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PROGRESS IN HEAVY ION FUSION[♮1]

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The Heavy Ion Fusion Accelerator Research (HIFAR) program is the only Inertial Confinement Fusion (ICF) program element 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 ICF.

The progress of the field of Heavy Ion Fusion has been documented in the proceedings of the series of International Symposia that, in recent years, have occurred every second year. The latest of these conferences was hosted by Gesellshaft für Schwerionenforshung (GSI) in Darmstadt, West Germany, June 28–30, 1988 [1]. For this report, I will select a few highlights from the conference, stressing experimental progress and prospects for future advances. I will devote a little extra time to report on the developments at the Lawrence Berkeley Laboratory (LBL) which is the center for most of the HIFAR program. The Director of the HIFAR program at LBL is Denis Keefe, who presented the HIF report at the last two of the meetings in this series, and in whose place I am appearing now.

The most comprehensive programs continue to be located in West Germany, the United States, Japan, and the Soviet Union. The U.S. is conducting accelerator research based on induction linear accelerator (linac) methods, while the other three nations pursue a method based on rf linacs combined with storage rings. In either method, the important long-term goal is achievement of very high-beam currents with low-beam emittance in order to meet the stringent requirements of inertial fusion targets. HIF system studies have been generated by each of these National Programs. Supporting research has been done in relevant

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areas of atomic physics and beam-plasma physics by laboratories in a number of countries including these four.

West Germany

The HIF program at GSI depends heavily on their large ongoing programs in heavy ion nuclear and atomic physics, which include the study of effects related to the "quark-gluon plasma" in fused high-energy-density heavy nuclei. In 1984 GSI received approval to start construction of a high-energy heavy-ion synchrotron (SIS) to expand their 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. The Symposium took place in the middle of the construction period, and afforded an opportunity to see the new buildings, many of the synchrotron magnets in place, and related hardware, as well as the UNILAC and more recent MAXILAC linear accelerators.

The storage ring will allow GSI to begin significant experiments in beam-plasma interaction physics. The single most important measure of success in such experiments is the temperature of the hot, dense plasma created by a short pulse of focused ions. The GSI construction plan calls for an initial "Phase I" in the Fall of 1989 with beam parameters that should yield about 1.5 eV temperature. Later, electron cooling will be added to the ESR and, using ions compressed to 70 ns, the target temperature should jump to about 20 eV. In both cases, the diameter of the focused beam is about 0.1 mm.

These experiments will move heavy-ion fusion into an "experimental" phase, as contrasted with the past decade, which has been primarily devoted to accelerator research and development, system studies, and supporting efforts in atomic physics and target design. The proposed experiments will allow studies not only of beam-plasma interaction, but also high-pressure hydrodynamic behavior and initial experiments in plasma radiation. We look forward to the experimental phase with anticipation.

Japan

The Japanese program in HIF has been centered at the Institute for Nuclear Studies, University of Tokyo. They described the design and construction plan for TARN-II, a heavy-ion synchrotron which will also incorporate electron-beam cooling. Design energy is up to about 400 MeV/nucleon. Bunch compression and fast extraction of the beam are planned, as well as slow extraction. The first beam is scheduled in 1988.

Development of a split-coaxial, radio-frequency quadrupole (RFQ) accelerator at the INS was also described. A working model using protons has been built and tested.

Supporting work for HIF in Japan comes from many centers and shows a remarkably well-integrated program. For example, the design of a high-gain ion beam target was reported from the Tokyo Institute of Technology. Other papers have come from the Laser Fusion Laboratory in Osaka and from various centers that are usually associated more with magnetic fusion.

Soviet Union

In the 1986 HIF Symposium Proceedings, Kapchinskiy *et al.* reported on an ongoing HIF project at the Institute for Theoretical and Experimental Physics in Moscow [2]. A complete rf-based accelerator system study was reported, as well as construction and operation of a large, very low-frequency (6 MHz) RFQ injector together with ion source. The proposed system design envisions 20 beams of 20-GeV Bi^{2+} ions, with a total energy on target of 6 MJ, operating at 10 Hz.

At this Symposium, D. Koshkarev and A. Talysin reported on the continuing ITEP studies. New since 1986 is a proposal under development to convert an older 9-GeV proton synchrotron into a heavy-ion synchrotron with 6-Tesla superconducting magnets. The first major goal of the synchrotron project would be to produce a total energy in the heavy-ion pulse of 1 kJ and compress it to about 10 ns. Koshkarev hopes that they will reach this goal in 1995. He also reported on a bismuth ion source which produces a 25 mA beam. In response to a question, Koshkarev reported that the size of the HIF project is about 90 scientists and engineers, clearly a vigorous activity.

Koshkarev also reported on preliminary studies of a potential problem with storage ring-based systems. A beam particle hitting the chamber wall causes the release of a large number of ions which then intercept the the stored ion beam. The phenomenon may have a critical threshold which depends on more detailed knowledge of the desorption coefficients. The ITEP group plans further work on the question. This phenomenon was studied in the first HIF Workshop in Berkeley in 1979 by Larry Jones [3], and was dubbed the "black cloud." It is one of the concerns that led the U.S. program to emphasize the single pass induction linac method.

United States

Most of the U.S. HIFAR program has now been concentrated at LBL under Denis Keefe. Smaller computation elements exist at NRL, University of New Mexico, SLAC and at LLNL. Notable among these is an expanded effort in theory, some systems work, and lately some engineering prototype studies led by Roger Bangerter at LLNL. At the HIF Symposium, papers by Darwin Ho and James Mark showed simulation studies of beam transport problems supported by Scott Branden. Also notable is a study by Bruce Langdon of effects in the reactor chamber due to the beam striking the target. Some effects, such as the charging up of the target, were shown to be of negligible concern, but the emission of soft X-rays from the hot target can induce higher states of ionization in the incoming beam which must be considered.

In recent years, the HIFAR team at LBL has designed and built a multiple-beam experiment based which has a number of features relevant to a heavy-ion driver. The innovative device, named MBE-4, combines acceleration and pulsewidth compression by ramping the voltage pulses applied to each induction module. The induction cavities and cores are threaded around all four beams, while electrostatic quadrupole focusing is incorporated for each beam. Beam current is increased by both the compression factor and the number of beams, compared to a single-beam linac.

In the last two Fusion Power Associates Symposia, Denis Keefe reported on the progress of MBE-4 [4]. Construction of MBE-4 is now complete and experiments are continuing with cesium ions accelerated from 0.2 MeV to 1 MeV, and with peak current at the output end of 90 mA in each of the four beams. The longitudinal pulse compression process requires that careful attention be paid to the accuracy of the voltage waveforms and also to effects due to the energy tilt from the head of the pulse to the tail. In MBE-4, the energy tilt is a greater percentage of the full energy than would be required in a full-scale driver. The results to date show variations in the six-dimensional emittance as a function of pulse parameters that are the subject of ongoing experiments.

The next stage of development for the induction linac program should be a larger-scaled experiment that would demonstrate:

1. higher beam power,
2. greater particle velocity obtainable by somewhat higher beam energy and by resorting to lighter ions (the plan is to use carbon instead of cesium).
3. the use of magnetic focusing,
4. beam combining to increase the current per beamlet,
5. the use of more beamlets.

The LBL team has proposed to construct a 16-beam accelerator called Induction Linac Systems Experiment (ILSE), which would include the above features.

The injector for ILSE would use the 2 MV pulsed-power system shown in Fig. 1. This project was started at Los Alamos and was transferred to LBL at the end of the last fiscal year in order to concentrate the funding for the HIFAR program. The carbon ion sources for the 16-beam injector are based on the metal vapor vacuum arc (MEVVA) type sources developed by Stan Humphries at the University of New Mexico.

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. Proceedings of the 1986 Heavy Ion Fusion Symposium, Washington, D.C., AIP Conference Proceedings No. 152, American Institutes of Physics, 1986.

3. Proceedings of the Heavy Ion Fusion Workshop, Berkeley, CA, Oct. 1979, LBL-10301, Lawrence Berkeley Laboratory, 1980.

4. D. Keefe, Proceedings of the Fusion Power Associates Symposia, 1976 and 1977.

Figure Caption

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.

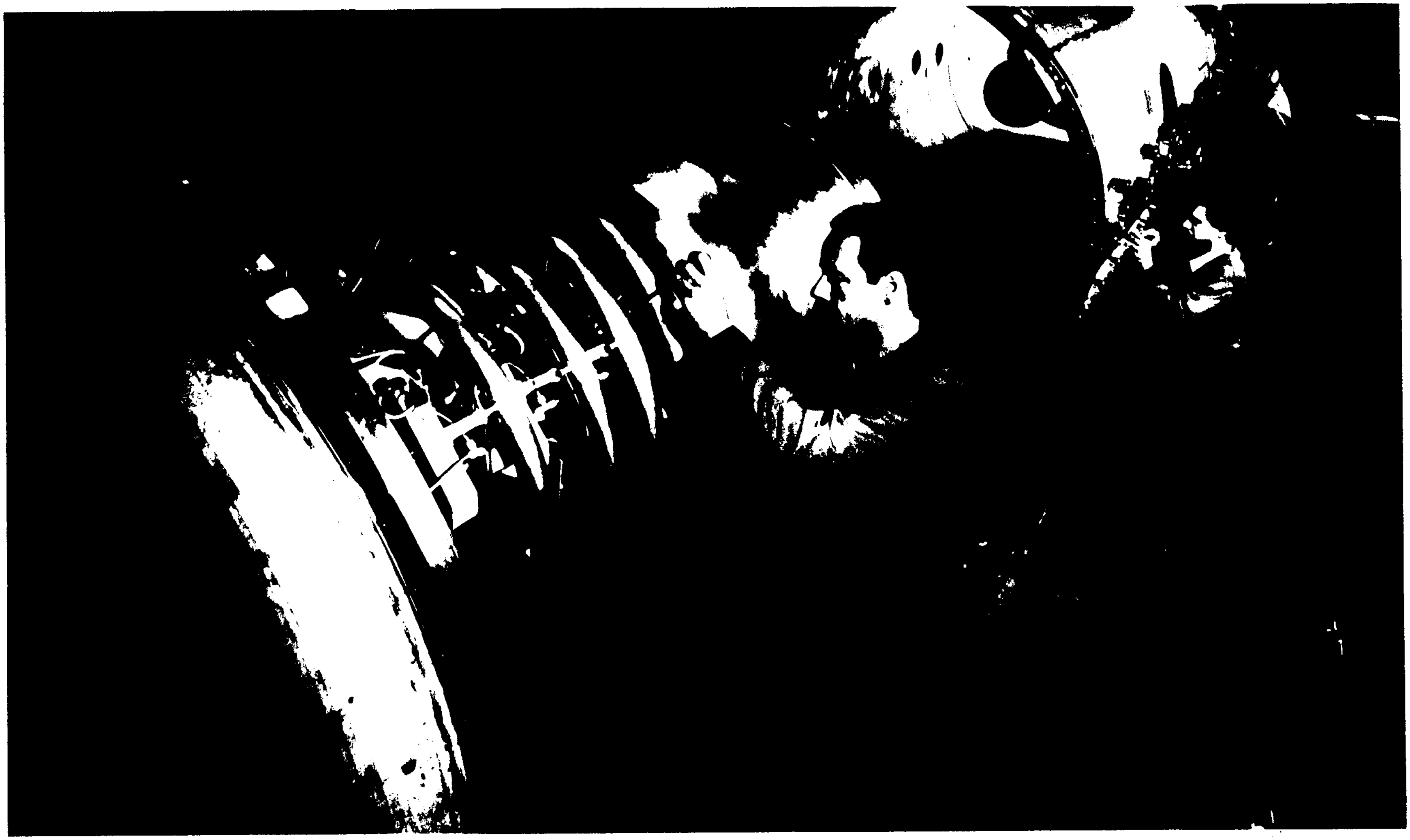

Fig. 1