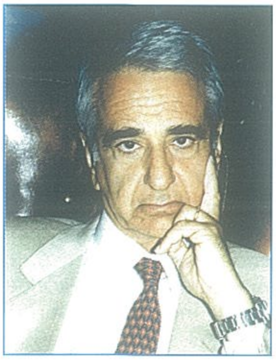
THE ORIGINS OF NUCLEAR INERTIAL CONFINEMENT FUSION (ICF) AND ITS BEGINNINGS IN SPAIN IN THE JEN AND THE DENIM

This paper deals with the origins of nuclear inertial confinement fusion based on the proposal by Nobel Prize Winner Nicolai G. Basov in 1962, and with the beginnings of this research, first at the JEN and afterwards at the DENIM.



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In 1962, N. Basov and O. Krokhin proposed to the Praesidium of the Soviet Academy of Sciences that, for the first time in history, lasers be used to produce thermonuclear fusion in micro-pebbles of deuterium and tritium (DT). The first calculations were made in 1963: when a laser of the order of one mega-joule uniformly illuminated the surface of a micro-pebble of one milligram of DT, a pressure wave of around two million atmospheres was generated on its surface by a process of ablation, which compressed and then heated the micro-pebble to some one hundred million degrees, resulting in DT fusion. These results were submitted by N. Basov to the 3rd Conference on Quantum Electronics held in Paris. It was then that we could say that ICF was born. In 1964, Soviet scientists N. Basov and Projorov and North American scientist C.H. Townes were awarded the Nobel Physics Prize for discovering the laser.

This important discovery was enthusiastically received by numerous scientists, and various papers were subsequently published in Europe, United States and Japan: in Europe, by Berry of the CEA in 1964, by Caruso of the ENEA in 1966, by Mulser and Witkowski of the MPQ in 1969, etc. In Japan, C. Yamanaka founded the Institute of Laser Engineering at the University of Osaka and did some exceptional work. In the United States, because of the possible military application of ICF, this research was classified as secret; however, after the first declassification early in the decade of the 70s, several papers written in the previous decade by Teller, Nuckolls, Kider, Brueckner, Jorna, Fraley, Bodner, etc. were published. After that, numerous laboratories were created that focused in whole or in part on ICF: the KFK and GSI laboratories in Germany, the LLE at the University of Rochester in USA, the CLF at the Rutherford Appleton Laboratory in the U.K., the LULI in the Polytechnic School of France, the DENIM in Spain, etc. In 1968, Basov and his collaborators obtained the first neutrons produced by an Nd laser on irradiating a flat target of lithium deuterate. After that point, theoretical work and experiments began to appear in rapid succession.

In Spain, it could be said that ICF began in 1966 as a result of two different events but with internally related effects. The first event was when I was invited to take part in the ICF-related experiments that Linhart was carrying out at the ENEA in Frascati. The second event was the unfortunate accident in Palomares, when a B52 with four 20-megaton nuclear fusion bombs crashed with the mother aircraft during refueling. The four deactivated bombs were automatically ejected with their respective parachutes. One fell into the sea and another on land and these were retrieved intact, but the parachutes of the other two bombs burned and, when they hit the ground, their chemical explosive lenses deflagrated, producing a plutonium oxide aerosol.

The military's high command and the JEN sent me on a mission to collect as many pieces as I could from the two bombs, so that they could be examined by the JEN. I found that there were large amounts of polystyrene sponge impregnated with plutonium oxide powder. At first I did not understand what this sponge was for, since I thought, just as the Americans had made us mistakenly believe, that the nuclear fusion bombs were made of an atomic plutonium bomb in the shape of a hollow sphere surrounded by chemical explosive lenses, with a layer of DT around these or else inside the plutonium sphere. Soon afterwards I learned that the purpose of the polystyrene sponge was to prevent the passage of shock waves and to permit X-ray transmission. The nuclear fusion bomb was not what they had made it out to be. It was formed by a uranium vessel of some 2 x 1 meters that was filled inside with polystyrene sponge; on one end there was an atomic plutonium bomb and on the other a vessel with DT or lithium 6 deuterium. When an atomic bomb explodes, a shock wave and an X-ray beam are produced. The shock wave is rapidly attenuated by the sponge, whereas the X-rays strike the uranium wall of the vessel unattenuated, undergoing multiphotonic resonant absorption, and soft X-rays are emitted that strike the DT vessel. This causes the nuclear fusion, in the same way that the micro-pebble DT is fused in ICF. This is known as the Ulam-Teller effect, which was rediscovered by Dautray in France and by Sajarov and Tamm in the USSR, and is the basis of the nuclear fusion bomb. I realized then that the physical processes of the nuclear fusion bomb and of ICF were very similar. In the nuclear fusion bomb, the trigger is an atomic bomb that produces energy equivalent to the explosion of 20 million tons of TNT, whereas in ICF the trigger is a powerful laser that produces energy during fusion equivalent to 100 kg of TNT. These capsules were subsequently called *holhraum*. Therefore, it seemed only logical that these types of capsules be used in ICF, which would be the basis of future fusion energy producing reactors.

The next step was to develop a radiation transport code that would simulate the Ulam-Teller effect, which I did with the invaluable help of Tomas Iglesias, head of the JEN's Computing Division. Just as other codes that I developed for neutron moderation in nuclear fission reactors, I called this code Islero. However, as the JEN's computer at that time was obviously inadequate for these calculations and also because the parameters (opacities) and state equation were not known, the results had only a qualitative worth. Therefore, the study of *holhraum* capsules was postponed until two-dimensional radiation transport codes were available.

In 1969, the President of the JEN, Admiral Otero, asked me to start selecting a small group of physicists and engineers to help in the calculation of both nuclear fission reactors and ICF reactors. Over several years, I selected the most brilliant students from the JEN reactor courses and the quantum mechanics and nuclear physics courses of the Higher School of Industrial Engineering. In 1970, I selected Carol Ahnert from the JEN courses and Jose M. Aragonés from the School of Industrial Engineers. In 1973, a special class, predominantly including Jose M. Martinez-Val, Manuel Perlado and Emilio Minguez, graduated. With this group, which was later joined by naval weapons engineers Guillermo Leira and Sanchez Tembleque, I began to develop all the

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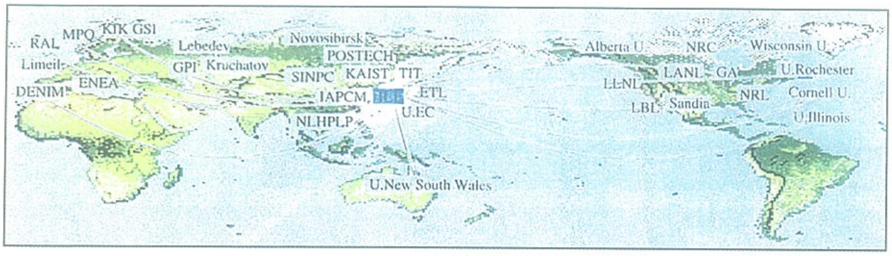

codes that simulated the different processes of ICF.

In 1974, during one of the reorganizations of the JEN, I as appointed as Director of the Technology Department, which included the Electronics, Engineering, In-Service Reactor, Reactor Theory & Calculation and Fusion Divisions. The Fusion Division would focus exclusively on magnetic confinement fusion (MCF). The Reactor Theory and Calculation Division would be in charge of both fission reactors under the direction of Rafael Caro, a competent physicist who I had been working with for nearly 17 years, and of ICF.

1974 to 1978 were difficult years. There were very few publications on ICF to work with due to the strict classification imposed by the United States. From the very beginning, we realized that to overcome this obstacle and to be able to become a part of the international scientific community, we had to do something dramatic. Therefore, taking advantage of an invitation to present our work in a conference to be held in Graz (Austria), for several months we prepared a paper that, without containing any major discoveries, did discuss our rediscovery of what the Americans had been keeping so secret. Although the Americans had been aware of my rediscovery of the Ulam-Teller effect since 1966, they thought it was an isolated event; and when the paper presented in Graz was published it caused an enormous impact. The fact that a group of Spaniards had been able to reach this level of research opened the doors of the international scientific community to us. A few months later, the paper made the rounds of the Los Alamos, Lawrence Livermore and Naval Research Laboratories, etc., to the disbelief of the majority who saw it.

However, two serious problems then arouse. On one hand, the new President of the JEN, Lieutenant General Olivares, who at first had supported our research on ICF, changed his mind in the late 70s, perhaps because of poor advice, and focused all the JEN's efforts on MCF. On the other hand, to be able to continue our research on ICF, we needed a sufficiently powerful computer, which did not exist at that time in Spain and which the President of the JEN did not think should be acquired. We were thus faced with the following dilemma: either accept the conditions of the JEN's President, or leave. We decided on the latter. In my case, as I had obtained the Nuclear Physics Chair seven years earlier, and that of Aragonés and Martinez-Val, who had been named Assistant Professors, requesting a voluntary sabbatical from the JEN and joining the University meant a significant cut in our salaries, but we did continue to be career civil servants. Perlado and Minguez had a harder choice; driven by their enthusiasm and dedication to scientific research, they took a shot in the dark and left a steady, secure job for the problematic and at that time poorly paid post of hired professor. Ahnert did the same later. All of them are currently Professors of Nuclear Physics or Technology, which confirms that I chose the very best. Leira decided to go back to the Navy so as not to abandon his military career. His was a great loss, as he combined an extraordinary capability for research and experimentation with a solid theoretical background, which is something rarely found.

Thus two problems had to be solved: creating a university institute, and obtaining 200 or 300 million pesetas for acquiring a powerful computer not then available in Spain and half of that for annual maintenance of the institute. To create the institute, we were able to count on the invaluable assistance of the Rector, Rafael Portaencasa, who was very interested in fostering scientific research in our university and who helped us to complete all administrative formalities in just a few months. In 1982, the creation of the Institute, which would subsequently be called the Nuclear Fusion Institute – DENIM – was published in the BOE (no. 73, March 23, 1982). Buying a computer was more complicated. I appealed to the ministries involved in scientific research, but they could only guarantee 5% for the initial investment and nothing for maintenance. I thus turned to the President of the Government, Adolfo Suarez, with the help of Vice-President General Gutierrez Mellado, who was convinced that the most effective, economic way to support scientific research was to subsidize certain university chairs to purchase the necessary equipment and attend conferences, and to increase the salary of professors in exchange for doing scientific research that they could choose at their own free will but that should be internationally recognized. The restrictive university law of that time thwarted this plan. Several years later, article 11 of the LRU eliminated this impediment. Gutierrez Mellado enthusiastically supported me in my appeal to President Suarez.

The fastest, most effective solution was to install a powerful computing center in the Institute that would serve as support for the Ministry of Defense. The Chairman of the Joint Chiefs of Staff, General Ignacio Alfaro, solved all the problems. I did not have do talk to him about maintaining the Institute, because he beat me to it when he said: *In aviation, when we purchase an aircraft, at the same time we agree to maintain it for its entire effective life, and here we will do the same.* Because of their decisive support of scientific research, I proposed to Rector Portaencasa that these two generals be awarded the University's Medal of Honor, which was unanimously approved by the Board of Directors.

After that, we were morally committed to demonstrating that the efforts made by the Government and the Rector had not been in vain. In the years that followed, several engineers and university graduates, who are currently Professors, joined the Institute; more than two hundred foreign scientists visited us, including four Nobel Prizes; and different calculation codes were developed for the processes that occur in ICF: two-dimensional in adaptive mesh (AMR) with radiation transport, thermodynamically balanced and unbalanced opacities, effect of radiation on materials by molecular dynamics and Montecarlo diffusion, material activation and tritium contamination studies, material damages, special configurations with DT and other nuclides, etc. These have been validated in numerous experiments carried out in other international laboratories with experimental facilities, primarily in the C.E.A.'s Phebus laser in Limeil-Valenton and in the LULI laser in the Polytechnic School of Paris.

In 1994 official aid to the Institute was suspended, and all hired researchers who for decades had been selected from among the most outstanding students had to be dismissed. The effect was detrimental because, since then, there are practically no Spanish students who want to devote their best years to scientific research, as their future depends on whoever is in charge at the moment, and therefore most researchers are foreigners from the E.U. Fortunately, in the 5th Framework Program, the E.U. established the ICF *keep-in-touch* program, in which Spain, Germany, France, Italy, the United Kingdom and finally Portugal take part. This program is coordinated by the ICF Coordination Committee of the Technical Group on Energy, which I have chaired since 1999.

At present, practically all E.U. efforts focus on MCF and in particular on ITER, whereas in the United States more work is being done on ICF.