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INDUCTION LINAC DRIVERS FOR HEAVY ION FUSION*

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ABSTRACT

The Heavy Ion Fusion Accelerator Research (HIFAR) program of the USDOE has for several years concentrated on developing linear induction accelerators as Inertial Fusion (IF) drivers. This accelerator technology is suitable for the IF application because it is readily capable of accelerating short, intense pulses of charged particles with good electrical efficiency. The principal technical difficulty is in injecting and transporting the intense pulses while maintaining the necessary beam quality. The approach used has been to design a system of multiple beams so that not all of the charge has to be confined in a single beam line. The beams are finally brought together in a common focus at the target. This paper will briefly present the status and future plans of the program, and will also briefly review systems study results for HIF.

INTRODUCTION

The Heavy Ion Fusion Accelerator Research (HIFAR) program is the only one addressing inertial confinement fusion in the Office of Energy Research (OER) of the DOE. The purpose of the HIFAR program is to evaluate the technology of heavy-ion accelerators for prospects as drivers for commercial power production from IF. Early in the study of HIF, two types of accelerators were identified as suitable driver candidates:

1. A rf linear accelerator that would sequentially fill a series of storage rings which would stack and multiply the current by the number of final stacking storage rings.
2. A single pass linear induction accelerator using accelerating wave forms to compress and confine the bunch during acceleration. To enable this approach to deliver enough energy to the target, multiple parallel beams are accelerated through the induction cores.

After several years, due to limited funding, the U.S. program was concentrated into the single approach of linear induction accelerators. The induction linac studies are concentrated at the Lawrence Berkeley Laboratory (LBL) which is the center for most of the HIFAR program.

The U.S. program in HIF is essentially limited to the accelerator research effort. Complementary programs of target physics and reactor design are funded by the Inertial Confinement Fusion Division of the DOE, and are parts of the Laser Fusion and Light Ion Fusion programs.

CHOOSING THE INDUCTION LINAC

There are several technical areas of concern in the rf linac/storage ring approach to an HIF driver that need to be satisfactorily resolved before there can be a likely prospect of obtaining funding to build a prototype fusion driver. However, the tests needed to resolve these questions require a substantial investment in a linear accelerator and one or more storage rings. Thus a few years ago, the rf program appeared to be stalled on a logical impasse unless some other physics program obtained facilities that could be used to test these areas of concern. One such question is the issue of the limit to the amount of current that can be stacked in a storage ring without inducing instabilities that cause beam loss and beam quality degradation. This question could not be resolved in any U.S. facility then existing or planned. It has only recently been tested in a preliminary experiment at the spallation neutron source (ISIS) at the Rutherford-Appleton Laboratory. However, more definitive tests await the completion of new facilities at Gesellshaft für Schwerionenforschung (GSI) at Darmstadt, W. Germany. In 1984 GSI received approval to start construction of a high-energy heavy-ion synchrotron (SIS) to expand their

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program. Motivated in part by HIF, the GSI group included the Experimental Storage Ring (ESR) in the design of the expanded facility. The synchrotron and storage ring, fed by their high-current linac complex, will make an impressive and versatile facility.

There is also the prospect of significant storage ring tests in the Japan at the Institute for Nuclear Studies of the University of Tokyo. Scientists there are completing the construction of TARN-II, a heavy-ion synchrotron which will also incorporate electron-beam cooling.

It has always been recognized that there are equally critical questions about the feasibility of the single pass induction linac approach. Significant among these is a determination of the maximum current that can be transported in a quadrupole focusing channel. It also was necessary to demonstrate the concept of longitudinal pulse compression. In contrast to the impasse facing the rf approach, the key issues for the induction linac method can mostly be tested with a small scale version of a fusion driver.

Another reason for choosing to emphasize the induction linac approach in the U.S. was that the rf approach is being pursued by the other major programs in the Soviet Union, Japan, and West Germany. The goal of fusion power is important in the energy future of our civilization and inertial fusion has a number of important advantages. If the target physics for IF turns out to be favorable, then the most promising driver technology known today is based on using high energy accelerator technology. Faced with the reality that the U.S. program would not support both approaches, it made sense to emphasize the one that was complementary to all the others. The spirit of international cooperation was displayed again in July of this year at the Heavy Ion Fusion Symposium hosted by GSI in Darmstadt. Virtually all of the material which is not otherwise referenced in this paper will be found in the proceedings of that symposium.[1]

SCENARIO STUDIES AND PARAMETER SPACE

There is a very large parameter space in which to specify the design for a HIF Power Plant. Even among the most basic accelerator parameters; beam current, number of beams, ion mass, ion charge state, beam particle energy, etc., the number of essentially free parameters is very large. Unless arbitrary constraints, or prejudices are applied, it is almost impossible to find a set of design parameters that can in any objective way be defined as "best."

In order to deal with this multidimensional space, the HIFAR program, together with the Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), the Electric Power Research Institute (EPRI), and the McDonnell Douglas Corporation, undertook a Heavy Ion Fusion Systems Assessment (HIFSA) study to find the sensitivity to as many variations of these parameters as could be understood. The study used several different types of reactor chambers, different target designs, each with its characteristic gain curves, and many different sets of accelerator parameters. The results of the HIFSA study appear in a special issue of the journal Fusion Technology.[2] The general scenario for the study can be visualized from Fig. 1.

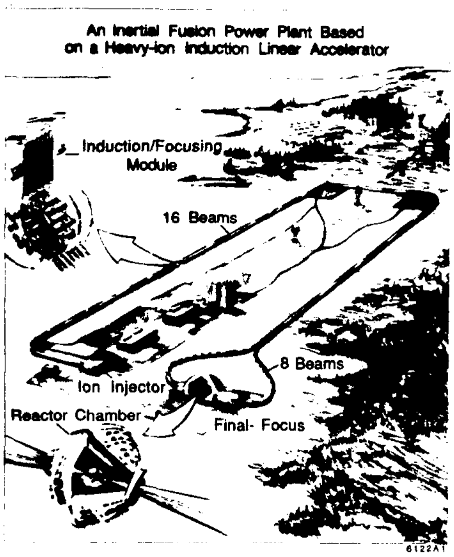

Fig. 1. An artist's drawing of an inertial fusion power plant based on a 16-beam heavy-ion induction linear accelerator. The system shown here uses the Cascade reactor chamber concept developed at the Lawrence Livermore National Laboratory —one of several concepts that have been studied. In this design, the inner wall of the chamber, which must absorb the effects of x-ray and debris bombardment, is a thick layer of ceramic granules, kept in place by rotating the chamber. The granules are cycled through a helium gas heat exchanger. Except for the pellet factory, the remainder of the plant relies on conventional technology.

There were some surprises from the HIFSA study. For example, because most high energy accelerators can be pulsed at very high rates compared with other drivers, it seemed likely that the optimum repetition rate would be limited by the reactor pulse rate. The clearing time for debris and dust or vapor from the absorbing material in the chamber usually sets the maximum pulse rate. However, when the economics of power generation are considered, there is a broad optimum repetition rate for the most favored reactor concepts, of around three to eight pulses per second, which is expected to be within the acceptable operating range. The reason for the upper limit to the acceptable range, based on simple system economics, is that to generate a given amount of power, higher pulse rate implies less yield per pulse. This results in higher numbers of targets, lower target gain and resulting higher operating cost for the power plant. Conversely, too low a repetition rate requires very high target yield, implying a large reactor and very high beam energy delivered to the target, thus raising capital costs.

The resulting broad range in pulse repetition rate is shown in Fig. 2. The bars in the figure show the near-optimum range (within 5% of the minimum) for cost of electricity for several beam parameters. Besides the surprising result for the range of pulse repetition rate, the desired ion mass was lower than expected and the beam emittance was higher than expected. As shown in the figure, emittances all went off the upper limit of the allowed range before finding the optimum value, implying that more work needs to be done in this area. Along with the lower mass result, it was found less costly to build a driver for ions of charge state three. The HIFSA study did not address the technical difficulty of handling the higher current, but it did cause a reevaluation of the bias toward singly charged ions of highest mass. In fact, since the need for neutralization in the final transport to the target is now clear, it may turn out that a single-charge ion in the mid-range of the periodic table, is near optimum. Most transport experiments have been made using cesium and that may be a good final choice.

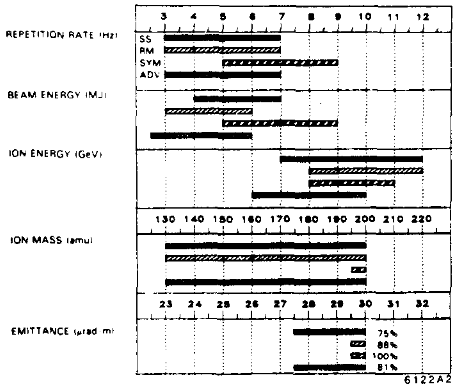

Fig. 2. Summary of a near-optimum parameter ranges for a 1000-MW (electric) wetted-wall cavity. In this figure the target assumption is denoted: SS = single shell, RM = single shell, range multiplied, SYM = symmetric, and ADV = advanced (from Zuckerman et al., Ref. 2).

A configuration of a sample accelerator near the cost optimum found by the HIFSA study is shown in Fig. 3. The conclusions of the HIFSA study are that:

1. there is a surprisingly broad range of parameters for the near-optimum cost of electricity, and
2. some broadening of the parameter range considered for HIF was indicated; for example, to use higher currents, and neutralized beams in the target chamber.

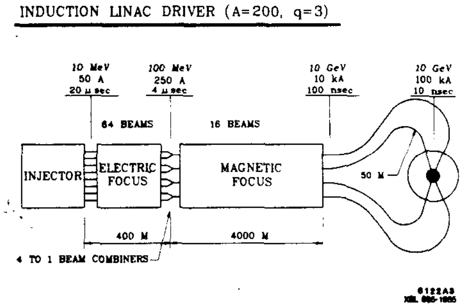

Fig. 3. Schematic of a driver with parameters near the cost optimum.

ACCELERATOR RESEARCH PROGRAM

The HIFAR Accelerator Research Program is concentrated at LBL. Additional smaller elements exist at NRL, Univ. of New Mexico, Univ. of Maryland, SLAC, and LLNL. There are three major experimental facilities at LBL:

1. the Single Beam Transport Experiment (SBTE),
2. the four-beam Multiple Beam Experiment (MBE-4),
3. the 2-MV 16-beam injector.

The experiments on SBTE established the stability boundaries for the safe propagation of high-current beams. It was found possible to transport beams with space charge forces strong enough to reduce the focusing effect of the quadrupole transport system to only $\sim 1\%$ of that for a zero current beam. This is a more favorable conclusion than was expected based on analytic theory and agrees with results based on numerical simulation. These results allowed considerable freedom for the use of high charge state beams for the HIFSA study.

The MBE-4 was designed specifically to test the physics of current amplification in a multi-gap accelerator (24 acceleration gaps). In addition, it is a first step to show the feasibility of accelerating multiple beams through the same induction acceleration structure. MBE-4 uses heavy ions (Cs^+), which results in low velocity beams for which the bunch length is short compared to the length of the apparatus. The longitudinal pulse length compression factor in MBE-4 is about the same as it would be in a full-scale driver (about a factor of four) which implies a much more vigorous and granular voltage ramping schedule than would be normally needed. The contribution to current amplification due to the velocity increase in MBE-4 (a factor of 2.2) is of course much less than in a high-energy fusion driver (~ 50). Thus the on-going experiments with MBE-4 provide a reasonably definitive test of the six-dimensional emittance dilution from longitudinal pulse compression. Figure 4 shows measured waveforms for the pulses at the beginning and end of MBE-4. The measured emittance for the compressed beam shows some increase that has not yet been fully explained. Thus, while the MBE-4 has been completed, there seems to be a substantial amount of experimental information still to be gained.

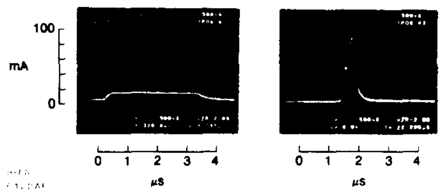

Fig. 4. Measured waveforms for one of the four beams in MBE-4. The injected pulse is shown on the left and the accelerated and compressed pulse is on the right.

In spite of the successes of SBTE and MBE-4, there are a number of physics issues that must be addressed before one could confidently propose to build a facility with the parameters shown in Fig. 3. This example driver exceeds current experience in the following aspects:

1. 3-MV injector versus 200 kV in MBE-4,
2. 16 to 64 beams compared to four beams,
3. beam combining in sets of four-to-one,
4. bending of space charge dominated beams,
5. final drift compression for bunching and removal of velocity tilt,
6. final focus transport, including neutralization, plasma and gas effects, etc.,
7. higher charge-state ion sources.

A test facility called Induction Linac Systems Experiment (ILSE) has been devised to test most of the above issues. It is proposed to use a lighter ion (C^+) to obtain higher velocity to demonstrate magnetic focusing and bending. Actual construction of ILSE is presently delayed because a substantial jump in program funds (about double) would be needed. Meanwhile, a 2-MV, 16-beam injection system, which was started at LANL, has been moved to LBL. A photograph of this system is shown in Fig. 5. If equipped with carbon ion sources, it is capable of becoming the injector for ILSE. The experimental part of the HIFAR program today is concentrating on the development of the 16-beam injector and on the operation of MBE-4.

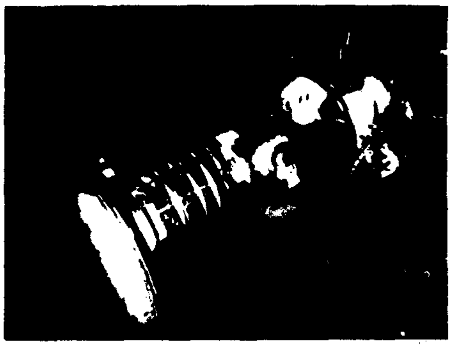

Fig. 5. Components of the 16-beam, 2 MV injector which was started at LANL and has now been transferred to LBL. High voltage is generated at the large terminal in the photograph by a MARX generator which can be seen in the foreground. Ions produced at the terminal voltage will then be accelerated through a column which is to be attached to the far side of the terminal. The entire injector operates within the pressure vessel visible in the background.

SUMMARY

The overall picture to be seen in HIF is a broad-based program of dedicated researchers in several countries. The program is maturing from a theoretical and numerical simulation-based program toward the emphasis on experimental progress. The down side of the U.S. HIFAR program is a feature that will be familiar to other fusion researchers; authorization and funding for the ILSE project has not been approved. While there is certainly much more to be learned from MBE-4, and much work remains on the 16-beam injector, nevertheless timely progress in the HIFAR program requires a project of the size and capabilities of ILSE with which to answer the original question: to evaluate the application of heavy-ion accelerators as drivers for commercial power production.

REFERENCES

1. *Proceedings of the 1988 Heavy Ion Fusion Symposium, Darmstadt*, W. Germany, June 1988, to be published. Work discussed in this report that is not otherwise referenced should be found in these proceedings.
2. *Fusion Technology*, Vol. 13, No. 2, Special Issue on Heavy Ion Fusion, Ed. Donald Dudziak, February 1988.