CONF-8010366--1

THE HEAVY ION FUSION PROGRAM AT ARGONNE

MASTER

by

R.L. Martin, R. Arnold, R. Burke and J. Watson

Prepared for

VII All-Union National Conference

on

PARTICLE ACCELERATORS

Dubna, USSR

October 14-16, 1980

ef

UofC-AUA-USDOE

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

Operated under Contract W-31-109-Eng-38 for the

U. S. DEPARTMENT OF ENERGY

THE HEAVY ION FUSION PROGRAM AT ARGONNE*

R. L. Martin, R. Arnold, R. Burke, J. Watson

Argonne National Laboratory, USA

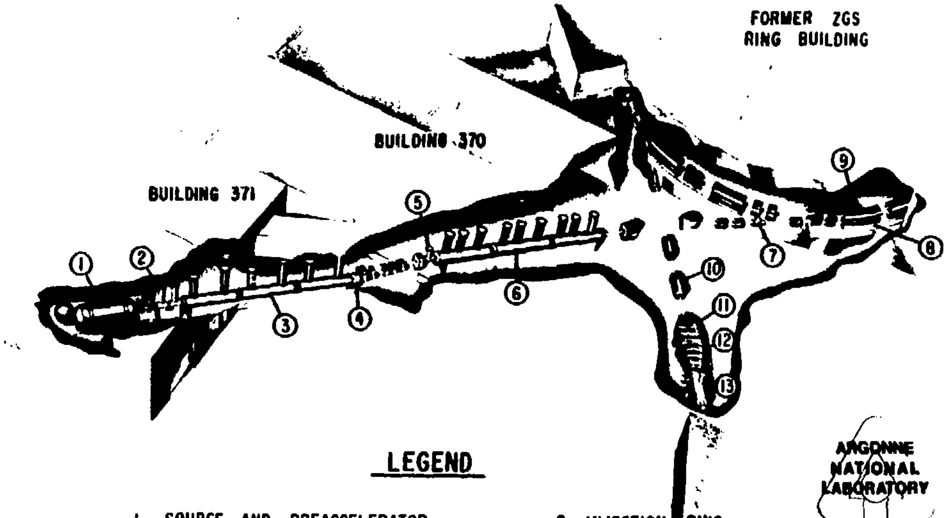
Abstract

Argonne's Heavy Ion Fusion (HIF) program is trying for two major achievements during the coming 4-5 years. The primary objective is to demonstrate accelerator operation in areas that are especially important for the use of heavy ion accelerator systems as drivers in inertial fusion power plants. These demonstrations comprise reliable operation of a front end (source, preaccelerator, and rf linac to ∿10 MeV) with adequate output beam current and emittance; tolerable emittance growth during further acceleration in an rf linac (including frequency transition, with simulated linac-beam combination, and intense beam stripping); strong debunching; multiturn injection with minimal beam loss and tolerable phase space dilution; beam compression; and efficient focusing. The second objective is to demonstrate efficient stopping of intense ion beams in material at conditions relevant to fusion pellet implosion. For this purpose, the apparatus of the primary (accelerator) demonstration would be modified to include a synchrotron accelerating the 220 MeV Xe^{+8} from the linac to 10 GeV. Three kilojoules could be produced by accelerating a beam with a relatively large emittance, which could be made focusable on a 0.5 mm spot by two-fold splitting in each transverse phase plane. In addition to targetted beam intensity, the system would also involve peak circulating currents like those required in the rings of actual HIF drivers. An important feature being studied for the synchrotron is the use of multiharmonic rf to reduce the longitudinal emittance and synchrotron oscillation frequency. In support of these objectives, Argonne's experimental program has developed a high intensity xenon source, a 1.5 MV preaccelerator and independently-phased linac cavities to produce a 25 mA, 2.0 MeV Xe^{+} beam with a normalized emittance of ∿0.02 cm mrad.

---

*Work Supported by the U.S. Department of Energy

HEAVY ION FUSION
BEAM DEVELOPMENT FACILITY
RF ACCELERATION SYSTEMS



LEGEND

1 SOURCE AND PREACCELERATOR
2 Lo β LINAC
3 12.5 MHz WIDEROE
4 STRIPPER
5 RF BEAM COMBINER
6 25 MHz WIDEROE
7 DEBUNCHER
8. INJECTION RING
9. STORAGE RING
10. TRANSPORT
11. SPLITTING
12. FOCUS
13 ENERGY DEPOSITION

ARGONNE NATIONAL LABORATORY

Figure 1

Accelerator Issues

The primary goal of Argonne's program on heavy ion fusion is to demonstrate adequate solutions to as many as possible of the issues involved with the rf linac/storage ring approach to heavy ion fusion. The facility proposed to accomplish this objective is shown in Fig. 1. It would make extensive use of existing facilities and equipment made available by the decommissioning of the ZGS in October 1979. It would consist of a xenon source operating at 60 mA, 1.5 MeV Dynamitron preaccelerator, independently phased cavities for initial rf acceleration to 3.1 MeV, and three sections of a Wideroe linac at 12.5 MHz for acceleration to 20 MeV. The beam would be stripped at 20 MeV to charge +8 followed by 25 MV of Wideroe linac at 25 MHz. The transition will include a vertical "dog-leg" to simulate the linear combination with a second 12.5 MHz linac beam into the 25 MHz linac. The final linac beam energy would be 220 MeV. It would be debunched and multiturn injected into a stacking ring to its space charge limit. Several stacks from this ring would be transferred with rotation from horizontal to vertical phase space, to a large aperture accumulator ring.

A first and second harmonic buncher should allow capture in the linac of 40 mA of the 60 mA Xe^{+1} beam from the preaccelerator with a normalized emittance of 0.1×10^{-6} cm-mrad. Numerical simulation indicates that a 25 mA, 1.0×10^{-6} cm-mrad beam will exit the first Wideroe tank at 8.8 MeV. It is expected that emittance growth in the linac will be small after this point. Considerably larger emittance growth could be tolerated and still satisfy the needs of the beam demonstration described here because injection is at relatively low energy with high beam current. For a power plant driver, however, the normalized transverse emittance from the linac should be $\leq 1.5 \times 10^{-6}$ cm-mrad. The study of emittance growth in the early sections of the linac is therefore an important part of the beam demonstration program.

Potential for emittance growth, both transverse and longitudinal, also exists in stripping to different charge states, in linear combination of linac beams, and in frequency transitions in the linac. In the Beam Development Facility (BDF), these operations will occur at 20 MeV. The beam will be stripped to charge 8 in a gas stripper (to insure reliability with the high average beam current anticipated). The stripping efficiency is expected[1] to be 20% yielding an electrical current of Xe^{+8} ions of 40 mA. This beam will then be matched into a 25 MHz Wideroe linac.

The peak beam current through the linac is the full current required of a power plant driver (although alternate buckets in the 25 MHz linac are not filled). The demonstration of the reliability with full scale currents of this initial acceleration is thus an important part of the program to prove the feasibility of the rf linac approach to heavy ion fusion.

The linac current of 40 mA at charge +8, however, is close to the space charge limit at 220 MeV for circulating current in a stacking ring with the aperture of the former Princeton-Penn 3 GeV synchrotron magnet (transferred to Argonne for this purpose). Therefore, in order to study multiturn injection, it will be necessary to collimate the linac beam to the desired current and emittance.

An interesting experiment will be the injection of a single turn of a current considerably in excess of the space charge limited current of a ring and studying the emittance growth.

After the linac, the accelerator demonstrations would be carried out at relatively low intensity compared to the characteristics of a full scale power plant driver. However, the ion energy is sufficiently low that space charge forces still play a dominant role and a great deal can be learned from beam manipulations under these conditions. Central issues in the circular machines are injection and beam loss due to charge changing collisions of beam ions among themselves and with residual gas atoms. Additional issues are the technology of 10^{-11} Torr vacuum systems in the presence of bombardment of the walls with beam ions, fast and efficient extraction of beams with large cross sections, and transfer between storage rings. The latter is likely the most practical approach to transverse stacking of 100 turns or more.

Beam loss due to collisions among beam ions may be hard to observe at low absolute intensity, and it might also be difficult to study the relevant effects of beam loss, such as vacuum chamber damage and background pressure increase. Intentional deposition of a substantial portion of the beam on the vacuum chamber walls, however, could result in useful information on this issue.

The growth time of the longitudinal microwave instability, indentified at the 1979 HIF Workshop[2] as a potential problem for a full scale power plant driver, will be much too long at the injection energy for its effects to be observed in the BDF. A possibility of studying this particular phenomena might exist with coasting proton beams of 50 MeV in Argonne's Rapid Cycling Synchrotron (formerly called Booster II and presently in use as a pulsed neutron source). In particular, the difference in the phenomena between an unmodulated and a bunched beam might be of some interest.

Additional important demonstrations of heavy ion applicability to inertial fusion could be provided by acceleration in the accumulator ring from 220 MeV to 10 GeV. After acceleration by a factor of 7 in momentum, the circulating current would be slightly in excess of 2A with the same bunching factor. The space charge limited instantaneous beam current at 10 GeV, however, is >20A. The beam at full energy can be bunched to short time durations without exceeding the space charge limits and the effects of high instantaneous circulating currents (generating image currents and driving residual ions into the wall at high velocity) such as might exist in the storage rings of a full scale driver, can be studied.

The use of synchrotron acceleration to achieve relatively high ion energies appears to be the most economic method of reaching adequate total beam energies to make initial physics experiments possible. Preliminary estimates of beam loss due to charge exchange scattering indicate less than 10% loss will occur in an acceleration time of 0.1 second. The required $\dot{B}$ in the ring is much less than for the rapid cycling synchrotrons (60 Hz) initially investigated for the HIF application.[3] Nevertheless, the rapid acceleration will require multiple harmonic rf systems[4] in order to preserve the initial bunching factor of $\sim \frac{1}{2}$ (to maximize the injection space charge limited current) and still maintain low enough momentum spread to allow final compression to the 10 nsec beam duration desired.

Splitting of the beam extracted from the synchrotron into 4 beams for final focusing is to be accomplished by sets of septum magnets in both the horizontal and vertical planes. The final focusing is to be done by a nested set of triplet magnets. Fields up to 6 T are required to achieve final magnet to focal spot distances of 0.75 m and spot sizes of 0.5 mm radius. Computer calculations including space charge have been made of such focusing systems but no detailed design is yet produced.

The xenon charge state of 8 chosen for the BDF is higher than would be tolerated in a full scale power plant driver if one were to depend on final focusing onto the target with vacuum in the reaction chamber. Space charge forces would be too strong to allow focusing onto small targets ($r \sim 2$ mm) over distances of 5-10 m without using an excessive (> 20-30) number of independent beams. The maximum charge for these conditions may be 4, or possibly even less. For the purposes of the BDF, however, the constraints include fitting into the available space of existing facilities. Thus, the linac voltage (assuming a given field gradient, MV/m, is achieveable independent of the ion charge state and its length is fixed) and the radius of the synchrotron are given. Under these conditions and assuming a maximum field of 14 kG for the synchrotron magnets, higher charge states lead to higher total energies. They also lead to higher ion energies since $B\rho$ is fixed. Since 10 GeV xenon ions appear reasonable for the present purposes, the charge state of 8 is about optimum. Results using this charge state should be quite applicable to any lower charge state in a final system.

We emphasize that the objectives of the BDF are to demonstrate the preservation of beam quality through all of the beam manipulations needed to accumulate, condition, and deliver heavy ion beams to ignite fusion targets, and to provide beams for near term physics experiments. New structure developments under way at other laboratories utilizing electric focusing and lower voltage sources (i.e., the MEQALAC at Brookhaven National Laboratory[5] and the R. F. Quadrupole at Los Alamos Scientific Laboratory[6]) could prove advantageous as the front end of an rf linac heavy ion fusion system. If this proves to be the case, the new structures could provide the beginning of a larger facility for further stages of the heavy ion fusion program.

Experimental Program

The ANL experimental program for the past two years has concentrated on developing the heavy-ion preaccelerator and low-beta linac. The preaccelerator and the initial linac cavities are operational. The preaccelerator has achieved pulsed 50 mA Xe^{+1} beams at 1.3 MeV.

A 100 mA low-emittance xenon (or mercury) source, a Penning discharge Pierce extraction source with a single 3 cm diameter aperture, was developed for this program by Hughes Research Laboratories.[7] Xenon currents of 100 mA have been extracted with no indication of plasma sheath instability. The high voltage power supply is a Radiation Dynamics, Inc. Dynamitron[8] which has been extensively modified for maximum pulsed current operation at 1.5 MV. The present oscillator will support more than 40 mA of beam-associated current with less than 0.25% voltage droop in 100 μs. A more complete description of the various elements of the preaccelerator has been published.[9]

A high gradient accelerating column is used to accelerate this low-emittance space charge dominated xenon beam. Both the source and ground electrode are re-entrant into the column. The acceleration occurs across 34 cm with a peak axial electrical field of 60 kV/cm. The outer shell is 117 cm long and consists of 30 ceramic rings and titanium discs which are epoxy bonded. All of the internal electrodes and rings are also titanium. The high conductance manifold and column are vacuum pumped by five 1000 ℓ/s helium refrigerator cryopumps. The internal structure of the outer shell would not support voltages above 1.4 MV and experienced some damage to the internal rings and the ceramics. As a precaution, the preaccelerator voltage is being limited to 1.1 MV until a new modified shell is completed.

The 12.5 MHz low-beta linac begins 4.5 m downstream from the preaccelerator and is preceded by a buncher. The independently-phased cavities (IPC's) have a small number of gaps (2-8) to provide broad flexibility in injection energy and acceleration gradient. The first Wideroe tank will have 28 gaps excited by two stubs. It will accelerate the Xe^{+1} beam from 3.1 to 8.8 MeV. Of the 40 mA from the preaccelerator, 25 mA should be captured and accelerated with acceptable emittance growth.

The first four IPC's are copper structures, the last one and the Wideroe tank are to be copper electroplated on steel. The long drift tubes all contain quadrupole magnets. The first three IPC's are arranged in a $\pi/5\pi$ configuration; the last two and the first Wideroe tank will be $\pi/3\pi$. The linac through IPC #3 is operational, and beam measurements are being made. The first Wideroe tank is under construction, although funding uncertainties preclude a firm schedule for its completion.

At appropriate positions along the beam line, diagnostics are installed to determine accelerator performance and tune the beam transport. In addition to biased Faraday cups and toroidal current transformers, a nondestructive beam position and profile diagnostic system (PAPS) has been developed.[10] Two PAPS were used to determine the emittance of the preaccelerator beam at 1.0 MeV by measuring the waist at the buncher and the size after drifting 2.5 m. This gave a normalized transverse emittance, $\varepsilon_{nX} = \varepsilon_{nY} = 0.019$ cm-mrad. The emittance is expected to drop to 0.01 cm-mrad at 1.5 MeV, but is already much brighter than other high current sources.

References

1. H. Betz, Reviews of Modern Physics, Vol. 44, No. 3, P. 74 (July 1972).
2. Heavy-Ion Fusion Workshop; Berkeley, 1979, (to be published).
3. Heavy-Ion Fusion Workshop; Argonne, 1978 (ANL-79-41).
4. Rutherford Laboratory Report, RL-74-028, February 1974.
5. A. W. Maschke, MEQALAC: A New Approach to Low Beta Acceleration, BNL 51029, June 1979.
6. R. H. Stokes, K. R. Crandall, J. E. Stovall, and D. A. Swenson, IEEE Trans. Nucl. Sci., Vol. NS-26, No. 3, p. 3469, (1979).
7. Vahrenkamp, R. P., Seliger, R. L., IEEE Trans. Nucl. Sci., Vol. NS-26, No. 3, p. 3101, (1979).

8. Cleland, M. R., Farrell, P., IEEE Trans. Nucl. Sci., Vol. NS-12, No. 3, p. 277, (1965).

9. Watson, J. M., et. al., IEEE Trans. Nucl. Sci., Vol. NS-26, No. 3, p. 3098, (1970).

10. Bogaty, J. M., Ibid, 3349.