SUMMARY OF THE 1988 HIF SYMPOSIUM

Terry F. Godlove
FM Technologies, Inc., Alexandria, VA 22304

ABSTRACT

The biennial Symposium on Heavy Ion Inertial Fusion was held at the Gesellschaft f. Schwerionenforschung (GSI), Darmstadt, West Germany, June 28-30, 1988. A major highlight was a shift in direction of the German and French programs toward experiments in beam-target interaction physics. These experiments will be a primary goal for GSI when they complete an expansion of their accelerator facility. Accelerator advances included results from the newly-completed multiple-beam induction linac at Berkeley and a number of advances in heavy-ion RFQ development. New calculations at Livermore were described on final focusing, beam propagation in reactors, and target charging.

I. INTRODUCTION

Energy production from inertial confinement fusion (ICF) using heavy ion accelerators to drive the fusion target represents an application for linacs--the subject of this Conference--of potentially great importance. Studies have shown that both RF linacs and induction linacs are suitable candidates for providing the necessary high-current beams to compress and heat thermonuclear fuel pellets. RF linacs require the addition of storage rings to perform beam current multiplication, while induction linacs require pulse waveform shaping to increase current during acceleration. In either case, the excellent electrical efficiency available from linear accelerators gives the system and target designers considerable flexibility in adjusting other parameters such as number of beams, repetition rate, and expected target gain.

The first decade of heavy ion fusion (HIF) research was characterized by conceptual design studies combined with accelerator research, the goal being to generate credible system designs. In the U.S. the DOE weapons' laboratories provided heavy ion target calculations, and smaller efforts were conducted to assess such things as the difficulties of final focussing and the effects of chamber gas. Reactor designs leaned heavily on studies performed for laser fusion.

By 1987 detailed system designs, including cost studies, had been published for both accelerator methods. Europe and Japan concentrated on RF-based designs, and published HIBALL, modified to become HIBALL-II [1], and HIBLIC [2]. The U.S. effort, led by Lawrence Berkeley Laboratory (LBL), emphasized the induction linac method. A comprehensive system study, the Heavy Ion Fusion System Assessment (HIFSA), was recently published in the U.S. program [3]. All of these studies yielded operating costs in an acceptable range, 5 to 6 cents/kWh, for optimized designs.

Including the first HIF workshop at LBL in 1976, four workshops and four international symposia have been held [4]. In this review I will summarize the reports given at the recent Symposium at the Gesellschaft f. Schwerionenforschung (GSI) in Darmstadt, West Germany, June 28-30, 1988 [5]. No attempt is made to review the history of the subject, nor is it possible to give complete coverage to all of the papers at the Symposium. Rather I will concentrate on current results and new calculations and designs. Articles which appear in the Proceedings are identified by the first author. The first decade of HIF accelerator research, 1976-86, has been reviewed by the present author [6]; and a comprehensive review through 1986, with a complete treatment of atomic physics and beam-plasma physics, has been given by Deutsch [7].

II. NATIONAL HIF PROGRAMS

Accelerator research for HIF is primarily conducted in West Germany, the United States, Japan, and the Soviet Union. The U.S. program is based on the induction linac method, while the other countries pursue the RF-linac/storage ring method. The long-term goal of the accelerator research is achievement of very high beam currents with low beam emittance in order to meet the stringent requirements of inertial fusion targets. In the important area of beam-target interaction physics, West Germany and France have moved to an experimental phase, particularly in the energy deposition of heavy ions in hot, dense matter.

West Germany

For many years GSI has had a large ongoing program in heavy-ion nuclear and atomic physics. In 1986 GSI received approval to start construction of a high-energy heavy-ion synchrotron (SIS) to expand their program. Motivated in part by their HIF program, the GSI group included a storage ring (ESR) in the design of the expanded facility. The synchrotron and storage ring, fed by their high-current linac complex, will provide an extremely versatile facility for all of these programs. The Symposium took place in the middle of their construction period, and provided an opportunity to see the new buildings, many of the synchrotron magnets in place, and the UNILAC and more recent MAXILAC linear accelerators.

The GSI programs were primarily described in papers by R. Bock, D. Bohne, and I. Hofmann. Although GSI is the focus of the facility construction, major contributions are made to the German program by a number of other institutions, including the Max-Planck-Institut f. Quantenoptik in Garching and the Johann-Wolfgang-Goethe University in Frankfurt. Other elements of the German program are included in later sections of this summary.

Although some beam-plasma interaction experiments have already begun, the storage ring will allow GSI to conduct experiments of much greater significance. 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 current GSI plan calls for achieving a beam suitable to achieve 1.5 eV temperature in late 1989. Cooling will then be added to the ESR stored ion beam and, using 10^{11} Xe^{44+} ions pulse-compressed to 70 ns, the target temperature should jump to about 20 eV. To achieve these temperatures, the beam diameter on target is required to be about 0.1 mm.

Japan

The Japanese program in HIF has been centered at the Institute for Nuclear Studies, University of Tokyo. T. Katayama and T. Tanabe described the design and construction plan for TARN-II, a heavy-ion synchrotron which will also incorporate electron-beam cooling. The synchrotron is designed for energies up to about 400 MeV/u. Bunch compression and fast extraction of the beam are planned, as well as slow extraction. Development of a split-coaxial, radio-frequency quadrupole (RFQ) accelerator at the INS was also described. A working model using protons has been tested.

Other Japanese research is being conducted at the Tokyo Institute of Technology. Symposium papers included studies of the IH type of accelerating structure for heavy ion linacs, an analysis of the propagation of rotating ion beams, and analyses of high-gain ion-beam targets. Also a study was presented of the Weibel-type instability as it relates to beam propagation in a reactor chamber.

Soviet Union

In the 1986 HIF Symposium Proceedings, Kapchinskiy et al described an ongoing HIF project at the Institute for Theoretical and Experimental Physics (ITEP) in Moscow [8]. 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 envisions 20 beams of 20-GeV Bi^{2+} ions, with a total energy on target of 6 MJ, operating at 10 Hz.

At the 1988 Symposium, D. Koshkarev and A. Talysin reported on the continuing ITEP research. New since 1986 is a proposal under development to convert an older 9-GeV proton synchrotron into a heavy-ion synchrotron based on 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 also reported on a bismuth ion source which produces a 25 mA beam.

In earlier HIF workshops, some concern was expressed about the potential problem of stray beam causing the release of large numbers of atoms from the chamber walls in the RF-linac/storage ring method. Collisions with normal beam ions would then occur. Koshkarev described preliminary studies of this issue. He concludes that the phenomenon will have a critical threshold which depends on more detailed knowledge of the desorption coefficients. The ITEP group plans further work on the question.

United States

Development of induction linac technology for intense electron beams began in the U.S. in the 1950's with the Astron accelerator at Lawrence Livermore National Laboratory (LLNL). Further development took place at LBL, then again at LLNL for their Advanced Test Accelerator. However, slow-moving ions require new designs, including the innovative use of multiple beams, to achieve high currents. In recent years, the LBL group has designed and built a multiple-beam experiment based on four beams which has a number of features relevant to a heavy ion driver. The device, named MBE-4, combines acceleration and pulse-width compression by ramping the voltage pulses applied to each induction module. The induction cavities and cores are looped around all four beams, while electrostatic quadrupole focusing is incorporated for each beam. Compared to a conventional single-beam linac, the beam current is increased by both the number of beams and the compression factor.

In 1986 the LBL group reported MBE-4 results at roughly the mid-point in construction. At the 1988 Symposium, papers by D. Keefe, T. Fessenden, and H. Meuth indicated construction to be complete and described the results. Cesium ions are accelerated from 0.2 MeV to 1 MeV and, with an output of 90 mA in each of the four beams, a power amplification factor of more than 20 has been achieved. The pulses are shortened from 2.5 µs to <0.3 µs. The results, while successful, indicate that great attention must be paid to the accuracy of the voltage waveforms, to precise alignment, and to effects due to the energy variation from the head of the pulse to the tail. The results are particularly impressive considering that the head-tail energy difference is severe at these low energies compared to a full-scale driver.

A new pulsed, 16-beam injector is also under development at LBL. The specifications call for an injection voltage up to 2 MV and current up to 500 mA/beamlet. The system, moved to LBL in 1987, was initially designed and constructed at the Los Alamos National Laboratory (LANL). H. Rutkowski et al reported on development of a gated vacuum-arc source for carbon ions. They reported that the source can easily supply the 25 mA/cm^2 needed for the injector. The design normalized emittance is 0.5π mm-mrad. An injector of this kind is clearly a long-lead component necessary to the future of the induction linac program.

Other research at LBL includes a major design effort for the proposed next stage experiment, called the Induction Linac System Experiment (ILSE). It is proposed to demonstrate, in a scaled model accelerator, the physics and technology of a large driver. Details were given in a paper by E.P. Lee. He described, for example, the design for bending and merging 16 beams to 4. The beams proceed from 25 focusing electrodes to an array of bending-and-focusing electrodes which combine the beams. They then proceed from these arrays, which are electrostatic, to a magnetic quadrupole focusing lattice. The entire system is achromatic to first order. Lee also described a 180° beam bending system which is also achromatic to first order. In a separate new analysis, by L. Smith and K. Hahn, the important question of transverse misalignments in the focusing elements of a large driver was analyzed.

Elsewhere in the U.S., an expanded theory group under the general direction of R. Bangerter at Lawrence Livermore National Laboratory (LLNL) reported several new calculations. D. Ho showed 2-1/2 D computer simulations of the longitudinal dynamics during the final stages of focusing and pulse compression. The results give an order-of-magnitude increase in peak power on target. New clculations of final transport in a reaction chamber were reported by A.B. Langdon. The long-standing issue of pellet charging by the ion beam was reported to be a negligible problem. On the other hand, photoionization of the beam from target radiation may be an important effect. Langdon also reported that microinstabilities in the beam-plasma interaction near the target do not appear to pose significant problems. J.W-K. Mark described continuing target design calculations for "direct-drive" type targets which offer potentially reduced driver requirements.

At the University of Maryland, M. Reiser's group continues to press forward with experimental studies of high-perveance particle beams using low-velocity electrons to simulate heavy ions. Recent studies involve the merging of five beams obtained by placing a mask in the main beam. The goal is to measure emittance growth and the characteristic merging length.

The U. Md. measurements are compared with computer simulations performed by H. Rudd and I. Haber at the Naval Research Laboratory (NRL), and with field energy theory. So far, the results appear to be in general agreement with theory. The beams merge very rapidly and emittance growth is about a factor of three. An interesting result of the experiments is that distinct images of the mask are seen at one-half betatron wavelength downstream, in spite of the rapid conversion of field energy into transverse emittance. Another issue is the effect of lens nonlinearity. Haber reported that the simulations indicate that substantial nonlinearity, perhaps 30% at the beam edge, may be tolerable.

III. ATOMIC PHYSICS AND BEAM-TARGET INTERACTIONS

Research in atomic physics and beam-target interactions related to HIF has increased considerably during the last few years, particularly in France and West Germany. The review by Deutsch [7] details this activity.

The Symposium included a dozen papers on the interesting subject of enhanced stopping power, referring to the increase in dE/dx in the hot, dense plasma of target material compared to measurements commonly made in cold matter. Enhanced deposition is now well established. Contributions to the stopping power by free electrons and by highly excited bound electrons are both important. In addition, the charge state of the incoming ion rapidly increases to higher values. For calculations one needs to know the effective charge. Some experiments have been done with low-intensity ion beams incident on hot, dense plasma generated by high-power lasers or by pulsed discharges. At the same time, plans are being developed to use the GSI beams when they become available. Comments on the 1988 Symposium papers follow.

J. Meyer-ter-Vehn summarized proposed experiments for the GSI facility, which will include beam-plasma interactions, the hydrodynamic behavior, and plasma radiation. With energies up to 100 MeV/u and focusing ability to 0.1 mm, a thin cylindrical plasma volume some mm long will be generated with temperatures up to tens of eV and pressures up to 10 Mbar or more.

D.H.H. Hoffmann reviewed both current beam-plasma experiments as well as future plans. Current experiments use an RFQ which produces 45 keV/u Ar and Kr beams, and the UNILAC, which provides 20 MeV/u. A linear discharge or Z-pinch is used to provide a pulsed plasma which lasts up to 100 μs. Energy loss is then measured as a function of time during the plasma pulse. Hoffmann found a factor of 2 to 2.5 enhancement over cold matter loss. He also described other experiments in which the MAXILAC beam is deflected onto a gas or solid target with the aid of a fast "kicker" and precision focusing elements. The normal 1 cm^2 beam is reduced to 1 mm^2 and the beam power is about 15 kW. The temperature on a tungsten target rose to 1 eV.

Several papers were given on the theory of ion stopping power and comparison with experiments. T.D. Beynon described a new general theoretical formalism which includes shell and higher-order corrections. Three papers by combinations of Th. Peter, R.C. Arnold, S. Avilov, and J. Meyer-ter-Vehn discussed non-linear effects, non-equilibrium charge states, and comparison of theory with experiments on ion stopping in a hydrogen plasma.

A combined French-German group, K. Weyrich et al, described a series of experiments on enhanced deposition of 1.4 MeV/u heavy ions in a highly ionized hydrogen plasma. R. Noll et al described similar experiments based on the use of a modified Z-pinch plasma. Another French-German group, D. Gardes et al, used the Orsay IPN Van de Graaff accelerator to obtain 2 MeV/u C and S ions incident on a hydrogen plasma.

In the area of target physics, papers by N. Tahir and K. Long, by R. Arnold and Tahir, by H. Kull and Arnold, and by V. Schneider discussed various aspects of hydrodynamic behavior and conversion of kinetic energy to radiation. Also, K. Niu and a group in Madrid (G. Velarde et al) reported on continuing studies of HIF targets. J.G. Linhart examined a different method of driving a pellet implosion, namely the use of a quasi-spherical imploding plasma liner, while H. Hora reported on another method based on volume compression.

E. Salzborn, University of Giessen, reviewed the status of ion-ion cross section measurements, important for calculating the expected losses in heavy ion storage rings. The paper, by F. Melchert and Salzborn, gives details of the crossed-beams technique as well as a summary of known cross-sections. It is clear that the Giessen group has invested a major effort to set up the apparatus which is now producing the needed measurements.

The loss calculations require measuring both the electron capture cross section and the ionization cross section, for like ions. At the time of the Symposium only a few such cases were measured. The data indicate that for the HIBALL-II driver scenario about 5% of the beam will be lost in the rings, corresponding to a calculated loss lifetime of about 84 ms. This level of loss is not too serious, but warrants reexamination.

IV. OTHER ACCELERATOR RESEARCH

A very interesting paper by R.L. Martin et al gives the results of an experiment on the longitudinal microwave instability of a coasting beam in a storage ring. The experiments were done on the ISIS synchrotron at the Rutherford Appleton Laboratory. The accelerator is capable of high current injection, up to 23×10^{12} protons/pulse. By allowing the injected beam to coast at the injection energy, 70 MeV, the expected threshold for the instability could easily be exceeded. With the aid of a special pickup electrode developed by Martin, they indeed found an rf signal grow, but then the signal saturated and decayed in about 0.5 msec.

It is possible that the stabilization mechanism predicted by Hofmann et al [9] is responsible for the ISIS results. However, quantitative comparison with theory may be difficult without more experiments and perhaps additional diagnostics. In any case, the results are encouraging for achieving high currents in HIBALL-like accumulator rings.

Some half-dozen papers were given on RFQ development, most from the well known group at the University of Frankfurt. R. Muller reviewed various causes of emittance growth and some possible solutions. H. Klein reviewed design criteria for high-current heavy-ion RFQs. A. Schempp described a design and modeling effort for a spiral-type RFQ operating at 27 MHz which the Frankfurt group believes will accelerate up to 25 mA of U^{2+} ions. Other Frankfurt papers involved experiments on high-voltage sparking limits, improved analytic formulae, and experiments with a 50 MHz four-rod split-coaxial RFQ.

A major experiment is underway at GSI on the important question of cooling of heavy ions with high-density electrons. The experiment, described by Becker et al, is a joint effort between GSI and the Universities of Frankfurt and Giessen. They plan to use a 4 to 20 MeV beam from the UNILAC. A study of funneling (using alternate RF buckets to combine beams in RF linacs) was reported by J. Stovall of LANL. Funneling has been proposed in all RF-linac/storage-ring scenarios to increase the linac beam current.

V. HIF PROGRAM DISCUSSION

Several invited papers were given on program management and related topics. W. Polansky discussed the status of the U.S. program, funded at about $6 million. S. Kahalas described the inertial fusion program conducted by DOE's Defense Programs, funded at about $155 million; one of these is the light ion fusion effort at Sandia National Laboratories, which was detailed by T. Lockner. W. Herrmannsfeldt discussed the serious social and political problems facing fusion, and G. Miley argued the case for advanced thermonuclear fuels. J.D. Lawson commented on a number of problems which must be addressed in future HIF programs.

In the final session Nobel Laureate Carlo Rubbia put forward several ideas to challenge the HIF community to think in new directions. To convert Bi^{+} to Bi^{++} Rubbia suggested using an intense 13-eV photon beam generated by a free-electron laser (FEL). He also suggested using direct bombardment of fusion targets by soft x-rays. To generate the x-rays Rubbia suggested the Stanford Linear Collider, either using the "beamsstrahlung" from colliding beams, or using an FEL based on the electron beam from the SLC.

On an international scale, the heavy ion method continues to exhibit steady progress in spite of the low level of funding relative to other fusion programs. Inertial fusion received high marks in 1986 from a major study conducted by the National Academy of Sciences [10]. HIF was not included in the study because the NAS charter was confined to DOE's Defense Programs. Recently, however, the U.S. Congress has requested that the DOE conduct a new study which includes civilian energy aspects of inertial fusion. Clearly heavy ion fusion should have a significant role in such a study. While no one disputes the many problems still to be faced, it is also true that heavy ion inertial fusion deserves a meaningful place among fusion energy alternatives.

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