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LETTER TO THE EDITOR

Quo vadis fusion?

George J. Linhart

Abstract. A brief history of the discovery of nuclear fusion, first as the motor of the stars and subsequently its first realization as H-bombs, is described. The efforts of trying to make it into a source of energy for mankind as a controlled nuclear fusion (CNF) are sketched out. We shall mention the main research approaches, so far explored, i.e. the magnetic confinement fusion (MCF), the inertial confinement fusion (ICF) and the beam-target fusion (BTF) and point out the main difficulties connected with these three ways to CNF. The present trend to concentrate the main research potential on just two embodiments of MCF and ICF, i.e. the Tokomak and the laser driven spherical pellet, is criticized arguing that other promising approaches may be left unexplored. Such approaches, some in which the use of advanced, a-neutronic fuels is envisaged appear at present more arduous, but perhaps eventually more simple and safe. A promising symbiosis of fusion-fission is also mentioned.

Key words: nuclear fusion • fusion research • fusion-fission

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Introduction

About 100 years ago physicists started asking questions about the energy source capable of accounting for the immense flux of radiation emitted by our Sun. Having measured the surface temperature T and the radius R of the sun, the energy W_r radiated by the sun within a time t can be expressed by:

$$W_r = 4\,\pi\,R^2 \cdot \sigma\,T^4 \cdot t \tag{1}$$

where: $\sigma = 5.75 \times 10^{-6}$ (erg/cm²·s·deg).

At that time, the only conceivable source of energy appeared to be the energy derived from a gravitational collapse, which can be written as

$$W_g \le G\,M^2/R\in \tag{2}$$

where $\in < 1$ since the collapse is not associated with the R (the surface of the sun) but with some effective $R_{\mathrm{eff}} < R$. G is the gravitational constant and M the mass of the Sun.

Assuming that as R decreases the surface temperature T increases, we shall suggest, for simplicity sake that $R^2T^4 \approx$ const. In that case

$$t \le \frac{GM^2}{4\pi R^3 \sigma T^4 \in} \sim \frac{25}{\in}\,(\text{Myears}) \tag{3}$$

Taking $\in \approx 0.5$ we obtain $t \le 50$ (Myears).

However, both geologists (James Hutton already in 1785) and palaeontologists ascribed to earth and therefore, also to the sun an age well in excess of 1 billion years (1 Gyear).

It soon became obvious that the gravitational collapse, could not account for this, two orders of magnitude, difference in *t*.

Soon after 1910, it was recognized that most of the mass of an atom is concentrated in a central nucleus which, when bombarded by other nuclei (E. Rutherford *et al.*), can undergo nuclear reactions, some of which can be exothermic, i.e. they can liberate energies of the order of MeV/reaction.

It was A. S. Eddington who suggested in the 1920's that the source of stars' energy were nuclear fusion reactions, which, fuse four protons p into an He nucleus. In stars of the size of our sun, the main fusion reaction chain is as follows [1, 7, 10]:

$$p + p \rightarrow D + e^+ + \nu, D + p \rightarrow He^3 + \gamma, He^3 + He^3 \rightarrow He^4 + 2p$$

where e^+ is a positron, ν is a neutrino and γ is a photon liberating many MeV/reaction cycle.

The amusing story associated with these discoveries is that when Rutherford was asked if any of the nuclear reactions he observed could become a source of energy, he replied that such a possibility was a "moonshine" when in fact it was a "sunshine". It became clear (the late 1930's) that the whole visible Universe is powered by nuclear fusion.

However, it became equally clear that to reproduce in a laboratory the temperatures and densities existing in the interior of our sun, and necessary for fusion reactions to proceed, appeared (in the 1930's) impossible.

The discovery of fission chain reactions and a subsequent development of the A-bomb (1940's) changed this pessimistic outlook and at the beginning of 1950's the A-bomb was used as a trigger of D-D and D-T reactions in a volume of fusionable material – the H-bomb was born (Fig. 1). The inventors of this fusion explosive soon tried to show that it could be used for peaceful purposes, including energy-generation (project Plowshare [6, 30]). This proved impossible for ecological reasons.

Followed many attempts to miniturize the H-bomb, frustrated by the extreme difficulty to scale down the fission trigger [5, 18]. However, a new possibility appeared to confine and control the nuclear flame. The nuclear fusion temperatures are of the order of 10 keV or higher. This implies that the fusionable material is a fully ionized plasma, i.e. a very good conductor of electricity. This offers a possibility that such a plasma can be acted on by magnetic fields, i.e. it can be compressed and/or confined by such fields. The ideas of using magnetic fields for heating and thermal isolation of plasma were soon transformed into a variety of experiments discussed in 1958 at the Geneva conference on "Peaceful Uses of Atomic Energy".

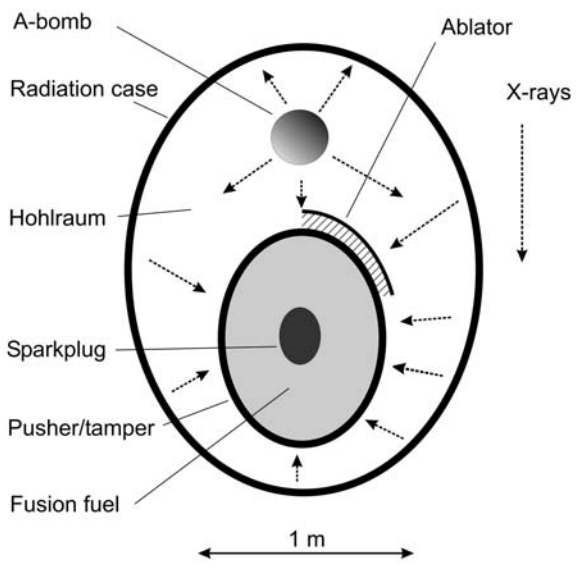

Fig. 1. A schetch of the principle of the H-bomb [8, 11].

This approach known as magnetic confinement (MCF) was clearly different from that of the explosive fusion devices, whose principle was later described and baptized as inertial confinement (ICF [8, 11, 21]). Even the original beam-target experiments (BTF) of Rutherford were recognized, in a modified form, as a potential fusion candidate [17, 22].

The mood of the Geneva conference was optimistic; so much so, that the Indian physicist Bhabha expressed an opinion, shared by many, that a fusion reactor will be working within 20 years. The subsequent history of controlled fusion contains many similar optimistic prophecies such as: the fusion reactor is round the corner. So far there were many corners with no fusion reactors in sight.

This failure to discover a valid candidate for a fusion reactor, together with the looming threats of a global energy crisis, lead to a decision to concentrate the research effort on the most promising approaches (in the 1990's), i.e. on a Tokomak for MCF and on a laser-trigger for ICF.

We shall first briefly survey the three above-mentioned ways to fusion and in conclusion point out the danger of concentrating the fusion research on one candidate only. We shall also mention the possibility of a hybrid fission-fusion reactor as an energy source which may be several corners nearer than a purely fusion reactor.

Magnetic confinement fusion (MCF)

The forefather of all MCF plasma configurations is a *Z*-pinch [2] stabilized by an axial magnetic field B_z (Fig. 2). The main confinement problem here is the end-loss of energy, which can be countered in two ways. The first is to replace the electrodes A_1, A_2 by some magnetic plugs (magnetic mirrors), the second way is to join the extremities, producing thus a toroidal configuration. The second is more promising in the form either of a Tokomak or of an internal field reversed configuration (FRC) [4, 24, 29].

When these devices work with a DT plasma as a fusion fuel one must try to overcome a number of drawbacks such as:

a) The deterioration of all materials used due to an intense neutron flux, the main vector of energy transport in a DT combustion.
b) The necessity of regeneration of the tritium inventory by the Jetter cycle or similar.
c) The inaccessibility of the structural items due to the toroidal or otherwise complicated geometry of the system.

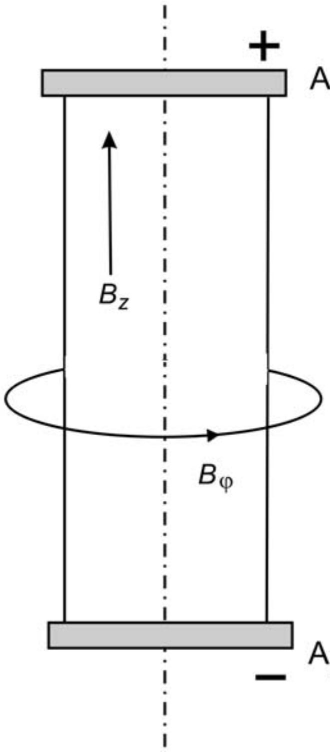

Fig. 2. *A* B_z stabilized pinch. A_1 and A_2 are electrodes.

d) The cooling of the first (vacuum) wall and the extraction of the nuclear ashes.

The a) and b) drawbacks could be eliminated if a non-neutronic fusion reactions could be considered, such as [3, 9].

(4) $$He^3 + D \rightarrow He^4 + p + 18.3 \text{ (MeV)}$$

or even weakly neutronic reactions, e.g.

(5) $$D + D \begin{cases} He^3 + n + 4 \text{ (MeV)} \\ T + p + 3.25 \text{ (MeV)} \end{cases}$$

If it were possible to use a cylindrical system instead of a toroidal one the difficulty c) and d) could become much less serious. The other advantage of such an axial system would be, in the case of a-neutronic or weakly neutronic reations, its adaptability for a direct conversion of the plasma energy into electricity.

Inertial confinement fusion (ICF)

Any explosive device in which the pressure of the exploding medium exceeds the mechanical strength of the confining walls follows the physics of inertial confinement. This has been well known in the case of chemical explosives. The simple analysis describing nuclear explosions was, for many years, confined to classified literature. In open literature it is found, after 1960 in several publications [15, 21] in which the term "inertial confinement" has been coined.

In a spherical geometry (Fig. 3) the energy W of a spark necessary to ignite a self sustaining, diverging nuclear detonation in a D-T spherical pellet is [16, 27].

(6) $$W \geq 10^3 \gamma \, (n_s/n_0)^2 \text{ (MJ)}$$

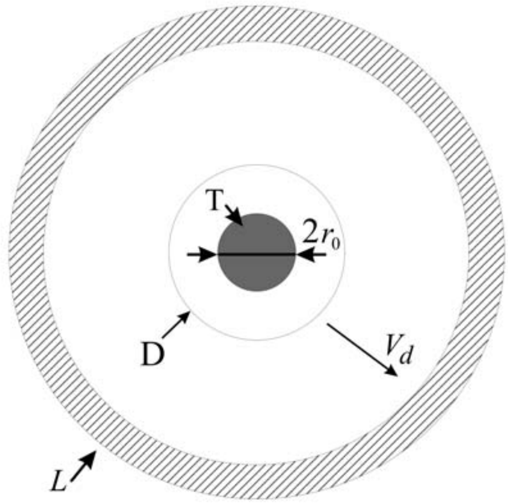

Fig. 3. A schetch of the inertial confinement concept – T is a trigger, D the detonation wave, *L* is a liner (tamper), the medium is DT or D.

in a spark whose radius r_0 is

(7) $$r_0 \geq 0.75 \, \gamma' \, n_s/n_0 \text{ (cm)}$$

where γ and γ' are factors depending on the real nature of the α-particle absorption in the DT plasma whose initial density is n_0 and where n_s is the density of a liquid DT. It follows that if a compression of $n_0/n_s = 100$ can be achieved, then the W and r_0 are resp. of the order of 100 (KJ) and 0.1 (mm). If $n_0/n_s = 1$, then $W \geq 1$ (GJ) and $r_0 \sim 1$ cm and, the energy source is most likely an atom bomb (see Fig. 1); even more so if the medium is deuterium in which case the trigger criterion is much more severe. The only energy source capable of such energy concentration appeared to be a ns high power laser. However, a single laser cannot easily perform both the compression and the spark formation. The main difficulties are the uniform irradiation of the pellet and the fine control of the laser power as a function of time. A more promising and simpler, but a brute strength approach, is to try to achieve a volume ignition of a DT pellet.

Subsequently, the proponents of a laser fusion suggested that one could use two different lasers: one, a relatively slow one (1 ns) which compresses the spherical target and a second one (1 ps) which provides the spark energy, a combination known as a fast ignitor [28].

The hopes that a radiation compression of a small DT target should work, at least in principle, were reinforced by underground tests of nuclear explosions in which DT spheres were imploded by the intense X-rays generated by the explosion [12].

Beam-target fusion

It can be shown that the energy loss W_e of an ion beam (e.g. a beam of tritons) hitting a solid target (e.g. a disc of D_2 ice) exceeds by almost two orders of magnitude the energy W_f liberated in the relatively few nuclear fusion reactions. However, the energy loss W_e diminishes rapidly if the target is a hot D-plasma or if a D-beam interacts directly with a T-beam [17, 26].

The gain $G = W_f/W_e$ in the case of the T-beam hitting D-plasma target cannot exceed $G = 6$ even if the target temperature $T_D > 100$ (keV).

The collision of the T-D beams offers a somewhat better prospects for G, unfortunately the intensity of the interacting beams is limited by the space charge repulsion effects [23] and therefore, the fusion energy density is too low for any reactor scenario.

Other approaches

Several other ways to obtain energy from nuclear fusion have been described such as muon catalyzed fusion, cold fusion, impact fusion and others. None of these appear to bring about a realistic source of nuclear energy, even though one should never abandon a hope of discovering a new and valid approach to nuclear fusion.

The present, dangerous research situation

None of the above-mentioned ways to a nuclear fusion reactor appears to be a clear candidate to develop on a large scale as a reactor prototype. However, the disappointment of not finding a fusion reactor beyond the last corner coupled with the knowledge of the coming global energy crisis resulted in a certain amount of impatience, producing pressure to choose the most promissing experiments as a basis for a large scale device. Thus, the powers to be decided to start a construction of a large Tokomak device, baptized ITER situated in the South of France. In the field of ICF efforts are concentrated on large (MJ) lasers for the ignition of spherical DT pellets. Were the material and intellectual resources unlimited, both these projects should be praised even if, as a way to fusion power, they may be blind alley efforts.

Let us, for an instant, not treat the physics and engineering limitations of these approaches, but point out that the scenario changes when our material and intellectual resources are not unlimited. The premature focusing of such resources will compromise the research along other, more difficult but, perhaps, eventually more fruitful lines of progress towards fusion power. The fact that the ITER project will cost more than 10 billion Euros is not as important (a war ship costs as much) as the vacuum it will create in a balanced research programme covering research projects so far not explored owing to the scarcity of the research personnel required. A similar, but less important effects will be produced by concentrating on MJ lasers, a research often sponsored by military authorities.

Let us now mention a few technical arguments against the ITER and MJ laser efforts.

A fusion reactor based on a D-T reaction in a toroidal geometry must resolve the drawbacks mentioned already as a), b), c), d) in the section 'Magnetic confinement fusion'. Let us describe in more detail the nature of these problems. The main danger in a) is the immense neutron flux, a part of which will certainly be absorbed by the superconducting coils. This neutron absorption can be cut down only by using sufficiently thick neutron reflecting layer, however this increases the dimensions of the coils, increasing the stored magnetic energy in the device. This energy can easily amount to more than 1 GJ, equivalent to 200 kg of TNT. Any departure from superconductivity will result in a dissipation of this energy in the part of the coil becoming a non superconductor. The result: an explosion, or at any rate a damage to the coils. This can be controlled if the current in the superconductors is inductively transferred to a system of copper conductors which dissipate the energy over a long time. Such a safeguard will require precious space. (Superconducting magnets in CERN are wound with cables consisting of a superconducting core and a copper sheath).

All this becomes more serious in the volume – restricted axial region of the torus. Similar problems arise in controlling the toroidal plasma current – required by the MHD stability criterion. Its maintenance is not an easy task, its dissipation may result in damage to the first (vacuum) wall. A similar, perhaps more serious effect will be the generation of He bubbles in the material of the first wall, causing embrittelment as well as wall-erosion by disruptions (Razumova effect). See Ref. [25].

The second effect of, even a small, neutron flux penetration into a superconductor will be structural damage on a nanometer scale and a subsequent loss of superconductivity.

The problems connected with b) are really tied up with the use of liquid Flibe (or similar). This liquid must perform at least two roles. The first, it must generate tritium through the Jetter cycle (i.e., Li + n = T + He) or similar and the second, it must carry to a heat exchanger the energy deposited by the neutrons. It must be also amenable to an efficient tritium separation and extraction. This Flibe layer must also be extremely well insulated thermally and neutron wise from the superconductors.

The problem c) can be resolved by making the whole structure into a form of a round cake cut into so many segments. Relatively easy if each segment did not contain Flibe tubes and superconducting coils. The problems connected with d) can be solved (?) implying, however, a number of technological complications.

All this has to be resolved, keeping in mind that the components must last quite a few years in order that the cost of the maintenance does not result in an astronomic cost of electricity generated. A serious concern of power companies is the availability of a reactor, i.e. the fraction of the year during which the system produces power. Present fission reactors have an availability of more than 90% which for a complicated Tokomak is out of question.

Moreover, the problems of security of operation (mechanical, radiation, T containment), may make the whole project impracticable.

In the case of ICF we already touched on some basic difficulties in the case of a spherical target ignited in the fast ignitor mode. Moreover, the ballistic problems of this approach appear astronomic – how does one hit with a ps laser beam a DT sphere whose compressed diameter is smaller than 1 mm from a distance of more than 10 m, with the timing of the second laser within less than ± 0.1 ns in a vessel filled with a turbulent plasma? [14].

A more credible approach may be to use a cylindrical geometry in which a DT detonation launched axialy, transits into a conical channel in which its energy

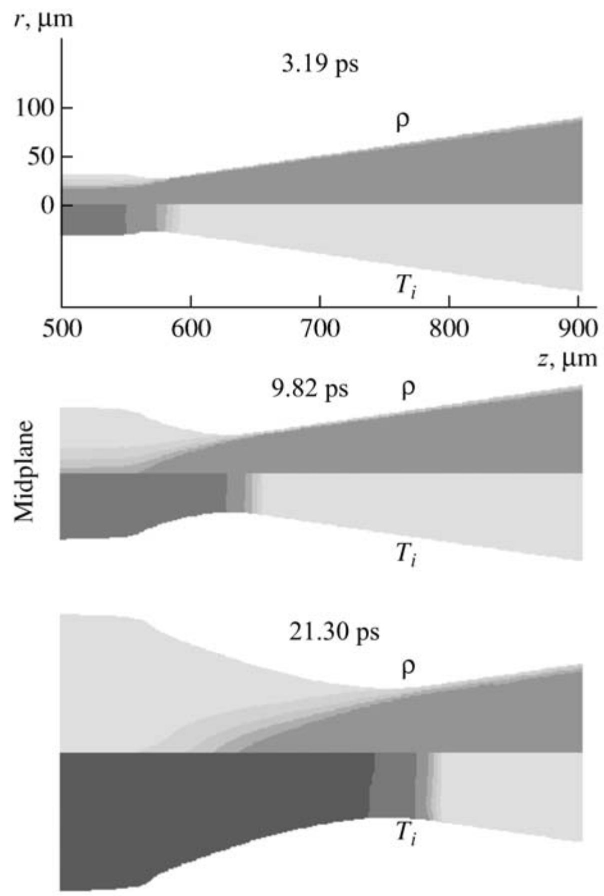

Fig. 4. D-T detonation propagating into a conical channel ($\alpha = 20°$) ρ is density, T the ion temperature [20]. Reproduced by permission of Pleiades Publishing, Ltd., from Linhart JG, Bilbao L, Miklaszewski R, Stepniewski W (2000) Detonation energy amplification in conical channels. Plasma Physics Reports 26;3:203–218.

is amplified to a level at which it is able to ignite a cylindrical detonation in a much larger channel filled with deuterium or D, He^4 mixture (Fig. 4). The agent responsible for both, the compression of the nuclear fuels and for the ignition of a spark, might be a Z-pinch in which an $m = 0$ instability develops a high density neck [19, 20].

An interesting line of research could be the combination of the Z-pinch as means of providing a dense D-T column and a beam, possibly of focused D ions, as a trigger of a cylindrical spark. Something similar has been tried in the days of experiments on large plasma focus devices (using a laser beam). Ballisticaly, it may be somewhat better than the fast ignitor approach because a charged particle beam can be guided by the B-fields of the Z-pinch towards the trigger region. Similar concepts involving an axial ignition rather than a spherical one are represented by the work of Badziak *et al.* [13].

The severe limitation of the beam-target approach (that may not be too serious if catalytic reactions could take place (Ref. [17])) seems to suggest that it could result more readily in a neutron source for a hybrid fusion--fission reactor (if a compact device can be constructed), particularly so for a thorium reactor. Thorium is much more abundant than uranium and does not produce long-lived radioactive waste. Some interesting research should be also done on the energy loss of T ions in a hot, magnetized plasma. After all the $G = W_f/W_1$ in a high magnetic field could be higher than expected. If this resulted in a $G > 5$, and if a direct plasma-electric energy conversion could be envisaged, than one may hope to aim at an advanced fuel fusion reactor.

Conclusion

The message resulting from all these observations is as follows:

1. Do not put too much hope on the ITER or MJ-laser approaches. They could be recent editions of corners beyond which there is no fusion reactor. In general, most D-T reactors have not a bright future, except perhaps as neutron sources for fission-fusion, perhaps involving a beam-target mechanism.
2. There are several interesting, so far neglected approaches, which should be sponsored and followed as vigorously as the ITER or laser projects, an example is found in [20, 31].

One cannot forget that most of our technological marvels, such as the steam engine, started as simple structures using currently available materials. The first fission reactor was assembled by Fermi's students in a hall of University of Chicago. It is somewhat disheartening to start with a device as complicated as ITER or a fast ignitor.

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Professor George Linhart is one of the pioneers of plasma physics and nuclear fusion. He is the author of the first book on "Plasma Physics" (North Holland, 1960, translated into Polish in 1963). He coined the term "Inertial Confinement" and provided the corresponding theory (1961, Conference on fusion in Salzburg). His more recent interests are Philosophy and History of Science.