% of the energy released from the D–T reaction is in the form of charged particles and therefore available for direct conversion. Secondly, direct conversion usually involves taking the plasma around some kind of Carnot cycle. The result is that for some fraction of the time the plasma is cooling, consequently the power output averaged over the cycle is lower than for a simple steady-state case. But direct conversion could have a much more important role in reducing the heat load on the first wall and limiters. However, to date I have not yet identified any practical scheme of this type.

Clearly, existing facilities must be pushed as hard as possible in the direction of ignition. JET could probably more than double the fraction of α-particle power to total power from the present 10%. However, this requires further investment in increasing the heating power and a viable organization in which to continue work after the formal end of the Joint Undertaking (December 1999). Proposals to upgrade JET to an ignition machine with a new load assembly have been made by many people in the last decade. They should be dusted off and compared with the alternative, much more mature, Ignitor proposal mentioned in my paper. I cannot comment on the potential of JT-60U.

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