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NEW DEVELOPMENTS IN HEAVY ION FUSION*

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Abstract

Beginning in 1984, the US Department of Energy plans a program aimed at determining the feasibility of using heavy ion accelerators as pellet drivers for Inertial Confinement Fusion (ICF). This paper will describe the events in the field of Heavy Ion Fusion (HIF) that have occurred in the three years since the Lausanne Conference in this series. The emphasis will be on the events leading towards the new energy oriented program. In addition to providing an overview of progress in HIF, such a discussion may prove useful for promoters of any "emerging" energy technology.

Introduction

Heavy Ion Fusion (HIF) began with an enthusiastic workshop in 1976 in Oakland/Berkeley.[1] Now, seven years later, a much smaller group remains to begin the task of determining if HIF is a feasible technology for commercial electric power production. The papers presented at the Lausanne Conference[2] discussed the scientific, technological and economic arguments which favor HIF as a practical energy system. For example, from the utility viewpoint, it is obviously desirable to make an early model of a fusion power plant as small as is practical. Consider the minimum fusion yield necessary to make a power plant that could, in theory, be economically feasible. The requirement for economic feasibility for ICF power is that the fraction of total power generated that must be recirculated, to operate the driver and other auxilliary equipment, must be about 33% or lower. Figure 1 shows fusion yield as a function of driver energy according to published gain curves.[3] The threshold for economic operation is shown for driver efficiencies of 5% and 25%, which are typical for lasers (e.g. KrF) and accelerators, respectively. The advantage of the higher efficiency expected from a heavy ion accelerator results in;

1. The ability to employ the simpler, single shell targets.

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2. A driver energy a factor of about two smaller.
3. A fusion yield per pulse an order of magnitude less.
4. A factor of conservatism that leaves a margin for the uncertainties in target and driver performance.

This paper will primarily be concerned with the events preceding the transfer of the HIF program into the Office of Energy Research of the USDOE. The purpose of the new ER program is to develop accelerator technology appropriate to HIF, leading eventually to civilian power applications for Inertial Confinement Fusion (ICF). HIF began with the claim that here was a well established technology with all the characteristics most sought after in an ICF driver. The program is now charged with establishing scientific evidence for this claim.

Events Since the Lausanne Conference

Since the Lausanne Conference, most of the effort in HIF has been concentrated the two principal technological approaches; the rf linac with storage ring accumulators and the single-pass linear induction accelerator. (The synchrotron had been examined earlier and was recognized as unsuitable for this application by 1979: other concepts, frequently variations of one of the principal approaches, get some attention as time and budgets permit.) Some accelerator physicists, who were familiar with proton rf linacs, pointed to the many operating accelerators of this type, (in one case, for the ISR at CERN, operating as an injector to a storage ring), as evidence of an existing technology that could solve the driver problem for ICF. Those most familiar with induction linac technology suggested that it might provide a simpler solution and could likely result in an economic and reliable accelerator system. Accelerating ions is a new application for the induction linac, and some basic experimental data, such as the beam current limit in a transport system, is needed. Both groups proposed building small "test bed" facilities as the first step towards demonstrating the accelerator technology.

Heavy ions were a late contender for the driver technology for ICF; the laser and light ion diode programs were already well established. Substantial changes in the direction of more stringent target requirements did as much as any other one factor to impede the fast progress hoped for by early enthusiasts. When HIF began, beam energies of 100 GeV, or even more, were considered appropriate for the targets being studied. At such a high kinetic energy, the relevant accelerator technology is quite similar to that of high energy physics accelerator systems. Present thinking is that 10 GeV is a practical upper limit, and that several megajoules are required. The result is that much higher currents of slow moving ions are needed, substantially changing the technical requirements on the accelerator system.

By the time of the Lausanne Conference, a plan had been devised in which two accelerator "test beds" were to be built, one for each technology, at an estimated cost of $25 million apiece. This work was to have begun in 1981. My report to the Lausanne Conference discussed the risk to the HIF program if the Congress did not approve a reasonably large fraction of the $15 million requested to start the design work for these projects. As it happened, only a small budget was passed, and in the two subsequent years the level of funding dropped to the present level of about $2 million per year.

After deep budget cuts, it was no longer practical to continue to do R & D on two accelerator technologies. The rf linac programs at Brookhaven National Laborator and at Argonne National Laboratory were both phased out. Studies continued on the two technological approaches at the Los Alamos National Laboratory (LANL) and at the Lawrence Berkeley Laboratory (LBL).

The International HIF Effort

Although budget levels and the rate of technical progress were dropping in the US, the years since the Lausanne Conference have seen a marked increase in worldwide interest in HIF. The following is not presented as a comprehensive review of non-USDOE funded activity, but it does show that there is significant activity outside of the US National Laboratories.

The West German program, with help from the University of Wisconsin, produced the HIBALL[4] report which is the best self-consistent fusion power park scenario yet written for inertial fusion. The innovative reactor system for HIBALL (the acronym stands for Heavy Ion Beams and Lithium Lead) uses woven tubes of silicon carbide to conduct streams of lithium lead, thus providing thin films of the liquid to absorb the products of the microexplosion that would damage a solid first wall of a reactor chamber. By inhibiting the flow, as compared to a free fall or pressurized spray, the use of the silicon carbide tubes greatly reduces the energy needed to pump the heavy material. One advantage of lithium-lead is the much lower vapor pressure which eliminates problems caused by poor vacuum in the final transport of the ion beams to the target pellet. A second advantage is its greater safety compared to pure lithium in the event of a catastrophic leak.[5]

The heavy ion accelerator for HIBALL was originally based on a rf linac for $Bi + 2$. The doubly charged ion makes it possible to achieve 10 GeV with a less expensive linac than would be required for singly charged ions. The HIBALL accelerator system was studied at the most recent HIF workshop at the Gesellschaft fur Schwerionenforschung (GSI).[6] The general conclusion of the workshop was that the storage rings for HIBALL were required to store currents in excess of expected limits. The designers had previously identified some problems with the final focus system. Since the workshop, they have modified the accelerator system to use singly charged ions, thus improving both the final transport efficiency and reducing the requirements on the storage rings. The redesigned system would cost significantly more, but could be used to run four or more reactor chambers. Thus the cost of the driver system (reported to be around $3 billion) would be about one-third or less of the total cost of the power park of capacity 4 GWe or more.

The heavy ion beam currents that must be contained in the HIBALL storage rings are expected to be significantly above the threshold for longitudinal instability. Generally, in order that the estimated cost of a power plant system should not be excessive, all heavy ion storage ring scenarios have been designed to push the stability limits. A major issue, therefore, is whether the growth rate of the instability is small enough to avoid significant loss of beam quality during the time that the current must be stored. The first machine which could test the relevant instability threshold and growth rate in the parameter space needed for HIF is the Spallation Neutron Source (SNS) under construction at Rutherford Appleton Laboratory (RAL) in Great Britain.[7]

The transverse stability limits for the beam current in a linear transport system are also important to the economics of HIF, especially for the induction linac which should be designed as nearly as practical to the space charge limit throughout its length. This problem has been studied analytically and numerically for several years and, most recently, experimental efforts have been started at several laboratories. Early experimental results from Maschke,[8] from the Univ. of Maryland-RAL collaboration,[9] from Klabunde et al at GSI,[10] and from the work at LBL,[11] all seem to confirm numerical studies predicting that such instabilities as do occur will not grow in a way that reduces beam brightness.

As was pointed out above, the linear induction method has only recently been used for accelerating unneutralized ion beams. One of the first tests of such an application was reported from Japan at Nagoya University.[12] The group at LBL has also begun beam tests accelerating Cs+ in a long-pulse induction module.[13] Previously, in the US, induction linacs have been proposed for accelerating neutralized ion beams for ICF. Tests have been reported by Humphries[14] (in a program that was funded for HIF but was a casualty of the budget cuts) and by John Nation's group at Cornell University.[15]

As further evidence of the spreading interest in the field, the next international workshop for accelerators applied to inertial confinement fusion will be hosted by the Institute of Nuclear Studies in Tokyo. The chairman for this meeting is Prof. Y. Hirao and the conference is scheduled for January 1984.

The Electric Power Research Institute, which obtains its funding from the utility industry, has sponsored a number of studies in inertial fusion related topics.[16] One of these is the Technical Risk Assessment of Inertial Fusion performed under contract with TRW, Inc. This study uses interviews with scientists to identify critical problems and then uses this information to develop an R & D plan leading to a demonstration power plant by the year 2010. Another EPRI contract[17] has studied the use of "advanced" fuels, specifically D-D, with a small tritium fraction, which eliminates the need for a thick lithium blanket to breed tritium. Because of the higher energy demands and lower yields of D-D targets, this approach requires the efficiency and economy-of-scale possible with heavy ion accelerator drivers.

The US National Plan for Accelerator Inertial Fusion

The Los Alamos National Laboratory has the role of "lead laboratory" for HIF. Funding for the Los Alamos ICF program has always come from the Office of Inertial Fusion (OIF) in the Defense Programs (DP) part of the USDOE. Heavy Ion Fusion is viewed as an energy strategy, not essential to the mission of DP, and thus funding has been greatly inhibited. By agreement between officers of the DOE at the Assistant Secretary level, a transfer of the HIF program to the Office of Energy Research (ER) was arranged, effective in October 1983. The new objective was to establish a base of experience with high-brightness, high-current, heavy-ion accelerators that could be used to evaluate this technology for application for an ICF driver for civilian power. With help from contributions from other laboratories, Roger Bangerter (LANL) compiled a draft program plan described in "Accelerator Inertial Fusion – A National Plan for the Development of Heavy-Ion Accelerators for Fusion Power."[18]

The National Plan calls for a two-stage program in which Stage I would use three years to do the necessary R & D to design a suitable test accelerator. Stage II would be to build the test accelerator and to perform a "High Temperature Experiment" (HTE). The National Plan acknowledges that it is impractical to expect to obtain funding to pursue both the induction linac and the rf linac/storage ring technologies. Thus, the Plan calls for concentration on one approach, the induction linac, while maintaining a small effort, mostly to observe developments from other programs, in the rf linac/storage ring method. Some of the justification for this choice lies in a technical argument; that the number of beam manipulations is less for the induction linac, resulting in a greater likelihood of preserving the necessary beam quality. Another argument stresses the eventual cost of an accelerator for a power plant which is generally predicted to be somewhat lower for conceptual designs using the the induction linac approach. It is likely that innovative developments will further reduce the cost of the induction linac system. This potential is documented in a report from LBL[19] in which a list of cost-cutting developments is given.

As this was written, the choice of technology had not been made, but realistically it would require a major program reversal to switch back to the rf linac system. The decision, which should be made soon, could still be reversed before the Stage II construction phase starts. The fact that the European HIF research is oriented toward the rf linac method effectively amounts to a program which is complementary to the induction linac program in the US.

Stage II of the National Plan calls for the construction of an accelerator facility which would be used to demonstrate the accelerator concepts needed for a full scale fusion driver. The facility has been named the "High Temperature Experiment" because it could be used to heat a small target or foil to temperatures in the range of 50-100 eV. It is important to recognize that the HTE is an accelerator demonstration project, and that achieving some tens of electron volts by around 1988-89 is not expected to provide especially new information for the physics of solid density plasmas. The importance will be in demonstrating that the intense heavy ion beam can be produced and focused in such a way as to reach significant temperatures. The high temperature is, in other words, primarily a beam diagnostic.

The one piece of high temperature physics that should be accomplished by the HTE is the experimental confirmation of the beam-target interaction. Due primarily to the surprisingly complex target interaction physics that was uncovered by the high-power laser experiments, there has always been some concern that the ion beam deposition physics may conceal some nasty surprises. For example, one worries about processes that could preheat a target pellet before the compression occurs. Among the possible causes of preheat that have been studied are fission fragments, knock-on electrons, various plasma instabilities in the target, etc. Preliminary results from light-ion experiments confirm predictions of some range shortening in hot matter. Range shortening is generally helpful, but it is not obvious that this effect will be great enough to improve target performance significantly.

As part of the preparation for the transfer of the HIF program to Energy Research, the DOE arranged for a special review of the physics issues of ICF that are peculiar to heavy ions. The final report[20] was generally very favorable with conclusions that contained the especially significant statements that "...the uncertainties in coupling physics for high energy heavy ions are minimal," and "The proposed National Plan for HIF seems to be a sensible and minimal next step in HIF." The report of this review does not contain a great deal of technical information; more details can be found in a recent review article by Bangerter.[21]

Induction Linac Program at LBL

The Heavy Ion Fusion Staff at LBL has prepared a plan[22] to develop the Induction Linac to meet the requirements of the National Plan. They propose a multiple beamlet structure to accelerate sodium or potassium ions to around 100 MeV for the HTE. The lighter ions are chosen because the target physics of a full scale reactor is simulated better with ions of similar velocity than by just having ions of similar atomic mass. Stripping, focusing and energy deposition are all better studied under conditions of similar velocity. Also, for the HTE it is necessary to get high instantaneous power, which is very difficult if the ions move too slowly. In anticipation of a much stronger program beginning with the new Energy Research budget, the LBL group has three major thrusts underway:

1. Conceptual design work for the HTE.
2. An experimental test of current transport limits.[11]
3. The development of induction linac modules for heavy ions.[13]

In conclusion, it is now possible to say that heavy ions are being accelerated, that high current beams are being transported, and that there is a DOE program to evaluate the feasibility of using heavy-ion accelerators for the civilian energy application of ICF. This DOE program is complemented by a vigorous international effort. It seems to me that HIF has turned an important corner and is starting to study the critical issues in a program that can lead to a new energy option.

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Figure Captions

1. Pellet yields are plotted according to published gain curves.[3] The range for each curve for which the condition for economic fusion power is valid (driver efficiency times target gain > 10) is indicated.

TARGET YIELD vs INPUT ENERGY

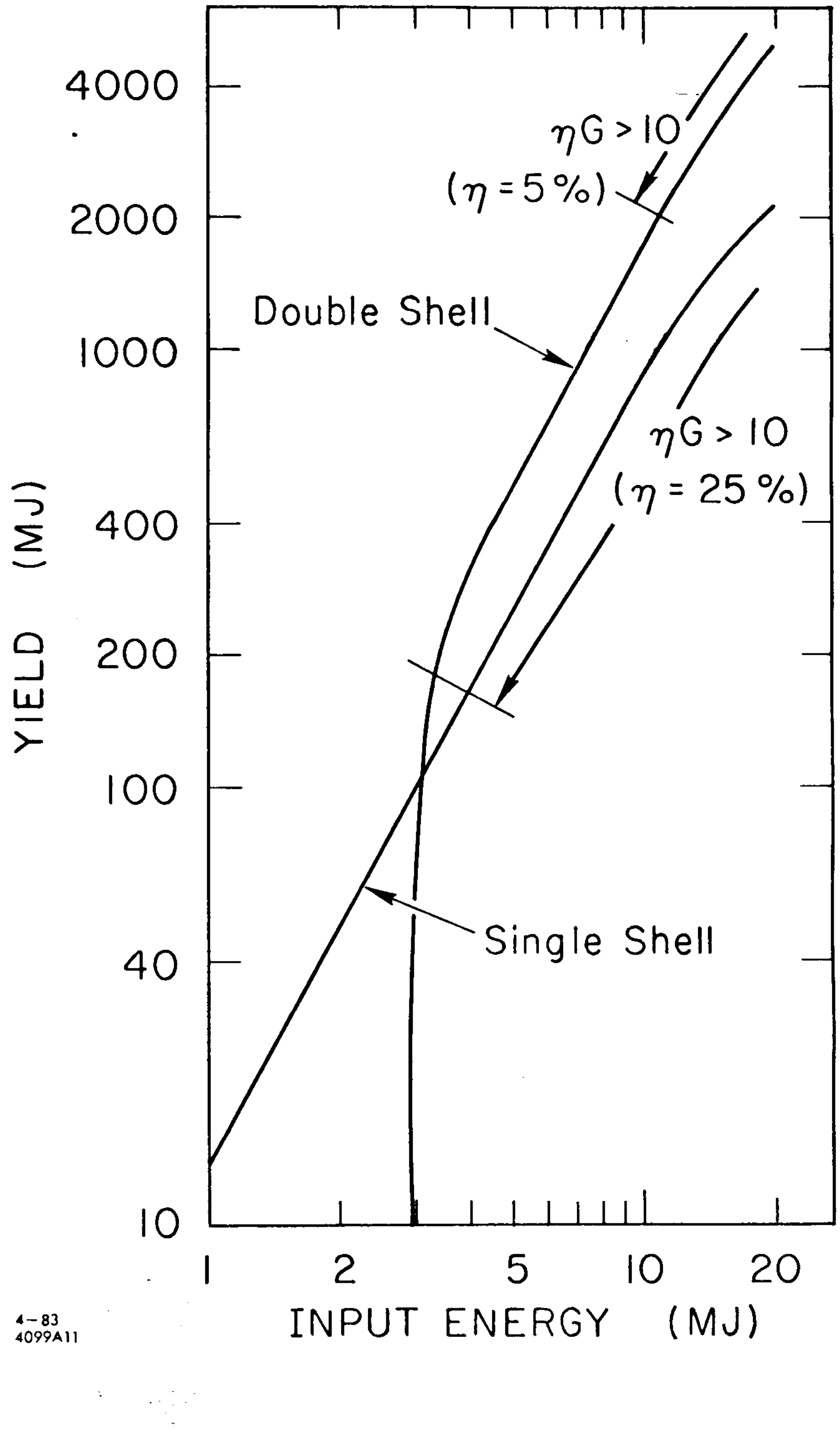

Fig. 1