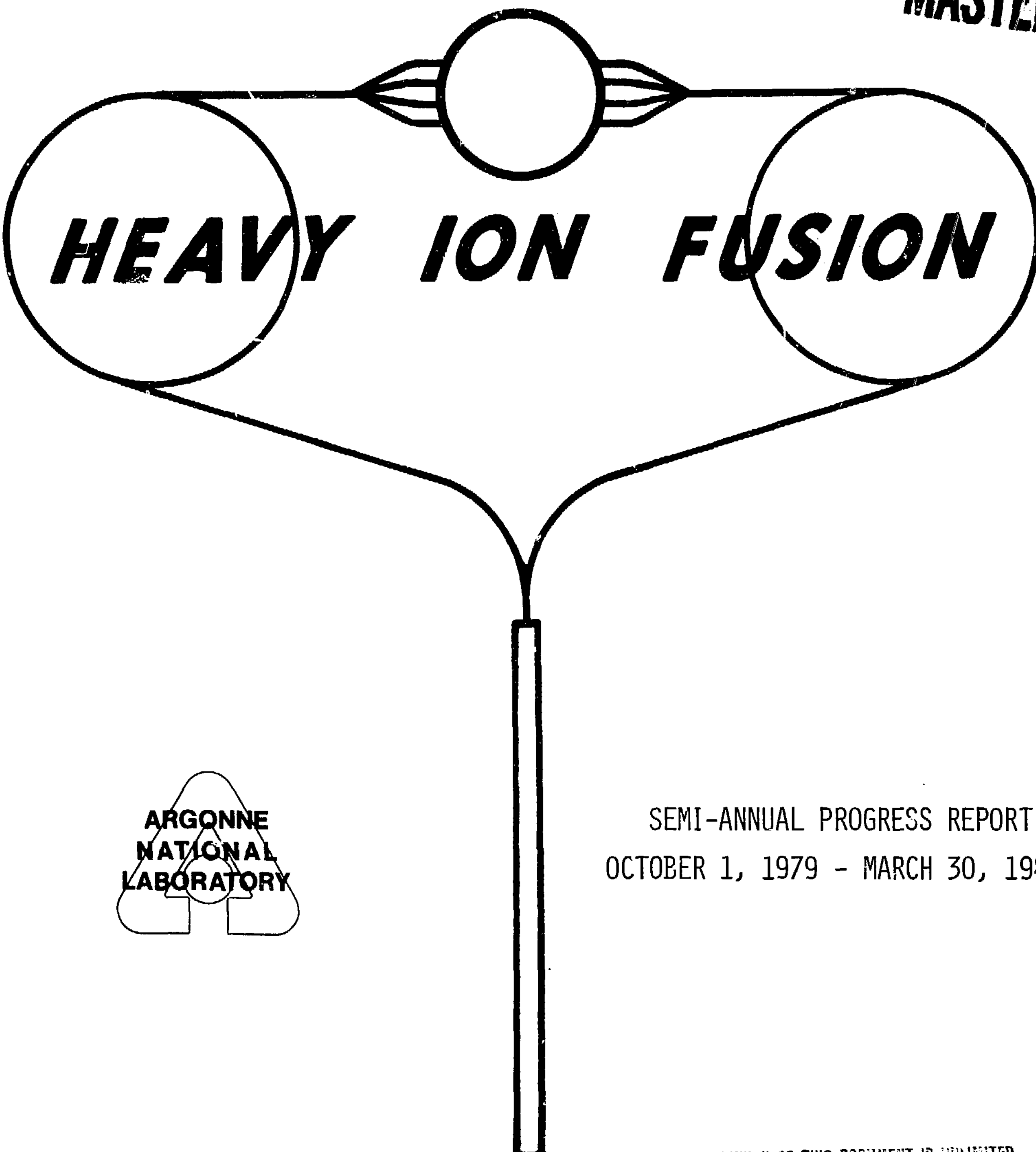
4

ANL-HIF-80-2

HEARTHFIRE

MASTER



ARGONNE
NATIONAL
LABORATORY

SEMI-ANNUAL PROGRESS REPORT
OCTOBER 1, 1979 - MARCH 30, 1980

SEMI-ANNUAL PROGRESS REPORT

OCTOBER 1, 1979 - MARCH 30, 1980

HEAVY ION FUSION PROGRAM

ARGONNE NATIONAL LABORATORY

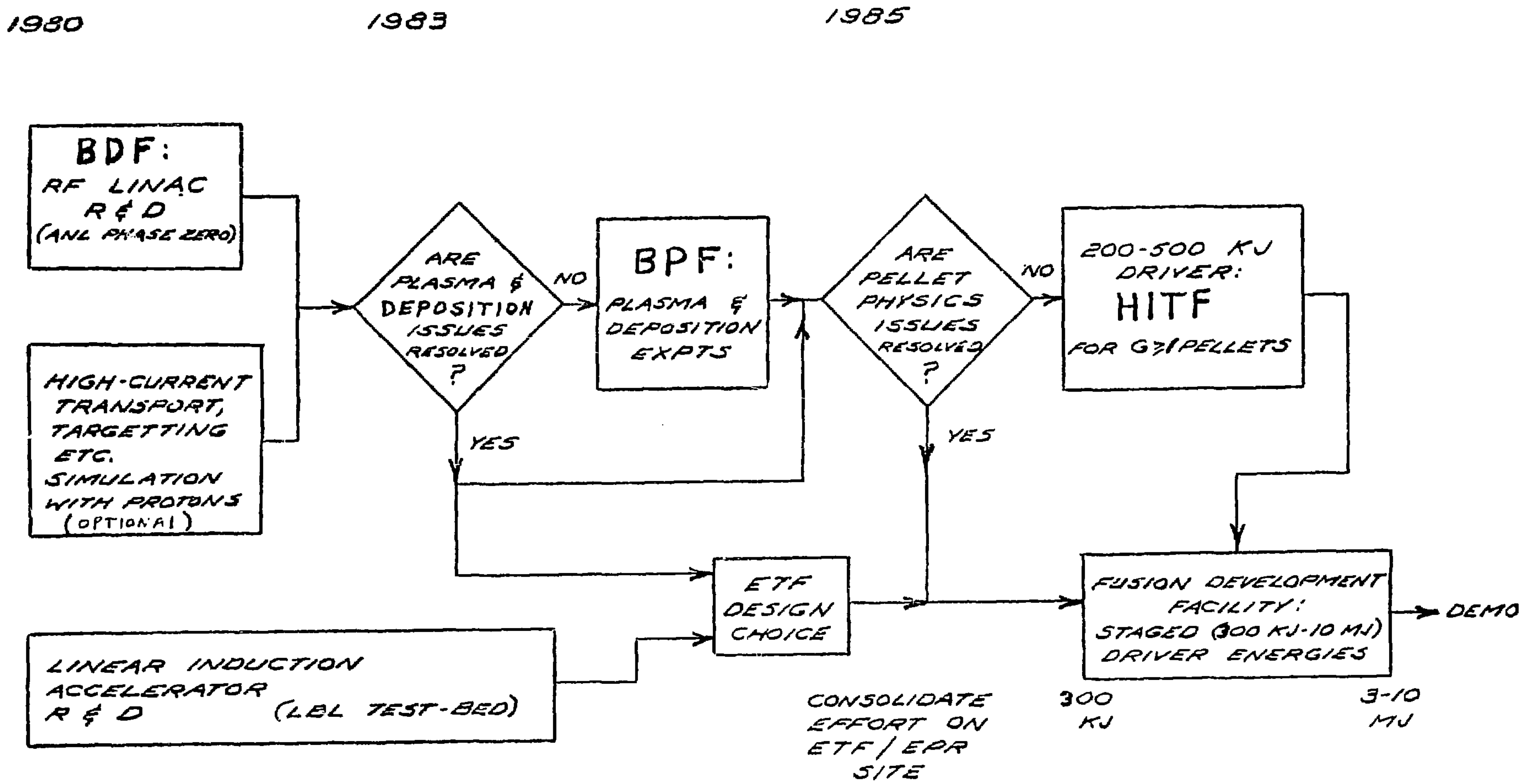
ACCELERATOR RESEARCH FACILITIES DIVISION

TABLE OF CONTENTS

		Page
I.	Introduction	1
II.	Conceptual Design and Program Planning	5
III.	Experimental Program	13
IV.	Excerpts from Workshop on Atomic & Plasma Physics	18
V.	Abstracts of Publications	22
VI.	List of Internal IBF Reports, 10/1/79 - 3/30/80	28

I. Introduction

In the autumn of 1979, it became apparent that construction of the HIF test-beds recommended by the Foster review of ICF would not begin in FY 1980, because of limitations set by Congress on restructuring the ICF program. As a consequence, HIF activity at ANL during FY 1980 has been primarily concentrated on conceptual design work, and on initial tests of the independently-phased rf acceleration cavities. Calculations for near-term foil-heating experiments were carried out, and a specific cost-effective synchrotron (Beam Development Facility) plan was developed. Program logics (Figure I.1 and I.2) were further refined, and some conceptual reactor issues (Figure I.3) were addressed.



NATIONAL HIF PROGRAM DEVELOPMENT LOGIC

FIGURE I.1

HEAVY-ION FUSION DEVELOPMENT SCHEDULES

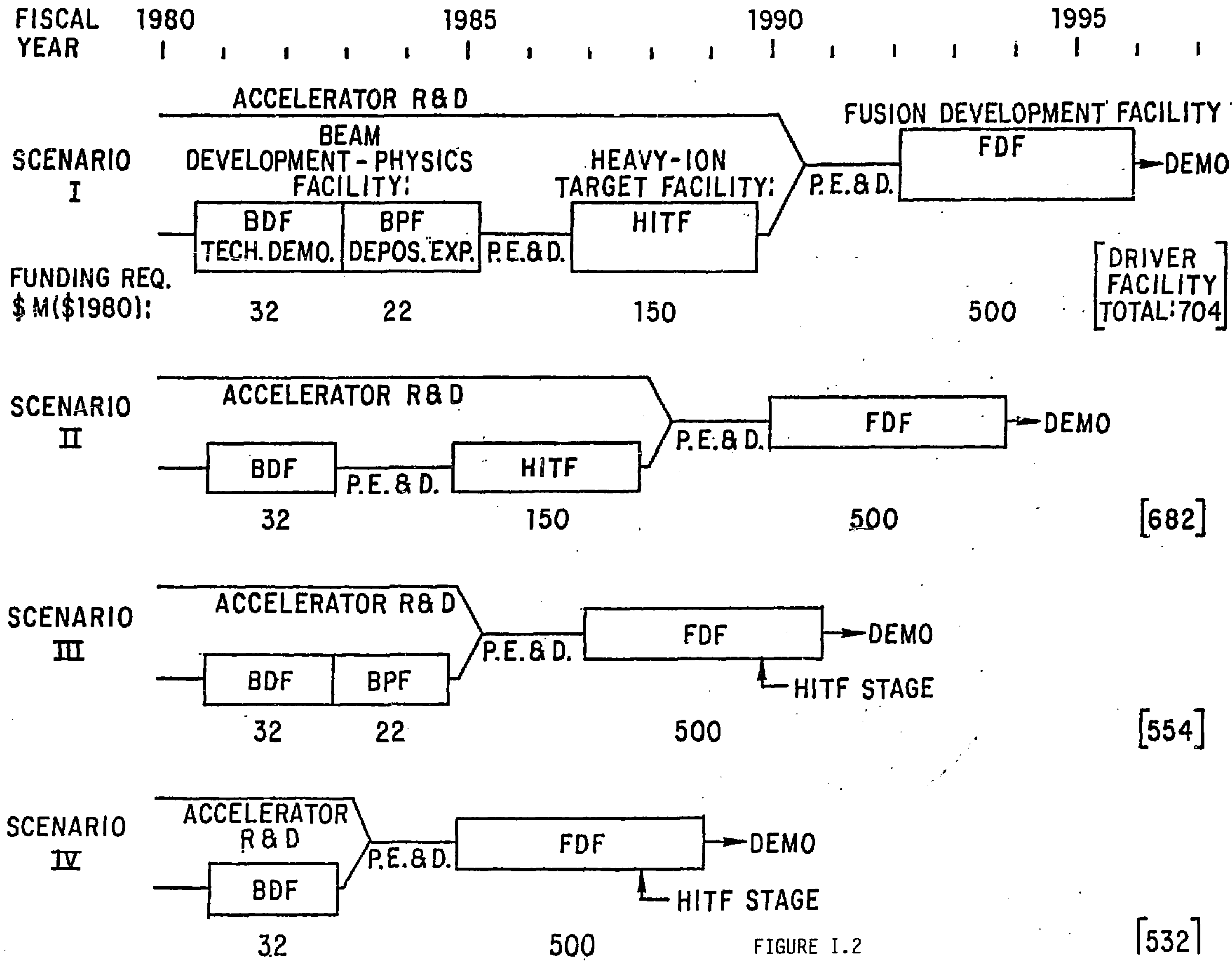


FIGURE I.2

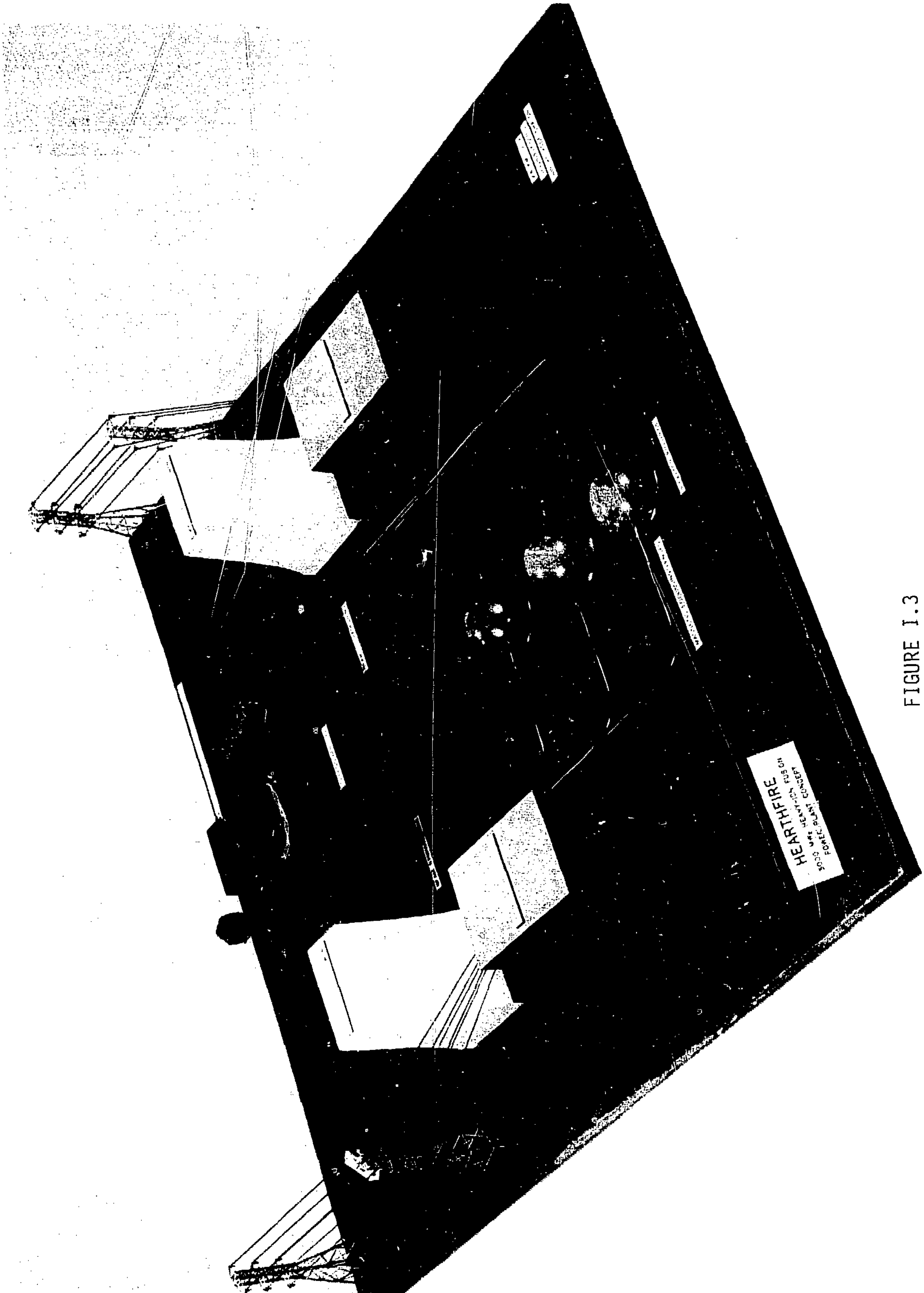


FIGURE I.3

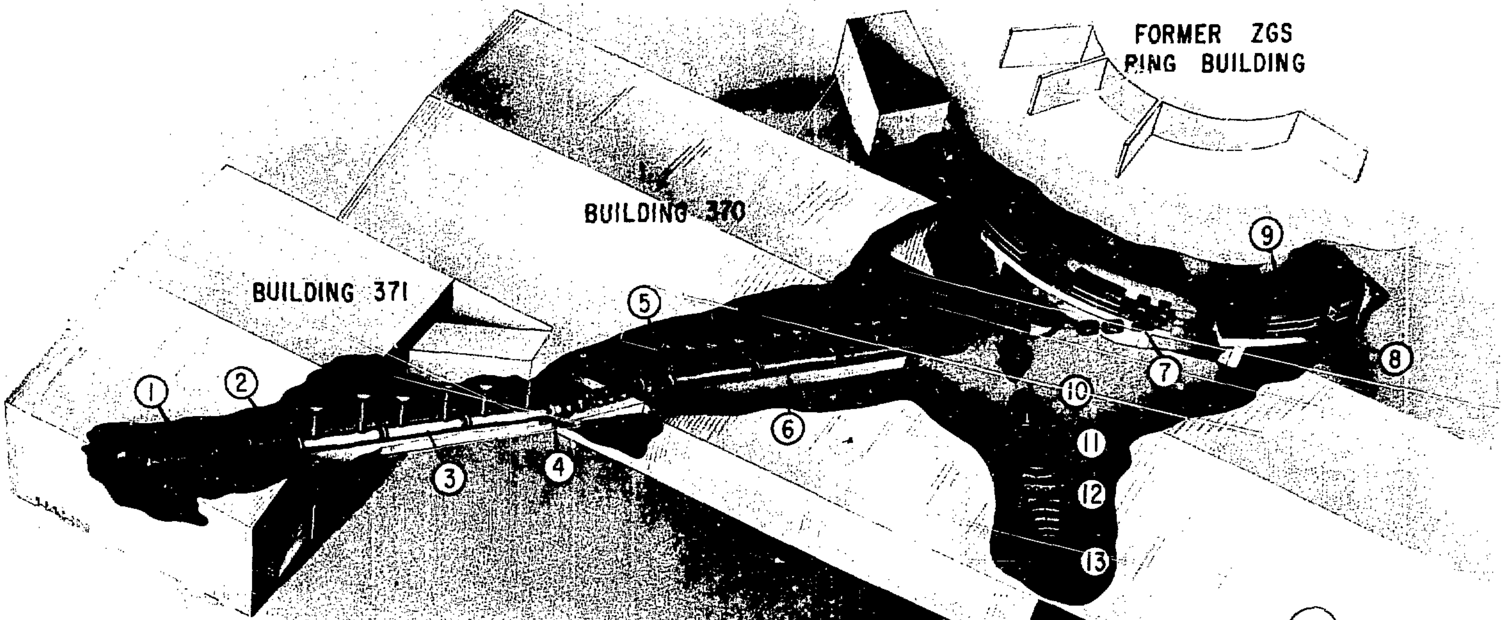
II. Conceptual Design and Program Planning

During the past four years, the near-term objective of the U.S. heavy ion fusion program has changed importantly. The original objective of a Heavy Ion Demonstration Experiment (HIDE) to produce 100 kJ, and, perhaps, 25 TW beams[1] was replaced in the fall of 1978 by a loosely-defined goal of less expensive demonstrations, mostly involving accelerator technology. By using a synchrotron, however, the revised Argonne program was able to preserve the capability of producing intense enough beams (5-10 kJ, 1-2 TW, 6.4 GeV Xe^{+8}) to study the stopping of intense heavy ion beams in hot ($T \sim 100$ ev), dense matter and also the phenomena associated with propagating such beams through various potential reactor-chamber atmospheres. This Phase I plan, however, was obsoleted by a further reduction in the scope of the U.S. HIF program in the spring of 1979. It was accepted almost without question that the new program scope would preclude generating beams of substantial intensity. The revised plan called for an accelerator demonstration facility (ADF) for the competing rf linac/storage ring (Phase Zero). Besides weak output beams, the beams in the storage ring would also be weak compared to the requirements for an ICF reactor's driver. During the first half of FY 1980, however, our design work has concentrated on the objective of obtaining a more intense, useful beam from this system without increasing its cost. Still stressing the advantages of a synchrotron, but incorporating improved design features, we currently expect to be able to carry out the accelerator technology demonstrations at an interesting beam intensity. We call the improved device the Beam Development Facility (BDF). We also expect to produce enough targeted beam intensity to study energy deposition issues, with a modest increase in cost over that expected for accelerator demonstration above. An artist's conception of the BDF is shown in Figure II.1.

Basic ADF

The most essential objective of the rf linac/storage ring ADF is 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 pellets. The only part of the ADF in which the intensity would be as high as ultimately needed is the injector, which includes the source and pre-accelerator, as well as all sections of the rf linac. A fortunate circumstance of the HIF development program is that, for rf accelerator systems, a large number of the accelerator demonstrations concern the low energy end of the injector. The main question is the beam current and emittance that can be delivered to the high energy portion of the injector, where only small additional beam loss and emittance growth are expected. The main isses are source current and brightness, rf capture efficiency (i.e., beam loss), frequency transitions, and stripper operation with intense beams. Emittance growth of space charge dominated beams is a primary interest and reliability must be demonstrated. Typical of the required parameters (derived from conceptual designs of high power systems) and a beam current of 40 mA and normalized emittance of 0.3 cm-mrad out of the linac. The basic ADF would be able to demonstrate these parameters, and also simulate (by appropriate time-dependent beam deflection) combination of linac beams to increase linac current at a frequency transition. This part of the system, especially the low energy end, has been the steady focus of our experimental program, and the status of this effort is described in Section III of this report.

HEAVY ION FUSION
BEAM DEVELOPMENT FACILITY
RF ACCELERATION SYSTEMS



ARGONNE NATIONAL LABORATORY

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
9. STORAGE
10. TRANSPORT
11. SPLITTING
12. FOCUS
13. ENERGY DEPOSITION

FIGURE II.1

After the linac, the accelerator demonstrations with the linac ADF would be carried out at low intensity. Central issues in the circular machines are injection and beam loss due to charge changing collisions of beam loss among themselves and with residual gas atoms. Additional issues are the technology of 10^{-11} Torr vacuum systems, fast extraction of beams with large cross-sections, and transfer between storage rings, which relates to the most practical approach to transverse stacking 100 or more turns. Many important studies can be carried out with low, absolute intensity. Injection, for example, would involve the space charge phenomena associated with working at the space charge limit, and the extraction and transfer demonstration would be useful despite the low intensity. Beam loss due to collisions among beam ions would be hard to observe at low absolute intensity, however, and it would also be hard to study the relevant effects of beam loss, such as vacuum chamber damage and background pressure increase. Moreover, it will be hard to investigate the relevance of the longitudinal microwave instability[2] with low beam current circulating in the ring.

Beam Development Facility

The BDF, on the other hand, would be able to deliver enough energy ($\gtrsim$ 3 kJ) to a small enough spot ($r_s \sim 5$ mm) to heat a foil target (ion range $\sim .2$ g/m^2) to a temperature ($T \sim 50$ eV) high enough to check energy deposition under conditions relevant to pellet implosion. In addition, the accelerator demonstrations by the BDF would be carried out with $I \gtrsim 10$ A in the ring and $I \sim 300$ A in the final transport and focusing system. The BDF design uses a compound waveform for the synchrotron's accelerating field, multiple splitting before final focusing, and large aperture magnets in the accelerator. It has been appreciated for many years[3] that improvements such as slowed synchrotron oscillations and enlarged bunching factor could be realized by using compound rf waveforms; but the technique is particularly suitable for a HIF synchrotron. The multiple cavities needed to create the desired waveforms represent less additional cost because more than one cavity is needed in any case to accommodate the large frequency swing encountered during acceleration, and the stringent requirements in HIF for total beam energy focusability provide an especially strong incentive.

A specific advantage of the special rf accelerating system is that it reduces the area of the rf "buckets" so that the longitudinal emittance of the linac beam is diluted less than would be the case for a single sinusoidal rf waveform that provides the same acceleration. This leads to a smaller momentum spread at the target, and hence less spot size increase due to chromatic aberration. Large aperture (20 cm diameter) magnets in the accelerator are used with splitting (4 x 4) prior to focusing to increase the total beam energy (by increasing the emittance and space charge limit at injection) without increasing the size of the focal spot.

The quadrupole magnets of the 16 final focusing lenses would also be integrated into a compact array. In addition to the improved schedule for accelerator demonstrations with interesting intensity and energy deposition studies, the use of a synchrotron in the BDF is intrinsically valuable because the improvements in performance would demonstrate that the synchrotron is attractive (because of the low cost) for the driver of future facilities in the ICF program.

Table I shows a typical parameter table for the BDF.

TABLE I

Parameters of Beam Development Facility with One Single-Pulse Synchrotron

Ion Source and DC Preaccelerator:	Xe^{+1} to 1.5 MeV at 40 mA
Low Velocity (12.5 MHz) Linac:	Xe^{+1} to 20 MeV at 25 mA
Stripper:	$Xe^{+1} \rightarrow Xe^{+8}$ at 20 MeV yielding 40 mA (el.)
25 MHz Linac:	Xe^{+8} to 220 MeV at 40 mA (el.)
Injection Ring (utilizing PPA magnets):	Xe^{+8} at 220 MeV
Radius -	25 meters
Injection -	4 turns (horizontal) from linac
Synchrotron Ring:	Xe^{+8}: 220 MeV injection, 10 GeV final energy
Radius -	25 meters
Injection -	4 turns, from injection ring
Acceleration Rise Time -	0.1 sec.
Repetition Time -	10 sec.
Final Instantaneous Beam Current -	25 A
Beam Pulse Energy -	3 kJ
Emittance at Extraction	7.5 π mr. cm.
Pulse Compression (post-acceleration):	x 24
Final Pulse Length/Power :	5 nsec/0.6 TW
Final Momentum Spread ($\Delta P/P$)	$\pm$ 0.5 x 10^{-2}
Transverse Beam Splitting:	x 4 horizontal, x 4 vertical
Target Spot Radius:	0.45 mm.
Ion Range (in cold Au foil):	.25 mm.
Maximum Temperature Achievable in Target (Au):	50 eV
Average Specific Deposition Energy:	1.0 MJ/g

Atomic and Plasma Physics Workshop

A topical workshop was held at Argonne on December 13-14, 1979, to identify data requirements of the heavy-ion fusion program in the areas of atomic physics and plasma physics. This was the first topical workshop with these specific goals. Although sessions have been included at the annual HIF workshops, there was a need for more widespread participation, particularly by atomic physicists, in defining the state-of-the-art and requirements for specific theoretical and experimental work in the atomic and plasma fields. Fifty-three scientists attended.

Excerpts from the report of this workshop are reproduced in Section IV of this progress report.

Target Development

There are two aspects of our current activities concerning heavy-ion targets: a) planning for energy deposition physics experiments in the beam development facility (BDF), and b) exploration of unclassified pellet designs for power producing reactors. The energy deposition experiment plans will cover numerical simulation of beam-foil interaction achieving $T \gtrsim 50$ eV. The reactor pellet studies involve their role in defining the primary physics uncertainties (e.g., dE/dX, equations of state, hydrodynamic stability) that are to be resolved in the early stages of the HIF program.

The longer range goals of the target activities are to develop (in collaboration with others) target designs of interest to Argonne's HIF program, to fabricate (or arrange to be fabricated) and develop handling techniques for targets or metal shells to be used in Argonne's programs, to develop a unique inspection system using 50 MeV protons, and to develop delivery systems that will be required in our program. Detailed taget design goals include:

- Unclassified Targets for G = 100 (3 MJ)
- Targets for 3-10 kJ Beam Physics Facility
- Breakeven Targets for 200 kJ HITF
- Follow Development of Classified Targets at LASL, LLL

Initial working assumptions (to be checked against early experiments) which we see as simplifying the planning of the HIF target program:

A. Energy deposition of heavy ions is not less than classical; can be estimated by currently available theoretical models.

B. Hot electrons are not generated because deposition layer is dense and collision rates are high (and no other important anomalous thermal transport phenomena are expected).

C. Pusher layers thick enough to avoid hydrodynamic (R-T) instabilities can be used.

D. Adequate illumination symmetry can be obtained (using a dozen or two beams, if necessary).

E. Target material tolerances are tractable on 1-3 mm radius shells.

F. Radiative thermal heating (e.g.,of the fuel) is not important during compression because pusher layer is dense and opaque.

G. Metallic equations-of-state can be experimentally determined in early experiments.

H. DT burn physics will be known adequately from other (non-HIF) experiments.

Guided by these preliminary assumptions, the principal initial HIF target physics will entail plasma-hydrodynamic one-dimensional calculations for specific targets and beam parameters, with calibration of EOS against early experiments. Detailed claculations can be done at LASL.

In addition, liaison with LASL and groups at other institutions serves to augment ANL's base of numerical studies, explore instabilities, and compare classified target design concepts as well.

Simple targets, as shown in Figure II.2, have been explored and a current result is shown in Table II.

By comparison, the minimum gain required for a reactor is approximately 50; this may require pulse shaping, increased power, or a different design.

Planning of the diagnostic experiments on the BDF has begun, with advice from NRL. Typical foil target diagnostics are:

1. Optical and x-ray emissions from back surface (thickness > range)
    - hydro motion
    - temperature

2. Range and temperature using series of foils with range > thickness.

3. Accelerated-mass measurements using impact on secondary foils behind rear surface.

The primary issues are seen to be the equation-of-state of metal foils (including ionization states at high temperatures), hydrodynamic stability, and the possibility of non-classical transport phenomena.

References

1. 1977 Brookhaven HIF Workshop.

2. 1979 Berkeley HIF Accelerator Technology Workshop; storage-ring section

3. Rutherford Laboratory Report, RL-74-028, February 1974.

HEAVY-ION DRIVEN INERTIAL FUSION TARGETS

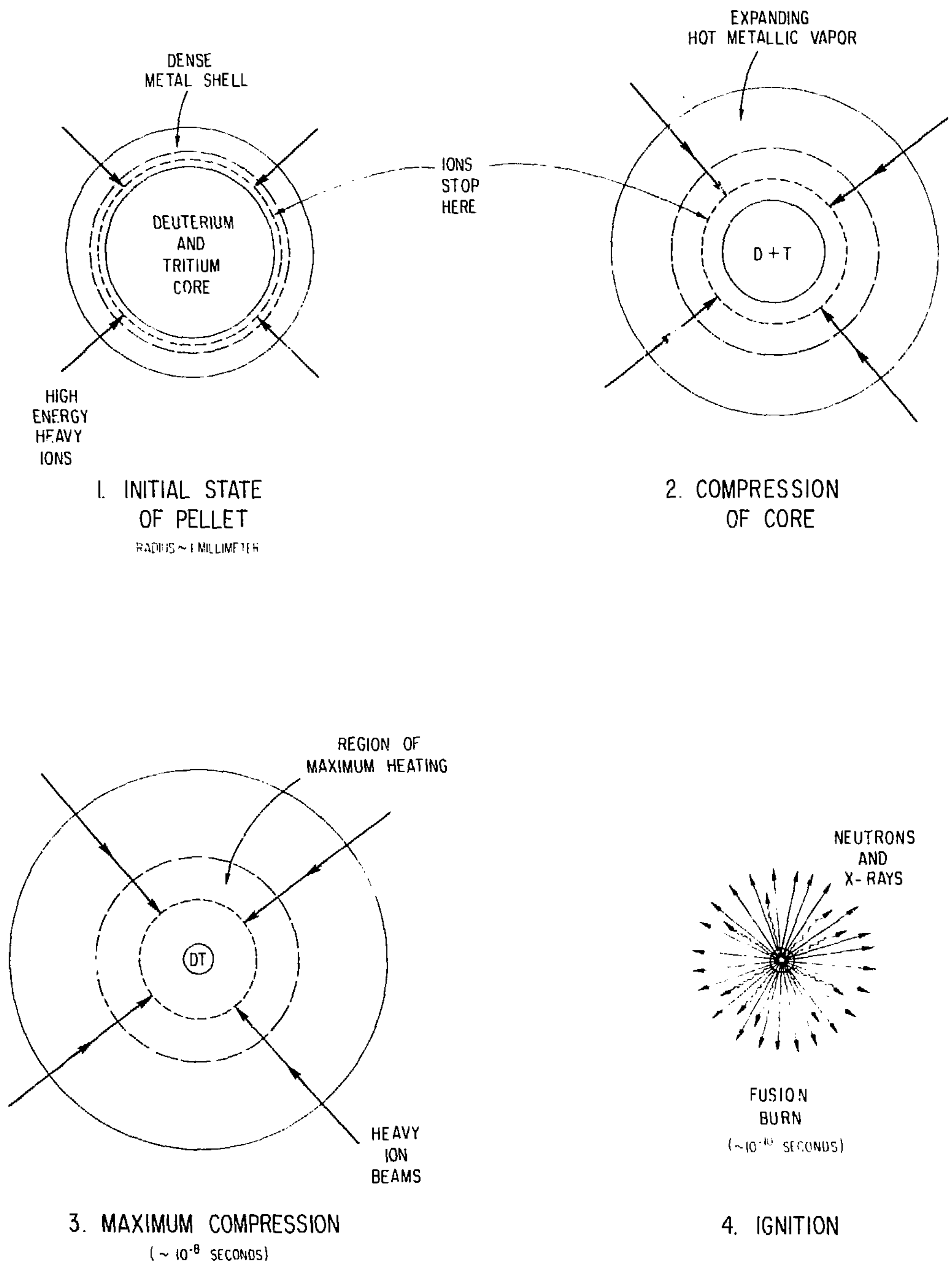


FIGURE II.2

TABLE II

Untuned Simple Target, Gain = 7

(Gula and Magelssen, Spring 1980)

Xe Beams, 6.4 GeV Kinetic Energy

150 TW for 7 ns.

Radius 1 mm.

Thickness of Au Shell 0.2 mm

Cryogenic DT Thickness 0.025 mm.

DT Gas Density 0.1 x solid density

III. Experimental Program

Introduction

The first half of FY 1980 has been a very busy and productive period for performance testing of the preaccelerator and first cavities of the linac. The facility as shown in Fig. III.1 is operational except for the cavities IPC-2 and IPC-3 which are nearly completed. The diagnostics for measuring currents and beam profiles have been used to measure beam emittance, linac bunching factors, and peak acceleration from IPC-1.

Construction of the first Wideröe tank has started, but funding for the rf amplifier was not available. The ZGS rf amplifier has been acquired through surplus and will be modified to provide 450 kW of pulsed power at 12.5 MHz to excite the first Wideröe tank.

Preaccelerator

Most of the preaccelerator effort so far this year has been to improve reliability and measure performance. The high voltage operation is being limited to 1.1 MV until a new outer shell for the column is constructed. A new outer shell has been designed and the ceramics ordered. It will utilize metal C-rings and metallized ceramics to avoid electric field concentrations at O-ring grooves which contribute to chipping. It will not be a bonded structure, so it will be potentially bakeable and easily repairable.

The preaccelerator conditioned easily to 1.0 MV and operates very reliably there with 40 mA of Xe^{+1} with 200 microsecond pulses at 1 Hz. The pulsed high voltage is measured to 0.1 percent by summing the column divider current at 300 kV with the impulse on a capacitive pickup plate facing the terminal within the machine. A voltage feedback circuit has been installed which regulates the oscillator to reproduce the high voltage to 0.1 percent. During the beam burst a feedforward impulse into the oscillator driver holds the energy droop to less than 0.25 percent.

The preaccelerator power supply and heavy ion source have developed into very reliable systems. After some problems with spark damage to electronic circuitry in the source terminal, experience has shown the proper means of protecting and isolating delicate modern electronics. A new terminal control system based entirely on fiber optics, multiplexed frequencies, and stepper motors has been constructed and will soon replace the remaining control rods. The sytem will allow very accurate adjustment and complete monitoring of the source parameters.

The transverse emittance of the beam was measured by forming a circular focus on PAPS-1 (Position and Profile System #1) and letting the beam drift to PAPS-2 without the QM magnets energized. The PAPS signals for the horizontal measurement are shown in Fig. III.2. The vertical signals were similar The beam radius grows from 0.95 cm to 1.6 cm in the 2.5 m drift distance. Assuming the worst case, an upright ellipse in phase space at PAPS-1, the measured normalized emittance is $\varepsilon_{NX} = \varepsilon_{NY} = 0.019$ cm-mrad. This agrees well with the expected emittance at 1.0 MeV. It should drop to near 0.01 cm-mrad at 1.5 MeV where the ideal electrostatic conditions will exist in the column.

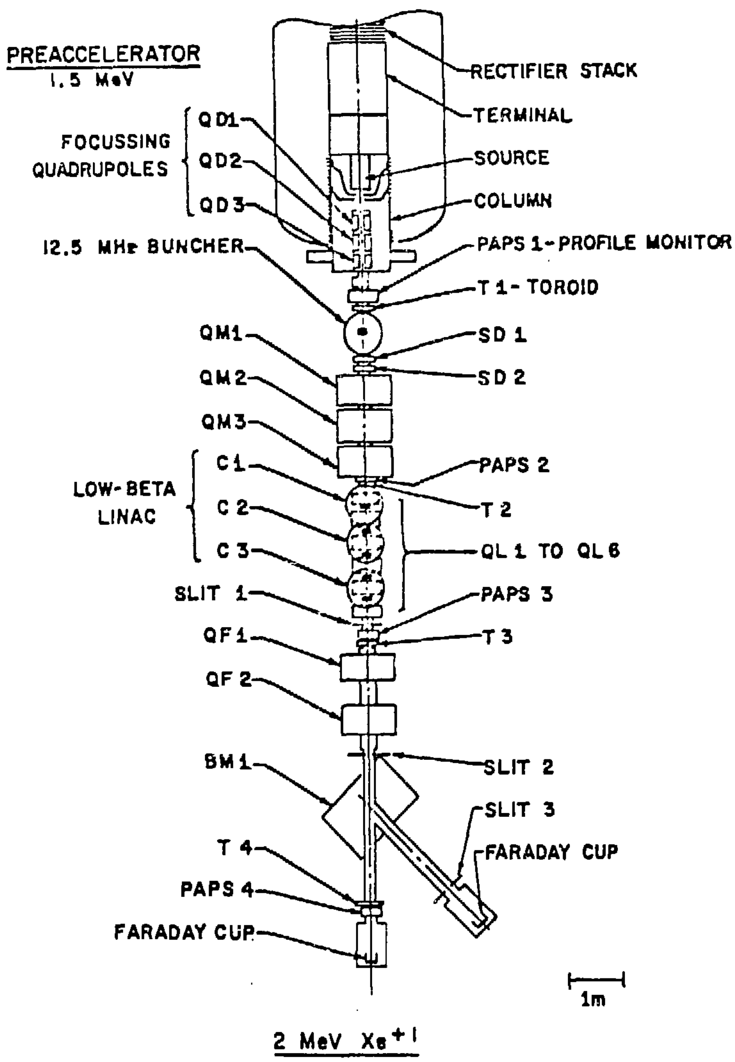
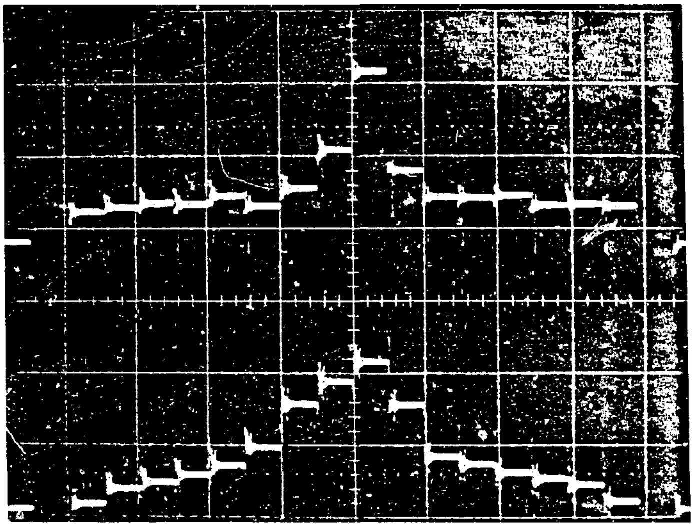


FIGURE III.1 ANL HIF Front End

PAPS MEASUREMENT MIDWAY IN PULSE WITH 10 μS WINDOW

FORM ROUND WAIST AT
PAPS 1
$R_0 = 0.95$ CM

BEAM DRIFTS $Z = 254$ CM
TO PAPS 2
$R = 1.6$ CM



ASSUME UPRIGHT ELLIPSE, $\varepsilon_N = \beta\gamma \frac{R_0^2}{Z}\left[\frac{R^2}{R_0^2} - 1\right]^{1/2} = \beta\gamma RR'$

$\varepsilon_{NX} = \varepsilon_{NY} = 0.0040 \times 4.7 - 0.019$ CM-MRAD

FIGURE III.2 ANL Preaccelerator Xe^{+1} Emittance Measurement

The development of accurate diagnostics for these intense heavy ion beams has been a challenge, even at these low energies. Small beam losses (a few percent) of heavy ions on the beam pipe walls produce electron currents greater than the ion beam. It has been necessary to use clearing electrodes upstream and downstream of diagnostics to null their effects. The proper biasing of Faraday Cups must also be experimentally determined for accurate results. The development of the PAPS system has been a very significant contribution to the non-destructive measurement of these beams. The modern sensitive electronics used to measure the ionization electron current profiles are capable of single pass measurements of 20 mA beams in a vacuum as good as 10^{-10} Torr. In the preaccelerator beam line the vacuum is typically 1×10^{-6} Torr which provides an excellent signal to noise ratio as long as external electrons are excluded.

Low-Beta Linac

Independently-Phased Cavities

IPC-1 and IPC-1′ were tested under beam conditions with IPC-1′ used as a single-harmonic buncher. At 1 MeV the bunching factor achieved was approximately 4.5 with less than 1 kW of power required (approximately 20 kV of gap voltage). The signal was somewhat confused by the separation of the isotopes which occurred with bunching: the bunched width was 15 nanoseconds and the isotope separation was approximately 15 nanoseconds/amu in the 3 m drift space.

With 25 kW of excitation power at 12.5 MHz, IPC-1 gives a 200 keV peak kick to a 1 MeV Xe^{+1} beam. This was measured using the downstream magnetic spectrometer. For the synchronous phase angle of 35°, the IPC-1 acceleration should be 160 keV. This agrees well with the design expectations. There was no indication of arcing induced by the beam.

The two drum-loaded four-gap cavities, IPC-2 and IPC-3, are nearly completed and should be operational by June. Their fabrication was resumed at the start of FY 1980. Each of these should accelerate the beam an additional 300 keV. After these are installed and IPC-1′ moved into the linac, the IPC section should be capable of 1 MeV acceleration above the preaccelerator energy.

The design of IPC-4 and IPC-5 is underway, however, because of lack of funds their construction will be delayed until FY 1981.

Wideröe Linac

The design of the first Wideröe tank was completed and construction of the outer electrodes has started. The fabrication of other long-lead items such as the magnets has also started. However, only a few parts will be completed in FY 1980 because of limited funds. It is hoped to finish one stub tank through copper electroplating to verify the basic design.

A section of tank was fabricated to simulate a section of the Wideröe for electroplating tests. It has been copper plated by one potential vendor so far. The mild steel tank is 4 feet long and 4 feet in diameter with end flanges and two ports for mounting long drift tubes. It was given a cyanide copper strike followed by 0.005 in. of acid copper. The solution contained levelers and brighteners. The inner surface finish was improved by the copper plating, but some adhesion problems were encountered in the O-ring grooves on the flanges. The empty tank is resonant at 200 MHz with a Q of only 64 percent of that expected for pure copper with a perfect finish. Since the average finish is approximately 100 microinches, most of this discrepancy should disappear at the Wideröe operating frequency of 12.5 MHz.

The ZGS rf amplifier is being transferred to HIF for modification as a driver for the first Wideröe tank until funding for new 450 kW amplifiers is available.

Xe-Xe Charge-Exchange Measurements

The 80 keV test beam has been modified for high vacuum (10^{-8} Torr) operation. A second beam line has been added using a duoplasmatron source to intersect at 90^{0} at the first downstream focus. Both beam lines are now operational; however, it has not been possible to fully neutralize the target beam. Evidently the source itself clears the few electrons produced at this low pressure. Without full neutralization the waist at the focus is not small enough for a favorable signal-to-noise ratio in the experiment. This can be ameliorated by transporting the beam in a poorer vacuum with greater differential pumping in the intersection region or by adding sources of electrons along the transport line.

The experimental effort on Xe^{+1} - Xe^{+1} has now been slowed for several reasons: first, it appears Gilbody has made a good measurement of this cross-section; second, higher charge state cross-sections (Xe^{+q} - Xe^{+q} for q ranging up to 8) are more directly relevant to the program; and third, because of the lack of adequate funding the experimental group was decreased for the remainder of FY 1980. At present the plan is to design a higher charge state experiment using the preaccelerator and linac beam. The 80 keV experimental setup will be used to test the detectors needed for that experiment and gain experience while repeating the singly-charged cross-section. Since the designs are still preliminary and the total effort required has not yet been determined, a commitment to a schedule for the higher charge state experiments has not yet been made.

IV. Excerpts from:

REPORT ON THE WORKSHOP ON ATOMIC AND PLASMA PHYSICS REQUIREMENTS FOR HEAVY ION FUSION

ANL 80-17

Argonne National Laboratory

December 13-14, 1979

Sponsored by the Accelerator Research Facilities Division

Workshop Committee

Yong-Ki Kim (ANL-RER Division) - Glenn Magelssen (ANL-ARF Division)

ABSTRACT

Atomic, molecular, and plasma physics areas that are relevant to inertial confinement fusion by energetic heavy ions are identified. Discussions are confined to problems related to the design of heavy ion accelerators, accumulation of ions in storage rings, and the beam transport in a reactor vessel.

TABLE OF CONTENTS

	ABSTRACT	
I.	INTRODUCTION	1
II.	PLASMA PHYSICS REQUIREMENTS FOR HEAVY ION FUSION	2
III.	ATOMIC AND MOLECULAR PHYSICS REQUIREMENTS	7
	A. The First Stage: Acceleration of Ions	8
	B. The Second Stage: Storage of Accelerated Ions	9
	C. The Third Stage: Beam Propagation in the Reactor Vessel	10
IV.	PRIORITIES OF MAJOR ATOMIC AND MOLECULAR DATA	15
	REFERENCES	17
	APPENDIX A - Workshop Program	18
	APPENDIX B - List of Participants	19

I. INTRODUCTION

The Workshop on Atomic and Plasma Physics Requirements for Heavy Ion Fusion was held on December 13-14, 1979, at Argonne National Laboratory. Fifty-three scientists, including three from Europe, attended. The objective of the workshop was to identify problems in atomic, molecular, and plasma physics relevant to inertial confinement fusion by energetic ions. Although the main burden for the success of heavy ion fusion must be borne by those who design the accelerators and pellets, there are a number of atomic, molecular, and plasma physics questions that strongly influence the choices of the accelerator, ion storage ring, focussing system and chamber gas. Reliable answers to these questions will not only enhance the success of heavy ion fusion, but also eventually lead to more efficient power reactors with savings of hundreds of millions of dollars.

The intent of this report is not to explore in depth the many atomic, molecular and plasma problem areas related to heavy ion fusion. Partial answers in some depth to some of the problems have been examined at earlier workshops and in the literature, and are referenced for those seeking additional information. Further, only those problem areas relating to ion propagation in the reactor chamber, to the accelerating region, and to the storage rings are discussed. For example, beam target interaction physics is not included. Our intent is to identify the plasma and atomic physics which we believe needs to be pursued in these areas, to show how, in some cases, the plasma and atomic problems interrelate, and to suggest avenues for solving some of the problems.

This report was formed by the editorial committee from the discussions and follow-up comments made by the workshop participants. We hope the problems and priorities listed in this report will serve as guidelines in planning current and future research activities, although our list must be updated periodically to keep pace with new developments in accelerator and pellet designs, as well as in atomic, molecular, and plasma physics.

IV. PRIORITIES OF MAJOR ATOMIC AND MOLECULAR DATA

Priorities depend very much on the accelerator and reactor pressure under consideration. Major categories of high priority are listed below.

Type of Data	Where They are Needed	Priority	Preferred Method
Ion-gas charge-changing cross-sections, (< 10^9 cm/sec)	Induction Linac	Primary	Experiment
Ion-gas stripping cross-sections (> 10^9 cm/sec)	rf linac, synchrotron (storage ring)	Secondary	Theory
Ion-ion charge-changing cross-sections (< 10^8 cm/sec)	rf linac, synchrotron (storage ring)	Primary	Experiment
Charge states (< 10^{-3} Torr)	Reactor	Primary	Theory with Benchmark Experiment
Charge states (10^{-3} – 10 Torr)	Reactor	Secondary	Theory with Benchmark Experiment
Secondary-electron distribution	Reactor	Secondary	Experiment
Electron degradation	Reactor	Secondary	Theory
Plasma diagnostics	Reactor	Secondary	Experiment

As mentioned earlier, the data needs and priorities must be reviewed periodically to accommodate for the changing requirements of accelerator and reactor design.

Program for the Workshop on Atomic and Plasma Physics Requirements for Heavy Ion Fusion - Argonne National Laboratory

Thursday, December 13

Morning sessions chaired by G. H. Gillespie (Physical Dynamics), Building 362, Room F-108

0830-0900	Registration - Building 362 Auditorium
0900-0910	Welcome Remarks - by R. L. Martin (ANL)
0910-0940	Atomic and Plasma Physics Questions in Induction Linac - C. Kim (LBL)
0940-1010	The Roles of Atomic and Plasma Data in Heavy Ion Fusion - R. C. Arnold (ANL)
1010-1040	Ion-Ion Charge-Changing Collision Processes - R. E. Olson (SRI)
1040-1100	Coffee Break
1100-1130	Systematics of Secondary-Electron Production - M. E. Rudd (Nebraska)
1130-1200	Plasma and Atomic Effects in Beam Focussing - S. Yu (LLL)
1200-1230	Beam Transport and Stability in the Target Chamber - R. F. Hubbard (JAYCOR)
1230-1400	Lunch
1400-1700	Free-for-all Discussions. Break up into Atomic and Plasma Physics groups. Atomic Physics discussions chaired by J. H. Macek (Nebraska) Building 362, Room E-188. Plasma Physics discussions chaired by S. Jorna (Physical Dynamics) Building 360, Room L-134.

Friday, December 14

Morning sessions chaired by D. A. Tidman (U. Maryland), Building 362, Room F-108

0900-1000	Summary of Atomic Physics Discussions - J. H. Macek
1000-1030	Coffee Break
1030-1130	Summary of Plasma Physics Discussions - S. Jorna
1130-1230	Discussions on Cross-Disciplinary Areas
1230-1400	Lunch

Afternoon session chaired by G. R. Magelssen (ANL)

1400-1530	Discussions and Conclusions on the Content of the Workshop Report
1530-1545	Concluding Remarks - T. Godlove (D.O.E.)

APPENDIX B

List of Participants

Workshop on Atomic and Plasma Physics Requirements for Heavy Ion Fusion

Jose Alonso	Lawrence Berkeley Laboratory
Richard Arnold	Argonne National Laboratory
Earl Beaty	JILA, University of Colorado
Joseph Berkowitz	Argonne National Laboratory
Gordon Berry	Argonne National Laboratory
Keith Brueckner	University of California, San Diego
Robert Burke	Argonne National Laboratory
Philip Burkhalter	Naval Research Laboratory
Kwok-tsang Cheng	Argonne National Laboratory
Yanglai Cho	Argonne National Laboratory
Chan Kyu Choi	University of Illinois, Urbana
Denis Colombant	Naval Research Laboratory
David Crandall	Oak Ridge National Laboratory
Jean-Paul Desclaux	Centre d'Études Nucleaires de Grenoble
John Detrich	Science Applications, Inc.
Michael Dillon	Argonne National Laboratory
Daryl Douthat	Kennedy-King College, Chicago
Brian Gilbody	Queen's University, Belfast
George Gillespie	Physical Dynamics, Inc.
Terry Godlove	Department of Energy
Harvey Gould	Lawrence Berkeley Laboratory
David Hammer	Cornell University
Timothy Heil	Harvard College Observatory
Richard Hubbard	JAYCOR
Robert Johnson	Science Applications, Inc.
Roger Jones	Los Alamos Scientific Laboratory
Siebe Jorna*	Physical Dynamics, Inc.
Charles Kim	Lawrence Berkeley Laboratory
Yong-Ki Kim*	Argonne National Laboratory
Kenneth Kulander	Lawrence Livermore Laboratory
Donald Lemons	Los Alamos Scientific Laboratory
Joseph Macek*	University of Nebraska
Glenn Magelssen*	Argonne National Laboratory
Ronald Martin	Argonne National Laboratory
Michael Mazarakis	Argonne National Laboratory
William Morgan	Lawrence Livermore Laboratory
Alfred Mueller	University of Giessen
Ronald Olson	SRI, International
Robert Peterson	University of Wisconsin, Madison
Robert Poe	University of California, Riverside
Larry Ratner	Argonne National Laboratory
Eugene Rudd*	University of Nebraska
Richard Sacks	Science Applications, Inc.
Ivan Sellin	Oak Ridge National Laboratory
David Spence	Argonne National Laboratory
Tong Wha Shyn	University of Michigan
Harunori Takeda	Argonne National Laboratory
Derek Tidman*	University of Maryland
Larry Toburen	Battelle Northwest Laboratory
Christian Wahl	Science Applications, Inc.
Jerry Watson	Argonne National Laboratory
Stephen Younger	National Bureau of Standards
Simon Yu*	Lawrence Livermore Laboratory

* Editorial Committee Member

V. Abstracts of Publications

Abstracts of papers presented at the 1979 HIF Accelerator Study
October 29 - November 9, 1979, Claremont Hotel, Oakland, California

Beam Brightness in Low Beta Linacs: A Sensitivity Study
by: R. J. Burke, Argonne National Laboratory
R. A. Sacks, Science Applications, Inc.

Introduction

Heavy ion drivers for inertial confinement fusion reactors depend on the ability to produce a high intensity, high quality beam with a minimum of in-machine loss. Deterioration of the beam quality, which subsequently leads also to beam loss, tends to occur in the early (low energy) stages of the acceleration process, since all nonlinear effects decrease with velocity. Accordingly, considerable effort has been invested (1-3) in studying the various mechanisms of emittance growth in low energy linear accelerators.

The current work does not directly address the specific causes for beam deterioration on a fundamental level. Rather, we present the results of a numerical study aimed at gaining an engineering characterization of the dependence of the accelerated beam quality and intensity on various parameters in the linac design, the initial beam configuration, and the initial current. A dramatic improvement is observed when injection energy is raised, and some tentative suggestions are offered for techniques of achieving this increase.

ANL Low Beta Development (Phase 0)
by: J. M. Watson

Introduction

The HIF group at Argonne National Laboratory is currently developing the initial Accelerator Demonstration Facility (ADF) for the rf linac reference concepts. This has been dubbed Phase 0 since it is a preliminary step before our two proposed ADF's which could deposit 10 kJ (Phase I) and 500 kJ (Phase II) on target. Phase 0 is a $25 million project over a three-year period. Unfortunately, much of the funding expected for this project was withdrawn from the FY 1980 budget, thereby delaying its completion by a year.

The basic configuration of Phase 0 is shown in Fig. 1. The low-beta front end consists of a high voltage preaccelerator followed by an array of 12.5 MHz independently-phased linac resonators and Wideroe linacs to accelerate 25 mA of Xe^{+1} to 20 MeV. The beam is then stripped to charge state +8 and accelerated in a 25 MHz Wideroe to 220 MeV. It will be injected into a ring (using the Princeton-Penn accelerator magnets) housed in the ZGS tunnel. The extracted beam will be compressed, split into four beams and focused onto target foils.

Phase 0 could demonstrate adequate beam quality and intensity through many stages common to a HIF driver:

Ion Source
Low-beta acceleration
Charge stripping
Frequency jump with simulated funneling
Multi-turn injection into a storage ring

Storage ring vacuum and instabilities
Extraction
Compression
Beam splitting
Final focus
Energy deposition

Storage Ring Injection
by: R. J. Burke

Introduction

Multiturn injection is an essential step in generating high power beams for heavy ion fusion. Systems have been proposed t.at use a hundred turns of injection or more, which must be done with minimal beam losses. To cause the stored beam to miss the back side of the inflector, adequate separation is required between the stored and incoming beams. This dilutes the phase space density, but the allowable dilution is also constrained by the limits on the brightness of the linac beam and the final focusing requirements set by the size of the fusion fuel pellet. The injection problem is thus bracketed by the constraints of beam loss on the one hand and phase space density on the other.

The most commonly proposed scheme to accomplish many turns of injection has been to inject N_1 turns into the horizontal plane of a ring used expressly for injection, transfer this accumulated beam to a storage ring after first interchanging the horizontal and vertical phase planes, and repeat the process N_2 times for a net multiplication of the linac current by N x N. For convenience, we assume $N_1 = N_2 = N$ and write $N^2 = NT$, the total number of turns injected into the first ring and destined for any one final storage ring.

Investigation of injection schemes at ANL has begun to incoporate detailed space charge effects using numerical simulation. The results so far confirm the expectation that space charge effects complicate the injection problem, and more dilution seems necessary to avoid excessive beam loss. The means to increase the dilution allowance are, however, very limited.

Study of Inter-Beam Interaction in Injection Process at the Space Charge Limit
by: H. Takeda and S. Fenster

Introduction

Augmenting a particle simulation program originally by I. Haber, beam dynamics of the injection process into a storage ring is studied. Although a real storage ring recently designed employs various kinds of magnetic elements, the essential features of its beam dynamics are determined by the quadrupole doublets. The lattice structure of the storage ring consists of 20 FODO periods. Figure 1 shows the lattice, and Table 1 shows the storage ring parameters.

The quadurpoles are assumed to be thin. Thus, by obtaining a FODO transport matrix for one period starting from beam injection point I, acceptance ellipse parameters $\alpha_{Aj},\beta_{Aj}{}^2$ are calculated at I for both x-x′ and y-y′ planes (j-x,y) for a given phase advance per period. In this paper, we discuss single plane (xx′) injection. We set the beam emittance ellipse parameters for the y-y′ plane (α_{By},β_{By}) equal to the acceptance ellipse (α_{Ay},β_{Ay}) and take the center of the beam ellipse in the y-y′ plane at the center of the beam transport system. Thus, the beam ellipse in the y-y′ plane is exactly matched, regardless of its emittance, so the beam ellipse in the y-y′ plane has the same periodicity as the storage ring elements. Thus, the four-dimensional efficiency and dilution of the injection process are equal to the two-dimensional ones in the x-x′ plane. We wish to check whether beam loss or phase space dilution can occur due to multibeam envelope oscillations dependent on the beam stacking method in injection.

The program keeps track of beam loss for a given aperture of a transport line; a special method accounts for septum losses. Chamber wall image force is not included in the calculation, and the septum has thickness equal to zero.

Computer Design of a High Current, High Energy Proton Linac
by: M. H. Foss

The accelerator produces enough beam to make the same number of neutrons on the average as 0.5 mA of 800 MeV protons. The beam is delivered to the target in 200 ns pulses at 50 Hz. The results are presented here because some of the problems are similar to HIF problems.

In the linac discussed here, the current at each point is constant throughout the pulse. Figure 1 demonstrates this scheme; a constant current is extracted from the ion source for a time dT = 2. This beam passes an accelerating gap at D = 0. The velocity profile is adjusted so that the beam is bunched. The time required for the beam to pass a point decreases linearly from dT = 2 to dT = 0 as the distance goes from D = 0 to D = 4.

In the accelerator, all of the acceleration is done by induction cavities. The machine is divided into three sections: a buncher, a debuncher, and a main accelerator. A 7.5 A, 2 ms. pulse from a 750 kV preaccelerator is compressed by a factor of 10 in the buncher and debuncher. These 200 ns pulses are then accelerated to 565 MeV.

Abstracts of papers presented at the 1980 CLEOS/ICF Conference, February 25-28, 1980, San Diego, California

TuD15 Design for a compact 200–500-kJ heavy ion driver

ROBERT J. BURKE, RONALD L. MARTIN, and RICHARD C. ARNOLD, Argonne National Laboratory, 9700 S. Cass Ave., Argonne, Ill. 60439.

The basic issues in the heavy ion driver approach to inertial confinement fusion are phase-space and space-charge constraints and system cost. All these are affected by the telescoping beam concept, which is able to deliver simultaneously a number of ion bunches through a single beam line. Each bunch is composed of ions of a single species, but separate individually prepared bunches contain different species of ions.

The phase-space constraints emanate from the requirement that the beam be focused on millimeter-sized fusion targets: geometric and chromatic aberrations put an upper limit on the 6-D phase space that a single bunch can occupy. This relates the targeting requirements, the brightness of the beam from the ion source, and the brightness-decreasing effects of all operations needed to generate the beam. With telescoping beams, the total number of bunches that may be used is increased (by a factor equal to the number of different species employed) beyond the maximum number of beams allowed by practicality or cost. The resulting increase in the total usable phase-space volume increases the amount of brightness loss that can be tolerated during beam generation.

Space charge puts an upper bound on the power that can be transported in an evacuated magnetically focusing beam line (for given ion and beam line parameters). Telescoping raises the effective limit because beam bunches arrive at the target simultaneously after they have followed one another through the transport lines.

The good effect of the telescoping concept on the size and cost of the pellet driver accelerator system is that, because of the increased number of beam bunches and total usable phase space and increased effective power limit per beam line, higher charge state and/or lower kinetic energy ions can be used. The system that will be described uses these effects to permit a system capable of ≥ 200 kJ to fit into buildings that formerly housed the Zero Gradient Synchrotron system at Argonne National Laboratory.

(Poster paper)

WD7 Argonne National Laboratory high-intensity Xe^+ injector for heavy ion fusion

JERRY M. WATSON, JOHN M. BOGATY, ROBERT J. BURKE, RONALD L. MARTIN, ALFRED MORETTI, KENNETH K. MENEFEE, JOHN S. MOENICH, EVERETTE F. PARKER, ROBERT L. STOCKLEY, MARTYN H. FOSS, TAT K. KHOE, and ROBERT L. KUSTOM, Argonne National Laboratory, 9700 S. Cass Ave., Argonne, Ill. 60439.

A preaccelerator and low-velocity rf linac are being developed at Argonne National Laboratory in a program to demonstrate the accelerator technology necessary for heavy ion fusion (HIF) power plants.

The most convenient heavy ion to use is Xe^+ from the standpoint of reliability of ion source and accelerating column construction. A low-emittance source was developed for the preaccelerator by Hughes Research Laboratories. It is a single-aperture Penning discharge source and has operated with Xe^+ currents as high as 100 mA. The operating performance of the high-gradient accelerating column and emittance measurements for 50-mA beams over 1 MeV will be discussed.

The high-voltage power supply for the preaccelerator is a modified Radiation Dynamics, Inc., 4-MeV dynamitron. It was modified for optimal pulsed operation at 1.5 MV. At 1.5 MV the voltage drop is <0.25% for 42 mA of beam-associated current during a 100-μsec beam pulse.

Beam capture in the 12.5-MHz low-β linac is optimized by using a single-harmonic buncher after the preaccelerator. A 4-m drift space precedes three independently phased accelerating cavities. These are lumped capacitor single- and double-drift tube resonators. The linac design and performance will be discussed.

A system of nondestructive beam diagnostics was developed that measures the position and profile of these pulsed heavy ion beams between the preaccelerator and linac. These will also be described.

(12 min)

WD6 Argonne plans for a heavy ion fusion rf linac accelerator demonstration facility (phase zero)

RONALD L. MARTIN, RICHARD C. ARNOLD, ROBERT J. BURKE, EUGENE P. COLTON, STANLEY FENSTER, MARTYN H. FOSS, TAT K. KHOE, ALFRED MORETTI, LAZARUS G. RATNER, HARUNORI TAKEDA, and JERRY M. WATSON, Argonne National Laboratory, 9700 S. Cass Ave., Argonne, Ill. 60439.

The feasibility of the rf linac (beyond the difficult front end) is a fact that most accelerator technicians would accept from existing experience; this was reflected in the analyses at the 1978 Heavy Ion Fusion (HIF) Workshop at Argonne National Laboratory. However, there are many beam manipulations that are specific to the rf linac HIF drivers. The efficiency, emittance growth, and effect of beam loss (on vacuum and components) during these beam manipulations are much more important with heavy ion beams for pellet fusion reactors than with the proton beams for research applications with which we are familiar. A minimum program to demonstrate the practicality of rf linac systems involves demonstration of some critical issues involving accumulator rings (injection, accumulation, extraction, emittance growth, beam lifetime, internal compression, etc.). A first accelerator system was designed to satisfy these requirements and also to have the capability of doing some interesting experiments on energy deposition in foils and on beam plasma instabilities. This was called phase 1 and estimated to cost 20 million dollars. A reduced program that would demonstrate all the critical accelerator issues, although at substantially lower current, was then developed and labeled phase 0. The layout of suitable minimal R&D equipment, with operating parameters, is shown in Fig. 1. Table 1 lists a comparison of the operating parameters of a 1-MJ reference driver, demonstration facility phase 1, and the minimal facility phase 0.

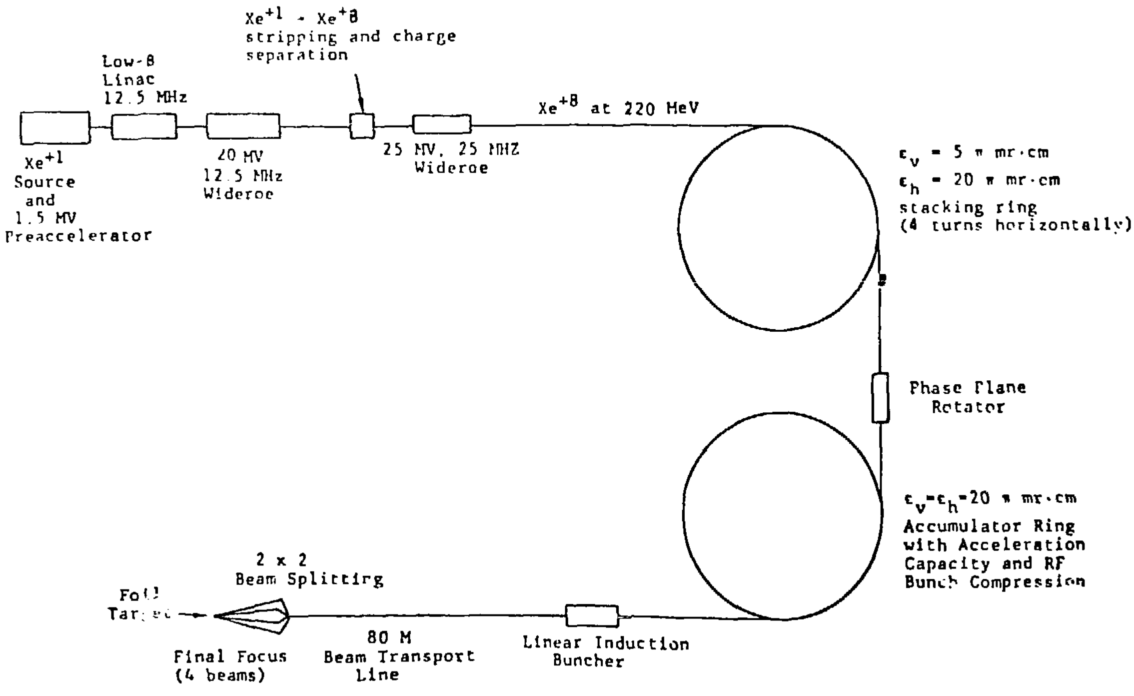
We estimate the cost of such a minimal program to be $25M for three years (FY 1980, 1981, 1982). It would include: Xe source, preaccelerator, buncher, first-stage low β (2 MV) (existing equipment); additional diagnostics, beam dump, matching, etc.; 20-MV, 12.5-MHz linac; stripper system, charge selection, diagnostics, matching, combination system; 25-MV, 25-MHz linac; transport line to ring building; two accumulator rings with 20–40-cm mrad acceptance, as well as injection system; debuncher and rebuncher rf, intermediate extraction system; phase space rotator; second injection system, internal compressor, and second extraction system; external compressor; external transport line; beam dump (from rings); and splitting septums (with matching system). Such a program has begun at ANL.

This minimal R&D program is designed to answer questions about the following rf linac accelerator design issues:

(a) Front end: source and column characteristics, reliability; rf capture, low β acceleration, current limitations; stripping efficiency, charge selection, rematching, recapture (longitudinal emittance control); 6-D emittance growth; transport limits of high space charge beams.

(b) Storage rings: debunching; injection (efficiency, emittance growth, effect of beam loss); beam lifetime—charge changing cross sections; filling of both transverse phase planes (transfer from one ring to another with phase rotation); internal beam rf compression (beam handling above space charge limit); extraction efficiency, reliability (effects of beam loss); demonstration of adequate vacuum technology under operational conditions; feasibility of single-pulse synchrotron acceleration (optional).

(c) Extracted beam: external compression—demonstration of acceptable dilution of longitudinal emittance; provision of short pulse duration for transport, propagation, focusing, and deposition demonstrations; demonstration of compression of successive pulses with ringing compressor for charge state telescoping; transport—checking of instability theory (transport power limits); injection of beams into common beam line for telescoping; splitting—demonstration of acceptable emittance dilution; demonstration of survivability of splitter; demonstration of multiple splittings (two or more in each plane); focusing on target spot—demonstration of ultimate achievement of expected emittance; aberration corrections, chromatic and geometric, in the presence of space charges. **(12 min)**



WD6 Fig. 1. Radiofrequency linac accelerator demonstration facility.

TUB12 Measurement of neutralization times of intense Xe^+ beams at low energies: beam-residual gas ionization cross sections

MICHAEL G. MAZARAKIS, DANIEL K. NIKFARJAM, and JERRY M. WATSON, Argonne National Laboratory, 9700 S. Cass Ave., Argonne, Ill. 60439.

This paper gives results on the neutralization time of intense Xe^+ beams and their dependence on beam energy and ionization cross sections. This work is part of the continuous studies on transport and charge neutralization mechanism of heavy ion beams by the Argonne National Laboratory Ion Beam Fusion Group.

Figure 1 outlines the experimental arrangement, described in detail elsewhere.[1] A 3-mA dc 100-keV Xe^+ ion source injects into a 4.5-m long transport line.

In these experiments ($\sim 1 \times 10^{-6}$ Torr static vacuum) the Xe^+ beam is space-charge neutralized all along its path. If a positive voltage is applied on one of the clearing electrodes, the electrons are removed from the beam, and the beam blows up as a result of its space-charge forces. The current recorded by the second-box Faraday cup corresponds to the fraction of the beam that makes it through its 1.3-cm aperture hole and is an inverse function of the degree of space-charge neutralization. The fully neutralized beam at that point has an ~3-mm diam envelope and passes entirely through the aperture.

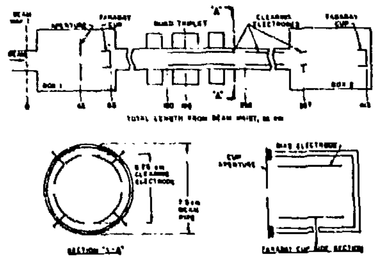
Pulsed positive voltages were applied on the short clearing electrode (Fig. 1), and the beam response on the second cup was observed using an oscilloscope. The time lapsed between clearing voltage cutoff and reestablishment of maximum current reading (= full neutralization, minimum-sized envelope) is the neutralization time.

The beam energy was varied by increments of 10 keV from ~40 to ~100 keV, and the neutralization times were recorded. Table 1 gives the measured neutralization times and the operating average residual gas pressure and gas composition. P_{Xe} and P_{N_2} are the xenon and nitrogen partial pressures of the residual gas. The last column gives the total-beam–residual-gas ionization cross sections deduced from the measured neutralization times t using the expression $\sigma = [t \cdot v \cdot (\eta_{Xe} + 2\eta_{N_2})]^{-1}$, where η_{Xe} and η_{N_2} are, respectively, the average number density of xenon atoms and nitrogen molecules in the residual gas along the beam path, and v is the velocity of beam ions.

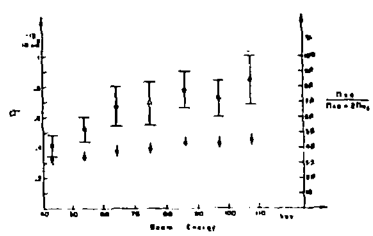
Figure 2 gives the ionization cross section σ (solid circles), while the lower points give the corresponding $\eta_{Xe}/(\eta_{Xe} + 2\eta_{N_2})$ for each measurement.

The ionization cross section tends to increase with a simultaneous increase in both beam energy and xenon fraction of the residual gas. These results were obtained with a low-vacuum setup (Fig. 1), where it was difficult to keep the residual gas composition constant. Current experiments with a new high-vacuum transport system will resolve the energy and gas composition dependence of the ionization cross section. **(Poster paper)**

1. M. G. Mazarakis *et al.*, IEEE Trans. Nucl. Sci. **NS-26**, 3042 (1979).



TUB12 Fig. 1. Experimental setup, clearing electrodes, and second-box Faraday cup details.



TUB12 Fig. 2. Total ionization cross sections (solid circles) for a residual gas number density composition indicated by the open circles.

TUB12 Table 1. Neutralization Times and Ionization Cross Sections as Functions of Ion Energies, Total Gas Pressure, and Gas Composition

Energies (keV)	Gas pressure $\times 10^{-6}$ Torr	Gas composition P_{Xe}/P_{N_2}	Neutralization time (μsec)	Ionization cross sec. $\times 10^{-16}$ cm^2
43	2.5	0.93	700 ± 100	4.1 ± 0.72
54	2.5	0.93	480 ± 50	5.2 ± 0.80
65	2.8	1.1	380 ± 50	6.7 ± 1.3
75	2.9	1.2	280 ± 50	6.9 ± 1.4
86	3.2	1.5	230 ± 30	7.8 ± 1.2
97	3.2	1.5	230 ± 30	7.2 ± 1.2
107	3.4	1.6	180 ± 30	8.4 ± 1.6

VI. ANL Ion-Beam Fusion Notes*
(written during the first six months of FY 1980)

Introduction to Particle Code (IBF Note #121, 11/1/79)
by: H. Takeda

Introduction

We are interested in the collective behavior of a beam in an accelerator system due to space charge.

Let us consider particle trajectories of a beam. Although we have large memory computer systems that have, at most, an order of one million memory storages, it is impossible to trace $10^{10} \sim 10^{11}$ particles.

We consider an ensemble of macro particles, each of which corresponds to about one thousand real particles. Upon given initial conditions (emittance, velocity, mass of particle, intensity, current, charge state of beam particle, etc.), we expect to be able to calculate collective beam phenomena from macro particle dynamics.

Heavy Ion Transport from Wideroe Linac to Accumlator Ring (IBF Note #122, 11/30/79)
by: E. Colton

We describe a scenario for transport of an intense heavy ion beam to the PPA ring which will be situated in the ZGS tunnel. The transport distance is $\sim$ 74.2 m from the 12.5 MHz debuncher to the vicinity of the injection septa. The transport was designed to carry a 2.5 mA bunched beam of 8.5 MeV Xe^{+1} ions with a geometrical emittance of 5.0 cm-mrad in both transverse planes. Futhermore, the beam is translated up in height by 1.37 m within Building 370. The system was tailored to satisfy the match conditions required for injection into the ring.

Redesign of the Wideroe Linac Quadrupole Magnet (IBF Note #124, 1/3/80)
by: R. Lari

---

* This list is included to provide a survey of the topics investigated at ANL during FY 1980. The reports themselves are informal and not generally suitable for circulation.

X-Ray and Pressure Conditions on the First Wall of a Particle Beam Inertial Confinement Reactor (IBF Note #125, 1/18/80)
by: G. Magelssen

Abstract

Because of the presence of a chamber gas in a particle beam reactor cavity, non-neutron target debris created from thermonuclear burn will be modified or stopped before it reaches the first reactor wall. The resulting modified spectra and pulse lengths and the cavity overpressure created by the momentum and energy exchange between the debris and gas need to be calculated to determine their effect on the first wall. The purpose of this paper is to present results of the debris-background gas problem obtained with a one-fluid, two-temperature plasma hydrodynamic computer code model which includes mutlifrequency radiation transport. Spherical symmetry, ideal gas equation-of-state, and LTE for each radiation frequency group were assumed. The transport of debris ions was not included and all the debris energy was assumed to be in radiation. The calculated x-ray spectra and pulse lengths and the background overpressure are presented.

ANL Accelerator Demonstration Facility (ADF) Storage Ring Vacuum System (IBF Note #127, 2/4/80)
by: J. Moenich

Introduction

The purpose of the Accelerator Demonstration Facility (Phase Zero) will be to assess the feasibiity of using a heavy ion beam as a driver for inertial confinement fusion.

The storage ring for this facility will pass through approximately 68 large magnets, and its shape and overall dimensions are dictated by the necessity to locate the magnets on concrete piers in the Zero Gradient Synchrotron facility at Argonne National Laboratory. The ADF storage ring system is nearly circular with a 562 foot perimeter consisting of sixty-six eight inch diameter straight sections, 16 sections curved on a 30-foot radius and injector and extractor sections. The curved section radius is determined by the radius of curvature of existing C-magnets whose bore also suggest the cross-sectional shape of these 16 parts. An elliptical cross-section with a major diameter of 9.5 inches and a minor diameter of 2.5 inches is being considered.

Storage of a circulating, high power xenon beam dictates a ring operating pressure of 1×10^{-10} Torr, and an ultimate pressure of $\sim 1 \times 10^{-11}$ Torr. Realizing such low pressures in the storage ring system is achievable but challenging and requires exacting techniques to produce the necessary results.

Vacuum Requirements:
2.5 mA Heavy Ion Transport from Wideroe Linac to Accumulator Ring
(IBF Note #125, 1/28/80)
by: J. Moenich

ANL/IBF Note #122 describes a scenario for transport of an intense heavy ion beam to the PPA ring which will be situated in the ZGS tunnel. The transport distance is ∿ 75 M from the 12.5 MHz debuncher to the vicinity of the injection septa.

The debuncher end of the transport line will operate at ∿ 1 x 10^{-7} Torr. Since the PPA ring will require a base pressure of ∿ 1 x 10^{-11} Torr, the injection end of the transport line must be reduced to this pressure to maintain the integrity of this requirement. From this observation it is apparent that construction and preparation of the transport line must be accomplished with as much detail and care as the PPA Ring Vacuum System itself.

This note describes a solution for achieving the pumping and pressure requirements of the transport line.

Determination of Beam Emittance α_0 and β_0 from Three Beam Width Measurements
(IBF Note #128, 2/8/80)
by: E. Colton and H. Takeda

Eddy Current Field and Power Loss in a Circular Vacuum Chamber
(IBF Note #129, 2/21/80)
By: T. Khoe

Interbeam Interactions and Envelope Oscillations
in Injection Processes at the Space Charge Limit
(IBF Note #130, 3/5/80)
by: H. Takeda

In this note, we will discuss the nonlinear space charge effect between beams during injection and associated envlope oscillations for different beam configurations in the phase space. The total beam current is set so that the whole beam reaches to the space charge limit. The detailed numerical model was described elsewhere (IBF Note #105).

The realistic storage ring assumes various kinds of beam transport elements, but an important beam dynamic is determined by the quadrupole doublet elements. We set up the lattice as simply as possible but still inherit the essence of the realistic lattice. This is done by utilizing thin lens approximation for quads and choosing proper drifting spaces.

Scaling Analysis of Accelerator Parameters for Deposition Experiments
(IBF Note #131)
by: R. Arnold

For the BDF, the proposed main accelerator is a single-pulse synchrotron (repetition time about 10 seconds), followed by beam-splitting to achieve target spots smaller than 1 mm radius.

The ramp-time of the synchrotron will be chosen fast enough to avoid losses $\gtrsim$ 10% of the beam through collisions of the ions with other ions or background gas; this time is at least 1/10 sec, if high enough charge states can be used. The initial emittance will be larger, and the injection energy smaller, than previous (Phase I) plans. Acceleration by factors of $\sim$ 50 in energy with adiabatic damping of transverse emittance, followed by up to 4 x 4 splitting, will allow small spot sizes to be targeted. One synchrotron ring will give rise to many beams on target (16, with 4 x 4 splitting).

We will analyze here the influence of choice of charge state q, ion mass A, injection energy E_i, injection emittance ε_i, and splitting factor S.

We assume the final BR of the synchrotron is fixed (at its maximum practical value, e.g., around 20 T-M).

Beams for Target Heating Experiment from Phase Zero
(IBF Note #132)
by: R. Burke

A year ago, we were working toward an accelerator system that would be able to produce beams for relevant beam propagation and energy deposition experiments. That Phase I plan was put aside when we were assured funding for a less ambitious program that would cost about one-half as much, but start a year sooner. The new program would also meet its objectives earlier, and could then be expanded into the Phase I. It was taken for granted that the less ambitious program (Phase Zero) could not do the experiments planned for Phase I.

A fresh look at the possibilities for a system compatible with the Phase Zero guidelines indicates that much more can be done with it than has been thought. Among the important features needed to make this possible, the use of a synchrotron is probably the most essential. There is a strong connection here to the assumption that interesting beams could not be produced by Phase Zero, because the idea that this project is an "rf linac - storage ring" project has been repeated often. Other features of a plan to achieve interesting beam parameters with an investment like that planned for Phase Zero would be the use of beam splitting just upstream of the final focusing system, multiple final beams, and a synchrotron with a relatively large aperture and the highest magnetic rigidity that is practical for a machine in the ZGS tunnel. This report gives a very brief summary of the plan, indicates accelerator system parameters, and presents my feelings about the practicality of some aspects based on our past studies and some new calculations.

Ion Fusion Storage Ring Preliminary Design, Injection, Extraction
(IBF Note #133, 3/17/80)
by: E. Crosbie

Final Focusing of 10-GeV Mercury Ions
(IBF Note #134, 3/18/80)
by: E. Colton and H. Takeda

As part of the ongoing research into the feasibility of heavy ion fusion we have investigated the characteristics of a four quadrupole transport line used to focus a beam of 10 GeV Hg^{+2} ions, nominally occurring in a 5×10^{-9} sec bunch with an instantaneous current of 60 amperes. The primary goals were to focus to a beam spot radius of 0.05 cm in a small distance $R_C < 1.0$ m (standoff) from the downstream end of the fourth quadrupole. The geometric transverse emittance was taken to be $\varepsilon = 2.0 \times 10^{-5}$ m; we utilized $R_C = 0.75$ m and superconducting quadrupoles with pole-tip fields of 6.0 T. The performance of the chosen system has been tested with regard to several different initial distribution functions, second-order chromatic aberrations, third-order geometric aberrations, aberrations due to multipole fields, and beam currents in excess of 1000 amperes instantaneous. We have also tracked the envelope behavior of different beams as they fly in toward the target.

Heavy Ion Driver Cost Scaling for Fixed Specific Deposition Energy
(IBF Note #135, 4/8/80)
by: R. Arnold

This note is a further development of simplified cost scaling models for linac and synchrotron HIF drivers first investigated a year ago, here expanded to include results of scaling analyses for deposition experiments (IBF Note #131). We consider variations in cost of drivers with alternate choices of charge-state ion mass number, final kinetic energy, and beam emittance, to find cost minima. It is necessary to fix the structure of the driver and not allow variations in system, e.g., in number of beamlines per storage ring, or changing from a non-telescoping to a telescoping design; we consider essentially "adiabatic" changes from a given point design. Thus, our scaling can only be valid over a limited range around a given point design.

The parameters which have primary influence on the target performance are selected to be the beam pulse energy Q and the specific deposition energy D. For the driver classes we consider, changes in pulse length (or instantaneous targeted power) do not have a major impact on cost. We will consider variations in q, A, etc., and minimize costs at fixed Q and D. This will allow us to obtain scaling laws for cost as a function of Q and D. The results do not themselves contain explicit feasibility information, so quantitative conclusions should be checked by examining point designs for technical feasibility.