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Conceptual Design for a Linear-Transformer Driver (LTD)-Based Refurbishment and Upgrade of the Saturn Accelerator Pulse-Power System

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Conceptual Design for a Linear-Transformer Driver (LTD)-Based Refurbishment and Upgrade of the Saturn Accelerator Pulse-Power System

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Abstract

The purpose of this work was to develop a conceptual design for the Saturn accelerator using the modular Liner-Transformer Driver (LTD) technology to identify risks and to focus development and research for this new technology. We present a reference design for a Saturn class driver based on a number of linear inductive voltage adders connected in parallel. This design is very similar to a design reported five years ago [1]. However, with the design reported here we use 1-MA, 100-kV LTD cavities as building blocks. These cavities have already been built and are currently in operation at the HCEI in Tomsk, Russia [2]. Therefore, this new design integrates already-proven individual components into a full system design.

Acknowledgments

We wish to acknowledge the invention of the LTD technology by Academician Boris Koval'cuk of the HCEI in Tomsk, Russia, and for his implementation of this technology in the construction of the SPHINX accelerator in Gramat, France. We also acknowledge the work and impetus of Dillon McDaniel of Sandia National Laboratories to develop a faster version of this LTD technology that makes it applicable to radiography and fast z-pinch machines. Furthermore, we acknowledge Alexander Kim and his staff at the HCEI for their experimental work to develop several versions of these fast cavities, and to demonstrate successful, full-size devices.

Contents

| | |
|-------------------------------------------------------|----|
| Executive Summary | 7 |
| Acronyms and Nomenclature | 8 |
| Introduction..... | 9 |
| Present Accelerator Configuration..... | 11 |
| Saturn Design with the 1-MA, 100-kV LTD Cavities..... | 13 |
| Key Technical Issues | 19 |
| Summary | 22 |
| References..... | 23 |

Figures

| | |
|--------------------------------------------------------------------------------------|----|
| Figure 1. Artist representation of Saturn..... | 12 |
| Figure 2. 1-MA, 100-kV LTD cavity with top lid removed..... | 14 |
| Figure 3. Cross-sectional view of the new design | 15 |
| Figure 4. Side view of the LTD design..... | 16 |
| Figure 5. Outer diode ring waveforms for the bottom MITL | 18 |
| Figure 6. 3-D drawing of the module configuration for the LTD design of Saturn | 18 |

Executive Summary

In this paper, we describe the application of Linear-Transformer Driver (LTD) technology to the design of a Saturn-class accelerator. The purpose of this effort is to identify strengths and weaknesses of this technology, and to provide direction for future development and research. The design presented here offers similar power and energy output as currently available on Saturn. It also offers additional capabilities not currently available with Saturn. The size of the machine is considerably reduced to a diameter of approximately 15 m and a height of 7.5 m (Saturn is 30 m in diameter and 5 m high.) Furthermore, there are no oil or water tanks in the LTD design, although each cavity is filled with oil in the pulse-forming sections. The accelerator uses vacuum transmission lines, and consists of twelve, twenty-cavity modules. The cavities in this design are the 3-m diameter, 1-MA LTD cavities with minor modification to decrease the rise time from 100 to 50 ns. Several prototypes of the 100-ns cavity have already been built, and operate as designed. There is also no vacuum/water insulating stack in this design, as there is with Saturn.

Major focus areas for further development are related to mating of these cavities into an accelerator system. Besides mechanical design issues, of most concern are magnetically-insulated vacuum transmission line effects. In particular, both computational and experimental work needs to be done to verify that multiple lines from the various modules can be joined together in parallel in vacuum without severe losses at magnetic nulls. If the accelerator is to be operable in either a positive or negative polarity, additional design effort needs to be done to accommodate that need. Finally, in spite of providing a compact, modular approach, the cost of the LTD design needs to be optimized to provide a reasonable, cost-effective design. Other key design issues are discussed in the text.

Acronyms and Nomenclature

| | |
|---------------|----------------------------------------------------------------------------------------------------------------------------------------------------|
| FWHM | Full-Width, Half Maximum: Description of the width of a voltage pulse. |
| HCEI | High Current Electronics Institute, Siberian Branch of the Russian Academy of Sciences, Tomsk, Russia. |
| K-line | X-ray electromagnetic radiation from an ionized plasma species related to decay of electrons to the K-shell ($n=1$) of the ion. |
| LTD | Linear Transformer Driver: Name used for the inductive voltage adder cavity that includes all high-voltage pulse production and forming circuitry. |
| MITL | Magnetically-Insulated Transmission Line |

Introduction

We present a conceptual design for a Saturn-class driver based on a number of linear inductive voltage adders connected in parallel. This design is modular, and is based on the Linear-Transformer Driver (LTD) technology, which is described later. It can provide current, voltage, and rise time comparable to Saturn. But it also offers the possibility of operating in either a positive or negative polarity by reversing the direction of the LTD cavities. This is a technique already used on the SPHINX accelerator in France. In addition, with many modules and many cavities per module, it is possible to tailor the shape of the output pulse of the machine by staggering the triggering of the individual devices.

A similar LTD design for Saturn was reported five years ago [1]. The main difference between that design and the one we present is that we now use as building blocks the 1-MA, 100-kV LTD cavities that we have already built and that are currently in operation at the HCEI in Tomsk, Russia [2]. In reference [1], we assumed we could use 500-kA, 50-kV LTD cavities with 100-kV switches. These cavities have not yet been designed or built, and although they are simpler and could operate at the ambient atmospheric air, no effort has been dedicated to produce these switches. In contrast, the switches used in the 1-MA cavities have been under development and studied for several years at the HCEI, and have proven to be very reliable. In recent tests one of those switches was fired for 20,000 shots without apparent deterioration. Therefore, this Saturn design uses components that are already proven and operating in LTD cavities, and with very little modification, could easily be incorporated into a full-system design.

With the LTD design, there is no need for Marx generators and pulse-forming networks. Each LTD inductive voltage adder cavity is directly fed by a number of fast 100-kV small-size capacitors arranged in a circular array around each accelerating gap. The basic building block of each cavity is the so called “brick” composed of two capacitors charged in opposite polarity and connected in series through a 200-kV switch to the buses which connect the capacitors to the cavity accelerating gap [2]. The number of bricks that feed in parallel each cavity’s accelerating

gap defines the total maximum current. By selecting brick components of low inductance and capacitance, voltage pulses as short as 20-50 ns FWHM can be achieved.

The voltage output of each of the 1-MA LTD cavities is low (100 kV with a matched load). Many stages, therefore, are required to achieve multi-megavolt accelerator output. Since the length of each stage is relatively short (22 cm), accelerating gradients of the order of 0.5 MV/m or higher (with overmatched loads) can be obtained.

The proposed new driver will be capable of delivering pulses of 14 MA, 31 TW, and 0.96 MJ to the diode load, with a peak voltage of ~ 2 MV and FWHM of 50 ns. Although its performance will be similar to Saturn, it will be smaller ($\sim 1/2$). This design with higher-current cavities has half the number of voltage adders and cavities than the previous design [1] and is more compact. No oil or deionized water tanks will be required. Each cavity, however, encloses a small amount of oil to avoid surface tracking of the solid-dielectric insulator that is a part of each cavity.

Present Accelerator Configuration

Saturn is a pulsed power accelerator presently in operation at Sandia [3], and is a dual-purpose machine. It can be operated as a large-area flash x-ray source for simulation testing or as a Z-pinch driver for K-line x-ray production. In the first mode the accelerator is fitted with three concentric-ring 2-MV electron diodes, while in the z-pinch mode the current of all the modules is combined via a post-hole convolute arrangement and driven through a cylindrical array of very fine wires. Saturn is a modification of the old PBFA I [4] accelerator used for ion fusion research. It is named Saturn because of its unique multiple-ring diode that is used while operating as an x-ray *Bremsstrahlung* source. As an x-ray source Saturn can deliver to the three-ring electron-beam diode a maximum energy of 750 kJ with a peak power of 32 TW, providing an x-ray exposure capability of 5×10^{12} rads/sec over a 500 cm^2 area. As such, it is the highest-power electrical driver for *Bremsstrahlung* production in the world. As a z-pinch driver Saturn can deliver up to 8 MA to a wire or gas-puff load. A 700-kJ total x-ray output was obtained with aluminum and tungsten-wire z-pinches, and 60-70 kJ in K-line radiation from aluminum.

Figure 1 is an artist representation of Saturn. Saturn uses conventional water-line pulse-power architecture. The driver starts with 36 Marx generators as the principal energy source. Following are a cascade of pulse compression stages to convert the microsecond FWHM Marx output to the 50-ns final pulse that powers the electron diode or the z-pinch load. Power is compressed with the following stages: Microsecond pulses are stored in 36 intermediate-store water capacitors. These are discharged through 36 electrically-triggered gas switches to charge 36 pulse-forming lines, which are discharged through 36 self-breaking water switches to launch short pulses into 36 triplate water transmission lines and impedance matching transformers. Finally, the short, now ~ 50 ns pulse is applied to the diode through a water-vacuum insulating ring interface. At that interface the 36 vertical triplate transmission lines are connected to three horizontal triplate disks with a water convolute. In the vacuum section the power is split into three parts and feeds three conical-triplate magnetically-insulated transmission lines (MITL) that power the three separate rings of the e-diode. A final pulse compression of 25:1 is achieved.

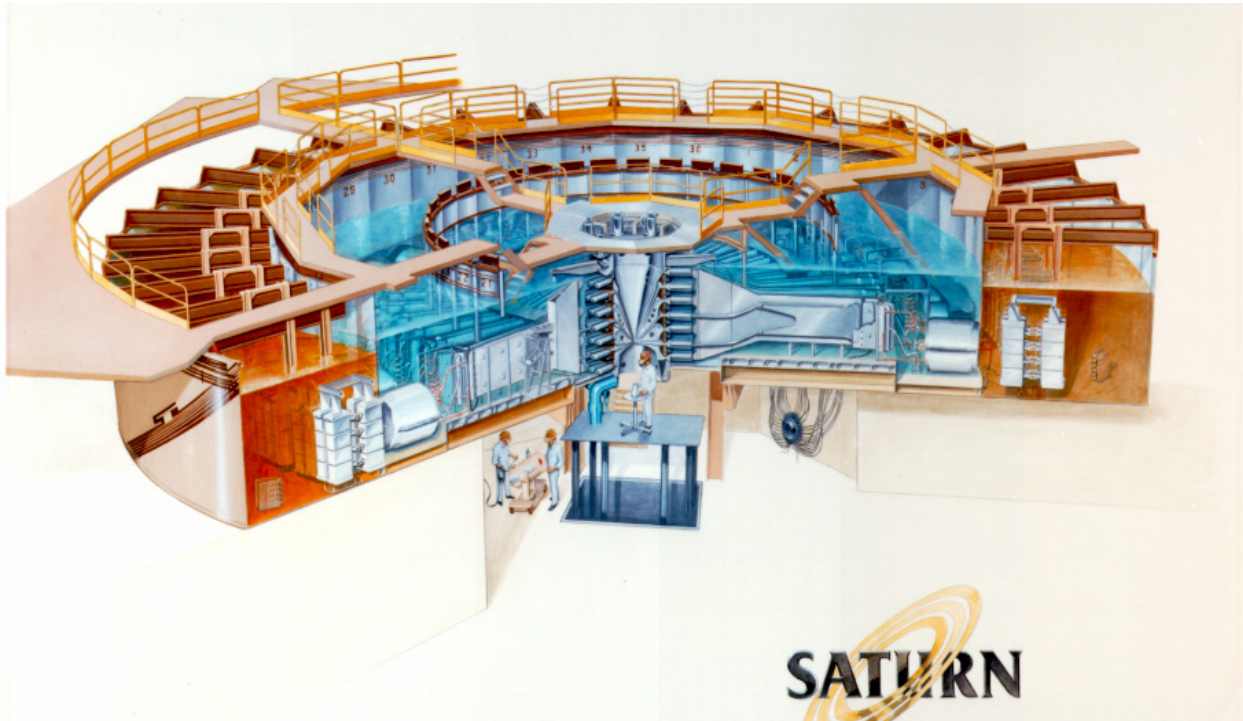


Figure 1. Artist representation of Saturn

The three diodes are concentric and, hence have different power requirements. The innermost diode requires less power than the outside one to achieve the same x-ray area average output. The diode design is such that a power partition with a ratio of 3:2:1 from outside ring to center ring is required. The bottom triplate MITL feeds the largest outer diode ring while the top MITL is connected with the innermost diode ring.

To accomplish all that, the device requires a substantial size. The overall diameter of the Saturn tank is 30 m and its height is 5 m. The 36 Marxes are immersed in a 250,000-gallon oil-filled annular tank while the rest of the device is in 250,000 gallons of deionized water. In our proposed design, using the fast LTD technology [5], the entire Saturn device will be 15.8 m in diameter (Fig. 3) and will be 7.5 m in height (Fig. 4.) In addition, no water and oil tanks are required. Except for the 7.5-m high, 3-m diameter cylindrical central section which is in vacuum, the entire accelerator is in air and readily serviceable.

Saturn Design with the 1-MA, 100-kV LTD Cavities

In our new design, we use as a building block the 1-MA, 100-kV cavity design of fig. 2 [2]. We select 12 modules of 1 MA, 2 MV each to produce a total current of about 12 MA. Each of the 12 modules is a self-magnetically-insulated voltage adder. No liquid or solid insulator is used between the inner cathode electrode and the outer anode cylinder. A coaxial geometry is adopted. The stages or LTD cavities of each module voltage adder are of relatively low voltage (~ 100 kV into a matched load.) Therefore, 20 stages per module will be necessary. The LTD cavities used in this design are identical to those of figure 2 currently in operation at HCEI.

However, to provide a faster rise time and shorter FWHM pulse, we selected smaller capacitance capacitors of 10 nF each and assumed that we could reduce the overall inductance of the brick from 232 nH to 80 nH, which provides a very fast, $\sqrt{LC} = 20$ ns, time constant for the system. Hence, no further pulse power compression is required. The power-pulse FWHM thus has the required width to be applied directly to the diodes. With these circuit parameters, the overall effective capacitance and inductance of our 40-brick cavity becomes 200 nF and 2 nH, respectively. Our 1-MA cavities now have an effective capacitance and inductance that is somewhat larger, namely, 800 nF and 6 nH, respectively. It is our hope that the smaller capacitors will have smaller inductance and that we could design a shorter current-loop brick.

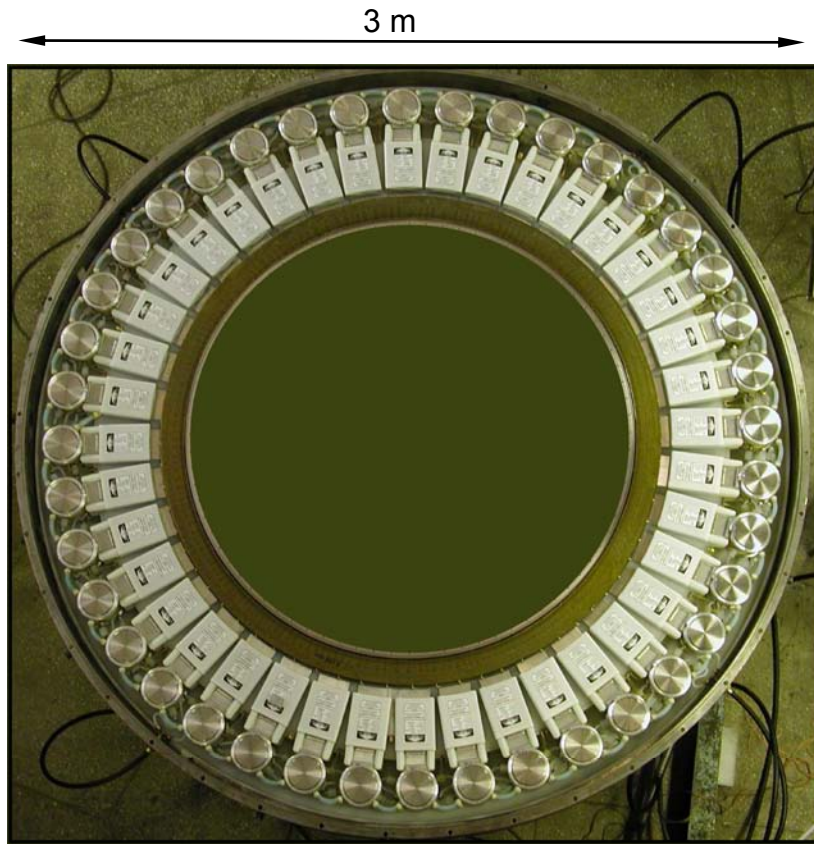


Figure 2. 1-MA, 100-kV LTD cavity with top lid removed

With the LTD design there is no need for Marx generators and pulse-forming networks. Each LTD inductive voltage adder cavity is directly fed by a number of fast 100-kV small-size capacitors arranged in a circular array around each accelerating gap. The basic building block of each cavity is the so called “brick” composed of two capacitors charged in opposite polarity and connected in series through a 200-kV switch to the buses which connect the capacitors to the cavity accelerating gap [2]. The number of bricks that feed in parallel each cavity’s accelerating gap defines the total maximum current. By selecting brick components of low inductance and capacitance, voltage pulses as short as 30-50 ns FWHM can be achieved.

The fastest capacitors available to date are the compact General Atomic double-ended capacitors model, model 3540 [6]. They are very small ($\sim 58 \times 150 \times 274$ mm) and have low inductance ($L = 25$ nH and $C = 20$ nF). These capacitors could be modified to be faster ($L = 10$ nH, $C = 10$ nF),

as considered here. Although the capacitor dimensions could be further reduced, for the purpose of our conceptual design the dimensions of the presently available double-ended model 3540 capacitors from General Atomic were used.

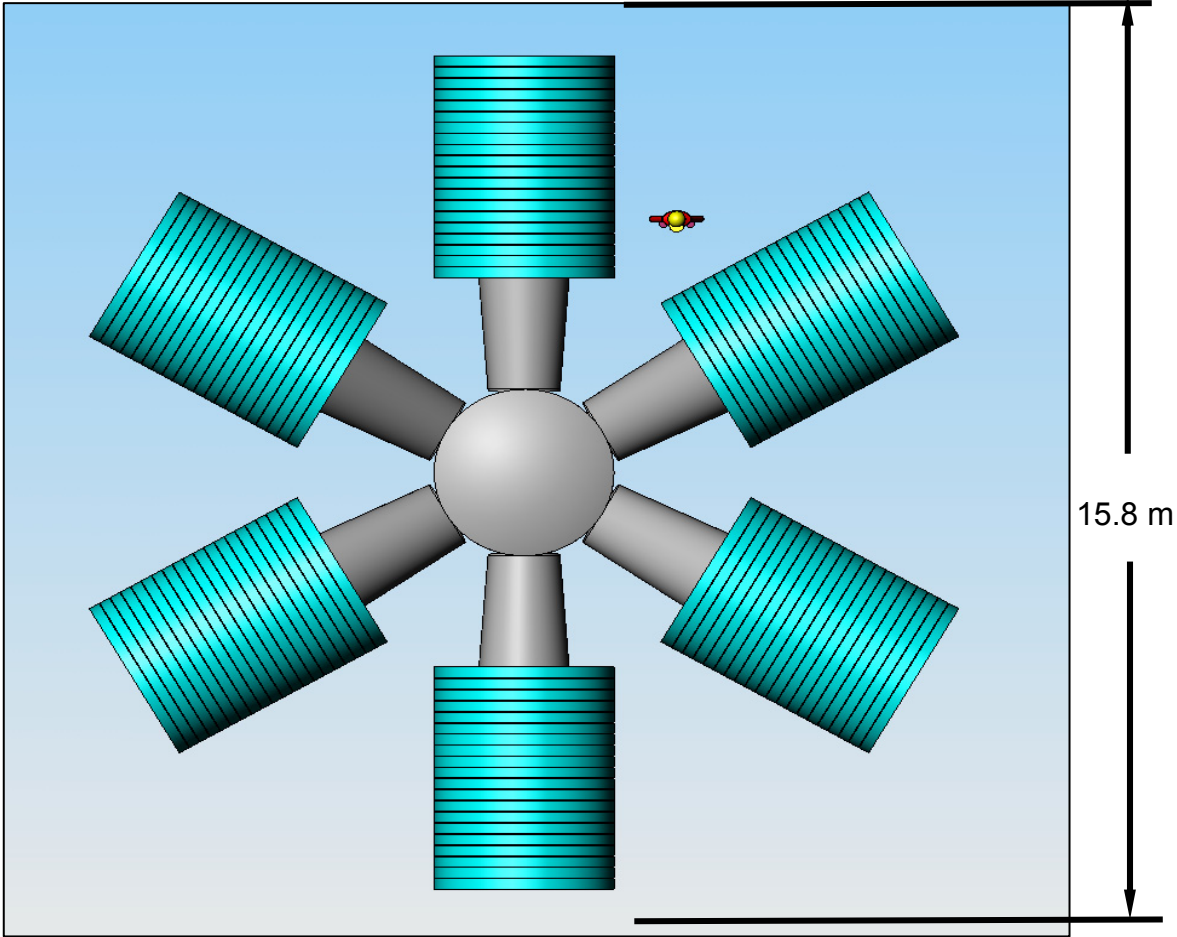


Figure 3. Cross-sectional view of the new design

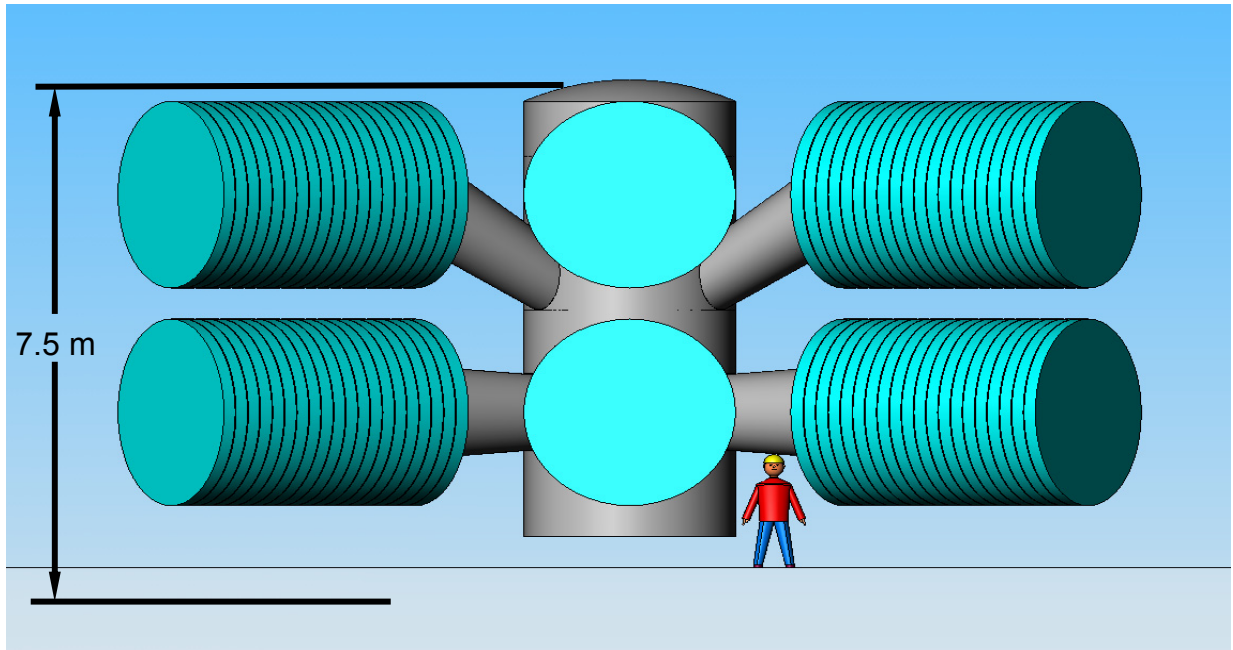


Figure 4. Side view of the LTD design

The accelerator gaps are magnetically insulated with 2-m diameter magnetic cores made of transformer iron. The iron tape is 18 mm wide and 80 micrometers thick. Each of the 4 core rings includes 995 turns, resulting in a total cross section of $57.3 \times 10^4 \text{ m}^2$ and a volt-second integral of 22.3 mV-s for a ΔB of 3.9 T. The dimensions of each module are as follows: the overall diameter is 3 m and the length 4 m (fig. 3). The cathode electrode is conical starting with a diameter of 1.62 m and terminating at the output end with a 1.56 m diameter cylinder. The anode electrode is a 1.642-m inner diameter cylinder formed by the inner cylindrical wall of each of the 20 cavities of the module. It tapers down to 1.2 m in diameter at the entrance of the vacuum central diode chamber. A 2-m long coaxial MITL vacuum transmission line connects each module to the respective conical triplate MITL of each diode ring. Note that there is no vacuum/water insulator. The MITL's are connected directly to the conical vacuum MITL's that drive the load. To maintain the 3:2:1 ratio of power to the load, two modules are connected to the top triplate conical MITL, four to the middle, and six to the lower triplate. Thus the power partition ratio to the diode rings is retained. Throughout the power flow from the voltage adders to the diode rings, self-magnetic insulation and impedance matching is rigorously maintained.

One of the advantages of the LTD design is that there is no insulating stack as is necessary in a water transmission line design such as currently used on Saturn. The only insulators in the design are the short, 2 cm long, plastic rings in each of the ~100-kV accelerating gaps of the modules. A total of 12 modules are required to provide the 12 MA current to the diode. A minimum anode-cathode gap of 1 cm was maintained throughout the entire power flow transport.

Table 1. Comparison of the LTD design with present Saturn performance

| LTD Design | | | | |
|-----------------------------------|------------------------|----------------------|--------------------|---------------------|
| Level | Zsource Ohms | Zload Ohms | Vload MV | I load MA |
| Top | 0.91 | 0.99 | 2.40 | 2.4 |
| Middle | 0.45 | 0.38 | 2.02 | 5.3 |
| Bottom | 0.30 | 0.33 | 2.2 | 6.7 |
| Present Saturn Performance | | | | |
| Top | 0.66 | 0.99 | 2.1 | 1.8 |
| Middle | 0.33 | 0.38 | 2.1 | 3.9 |
| Bottom | 0.22 | 0.33 | 2.1 | 6.2 |

Table 1 summarizes the peak pulse power parameter of the LTD design and compares it with the present Saturn performance. The design was done analytically and verified numerically using the circuit design code SCREAMER [7].

Figure 5 shows the voltage, current, and power for the outer-diode ring connected to the bottom MITL. Similar pulse waveforms are applied to the other two diode rings. Figure 6 is a three-dimensional drawing of the entire accelerator showing the module layout. This design can also deliver a maximum current of 12 MA to a z-pinch load. In this case only two conical MITL triplates will be used with each driven by six voltage-adder modules.

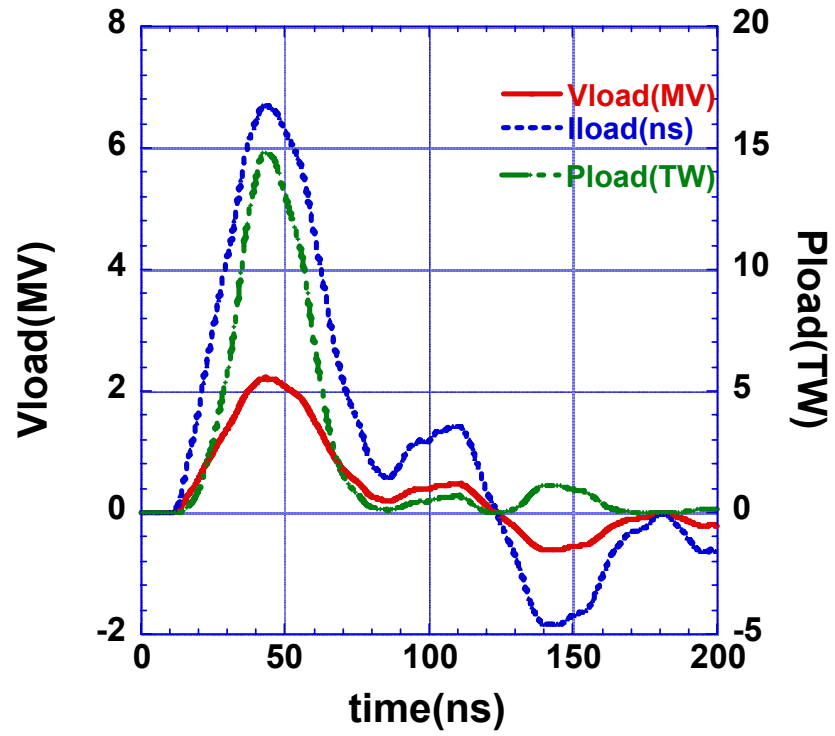


Figure 5. Outer diode ring waveforms for the bottom MITL

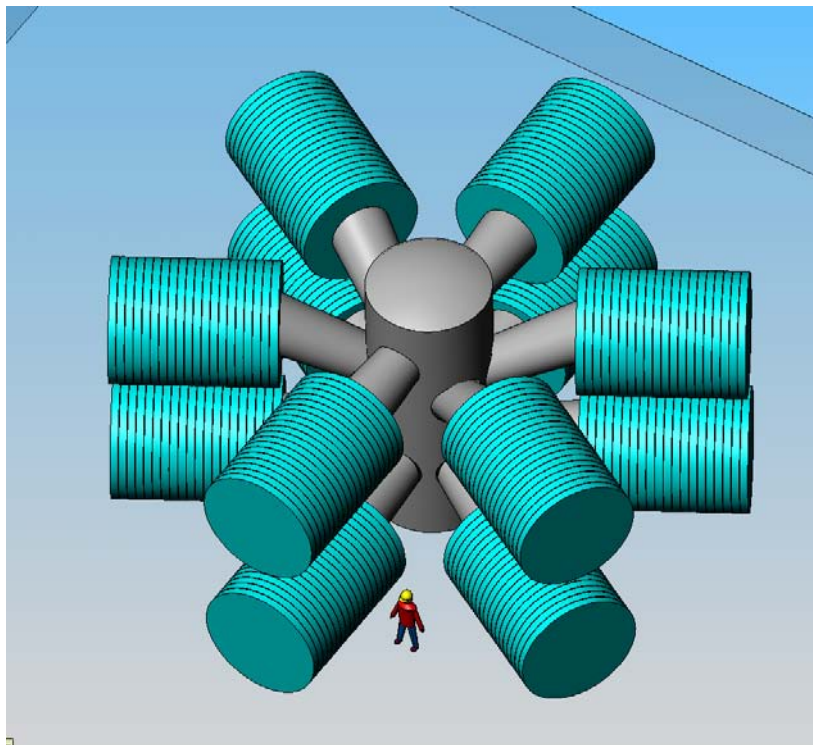


Figure 6. 3-D drawing of the module configuration for the LTD design of Saturn

Key Technical Issues

Although this reference design does offer potential space savings, uses existing, already designed and operating modules, and adds new operational capabilities, there are still key issues that need to be addressed in future research and development. Foremost are potential vacuum-convolute losses, power transmission in multi-cavity modules, voltage optimization, positive or negative polarity operation, and behavior with various loads. In addition, there are electrical engineering issues related to brick design, triggering, and pulse shaping. Mechanical issues are related to cavity size, gas-switch purging, mechanical support of the center conductors in each module, support of the vacuum MITL conical triplates without an insulator, support of the modules, techniques for replacing defective cavities, and techniques for reversing polarity of the machine. Finally of concern is cost.

Vacuum convolute: The vacuum transmission lines from each module join at the input to the conical MITL triplates in a vacuum convolute. Magnetic nulls exist at the convolute that can be the source of severe current loss. These effects must be investigated computationally with three-D PIC codes such as Quicksilver, and eventually also verified experimentally. If losses are too severe it might be necessary to operate the adder modules with water transmission lines, which would require careful analysis of water breakdown, and/or operation at unmatched impedance. It would also require use of a water/vacuum insulator.

Power transmission in multi-cavity modules: From experiments we now well understand the characteristics of single modules, and have initial experience with a limited number of cavities added together. Both simulation and experiments need to be done with modules with more than a few cavities to investigate potential losses due to triggering, impedance mismatching, or magnetic insulation losses.

Voltage optimization: With vacuum transmission lines directly driving the conical MITL triplates, there is no need for a vacuum/water insulator. This greatly reduces the inductance of the load and thereby reduces the drive requirements. Thus, it may be possible to drive the same

loads used on Saturn with lower voltage LTD modules with fewer cavities. This could have a substantial, favorable impact on the cost of the machine.

Positive or negative polarity operation: In principle it is possible to mechanically reverse the direction of the modules to change the polarity of the machine. Power transmission in the LTD-module MITL's with reversed polarity has not been investigated, and MITL modification may be required.

Behavior with various loads: The initial circuit simulations presented here used a fixed inductance load. These must be repeated with both collapsing impedance diode loads, and changing-inductance z-pinch loads. Additionally, magnetic insulation losses at a post-hole convolute must be included for the z-pinch loads.

Brick design: As noted in the text, improvements are needed in brick design to lower inductance to thereby achieve the required short rise times.

Triggering: With the 240 cavities required for this design, and the 40 switches per cavity, 9600 switches will need to be triggered. A system to do this must be designed and tested.

Pulse shaping: In principle it is possible to tailor the stagger the timing of the individual modules as well as the modules to achieve a variety of pulse shapes. This may provide an LTD Saturn with the capability to do materials experiments, or to do longer-pulse z-pinch shots. But effects of pulse shaping on the magnetic insulation need to be investigated. Furthermore, this capability will also require a flexible trigger system.

Cavity size: If the smaller capacitors are used, as suggested in the description of the design above, it may be possible to reduce the size of the cavities to reduce inductance and cost. This redesign should be done before a full-size machine is built.

Gas switch purging: Experience has shown that purging the gas switches increases repeatability and switch lifetime. A system to purge the 9600 switches needs to be designed.

Mechanical support of the center electrodes: The center conductors extend from the back end of the LTD modules to the vacuum convolute. How are these conductors mechanically supported without shorting out the transmission line or without using insulators? How are they supported when changing cavities in the module, or when reversing the direction of the modules?

Mechanical support of the conical MITL triplates: Presently the vacuum MITL's in Saturn rest on metal anode/cathode rings that are supported by the vacuum insulator. It is not clear how to support these without an insulator.

Mechanical support of the LTD modules: A mechanical stand needs to be designed to support the LTD modules. It needs to allow easy access to individual cavities for repair and for reversing polarity.

Techniques for replacing defective cavities: Can cavities be replaced quickly with minimal impact to the rest of the module? Or is it easier to replace entire modules and repair offline?

Techniques for reversing polarity of the machine: A mechanical procedure is needed to rotate all of the modules of an LTD Saturn with minimal disruption to the operation of the machine. This effort needs to also consider electrical and mechanical connections for triggering, charging, diagnostics, gas purging, oil fill, etc.

Cost: Of primary concern is the cost of a modular LTD design for Saturn. The design presented here requires 240 cavities, each with 80 capacitors and 40 switches, a housing, an oil/vacuum insulator, an iron-core inductor, and miscellaneous cabling, connectors, and insulation. Cost of these cavities has been well over \$100k, but if we assume that amount, the cost of the cavities for the Saturn replacement would be \$24M. Other associated costs with the design likely will increase the total cost to be in the range of \$30M to \$40M. Methods to reduce the cost of these cavities, and to reduce the number of cavities required, could have a significant impact on the total cost of the machine.

Summary

We have developed a reference design for an alternative pulsed power driver for the Saturn accelerator using the LTD technology. This design has similar power and energy output as now available on Saturn, as demonstrated with circuit code simulations. Moreover, the LTD design provides additional capabilities that are now not available on Saturn. These include the possibility of operating the machine, either in a positive or negative polarity, and the capability to tailor the shape of the output pulse. Furthermore, the diameter of the machine is appreciably reduced from the present 30 m to 15 m. The overall height is somewhat higher, increased from 5 m to 7.5 m. This was necessitated by the larger diameter 1-MA LTD cavities. The expensive and difficult to maintain large oil and deionized water tanks are eliminated together with the requirement for a central water-vacuum interface insulating stack. This design uses our new 1-MA cavities with proven architecture and components, and could be realized in the near future.

We have identified key research and development topics that need to be addressed for a full accelerator design. These are vacuum power flow and possible current loss at the vacuum convolute, possible reduction of the voltage requirement because of the lower load and feed inductance, investigation of operating transmission lines in either positive or negative polarity, modifications to the cavity “brick” design to minimize inductance, triggering and pulse shaping, gas switch purging and other mechanical system design, cavity size reduction, mechanical support of the vacuum transmission lines, and mechanical designs to simplify maintenance. In addition, work is also needed to reduce the cost of the individual components, and resulting total machine cost.

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