FISCAL YEAR 1978

ANNUAL PROGRESS REPORT

HEAVY ION FUSION PROGRAM

ARGONNE NATIONAL LABORATORY

TABLE OF CONTENTS

I. Overview of the Argonne National Laboratory Program

The heavy ion fusion program at Argonne in FY 1978 had two components: design activities and an experimental R&D program. Separate reports on these two activities will follow.

We have defined and examined two reference designs. HEARTHFIRE Reference Concept #2 is a 1 MJ, 160 TW rf linac-accumulator system. Since before the first workshop in July 1976, the very significant advantages of conventional linac-accumulator systems over synchrotron-accumulator systems in terms of repetition rate (hence, average beam power) and efficiency had been recognized.[1] The major drawback at that time appeared to be the relatively high cost of linacs per unit of ion energy. Consequently, we spent the majority of our design effort in FY 1978 investigating synchrotron acceleration for this application. HEARTHFIRE Reference Concept #3, outlined in ANL/ACC-6 which was distributed in June 1978, is a description of a 1 MJ, 160 TW synchrotron-accumulator system.

There are many similarities between the two systems. The injector for the synchrotrons, of course, is an rf linac so all of the low energy questions of both systems are nearly identical; and the final beam transport and focussing questions are nearly independent of what type of acceleration is used to arrive at this point. Also, the charge states proposed are similar (Hg^{+8} vs. Xe^{+8}) but for somewhat different reasons.

One of the major uncertainties of synchrotron-accumulator systems has been the ionic charge-changing cross sections. Accumulation in much less than 1 sec is difficult if multiple synchrotron pulses are required. Hence, cross sections of 10^{-16} cm^2 would lead to unacceptable beam loss. The resolution to this problem, we believe, is in the choice of Xe^{+8}. This ion has closed shells of principle quantum number 4. It, therefore, should be a very small ion with tightly bound electrons. We estimate that the charge changing cross sections (including ionization) are an order of magnitude less than those of Xe^{+1} (and even Xe^{+7}), and is probably less than 10^{-17} cm^2 in the energy range of interest. Beam loss due to this effect of less than 10% in 1 sec would be expected with this ion. Other ions with the same electronic configuration would be Ba^{+10}, Cs^{+9}, I^{+7}, and so on to Ag^{+1}. Xenon appears to be an appropriate choice from the point of view of source and accelerator technology, although very bright Cesium sources can be made, and Iodine is unique in having only a single stable isotope. If lower charge states were desired for synchrotron based systems, it would seem desirable to develop other sources in this series.

For linac-accumulation systems, the charge changing cross sections are thought to be of minor importance since accumulation can be done in a few milliseconds. Our earlier work[2] had indicated that a cost advantage was realized in going to lighter ions had higher charge states. The technical difficulty is increased, however, for choices in this direction. In addition, the cost minimum was rather broad, so that rational choices depend more on source technology, on the degree of confidence in the beam manipulations required, or other factors, than on cost. For this system, we have chosen Mercury ions because they are somewhat heavier than Xenon, and because we believe the source technology with this ion is quite advanced. Hughes Research Laboratories has built mercury sources as ion thrusters with 90% of the injected mercury atoms appearing in the beam as ions. Mercury is not chemically active and can be prevented from depositing on electrode surfaces (or removed if deposits occur) by maintaining such surfaces at 50-100° C. Thus, a relatively small development program could demonstrate the reliability of a high gradient column transmitting an intense Mercury ions. The charge state of eight was chosen for HRC #2 as the highest that we were comfortable with in terms of number of rings and beam lines to transmit the desired power. A lower charge state would increase the confidence level in the credibility of the system and somewhat increase its cost.

The most difficult problem of rapid cycling synchrotrons for this application, and one recognized prior[3] to the 1977 workshop at Brookhaven, is the low bunching factor allowed if one wants to maintain a small $\Delta p/p$ with a high $\dot{B}$. In HRC #3, to accelerate with a $\dot{B}$ of 130 T/sec (60 Hz repetition rate in the synchrotron), the maximum allowed bunching factor is 0.075. As a consequence, the space charge limit per pulse in the synchrotron is correspondingly reduced so that eight synchrotrons, each operating at 60 Hz, are required to accumulate enough ions in 1 sec. The cost advantage initially perceived for synchrotron-accumulator systems is thus reduced. This raises serious questions of direction: whether the cost advantage for synchrotron-accumulator systems (now projected at little more than $100 M for a 1 MJ driver) justifies the added difficulty, complexity, and greater uncertainty in the result as compared to rf linac-accumulator systems. Our general feeling at this time is that the higher level of confidence of rf linac-accumulator systems overshadows any cost advantage that might remain with rapid cycling synchrotron. It seems especially clear in view of the many other nonaccelerator related uncertainties of inertial confinement fusion (involving pellets, reactors, tritium handling) that minimizing the cost for the first "proof-of concept" effort should be a secondary goal. Therefore, we believe the main emphasis of the program should be placed on rf linac systems. This conclusion in no way, of course, impacts Argonne's R&D program which is focussed on producing a reliable front end (source, preaccelerator, low beta linac) common to either rf linac or synchrotron systems.

One should not lose sight of the fact that single pulsing synchrotrons may yet play an important role in the development of heavy ion fusion. Repetition rate and efficiency are not so important in the development and demonstration of the technology, nor in ion-target coupling experiments, as they are in commercial power production. Single pulsing synchrotrons avoid many of the problems referred to above and might represent a significant cost savings for the development program.

Our 1 MJ reference designs will be described next in detail. We should emphasize that it is essential in both systems to maintain the longitudinal emittance area of the beam at the exit of the linac. This requirement relates to the momentum spread, $\Delta p/p$, which can be transported and focussed on the target. Final compression of the beam increases the momentum spread so that dilutions of the longitudinal emittance of the linac beam of a factor of only a few are allowed if one is to have $\Delta p/p$ on the target $\leq 3 \times 10^{-3}$, which appears to be a maximum value without serious chromatic corrections (dependent, of course, on the size of the target). Therefore, debunching (decreasing $\Delta p/p$ and increasing the bunch length) at the end of the linac seems essential and is included in both system designs. In addition, in the synchrotron-accumulator system of HRC #3, the preservation of longitudinal emittance was the reason for the complicated (and time consuming) debunching-rebunching operations in stacking rings. Some of these requirements could be alleviated somewhat by achromatic transport lines and chromatic corrections to the final focussing elements. Investigation of chromatic corrections using sextupole magnets, suggested by Brown,[4] are being carried out and is the subject of a paper by Colton included here and published in the 1978 workshop proceedings.[5]

Another aberration of the final focussing system is the third-order geometrical aberration. The importance of this effect was pointed out by Garren and Neuffer and discussed at a meeting held in Berkeley early this summer. The effect is very sensitive to the radius, a, of the beam in the final triplet and is proportional to a^4. Outstanding questions were where the main contributions of this aberration were coming from and whether a system of octupole magnets could be used to correct the aberration. Work by Fenster reported here and published in the 1978 workshop indicates that the effect is almost entirely due to the fringe fields of the quadrupoles. Calculations with a system including six realizable octupoles indicate that one can nearly eliminate the aberration for a 20 GeV Xe beam with a maximum radius of 30 cm. Space charge forces were not included in this calculation. However, they are not very dominant with beams of such large size in the final focussing system.

We will finally give a status report on our experimental program. Our goal is to achieve as high a preaccelerator voltage as we find practical. Space charge limited currents in the initial section of the linac are sensitive to the preaccelerator voltage (since sources of adequate currents are only achieved by extracting singly charged ions). In addition, the resulting higher velocity ions allow a higher initial linac frequency, hence fewer frequency transitions to final, more economic linac structures. Our initial goals are 30 mA of Xe^{+1} at 1.5 MeV and initial linac sections of 12.5 MHz.

References

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4. K. Brown, "A Design Procedure for Correcting Second-Order Geometric and Chromatic Aberrations in a Beam Transport System," Report BNL-50769 (1977).

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6. S. Fenster, "Octupole Correction of Third Order Aberration," 1978 HIF Workshop proceedings.

II. Design Activities

Summary

During 1978, Argonne's heavy ion fusion design studies continued to develop systems based on synchrotrons as well as linac/storage ring systems. Since it is generally recognized that workable Heavy Ion Fusion (HIF) systems can be designed but that such systems may be too costly, the emphasis of our design studies has been to minimize cost. This has involved developing concpets for components, for example, clustered quadrupoles for parallel beam transport lines, but the most important issue has continued to be realization of the cost savings possible with synchrotrons.

Viable synchrotron systems designs were worked out at both of the previous HIF workshops.[1,2] Both designs used single charged ions, however, and needed 2 GV linac injectors. Also, with singly charged ions, the ability to hold beam losses to an acceptable level was uncertain. On the other hand, our cost studies[3] have indicated that multiply stripped ions are advantageous for synchrotron as well as linac systems. These ions also make the expectation for beam loss more optimistic. The main problem is, of course, the reduced space charge limit; and the approach that we have been taking to this problem is the use of multiple, rapid-cycling synchrotrons that fill storage rings. The complications of these designs, however, are leading to the conclusion that the rapid cycling option is not attractive. This conclusion has no bearing, of course, on the prevailing view that synchrotron systems can (a) probably be made to work, albeit with more effort than rf linac systems, (b) have deficiencies as reactor drivers, but (c) may be less expensive than the alternatives. Rather, the results of our work on the rapid cycling option indicate that our design work for synchrotron systems should concentrate on finding ways to minimize the cost of systems which are more similar to the less complicated designs worked out in previous years.

The linac system that we prepared for the 1978 HIF workshop contains a novel approach to transverse stacking, which may be the most interesting question about the workability of these systems. The real issue for these systems, however, is well known to be cost minimization, which can be approached by optimizing the parameters, finding cost effective design concepts and working on unit costs. Following the first two of these approaches is manifested in our designs by the use of multiply stripped ions, the clustered beam lines, and compressors that handle multiple beams. Unit cost reduction is more difficult to address. In fact, the real gains to be made in unit costs are likely to result from large scale industrial involvement in producing power using HIF, predicting the impact of which will require years of work with annual funding well beyond the FY 1978 HIF budget. Without the benefit of unit cost reduction, our expectation remains that synchrotron systems still have a cost advantage, as long as the efficiency and repetition rate of linac systems are not issues of overriding importance.

The linac system (HEARTHFIRE Reference Concept #2) and the synchrotron system (HEARTHFIRE Reference Concept #3) are described in separate reports,[4,5] and the following concentrates on qualitative aspects of the designs. Some of the important design issues are suggested by the parameters given in Table I.

Choice of Ion Parameters

The considerations involved in choosing the ion mass, charge state, and kinetic energy for our HIF systems have included ion source availability and practicality, overall system cost, targetting, and beam losses. The state of ion source technology has held us to using two ions, mercury and xenon, for which sources with the necessary high brightness seem in hand[6] and which promise a minimum of chemical or other problems likely to depreciate the reliability of the system.

For choice of the charge state and kinetic energy, the issues are not so plain. Cost studies indicate advantages for higher charge states and kinetic energies because of the reduction of the sizes of linacs and circular machines with higher charge states and the increased storage per circular machine with increased ion kinetic energy. Targetting requirements, however, limit the maximum kinetic energy. For synchrotron systems, which thrive on high kinetic energy, this effectively sets the choice for the kinetic energy at the maximum allowed by targetting. Using maximum range ions with linac systems is not as traceable to one predominating reason. Additional reasons include the length and strength of final focussing elements, beam losses, and the beam power transport limit, which increases with charge state for a given linac length.

Consideration of beam loss reinforces the selection of multiply charged ions, particularly for synchrotron systems. As is well known, the relatively long time required for a synchrotron system to build up the total beam energy creates a need for an ion that is resistant to beam loss processes; and the sharp drop in the cross section for beam-beam charge changing collisions expected for Xe^{+8} as compared to Xe^{+7} is the basis for using Xe^{+8} in the synchrotron system.[7] Using this relatively high charge state reinforces the choice to use the maximum allowed kinetic energy, as this offsets the effect of the higher charge state on the number of particles that can be injected into the synchrotron at the space charge limit.

The especially low beam-loss cross section for Xe^{+8} also helps explain why xenon is used only for the synchrotron system. While consideration of the range in the target allows a higher kinetic energy to be used with mercury than with xenon, and therefore relaxes the space charge problem somewhat, this gain would be more than offset by the much higher charge state needed for a mercury ion to have as low a cross section as Xe^{+8} for beam-beam charge changing collisions. On the other hand, the much reduced importance of beam losses for the rapidly charging linac systems leaves them free to make use of the shorter range properties of mercury. To best represent the current viewpoint of the design studies, however, it should be noted that the potentially higher practicality of high voltage accelerating columns for xenon compared to mercury could be an overriding factor. Thus, the use of mercury for the linac system is at least not as consequential as is the use of xenon for the synchrotron system.

Transverse Phase Space Considerations

The consequences of using a high charge state ion in a synchrotron system become apparent when the details of injecting, accelerating, manipulating, and eventually targetting the beam are studied. The transverse phase space is typically considered first. Through the linacs of either the synchrotron system (Fig. 1) or the linac system (Fig. 2), the objective is to accelerate a beam with a current sufficient to keep the number of turns of transverse injection to a practical number and with a minimal transverse emittance. When this beam is injected into the synchrotrons, it is found that a relatively few turns of injection reach the low space charge limit caused by the high charge state. Thus, at this step, considerable dilution in the transverse phase plane is tolerable, and in fact, needed to maximize the space charge limit. The direct approach is to inject the synchrotrons with a beam whose normalized emittance is equal to the value chosen for final targetting reasons. This requires, however, that all subsequent stacking would have to be in the longitudinal phase space; and this was found to produce a momentum spread in the beam that was larger than wanted at the final focussing lenses. The approach to this problem was to lower the transverse emittance of the beam injected into the synchrotrons and transversely stack synchrotron pulses in special rings, called rebunchers, until the maximum emittance is reached. The larger values of the relativistic parameters and the bunching factor allow a much higher space charge limit and the rebuncher rings could accommodate more particles per pulse than the synchrotrons with the same normalized emittance. Thus, even though more synchrotron pulses were required, this procedure resulted in less longitudinal stacking in the final storage rings.

The total 36 turn transverse stacking in HRC#3 consists of nine turns into the synchrotrons by two into the rebuncher rings by two into the storage rings. The stacking in the synchrotrons involves both the horizontal and vertical phase planes with the emittances equal in the two planes after loading. Stacking in the rebunchers and storage rings uses only the horizontal plane. The beam is rotated in a solenoid magnet during transfer between the rebunchers and storage rings, and the emittances in the two planes are again equal in the storage rings.

In this scheme, the available dilution in the transverse plane is used up at injection into the synchrotrons and transverse stacking in the rebunchers and storage rings uses a technique with the possibility of low dilution. The principle of this technique, proposed by Khoe in 1971,[8] is to create a separatrix in the transverse phase space in the form of a figure eight surrounding two stable areas so that previously stored beam resides in one and a new pulse can be injected into the other, as shown in Fig. 3. The two areas are caused to adiabatically merge by slowly adjusting the dipole, quadrupole, and octupole magnets used to generate the figure eight.

As shown by the entry in Table I of "none" for multiturn injection in the linac based system, the problems of transverse stacking were further explored for HRC#2. Multiturn injection was avoided by merging beam lines, external to the rings, with septum magnets. The penalty of this technique is the apparent complication, as seen in Fig. 2. However, the reason it was suggested is that it offers the possibility of combining both a small beam loss and a small dilution factor, as is described in the discussion of using the technique to combine the beams from the four rings of the CERN booster.[9]

Proposing this technique underscores the importance and difficulty of many-fold stacking in the transverse plane with both low beam loss and low emittance dilution. The problem is that intense heavy ion beams have a great potential for destroying whatever they strike because of the short range of the ions, and the impact of this destructive power is compounded by the high vacuum requirements. These specificatious for injecting HIF machines are significantly different than those for proton machines, which frequently operate with an injection efficiency of 50% or less to maximize density in phase space. For HIF the question is how much dilution must be accepted to avoid losing even a small percentage of the beam.

It seems possible to accomplish beam combination with septum magnets without loss and with an emittance dilution factor of about 1.4. This is much smaller than the dilution that is apparently necessary to avoid loss during multiturn injection, due to the effect of space charge on the latter. In the synchrotron system (HRC#3), a factor of three was allowed in each plane for injection of only three turns in each plane. For the sixteen turns in each plane of HRC#2, the dilution factor would need to be considerably larger, even if a special ring were used in which the beam would be injected into only one plane and then transferred to the final storage rings, again injecting into only one plane.

The impetus for using septum magnets to combine beam lines is that, without resorting to higher linac current (which is, however, feasible), the low dilution of the tèchnique is mandatory.

Dilution would be essentially the same whether the stacking ring is small and in circumference and filled and emptied many times during the filling of each storage ring or large in circumference and injected with the total number of particles that can be accommodated in each of the storage rings. The advantage of the latter is that it avoids a number of beam extraction events, but it has the disadvantage of exceeding the ordinary space charge limit. Although it may be possible to exceed the space charge limit for a small number of turns, this is not a simple question. Recognizing this, we considered employing a number of stacking rings which together would store all the particles for a single storage ring, but rejected this as without special merit in favor of the conservative, though possibly expensive, approach of merging beam lines.

Longitudinal Phase Space

As indicated above, we found considerable coupling of the problems of the transverse and longitudinal phase spaces, particularly for the synchrotron system. For these systems, the minimum longitudinal phase space area per pulse is the greater of (1) the sum of the areas of the linac bunches in a length of linac beam equal to the circumference of the synchrotron or (2) the sum of the beam bucket areas required for synchrotron acceleration. In the HRC#3 design, we strained to minimize dilution of the area occupied by the linac bunches. The means that we employed were to substitute some transverse stacking for some longitudinal stacking after the synchrotrons, debunch the linac beam by a large factor, and carry out adiabatic manipulations in the rebuncher and storage rings.

As expected, the longitudinal phase space was easier to handle for the linac system. Since all stacking could be in transverse space, the momentum spread of the beam at the final focussing lenses could be made substantially less than the prescribed value. The available margin led, in fact, to consideration of substituting some longitudinal stacking as a means of reducing the number of turns of transverse injection; but this was rejected as this approach did not seem needed.

Discussion of Reference Designs

Due to difficult manipulations which seem hard to avoid, the message from the HRC#3 design seems to be that rapid cycling is at best a very hard way around the low space charge limit caused by using multiply stripped ions. The real problems in the manipulations in HRC#3 are in avoiding dilution after injection into the synchrotron. In the transverse phase space, this requires dilutionless two-turn injection twice, plus other beam handling. Likewise for the longitudinal phase space, the debunching of the linac beam is not extreme, but avoiding dilution through the operations of capture in stationary buckets and acceleration in the synchrotron, debunching and rebunching twice, and various compression operations would seem to require extreme precision.

Conclusions about the workability of HRC#3, however, should not be applied to synchrotron systems in general, because it seems quite probable that the design choices leading to the complicated beam manipulations can be avoided. On the other hand, the most fundamental problem, beam loss, continues to appear tractable. Though undeniably difficult, the vacuum required to allow up to a second to accumulate beam seems feasible, and the loss from intrabeam collisions appears to be less of a problem than that resulting from collisions with background gas. Although very important in the context of an on-line power plant, the deficiencies of synchrotrons concerning repetition rate and efficiency do not rule them out for important demonstrations in the inertial fusion program. Therefore, it seems advisable to improve the design of synchrotron systems, especially by taking a design path that avoids some of the prominent pitfalls illustrated by HRC#3, which mostly concern rapid cycling.

The technical problems of the linac system, HRC#2, are less significant. The novelty of the delay lines and delay rings used for transverse stacking may attract question, but their flaw seems, if anything, to be a possible increase in the cost. Combination with septum magnets is certainly a means to minimize both dilution and beam loss, and the most difficult switching problem, that of the first switch in the delay line network, seems quite tractable in view of the small aperture in the switching magnet needed to accommodate the beam and the liberal dimensions that may be used to separate the various routes through the delay lines. On the other hand, the bare accommodation of the needed transverse stacking that makes beam combination with septum magnets necessary could be avoided by increasing the multiplicity of the sources. Likewise, the large factor by which the linac beam would be debunched to minimize the final momentum spread invites questions; but the dilution that might be expected is acceptable. Cost remains the important issue; and, while some concepts used in this system may have increased the cost without sufficient reason (e.g., delay lines and rings), and the savings possible with suggested new concepts (e.g., clustered beam lines) need to be evaluated, rather major efforts are needed to assess the ultimate cost of the components (e.g., rf power, linac structures, superconducting magnets) in the context of major power production using HIF.

Additional Design Activities

Clustering quadrupole magnets wherever parallel beam lines are employed is under consideration because of the cost savings of the magnets themselves and also for other advantages of compactness. An iron yoke is only needed around the entire cluster, and some savings in the cryostats should also be possible. The favored concepts for pellet irradiation currently call for packing beams into a small number of tight bundles, and clustering has an obvious use in this regard. Multiple final beam transport lines may profit from cost reduction; and a very compact cluster could make it possible to accelerate parallel beams in a single structure, which could lead to significant cost savings for a linac tree or final compression system.

Pellet irradiation by beams packed into tight clusters also minimizes the number of penetrations of the reactor vessel. A reactor concept that has been conceived in the design studies that shows the virtue of combining all the beams into two clusters, even if the area of the clusters is greater than the sum of the beams it comprises, is shown in Fig. 4. This departure from the falling lithium concept, proposed at Argonne National Laboratory (ANL) in 1974 in connection with an Relativistic Electron Beams (REB) driven reactor [10] was suggested by the fact that accelerator beams normally lie in the horizontal plane. This would require messy penetrations of a falling moderator. As can be seen by inspection of Fig. 4, the flow path of the liquid through the centrifugally positioned blanket can be arranged to provide structural protection from neutrons over all of the solid angle seen by the reacting fuel except that actually occupied by the beam port.

Finally, the design studies have been considering an approach to realizing high power at the pellet that complements the existing concepts of multiple beams and longitudinal compression. This concept, called telescoping beams, allows separate beam bunches to interpenetrate each other in real space by generating bunches of ions of different species so that their phase spaces are independent. Accelerated and manipulated separately until the final transport, a bunch of higher velocity ions switched into a beamline after a lower velocity species will overtake and penetrate the latter. With different velocities, the requirement is that the charge state and mass of the different species be appropriately selected to equalize their stiffness, the elementary condition for handling the different species in a common beamline. The advantages of this concept can be looked at from either of the complementary points of view that it increases (a) the total volume in phase space or (b) the number of bunches at the designer's disposal. More bunches allow more total phase space, and this means relaxation of the brightness requirements. Whatever one imagines the limit to be on the number of beams, telescoping allows a number of bunches greater than this limit.

Our earliest cost minimization studies indicated that low cost systems involve a large number of bunches, although we assumed each bunch required a beam line. An example of such systems were linac/storage ring systems operating with high charge state ions. Basically using a high charge state, such systems can easily accommodate a series of charge states. The complication of accelerating different species, as well as the need for a switch in the beam line, must be noted; but the elementary advantage in expanding the usable volume in phase space has the potential to be more important.

References

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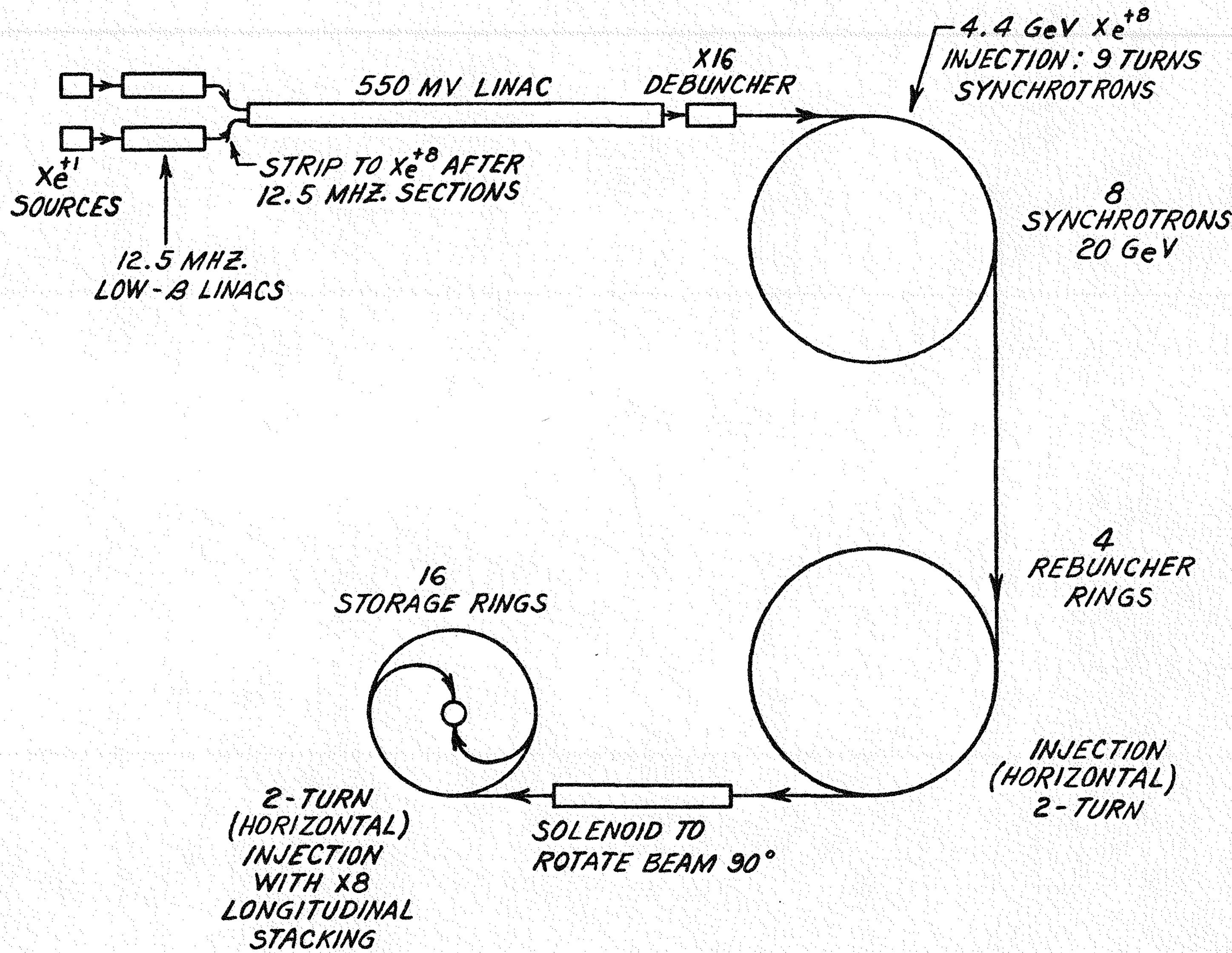
Table I

PARAMETERS OF TWO REFERENCE DESIGNS

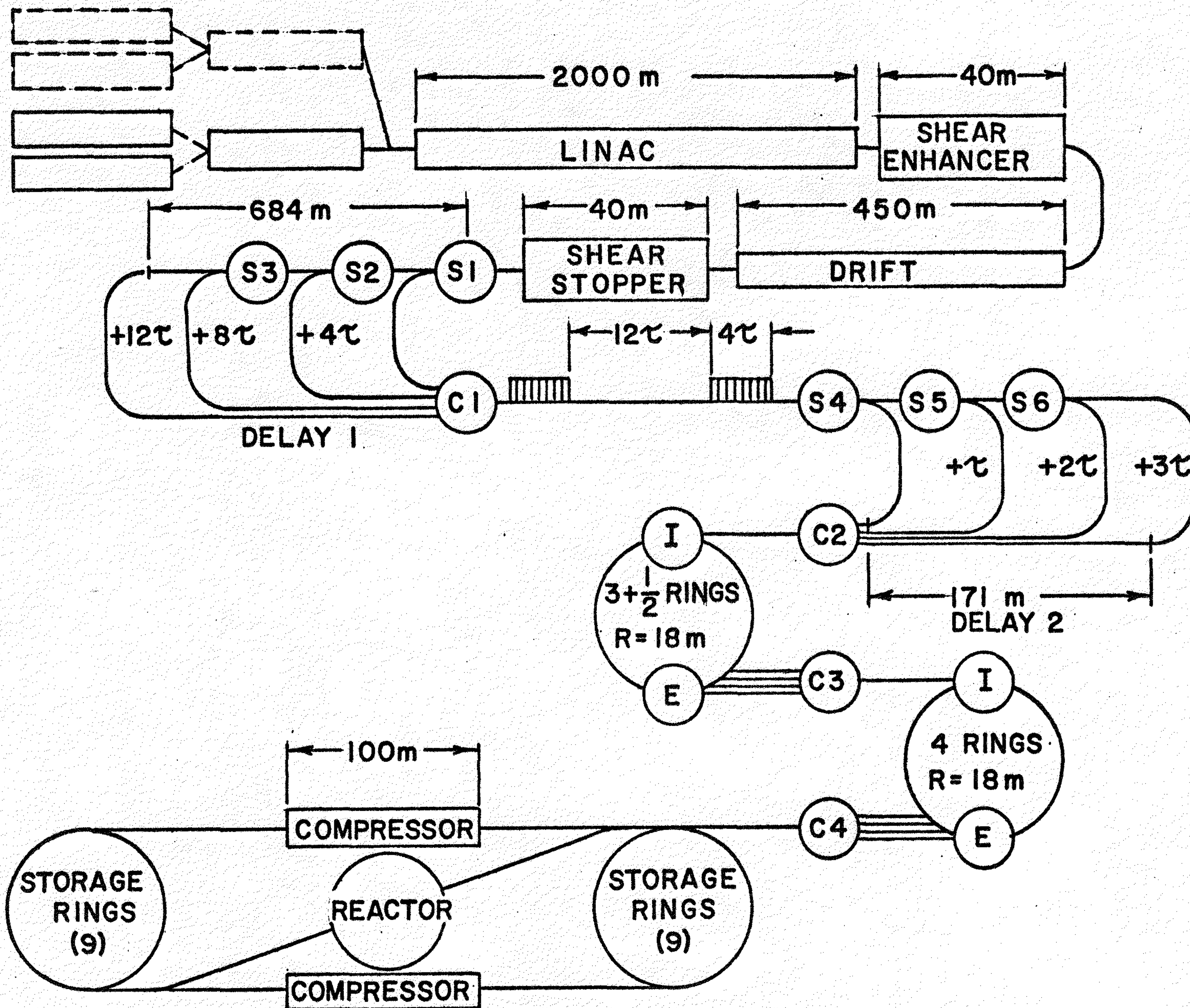
	Synchrotron (HRC #3)	Linac (HRC #2)
Total Energy	1 MJ	1 MJ
Total Power	100 TW (peak) shaped	160 TW unshaped
Time Per Pulse	1 sec	$\lesssim$ 0.01 sec
Ion	20 GeV Xe^{+8}	20 GeV Hg^{+8}
Pellet Radius	0.8 mm	1.1 mm
Port Radius	30 cm	20 cm
Chamber Radius	5 m	5 m
No. of Beams	24	18
Beam Emittance	4.7 cm·mr	4.4 cm·mr
Momentum Spread	0.25%	0.035%
No. of Rings	16	18
No. of Synchrotrons	8	-
Linac Voltage	550 MV	2500 MV
Multiturn Injection	x 9 x 2 x 2	None
Longitudinal Stacking	x 8	None
Linac Debunching	x 16	x 107
Debunch/Rebunch	Twice	Once
Final Compression	x 65 (in ring)	x 73 (external)

1 MJ / 100 TW (PK) / 1 HZ
HEARTHFIRE REFERENCE CONCEPT #3
SYSTEM CONFIGURATION



24 BEAM-LINES
TOTAL

Figure 1



1 MJ SYSTEM USING RF LINAC

Fig. 2

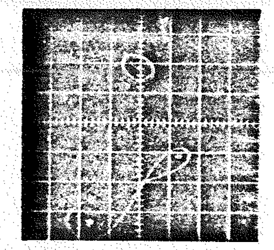


Figure 1

$\theta_1 = 4$ radians

$\varepsilon_0 = 0.0265$ cm

$\varepsilon_1 = 1.13$

$\varepsilon_3 = 0.33\ \mathrm{cm}^{-2}$

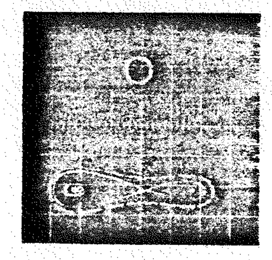


Figure 2

$\varepsilon_0 = 0.0265$ cm

$\varepsilon_1 = 1.13$

$\varepsilon_3 = 0.33\ \mathrm{cm}^{-2}$

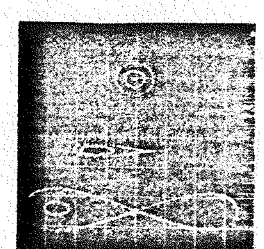


Figure 3

$\varepsilon_0 = 0.1811$ cm

$\varepsilon_1 = 0.0$ (top)

$\varepsilon_1 = 0.96815$ (middle)

$\varepsilon_1 = 1.13$ (bottom)

$\varepsilon_3 = 0.0004\ \mathrm{cm}^{-2}$

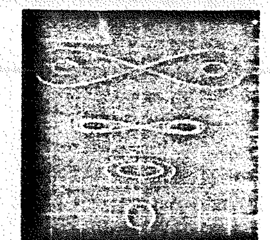


Figure 4

$\varepsilon_0 = 0.0$ cm

$\varepsilon_1 = 1.13$ (top)

$\varepsilon_1 = 1.00$

$\varepsilon_1 = 0.80$

$\varepsilon_1 = 0.00$ (bottom)

$\varepsilon_3 = 0.0004\ \mathrm{cm}^{-2}$

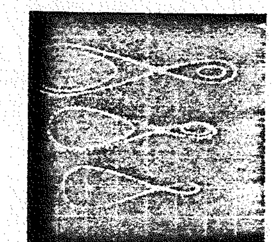


Figure 5

$\varepsilon_0 = 0.8858$ cm

$\varepsilon_1 = 1.13$

$\left.\begin{array}{l}\varepsilon_3 = 0.0004 \text{ (top)} \\ \varepsilon_3 = 0.0006 \\ \varepsilon_3 = 0.000883 \text{ (bot)}\end{array}\right\}\ \mathrm{cm}^{-2}$

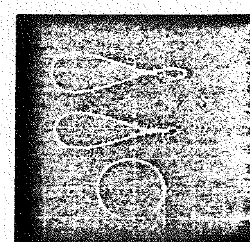


Figure 6

$\varepsilon_0 = 0.8858$ cm

$\varepsilon_1 = 1.13$ (top)

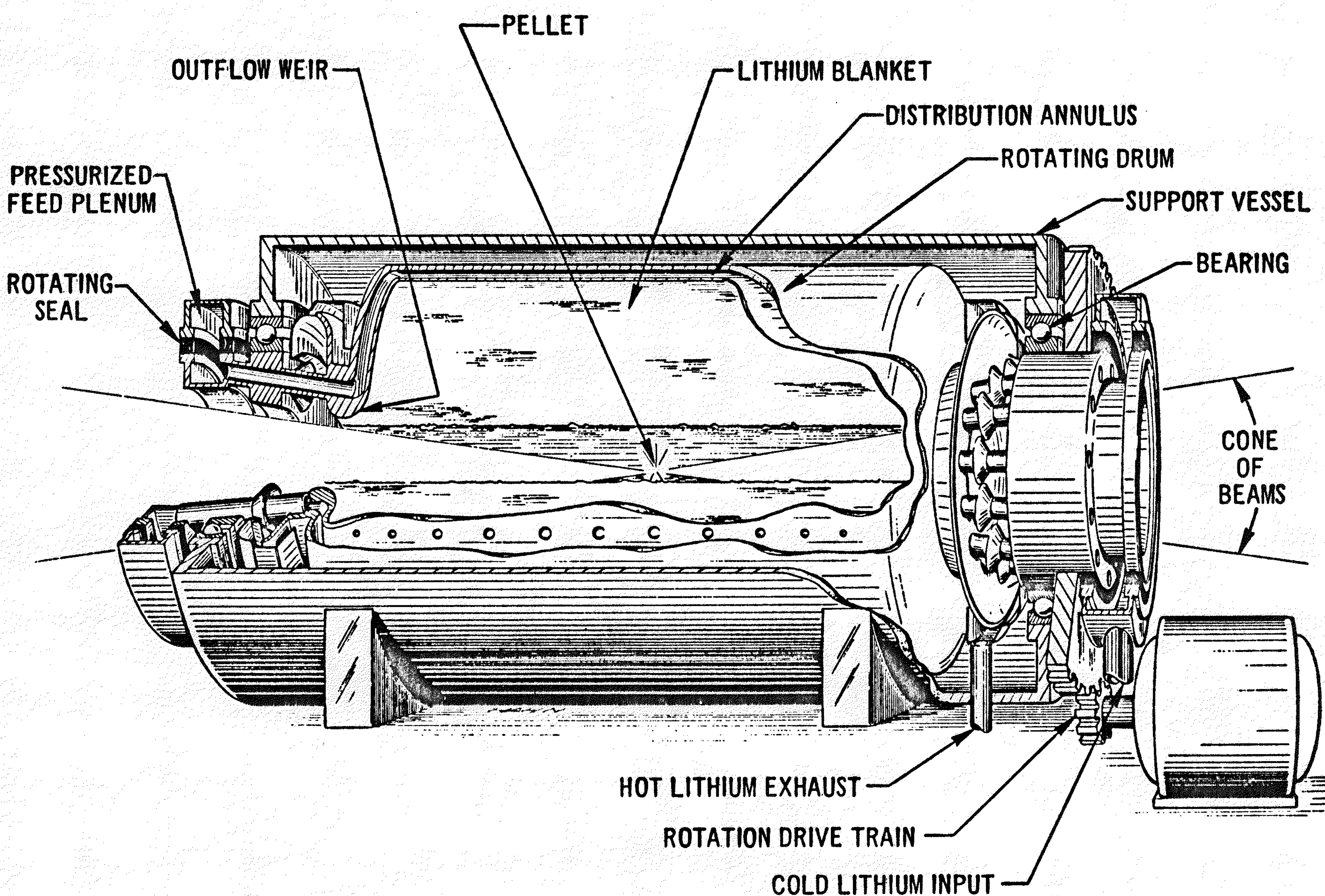
$\varepsilon_1 = 1.09081$ (middle)

$\varepsilon_1 = 0.00$ (bottom)

$\varepsilon_3 = 0.000883\ \mathrm{cm}^{-2}$

NOTE: For all figures, $\nu_x = 0.84$, $\nu_z = 0.79$, and $\theta_1 = \pi$, except Fig. 1.

Fig. 3



REACTOR WITH CENTRIFUGAL BLANKET

Fig. 4

III. ANL Experimental R&D:

Ion Source, Preaccelerator, and Low-Beta Linac

Introduction

The primary goal of the HIF experimental program at Argonne National Laboratory (ANL) is to develop an injector which would satisfy the requirements of an accelerator-based power plant. The injector under development consists of a high-intensity heavy ion preaccelerator and low-beta linac. The injector will be pulsed with instantaneous Xe^{+1} currents up to 100 mA with a normalized emittance of 0.01 mrad cm.

Our experimental program began in July 1977 with the acquisition of a surplus Dynamitron from the Goddard Space Flight Center. This type of parallel-fed voltage multiplier should be an excellent power supply for the preaccelerator. It has high current capability with little stored energy and the use of high-pressure insulating gas greatly reduces the space necessary for very high-voltage operation.

To achieve the current and emittance requirements it was clear that a new source and accelerating column would be needed. Hughes Research Laboratories (HRL) were contracted to develop the source. In their ion-implantation research HRL had already developed a Penning discharge source capable of 4 mA of Ar^{+1} with a normalized emittance of 0.002 mrad cm at 90 keV. We obtained one of these sources for our test stand and it is routinely operated at 80 keV with 2.5 mA of Xe^{+1} with a normalized emittance of .001 mrad cm. The 100 mA single aperture source was constructed and tested at HRL prior to delivery to ANL.

A new high-gradient accelerating column has been assembled. The high voltage gradient is necessary because of the large space charge forces at current densities up to 15 mA/cm^2. The column is similar to those used on the major proton accelerators except that special protection from ion bombardment of the ceramic walls is provided.

The general layout of the portion of the injector we are constructing and its experimental beam line is shown in Fig. 1. The experimental hall where the injector is being assembled is shown in Fig. 2. The preaccelerator is within the concrete vault. The control room is on the lower right and the beam line on the lower left. The preaccelerator is followed by an rf buncher and three sections of low-beta linac. These are independently-phased cavities with magnetic focussing quadrupoles between pairs of accelerating gaps. The first unit has two gaps and the second and third units have four gaps each. The buncher and first accelerating structure are nearing completion. The design of the next two units will be finished early in FY 1979. The experimental area downstream will be used to evaluate component performance by measuring current, charge state, and emittance. Neutralization and transport experiments could also be performed here.

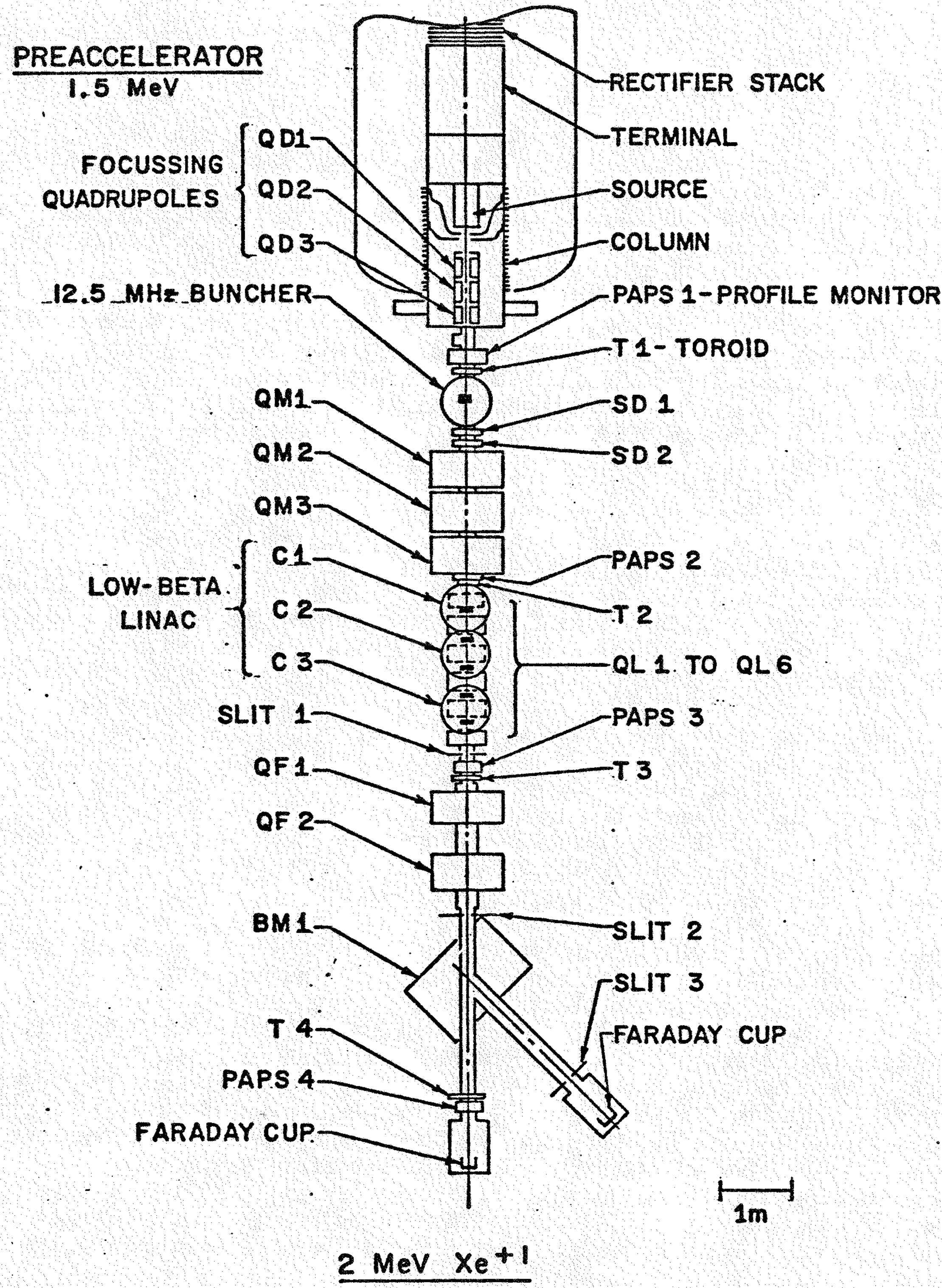


Figure 1 HEARTHFIRE Injector Layout

Fig. 2 Injector Experimental Hall

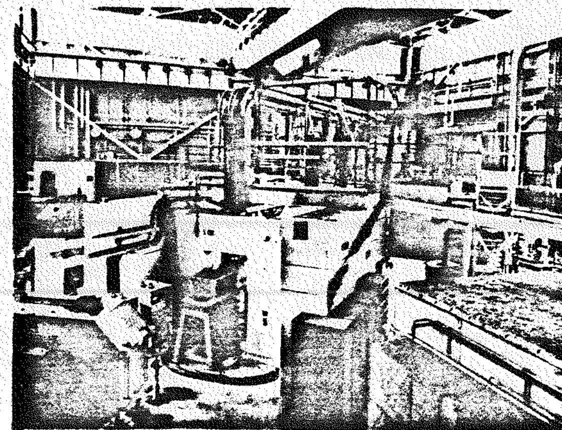


Fig. 3 1.5 MV Preaccelerator Power Supply

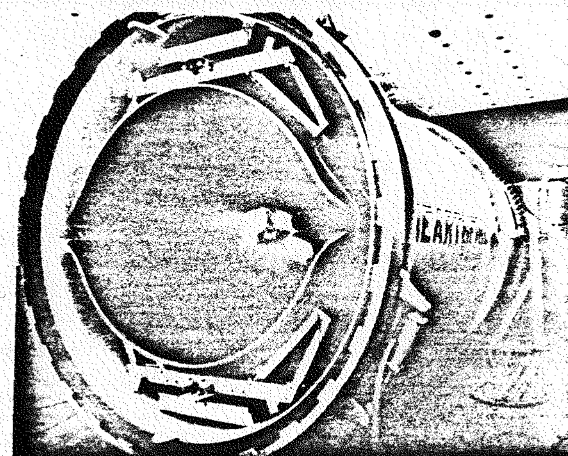
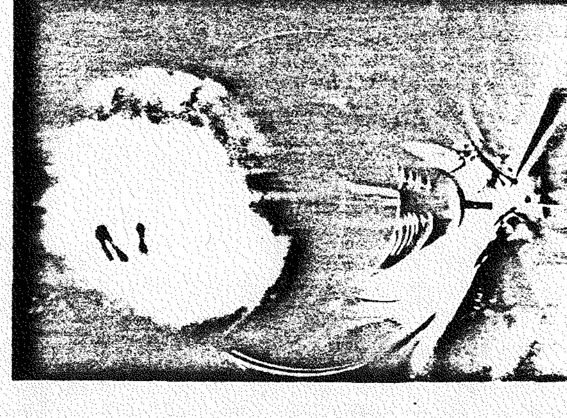


Fig. 4 1.5 MV Preaccelerator Rectifier Stack and Terminal



Our approach is to try to operate the preaccelerator at the highest possible voltage in order to simplify the low-beta linac. Our short term goal is to operate at 1.5 MeV. The linac could then start with reasonably sized structures at 12.5 MHz. Higher intrinsic current limits are then possible and the number of frequency transitions and the accompanying losses in the matching sections are reduced. The high preaccelerator voltage may be needed for adequate performance by an injector.

Preaccelerator

High Voltage Power Supply

The high voltage power supply is a modified Radiation Dynamics Incorporated 4 MeV Dynamitron which is shown in Figs. 3 and 4. This is a parallel-fed capacitively-coupled voltage multiplier driven by a 110 kW oscillator operating at 105 kHz. We have made extensive modifications to increase the current capability and allow pulsed operation. A new solid-state rectifier stack was installed with two 40-rectifier circuits in a full-wave configuration. With adequate oscillator power, the stack is capable of 100 mA operation at 2 MeV. The rf electrodes were also moved closer to the stack to improve the capacitive coupling and they were fitted with new rigid supports to prevent bouncing during pulsed operation. The toroidal transformer turns ratio was reduced to further stiffen the supply and improve the power match to the oscillator. Other mechanical modifications were made such as lengthening the tank 3 feet and adding a quick-opening flange at the end where the new column will be located (in the original configuration the low-gradient column was inside the rectifier stack).

In the summer of 1978 we extensively tested the capability of this power supply in pulsed and dc operation. These machines had never before been pulsed. We used a variable chilled-water resistor as a current load. With the present small oscillator we are able to ramp the machine from 0.5 MV to 1.5 MV in 7 msec with a stack current of 70 mA. It is capable of 30 mA of dc current at 1.5 MV. The machine conditioned easily with 65 psig of SF_6 to voltages as high as 2.7 MV. We found that voltages above the dc-conditioned voltage could be tolerated for high voltage pulses on the order of 100 msed.

The initial operation with the source will attempt 30 mA beam pulses since the oscillator can be ramped during the beam spill so that no voltage sag should occur. By adding a second pass tube with energy storage in parallel with the original pass tube, pulses up to 60 mA should have no voltage sag. Well-regulated pulses of 100 mA will probably require a larger oscillator. Such oscillators are available from Radiation Dynamics Inc.

This type of power supply performs very well for pulsed duty up to 2 MV and probably higher. With the new terminal and column the total capacitance is approximately 500 pf, so the damage from a spark is minimal. If adequate gas handling capability is provided, the advantage of a small-sized vessel outweighs the nuisance of an insulating gas. We are installing a system which will allow a turn-around time of less than 2 hours.

Heavy Ion Source

The low-emittance heavy ion source for our preaccelerator was developed by Hughes Research Laboratories and is described in detail in the 1978 HIF workshop proceedings.[1] It utilizes a low-voltage Penning discharge coupled with a single-aperture Pierce extraction electrode configuration. A schematic drawing of the source is shown in Fig. 5. The 100 mA source has undergone performance tests at HRL. The gas valve is pulsed and the beam is pulsed by modulating the anode. It achieves 100 mA within 10 μsec of turn-on. The optimal operating parameters for 30 mA of Xe^{+1} were determined before the source was shipped to ANL.

Since September 1977 we have been using the 2.5 mA version of this source on our test stand to study the operation of the source and to do transport experiments with 80 keV Xe^{+1}. The smaller source turns on in 3 μsec and has a measured normalized emittance of 0.001 cm mrad. The details of its performance are given in a paper included here, and published in the 1978 HIF workshop proceedings.[2]

Accelerating Column

At the close of FY 78, fabrication of the high-gradient accelerating column was nearing completion. It consists of titanium and ceramic rings which are epoxy bonded. An indium O-ring isolates the bond from the internal vacuum. The details of the design are shown in Fig. 6. The ceramic wall is protected from ion bombardment by interlocking T-shaped rings which also serve as the voltage tap points for the two intermediate electrodes. The two electrodes are shown tapped for 30 mA Xe^{+1} operation. This is a Pierce geometry through the second intermediate electrode, followed by a constant gradient. The expected trajectories for 30 mA and 100 mA Xe^{+1} operation are shown in Fig. 7. The 100 mA case represents a current density of 15 mA/cm^2 and indicates the beam is becoming divergent in the constant gradient region. The completed shell and T-shaped ring are shown in Fig. 8.

The ion source is re-entrant into the terminal end of the column. The ground electrode is also re-entrant and houses a magnetic quadrupole triplet to focus the beam on the linac buncher accelerating gap. These magnets will be completed by November 1978.

Low-Beta Linac

Despite severe limitations due to low funding levels we are developing the first sections of a low-beta linac which will operate at 12.5 MHz. In order to test several different structures and construction techniques, the first independently-phased cavities are very different in design.

The first, which will be used as a buncher, is a single drift tube lumped inductor resonator. The outside shell of the resonator is made of aluminum except for the copper bottom can. The inside inductor and drift tube are made of copper. The inductor is a coil of 2-1/3 turns in a 20 in. diameter.

The first accelerating structure is also a single drift tube resonator which is capacitively-loaded by a plate near the drift tube. It is shown schematically as the first element in Fig. 10, which is our system design up to 4 MeV. The capacitively-loaded cavity is made entirely of copper and should require only 10 kW to achieve 100 kV across the accelerating gaps. The outer electrode and frequency-tuning ball are shown in Fig. 11.

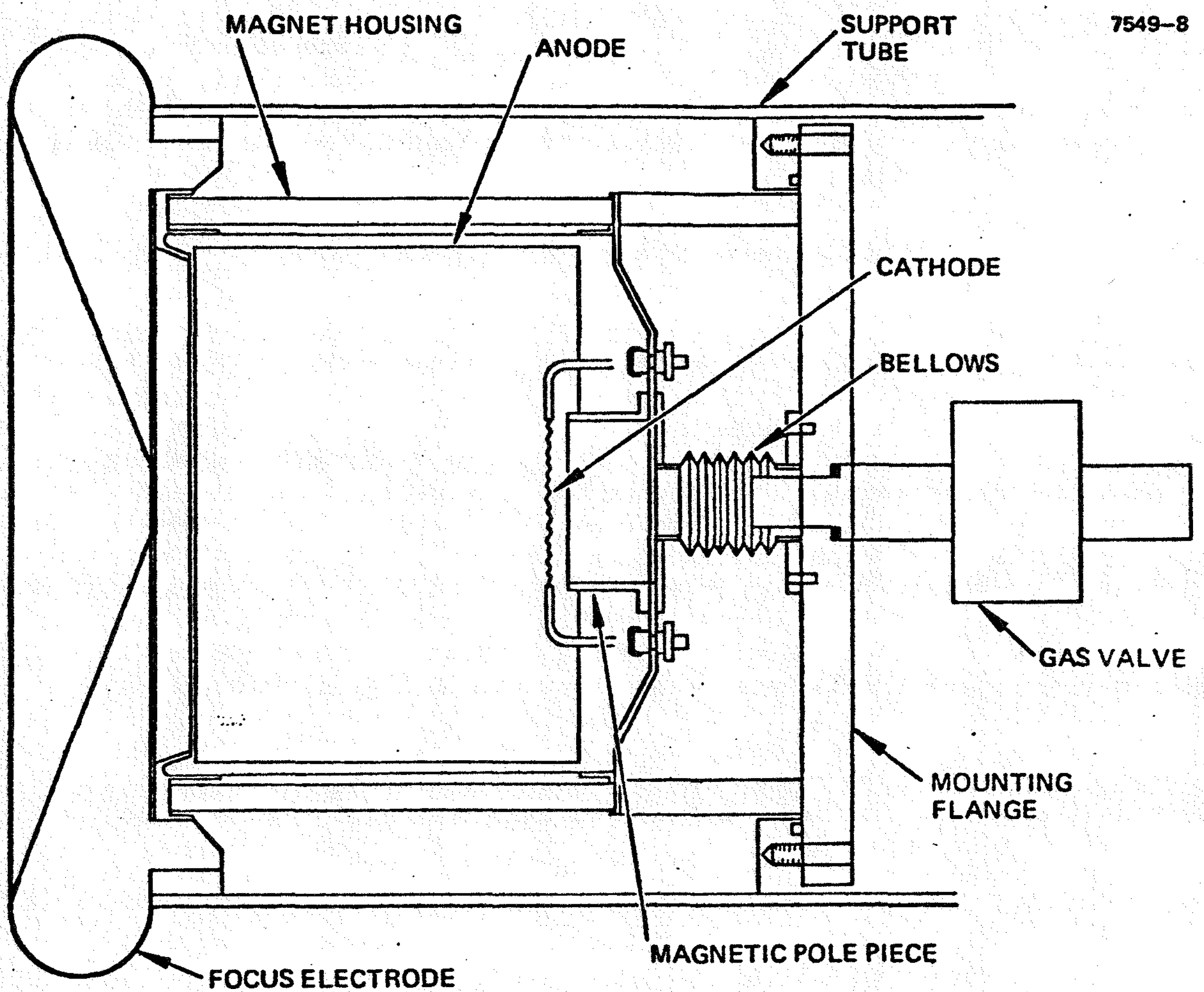


Figure 5. Schematic of ion source and mounting structure

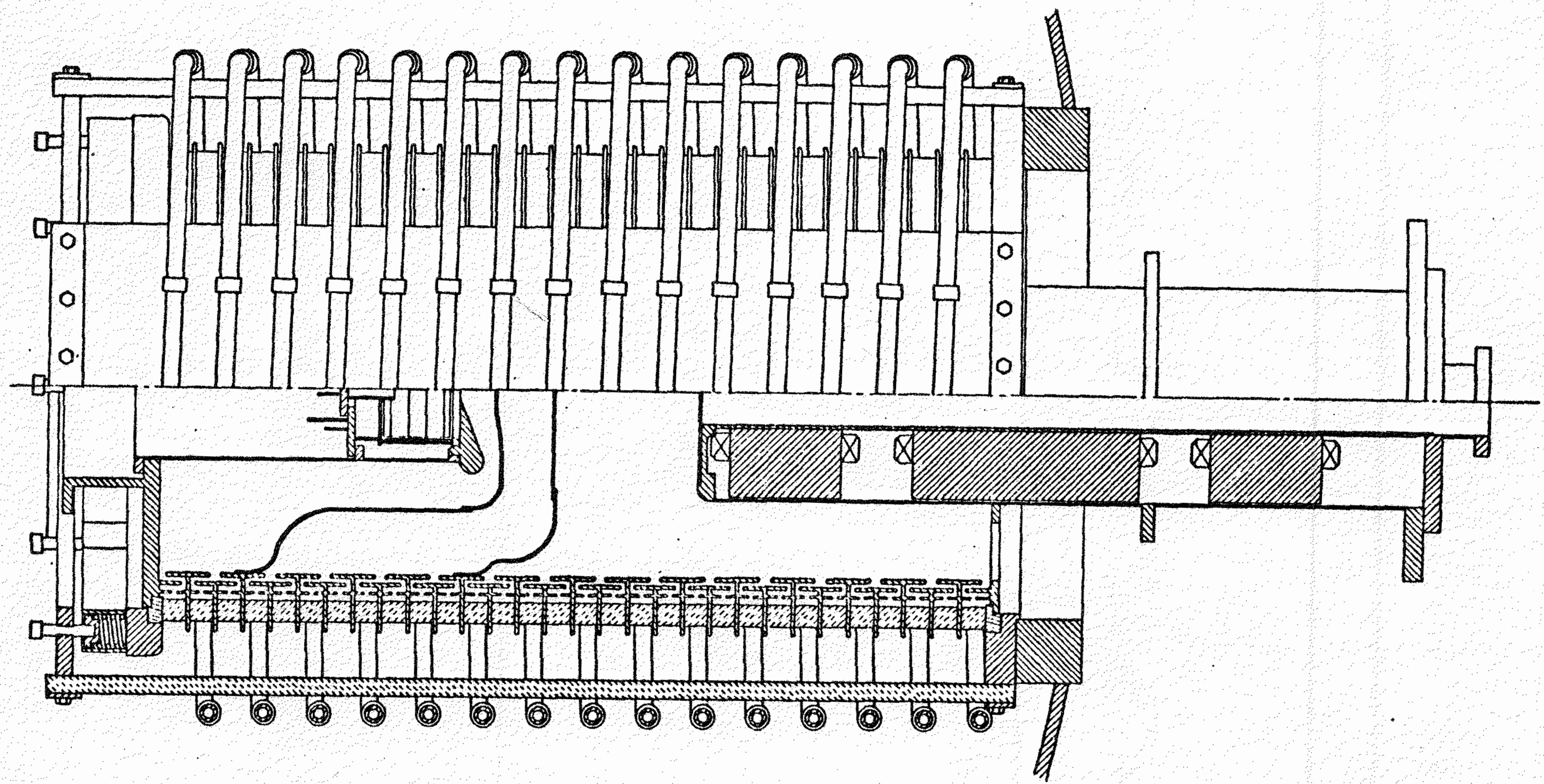
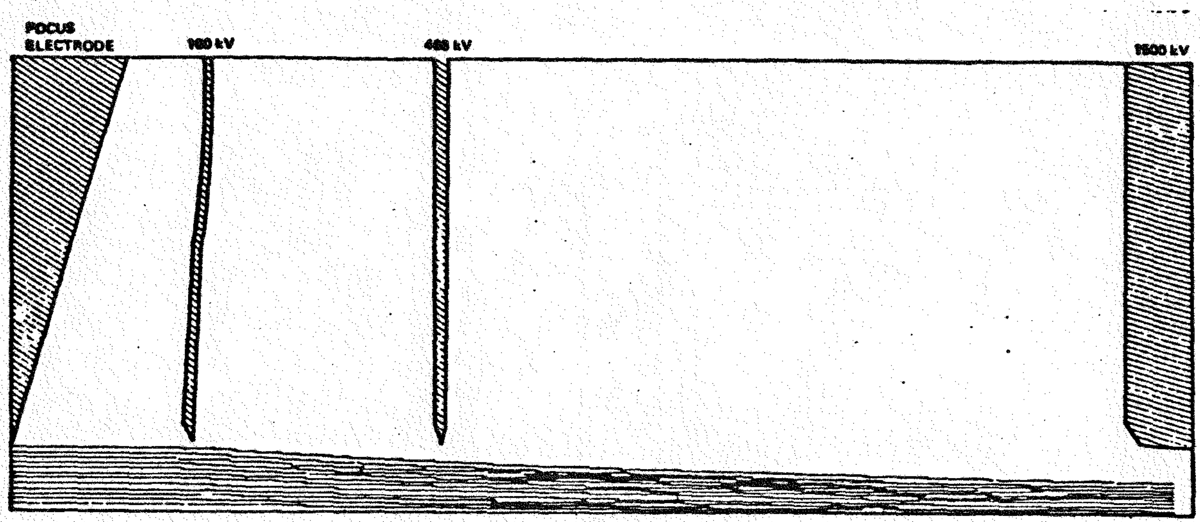
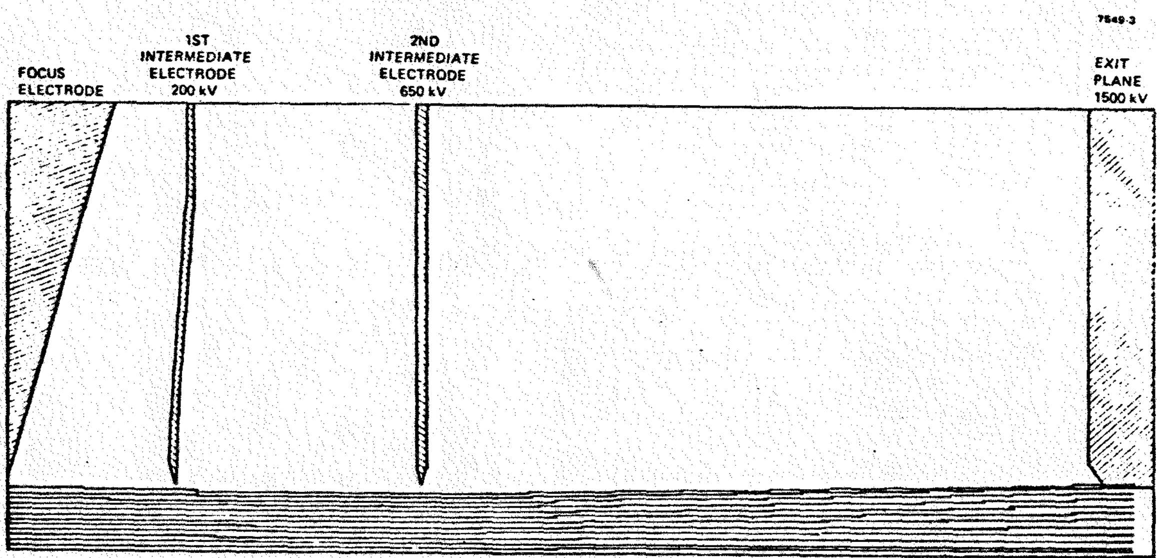


Figure 6 High-gradient Accelerating Column



Ion trajectories for 30 mA of Xe^+



Ion trajectories for 100 mA of Xe^+

Fig. 7 Calculated Beam Trajectories in Accelerating Column

Figure 8 Accelerating Column Shell and T-Shaped Ring

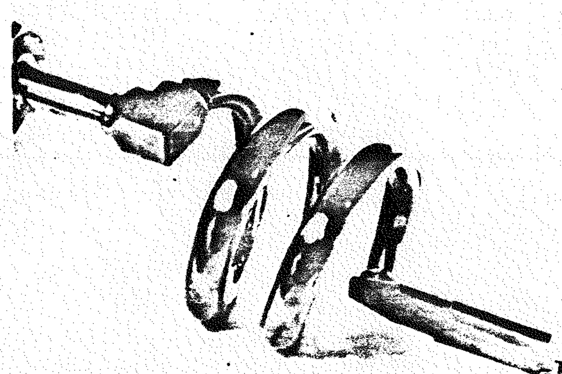


Figure 9 Helix and Drift Tube of Lumped-Inductor Cavity

The design of the two drum-loaded resonators was nearly complete at the end of FY 1978. They will have two drift tubes per resonator. The drum-shaped capacitor has a wider gap to the outer electrode, so these structures should be capable of higher voltages. The inner and outer electrodes will be copper.

The design of the first tank of the multi-gap Wideroe will accelerate Xe^{+1} from 2 MeV to several MeV is underway. If funding is adequate, construction of this unit could begin in FY 1979.

To excite the first cavities, we have constructed a 25 kW 12.5 MHz amplifier and have ordered five more from Instruments for Industry, Inc. These should be delivered in January 1979. Bids have been requested for the 250 kW amplifiers which will be needed for the multi-gap structures.

These first cavities will utilize conventional quadrupole magnets for beam focussing. These magnets have been designed and are being fabricated in our shops. These will have a maximum gradient of 46 T/m. This imposes a transport limit near 25 mA of Xe^{+1} for these structures. Our superconducting group is presently developing small quadrupoles with a maximum field gradient of 140 T/m. These could be used to significantly upgrade the front end of the low-beta linac.

80 keV Xe^{+1} Test Beam

We have set up the 2 mA Xe^{+1} HRL ion source to inject into a 4 m long transport line. Most of our operation has been at 80 keV. At present, the vacuum capability is in the 10^{-6} Torr range throughout the line. This will be improved to 10^{-8} next year. The transport line is shown in Fig. 12. The source is in the high voltage cage to the right. The source and some of its support equipment are shown in Fig. 13. Figure 14 is a photograph of the Xe^{+1} beam as it exits the source. The waist near the source has a 2 mm diameter.

We have used this beam line to study the operation of the source, the problems associated with transporting intense heavy ion beams (2 mA is considerably above the space charge limit), and to investigate the parameters of neutralization. In this rather poor vacuum we have been able to transport and focus 90% of the beam 4 m from the source. The source has operated very reliably with a normalized emittance of 0.001 mrad cm. We have also pulsed the source via an optical link and measured plasma formation times of 3 μsec.

Further details of the test beam are reported in the paper by Mazarakis, Price, and Watson.[2]

While the higher vacuum system is being assembled, a second beam line will be installed to be used to measure Xe^{+1} - Xe^{+1} cross sections up to 80 keV. The second beam will use a collimated duoplasmatron source set up by an ANL-University of Chicago collaboration.

We are also considering lengthening the beam line to study instabilities which may occur in periodic transport lines.

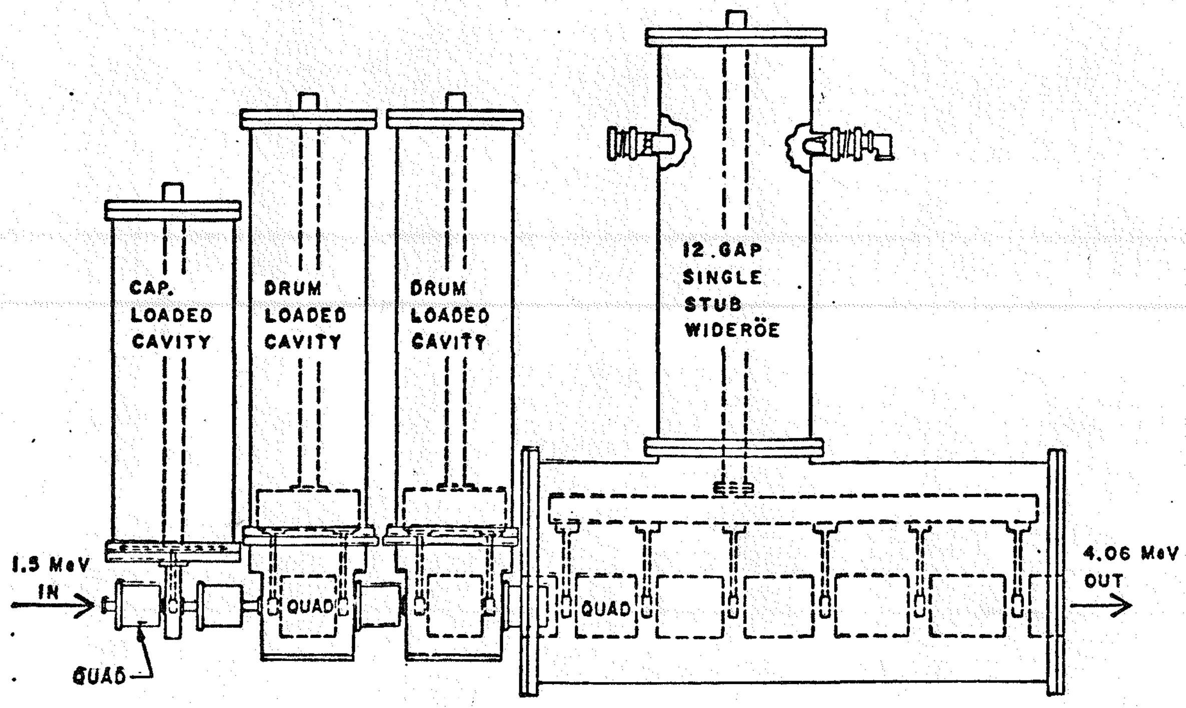


Figure 10 Low-Beta Linac to 4 MeV

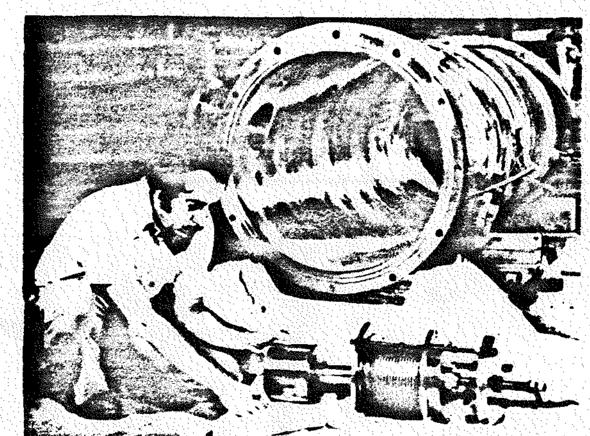


Figure 11 Outer Electrode and Tuning Ball of Capacitively Loaded Cavity

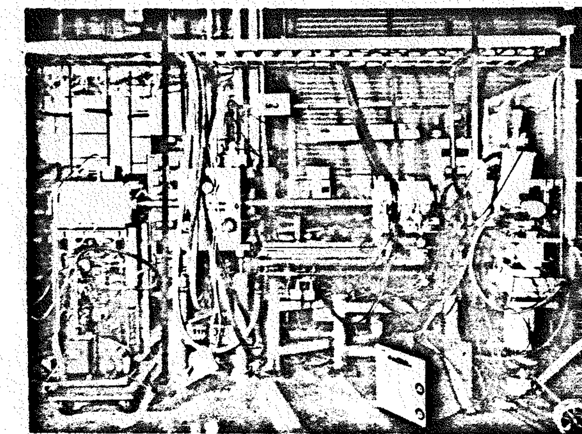


Figure 12 80 keV 2 mA Xe^{+1} Transport Line

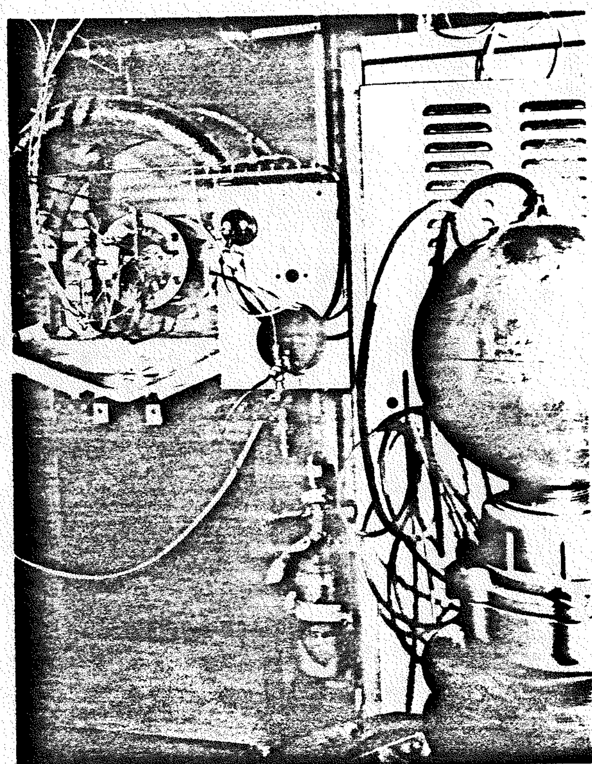


Figure 13 2 mA Xe^{+1} Source and Support Equipment

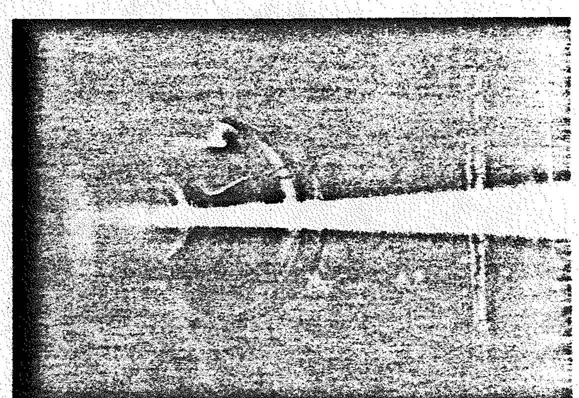


Figure 14 2 mA Xe^{+1} Beam Out of Source at 80 keV

References

1. R. P. Vahrenkamp and R. L. Seliger, "A Heavy Ion Source and DC Pre-Accelerator Design for Ion Beam Fusion," Proceedings of the 1978 HIF Workshop.

2. M. Mazarakis, D. Price, and J. Watson, "The Argonne National Laboratory Heavy Ion Beam Transport Experiments with 2 mA 80 keV Xe^{+1} Source," Proceedings of the 1978 HIF Workshop.

IV. 1978 HIF Workshop at ANL

This workshop was the third in a series of annual workshop meetings on Inertial Fusion Driven by Beams of Heavy Ions at GeV Energies. It was held September 19 through 26, 1978, at Argonne National Laboratory. There were 158 participants, representing U.S. national Laboratories, other government laboratories, universities, and industries; European and Japanese representatives also attended.

The workshop had three primary goals:

1. Critical examination of reference designs for prototype one-megajoule reactor drivers (previously distributed by ANL, BNL, and LBL), including the suitability of heavy-ion demonstration experiments based on these designs, and possible upgrading to a few megajoules.

2. Exchange of information on the progress of heavy ion fusion programs at the participating institutions.

3. Communication of information on heavy ion fusion in order to enhance industry and university support for the civilian heavy ion fusion program, as suggested by a recent U.S. DOE Fusion Review.

At the workshop, four different conceptual driver designs were presented. To accomplish the first goal of the workshop, technical review of these designs was carried out by parallel workshop sessions, examining the areas of ion sources, low-velocity linacs, beam manipulations, beam transport and focussing, plasma effects in the reactor chamber, ionic collision cross sections, and cost estimation.

The second workshop goal, information exchange, was accomplished through presentations on the first day from each of the principal laboratories currently funded by DOE (ANL, BNL, LBL, and LLL) for work in heavy ion fusion, and by invited talks and informal discussions in the workshops.

On Monday, September 25, tutorial sessions were held on all aspects of heavy ion fusion, primarily for industrial and university observers, in pursuit of the third goal. These tutorial sessions were videotaped for wider distribution, and are now available on loan from Argonne.

In addition to the working review sessions, plenary invited talks were held on the mornings of September 20 - 22 covering topics of interest to the participants. Some of the texts for those talks were provided by the authors for reproduction in the Proceedings.

The conclusions of the technical review were assembled by a committee of four (L. Teng, Chairman; D. Sutter; D. Judd; and F. Mills). Their report, included in the Proceedings, provides a technical overview of the current status of heavy-ion reactor driver design.

V. FY 1978 HEAVY ION FUSION REPORTS

S. Fenster, "Collimating Triplet with Space Charge," IBF-52 (October 3, 1977).

A. Langsdorf, "Some Thoughts on Acceleration Tubes for High-Current Pulsed Beams of Heavy Ions at High Voltages," IBF-53 (October 6, 1977).

K-T. Cheng, G. Das, Y-K. Kim, R. Raffenetti, "Atomic Cross Sections for Heavy-Ion Fusion," IBF-54 (October 4, 1977).

M. Foss, "A Cavity Resonant at 12.5 and 25 MHz," IBF-55 (October 14, 1977).

E. Colton, "Final Focussing of 35 GeV Bismuth Ions," IBF-56 (November 7, 1977).

T. Khoe, "Bunching Factor in Transverse Space Charge Calculations," IBF-57 (November 4, 1977).

J. Bogaty, "Notes on the Pulsing of Dynamitron," IBF-58 (October 31, 1977).

R. Martin, "100 kJ Ion Beams for Pellet Implosions," Proceedings of the Second International Topical Conference on High Power Electron and Ion Beam Research and Technology, Ithaca, New York, Vol. I, p. 113 (October 1977).

J. Bogaty, "Preliminary Results of Dynamitron Pulsing," IBF-59 (November 18, 1977).

K-T. Cheng, Y-K. Kim, "Atomic Data for Xenon Ions," IBF-60 (December 13, 1977).

R. Lari, "A Design for the Low Beta Linac Quadrupole Magnets," IBF-61 (January 3, 1978).

R. Lari, "Design of the High Gradient Accelerating Column Quadrupole Magnets," IBF-62 (January 3, 1978).

R. Kustom, "Beam Deflecting System for Filling Buckets in the Higher Frequency Linac at the First Frequency Transition," IBF-63 (January 11, 1978).

Y-K. Kim, "Full Stripping of Xenon Ions," IBF-64 (January 13, 1978).

T. Khoe, "Transverse Space Charge Limit in Low Beta Linac," IBF-65 (January 16, 1978).

S. Fenster, "Xenon Transport Experiments with 3 mA Beam General Considerations and Neutralized Beam," IBF-66 (January 26, 1978).

R. Martin, "The Argonne Heavy Ion Fusion Program," Proceedings of the Topical Meeting for Inertial Confinement Fusion, San Diego, California, Inertial Confinement Fusion Technical Digest, 78CH1310-2QEA, p. WB13-1 (February 1978).

J. Bogaty, "Final Report on Unmodified Dynamitron," IBF-67 (March 1, 1978).

E. Colton, "Thin-Lens Treatment of the Final Focusing Triplet," IBF-68 (March 13, 1978).

R. Arnold, R. Burke, M. Foss, T. Khoe, R. Martin, "HEARTHFIRE Reference Concept #3: A Rapid Cycling Synchrotron System," ACC-6 (June 16, 1978).