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Energetic and economic balance for an inertial fusion power plant

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Abstract

Starting from the energetic diagram of a possible inertial fusion nuclear power plant, the energy balance is analysed as a function of the component energetic parameters, then the thermonuclear energy gain in the fusion chamber versus the recycling energy fraction and the driver efficiency is calculated. A new method for evaluating energetic and economic gain conditions which must be satisfied to design an efficient inertial fusion nuclear power plant is proposed. These conditions are strongly dependent on the values assumed by the recycling energy fraction used to feed the power plant. A simple expression was obtained for the recycling energy fraction, taking into account the construction, operating and dismantling costs of an IFC nuclear power plant. By this approach, a correlation among the various energetic and economic parameters was found, which, starting from the results obtained up to the present, leads to the identification of future research targets. The original mathematical model developed will allow the energetic and economic criteria to perform a comparative analysis of both current and planned inertial fusion experiments to be identified, in order to evaluate those which, at present, seem the most promising solutions for future ICF nuclear power plants.

1. Introduction

The main goal of this work is to develop a new methodology for energetic and economic analysis, useful for the evaluation of both experimental and industrial power production plants. In this work this method is applied to inertial fusion devices. The first aim is to evaluate the results which the current or short-term future research experiments may achieve at present; the second is to identify both the minimum requirements needed to design a "commercial" inertial fusion power plant to establish which system at present offers, if adequately improved, the best chance of success. For experimental installations such as the ignition demonstration facility, the energetic and economic analysis will be useful for completing the evaluation of physics and engineering issues. Since the developed method is complex, a concise explanation and the first conclusions are reported. Concerning the energetic aspects further details can be found in Ref. [1].

2. Energetic block diagram of an inertial fusion power plant

First, it appeared convenient to develop an energetic block diagram of a possible inertial fusion power plant (Fig. 1) as a reference for the above-mentioned energetic–economic analysis. The diagram is built on six fundamental blocks:

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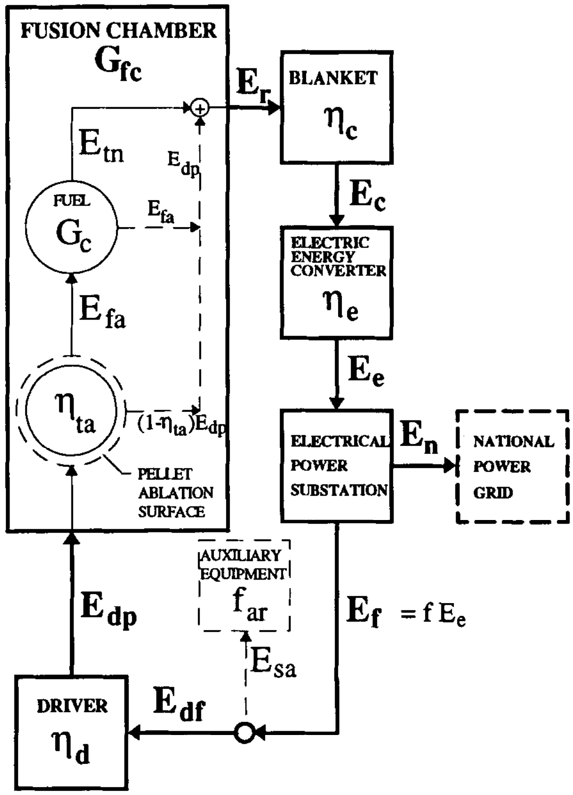

Fig. 1. Energetic block diagram of an inertial fusion power plant.

(1) the electric power substation, through which the electric power produced in the plant is passed into the power grid and from which the electric power to feed the plant (i.e. to feed the driver and the auxiliary equipment) is taken;
(2) the driver, a laser or a heavy ion beam system, which provides the fusion chamber with the energy pulse needed to achieve the fusion conditions of the fuel, which is in the pellet;
(3) the auxiliary equipment, such as cooling pumps, vacuum system, system to inject the pellets in the fusion chamber and control systems;
(4) the fusion chamber, where the pellets are introduced one by one and then burnt;
(5) the blanket, where the energy E_r, which reaches the fusion chamber walls, is multiplied, converted into heat and then carried over by the coolant;
(6) the electric energy converter, where the heat contained in the coolant is converted into electric energy, which is then transferred to the power grid.

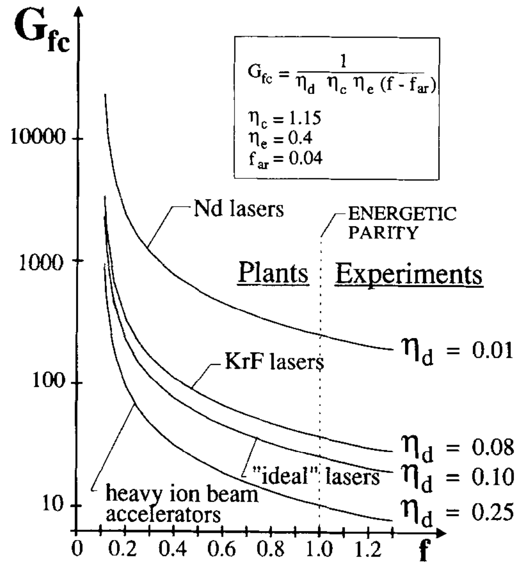

Fig. 2. Energy gain in the fusion chamber (G_{fc}) vs. the recycling energy fraction (f) and the driver efficiency (η_d).

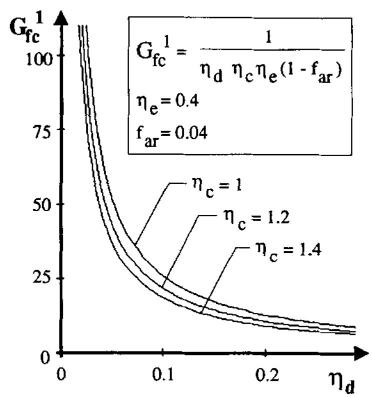

Fig. 3. Minimum fusion chamber energy gain value needed to satisfy the energetic gain condition ($G_{fc}{}^1$) as a function of driver efficiency (η_d) and blanket thermal energy conversion efficiency (η_c).

The energetic quantities shown in Fig. 1 are explained in the list of symbols at the end of the paper.

3. Energetic balance of the plant

The systems in (2) and (3) above collect the energy

$$E_f = fE_e \quad (1)$$

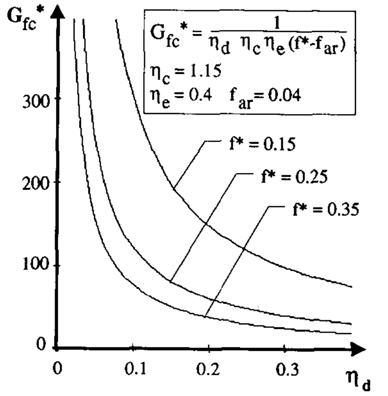

Fig. 4. Minimum fusion chamber energy gain value needed to satisfy the economic gain condition (G_{fc}^*) as a function of driver efficiency (η_d) and recycling energy fraction value corresponding to the achievement of plant economic parity (f^*).

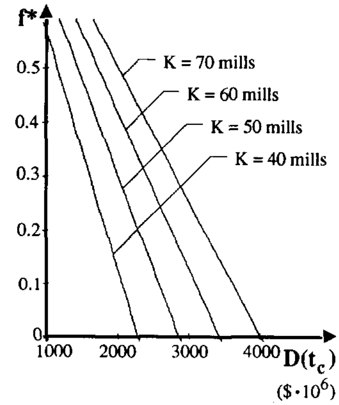

Fig. 5. Recycling energy fraction value corresponding to the achievement of plant economic parity (f^*) as a function of plant construction costs ($D(t_c)$) and current kWh commercial price (K).

from the electric power substation in order to work. The relevance of f should be noted; in fact, a reduction in f implies an increase in the net electric energy produced by the plant. In Fig. 2 the energy gain in the fusion chamber (G_{fc}) is plotted, under energetic balance conditions, as a function of the recycling energy fraction (f) and the driver efficiency (η_d); reasonable values have been fixed for the other parameters. By increasing the fusion chamber energetic yield (i.e. by raising the G_{fc} value) and/or the driver efficiency η_d, it is possible to reduce the f value.

4. Conditions to obtain an energetic gain from an inertial fusion plant

In order to achieve inertial fusion devices which do not have merely experimental relevance, it seems necessary that their development takes into account the production of a further net amount of energy to be used beyond the plant running. The first important condition, necessary but not sufficient, which is to be satisfied for the feasibility of industrial inertial fusion reactors is what we called the "energetic gain condition"; this condition can be expressed as follows:

$$G_{fc} > G_{fc}^{1} \tag{2}$$

where G_{fc}^{1} is the minimum energy gain value in the fusion chamber needed to satisfy the energetic gain condition. The analysis of the G_{fc}^{1} value demonstrated that, in the relevant value intervals of the energetic

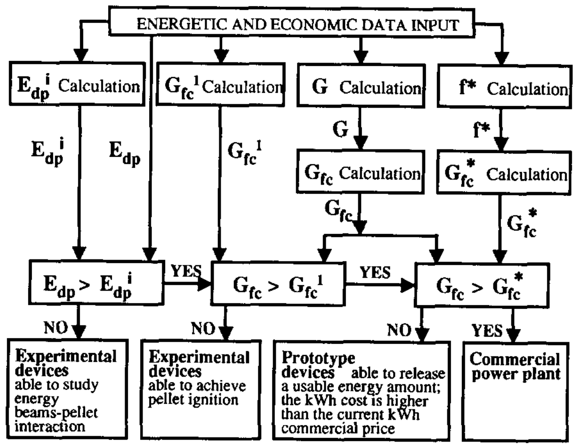

Fig. 6. Block diagram of the energetic–economic method for the analysis of inertial fusion systems.

parameters on which it depends, the G_{fc}^{1} value is strongly influenced by the η_d value only. An example is plotted in Fig. 3.

5. Conditions to obtain an economic gain from an inertial fusion plant

The most important condition which an inertial fusion power plant must satisfy in order to achieve commercial success is to be economically competitive with other types

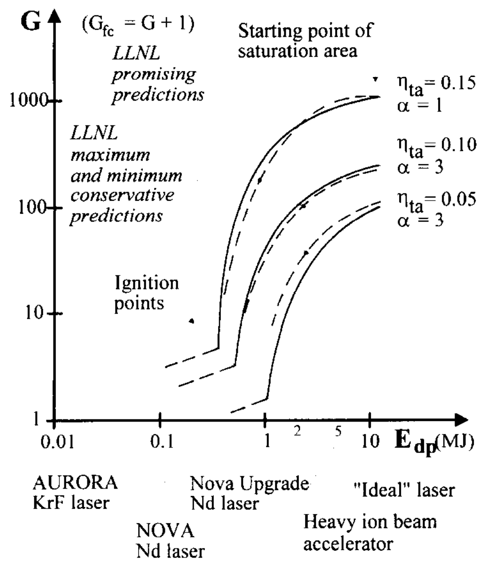

Fig. 7. Thermonuclear energy gain (G) as a function of driver pulse energy (E_{dp}), total pellet absorption efficiency (η_{ta}) and isentrope parameter (α) [6].

of power plants. Such a condition, which we called the "economic gain condition", can be expressed as follows:

$$G_{fc} > G_{fc}^* \quad (3)$$

where G_{fc}^* is the minimum fusion chamber energy gain value needed to satisfy the economic gain condition. The analysis of the G_{fc}^* value demonstrated that, in the relevant value intervals of the energetic and economic parameters on which it depends, the G_{fc}^* value is strongly influenced by the η_d and f^* values only. An example is plotted in Fig. 4.

It must be pointed out that f^* represents the recycling energy value corresponding to the achievement of the plant economic parity. In order to achieve an economic gain, the condition $f < f^*$ should be satisfied. Studies on f^* showed its strong dependence on the plant construction costs and the current kWh commercial price. An example is plotted in Fig. 5.

6. Description of the energetic–economic method

The combined use of the expressions and conditions relating to the aforementioned energetic and economic gains allows the formulation of the energetic–economic method for the analysis of inertial fusion systems, which is the object of this work. Fig. 6 shows a block diagram which represents the application of the method. The diagram emphasizes the relevance of the ignition, energetic and economic gain conditions which have to be satisfied for the success of ignition experiments, prototype systems for energy production and commercial power plants, respectively. The calculation of the values of $E_{dp}{}^{i}$, $G_{fc}{}^{1}$, G_{fc}^* and G_{fc} (E_{dp} is an input datum) is necessary for use of the three aforementioned

Table 1
Values of parameters for comparing different drivers employed in inertial fusion

Parameter	Nova Nd laser	Aurora KrF laser	Nova Upgrade Nd laser	"Ideal" laser	Heavy ion beam accelerator
E_{dp} (kJ)	100	10	200	10 000	5000
η_d	0.01	0.08	0.01	0.10	0.25
$E_{dp}{}^{i\,a}$ (MJ)	0.5–1	0.5–1	0.5–1	0.5–1	0.5–1
G^{a}	(No ign.)	(No ign.)	21–108	97–253	65–195
$G_{fc}{}^{a}$	(No ign.)	(No ign.)	22–109	98–254	66–196
$G_{fc}{}^{1}$	226	28	226	23	9
f^*	0.247	0.247	0.247	0.247	0.247
G_{fc}^*	1048	131	1048	105	42
$E_{dp} > E_{dp}{}^{i}$	No	No	Yes	Yes	Yes
$G_{fc} > G_{fc}{}^{1}$	No	No	No	Yes	Yes
$G_{fc} > G_{fc}^*$	No	No	No	Yes	Yes

[a] Value range corresponding to $\eta_{ta} = 0.05$–0.10.

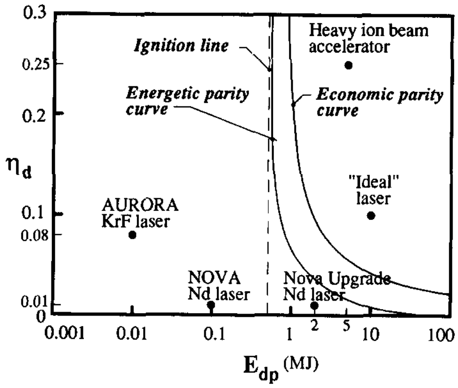

Fig. 8. Achievable results from different drivers.

conditions. Figs. 3, 4 and 7 show examples of G_{fc}^1, G_{fc}^* and G (G_{fc}) as functions of the parameters which, in the relevant value intervals, have the greatest influence on them.

7. Results from the applying energetic–economic method

The analysis of the energetic–economic method led to a first important conclusion: the success both of the experiments and of the future "commercial" inertial fusion power plants depends, above all, on the performance (and especially on the η_d and E_{dp} values) of the drivers which will be employed. The possibilities of satisfying the conditions of ignition, energetic gain and economic gain for inertial plants which use different drivers can be inferred from the analysis of Fig. 7, from comparison between Figs. 3 and 7 and from comparison between Figs. 4 and 7, respectively. Table 1 reports value examples of comparison terms which are useful for evaluating the extent to which the conditions of ignition, energetic gain and economic gain are satisfied. From Fig. 7 it can be inferred that the present experimental laser systems are not able to achieve ignition because of the low driver pulse energy (maximum values $E_{dp} = 10-100$ kJ [2,3]). In the long term, the first devices to achieve ignition should be neodymium lasers (Nova Upgrade: $E_{dp} = 1.5-2.0$ MJ [4]). Such lasers, at conservative values of η_{ta} (0.05–1.10) [2], could achieve G_{fc} values of about 50–100, which, however, do not allow energy parity to be reached since the neodymium laser efficiency η_d is too low. The first fusion device to satisfy such a condition could be a KrF laser, which, owing to its higher efficiency, only needs an adequate impulse energy increase. The present situation can change if, with neodymium lasers, flashlamp pumping is replaced by diode pumping, which allows the laser efficiency η_d to be greatly improved up to $\eta_d = 0.1$ or more. However, both Nd and KrF lasers are far away from the requirements needed to satisfy the economic gain condition. Such requirements are shown in Figs. 3, 4, 7, and Table 1 as the "ideal" laser requirements ($\eta_d \approx 0.1$; $E_{dp} \approx 10$ MJ); it is unlikely to achieve such goals in the short term. In conclusion, these "ideal" laser performances could be achieved either by further developing the KrF laser, in order to raise its energy and efficiency, or by adopting diode pumping with neodymium lasers.

The fusion systems using heavy ion beam accelerators [5] show more promising prospects, if the design expectations are fulfilled. Their high efficiency ($\eta_d \approx 0.25$) would allow the economic gain condition at relatively low G_{fc} values (≈ 50), thus using relatively reasonable energy pulses (about 5 MJ). In theory, these values seem realistically achievable. As a conclusion, Fig. 8 shows the gap between the current experiments and the goals to be be reached. The energetic and economic parity curves were calculated using reasonable values for the parameters involved.

8. Conclusions

The energetic–economic method for the analysis of inertial fusion systems as discussed here, allows the following goals to be reached:

(1) the evaluation of the results which are obtainable by current research studies;
(2) the evaluation of the minimum requirements needed to achieve:
  (a) experimental devices able to achieve pellet ignition;
  (b) inertial fusion devices able to release a usable energy amount;
  (c) "commercial" inertial fusion power plants;
(3) the evaluation of the current experimental devices which seem the most promising for achieving the aforementioned minimum requirements;
(4) the comparison between inertial fusion power plants which employ different drivers;
(5) the evaluation of the most promising research lines.

It is useful to observe that this method would remain effective even though new relevant technologies may subvert the current evaluations. In fact, input data can always be modified in order to update results. The application of the method, using the current values of the running systems and soon to be available designs, allows the following considerations.

None of the present experimental ICF systems is even able to reach ignition. In the short term it is expected that ignition could be achieved by using more and more powerful experimental laser devices. However, these devices will be far away from the energy balance point owing to their low efficiencies. In the long term, the use of heavy ion beam accelerators as drivers seems to be the most promising choice to satisfy the energetic gain condition, since the accelerator efficiency is higher than the laser efficiency. Since both laser and heavy ion beam systems are in rapid and continuous evolution, from the point of view of power, efficiency and cost, it is difficult, at present, to predict which system will be the most suitable as an ICF ignitor. However, the method outlined here can help to perform an energetic and economic analysis of an ICF power plant.

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Appendix A: Nomenclature

$D(t_c)$	plant construction costs, up to the stage of its going on duty
E_c	coolant thermal energy
E_{df}	driver feeding energy
E_{dp}	driver impulse energy
E_{dp}^{i}	minimum driver impulse energy value needed to satisfy the condition of ignition
E_e	gross power plant electrical energy
E_f	power plant feed energy
E_{fa}	fuel absorbed energy
E_n	net power plant electrical energy
E_r	energy delivered to the fusion chamber walls
E_{sa}	auxiliary equipment supply energy
E_{tn}	thermonuclear energy delivered by the fusion reactions in the fuel
f	recycling energy fraction; $f > 1$ obviously means that the power plant absorbs more energy than the amount produced, which is a typical feature of current experimental devices
f^*	recycling energy fraction value corresponding to the achievement of the plant economic parity
f_{ar}	E_{sa}/E_e, auxiliary equipment recycling energy fraction
G	E_{tn}/E_{dp}, thermonuclear energy gain
G_c	E_{tn}/E_{fa}, pellet energy gain
G_{fc}	E_r/E_{dp}, fusion chamber energy gain
G_{fc}	$G + 1$
G_{fc}^{i}	minimum fusion chamber energy gain value needed to satisfy the energetic gain condition
G_{fc}^*	minimum fusion chamber energy gain value needed to satisfy the economic gain condition
K	current kWh commercial price
α	isentrope parameter
η_c	E_c/E_r, blanket thermal energy conversion efficiency
η_d	E_{dp}/E_{df}, driver efficiency
η_e	E_e/E_c, electric energy converter efficiency
η_{ta}	E_{fa}/E_{dp}, total pellet absorption efficiency versus driver energy; this quantity gives the total driver–fuel coupling efficiency

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