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# MULTI-STAGE INTENSE ION BEAM ELECTROSTATIC ACCELERATOR FOR ICF*

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## Summary

The design of a multi-aperture, channel focused, multi-stage low β electrostatic accelerator is made to produce well controlled intense light ion beams as drivers of Inertial Confinement Fusion (ICF) targets. Unlike the case of diode accelerators, the Light Ion Fusion Experiment (LIFE) accelerator system[1] contains separate-function elements to launch 3 to 10 MeV, 23 kA accelerated current, $He^+$ beams in 400 ns pulses where 20:1 axial pulse compression would occur during the neutralized and ballistically focused transport. Each beam line would impart 50 kJ implosion energy in ∿ 20 ns on 5-6 mm radius targets located 10 m downstream and a system of 40 beam lines would deliver 2 MJ. Methods of producing beam neutralization with initial electron temperature $T_{eo}$, satisfying analytically derived constraints for both radial (45:1) and axial (20:1) pulse compressions during transport are given separately.[2] Also, the development of a pulsed intense cold plasma ion source capable of producing 1 A/cm² and $T_i$ ∿ 0.15 eV $He^+$ beamlets over large extraction surfaces which is suitable for this application is presented[3] in these proceedings.

## Accelerator Design

The key elements, functions and corresponding parameter values in the LIFE accelerator system are designated in Fig. 1. The design is driven by the stringent emittance requirement of $\epsilon_{NT}$ ∿ $3 \times 10^{-5}$m-rad, for the delivery of 0.5 MA beams of 3 to 10 MeV $He^+$ ions in ∿ 20 ns pulses onto ∿ 6 mm radius targets located 10 m away, the necessity of providing control in beam steering and focusing, and the desire of employing relatively low power technology by accelerating 25 kA beam current in 400 ns pulses with strong axial pulse compressions (20:1) programmed to occur during the ballistically focused and neutralized transport of beams. Light ion diodes with or without separate function ion sources are capable of accelerating MA currents to several MV kinetic energy in ∿ 40 ns pulses, however, beam divergence being large (∿ 20 mrad) such beams are limited in power focusing range, propagation is restricted to the case of injecting beams into preformed high-reverse-current plasma channels, control in beam steering and focusing is difficult to achieve, and axial pulse compression is severely constrained so that high power technology is needed to energize the diodes. Consequently, the design of a multi-aperture, channel focused, multi-stage low β electrostatic accelerator was motivated to produce light ion ICF drivers with beams capable of propagating in $10^{-3}$ torr ambient gas in the actively neutralized and ballistically focused manner.

The accelerator design is based on the following features. A separate, pulsed intense cold plasma ion source developed[3] at TRW is used with $n_i \simeq 10^{13}$cm$^{-3}$ and $T_i \simeq 0.15$ eV in order to extract 1 - 1.5 A/cm² $He^+$ ions in 400 ns pulses over a surface of 1.1 m radius. Ion extraction voltage is applied in the immediate afterglow of pulsed plasma induction where in ∿ 20 μs time ion temperature cools down by ion-neutral collisions to the required level[3] while ion density remains relatively unchanged. Multi-aperture ion extraction is made using 6 mm radius holes resulting to an invariant channel emittance of $5 \times 10^{-8}$m-rad. A separate function, multi-aperture, weak channel focused electrostatic accelerator is used to accelerate in stages a total of 23 kA beam current to about 3 MeV; a 400 ns flat-top voltage is applied, divided among parallel planes of acceleration gaps where overall structure radius in 1.1 m. The voltage distribution chain is designed to compress the beamlets radially, from 6 mm at extraction down to 0.3 mm at 3 MeV. The EGUN code by W.B. Herrmannsfeldt is employed to arrive at the beamlet acceleration optics design shown in Figure 2. This feature prepares the 1 A beamlets for injection into strong focusing channels of periodic electrostatic quadrupoles (ESQ) situated between following acceleration gaps, where acceleration is made in a time varying manner from 3 to 10 MeV, such that 20:1 axial pulse compression occurs in the 10 m ballistic

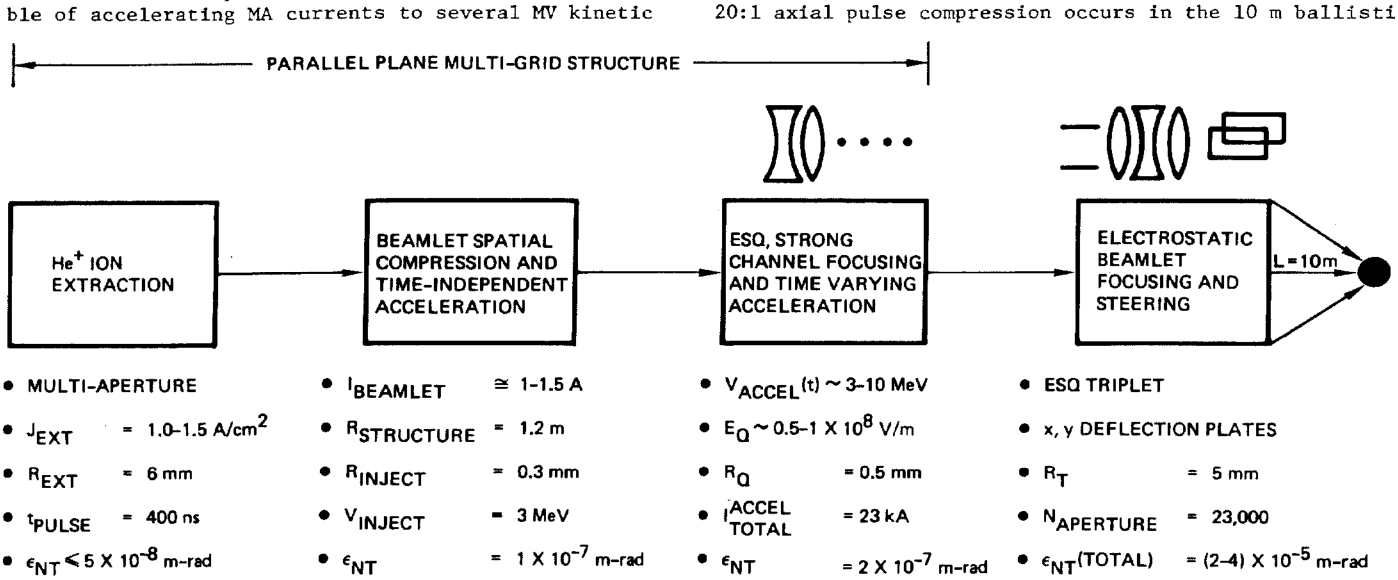


Figure 1. Parameters of the LIFE ICF Driver -- Multi-Aperture, Channel Focused, Multi-Stage, Low β Electrostatic Accelerator.

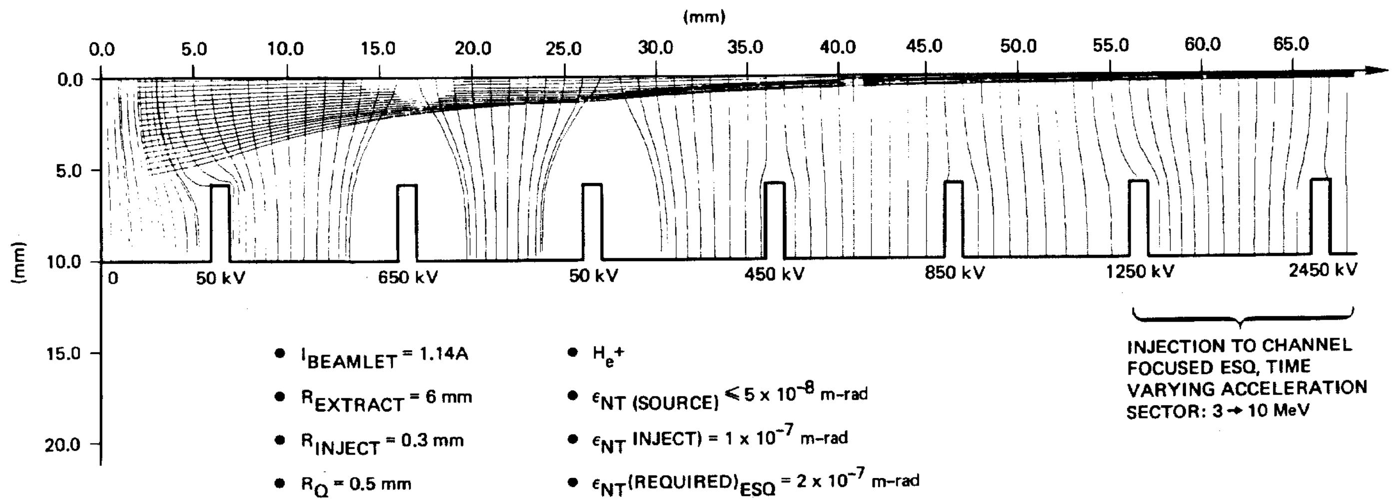


Figure 2. The Extractor-Injector Design for Beamlet Injection into ESQ Strong Channel Focused Accelerator

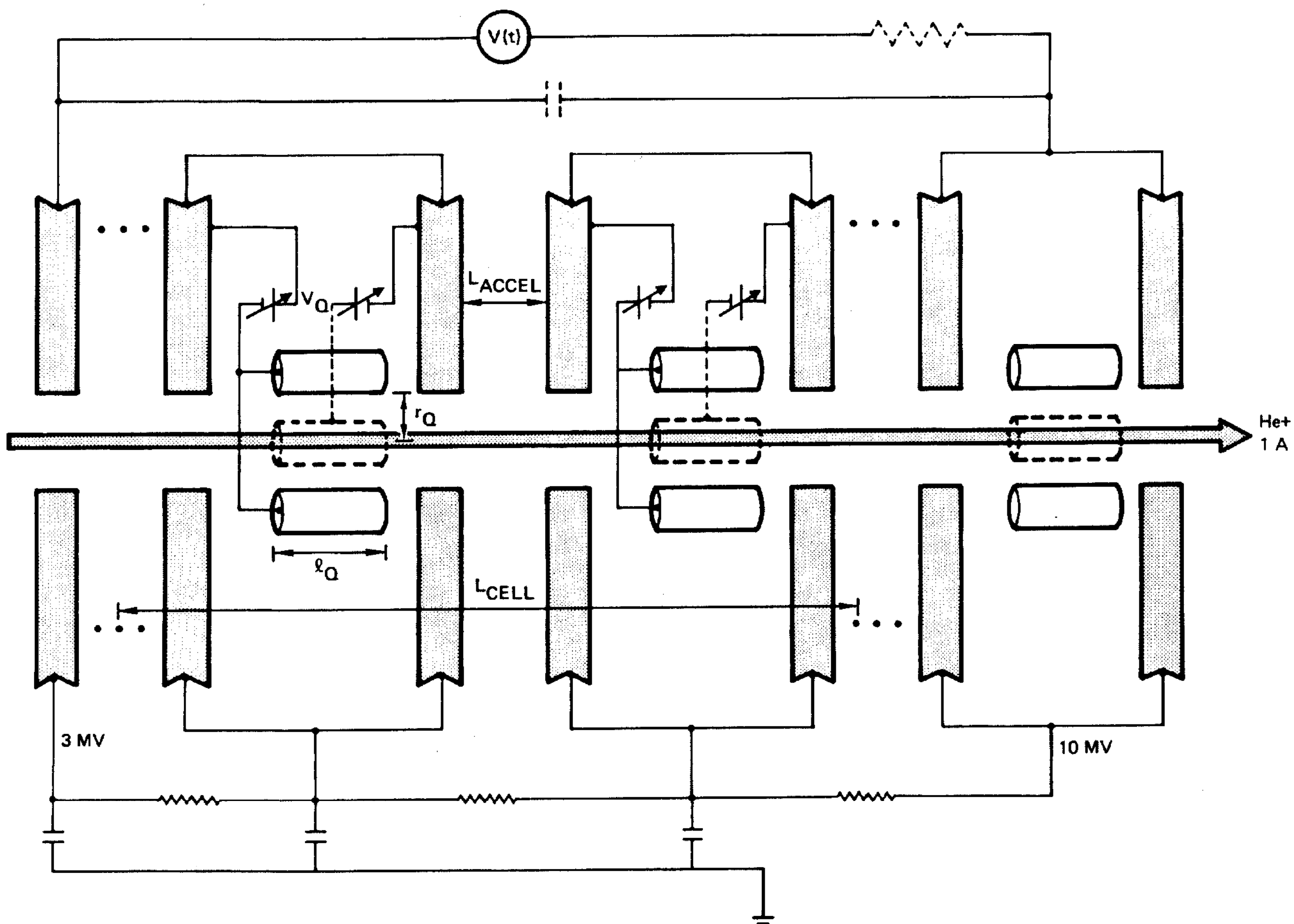


Figure 3. 3 - 10 MeV Acceleration with Time Varying Voltage Waveform and ESQ Strong Channel Focusing.

propagation region at the target. A waveform regulation of 1-2% is required for $0 < t \leq 400$ ns in the prescribed acceleration voltage $V_b(t)$, producing an uncertainty of $\Delta\tau < 5$ ns in the beam power profile at the target, which is also consistent with the switching jitters in a multi-beam system. The periodic ESQ strong focusing channels are required to confine and control the time varying acceleration of beamlets and to compensate for the time dependent lensing action found at the injection interface. The geometry of the strong focusing channels and acceleration gaps is shown in Fig. 3, where pulsed ESQ voltages are made to vary according to the time dependent acceleration waveform, $V_Q(t) \sim V_b(t)$.

The normalized channel emittance at 3 MeV injection is calculated to be $\epsilon_{NT}$ (channel) = $1 \times 10^{-7}$m-rad. Allowing a further factor of 2 emittance growth in the 3 - 10 MeV ESQ focused section, the combined emittance of the beam is $\epsilon_{NT} = \sqrt{N}\ \epsilon_{NT}$ (channel) $\simeq 3 \times 10^{-5}$m-rad, consistent with focusing requirements. The 3 - 10 MeV $He^+$ emerging parallel beamlets are independently steered by deflection plates and focused on target by an ESQ

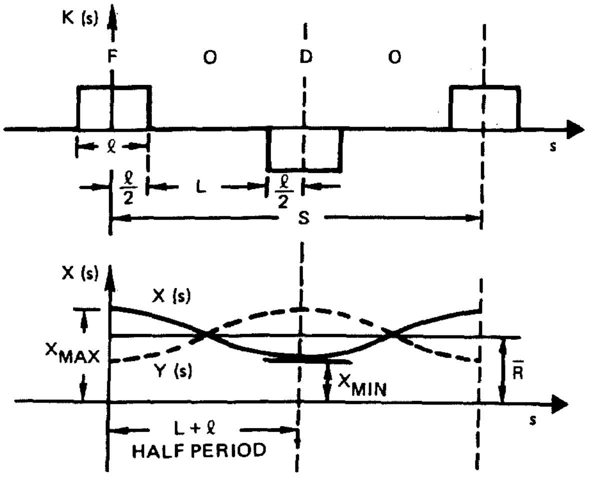


Figure 4. Gradient and Beam Envelope Depicted in the Periodic Strong Focusing Electrostatic Quadrupole Channels.

output optics. Adjacent to this optics a neutralizer cell[2] is located to produce active neutralization of emerging beamlets. The geometry is such that these neutralized beamlets pointing to a common focus begin to coalesce after 8 m of free propagation and the combined beam undergoes a 45:1 adiabatic radial compression in the last 2 m of neutralized and ballistically focused propagation.[2]

The design of ESQ strong focusing channels[4] is made according to scaling relations of space charge limited transport as listed in Table I. Other numerical simulation and theoretical analyses have indicated that stable beam confinement can be obtained for tune shift parameter values of $\mu_o \cong 60^o$ and $\mu/\mu_o \geq 0.4$ where the space charge parameter is $k = 1 - (\mu/\mu_o)^2$. Using Eq. 1, 2 and 3 we find that 1 A $He^+$ beamlets can be confined in ESQ channels with $r_Q = 0.75$ mm; when these are injected at 3 MeV, the normalized channel emittance is $1.5 \times 10^{-7}$ m-rad, the transportable current is 1 A and the required pulsed ESQ field strength is $E_Q = 3.5 \times 10^7$ V/m, where period length is S = 32 mm, quadrupole length is $\ell_Q$ = 8 mm and separation between quadrupoles is L = 8 mm.

Finally, Fig. 5 shows the manner of current amplification occurring in the neutralized ballistic transport of 10 m where 20:1 axial pulse compression programmed by the accelerator produces 0.5 MA current in ∿ 20 ns on 5 mm radius targets.

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1. Z.G.T. Guiragossian, Proceedings of the Heavy Ion Fusion Workshop, Report LBL-10301 CONF-7910122 (1980), p. 426.

2. Z.G.T. Guiragossian, J.L. Orthel, D.S. Lemons and L.E. Thode "Method of Active Charge and Current Neutralization of Intense Ion Beams for ICF" in these proceedings.

3. T.C. Christensen and Z.G.T. Guiragossian, "Performance of Intense Pulsed Ion Source," in these proceedings.

4. A.W. Maschke, "MEQALAC: A New Approach to Low β Acceleration" Report BNL-51029 (1979), cf. also E.A. Abramyan, IEEE, Trans. Nucl. Science NS-18 447 (1971).

Table I. Scaling Relations for ESQ Transport

| | |
|---|---|
| $k$ | = ratio of space charge gradient to external field gradient |
| $k$ | $= E'_s/E'_Q$ |
| $\omega_p$ | $= (qE'_s/m)^{1/2}$ = beam plasma frequency |
| $E'_Q$ | $= E_Q/r_Q$ |
| $\omega_o$ | $= (qE'_Q/m)^{1/2}$ = beam betatron oscillation frequency without space charge |
| $\omega$ | $= \omega_o (1 - k)^{1/2}$ = beam betatron oscillation frequency with space charge |
| $\mu_o$ | $\simeq \theta^2 (1 + L/\ell_Q)$ = phase shift in one focusing period without space charge |
| $\theta^2$ | $= \dfrac{Z_b e E_Q \ell_Q^2}{A_b m_o c^2 \beta^2 \gamma}$ = focusing strength parameter |

1. Maximum transportable beam current:

$$I_{max}(A) = \frac{1}{2} I_o \eta^2 k_3^2 \mu_o^2 k (\beta\gamma)^3 \frac{Z_b}{A_b}$$

$$I_o = \frac{4\pi\epsilon_o m_o c^3}{e} \; ; \; k_3 = \frac{\ell_Q}{S} \; ; \; k_4 = \frac{r_Q}{S}$$

2. Normalized transverse emittance:

$$\epsilon_{NT}(\text{m-rad}) = \eta^2 \mu_o k_3 \sqrt{1 - k}\, (\beta\gamma) \cdot r_Q$$

3. Required ESQ field strength:

$$E_Q(\text{V/m}) = \frac{2 m_o c^2}{e} \frac{\mu_o}{S} \frac{k_3}{k_4} (\beta^2\gamma) \frac{A_b}{Z_b}$$

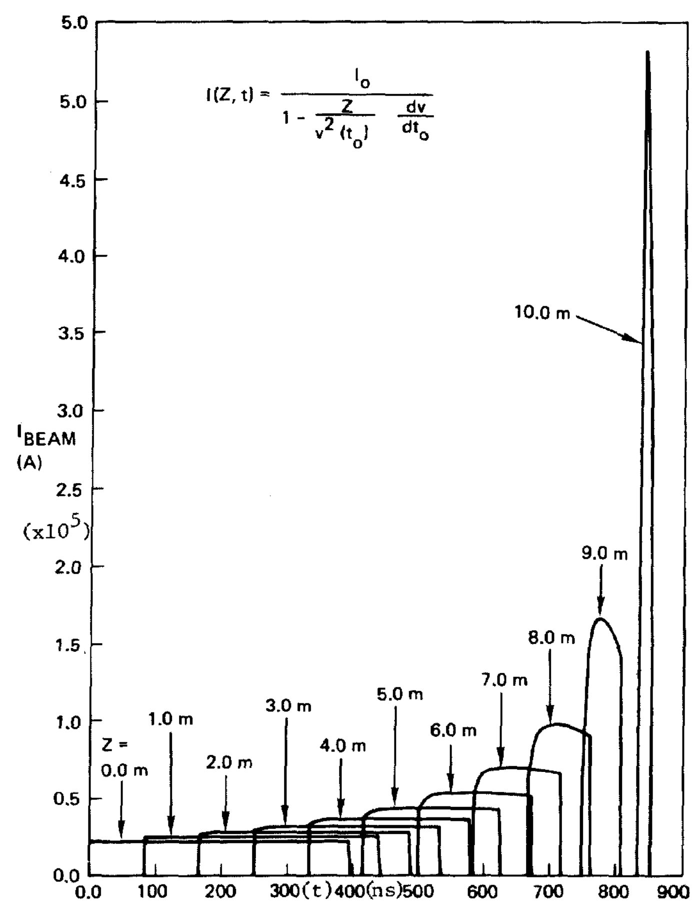


Figure 5. Beam Current Amplification of 20:1 Occurring in 10 m of Neutralized Ballistic Transport.