I) Nuclear Fusion Research Today and the Seminal Tamm-Sakharov Paper.

II) Current Human Rights Issues in the International Scientific Community (post “Sakharov Era”).

* Occasional comments on my interactions with the Russian physics community, and friends of A. Sakharov in particular, from the sixties on.

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Paper 2

Theory of the Magnetic Thermonuclear Reactor, Part II†

The properties of a high-temperature plasma in a magnetic field were discussed in a paper by Tamm [1], in which he demonstrated the possibility of the realization of a magnetic thermonuclear reactor (MTR). In this paper we shall consider other questions concerning the theory of MTRs.

I. Thermonuclear reactions. Bremsstrahlung
II. Calculation of the large model. Critical radius. Local phenomena near the wall
III. Power of magnetization. Optimal construction. Performance of active matter
IV. Drift in a nonuniform magnetic field. Suspended current. Inductive stabilization
V. Problem of plasma instability

I. THERMONUCLEAR REACTIONS. BREMSSTRAHLUNG

The following reactions may take place in an MTR:

$$D^2 + D^2 \rightarrow H^3 + p + \underline{3\ MeV} + \underline{1\ MeV}$$
$$D^2 + D^2 \rightarrow He^3 + n + \underline{0.82\ MeV} + 2.46\ MeV \qquad \text{primary reactions}$$
$$He^3 + D^2 \rightarrow He^4 + p + \underline{14.5\ MeV} + \underline{3.7\ MeV}$$
$$H^3 + D^2 \rightarrow He^4 + n + 14\ MeV + \underline{3.5\ MeV} \qquad \text{secondary reactions}$$

Energies supplied by the charged particles and which maintain the

Source: Теория магнитного термоядерного реактора, часть II, в сборнике Физика плазмы и проблема управляемых термоядерных реакций, т. 1, Изд-во АН СССР, 1958. Reprinted from *Proceedings 1957 Geneva Conference on Peaceful Applications of Atomic Energy*, Vol. 1, pp. 21–34, 1961, Pergamon Press, with permission from Pergamon Press Ltd.

†Work done in 1951; Parts I and III were written by I. E. Tamm.

equal to the product of some α and the probability of charge exchange; $\alpha \ll 1$. Let the total current of fast neutral particles be j_n. We have $\pi_0 \sim \frac{3}{2}T'j_n + \pi_1$, where π_0 is the heat flow in the region $x > x_1$, and π_1 is the heat flow in the region $x < x_1$, which, according to the analysis below, is many times smaller and can be disregarded.

According to the theory of albedo, the probability of ionization of fast neutral particles is $1 - 1/(1 + \sqrt{\alpha}) \simeq \sqrt{\alpha}$[†]. Therefore the ion current is $j_i = \sqrt{\alpha} j_n$. The probability of ionization of slow particles is αj_n, i.e., smaller than the probability of ionization for a fast particle; it can be neglected. At $x < x_1$, n is small. Therefore $\pi_1 \sim \nabla n^2$, and the temperature can be considered as constant:

$$\pi_1 = \frac{7}{2} T' j_i = \frac{7}{2} \frac{4 \times 10^{-10} \sqrt{T'}\, \nabla n^2}{H^2}$$

$$\pi_1 = \frac{7}{3} \sqrt{\alpha}\pi_0 \tag{2.5}$$

$\nabla(n^2) = n_1^2/\alpha$, where $n_1{}'$ is the number of ions at point x_1.

$$x_1 = \frac{1}{\sigma n_1} \frac{v_0}{v_1} \tag{2.6}$$

where σ is the charge-transfer cross section, v_0 is the velocity of slow neutral particles, and v_1 is ion velocity.

At present, matching solutions in the regions $x < x_1$; $x_1 < x < x_2$, and $x > x_2$ have not been considered. We limit ourselves to a preliminary evaluation of the thermal current, for which it is possible to have a temperature jump of 10 eV (applicable to conditions of a large model; with a small model a temperature jump is certain to occur). We take $n_1 = 1.4 \times 10^{15}$ cm^{-3}, $\alpha = 1$ (i.e., we are near the limit of applicability of the above-mentioned theory), $T' = 1.6 \times 10^{-11}$ ergs, $\sigma = 3 \times 10^{-15}$ cm^{-2}, $H = 50{,}000$ G, $v_0/v_1 = 0.05$ (wall at room temperature). We obtain $x_1 = 0.01$ cm (i.e., order of magnitude of the Larmor circle for ions, and in this case we are near the limit of applicability of the theory); $\pi = 5 \times 10^8 \sim 50$ W/cm^2, which has the correct order of magnitude.

III. POWER OF MAGNETIZATION. OPTIMAL CONSTRUCTION. PERFORMANCE OF ACTIVE MATTER

The basic parameters of MTR are shown in Fig. 2. We will find the optimal relation of ∂ to d, securing a minimum mass of copper and power

[†] Ionization is similar to absorption, and charge transfer is similar to scattering. The albedo of half-space is $2/(1 + \sqrt{\alpha}) - 1$.

ergy (assuming that, on the average, reaction takes place in half the volume of the tube with the above-mentioned speed of reaction) is

$$W = 8.8 \times 10^{15} \text{erg/sec} = 880{,}000 \text{ kW}$$

With this, the number of burned D nuclei per second is

$$\frac{8.8 \times 10^{13} \text{erg/sec}}{1.6 \times 10^{-6} \text{erg/MeV}} \frac{4}{3.3\text{MeV} + 4\text{MeV}} = 3 \times 10^{22} \frac{\text{D nuclei}}{\text{sec}}$$

(which amounts to 150 g/24 hours). One can expect to obtain about 100 g/24 hours of tritium or 80 times more than U^{233}.† Increasing the power P and the weight of the copper by a factor of 2.5 increases this output 8.5 times (without change in current density). Increasing current density n times, we can reduce linear dimensions by a factor of $n^{1/2}$ without changing the product H_0R_0. In this case the weight of copper will be reduced by a factor of $n^{3/2}$, and the power of magnetization and the yield of active substances will increase by a factor of $n^{1/2}$.

IV. DRIFT IN A NONUNIFORM MAGNETIC FIELD. SUSPENDED CURRENT. INDUCTIVE STABILIZATION

The magnetic field in a MTR (with neglected screening by plasma currents) coincides with the field of the direct current. Nonuniformity of the magnetic field leads to rather dangerous drift effects (Fig. 3). For the particle having mass M at point A the field is directed along the z-axis and the gradient of the field along the x axis, $\partial H_z/\partial x = -H_z/x$.

Suspended Current

Let us consider the motion of charged particles in the magnetic field induced by the coil of the MTR (~50,000 G) and by the current on the

†We note, however, that the energy value of U^{233} which can burn in simple reactors significantly exceeds the release of heat in a thermonuclear reactor.

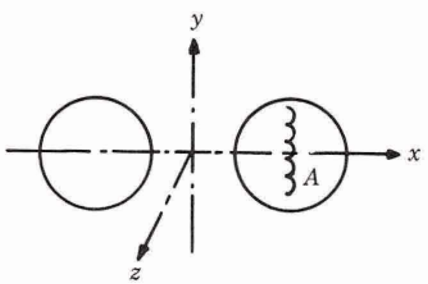


Figure 3

Direct Current—200,000 amp. The total power necessary to sustain a direct current is 2000 to 10,000 kW. Great difficulties would be encountered in the transfer of this energy (in the form of radio frequency) to the ring and in the rectification of the alternating current.

A second means of antidrift stabilization, which is technically much more feasible and which is therefore necessary to examine carefully, is the formation of an axial current directly in the plasma by the method of induction. It is not clear if, in using this method, the high-temperature plasma is not destroyed at the moment when the induction current vanishes.

V. PROBLEM OF PLASMA INSTABILITY

It is necessary to determine whether in plasma with a magnetic field disturbances exist which, according to the equations of plasma dynamics, grow in time (exponentially, or according to a power law). It is necessary to consider a series of cases. Most theoretical and experimental studies have dealt with the current flow in a plasma parallel to the external magnetic field, where turbulent instabilities of the plasma were found. One might also suspect the presence of instability in a nonuniform plasma in the presence of a drift current. At the present time this problem has merely been postulated.

APPENDIX

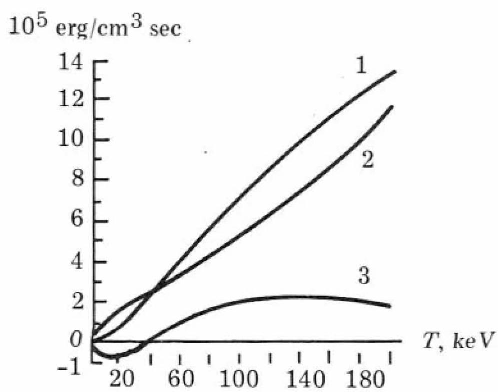
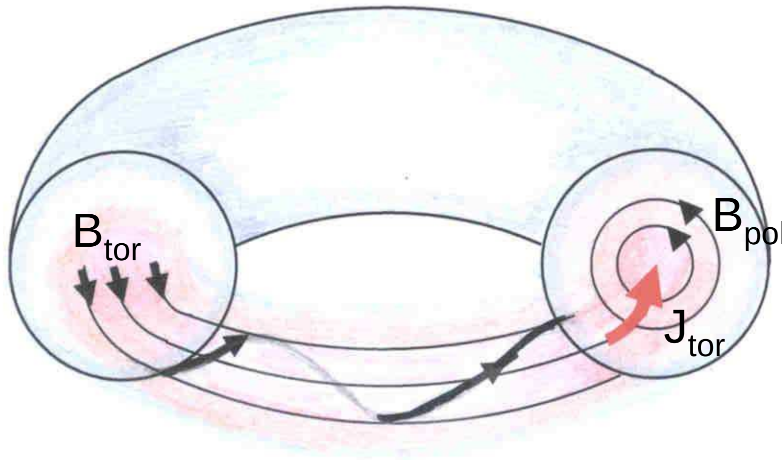


Figure A.1 1: Energy supplied by charged particles; 2: energy of *Bremsstrahlung*; 3: their difference.



B_t = Toroidal field component

B_p = Poloidal (meridian) field component

$$J_{tor} = \frac{c}{4\pi}\left(\nabla \times \mathbf{B}_{pol}\right)$$ = Toroidal current density

$\mathbf{B} \cdot \nabla \psi = \text{const} \Rightarrow$ Magnetic surfaces

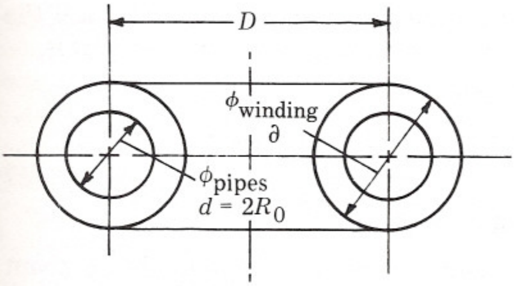


Figure 2

of magnetization in the self-sustaining region. The ratio D/∂ is obviously determined by engineering considerations and is of the order 3–5.

The product $d(\partial - d)$ is proportional to H_0R_0 and should be considered as given. We are looking for a minimum of $D(\partial^2 - d^2) \sim \partial(\partial^2 - d^2)$, which can be found to occur at $\partial \approx 2.2d$. We take

$$\begin{aligned} \partial &= 2d \\ D &= 6d \end{aligned} \tag{3.1}$$

and the power of magnetization $P \sim H_0^2 d$. Power emitted from nuclear reaction and yield from active matter is

$$W \sim n_0^2 d^3 \sim H_0^4 d^3 \sim P^2 d$$

For characterization of numerical coefficients in these formulas we will consider the following example (in the following, we will always have this particular example in mind whenever we mention numerical parameters):

$H_0 = 50{,}000$ G	
$d = 4$ m, $\partial = 8$ m, $D = 24$ m	Volume $= 0.96 \times 10^9$ cm^3; Area $= 0.96 \times 10^7$ cm^2
$n_0 = 3.0 \times 10^{14}$ cm^{-3}	Release of thermonuclear power
$T_0 = 100$ keV	17.6×10^6 erg/cm^3 sec

The weight of the copper in the winding (taking a filling factor $k = 0.5$) is 13,000 tons. The current density in the winding is 400 amp/cm^2 (average 200 amp/cm^2).

The power of magnetization is about 400,000 kW (and slightly larger when the nonuniform wrapping of the coil and other structural considerations are taken into account). Release of thermonuclear en-

MTR Parameters

$R_0 = 12 \text{ m}$

$a \simeq 2 \text{ m}$

$a_M \simeq 4 \text{m}$ (radius of magnet cavity)

$B_T \simeq 5 \text{ T}$

$V_p \simeq 10^3 \text{ m}^3$

$n_0 \simeq 3 \times 10^{14} \text{ cm}^{-3}$

$T_0 \simeq 100 \text{ keV}$

$$I_p = I_M \frac{a^2}{R_0^2} \frac{1}{q_E}$$

$$I_M = 5 B_T R \simeq 300 \text{ MA-turn}$$

$$I_p \simeq 300 \times \frac{1}{36} \left(\frac{2.5}{q_E} \right) \frac{1}{2.5} \simeq 3.3 \text{ MA}$$

$B_p \simeq 0.33 \text{ T}$

- Tokamak Devices

- Invention of Poloidal Field Transformer System (Alcator Devices and their Development)

- Second Stability Region $\Rightarrow$ D-He^3 and D-D self sustained burning proved to be possible with current technologies ("Tamm-Sakharov Dream")

- The problem of sustaining the plasma current for relatively long time intervals in relevant fusion burning regimes is yet to be solved

Ignition conditions: $P_\alpha = P_L$

$$\varepsilon_\alpha n^2 \langle \sigma \mathrm{v} \rangle / 4 = 3nT / \tau_E$$

$$\langle \sigma \mathrm{v} \rangle \propto T^2$$

$$P_\alpha \propto n^2 T^2$$

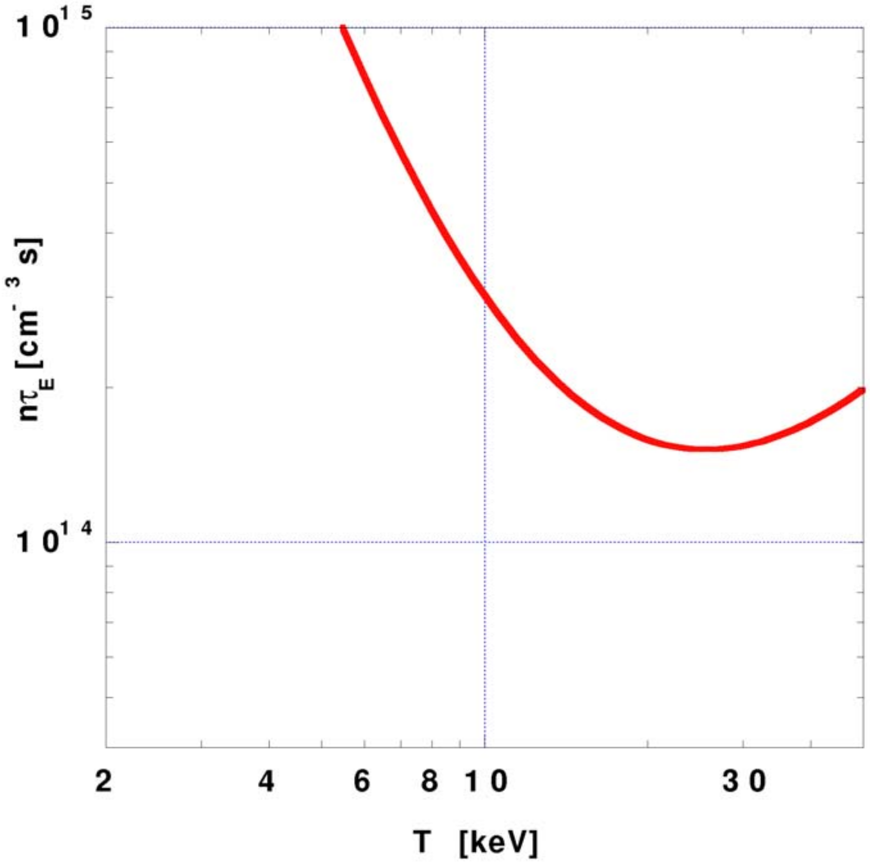
From stability considerations: $p \propto B_p^2$

$$\Rightarrow P_\alpha \propto B_p^4$$

Furthermore

$$T_e \sim T_i$$

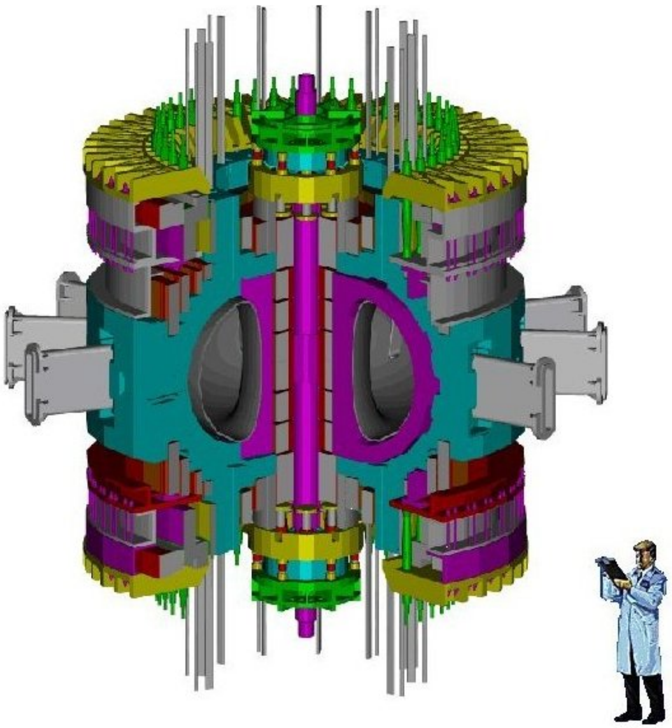
$$Z_{eff} \sim 1$$



Unexpected discoveries

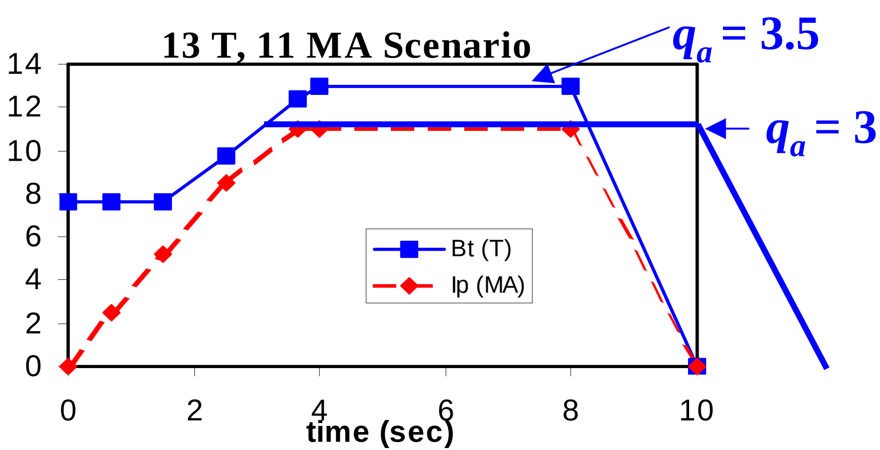
- Investigating the physics of fusion burning plasmas in depth is likely to produce unexpected discoveries that can facilitate greatly the path to a significant fusion reactor.
- The best example of this is the discovery of the delayed neutrons in the fission process that has made the control of fission reactors practically possible.
- A more recent example in plasma physics is the discovery of the spontaneous rotation phenomenon that is expected to be present in fusion burning plasmas and may have beneficial effects.
- Another less recent finding is that of “Profile Consistency” that now serves as a guidance in the numerical simulations of the plasmas to be obtained in future experiments.

IGNITOR

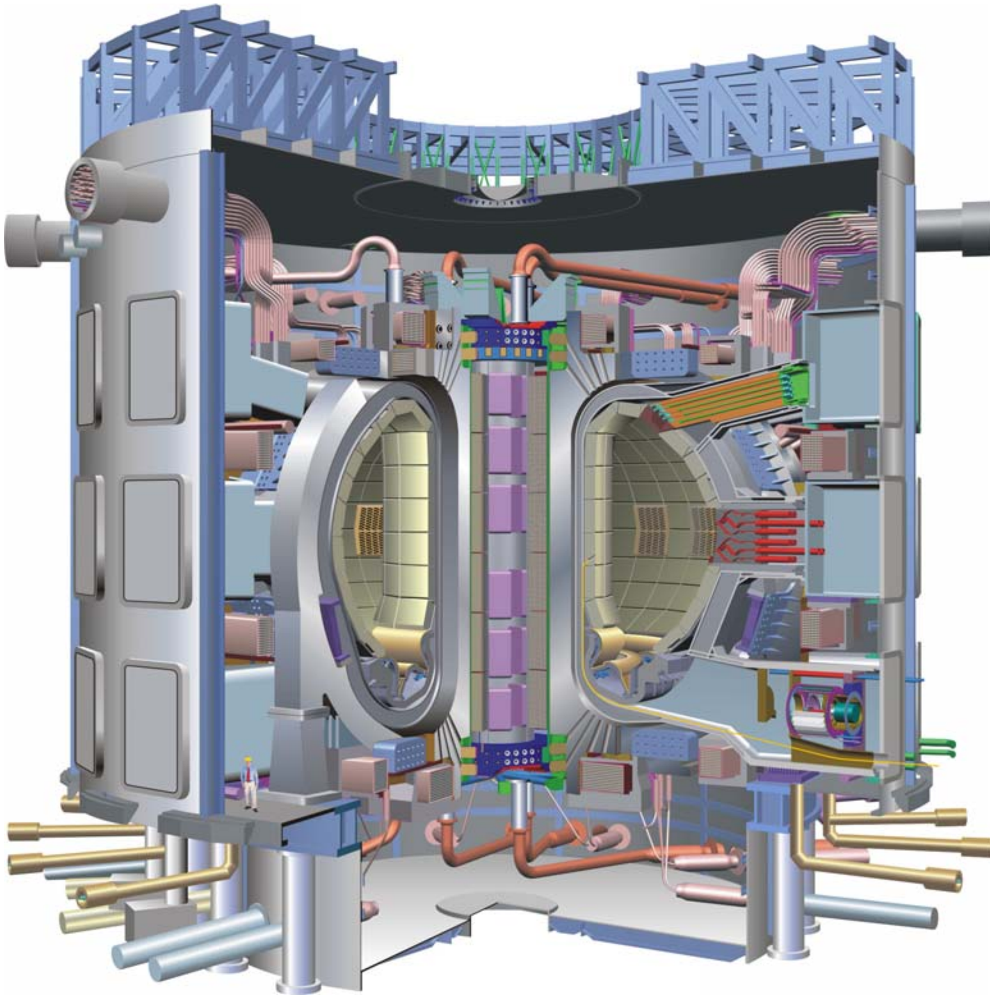


Plasma Current I_P	11 MA
Toroidal Field B_T	13 T
Poloidal Current I_θ	8 MA
Average Pol. Field $\langle B_p \rangle$	3.5 T
Edge Safety factor q_ψ	3.5
RF Heating P_{icrh}	<18 MW

R	1.32 m
a	0.47 m
κ	1.83
δ	0.4
V	10 m^3
S	36 m^2
Pulse length	4+4 s



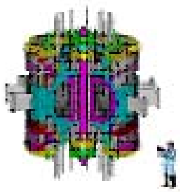
ITER



From http://www.iter.org/

Plasma Major Radius	6.2 m
Plasma Minor Radius	2 m
Plasma Volume	840 m^3
Plasma Current	15 MA
Toroidal Field on Axis	5.3 T
Fusion Power	500 MW
Burn Flat Top	>400 s
Power Amplification	>10

The poloidal magnetic field pressure is the driving parameter of the Ignitor and Columbus designs



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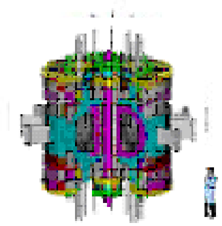
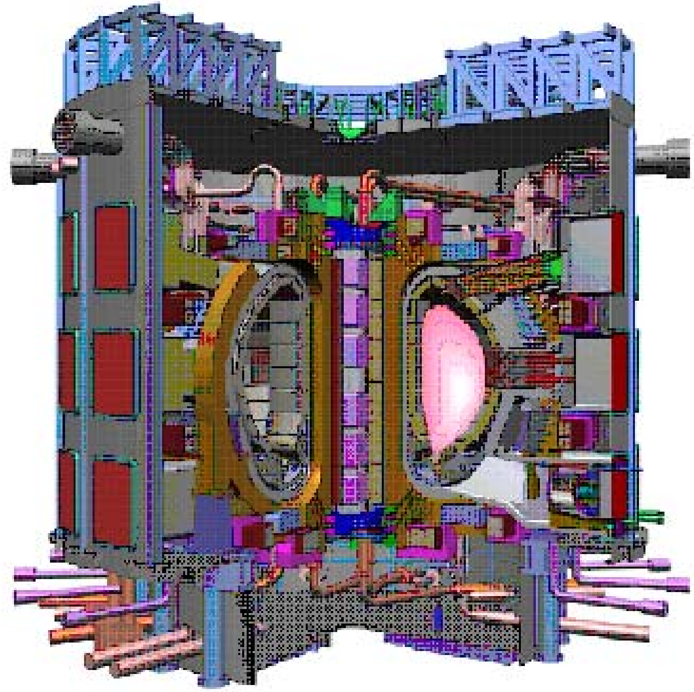


COLUMBUS



ITER-FEAT

$q_\psi \simeq 3.6$

IGNITOR	COLUMBUS	ITER-FEAT
$\bar{\bar{B}}_p \simeq 3.4\ \mathrm{T}$	$\bar{\bar{B}}_p \simeq 3.4\mathrm{T}$	$\bar{\bar{B}}_p \simeq 1\mathrm{T}$
$I_p \simeq 11\mathrm{MA}$	$I_p \simeq 12.2\mathrm{MA}$	$I_p \simeq 12.5\mathrm{MA}$

$q_\psi \simeq 3$ $(lower\ \ safety\ \ factor)$

$\bar{\bar{B}}_p \simeq 1.15\mathrm{T}$

$I_p \simeq 15\mathrm{MA}$

q_ψ= safety factor for plasma stability I_p = plasma current $\bar{\bar{B}}_p$= confining (poloidal) magnetic field

The Problem of Nuclear Fusion Energy

By ERNESTO MAZZUCATO

ITER is a large international project aimed at demonstrating the feasibility of fusion energy. Partners in this effort are the European Union, Japan, China, India, South Korea, Russia and the U.S.

A recent article in The Economist (*A white-hot elephant*, Nov 23rd 2006) makes a startling connection between the war in Iraq and ITER. Referring to the process of selecting a site for the fusion project, it states that *'the subsequent wrangling looked like a proxy for rows over the war in Iraq'*. Indeed, the similarity between the two projects runs much dipper, since, like the war in Iraq, the political support of ITER stems from misleading propaganda. By now the case of the war in Iraq is of public domain, that of ITER is not.

ITER is an acronym for International Thermonuclear Experimental Reactor. To boost its importance, we are reminded (www.iter.org) that ITER means *the way* in Latin. It sounds as if the Intelligent Designer, after telling Adam and Eve to be fruitful and multiply, added: *'do it as much as you like, all problems will be taken care by ITER'*. Well, we did it recklessly and now we are in serious trouble, but is ITER really *the way* to the solution of our problems? Here are some facts to consider.

First – The official construction cost of ITER is $6 billion. The EU will contribute 45%, while the other six partners will equally share the remaining 55% ($3.3 billion). The U.S. Department of Energy (DOE) estimates that this will cost $1.122 billion to taxpayers instead of $550 million (one sixth of $3.3 billion). Since DOE is not a philanthropic institution, we must assume that a similar discrepancy is in the budgets of the other six partners as well. Presently, seven more countries are considering joining ITER: Brazil, Mexico, Canada, Bulgaria, Lithuania, Slovakia and Kazakhstan (no word from Borat, yet). All will have to pay an entrance ticket, adding new cash to the coffer. Conclusion: either the real construction cost of ITER is much larger than the official figure or somebody is getting rich on fusion.

Second – ITER will produce 500 megawatt (MW) of fusion power, equivalent – we are told – to a tenfold gain (defined as the ratio between the total fusion power and the external power needed for heating the fuel). Unfortunately, 20% of these 500 MW (they used to be 410 before miraculously growing to 500) will be trapped into the reactor chamber. ITER doesn't plan to transform the remaining 400 MW into usable energy, i.e., electricity. However, even if it did, it could generate – to be generous – no more than 160 MW, less than the electric power needed for its operation. Conclusion: the real gain of ITER, i.e., the ratio between output and input electric powers, is smaller than one.

Third – ITER will be able to operate at full power only for a maximum of 400 seconds. After that, it will need to be shutdown, to restart later for another pulse. The supporters of ITER are quick to stress that their main objective is to test the physics and engineering of fusion reactors, not to generate continuous power. However, they do not mention that all physics objectives of ITER could be achieved with smaller and much less expensive devices, and that most engineering problems of fusion reactors will not be solved by ITER, including how to make their operation steady state.

Fourth – From all of the above, we must conclude that the cost of electricity from an ITER-like reactor will be enormous. Again, we are told that this is not a problem since it can be fixed by increasing the reactor's size. Indeed, assuming that the latter will operate at the same fuel temperature of ITER, our present understanding indicates that the total fusion power will increase only linearly with the reactor's linear dimension, while costs will rise at least squarely. Conclusion: The economy of scale does not work in this case – a bigger reactor will be even less economical than ITER.

Quoting The Economist, it is clear that *'like the International Space Station, ITER had its roots in superpower politics. As with the Space Station, the scientific benefits may not justify the price'*. The result is that, rather than promoting the commercialization of fusion, ITER will risk of destroying its credibility.

It took three years to understand the fallacy of the war in Iraq and to get rid of some of its sponsors. Unfortunately, we will not be so lucky with ITER. The recent signing of the International Fusion Energy Agreement by the seven partners in Paris (Nov. 21, 2006) will secure thirty years of life to ITER. At the end, none of its present sponsors will be fired – they will all be retired or dead.

The author is a Distinguish Research Fellow at the Princeton Plasma Physics Laboratory of Princeton University. Opinions are the author's and not necessarily shared by Princeton University, but they should be.

F. Aharonian (multi TeV astronomer, now at Dublin + Heidelberg, formerly at I.K.I., Moscow): The modus operandi of the Eurocracy (e.g. their Frame Programs) reminds him of that of the Soviet Union.