ARGONNE NATIONAL LABORATORY
Argonne, Illinois

HEARTHFIRE

DESIGN BASE FOR THE HIGH CURRENT LOW VELOCITY RF LINAC*

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Accelerator Research Facilities Division
Accelerator Report
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ABSTRACT

The particle beam parameters needed for inertial fusion can be achieved with conventional accelerator technology if heavy ion machines attain the level of performance of the most intense high energy proton machines. Many of the problems posed by this goal pertain to the low energy portions of the accelerator system. In particular, the implied particle current in the rf linac is 10^3-10^4 times the values achieved with existing heavy ion machines. Much of this discrepancy is simply attributable to the great differences between the design considerations relevant to accelerators for fusion and those which have determined the performance of the existing machines. Nevertheless, the real problems are significant.

Space charge forces predominate among design considerations, and the accelerator must accommodate a system of focussing elements capable of transporting beam currents that press the theoretical limits of practical devices. For this reason, ions must be accelerated through the low velocity region in the lowest charge states (essentially +1) and the concomitant low velocities call for the lowest frequency accelerating structures.

The basic concept chosen at Argonne National Laboratory is cavities containing single drift tubes mounted on $\lambda/4$ supports. Such structures pose the least problem for the beam transport system, and one cavity is placed between adjacent quadrupole magnets. The average voltage gain of the first cells of the low velocity section is moderate; and, although probably acceptable and improved by the end of the 10 MV section, the low initial gain adds to the motivation provided by the transport problem to increase the preinjector voltage substantially above 750 kV.

The principal uncertainty in the design pertains to the ability to control the space charge forces in accord with theoretical predictions.

I. Introduction

The advantage of heavy ion beams for attaining the very high power required to ignite inertially confined fusion reactions is that their high rate of energy transfer permits very high energy per particle, thereby minimizing the required current. For instance, it is believed that beams of 100 GeV uranium can be used efficiently to ignite fusion reactions.[1] Then, 6000 A produces 6×10^{14} W, a power level regarded by the designers of fusion targets as virtually assuring high energy multiplication from thermonuclear reactions.[1] Although this current seems more tractable than the 2.5×10^{8} A of 1 MeV electrons or 6×10^{6} A of 10 MeV protons that are calculated[2] to be required to obtain even a modest energy multiplication, the 6000 A must be considered in the light of normal high energy accelerator practices. In this context, 6000 A at first seems impressive indeed. However, such high current has not been of interest in the research for which the high energy beams are normally used. The currently widespread interest in using conventional accelerators for inertial fusion has come directly from proposals for straightforward mechanisms to greatly increase the current.

The main mechanisms that have been proposed to attain high currents at fusion targets are routing multiple beams for simultaneous arrival (proposed by Martin and Arnold)[3] and longitudinal compression (proposed by Maschke).[4] The current multiplication by the first mechanism is simply the number of beams. Thus, a factor of ten would entail no problems and amplification by 100 may be practical for some beam and target parameters. Longitudinal compression may push the peak current beyond the recognized space charge limit in a circular machine. However, if carried out in the time required for a small number of ion revolutions, the beam may be stable. Preliminary experiments[5] at Brookhaven National Laboratory indicate feasibility for this plan. Although the concept has not yet been placed on a firm basis, increases of the peak current by a factor of ten appear reasonable and a factor of fifty conceivable. Therefore, using both techniques, an amplification of 100 appears assured and 1000 not unreasonable and the distance from, for instance, the 40 A attained in the intersecting storage rings (ISR) at CERN[6] to 6 kA seems not so large.

This optimistic outlook is gained, however, by comparing achievements with proton machines to requirements for heavy ion machines for which there are special problems. One area where a heavy ion accelerator system for igniting fusion fuel pellets should exceed the capabilities of the existing heavy ion research machines by a wide margin is the low velocity portion of the rf linac. Although it appears possible to achieve the necessary improvement, the probable difficulty recommends a review of the reasoning behind the conclusion that every effort should be made to maximize the linac current.

II. Justification for High Linac Intensity

A. Beam Loss Considerations. A common problem of circular heavy ion machines is beam loss due to collisions that change the ionic charge. In addition to the usual mechanism of collision of a beam ion with an atom of residual background gas, it was recognized early in the design studies at Argonne that the beam intensities required for fusion with heavy ions would make charge changing collisions of beam ions among themselves a potentially important cause of beam losses. Losses from collisions with background gas can be reduced to a manageable level by a combination of ultrahigh vacuum and short residence time of the beam ion in the circular machine. Intrabeam collision loss may also be solved by a sufficiently short storage time in the circular storage device or accelerator. In addition, the cross sections for charge changing by either mechanism decrease as the ionic charge state is increased but charge states above +10 are required to change the complexion of the problem. Therefore, except for the use of ultrahigh vacuum, which has no effect on ion-ion collision losses, the solutions to the beam loss problems have important implications for the performance that will be required of the rf linac involved in the accelerator system.

One effect is that the beam loss problem may require the linac to accelerate the beam to full energy. Since higher average currents are normally attained with linacs than with circular accelerators, the time to accumulate the total number of high energy ions needed to make up an ignition pulse is less if the circular accelerator is omitted. Unfortunately, linacs are typically much more expensive than synchrotrons per unit of energy gained; so that from an economic viewpoint, a 100 GV high intensity heavy ion linac is less attractive. An alternative is to use lower ion energy or higher charge state either of which reduces the linac voltage and cost.

In any case, the desired linac current exceeds the state of the art for heavy ion machines by orders of magnitude. For example, 10 mA are required to produce in 10 msec the 6×10^{14} particles needed for a total energy of 10 MJ at 100 GeV each. For lightly charged ions, even 10 msec may be too long.[7] A longer time may be acceptable for highly stripped ions, but the required charge states cannot be obtained in sufficiently intense beams directly from ion sources. Stripping after acceleration to 10 MeV (or substantially more) is necessary, and the prestripper linac must carry a higher particle current to compensate for stripping inefficiency. Thus, even though the particle current of the injector may be as low as 2 mA (accumulation time = 52 msec for 10 MJ of 100 GeV particles), the electrical current may be more like 50 mA and the particle current in the more difficult prestripper more like 10 mA. Any one of these figures represents a large increase in the state of the art.

B. Downstream Injection Considerations. The major impetus for a high linac current, however, comes from the problems of injecting into circular machines over lengths of times spanning many revolutions in the machine. To take an example, the previously noted value of 40 A stored in the ISR would correspond to 4000 turns of injection with a 10 mA beam. On the other hand, with only 40 turns, it is not uncommon to lose 50% of the particles provided by the injector. Such high losses with heavy ions would probably lead to serious vacuum problems and damage to the chamber, especially for injection of full energy particles. The overall electrical efficiency would also be seriously reduced by inefficient injection involving full energy particles. More efficient injection techniques such as resonance injection, which have been studied theoretically,[8] and stacking techniques that employ additional rings expressly for the stacking problem[9] may turn out to be viable for stacking more than 40 turns, but the motivation for a linac current greater than 10 mA is apparent.

Existing heavy ion linacs accelerate beams that do not exceed 10 μA of particle current,[10, 11] and the currents of ions of mass >100 as required to drive fusion pellets are smaller. Recognition that this is the state of the art was the reason that the first HEARTHFIRE reference design explored the possibility that molecular dissociation[12] injection could permit a very large number of turns to be stacked efficiently, as does the analogous and highly successful H^- stripping injection.[13] Although the design study indicated that it should be possible to make the concept work, it was felt that molecular dissociation injection as conceived would entail considerably more complexity and expense than more conventional techniques. Thus, molecular dissociation injection is regarded as a potential backup should conventional techniques prove inadequate.

To realize satisfactory performance with conventional injection techniques, 50 mA probably represents a minimum injector (particle) current. The advance beyond the state of the art represented by this current naturally suggests stiff design requirements. Meeting these requirements, while difficult, appears to be possible. Nevertheless, the real problems are impressive and it is tempting to try to transfer the burden to some other place in the accelerator system. That this is not a judicious solution is easily seen.

Teng[1] noted that the basic problem in using conventional accelerators for inertial fusion is to amplify the current produced by the ion source. Thus, the total current at the target may be written

$$I = I_L \times A \times S \times L \times B$$

where L and B represent longitudinal compression and multiple beams, S represents the transverse stacking, A represents the current increase during acceleration in a circular machine, and I_L is the linac current. By taking values for the most predictable factors, the possibilities for the uncertain operations may be illuminated. Thus, letting B = 40 (reasonably large), A = 4 (reasonably modest, but a synchrotron may be too slow to be useful at all in the face of potential beam losses), and assuming $I_L = 0.05$ A, the 6000 A needed for 6×10^{14} W of 100 GeV ions requires that S x L = 750. (The direct tradeoff between S and L entails, for example, increasing the circumference of the ring so that injection for a given length of time results in fewer injected turns, but the initial bunch lengths are also increased so that more compression is needed.) The virtue of holding the S x L product to this level is a strong deterrent to the wish to decrease any other factor. Indeed, if reductions are to be made in any of the individual factors, one would like to reduce the number of beams and may be forced to reduce or abandon the effect of acceleration in circular accelerators. Thus, a strenuous attempt to solve the problems of accelerating a particle current of 50 mA, and even to exceed this goal, is justified.

III. Selection of the Linac Concept

Accelerating a heavy ion particle current of 50 mA or more poses a challenging set of coupled requirements for the source, preaccelerator, and low energy end of the rf linac. The linac design is tightly constrained by the problems of controlling the space charge forces of the slow ion beam. The preaccelerator must pass unprecedented currents of heavy ions: A preaccelerator voltage of 750 kV appears barely adequate for the rf linac to accelerate an average (over a linac pulse) xenon particle current of 50 mA. Less current can be realized with heavier ions, and attacking the problems of higher voltage preaccelerator tubes is necessary. And, finally, the source must produce beams of adequate current and brightness with extraction parameters that allow matching into a high gradient column and without loading the high voltage accelerating tube with neutral gas.

The most serious of the low velocity acceleration problems is transport of space charge dominated beams. Due to the effects of the transverse space charge forces, the maximum particle current (in amperes) that can be transported in a channel of strong focussing quadrupole magnets may be written[14]

$$I_{max} = 1.06 \times 10^{6} \, F(\alpha, \mu) \frac{A^{1/3}}{q^{4/3}} \epsilon_n^{2/3} (\beta\gamma)^{5/3} B^{2/3}$$

where ϵ_n, the normalized emittance, is expressed in meter · radians, B, the pole tip magnetic field, is expressed in Tesla, α is the quadrupole packing factor, and μ is the phase advance per cell. The transport problem at the beginning of the linac is seen by substituting $\beta\gamma \approx \beta = (2\,qeV/Amc^2)^{1/2}$ where V is the voltage of the preaccelerator and m is the mass of a proton. Thus, the maximum transportable current is

$$I_{max} = 6.3 \times 10^{-2} \, F(\alpha, \mu) \, \epsilon_n^{2/3} \frac{V^{5/6}}{(qA)^{1/2}} B^{2/3}$$

where V is expressed in volts.

$F(\alpha, \mu)$ is made large by using large values of α and smaller values of μ. The disadvantages of a large packing factor of magnets are obvious (reduced average voltage gain and increased expense); and smaller values of μ require larger apertures,[14] which are undesirable in the magnets and also in the accelerating cavities. For present purposes, $F(\alpha, \mu) = 2$ is adequately representative. [$F(\alpha, \mu) = 2$ may be associated with $\alpha = 1$ and $\mu = 60^o$ or $\alpha = 0.5$ and $\mu = 45^o$.][14] Then, for $\epsilon_n = 10^{-6}$ meter · radian, B = 1.5 T and V = 0.75 x 10^6 V, $I_{max} = \frac{1.3}{(qA)^{1/2}}$ A. For a mass 200 ion, I_{max} = 92 mA.

Since this represents peak current and acceleration requires a minimum bunching factor of about three, one sees that currents around 50 mA will be difficult to realize and require the lowest charge states, preferably +1. It is also clear that the low velocity part of the rf linac will be predominantly quadrupole magnets since obtaining the assumed $F(\alpha, \mu) = 2$ by using half the length for quadrupoles ($\alpha = 0.5$) necessitates $\mu = 45^o$. This entails ratios of maximum and minimum transverse beam sizes (i.e., the increase of the bore actually needed over the minimum possible) of 1.29 and 1.44 and an effective emittance growth by 1.36.[14] Lower packing factors worsen this situation.

Thus, transport considerations for the space charge dominated beams favor the lowest charge states which imply the lowest velocities for a given preaccelerator voltage. The low velocities imply short drift tube and gap lengths, and short drift tubes require small apertures to prevent serious loss of effective accelerating voltage due to field penetration into the tubes. However, the transverse emittance and space charge forces cannot be accommodated in small apertures. One is forced, therefore, to the lowest practical rf frequency to achieve reasonable drift tube length and aperture. (Using the $3\,\beta\lambda/2$ mode to achieve a given drift tube length with a higher frequency results in reduced average voltage gain due to the shorter gap. From the detailed calculations of Section IV, it is clear that there is none to spare.)

The spiral, co-axial, split ring, and Wideroe structures can be operated at frequencies that allow acceptable drift tube dimensions; but increasing awkwardness and susceptibility to mechanical vibrations places the lower limit of the frequency at about 10 MHz. The choice from among these candidates is made almost wholly on the basis of the ability to accommodate the quadrupoles needed for beam transport.

Thus, a structure with one drift tube per cavity has been chosen for the first stages of the linac because it is able to accommodate the highest packing fraction of transport magnets. Located outside the independently phased cavities, the size and weight of the magnets are not seriously limited and the use of single drift tube cavities allows the quadrupole spacing to be minimized. On the other hand, with at least two drift tubes per cavity, the split ring could not achieve as high a packing factor.

The Wideroe appears least able to cope with the transport of intense beams because there are many drift tubes in each cavity so the magnets must be located inside the drift tubes. However, the dimensions of the quadrupoles needed to transport 50 mA of slow ions make this impractical. For example, the calculations in the following section show a need for quadrupoles about 30 cm long. At 10 MHz and $\beta = 0.0035$ (750 keV xenon), $\beta\lambda/2 = 5.25$ cm and the drift tube length is less. This poor match to the desired 30 cm quadrupole length is compounded by the poor aspect ratio resulting from the short length and large (4 cm) bore. Operating on the $3\beta\lambda/2$ mode would improve the situation somewhat; however, only the supports of every other drift tube are capable of bearing the weight of a substantial quadrupole magnet (as in the UNILAC design).[10] Therefore, the current that may be accelerated with the optimum arrangement in a Wideroe will be substantially less than with the single drift tube cavity and there is a premium on every milliamp.

Both the spiral and coaxial resonators are suitable for operation with one drift tube per cavity. The choice from among the possibilities will be based on construction and performance considerations. These are discussed in Section V for the spiral, coaxial, and folded coaxial concepts.

IV. Theoretical Considerations

A. Transit Time Factors. The distance between the center of accelerating gaps is an odd multiple of $\beta\lambda/2$ (Sloan-Lawrence type structure), where β is the velocity of the ion normalized to the speed of light and λ is the free space wavelength of the cavity frequency. For purposes of computation, the drift tube is assumed to be a hollow conducting cylinder on which the accelerating potential is applied. The effective length of the accelerating cavity is assumed to be twice the length of distance between the centers of the axial gaps. The applied voltage on the boundary is assumed to linearly increase and decrease from zero to some maximum value, or vice versa, over the length of axial gaps. The spatial dependence of accelerating field over the 2ℓ length of the accelerating cavity is given by:

$$E_z = \frac{2V_o}{\ell} \sum_{n=0}^{\infty} (-1)^n \frac{\sin(h_n g/2)}{(h_n g/2)} \frac{I_o(h_n r)}{I_o(h_n a)} \sin h_n z \qquad (1)$$

where V_o = drift tube voltage

ℓ = center to center distance between accelerating gaps

h_n = $(2n+1)\ \pi/\ell$

g = gap spacing

a = radius of accelerating tube

I_o = modified Bessel function

The energy gained by a particle in transit through the cavity is

$$\Delta T = qe \int_{-\ell}^{\ell} E_z \sin \frac{2\pi z}{\beta\lambda}\, dz \qquad (2)$$

where qe = charge of the particle

f = cavity frequency

Integration of Eq. (2) using the value of E_z given in Eq. (1) leads to the following expression for energy gain, when $\ell = \beta\lambda/2$

$$\Delta T = 2qeV_o t_f(r) \tag{3}$$

where

$$t_f(r) \simeq \frac{\sin 0.5\, h_n g}{0.5\, h_n g}\,\frac{I_o(h_n r)}{I_o(h_n a)}\left[\frac{\sin(1-\beta_s/\beta)\,\pi}{(1-\beta_s/\beta)\,\pi} - \frac{\sin(1+\beta_s/\beta)\,\pi}{(1+\beta_s/\beta)\,\pi}\right]$$

Terms of $n \geq 1$ are neglected in the expansion of Eq. (3) since they do not significantly contribute to the energy gain. The expression for $t_f(r)$ can be rewritten as

$$t_f(r) \simeq t_{fs}(r)\, f_\ell(\beta) \tag{4}$$

where $t_{fs}(r)$ is the value for $t_f(r)$ when $\beta = \beta_s$ and $f_\ell(\beta)$ is the expression in the braces.

Similarly, expressions for the effective defocussing fields for the transverse motion can be derived. These are

$$E_x(\text{eff}) = \frac{\pi V_o}{\beta_s \lambda \ell}\, t_{fs}(o)\, f_t(\beta)\, x \qquad \text{and} \tag{5}$$

$$E_y(\text{eff}) = \frac{\pi V_o}{\beta_s \lambda \ell}\, t_{fs}(o)\, f_t(\beta)\, y$$

where

$$f_t(\beta) = \frac{\sin(1-\beta_s/\beta)\,\pi}{(1-\beta_s/\beta)\,\pi} + \frac{\sin(1+\beta_s/\beta)\,\pi}{(1+\beta_s/\beta)\,\pi} \tag{6}$$

Table I lists the values of $f_\ell(\beta)$ and $f_t(\beta)$ for various values of β/β_s.

Table I. Values of $f_\ell(\beta)$ and $f_t(\beta)$ for Different Values of β/β_s

β/β_s	1	1.1	1.2	1.3	1.4	1.5
$f_\ell(\beta)$	1	1.03	1.04	1.03	1.02	0.99
$f_t(\beta)$	1	0.94	0.87	0.8	0.73	0.66

B. Bunch Width. In the absence of space charge, the adiabatic approximation for longitudinal motion is given by

$$\frac{d^2\phi}{ds^2} = \frac{2\pi f\, qE_a}{\beta^3\gamma^3 c^3 Am}\left(\cos\phi - \cos\phi_o\right) \tag{7}$$

where $E_a = \dfrac{2V_o t_{fs}(o)}{L}$

L = distance between quadrupole centers

ϕ_o = phase of the center of the bunch, equal to ϕ_s for "synchronous" acceleration

A = atomic weight of particle

A modified version of Eq. (7) giving the same location of the unstable fixed point is

$$\frac{d^2\phi}{ds^2} = \Omega_o^2\left(\phi - \phi_o + \frac{(\phi - \phi_o)^2}{2\phi_o}\right)\sin\phi_o \tag{8}$$

where $\Omega_o^2 = \dfrac{2\pi f\, qE_a}{\beta^3\gamma^3 Amc^3}$

The use of Eq. (8) allows development of a simpler expression for the width and area of the phase stable region. The expression for the area of the phase stable region, S, derived from Eq. (8) is

$$S = 4.8\sqrt{\sin\phi_o}\;\phi_o^2 \tag{9}$$

It can be shown that by using Eq. (8), the difference in calculating area is less than 8% for the angles of ϕ_o from 0 to 60°. Furthermore, space charge effects are much more easily included in Eq. (8).

The space charge fields are calculated by approximating the bunch by a rotation ellipsoid with uniform charge density. The field components are given by

$$E_z = \alpha G_\ell z \tag{10}$$

$$E_x = \alpha G_t x$$

$$E_y = \alpha G_t y$$

where $\alpha = \dfrac{3IZ_o\lambda}{8\pi b_2^3}$

I = average current

Z_o = 120 π

b_1 = semi axis of ellipsoid in transverse direction

b_2 = semi axis of ellipsoid in longitudinal direction

Values of G_ℓ and G_t are listed in Table II.

Table II. Values of G_ℓ and G_t as a Function of b_1/b_2

b_1/b_2	0.8	0.9	1.0	1.1	1.2	1.3	1.4
G_ℓ	0.86	0.75	0.67	0.59	0.53	0.48	0.43
G_t	1.13	0.86	0.67	0.53	0.43	0.35	0.29

The effect of space charge in the longitudinal motion appears in Eq. (8) as

$$\frac{d^2\phi}{ds^2} = -\Omega_o^2 \left[(1 - k)(\phi - \phi_o) + \frac{(\phi_o - \phi_o)^2}{\phi_o^2} \right] \sin \phi_o \tag{11}$$

where $k = \frac{E_z}{E_a \sin \phi_o} \frac{\beta\lambda}{2\pi z}$

where the value of E_z is given in Eq. (10). The unstable fixed points are reduced by the presence of space charge from $-\phi_o$ to $-(1 - 2k)\ \phi_o$ and from $2\phi_o$ to $(2 - k)\ \phi_o$. The bucket width, $\Delta\phi$, from one turning point to the other is $3(1 - k)\ \phi_o$. The length of the bunch and, therefore, the longitudinal length of the ellipsoid is the product of $\Delta\phi/2\pi$ and the bunch to bunch length 2ℓ or

$$b_2 = \frac{\Delta\phi}{2\pi}\left(\frac{\beta\lambda}{2}\right) = \frac{3(1 - k)\ \phi_o \beta\lambda}{4\pi} \tag{12}$$

This value of b_2 when substituted into Eqs. (10) and (11) results in the following equation for k

$$k(1 - k)^3 = \frac{4\pi I Z_o G_\ell}{9\phi_o^3 \beta^2 \lambda E_a \sin \phi_o} \tag{13}$$

A maximum value for k can be found in Eq. (13) to be 0.25. Therefore, the quantity on the righthand side of Eq. (13) must be less than or equal to 0.1055 to remain less than the space charge limit.

C. Transverse Motion. Because of the effects of the quadrupole magnets, the x and y dimensions of the beam will be different in transit through the cell. The geometrical mean value is chosen for the space charge calculations. Since the x and y motions are similar, only the x motion will be described.

The nonrelativistic equation of motion for the x coordinate is

$$\frac{d^2x}{ds^2} + \frac{qc}{Amc^2\beta^2}\left[\pm B'\beta c\, x - (E_x)_{rf} \sin \phi_s - (E_x)_{sc}\right] = 0 \qquad (14)$$

where B' = quadrupole field gradient.

Using the value for the rf defocussing field given by Eq. (5) and the value of space charge defocussing field given by Eq. (10), Eq. (14) becomes

$$\frac{d^2x}{ds^2} + \frac{qe}{Amc^2\beta_s^2}\left[\pm B'\beta c - \frac{\pi L}{\beta_s \lambda \ell_c} E_a \sin \phi_s - \frac{3IZ_o\lambda G_t}{8\pi b_2^3}\right] x = 0$$

D. Design of Elements in Low Beta Structure. The worst case possibility is assumed to be for a preaccelerator voltage of 750 kV. If the "synchronous" ion is singly charged xenon, the particle will have an initial β of 0.0035. The velocity profile of the structure can be changed by appropriately phasing the independent accelerating cavities. The design goal for average current is 50 mA with a normalized transverse emittance of 6×10^{-7} meter · radian.

The frequency of the accelerating cavities for this design is 12.5 MHz or λ = 24 m. The bore radius of the accelerating tube is 0.02 m, and the accelerating gaps are 0.01 m. The cell length is 0.375 m, and V_o is 100 kV. The value of E_a is 0.32 MV/m. For $\phi_o = 69^o$, b_2 is 0.018 m and G_ℓ is 0.59. The value of the quantity of the righthand side of Eq. (13) is 0.1012, which is less than the longitudinal space charge limit.

The quadrupoles are designed with an average current of 50 mA, a quadrupole length of 0.3 m, a B' of 46 T/m, an ℓ of 0.042 m, a b_2 of 0.018 m, a ϕ_o of 69^o, and a G_t of 0.53. The phase advance per cell is 37.5^o (instead of 127^o

per cell without space charge effects). The transverse acceptance in the presence of space charge is 1.7×10^{-4} meter · radian.

The same cavity can be used for higher velocities of the particles, up to $\beta = 0.0051$ or $T = 1.6$ MeV. Since the longitudinal space charge limit increases proportionately to β^2, the phase stable angle can be decreased with a resulting higher gain per cavity. Also, the same quadrupoles can be used since the transverse defocussing effect of the rf field also decreases, as can be seen in Table I.

V. Cavity Features

In recent years, the spiral resonator has received considerable attention as a simple low cost low beta heavy ion accelerator. Work at Frankfurt has demonstrated shunt impedance in the neighborhood of 40 MΩ /m and electric field strength on axis of 16 MV/m with frequency and amplitude control feedback for a 108.5 MHz resonator.[15] Work at Los Alamos[16] demonstrated similar values of shunt impedance and field strengths of 2.6 MV/m without feedback control at 50 MHz. These and the excellent results of Argonne's program with the very similar split ring structure[17] support our choice of the spiral resonator as the primary candidate for the low beta linac for the ion beam fusion program. Other candidates which are actively being considered are the 1/4 wavelength folded transmission line and 1/4 wavelength coaxial cable resonator. Because of the low beta (0.0035) and large aperture required (4 cm), the operating frequency has been selected as 12.5 MHz.

The first phase of the program to develop the 12.5 MHz low beta linac will consist of the construction of low power test models. The models will be used to determine the resonant frequency, shunt impedance, and mechanical stability of the cavities. The first model of the spiral resonator is shown in Fig. 1. It is an Archimedean spiral wound out of 3.5 cm o.d. copper water tubing with a constant pitch of 10 cm. The drift tube has an aperture of 4 cm and is 3.1 cm long. There is an adjustable nominal 1 cm gap between the end plate drift tubes and central drift tube. The rf power will be fed in and monitored on rotatable loops located at $\pm 45^{\circ}$ and 90°. The outside diameter of the resonator is 122 cm and has an adjustable nominal width of 7 cm in the axial direction. The spiral tubing is over 6 m in length, nearly a 1/4 wavelength at 12.5 MHz.

Models of the 1/4 wave folded transmission line and 1/4 wave coaxial line resonator are shown in Figs. 2, 3, and 4. A simple constant diameter model of the 1/4 wave coaxial resonant line has been constructed and is undergoing low power testing.

Table III shows the expected gap impedance, shunt impedance, and rf power requirements to reach 100 kV on the gap for the various resonators.

The calculation was based on modelling the cavities as transmission lines. The spiral resonator was modelled as a strip line. Because of the wide spacing between turns, this should be a good approximation. The folded transmission line and coaxial resonator were modelled as coaxial cables. The gap impedance was calculated using the transmission line equation

$$Z_{gap} = \frac{Z_o(Z_r + Z_o \tanh \gamma \ell)}{Z_o + Z_r \tanh \gamma \ell}$$

where Z_o = characteristic impedance of the line

Z_r = load impedance

γ = $\alpha + j\beta$, the propagation factor

α = attenuation constant

β = phase constant

Also included in the table is a modified spiral resonator. The modified resonator has an axial length of 7 cm to a radius of 25 cm and an axial length of 33 cm from a radius of 25 cm to 61 cm.

The table demonstrates that the shunt impedances of the modified spiral resonator, folded line and 1/4 wave coaxial line are ample and the power requirements are reasonable, at most 34 kW. Therefore, the selection of the resonator may be affected as much by the ease of construction, size, cost, and mechanical stability as by the rf power requirements. Methods of increasing the shunt impedance of the modified spiral resonator and folded transmission line are continuing to be explored. We are confident that modifications will get the rf power requirement below 20 kW for the folded line and 15 kW for the spiral line.

Table III. Impedance and RF Power Requirements

Resonator	Gap Impedance in kΩ	Shunt Impedance in MΩ/m	RF Power Requirement in kW for 100 kV on Gap
Spiral Line (Fig. 1)	82	9.4	61
Modified Spiral Line	275	31.4	18
Folded Transmission Line with Inside Short (Fig. 2)	145	16.6	34
Folded Transmission Line with Outside Short (Fig. 3)	235	26.8	21
Coaxial Line (Fig. 4)	407	46.5	12

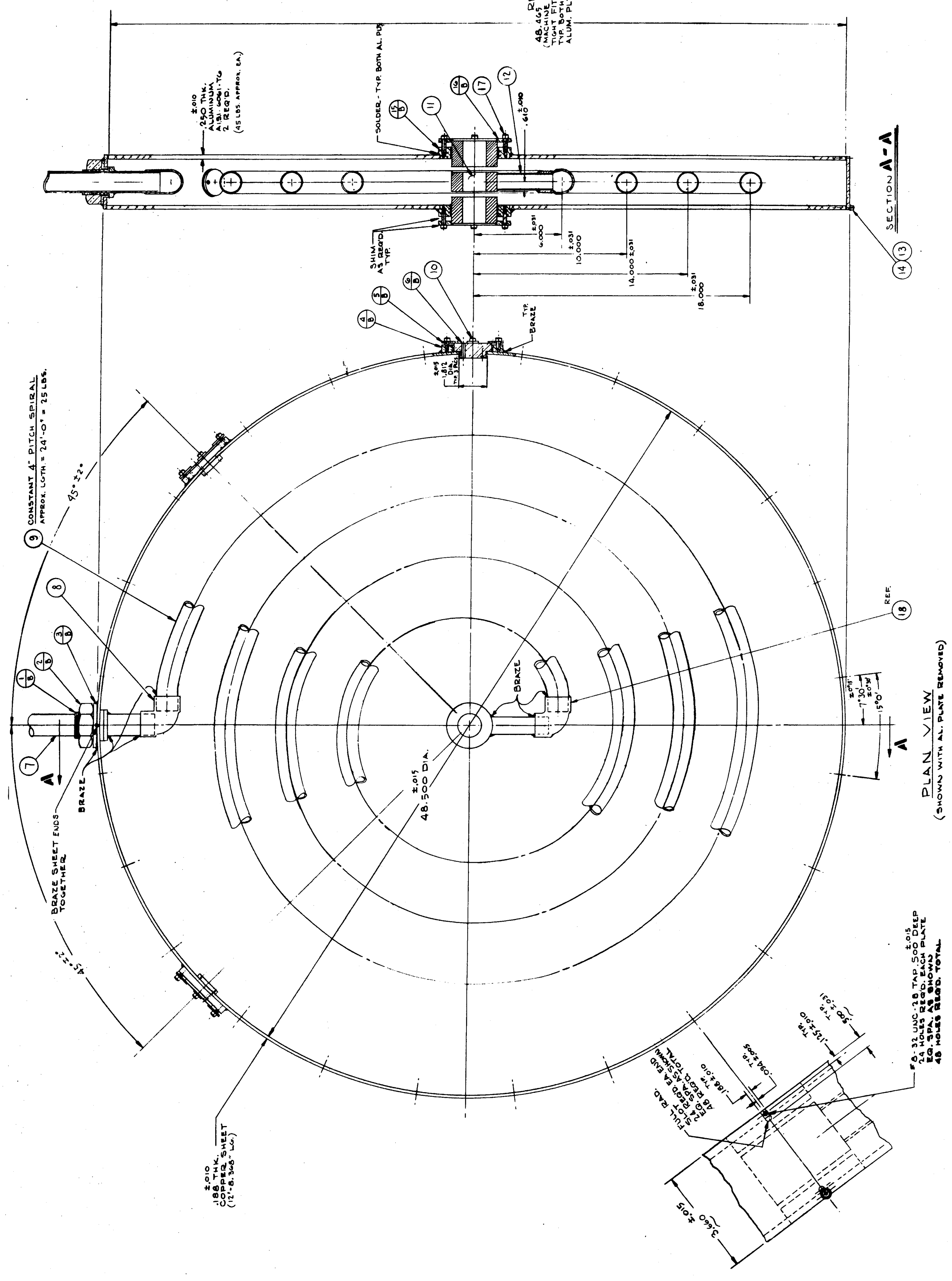


Fig. 1 12.5 MHz Spiral Resonator Model

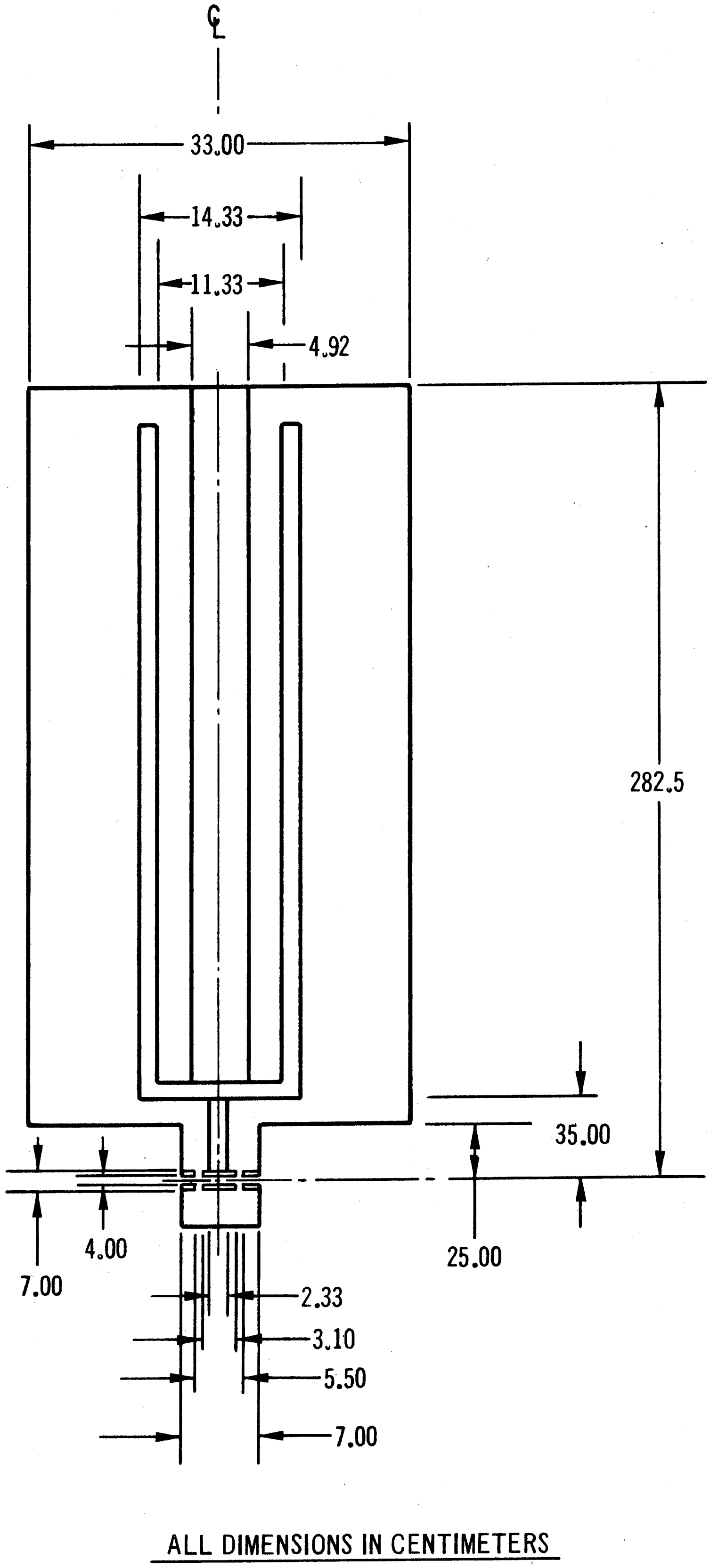


Fig. 2 12.5 MHz Folded Transmission Line Resonator Model with Inside Short

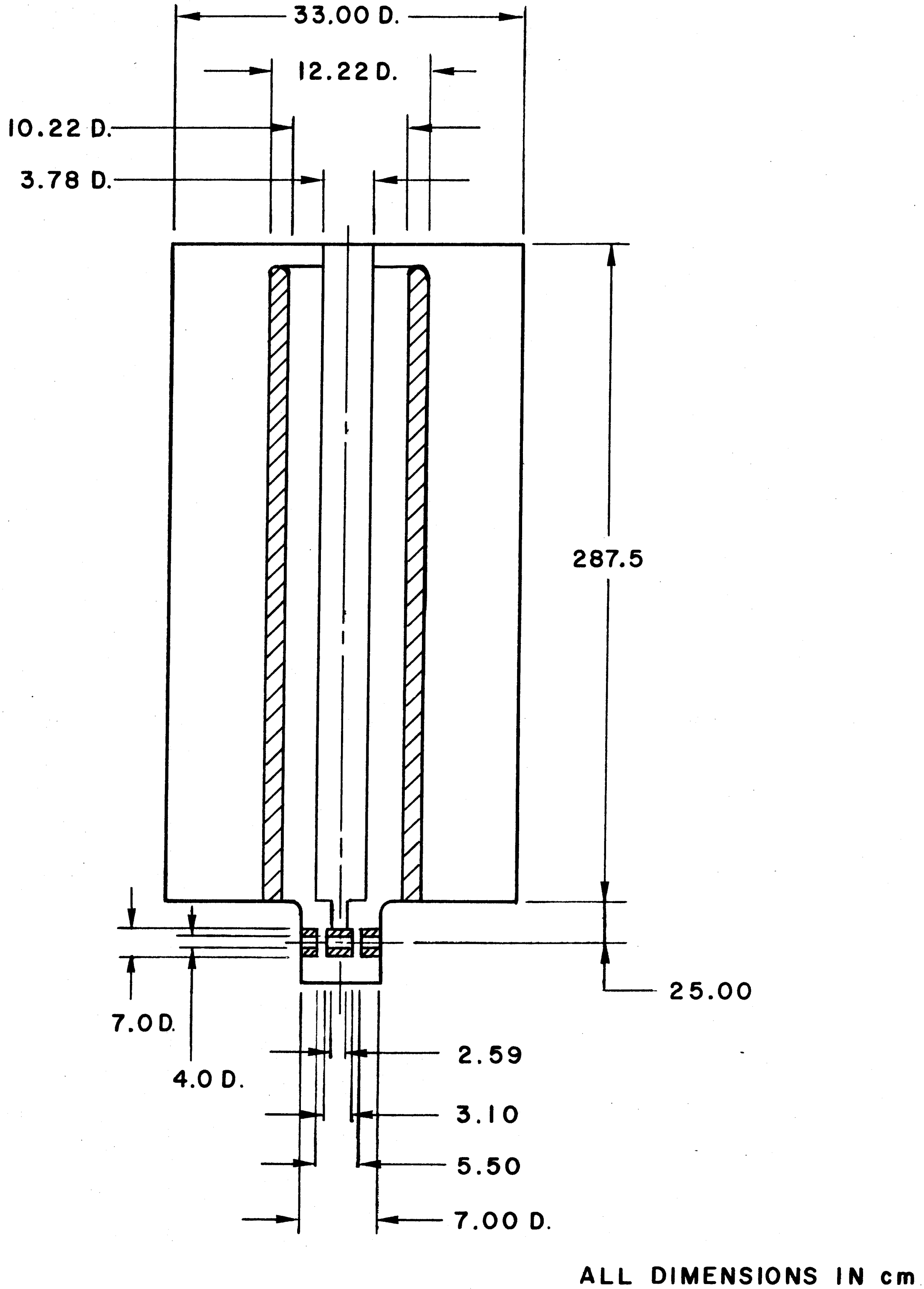
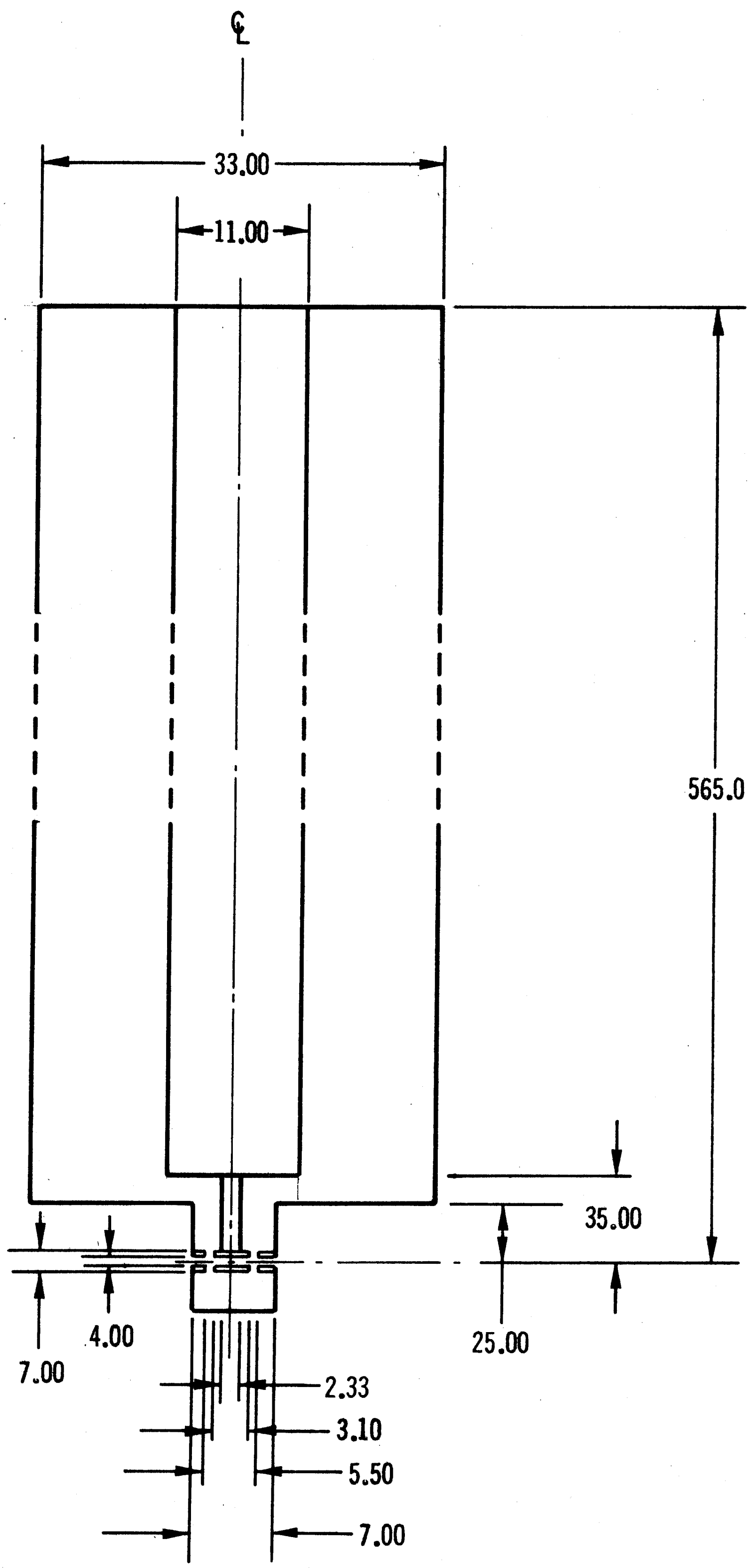


Fig. 3 12.5 MHz Folded Transmission Line Resonator Model with Outside Short



ALL DIMENSIONS IN CENTIMETERS

Fig. 4 12.5 MHz 1/4 Wavelength Coaxial Resonator Model

VI. Discussion

The necessity of and difficulty of attaining high linac current for heavy ion fusion accelerator systems are apparent. The crux of the problems is transport of space charge dominated beams. Therefore, development of rf cavities will be paralleled at Argonne by experimentation with transport of space charge dominated beams. A special concern in this experimental program will be to verify that the intense beams can be matched into the transport system as has been assumed in theoretical analyses carried out to date.[14, 18] While the feasibility of the highest linac currents will require favorable results from these experiments, the choice of linac concept is not at stake since the selection has already been made in favor of the concept with the greatest capability for beam transport.

A. Flexibility and Control. In addition to being most suited to solving the transport problem, the single drift tube cavity has other important assets. Independent rf phasing of these cavities avoids restriction to a fixed velocity profile along the accelerator's length. One effect is that nearly the maximum accelerating voltage can be applied to a range of ion masses and charge states. This flexibility will be an important feature until much more information is obtained about the relative merits of different ions. This has the important consequence that the lack of information about the ion properties need not hold back development of the linac.

In addition, independent phasing of resonators provides the capability to compensate for variations in the performance of individual cavities--including complete loss of accelerating field. In view of the potential of intense heavy ion beams for surface damage (either sudden or over an extended period), the ability to tolerate substantial malfunction is likely to be important. With computer control of phase and field strength, optimal tuning may be achieved under many conditions. Phase and amplitude control for each cavity will require numerous beam sensors, preferably one between each cavity. The most important consideration, however, is simply that a high degree of control and flexibility such as is offered in principle with independently phased cavities is likely to be indispensable.

B. Implications for the Preaccelerator. An obvious possibility for easing the problems of low velocity rf acceleration is to employ a higher voltage preaccelerator. A 3 MV accelerator would allow double the characteristic lengths for cavity design and increase the maximum transportable current ($\sim V^{5/6}$) by a factor of 3.2 compared to a 750 kV preaccelerator. Both the Cockcroft-Walton and dynamitron type high voltage power supplies are capable of the required power output,[19,20] and other concepts of comparable capability are possible.[21] The real problems lie in the high voltage accelerating tube.

Experience with high current (50-300 mA) ion beams is restricted to protons and voltages about 750 kV, adequate to meet the needs of the linacs used to inject high energy proton accelerators. The experience of multimegavolt dc accelerators is restricted to currents of less than 1 mA, and normal practice is a few μA or less. It may be argued that the need has not previously existed for high current multimegavolt heavy ion beams, that the normally low currents are for machines run dc, that the appropriate power supplies have only been available recently, and that, in at least the case of the dynamitron, the design of the power supply has been coupled (for convenience rather than necessity) to the accelerating tube resulting in a long low gradient column poorly suited for intense ion beams. Improvements over past performance are doubtlessly possible, but high currents of heavy ions at 750 kV are yet to be demonstrated. Nevertheless, the dividends in terms of a relaxation of the problems of accelerating 50 mA in the rf linac or the possibility of going beyond 50 mA in the linac and easing the downstream problems make it essential to attempt to develop maximum voltage preaccelerators for high current heavy ion beams.

Acceleration of the intense heavy ion beams in the preaccelerator column will require some form of focussing to counteract the space charge forces. Inclusion of electrostatic or even magnetic quadrupole lenses at special stations along the accelerating column is conceivable, although the latter are much weaker at the very low velocities where the problem is greatest and entail supplying large amounts of electrical power. The alternative use of an electrode structure with an increasing voltage gradient, a Pierce structure, has been used successfully with intense proton beams at 750 keV. However, the limits of practical field strengths are already pushed in the use of Pierce columns at 750 keV to inject high currents into proton linacs and a CERN design[22] for a proton accelerating structure to 1.5 MeV was a hybrid that departed from the Pierce condition when the required electric field reached a limiting value and continued with a constant gradient to the maximum voltage.

The problem is still more difficult for heavy ions since the required field gradient increases with the mass of the accelerated particle. Although the field requirement increases slowly with the atomic mass, the field strength required for mass 200 ions is several times that needed for protons while a factor of 1.5 (or less) increase in the field entails doubtful feasibility.

The possible solutions to the problem involve accelerating at reduced current density. However constraints are placed on the quality of the beam obtained from the source by the requirements for final focussing and stiffened by dilutions during acceleration, accumulation, and manipulation. Assuming that little can be done to improve the divergence of the bright sources[23] under consideration, current densities on the order of 20 mA/cm^2 are required. Since this current density of heavy ions causes the voltage gradient of a Pierce column to exceed realistic values after a voltage drop of about 200 kV, expansion of the beam after extraction from the source is required. This also may be accomplished with discrete lenses or appropriate shaping of the accelerating field,[24] and the various possibilities are being studied at Argonne and the Hughes Research Laboratories pursuant to the design of a 1.5 MV column to be used with the dynamitron to accelerate 100 mA of heavy ions.

C. Electrostatic Lenses. The merits of electrostatic lenses must be considered in view of the relative strength of the electrostatic compared to the magnetic force at the very low velocities realized in the early stages of acceleration. With equal dimensions, an electrostatic quadrupole with a maximum surface field of 21 kV/cm has the same focussing properties as a magnetic quadrupole with a maximum magnetic field of 2 T (both fields being found in the slot and not on the pole tip) for $\beta = 0.0035$. Although 21 kV/cm is a conservative field level, electrostatic lenses are still likely to be less reliable than magnetic lenses. Neither efficiency nor cost seems to clearly favor electrostatic lenses: Superconducting or cryogenic magnets may be used; the construction of electrostatic lenses is nontrivial; and more detailed analysis including beam dynamics and such practical considerations as the axial spaces required by lens electrodes indicates that the overall reduction in the length of the focussing elements would be a factor of 0.7 for electrostatic lenses with a 50 kV/cm maximum electrostatic field compared to magnetic lenses with a 2 T maximum magnetic field. In addition a strong effort will be made at Argonne to increase the ion velocity achieved by the preinjector, further decreasing the potential advantage of practical electrostatic lenses. In any case, the advantage is dissipated before the ions reached 10 MeV. Moreover, in view of the unprecedented intensity of the planned heavy ion beams, the expected problems in controlling their space charge forces, the additional mechanisms for beam losses possessed by heavy ions compared to protons, and the greater surface problems that will follow from beam interception of heavy ions compared to protons, electrostatic focussing elements would probably represent an unwarranted sacrifice of reliability.

VII. ANL Program

The ANL ion beam fusion program is concentrated in three major areas: development of an intense source, the highest possible preaccelerator voltage, and a high current rf linear accelerator for about the first 10 MeV of the acceleration cycle.

The low β linac is the focus of this report. Basically, the program plan for the low β linac can be summarized as follows: (1) An analytical study will be undertaken to define the critical problems in accelerating and transporting low β high intensity beams. (2) Alternate types of low frequency resonant cavities will be investigated for their applicability to an individually phased accelerator array. (3) Various transport schemes will be compared. (4) An integrated low β accelerator design will be pursued which includes the individually phased accelerating cavities and their rf power sources capable of operating with as low an injection energy as 750 keV, although preferably higher, and the focussing elements and their power supplies.

Commissioning of the low β accelerator with the preinjector and vacuum system should take between 1-1/2 and 2-1/2 years depending on the level of funding.

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