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K. V. Roberts

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The physics of magnetic fusion reactors

By K. V. Roberts
Euratom/U.K.A.E.A. Fusion Association, Culham Laboratory, Abingdon, Oxfordshire OX14 3DB, U.K.

Once ignition has been achieved the physics problems of the tokamak reactor differ from those considered hitherto which have mainly concerned stability, confinement and heating. The reacting plasma must be controlled and optimized through a cycle that comprises start-up, burn and shut-down phases. Efficient methods are required for extracting the thermonuclear energy which is deposited as heat within the plasma, for injecting fresh D–T fuel, for extracting the ash and impurities, for protecting the wall of the combustion chamber and for preventing contamination of the plasma. The most difficult problems appear to be concerned with radiation damage, low power density and the complex topology and large size of reactors currently being designed.

1. Introduction

Because of the technological difficulty of the controlled thermonuclear research (c.t.r.) project it is useful to go back to first principles from time to time to re-examine the impact of the physics on the engineering. This is particularly opportune currently as the first stage of the project – the achievement of near-reactor conditions in a laboratory plasma, and perhaps of ignition – is likely to be completed within the next few years by the large tokamak devices such as JET, T.F.T.R., and others that are now under construction. It is therefore appropriate to turn to the physics of the next stage, that of maintaining and exploiting a burning plasma in a steady or quasi-steady state. The physics of such a plasma is somewhat different from that of the lower-temperature plasmas encountered so far, and in addition one must move outwards from the combustion chamber and consider the constraints that are imposed by the external structure.

The aim of the c.t.r. project is to obtain useful energy by building up the light elements – hence the term 'fusion' – rather than by breaking down the heavy elements as in nuclear fission. The term is a slight misnomer because the main overall reaction

$$\mathrm{D} + {}^{6}\mathrm{Li} \rightarrow 2\,{}^{4}\mathrm{He} \quad \Delta E = 22.4\ \mathrm{MeV} \tag{1}$$

is a rearrangement of deuterium and lithium nuclei to take advantage of the tight binding energy of the α-particle. Whereas in fission the neutron has zero charge and can therefore penetrate the nucleus at low energy, in fusion the reacting nuclei must have an energy of many kiloelectronvolts to overcome their mutual Coulomb barrier. This means in practice the use of a fully ionized plasma, and since the nuclear cross section is relatively low it is necessary that the electrons should have a temperature of at least several kiloelectronvolts if they are not to slow down the ions by Coulomb scattering before they have a chance to react.

This is the origin of the term 'thermonuclear', although it should be emphasized that while the electrons usually have a true Maxwellian distribution at temperature T_e (apart from run-aways and drifts due to an electric current), the ions may or may not have a Maxwellian distribution at a temperature T_i (not necessarily the same as T_e) and may be anisotropic in velocity space.

Although the overall reaction (1) is thermonuclear it is too slow for current practical use, because of the triple charge on the lithium nucleus, and it is necessary to proceed by the two-stage cycle

$$\mathrm{D+T} \rightarrow {}^{4}\mathrm{He}\,(3.52\ \mathrm{MeV}) + \mathrm{n}\,(14.06\ \mathrm{MeV}), \tag{2}$$

$${}^{6}\mathrm{Li+n} \rightarrow {}^{4}\mathrm{He+T} \quad \Delta E = 4.80\ \mathrm{MeV}, \tag{3}$$

$${}^{7}\mathrm{Li+n} \rightarrow {}^{4}\mathrm{He+T+n} \quad \Delta E = -2.47\ \mathrm{MeV}, \tag{4}$$

in which only reaction (2) is thermonuclear. This involves only unit nuclear charges and is the fastest thermonuclear reaction. Reaction (4) provides a useful multiplication of the tritium fuel.

2. Characteristic features of the fusion reactor

Several characteristic features of the fusion reactor follow from the foregoing. Since the plasma is a hot gas it must be prevented by non-material means from flying apart at the speed of sound (*ca.* 10^6 m/s) before it has had time to react. A toroidal magnetic fusion reactor (§6) has a critical size (§7) determined by thermal energy loss, and hence also a critical power (§7). This makes the c.t.r. research and development programme different from that of almost all other technological projects. Most new technological devices start quite small – often in the workshop of an individual inventor – and can be progressively scaled up as their feasibility is demonstrated stage by stage. Fission reactors have a critical size but prototype versions can operate cold and at zero power. A tokamak reactor has to be large, of the order of hundreds of megawatts thermal energy, if it is to operate at all.

The use of 14 MeV neutrons requires a blanket surrounding the combustion chamber to convert their kinetic and binding energies into heat, to regenerate the tritium, and to provide shielding. Compared with the direct reaction (1) which could in principle operate at almost 100% efficiency by converting the plasma energy into electrical power, the cycle (2)–(4) has a thermodynamic efficiency that is determined by the temperature of the blanket, and is unlikely to exceed 40%. The ratio of energy to neutrons emitted is also only about one third that of the fission process, and 14 MeV neutrons can induce a wider class of subsidiary nuclear reactions in the structure than can fission neutrons, so that for a given level of induced radioactivity and structural damage a D–T reactor must operate at lower power density. Studies have been made of other thermonuclear reactions that do not involve neutrons, between so-called exotic fuels such as (p, ^{11}B), but currently these all appear to be too slow.

Finally, tritium is a radioactive fuel, and being an isotope of hydrogen it has a tendency to diffuse through metals at high temperature, so that it must be adequately contained during production, separation and recycling. One should of course emphasize that the radioactivity and after-heat problems are much less severe for fusion than for fission reactors and that there is no question of a pure fusion reactor becoming supercritical or undergoing a melt-down.

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3. Plasma confinement

The most fundamental requirement (Lawson 1957) is to hold the plasma (and its thermal energy) together long enough to allow the thermonuclear reactions at least to reproduce the energy investment needed to heat it, allowing for any thermodynamic inefficiency. This leads to the Lawson criterion

$$n\tau \gtrsim 3 \times 10^{20}\ \mathrm{m^{-3}\ s}, \tag{5}$$

where n is the plasma density and τ is the containment time. Three methods of confinement have been envisaged so far: gravitational (stars), inertial (big bang, super novae, weapons, and inertial confinement fusion) and magnetic. Only the latter two methods are practicable for c.t.r. (Ribe 1975) and only magnetic confinement will be dealt with in this paper.

Magnetic confinement relies on the fact that except for collisions, turbulence, and drifts due to electric or non-uniform magnetic fields, the electrons and ions are constrained to move in helices along the magnetic field lines. Although the individual particle orbits may be very complicated, to a good approximation the plasma behaves like an electrically conducting fluid that is closely attached to the magnetic field, so that the two together form a single 'plasma-field structure' which can undergo many types of oscillation and instability with a wide range of frequencies and wavelengths. The plasma can flow along the field lines at the speed of sound v_s (*ca.* 10^6 m/s), equalizing its pressure, but can only diffuse slowly across them.

There are two main types of confinement device, open and closed, each of which can be pulsed or steady state. Open-ended long linear devices (Chen 1979) rely on the magnetic field only for radial confinement and on inertia for longitudinal confinement. Their length L must therefore be hundreds of metres for practical plasma densities and the pulse duration $\tau \sim L/v_s$ is very short. Mirrors rely on the fact that charged particles behave as magnets with potential energy μB, where B is the magnetic field strength and $\mu = \frac{1}{2}mv_\perp^2/B$ is the magnetic moment, m being the particle mass and $v_\perp$ the perpendicular velocity. Since the energy $E = \frac{1}{2}mv_\parallel^2 + \mu B$ is constant for motion along the field lines, where $v_\parallel$ is the longitudinal velocity, particles whose central ratio $v_\parallel/v_\perp$ is not too large will be turned around by regions of stronger magnetic field (mirrors) at the ends of the device. Other particles are said to lie within the loss cone and these escape immediately. There is, however, a continual scattering of particles into the loss cone by Coulomb collisions, and since this scattering rate is greater for the electrons the plasma becomes positively charged, repelling slow ions and retaining slow electrons so that the loss cones become hyperboloids. Critical problems for the mirror reactor (Ribe 1975) are the excessive plasma loss rate and longitudinal heat transport by the electrons. If these could be solved the mirror might have engineering advantages since it can operate in steady state, is topologically simpler than a tokamak, is less likely to be troubled by impurities and is thermally stable.

Closed confinement devices employ topologically toroidal magnetic fields which usually have a rotational transform so that they form a set of nested magnetic surfaces on each of which the plasma pressure p is constant. In static equilibrium

$$\nabla p = \boldsymbol{j} \wedge \boldsymbol{B}, \tag{6}$$

where $\boldsymbol{j}$ is the current density. In a practical D–T reactor, which cannot employ floating superconducting rings because of the high neutron flux, the rotational transform must either be produced by a toroidal current I as in the tokamak or pinch, or by distorting the magnetic surfaces from azimuthal symmetry as in the stellarator. Although the stellarator can operate in steady state its geometry is relatively complex and the currently most favoured device is the ignition tokamak on which this article will concentrate. Beam-driven tokamaks operating below the ignition point have been discussed by Jassby (1977).

A tokamak reactor consists of a toroidal (usually with a circular or D-shaped minor cross section) combustion chamber, surrounded by a neutron shield or 'blanket' in which tritium is regenerated and in which the neutron, kinetic and absorption energies are converted into heat. The blanket must be thick enough to shield the main toroidal field coils which for economic reasons must be superconducting to avoid copper losses.

A purely toroidal field B_ϕ cannot provide plasma equilibrium since B_ϕ decreases as r^{-1}, where r is the distance from the major axis, and the plasma ring would rapidly be pushed outwards. In azimuthally symmetric devices such as the tokamak and the pinch this outward motion is prevented by a second poloidal field B_θ produced by a toroidal current I and by an additional field parallel to the major axis of the torus.

4. Thermal cycling and maintenance

Until now it has been necessary to induce the current by transformer action which means that the tokamak reactor is a pulsed device although the pulses could be quite long – 100–1000 s or more – depending on the available volt-seconds and on the plasma resistance which is proportional to Ra^{-2}, where a and R are the minor and major radii. Pulsed operation leads to thermal cycling which requires careful engineering analysis since it may damage the first-wall and blanket structure. The combination of toroidal and poloidal field coils with the cooling circuits also makes the reactor topologically complicated and therefore difficult to dismantle, repair and reassemble quickly. Yet this is essential in view of the large minimum size of an economic fusion reactor (§6) which means that a utility cannot afford to have it out of action for long.

It is particularly necessary to be able to replace sections of the first wall, which is buried within the blanket structure but is subjected to high particle and radiation fluxes of several kinds as well as to thermal cycling. The main solutions proposed (Mitchell 1978) are modular construction and advanced remote-handling techniques, necessary in view of the complexity and radioactivity of the blanket structure.

In principle there is no theoretical reason why the toroidal current should not be maintained indefinitely if a suitable e.m.f. can be provided within the plasma. Three possibilities are: a beam-driven current (Ohkawa 1970), experimental evidence for which has now been found at Culham both in the Levitron (Start *et al.* 1978) and in DITE (Paul *et al.*, this symposium; Sweetman *et al.* this symposium); a current driven by plasma diffusion ('bootstrap current', Bickerton *et al.* (1971)); and perhaps turbulent dynamo action as in the Earth's core. If a constant current could be maintained then thermal cycling would be greatly reduced.

5. Operating phases

Operation of a pulsed reactor consists of three main phases: start-up, burn and shut-down. During the start-up phase the required plasma-field structure must be established and the temperature raised to its optimum working level of about 10–15 keV. Although ohmic heating by the toroidal current can provide the initial temperature rise to about 1 keV, the resistivity and therefore the heating rate decrease as $T_e^{-\frac{3}{2}}$; in a tokamak ohmic heating cannot in practice overcome the thermal losses, so some form of auxiliary heating is required. There is little doubt that this can be done successfully; an ion temperature of 6.5 keV has already been reached by fast neutral beam injection in the P.L.T. device at Princeton (Murakami & Eubank 1979), and the use of radiofrequency heating is also practicable.

The achievement of ignition represents a barrier that must be crossed, and in the burn phase on the other side the plasma physics becomes rather different. Currently, the problems are those of stable plasma and energy confinement, heating to ignition, and impurity control. During the burn phase they will be more similar to those of an ordinary combustion device: heat transfer rather than energy containment, fuel injection and ash removal rather than particle containment, and again stability and impurity control. Instead of heating the plasma the requirement will be to extract the heat and to hold the temperature down since the system is thermally unstable at its optimum operating point of about 15 keV. One therefore needs some analogue of the control rods used in a fission reactor, although again it should be emphasized that the problem is not to avoid a dangerous situation – which cannot occur – but to prevent the burn from taking place at too high a temperature, which would be less efficient.

The temperature balance equation has the approximate form

$$\mathrm{d}T/\mathrm{d}t = C_1 T^{-\frac{3}{2}} - C_2 T^{\frac{1}{2}} - C_3 T + C_4 T^{n(T)} \qquad (7)$$

in which the terms represent ohmic heating, bremsstrahlung, anomalous thermal loss and thermonuclear heating respectively, and C_1–C_4 are constants. The term $n(T)$ is a decreasing function of T, with $n(T) \approx 2$ at the desired operating point. In general, equation (7) has three equilibrium points at which $\mathrm{d}T/\mathrm{d}t = 0$, the upper and lower points being stable and the intermediate point (the ignition point) being unstable, while the operating point itself is not an equilibrium point. Auxiliary heating is therefore needed to raise the temperature to the ignition point, but thereafter some form of auxiliary cooling and feedback temperature-stabilization is required.

During the shut-down phase the plasma must be allowed to cool and the current to decrease in a controlled way, preventing a sudden disruption of the plasma-field structure or an excessive rate of heat loss to the wall.

6. Reactor size and power

It is important to understand the factors that determine the minimum size, minimum power output and maximum power density of a fusion reactor since they affect both the economics and the research and development programme. They are concerned with such questions as blanket thickness, toroidal geometry, wall loading, the ratio of energy to neutrons emitted, α-containment and thermal loss (Hancox, this symposium).

Since a shield is necessary for both fission and fusion reactors, let us make the crude assumption that all relevant dimensions are optimized to be equal to a common parameter a, the shield thickness. A fission reactor would then be represented by a core of radius a surrounded by a shield of thickness a, total volume $\frac{4}{3}\pi(2a)^3$. A fusion reactor has a torus with minor radius a and aspect ratio $R/a = 4$, enclosed by a blanket of thickness a and outer magnet coils of thickness a. There is a central gap of radius a to allow access and to accommodate the poloidal flux. Such a device fits within a cylinder of radius $7a$ and height $6a$, with total volume $\pi(7a)^2 6a$. The fusion:fission volume ratio is therefore 27.6. Although this estimate can only be approximate it does give some idea of the probable size of a tokamak reactor.

There is also a problem about the power loading of the first wall of area $2\pi a\ 2\pi R = 16\pi^2 a^2$. A minor radius $a = 1$ m together with a power loading 1.5 MW m^{-2} gives the very low figure of 237 MW thermal output. To increase the power it is necessary either to increase the minor radius considerably, as in most current reactor designs (Ribe 1975), or to increase the wall loading. A 5 GW thermal output could be achieved with $a = 1.8$ m and a wall loading of 10 MW m^{-2}. This emphasizes that the important physics problems of the fusion reactor are likely to be those of radiation damage to the first wall and the blanket, coupled with the engineering requirement for rapid disassembly and repair techniques.

The overall volume power densities (MW m^{-3}) of current fusion reactor designs are low compared with those in existing fission reactors and this affects both economics and the energy accounting. It results partly from the low energy : neutron ratio of the fusion reaction, and partly from the large volume. In typical current designs fusion:fission power density ratios range from 1:80 for the light-water reactor to 1:400 for the liquid-metal cooled fast-breeder reactor. This again emphasizes the importance of raising the wall loading to 10 MW m^{-2} and of investigating the plasma physics of steady-state tokamak operation, to minimize damage by thermal cycling.

7. Critical parameters

An ignition tokamak has a critical toroidal current I determined by the need to contain the α-particles in the poloidal field. Since $I \approx B_\theta a$, a prescribed ratio a/a_L (where a_L is the Larmor radius of the α-particles) implies a prescribed toroidal current. The minimum current for effective α-particle containment is $I \approx 3.5$ MA, a design characteristic of devices such as JET. Reactor designs have currents ranging up to 20 MA.

There is also a critical size and a characteristic power:unit-length ratio determined by anomalous thermal losses. Although the energy-loss processes in toroidal systems are not well understood, a simple but useful scaling law for the energy containment time

$$\tau_E = 5 \times 10^{-21}\, na^2 \text{ s} \tag{8}$$

(where a is the minor radius in metres and n is the mean density in particles per cubic metre) gives good agreement with a wide range of tokamak measurements, although individual cases may differ by a factor two. Combined with the Lawson criterion (5) this leads to a critical product

$$na = 2.5 \times 10^{20} \text{ m}^{-2} \tag{9}$$

which interestingly has the same dimensional form as in a fission reactor. The interpretation is that 'an element of thermal energy must be able to reproduce itself before it diffuses out of the system'. The parameter na also determines the penetration or escape of neutral particles, including injected neutral beams, while the thermonuclear power : unit length ratio is proportional to $(na)^2$.

Since the total plasma thermal energy is proportional to nTa^2R, (8) leads to a characteristic power loss

$$P \approx RT \text{ MW}, \tag{10}$$

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where R is the major radius in metres and T is the temperature in kiloelectronvolts. From this one can estimate that about 70 MW of injected power would be needed to raise the temperature of the 5 GW reactor discussed in §6 to its ignition point at about 10 keV.

One can also see that the power loss at the operating temperature of 15 keV would only be 100 MW, which is small compared with the 1 GW of α-particle power that is deposited in the plasma and must be continuously removed. This emphasizes the fact that during the burn phase, the physics problem will not be that of good energy containment but of effective and controlled energy extraction, and that it is necessary to devise and to test methods for achieving this.

8. Concluding remarks

It is very probable that reactor-like conditions will be achieved within the next few years in the large devices now under construction. Many plasma problems will then remain, requiring detailed experimental diagnostics, theory and computation. However, it can reasonably be expected that these will be solved so that one can routinely obtain a well controlled stable reacting plasma of sufficient purity.

Much more serious, because they are already easier to foresee, are the physical and technological limitations of the outer structure. One will need a better understanding of 14 MeV neutron radiation damage, better materials, a robot technology capable of making rapid repairs in high radiation fields, and some way of increasing the power density.

In view of these problems, several physicists consider that the logical next stage that should now be seriously examined is the old idea of a hybrid fusion–fission system, in which the 14 MeV neutrons are exploited to produce fission energy and neutron multiplication in a blanket of fertile ^{238}U or ^{232}Th, together with the fissionable fuels ^{239}Pu or ^{233}U.

Bethe (1979), for example, points out that the breeding of ^{233}U in fusion 'fuel factories' could reduce the proliferation problems associated with plutonium, subsidize the next stage of the c.t.r. project, and avoid the impracticable requirement for early fusion reactors to run reliably 'round the clock'. The breeding time in hybrid systems is also much less than in fission breeder reactors so that a projected shortage of fissionable fuel might be avoided in this way.

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