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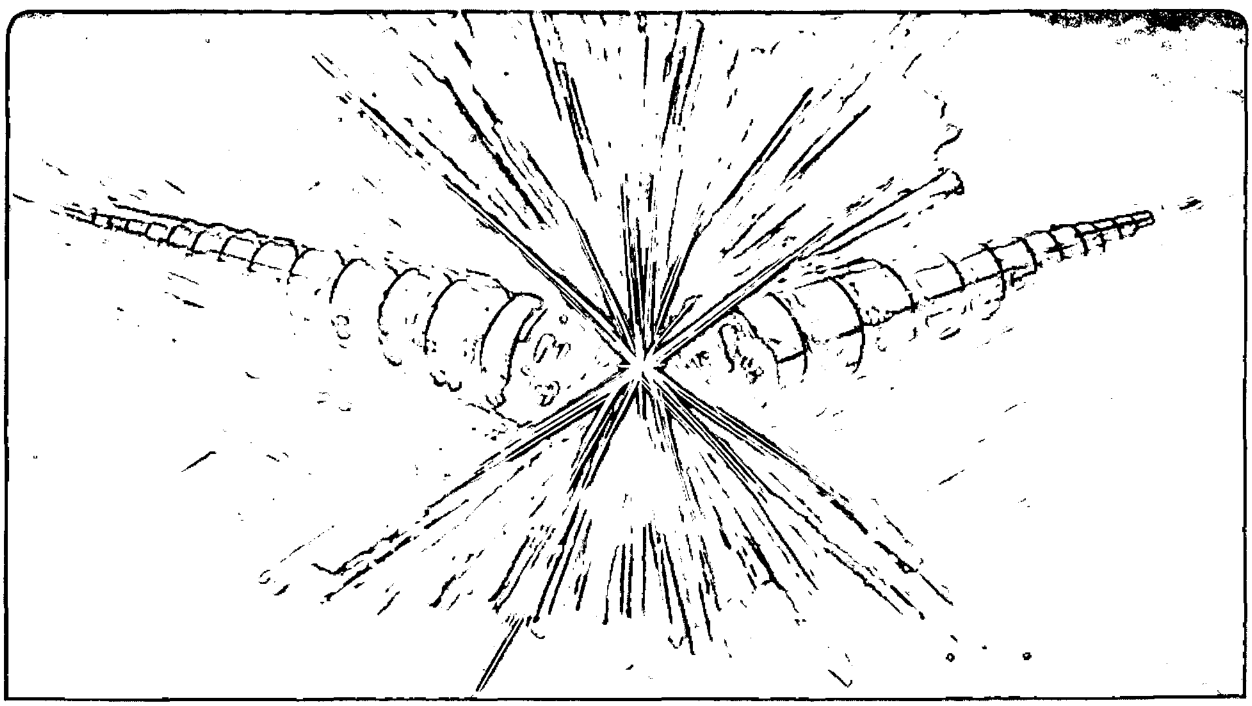

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Abstract

LBL, with the participation of LLNL and industry, proposes to build Elise, an electric-focused accelerator as the next logical step towards the eventual goal of a heavy-ion induction linac powerful enough to implode or "drive" inertial-confinement fusion targets. Elise will be at full driver scale in several important parameters—most notably line charge density (a function of beam size), which was not explored in our earlier experiments. Elise will be capable of accelerating and electrostatically focusing four parallel, full-scale ion beams and will be designed to be extendible, by successive future construction projects, to meet the goal of the USA DOE Inertial Fusion Energy program (IFE). This goal is to address all remaining issues in heavy-ion IFE except target physics, which is currently the responsibility of DOE Defense Programs, and the target chamber. Thus Elise is the first step of a program that will provide a solid foundation of data for further progress toward a driver, as called for in the National Energy Strategy and National Energy Policy Act.

Introduction

The goal of the Heavy Ion Fusion Accelerator Research Program is to develop accelerators for fusion energy production. Heavy-ion fusion, like laser fusion, uses intense beams to ignite small targets containing thermonuclear fuel. The "burning" fuel creates a burst of energy that can be contained in a target chamber. The beams from the particle accelerator or laser (the "driver") are focused onto the target, located at the center of the chamber, by lenses outside the chamber. (The targets typically would have a radius of a few millimeters and the target chamber would have a radius of a few meters.) In this scheme, which is called inertial fusion energy (IFE), the fuel burns so rapidly that it is confined by its own inertia.

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IFE research programs using the Nova and Omega lasers, and the PBFA-II light-ion accelerator along with the Halite/Centurion program conducted at the Nevada Test Site using nuclear explosives, have already put to rest fundamental questions about the feasibility of inertial fusion. It now appears possible to develop and build a demonstration power plant by the year 2025. Plans for this development are outlined in the National Energy Strategy.[1] The cornerstone of the Strategy's IFE plan is heavy-ion driver research.

The emphasis on heavy-ion drivers is readily understandable. For engineering and economic feasibility, drivers must be both reliable and efficient. They must also have a high pulse repetition rate (several pulses per second) and long life (about 30 years). Existing drivers—lasers and light-ion accelerators—are excellent for near-term research, but they have been designed for a low repetition rate, typically a few shots per day. Therefore, development of new drivers is needed for power production. During the last decade, nearly all high-level DOE and congressionally mandated committees have identified heavy-ion accelerators as the most promising drivers for power production.

These accelerators, designed to use the heavier ions such as xenon, cesium, or bismuth, are similar in many respects to the large accelerators that are used worldwide for basic research in high-energy physics; many of the above mentioned requirements for IFE have been demonstrated in existing accelerators. In particular, these accelerators usually have excellent reliability and long life. The new, additional requirement for fusion is the production of very high instantaneous beam power (greater than 10^{14} watts) in a beam that can be focused to hit a small target. There are two main methods of accelerating a heavy-ion beam in accordance with these requirements: induction and radio-frequency (rf) acceleration. Researchers in the US have chosen the induction accelerator because its relative simplicity and lower estimated cost appear to make it a more-promising driver candidate.

To establish an experimental basis for induction accelerators in this new high-power regime, we proposed, originally in 1988, a series of experiments known as the Induction Linac Systems Experiments, or ILSE. In 1988 the ILSE program was reviewed by DOE and JASON panels. Both groups endorsed the ILSE program, but it was placed on hold by DOE pending the outcome of National Academy of Sciences and Fusion Policy Advisory Committee reviews.[2, 3] Both of these reviews gave the ILSE program excellent marks. An updated ILSE concept was reviewed in November 1991 by a DOE advisory panel, again with highly favorable results. Following the approval of mission need in March, 1992, we prepared a Conceptual Design Report in support of a proposal to proceed with construction. Construction approval was not granted in 1992, and again in 1993 with a lower cost of construction. The Fusion Energy Advisory Committee (FEAC) reviewed the IFE program in 1993[4]. This committee also recognized the opportunity the ILSE program provides for heavy-ion driver research and affirmed that this driver research is the primary focus of the IFE program.

Recognizing that in this period of tight budgets, it is difficult to embark on the integrated demonstration project, ILSE, we are proposing the Elise project. Like ILSE, Elise is a linear induction accelerator facility, which will produce an intense ion beam to test many of the features of a heavy-ion induction accelerator driver for IFE production. Upon completion, Elise will be the largest ion induction accelerator ever built and will be capable of acceleration and electrostatic focus transport of multiple, driver-scale ion beams similar to the electrostatic-focus sections of the ILSE accelerator. In addition, Elise will be designed to be extendible such that it will ultimately be able to address the remaining physics issues for heavy ion drivers. For this reason, the Elise accelerator will be designed to transport up to four parallel ion beams to retain the potential for beam- combining in later experiments. An existing single-beam, full-scale beam injector will be used for this project, to reduce costs. At the proposed pace of construction, Elise will take 3 1/2 years (this is as long as required to build as the ILSE accelerator), heavy ion driver research would lag behind the schedule of the National Energy Strategy for a demonstration IFE power plant by 2025.

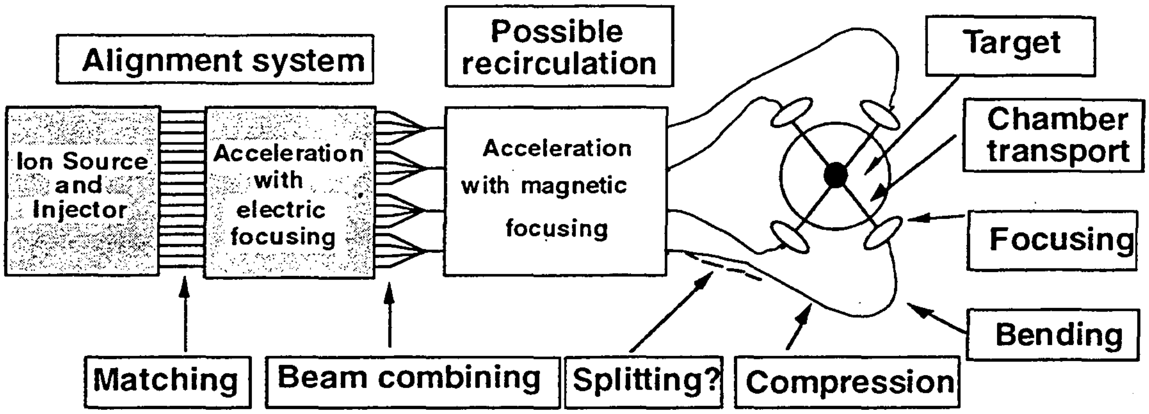
Scientific and Technical Goals of Research on Induction Linacs for IFE

The fundamental scientific issue for HIF accelerators may be stated briefly: how to produce a short beam pulse (about 10 ns) with an instantaneous power of more than 10^{14} W and good enough quality to be focused to a spot with a radius of a few millimeters. To minimize the space-charge forces and collective effects associated with high currents, it is desirable to achieve the required beam power by maximizing ion kinetic energy while minimizing beam current. However, an upper limit on ion kinetic energy is set by the desired target penetration. For the target to achieve high energy gain, penetration must lie in the range of 0.02 to 0.2 g/cm^2. For light ions such as protons, this requirement limits the kinetic energy to about 10 MeV. Therefore, to produce a power of 4 x 10^{14} W, a beam current of 40 MA would be required. For heavy ions the energy limit is much higher. For example, a cesium beam with a penetration of 0.1 g/cm^2 has an ion kinetic energy of about 4 GeV, corresponding to a current requirement of about 100 kA. The combination of higher energy and lower current implies that the space-charge forces and collective effects are much smaller than for protons.

A schematic diagram of a generic induction accelerator designed to produce 100 kA of cesium ions at 4 GeV is shown in Figure 1. To achieve 100 kA, it uses several methods: multiple beams, beam combining, acceleration, and longitudinal bunching. Typical values of ion kinetic energy, beam current, and pulse length at various points in the accelerator are shown in the figure.

Initially each of 64 beams has a current of ~0.42 A at ~2 MeV. The beams are accelerated to ~100 MeV in an electrostatically focused accelerator. Thus, the velocity of each particle increases by about a factor of 7. At ~100 MeV, the 64 beams are transversely combined in groups of four to form 16 beams. In the electrostatic-focus section, the physical length of the beams remains approximately constant; therefore, the combination of acceleration and merging increases the current of a single beam to 7 x 4 x 0.42 ≈ 12 A. Acceleration to 4 GeV in the magnetically focused section produces an increase in velocity by a factor of 6.3 and would therefore give a current of 75 A per beam if the physical beam length remained constant. However, it does not remain constant. For economy and efficiency, it is desirable to compress the beam longitudinally by accelerating the tail to a slightly higher velocity than the head. In the example in Figure 1, a compression factor of 8 is assumed, leading to a current of 625 A/beam. As the beam leaves the accelerator, the head-to-tail "velocity tilt" is adjusted so that as the beam drifts toward the target, it is compressed by another factor of 10. This final compression gives 6250 A/beam, or, with 16 beams, the aforementioned power of 4 x 10^{14} W.

Induction accelerator technology has the ability to accelerate multi-kiloampere ion beams and to hold them together transversely with readily achievable electric and magnetic fields. The real issue is beam quality, which can be described in terms of beam temperature and thus beam emittance. In general, it is possible to build ion sources whose beams are much colder than necessary, so there is, in principle, a comfortable margin for error in heavy-ion fusion. The final-focus system sets the maximum limit upon acceptable beam temperature; one of our goals is to show that low beam temperature can be maintained up to that point in the system.



2 MeV	100 MeV	4 GeV	4 GeV
0.42 A/beam	12 A/beam	625 A/beam	6250 A/beam
37 μs	1.3 μs	100 ns	10 ns

Figure 1. The accelerator systems and beam manipulations found in typical heavy-ion driver designs are represented by boxes. A highly accurate alignment system, not shown, will be used throughout. The shaded boxes represent systems that have been tested in past exprerimenls. The remaining issues, except target physics, will be tested in Elise and its anticipated experimental program. Typical values of energy, current, and pulse length are shown at various stages.

Earlier experiments at LBL have addressed some important issues related to beam quality. A high-brightness, 1-A cesium source was built and tested between 1977 and 1984. It gave a source temperature of 0.1 eV, about four orders of magnitude lower than the maximum value allowed at the final focus. The Single Beam Transport Experiment (SBTE), performed at LBL between 1981 and 1985, showed that it is possible to transport intense ion beams in an electrostatic-transport system without emittance growth. The SBTE was followed by the four-beam Multiple Beam Experiment, MBE-4, from 1985 to 1991. MBE-4, the first multiple-beam induction ion linac ever built, demonstrated simultaneous acceleration of multiple beams and longitudinal-beam bunching with adequate preservation of beam quality. These past experiments are summarized and compared to Elise and driver goals in Table 1.

The encouraging results from these experiments provide strong justification for the construction of Elise. SBTE and MBE-4 beams were space-charge-dominated, so they successfully tested much of the important physics on a small scale, but it is now necessary to move to larger-scale experiments. We have therefore adopted the design criterion that the Elise beams should be at full driver scale in selected parameters. One of the most significant of these parameters is line charge density, which was not tested at driver scale in SBTE and MBE-4. In the electrostatic section of Elise, each beam should be able to transport a line charge density of 0.25 μC/m.

The relatively low current of SBTE and MBE-4 is by no means the only reason why a new facility is needed. As Figure 1 shows, only some systems have been tested experimentally; many accelerator components and beam manipulations remain to be tested. We have designed Elise to begin addressing all the remaining items in that figure except target physics, which is currently the responsibility of DOE Defense Programs.

Table 1. How past experiments compare to Elise and a driver (Cs^+).

	Line charge density	Initial current	Final kinetic energy	Initial Tp	Final Tp
Cs ion source	0.5–1 μC/m	1 A	2 MeV	~0.1 eV	n/a
SBTE	0.03 μC/m	20 mA	200 keV	~0.1 eV	~0.1 eV
MBE-4	0.01 μC/m	~5–10 mA	1 MeV	~0.1 eV	~0.1 eV
Elise (K^+)	0.25 μC/m	~1 A	5 MeV	~0.1 eV	To be measured
Driver	~0.25 μC/m	0.42A	~4 GeV	~0.1 eV	<1 keV

* *The Elise numbers in this table are ultimate values that will not be achieved until some time after initial commissioning. In this table, T_p is the beam temperature perpendicular to the direction of beam propagation.*

Some Issues to be Addressed Experimentally with Elise

By building and commissioning Elise itself and by subsequently performing an experimental program, we will examine nearly all driver issues either directly or in scaled form. While Elise will initially use ions in the range of neon to potassium, cesium can be used; and, in any case, the results will be scaleable to ions with different charge-to-mass ratios, such as the mass 100–200 ions typical of a driver. We list here the experiments and systemwide issues in the Elise Program and comment on the comparable features as incorporated in a driver. Because beam quality is a common theme, we will first address beam heating and emittance growth. In principle, three types of processes might contribute to beam heating or emittance growth:

1. Random errors in transverse-focusing and accelerating waveforms. (Systematic errors must of course be avoided in design and construction.)

2. Instabilities.

3. One-time manipulations, such as merging or the transition from one accelerator section to another.

Random Errors For random errors, we expect the effects to grow statistically in proportion to the square root of the number of accelerator elements. The minimum number of elements needed to test this type of random growth is set by two considerations. There must be enough elements to make statistical considerations valid, and there must be enough elements to determine if there is an important effect. The first consideration is more stringent. We therefore adopt, as a design criterion for Elise, the rule that the number of transverse focusing periods (n_p) and the number of accelerating gaps (n_g) should both be greater than 25. A driver might have $n_p \sim 10^3$ and $n_g \sim 10^4$.

An option for the 180° bend experiment in which the bend is completed, forming a closed orbit, would permit us to increase the effective n_p and $n_g$by one to two orders of magnitude, thus providing a driver-class effective path length with which to test these effects.

Instabilities No transverse instabilities have been observed on MBE-4 and none are expected in a driver, but if significant instabilities were to exist, they would be observable with $n_p \sim 25$ There is a potential longitudinal instability, which depends on beam current rather than line charge density. Achieving enough current to test this instability fully would require high kinetic energy and lead to excessive Elise costs. Some relevant experiments are possible at Elise scale, but we are now addressing the issue with a combination of measurements on large induction cores, theory, and numerical simulation. These issues, too, could be addressed at a more driverlike scale if the Elise bend were carried completely into a closed orbit.

Manipulations Emittance growth during one-of-a-kind manipulations will be tested by performing each of these manipulations in the Elise experiments. Because the Elise line charge density is that of a full-scale driver, the experiments will be highly relevant to driver conditions.

Experiments for Elise

We give here a brief description of eight classes of experiments that can be performed with the Elise accelerator.

Experiments in the Linear Accelerator

1. *Matching the beams provided by the injector to those used in the accelerator.* The driver-sized beam from the existing single-beam injector must be compressed and matched into the electrostatically-focused accelerator.

2. *Acceleraion of beams with electrostatic focusing.* Issues addressed in this section include: acceleration schedule, voltage waveforms necessary to control beam ends, beam mismatch at half-period changes, and alignment. The effect of all of these on beam emittance will be studied. Most of these issues were investigated in MBE-4, but with much smaller beams than would be in a driver. Because Elise beams and half period are the same size as those in a driver, structures will be built to driver scale, and quadrupole voltages will equal those in a driver. Better quality fields than those in MBE-4, and an improved alignment system, will allow a charge-per-unit-length equal to a driver beam, and investigation of the dynamic aperture.

3. *Pulse shaping and longitudinal control.* To achieve high gain, a fusion target requires a properly shaped pulse. Elise will allow us to test various acceleration schedules to control pulse shape. Longitudinal-control techniques such as active feedback can be studied.

4 *Alignment and steering.* Elise will allow us to examine the practical accelerator trade-offs between steering and alignment. Eliminating the need for steering in Elise requires that the alignment of the focusing elements be controlled to within ± 0.1 mm. For a driver, the alignment tolerance is ± 0.01 mm, or 10 times closer (in some designs, the requirements are even more stringent). Steering may be difficult in current-amplifying linacs because the energy of the beam at the position of the steering element is time-dependent. Steering with time-dependent voltages will be investigated just after the electrostatic-focus accelerator, whereas steering with time-independent focusing will be studied in the magnetic-focus accelerator. Steering in the recirculator is also an important issue that would have to be addressed.

Experiments Downstream from the Elise Accelerator

5. *Magnetic bending of an intense ion beam.* Although it may be possible to illuminate an inertial-fusion target from one side, most very-high-gain target designs require that the final beams be transported in bending magnets and turned through angles as large as 270°. (Target gain plays an important role in the economic attractiveness of IFE.) Bending through large angles is common today in high-energy accelerators, but with low-current beams. The standard achromatic solutions for the optics are perturbed significantly by space-charge effects in intense beams. These effects, as measured by the "perveance" parameter, can be made slightly larger in Elise than in a driver, thus enabling Elise to provide a stringent experimental test of the relevant physics.

6. *Recirculating experiments.* The Elise beam can be injected into a recirculating-induction ring — a scheme that, in conceptual studies, has shown promise for reducing the cost of a heavy-ion driver. However, for high currents this type of acceleration is not as well understood as linear induction acceleration. A more thorough examination of the physics of recirculation is in progress. The Elise Program would provide the first opportunity to experimentally investigate this type of heavy-ion acceleration at significant scale. Inserting the beam into the ring and extracting the beam from it are two of the key manipulations that must be studied. If successful, an acceleration ring could increase the ion energy of Elise to 100 MeV or more.

7. *Drift-compression current amplification.* This manipulation amplifies the beam power just prior to the target. An energy tilt at the exit of the accelerator causes the beam length to shorten and the beam power to increase as the beam travels to the target. This is a fundamental and vital test of new beam physics in which the beam energy tilt is removed, rather precisely, by longitudinal collective accelerating forces at the beam head and decelerating forces at the tail. In other words, the velocity tilt causes beam compression over the drift distance, as previously mentioned, but eventually the space-charge forces remove the velocity tilt. The challenge is to arrive at the final focus with a highly compressed beam in which space-charge forces have removed most of the velocity tilt (thus avoiding chromatic problems in final focus) but have not yet caused beam blow-up. The

Elise beam will have enough line-charge density to remove an energy tilt of more than 10%, compared to an expected tilt of about 5% in a driver.

8. *Focusing, with or without neutralization, onto a small target spot.* Here again, the higher perveance of the final Elise beam will allow us to experiment under conditions more demanding than those in a driver. Although there is extensive theory, relatively little is known experimentally about the behavior of space-charge-dominated beams in the target chamber. This will be our first opportunity to examine chamber-physics effects and to investigate assisted chamber-propagation schemes such as *z*-pinch transport to the target. Beam-splitting schemes to reduce current and emittance, correction of geometrical aberrations, and correction of chromatic aberrations can also be studied. If aberrations can be corrected, the requirements on beam quality can be relaxed, so such experiments are important.

In summary, Elise represents a step beyond existing experimental facilities both in quantitative parameters and in the variety of the work that can be performed. It will be a highly flexible experimental capability with which we can address many of the remaining accelerator issues for inertial fusion. Past progress justifies the new facility, and future progress requires it.

Elise Physics Design

The physics design of Elise closely follows and benefited from the design of the ILSE accelerator that has been developed over the last few years. Elise, essentially, is the electric focused accelerator section of the larger ILSE accelerator.

In Elise, beams of ions from the injector are matched into an alternating-gradient electrostatic-focus section with 32 induction cells. There they are accelerated to 5 MV, with some compression of the beam pulse to further amplify the current. In a later phase, not part of the currently proposed "project" phase, a beam combiner introduced between the electric- and magnetic-focus section will merge four beams into one, thereby testing a potentially important driver feature. Then one beam continues into a magnetic-focus accelerator section with 32 blocks of cells for further acceleration to 10 MV, again with current amplification.

Transport physics, longitudinal physics and current amplification, and longitudinal space-charge effects were among the factors considered in the physics design. We adopted a self-replicating scheme for current-amplifying pulse shapes in which the profile of current versus time at a fixed location is preserved throughout the accelerator, while the magnitude increases as the bunch shortens in time. Longitudinal space-charge effects will be controlled with the same special fast -responding cores used to correct cumulative acceleration-waveform errors.

Figure 2 presents a block diagram of the physics design of Elise and future extensions and a possible arrangement of some of the experiments. Beams will be obtained from an injector at an energy of approximately 2 MeV, shown in Figure 3. The existing LBL injector is designed to provide one beam of K^+ at driver line charge densities. It will be used for the initial operation of Elise. A separate 4-beam injector must be fabricated at a later date. The nominal pulse width of the reference design is 1 μs. The injector is followed by a matching section that shapes the beam(s) to the proper radius and "squeezes" them together for insertion into the electrostatically focused induction linac. To prepare the beam(s) for compression, the electrostatic-focus section imparts a velocity shear or "tilt" as it accelerates them to 5 MV. A velocity tilt means that the tail of a beam bunch is accelerated more than the head; this causes the rear particles to catch up with the front ones, compressing the bunch and therefore increasing the current.

Elise contains 32 accelerating cells, which are physically grouped into blocks of eight. The cell blocks are separated by two half lattice periods, which provide diagnostic access to the beams. As the energy increases, the length of the half lattice period increases from 33 cm in the first three blocks to 41 cm in the fourth block.

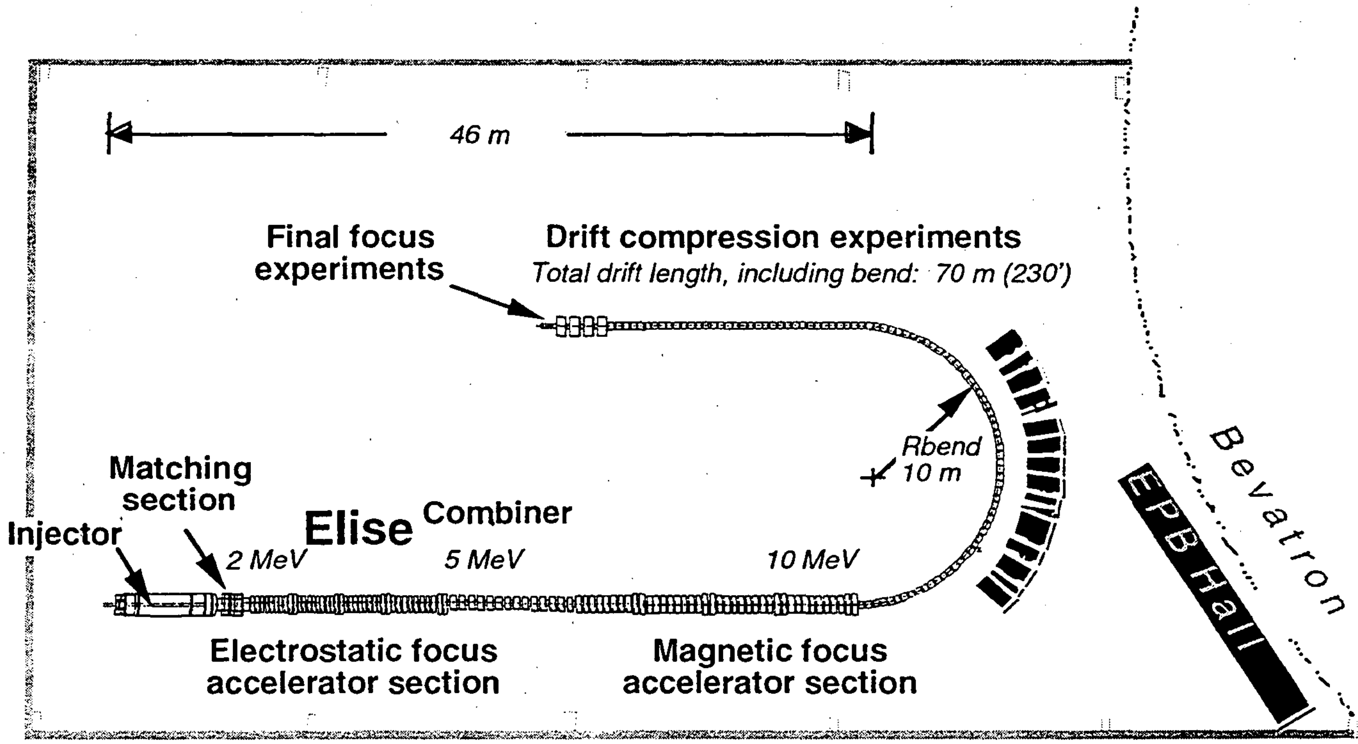


Figure 2. Block diagram shows a layout of the Elise accelerator along with possible accelerator and experimental extensions in the External Particle Beam (EPB) Hall of the recently shut-down Bevatron.

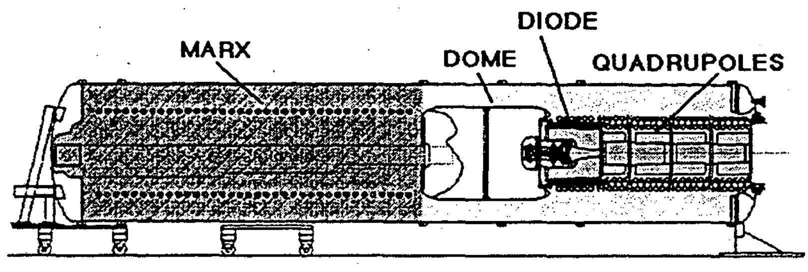


Figure 3 The existing LBL injector

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