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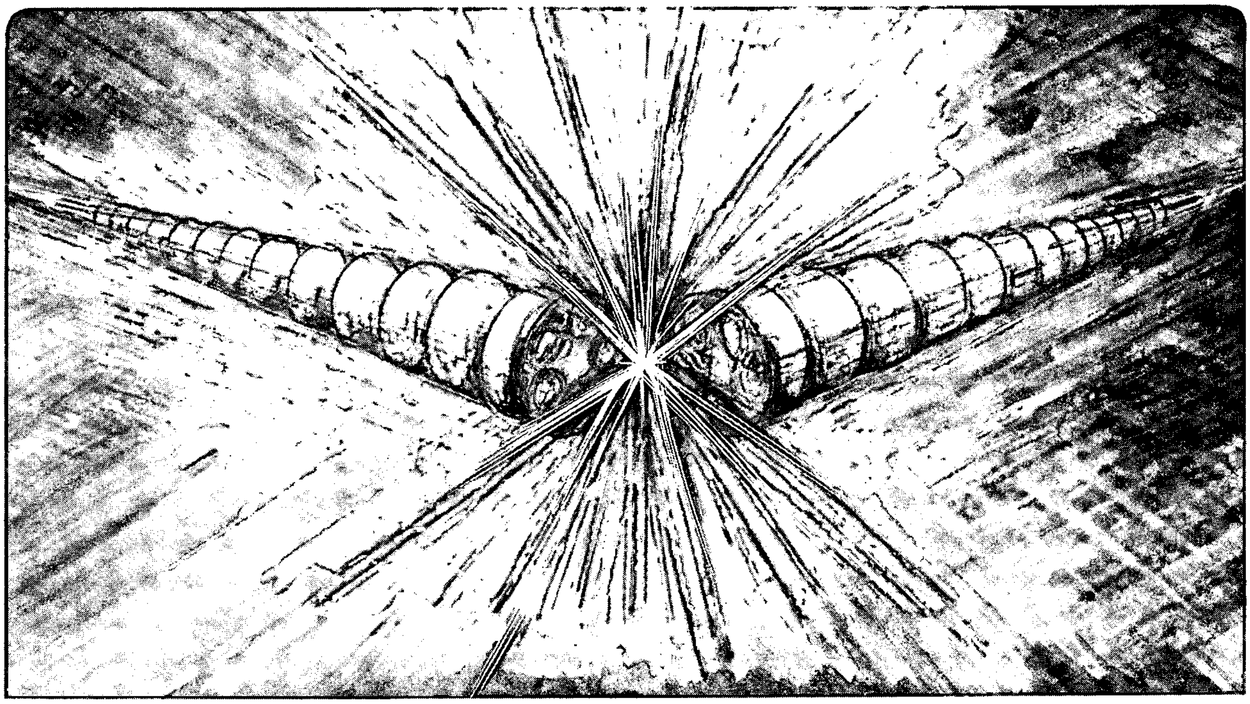

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ENGINEERING RESEARCH AND DEVELOPMENT FOR THE ELISE HEAVY ION INDUCTION ACCELERATOR*

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Abstract

The Fusion Energy Research engineering team has been conducting Research and Development Associated with the Construction (RDAC) of the Elise accelerator since the approval of Key Decision one (KD1 is start of construction). The engineering design effort has worked in close cooperation with the physics design staff to achieve all parameters of the Elise accelerator. The design included the 2 MV injector, matching section, combiner, induction cells, electric/magnetic quadrupoles, alignment system and controls. All major designs and some hardware testing will be discussed.

1. Introduction

For about a decade, the Fusion Energy Research group at LBNL has been exploring the use of induction accelerators and has been carrying out a number of small experiments in heavy ion beam transport physics to understand the viability of the technology as a driver for inertial fusion targets. In order to make further advances in this field and to develop economically competitive technology, a proposal has been made by LBNL in partnership with LLNL to build a 5 MeV accelerator, Elise, to conduct a series of more advanced experiments. The isometric view of Elise showing the existing injector followed by 3 MeV of induction modules is shown in Figure 1.

FIGURE 1

Approval for Elise construction was received about a year ago and we have been carrying out research and development on all the major components critical to the accelerator. For economic

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reasons, Elise will be located in the external beam hall of the now shut down Bevatron and the initial experiments will use the existing single beam injector.

The injector has been operational for two years and now a matching section in the beam transport has been added. A significant effort has been invested in the investigation of the magnetic materials that are appropriate for Elise and we are in the process of optimizing the design in terms of satisfying all the physics requirements at a minimum cost. A line modulator based on a glass thyratron switch with nonlinear PFN has been tested to full power. The electrostatic quadrupole for beam transport has been built and is currently being tested. A magnetic quadrupole which will be needed for the continuation of Elise has also been built and tested. The alignment system has been investigated in conjunction will the electrostatic quadrupole and we feel confident that the tolerances required for beam transport will be met. The engineering development effort has concentrated on meeting all the performance requirements at a minimum cost since economic competitiveness will ultimately decide if a heavy ion driver will be a feasible way to achieve power production.

Recently the overall architecture of the Elise Accelerator has evolved to incorporate 60 induction cells some combined in pairs to form 51 induction modules. The new arrangement packs acceleration cells into a compact configuration (Fig. 2). Two quadrupole gaps are used for permanent diagnostic locations. Most of the space reserved for diagnostics in the CDR version has been eliminated and converted to induction modules in an effort to increase induction core fraction and reduce overall machine costs. To replace the fixed diagnostics capability, a scheme using a floating diagnostics box has been developed. Under this scenario, the induction modules will be mounted on rails, allowing the machine to be quickly opened to allow insertion of diagnostics at any position. A quick opening vacuum system is being developed which will be remotely actuated, since direct access to the flanges between induction modules is very limited.

FIGURE 2

2. The injector and matching section

The 2 MV injector has been operational since January 1994. It has been operated at 2 MV and has produced 800 mA of K+ ions. Figure 3 shows a cross-section of the pressure vessel housing the Marx generator, the ion-source electronics and the electrostatic quadrupole transport section. The Marx generator consists of 38 stages of a simple two-harmonics network which produces a flat-top voltage to better than 0.5%. Figure 3 shows a schematic of the network and the output voltage pulse. The 10-90% risetime is less than 1 μs and the flat-top is 4 μs. The output voltage pulse can be adjusted to have a slight increasing ramp by changing the conductivity of the liquid resistor. The acceleration column is 2.4 m long and consists of a diode section and four ESQ sections (Figure 4). Each section consists of a series of ceramic rings 71 cm OD brazed together with thin niobium flanges between each ring. The ESQ electrodes are mounted on plates captured between the ends of the brazed ceramic sections. Stainless steel x-ray shields are attached to the inside edge of each niobium ring. These also hide the triple points formed at the niobium to ceramic joints. A water resistor is electrically attached to the outside edge of each niobium ring. Semi-rigid polyethylene tubing is used in a helical configuration.

FIGURE 3

Niobium flanges were used at the ends of each brazed section to provide a means of bolting the sections together. The strength of these joints was a major concern. After careful analysis, consultation with the ceramic manufacturer, and review of available test data, 17,000 cm-Kg was selected as a design limit for the bending moment at the joints between sections. As a result, careful procedures had to be developed in order not to exceed this limit during any phase of assembly and installation.

The installed column weights 2800 Kg. and is supported by 2 fiberglass tension struts on each side attached to a heavy collar between the diode and the first ESQ. This arrangement is shown in Figure 4. This arrangement provides the required vertical support force of 2300 Kg. necessary at the 1.8 meter point on the column. Also, the rods load the column in 9200 Kg. compression since they are oriented primarily horizontally. This load turns out to be very useful as it keeps the tensile stress at the end flanges of the brazed sections below the level equivalent to the 17,000 cm-Kg. design limit. In other words, if the column was simply supported by a vertical support at the 1.8 meter point, without the compressive force created by the struts, the brazed joints would crack and come apart.

FIGURE 4

The matching section consists of six ESQ each decreasing in size to focus the potassium beam to the desired diameter. Figure 5 shows a cross-section of the matching section. The first three quadrupoles will be statically mounted in the vacuum tank while the last three will be able to articulate while under vacuum to allow steering of the beam. Large quadrupole position offset adjustments are also possible from within the tank to facilitate beam bending experiments.

FIGURE 5

3. Magnetic Material and Induction Cells

The voltage gradient dictated by the half lattice period and the pulse duration will establish the volt-seconds required by the cells. For Elise, a voltage gradient of 300 to 400 kV/m and a pulse duration of one to two microseconds will require cores of one to two meters in diameter. It is imperative to find a material with the maximum flux swing and the minimum magnetizing current. A significant effort has already been invested in the investigation of the magnetic materials which are appropriate for this application. There are several materials which satisfy the technical requirements for ILSE. The conventional Ni-Fe alloys that have been used for many decades and the relatively new amorphous materials (Metglas*) satisfy these requirements. The choice of materials is therefore based on economic advantages. Recent investigation shows that the Metglas alloys hold an economic advantage over the conventional Ni-Fe alloys. The Allied Metglas amorphous material 2605 series can be mass produced as a thin ribbon (15-20 μm) with high

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* *Registered trademark of Allied-Signal.

resistivity and practically any width. This material is used extensively by the 60 Hz power industry. For this application, annealing is essential in order to achieve maximum flux swing and minimum loss. Annealing is typically done after the ribbon is wound into a core without interlaminar insulation. Interlaminar insulation is not required for the 60 Hz application because the volts per layer of ribbon are very small (mV). For the Elise application where the rates of magnetization are between 2-6 Tesla/μs and 10-20 V per layer can be generated, some insulation will be required to maintain low eddy current losses hence annealing with interlaminar insulation is not feasible. We have therefore chosen to use the amorphous material unannealed or as cast. We pay a small penalty in slightly more rounded B-H loop or higher losses but at a greatly simplified way of winding the metallic ribbon using 2.5 μm mylar as interlaminar insulation. In our material studies, we found that 2605 SC was the optimum material in terms of loop squareness and low loss. The original conceptual design report (CDR) used this material for the baseline cost estimates. The cost of this material, however, is 2-3 times greater than the material SA1 which is mass produced in the Conway, South Carolina plant for the 60 Hz industry. Initial tests on the SA1(TCA) material indicated considerably greater losses and a more nonlinear B-H loop. We are currently re-investigating cost trade-offs in using this less expensive material (instead of 2605 SC) which could lead to a more difficult PFN design, hence, more costly modulator. This material can be manufactured in widths of 4" or greater which also puts some constraints on the half lattice period(HLP). Figure 6 shows the latest design using a combination of 5.6" and 6.7" wide SA1 material which yields the desized HLP. The testing and optimization process will continue for the near future with a final decision on the geometry in FY 96.

FIGURE 6

4. Electrostatic Quadrupole

The electrostatic quadrupole (ESQ) in Elise is housed inside the induction accelerator cell (Figure 7). Figure 8 shows the details of the new ESQ with end plate removed. The design minimizes the outside diameter of the ESQ since this strongly effects induction core size, hence, drive power and costs of the cells and the drive system. The location of the ESQ's imposes several constraints and demand on the high voltage feed-throughs, the supports and alignment system since the spacing between modules will be less than 5 cm. A high voltage feed-through which fits this spacing and is vacuum tight has been designed and tested and is shown in Figure 9. This feed-through held twice the operating voltage level and is relatively inexpensive to manufacture.

The ESQ will contain 4 beam channels even though only one will be used initially for Elise. Nine stainless steel electrodes are cantilevered off 2 end plates at opposite polarities. Very tight mechanical tolerances and special assembly techniques are required to meet the quadrupole alignment tolerances of +/- 100 μm in the accelerator. The ESQ's are supported by a center ground plane which is offset from the induction module gaps. This offset arrangement (as opposed to requiring gaps between induction modules to always fall on the ESQ centerline) permits a much higher packing factor for the induction cores. The spool between modules supports and moves the ESQ for alignment adjustments. The ESQ is currently undergoing testing to determine its high voltage breakdown limit. During this initial testing the ESQ was able to hold well over operating voltage but has not yet achieved the 2 times operating voltage goal. Additional tests are planned to determine effect of placement within an enclosure and the effect of beam proximity. The 5 cm space between modules also contains the high voltage feed through for the ESQ.

FIGURE 7

FIGURE 8

FIGURE 9

5. Magnetic Quadrupole Design and Tests

As previously mentioned, the initial transport of the Elise accelerator from the 2 MV injector to the 5 MeV level is provided by electrostatic quadrupole. At the 5 MeV level, it becomes more effective to use magnetic quadrupole focusing. The physics design requires a constant field of 2 Tesla for the beam pulse duration of 1-2 μs. The first prototype was designed to achieve these parameters with an aperture radius which is one third the effective coil length. The aperture radius has been set at 7.5 cm and the effective magnetic length at 25 cm (Figure 10). In this first prototype the engineering effort has concentrated on achieving electro-mechanical reliability, ease of manufacturing and low cost. To achieve the 2 T field, 5.4 kA of current were required. Since a uniform field is required for only 1-2 µs, a pulsed power supply was designed. The half sinusoidal pulse was chosen to be 1 ms in duration which provides more than sufficient flat field with 10 kV across the leads and about 1500 Joules in overall losses. The power supply is driven in a bipolar mode of ±5 kV to lower the voltage between leads and ground. The power supply also incorporates an energy recovery system to reduce the power input requirement. The magnetic quadrupole was tested for many hours at one hertz. A flaw in the potting of the coil resulted in arcing to the beam pipe at ground. The second prototype incorporates improvements in the engineering design as well as in the field quality. This improved design, however, will not be constructed until later since it will not be needed for the Elise accelerator.

FIGURE 10

6. Summary

The Fusion Energy Research group at LBNL in partnership with LLNL has undertaken the development of an induction accelerator for heavy ion inertial confinement fusion. This accelerator will address many of the transport issues for driver scale beams and will resolve many technology issues associated with magnetic materials, waveform generators, alignment and electric/magnetic quadrupoles. Most importantly, this accelerator will answer many questions associated with economic viability and reliability of an eventual driver for inertial confinement fusion as a power source.

Acknowledgments

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W. Greenway, R. Hipple, C. Houston, T. Katayanagi, J. Pruyn, C. Schmitt, W. Strelo, J. Stoker, M. Stuart, W. Tiffany

Fig. 1. Isometric view of the Elise accelerator.

Figure 2. Elise conceptual design packs accelerating modules into a compact configuration.

Fig. 3. 2 MV injector showing the Marx generator, ion source and acceleration column.

Fig. 4. 2 MV injector column showing the diode and ESQ sections supported by fiberglass struts.

Fig. 5. Cross section of matching section.

Fig. 6. Detailed cross section of radially segmented induction cells.

Fig. 7. ESQ inside induction module.

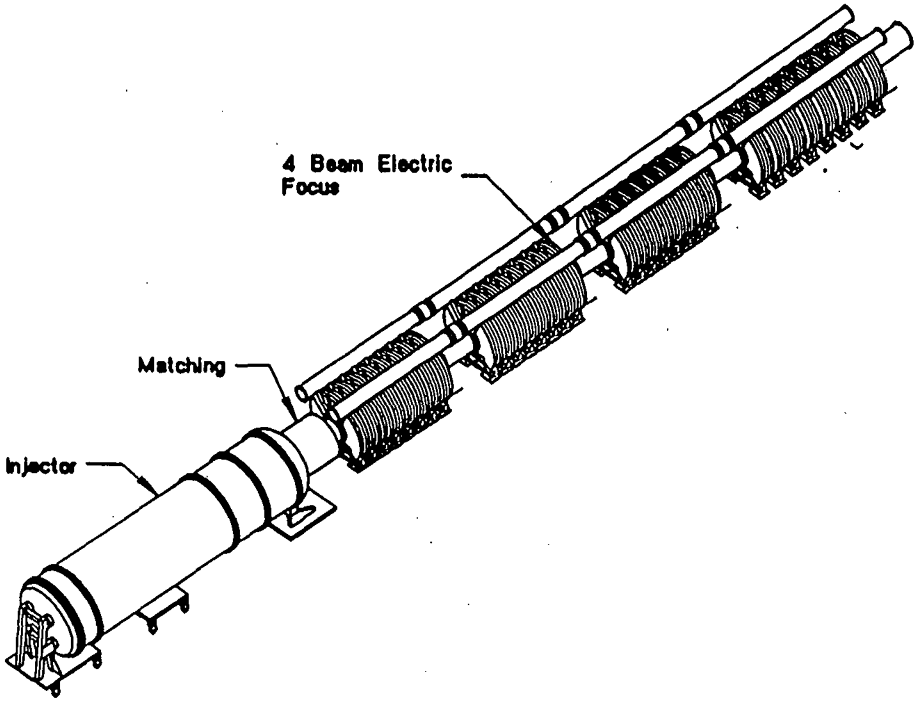
Fig. 8. Details of new ESQ with end plate removed.

Fig. 9. Cross section of high voltage feed through for ESQ bias.

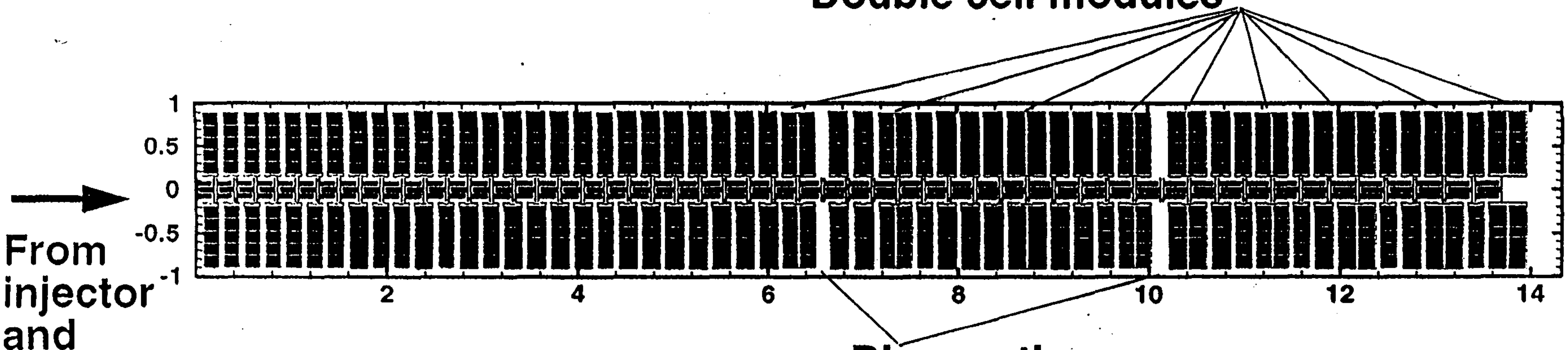
Fig. 10. Cross-section of magnetic quadrupole housed within the induction module.

Fig. 1 L. Reginato 1/4 pp

Isometric View of the ELISE Accelerator



Modules come in single and double cell varieties



Double cell modules

From injector and matching section

Diagnostic access space

Lattice half period increases roughly as square root of the energy (to maintain a "matched" beam envelope) so longer cores and/or multiple-cell modules are used near the end of the machine

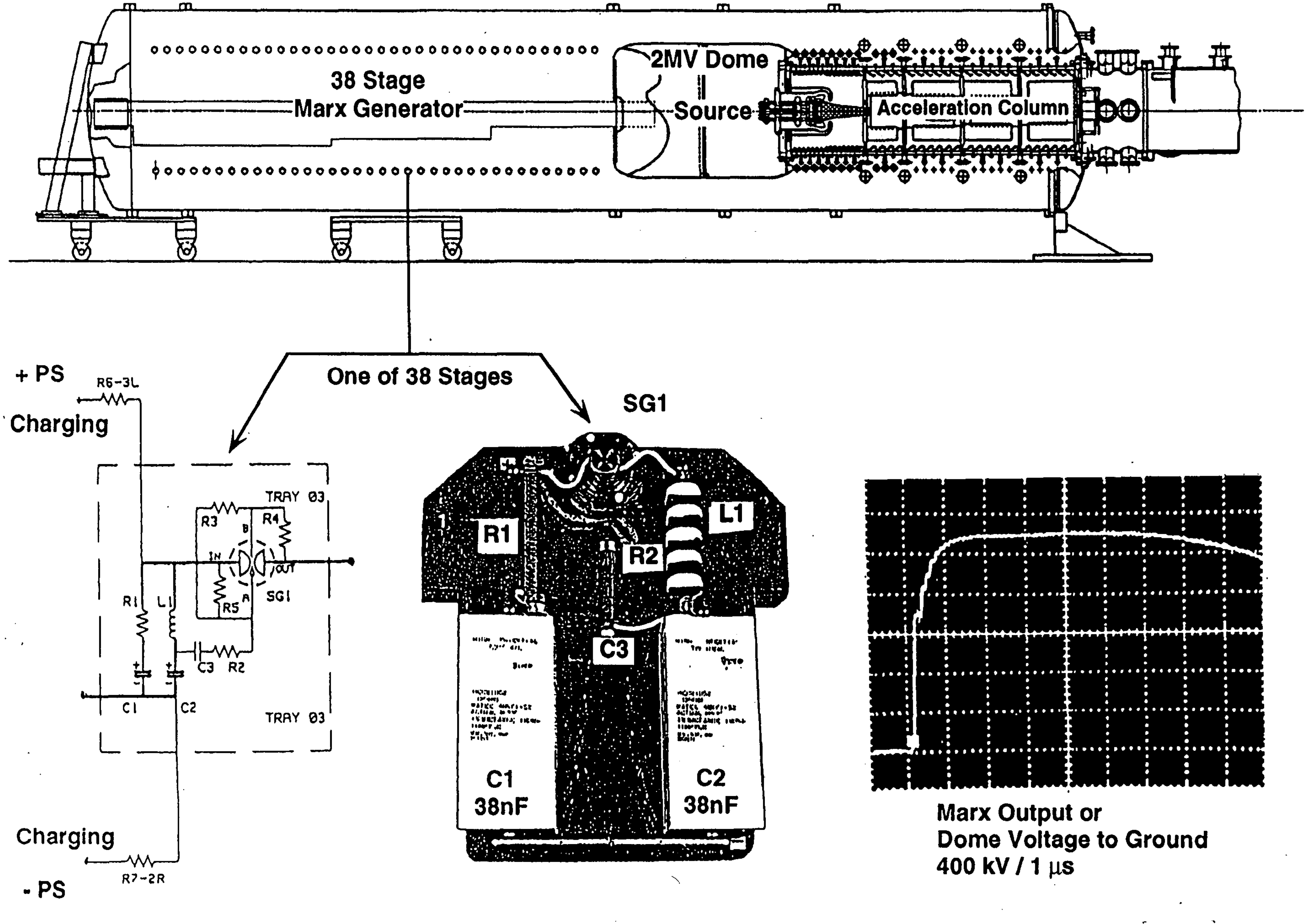

38 Stage
Marx Generator
2MV Dome
Source
Acceleration Column
One of 38 Stages
+ PS
R6-3L
Charging
TRAY 03
R3
R4
B
IN
OUT
A
R5
SG1
R1
L1
C3
R2
C1
C2
TRAY 03
Charging
R7-2R
- PS
SG1
R1
L1
R2
C3
C1
38nF
C2
38nF
Marx Output or
Dome Voltage to Ground
400 kV / 1 µs

Fig. 4 L. Reginato 1/4 pp

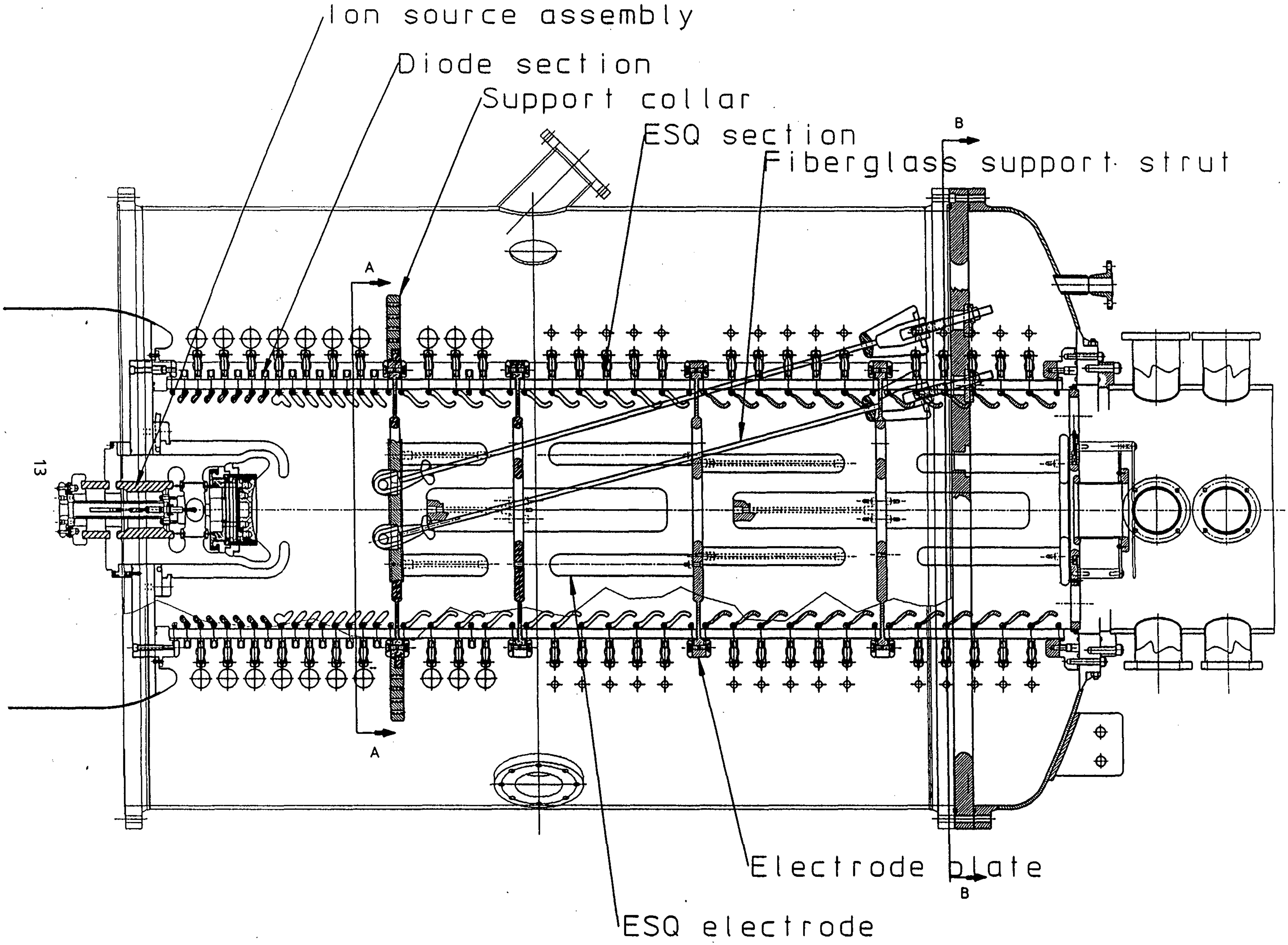


Fig. 5 L. Reginato 1/4 pp

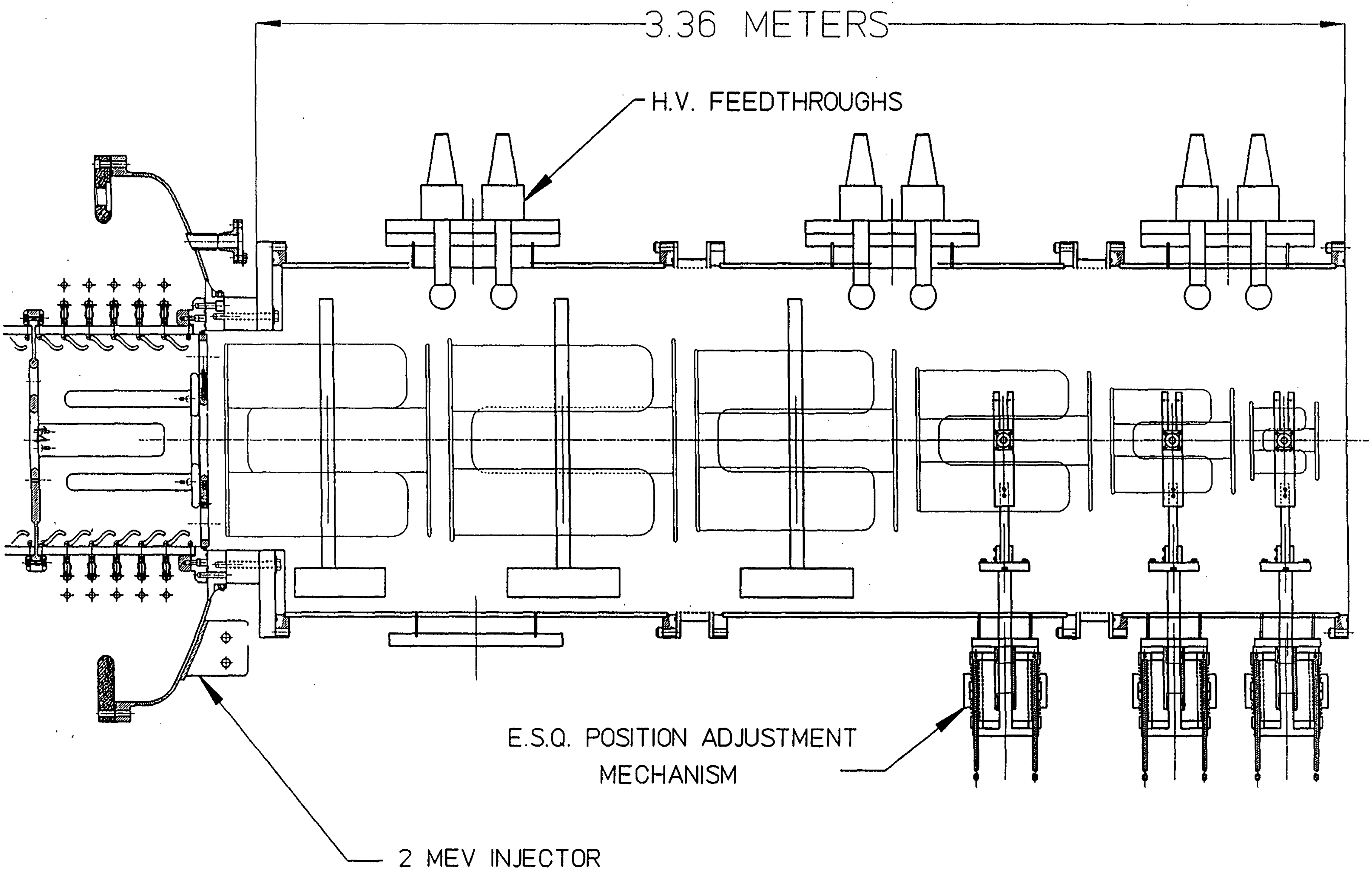


FIG 6

Single Cell ESQ Acceleration Module

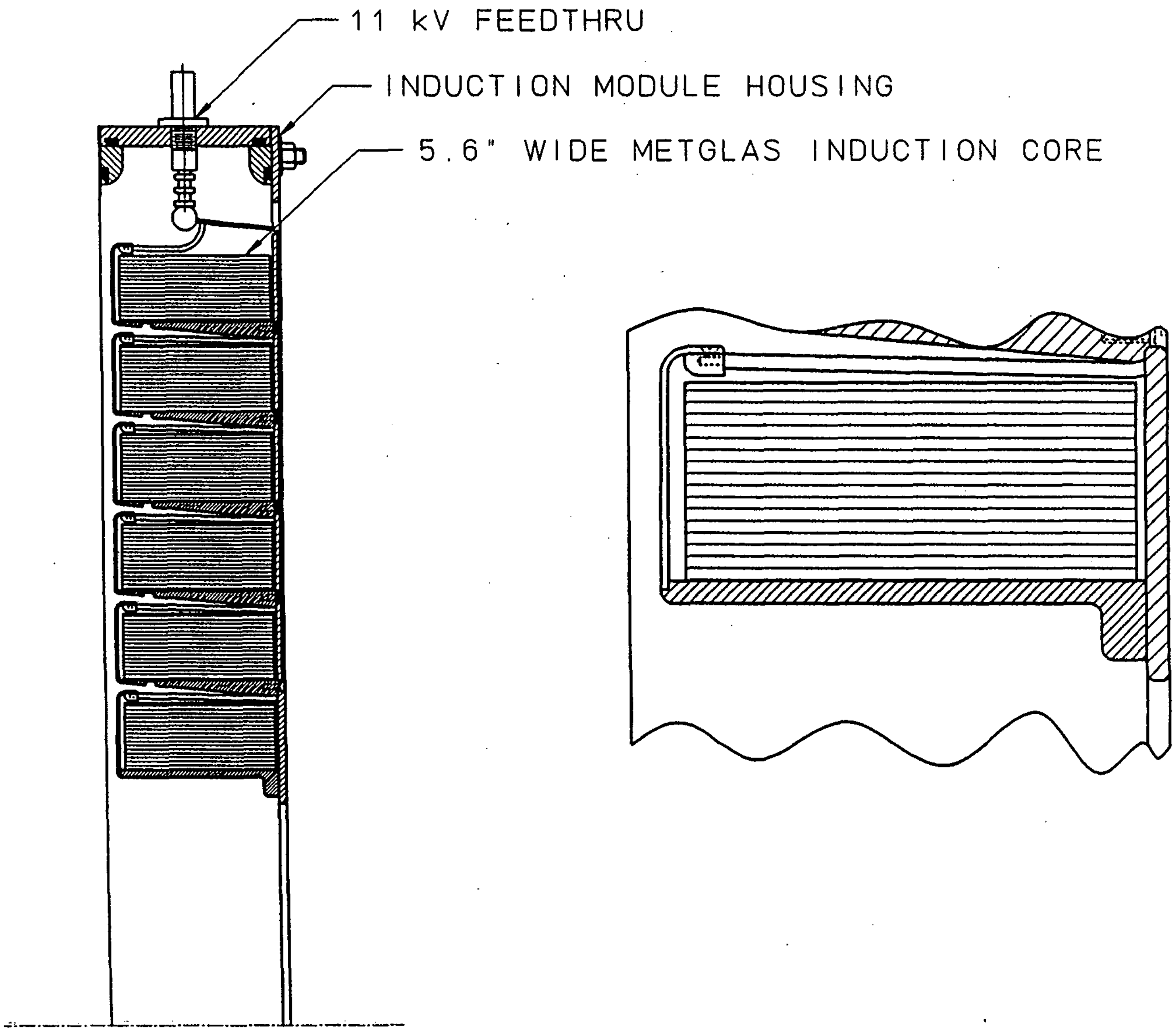


Fig. 7 L. Reginato 1/4pp

Typical Elise Induction Module Configuration

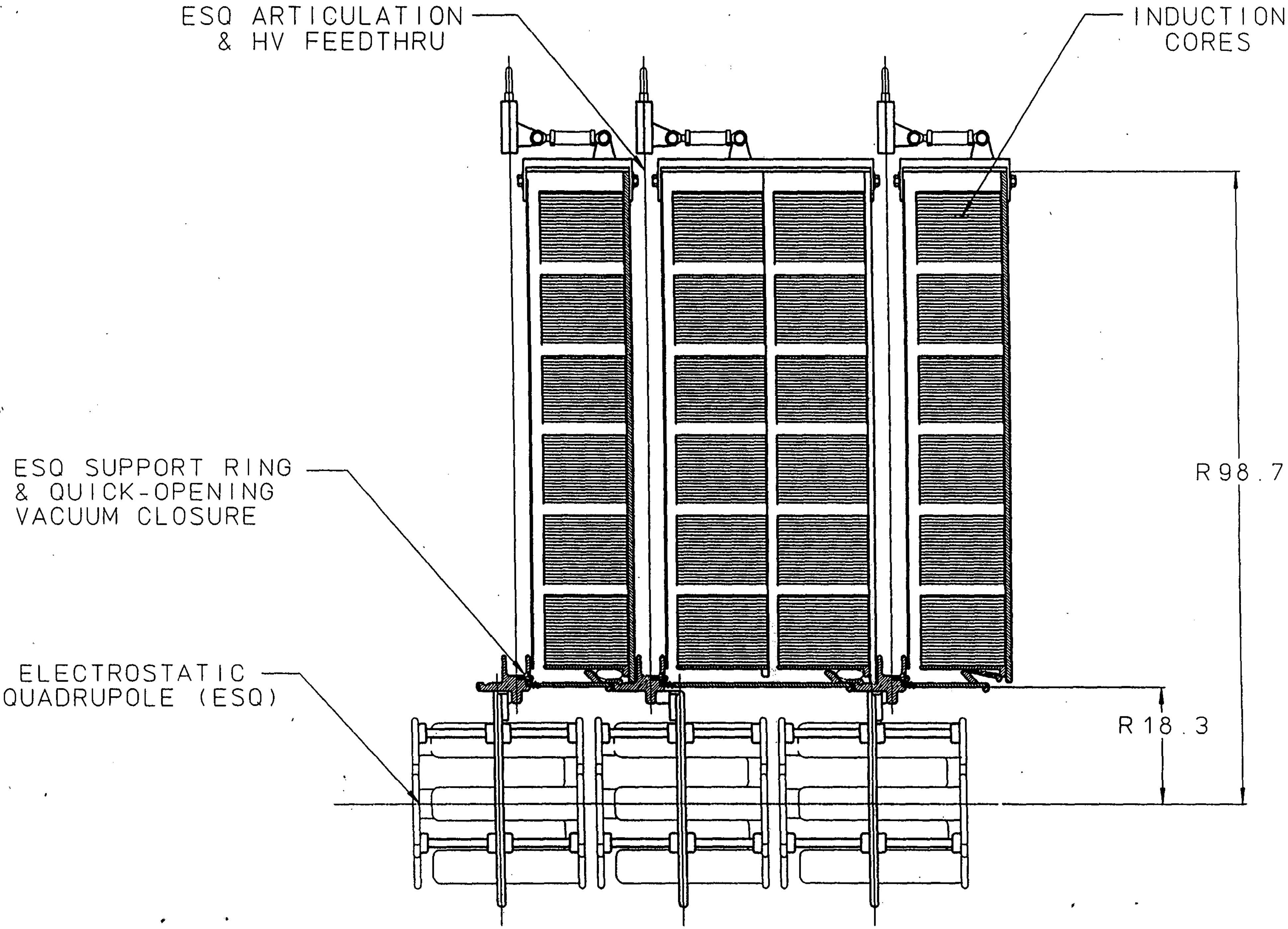


Fig. 8 L. Reginato 1/4pp

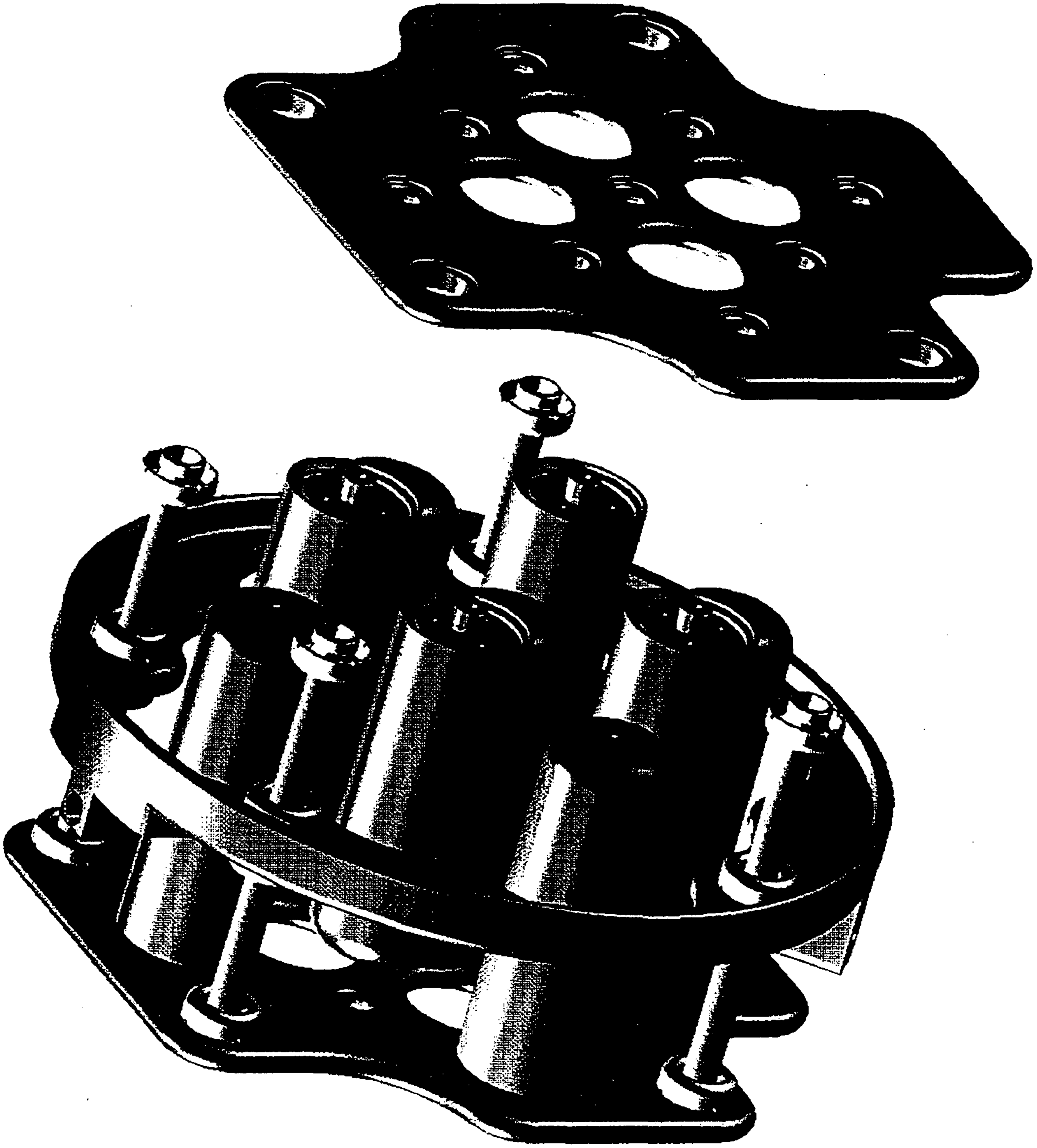


Fig. 9 L. Reginato 1/4pp

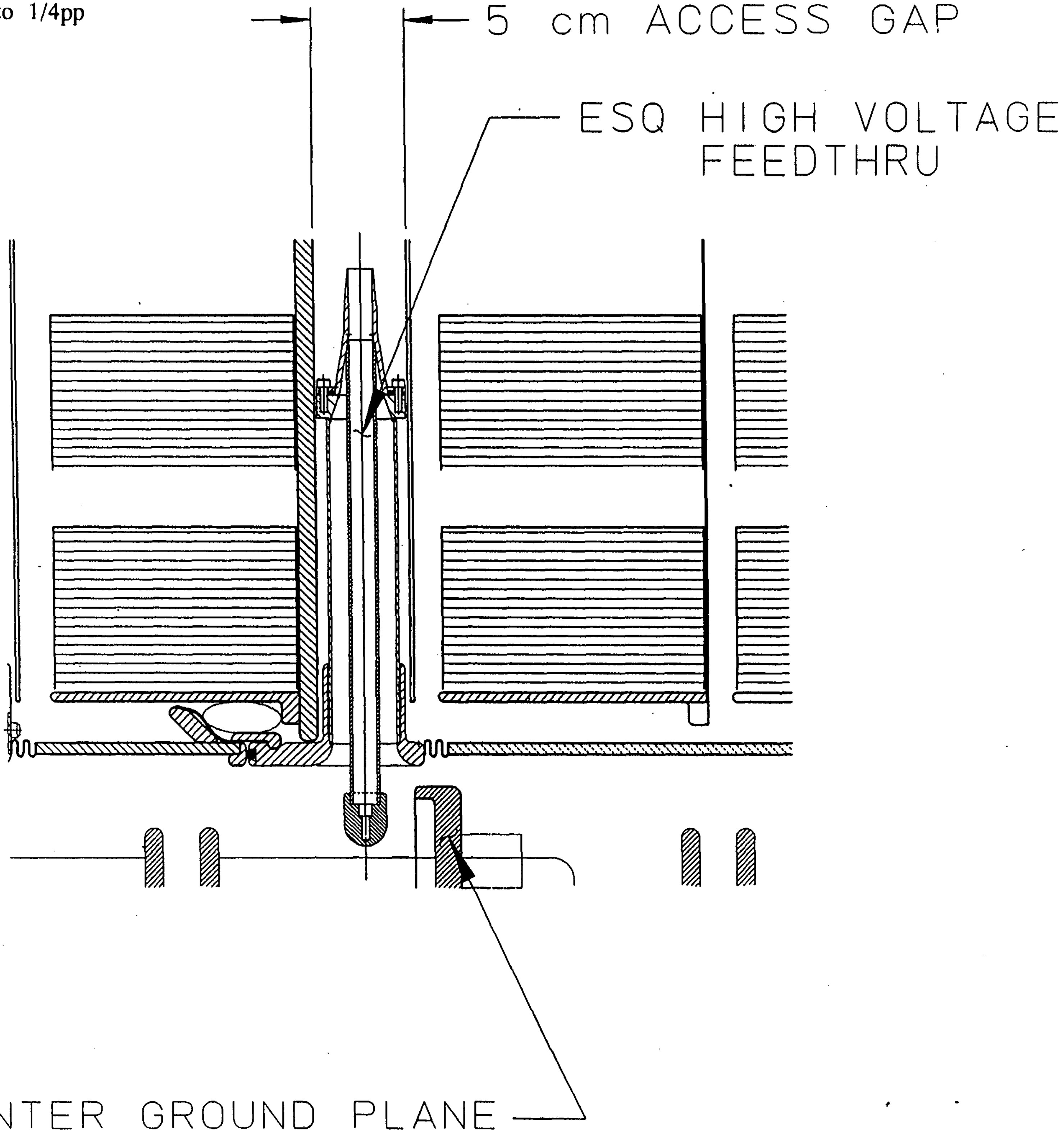


Fig. 10 L. Reginato 1/4 pp