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Elise Plans and Progress

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ELISE PLANS AND PROGRESS

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Abstract

Elise is a heavy ion induction linear accelerator that will demonstrate beam manipulations required in a driver for inertial fusion energy. With a line charge density similar to that of heavy ion drivers, Elise will accelerate a $\geq 1$ $\mu$s beam pulse of $K^+$ ions from an initial energy of 2 MeV to a final energy $\geq 5$ MeV. In the present design, the Elise electrostatic quadrupoles (ESQ) will have a 2.33 cm radius aperture operating at $\pm 59$ kV. The half-lattice periods range from 21 cm to 31 cm. The entire machine will be approximately 30 m long, half of that is the induction accelerator and the remaining half is the injector (including the Marx generator) and the matching section. Elise will be built in a way that allows future expansion into the full ILSE configuration, therefore it will have an array of four ESQ focusing channels capable of transporting up to a total of 3.2 A of beam current. Elise will also have an active alignment system with an alignment tolerance of less than 0.1 mm. Initially, only one beam channel will be used during nominal Elise operation. At the currently expected funding rate, the construction time will be 4.75 years, with FY95 being an extra year for research and development before construction. Total project cost is estimated to be $25.9 M including contingency cost.

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1. Introduction

The main driver approach of the U.S. heavy ion fusion program is to accelerate multiple beams using induction technology for a linac or recirculating configuration. The standard multi-beam induction accelerator system, as shown in Fig. 1, consists of components such as ion sources, injectors, matching sections, an acceleration section with electric focusing, beam combiners, an acceleration section with magnetic focusing, drift compression lines, and a final focusing system. Electrostatic focusing is more effective than magnetic focusing at the front end of the machine because of low ion velocity. The initial beam current of 1 A/beam is based on beam transport considerations, and is not limited by ion sources. The final particle energy and beam current delivered to the target is in the order of 10 GeV and 4 kA per beam. To reach such high current, multiple beams undergo pulse compression in time by a factor of $10^3$ from an initial 1 A, 10 μs beam down to about 10 ns. An additional factor of 4 in current is realized by combining four beams to one at ≈100 MeV. Due to its intrinsically low impedance, an induction accelerator has the advantage of being able to accelerate large beam currents with high power efficiency. For economical reasons, a fusion driver should have a repetition rate of 3-10 Hz and a life time of about 30 years. At 65% duty factor, the total number of pulses is about $3 \times 10^9$.

Lawrence Berkeley National Laboratory, in collaboration with Lawrence Livermore National Laboratory and industrial partners, has proposed the Induction Linac Systems Experiments (ILSE) to study the beam dynamics issues and develop the technology of heavy ion induction drivers. ILSE’s full capability can be summarized as follows (the last four items are downstream experiments using the output beam from ILSE):

i) inductive acceleration using either electric or magnetic focusing;

ii) beam combining with limited emittance growth;

iii) beam pulse shaping and longitudinal control;

iv) accelerator alignment and beam steering;

v) demonstrate the accelerator technology and the associated cost.
vi) magnetic bending of a space-charge-dominated ion beam;

vii) drift-compression current amplification;

viii) final focusing experiments, with or without space charge neutralization;

ix) induction recirculator experiments.

FIGURE 1, 1/4 pp
Fig. 1. Block diagram of the standard multi-beam induction accelerator system for heavy ion fusion driver.

Comparing previous induction linac experimental test beds with the parameters of a fusion driver, ILSE appears as the next logical step in the IFE program plan. Table 1 shows the parameters of the Single Beam Transport Experiment (SBTE) [1] performed at LBNL between 1981 and 1985, the Multiple Beam Experiment (MBE-4) [2] from 1985 to 1991, the proposed ILSE and a typical driver. To save cost, ILSE will only have a final energy of about 10 MeV, however the ILSE beams will have a driver-scale line charge density and driver beam radius for studying high intensity heavy ion beam physics. The full ILSE configuration has an array of four electrostatic quadruple (ESQ) focused acceleration channels capable of transporting up to a total of 3.2 A of beam current from the injector. The four beams are combined into one before entering the magnetic focusing channels for further acceleration.

TABLE 1
Table 1. Parameters of induction linac experiments.

The ILSE proposal, originally made in 1988, was revised in 1993 to a reduced cost of =$50M on a four-year construction schedule. Due to funding limitations, the project is now divided into two stages. The first stage, called Elise, will only contain the electric focused acceleration section and will use an existing single beam injector. The second stage will include a four-beam injector, a beam combiner and a magnetically focused acceleration section. Elise is estimated to cost $25.9M,
i.e., about half the size of ILSE. The project received Key Decision 1 approval from the US Department of Energy in December 1994. Detail design work will take place in FY96 and the full design and construction period has been elongated to 4.75 years in order to fit the anticipated funding rate limitation. Upon completion, Elise will be the largest ion induction accelerator ever built and it will be a significant step towards the development of a fusion driver.

2. Design Requirements

2.1 Technical Design Parameters

The key technical design parameters for Elise are depicted in Table 2. Elise will accelerate the ions from 2 MeV to ≥ 5 MeV. In order for Elise to be expandable to ILSE, it will have 4 beam channels but only a single beam channel will be in operation using an existing 2 MeV injector. [3] The injector has demonstrated > 0.8 A of K⁺ beam with a normalized beam emittance of less than 1.0 π-mm-mrad. According to Table 2, a driver-like 3 MeV Hg⁺ beam (A = 200) has bunch length and pulse length at injection of about 25 μm and 15 μs respectively. At 0.42 A of beam current, the corresponding line charge density (λ) is 0.25 μC/m.

We have chosen to limit the Elise pulse length to less than 2 μs so that accelerator length can be kept to within 15 m long. The beam leaving the injector is expected to have a rise plus fall time totaling more than 0.7 μs, therefore a pulse length with the flat-top shorter than 1 μs is considered to be not cost-effective.

A driver beam must be focussable down to a few mm spot radius at a target inside a reactor chamber. This focusing capability is determined by the beam quality at the final focusing stage, i.e., the beam transverse and longitudinal emittance must be adequate at that point. For a 15 mrad convergence angle and a 3 mm focal spot radius, the required normalized transverse emittance is ≤ 15 π-mm-mrad. If space-charge plays a role in final transport (due to insufficient neutralization), an emittance of ≤ 10 π-mm-mrad is required. Scaling the performance of our existing injector to a heavy ion beam such as Hg⁺, the injected Hg⁺ beam will have a normalized emittance of 0.5 π-mm-mrad. Thus the total emittance budget from the injector to the final focus is a factor of 20, but
a significant fraction of that will be taken up by emittance growth from merging multiple beams. The percentage of emittance growth in Elise's acceleration channel depends on the initial emittance at injection, our aim is to keep Elise's output beam at $\leq 1.0 \pi$-mm-mrad.

The longitudinal emittance requirement is determined by chromatic aberrations of the final focusing system. In a typical system, the momentum spread $\delta p/p$ should not exceed 0.5% in final focus. The corresponding energy spread $\delta T/T$ is 1.0%. Thus for a 10 GeV, 10 ns beam with conventional final focus and transport, the longitudinal emittance ($\delta T\tau$) must be less than 1 eV-s.

Elise will have an alignment tolerance of 0.1 mm. Our random error propagation analysis showed that for 54 half-lattice periods the accumulation can be up to 20 times the size of individual alignment errors, i.e., 2 mm of beam displacement. Hence the bore radius must be large enough to accommodate 2 mm beam displacement without incurring significant beam loss.

Another possible beam loss is due to collisions with the background gas. The cross-section for K+ electron loss at 2 MeV energy in nitrogen gas is $4 \times 10^{-16}$ cm$^2$ (insensitive to beam energy in this energy range). The cross-section for electron capture is 5 times smaller (and decreases with higher energy). [4] For a length of 15 m at $1 \times 10^{-6}$ Torr (room temperature), the beam loss is estimated to be about 2%. We will design Elise to achieve vacuum in the upper $10^{-7}$ Torr range.

| TABLE 2 |
| Table 2. Key technical design parameters for Elise. |

2.2 Design Optimization

For typical heavy ion fusion beams, e.g. $\lambda=0.25$ $\mu$C/m at low energy, the space-charge force is very large thus a large quadrupole field is required for beam transport. A major effort in conceptual design has been the cost optimization between transport and acceleration.

The particle energy at which the beam focusing changes from electric to magnetic is determined by comparing the cost of accelerators with electrostatic quadrupoles and magnetic quadrupoles. For a heavy ion fusion driver, superconducting magnetic quadrupoles will be used and the transition takes place at $=100$ MeV beam energy. The optimal magnetic quadrupole aperture radius
is = 6 cm. Furthermore as shown in section 3.1, the optimum ESQ aperture radius is only 2.3 cm (mainly due to the non-linear scaling of electrical breakdown), so it would be economical to combine beamlets from several ESQ channels into a single magnetic quadrupole channel. In order to keep cost down, we would like to demonstrate magnetic focusing in ILSE at a much lower beam energy, so the limiting factor is our technical capability to construct short high quality magnetic quadrupoles with negligible end effects. Our present goal is to make the transition at approximately 5 MeV where the matched half-lattice period is about 30 cm, using high field pulsed quadrupoles which include some of the design considerations relevant to superconducting quadrupoles.

3. Design Status

In this section, we discuss some of the key principles used in designing Elise and the characteristics of today's design. More details can be found from the other two papers presented in this symposium on the subjects of Elise physics [5] and engineering [6]. Even though the present design has many areas significantly different than the ones described in the Conceptual Design Report (CDR) for ILSE [7] and for Elise [8], many physics and hardware discussions contained in the CDR are still valid.

3.1 Optimum Current Density

For space-charge dominated beams, the maximum transportable beam current is given as

\[ \frac{4QL^2}{\bar{a}^2} = 2(1 - \cos \sigma_0) \]  

where \( \bar{a} \) is the mean beam radius, \( \sigma_0 \) the undepressed phase advance per lattice period, \( L \) is the half lattice period length and the depressed phase advance is negligibly small for the given emittance. [9] For stable operation, \( \sigma_0 \) must stay below 85°. The dimensionless perveance \( Q \) is defined as
\[ Q = \frac{2qel}{(\gamma \beta)^3 mc^3 4\pi \varepsilon_0} = \frac{\lambda}{4\pi \varepsilon_0 V} \] (2)

where \( q \) is the charge state, \( \gamma \) and \( \beta \) are the relativistic factors and \( V \) is the accumulated beam voltage. The line change density \( \lambda \) is therefore given by

\[ \lambda = 4\pi \varepsilon_0 V \left( \frac{a}{2L} \right)^2 2(1 - \cos \sigma_0) \] (3)

For an electrostatic quadrupole with field occupancy factor \( \eta \), the half lattice period can be solved using a thick lens approximation [10]:

\[ L = b \left[ \frac{2(1 - \cos \sigma_0)}{\eta^2(1 - 2\eta/3)(V_q/2V)^2} \right]^{1/4} \] (4)

here \( V_q \) is the voltage across the quadrupole electrodes.

An ESQ cross-section is shown in Fig. 2. The aperture radius \( b \) is governed by the equation:

\[ b = 1.25a + c \] (5)

where \( a \) is the maximum beam radius and \( c \) is the beam clearance (based on an estimate of the beam steering random error and accelerator alignment limits). The coefficient 1.25 is due to a limitation in the image force from the electrodes. The ratio \( a/\bar{a} \) is a function of the quadrupole strength and \( \eta \) (see ref. 10) and is approximately 1.2 - 1.3. The electrode radius \( (R_e) \) is selected to make the dodecapole component of the focusing electric field vanish: \( R_e/b = 1.146 \) (=8/7).

**FIGURE 2, 1/8 pp**

Fig. 2. Cross-sectional view of an ESQ channel.

In an ESQ breakdown test at LBL [11], we found that the breakdown threshold for the ESQ is proportional to the square root of the spacing between quadrupole electrodes and an ESQ with \( b = 2.2 \) cm and \( R_e = 2.53 \) cm broke down at 230 kV between the quadrupole electrodes. For a conservative safety margin, we set the normal operating point at \( \leq 50\% \) of the breakdown threshold value.

A useful figure of merit in optimizing beam current density is the total transported multi-beam current divided by the area occupied by the ESQ array. In our design, the effective length of the
ESQ is 6 cm shorter than the physical length of the half lattice period, hence \( \eta = (L-6)/L \).

Obviously \( \eta \) grows with \( L \); typical values of \( \eta \) range from 0.71 at the beginning to 0.81 at the end of Elise. In our design, we use Eq. 4 to calculate \( L \) as a function of the aperture radius \( b \) (let \( \sigma_0 = 75^\circ \)) and adhere to the square root scaling law for the quadrupole voltage. Using Eq. 5, the beam radius is determined and then the transportable beam current is obtained from Eq. 3. Figure 3 shows the \( J_{ave} \) for various beam clearances. The optimum aperture radius can be as small as 5 mm if the required beam clearance is only 2 mm resulting in a very large \( J_{ave} \). This is certainly an opportunity for future system improvement.

In fact, the optimal aperture radius can be derived analytically by assuming that the maximum quadrupole voltage is proportional to \( b^\alpha \), where \( \alpha \) is typically between 0.5 to 1.0. It can be shown that [12]

\[
J_{ave} = \frac{g(b - c)^2}{b^{3+\alpha}}
\]  

(6)

where \( g \) is some proportional constant. The optimum value of \( b \) is obtained by taking the derivative of the last equation, thus

\[
b_{opt} = \frac{(3 + \alpha)c}{(1 + \alpha)}
\]  

(7)

For \( \alpha = 0.5 \) (found in our breakdown test), and \( c = 1 \) cm, the optimum aperture radius is 2.33 cm.

**FIGURE 3, 1/4 pp**

Fig. 3. \( J_{ave} \) as a function of the aperture radius and beam clearance.

For Elise we have selected a very conservative beam clearance of 10 mm which has an optimum \( b \) at 2.33 cm and the corresponding ESQ voltage (at 50% breakdown threshold) is 118 kV (±59 kV w.r.t. ground potential). Upon successful demonstration of ESQ alignment and beam steering, we can fill the channel with more beam until the beam radius reaches the clearance limit. For example, with a beam clearance of 2 mm, the \( J_{ave} \) can be as high as 219 A/m² and the corresponding line charge density is 0.345 \( \mu \)C/m.
3.2 Matching the Beam Envelope

In the previous Elise conceptual design\textsuperscript{8}, the machine used 4 blocks of acceleration sections and only 2 different half-lattice period lengths throughout. The advantage of this approach is a possible cost saving in fabricating many parts with the same dimensions. However the disadvantage is that the mismatch in $L$ significantly reduces the transportable $\lambda$. Elise will be designed with continuously varying half lattice periods.

At the start, the half lattice period is 20.8 cm (at 2 MeV with $\sigma_0 = 75^\circ$). As the particles gain energy, a smooth beam envelope can be obtained by matching the envelope angles between lattice periods:

$$\frac{\eta LE'}{\sqrt{V}} = \text{constant}$$  \hspace{1cm} (8)

Here $E'$ is the quadrupole field gradient. By keeping the quadrupole voltage and aperture radius constant throughout the machine, the matching condition reduces to a simple matter of keeping the effective length ($\eta L$) proportional to the square root of particle energy.

By combining Eqs. 4, 5 and 8, and keeping the quadrupole voltage constant, we find that $\lambda$ is proportional to $a^2 (1-2\eta/3)$. Thus as $L$ and $\eta$ grows (with the beam voltage), the ratio $a/a^-$ gets smaller, and both $\sigma_0$ and the transportable $\lambda$ are reduced. For example, as $\eta$ changes from 0.71 at the beginning of Elise to 0.81 at the end, the phase advance changes from $75^\circ$ to $60^\circ$ and the transportable $\lambda$ drops by 10.5%. Although having $\lambda$ decrease is not the intended schedule for a long driver, it is a match for Elise because the machine is so short that the bunch length will actually be elongated for most acceleration schedules (including those with pulse compression). For a driver, the acceleration rate is slow therefore $\eta$ increases very slowly towards 1.0. In fact, by enduring a slight mismatch, we can use the simpler scaling of

$$\frac{LE'}{\sqrt{V}} = \text{constant}$$  \hspace{1cm} (9)

Combine this with Eq. 4, we now find that both $\sigma_0$ and $\lambda$ increase with increasing $\eta$. 

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3.3 Accelerator Hardware

Figure 4 shows a picture of the ESQ array and Fig. 5 is a schematic diagram of the ESQ structure and the acceleration modules. The ESQ electrodes are mounted on two end plates which are cantilevered from the middle ground plate by insulator rods. Each ESQ is kinematically supported and can be articulated for minor alignment adjustment. The gap between acceleration modules is typically 5 cm, it provides access for the ESQ support ring articulation, high voltage feedthroughs and vacuum pumping.

FIGURE 4, 1/4 pp
Fig. 4. A picture of the ESQ array.

FIGURE 5, 1/2 pp
Fig. 5. Schematic diagram of the ESQ's and the acceleration modules.

The basic element of an induction acceleration is the induction core; it is made of many thin layers of magnetic material with insulation in-between layers to reduce eddy currents. A core is energized by sending a fast pulse of current through the primary winding. The beam, which forms the secondary "winding", receives an induction voltage equals to the pulser voltage (for a 1:1 winding ratio). Several cores can be electrically energized in parallel with their induction voltages added in series by the beam. Magnetic materials are available in the form of tapes at standard widths and thicknesses. For example, our present design uses 5.6" and 6.7" wide, 1 mil (25.4 μm) thick Metglas® tapes and 0.1 mil thick mylar insulation. There are also 2" and 4" wide Metglas® tapes available at a higher cost (per kg). Our goal is to wind these tapes at 75% packing factor of Metglas® volume inside the core volume.

An acceleration module is composed of one or more cells axially linked together and each cell has several layers of induction cores in the radial direction. Initially, the half lattice period is only long enough for modules with a single cell. At the high energy end of the accelerator, the half lattice period becomes long enough to accept acceleration modules containing double cells. The
acceleration module has a metal housing with a small positive gauge pressure of SF₆. The purpose of the SF₆ is to fill the air space inside a module for better voltage holding so as to improve the packing factor.

Since \( L \) is varying continuously while the module period is quantized (according to the tape width and the number of cells), the two periods do not match. In other words, the inter-module gaps do not always line up at the same place with respect to the ESQ structure unless we purposely match them up at the expense of introducing extra spacing thereby lowering the longitudinal packing factor. In order to accommodate the physical mismatch, each ESQ is mounted with an unique offset from its support ring. One important design criterion is to avoid the inter-module gaps from lining up against the end-plate and ground-plate regions in order to allow the voltage feed-throughs to reach the quadrupole electrodes.

Beam acceleration occurs at the gap between end plates of neighboring ESQ's. In designing the lattice, the acceleration voltage is determined by the size of the acceleration module and the acceleration module is selected according to the available space provided by the half lattice period.

A pulse forming network (PFN) is used to drive the induction core. Due to the non-linear magnetic behavior, the pulse current is not constant thus the PFN must have a tapered impedance. The thyratrons (existing surplus units) operate at a nominal voltage of 22.2 kV delivering 11.1 kV into a matched load. At this voltage, a 2.5 \( \mu \text{s} \) pulse will require 0.028 V-\( \text{s} \) flux change per core to avoid saturation. Assuming a \( \Delta B \) of 2 Tesla, the cross-sectional area of a single 75\% packed core is 185 cm\(^2\).

We will control each of the 51 pulser voltage to within 1\% variation such that the accumulated energy ripple can be less than 0.1\%. This can be done by using fast correction pulsers on separate small cores with either an active feedback or feed forward circuit and applies the correction pulse about once every four or five lattice periods. The "ear" pulses compensate for the space charge expansion force at the front and back of a beam bunch. These pulses are on the order of 10 kV for 0.5 \( \mu \text{s} \). The front ear can be generated by using the rising edge of the main acceleration pulse whereas the back ear must be generated by an additional pulser.
In the original Elise conceptual design, there is a diagnostic section at every 8 HLP (i.e., at the end of each block). The section is normally occupied by 2 ESQ’s with no acceleration. In performing beam diagnostics, the ESQ’s will be removed and replaced by diagnostic equipment such as an emittance scanner. Instead of having these diagnostic stations, the present design has the entire induction section mounted on rails to provide quick access for beam diagnostics and maintenance. A pneumatically operated vacuum closure can remotely disconnect the accelerator at any lattice point.

3.4 Cost Optimization

There are three major cost factors in an induction linac: the ESQ transport cost (including the vacuum vessel and the ESQ DC power supplies), the magnetic material cost, and the pulser cost. The ESQ transport cost is proportional to the number of half lattice periods in the accelerator, so from that standpoint it is more advantageous to maximize the acceleration voltage per gap.

The magnetic material cost is more complicated. For a given flux change, the total cross-sectional area of the cores is fixed but the volume of required magnetic material depends on the ratio between the radial dimension and the axial dimension. For a fixed cross-sectional area, the core volume increases with the diameter, thus it is more advantageous to minimize the module size leading to a lower acceleration voltage per gap. Aside from the cost of raw material and the associated cost of fabrication, housing and support structure, the pulser cost is also proportional to the mass (or volume) of the induction cores due to hysteresis and eddy current loss.

The four most common magnetic material in use today for induction cores are ferrite, nickel-iron, silicon steel, and Metglas® (made by Allied Signals Inc.). Ferrite is good for very short pulses but it has small ΔB and it is too expensive to be considered for a fusion driver. Like ferrite, Ni-Fe is an acceptable material but it is still too expensive for our use. The raw material for silicon steel is inexpensive but it is difficult to make tapes thinner than 2 mils. Metglas® seems to be the best choice. It is available in thickness ≤ 1 mil, it has high enough resistivity (and skin depth), and it is reasonably inexpensive. The wider Metglas® tapes (5.6” and 6.7”) are used by the 60 cycle
utility transformer industry so they are sold at a price 3 to 4 times lower than the less common narrower (2") tapes.

We have used a specialized computer program to examine the cost of various designs using modules made of different width Metglas® tapes and different numbers of cores per cell. Figure 6 depicts the variable cost of building Elise using various size modules (not including fixed costs). The cost optimization results can be summarized as follows:

1) the wider tape is more cost-effective (mainly due to a lower raw material cost and a higher packing factor).
2) approximately 1 m outer radius is the optimum module size regardless of which Metglas® tape width is used in the design.
3) using a longer pulse length rather than a higher beam voltage yields more delivered beam energy downstream. (mainly due the fixed rise and fall time of the current pulse and a lower loss from a smaller dB/dt).

There is an additional advantage in using the transformer grade (wider) Metglas® tapes because they would be more uniform and reliable both in their magnetic and physical properties. It is more than likely that the wider tape is easier to wind than the narrow one which had a problem of “coning” due to non-uniform tape thickness.

FIGURE 6, 1/4 pp
Fig. 6. Cost optimization among various tape widths.

3.5 Present Design and Performance

Based on the optimization results, we have produced an improved conceptual design for Elise. The lattice is shown in Fig. 7. In this design, the half lattice periods are matched with the beam energy using a constant current acceleration schedule, i.e., square pulses at all gaps and fully utilize all the available flux change. The final beam energy is 5.7 MeV. By using a different acceleration schedule (trapezoidal pulse shape), the same lattice can compress the current pulse
length from 1.5 μs to 1.15 μs leading to a 31% current amplification. In this case, the beam head will have 5.1 MeV and the beam tail will have 6.8 MeV (=15% velocity tilt).

Among the 54 HLP’s, there are 2 gaps that do not have acceleration voltage. This occurs because the accumulated module length outruns the accumulated ESQ length. We intend to make use of these 2 special extra wide gaps for monitoring the beam intensity profile and for vacuum pumping. A summary of the design parameters and performance is shown in Table 3.

**FIGURE 7, 1/4 pp**
Fig. 7. Elise lattice design

**TABLE 3**
Table 3. A summary of the present Elise conceptual design.

4. **Conclusion**

In general, Elise will be designed in such a way that it is compatible to the full ILSE configuration and the technology employed in Elise should be driver-like such that the knowledge gained from the project is useful for projecting the costs in a fusion driver. Compared to the earlier conceptual design, the present Elise design has a smaller aperture, variable half-lattice periods, offset ESQ supports, wider Metglas® ribbons and a larger module diameter. It produces more than twice as many joules at about the same cost. The emittance diagnostic stations are eliminated, but the machine will be designed for easy disconnect in order to insert diagnostic equipment. Almost all of these changes improve the cost-effectiveness of the machine. The most critical technology issue in the Elise project is the fabrication of compact low-loss induction cores. Overall, the project is making steady progress and should be completed within the planned budget and schedule.

5. **Acknowledgment**
The authors wish to thank the support of the physics and engineering staff at both LBNL and LLNL Heavy Ion Fusion Programs.

References
**Figure Caption**

Fig. 1. Block diagram of the standard multi-beam induction accelerator system for heavy ion fusion driver. The values of beam energy and current are round-off numbers for order to magnitude estimation.

Fig. 2. Cross-sectional view of an ESQ channel.

Fig. 3. $J_{ave}$ as a function of the aperture radius and beam clearance.

Fig. 4. A picture of the ESQ array.

Fig. 5. Schematic diagram of the ESQ's and the acceleration modules.

Fig. 6. Cost optimization among various tape widths.

Fig. 7. Elise lattice design.
Table 1. Parameters of induction linac experiments.

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<th>MBE-4</th>
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<th>Driver</th>
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Table 2. Key technical design parameters for Elise

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<th>Parameter</th>
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</tr>
<tr>
<td>Initial pulse duration</td>
<td>1.0 µs</td>
</tr>
<tr>
<td>Initial line charge density</td>
<td>0.25 µC/m</td>
</tr>
<tr>
<td>Number of beams</td>
<td>1</td>
</tr>
<tr>
<td>Final average ion kinetic energy</td>
<td>5 MeV</td>
</tr>
<tr>
<td>Final beam energy</td>
<td>4 J</td>
</tr>
<tr>
<td>Ion mass number</td>
<td>39 (K⁺ ion)</td>
</tr>
<tr>
<td>Ion charge state</td>
<td>+1</td>
</tr>
</tbody>
</table>
Table 3. A summary of the present Elise conceptual design.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerator outer radius</td>
<td>1 m</td>
</tr>
<tr>
<td>Accelerator length</td>
<td>14 m</td>
</tr>
<tr>
<td>Number of half lattice periods</td>
<td>54</td>
</tr>
<tr>
<td>Longitudinal packing fraction</td>
<td>68%</td>
</tr>
<tr>
<td>Radial packing fraction</td>
<td>75% Metglas® core, 63% Average</td>
</tr>
<tr>
<td>Total flux-change</td>
<td>9.25 V-s</td>
</tr>
<tr>
<td>Half lattice periods</td>
<td>0.208 m --&gt; 0.311 m</td>
</tr>
<tr>
<td>Occupancy factor</td>
<td>0.71 --&gt; 0.81</td>
</tr>
<tr>
<td>Initial energy</td>
<td>2 MeV</td>
</tr>
<tr>
<td>Initial current pulse length</td>
<td>1.5 μs flat-top (= 2.5 μs voltage)</td>
</tr>
<tr>
<td>Final energy (const. current)</td>
<td>5.7 MeV</td>
</tr>
<tr>
<td>Final energy (with current amp.)</td>
<td>5.1 MeV / 6.8 MeV</td>
</tr>
<tr>
<td>Current amplification</td>
<td>1.31</td>
</tr>
<tr>
<td>Velocity tilt</td>
<td>15.4%</td>
</tr>
</tbody>
</table>
ion source and injector

acceleration with electric focusing

acceleration with magnetic focusing

possible recirculation

target

chamber transport

final focusing

bending

matching

beam combining

compression

2-3 MeV

~100 MeV

~10 GeV

~10 GeV

~1 A/beam

~10 A/beam

~400 A/beam

~4000 A/beam

J. Kwan et al. Fig. 1
J. Kwan et al., Fig. 2
J. Kwan et al., Fig. 5

ESQ ARTICULATION & HV FEEDTHRU

ESQ SUPPORT RING & QUICK-OPENING VACUUM CLOSURE

ELECTROSTATIC QUADRUPOLE (ESQ)

INDUCTION CORES

R 98.7

R 18.3
Double cell modules

Diagnostic access space

J. Kwan et al., Fig. 6
Fig. 7

J. Kwan et al.,