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IN MEMORIAM

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General of Division and military pilot of the Aeronautical Engineering Corps of the Air Force
1958-1963
Analysis of laser-fission-fusion systems: Time-dependent coupled nuclear-thermohydrodynamic analysis and applications

By Guillermo Velarde, Carmen Alcover, José M. Aragonés, Manuel Gomensoro-Alonso, Guillermo Soria, Ricardo Ibarz, Javier Muñoz, and Manuel Perlado

IAEA TM Physics IFE Targets and Chambers, Tashkent (Uzbekistan) / J.M. Perlado

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Abstract
The analytical analysis of laser-fission-fusion systems, requires a precise control of the nuclear fuel treatment with dedicated space-time dependence of the different processes involved: laser-plasma interaction, ablation and implosion, fusion ignition, neutron moderation, fuel burnup and breeding, power generation and environmental. Computer codes and numerical methods for hydrogen plasma neutrons in different geometries, are currently used to simulate the described electromagnetic-hydrodynamics calculations. A computer program (HYNIC) for detailed thermonuclear-fission coupled to a detailed nuclear program (CLARIS), and a Monte Carlo program (MCNP) for the analysis of the fission product chain has contributed to simplify the description of the processes and to study all of the energy and mass transport stages involved in the fuel cycle. The energy description of nuclear chains is also simplified to reduce the complexity of the code and to solve the problem with the minimum assumptions of the initial and boundary conditions.

1. Introduction
A number of studies [1-3] have been performed during the last decade in several confined fusion facilities, employing lasers, relativistic electrons or ions in order to maximize microplasmas. The present size of these microplasmas, relative to pure fusion, without fission has been presented in the International Conference Fusion Conference (IEEE/OAE, 1977).

1.1. Ablation and compression processes. Instabilities
To achieve efficiently the process of ablation and subsequent compression of the microplasmas, it is required that the laser focus be an axicon, followed by a plessuer-ripple layer. This layer, together with the O-T layers, produce a gradient of fields that optimizes the instabilities of the laser-plasma [1-5]. The boundary surfaces between plasma and different layers of the microplasma, are available. These instabilities can be attenuated by the gradient of temperatures. Taking into account the present considerations, microplasmas with multifacets of different materials have been proposed [6, 10, 11, 12]. One of these has been shown in fig. 1.

2. Energy balance in laser-fusion systems
In the case of laser-fusion systems, the laser energy required to heat the fuel to ignition temperatures is [7, 12],

\[
\text{E}_{\text{L}} = \frac{\text{E}_{\text{F}}}{\text{E}_{\text{L}} + \text{E}_{\text{B}}} + \frac{\text{E}_{\text{F}}}{\text{E}_{\text{L}} + \text{E}_{\text{B}}}
\]

with \(\text{E}_{\text{F}}\) the laser energy, \(\text{E}_{\text{B}}\) the radiation energy, and \(\text{E}_{\text{L}}\) the laser energy needed to heat the fuel.

3. Description of the codes

3.1. HYNIC (Hydro-Nuclear Interaction Code)
This code is designed to simulate the time-dependent coupled nuclear-thermochemical reactions for different conditions. The code can be used to simulate various conditions of equilibrium reactions.

3.2. CLARIS (Computerized Laser-Accelerated Reaction and Interactions System)
This code is designed to simulate the time-dependent coupled nuclear-thermochemical reactions for different conditions. The code can be used to simulate various conditions of equilibrium reactions.

3.3. MCNP (Monte Carlo Neutron Transport Code)
This code is designed to simulate the time-dependent coupled nuclear-thermochemical reactions for different conditions. The code can be used to simulate various conditions of equilibrium reactions.

References
The results obtained for $\alpha / \beta$, as well as the $\alpha$ values as a function of $\rho_{\text{ex}}$, are given in Table 2. The fit values used by Cole and Danson (1989) are also given. The small differences can be due to the different cross section libraries. In our results, only the prompt neutrons are included in $\alpha$.

3.1.3. NORMA II - DIT calculation with variable density
The distributions of radii and densities $\alpha (\rho) / \beta$ and $\alpha (\rho)$, calculated by NORMA II, are taken into account, so that a distributed density is considered at each time. The DIT code has been used to solve the appropriate equations, obtaining the DIT $\alpha / \beta$ values of $\alpha (\rho)$ given in Fig. 13. To accede the variation of a time scale, the Fig. 10 of the space-time-dependent distribution of density, free to be taken into account. During the compression, and also during the expansion phase, considered the attenuation of $\alpha (\rho)$ with variable density (DIT $\alpha / \beta$) are always greater than the velocities

monic waves. The long-wave increases the density toward the center, so that at 40% the maximum density occurs close to the center of the sphere. The diffusing waves broaden the peak of density reducing its maximum, so that the configuration is less spherical.

Superheating decreases uniformly on the density distribution is flattened by the expanding waves, which expand the internal zones. The change in extreme iterations NORMA-CLARA $\alpha / \beta$ to $\alpha / \beta$ is relatively small and the convergence is alternate, because the energy generation results in a faster expansion, which yields a lower energy generation in the next iteration. The evolution of line of the outer radius, and hence of the average density, is not perturbed by the generation of energy until $52.2+7.5$, when the expansion waves reach the outer radius, and the expansion is expanded very fast and the average density begins to decrease (Figs. 11 and 12). It is concluded from these results and that both the thermohydraulic and nuclear processes are mutually space-time dependent. The evolution of the neutron flux, and hence of the power and energy distributions, depends strongly on the detailed density distribution. The average density is not significant in all the neutron process. The hydrodynamic process is also strongly dependent on the detailed power distribution.

During the expansion process, as the configuration changes very fast with time, the steady-neutrons solutions (DIT $\alpha / \beta$) are significantly different from the dynamic solution (CLARA $\alpha / \beta$), as can be seen in Fig. 13.

3.1.3. NORMA-CLARA calculations with breakup
Some conditions of the previous cases are considered, with a point source at the origin. The breakup calculation included in CLARA is used to take into account the depletion of Pu 239 and Pu 240, and the production of Pu 241, N 232 and fission products.

To compare the effect of breakout without hydrodynamic feedback of fast neutron generation, a first case CLARA $\alpha / \beta$ was not using the distributions of $\alpha (\rho) / \beta$ and $\alpha (\rho)$ of the NORMA $\alpha / \beta$ case without internal energy sources. The $\alpha (\rho)$, including calculated breakup, is shown in Fig. 13 (NORMA II - CLARA $\alpha / \beta$). The breakup effect becomes significant at about 50 ps, which has immediately a maximum and decreases very sharply because the zones with higher density, are forced more rapidly to the high speed of the fast neutron ones, with the unburned zone of very low densities. To compare iterations, the NORMA $\alpha / \beta$ results of the previous iterations without breakup are used as a starting point of the configuration, with which the CLARA $\alpha / \beta$ calculation with breakup is started, so that the configuration is the same one that considered in the previous CLARA $\alpha / \beta$ case without breakup. The fast neutron power distributions calculated in CLARA $\alpha / \beta$ are used in the hydrodynamic-nuclear calculation NORMA $\alpha / \beta$. The new hydrodynamic configurations are used in CLARA $\alpha / \beta$, and the new successively to the correlated calculations NORMA $\alpha / \beta$ - CLARA $\alpha / \beta$. From the last NORMA $\alpha / \beta$ - CLARA $\alpha / \beta$ case, the following values are obtained:

- Maximum energy: $E_{\text{max}} = 6.7 \times 10^{24} \text{ J}$
- Maximum breakup energy: $E_{\text{breakup}} = 4.2 \times 10^{24} \text{ J}$
- Maximum specific energy: $E_{\text{specific}} = 6.2 \times 10^{24} \text{ J} / \text{mol}$
- Maximum specific gain of energy: $E_{\text{gain}} = 3.9 \times 10^{24} \text{ J} / \text{mol}$
- Maximum specific burnup: $E_{\text{burnup}} = 3.0 \times 10^{24} \text{ J} / \text{mol}$
- Maximum specific power: $E_{\text{power}} = 2.5 \times 10^{24} \text{ W} / \text{mol}$
- Maximum specific density: $\rho_{\text{max}} = 6.7 \times 10^{24} \text{ g} / \text{cm}^3$
- Maximum specific temperature: $T_{\text{max}} = 1.2 \times 10^{24} \text{ K}$

8/3/18

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Permanent Connection with Los Alamos for many years with stays of Professors there and common projects that after follow with Lawrence Livermore National Laboratory

Stays in KFK for Simulation of Targets and common programmes in Experiments at that time with KHALIF ion facility and after with design of HIBALL-II first full European IFE reactor
Dear Professor Valadez,

I enjoyed very much meeting you at the recent conference in Lausanne and to learn about the very impressive work you and your colleagues are doing in the field of ion-beam interaction.

As the theoretical work your group at ICM has been doing is closely linked to the problems of ion-beam-solid interaction, I am particularly interested in your research and I believe that our groups could benefit from a closer cooperation. This is particularly true in view of the theoretical aspects that I am currently working on. I would be very interested in hearing more about your experimental results and how they can be applied to the design of high-energy density target devices.

As you know, the NIKKEI Laser Laboratory in Japan has been leading the world in laser-driven target experiments. We have recently achieved some impressive results with our high-energy laser, which has a wavelength of 10.6 μm. Our laser has a pulsed output of 10^14 watts and a pulse duration of 10 ns. We have successfully demonstrated the ability to create high-temperature plasmas and high-energy density targets.

I would be very interested in learning more about your experience with high-energy laser targets and how you have approached the design of these targets. I believe that there is a lot that we can learn from each other and that a closer cooperation could be mutually beneficial.

Looking forward to your reply,

Sincerely,

Tomas Laforet

P.S. I enclose a copy of the final version of the report we gave at the Lausanne meeting P.S.
This article discusses the effect of different pg energetic spectra of neutrons leaking from an inertial confinement fusion (ICF) pellet, on integral parameters, characterizing the blanket performance. We have computed time-dependent and steady state neutron calculations to determine the neutron and gamma spectra from the target. Results show, that assuming a fuel burnup-average SR parameter,\( \langle \theta \rangle \), in the steady state method, realistic spectra \( \sigma \) can be obtained. The influence of the fuel \( \sigma_{\text{ICF}} \), \( \sigma_{\text{SA}} \) pusher parameter as well as that of the gama's escaping from the target, on the chamber response has been analyzed.

1. INTRODUCTION

In the analysis of a fusion blanket, we have to consider several parameters in order to determine its feasibility, including: energy deposition by neutrons and gammas per fusion born neutron, tritium breeding ratio (TBR), helium and hydrogen production, as well as the number of fissions per atom.

The neutron spectra from the target is the key data for the calculations. Unfortunately, one cannot consider a "unique" spectrum because a geometric target design, which could lead to positive gains, has not yet been found. Previous studies have shown that different spectrums of colliding neutrons \( n_\text{coll} \) have an important influence on several reactor parameters.

In view of the important effect of the source spectrum on blanket calculations, we intend in this paper to calculate accurately neutrons fusion spectra from ICF targets, and to perform an extensive sensitivity study of the parameters of the reactor versus possible spectrums.

In Sec. I the complete calculational method used for cross section library generation, source evaluation and blanket analysis is provided. In Sec. II the possibility to obtain neutron-gamma fusion spectra leaking from the target by means of a steady state method is discussed. The achieved results are compared with those obtained by integration of the time dependent spectra. Section IV is concerned with the effect of target compression on the cavity response. The effects of neutron moderation and gamma generation on the target will be discussed. Fuel and pusher influence will be considered separately. Calculations will be carried out for HIBALD \( \{\} \) and SOLAS \( \{\} \) designs. Finally conclusions are given in Sec. V.

II. CALCULATION METHOD

The structure of our calculational procedure is shown in Fig. 1.

Cross Section library generation

A coupled neutron-\( \gamma \) gamma group cross section library was used for blanket analysis. One in 15 neutron-\( \gamma \) groups was employed for source calculation in which the lowest energy group is assumed thermal. The first 14 groups in both libraries have the same energy structure. These libraries have been processed by NJOY17 and ANGIO \( \{\} \) codes from ENDF/B-VII.1 and BSE/BOOM libraries.

Source calculation

Since the characteristics of the neutrons escaping from the target have an important influence on cavity response, it is essential to perform detailed neutronic calculations for the target to account for spectrum softening and neutron multiplication.

A very accurate treatment of neutron transport, including anisotropic scattering, can be accomplished by solving the time dependent neutron transport equation. This equation can be numerically solved by the one-diagonal Sin code CLASA \( \{\} \). This code is coupled with the hydrodynamic one NORMA \( \{\} \) resulting in the coupled code NOCSA \( \{\} \) which has been used to obtain time dependent target spectra.

A time integrated spectrum of the neutrons escaping from the pellet can be calculated by:

\[ \text{FUSION TECHNOLOGY} \quad \text{VOL. II} \quad \text{JULY 1983} \]
Fig. 5. Neutrons leaking from target

Fig. 7. Effect of fuel $\langle PR \rangle_B$ parameter on the blanket properties

Fig. 8. Effect of fuel $\langle PR \rangle_B$ on the blanket properties
In 1988 the European Conference on Laser Interaction with the Matter (ECLIM) was held in Madrid (Spain), organized by the Institute of Nuclear Fusion (DENIM). During this conference, its Director, Professor Guillermo Velarde, Chair of the ECLIM, with Dr. Erik Storm from US Lawrence Livermore National Laboratory (LLNL) asked all the scientists participating in the ECLIM to sign the Madrid Manifesto requesting declassification of information related to ICF to allow work in energy production for civil applications. About 130 scientists around the world signed the Manifesto.
Participants ECLIM 1988
Firma del Madrid Manifesto

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The (Bomb) Secret’s Out
Foreign Movers to Harness Electricity From Fusion Forces U.S. to Open Up

By William J. Broad
New York Times Service

NEW YORK — The U.S. government, which handed for decades to keep the work of the hydrogen bomb a secret, is high-lighting aspects of its designs and in fact American scientists publish them in scientific literature.

The reason for this reversal is not just moral policy, the end of the Cold War or the collapse of the Soviet Union as a military adversary. Scientists in plasma physics and related research, hydrogen bomb experts believe that the generation of electricity from hydrogen, have openly

Continued secrecy for similar research in the United States was seen as stifling the exchange of ideas, inhibiting progress and harming international competition.

At least three U.S. scientists have been ordered to avoid meetings with foreign scientists, or have already done so, to avoid a risk of discussing classified information.

As a result, the Department of Energy, the keeper of the secrets, carried out one round of tightening in 1986, and said it was

BEFORE

BOMB: Foreign Competition Forces U.S. to Put Secrets in the Marketplace

(Credit: AP Photo/Jim Cooper)

Nuclear weapons experts fear that nations that have access to the technologies needed to build nuclear weapons could eventually launch a nuclear power program.

This was because, for example, they know the design of the bomb and how it is assembled.

Today, a half century after the first nuclear test, experts say that nations could build a nuclear weapon if they had the necessary information.

The administration’s scientists in charge, for example, are already discussing the issue and are looking for ways to address it.

The administration wants to continue to cooperate with other countries, but it is unclear how much cooperation is possible given the current political climate.

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EDWARD TELLER AWARD (1997)

During the Award Ceremony, Professor Teller praised Velarde in the following terms: “We must recognize what is around us and understand the possibility of putting it to use, which is something that is of benefit to everybody and should be done by the community without hesitation and with practically no secrecy. Sir, you have perhaps done more than anyone in ICF to promote this most important direction”. (Edward Teller Lectures. Lasers and Inertial Fusion Energy. Imperial College, 2004)
SANTA CRUZ DE MARCENADO AWARD (2011)

The most important prize of the Armed Forces

AND

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Senator Lugar opening ISPAT Conference in Madrid
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Plaque in recognition to Professor Guillermo Velarde by his students (1998)
Panel devoted to the Instituto Fusion Nuclear in the Museum of Aeronautics and Astronautics