MASTER

LIGHT ION FUSION EXPERIMENT (L.I.F.E)
CONCEPT VALIDATION STUDIES*

FINAL REPORT
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BY

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LIGHT ION FUSION EXPERIMENT (L.I.F.E.)
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ABSTRACT

This report reflects the considerable advances made for the objectives of the contractual program, validating by detailed analytical studies the concept of a new Light Ion Fusion Experiment for Inertial Confinement Fusion. The studies have produced an analytical design of a novel electrostatic accelerator based on separate function and strong channel focusing principles, to launch 3 to 10 MeV, 23 kA, He^+ neutralized beams in 400 ns pulses, delivering on a 5 mm radius target located 10 m downstream, 50 kJ of implosion energy in ~ 20 ns impact times. The control, stability and focusing of beams is made by electrostatic quadrupoles, producing overall beam normalized emittance of $\sim 3 \times 10^{-5}$ m-rad. Key analytical discoveries have been made for the stability of ballistically focused and neutralized transport of these intense ion beams. These are: 1) ambient Lithium vapor gas pressure can be in excess of 10^{-3} Torr for a LIFE ICF reactor system; 2) initial temperature of electrons neutralizing co-located ion beamlets from the LIFE accelerator system can be $T_{e0} = 40$ eV for the 10 m stand-off from 5 mm radius targets, including the influences of 45:1 radial and 20:1 axial beam pulse compressions. Laboratory scale experiments are designed to validate the identified critical issues in the accelerator system and the ballistically focused transport of neutralized intense ion beams.

I. EXECUTIVE SUMMARY

This final report reflects on the work performed at TRW in the period of July 1979 to May 1980 for the U.S. Department of Energy Office of Inertial Fusion, under contract No. DE-AC08-79DP40109. The statement of work in this effort included theoretical analyses, conceptual design and system studies for a new Light Ion Fusion Experiment (LIFE). The following tasks were planned and performed:

- Task 1. Conceptual design and analysis of a new light ion accelerator system for ICF based on the principles of producing multi-aperture, channel focused beams with suitable emittance and brightness to ballistically focus onto ~ 0.5 cm radius targets in 10 m and deliver on target 3-10 MeV, ~ 0.5 MA, ~ 20 ns pulses, as one of the modules of a multi-beam driver system.
- Task 2. Theoretical analyses and numerical simulations to determine the stability conditions of neutralized intense light ion beams in ballistically focused transport, and the search of methods of producing charge and current neutralization satisfying these stable focusing conditions.
- Task 3. Design of a scaled accelerator and beam neutralizer system for a concept validation experiment, to demonstrate the stability of intense light ion beams during ballistically focused propagation and the quality at the focus of beams.

Task 2 was implemented in collaboration with the X-3 Intense Beam Theory Group at LASNL, principally with Dr. D. S. Lemons and Dr. L. E. Thode. The performance of some elements in Task 1 and Task 3 was reinforced by a development effort at TRW which was conducted in parallel under the auspices of the Ballistic Missile Defense Advanced Technology Center, to produce an intense pulsed cold plasma ion source for a different high

energy accelerator system¹ and mission goals. The performance in both of these complimentary efforts for DOE and DOD was strengthened by a substantial amount of TRW capital equipment investments and the parallel TRW Internal Research and Development funded projects², some of which are being expanded³ in 1981. Considerable collaborative work was also performed in discussions with Dr. A. W. Maschke (BNL) and Dr. S. Humphries, Jr. (SNLA) at no cost to the contract, and in consultations with Dr. W. B. Herrmannsfeldt (SLAC), Prof. G. A. Moses (University of Wisconsin) and I. D. Smith (Pulse Sciences). Therefore, these are the reasons why in all the tasks it was possible to achieve considerable and in-depth results which otherwise would have been limited if the work had been performed only within the bounds of the given contractual support to TRW.

In March 1980 a project mid-term technical review was held at SNLA, with the participation in the panel of about 20 colleagues from DOE, LLNL, LASNL and SNLA. Based on the recommendations of the DOE Review Panel and on the recently stressed relevance to the Heavy Ion Fusion program⁴⁻⁷, a follow-on experimental test was proposed⁸ to characterize key elements in the methods of producing neutralized intense ion beams, suitable for the ballistically focused transport of such beams in a laboratory scale setup. Several theoretical concerns which were raised during the mid-term review have been addressed by the TRW-LASNL research team during the period of March - November 1980, producing satisfactory results by means of further analyses and numerical simulations. All of the new results were reported at the Heavy Ion Fusion workshops and the San Diego APS Plasma Physics conference, and are summarized in this report. Further associated work will be reported at the 1981 Particle Accelerator Conference.

The accomplishments⁹⁻¹⁷ are summarized as follows:

1. The conceptual design of the LIFE Accelerator System has been made on the basis of using separate-function hardware elements. Each element can be optimized to fulfill the requirements of

producing an intense light ion beam ICF driver, consistent with the up-to-date design concepts of feasible targets. The parameters of a driver system to deliver on target by two-sided illumination, 2 MJ total energy, 150 TW total power, 95 TW/cm² focused power flux and about 50 MJ/g energy deposition density, with a stand-off capability in excess of 10 m is given in Figure 1. Each beam-line of the 40 beam accelerator system is designed to produce 3 - 10 MeV, He⁺, 23 kA accelerated current with 20:1 axial pulse compression, and a normalized beam emittance of $\sim 3 \times 10^{-5}$ m-rad, suitable to focus onto 0.5 cm radius targets from a distance of 10 m, by means of ballistically focused, charge and current neutralized beam transport. As compared to the pulsed power diode approach, the principal advantages of this accelerator system are: 1) the use of modular, and relatively low power technology which is required to energize the accelerator, 2) the feature of having highly controllable beams, 3) a beam propagation technique that is now found to be essentially the same as for the case of heavy ion drivers and, 4) an ICF reactor scenario which for different reasons, needs to be identical to the one for heavy ions (10^{-3} torr Li). The studies in this area conclude that it would be feasible to implement the LIFE accelerator system for which the required technologies could be developed in a straightforward way, as an extension of the existing state-of-the-art in High Energy Physics and pulsed accelerator technologies, and it would be judged worthwhile to do so provided that the key propagation physics issue of ballistically transporting and focusing neutralized intense ion beams can be validated by a suitably scaled experiment in 10^{-3} torr ambient gas. The key derived parameters of the multi-aperture, strong channel focused, multi-stage, electrostatic accelerator system are displayed in Figure 2.

- 2. Theoretical analyses and numerical calculations have been completed, investigating the stability of neutralized ion beams propagating in

L.I.F.E. SINGLE BEAM PARAMETERS FOR A 2 MJ, 150 TW, 95 TW/cm², 40 BEAM-LINE ICF DRIVER SYSTEM

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Figure 1

THE L.I.F.E. ICF DRIVER IS A SYSTEM OF MULTI-APERTURE, CHANNEL FOCUSED,
MULTI-STAGE, LOW β ELECTROSTATIC ACCELERATORS

● PARAMETERS OF A SINGLE BEAM LINE ARE:

- MULTI-APERTURE
- $I_{\text{beamlet}} \approx 1-1.5 \text{ A}$
- $V_{\text{accel}}(t): 3-10 \text{ MeV}$
- ESQ TRIPLET
- $J_{\text{ext}} = 1.0-1.5 \text{ A/cm}^2$
- $R_{\text{structure}} = 1.2 \text{ m}$
- $E_Q \sim 0.5-1 \times 10^8 \text{ V/m}$
- x, y DEFLECTION PLATES
- $R_{\text{ext}} = 6 \text{ mm}$
- $R_{\text{inject}} = 0.3 \text{ mm}$
- $R_Q = 0.5 \text{ mm}$
- $R_T = 5 \text{ mm}$
- $t_{\text{pulse}} = 550 \text{ ns}$
- $V_{\text{inject}} \approx 3 \text{ MeV}$
- $I_{\text{total}}^{\text{accel}} = 23 \text{ kA}$
- $N_{\text{aperture}} = 23,000$
- $\epsilon_{\text{NT}} \leq 5 \times 10^{-8} \text{ m-rad}$
- $\epsilon_{\text{NT}} = 1 \times 10^{-7} \text{ m-rad}$
- $\epsilon_{\text{NT}} = 2 \times 10^{-7} \text{ m-rad}$
- $\epsilon_{\text{NT}}(\text{total}) = (2-4) \times 10^{-5} \text{ m-rad}$

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Figure 2

the ballistically focused mode. A substantially relaxed requirement for the initial electron temperature is derived for the neutralizing electrons which are launched with the ions and adiabatically compressed in both radial (45:1) and axial (20:1) dimensions during the ballistically focused transport of the intense ion beams. It is found that a $T_{e0} \approx 40$ eV can be tolerated in order to focus onto 0.5 cm radius targets from a distance of 10 m the 3 - 10 MeV He^+ beams generated by one of the modules of the multi-beam 2 MJ driver system. Initially co-moving electrons which are also co-located with ions are required. Other schemes which rely on the side-injection of electrons to neutralize the ballistically focused ion beams have also been examined. It is found that these would quickly produce an intolerable amount of electron heating which acts to prohibit the desired adiabatic beam compression at the required level. It is concluded that all similar side-injection schemes should be discarded especially for the neutralization of light ions. The required initial temperature of co-located and co-moving electrons is bracketed by the adiabatic compression (45:1 radially, and 20:1 axially) and focusing requirements obtained from the recently derived¹³⁻¹⁴ envelope equations. These equations which describe the radial compression of neutralized beams have been applied for the realistic conditions in beam transport in which neutralized beamlets having radius expanded at launch of 6 mm with 14 mm center-to-center distance and steered to point to a common focus would propagate freely until ion beamlet edges begin to coalesce, and thereafter, the merged uniform beam undergoes radial compression. It is found that three-dimensional electron heating evolves quickly from the initial two-dimensional state which is a helpful effect. Upon suggestion by Humphries¹⁸ elements of our analysis have been extended to estimate also the influence of axial compression on the size of the ballistically focused radius. The combined envelope equation is applied

and the results are displayed in Figure 3. Thus, accounting for both effects, an overall requirement for T_{eo} is found: $T_{eo} \approx 40$ eV for $L = 10$ m, and $R_{\text{target}} = 0.5$ cm. The required initial ion temperature T_{io} is also correlated with T_{eo} in the manner shown in Figure 3. The resulting analysis demonstrated that $T_{eo} \approx 30 - 50$ eV, and $T_{io} \approx 2 - 4$ eV can be tolerated to ballistically focus the intense ion beams undergoing both radial and axial compression onto 0.5 cm radius targets from a distance of 10 m; while geometric focusing is 200:1, radial adiabatic compression is 45:1 and axial pulse compression is 20:1. The propagation time of 850 ns is too rapid for temperature equilibration of ions and electrons to occur which requires in excess of 10 ms time.

The classical Pierce instability¹⁹⁻²⁰ recently has been invoked as a damaging mechanism²¹⁻²² especially for the ballistic propagation of light ion beams that rely on co-moving electrons for the neutralization of these ICF drivers. A theoretical analysis was made²³ showing that this application is incorrect, requiring unphysical boundary conditions and resulting in erroneous conclusions.

A new method of actively^{8,16} producing charge and current neutralization of intense ion beams as the beams just emerge from the accelerator system has been developed. The validity of the method has been studied by detailed analytical calculations and two-dimensional simulations. Including the influences of plasma sheath profile, the co-located ion beam space charge and lens aberration in the electron extractor scheme, it is shown that co-moving electrons can be launched with initial temperature of less than 40 eV. Also, a passive auto-neutralization²⁴ scheme proposed by Humphries has been examined and found that in the case of LIFE beam parameters, auto-neutralized beams would also have a T_{eo} of 20-60 eV which may improve by launching electrons at higher than thermal speeds. Thus, both active and auto-neutralization methods can be used suitably

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Figure 3

to produce co-moving and co-located electrons for the ballistically focused propagation of LIFE beams. All of the above analyses point out the importance of performing in the near term scaled experimental investigations in an area which so far is lacking meaningful input from tests, as outlined by the following.

3. The design of a scaled concept validation experiment to investigate the ballistically focused propagation of neutralized intense ion beams has been made. The methods of producing co-moving electrons by active and/or auto-neutralization schemes can be tested by the use of $\sim 0.5 \mu\text{s}$ flat-top pulses of $\sim 0.5 \text{ MeV}$, $2 - 100 \text{ A}$, less than 1 mrad divergent, He^+ parallel beams. However, the validation of critical issues in the ballistically focused propagation of intense neutralized ion beams requires that both radial and axial adiabatic compression of beam pulses are also occurring during the transport. Since the co-moving electron energy should be more than the theoretically tolerable initial electron temperature, a meaningful ballistic propagation test requires that the acceleration voltage be from 2 to 5 MeV for He^+ beams. Because beam current density is also an important scalable parameter, a total accelerated beam current of $1 - 2 \text{ kA}$ in $0.5 \mu\text{s}$ pulses and suitable geometries appears adequate to perform significant ballistic focusing tests over propagation distances of $6 - 8 \text{ m}$. The conceptual design details of such an experiment has been worked out including the elements of novel diagnostics and instrumentation, ion source and accelerator, costs and schedule. The experimental layout is depicted in Figure 4. At the time of this writing a TRW proposal⁸ submitted to DOE/OIF to experimentally validate the above methods of intense ion beam neutralization is under consideration.
4. The ICF reactor scenarios for LIFE beams are merely limited by the multiple scattering considerations. It is found that 10^{-3} torr Li vapor will be acceptable, since the smearing at the focus will be 1 mm in the worst case for the 3 MeV part of the beam and 0.3 mm for 10 MeV , during 10 m of transport at 10^{-3} torr gas pressure.

BALLISTIC PROPAGATION WITH CO-MOVING ELECTRONS EXPERIMENTAL LAYOUT

FIGURE 4

II. CONCEPTUAL DESIGN OF A NEW LIGHT ION ICF DRIVER

In this section the specific features of the LIFE accelerator concept are presented. The theoretical considerations in accelerator physics and target requirements are discussed and a conceptual design of the accelerator and energizing system given. The accelerator design considerations are bracketed by the stringent emittance requirements due to the ballistically focused propagation range and the high gain target features. Finally, critical issues and a development plan of the accelerator system are outlined.

II.1 FEATURES

The LIFE ICF driver system is conceived to produce the following conceptual features:

- (1) A light ion intense beam accelerator system, utilizing separate function hardware elements to achieve the desired objectives has the following design features:
 - A separate, pulsed intense cold plasma ion source is used with $n_i \approx 10^{13} \text{ cm}^{-3}$ and $T_i \approx 0.1 \text{ eV}$ to extract $1 - 1.5 \text{ A/cm}^2 \text{ He}^+$ ions in μs pulses, in the afterglow regime of plasma induction by pulsed RF power, using a large vessel with surface magnetic confinement. Multi-aperture ion extraction is made using 6 mm radius holes resulting to an invariant normalized emittance per aperture of $\epsilon_{NT}(\text{single}) \leq 5 \times 10^{-8} \text{ m-rad}$.
 - A separate function, multi-aperture, channel focused multi-stage electrostatic accelerator is used to extract and accelerate a total of 23 kA beam current to about 3 MeV with $\sim 500 \text{ ns}$ flat-top applied voltages. The multi-aperture structure is made of parallel planes with overall radius of 1.1 m. The voltage distribution chain between extraction and 3 MV is designed to compress radially the beamlets from 6 mm down to about 0.5 mm. A factor of 2 in beamlet

emittance growth is allowed to occur and beamlets are prepared to be injected in a matched fashion into strong focusing electrostatic quadrupole (ESQ) channels.

- A similar parallel plane electrostatic accelerator section is used, with time varying applied voltages in acceleration gaps between the ESQ planes, to produce 3 to 10 MeV He^+ beamlets which are confined and controlled by the ESQ strong focusing channels. Phase space matching at ESQ injection is made by adiabatic and near paraxial conditions. The time varying voltage waveform is designed to cause strong (20:1) beam pulse axial compression to occur during a 10 m long ballistically focused transport region. A further factor of 2 in beamlet emittance growth is permitted to occur in this acceleration chain. An overall normalized emittance of $\epsilon_{NT} \approx 3 \times 10^{-5}$ m-rad is derived for 23 kA accelerated beams, so that such a beam line is capable of focusing onto 0.5 cm radius targets from a distance of 10 m.
- Emerging 3 - 10 MeV parallel beamlets are independently steered and focused onto pellets by a set of electrostatic parallel-plate x - y deflectors and an ESQ triplet, expanding the 0.75 mm radius of emerging beamlets to 6 mm with the same 14 mm center-to-center separation and beamlet waist occurring near mid-range to propagate in the ballistically focused manner, with 200:1 radial geometric focusing and 45:1 radial compression,

(2) An intense beam neutralizer system, to achieve the desired objective of launching the emerging ballistically focused beams with 10 m stand-off capability has the following design features which are derived from the beam stability analysis:

- Initially co-moving electrons which are also co-located with ions are required to launch the neutralized transport of ballistically focused beams.

- Initial electron temperatures of $T_{eo} = 30 - 40$ eV are acceptable in order to focus the 23 kA 400 ns beams undergoing 20:1 axial compression and 45:1 radial compression, focusing onto 0.5 cm radius targets in 10 m.
- Initial ion temperatures of $T_{io} = 2 - 4$ eV are acceptable.
- Adiabatic radial compression occurs when beamlet edges begin to coalesce in the last two meters of the ballistic transport; the launched neutralized beams propagate without radial compression in the first 8 m; with 45:1 radial compression occurring when the ESQ focused beamlets coalesce beyond a mid-range waist condition whereby a solid focused beam evolves near the targets.
- Active or auto-neutralization of intense ion beams is made by the use of passing the beams as they emerge from the accelerator into a neutralizer cell where electrons could be initiated at higher than thermal speeds upon emerging from the cell,
- A pulsed He^+ plasma neutralizer cell with electrons emitted by radially situated filaments is used, with plasma to beam density ratio of $n_p/n_b > 100$ to produce co-moving and co-located electrons with ions.
- A precise neutralization is not necessary; initial non-neutrality of 5 - 10% is tolerable.
- In one method, actively produced charge and current neutralization is made by electron extraction and acceleration at the downstream end of the cell. In another method, auto-neutralization is made with electrons accelerated by the space charge potential of ion beamlets. In both methods the initial temperature is consistent with what is required to focus onto 0.5 cm radius targets in 10 m.

- The required ambient gas pressure is 10^{-3} torr, limited by the multiple scattering smearing of the 0.5 cm radius focus, in the 10 m transport of 3 - 10 MeV He^+ beams; 10^{-3} torr of Li produces less than 1 mm smearing.

These specific features are summarized in Figures 1 and 2. A further capability of shaping the target-incident beam power profile for the individual beam lines is made possible by providing a voltage waveform regulation at the level of 1% - 2%. Otherwise, a voltage regulation of about 4% is adequate. A multiple of 40 beam lines of the type described is envisaged to have a 2 MJ light ion ICF driver, delivering 150 TW beam power on targets at 95 TW/cm^2 with energy density of 50 MJ/g.

- (3) As compared to the mainline approach of diodes with or without separated ion sources, the principal advantages of this light ion driver system seems to be the following features:
- Use of modular hardware elements in separate functions.
 - Use of low power technology to energize the accelerator system.
 - Enhanced beam control and flexibility of control both in the production and focusing of intense ion beams.
 - An ICF reactor design which is identical to what would be required for the heavy ion drivers, using 10^{-3} torr Li vapor.
 - A beam propagation mode which is identical to what would be required at least initially for the demonstration of heavy ion drivers.
 - An ability to deliver power shaped beams according to the choice of target designers, where implosion uniformity is enhanced because each beam-line could produce the same power profile in a multi-beam ICF driver system.

The outstanding critical issues requiring further studies and concept validation experiments are addressed at the end of this and the following sections.

II.2 ACCELERATOR SYSTEM

In order to scope the accelerator system design parameters, an analysis was made on the desired time-dependent voltage waveform, to define the constant voltage V_0 , and time varying voltage $V(t_0)$ components of the beam kinetic energy:

$$E_b = V_0 + V(t_0) \quad (1)$$

as a function of the desired power profile on targets $P(t)$, the accelerated beam's pulse time t_0 , ($0 < t_0 < t_p$), and the ballistic propagation distance L . Beams emerging from the accelerator at times t_0 with velocities $v(t_0)$ will arrive at the target at times t , given by:

$$t = t_0 + \frac{L}{v(t_0)} \quad , \quad (2)$$

and the energy delivered to targets by beam particles launched between t_0 and $t_0 + dt_0$ will be:

$$dE(t) = P(t) dt = \frac{I_0}{Z_i e} M_i c^2 [\gamma(t_0) - 1] dt_0 \quad . \quad (3)$$

I_0 is the accelerated beam current, extracted from a time independent ion current plasma source where to a good approximation the constancy of I_0 is preserved throughout the acceleration chain. Combining equations (2) and (3), with no acceleration occurring in the propagation region,

$$\left. \begin{aligned} v(t_0) &= v(t) \\ \frac{dt_0}{dt} &= 1 + \frac{L}{v^2(t)} \cdot \frac{dv(t)}{dt} \end{aligned} \right\} \quad (4)$$

the power profile incident on targets is obtained:

$$P(t) = \left(\frac{I_0 M_i c^2}{Z_i e} \right) \left[1 + \frac{L}{v^2(t)} \frac{dv(t)}{dt} \right] [\gamma(t) - 1] \quad (5)$$

Equation (5) can be solved numerically for $v(t)$ once a desirable power profile $P(t)$ is given by the pellet designers.

There are several parameters associated with power profile shaping which target designers could specify as indicated²⁵ in Figure 5. The power shape time base of such targets could be in the range of 50 - 70 ns. Targets requiring beam pulse power shaping for added effectiveness seem to also require a broader time base, whereas those designed to work without pulse shaping tend to require hard edged pulses of narrower time base (10 - 20 ns). In the absence of a specific target design which should be optimized for the LIFE driver, an arbitrary choice of $P(t)$ was made as given in Figure 6 and the following calculations were carried out. Specifying $P(t)$, V_0 , $E_b^{\max}$ and L , uniquely determines the parameters $t_p, V(t_0)$, I_0 , the beam current amplification in flight $I(z,t)$, the beam density profile in flight $n_b(z,t)$, assuming that a solid beam is radially compressing, and the required voltage regulation $\Delta V(t_0)/V(t_0)$, in order to deliver a power shape on target. Several sets of calculations were made to arrive at baseline accelerator system parameters which would also be consistent with up-to-date target design considerations. Prominent among target design considerations is the range-energy deposition of light ions in suitable target materials as a function of target density, target temperature, beam ion specie and kinetic energy. These highly dynamical conditions are exemplified by a set of static calculations shown in Figures 7 - 10 which have been performed²⁶ at SNLA by T. A. Mehlhorn. At a given E_b , Z_b , A_b , Z_t , A_t , the range of beam ions varies in heated materials because stopping power is a function of the degree of ionization and electron temperature. Initially, stopping power increases with T_e and as the free electron thermal velocity v_{eT} exceeds v_b , stopping power decreases and the range relengthens. These ion deposition physics effects are classically well understood, however possible anomalous deposition phenomena may exist at high temperatures which could only be addressed by suitable intense ion beam experiments. On the basis of recent target design ideas, a kinetic energy range of 3 to 10 MeV for He^+ incident beams appears to be acceptable²⁷. Therefore in equation (1), V_0 is fixed at 3 MeV and $E_b^{\max} = 10$ MeV is also determined by requiring an average deposition range of $R = 20$ mg/cm².

THERE MAY BE
SEVERAL PARAMETERS ASSOCIATED WITH PULSE SHAPE

Typical pulse shape showing some of the parameters required for its specification.

Figure 5

$P(t)$: DESIRED SINGLE BEAM POWER PROFILE ON TARGET

Figure 6

TAM - 2/80

Figure 7

TAM - 2/80

TAM - 2/80

Figure 9

Figure 10

An accelerator stand-off distance of $L = 10$ m appears to conform with several considerations, foremost involving the achievable beam emittance from the LIFE accelerator system, the maximum voltages attainable in the standing column, the desirable strength of axial pulse compression, the feasible reactor scenarios with 10^{-3} torr ambient gas, and the neutralized beam's efficient ballistic focusing onto the target surfaces. All of these considerations seem to congregate on a desirable ballistic transport range of $L = 10$ m. Because the specific deposition of 3 - 10 MeV He^+ beams, $(\frac{1}{E} \frac{dE}{dx})^{-1} \approx 50 \text{ cm}^2/\text{g}$, is 10 times larger²⁸ than the specific deposition of 10 GeV U^+ beams, the target radius can be $\sqrt{10}$ times larger for the same absorbed power and energy density, and the radius of He^+ targets can be scaled from heavy ion target designs. Therefore, ballistic focusing of He^+ beams onto targets in excess of 0.5 cm radius appears to be also acceptable.

Thus, specifying $L = 10$ m, $R_t = 0.5$ cm, $V_0 = 3$ MeV, $E_b^{\text{max}} = 10$ MeV and using for example the power profile per beam-line as shown in Figure 6, the following distributions have been calculated for the He^+ driver modules. In Figure 11 the time correlation of equation (2) is displayed, the beam velocity distribution upon launch from the accelerator is shown in Figure 12 and the velocity distribution on target is given in Figure 13. The equivalent beam kinetic energy distributions are demonstrated in Figure 14 and 15, respectively. It is seen in Figure 14 that the required voltage waveform in the time-dependent accelerator section has a non-linear smoothly rising shape to accelerate from 3 to 10 MeV. Starting with a shaped power time base of 20 ns, an accelerated beam pulse duration of 400 ns is required. Figure 16 shows the rate of beam current amplification during the ballistically focused transport, caused by the time varying accelerator voltage waveform. The required accelerated beam current is $I_0 = 23$ kA in 400 ns which is a derived value in order to deliver on target a peak power of 3.75 TW and 50.8 kJ by one of the accelerator modules; 40 of these beam-lines which are off-set from the target by 10 m and arranged in a suitable geometry

$$t(t_0) = t_0 + \frac{z}{v(t_0)}$$

t_0 : BEAM TIME UPON LAUNCH FROM ACCELERATOR

t : BEAM TIME AT TARGET

Figure 11

$$v(t) = \int dv(t) = \int \frac{v^2(t)}{Z} \left[\frac{eP(t)}{(\gamma - 1)Mc^2 I_0} - 1 \right] dt$$

$$t_0(t) = t - \frac{Z}{v(t)}$$

Figure 12

$v(t)$: BEAM VELOCITY PROFILE ON TARGET

Figure 13

$E(t_0)$: BEAM KINETIC ENERGY PROFILE UPON LAUNCH FROM ACCELERATOR

Figure 14

$E(t)$: BEAM KINETIC ENERGY PROFILE ON TARGET

Figure 15

$I(Z,t)$: BEAM CURRENT PROFILE IN FLIGHT TO TARGET AT $Z = 10.0$ m

I vs t

Figure 16

would be needed to deliver 150 TW, 2 MJ, 95 TW/cm^2 and $\sim 50 \text{ MJ/g}$ on targets. An axial pulse compression and current amplification of 20:1 is obtained, thus reducing considerably the demand of supplied peak power to energize the accelerator system. Consequently, as compared to diodes where current amplification by beam bunching is inherently limited so that 0.85 MA currents in 20 ns needs to be accelerated²⁹, this light ion accelerator system required a much lower power technology. Figure 17 gives the equivalent evolution of the beam's linear density during transport. Beam pulse axial compression is occurring linearly at a constant rate of $\Delta\tau (\text{pulse})/\Delta t (\text{flight}) \approx 0.46$.

In Figure 18 the beam density distribution $n_b(z,t)$ in the ballistic transport region is given showing the manner in which both radial and axial pulse compression is increasing n_b , assuming that a beam of uniformly full cross section with initial radius a_0 is launched. Actually, many beamlets pointing to a common focus would be launched from the multi-aperture accelerator system. As discussed in the accelerator design subsection, the multi-aperture geometry would consist of 6 mm radius holes with 2 mm edge-to-edge metal for the extraction and constant voltage acceleration sectors. At 3 MeV beamlet radius would be less than 0.75 mm and the multi-aperture beam would be confined by strong focusing electrostatic quadrupoles situated between acceleration gaps. However, the beamlet center-to-center separation in the 3 - 10 MeV sector would remain the same as it was at extraction. the output optics would expand beamlet radii from 0.75 mm to 6 mm and produce a mid-range waist in the propagating beamlets. Consequently, the 1 A beamlets extracted at the current density of 1 A/cm^2 from the pulsed plasma ion source would be launched also near 1 A/cm^2 , having the geometry of 14 mm center-to-center separation and about 6 mm beamlet radius. The overall multi-aperture beam radius will be $a_0 = 110.5 \text{ cm}$ which is defined by the initial transparency to beams of $\eta = 0.577$ and the total extracted current of $I = 23 \text{ kA}$. As co-moving and co-located electron-ion beamlets emerge from the last element of the accelerator/output-optics/neutralizer-cell system, beamlets pointing to a common focus would propagate almost freely with only axial compression occurring until the ion beamlet edges begin to coalesce. (Actually, the beamlets would expand a negligible amount from their initial radius before they coalesce, due to the small pressure caused by the electron temperature in the beamlets). At this point, the merged uniform beam would propagate

$N_L(Z,t)$: BEAM LINEAR DENSITY PROFILE IN FLIGHT TO TARGET AT $Z = 10.0$ m

dN/dz vs t

Figure 17

$n_b(z, t)$: BEAM DENSITY PROFILE IN FLIGHT TO TARGET AT $Z = 10.0$ m.

dN/dV vs t

Figure 18

under conditions of both radial and axial adiabatic compression. The compressed beam radius in flight is approximately given by the straight line purely ballistic envelope equation:

$$a_b(z) = a_F + (a_0 - a_F) (1 - z/L) \quad , \quad (6)$$

and the propagation distance measured from the accelerator last focusing element where radial compression begins is calculated using the mid-range beamlet waist condition:

$$z_1 = \frac{(R_{cc} + R_Q)L}{R_{cc} + R_Q + a_F} \quad , \quad (7)$$

where in the output optics R_Q is the expanded beamlet radius of 3 - 10 MeV launched beam, $R_Q \sim 6$ mm, R_{cc} is the initial center-to-center distance between beamlets, $R_{cc} = 14$ mm, and a_F is the final focused beam radius; using $a_0 = 110.5$ cm, $L = 10$ m, $z_1 = 8.0$ m, and $a_F = 0.5$ cm, a value of $a_b(z_1) = 22.5$ cm is obtained, whereby the radial compression ratio is $a_b(z_1)/a_F = 45$. It is seen that the feature of producing 1 A, 0.75 mm radius beamlets by means of the ESQ confined, strong channel focused acceleration from 3 to 10 MeV with the above output optics is also helpful to the ballistically focused transport of intense light ion beams. As it is discussed subsequently, the ESQ feature performs the uniform focusing of 3 to 10 MeV beams, confines beamlets to less than 0.75 mm radius during acceleration and produces a suitable beamlet output optics which in turn delays the onset of radial compression to occur in the last 2.0 m distance from the target, thus increasing the tolerable initial electron temperature required to ballistically focus the beams from a stand-off distance of 10 m. Therefore, the last three entries in Figure 18 correspond to the actual beam density values to be attained in the propagation of the beam; further upstream, the actual $n_b(z,t)$ would be less than what is shown in Figure 18, with $n_{b0} \sim 10^{10} \text{ cm}^{-3}$.

Referring to Figure 5, it is expected that the time base of power profile for the targets to be designed for this light ion driver system would be in the order of 50 - 70 ns, rather than the 20 ns time based profile assumed in Figure 6. If that is the case, the calculations shown in Figures 11 - 18 can be repeated, producing a slightly different set of accelerator design parameters; the accelerated current pulse duration t_p would increase and, the axial compression ratio, V_0 , $E_b^{\max}$,

I_0 and L would be somewhat modified. However, determination of the actual power profile's time base is more critical to the determination of the required voltage regulation in the time-varying accelerator sector which is necessary in order to produce the desired beam power shaping on targets. This can be estimated by differentiating the voltage shape in Figure 14 and assuming a tolerable timing error in the beam's arrival time on targets, Δt , which is also limited by the uncertainty in a beam-line's timing due to power switching jitters. A beam power profile time base of 50 - 70 ns could tolerate a $\Delta t \sim 5$ ns which is also consistent with the module-to-module timing jitter anticipated in the power switching technology³⁰. Accordingly, using a value of $\Delta t = 5$ ns, the required regulation in the time-varying voltage is presented by the calculation given in Figure 19, showing that $\Delta V(t_0)/V(t_0) \approx 1\%$ for $0 \leq t_0 \leq t_p$ would be acceptable. However, if beam power shaping is not used, as is the case for the diode light ion drivers, a coarser voltage regulation could be employed similar to the diodes.

II.2.1 THEORETICAL CONSIDERATIONS

The design of the low β electrostatic accelerator system with elements displayed in Figure 2 relies on theoretical considerations involving the behavior of beam extraction from intense plasma ion sources, the optics of beams in electrostatic accelerator apertures, the strong focusing confinement of beams by electrostatic quadrupoles in time-varying voltage acceleration gaps, and the focusing of beams onto 5 mm radius targets located some 10 m downstream. Other important applications would also be served by the design of such an accelerator system as outlined in Figure 20.

At a plasma ion source with plasma density n_p , electron temperature T_e , and ion temperature T_i , ions are extracted across a weakly focusing plasma sheath with emission limited current density³¹ given by:

$$J_{\text{ems}} = 0.3444 n_p e c \left[\frac{2T_e}{M_i} \right]^{\frac{1}{2}}. \quad (8)$$

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Figure 19

THE DESIGN OF GOOD EMITTANCE, INTENSE ION BEAM EXTRACTORS AND MULTI-APERTURE
LOW β ELECTROSTATIC ACCELERATORS IS REQUIRED FOR SEVERAL APPLICATIONS

- He^+ , $t_{\text{pulse}} \sim 0.5 \mu\text{s}$, $I_{\text{accel}} = 23 \text{ kA}$, $V_{\text{accel}} = 3 - 10 \text{ MeV}$, FOR A LIGHT ION ICF DRIVER (L.I.F.E)
- Ne^+ , $t_{\text{pulse}} < 1 \text{ ms}$, $I_{\text{accel}} \sim 5 \text{ A}$, $V_{\text{accel}} = 50 - 100 \text{ keV}$, FOR INJECTION INTO MULTI-APERTURE, ESQ FOCUSED, RF LINACS (MEQALAC)
- Xe^+ OR U^+ , $t_{\text{pulse}} \sim 1-2 \mu\text{s}$, $I_{\text{accel}} \sim 60-600 \text{ A}$, $V_{\text{accel}} = 0.1 - 1 \text{ MeV}$, FOR HEAVY ION ICF DRIVERS -- INDUCTION OR RF MEQALAC ACCELERATORS.

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Figure 20

where M_i is the ion mass in units of eV/c^2 ($M_{\text{He}} = 3727.41 \text{ MeV}/c^2$) and T_e is in units of eV ($T_e \sim 3 \text{ eV}$). The turbulence level in the plasma density influences the divergence of extracted beams in the manner³² shown in Figure 21. Therefore, ion extraction at quiescent plasma conditions is required. At extraction, current density is also defined by Child's law for space charge limited flow³³:

$$\frac{J_{\text{ext}} \cdot g^2}{V_{\text{ext}}^{3/2}} = \frac{4}{9 Z_0} \sqrt{\frac{2}{M_i}} \quad (9)$$

where $Z_0 = 1/(\epsilon_0 c)$ is the impedance of free space, V_{ext} is the potential at extraction gap and g is the separation of electrodes. Consequently, $J_{\text{ext}} = J_{\text{ems}}$, and for a given extraction geometry, an optimum perveance value $P_0 = I_{\text{ext}} / V_{\text{ext}}^{3/2}$ exists such that beam divergence is minimized. This behavior is characterized³² by the data shown in Figure 22. Hence, for constant emission current ion sources such as in the case of using

VARIATION OF BEAM DIVERGENCE AT EXTRACTION AS A FUNCTION OF PLASMA DENSITY AGITATION AND EXTRACTOR GEOMETRY

Figure 21

CONSTANT PERVEANCE IS NECESSARY AT EXTRACTION

- BEAM DIVERGENCE IN SINGLE GAP EXTRACTOR/ACCELERATOR IS SET BY PERVEANCE
- VOLTAGE RAMPING WILL DEFOCUS BEAM FROM SINGLE GAPS.
- CONSTANT VOLTAGE EXTRACTION AND ACCELERATION TO ~ 3 MeV IN MULTI-GRID SYSTEM DECOUPLES PERVEANCE CONDITION FOR VOLTAGE INCREASES IN FOLLOWING STAGES.

$$\theta_b = 0.27 S [1 - 2.25 P/P_o]$$

$$P_o = 1.72 \times 10^{-7} S^2$$

$$S = .R\sqrt{d_1}$$

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Figure 22

a pulsed intense plasma source, maintaining an optimum perveance can only be accomplished by also having a time independent V_{ext} , otherwise beam divergence would be deteriorated. This is the reason why a high voltage diode with a separate function plasma ion source is inherently limited in producing strong current amplification by a suitable time-varying extraction/acceleration voltage; since the extraction and acceleration functions are combined in a diode, this limitation can be overcome only at the expense of further deteriorating the produced beam divergence. The extraction hole size, R_{ext} is also an important parameter along with the aspect ratio³⁴ R_{ext} / g_{ext} . In Figure 23 it is found that aperture field edge effects can be minimized by the use of large apertures³⁵, $R_{ext} = 6$ mm, and an ion optics which quickly reduce the beam size to nearly paraxial conditions, to produce improving beam divergence behavior as a function of increasing kinetic energy.

The normalized channel emittance of the source is another limiting factor. This is given by:

$$\left. \begin{aligned} \epsilon_{NT}(\text{source}) &= R_{ext} \cdot \beta_i \\ \beta_i &= v_{iT}/c \\ v_{iT} &= \left[\frac{2 T_i}{M_i} \right]^{1/2} c \end{aligned} \right\} \quad (10)$$

so that for a given extractor aperture, $\epsilon_{NT}(\text{source})$ scales as $T_i^{1/2}$. Small source emittance for large R_{ext} can be obtained by extracting cold ions. For example, $\epsilon_{NT}(\text{source}) = 5 \times 10^{-8}$ m-rad, at $R_{ext} = 6$ mm and $T_i \approx 0.15$ eV. A pulsed intense cold plasma ion source achieving this temperature has been developed¹⁷ at TRW. During acceleration, the capability of transporting higher currents in a channel is enhanced. However, the current in a channel is limited by J_{ext} , and consequently, current density amplification should be designed to occur for higher energy beams injected into the smaller aperture ESQ channels, following the requirements:

LARGER CIRCULAR APERTURES MINIMIZE SENSITIVITY TO ABERRATION AND ALIGNMENT TOLERANCE

• APERTURE DESIGN:

- CHANNEL FOCUSING
- EDGE EFFECTS
- SPACE CHARGE

• APPROACH:

- MAINTAIN BALANCE ON SPACE CHARGE BY INITIAL SHARP FOCUSING
- MAINTAIN BEAM SIZE AT $\sim 1/2$ HOLE SIZE

Figure 23

$$\pi R_{\text{ext}}^2 \cdot J_{\text{ext}} = I_{\text{ext}} \geq I(\text{channel}) = \pi r_Q^2 \cdot J(\text{channel}), \quad (11)$$

and,

$$\epsilon_{\text{NT}}(\text{source}) = R_{\text{ext}} \cdot \beta_i \leq \epsilon_{\text{NT}}(\text{channel}). \quad (12)$$

Beamlets accelerated in the multi-aperture, parallel plane, electrostatic, multi-stage accelerator experience a weak channel focusing due to the electric field profile at the electrode holes. The aperture's lensing action³⁶ is given by the focal length f :

$$\frac{1}{f} = \frac{E_2 - E_1}{4 V_b} \quad (13)$$

where E_2 is the electric field strength at the downstream side of the aperture, E_1 is at the upstream side and V_b is the voltage specifying particle speed which is taken to be constant in passing through the aperture. If $E_2 > E_1$, the aperture acts as a converging lens, and for $E_2 < E_1$ diverging beam optics are obtained. This feature can be used to radially compress the accelerated beam and produce a desirable amplification of beamlet current density, prior to injecting the beams into the ESQ channels. It is seen in equation (13) that a variable focusing action will result if the voltages at the multi-aperture grids, V_b , are made to change as a function of beam pulse time, even though the difference in gradients $E_2 - E_1$ could be kept the same. In particular, there will be a time dependent lensing action found at the boundary between the constant voltage V_0 and time-varying voltage $V(t_0)$ accelerator sectors which must be compensated in order to obtain the same beam divergence in the emerging beam pulse. If weak focusing channel optics are used throughout the acceleration chain, constant divergence for 3 MeV and 10 MeV beams can be obtained if also the accelerated beamlet radius r_b is made to decrease as a function of t_0 . In this case, it is found that r_b should be made to decrease according to $r_b(t_0) \sim V(t_0)^{-3/4}$.

This feature could be implemented if the voltages on grids were varying in different functions of time, so that a simple power source energizing a voltage distribution chain for the multi-grid $V(t_0)$ accelerator sector could not be used. These difficulties are removed by the use of strong focusing channel optics, matching the constant perveance and time-varying perveance accelerated beams.

The present choice of using periodic strong focusing lenses to confine the space charge of intense beamlets is made on the basis of recent theoretical knowledge which has evolved in the last three years. This has occurred primarily as a result of initiatives at BNL (A. W. Maschke) and LBL (D. Keefe, L. Smith and co-workers) to develop high current and low emittance heavy ion accelerators with which to drive the micro-explosion of ICF pellets. The multi-aperture feature of the LIFE accelerator system is well suited for the use of planes of ESQ matrices between electrostatic acceleration gaps, to provide periodic strong focusing confinement of beams in the time varying 3 to 10 MeV acceleration sector. Consequently, it should also be stressed that the technology development of the LIFE accelerator system will be very relevant to the heavy ion fusion program because for the low β acceleration of heavy ions there exists now a convergence of design concepts in both the induction and RF linac approaches to employ the multi-aperture and ESQ strong focusing features; similarly, as stressed in the following section, the neutralized and ballistically focused propagation feature of LIFE beams will also be very relevant at least initially to the heavy ion fusion program.

The convergence of considerations in low β acceleration has occurred for the following reasons. Whereas conventional accelerators could produce ion beams of the required emittance, say, $\epsilon_{NT} \sim 5 \times 10^{-5}$ m-rad, the space charge limitations especially in the low β region always restricted the amount of accelerated current in single apertures. Therefore, the problem has been to find new means of increasing the amount of accelerated beam current while also preserving or improving

the quality of beam emittance. The normalized transverse emittance of beams, $\epsilon_{NT} = \beta\gamma x x'$ is primarily set by conditions in the low β region of an accelerator system - by contributions from the ion source, the extractor, the buncher and the low β accelerator which acts in the role of injecting beams into the follow-on high β acceleration system; ϵ_{NT} could always increase during high β acceleration due to machine imperfections and space charge forces. To overcome the conflicting requirements of high current and low emittance a new low β acceleration approach was needed for the heavy ion fusion program where the ultimate limitation in total current and beam emittance could rest mostly in the provision of practical ion sources. A promising solution of this problem has been advanced by A. W. Maschke³⁷ using multi-aperture, strong channel focused beams whereby many beamlets can be extracted, accelerated and actively confined at their own space charge limit by periodic strong focusing lenses.

The principle of periodic strong focusing³⁸ of beams which has been used successfully in very high energy accelerators, confining beams by magnetic quadrupole lenses during the course of high β acceleration, can now be extended to the very low β regime. Maschke has observed³⁷ that on the basis of focusing strengths, Θ^2 , at low β an electrostatic quadrupole focuses more effectively than a magnetic quadrupole where the corresponding field strengths are related by:

$$\left. \begin{aligned} \Theta^2 &= \frac{Z_b e (E_Q / r_Q) \ell_Q^2}{A_b m_0 c^2 \beta^2 \gamma} = \frac{Z_b e (B_Q / r_Q) \ell_Q^2}{A_b m_0 c \beta \gamma} \end{aligned} \right\} \quad (14)$$

in which r_Q is the bore radius and ℓ_Q is the length of quadrupoles. The electric field strength in an electrostatic quadrupole, E_Q is limited by the field emission of electrons which is independent of r_Q . Field emission of electrons occurs at $E \sim (3 - 5) \times 10^9$ V/m, whereas arc-over surface

breakdown³⁹ initiated by electron emission from microscopic protrusions occurs at $EV \sim (1 - 5) \times 10^{10} \text{ V}^2/\text{m}$, where $E_Q = 2 V_Q/r_Q$. Therefore, in μs pulsed ESQ geometries the practical limits could be $E_Q \lesssim 2 \times 10^8 \text{ V/m}$ and $V_Q \lesssim 20 \text{ kV}$ for $r_Q \geq 0.2 \text{ mm}$. However, in magnetic quadrupoles B_Q is always limited by the current density in induction coils as r_Q is scaled down. Moreover, the low β confinement of beams produces impossible demands in magnetic field strengths, ruling out entirely the use of magnetic quadrupoles. For example, at $\beta = 0.003$, an attainable value of $E_Q = 3 \times 10^7 \text{ V/m}$ corresponds to a pole-tip strength of $B_Q = 33 \text{ Tesla}$ for magnetic quadrupoles. It is observed that electrostatic quadrupoles provide strong focusing action at relatively low power consumption and pole-tip fields of $E_Q = 10^7 - 10^8 \text{ V/m}$ to confine the space charge of very low β beams. ESQ geometries are amenable to small bore size construction³⁷ in matrix arrays for bore radii in the range of $0.1 - 10 \text{ mm}$. Thus, multi-aperture planes of ESQ matrices can be placed between acceleration gaps³⁷, with suitably chosen voltage polarities and amplitudes which are defined by well known strong-focusing scaling relations. The use of electrostatic quadrupoles in a different geometry which combined the functions of focusing and electrostatic acceleration has also been made earlier by E. A. Abramyan⁴⁰.

The key parameter in the strong-focused transport of intense beams is k which is the ratio of the beam's space charge field gradient to the restoring external field gradient:

$$k = \frac{E'_S}{E'_Q} = \left(\frac{Zen_b}{\epsilon_0} \right) \cdot \frac{r_Q}{E_Q} \quad (15)$$

The space charge parameter, k couples the beam plasma frequency, ω_p with the beam betatron oscillation frequencies, ω_0 (without space charge) and ω (with space charge), in the rest frame of the beam:

$$\omega_p^2 = \frac{qE'_S}{M} = \frac{q^2 n_b}{\epsilon_0 M} \quad (16)$$

$$\omega_0^2 = \frac{qE'_Q}{M} \quad (17)$$

$$k = \frac{\omega_p^2}{\omega_0^2} = 1 - \left(\frac{\omega}{\omega_0} \right)^2, \quad (18)$$

where beam current is: $I = Z_b e n_b \pi x^2 \beta c$. (19)

The equation of motion:

$$M\ddot{x} = qE_x = q(E_Q + E_S), \quad (20)$$

can be expressed in terms of k in the linear approximation of the field:

$$E_x \cong E' x = (E'_Q + E'_S) x, \quad (21)$$

obtaining,

$$\left. \begin{aligned} \ddot{x} + \frac{qE'_Q}{M} (1 - k) x &= 0 \\ \ddot{x} + \omega^2 x &= 0 \end{aligned} \right\} \quad (22)$$

In terms of the betatron phase shifts in one focusing period of length S , μ_0 (without space charge) and μ (with space charge), the betatron frequencies in the laboratory frame are given by:

$$\omega_0 = \frac{\mu_0}{S} \beta c \quad (23)$$

$$\omega = \frac{\mu}{S} \beta c \quad (24)$$

where $\omega_{cm} = \omega_{lab} \gamma$ (25)

Using the definition of ϵ_{NT} :

$$\Delta x \Delta p = \epsilon_{NT} Mc, \quad \epsilon_{NT} = (\Delta x) v_x / c, \quad (26)$$

and the nature of periodic oscillations in the rest frame of the beam:

$$x = x_0 \sin \omega t; \quad v_x = x_0 \omega \cos \omega t \quad (27)$$

the following scaling relation is derived:

$$\left. \begin{aligned} \epsilon_{NT} &= \bar{x}^2 \frac{\omega}{c} = \bar{x}^2 \omega_{lab} \frac{\gamma}{c}; \\ (\bar{x})^2 &= \int x_0^2 (\sin \omega t \cdot \cos \omega t) \frac{dt}{T} \end{aligned} \right\} \quad (28)$$

$$\omega = \omega_0 \sqrt{1-k} = \frac{\mu_0}{S} \beta c \sqrt{1-k} \quad (29)$$

$$\left. \begin{aligned} \epsilon_{NT} &= \eta^2 \mu_0 k_3 \sqrt{1-k} (\beta \gamma) r_Q & (a) \\ \eta &= \frac{\bar{x}}{x_{max}} = \frac{\bar{x}}{r_Q}; \quad k_3 = \frac{r_Q}{S} & (b) \end{aligned} \right\} \quad (30)$$

Similarly, the normalized geometrical acceptance of the focusing channel (without space charge) is obtained:

$$\alpha_{NT} = \bar{x}_0^2 \frac{\omega_0}{c}; \quad k = 1 - \left(\frac{\epsilon_{NT}}{\alpha_{NT}} \right)^2 \quad (31)$$

The phase shift in one focusing period (without space charge), μ_0 is only a function of the periodic quadrupole channel geometry which is depicted in Figure 24 and the strength parameter of Equation(14). Approximate expressions⁴¹ valid for $\mu_0 \ll 1$ and $\theta \ll 1$, for the parameters μ_0 and η are:

INTENSE BEAM CONFINEMENT BY PERIODIC STRONG FOCUSING FODO CHANNEL

- Space charge parameter

$$k = \frac{E'_{sc}}{E'_Q} = \left(\frac{\omega_p}{\omega_0} \right)^2 = 1 - \left(\frac{\omega}{\omega_0} \right)^2 = 1 - \left(\frac{\mu}{\mu_0} \right)^2$$

- Beam stability & control
(analysis and simulations)

$$\frac{\mu}{\mu_0} \geq 0.4, \quad \mu^0 \sim 1$$

- Tune with space charge

$$\mu = \mu_0 \sqrt{1 - k}$$

- FODO Parameters

$S = L_{\text{cell}}$, period length

ℓ_Q , quadrupole length

L , separation between Q's

$$S = 2 \ell_Q \left(1 + \frac{L}{\ell_Q} \right)$$

r_Q , bore radius of Q's

$$n = \frac{r}{r_Q}$$

$$k_3 = \frac{r_Q}{S}; \quad k_3 < \frac{1}{8}$$

$$k_4 = \frac{\ell_Q}{S}; \quad k_4 < 0.4$$

$$\kappa_x(y) = \pm \frac{Z_b e E_0}{A_b m_0 c^2 \beta^2 \gamma r_Q}$$

Gradient and envelope functions in a periodic quadrupole channel of the FODO type.

$$\mu_0 \cong \theta^2 \left(1 + \frac{L}{\ell_Q}\right) ; \quad (L = \text{separation between ESQ's}) \quad (32)$$

$$n^2 \cong \left(\frac{1 - \mu_0/2}{1 + \mu_0/2} \right)^{1/2} \quad (33)$$

Equations (32) and (14) thus provide a scaling relation for the ESQ field to maintain the periodic focusing of beams:

$$E_Q = 2 \frac{m_0 c^2}{e} \cdot \frac{\mu_0}{S} \cdot \frac{k_3}{k_4} (\beta^2 \gamma) \frac{A_b}{Z_b} \quad \left. \vphantom{\frac{m_0 c^2}{e}} \right\} \quad (34)$$

where

$$S = 2 \ell_Q \left(1 + \frac{L}{\ell_Q}\right) ; \quad k_4 = \frac{\ell_Q}{S} ; \quad V_Q = \frac{1}{2} E_Q r_Q .$$

The maximum transportable current in a periodic focusing channel is obtained from equations (15), (17), (19), (23) and (30-b), with quantities expressed in the laboratory frame:

$$q n_b = \epsilon_0 E'_S = \epsilon_0 k E'_Q = \epsilon_0 k \frac{(My)}{q} (\omega_0 \gamma)^2 = \frac{Mc^2}{q} \epsilon_0 \gamma^3 \beta^2 \frac{\mu_0^2}{S^2} \quad \left. \vphantom{\frac{Mc^2}{q}} \right\} \quad (35)$$

and

$$x^2 = (\sqrt{2} \bar{x})^2 = 2 n^2 r_Q^2$$

so that,

$$I_{\max} = \frac{I_0}{2} n^2 k_3^2 \mu_0^2 k (\beta \gamma)^3 \frac{A_b}{Z_b} \quad (36)$$

where $I_0 = 4 \pi \epsilon_0 \cdot m_0 c^3 / e$ is the Alfven-Lawson limiting current.

Equations (30) for ϵ_{NT} , (34) for E_Q and (36) for $I_{\max}$ are the key scaling relations for a periodic strong focusing channel. It is seen that the space charge parameter k which depresses the phase shift μ_0 is a key determinant in obtaining maximum current and minimum emittance beams. An optimum value of k is desired, consistent with beam stability conditions against the perturbations of the space charge force which cause beam blow-up

and emittance growth during channel focused transport. The study of these beam envelope instabilities has been made by the LBL group⁴² using analytical techniques and the assumption that the beam is characterized by the Kapchinskii and Vladimirskii⁴³ distribution functions (K-V). The four-dimensional K-V phase space distribution function has the property of producing uniform particle density, with ellipses in any two-dimensional projection. The K-V envelope equations for the x, y beam transverse dimensions are as follows:

$$\left. \begin{aligned} \frac{d^2 x}{dz^2} + \kappa_x \cdot x - \frac{2K}{x+y} - \frac{\epsilon_x^2}{x^3} &= 0 \\ \frac{d^2 y}{dz^2} + \kappa_y \cdot y - \frac{2K}{x+y} - \frac{\epsilon_y^2}{y^3} &= 0 \end{aligned} \right\} \quad (37)$$

where, $\epsilon_{x(y)}$ is the un-normalized emittance, $\epsilon = xx' = \epsilon_{NT}/(\beta\gamma)$; K is the generalized perveance,

$$K = \frac{I}{I_0} \cdot \frac{2}{(\beta\gamma)^3} \quad ; \quad (38)$$

and $\kappa_{x(y)}$ is the quadrupole focusing strength parameter,

$$\kappa_{x(y)} = \pm \frac{Z_b e E_Q}{A_b m_0 c^2 \beta^2 \gamma r_Q} \quad , \quad (39)$$

for ESQ voltages $V_Q = \pm \frac{1}{2} E_Q r_Q$ at symmetric pole-tips. The phase space rotation ϕ is related to the strength parameter by: $2\phi = \theta = \sqrt{\kappa} \ell_Q$. The result of analyses on beam envelope instabilities and space charge effects show that stable beams are obtained for:

$$\left. \begin{aligned} \mu_0 &= 60^\circ \\ \text{and } \frac{\mu}{\mu_0} &\geq 0.4 \quad ; \quad k = 1 - \left(\frac{\mu}{\mu_0}\right)^2 \leq 0.84 \end{aligned} \right\} \quad (40)$$

Similar results have been obtained by Haber and Maschke⁴⁴ using numerical simulation techniques. Also, Reiser⁴¹ has shown by a smooth-approximation theory (where $\bar{x}$, $\bar{y}$, $\bar{x}'$, $\bar{y}'$ are constant within a period S) that the phase shift μ and the amplitude function $\beta(s)$ with space charge can be determined uniquely in terms of the corresponding parameters without space charge:

$$\left. \begin{aligned} \beta(s) &= \beta_0(s) (u + \sqrt{1 + u^2}) \\ \mu &= \mu_0 (\sqrt{1 + u^2} - u) \end{aligned} \right\} \quad (41)$$

where the dimensionless space-charge parameter, u is defined by:

$$u = \frac{KS}{2\mu_0 \epsilon_x} \quad (42)$$

and the K-V beam envelope is obtained in terms of the betatron amplitude function by:

$$\left. \begin{aligned} x(s) &= \sqrt{\epsilon_x \beta(s)} & ; & \quad x_0(s) = \sqrt{\alpha_x \beta_0(s)} \\ x'(s) &= \sqrt{\epsilon_x / \beta(s)} & ; & \quad \mu = \int_s^{s+S} \frac{ds}{\beta(s)} \end{aligned} \right\} \quad (43)$$

Nevertheless, the issue of stability of beams against perturbations remains as a continuing concern because the analyses so far performed are at best the two-dimensional idealization of the three-dimensional beam confinement problem. The analyses also assumed uniform particle density with linearized space charge and restoring forces. In reality, these forces are linear only near the center of beams and practical beam densities have non-

uniform envelopes. Therefore, an investigation of the problems can be carried out analytically to obtain useful scaling relations, but the attaining of realistic solutions of these problems does require experiments to test the validity of these scaling relations. Fortunately, tests to validate the performance of multi-aperture strong channel focused beams can be performed economically by doing the tests with one or two beamlets, transported by several tens of ESQ planes with space charge limited currents. Thus, one of the benefits in the development of the LIFE accelerator system would be the laboratory scale experiments with 1 - 5 MeV He^+ beams at 1 - 1.5 A current per channel, to address these important concerns by suitable tests.

One of the surprising discovery first made by Maschke³⁷ in the area of strong focused beam transport has been the statement that the amount of transportable beam current in a channel is explicitly independent of the quadrupole bore size, as is observed in Equation (36). The maximum transportable current scales as $(\beta\gamma)^3$ where the Lorentz factors are defined at beam injection into the channels, and $k_3 = r_Q/S$, the channel's aspect ratio is limited by practical considerations to be $k_3 \leq 1/8$; whereas, observed in Equation (30) ϵ_{NT} scales as $(\beta\gamma) \cdot r_Q$. Therefore, by extracting small size beamlets in a multi-aperture structure and injecting these into ESQ strong focusing channels at low β , the following advantage is derived. A large amount of total beam current can be stacked which otherwise would be severely limited by space charge, equal to:

$$I_{\text{tot}} = N \cdot I_{\text{max}}(\text{channel}) \quad (44)$$

where N is the total number of channels. The total emittance of the beam would be given by:

$$\epsilon_{NT}(\text{total}) = \sqrt{N} \cdot D \cdot \epsilon_{NT}(\text{channel}) \quad (45)$$

where D is an emittance dilution factor of about $D \sim 3/2$. The brightness of the total beam is approximately the brightness found in the specific channels:

$$B_{\text{tot}} = \frac{2 I_{\text{tot}}}{\pi^2 \epsilon_{\text{NT}}^2 (\text{tot})} = \frac{2 I_{\text{max}}(\text{channel})}{\pi^2 D^2 \epsilon_{\text{NT}}^2 (\text{channel})} = \frac{B(\text{channel})}{D^2} \quad (46)$$

and scales according to:

$$B(\text{channel}) = \frac{I_0}{\pi^2 \eta^2} \left(\frac{k}{1-k} \right) \frac{\beta \gamma}{r_Q^2} \frac{A_b}{Z_b} \quad (47)$$

Thus, to achieve high brightness channels the space charge parameter k should be as large as possible, consistent with the stability requirement of $\mu/\mu_0 \geq 0.4$ and also, consistent with the need of beam emittance limitation, beam injection should be made at higher β and into smaller r_Q apertures. The ultimate brightness of the channel will be limited by the brightness of the ion source:

$$B(\text{channel}) \leq B(\text{source}) = \frac{J_{\text{ext}}}{\pi} \left(\frac{M_i c^2}{T_i} \right) \quad (48)$$

One of the important beam stability requirements is to maintain at a constant value the tune shift μ_0 over the many periods of strong focusing quadrupoles, as low β acceleration proceeds to the high β regime by the successive acceleration gaps which are situated in the free spaces between the ESQ planes. In maintaining the constancy of μ_0 a scheme must be devised such that ϵ_{NT} does not increase beyond the value set at beam injection and also E_Q does not increase, surpassing the arc-over breakdown limit. Among the important parameters, V_Q , r_Q , ϵ_{NT} , I , μ_0 , k , S and ℓ_Q a practical scaling in β is required. It is shown that constancy in ϵ_{NT} , γV_Q , and μ_0 can be maintained⁴⁵ by scaling ℓ_Q with $\beta \gamma$, where r_Q and k are also kept fixed. By taking the ratio $\epsilon_{\text{NT}}/(\gamma V_Q)$ from Equations (30) and (34):

$$\frac{\epsilon_{NT}}{\gamma V_Q} = \frac{n^2 e}{m_o c^2} \sqrt{1-k} \frac{Z_b}{A_b} \left(\frac{\ell_Q}{\beta \gamma} \right) \quad (49)$$

it is seen that $\epsilon_{NT}/(\gamma V_Q)$ remains constant if the quadrupole lengths in periodic focusing cells are increased during beam acceleration linearly with beam momentum: $\ell_Q \sim \beta \gamma$. By inserting the cell length expression of Equation (34) into Equation (30-a):

$$\epsilon_{NT} = \frac{1}{2} n^2 \mu_o \sqrt{1-k} r_Q^2 \left(\frac{\beta \gamma}{\ell_Q} \right) \frac{1}{(1 + L/\ell_Q)} \quad (50)$$

it is found that if $\ell_Q \sim \beta \gamma$ and $L/\ell_Q = \text{constant}$ then ϵ_{NT} remains constant for $\mu_o = \text{constant}$, where r_Q and k are also kept fixed throughout acceleration.

Similarly, inserting Equation (14) into Equation (32):

$$\mu_o = \frac{Z_b e}{A_b m_o c^2} \left(\frac{\gamma E_Q}{r_Q} \right) \left(\frac{\ell_Q}{\beta \gamma} \right)^2 \left(1 + \frac{L}{\ell_Q} \right) \quad (51)$$

it is observed that $\gamma E_Q = \text{constant}$ for $\mu_o = \text{constant}$, under the conditions of $\ell_Q \sim \beta \gamma$, $L/\ell_Q = \text{constant}$ and $r_Q = \text{constant}$. Thus, ESQ voltages can also relax according to $V_Q \sim 1/\gamma$. This type of scaling would be more appropriate for the heavy ion accelerators.

In the LIFE accelerator system, $\text{He}^+ 1 \text{ A}$ beamlets will be injected into ESQ channels at 3 MeV and accelerated in a time dependent manner from 3 to 10 MeV. Therefore, the constancy of μ_o can be preserved by also varying $V_Q \sim E_b$ at constant ℓ_Q and r_Q which is a time dependent variation over a factor of 3.3. The focal length of the strong focusing lenses are also preserved by scaling $V_Q \sim E_b (t_o)$:

$$\frac{1}{f} = \frac{Z_b}{E_b} \cdot \frac{V_Q \ell_Q}{r_Q^2} \cdot \left(\frac{2\gamma}{\gamma+1} \right) \quad ; \quad \gamma \approx 1 \quad (52)$$

However, under these conditions ϵ_{NT} would vary as $\beta \gamma$ reaching its design limit at 10 MeV.

II.2.2 ACCELERATOR CONCEPTUAL DESIGN

An accelerator system conceptual design has been made for one of the beam-lines of the 2 MJ ICF driver, for the case of accelerating 23 kA He^+

beams in 400 ns pulses at energies of 3 to 10 MeV. The design is based on the available use of a pulsed intense cold plasma ion source developed⁽¹⁷⁾ at TRW and the functional elements of the accelerator concept displayed in Figure 2. Briefly, the capabilities of this source and its suitability for this application can be seen by the information presented in Figures 25-28; details are given elsewhere^{1,17}. The operation of the source is shown in Figure 25, where plasma induction is made by pulsing a 300 kHz, 100 kW RF oscillator which is AC-coupled to the antenna visible inside the plasma vessel. The vessel contains a 24 inch diameter cage which is lined with permanent cusp field magnets except at the extraction surface so that electron confinement is enhanced. The source produces uniform ion density for an extraction area inside a 6 inch wide radial band from the cage magnets. RF pulsed plasma induction can be made for several ms duration, at a rate which matches with the pulsing of the accelerator system. Ions can be extracted either during the plasma induction period or in the quiescent afterglow regime. The scaling of plasma density as a function of RF power and gas pressure is demonstrated in Figure 26. The behavior in plasma density n_p and electron temperature T_e as a function of time in the afterglow is given in Figure 27. As shown in Figure 28, in this regime ion temperatures T_i cool down rapidly, reaching a level of 0.1 - 0.2 eV in a few tens of μs , while plasma density remains constant. Thus, there exists an adequate time window for the extraction of μs duration pulses of cold ions at high current densities which require high T_e and n_p values from equation (8). It is seen that values of $J_{ext} \approx 1 A/cm^2$ and $T_i \sim 0.15$ eV are achievable for the extraction of He^+ beams over large surfaces. Based on measurements, a theoretical model has been developed to scale the RF power and gas pressure to produce the desired current density and extraction area.

Using the information in Figures 28 and 23, equation (10) yields the normalized transverse emittance for the beamlets extracted from apertures of $R_{ext} = 6$ mm; at 20 - 30 μs in afterglow time: ϵ_{NT} (source channel) = 5×10^{-8} m-rad. The flat extraction grid will consist of 6 mm radius holes with 14 mm center-to-center separation and 2 mm of metal from edge-

Figure 25

PULSED INTENSE COLD PLASMA He ION SOURCE

Figure 26

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Figure 27

ION TEMPERATURE MEASUREMENT IN AFTERGLOW OF RF INDUCTION PLASMA

Figure 28

to-edge, producing a fraction of $\eta = 0.577$ transparency to beams. A total current of $I_0 = 23$ kA will be extracted in an accelerator radius of $a_0 = 110.5$ cm at a current density of $J_{\text{ext}} = 1$ A/cm²:

$$I_0 = \pi a_0^2 \eta J_{\text{ext}} \quad (53)$$

From equation (8), using $T_e = 3.7$ eV in the immediate afterglow of He plasma induction, the required plasma density is $n_p = 1.4 \times 10^{13}$ cm⁻³.

He⁺ ion extraction and acceleration to 3 MeV for 400 - 800 ns flat-top voltage pulses will be performed by a designed multi-aperture weakly channel focused multi-stage accelerator. This part of the accelerator will serve as the injector of beamlets to the follow-on time-varying voltage, 3 to 10 MeV accelerator sector which contains the strong focusing ESQ planes. The acceleration gaps in both sectors will consist of flat parallel plane structures made of 1-2 mm thick metal, energized by two separate pulsed power circuits, one for V_0 and the other for $V(t_0)$ which is floated on the first supply. The two-dimensional electrostatic code EGUN⁴⁶ by Hermannsfeldt was used to perform the extractor/injector designs. This code was modified⁴⁷ at TRW to calculate the plasma sheath profile and define the optics of ion extraction from the plasma source. Since He⁺ ions will be extracted from a sufficiently high plasma density source, the Debye length will be very small ($\lambda_D = 3 \times 10^{-4}$ cm) relative to the extraction dimensions, $\lambda_D \ll R_{\text{ext}}$. In this case the sheath can be treated as a deformable equipotential surface with the emission profile determined by requiring that the current flow across the sheath be also space charge limited. As shown below, beamlet emittance control and transport of beamlet current at the required level can be accomplished by injecting the beams into 0.5 - 0.75 mm radius ESQ channels. Therefore, an injector design was made as demonstrated in Figure 29 to produce the radially compressed beamlets at ~ 3 MeV, consistent with the requirement of equation (11). The design produced 0.3 mm radius beamlets with $\epsilon_{NT} \approx 1 \times 10^{-7}$ m-rad for injection into the ESQ channels. A different design for injecting into ESQ channels at

EXTRACTOR - INJECTOR DESIGN IN ESQ CHANNEL FOCUSED L.I.F.E ACCELERATOR

Figure 29

much lower β for another application is given elsewhere⁴⁸.

The design of the ESQ strong focusing channels is made to fulfill the stringent emittance control and stability requirements in the time-varying voltage accelerator sector, consistent with the need of ballistically focusing He^+ beams onto $R_t = 0.5$ cm radius over a distance $L = 10$ m, with geometric convergence angle θ_b given by the overall beam radius at launch $a_0 = 110.5$ cm which includes $N = 23,000$ beamlets.

$$\tan \theta_b \approx \theta_b = \frac{a_0}{L} \quad (54)$$

$$\epsilon_b = R_t \frac{a_0}{L} \quad (55)$$

$$\epsilon_{NT}(\text{total}) = \beta \gamma \epsilon_b \quad (56)$$

$$\epsilon_{NT}(\text{channel}) = \epsilon_{NT}(\text{total})/N^{1/2} \quad (57)$$

Thus,

$$\epsilon_{NT}(\text{total}) = \begin{cases} 4.0 \times 10^{-5} \text{ m-rad at 10 MeV} \\ 2.2 \times 10^{-5} \text{ m-rad at 3 MeV} \end{cases} \quad (58)$$

requiring a normalized emittance in launched He^+ beamlets to be:

$$\epsilon_{NT}(\text{channel}) = \begin{cases} 2.7 \times 10^{-7} \text{ m-rad at 10 MeV} \\ 1.5 \times 10^{-7} \text{ m-rad at 3 MeV} \end{cases} \quad (59)$$

This requirement is satisfied by the injector design which produced $\epsilon_{NT}(\text{channel}) = 1 \times 10^{-7}$ m-rad. Maschke's key design equations (30), (34) and (36) expressed in MKS units, and using for $m_0 = 931.502 \text{ MeV}/c^2$ and $I_0 = 3.107 \times 10^7 \text{ A}$, become:

$$\epsilon_{NT}(\text{channel}) = n^2 k_3 \mu_0 (1-k)^{1/2} (\beta\gamma) r_Q \text{ (m-rad)} \quad (60)$$

$$V_Q(\text{channel}) = 9.315 \times 10^8 \mu_0 \frac{k_3^2}{k_4} (\beta^2 \gamma) \frac{A_b}{Z_b} \text{ (V)} \quad (61)$$

$$I(\text{channel}) = 1.554 \times 10^7 n^2 k_3^2 \mu_0^2 (\beta\gamma)^3 \frac{A_b}{Z_b} \text{ (A)} \quad (62)$$

These design equations have been validated by experiments performed^{49,50} at BNL.

In the LIFE accelerator system, the periodic strong focusing ESQ elements will be situated in between acceleration gaps, in the manner which is shown in Figure 30. Using the stable beam transport conditions of equation (40), the geometry of ESQ channels becomes defined by the smaller ϵ_{NT} requirement of equation (59), the need of confined transport of 1 A He⁺ beamlets across the accelerator system, and the voltage breakdown limitation at the ESQ apertures. These three requirements can be met by several parameter choices of r_Q , l_Q , S and the injection energy of beamlets. During acceleration from 3 MeV to 10 MeV, the ϵ_{NT} requirement in equations (59) and (60) is maintained, the $I(\text{channel})$ requirement in equation (62) is over-fulfilled, and the V_Q relation in equation (61) is satisfied by time-varying the voltage according to $V_Q \sim E_b(t_0)$. The following choice of ESQ parameters have been derived:

(period length)	$S = 32 \text{ mm}$	
(quadrupole length)	$l_Q = 8 \text{ mm}$	(63)
(separation between quadrupoles)	$L_Q = 8 \text{ mm}$	
(ESQ aperture radius)	$r_Q = 0.75 \text{ mm}$;	

where the pulsed ESQ field strength should be:

$$E_Q = \begin{cases} 3.5 \times 10^7 \text{ V/m} & \text{at } 3 \text{ MeV} \\ 1.2 \times 10^8 \text{ V/m} & \text{at } 10 \text{ MeV} \end{cases} \quad (64)$$

Figure 30

TIME VARYING VOLTAGE STANDING COLUMN ACCELERATOR
WITH ELECTROSTATIC QUADRUPOLE CHANNEL FOCUSING

Employing a 0.75 mm separation between the ESQ matrix plane and the 1 mm thick flat multi-aperture metal plane, an acceleration gap of 4.5 mm is obtained for each strong focusing half period, as observed in Figure 30.

A matched injection of the near laminar beamlets into the strong focusing ESQ channels is needed in order to have minimal beam losses. The matching is helped by having near paraxial optics for the injection of beamlets with radius restricted by:

$$r_b(\text{inject}) \leq 1/2 r_Q . \quad (65)$$

The injection matching can also be helped by having an adiabatic turn-on of the strong focusing forces at the onset of betatron motion. The injector design of Figure 29 and the ESQ geometry design of equations (63) fulfill the requirement of equation (65). Nevertheless, experimental tests will be needed to validate this important issue.

Parallel beamlets will emerge from this accelerator system with 20:1 axial beam pulse compression programmed to occur in 10 m of transport. Beam steering and ballistic focusing will be accomplished by separate function elements. This feature will simplify the accelerator construction, produce a rigid and easily accessible mechanical assembly, and make beam quality less dependent on various tolerances. However, the main benefit will be the excellent provision of control in ballistically focusing the beam.

Beamlet steering and focusing will be accomplished by a dual set of parallel plate x, y electrostatic deflectors and an ESQ triplet lens focusing system. All of these elements can be assembled in planar matrix form, just as the case of the ESQ planes in the accelerator system, by employing the fabrication and assembly techniques^{49,50} currently in use at BNL and more recently at LBL. This output optics will be made to track the time correlation of the 3 to 10 MeV accelerated beam pulse. Therefore, the maximum voltage on deflection plates will be for the steering of 10 MeV beamlets situated at the extreme edges of the accelerator system. Parallel emerging beamlets will be deflected by an angle θ in

traversing an electrostatic steering plate having transverse electric field E and length l , which is given by:

$$\left. \begin{aligned} \tan \theta &= \frac{E(\text{MV/m}) \cdot l(\text{m})}{\beta p_b(\text{MeV/c})} = \frac{E \cdot l}{\beta^2 \gamma M_i c} \\ \tan \theta_{\max} &= \tan \theta_b = \frac{a_0}{L} \quad , \quad \beta \gamma = 0.0733 \end{aligned} \right\} \quad (66)$$

Designing for $E_{\max} \approx 5 \times 10^7$ V/m, $a_0 = 110.5$ cm and $L = 10$ m for He^+ beams at 10 MeV, a value of deflection plate length $l = 44$ mm is obtained.

In addition to providing individual beamlet steering, the key function of the output optics is to expand the 0.75 mm radius at the end of beamlet acceleration to about 6 mm and to refocus onto distant targets using a mid-range waist condition. From general principles, the minimum focused spot radius $R_t(\text{min})$ at a distance L is obtained by:

$$R_t(\text{min}) = \frac{\epsilon L}{R_Q} \quad (67)$$

for a last-element lens radius R_Q and beam emittance $\epsilon = \epsilon_{NT}/\beta\gamma$; smaller spot size focus is obtained by initially expanded beams for the same emittance and ballistic transport range. The use of mid-range waist condition in this optics is also made to delay the onset of beamlet coalescing, permitting free neutralized propagation to occur for 8 m, whereby adiabatic radial pulse compression and heating would start 2 m ahead of targets in LIFE beams; cf. Fig. 51.

A considerable flexibility and control in achieving precise ballistic focusing of beamlets is introduced by this output optics because the steering of beamlets can be controlled either individually or in rows and columns. The ballistic focusing procedure could be the following. Initially, parallel and neutralized beamlets could be made incident on a witness screen located 10 m downstream. Beamlet center-to-center separation being 14 mm, channel emittance and lack of neutralization effects can be recorded for the entire beam with good resolution. Steering pulsed voltages could be applied by rows and columns at 2 or 3 intermediate values where witness plates could still record the individual beamlets. Thus, a map of the functional dependence of applied voltage versus beamlet deflection for each channel can be obtained; the functional forms are likely to have slight differences

due to channel aberrations and mechanical imperfections which could vary from channel to channel. However, the recording of a map in this form needs to be done only once, and with it, an on-line computer system would make it possible to bring all the beamlets to a common focus, independent of the accelerator system related imperfections.

II.2.3 PULSED POWER CONCEPTUAL DESIGN

A brief description of the accelerator energizing system is made based on pulsed power methods. The requirements for this study were the following salient features:

1. A time independent voltage and constant current pulsed power source with which to extract 23 kA total beam current in 400-800 ns pulses and accelerate to 3 MV by energizing the multi-stage injector/accelerator with a voltage distribution as given in Figure 29; this is designated as the V_0 supply.
2. A time varying voltage and constant current pulsed power source which is floating on the V_0 supply, to accelerate from 3 to 10 MV the injector pulses by a voltage waveform as prescribed in Figure 14, with waveform regulation in the range of 1%-2% as specified by the calculation in Figure 19; this is designated as the $V(t_0)$ supply.
3. A pulsed-power electrical efficiency in the range of 50-80%.
4. A flexibility of independent experimental control of the extraction voltage in the V_0 supply, and variability of 20% in the waveform throughout the pulse in the $V(t_0)$ supply.

Since relative to the diodes a much lower power level is involved in this accelerator system, a comprehensive scoping study was made on new identified methods with a view of satisfying the above requirements. The identified methods are depicted in Figure 31, in which the tapered impedance lumped element transmission line technique is found to satisfy the requirements. Calculations for the efficiency and impedance tapering were carried as a function of beam loading, as outlined in Figure 32 with results for some of the considered cases as shown in Figure 33. Some of the transmission line geometries studied for the lumped and distributed element cases are shown in Figure 34 and other pulse forming networks that could be considered are given in Figure 35.

TYPES OF PULSE-POWER DRIVER CONSIDERED

1. TAPERED-IMPEDANCE TRANSMISSION LINE

2. MARX-LIKE PFN WITH ACTIVE PULSE SHAPING

Figure 31

CALCULATION METHOD FOR TAPERED LINE

WAVEFORM PARAMETERS:

$$T_0/t_0 = \frac{\text{PULSE DURATION}}{\text{FLIGHT TIME OF SLOWEST ION}}$$

V_F = FRACTION OF INITIAL VOLTAGE PROVIDED BY SEPARATE SOURCE

DESIGN PARAMETERS:

λ = INITIAL VOLTAGE LOADING

- $z_1 \dots z_9$ ARE CALCULATED EXPLICITLY IN TURN
- EFFICIENCY CAN THEN BE DETERMINED

Figure 32

EFFICIENCY vs LOADING, $T = 0.55 t_0$ (4.93: 1 VOLTAGE RAMP)

Figure 33

PROTOTYPE CASE-EFFICIENCY, IMPEDANCE RATIO VS. BEAM LOADING ($V_F=0.077$)

DESIGNS USING HIGH DIELECTRIC CONSTANT LINES

SINGLE STAGE LUMPED SECTION OIL LINE

Figure 34

OTHER PFNs

(a) MARXED PEAKING-CIRCUIT

$$L_1 \neq L_2 \neq L_3$$

S_1, S_2 ETC PHASED

(b) TWO-STAGE PEAKING
CIRCUIT

$$V_1 > V_2$$

Figure 35

It is concluded that the tapered impedance, water dielectric, lumped element transmission line method provides all of the desired features and a prototype design was made to be used in a laboratory test stand facility, to verify the anticipated performance of such a novel approach.

A scoping analysis was made to determine the geometry of the pulsed power and accelerator system interface. Radially symmetric leads from the accelerator planes will be fanning out in a vacuum interface which would be more than 2 m in length. The leads will be connected to a graded column oil-vacuum interface, and the overall housing of the oil tank would be about 4-5 m in diameter. A schematic of the accelerator's pulsed power housing is given in Figure 36.

Further design effort was concentrated on a 0.5 MV time varying voltage pulse power prototype system to be used in the anticipated follow-on experimental investigations. The designed circuit for this system is demonstrated in Figure 37. The design of the variable tuned transmission line is shown in Figures 38 and 39 and the housing of this line is displayed in Figure 40.

II.3 BEAM PROPAGATION AND NEUTRALIZER DESIGN

A new method was devised¹⁶ to produce active charge and current neutralization of ballistically focused intense ion beams by co-moving and co-located electrons, relying on the extraction and acceleration of electrons, from a plasma cell. The neutralizer cell can be used in either this active neutralization mode or for the auto-neutralization²⁴ mode. The neutralizer cell will be located immediately after the accelerator system's last focusing element so that emerging ion beamlets pass through a confined He plasma with density n_{ep} and active electron extraction is made at the downstream end. The plasma density will be more than the beam density n_b :

$$n_{ep} \geq n_b (E_e/T_{ep})^{1/2} \quad (68)$$

where E_e is the required co-moving electron energy and T_{ep} is the electron temperature in the cell. The objective in active neutralization is to launch charge and current neutralized beamlets in which $n_b = n_e$, $V_b = v_e$ and initial electron temperature is $T_{eo} \approx 30 - 50$ eV for the 3-10 MeV ballistically focused He^+ beams.

TRW
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Figure 36

Figure 37

INDUCTIVELY TAPERED WATER TRANSMISSION LINE FOR 1 kA, 100-500 kV,
1.2 μ S, PREPROTOTYPE HIGH VOLTAGE WAVEFORM GENERATOR

Figure 38

TRANSMISSION
LINE CONSTRUCTION
500 kV, 1 kA, 1.2 μ S

Figure 39

1 IN. = 2 FT

TRANSMISSION LINE
TANK LAYOUT

Figure 40

This is accomplished in a specific design¹⁶ in which electrons are extracted across the plasma sheath formed at the electron-ion beamlet extraction apertures and accelerated by an applied potential from thermal to co-moving speeds, while the electrons also experience the space charge force of co-located ions. In the auto-neutralization²⁴ mode the electron acceleration would occur naturally by the space potential of the traversing intense ion beamlets.

Since the extracted electron current density is constant, $J_e = \rho_e v_e$, as v_e increases in the acceleration gap to approach V_b , n_e must also decrease from a large value to approach n_b as sketched in Figure 41(a). The desired shape of the applied potential to accelerate these electrons is also shown in Figure 41(b). However, the desired potential profile is not consistent with both the one-dimensional Poisson equation, $d^2\phi/dz^2 = -4\pi\rho_{net}$ and the behavior of ρ_{net} in the acceleration gap. In approaching charge neutrality, ρ_{net} is always negative, producing positive gradient in ϕ . But at a distance $z > a$, the 1-D potential profile shown in Figure 41(b) has negative curvature, hence the inconsistency. The actual solution for the 1-D problem produces spatially oscillating potentials with period of order $\lambda_b = V_b/\omega_{be}$ and the potential fluctuates with amplitude depending on the amount of initial current neutralization. However, Humphries²⁴ has found that these fluctuations instead of continuing to occur with amplitude of $4E_e$ readjust themselves to an average amplitude equal to E_e , in a few oscillations.

In order to find the configuration that produces the lowest T_{eo} for launched co-moving electrons which are co-located with ions, the 2-D accelerator design code⁴⁶ EGUN was modified to include a positively charged cylinder representing ion beamlets, while electrons are extracted across a plasma sheath and accelerated by an applied potential, such that electrons would experience an overall potential:

$$\phi(r, z) \rightarrow \phi_0 = \frac{1}{2} m_e v_b^2 \quad (69)$$

ELECTRON EXTRACTION & ACCELERATION FROM NEUTRALIZER PLASMA CELL

IDEAL SPACE POTENTIAL TO CO-MOVE ELECTRONS

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Figure 41

Since the applied potential $\phi \approx \phi_0$ is a small perturbation for 10 MeV He^+ ions, the ion trajectories need not be treated dynamically to simulate the small region of the neutralizer cell's extraction gap. Electron dynamics in several 2-D simulations were studied to gain insight into the electron optics influenced by plasma sheath, ion space charge, and lens aberration effects. The following understanding has emerged and a successful solution has been found.

(1) Since $n_p/n_b > 100$, as ion beamlets enter the neutralizer cell their space charge becomes completely neutralized. At the downstream end, an acceleration gap is formed by having an interface grid which terminates the plasma volume at $\phi = 0$ and an extraction grid at $\phi = \phi_0$, separated by a distance d such that beamlet electron current is extracted matching the ion current, $I_e = I_b$, and also co-moving electrons are generated, $E_e = e\phi_0 = (m_e/M_b)E_b$. Because in emerging co-located electron-ion beams electrons oscillate radially and axially, and in the 1-D case the amplitude of oscillations decreases⁵¹ as electrons approach co-moving speeds with period of $\lambda_b = 2\pi v_b/\omega_{be}$, in the 2-D case, it is also important that electron acceleration up to co-moving speed occurs in a distance smaller than λ_b . Thus $d < \lambda_b$ acceleration gaps are required for electrons.

(2) In 2-D cylindrical geometry the Poisson equation is expressed as:

$$\nabla^2 \phi = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \phi}{\partial r} \right) + \frac{\partial^2 \phi}{\partial z^2} = -4\pi \rho_{\text{net}} \quad (70)$$

The radial term can be made to become a positive definite term, compensating for the axial term becoming negative beyond $z > a$, such that the desired potential profile shown in Figure 41(b) could be obtained. An equipotential map which has the property of producing radial term

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \phi}{\partial r} \right) > 0$$

is sketched in Figure 41(c). This is obtained in the presence of the co-located ion beam space charge by shaping the grids. Since an equipotential gradient of this type produces defocusing action on electron trajectories, electrons entering from the left hand side must be introduced in an over-focused manner. This is accomplished by having a concave plasma sheath profile and/or a thick interface grid which will start electron trajectories at $z = 0$ initially in a convergent manner. Thus, as electron trajectories proceed to enter the region where the radial term is positive, they are defocused and the net action is the production of parallel electrons, co-moving and co-located with ions.

(3) In the process of electron acceleration to reach energy equal to $e\phi_0$, radial and axial oscillations can be suppressed further by having the thickness of the downstream grid be $t_g > \lambda_b$. The potential is thus clamped at ϕ_0 over several oscillation periods, damping the amplitude of fluctuations in launched electrons and helping further to produce co-moving electrons with minimal initial temperature T_{eo} .

Based on these design principles two-dimensional simulations of co-moving and co-located electron-ion beamlets were performed. In Figure 42 the trajectories of co-moving electrons are shown. In this example, electrons are co-located with an He^+ beamlet having 4 mm radius at 1 A/cm^2 and 10 MeV. Current neutrality in launched beamlets would be null to within a few percent: $I_b = 0.50 \text{ A}$, $I_e = 0.52 \text{ A}$. The map of space equipotentials is also shown in Figure 42. It is seen that the intermediate defocusing action discussed above is occurring near the acceleration gap. In this simulation the plasma sheath was made to produce an extracted electron current density $J_e < J_b$; however, because the area of electron extraction was larger than the ion beamlet cross section, almost equal currents were obtained. This feature influences the electron optics such that outer trajectories form an intermediate focus at a point further downstream in the acceleration grid than the focus of central electron rays. This is a beneficial effect because it helps to suppress electron oscillations by axially spreading the charge of electrons over the ion beamlet, inside the thick acceleration grid. A similar simulation is shown in

TWO-DIMENSIONAL SIMULATION OF CO-MOVING & CO-LOCATED ELECTRON & ION BEAMS

Figure 42

Figure 43 for the case of electron extraction across a flat sheath. The calculated behavior of the space potential in both simulations is displayed in Figure 44. It is seen that radial and axial dependence in attaining ϕ_0 have been minimized, the results are practically insensitive to the shape of the plasma sheath, and the desired potential profile has been obtained. An estimate of the initial electron temperature T_{eo} of emerging beams is obtained by analyzing the distributions of electron trajectories in energy and angle of emission. The distribution weighted statistical value is $T_{eo} \approx 10$ eV. The case of passive auto-neutralization can also be aided by employing this system to start the motion of co-located electrons with higher than thermal speeds; say $E_e \sim 100 - 300$ eV.

A neutralizer cell for use in both the active or auto-neutralization mode has been designed as shown in Figure 45. A pulsed Helium plasma will be confined in the cell by means of electrostatic isolation on the accelerator side and electron confinement will be enhanced by multi-pole cusp field permanent magnet rods located wherever practical on the interior surface of the volume. These permanent magnet rods will serve as neutron stoppers protecting the accelerator system in the ICF application. At the upstream and downstream ends, 110.5 cm radius grid planes with apertures somewhat larger than in the accelerator will pass the ion beamlets, and electrons will be extracted in the manner shown in Figure 42. Passage of the 400 ns in duration beam pulse will be timed to occur in the immediate afterglow of the He plasma discharge, typically 10 μ s after discharge power is shut off, where quiescent plasma conditions prevail. As indicated in Figure 45, radially placed electron emitting heated filaments will be pulsed at about -100 V to create a plasma discharge where buildup time is given by:

$$n_{ep} = n_o \left[1 - \exp\left(-\frac{t}{R/C_s}\right) \right] ; \quad (71)$$

TWO-DIMENSIONAL SIMULATION OF CO-MOVING & CO-LOCATED ELECTRON & ION BEAMS (EXTRACTION ACROSS FLAT PLASMA SURFACE)

Figure 43

PROFILE OF POTENTIAL FROM 2-D SIMULATIONS TO PRODUCE ACTIVELY CHARGE & CURRENT NEUTRALIZED BEAMS

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Figure 44

BEAM NEUTRALIZER PLASMA CELL TO PRODUCE CO-MOVING & CO-LOCATED ELECTRONS

Figure 45

R is the radial extend of the filaments from the axis of the plasma cell, $R = 125$ cm, and $C_s = c (T_{ep}/M_i)^{1/2}$ is the ion sound speed. During discharge in about 2×10^{-3} torr He gas, the plasma electron temperature^{1,17} is $T_{ep} = 6.7$ eV, consequently, $C_s = 1.3 \times 10^6$ cm/s and the plasma buildup time is:

$$t = \frac{R}{C_s} \approx 100 \text{ } \mu\text{s} \quad . \quad (72)$$

Electrons will be emitted from the radially located Tungsten dispenser cathode filaments during and after the plasma discharge pulse. These rugged filaments have a long life time, and are commercially available units⁵². The filament heater power supply could be pulsed for a low repetition rate full beam size experiment (~ 0.1 Hz) or it could be maintained on DC in the high pulse rate ICF reactor applications (10-20 Hz). Typically, the required heater power is 15 V at 2-4 A per filament unit to produce 1000°C emission temperature.

The required plasma density, n_{ep} to produce active charge and current neutralization of these ion beams will be determined experimentally. Several factors influence the determination of n_{ep} , some of which are unknown and need to be investigated experimentally. For example, the electron flux conservation argument produces a limit on n_{ep} for charge and current neutralization, if it is also assumed that active electron extraction occurs at the plasma emission current density limit, in the presence of co-located ion beams. If n_{ef} , T_{ef} are the parameters of electrons produced by the radial filaments, n_{ep} , T_{ep} are those in the plasma prior to extraction, and n_e , v_e are the electron parameters outside of the neutralizer cell, then flux conservation requires that:

$$n_{ef} v_{ef} = n_{ep} v_{ep} = n_e v_e \quad . \quad (73)$$

Charge and current neutralization require:

$$\left. \begin{aligned} n_e &= n_b \\ v_e &= v_b = c \left(\frac{2E_e}{m_e} \right)^{1/2} = c \left(\frac{E_b^2 + 2M_b E_b}{M_b^2} \right)^{1/2} ; \end{aligned} \right\} \quad (74)$$

whereby, $n_{ep} \geq n_b (E_e/T_{ep})^{1/2}$,
with T_{ep} as the electron temperature during extraction.

Beamlets emerging from the accelerator system will have 1 A current in 0.75 mm radius, or an ion current density of $J_b = 57 \text{ A/cm}^2$. The output optics will expand beamlet radii to about 6 mm in order to create a mid-range waist, so that 1 - 2 A/cm^2 beamlets will be passing through the neutralizer cell. Therefore, unbunched beam density in the neutralizer would be:

$$n_b = \frac{J_b}{Z_b e c \beta} = \begin{cases} 1 \times 10^{10} \text{ cm}^{-3} & \text{at 3 MeV} \\ 0.6 \times 10^{10} \text{ cm}^{-3} & \text{at 10 MeV} \end{cases} \quad (75)$$

and co-moving electron energy $E_e = 400 - 1300 \text{ eV}$, respectively. The electron temperature in He plasma near 10 μs in the afterglow regime is $T_{ep} = 3.7 \text{ eV}$ (see Figure 27). Therefore, using equations (75) and (68):

$$n_{ep} = 3 \times 10^{12} \text{ cm}^{-3} \quad (76)$$

is the plasma requirement for the neutralizer cell with a safety factor of 25.

The plasma volume in the cell will act in two beneficial ways:
1) the plasma will form a sheath around the filaments with thickness of about $10 \lambda_D$, producing high perveance emission of electrons in afterglow due to the rise of the plasma potential which will self adjust for the passage of the ion beam, and 2) the plasma will serve to make the potential across the ion beam be uniform, allowing for uniform extraction and acceleration of electrons to occur at the downstream end, so that active charge and current neutralization could also be made uniformly in all ion beamlets. Since filament emission will continue to occur during active electron extraction, neutrality

in the cell will be always maintained. Electron in-fall time will occur at the scale of ω_{pe}^{-1} , typically requiring $10 \omega_{pe}^{-1}$ time to space charge neutralize across the ion beam. In the case of $n_{ep} \gg n_b$, this transit time is independent of the radial location of filaments with respect to the axis of the cell. Each filament unit will be capable of emitting electron current density of up to 8.5 A/cm^2 in pulsed operation.

The neutralizer cell dimensions will be 125 cm radius and 75 cm long with grid plane radius 110 cm on axis, representing a plasma volume of $V_p = 3680$ liter. The pulsed plasma discharge power requirement in order to produce $3 \times 10^{12} \text{ cm}^{-3}$ plasma density in He gas is estimated by:

$$\left. \begin{aligned} E &= eV_p n_{ep} E_{i-e} / (1 - e^{-1}), \\ \text{and} \quad P &= \frac{E}{R/C_s} \end{aligned} \right\} \quad (77)$$

In He gas the energy required to create an electron-ion pair due to ionization, excitation and kinetic loss effects is calculated¹⁷ to be:

$$E_{i-e}(\text{He}) = 89 \text{ eV}. \quad (78)$$

Therefore, to produce the required plasma density in the neutralizer cell during one buildup time, an energy of 240 J will be needed for a period of about 100 μs ; whereby, $P = 2.4 \text{ MW}$, and for $V(\text{discharge}) = 100 \text{ V}$ a total $I(\text{discharge}) = 24 \text{ kA}$ will be distributed over the 24 filament units. This pulsed power requirement will be implemented by a separately triggered system.

Helium gas is chosen for the neutralizer cell to have the same gas specie in the upstream ion source vessel and the downstream cell, where a gas diffusion path exists between these via the multi-aperture accelerator structure. The He gas pressure requirement in the source is

3×10^{-3} torr, about the same as in the neutralizer cell, so that differential pumping will be made available between the two elements which is also consistent with the operation of the accelerator.

II.4 CRITICAL ISSUES AND DEVELOPMENT PLAN FOR THE ACCELERATOR SYSTEM

The critical accelerator physics issues in the LIFE system are concerned with the stability and control of beams in the constant voltage and time varying voltage acceleration stages which can be resolved in the near term by means of laboratory scale test stand experiments. Relevant experiments on beam stability, emittance growth, focusing and space charge limited current transport in the ESQ channels can be implemented in an economical setup. A reasonably stiff light ion beam in a few beamlet channels, injected into several ESQ planes would be needed for such a scaled experiment. Emittance growth during ESQ transport is expected to occur due to accumulative effects from hardware imperfection and the influence of these could only be detected when the beam is made to experience a large number of betatron oscillations. A factor of 2 in emittance growth has been allowed to occur in the injector section and another factor of 2 in the ESQ focused time varying section of the designed LIFE accelerator system.

A facility design has been made to implement these important laboratory scale test stand experiments, based on upgrading some of the existing equipment at TRW. Figure 46 shows the schematic drawing of an accelerator test stand facility which is designed to produce 0.5 MeV He^+ beams in 500 ns flat-top pulses and a total current in the range of 2 - 100 A. The developed pulsed ion source shown in Figure 25 will be used to extract 0.1 - 0.2 eV cold He^+ ion beamlets with up to 0.25 A/cm^2 current density using the existing power supplies. The multi-aperture multi-grid electrostatic accelerator will be a scaled down version of the injector design shown in Figure 29, with overall radius of 15 cm, 6 mm beamlet radius at extraction and 0.577 transparency to beams. A droop-compensated Marx pulse generator for acceleration to 0.5 MeV in 500 ns flat top pulses has been designed, based on commercially available and economical units. The pulsed power design for this experimental accelerator is displayed in Figure 47, and the design of the tapered column serving as the oil-vacuum

interface is given in Figure 48. Injection into several planes of ESQ strong focusing periodic channels will be made for the required experimental investigations. Beam stability, control, focusing, steering and emittance growth related issues can be investigated in the near term. These measurements will help validate the critical accelerator physics issues for the LIFE system and moreover, will be helpful as an independent check of similar tests in different parameter regimes which are anticipated for the heavy ion fusion accelerator development program.

Figure 46

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DROOP-COMPENSATED, MARX PULSE-GENERATOR FOR 0.5 MeV,
0.5 μ s FLAT-TOP PULSES

Figure 47

HIGH VOLTAGE TAPERED COLUMN FOR ACCELERATOR RADIAL & AXIAL SUPPORT AND VACUUM-OIL INTERFACE

Figure 48

III. NEUTRALIZED BALLISTIC PROPAGATION AND FOCUSING

An in-depth theoretical analysis with numerical simulations was performed by the TRW-LASNL research team, addressing all possible critical concerns in the neutralized ballistic propagation and focusing of intense ion beams. The studied areas included the following topics: The tolerable ambient gas pressure for a LIFE ICF reactor scenario which is predominantly limited by multiple scattering for this propagation method; the required initial electron temperature to ballistically focus the neutralized beam; the acceptable methods of intense ion beam neutralization; the influences of strong radial and axial beam pulse compression on focusing; and the influence of Pierce type instabilities thought to be damaging for this propagation mode. New theoretic formalisms^{13,14} on adiabatic radial compression of neutralized beams were developed by D. S. Lemons and L. E. Thode at LASNL, and the recent investigations on auto-neutralization,²⁴ together with an extension of the developed formalism treating the simultaneous occurrence of both axial and radial compressions were included in the analyses of LIFE beams.

The analytical discoveries are summarized as follows:

- 10^{-3} torr of Lithium vapor is acceptable in a reactor scenario of the LIFE ICF driver
- side-injection of neutralizing electrons is unacceptable
- the required initial electron temperature for LIFE beams is $T_{e0} \approx 30\text{-}50$ eV to focus onto 5 mm radius targets in 10 m.
- both active or auto-neutralization methods produce a T_{e0} which is consistent with what is required for LIFE beams
- 45:1 radial adiabatic compression and 20:1 axial pulse compression is acceptable to ballistically focus onto 5 mm radius with a stand-off capability of 10 m
- it is not necessary to have precise amount of initial neutralization.

A summary of the theoretical analyses which produced these important conclusions is presented in the following.

III.1 MULTIPLE SCATTERING OF IONS AND REACTOR GAS PRESSURE

Let x_{rms} be the standard deviation of net deflections caused by multiple scattering of ions, projected onto any plane which contains the particle trajectory.

$$x_{\text{rms}} = \frac{1}{\sqrt{3}} L \theta_{\text{rms}} \text{ (plane)} = \frac{1}{\sqrt{6}} L \theta_{\text{rms}} \quad (79)$$

The multiple scattering distribution angle θ_{rms} is given⁵³ by:

$$\theta_{\text{rms}}^2 = \frac{8\pi Z_g (Z_g + 1) Z_b^2 e^2 n_g L}{(4\pi\epsilon_0)^2 p^2 \beta^2 c^2} \cdot \ln \left(\frac{a_0}{\pi/p \cdot Z_g^{1/3}} \right), \quad (80)$$

where n_g is the gas atomic density, L is the gas thickness, a_0 is the atomic Bohr radius and p is the particle momentum. In practical units,

$$\theta_{\text{rms}}^2 = \frac{5.2113 \times 10^{-29} Z_g (Z_g + 1) Z_b^2 n_g (\text{m}^{-3}) L (\text{m})}{(\beta \gamma M)^2 \beta^2} \cdot \ln \left(191.85 \frac{\beta \gamma M}{m_e Z_g^{1/3}} \right), \quad (81)$$

where M is in units of MeV/c^2 . At STP, the gas atomic density is related to the pressure by:

$$n_g (\text{cm}^{-3}) = 3.219 \times 10^{16} P (\text{torr}) \cdot n_a, \quad (82)$$

where n_a is the number of atoms per gas molecule. Thus, using Lithium vapor for the gas medium at 10^{-3} torr pressure, consistent with the requirement of heavy ion beams, we obtain for a gas thickness of $L = 10$ m:

$$\theta_{\text{rms}} = \begin{cases} 0.24 \text{ mrad at } 3 \text{ MeV} \\ 0.075 \text{ mrad at } 10 \text{ MeV} \end{cases} \quad (83)$$

and,

$$x_{\text{rms}} = \begin{cases} 1 \text{ mm at } 3 \text{ MeV} \\ 0.3 \text{ mm at } 10 \text{ MeV} \end{cases} \quad (84)$$

for the LIFE He^+ beams.

Thus, in the worst case, a 1 mm smearing of the 5 mm radius final focus will be obtained in traversing 10 m of Lithium vapor at 10^{-3} torr.

III.2 DETRIMENTAL SIDE-INJECTION OF ELECTRONS

In one of the earlier approaches to the active neutralization problem the geometry of interleaved electron-ion beams was examined. This geometry was considered because it could easily be applied for multi-aperture accelerator

produced ion beams. The geometry of interleaved beams applies to either annular rings, slots or holes. All of these cases correspond to side-injection of electrons, where the electrons are co-moving but are not co-located initially with the ions. A two-dimensional simulation with the code CCUBE was performed to study the dynamics of electrons and ions, and to gain insight into the focusing requirement of ions. The parameters used in the simulation were: $n_b = n_e = 10^{10} \text{ cm}^{-3}$, $M_b/m_e = 3670$ and $\beta_b = \beta_e = 0.0728$ for 5 MeV D^+ beams; 3 mm thick annular ion beams were interleaved with 1 mm thick annular electron beams where 2 mm edge-to-edge separation between beams existed. Results¹⁰ obtained by D. S. Lemons at LASNL are shown in Figure 49.

The initial ion electron charge separation at injection produces considerable stored electrostatic energy which is rapidly transferred to the electrons. Although ions seem to propagate undisturbed in this simulation, the ion time scale, ω^{-1} is too long in the simulation to observe the disturbance of ions.^{bi} However, an estimate of the equivalent electron temperature from the dynamics can be made by calculating the average electrostatic energy per electron, W_e due to the charge separation of electron and ion beamlets. In infinite sheet geometry this is given by:

$$W_e = 2\pi r_e n t (s + 2/3 t) m_e c^2 \quad (85)$$

where $n = n_b = n_e$, t is the sheet thickness in both beams, s is the separation between beam edges, r_e is the classical electron radius and m_e is in units of eV/c^2 . For example, assuming $n = 10^{10} \text{ cm}^{-3}$, $t = 5 \text{ mm}$, $s = 3 \text{ mm}$, $W_e \sim T_e \sim 3 \text{ keV}$ is obtained, and higher temperatures would result from denser beams. This makes all side-injected electron approaches invalid for the desired performance in ballistically focused propagation of current neutralized intense beams. Therefore, it is concluded that all similar schemes of side injection of electrons should be discarded especially for light ions, instead, it is required to have initially co-located electron-ion beamlets to overcome this space charge heating problem.

TIME = 24.5000

FIGURE 49(a)

TIME = 24.5000

FIGURE 49(b)

FIGURE 49(a)-49(b). Ion beam (a) and co-moving electron (b) particle plots in $X2-X1$ (i.e., $r-z$) space. Simulation parameters are $\beta = 0.0728$ and $m_b/m_e = 3670.5$. Particles are completely cold. Distances and times are in units of c/ω_{pe} and ω_{pe}^{-1} respectively.

III.3 CONSIDERATIONS IN ADIABATIC COMPRESSION AND INITIAL NEUTRALIZATION

The current and charge neutralized ballistic propagation of intense ions which are produced from multi-aperture accelerators is characterized by the following description. As co-moving and co-located electron-ion beamlets emerge from the last element of the accelerator/neutralizer cell system, beamlets pointing to a common focus propagate relatively freely until ion beamlet edges begin to coalesce. At this point, the merged uniform beam propagates under conditions of radial and axial adiabatic compression, raising the electron temperature in the case of radial compression according to:

$$T_e(z) = T_{e0} [a_0(z_1)/a_0(z)]^2 \quad (86)$$

where the compressed beam radius in flight, assuming purely ballistic propagation is given approximately by:

$$a_0(z) = a_F + (a_0 - a_F) (1 - z/L), \quad (87)$$

the propagation distance z_1 where compression begins is a function of the output optics and in the case of expanded beamlets to the radius of the last lens R_Q which produces a mid-range waist condition in the focused propagation of beamlets is given by:

$$z_1 = \frac{(R_{cc} + R_Q) L}{R_{cc} + R_Q + a_F} \quad (88)$$

where R_{cc} is the initial center-to-center separation between beamlets, a_0 is the initial overall beam radius, a_F is the final focused beam radius, L is the total propagation distance, and T_{e0} is the initial temperature of launched electrons. Using $R_Q \sim 6$ mm, $R_{cc} = 14$ mm, $a_F = 5$ mm, $L = 10$ m, it is seen that adiabatic radial compression in LIFE beams begins to occur in the last 2.0 m of ballistic propagation. (Actually, during free propagation the beamlets will expand by a negligible amount, slightly decreasing z_1 the distance at which beamlets begin to coalesce. This expansion will be negligibly small because the electron temperature which causes this expansion is relatively cold and further expansions cool down the temperature).

It is not necessary to launch these beams with precise amounts of initial current and charge neutralization, $n_b = n_e$ and $V_b = v_e$. Electron mobility being high, the central core of the beam will always be charge and current neutralized. That is, if initially $n_{e0} > n_b$, excess electrons will be lost and the ion beam will remain neutralized; if $n_{e0} < n_b$, and electrons are provided uniformly across the beam, then these electrons will move to the central core of the beam which will always be charge and current neutralized

and the exposed ions at the radial edge will expand by space-charge forces and be lost during ballistic propagation. In both cases the process will occur in a time scale of $10 \cdot \omega_{be}^{-1} \sim 2$ ns. Subsequently, the radial edges of the beam will have a sheath in a distance scale of a few $\lambda_D = v_{eT}/\omega_{be}$. Thereafter, electrons will be lost from the beam by crossing this sheath at a rate given by the ion acoustic speed which is very slow relative to the entire propagation time. The behavior of electron dynamics as described in this paragraph has been verified by a 2-D CCUBE simulation in which the electric field profile at the radial edge sheath has also been determined.²³

III.4 THEORY OF RADIAL AND AXIAL ADIABATIC BEAM PULSE COMPRESSION

New envelope equations have been derived^{13,14,23} by D. S. Lemons and L. E. Thode at LASNL to describe the effectiveness of charge and current neutralized ballistic focusing of intense ion beams, as adiabatic compression builds up pressure to influence the spot size at the waist of the focus. One of the envelope equations describes the evolution of the rms radius in the transport of ballistically focused and neutralized beams, and the other describes the evolution of the radial edge envelope in such beams. The first one is more appropriate to use because it treats radial compression in terms of the average radial expansion forces in the beam, whereas in the second radial edge envelope equation, the maximum possible radial expansion force in the beam is assumed to characterize compression everywhere. The rms envelope equation is characterized in terms of the initial electron T_{eo} and initial ion T_{io} temperatures, the geometric convergence angle θ , the beam kinetic energy E_b , the initial and final envelope radii R_0 and R_F , and the specific heat ratio at constant pressure and volume for the ions and electrons, γ_i and γ_e . The full equation is:

$$\frac{1}{2} E_b \tan^2 \theta = \frac{Z_i T_{eo}}{(\gamma_e - 1)} \left[\left(\frac{R_0}{R_F} \right)^{2(\gamma_e - 1)} - 1 \right] + \frac{T_{io}}{(\gamma_i - 1)} \left[\left(\frac{R_0}{R_F} \right)^{2(\gamma_i - 1)} - 1 \right], \quad (89)$$

characterizing the ballistically focused and neutralized propagation in which ion and electron heating occurs according to the general adiabatic law:

$$\left. \begin{aligned} PV^\gamma &= \text{constant} \\ T_e R^{2(\gamma_e - 1)} &= \text{constant} \\ T_i R^{2(\gamma_i - 1)} &= \text{constant} \end{aligned} \right\} \quad (90)$$

Because we expect the electron compressive heating to take place in three dimensions while the ions will be heating in two dimensions, the tolerable initial electron temperature for light ion beams will be much greater than the required initial ion temperature:

$$\text{for, } \left. \begin{array}{l} Z_i T_{eo} \gg T_{io} \\ T_{io} \approx 2-4 \text{ eV} \end{array} \right\} \quad (91)$$

Therefore, in equation (89), at first the T_{io} term can be neglected, and the equation can be used to estimate the required T_{eo} , subsequently the full equation can be used to arrive at the correlated requirements in terms of T_{eo} and T_{io} . Following this prescription, equation (89) sets the following tolerable limit on T_{eo} :

$$Z_i T_{eo} \leq \frac{(\gamma_e - 1) \tan^2 \theta E_b}{2 \left[\left(\frac{R_o}{R_F} \right)^{2(\gamma_e - 1)} - 1 \right]} \quad (92)$$

The rms radius of the beam at the start of radial compression is:

$$\text{and, } \left. \begin{array}{l} R_o = a_o(z_1)/\sqrt{2} \\ R_F = \frac{a_F}{\sqrt{2}} = \left(\frac{a_T}{\sqrt{f}} \right) \frac{1}{\sqrt{2}} \end{array} \right\} \quad (93)$$

where $a_o(z_1)$ is the beam radius when beamlets coalesce and the onset of adiabatic radial compression occurs given by equations (87) and (88), and f is the fraction of the ballistically focused beam area which overlaps with the target:

$$\pi a_T^2 = f \cdot \pi a_F^2 \quad (94)$$

The geometric convergence angle is given by the radius of the accelerator a_o and its stand-off distance from the target L :

$$\tan \theta = \frac{a_o}{L}, \quad a_o = 110.5 \text{ cm}, \quad L = 10 \text{ m} \quad (95)$$

The envelope equation shows that in well neutralized beams, where

$$\frac{a_0(z)}{\sqrt{2}} \gg \lambda_D ; \quad \lambda_D = \frac{v_{eT}}{\omega_{be}} \quad (96)$$

the ballistic focusing of beams is independent of beam density n_b ;

$$\left. \begin{aligned} \omega_{be}^2 &= \frac{n_b Z_i c^2}{\epsilon_0 \gamma m_e} \\ v_{eT}^2 &= \frac{2T_e(z)}{m_e} \end{aligned} \right\} \quad (97)$$

For the compressive stage of ballistic propagation it now remains to determine if neutralizing electrons are heated in two dimensions (2-D) or three dimensions (3-D). the following values of γ correspond to the dimensionality of adiabatic electron heating:

$$\left. \begin{aligned} 2\text{-D}, \quad \gamma &= 2 \\ 3\text{-D}, \quad \gamma &= 5/3 \end{aligned} \right\} \quad (98)$$

and in general,

$$\gamma = 1 + \frac{2}{2 + T_{||}/T_{\perp}} \quad (99)$$

It is noted that non-adiabatic electron heating occurs if:

$$V_b \tan \theta \geq v_{eT} \quad , \quad (100)$$

in which case equation (92) would not be immediately applicable, instead, the electron temperature would rise quickly until its thermal velocity corresponds to its radial compression velocity and thereafter T_e would evolve according to the scaling law of adiabatic compression.

At first glance, it may be argued that most of the heating of electrons during ballistic propagation would be in two-dimensions. However, it is shown¹⁶ that starting with 2-D electron heating in transport, since $T_{\perp} \gg T_{||}$ in adiabatic compression, the Velocity Anisotropy Weibel instability⁵⁴ will act to equilibrate quickly the electron temperature, thus producing a state of 3-D electron heating in ballistic propagation of

beams. Equilibration occurs rapidly during adiabatic compression because the Weibel instability growth rate, Γ_W is much larger than the beam's radial compression rate.

The growth rate of the Velocity Anisotropy Weibel instability is given by:

$$\Gamma_W = \frac{2}{3(3\pi)^{1/2}} \cdot \left(\frac{v_e T_0}{c} \right) \cdot \omega_{be_0} \cdot \left(\frac{n_b}{n_{b0}} \right)^{1/2} \cdot \left[\left(\frac{T_\perp}{T_0} \right)^{1/3} - \left(\frac{T_0}{T_\perp} \right)^{2/3} \right]^{3/2} \quad (101)$$

where $T_{\parallel 0} = T_{\perp 0} = T_0$ for initially 2-D electron heating conditions. From Equation (98) and (99) we also have $T_\perp a^2 = \text{const.}$ and $n_b a^2 = \text{const.}$ Consequently, Equation (101) is re-expressed as:

$$\Gamma_W = 0.217 \left(\frac{v_e T_0}{c} \right) \cdot \omega_{be_0} \left(\frac{a_0(z_1)}{a(z)} \right)^2 \cdot \left[1 - \left(\frac{a(z)}{a_0(z_1)} \right)^2 \right]^{3/2} \quad (102)$$

Now, the rate of beam convergence in ballistically focused beams is:

$$\frac{\dot{a}}{a} \approx \frac{V_b \tan \theta}{a_0} \quad (103)$$

therefore, the Weibel instability growth rate relative to the beam compression rate is given by:

$$\frac{\Gamma_W}{(\dot{a}/a)} \sim 0.217 \left(\frac{v_e T_0}{V_b} \right) \left(\frac{\omega_{be_0} a_0}{c} \right) \cdot \left(\frac{a_0(z_1)}{a(z)} \right)^2 \frac{1}{\tan \theta} \quad (104)$$

Assuming $T_{e0} = 30$ eV, for $E_b = 3 - 10$ MeV, $I_b = 23$ kA, He^+ beams with n_{b0} given at $z_1 = 8$ m in Figure 18, $\tan \theta = 0.1105$, and $a_0 = 110.5$ cm, the numerical value of equation (102) or (104) is:

$$\frac{\Gamma_W}{(\dot{a}/a)} = (31 - 76) \cdot \left(\frac{a_0(z_1)}{a(z)} \right)^2 \left[1 - \left(\frac{a(z)}{a_0(z_1)} \right)^2 \right]^{3/2} \approx 53 \left(\frac{a_0(z_1)}{a(z)} \right)^2 \quad (105)$$

Thus, almost immediately after the beamlets coalesce and adiabatic radial compression starts in the last leg of ballistic propagation, equation (105) shows that the electron temperature isotropization rate exceeds by two orders of magnitude the beam compression rate. Consequently, three-dimensional (instead of 2-D) adiabatic electron heating will predominate, and equation (92) with $\gamma=5/3$ shall describe the ballistically focused and neutralized beam propagation with the requirements that:

$$T_{eo} \leq \frac{\tan^2 \theta \cdot E_b}{3 Z_i \left[\left(\frac{a_o(z_1) \sqrt{f}}{a_T} \right)^{4/3} - 1 \right]} \quad (106)$$

$$\text{and,} \quad T_{eo} \geq \frac{1}{2} m_e \beta_b^2 \tan^2 \theta \quad (107)$$

The above formalism characterizing the radial compression of ballistically focused and neutralized beams with the $R^{4/3}$ scaling of equation (106) has been extended to include the influence of also the axial pulse compression effect. In the presence of both radial and axial compression, equation (86) is replaced by:

$$\left. \begin{aligned} T_e(z) &= T_{eo} \left[V_o(z_1)/V(z) \right]^{2/3} \\ V(z) &= \pi a_o^2(z) \cdot \ell_b(z) \end{aligned} \right\} \quad (108)$$

where $\ell_b(z)$ is the axially compressed beam pulse length. An envelope equation describing the simultaneous occurrence of both axial and radial pulse compressions is obtained by assuming that axial compression is occurring in the absence of either external or internal forces. Since the ions are not subjected to external forces during ballistic propagation, the initial and final rates of axial compression would be the same, $\dot{\ell}_b(z=0) = \dot{\ell}_b(z=L)$. The term $(R_o/R_F)^{2(\gamma_e - 1)}$ in Equation (89) is now replaced by $(V_o/V_F)^{(\gamma_e - 1)}$, however the equivalent term for ions is preserved because it is relatively difficult by the factor of $\tan^{-2} \theta \approx 100$ to perturb

the large axial directed motion of ions by the pressure of electrons or the thermal ion expansion. Thus, in the case of ions only transverse temperature need be considered, producing:

$$\frac{1}{2} E_b \tan^2 \theta = \frac{3}{2} Z_i T_{eo} \left[\left(\frac{R_o}{R_F} \right)^{4/3} \cdot \left(\frac{\ell_o}{\ell_F} \right)^{2/3} - 1 \right] + T_{io} \left[\left(\frac{R_o}{R_F} \right)^2 - 1 \right] \quad (109)$$

$$\left. \begin{array}{l} \text{where,} \quad \gamma_e = 5/3 \quad , \quad (3\text{-D electron heating}) \\ \quad \quad T_e = T_{e\perp} = T_{e\parallel} = T_{eo} (V_o/V_F)^{\gamma_e - 1} \\ \text{and,} \quad \gamma_i = 2 \quad , \quad (2\text{-D ion heating}) \\ \quad \quad T_i = T_{i\perp} = T_{io} (R_o^2/R_F^2)^{\gamma_i - 1} \end{array} \right\} \quad (110)$$

are employed. Equation (109) could be modified by non-linearities in the axial compression rate due to internal forces caused by transverse-axial temperature asymmetries, however, it is expected that this would be a minor modification.

Consequently, the required initial electron temperature for ballistic propagation undergoing both radial and axial pulse compressions is given by:

$$T_{eo} \leq \frac{\tan^2 \theta \cdot E_b}{3 Z_i \left[\left(\frac{a_o(z_1)\sqrt{f}}{a_T} \right)^{4/3} \cdot \left(\frac{\ell_o}{\ell_F} \right)^{2/3} - 1 \right]} \quad , \quad (111)$$

where ℓ_o and ℓ_F are the initial and final pulse length in the ballistic propagation range with $\ell_o/\ell_F = 20$. In Figure 3, using Equation (111) the required T_{eo} is calculated as a function of the stand-off range, L , and the fraction of focused beam on target, f , for 10 MeV He^+ beams undergoing 45:1 radial and 20:1 axial pulse compressions. It is found that for $f = 100\%$, $L = 10$ m, and target radius $a_T = 5$ mm, LIFE beams shall require a

$$T_{eo} \leq 35 \text{ eV} \quad (112)$$

for the initial electron temperature neutralizing the He^+ beamlets.

Using the upper bounds of T_{eo} from Equation (111) and Figure 3, it is now possible to estimate also the tolerable requirement for the initial ion temperature T_{io} at the start of ballistic propagation. This is made by re-expressing Equation (109):

$$T_{io} = \left\{ \frac{E_b}{2} \tan^2 \theta - \frac{3}{2} z_i T_{eo} \left[\left(\frac{a_o(z_1) \sqrt{f}}{a_T} \right)^{4/3} \left(\frac{\ell_o}{\ell_F} \right)^{2/3} - 1 \right] \right\} \left[\left(\frac{a_o(z_1) \sqrt{f}}{a_T} \right)^2 - 1 \right]^{-1} \quad (113)$$

Thus, a correlated requirement in T_{io} and T_{eo} is obtained for the ballistic focusing of neutralized ion beams undergoing both radial and axial pulse compressions. This correlation is calculated for the LIFE baseline parameter case and is shown in the insert of Figure 3, concluding that jointly the requirements are:

$$\left. \begin{array}{l} T_{eo} \leq 30 - 50 \text{ eV} \\ T_{io} \leq 3 - 4 \text{ eV} \end{array} \right\} \quad (114)$$

It should also be noted that the 3-D electron heating will improve further the validity of the envelope equation for well neutralized beams where it is required that $a_o(z)/\sqrt{2} \gg \lambda_D$. Whereas in 2-D electron heating $\lambda_D = \text{const.}$ during ballistic propagation, in 3-D adiabatic electron heating the Debye length scales as $\lambda_D \sim T_{eo}^{1/2} a_o(z)^{1/3}$ and the large inequality is preserved down to mm spot size beams.

It has been argued that such a large temperature difference between the ion and electron species of the neutralized beam would equilibrate and cause an excessive rise in the ion temperature which could destroy the quality of beam focus. It is shown that this concern is invalid because the temperature equilibration time, t_{eq} , is too long as compared with the neutralized beam's propagation time; t_{eq} is given⁵⁵ by:

$$t_{eq} = \frac{3}{8\sqrt{2}\pi} \frac{1}{r_e \cdot r_i \cdot n_i \cdot c \cdot Z_i^2 \cdot \ln \Lambda} \left[\frac{T_e}{m_e} + \frac{T_i}{M_i} \right]^{3/2} \quad (115)$$

$$\ln \Lambda = 23.463 - \ln \left[\frac{Z_i \sqrt{n_e}}{T_e^{3/2}} \right]$$

where r_e and r_i are the classical radii of particles and masses are in unit of eV/c^2 . Consequently, for $T_e = 40 \text{ eV}$, $n_e \sim 10^{12} \text{ cm}^{-3}$ and $T_i = 1 \text{ eV}$, a value of $t_{eq} = 18 \text{ ms}$ is obtained which is too long as compared to the μs time for the 3 - 10 MeV He^+ beam propagation in 10 m.

Recently, Humphries and co-workers have made a 1-D numerical simulation study on the process of auto-neutralization²⁴ in which electrons are accelerated to co-move with ions influenced by the space charge of the co-located traveling ion beams. The electron dynamics have been studied by introducing electrons of zero velocity with a small spread and equal electron and ion charges. The 1-D potential experienced by electrons is defined by the uniform ion density n_b and constant velocity V_b . It is found that initially the potential oscillates between $\phi = 0$ and $\phi = 4 E_e$ with periodicity $\lambda = 2\pi V_b/\omega_{be}$, where E_e is the co-moving electron energy, $E_e = (m_e/M_i) E_b$; however, after a few oscillations later in time, it is found that the electron distribution is relaxed and the potential is settled to $\phi = E_e$, producing both current and charge auto-neutralization. From the velocity distribution of these electrons a measure of the electron temperature is numerically deduced, whereby:

$$T_{eo} = (0.043) E_e = 0.043 \cdot \left(\frac{m_e}{M_i} \right) E_b \quad (116)$$

Thus, inserting $E_b = 3 - 10$ MeV for the He^+ LIFE beams, we find that auto-neutralization would produce:

$$T_{eo} = \begin{cases} 20 \text{ eV at } E_b = 3 \text{ MeV} \\ 60 \text{ eV at } E_b = 10 \text{ MeV} \end{cases} \quad (117)$$

which is consistent with the requirement of Equations (111) and (114), for the ballistic focusing of LIFE beams undergoing both (45:1) radial and (20:1) axial compression. It is expected that T_{eo} from auto-neutralization can be further reduced by initiating the motion of co-located electrons at higher than thermal speed, say at $E_e \sim 100 - 300$ eV by the method shown in Figure 45.

We conclude that both active and auto-neutralization methods of producing co-moving and co-located electrons would be equally suitable for LIFE beams and that both methods should be tested by measuring the resulting T_{eo} in the same experimental setup as presented in Section IV.

The theoretical studies were concluded by addressing the issue of a Pierce type instability in the ballistic propagation of neutralized intense ion beams. Recently, it was invoked^{21,22} that this instability would be a damaging mechanism. But, a theoretical analysis²³ shows the Pierce instability is not a problem for the propagation of neutralized ion beams in the ICF application. This is because the occurrence of the Pierce instability for a neutralized beam requires that a good electrical connection exists between the front and the end of the beam pulse. In ion beam ICF reactors, this electrical connection will not exist unless there is a conducting ambient plasma in the reactor vessel, because in all cases just as in the case of LIFE beams the accelerator launched beam pulse length ℓ_b will be smaller than the propagation range L , and nowhere during ballistic propagation shall the two ends of the beam be electrically connected. In a 10^{-3} torr reactor vessel there is no electrical connection between the pellet and the driver's last element. The pellet surface corresponding to the right hand boundary of the problem should be a floating surface. The left hand boundary condition at the ion driver's last element or the reactor port should be that the electric field vanishes, since charge and current neutralized beams are injected.

However, it may still be argued that a tenuous background plasma shall always be present in the propagation region which electrically will connect the moving beam front with the target end. Under these conditions, it is also found²³ that the Pierce instability effect is mitigated by the finite background plasma conductivity given⁵⁶ by:

$$\sigma_{||} = \frac{1.76 \times 10^{14} (T_{ep})^{3/2}}{Z_{ip} \cdot \ln \Lambda} \quad (s^{-1}) \quad (118)$$

with the Coulomb logarithm of Equation (115). Such a conductivity will tend to short the electrostatic fields produced by the instability even as it acts to provide the electrical connection necessary for the Pierce instability. Maximized over all values of $\sigma_{||}$, it is found that Pierce instability growth rates are still insignificant for LIFE beam parameters. Assuming about 1% gas ionization in 10^{-3} torr Li with $T_{ep} \sim 3$ eV a reasonable estimate of $\sigma_{||}$ is obtained and therefore it is seen in Figure 50 that LIFE beams will actually be stable.

PIERCE INSTABILITY ANALYSIS

$$\theta_b = \frac{\omega_p L}{V_b}$$

Figure 50

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Figure 51

IV. A SCALED BALLISTIC PROPAGATION EXPERIMENT

The possibility of having either the active or the auto-neutralization methods to neutralize the intense ion beam, with suitable initial electron temperatures within the ballistic focusing requirement has enhanced the need of continuing the reserach by means of a laboratory scale ballistic propagation experiment. The design of such an experiment was made with the following test beam parameter choices:

- Ion specie: He^+
- Source current density: $0.3 - 0.45 \text{ A/cm}^2$
- Total accelerated beam current: 2 kA
- Acceleration voltage: 1-5 MeV
- Accelerated beam pulse: $0.5 \mu\text{s}$
- Co-moving electron energy: 140-690 eV
- Ballistic propagation distance: 8 m
- Starting beam overall radius: 50 cm
- Ambient gas pressure: 10^{-3} torr
- Radial adiabatic compression: 30:1
- Axial adiabatic compression: 20:1
- Total beam energy: 2 kJ.

It should be noted that the velocities in such a test beam would be about four times smaller than the speed of 5 GeV U^+ beams, so that the information acquired by the ballistically focused experiment should also apply to the neutralized propagation of heavy ion beams. A comprehensive design for the diagnostic and instrumentation elements of this experiment has also been performed, some of which contain new techniques as required by such an unprecedented experiment. These have been presented in a separate document⁸ submitted to DOE and are not repeated in this report. The design of the experimental set-up is shown in Figure 4.

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