ENERGY STORAGE OPTIONS FOR SHIVA UPGRADE*

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ABSTRACT

The Shiva Glass Laser at LLL will use 20-25 MJ of Capacitive energy storage. An improved laser system is proposed that will increase this energy requirement by a factor of ten: 25 MJ for Faraday rotators, and 150 MJ for flashlamps. This paper discusses alternative options to capacitors for driving both types of loads. Included are homopolar generators that discharge in ∿ 0.1 sec that will drive Faraday rotators directly. Similar generators can be used to drive inductive stores for flashlamp power. The features of the flashlamp system include a wide distribution of 10kJ load elements, and a half-millisecond discharge time requirement. The possibilities of providing open-switching for inductive storage and of driving many flashlamps in parallel are discussed.

Energy Storage Options for Shiva

In the fall of 1977 the LLL Shiva glass laser will be operating with a 22 megajoule power conditioning system. Soon after that, improvements are proposed for Shiva that will increase the laser output at least by an order of magnitude.

The power conditioning for this upgrade requires that 175 MJ be delivered to flashlamps and Faraday rotator coils. The energy and power requirements, and the distribution of these two loads are distinctly different, Figure 1.

The flashlamps are characterized as approximately two-ohm nonlinear resistive loads. They are widely distributed: sixteen to forty-eight flashlamps are used in each of the six or seven neodynium glass disc amplifiers that make up each of the proposed 40 to 60 laser chains. The Faraday rotators are much fewer in number, only two or three are used in each laser chain, and they are simple inductive loads. Also, because the rotation fields can be established in a rather leisurely fashion, a few tenths of a second, the total power requirement is much less than that for the flashlamps. However, 100 MW for the rotator coils is still higher than one can economically obtain from the utility system. Therefore, for either load, energy storage is necessary.

On Shiva, both load types are driven with capacitors. In Figure 2, a cutaway of the Shiva building shows the space frame above, with the

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The Shiva Glass Laser at LLL will use 20-25 MJ of Capacitive energy storage. An improved laser system is proposed that will increase this energy requirement by a factor of ten: 25 MJ for Faraday rotators, and 150 MJ for flashlamps. This paper discusses alternative options to capacitors for driving both types of loads. Included are homopolar generators that discharge in~ 0.1 sec that will drive Faraday rotators directly. Similar generators can be used to driveÂ·Â·Â· inductive stores for flashlamp power. The features of the flashlamp system include a wide distribution of lOkJ load elements, and a half~fili?~cond discharge time requirement. The possibilities of providing open-switching for inductive storage and of driving many flashlamps in parallel are discussed.

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elements of each laser chain, and the many racks of capacitors in the basement (Figure 3). Capacitors are very convenient because they can be charged over a long period, they can be discharged rapidly, and they come in small packages of a few kilojoules each, Figure 4, this makes them ideal for driving a large number of flashlamp loads.

For example, on Shiva, a pair of lamps is driven in series with a single capacitive store of about 20 kJ, Figure 5. This store consists of four 5-kJ capacitors in parallel that are connected to a circuit board. This board contains the various elements of the circuit, Figure 6, including a charging resistor R_1 and a pulse-forming inductor L for shaping the discharge pulse. A number of these circuits can be connected together at the switch and charged in parallel. Up to 32 circuits can be switched with a balanced, series-pair of size D ignitrons, Figure 7.

The disadvantages with this capacitive method of energy storage are its large size because of its low energy density, and its cost. For example, the Shiva 22 megajoule capacitor bank will occupy about two-thirds of the 85 x 160 foot basement, clear up to the 13-foot ceiling. Its installed cost, including racks of capacitors, PFN circuits, power supplies, switches, controls, cables, and flashlamps will be about 25¢/Joule at todays prices. About 60% of these costs, 15 or 16¢/Joule, are "replaceable" if a suitable alternative to capacitors, PFN circuits, power supplies, and switches is developed. In a 175 MJ version, therefore, about $27M worth of capacitive storage system could be superseded by a suitable alternative.

The principal difficulty with every known cost-effective alternative system that would replace capacitors is that each is large: unless the size of the alternative store is in the megajoule range, it will probably not be cost competitive. Also no store is as yet developed to the high degree of flexibility and reliability as the capacitors.

Flashlamp Loads

These difficulties are especially manifest for the flashlamp loads. A large source means that many flashlamps must be driven in parallel, and it is not the nature of flashlamps to willingly share parallel discharge paths with equal current division. However, this difficulty appears surmountable by use of preionization circuits[1], non-linear series resistors and current balancing inductors.[2] A test program is presently underway at LLL to establish the most cost-effective method for achieving uniform parallel current division in the Shiva flashlamp circuits.

Another difficulty with the Shiva flashlamp system is that it must be very high power. To overcome the fluorescent decay of the neodynium laser glass, the lamps must be pulsed in about a half-millisecond. For 150 megajoules of energy, therefore, the average system discharge power is several hundred gigawatts. At present, only two systems (other than high voltage capacitors) appear to be capable of supplying these high power levels. One is an explosively driven flux compression device, currently under development by Cowan, et. al. at Sandia/Albuquerque. The other is an inductive store.

The flux compression device looks attractive, because it can produce an ideal pumping wave-shape for the flashlamps -- namely an exponentially rising current pulse; however, the problems associated with containment of one or two hundred pounds of HE exploding in the basement every shot make the system much less appealing. To be cost-effective, the system is best suited to be a single large generator. This means that flexibility would be lost, and it would be awkward to have to fire the big generator just to dry-run individual parts of the system. In its present form, the flux-compression device generates energy in the 10's of kJ range, therefore, scaling up by 4 orders is required to reach the 100's of MJ level.

Inductive storage, on the other hand, is attractive because most of the technology is here and large scaling jumps are not required. The opening switch requirement does not look too difficult for the flashlamp application, since the opening time may be the order of 100 μsec and the voltages need not exceed about 30 kV.

Sizing of the inductive store for driving flashlamps will depend upon the magnitude of the current that can be handled by a single opening switch. For example, a Shiva flashlamp circuit requires about 20 kJ of energy and 4 kA peak current, or about 5 joules per amp. Therefore, a megamp switch would drive about 5 MJ of flashlamps.

By center tapping or balancing the inductive store, it is possible to drive two of these circuits in series. This would require that the voltage opening capability of the switch be doubled from 15 to 30 kV. In this case a megamp opening switch would drive 10 MJ of flashlamps. In summary, therefore, once the opening switch is sized, the energy of an individual inductive storage system for driving the flashlamps will be determined.

Faraday Rotator Loads

The Faraday rotator coils are larger, more discrete loads than the flashlamps and there is no particular requirement for driving them any faster than is required by circuit L/R time constant restraints. (Faraday rotators are used as optical diodes or check valves and not as shutters or Q-switches.) Furthermore, the rotator coils can be operated in series - parallel circuits, so it is much more straightforward to match the load to any given generator "source".

The energy requirement for the Faraday rotators for ~~improving~~ Shiva ($\sim$ 25 MJ) is not especially large, but if one could pare even four cents per joule from the cost of driving these loads by replacing the capacitive store, the megabuck saved will make the effort worthwhile. The real payoff, however may come about because the rotator coils are really an inductive store. The same technology for driving the rotators could be applied to drive the inductive stores for flashlamps.

A number of methods for supplying high current to an inductor are available. A study[3] has shown that DC power supplies (or batteries) and capacitors are the most cost-effective competitors. However, if the inductors are Faraday rotator coils, made from room-temperature copper, then the DC power supply must produce power at about $4 per kilowatt to compete with energy storage capacitors. It is doubtful that a high current DC supply could be obtained for less than $20/kW, so one must conclude that capacitors are the most cost-effective method after all. The problem reduces simply to finding the best capacitive store.

Homopolar Generator

Another type of power supply, a homopolar generator, can be represented as a low voltage capacitor that is capable of storing a very high charge. For example, the University of Texas at Austin has made a 5 MJ homopolar that has been operating for several years.[4] It will supply almost a quarter megacoulomb of charge.

Since the replacement costs for this type of machine is the order of a penny per joule, it looks very attractive as an alternative to 5¢/J electrolytics or to 7 to 12¢/J oil-paper capacitors.

One example of how such a machine might be used is given in Figure 8. Here, a pair of counter-rotating wheels are driven to high speed, storing perhaps 10 MJ as inertial energy. The technique shown here was pioneered by NRL.[5] To produce the current pulse, the brushes are lowered onto the wheel rim, and the magnetic field is excited. In this configuration, the machine self-excites its own magnetic field as well as the fields of the Faraday rotators.

The NRL self-exciting machine is designed with no magnetic iron. It is specifically made so that the coils for the generator can also be the inductive store. This is a unique way to combine several functions into a single economical package. The disadvantage with an air-core design such as this is that the machine needs a lot of energy in its own field. If an iron yoke is used, then the field energy required is reduced an order of magnitude, and the field coil can be driven with a reasonably small DC power supply (e.g. the 5 MJ Texas machine uses 25 kW of power to excite the field).

Therefore if the machine is used solely for driving external loads such as the Faraday rotator coils, then it probably should be of an iron yoke design. If the requirement instead is to drive an inductive store, then the air-core, self-exciting design has merit because most of the energy stored in the field is returnable as useful power. In either case, our study has shown that the homopolar generator has the potential to replace energy storage capacitors in the large Shiva power conditioning system.

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SHIVA UPGRADE

POWER CONDITIONING OVERVIEW

	FLASHLAMPS	FARADAY ROTATORS
ENERGY	150 MJ	25 MJ
TIME	1/2 MSEC	1/4 SEC
POWER	300 GW	100 MW
NUMBER OF LOADS	15,000	132

FIGURE 1

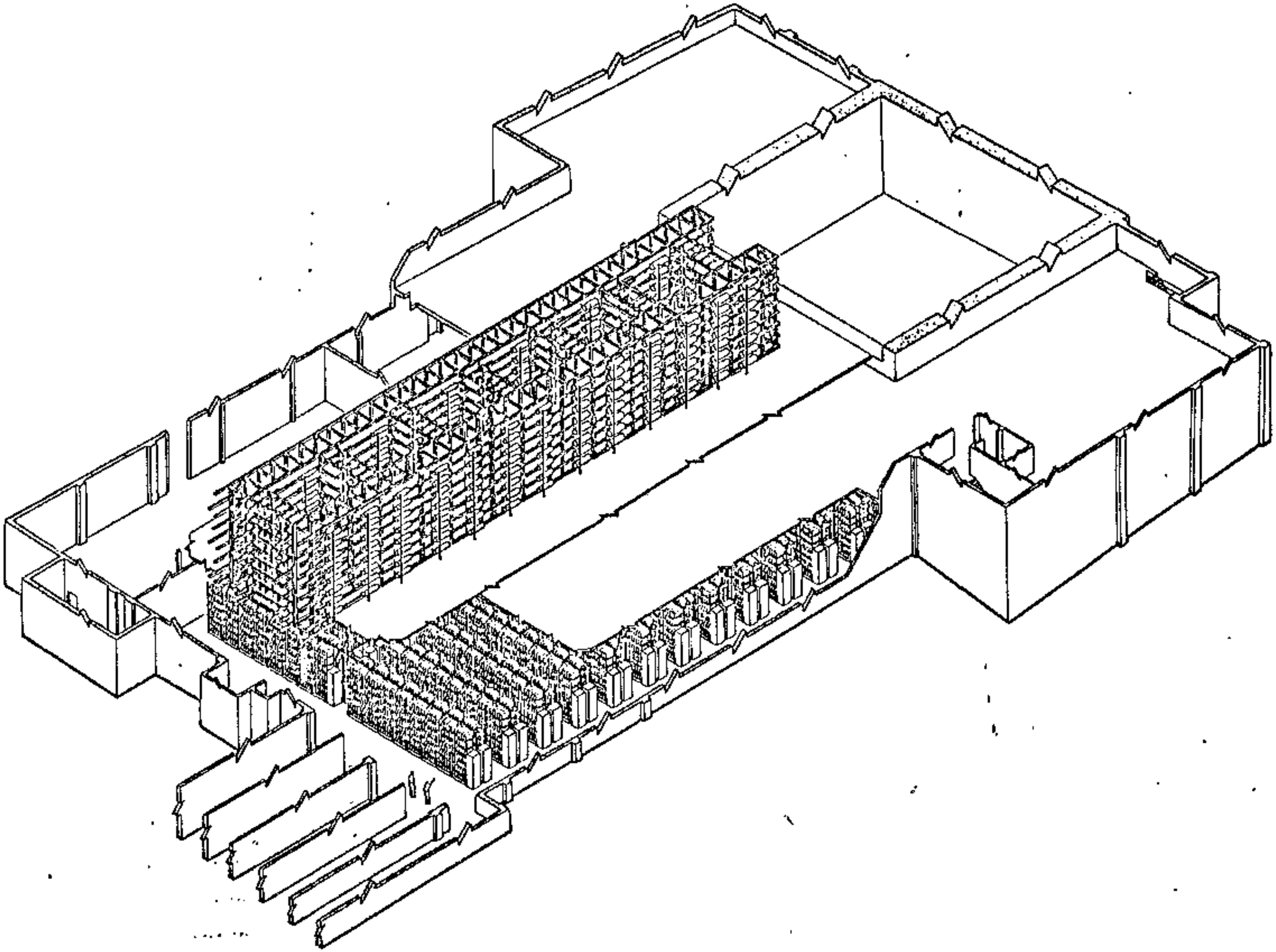


Figure 2: Laser building cutaway. The power-conditioning apparatus is housed in the basement, directly below the space frame.

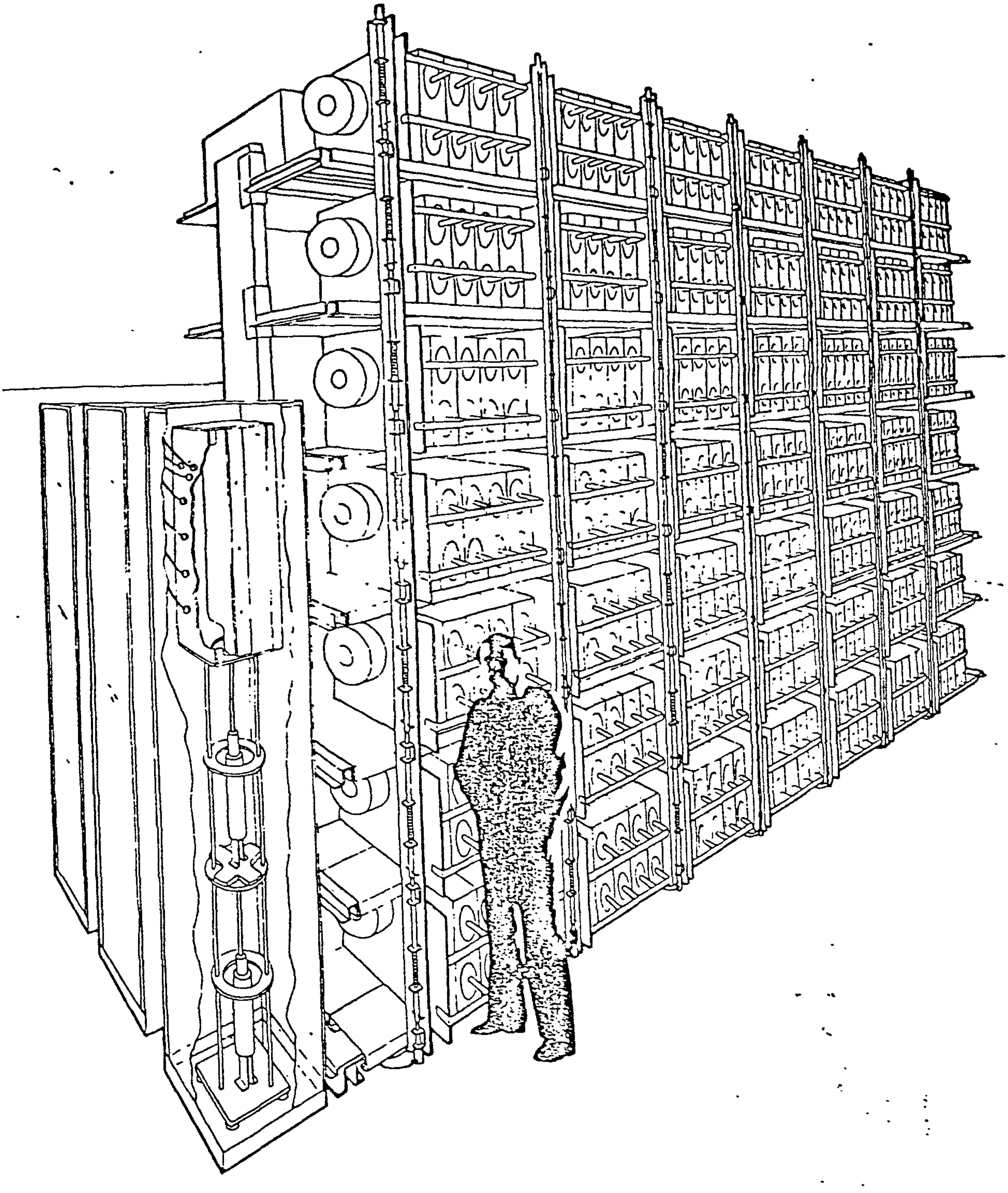


Figure 3: Capacitor Bank Array. A typical rack of capacitor banks is 12 ft. high and 400 in. long. Seven-high dump switches are mounted vertically, and fastened to the shelves. Dual ignitron switches are located in cabinents at one end of the rack.

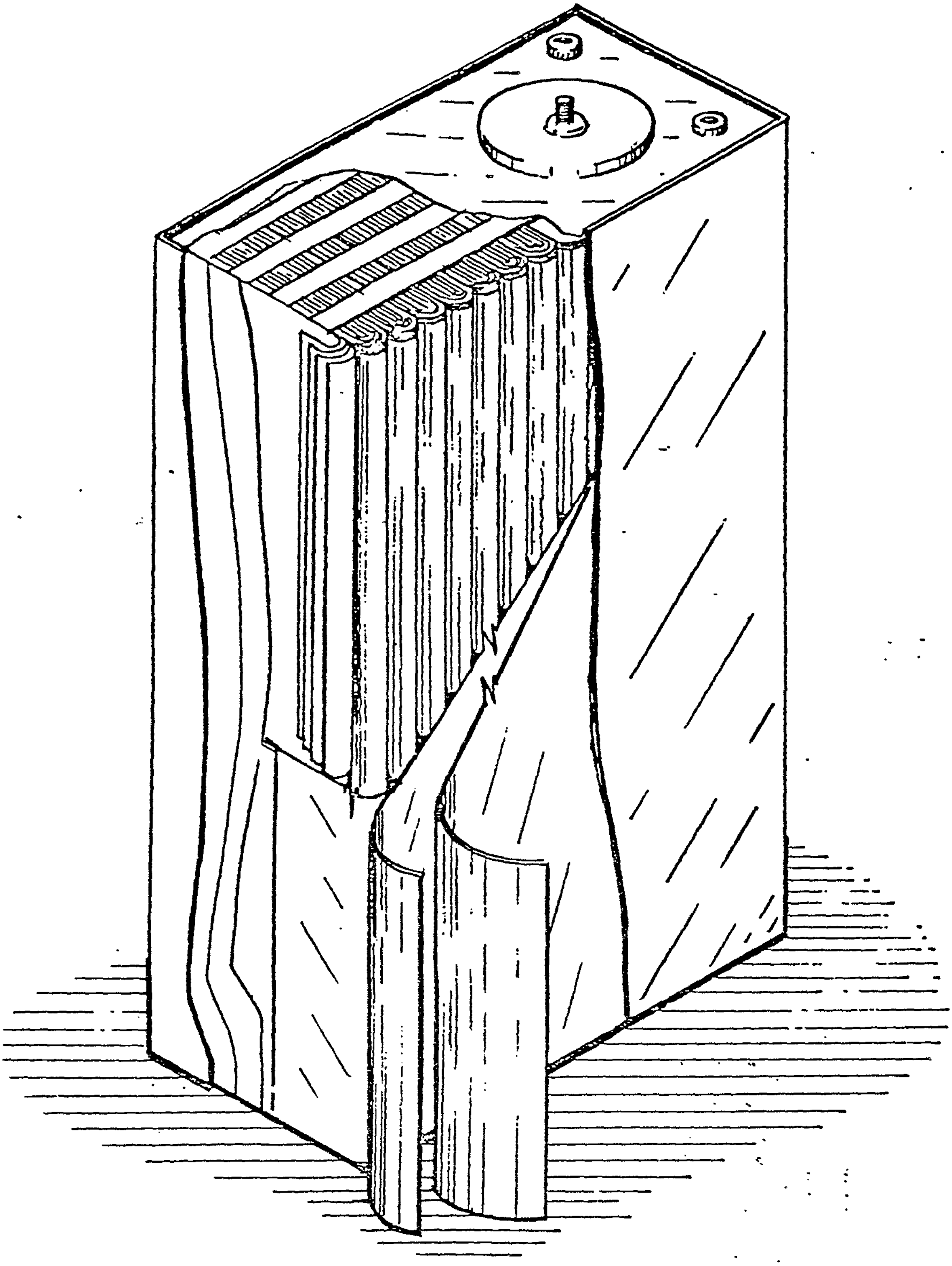
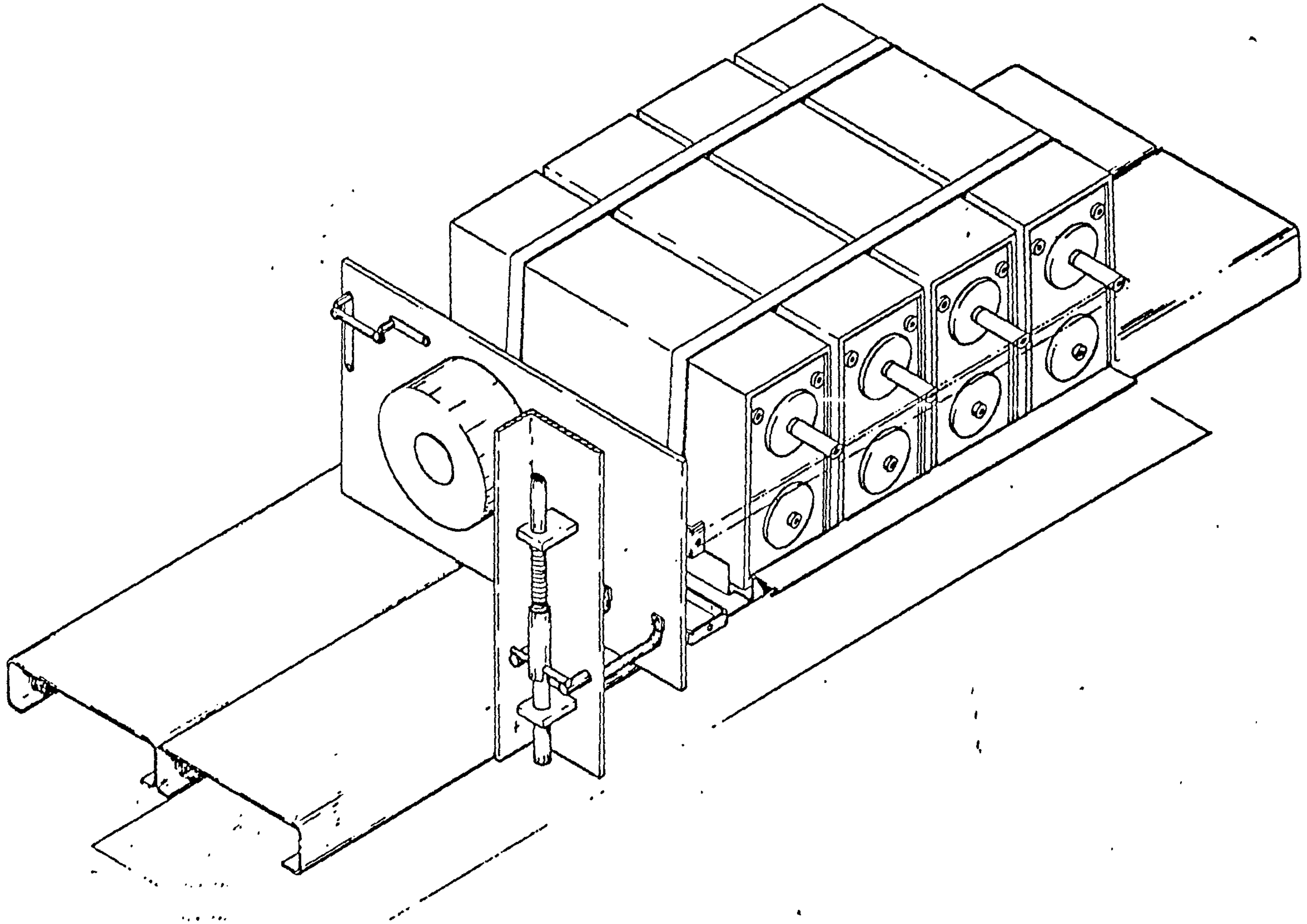


Figure 4: 5kJ Energy Storage Capacitor. This cutaway view shows the individual pads. The capacitors have two series sections, connected to two terminals and insulated from the case.



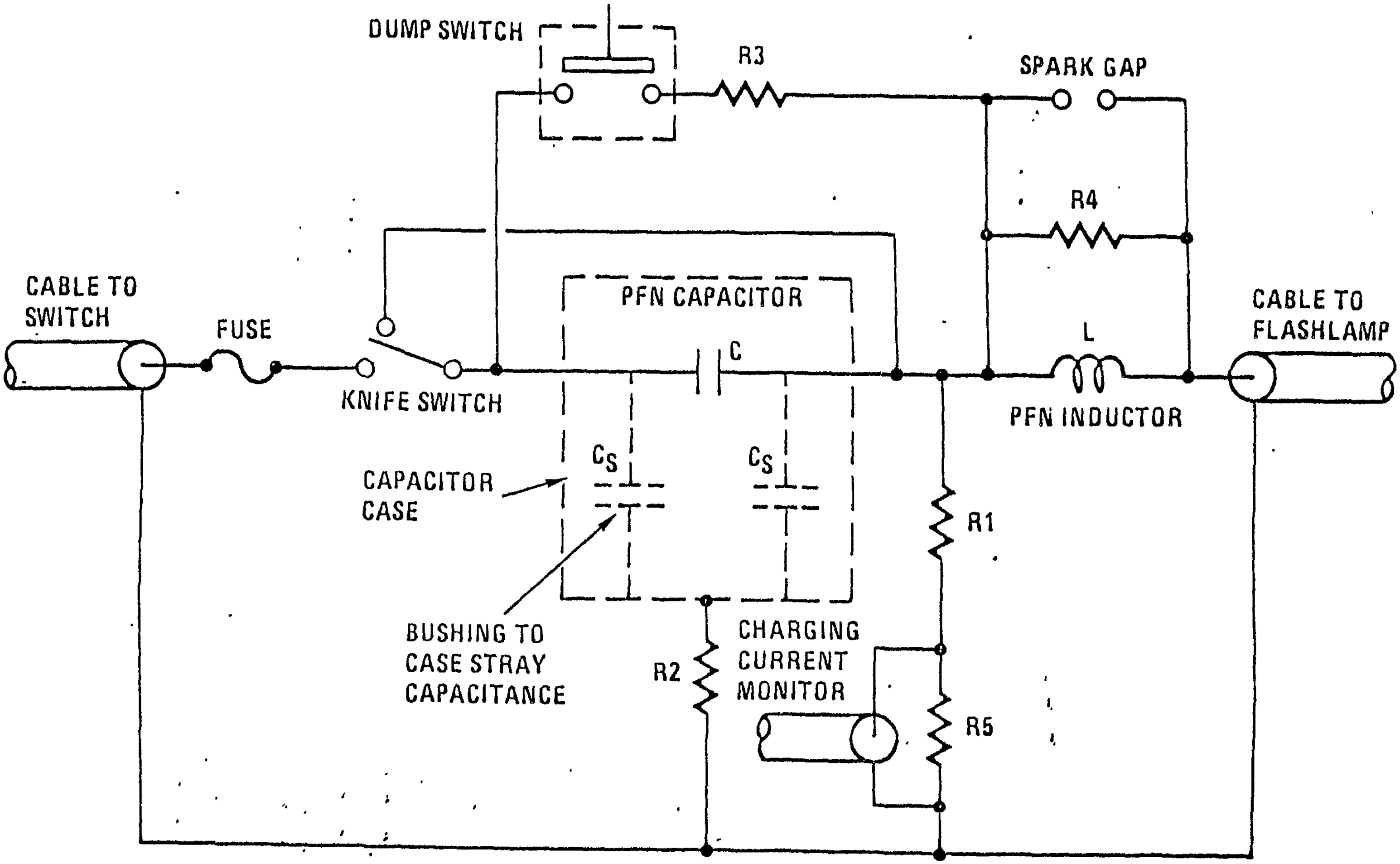


Figure 6: Capacitor Bank Module Schematic.

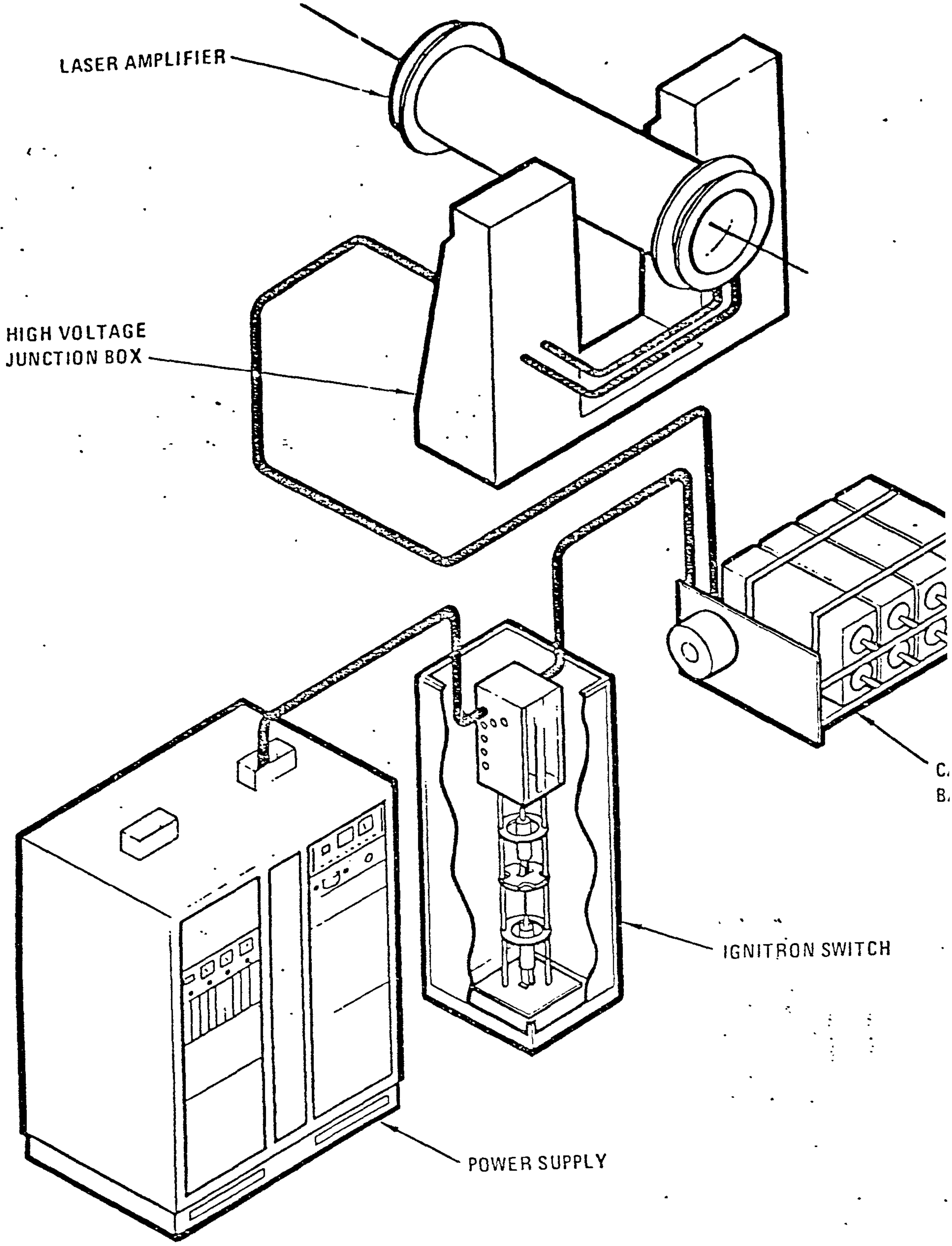


Figure 7: Circuit Diagram. A fan out is made at the ignitron switch for as many as 32 capacitor banks.

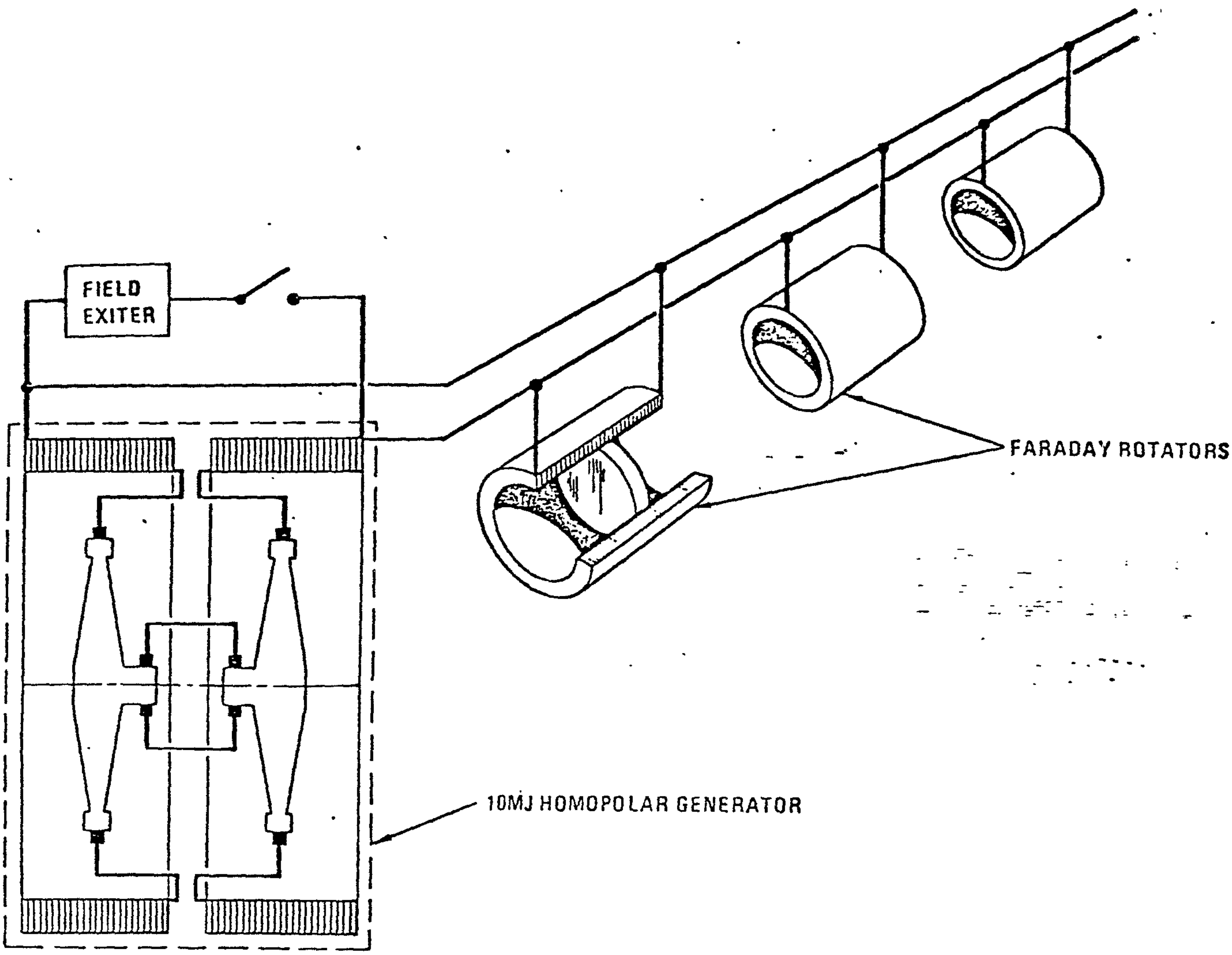


Figure 8: Power Concept for Faraday Rotators.