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Author
Kwan, Joe W.

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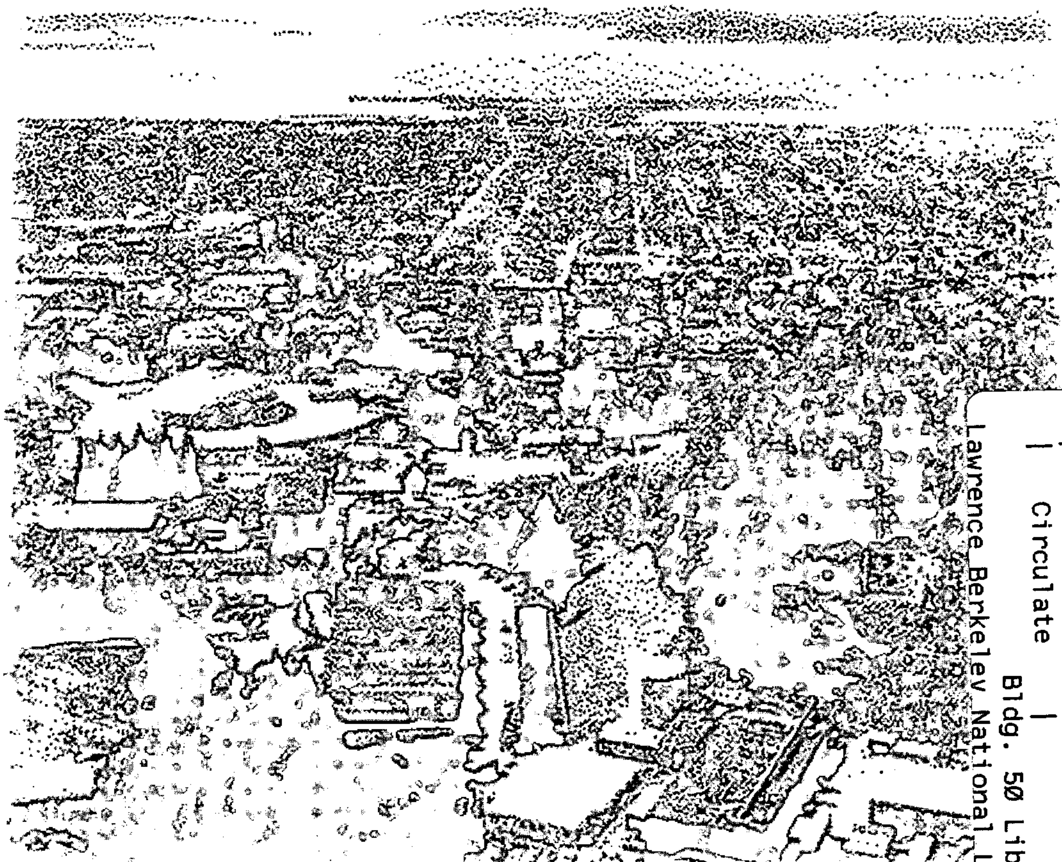

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Joe W. Kwan

Accelerator and Fusion Research Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

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I. PROJECT SCOPE

The Fusion Energy Research Program at Lawrence Berkeley National Laboratory is funded by the Department of Energy to build Elise, an electrically-focused induction accelerator as the next step towards the ultimate goal of developing a power-plant driver. Elise is a heavy ion induction accelerator with electric focusing that will advance the understanding of high current, heavy ion accelerator physics so that many of the basic technical questions concerning the suitability of this approach, as a driver for Inertial Fusion Energy, can be resolved. Elise will address many of the heavy ion driver physics issues using a low energy induction linac (5 MeV, 1 A). The project was approved (KD-1) by the Department of Energy in December 1994. At the currently expected funding level, the construction time will take 4-3/4 years and cost $25.9M. Fig. I.1 depicts the project schedule and funding profile. The construction time is dedicated by the funding profile, i.e., the project can be shortened if funding is available at a faster rate. In fact, the original Elise proposal was to complete the project in 3-3/4 years at a cost of $24.9M.

The objective of this project is to build an induction linear accelerator, using the existing 2 MeV single-beam injector and a new electrostatic quadrupole focusing channel, to accelerate high current heavy ions (atomic mass ≥10) beams to more than 5 MeV. The knowledge gained and the technologies developed in this project should provide a basis for evaluation of the feasibility and the cost effectiveness of heavy ion drivers for inertial fusion. The completed accelerator will be used for studies of longitudinal beam bunch control, final focus, and other key technical issues relevant to a full-scale driver.

Elise will have four ESQ channels, but only one channel will be operated. A follow-on extension of Elise, named ILSE, will replace the single-beam injector with a four-beam injector at the front of Elise, a combiner at the rear, and be followed by a magnetically-focused induction acceleration section to further accelerate the 5 MeV beams (from Elise) to more than 10 MeV with a total current approaching 10A (using all 4 channels). Magnetic focusing is considered more suitable for higher energy beam transport; therefore, ILSE is an essential step in the path of developing a full scale driver.

Elise Induction Linac--Project Schedule

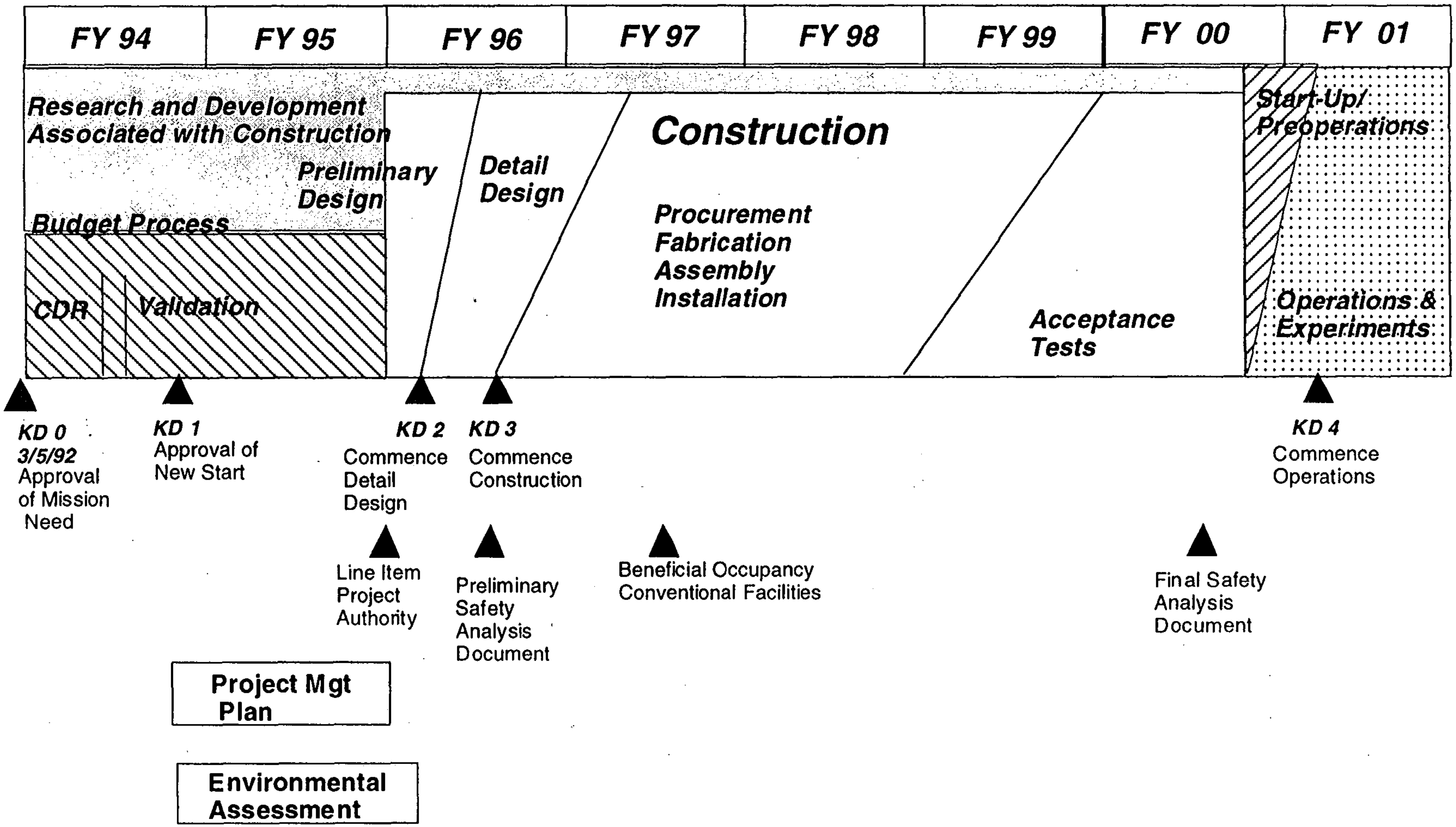


Figure I-1. Elise Project Master Schedule

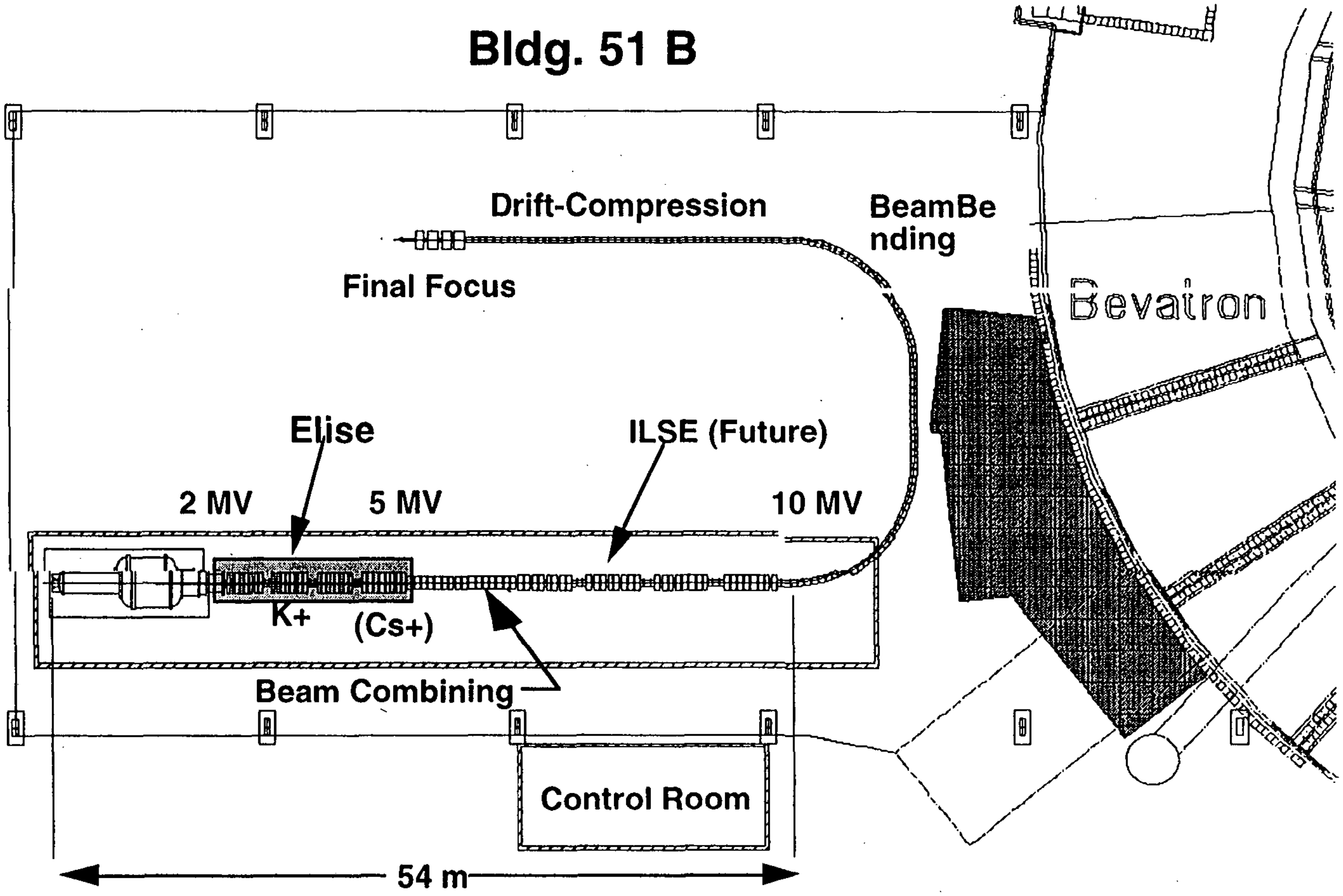


Figure II-1. Top-view Layout of Elise.

II. DESIGN REQUIREMENTS

The Elise Construction Project includes two elements: special research facilities and conventional facilities (modification to an existing LBNL building). To save in facility cost, Elise will be constructed by modifying an existing site at LBNL. Figure II-1 gives a plan view of the facility.

A. Special research facilities requirements

(1) Construction of an induction accelerator capable of increasing the ion energy of four parallel beams from 2 MeV to 5 MeV, uses electrostatic transport with a minimum pulse duration of 1 microsecond. Initially, only one transport channel will be used. The facility will be designed for a 10 year operational life. The induction accelerator is approximately 15 m long, 2 m in diameter, and contains more than 130 metric tons of magnetic material.

(2) The front end of the accelerator will be attached to a matching section which is connected to a 2 MeV single-beam injector with a potassium ion source (an assembly about 10 m long). The injector already exists and the matching section is presently being fabricated; both components are developed within the base program of the Fusion Energy Research Program and will be incorporated into, or as parts of the Elise Project.

(3) There will be sufficient diagnostics to achieve optimum beam transport through the accelerator and to reach the design final beam current, energy, and emittance.

(4) The project will include ancillary equipment and instrumentation for achieving adequate alignment, vacuum, data acquisition, accelerator control, and operational maintenance.

B. Conventional facilities requirements

(1) Building 51B, the External Proton Beam (EPB) hall of LBNL's Bevatron Complex will be modified to accommodate the accelerator. Existing shielding and structures will be removed and a new concrete slab will be added to provide a smooth, strong surface for supporting the accelerator. An insulated steel frame structure including an energy management system, a standard lighting system, and a fire protection system will be built within the EPB hall to house the accelerator.

(2) A separate control room will be constructed inside the existing prefabricated building 51G which will be relocated for optimum use at a nearby site.

(3) Existing utilities in building 51B will be relocated to service the Elise accelerator facility requirements. These include electric power, water, lighting, fire protection, heating, ventilation and air conditioning.

C. Technical parameters requirements

The key technical design parameters for Elise are listed in Table II-1. The existing injector has already demonstrated >0.8A of K^+ beam with a normalized beam emittance of less than 1.0 π-mm-mrad. 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. 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 a "flat-top" shorter than 1 μs is not cost-effective based on dollars per joule calculation.

The longitudinal emittance requirement is determined by chromatic aberrations of the final focusing system. In a typical driver system, the momentum spread $\delta p/p$ should not exceed 0.5% in the final focus. The corresponding energy spread $\delta T/T$ is 1.0%. For example, a 10 GeV, 10 ns beam with conventional final focus and transport must have a longitudinal emittance ($\delta T\tau$) less than 1 eV-s. Our goal is to control the pulser voltage to within 1% variation such that the accumulated beam energy ripple can be less than 0.1%.

Elise has an alignment tolerance of 0.1 mm. Our random error propagation analysis shows that up to 2 mm of beam displacement is allowed. A possible beam loss mechanism is collisions with the background gas. The cross section for K^+ ionization at 2 MeV energy in nitrogen gas is 4×10^{-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 1×10^{-6} Torr (room temperature), the beam loss is estimated to be about 2%. We will design Elise to achieve vacuum in the 10^{-7} Torr range.

Table II-1. Elise Technical Design Parameters

PARAMETER	UNITS	VALUE
Initial Ion Kinetic Energy	MeV	2
Initial Beam Current	Amperes	0.8
Initial Pulse Duration	Micro-seconds	1.0
Initial Beam Line Charge Density	Micro-coulombs per meter per beam	0.25
Initial Number of Beams	none	1
Final Average Ion Kinetic Energy	MeV	5
Final Beam Current	Amperes	1.0
Final Pulse Duration	Micro-seconds	0.8
Final Beam Line Charge Density	Micro-coulombs per meter per beam	0.2
Initial Number of Beams	none	1
Length of Linac	meters	15 (approx.)
Number of Acceleration Gaps	none	32
Ion Mass Number	atomic mass units	39
Ion Charge	electron charge	+1
Commissioning Criteria at the Output of Elise Accelerator		
PARAMETER	UNITS	VALUE
Beam Charge/Pulse at 5 MeV Avg Energy	Micro-coulomb	≈>0.2
Velocity Shear (Tilt)	Percent	≈>3
Emittance (Normalized, RMS of 90%)	π-mm-mrad	≈<1
Ion Kinetic Energy Averaged over 0.2 Micro-coulomb Charge/Pulse.	MeV	≈>5

III. WORK BREAKDOWN STRUCTURE

A work breakdown structure diagram is shown in Fig. III-1. The two major subsystems are the construction of the induction linac and the conventional facilities. Developmental work is required in many areas of mechanical and electrical design. Cost estimates of the WBS Tasks (based on the 1994 conceptual design) are shown in Table III-1. With inflation escalation and a fixed overhead rate of 8.61%, the total project cost (TPC) is $25.9M.

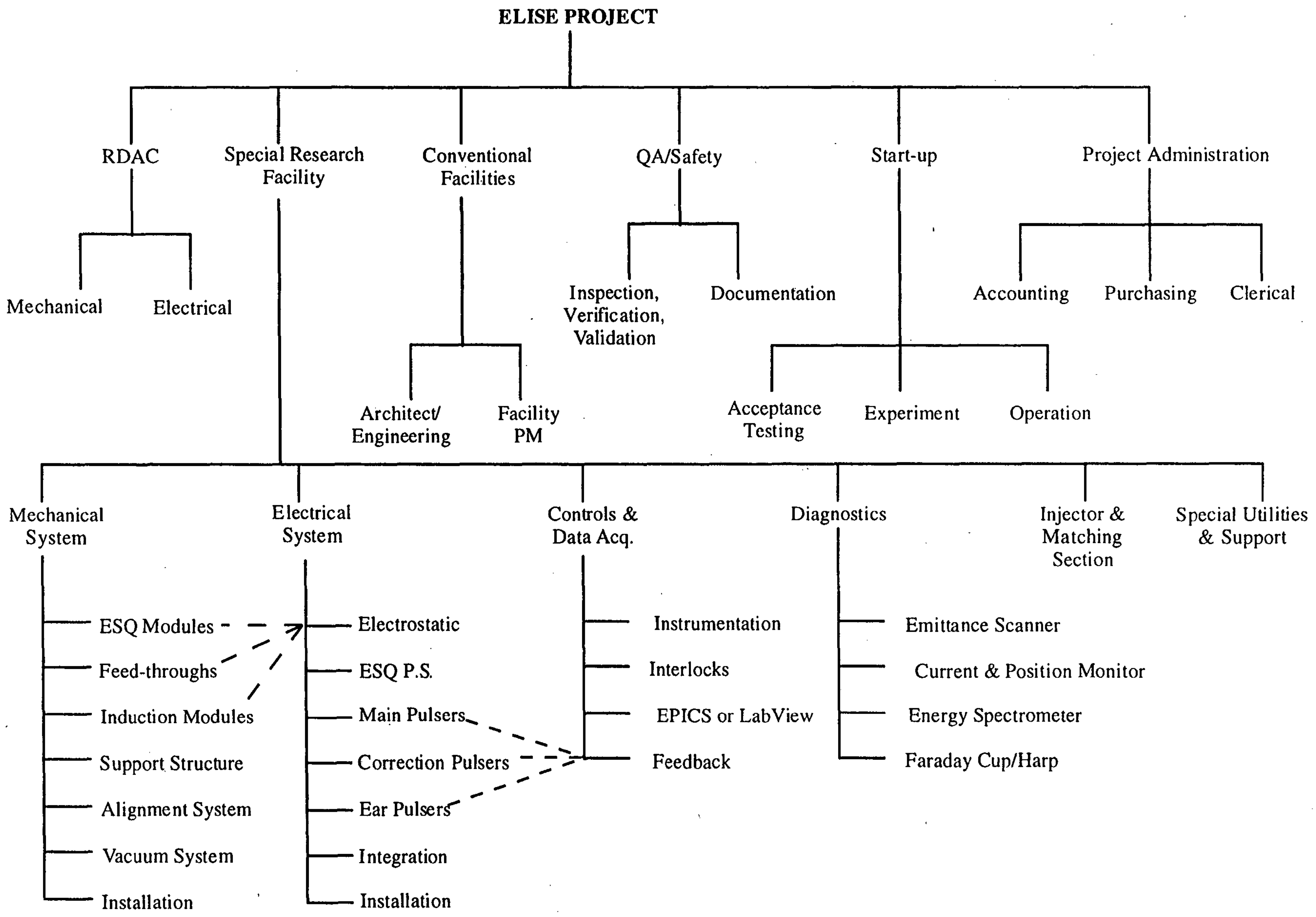


Fig. III.1 Elise Work Breakdown Structure Diagram.

Table VI-1. WBS and Cost Estimate of Elise Project.

Elise Induction Linac rev. 6/9/95

Escalation and Contingency Analysis
for the Total Estimated Construction and Project Cost

WBS Tasks	WBS/Change Control Level	Cost (FY94 k$)	Cost (then-yr) (15.0% escal.)†	Overheaded TECC*	TPC
1. Induction Linac Systems Experiment	1/1	16164	18590	20190	25900
1.1. Project Management & Administration	2/2	1539	1770	1922	
1.1.1 Project Office Effort	3/3	1374	1580	1716	
1.1.2 Supplies & Expense (12% of 1.1.1)	3/3	165	190	206	
1.2. Special Research Facilities	2/2	10510	12087	13128	
1.2.1. Engineering, Design & Inspection	3/2				
1.2.1.1 Electrical ED&I	4/3	1669	1919	2084	
1.2.1.2 Mechanical ED&I	4/3	1462	1681	1826	
1.2.2. Injector	3/4	88	101	110	
1.2.3. Matching Section	3/4	44	51	55	
1.2.4. Electric Focus Acceleration Section	3/2	5400	6210	6745	
1.2.7. Alignment System	3/2	450	518	563	
1.2.8. Vacuum System	3/2	272	313	340	
1.2.9. Diagnostics	3/2	201	231	251	
1.2.10. Controls and Data Acquisition Systems	3/2	637	733	796	
1.2.11. Special Utilities & Support	3/2	287	330	358	
1.3. Conventional Facilities	2/3	1033	1188	1290	
1.3.1. E D & I @ 18% of construction	3/3	150	173	188	
1.3.2 Construction	3/3	821	944	1025	
1.3.3 Project Management	3/3	62	71	77	
1.4. Contingency	2/2	3082	3545	3850	
1.4.1. Project Management Contingency	3/3	385	443	481	
1.4.2. Special Research Facilities Contingency	3/3	2490	2864	3111	
1.4.3. Conventional Facilities Contingency	3/3	207	238	258	
CDR Preparation					60
RDAC FY94					200
RDAC FY95					3000
Project Documentation					200
RDAC during construction					1250
Start-up and Pre-ops					1000

† Escalation based on DOE anticipated Economic Escalation Rates as of November 1994.
*Assuming 8.61% overhead and Elise is exempted from any future increase in LBL overhead rate throughout the construction period.

IV. PHYSICS DESIGN

A. Optimizing the ESQ dimensions

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

An ESQ cross-section is shown in Fig. IV-1. The aperture radius (b) is governed by the equation:

$$b = 1.25a + c \quad . \tag{1}$$

where a is the maximum beam radius and c is the clearance from beam edge to electrode surface. The coefficient 1.25 arises because image forces from the electrodes restrict the useful aperture. The electrode radius (R_e) is selected to make the dodecapole component of the focusing electric field vanish: $R_e/b = 1.146$ ($\approx 8/7$).

According to a previous ESQ breakdown test (performed at LBNL), the breakdown threshold for an ESQ is proportional to the square root of the spacing between the quadrupole electrodes; in particular, an ESQ with b =2.2 cm and R_e =2.53 cm breaks down at 230 kV between the quadrupole electrodes. For a conservative safety margin, we would like to set the normal operating point at $\leq 50\%$ of the breakdown threshold value.

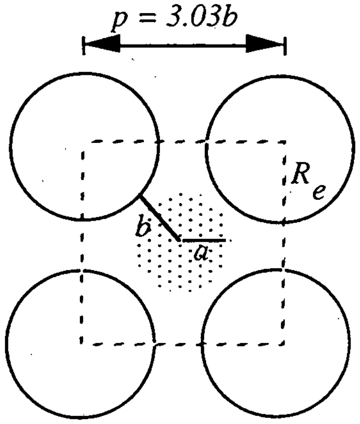


Fig. IV-1. Cross-sectional view of an ESQ channel.

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. Figure IV-2 shows the J_{ave} for various beam clearances. The optimum aperture radius is 5 mm if the required beam clearance is only 2 mm resulting in a very large J_{ave}. In fact, the optimal aperture radius can be derived analytically by assuming that the maximum quadrupole voltage is proportional to b^{α}, where α is typically between 0.5 to 1.0; subsequently

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

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

$$b_{opt} = \frac{(3+\alpha)c}{(1+\alpha)} \tag{3}$$

For $\alpha = 0.5$ (as found in our breakdown test), and $c = 1$ cm (a very conservative choice), the optimum aperture radius is 2.33 cm. Upon successful demonstration of ESQ alignment and beam steering, we can fill a 2.33 cm (radius) channel with more beam until the beam radius reaches the clearance limit. For example, at a beam clearance of 2 mm, the J_{ave} for this aperture size can be as high as 219 A/m^2 (and the corresponding line charge density is 0.345 μC/m).

In our design, the effective length of the ESQ is 6 cm shorter than the physical length of the half lattice period L, hence $\eta = (L-6)/L$. Obviously, η grows with L; typical values of η 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 σ_0 =75° for maximum stable beam transport):

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

where V is the beam energy expressed in volts and the quadrupole voltage V_q is determined from the square root scaling rule. At 50% of breakdown threshold V_q is 118 kV or ±59 kV w.r.t. ground potential. The half-lattice period is 20.8 cm at beam energy of 2 MeV. As the particles gain energy, a smooth beam envelope can be obtained by matching the envelope angles between lattice periods:

$$\frac{\eta L E'}{\sqrt{V}} = \text{constant} \tag{5}$$

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 (ηL) proportional to the square root of particle energy.

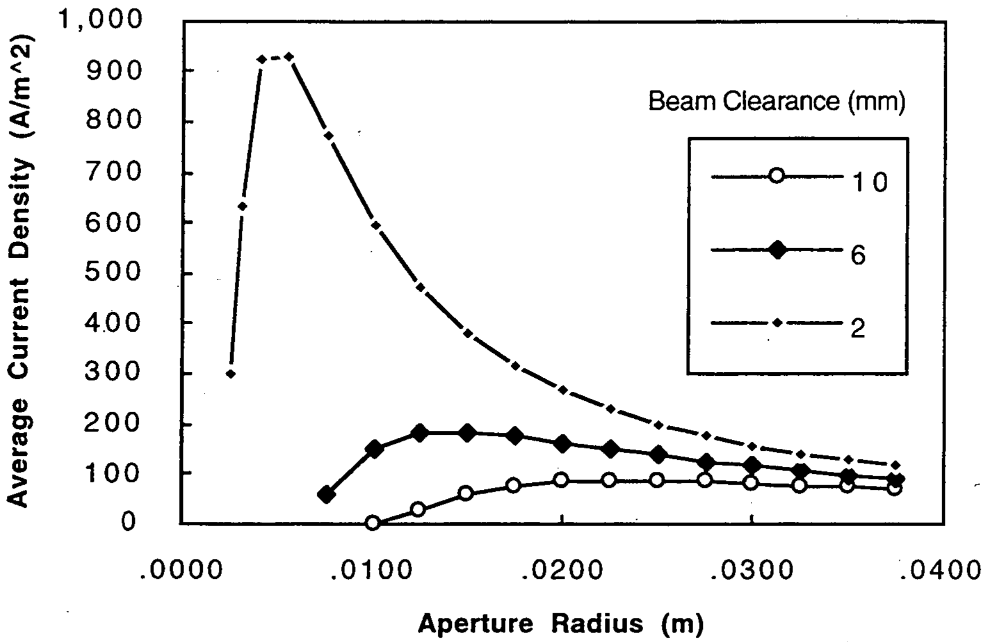


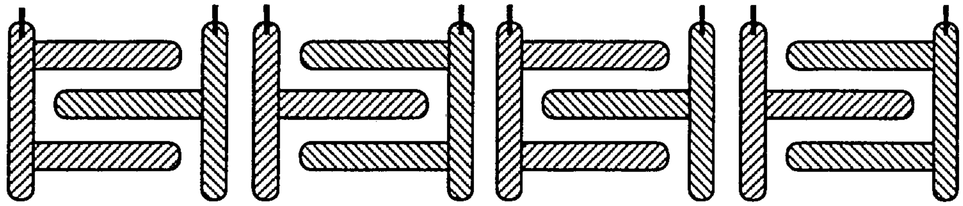
Fig. IV-2. J_{ave} as a function of the aperture radius and beam clearance.

The transportable beam current line charge density, λ, is a function of the beam energy, the undepressed phase advance, the half-lattice period, and the average beam radius, $<a>$, where the ratio $a/<a>$ (a function of the quadrupole strength and η) is $\approx$ 1.2 - 1.3:

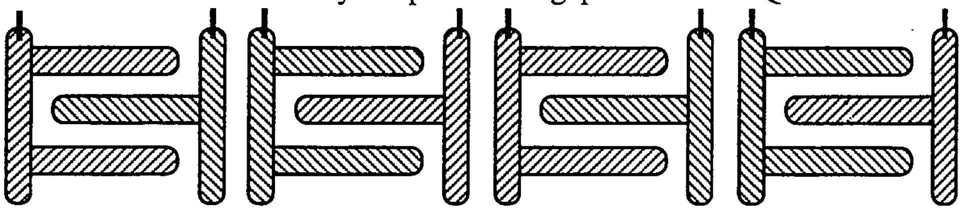
$$\lambda = 4\pi\varepsilon_0 V\left(\frac{<a>}{2L}\right)^2 2(1-\cos\sigma_0) \tag{6}$$

B. Unipolar vs. bipolar ESQ's

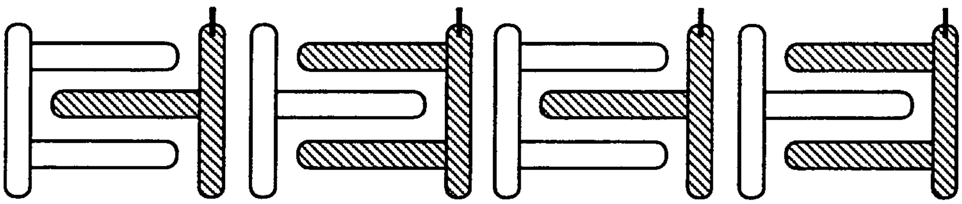
As shown in Fig. IV-3, voltages on the ESQ electrodes can be arranged either in the bipolar or unipolar configurations. For bipolar ESQ's, ±V potentials are applied to the two pairs of electrodes whereas for unipolar ESQ's a +2V (or -2V but not both). Generally positive bias is preferred for better voltage holding capability. As long as the beam energy is much higher than the focusing potential, the two cases only have a minor difference in the beam physics. There are fewer feedthroughs and power supplies in the unipolar case but the voltage requirement is twice as high. Both bipolar and unipolar cases can have combined electrodes to utilize the geometry as in case 5 thus reducing the number of accelerating gaps by a factor of 2 (one would double the acceleration voltage per accelerating gap to acquire the same overall acceleration gradient). This geometry is especially attractive for unipolar ESQ



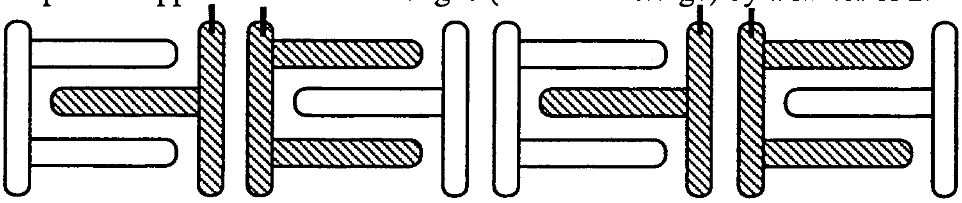
Case 1. Bipolar ESQ focusing. Ions are accelerated within the ESQ and decelerated at the gap between ESQ's by electrostatic field. Main beam acceleration is inductively coupled at the gap between ESQ's.



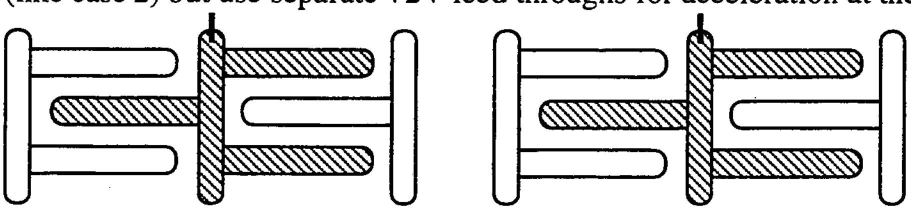
Case 2. Bipolar ESQ focusing. Ions are accelerated and decelerated within the ESQ pairs. Main beam acceleration is inductively coupled at the gap between ESQ's. An improved configuration than that in case 1.



Case 3. Unipolar ESQ focusing. Similar to case 1 but reduces the number of power supplies and feed-throughs (@ twice voltage) by a factor of 2.



Case 4. Unipolar ESQ focusing. Electrodes of same potential are grouped together (like case 2) but use separate +2V feed throughs for acceleration at the gap.



Case 5. Combining electrodes of same bias voltage can further reduce the number of feed throughs but also reduces the number of acceleration gaps.

Fig. IV-3. Biploar and unipolar ESQ configurations.

because the non-combined electrodes are at ground potential (require no feedthrough) which can be arranged to encapsulate the combined electrode forming a doublet module. In the remainder of this paper, bipolar ESQ refers to the configuration depicted in case 2, and the unipolar ESQ refers to the configuration depicted in case 5.

There are several ways to support the ESQ electrodes. One way is to use parallel insulator rods cantilevered from the end plates. Another possibility is to use insulators slanted at an angle to gain mechanical and/or electrical advantages. To that end, one may even consider insulator support in the radial direction in a capsulated unipolar design. Although this method may require a larger vacuum jacket (hence a larger inner diameter for the acceleration cores), the electric field along the radial insulators is more predictable than along the parallel rods. The selection between bipolar and unipolar quadrupoles depends mostly on engineering and economic reasons but not physics requirements. The following table summarizes the pros and cons of the two configurations. We have chosen the bipolar ESQ as the baseline design for Elise mainly because of the lower voltage requirement. Interestingly, since the ESQ focusing voltage scales with the physical dimension, a much smaller ESQ aperture (than the present 2.33 cm radius selected for Elise) will lead to a much smaller focusing voltage and consequently the unipolar configuration may become a better choice.

Table IV-1. Comparison between bipolar and unipolar ESQ configurations.

Bipolar	Unipolar
More power supply units.	Higher power supply voltage, thus unit cost (perhaps overall cost) is higher.
Lower risk on HV feedthrough due to lower voltage requirement.	Higher risk but smaller number of feedthroughs and gaps required.
3 degrees of freedom articulation (each singlet).	5 degrees of articulation for each doublet
Singlet is lighter, so easy to manipulate, especially via cantilevered mounting.	Doublet is heavier, so harder to manipulate.
Double the number of acceleration gaps as in the unipolar case but half the voltage per gap.	Higher acceleration voltage per gap may cause higher beam noise.
Possibly smaller vacuum jacket radius, thus smaller inner core radius.	Larger jacket radius required in the capsulated doublet design.
More feedthrough gaps	Fewer gaps so a higher longitudinal packing fraction for the core material.
More parts	Fewer parts
Higher overall cost but less risk	Slightly lower overall cost but higher risk
More difficult to insert beam diagnostic equipment	Easier access for diagnostics since part of the ESQ is at ground potential.

C. Acceleration schedules

The basic element of an induction accelerator 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 equal 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 ribbon at standard widths and thicknesses.

Since *L* varies continuously while the module period is quantized (according to the ribbon 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 space, 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; otherwise there will not be enough room for the voltage feed-throughs to reach the quadrupole electrodes.

An acceleration module is composed of one or more cells axially linked together. Each cell can have several 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 SF_6. The purpose of the SF_6 is to fill the air space inside a module for better voltage holding to improve the packing factor.

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. We will control each of the pulser voltages to within 1% variation so 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 that applies the correction pulse about once every four or five lattice periods. In addition, the "ear" pulses compensate for the space charge expansion force at the front and back of a beam bunch. These pulses have a magnitude of the order of 10 kV and a duration of about 0.5 μs. 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 8th half lattice period (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.

It is important to distinguish some fundamental differences between Elise and a full-scale driver. For a driver, the initial beam pulse length is longer. As an example consider a pulse length of 20 μs which is 10-20 times the pulse length for Elise. If a driver and Elise have the same core dimensions (therefore the same amount of volt-seconds per meter), the 10 times longer driver pulse length implies a 10 times smaller acceleration gradient. In practice, the driver cores may be slightly larger; however, they will not be much larger. Since the core volume scales roughly as the square of the core outer diameter, a very large diameter core is uneconomical. In a driver the cores are expected to have approximated 0.5 volt-second per meter. For this example, the acceleration gradient at the front end is approximately 25 kV/m, about a factor of 10 lower than that of Elise. In this sense, the acceleration schedule in a driver is significantly more relaxed than the schedule in Elise.

The accelerating pulse shape can be square, triangular, trapezoidal or some more complex function. Square pulses are useful for either constant current (case I in Fig. IV-3) or constant λ (case II). For constant current, the pulses are turned on before the beam arrives and therefore the beam is accelerated as soon as it enters the linac. All beam particles receive the same boost in energy at each location and the output is mono-energetic which simplifies the combiner design. The major disadvantage of this case is the elongation of the bunch length, opposite to what we like to do for current amplification.

In the constant λ case (case II), the entire beam will be loaded into the machine first and then all the particles are accelerated together by keeping the bunch length constant. This "load-and-fire" initial condition prevents the beam bunch from elongating, but it does not fully utilize the maximum available flux-change at the front-end of the machine (especially bad for a long pulse situation). It also calls for a constant average accelerating field everywhere which further limits the use of available flux-change at the rear end of the machine. At a given location, there is a beam head-to-tail energy variation experienced by the focusing element (i.e. the ESQ). A large energy variation will result in mismatches that can lead to emittance growth. Finally, in order to produce a mono-energetic beam downstream, the accelerator must turn off all the accelerating voltages as soon as the beam head reaches the accelerator exit ("unloading"). The complication in loading and unloading as well as the inefficient use of volt-second at the front end of the machine is more of a problem for Elise than for a driver due to Elise's large bunch length to machine length ratio.

In principle, the occupancy factor η increases towards the end of the accelerator leading to a higher transportable λ. Thus it is possible to design an accelerating schedule to exploit this effect (case III). Nevertheless, beam bunch compression is difficult to achieve in such a short machine and the increase in transportable λ is actually quite small ($\approx$7%).

A variation of case II is to abandon the restriction of constant average accelerating field, thus λ does not remain constant. With the same initial condition (i.e., the load-and-fire), square pulses are applied everywhere using a maximum pulse height allowed by the available volt-second or the designed spark-down limit ,whichever is less (case IV).

Square pulses are conceptually simple, but they may not be easier to produce than other pulse shapes such as triangular or trapezoidal pulses, especially if the beam energy ripple is expected to be within 0.1% (i.e. $\approx$ 1 % tolerance from the ideal the pulse shape) as required by the final focus limit in a driver. A system with triangular or trapezoidal pulses at the machine front end and square pulses in the rest of the machine will accelerate beam particles as soon as they enter the machine, but it will limit the elongation by imparting higher energy at the back of the bunch (case V). This method provides an easy way to employ all the volt-seconds available in the machine; thus the output beam has the highest average energy but will not be mono-energetic.

The last case to consider (case VI) is to remove all restrictions to the pulse shape, allowing it to be tailored to fit each gap. An example is the self-similar compression (only true in the single particle approximation) using the Kim-Smith accelerating schedule as described in the original CDR. This procedure requires the acceleration wave form applied to the beam to be triangular until the beam tail enters the accelerator. Our plan is to build pulse-forming networks (PFN) that can produce various waveforms such that many different types of acceleration schedules can be tested.

D. Optimizing the machine performance and computer simulations

The criterion in designing the Elise lattice is to maximize the packing density of acceleration cores, consistent with breakdown limits, access for pulse-power feeds and diagnostics, and preservation of some modularity. The criterion was $1J. This requires the juggling of parameters to optimize cost and performance is handled by a computer optimization code written in MATHEMATICA®. The present design has average acceleration voltages varying somewhat erratically between 55.7 kV and 153.75 kV, with gaps for diagnostics in place of two cells. Despite the irregular acceleration, simulations using the envelope/fluid code CIRCE indicate that the beam remains near transverse equilibrium along its length for various acceleration schedules and "ear" pulses.

The longitudinal beam dynamics have also been simulated by the 1-D PIC code SLIDE to study the voltage waveforms at the acceleration gaps. Assuming a 2 MeV injected beam having 0.3 μs rise time, 1.5 μs flat top, and 0.4 μs fall time with 0.25 μC/m at the flat top, a constant current scenario using square pulses for acceleration will produce an output beam (after 54 half-lattice period) with 5.7 MeV and approximately 10% erosion of the flat top. On the other hand, if trapezoidal waveforms are used for acceleration, the output beam has an energy tilt (5.2 MeV head and 6.5 MeV tail) and a pulse length (ignoring rise and fall time) of 1.1 μs.

Since the constant current case is more effective in utilizing the available volt-seconds, it is used to optimizing the machine cost (maximum delivered joules per dollar). The results of the cost study yielded insight in four areas of optimization: core length, module outer radius, pulse duration, and final ion energy. Fig. IV-4 illustrates a series of models for different core lengths. The dollars per joule (some fixed costs are excluded in this computation) is plotted as a function of the number of cores per cell. The pulse duration is held constant in this series of curves. On a given curve, increasing the number of cores per cell increases the outer radius of the induction modules. As the core length increases, the outer radius decreases at fixed number of cores per cell (the volt-seconds per core and the core area are fixed). Two observations can be made: the outer radius of the machine is optimum at about 1.0 m, while the optimum ribbon width occurs at 5.6" or 6.7" (or a combination of the two). An optimum in module radius occurs because as the number of cores per cell increases, the outer radius of the module increases; hence the core volume rapidly increases, and so do the costs (the machine length is shorter in this case, but the reduction in transport cost is not sufficient to offset the cost due to rapid increase in core volume). The wider ribbons are beneficial simply because there are less inter-modular empty space and wider ribbons are sold at a lower unit price (per kg).

Another result of the cost optimization is the tradeoff between pulse duration and ion energy when the cost of the machine is constrained. In this tradeoff it was found that if the goal is to design a machine in which the pulse energy is maximized, then increasing the pulse duration tends to win over increasing ion energy. Increasing the pulse duration requires larger and more costly cores, but because the core losses are reduced per unit core volume (due to lower dB/dt), the pulser requirement favors longer pulse length over higher beam voltage. Nevertheless, our design limits the pulse length to 1.5 μs flat top in order to ensure that the output beam has energy > 5 MeV for various acceleration schedules. Fig. IV-5 shows the present Elise lattice design with 54 half-lattice period. The machine characteristics are summarized in Table IV-2.

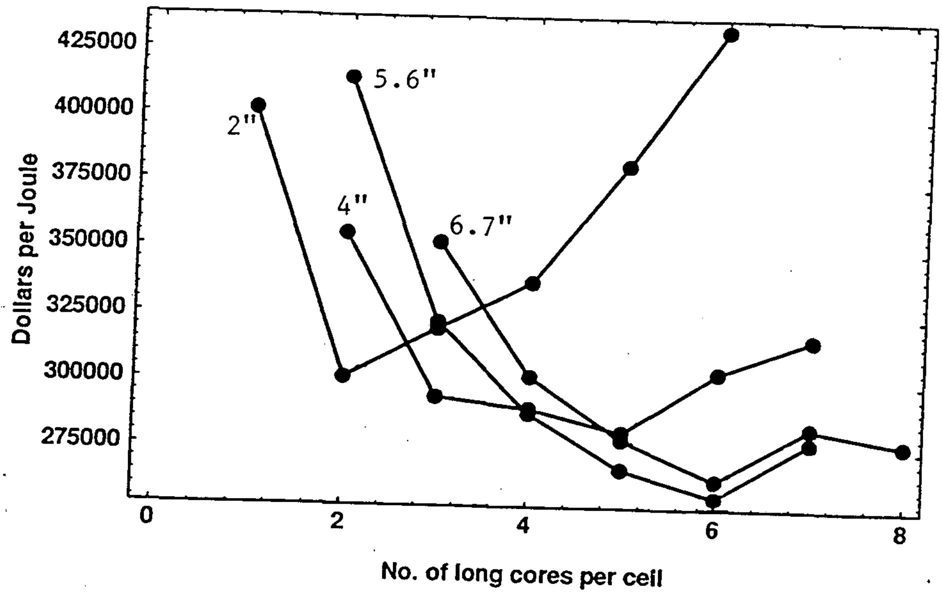


Fig. IV-4 Cost optimization among various ribbon widths.

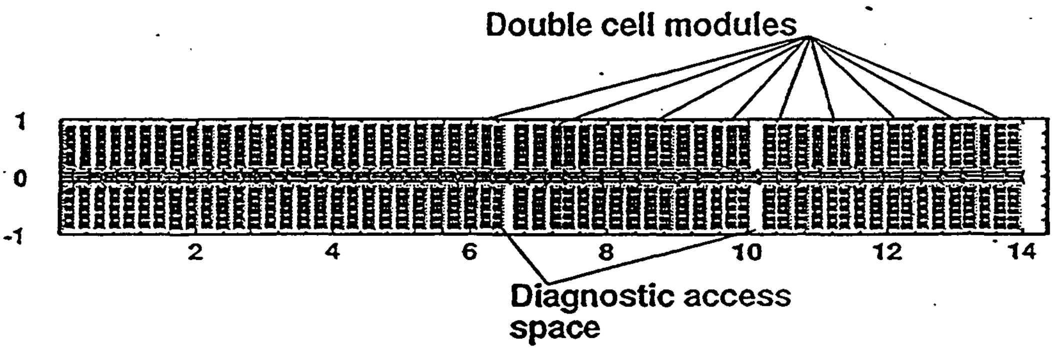


Fig. IV-5 Elise lattice design.

Table IV-2. A summary of the present Elise conceptual design.

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

V MECHANICAL SYSTEM

The general mechanical requirements for this machine are as follows: (1) package 150 tons of magnetic core material as densely as possible; (2) make electrostatic quadrupoles (ESQs) compact and precise; (3) provide ready access in as many locations as possible to vacuum space for diagnostics and maintenance; (4) provide high voltage feedthrough access for ESQs; (5) support and align ESQs so they remain aligned regardless of floor motion or thermal effects; (6) integrate electrical and mechanical designs of ESQ, feedthroughs, and vacuum enclosure to provide maximum electrical reliability; (7) and reduce costs by reducing core inside diameter, simplify components, assemblies, ancillary systems, and optimizing machine configuration (i.e. core material vs. all other costs).

Through an iterative and collaborative effort between physics and engineering, the following general architecture for the Elise machine are developed: (1) 51 induction modules requiring 334 cores and 130,000 kg Metglas®; (2) mounting the entire 14-meter acceleration section on rails for quick access for diagnostics and maintenance; (3) a remotely actuated vacuum closure to permit opening of the vacuum enclosure at each ESQ; (4) use 54 ESQs of unique length for beam transport; (5) an offset of all ESQs longitudinally from their respective support gap centerline (all offsets are different); (6) kinematically supported and articulate quadrupoles; and (7) ESQ support and high voltage feedthroughs within the 5 cm gap between acceleration modules. Fig. V-1 shows an overall elevation view of Elise and Fig. V-2 shows a typical module of the transport section.

During FY 1995, 34.7 man months of mechanical engineering effort were used on the Elise RDAC activities. The distribution in kinds of effort was 43% engineering, 25% associate, and 32% technical. The overall mechanical design of Elise has evolved from general concepts in the CDR to significantly refined concepts which meet all the mechanical requirements. In many areas design solutions are being tested using prototype hardware.

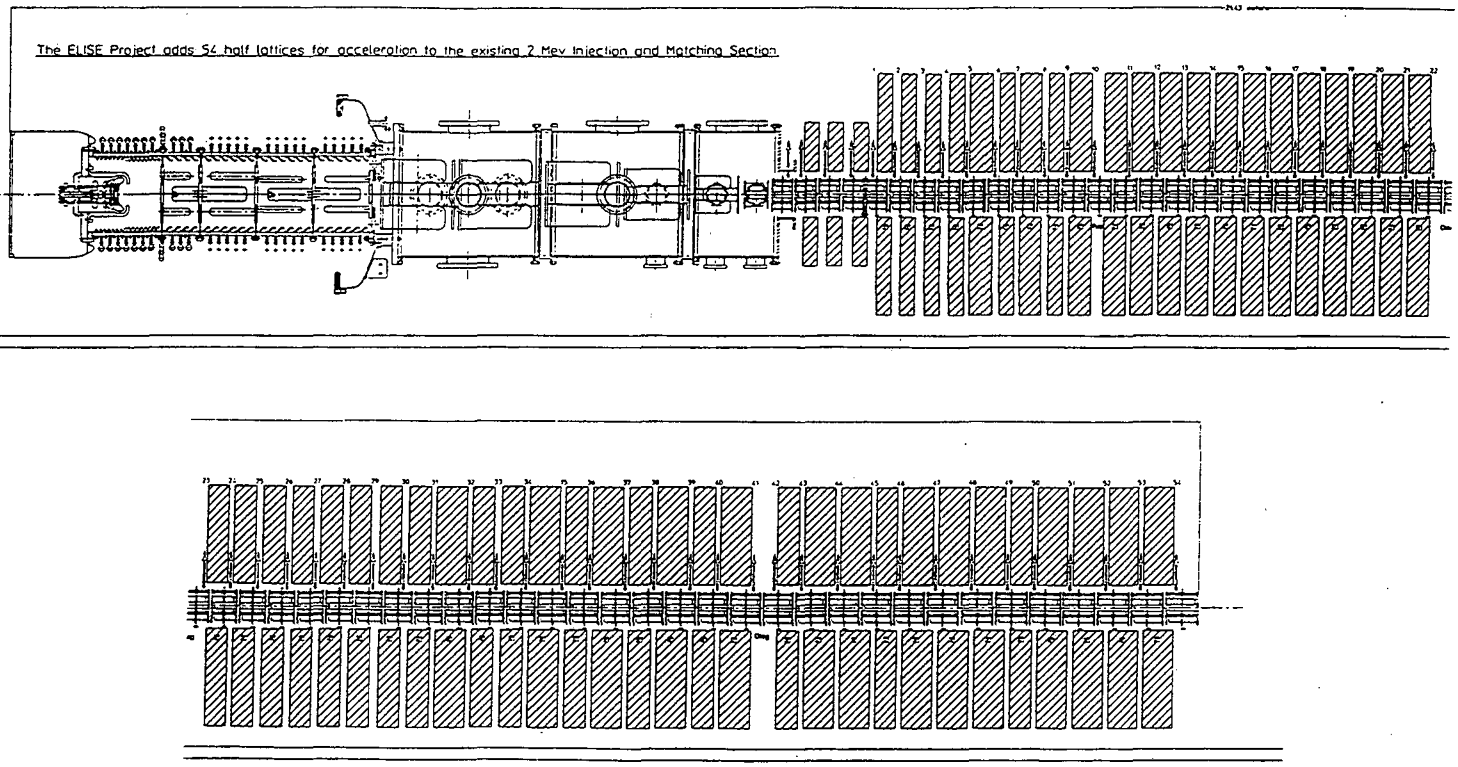


Fig. V-1 Overall layout of Elise.

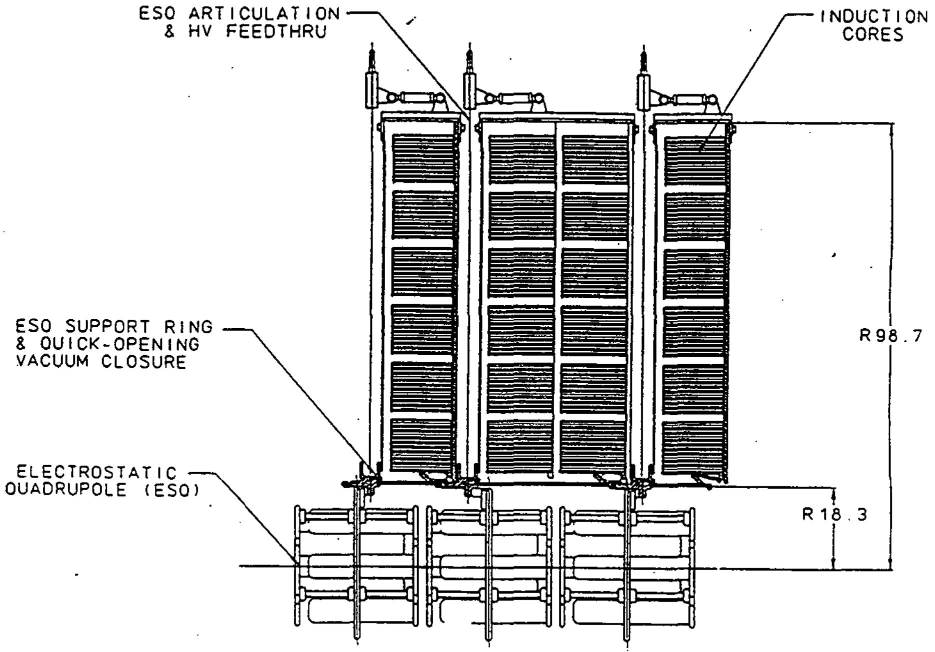


Fig. V-2 Typical modules of Elise induction cells and ESQs.

A. Design of the 4-channel ESQ array

Figure V-3 shows both a computer aided design drawing and a photo of the present ESQ design. Two important considerations for the ESQ are dimensional accuracy and electrical reliability. Dimensional accuracy means fabricating and assembling the ESQs, so that the surfaces of the 9 electrodes are very accurately located with respect to each other – better than 25 μm. Features such as diameters and locating holes are held to tolerances of 2.5 μm. The locating features for the electrode ends will be a slight interference fit with the mating feature on the mounting plates. Electrodes and plates are made of 304 stainless steel. The two electrode sub-assemblies, that is, each plate with its respective mounted electrodes, are each attached to a ground potential center support ring through ceramic insulator standoffs.

The problem of how to precisely locate the opposing electrode assemblies with respect to each other is tackled by grouting the insulator ends into place. The two assemblies are moved into precise relation on X·Y stages and then epoxy grout is injected into a cavity at the base of the insulator flower pots at one plate. This has the advantage of not creating stresses and movements between parts as often occurs when fasteners are tightened up.

For purposes of development and testing, the goal is to condition the ESQ electrodes up to 2 times operating voltage in a high voltage test stand without the presence of an ion beam. Spacing between electrode ends and end plates of opposite polarities is set at 2 cm, about 60 kV/cm at operation.

The triple points at the ends of the insulator rods are shielded using a stainless steel "flower pot". A variety of geometries have been tested and many are able to condition up to 3 to 4 times operating voltage. The typical geometry is shown in Fig. V-4. One new feature is the way the flower pot is joined to the ceramic insulator. The design here uses a 25 to 50 μm interference fit between the insulator and the flower pot bore. Assembly and disassembly is easily done by heating the flower pots to 300 °C.

The location and orientation of insulators is a major consideration. In order to keep the ESQ compact and simple, four insulators are placed parallel to, and spaced equally from both the positive and negative electrodes. The initial consideration for this spacing are based on the vacuum gap separation between insulator and flower pots and electrode surfaces. At 28 mm spacing, the corresponding gradient is 43 kV/cm. Initial testing of the ESQ has shown a strong degradation of the insulator capability depending on its location and orientation within the ESQ assembly. Although individual insulators are capable of conditioning to hold 240 kV without surface discharge, the ESQ assembly could not be conditioned beyond ±90 kV, due to discharges along the insulator surfaces. This amounts to a loss of 63% in voltage hold-off

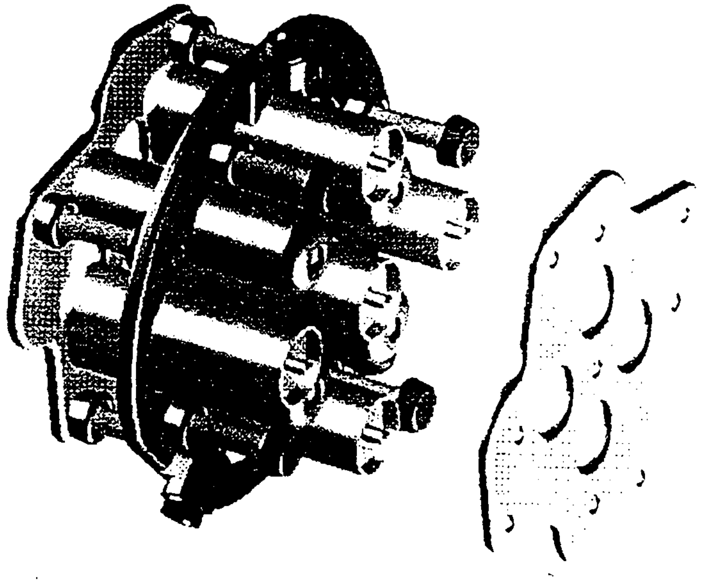


Fig. V-3a ESQ computer design model with one end plate removed.

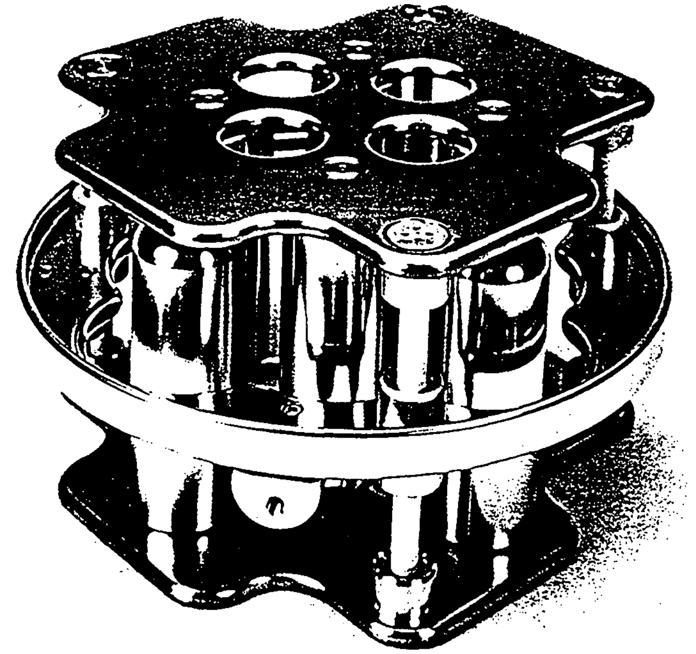


Fig. V-3b Photograph of a recently built and tested ESQ.

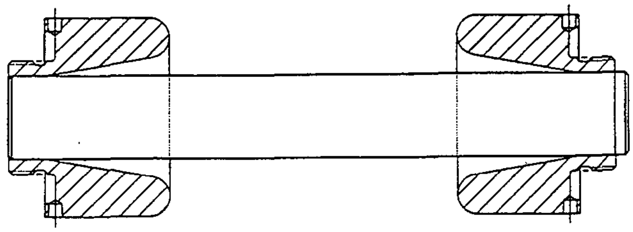


Fig. V-4 Alumina insulator assemblies, 8 cm long, with stainless steel "flower pots" can hold off 240 kV.

capability. Furthermore, in all the ESQ testing, most of the arcing occurs along the insulator surface, between the positive end plate and ground plate. Discharging of insulators between the negative plate and ground occurs much less frequently. One possible explanation for this polarity effect is that the field lines near the end of the negative electrode (i.e. at the positive end of the ESQ) intersect the insulator surface at an oblique angle in such a way that electrons are accelerated towards the insulator surface. On the other hand the oblique field lines near the end of the positive electrode tend to accelerate electrons away from the insulator surface. This effect is illustrated in Fig. V- 5.

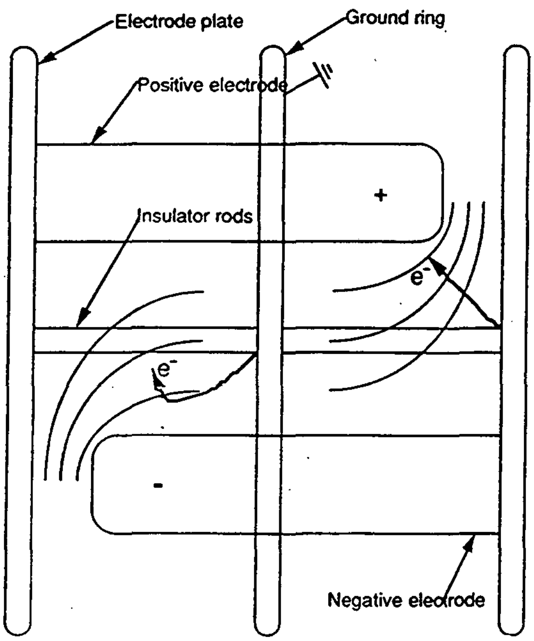


Fig. V-5 More breakdowns occur at the insulators near the end of the negative electrodes possibly due to a polarity effect shown here.

An experiment to study both the proximity and polarity effects described above has recently been completed. The experimental setup is shown in Fig. V-6. In this experiment, the distance between the single electrode and the insulator is varied. In moving from the near position of 8 cm insulator to electrode spacing to the outer position of 34 cm spacing, the typical insulator breakdown voltage increases 50% from 140 KV to 210 KV. This demonstrates a clear proximity effect. The results also tentatively show evidence of a polarity effect in that as the electrode oriented with outer end near the test insulator is moved inward (see Fig. V-3), the degradation of breakdown voltage is 60% higher when the electrode polarity is negative than when it is positive. More test data are necessary to confirm this result.

Other arrangements of insulators in the design of the ESQ have been considered, namely, radial and angled orientations. Although each has some advantage, such as rigidity or more optimum insulator fields, both require some increased fabrication complexity.

Another concern related to the ESQ is how much will the voltage holding margin be eroded in the presence of an actual ion beam. In other words, the margin of 200% operating voltage may be an over estimate while the presently achievable 150% operating voltage may be sufficient. To find the required design margin, an experiment is being constructed which will enable beam transport through 2 ESQs at the end of the existing 2 Mev Injector Matching Section to determine ESQ breakdown effects with a variety of beam conditions.

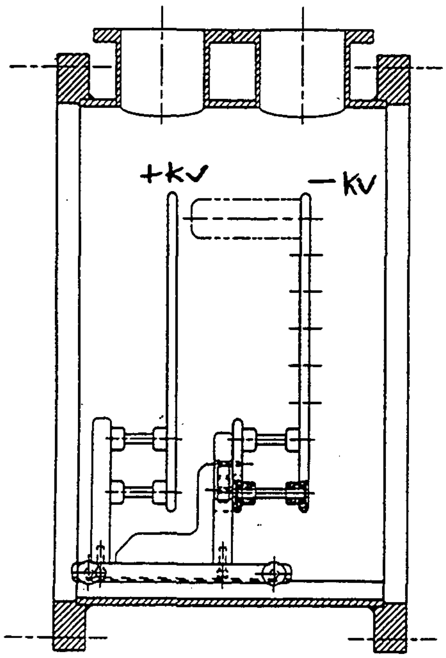


Fig. V-6 The electrode/insulator proximety effect has been experimentally measured.

B. ESQ Articulation & Vacuum Enclosure Design

The design of the ESQ articulation, vacuum, and alignment systems are all tied closely together. Each ESQ is rigidly attached to its respective vacuum enclosure consisting of a short spool and cylindrical induction gap insulator. These subunits are then mounted to a 3 cornered web which articulates with 6 degrees of freedom through the use of kinematic support struts .

The 5 cm gap between core module housings is too narrow to incorporate a conventional vacuum connection. Direct access for disconnecting the vacuum enclosure, through use of bolts or other clamping devices, in the gap area is difficult. Much of the 5 cm space is needed for the high voltage feedthroughs and ESQ support and articulation mechanism. One promising solution, shown in Fig. V-7, is to use a remotely actuated pneumatic bladder to actuate a seal. A prototype seal of this type has been tested. This mechanism is actually housed inside the core module area and not in the gap area. The seal arrangement also solves the flexibility problem. The elastomeric rectangular seal has a low enough shear modules to enable the small transverse motions between adjoining sections to be made . The required motions will be very small, of the order of 50 μm, since the active alignment system will keep each vacuum enclosure section aligned to its neighbors within this tolerance (actually the alignment system aligns the ESQs but since the ESQs are rigidly mounted to their respective vacuum enclosures, the result is that the enclosures remain well aligned to each other).

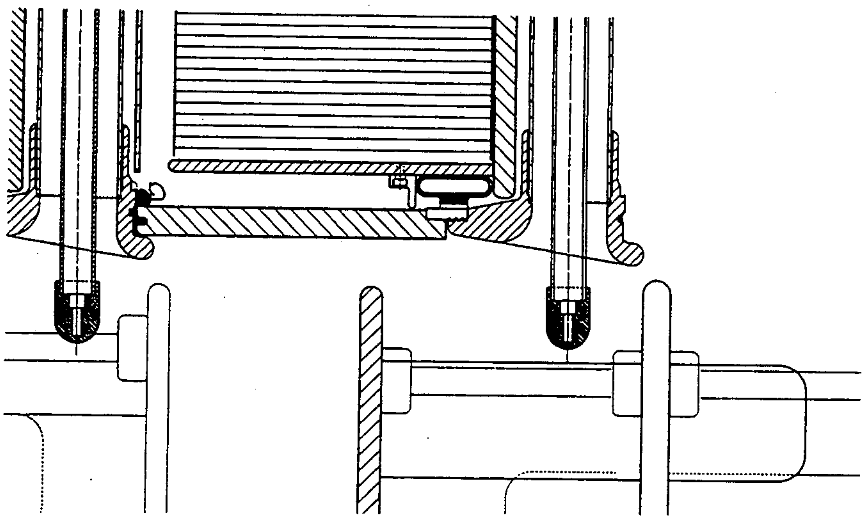


Fig. V-7 A pneumatic bladder inside the core housing actuates a vacuum seal.

The measured stiffness of a prototype seal of this type is about 0.12 kg per micron. Finite element analysis shows that the stiffness of adjacent ESQs for force transmitted through this joint is about 0.71 kg per micron. This 6:1 coupling of motion between adjacent ESQs will enable alignment corrections for individual ESQs to be made without triggering realignment of their neighbors. It may be necessary to monitor the motorized actuator forces to insure that an alignment system fault condition doesn't arise in which adjacent ESQs are driven far out of alignment. Force limiters on the actuator system would prevent resultant damage to the vacuum enclosures if this condition arose.

As described above, each ESQ is mounted to a spool which is in turn supported by a web which attaches at its 3 outer corners to the structure outside the induction module diameter. The web, shown in Fig. V- 8, is thin as it must fit inside the 5 cm gap between modules and still reach outside the 2 meter module diameter. The simplest and cheapest design is to machine this structure from a 1.5 inch thick aluminum plate. This may result in the natural harmonic frequency of the ESQ and web being too low. Finite element analysis of this structure shows resonances at 20 hertz frequencies which are in the range of sensitivity to mechanical pumps, fans, motors and other types of excitation. Two solutions are to stiffen the web or to reduce the mass of the web. A composite design utilizing a honeycomb or foam core would do the job, although there would be an extra cost for this type of structure. Alternatively, the monolithic type of structure may be workable with a viscous damper attached to the web close to the spool.

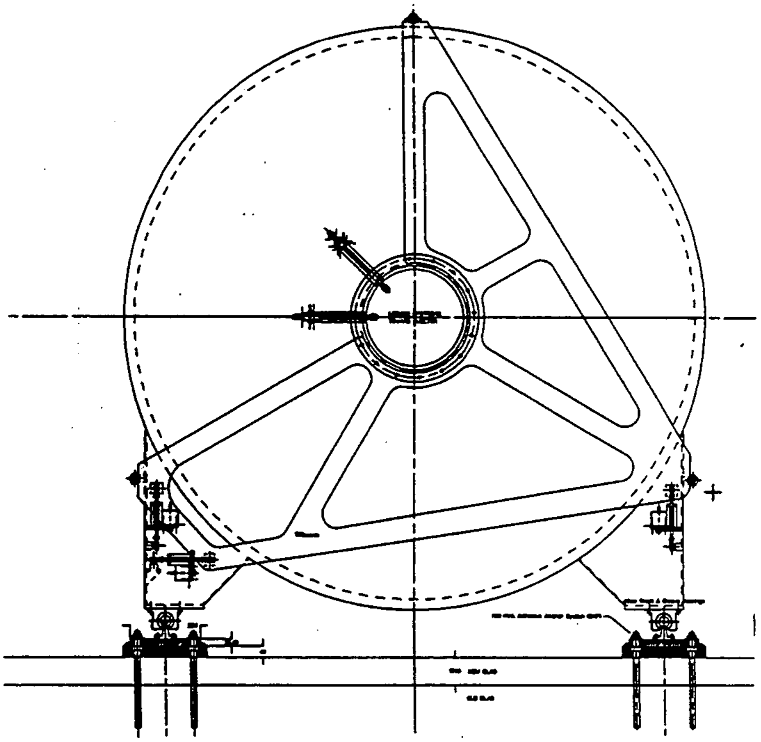


Fig. V-8 A web structure supports the ESQ. Six kinematic struts attached at its outer corners.

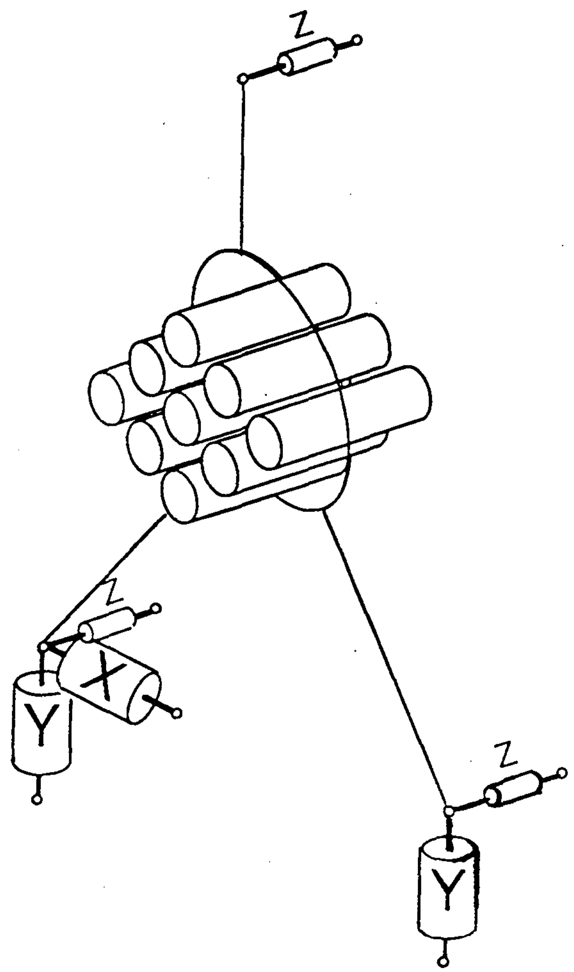


Fig. V-9 A 6-strut support system is used for articulating and alignment of the ESQs.

The articulation of the ESQ, illustrated in Fig. V- 9, is accomplished by 6 adjustable struts attached at the 3 corners of the web forming a 6 strut kinematic support system. The 3 struts oriented in the Z direction are manually adjustable and are set at installation of the ESQs. These struts control the pitch, yaw, and Z position of each ESQ. Precise orientation of the ESQ in these degrees of freedom is not required. For example ±5 mradians is the ESQ alignment tolerance in the pitch and yaw orientations. On the other hand, precise alignment in the X, Y, and roll of degrees of freedom are necessary. The 3 actuators in the X-Y plane which control these directions are motorized and allow automatic corrections to be made in these directions as required.

C. Alignment Systems

The stringent alignment requirements for the ESQs require an active alignment system that will sense and automatically correct ESQ positions. The stated requirement for ESQ alignment is

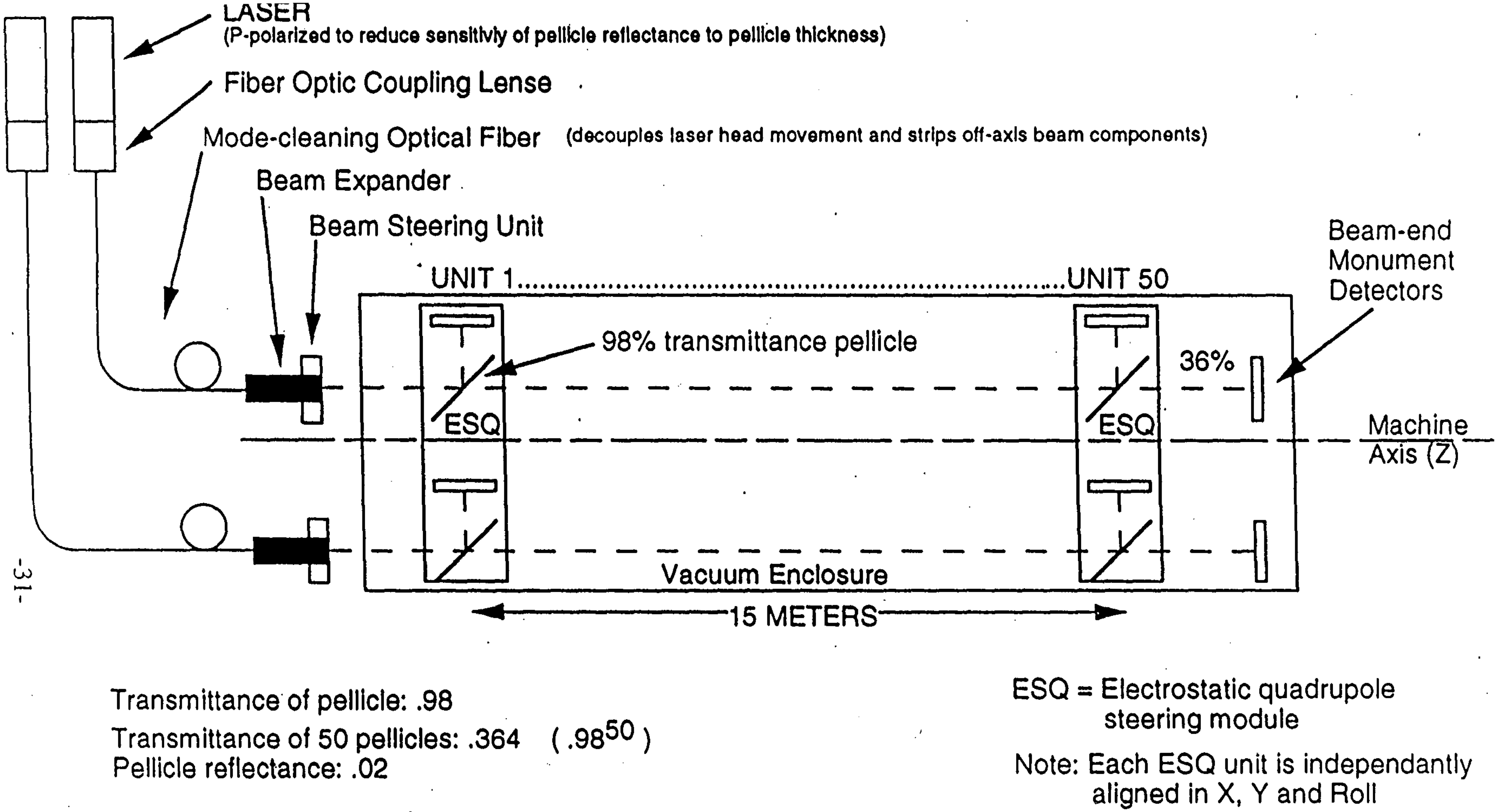


Fig. V-10. A schematic diagram of the ESQ alignment system using laser optics.

that each ESQ must remain in position with respect to its neighbors within 100 μm in the plane transverse to the beam direction.

The alignment system, as shown in Fig. V-10, utilizes two solid state laser beams as straight line references. Optical fibers are used to bring the laser light inside the beamline vacuum enclosure; thus any motion in the laser heads will not affect the beam references. Feedback to laser beam steering units from stationary downstream detector monuments will act to stabilize the beam from drifting due to temperature or floor motion.

Two pellicles, thin optical quality films which partially reflect light, are mounted on the ESQ center plane, one on each side of the ESQ centerline. Each pellicle reflects 2% of the laser beam to a 4-quadrant photodiode sensor on the ESQ module for position detection. Using the position information from these sensors the X,Y, and roll position of each ESQ can be determined. Beam intensity decreases to 36% of the original intensity after going through a series of 50 ESQs. Beam distortion from each pellicle is thought to be insignificant compared to quad-to-quad alignment limit. This will be verified by future testing.

Since the pellicle-sensor assemblies are mounted directly on the ESQs, it is possible to achieve accurate fiducialization between field centers and sensor null points. The calibration can be done on a bench before the final alignment.

The laser light striking the photo diode sensors is amplified at the sensor by a 4-amplifier integrated circuit that uses a common thin-film resistor network to control the gain of all the signals. This ensures that the signals from the sensors have low noise and, because all components are closely matched, it will allow accurate nulling of signals and minimize the effects of component aging and temperature drift. The buffered signals are transmitted to a local controller for each ESQ. This controller digitizes each quadrant, computes the differential signals, and transmits them to a master controlling host over a 2-wire telephone style cable bus common to the other ESQ controllers. The local controllers will also drive the alignment position stepmotor-actuators and perform house-keeping chores such as actuator travel-limiting.

The centralized host will poll all the controllers on a periodic basis to collect alignment data. Position commands are then sent to the individual modules for corrections. This will allow statistics on machine alignment to be gathered and a global historical view of ESQ positions to be maintained. Because all communication with the controllers is composed of simple ASCII commands, almost any host can be used, including multiple hosts.

D. Vacuum System

The beamline vacuum requirement for Elise is in the 10^{-7} Torr range. Pumping access in the machine is provided at the ends of the beamline and at the special "large" spaces between induction modules at half lattice periods (HLP) 11, 23, and 42 (the old CDR design provided pumping access between every induction module). The highest pressure in the beamline will, therefore, be between HLP 32 and 33, about 10 HLPs from the nearest pump location. The results of calculating beamline pressure as a function of distance from pump location are shown in Fig. V-11. For the 32 and 33 locations, the pressure is estimated to be 1.4 x 10^{-7} torr.

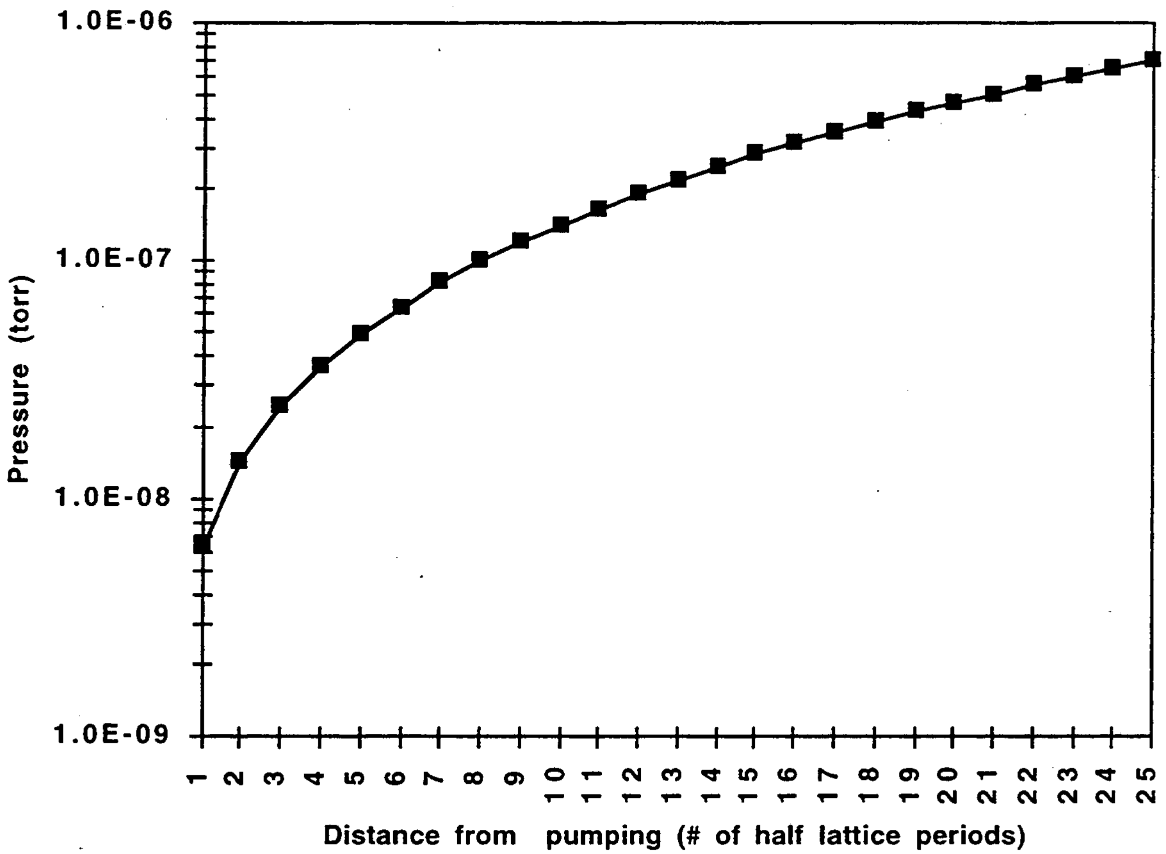


Figure V-11. The effects of pumping frequency on beamline vacuum pressure.

The pumping required is 8000 liter per second at each pump station and assumes a 1000 liter per second duct conductance between the pump and the beamline. In this calculation, the beamline is simply modeled as a series of baffled annular pipes resulting in a molecular transmission probability of 0.17 through each section and a conductance for each half lattice section of 2060 liters/second. The outgassing loads from each of the beamline components is shown in Table V-1.

TABLE V-1 - Outgas loads from beamline components

Component	Material	Surface area (cm2)	Qty	Total surface (cm2)	Outgas rate (T-l/sec/cm2)	Gas load (T-l/ sec)
Spool	Stainless steel	1131	1	1131	1.00E-10	1.13E-07
Gap insulator	Alumina	2206	1	2206	1.15E-09	2.54E-06
ESQ Ground ring	Stainless steel	709	1	709	1.00E-10	7.09E-08
ESQ end plate	Stainless steel	684	2	1368	1.00E-10	1.37E-07
ESQ electrodes	Stainless steel	368	9	3313	1.00E-10	3.31E-07
ESQ insulator	Alumina	44	8	351	1.15E-09	4.04E-07
ESQ flower pots	Stainless steel	29	16	464	1.00E-10	4.64E-08

E. Acceleration module

The present induction core design remains largely what it was in the 1994 Elise CDR. Design work focused on other areas (described above) until the Metglas® ribbon width was decided. Many alternative arrangements of cores have been considered - the overall Metglas® packing factor and cost as the main considerations. The most recent design uses 4-inch and 6-inch ribbon widths to produce modules having similar outside diameters. The order of 4-inch and 6-inch modules is arranged to match the intermodular gaps (for feedthroughs and supports) with the positions of the ESQs.

We chose a simple flat plate to support the cores. An analysis was done to determine the minimum thickness of this plate. Results show that a very thin plate can be used and remain surprisingly flat due to the large stiffness of the core winding mandrels in the direction of the machine axis. For instance, a 3-mm plate would stay flat to 0.2 mm under a 3000-kg core weight. A deformation plot is shown in Fig. V-12.

Another consideration in the design of the core module housings is the balance of internal pressure, which is created by a sealed insulating gas recirculation system, to the external atmospheric pressure. Due to the large surface area, even a very small pressure difference across the plate can produce a significant deflection. For instance, a 4 mm thick plate without reinforcement with 0.01 psi across it will deflect about 1.5 mm.

Finally (crossing into the area of cost discussed in other sections), because not much design work on the core housings was done, the cost of this area is far from optimized. The costs reported in the 1994 CDR for induction core housings were simply extrapolated from actual costs for a prototype test stand built in 1992. Optimization of design and fabrication processes should result in significant reductions of cost in this area.

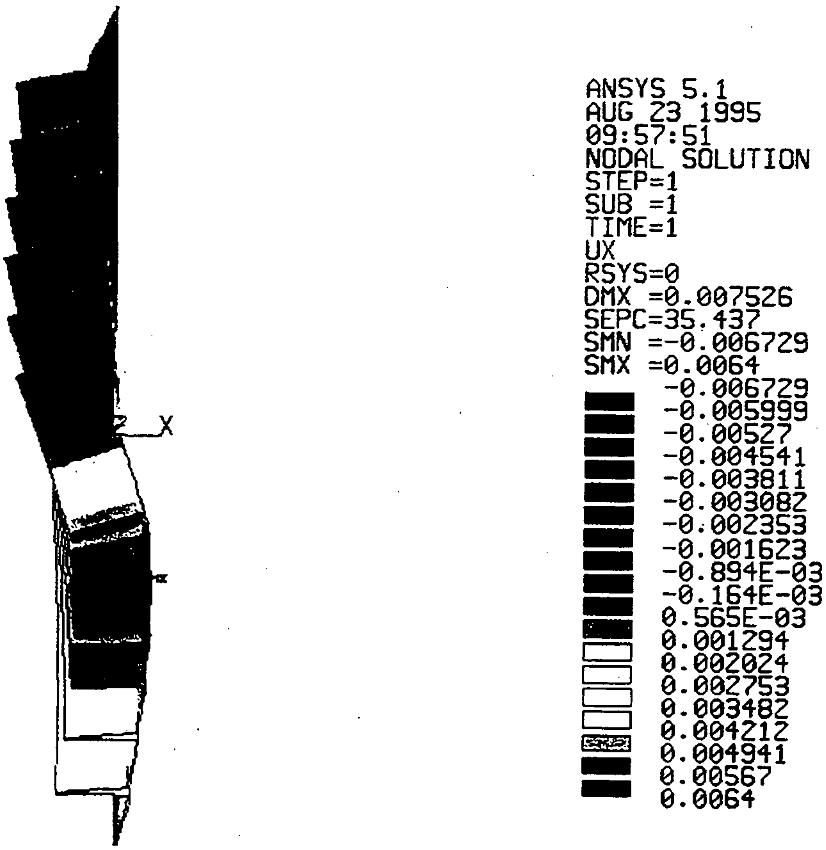


Fig. V-12 Core windings can be supported on a 3 mm thick plate and remain flat to 0.2 mm.

F. Highlight of changes from 1994 CDR

One of the goals of the Elise RDAC is to increase the Metglas® packing factor. The longitudinal factor is increased from 38% for the 1994 machine to 59% for the present Elise design. The most significant contributor to this large increase is the elimination of permanently located beam diagnostics in the original design. Table V-2 shows a comparison and make up of packing factors for the old and new Elise designs.

TABLE V-2 - Metglas® Packing Factor for Old and New Elise

	1994 CDR Elise*	New Elise
Total Length	14.00 meters	13.94 meters
Fraction Diagnostics	20.0%	0
Fraction Intra-module "gaps"	21.0%	21.7%
Fraction non-Metglas› volume inside modules (plates, gaps, etc.)	21.3%	19.7%
Fraction Metglas›	37.7%	58.7%

* The 1994 Elise CDR machine contained 2 drift ESQs at the end. If these are eliminated then all the 1994 fractions should be reduced by about 6%.

It's not apparent from Table V-2 that much has been done with the intra-module gaps and the non-Metglas® occupancy within the modules. In order to achieve a higher average current density, the average HLP was reduced by 35% in the new machine. Both the intra-module gaps and non-Metglass® occupancy have been significantly reduced in order to maintain each of their contributions to the non-Metglas® space in the machine at the 20% level. Therefore, the space available between modules for feedthroughs and ESQ supports and the space used for insulation and support plates inside the modules are now significantly smaller. The reduction in the module gaps required a significant change in design for the hardware in these gaps.

Another major change in the design is the introduction of continuously varying electrostatic quadrupole lengths to better match the HLP to the beam energy. This is conceptually very simple and only requires some modest increase in effort for fabrication and organization of bookkeeping for design and assembly work.

One consequence of keeping the module gap as small as possible is that the ESQ centers no longer align with the module gaps. This offset requires a dog-legged support from the module gap to the ESQ center ring.

G. Cost Estimation

Cost algorithms used for the optimization studies are based on the detailed cost estimates contained in the 1994 Elise CDR. Scaling factors, usually length, area, or volume ratios, are used to project the cost of components for various machine configurations. Relative costs are compared for several machine options. A quadrupole in the present Elise configuration costs the same as a quadrupole in the 1994 CDR machine, in proportion to its size. A bottom up cost estimate of the final Elise configuration has not been done. We believe that the present machine will cost less than the 1994 CDR machine although there is some uncertainty due to the fact that several significant features exist in all the new machine options which did not exist in the CDR machine. Furthermore, some features like alignment and ESQ articulation were significantly redesigned, making the cost estimate less accurate. Another example of cost uncertainty is the volume of Metglas® in the present Elise design which is 2.8 times that required in the 1994 machine. Extrapolating cost for Metglas® housings and supports to this extreme is somewhat risky. Fortunately, most of these changes go in the direction of simplification and reducing costs. As a result most cost estimates are probably overly conservative and Elise could be built within the approved project cost.

VI ELECTRICAL SYSTEM

The induction core material is a critical component of the induction accelerator impacting the machine performance and cost. Cost optimization includes the materials losses (Joules/m^3) which dictates the power of the pulse modulator, hence the cost of driving the cores. A large effort is spent on investigating the magnetic materials for the Elise induction accelerator modules and on optimizing the design of the induction modules.

A. Magnetic Materials

A variety of magnetic materials have been used in previous induction accelerators. For short pulse duration (less than 100 ns) ferrites have been used. For the longer pulse lengths the nickel-iron alloys and amorphous materials (Metglas®) have been used. A driver require pulse durations from hundreds of microseconds at the low energy end to about 100 nanoseconds at high energies. The Elise accelerator represents the low energy end of a driver and is designed with a pulse duration of a few microseconds. Although the material quantities required for Elise are small compared to a full driver, it is crucial for economic and efficiency reasons to select the best magnetic material for our pulse regime. A considerable effort has been spent in the past decade in the investigation of magnetic materials which are best suited for this application. A number of alloys were re-tested and compared to the previous magnetic properties data. In the past decade the magnetic properties are unchanged, but the uniformity and the manufacturability have improved. There have been dramatic cost reductions in the amorphous ribbon produced by Allied Signal for the 60 Hz power distribution industry. This is the main reason why our testing effort has concentrated on the amorphous alloys.

Russian and American Ni-Fe material was also tested which would be quite acceptable for Elise. This material was dropped from consideration early in the project simply because the cost for the American made, even in mass production, was estimated to be one order of magnitude greater than the amorphous alloys. The Russian Ni-Fe cores were likewise acceptable, but it was not possible to obtain any commitments on the manufacturing and price quotation of larger cores for Elise.

The amorphous alloy that is manufactured for the 60 Hz power industry is the lowest cost magnetic material available. This material is annealed after winding to achieve the lowest loss. Annealing is necessary to make this material competitive at 60 Hz. Insulation between layers is not necessary since the surface resistivity is sufficient to hold off the few mV generated per layer at these very low rates of magnetization. For Elise, where the rate of magnetization (dB/dt) is many orders of magnitude greater, there are several volts per layer of ribbon, thus electrical insulation is required between layers. Annealing embrittles the material and winding the cores afterwards in mass production is difficult. Previous efforts at LBNL and elsewhere have concentrated on finding interlaminar insulation that can withstand annealing temperatures, has no deleterious effects on the magnetic properties and is inexpensive. These efforts were successful except for the high cost of the insulation. For the last few years, therefore, our efforts have concentrated on testing the materials "as-cast" and to compare them to the annealed ones. Our tests on as-cast alloys indicate that at the rate of magnetization for the Elise cores (2-10 Tesla/μs) the only difference is that the remnant flux (B_r) is lower for the as-cast, but the flux swing and the losses are about the same as the annealed material. If the cores were pulsed from $-B_r$ to B_{sat} we would obtain a slightly lower ΔB with the as-cast cores. However, since the cores must be reset from B_r to $-B_r$ or to $-B_{sat}$ before each acceleration pulse, it was possible to achieve the full flux swing on the as-cast cores simply by maintaining the reset current through the core while applying the acceleration pulse.

During our testing program, it was observed that some batches of the alloy 2605 SC displayed higher losses and lower flux swing. It was not possible to determine the cause of these bad cores. Performance degradation could have been due to overstressing the material during the winding process to achieve high packing factors, shorted layers of ribbon due to the mylar slippage or perforations or could have been due to variations in the quenching phase of the alloy during manufacturing. We are working with Allied Signal Co. to avoid bad batches by careful control of the manufacturing process and careful winding techniques. If it is desirable for the cores to be more rigid, it should not be difficult to apply some adhesive between layers in the winding process without decreasing the packing factor. We are continuing to investigate whether full or partial annealing can improve the material properties.

In previous years our studies concentrated on testing "pulse quality" alloys such as the 2605 CO, S3, S2 and SC. Our tests showed that the 2605 SC was optimal for Elise (Fig. VI-1). The conceptual design report (CDR 1994) used this material for our baseline cost estimates. The material was manufactured at the specialty products division of Allied Signal in Parsippany, N.J. in 2-inch widths. This width was convenient in that it allowed the half lattice period to increase in approximately the same increments. In the present status of very tight budgets, it is imperative to reduce the cost as much as possible. One way to cut cost is to use the TCA alloy (recently renamed as SA1) material which is being produced by Allied Signal at Conway, S.C. for 60 Hz industrial uses at one fourth the cost of pulse quality material in ribbon widths no smaller than 5.6 inches. The material has a composition similar to that of 2605 SC, so it may be suitable for our application. Using the wider ribbon, the overall packing factor (ratio of magnetic material to overall area) is improved yielding more volt-seconds for the machine. It may be possible to

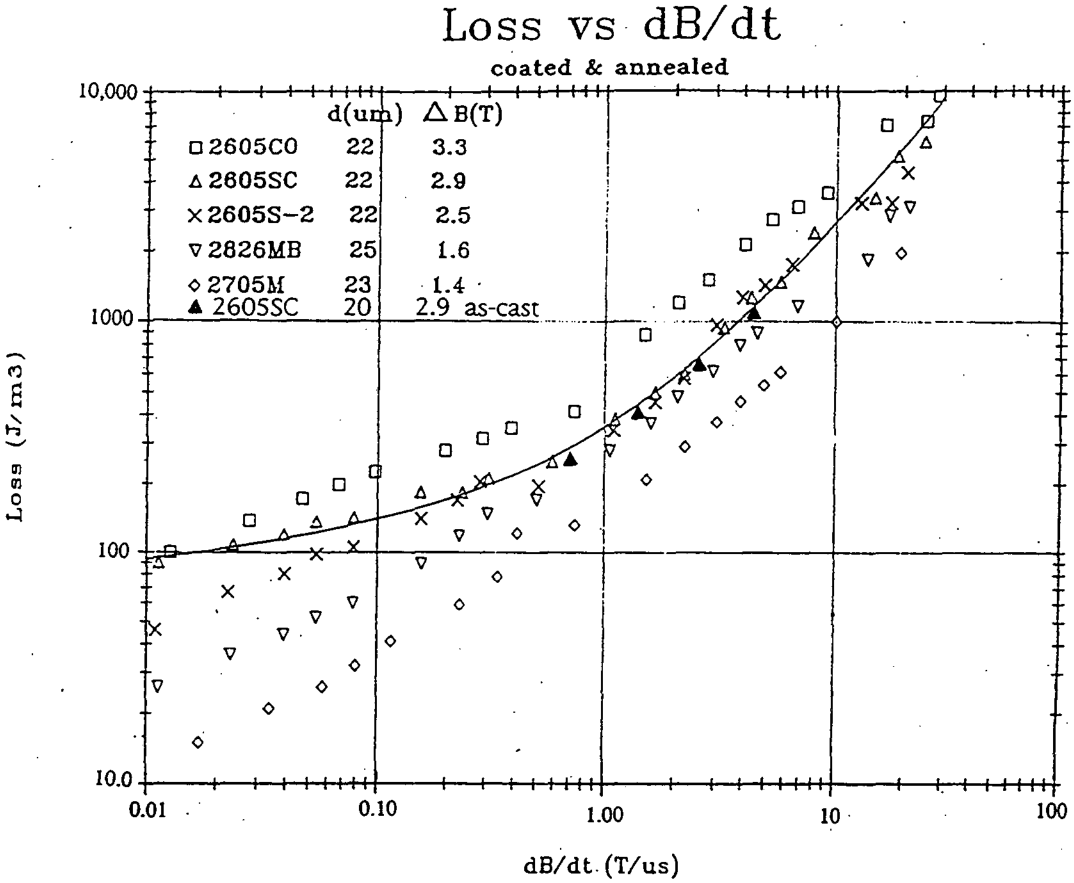


Fig. VI-1 Energy loss as a function of rate of magnetization for various materials.

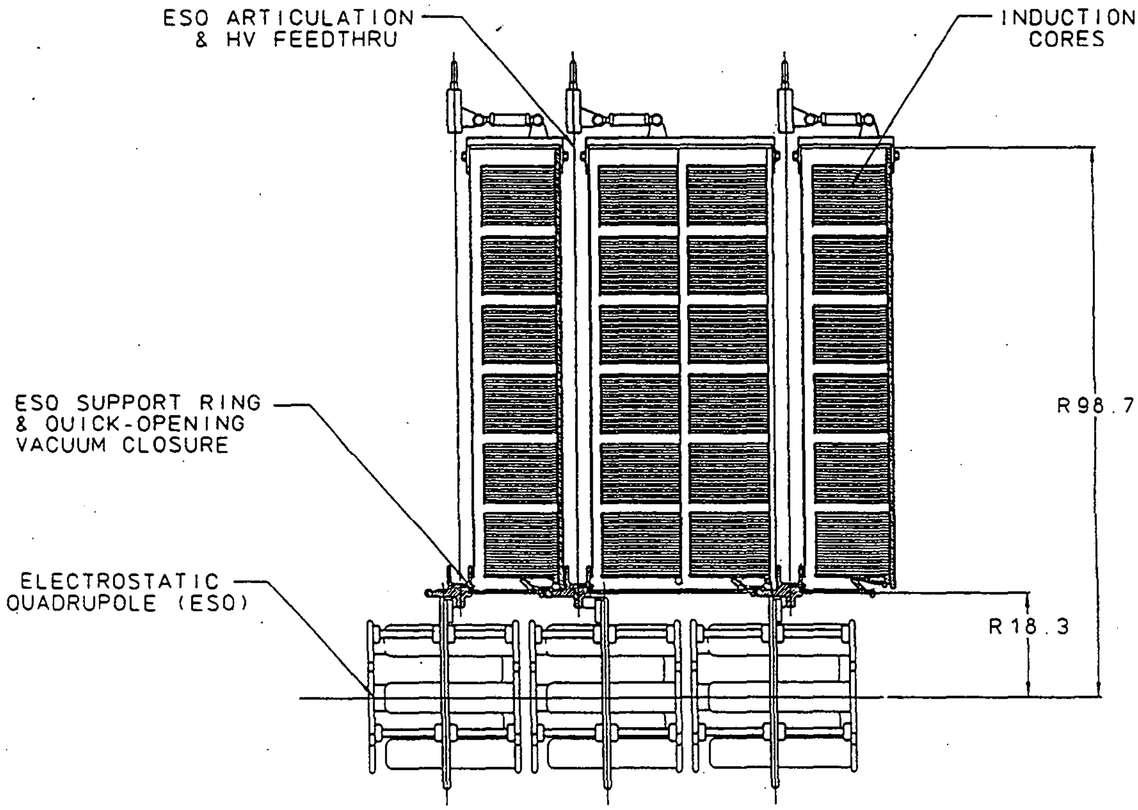


Fig. VI-2 Typical modules of Elise induction cells and ESQs.

further improve the packing factor in the radial direction by decreasing the spacing between the radially stacked cores (Fig. VI-2).

Along with the cost optimization (designs based on using the wider Metglas®), we also started testing the TCA alloy at pulsed high rate of magnetization. The original expectation was that TCA would be acceptable as a replacement to 2605 SC. Unfortunately, tests on several samples of 6.7" wide TCA alloy showed a lower flux swing and higher losses than the best 2605 SC material (Fig. VI-3). The higher losses can be partially explained by the fact that the average thickness of the TCA samples was 1.05 mils thick rather than 0.8 mils for the 2605 SC and at high rates of magnetization the eddy current losses are important. More importantly, the TCA material that we tested did not even peroform well at 60 Hz. We therefore concluded that the Metglas® material supplied by the manufacturer must be better quality assured in order to perform more meaningful tests.

Alloy	(tesla/µs) dB/dt	(Joules) Losses	(Tesla) ΔB	
2605 SC	2.0	11	2.6	20µm
2605 SC	2.4	14	2.7	
SA1	1.4	13	2.0	27 µm
SA1	1.4	13	2.0	
SA1	1.3	14	1.9	
SA1	1.3	12	2.0	
SA1A	1.5	16	2.2	
SA1A	1.4	14	2.1	
SA1A	1.6	18	2.2	
SA1A	1.3	13	2.1	

A - Annealed cores

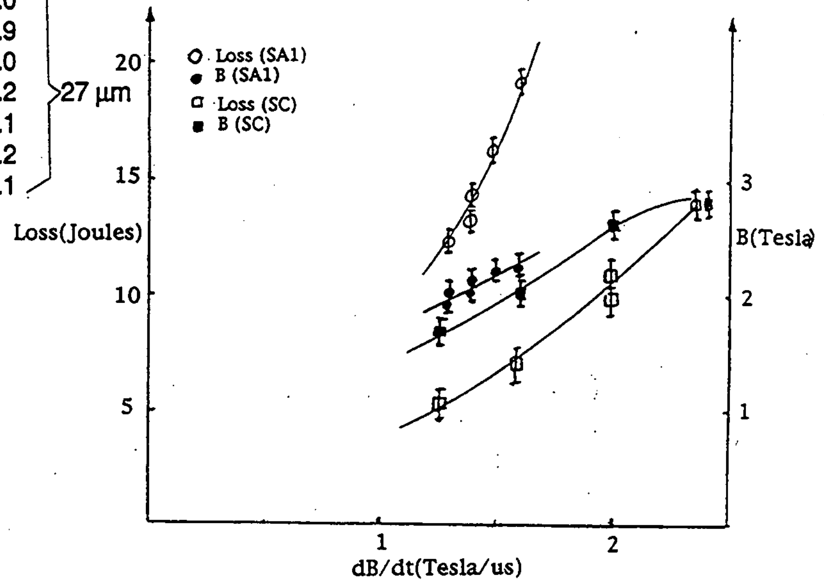


Fig. VI-3 Energy loss as a function of rate of magnetization for 2605SC and SA1.

Aware of the test results on the TCA alloy, members of our industrial team discussed the issues with Allied Signal and asked the question whether 2605 SC could be mass produced at their batch casting plant in South Carolina. The answer was a qualified yes. If the quantities ordered were greater than 100 metric tons and the material was 5.6" or wider, the alloy composition could be modified and a batch casting machine could be dedicated to manufacturing the 130 metric tons of 0.8 mil 2605 SC required by Elise. The cost reduction would not be quite as dramatic as for the TCA ($3.30/kg) but would be one third the cost of original Elise estimates or $5.00/kg instead of $15.00/kg. We have tentatively adopted the 2605SC in our baseline design. At the same time, we are confirming our investigation into annealing, insulating and winding magnetic tapes.

The typical losses and magnetic properties are shown on Fig. VI-1. Most of the testing was carried out at the 1-2 μs pulse duration. Eventually a driver will require considerably shorter pulses, so more testing should be carried out at the 100-300 ns pulse duration.

B. Pulsers

Once the acceleration schedule is determined by the physics design of Elise, a number of options are available for driving the induction modules. The pulsers or modulators must supply many kiloamps at many kilovolts and should have a long life. The voltage waveform must be controlled to better than 1%. This requirement determines the pulse generators required to drive the cores. To achieve this type of accuracy, both the hard tube modulator and the solid state modulator are considered. Several hard tube modulators are operating at LBNL and their performance would certainly satisfy Elise. However, their cost is nearly one order of magnitude greater than the standard line modulator. A solid state modulator was purchased (from Anderson) and thoroughly tested. The solid state modulator has 2000 MOSFETS in a series parallel array to achieve the kilovolts-kiloamperes of drive required by Elise. This modulator likewise can satisfy the waveform accuracy required, but the cost is also an order of magnitude too high. The cost is not so much in the individual MOSFETS but in all the ancillary protection circuitry to insure voltage and current sharing and the isolating fiber optics trigger system.

Economic constraints left only the line modulator as the option for driving the induction cells. Previously constructed modulators and computer simulations of the Elise drive chain indicated that better than 1% was not possible with a line modulator driving the highly nonlinear load of the induction cell. We concluded that in order to meet the waveform requirements and remain within the economic constraints, the main modulators must be of the line type, but the fine control of a few percent will be supplied by active solid state devices called fast waveform correctors. Since the fast correction pulses supply only a few percent of total energy, the total cost will be minimized. A fast correction prototype has been built and tested at Science Research

Laboratory under a Phase I SBIR funding. A high power device will be constructed and tested with the real induction cells at LBNL if Phase II is funded. A block diagram of the complete drive system is shown in Fig. VI- 4.

The choice of a line modulator still leaves many options in terms of switching devices and types of pulse forming networks. The high voltage/high current requirement for driving the cores limits us to choosing either thyratrons or spark gaps. Spark gaps allow pulsers in the hundreds of kilovolts and kiloamperes reducing the total number required, thus leading to the lowest cost pulsers. Ultimately spark gaps may not be able to meet the lifetime requirements of a driver. The argument can be made, however, that for initial experiments they offer a minimum cost solution.

Thyratrons are the mainstay of many modulators for driving r.f. accelerators, kicker magnets, and induction accelerators. They have a well documented lifetime which is greater than 10,000 hours or at 10 Hertz translates into nearly 10^8 pulses, close to the requirements of a driver.

They have operated for 10^8 pulses in the Astron Injector induction linac, and may be good for a longer life. Using thyratrons requires more pulsers simply because they cannot switch the high peak power of the spark gaps and lead to a more expensive solution but one which is much closer to a driver solution.

The choice for Elise is simple since we have access to many surplus thyratrons at no cost to the program. If these thyratrons were not available, the choice would probably have been the same. Glass thyratrons are reliable and with some development may offer both a technical and economic solution for a driver.

The pulse forming network (PFN) must drive a highly nonlinear load. The PFN chosen is one which has an impedance that matches temporally that of an induction core, that is, decreases in impedance by a factor of two from the beginning to the end of the pulse. This network is best synthesized using coupled solenoids wound on the same form and capacitors of increasing value. The inductance of each stage can easily be varied by inserting a flux excluding pipe inside the insulating coil form or a high permeability material thus matching the PFN impedance temporally to that of the core. Fig. VI-5 shows the plug-in PFN board which is easily adjustable. The thyratron available to us is the CX 1538 which is capable of switching 5 kA at 30 kV or a peak power of 75 MW for a few microseconds. Without investing a large effort it is possible to obtain a voltage waveform with variations of $\pm 3\%$ as shown in Fig. VI-6.

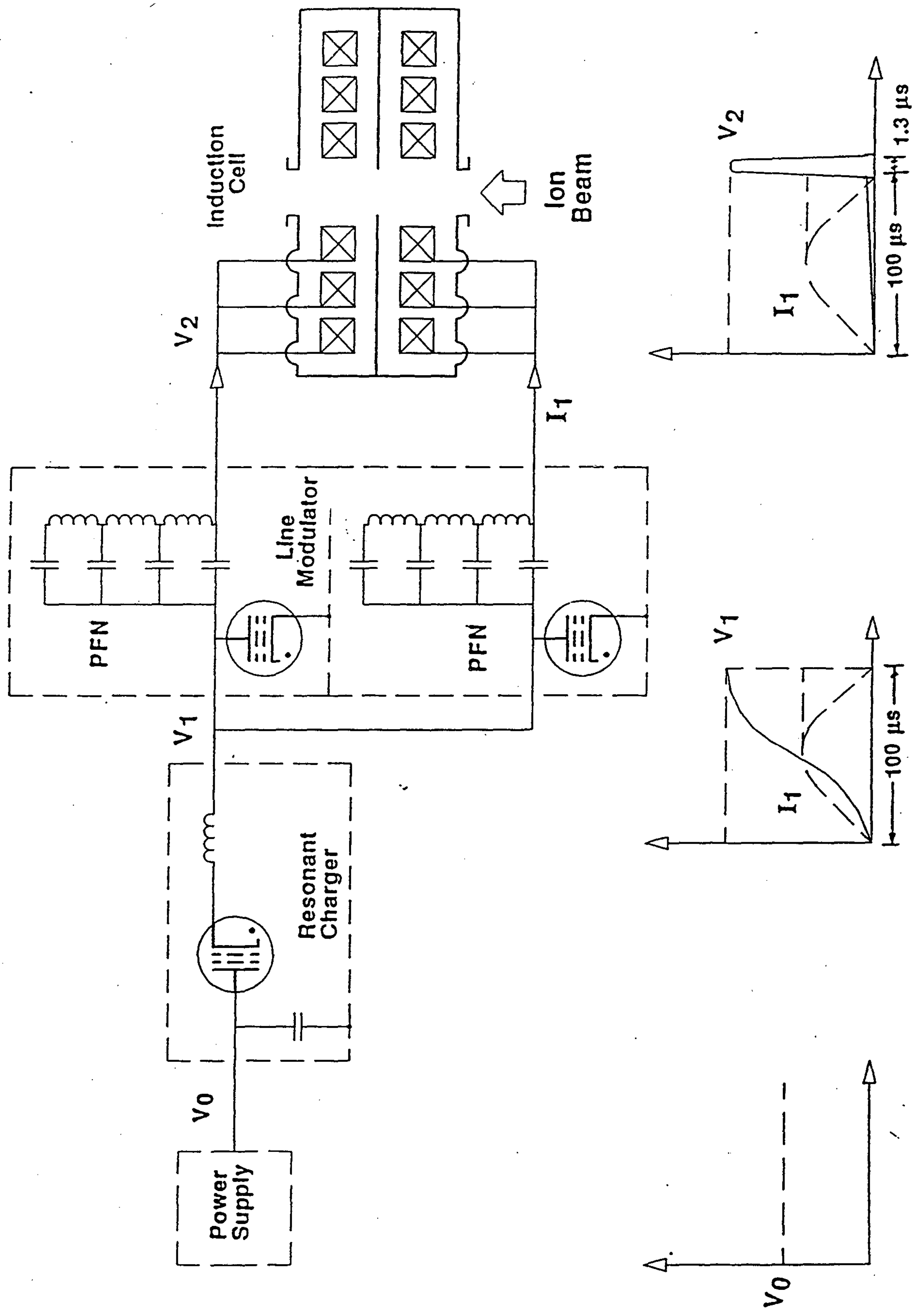


Fig. VI-4 A line modulator is used to drive the Elise induction cells.

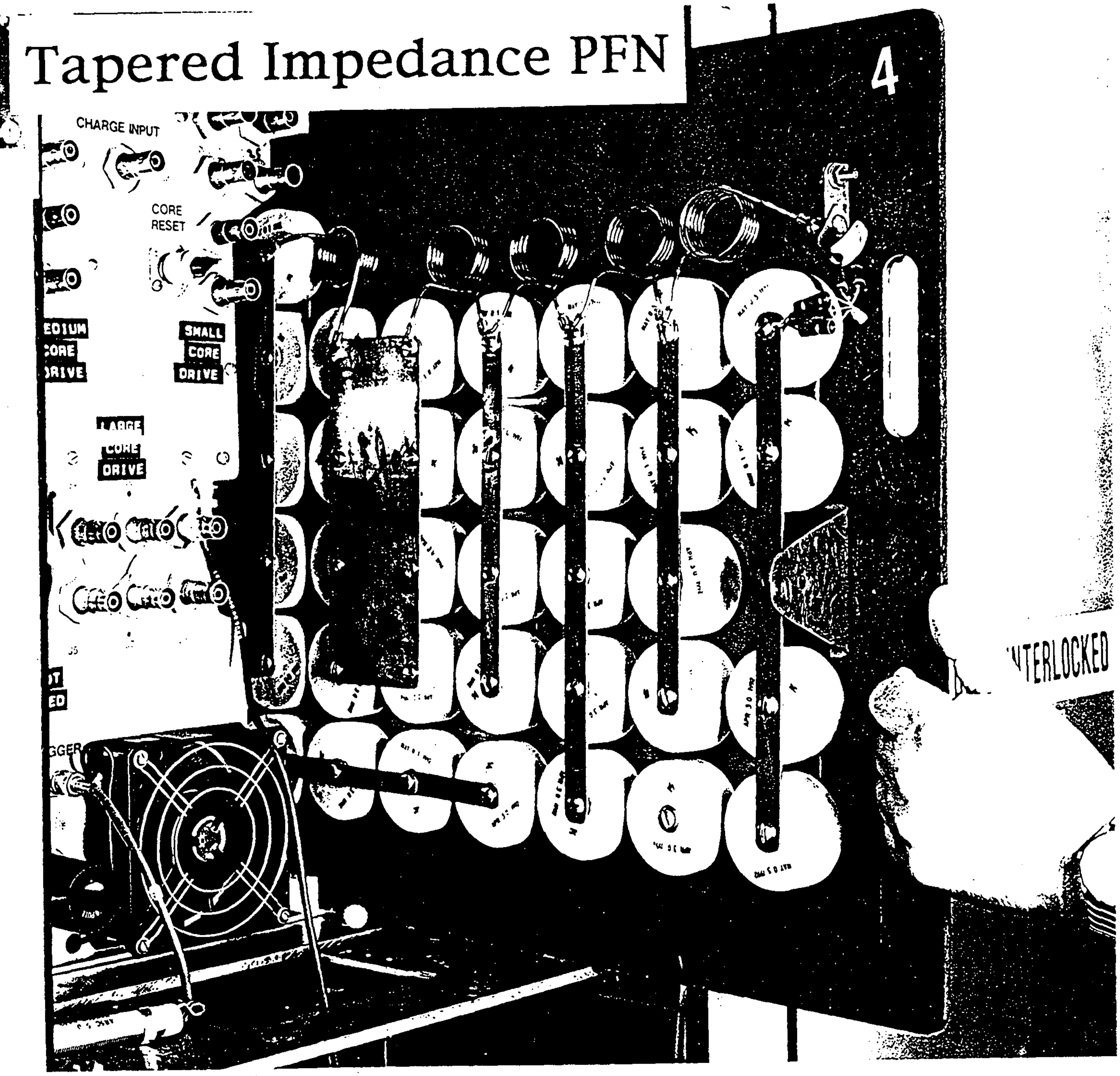


Fig. VI-5 A photograph of the PFN prototype.

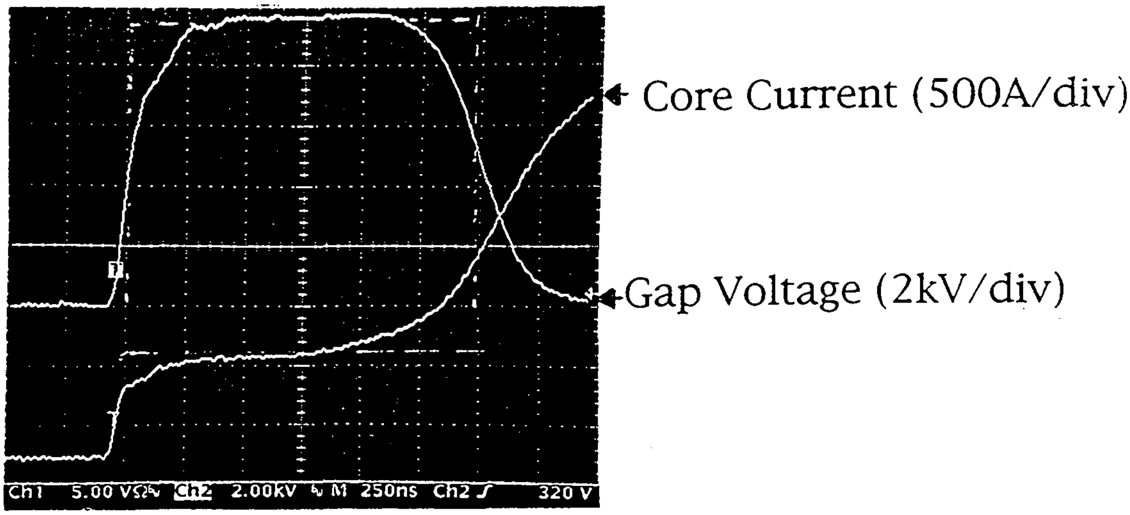


Fig. VI-6 Test result of a small induction core (voltage and current).

C. ESQ Power Supply & HV Feedthrough

The electrostatic quadrupoles housed within the acceleration modules require DC bias voltages of about ±70 kV. Sufficient space is allocated between the modules to allow for placement of the high voltage feedthrough. In order to reduce cost, several quadrupoles will be fed by a single power supply with resistive dividers to allow for different voltages to each power supply (Fig. VI- 7). These power supplies are very low power (practically zero current) and will be procured through a competitive bid process. These commercially available units will be regulated to better than 0.1% and will be adjustable through the computer control system.

The high voltage feedthrough to bias the ESQ poses a non-trivial problem since it is highly desirable to minimize the spacing allowed between induction modules. The commercially available feedthroughs which also offer good vacuum interface tend to be quite large. A small in-house effort has resulted in two designs which should satisfy our criterion that the high voltage feedthrough holds off twice the operating voltage. The first option is to bring the high voltage in concentric conductors to the outside diameter of the induction modules where there is not a size limitation and a commercial unit can be used. The second option is to use a re-entrant ceramic tube which is vacuum sealed at the ends and will house the high voltage cable. Several such connectors have already been constructed and tested in the matching section experiment (Fig. VI-7). Their breakdown voltage approaches twice the operating voltage of ± 70 kV.

The pulsed acceleration voltage applied to the induction modules will appear across the adjacent pairs of electrostatic quadrupoles. Since the high voltage DC bias will be fed from a high impedance source, one must insure that a very small fraction of the pulsed voltage appears across the power supply and most of it appears between adjacent pairs. This is accomplished by providing a cable termination inside the high voltage power supply. This termination, typically 50 ohms, is obviously AC coupled and dissipates no power (Fig. VI-8). This 50Ω termination also provides a diagnostic tool for measuring the beam amplitude since the beam passing through the ESQ aperture induces a displacement current through the resistor which can be monitored.

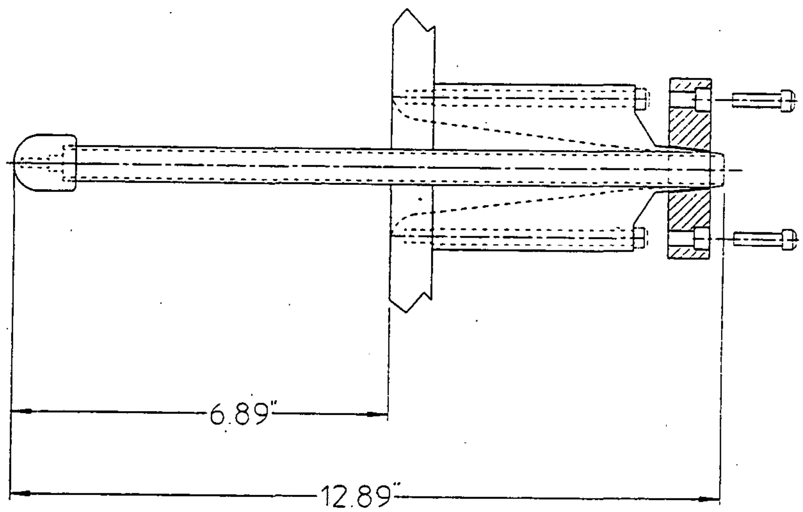


Fig. VI-7 High voltage feedthrough used to bias the ESQ electrodes.

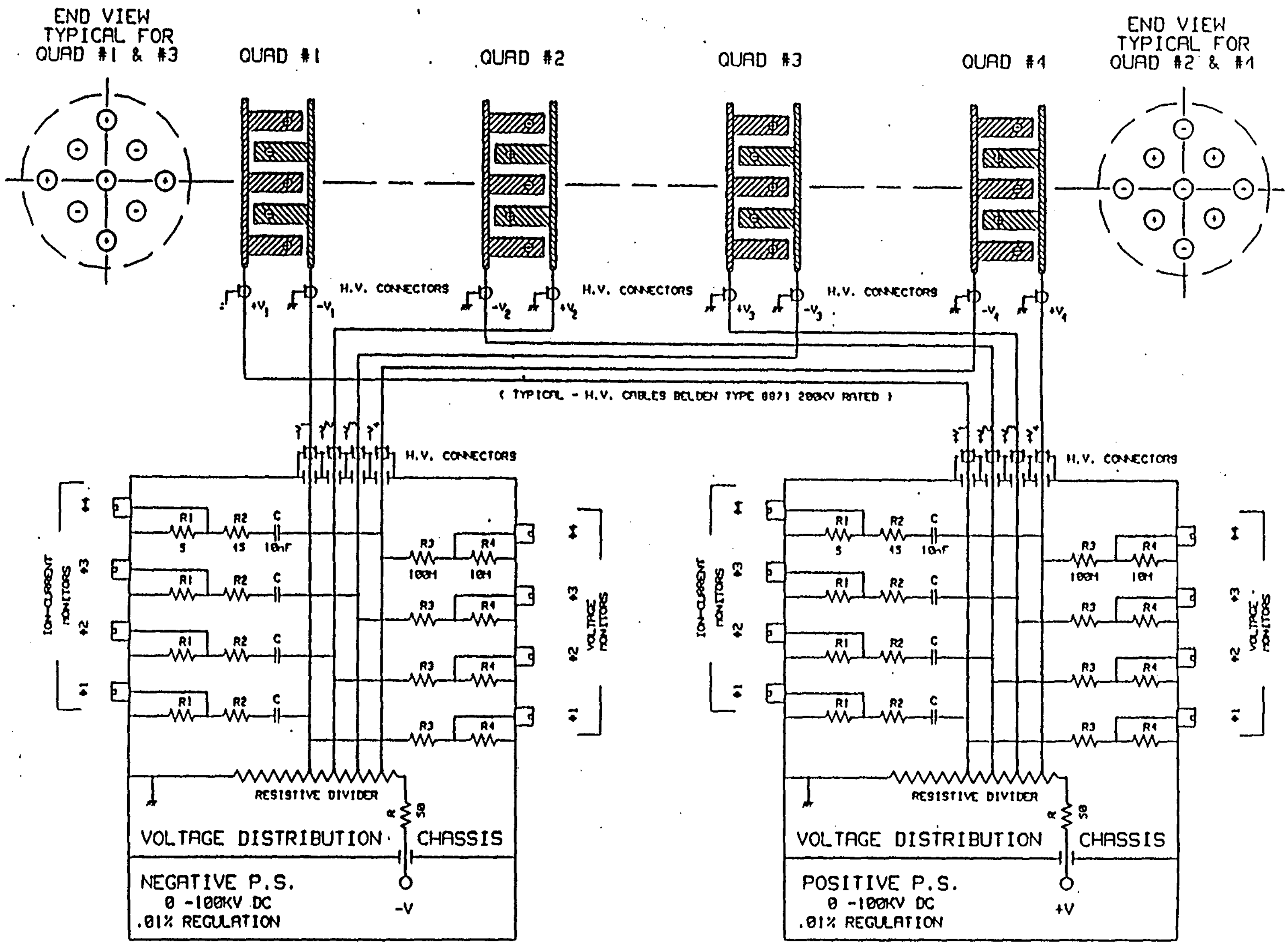


Fig. VI-8 Wiring diagram for the acceleration voltage to the ESQ electrodes.

VII. CONVENTIONAL FACILITIES

The conventional facilities portion of the Elise project will provide a new, non-combustible, weather tight, 6000 sq. ft., single-story, steel-framed, metal structure for the various components of the Elise accelerator. It will be located within the existing Building 51B External Proton Beam (EPB) Hall and will also relocate an existing, 1,334 sq. ft., single-story, steel-framed, metal building (Building 51G) which will be remodeled for use as the control room (see Fig. VII-1 and Fig. VII-2). As shown in Fig. VII-3, the accelerator will be mounted on a rail system that will bear directly on the floor. The conventional facilities will include the foundation for this system.

The topping slab in the accelerator building will be designed and specified to provide a hard, dust-free, level and smooth surface for the movement of the air-pallet equipment. The rail system supporting the accelerator will have the following tolerances and parameters:

(i) Vertical deviation from level over the entire length of track is ±0.25 inch

(ii) Vertical deviation from level over 10'-0" of track is ±0.0625 inch

(iii) Minimum thickness for threading and tapping is 1.00 inch.

An existing overhead crane in the EPB Hall will provide service for lifting accelerator components weighing several tons. Within the structure housing the accelerator, there will be areas allowing for the use of air pallets. Clearances are to be maintained for the installation of a new bridge crane which will span the width of the accelerator building (see Fig. VII-4). The bridge crane will transmit vertical and lateral forces into the accelerator building itself and will ride on a rail system (separate from the rails for the accelerator itself) to be incorporated into the building structure. The bridge crane shall have a capacity of 6 tons.

Louvered openings are to be provided at alternate bays adjacent to the electrical equipment at high and low levels in order to allow installation of ventilation system for cooling the electronic equipment. An exhaust system is required for emergency removal of sulfur-hexafluoride gas (which is used in the accelerator housing to improve high voltage capabilities) at the rate of about 200 CFM at a pressure of one atmosphere. The exhaust system shall also remove residual sulfur-hexafluoride gas from the injector pit when present. An existing exhaust system consisting of a 24" diameter duct with a 1 hp contrifugal blower and a 3 hp axial blower mounted in series on the west wall extends to the roof. The existing system is to be evaluated for refurbishment and reuse or for demolition and replacement.

Motors for building utilities, such as fans, air-conditioning, compressors and pumps that are larger than 400 Watts (1/2 HP) will utilize 208, or 480 Volts 3-Phase power with 120 Volt controls. Motors that are 400 Watts or less will be 120 Volt, single-phase. The A/E will design a ground grid system for the Accelerator Builiding, Control Room (Building 51G) and Substation which will tie into the existing Building 51B ground system and that will provide a ground resistance of 5 ohms or less. The ground system will have a means to periodically check the integrity of the system by Fall of Potential measurements.

Construction of the conventional facilities is estimated at $930K and will take not more than 2 years. LBNL's Facility Dept. has done preliminary studies and has written project design requirements for A/E Title I RFP.

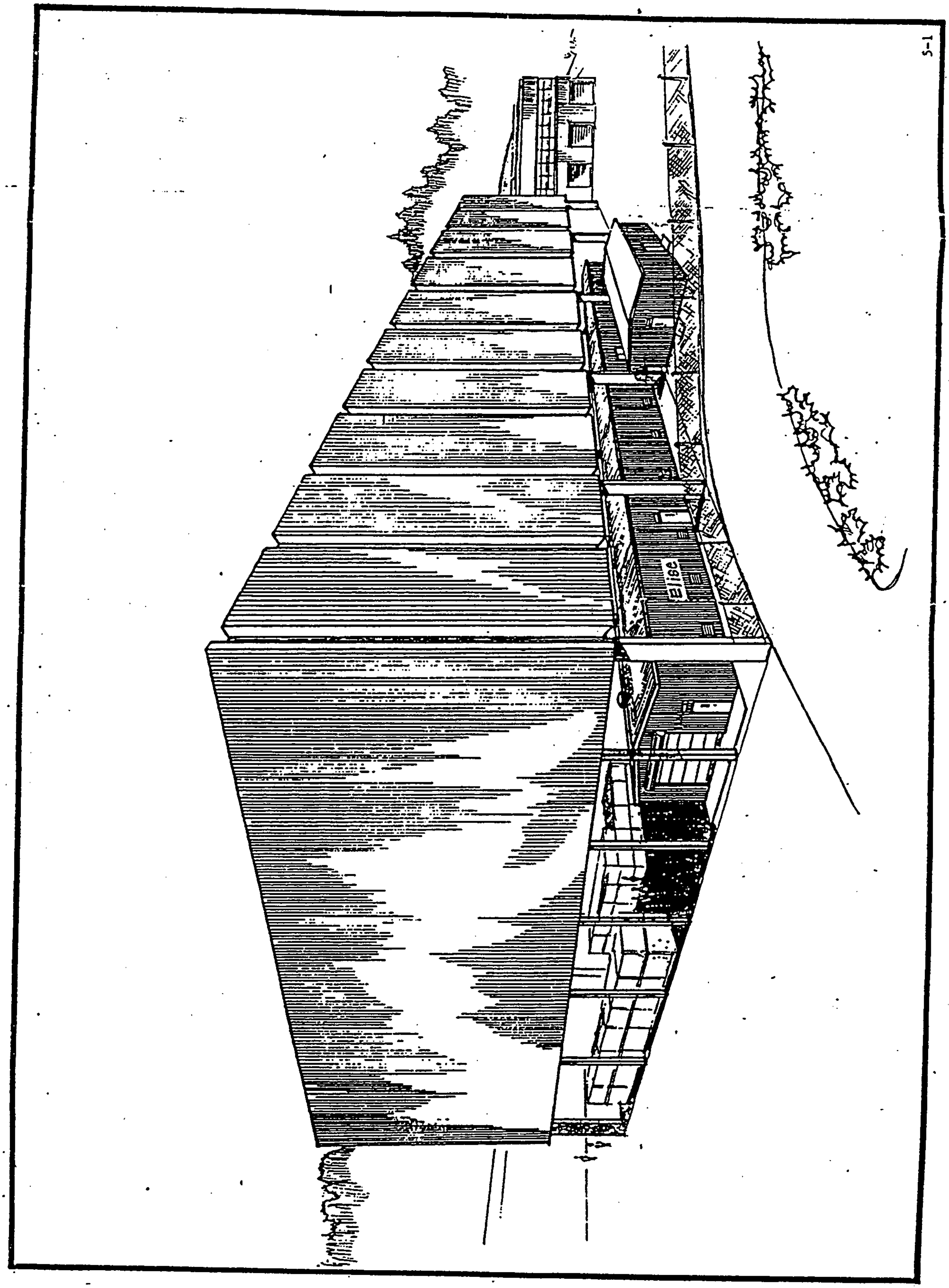


Fig. VII-1 Elise Perspective with Building 51 B External Proton Beam (EPB) Hall.

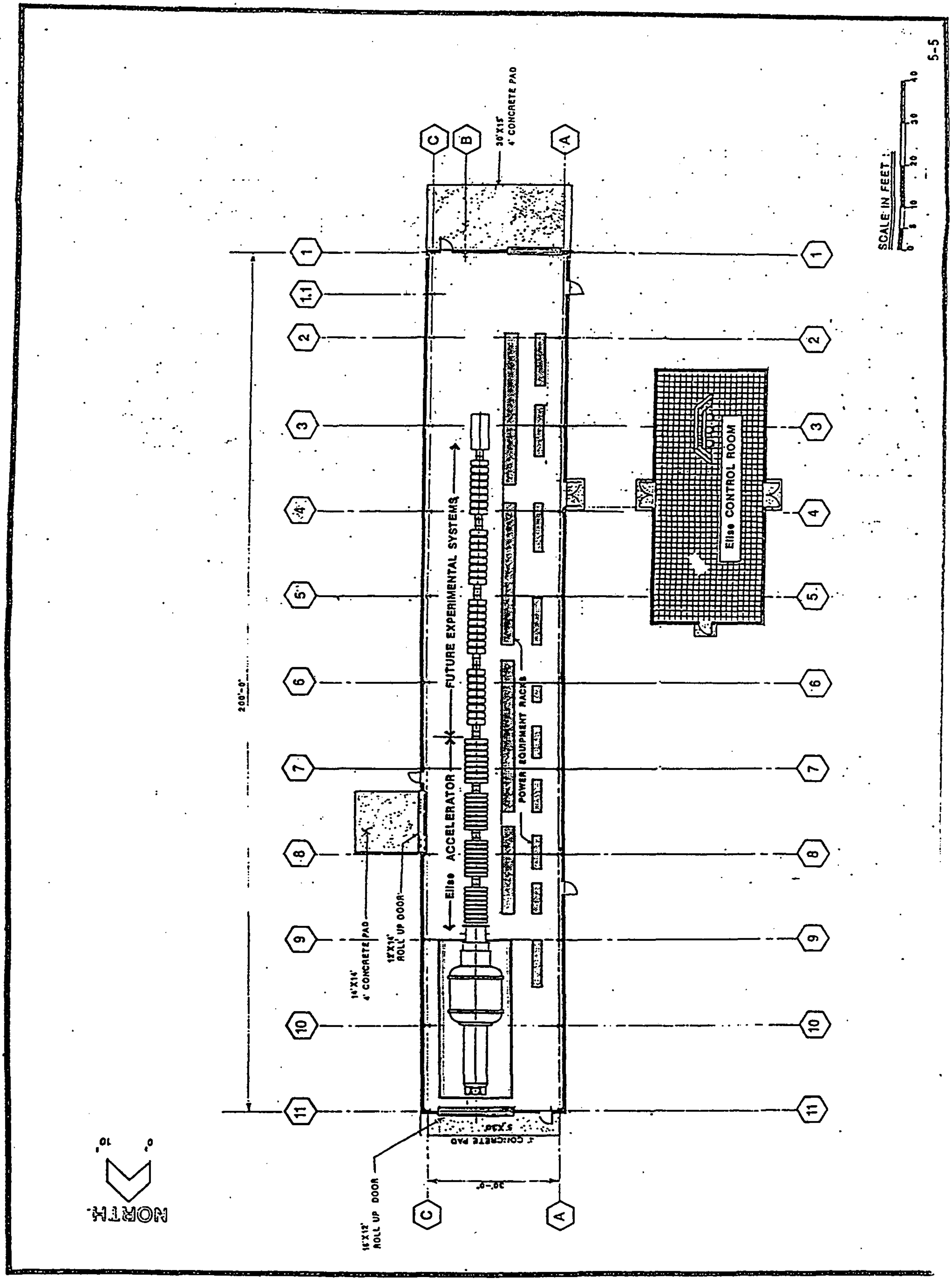


Fig. VII-2 Elise Floor Plan Layout.

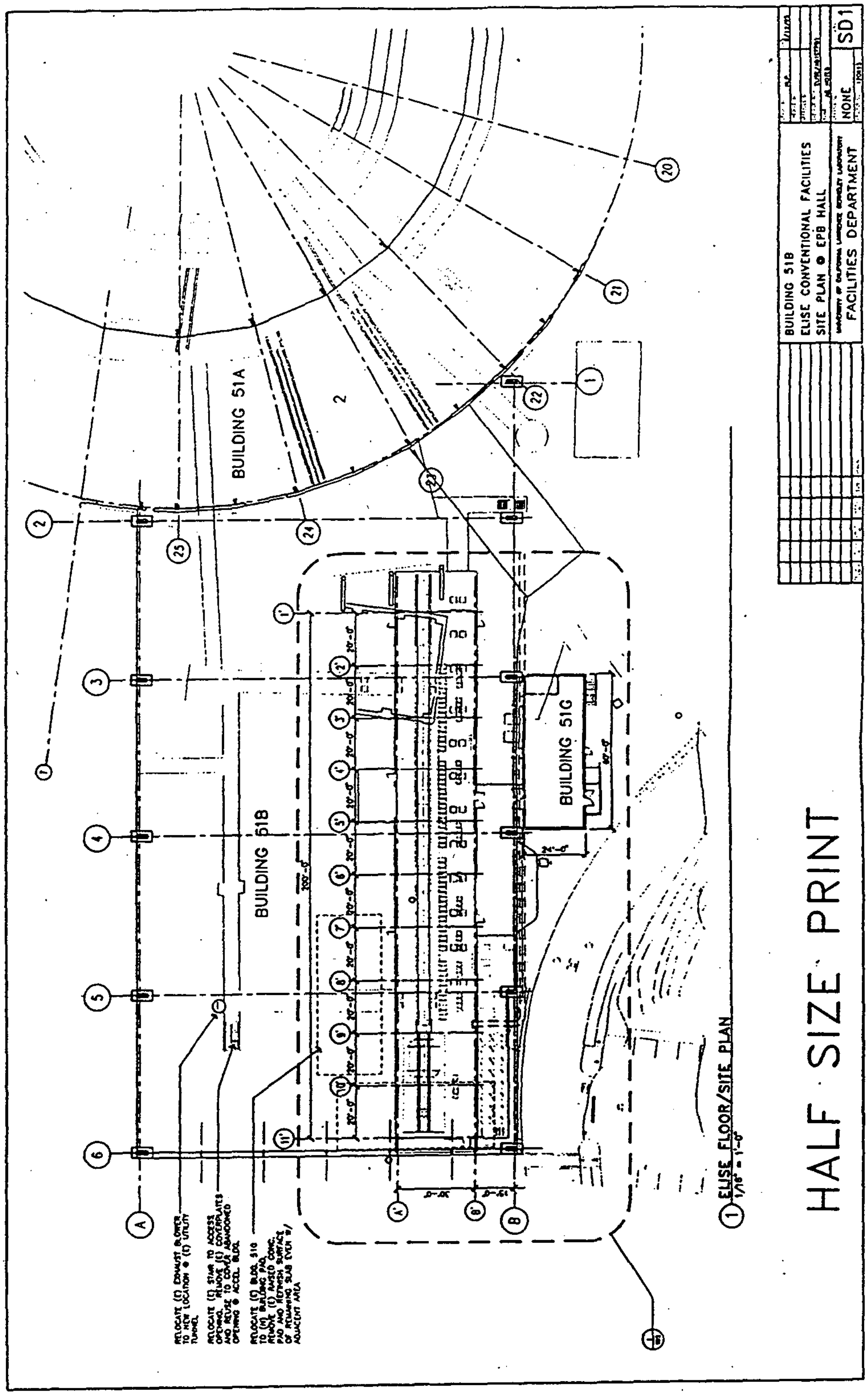


Fig. VII-3 Elise Layout showing the railings for mounting the accelerator.

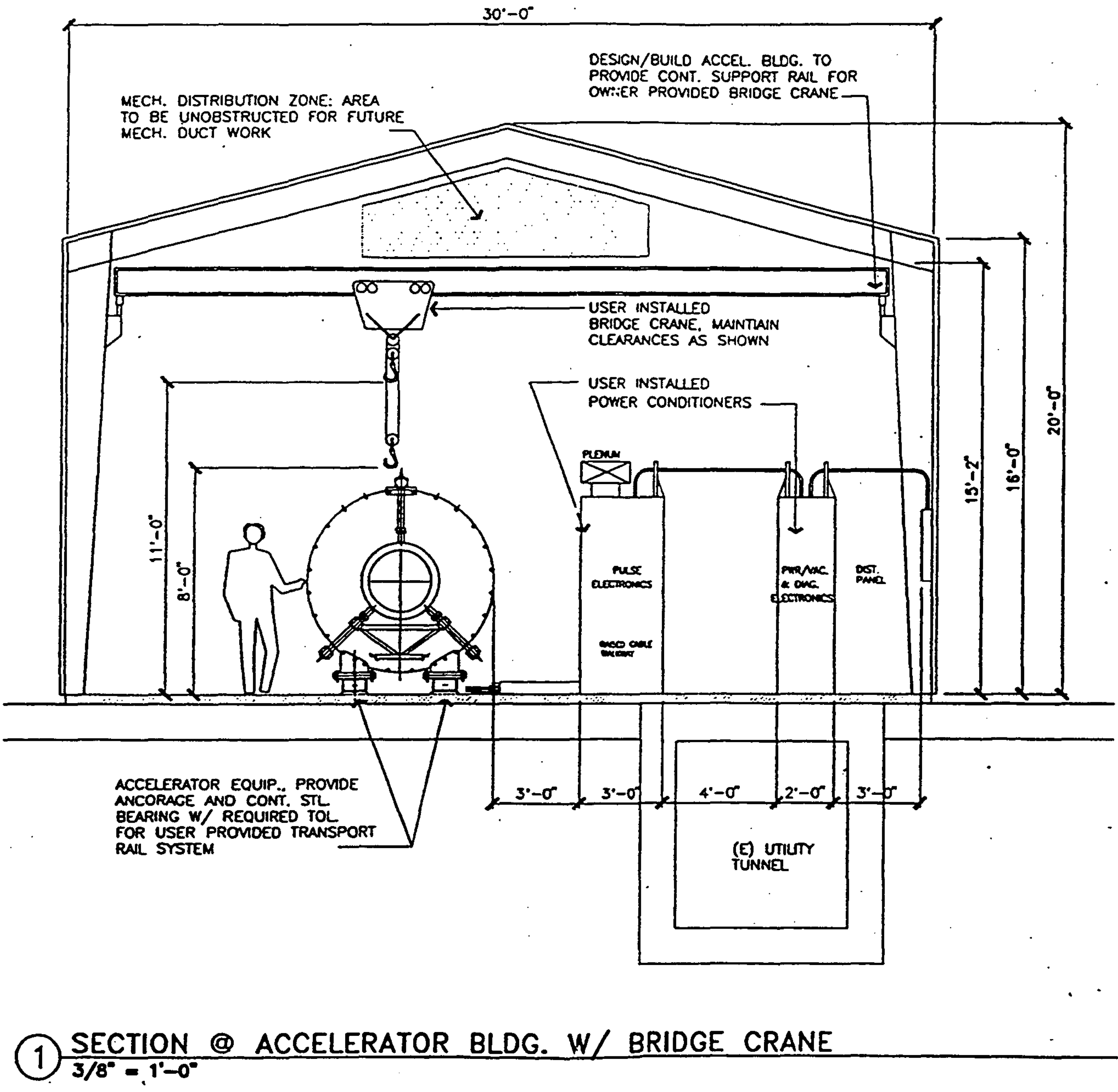


Fig. VII-4 Elise endview showing overhead bridge crane.

VIII. SUMMARY

The Elise project was approved (KD-1) by the Department of Energy in December 1994. The construction time is expected to take 4-3/4 years and cost $25.9M as dictated by the proposed funding profile. The objective of this project is to build an linear induction accelerator, using the existing 2 MeV single-beam injector and a new electrostatic quadrupole focusing channel, to accelerate high current heavy ions (atomic mass ≥10) beams to more than 5 MeV. Elise will have four ESQ channels, but only one channel will be operated. A follow-on extension of Elise, named ILSE, will further accelerates the 5 MeV beams (from Elise) to more than 10 MeV using magnetic quadrupole focussing. With Elise/ILSE, many of the basic technical questions concerning the suitability of this approach, as a driver for Inertial Fusion Energy, can be studied.

Elise will be located at the External Proton Beam (EPB) hall of LBNL's Bevatron Complex. Physically the induction accelerator is approximately 15 m long, 2 m in diameter, and contains more than 130 metric tons of magnetic material. The accelerator will have a column jacket of approximately 37 cm diameter and the bore diameter in each channel is 4.66 cm. The alignment tolerance is 0.1 mm.

Many design improvements have been made since KD-1 in an effort to boost the performance of the machine. For example, the entire 14-meter acceleration section will be mounted on rails together with a remotely actuated vacuum closure system to permit opening of the vacuum enclosure at each ESQ therefore providing quick access for diagnostics and maintenance. To minimize the machine length, the ESQ support and the high voltage feedthroughs are designed to fit within a 5-cm gap between acceleration modules.

We have performed engineering testings of the ESQ high voltage requirements and the magnetic material for the induction cores. We have selected the 2605 SC Metglas® as the core material. To achieve better performance the new design will use 2.5 times as much Metglas® as before, leading to a volume discount in the cost. According to Allied Signal Inc., the supplier for Metglas®, a batch casting machine can be dedicated to manufacture the 130 metric tons of 0.8 mil thick, 5.6" or wider format, 2605 SC required by Elise. The cost is about $5.00/kg (instead of $15.00/kg as originally estimated in the Elise CDR).

The choice of using a line modulator for driving the cores still leaves many options in terms of switching devices and types of pulse forming networks. The high voltage/high current requirement for driving the cores limits us to choosing either thyratrons or spark gaps. For Elise we will use thyratrons because we have access to many surplus thyratrons at no cost to the project. If these thyratrons had not been available, the choice would probably have been the same. Glass thyratrons are reliable and with some development might offer both a technical and an economic solution for a driver. Spark gaps allow pulsers in the hundreds of kilovolts and kiloamperes reducing the total number required thus leading to the lowest cost pulsers. However, the spark gap lifetime and reliability must be improved by several orders of magnitude for driver use. The PFN chosen is one which has an impedance that matches temporally that of an induction core, that is, decreases in impedance by a factor of two from the beginning to the end of the pulse. It is not difficult to obtain a voltage waveform with variations of $\leq \pm 3\%$.

As part of the Elise R&D associated with construction, we have contracted an industrial team led by Westinghouse* to investigate issues related to the Elise design and construction. (Other team members include SAIC, SRL, Northrop Grumman, TRW, Maxwell, Univ. Pittsburgh, and Univ. Wisconsin.) Their work scope includes the development of magnetic material, pulsers, low-cost switches, accelerator manufacturing and planning. A written report was submitted by Westinghouse to LBNL on March 31, 1996.

ILSE has already received the environmental assessment approval--Finding of No Significant Impact (FONSI). A copy of the document is included in Appendix A. Also included in the Appendix is the Project Management Plan which was developed after receiving the KD-1 approval. Unfortunately, the project has not received construction funding in FY96 (hence no KD-2) and is indefinitely postponed.

IX. APPENDIX

U.S. Department of Energy (DOE)

Finding of No Significant Impact

Induction Linac System Experiments in Building 51B

at

Lawrence Berkeley National Laboratory, Berkeley, California

AGENCY: U.S. Department of Energy (DOE)

ACTION: Finding of No Significant Impact (FONSI)

SUMMARY: The U.S. Department of Energy (DOE) has prepared an Environmental Assessment (EA), (DOE/EA-1087) evaluating the proposed action to modify existing Building 51B at Lawrence Berkeley National Laboratory (LBNL) to install and conduct experiments on a new Induction Linear Accelerator System. LBNL is located in Berkeley, California and operated by the University of California (UC). The project consists of placing a pre-fabricated building inside Building 51B to house a new 10 MeV heavy ion linear accelerator. A control room and other support areas would be provided within and directly adjacent to Building 51B. The accelerator system would be used to conduct tests, at reduced scale and cost, many features of a heavy-ion accelerator driver for the Department of Energy's inertial fusion energy program.

Based upon information and analyses in the EA, the DOE has determined that the proposed action is not a major Federal action significantly affecting the quality of the human environment within the meaning of the National Environmental Policy Act of 1969. Therefore, an Environmental Impact Statement is not required.

DESCRIPTION OF THE PROPOSED ACTION:

The proposed action is to modify existing Building 51B at LBNL to accommodate a new 10 MeV heavy ion linear accelerator, experimental extensions, and adjacent support areas. The accelerator system that would be installed would be used to perform experiments that would advance the understanding of high current, heavy ion accelerator physics. The physics issues that would be addressed in the experiments include beam combining, longitudinal beam bunch control, final focus, and other technical issues. Fabrication and maintenance of accelerator components would take place in existing LBNL electrical and mechanical shops. To operate the proposed ILSE project, a total of 6 personnel would occupy Building 51B. A maximum of 3 would be new employees. The staff in the support shops would not be increased above previous levels during peak occupancy.

ALTERNATIVES:

Five alternatives to the proposed action were considered: (1) no action, (2) LBNL Building 71 alternative, (3) LBNL Building 58 alternative, (4) LBNL Building 64 alternative, and (5) an off-site location: Richmond Field Station.

(1) Under the no action alternative, the proposed ILSE project would not be implemented and proposed modifications to Building 51B would not be undertaken. The no action alternative would have no effect on the environment above existing conditions. This alternative, however, would not allow DOE to test, at reduced scale and cost, features of a heavy-ion accelerator driver for inertial fusion energy.

(2) The LBNL Building 71 alternative consists of converting a portion of Building 71 from its current use as a Center for High Beam Physics, and constructing a building addition to provide adequate space for the ILSE project. This would necessitate cutting into the adjacent hillside to make room for the addition, and constructing a retaining wall. This alternative would result in slightly greater short-term impacts to air quality, traffic and parking, and noise during construction of the building addition and would have potential impacts relating to geology, soils, and seismicity because of its location adjacent to a hillside. In addition, the Building 71 alternative would incur additional environmental impacts and a higher cost than the proposed action because the building is currently occupied by other programs that would have to be relocated. The environmental effects associated with facility operations would be similar to the proposed action.

(3) The LBNL Building 58 alternative consists of converting a portion of Building 58 from its current use by the Heavy Ion Fusion Program and the Superconducting Magnet Group and constructing a building addition east of the existing building to provide adequate space to house the ILSE project. The addition would measure approximately 48 ft. by 240 ft. and would require extensive soil excavation and construction of retaining walls. The potential environmental impacts of the Building 58 alternative are similar to the Building 71 alternative because of the necessity to relocate existing programs and construct a building addition. An advantage of placing ILSE in Building 58 would be that the electrical and mechanical shops would be in the same building as the accelerator, and therefore the transport of fabricated accelerator parts between buildings would not occur. As a result, on-site traffic and air emissions from transport vehicles would be slightly less than under the proposed action. However, these benefits would be more than offset by the environmental effects associated with the additional construction that would be required.

(4) The LBNL Building 64 alternative consists of constructing an approximately 13,000 gross square foot building addition on a paved area currently used for storage. Some surface grading,

retaining walls, and minor modifications to the adjacent roadway would be required. The potential environmental impacts are similar to the Building 71 alternative because the space is inadequate to accommodate the proposed activities and therefore additional construction would be required to expand the building.

(5) The alternative offsite location is at the University of California-owned Richmond Field Station (RFS) located approximately 7 miles northwest of the LBNL site. This alternative would require construction of a new building to house the ILSE accelerator and would have greater environmental effects than the proposed action: The RFS is located within or near sensitive zones for historical and cultural resources, within the 100-year coastal flood zone, and near wetlands. Implementation of this alternative might result in negative effects to these resources. Implementation of this alternative also would add additional daily commute trips to the local street and freeway system, marginally contributing to existing traffic congestion and resulting in additional air pollutant emissions.

ENVIRONMENTAL IMPACTS:

The proposed action would have negligible or no impacts on hydrology and water quality, geology, land use, visual quality, and sensitive biological and cultural resources. Potential impacts in the areas of noise, traffic, air quality, human health, waste generation, and utilities and services are summarized below.

Impacts from Renovation

Renovation activities are expected to generate increased noise levels and short-term vehicle exhaust and airborne particulates. The increased noise levels and air contaminants are not expected to pose a threat to human health because of the low levels that would be generated, the short duration of construction, and the measures that would be taken as a normal part of construction to ensure workers and the environment are protected. Short-term transportation effects would include trips by construction workers to and from the site. The effects to traffic and parking would be minor and of short duration.

Precautions would be taken to ensure that an air release of the lead-based paint present on the building's structural steel would not occur during building modification, in accordance with the LBNL Lead Compliance Program and BAAQMD requirements. About 150 cubic yards of construction waste would be generated. Recycling or disposal of the waste would be the responsibility of the construction contractor. The concrete flooring that would be removed from Building 51B as part of the excavation of a recessed foundation for the accelerator injection subsystem, would be surveyed for radiological activity; if no radiation is detected, the concrete would be recycled or disposed of as non-hazardous waste at an approved landfill. The small quantities of hazardous wastes that would be generated during renovation activities (such as paint and solvents) would be recycled or disposed of in compliance with LBNL standard procedures for handling and disposing hazardous wastes. Only a very limited amount of grading and excavation would be required, with little or no soil remaining for disposal. Samples would be collected of any soil to be disposed of and analyzed for contaminants to determine whether or not it would be classified as hazardous waste. If so, the soil would be handled and disposed of in accordance with LBNL policies and regulations for disposal of hazardous waste.

Existing provisions of utilities, services, and energy at LBNL are expected to be adequate for renovation activities.

Impacts from Operations

Air Quality. Project operations would have minimal air emissions. Inert gases, including helium, nitrogen, and argon would be used in small quantities and released to the atmosphere. Sulfur hexafluoride (SF_6) would be used as an accelerator insulating gas that may need to be replaced if it is unintentionally mixed with air during project operations (SF_6 is classified as an irritant by the Uniform Fire Code, Article 80). In such an event, the SF_6/air mixture would be vented to the atmosphere through a stack on the roof of Building 51B. The maximum amount released would be less than 90 kg/hr. (.1 ton/hr.), and would not require a permit from the Bay Area Air Quality Management District. Air emissions from solvents that would be used in the electrical and mechanical shops would increase but would remain within LBNL's existing BAAQMD permit limit for precursor organic compound solvents for the buildings that would support the project.

Human Health. The project would have minimal impact on public health. Health hazards to workers include electrical hazards, compressed gas hazards, oxygen-deficiency hazards, ionizing and non-ionizing radiation hazards, and potential hazards associated with the use of hazardous materials.

Electrical Hazards. ILSE electrical systems consist of pulsed high voltage and DC and AC high-voltage power supplies. These high voltage sources would be completely enclosed and interlocked. Energy storage systems would be equipped with bleeder resistors that discharge the capacitors when the voltage source is removed. Safe work practices would be enforced.

Compressed Gas Hazards.. Compressed gases that would be used in the operation of the accelerator would include compressed air, helium, nitrogen, and argon. In addition, a pressurized SF_6 and/or Co_2 gas system would be installed which would consist of a generator tank, gas recovery system, and sixteen storage tanks. These tanks would be equipped with pressure relief valves. Pressure systems would be designed, installed, and operated by qualified personnel who have been trained in, and are knowledgeable of, American Society of Mechanical Engineers (ASME) and LBNL Health and Safety requirements.

Oxygen-Deficient Atmosphere. CO_2 and/or SF_6 would be used in quantities sufficient to pose an oxygen deficiency hazard in the event of a leak or rupture. To protect workers against this hazard, oxygen-deficiency sensors and alarms would be installed as appropriate in areas where a gas leak may decrease the atmospheric oxygen level to less than 19.5% of the total amount of air.

Ionizing Radiation. Normal operation of the accelerator would not produce ionizing radiation. However, ionizing radiation in the form of low-level x-rays could be created if high-voltage breakdown were to occur due to the focusing systems inside the beamline. Because of the shielding created by the wall thickness of the beam line, and the outside core materials and housing, the amount of x-ray that would escape from the beam line would be well below the 5 mrem/hr at 30 cm limit set by the ACGIH TLVs. As a safety precaution, as new sections of ILSE are completed and tested, each section would be monitored by the EH&S Division. If deemed necessary, thin sheets of lead would be added to reduce radiation levels to ensure that x-ray levels are below the TLV. All personnel working with the ILSE apparatus would be issued appropriate personnel dosimetry devices. Passive area radiation monitors would be installed to aid conformance with the As Low As Reasonably Achievable (ALARA) principle and for workplace monitoring. Visitor access would be controlled in accordance with LBNL policy.

Non-Ionizing Radiation. Equipment is not expected to generate high electrical or magnetic fields outside the beamline. To verify the absence of these potential hazards, selected would be surveyed for electrical and magnetic fields during beam operation to ensure that levels are below the ACGIH Threshold Limit Values (TLV).

Hazardous Materials Use. Hazardous materials that would be used include distillate oil, solvents, and other materials typically used in electrical and mechanical shops, such as paint, sealant, resins, and epoxy. In addition, acetylene, which is a flammable gas, and oxygen would be used. A maximum of four 200-ft^3 and two 100-ft^3 cylinders of each gas would be stored at any one time. Containers of hazardous materials (e.g., distillate oil) would be stored in 30- or 55-gallon drums with properly designed secondary containment to prevent accidental releases into storm drains or the sanitary sewer.

The oil that would be used in the injector vessel would consist of a light- to non-halogenated non-PCB containing mid-distillate hydraulic oil. The principal risk associated with use of the oil would be a spill as a result of a hose rupture. In such an event, a maximum of 40 gallons of oil would spill into the pressure vessel, which would constitute secondary containment. The oil would be removed and disposed of as hazardous waste.

The insulating oil that would be used in each of the 76 capacitors would also be a non-halogenated and non-PCB containing oil. The total amount of oil in each capacitor is one liter maximum. In the event of a spill, the oil would be released into the bottom of the vacuum vessel, which would constitute secondary containment. The oil would be removed and disposed of as hazardous waste. In addition, the automatic grounding relays that ground the capacitors would be mounted in a 55-gallon drum filled with Diala insulating oil. This drum would have secondary containment. There will also be two tanks containing Diala insulating oil, that will contain voltage dividers for the matching section. These tanks will contain 75 gallons of oil each. These tanks also will have secondary containment. In the event of a spill, the oil would be removed and disposed of as hazardous waste.

As discussed above, pressurized gases that would be used during operation consist of CO_2 and/or SF_6 as an insulating gas in the generator tank. In the unlikely event of an accidental total release of SF_6 or CO_2, the gas would be vented through a stack to the atmosphere. The exposure concentration would be 340 parts per million at 100 meters which is 3 times lower than the TLV for SF_6 and CO_2.

Hazardous Wastes. An estimated 120 lb. of solid and 300 gallons of liquid hazardous wastes, such as solvents, paints, Diala oil, sealants, resins, and epoxy, would be generated annually in the shops that would support the project. These quantities represent .003 percent of LBNL's total amount generated in 1994. These increases in waste generation would not require additional waste storage space in LBNL's Hazardous Waste Handling Facility nor substantially affect current levels of waste transport or disposal. Wastes would be handled, sorted, and disposed using approved procedures by qualified LBNL personnel in accordance with DOE orders and Federal and State regulations. ILSE activities would not generate radioactive or biomedical wastes.

After completion of the proposed ILSE project (anticipated to last about 10 years), the accelerator and support equipment would be dismantled and either shipped to other DOE accelerator facilities for reuse or disposed of as solid waste. None of the components would be radioactive.

Traffic, Parking, and Noise. The 6 employees who would occupy Building 51B represent only one fourth the number of people who occupied this building during its previous occupancy. The number of people who would occupy the supporting shops would be no more than the number that occupied the buildings during their peak period of occupancy. Daily trips at LBNL would remain below the goals set forth in the agreement with the City of Berkeley, and level of service (LOS) along access roads would not change. Adequate parking would be available to maintain the ratio of employees per parking space established in LBNL's Long Range Development Plan.

Operation of the proposed project would produce little noise, the major sources of which would be heating/cooling equipment and alternator that are in current use. It is not anticipated that there would be an increase in the ambient noise level at on-site LBNL receptors and at the nearest Berkeley residential neighborhood.

Utilities, Services, and Energy. Proposed project operations are expected to result in a minor incremental increase in the use of water, gas, electricity, and the production of wastewater above existing levels. Available levels of service are expected to be more than adequate for the proposed project. Other services, including communications, emergency notification, fire, and police are also expected to be adequate to support the proposed project.

Environmental Justice. As discussed above, the proposed project would have minimal impact on public health and the environment. Based upon a preliminary assessment of the economic and demographic make-up of the communities that surround LBNL, it appears that there are not disproportionately high and adverse human health or environmental effects from LBNL activities on minority and low-income populations.

Cumulative Effects. Potential cumulative effects are anticipated for regional air quality and waste generation. The San Francisco Bay area does not meet emission standards (nonattainment status) for carbon monoxide, ozone precursors, and particulate matter less than 10 microns in size (PM_{10}). Construction and operation of the proposed project would provide a minor contribution to these emissions in the region.

The proposed project would increase the quantity of various types of hazardous wastes that are being generated at LBNL by .003 percent. California lacks adequate disposal capacity to handle current or projected quantities of hazardous wastes generated within the State. Therefore, LBNL and other California generators continue to rely on licensed hazardous waste treatment and disposal facilities located outside California.

DETERMINATION

Based on the information and analysis in the EA, DOE has determined that the proposal to construct and operate the Induction Linac System Experiments project does not constitute a major Federal action significantly affecting the quality of the human environment within the meaning of the National Environmental Policy Act of 1969. Therefore, a Finding of No Significant Impact is made and an Environmental Impact Statement is not required.

PUBLIC AVAILABILITY

Copies of this EA (DOE/EA-1087) are available from:

Carl Schwab
U.S. Department of Energy
Berkeley Site Office
Lawrence Berkeley National Laboratory
1 Cyclotron Road, Mail Stop 50B-3238
Berkeley, CA 94720
(510) 486-4298

For further information regarding the DOE NEPA process, contact:

Anthony J. Adduci
DOE/OAK NEPA Compliance Officer
U.S. Department of Energy
1301 Clay St.
Oakland, CA 94612
(510) 637-1807

Issued in Oakland, CA. this 8th day of September, 1995.

Martha Gonzales
for James M. Turner, Ph.D.
Manager
Oakland Operations Office

ELISE - A HEAVY ION FUSION RESEARCH ACCELERATOR

PROJECT MANAGEMENT PLAN
(PROJECT NUMBER 96-E-310)

Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

November, 1995

Prepared for U.S. Department of Energy under Contract No. DE-AC03-76SF00098

ELISE

PROJECT MANAGEMENT PLAN

APPROVAL SHEET

LBL

____
William A. Barletta, Division Director
Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory

____
Roger Bangerter, Program Head
Fusion Energy Research Program
Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory

____
Joe W. Kwan, Project Manager
Fusion Energy Research Program
Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory

DOE

____
Office of Fusion Energy,
Office of Energy Research,
U.S. Department of Energy

____
Florencio Ramirez, Project Manager
Engineering and Facilities Management Division
U.S. Department of Energy
Oakland Operation Office

Table of Content

I. INTRODUCTION

This Project Management Plan (PMP) describes the plans, organization, baselines and control systems that will be used to manage the Elise project. To the extent that there are any inconsistencies or conflicts between this plan and the terms and conditions of contract DE-AC03-76SF00098, the LBNL Architect and Engineering Subcontracting Manual, the UCLBNL Construction Subcontracting Manual, the LBNL Procedures Manual, the LBNL Procurement Guide, the LBNL Operating and Assurance Program Plan, or the standard policies and procedures of the University, the provisions of those documents shall prevail over this plan.

This PMP will be periodically reviewed and revised by the Project Manager to reflect new project developments and/or agreements among the major participants. Approval to revisions of this plan is by signature of original parties or current office holders.

A draft of the Environment Assessment Report is currently being prepared to analyze and evaluate the potential impacts associated with the construction and operation of this facility.

II. PROJECT DESCRIPTION

The *National Energy Strategy and National Energy Policy Act* call for a demonstration inertial fusion energy (IFE) power plant by about 2025. So far, heavy-ion accelerators have been identified as the most promising IFE drivers for power production. In particular, the induction accelerator approach is favored because of its potential reliability, efficiency, and high repetition rate. The Fusion Energy Research Program at Lawrence Berkeley National Laboratory is funded by the Department of Energy to build Elise, an electric-focused induction accelerator as the next step towards the ultimate goal of developing a power-plant driver. Elise is a heavy ion induction accelerator with electric focusing that will advance the understanding of high current, heavy ion accelerator physics so that many of the basic technical questions concerning the suitability of this approach, as a driver for Inertial Fusion Energy, can be resolved. Elise will address many of the heavy ion driver physics issues using a low energy induction linac (5 MeV, 1 A). The project was approved (KD-1) by the Department of Energy in December 1994. At the currently expected funding level, the construction time will take 4-3/4 years with FY95 providing an extra year for R&D before construction. A follow-on extension of Elise, named ILSE is not yet approved. ILSE would add a four-beam injector and a magnetic-focused induction accelerator to Elise and further accelerates the 5 MeV beams from Elise (using all 4 channels) to more than 10 MeV with a total current approaching 10A. Magnetic focusing is considered more suitable for higher energy beam transport, therefore ILSE is an essential step in the path of developing a full scale driver.

The objective of this project is to build an induction linear accelerator, using the existing single beam injector and a new electrostatic quadrupole focusing channel, to accelerate high current heavy ions (atomic mass ≥10) beams from 2 MeV to 5 MeV. The knowledge gained and the technologies developed in this project should provide a basis for evaluation of the feasibility and the cost effectiveness of heavy ion drivers for inertial fusion. The completed accelerator will be used for studies of longitudinal beam bunch control, final focus, and other key technical issues relevant to a full-scale driver.

III. MANAGEMENT ORGANIZATION

There are three key management participants: The Office of Fusion Energy at DOE Headquarters; DOE's Oakland Operations Office (OAK); and the Lawrence Berkeley National Laboratory (LBNL). The contact persons for the Elise project from each of the above organizations are:

From OFE-HQ: Dr. Mark Wilson, Division of Advanced Physics and Technology
From OAK/EFM: Mr. Florencio Ramirez, Engineering and Facilities Management Division
From LBNL: Dr. Joe Kwan, Accelerator and Fusion Research Division

Organizational relationships amongst the participants and within each organization are shown in Figure III-1 and III-2.

A. DOE Responsibilities

1. DOE Office of Fusion Energy (OFE)

The Office of Fusion Energy in the Office of Energy Research has primary programmatic responsibility for the Elise Project. Within OFE, the Advanced Physics and Technology (APT) Division has responsibility for implementing the Elise project. In fulfilling this responsibility, APT will provide programmatic guidance, technical direction, overview and assistance. APT will monitor the overall progress and performance of the Elise project, establish Elise budgets, and provide Elise funding. Within APT, the Elise project is managed by the Elise program manager. The Elise program manager will review and have approval of any changes in accelerator configuration, key technical design parameters, or general requirements documents. The responsibilities of OFE include the following:

a. Approve project objectives and significant changes thereto;

b. Concur in the cost, schedule, and technical baselines established as the base for issuance of the Key Decisions for the project;

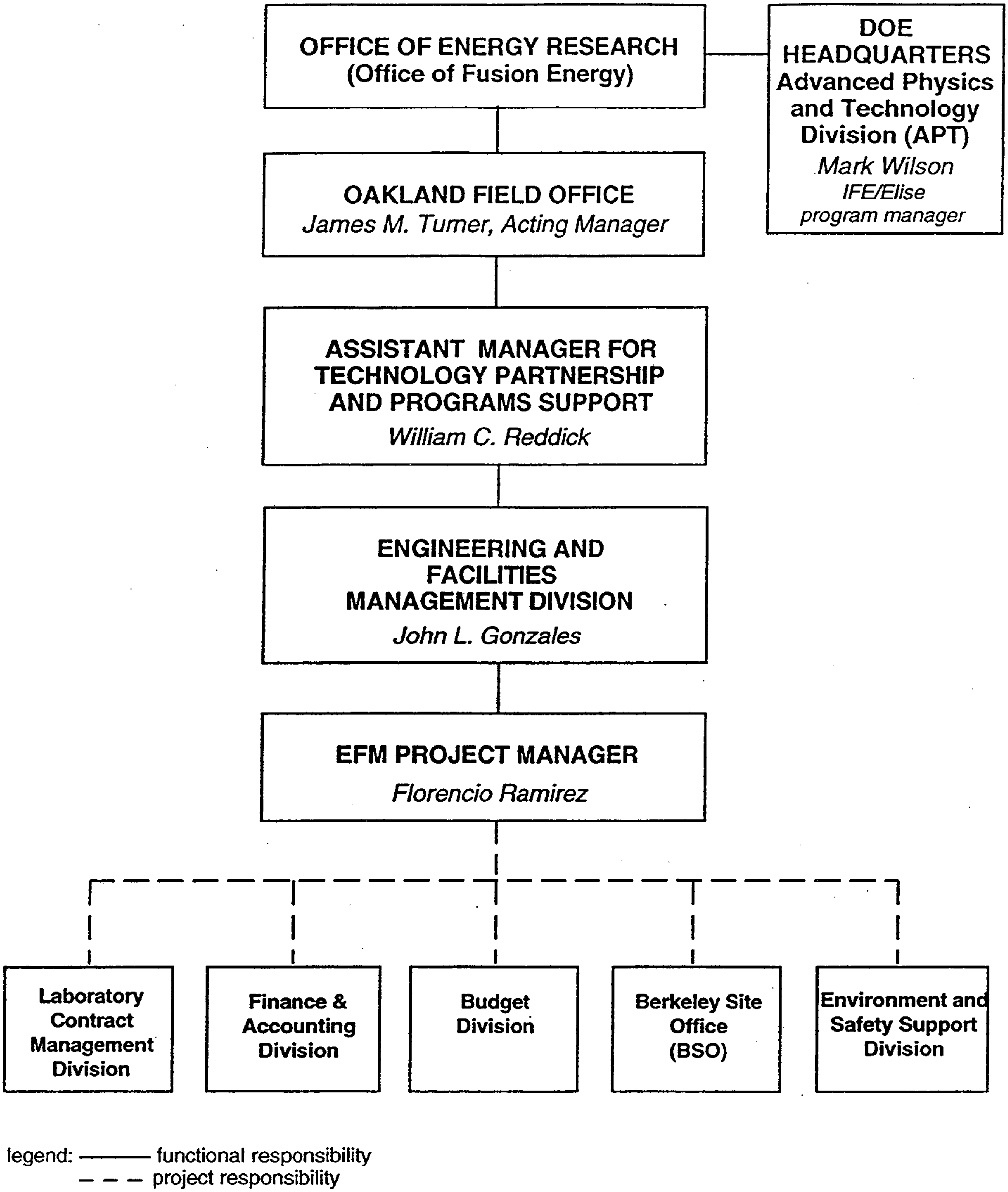


Figure III-1 DOE Organizational Chart

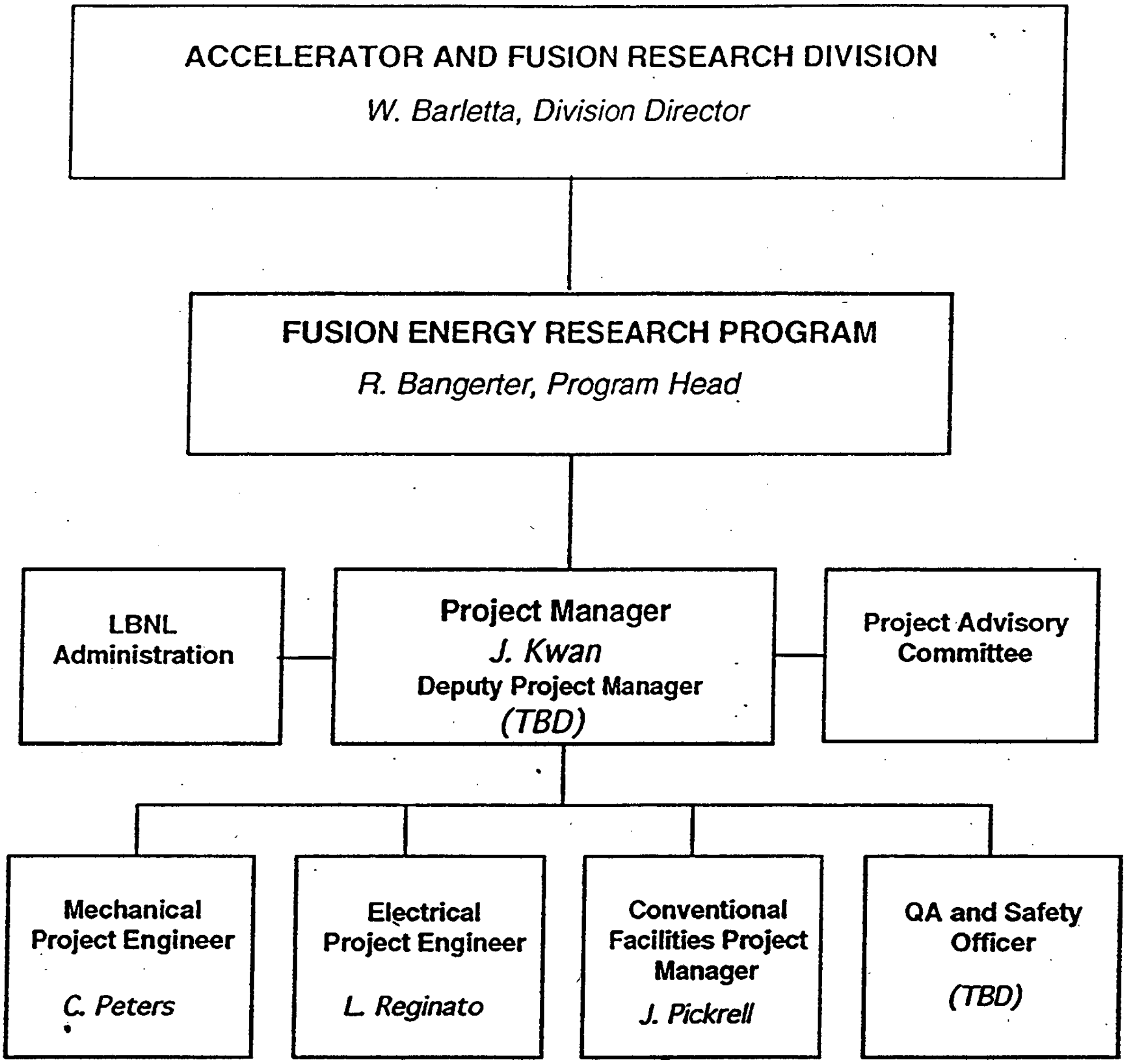


Figure III-2. LBNL Organizational Chart

c. Review and approve changes in: project costs above $500,000 at WBS level 2; annual contingency exceeding 50% of total project contingency; completion date; more than 3 months changes in key project milestones, or significant modifications on the commissioning criteria.

d. Approve the Project Data Sheet for Elise prepared by the OAK EFM Division and LBNL;

e. Participate in major project reviews as well as keeping track of the progress through periodic project reports provided by LBNL.

2. DOE Oakland Operation (OAK)

The responsibility for DOE management of the Elise construction project has been delegated by the Office of Fusion Energy to the Manager of the Oakland Operation Office (OAK). The Oakland Operation Office is responsible for administering DOE contract DE-AC03-76SF00098. Within DOE OAK, management and administration (including planning, cost control, schedule control, and communications with OFE) of the Elise Project has been assigned to the Project Manager in the OAK Engineering and Facilities Management Division.

The EFM Project Manager is supported by the functional divisions and offices of the OAK matrix organization. Overview of the Elise Project is provided to the OAK Manager's Office by the Director of the Engineering and Facilities Management Division, to whom the EFM Project Manager reports.

The OAK responsibilities for which EFM has the lead role include the following:

a. Initiating actions to resolve problems that have potential for causing a key milestone schedule slippage of two months or more, an increase of the lesser of 10% or $500K in discreet costs (WBS level 3) or a significant deviation from approved technical baselines;

b. Report monthly and quarterly on Project cost and schedule performance and conduct periodic reviews of the Project; continuously monitor key milestone performance against approved cost, schedule, system requirements, and technical objectives;

c. Maintain Project controls at WBS Level 3 by review and approval of management and system requirements documents; allocate contingency; approve budget, cost schedule, or system requirements change requests;

d. Participate in key technical discussions and regular Project design reviews to assure project compliance with the Project Data Sheet, DOE Orders, and Federal regulations (including environment, safety & health, safeguards & security, quality assurance, etc.);

e. Provide and coordinate, as needed, management audit of the Project, including review of management controls, business policies, procedures, practices, financial audits and audits of the quality assurance programs;

f. In consonance with LBNL, periodically update the Project Management Plan as needed;

g. Review and approve Title I, Title II and Construction for the conventional facilities (WBS Level 3); review and approve lump-sum construction subcontracts greater than $1,500,000 and cost type subcontracts greater than $500,000;

h. Review and provide comments on the Construction Project Data Sheet as required for each budget cycle; issue directives and directive modifications to authorize the use of funds;

i. Accept, from LBNL, the completed facilities for DOE.

B. LBNL Responsibilities

The LBNL Associate Laboratory Director for Operations has the primary authority and responsibility for designing and constructing the Elise Project within the limits specifically authorized in DOE Contract DE-AC03-76SF00098. The Associate Director delegates this responsibility through the Director of the Accelerator and Fusion Research Division (AFRD) to the Project Manager, who reports to the Head of the Fusion Energy Research Program within the Accelerator and Fusion Research Division. Specific project responsibilities are indicated below:

1. Fusion Energy Research Program Head

Research activities in the Fusion Energy Research Program include both the Elise Project and the base program. The program Head is a member of the Project Advisory Committee (see section III.C) which reviews the progress of the Elise Project to ensure conformance with the approved project scope, budget and schedule, and with LBNL's policies and procedures.

2. Elise Project Manager

The Project Manager is responsible for directing the design and construction activities and the associated research and development with the goal of achieving the Project's technical objectives while confining the project to within the approved budget and schedule. He coordinates the project activities within AFRD and other LBNL divisions as well as with outside subcontractors. Other responsibilities of the Project Manager include the following:

a. Prepare overall Project cost estimates and time schedules;

b. Insure that work planning and execution is properly organized according to the Work Breakdown Structure (WBS);

c. Approve Change Orders and subcontract modifications (also see sections III.A.a.1 and III.A.b.3); if required, the Project Manager will prepare and forward Baseline Change Proposal(s) (BCP) to OAK for review and approval.

d. Monitor and control the project scope, expenditure and performance schedule;

e. Prepare reports to DOE and LBNL management;

f. Establish an effective quality assurance and EH&S program for the Project.

3. Deputy Project Manager

The Project Manager may select a Deputy Project Manager who will assume the responsibilities of Project Manager at times designated by the Project Manager. He will also be given special assignments and responsibilities by the Project Manager as the need arises.

4. Project Engineers

The Mechanical and Electrical Project Engineers are responsible for designing and constructing the project to meet the technical specifications as well as cost, schedule, and safety requirements. Their responsibilities also include submittal of work authorization requests and providing percent-complete reports on all mechanical and electrical work-in-progress respectively.

5. Conventional Facility Project Manager

The Conventional Facility Project Manager matrixed from the LBNL Facilities Department is responsible for the design, specifications, and construction of buildings and structures related to the Elise Project. His other responsibilities include the following:

a. Specification and implementation of all utility systems required by the Project;

b. Coordination and appropriate supervision of outside contractors and A&E;

c. Design and construction of accelerator shieldings, if needed;

d. Site work related to the above and its coordination with other LBNL activity in the area;

e. Submit work authorization requests and provide percent-complete reports on all conventional facility work-in-progress;

6. QA and Safety Officer

The QA and Safety Officer reports to the Project Manager and assists him on quality assurance and safety issues. He is responsible for assessing the risk or consequences associated with the failure of each system to conform to design requirements, organize QA and EH&S training, keeping records and prepare documentation for inspections and audits. The Elise QA and Safety Officer will work closely with the personnel from AFRD and EH&S Division to ensure that the Project is adhered to LBNL policies, DOE orders, and other applicable state and local regulations.

C. Project Advisory Committee (PAC)

The function of PAC is to ensure that the Project facilities are designed and constructed to meet the original objectives and that all Project activities are properly coordinated. It also reviews and evaluates any Change Requests and provides advice to the Project Manager. The committee members include the Head of Fusion Energy Research Program, Elise Project Manager, Deputy Project Manager, Project Engineers, QA and Safety Officer, other scientific staff and special consultants (either from LBNL, LLNL or from outside the laboratories) as required.

IV. WORK PLAN

A. Work Description

The Elise Construction Project includes two elements: special research facilities and conventional facilities (modification to an existing LBNL building). Figure IV-1 gives a plan view of the facilities.

1. Special Research Facilities

a. Construction of an induction accelerator capable of increasing the ion energy of four parallel beams from 2 MeV to 5 MeV, using electrostatic transport. Beginning minimum pulse duration to be 1 microsecond. Initially, only one transport channel will be used. The facility will be designed for a 10 year operational life. The induction accelerator is approximately 15 m long, 2 m in diameter, and contains more than 50 metric tons of magnetic material.

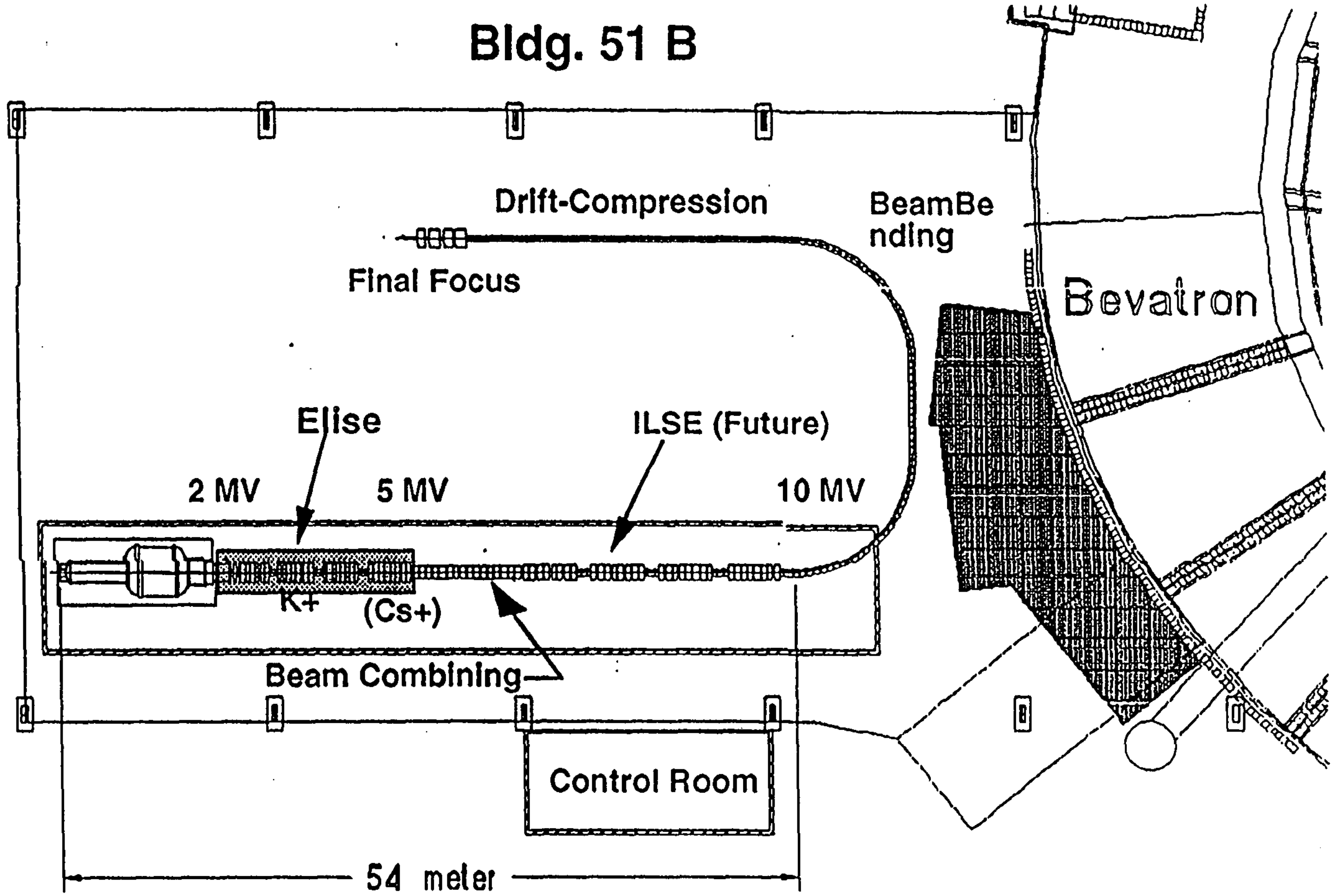


Figure IV-1. Top view Layout of Elise.

b. The front end of the accelerator will be attached to a matching section which is connected to a 2 MeV single-beam injector with a potassium ion source (an assembly about 10 m long). The injector already exists and the matching section is presently being fabricated; both components were developed within the base program of the Fusion Energy Research Program and will be incorporated as part of the Elise Project.

c. Sufficient diagnostics to assist the operation of achieving optimum beam transport through the accelerator and to establish the final beam current, energy, and emittance.

d. Ancillary equipment and instrumentation for achieving adequate alignment, vacuum, data acquisition, accelerator control, and operational maintenance.

2. Conventional Facilities

a. Building 51B, the External Proton Beam (EPB) hall of LBNL's Bevatron Complex is to be modified to accommodate the accelerator. Existing shielding and structures will be removed and a new concrete slab will be added to provide a smooth strong surface for supporting the accelerator. An insulated steel frame structure including an energy management system, a standard lighting system, and a fire protection system will be built within the EPB hall to house the accelerator.

b. A separate control room will be constructed inside the existing prefabricated building 51G which will be relocated for optimum use at a nearby site.

c. Existing utilities in building 51B will be relocated to service the Elise accelerator facility requirements. These include electric power, water, lighting, fire protection, heating, ventilation and air conditioning.

B. Work Execution

1. LBNL Engineering and Design

With the exception of A/E activities for the conventional facilities, most of the engineering and design activities will be done by LBNL mechanical, electrical and Facilities personnel. Support personnel will be provided by the LBNL Engineering Division, on a matrixed basis, and will work directly for, and be responsible to, the appropriate Project Engineers.

2. Fabrication in LBNL Shops

Fabrication of technical components will be done in-house, utilizing LBNL's mechanical, electrical, and craft shops, and by outside vendors working under LBNL subcontracts.

Decisions on whether to use in-house shops or outside vendors will be made on a case-by-case basis. In general, work that requires close engineering supervision, interaction between many trades or shops, elements or procedures of low familiarity to outside vendors, or capabilities unique to LBNL will be done by in-house shops. In-house LBNL fabrication work will be specified in detailed Job Orders authorized by the Project Engineers.

3. Outside Vendors

Most outside purchases and fabrication subcontracts will be awarded on a fixed price competitive bid basis. Purchase orders will be processed by the LBNL Purchasing and Accounting departments after authorization by the appropriate Project Engineers and/or the Project Managers. In some cases, LBNL will provide fabrication procedures to the outside vendors and the outside vendors will produce documentation certifying that proper procedures were used.

4. Management of Conventional Facilities Construction

The conventional facilities construction will be managed by a Project Manager from the LBNL Facilities Department. The Facility Project Manager will coordinate activities between the outside A&E firm and various LBNL departments and will oversee the day-to-day work at the site as well as report progress to the Elise Project Manager.

5. Inspection and Acceptance of Conventional Facilities

The building structures, utilities, and site work of the conventional facilities will be inspected by professional inspectors (either LBNL employees or outside A/E firm) during the construction period and prior to beneficial occupancy in accordance with the plans and specifications.

Upon completion of the work, appropriate authorities representing the Project/LBNL and DOE/OAK will inspect the facilities. Once accepted, title to the facilities passes directly from the vendor to the Department of Energy.

6. Operating Funded R&D Associated with Construction

The R&D associated with the construction (RDAC) of the Elise special research facilities will be carried out primarily by LBNL employees using LBNL resources except in cases where the work can be done more effectively by personnel at universities, other national laboratories, or industry.

Similar to the Project design and construction, the RDAC activities are supervised by the Project Engineers and managed by the Project Manager. Funding for RDAC is not included in the Total Estimated Construction Cost but is a part of the Total Project Cost.

V. QUALITY ASSURANCE

A. Quality Assurance Plan

Quality control for engineering, construction and inspection must comply with DOE's Quality Assurance requirements and DOE Order 5700.6c. These requirements are implemented in accordance with LBNL's QA program described as the "Operating and Assurance Program Plan". More specific controls and activities are documented in the AFRD Function Note Book and a new Elise Project Notebook will be prepared by the QA and Safety Officer. Other related QA documents are the Facility Note Books (which contains the Conduct of Operation and Maintenance Management Plan) for Building 51 and Building 58. Work-in-progress will be controlled either by existing procedures or by project-specific procedures that will be developed as the need arises. Decision on whether new procedures are needed or not will be made by the Project Engineers and/or the Project Manager.

B. Quality Control

1. Engineering Design

Specifications and designs are subjected to (i) a series of approvals by authorized engineering and scientific staff within the Fusion Energy Research Program and the Facilities Department, Fire Department and Environmental, Health and Safety Division as needed; and (ii) design reviews participated by experts from inside and outside the Laboratory. Critical design concepts are subjected to extensive testing and analysis using computer simulation, models, and prototypes before they are finalized and adopted.

The project office will maintain an on-line Master Index of all project documents. Similarly, all engineering drawings are maintained by a CAD data-base system and hard copies of all released drawings will be filed in the engineering files. Hard copies of all other documents are filed according to the WBS numbers in the project office. Adhering to prescribed procedures in using the data-bases will ensure that everyone is working with updated information.

2. Signatures

Drawings are not released to the shops without proper authorized signatures to certify that the drawings are appropriately detailed, meet applicable standards and codes (including those for safety), and satisfy the design requirements. Drawings are released for fabrication by issuing Job Orders (for LBNL shops) or Requisitions (for outside vendors); both documents require the signatures of the appropriate Project Engineer before they are released. After checking for completeness and proper signatures, the Engineering Department print room will prepare print packages for Job Orders using standard LBNL control procedures.

Changes to drawings should follow the same route as an original drawing with the authorized signatures. In most cases, the new drawing will use the same drawing number as the old one by appending a revision letter starting with "A". Revisions to drawings are incorporated into in-process work only with the issuance of a Change Order signed by the appropriate Project Engineer. For drawings that are created using Computer Aided Design (CAD), hard copies of CAD documents will be considered the originals.

Apart from drawings, technical specifications are also controlled by requiring the signature of the appropriate Project Engineer or the Project Manager. The technical specifications and price estimates are routinely reviewed by the Purchasing Department before release to vendors to insure compliance with existing laboratory practices.

All construction drawings, calculations and engineering reports prepared for the conventional facilities shall contain the signature and registration number of the responsible, California registered, architect or engineer.

3. Inspection of Fabrication

All tests or inspections performed by in-house shops are documented and copies are transmitted to the originating party for retention in their files and the quality control files.

The quality of outside fabrications is insured by seeing that qualified vendors are solicited for any procurement based on past LBNL experience. In the event that the qualifications of a vendor are not fully known to LBNL, a team of qualified personnel may be assembled to inspect the vendor's facility and assure its ability to perform the work. Inspections will also be carried out during the period of fabrications.

For critical components (as identified by the Project Manager), an Inspection and Acceptance Report will be issued by LBNL inspectors; payment is withheld until the components are confirmed to meet the specifications. For large procurements of many of the same components, the first batch is required to be inspected and tested by LBNL personnel before the vendor produces the remainder.

4. Inspection of the Conventional Facilities Construction

All phases of the construction will be inspected by experienced LBNL inspectors who will report to the Facility Project Manager. The inspection will ensure that work is performed in accordance with LBNL's "Operating and Assurance Program Plan", and the Facilities Department's "Project Management Group Policy and Procedures". All constructed systems, equipment, materials and facilities will be reviewed by LBNL with acceptance made by the Project Manager with the concurrence of the engineering, construction and purchasing support team. The Facilities Acceptance procedure is described in both the "Project Management" and "Design Management" Manuals.

C. Safety Analysis and Review

1. NEPA

An environmental assessment has been prepared in accordance with requirements of the National Environmental Policy Act (NEPA). Finding of No Significant Impact (FONSI) was confirmed and the document was signed by DOE/OAK on Sept. 11, 1995.

2. Preliminary Safety Analysis Report (PSAR)

A Preliminary Safety Analysis Report of the Project, as required by DOE Order 5481.1A, will be submitted in FY96 during Title II Engineering phase.

3. Final Safety Analysis Report (FSAR)

A Final Safety Analysis Report of the Project will be submitted in FY2000 upon completion of the construction phase.

VI. WORK BREAKDOWN STRUCTURE

Elise WBS Tasks (at level 3 and above) and their cost estimates are shown in Table VI-1. Also included in the table is the assignment of change control levels to the WBS tasks (see section IX for further details in change controls).

Table VI-1. WBS and Cost Estimate of Elise Project.

Elise Induction Linac rev. 6/9/95

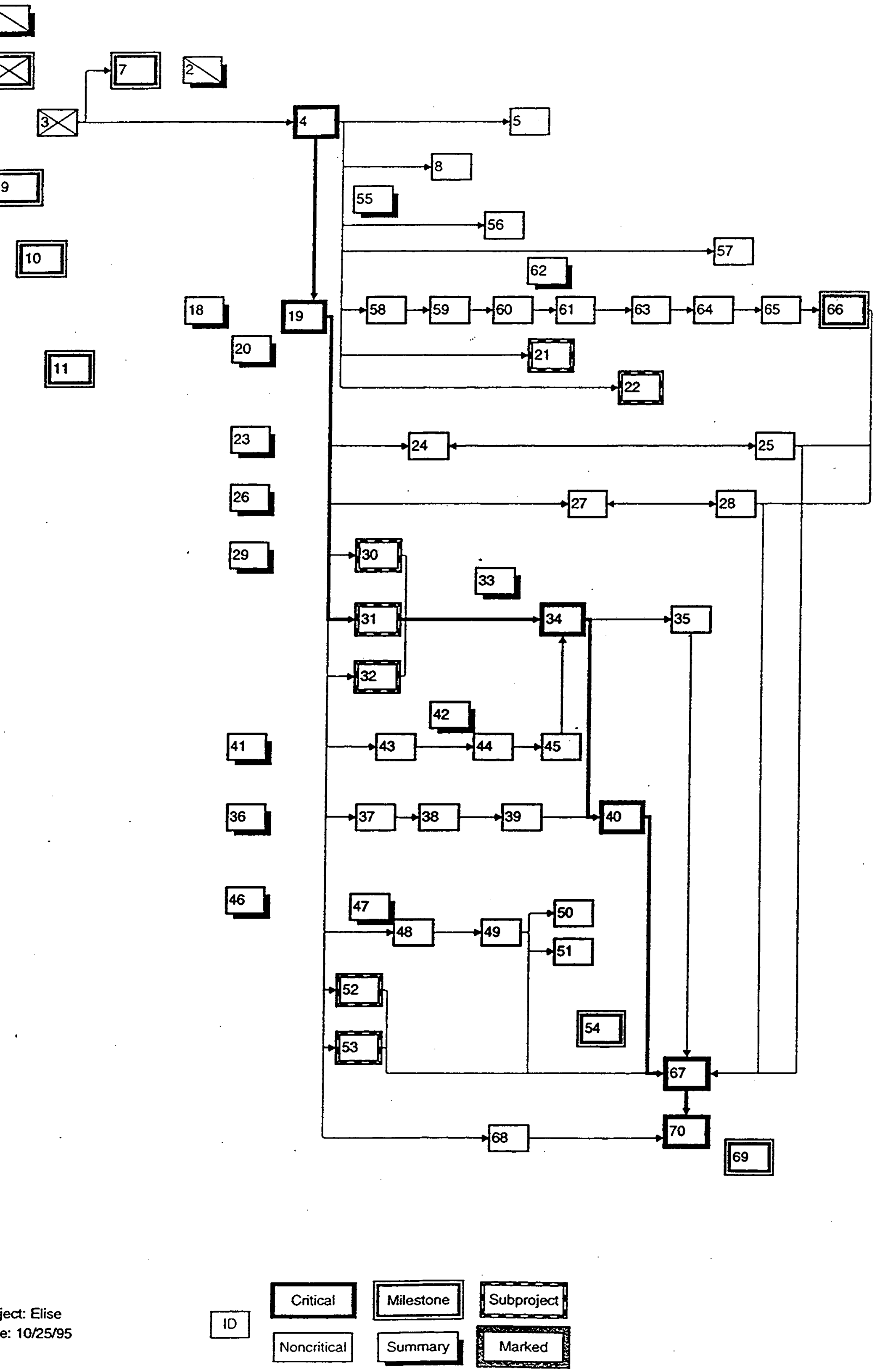
Escalation and Contingency Analysis for the Total Estimated Construction and Project Cost

WBS Tasks	WBS/Change Control Level	Cost (FY94 k$)	Cost (then-yr) (15.0% escal.)†	Overheaded TECC*	TPC
1. Induction Linac Systems Experiment	1/1	16164	18590	20190	25900
1.1. Project Management & Administration	2/2	1539	1770	1922	
1.1.1 Project Office Effort	3/3	1374	1580	1716	
1.1.2 Supplies & Expense (12% of 1.1.1)	3/3	165	190	206	
1.2. Special Research Facilities	2/2	10510	12087	13128	
1.2.1. Engineering, Design & Inspection	3/2				
1.2.1.1 Electrical ED&I	4/3	1669	1919	2084	
1.2.1.2 Mechanical ED&I	4/3	1462	1681	1826	
1.2.2. Injector	3/4	88	101	110	
1.2.3. Matching Section	3/4	44	51	55	
1.2.4. Electric Focus Acceleration Section	3/2	5400	6210	6745	
1.2.7. Alignment System	3/2	450	518	563	
1.2.8. Vacuum System	3/2	272	313	340	
1.2.9. Diagnostics	3/2	201	231	251	
1.2.10. Controls and Data Acquisition Systems	3/2	637	733	796	
1.2.11. Special Utilities & Support	3/2	287	330	358	
1.3. Conventional Facilities	2/3	1033	1188	1290	
1.3.1. E D & I @ 18% of construction	3/3	150	173	188	
1.3.2 Construction	3/3	821	944	1025	
1.3.3 Project Management	3/3	62	71	77	
1.4. Contingency	2/2	3082	3545	3850	
1.4.1. Project Management Contingency	3/3	385	443	481	
1.4.2. Special Research Facilities Contingency	3/3	2490	2864	3111	
1.4.3. Conventional Facilities Contingency	3/3	207	238	258	
CDR Preparation					60
RDAC FY94					200
RDAC FY95					3000
Project Documentation					200
RDAC during construction					1250
Start-up and Pre-ops					1000

† Escalation based on DOE anticipated Economic Escalaton Rates as of November 1994.
*Assuming 8.61% overhead and Elise is exempted from any future increase in LBL overhead rate throughout the construction period.

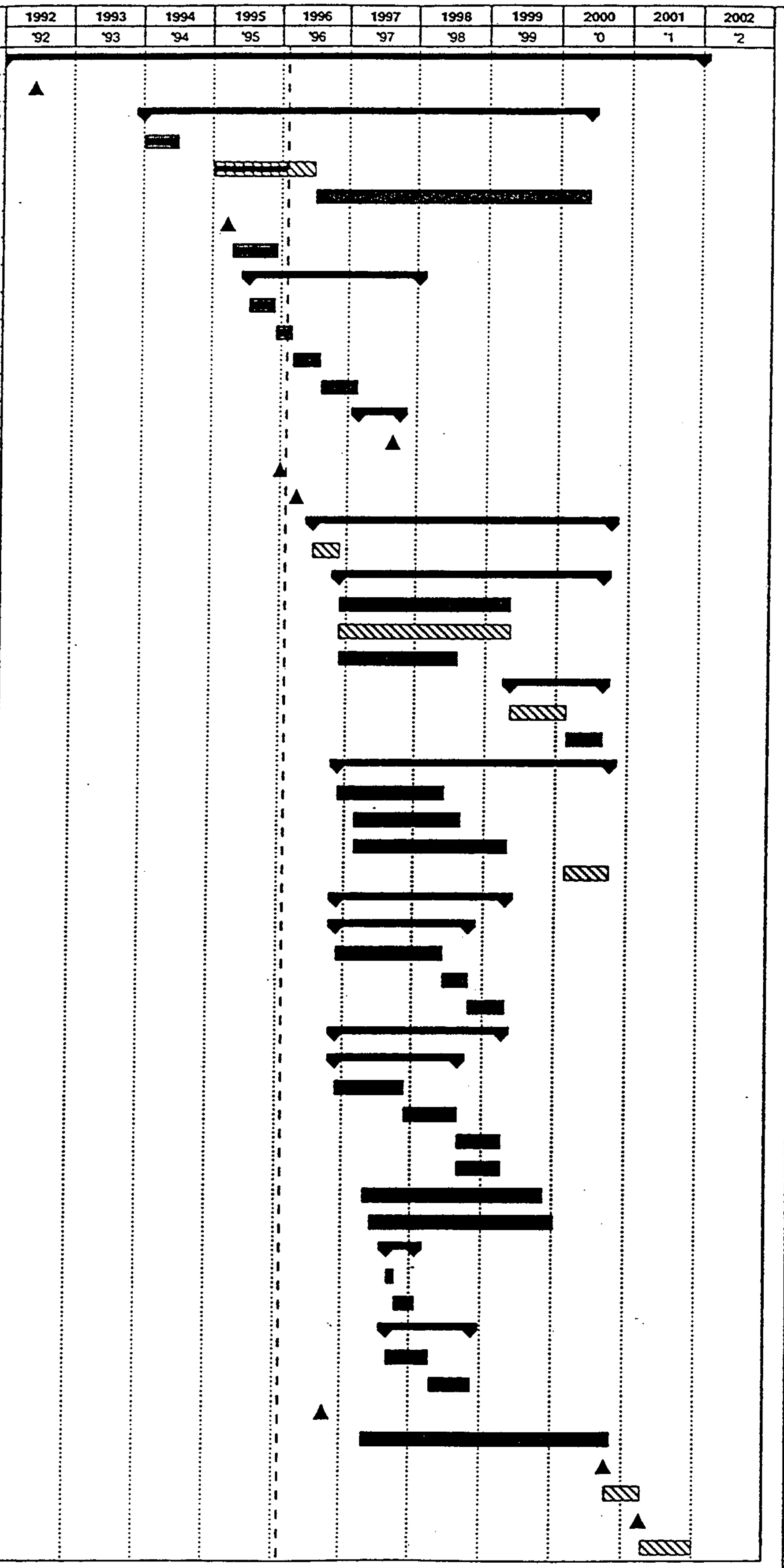
VII. PRECEDENCE CHART

A PERT chart and a Gantt Chart for Elise are shown in Figure VII-1 and Figure VII-2 respectively. The critical path depends on the fabrication of acceleration modules, accelerator assembly and alignment.



ject: Elise
e: 10/25/95

ID	Name	WBS
1	Elise Project	1
6	Key Decision 0 (KD0)	
2	RDAC	1.5
3	Conceptual Design	1.5.1
4	Pre-construction RDAC	1.5.2
5	Construction RDAC	1.5.3
7	Key Decision 1 (KD1)	
8	NEPA/CEQA/PSAR	1.1.3
55	Conventional Facilities	1.3
58	Architect/Engineer Selection	1.3.3.1
59	Architect/Engineer Negotiation	1.3.3.2
60	A/E Title 1	1.3.2.1
61	A/E Title 2	1.3.2.2
62	A/E Title 3 (construction)	1.3.2.3
66	Beneficial Occupancy	
9	Project Start	
10	Key Decision 2 (KD2)	
18	Special Research Facilities	1.2
19	System Design and Specifications	1.2.1-
29	Electric Focus Acceleration Section	1.2.4
30	Beam Transport Components	1.2.4.1
31	Acceleration Modules	1.2.4.2
32	Accelerator Power Systems	1.2.4.3
33	Electric Focus Section Assembly and Installati	1.2.4.4
34	Mechanical, Install Electric Focus Section	1.2.4.4.1
35	Electrical, Install Electric Focus Section	1.2.4.4.2
36	Alignment System	1.2.7
37	Straight Line Reference Alignment System	1.2.7.1
38	Quadrupole Fiducials for Alignment	1.2.7.2
39	Data Acquisition and Controls of Alignment Sy	1.2.7.6
40	Assembly & Integration of Alignment System	1.2.7.7
41	Vacuum System	1.2.8
42	Electric Focus Accel Section Vacuum System	1.2.8.4
43	Procure & Fab	1.2.8.4.1
44	Installation	1.2.8.4.2
45	Controls for Vacuum System	1.2.8.5
46	Diagnostics	1.2.9
47	Diagnostic Box	1.2.9.2
48	Procurement	1.2.9.2.1
49	Fab & Install	1.2.9.2.2
50	Matching Section Rogowskis Diagnostics	1.2.9.3
51	Electric Focus Accelerator Rogowskis Diagnos	1.2.9.4
52	Controls and Data Acquisition Systems	1.2.10
53	Special Utilities & Support	1.2.11
23	Injector	1.2.2
24	Injector HV Generator/Extractor	1.2.2.6
25	Injector Relocation	1.2.2.7
26	Matching Section	1.2.3
27	E. Matching Section	1.2.3.7
28	M. Matching Section (Relocation)	1.2.3.8
11	Key Decision 3 (KD3)	
68	Experiment Design & Fab	3
54	Complete Construction	
67	Start-up/Pre-operations	2
69	Key Decision 4 (KD4)	
70	Operations & Experiments	4



Project: Elise
Date: 11/2/95

Critical — Noncritical — Progress — Milestone ▲ — Summary — Rolled Up ◇

VIII. PROJECT BASELINES

A. Cost Baseline

	ITEM	TOTAL COST (in escalated $K)
1.	Engineering, Design and Inspection	4,098
2.	Construction Cost	10,243
3.	Project Management	1,999
	SUBTOTAL	16,340
4.	Contingency	3,850
	TOTAL ESTIMATED COST (TEC)	20,190

Other costs related to activities in the preparation of the conceptual design, R&D before and during the project , and start-up amount to $5.71M. The Total Project Cost (TPC) including the TEC is therefore $25.9M. Note that the above estimation assumes a constant LBNL overhead rate of 8.61% on the TEC.

B. Contingency Management

Contingency for the Elise Project will be maintained in a separate lump sum amount for the entire project and will be controlled by the PM or at a higher level in accordance with Section IX Change Control. Contingency is available for unforeseen excursions above the initial cost estimates, for the normal cost increases and decreases encountered as the project design evolves, for approved changes within the TEC, and to deal with incorrect cost assumptions such as economic escalation. The above contingency ($3,850K) was obtained from an analysis of the WBS tasks in the Conceptual Design. Contingency analysis will be periodically performed by the PM to determine if the remaining contingency amount is adequate for completion of the project.

C. Time Baseline

R&D associated with Construction (RDAC) began in FY94 and will continue throughout the construction period. The Project is expected to start in the first quarter of FY96 (KD2) and is estimated to take 4-3/4 years for completion (dictated by the present anticipated funding profile). The Budget Authority (BA) is shown in Table VIII-1 below:

Table VIII-1. Elise Resource Plans (Budget Authority Expenditure in $M)

Activity	FY94	FY95	FY96	FY97	FY98	FY99	FY00	FY01	TOTALS
PACE	0	0	3.15	4.55	4.55	4.55	3.40	--	20.20
OPEX	0.26	3.1	0.45	0.25	0.25	0.25	1.14	--	5.7
TPC	0.26	3.1	3.60	4.80	4.80	4.80	4.54	--	25.90

The Elise Project Master Schedule is shown in Figure VIII-1 and a time line diagram showing the schedule for the major project tasks is shown in Figure VIII-2. Table VIII-2 below shows the Associate Director for Fusion Energy Milestones, these are Level 1 milestones:

Table VIII-2. Elise Level 1 Milestones

Key Decision	Milestone Description	Date	Status
KD #0	Approval of Departmental Mission Needed	3/92	Complete
KD #1	Approve New Start	12/94	Complete
KD #2	Authorize Detail Design	1/96	
KD #3	Start Construction	6/96	
KD #4	Authorize Start of Operations	12/00	

Table VIII-3 listed the Advanced Physics & Technology Division Milestones which are Level 2 milestones:

Table VIII-3. Elise Level 2 Milestones

Milestones	Milestone Description	Date	Status
Elise.1-0	Action Description Memorandum Update issued	7/94	Complete
Elise.1-1	Concur in Project Management Plan	5/95	
Elise.1-2	Environmental Assessment (EA) submitted	6/95	
Elise.1-3	Environmental Assessment approved (FONSI)	9/95	
Elise.1-4	Project Start	10/95	
Elise.1-5	Review preliminary Elise Design for physics consistency, recommend start of detail design of special research facilities	1/96	
Elise.1-6	Beneficial occupancy of conventional facilities	9/97	
Elise.1-7	Complete assembly and test of special research facilities	6/00	
Elise.1-8	Accelerator acceptance tests completed, and conduct Operational Readiness Review	12/00	

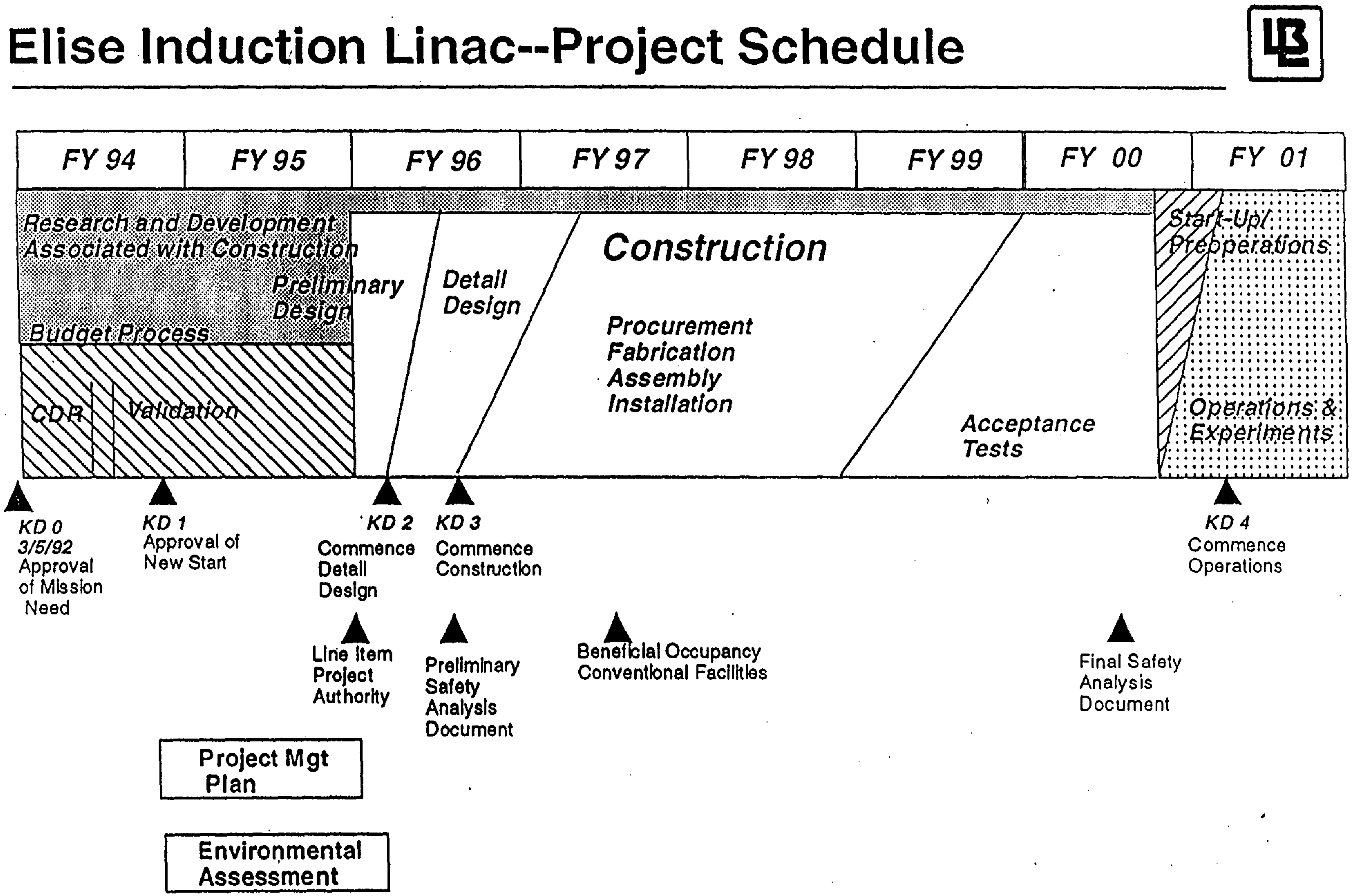


Figure VIII-1. Elise Project Master Schedule

Elise bar chart

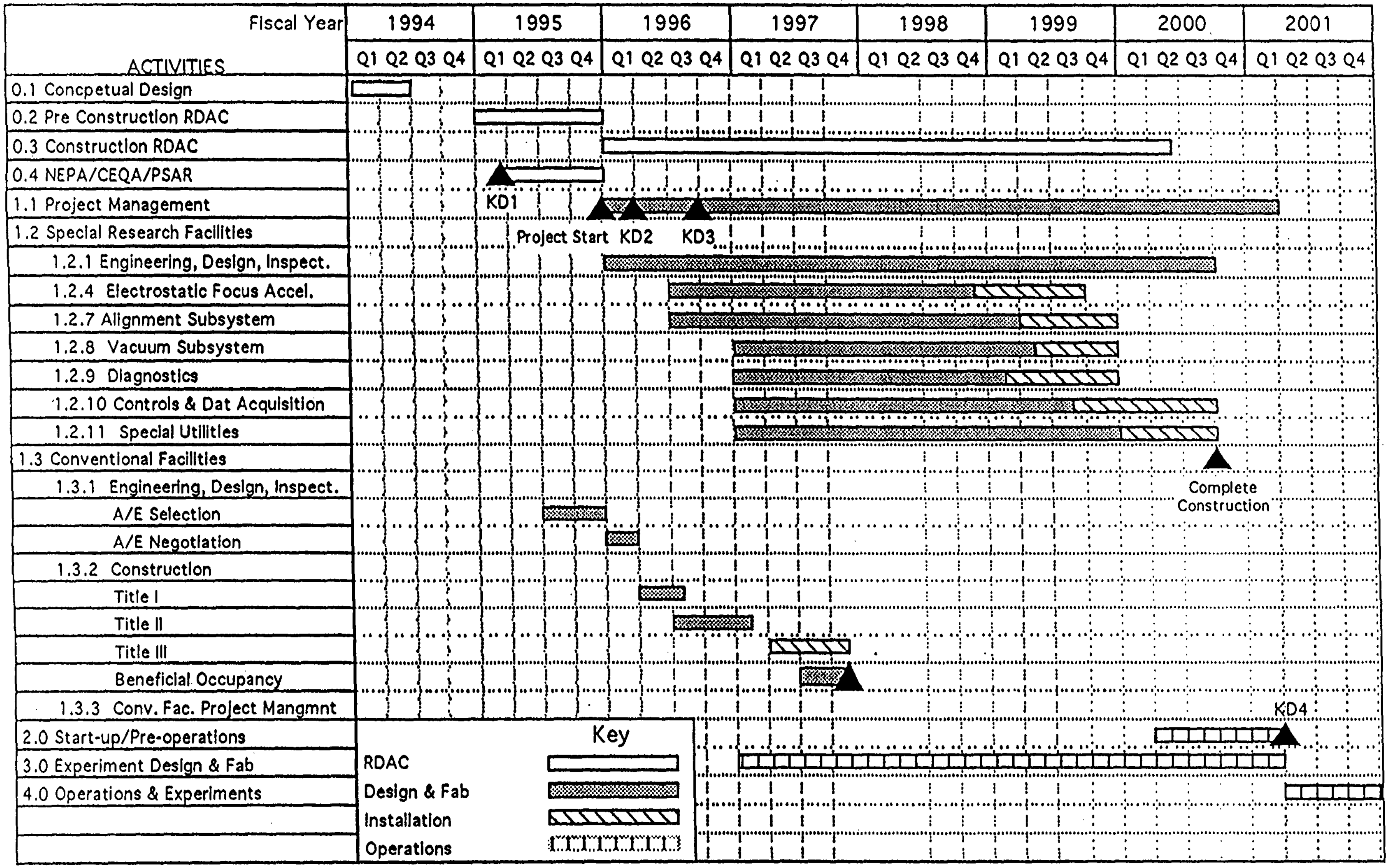


Figure VIII-2. Schedule of major WBS tasks.

D. Technical Baseline

Until the actual Start of Construction, Chapters 2-5 and 7 and Appendix B of the Conceptual Design Report (CDR) are designated the Elise General Requirements Document in conjunction with the Key Technical Design Parameters and Commissioning Criteria (see Table VIII-4) approved by DOE. A Construction Design Document, which will then become the new baseline upon DOE approval, will be issued shortly after Project Start prior to the Key Decision 2 (KD-2). Any further revision in the technical baseline will follow the Change Control procedures described in this Project Management Plan.

Table VIII-4. Elise Technical Design Parameters

PARAMETER	UNITS	VALUE
Initial Ion Kinetic Energy	MeV	2
Initial Beam Current	Amperes	0.8
Initial Pulse Duration	Micro-seconds	1.0
Initial Beam Line Charge Density	Micro-Coulombs per meter per beam	0.25
Initial Number of Beams	none	1
Final Average Ion Kinetic Energy	MeV	5
Final Beam Current	Amperes	1.0
Final Pulse Duration	Micro-seconds	0.8
Final Beam Line Charge Density	Micro-Coulombs per meter per beam	0.2
Initial Number of Beams	none	1
Final Beam Energy	Joules	4
Length of Linac	meters	15
Number of Acceleration Gaps	none	32
Ion Mass Number	atomic mass units	39
Ion Charge	electron charge	+1
Commissioning Criteria at the Output of Elise Accelerator		
PARAMETER	UNITS	VALUE
Beam Charge/Pulse at 5 MeV Average Energy	Micro-Coulomb	≈>0.2
Velocity Shear (Tilt)	Percent	≈>3
Emittance (Normalized, RMS of 90%)	π-mm-mrad	≈<1
Ion Kinetic Energy Averaged over 0.2 micro-Coulomb Charge/Pulse.	MeV	≈>5

IX. CHANGE CONTROL

The change control process will be governed by the thresholds listed in Table IX-1. There will be four levels involved in the approval of change control process. The lowest change level will be level 4, which is the level controlled by the Project Manager (if necessary the Project Manager will consult with the Project Advisory Committee). Level 3 will be controlled by DOE/OAK Change Control Board, and Level 2 will be controlled by the Advanced Physics and Technology Division in DOE/HQ. Level 1 is controlled by the Office of Fusion Energy in DOE/HQ. Level 1,2, and 3 will be documented by DOE/OAK's baseline change proposal form. A log of all changes will be maintained by the Project Manager.

In order to change the cost, schedule, or technical baseline of a task at the WBS level 3 or higher, the Project Engineer must submit a Change Authorization Request which contains an explanation of the need for the change, a justification, an analysis of the cost, schedule, and technical impact, and alternative solutions. New baselines are established upon approval of a change request by the appropriate authorities (depending on the change level).

Table IX-1 Change Control Thresholds

	Level 1 OFE	Level 2 APT	Level 3 DOE-OAK	Level 4 LBNL
Technical	Change in mission. Change in site	Change in accelerator configuration or key technical design parameters. Change in scope	Changes affecting ES&H requirements, conventional facilities not affecting key technical design parameters or accelerator configuration	Changes in system requirements or design not affecting key design parameters or accelerator configuration.
Schedule	Greater than 6 months change in level 1 milestones	Greater than 3 months but less than 6 months change in level 1 milestones	Greater than 1 month but less than 3 months change in level 1 or level 2 milestones	Any change in project schedule not defined as level 1 or level 2 milestones.

Cost	Change in TPC or TEC	Change in WBS level 2 greater than $500k. Change in the contingency allocation (annual) exceeding 50% of the total at WBS level 3.	Change in cost of conventional facilities exceeding 10% in total cost. Change at WBS level 2 less than $500k, and above $250k at WBS level 3. Change in the contingency allocation (annual) less than 50% of the total contingency at WBS level 3.	Change in cost at WBS level 3 up to $250k.

X. REPORTING AND REVIEWS

A. Reports Prepared by OAK/EFM

1. OAK Project Manager's Progress Report
2. OAK Project Manager's Quarterly Supplemental Report

B. Reports Prepared by LBNL

1. Monthly Progress Report Narrative

   The Project Manager is responsible for submitting a Monthly Progress Report which may include items such as major accomplishments, developments affecting cost estimate and schedule, brief assessment of the overall project, EH&S issues, work performed and other project management data.

2. Quarterly Earned Value Performance Report

   At the end of each quarter, LBNL project management will provide data for earned value reporting for submission to DOE-Headquarters. Data such as budgeted cost for work schedule, budgeted cost for work performed, and actual cost of work performed will be included. Reporting should be extended down to level 4 of the project WBS.

3. Other Reports
   a. Construction Project Data Sheet
   b. Conceptual Design Report
   c. Project Management Plan
   d. Environmental Assessment Report
   e. Safety Analysis Report (Preliminary and Final)
   f. Semiannual Cost Estimate
   g. Technical and Engineering Notes

C. Meetings and Reviews

The following meetings and reviews are formally scheduled and documented:

1. Bi-monthly Review

   A bi-monthly meeting will take place between the Project Manager and EFM to review the current status of Project work and to discuss outstanding issues.

2. Annual Review

   A thorough review of the Project's cost, schedule, and technical status will be held by DOE. Presentations by key Project personnel will address issues from an agenda agreed to in advanced by OFE, EFM and the Project Manager. The Project is expected to last 4-3/4 years, therefore there will be more than 5 major reviews throughout the project life.

3. Project Advisory Committee (PAC) Meetings

   The monthly PAC meeting will address issues concerning both technical and managerial problems. Major decisions that have significant impact to the Project scope, cost and schedule will be resolved in the PAC meeting.

4. Weekly Technical Group Meetings

   The Mechanical Project Engineer and the Electrical Project Engineer will take turns holding a weekly engineering meeting to discuss and resolve problems related to design and interface issues.

5. QA and EH&S Meetings

   These meetings will be held in accordance with the format and frequency specified by the AFRD management.

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