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Operating the First Water-Insulated Mykonos II LTD Voltage Adder[1]

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Abstract – The LTD technological approach can result in very compact devices that can deliver very fast, high current and high voltage pulses straight out of the cavity without any complicated pulse forming and pulse compression network. Because the output pulse rise time and width can be easily tailored (pulse shaped) to the specific application needs, the load array, a gas puff, a liner, an isentropic compression load (ICE) to study material behavior under very high magnetic fields, or a fusion energy (IFE) target. Ten 1-MA LTD cavities were designed and built in the High Current Electronic Institute (HCEI) at Tomsk, Russia, under a Sandia Laboratory contract. The cavities were originally designed to run in a vacuum or Magnetic Insulated Transmission Line (MITL) voltage adder configuration. Following successful operation in this mode, we are gradually modifying them to make them capable of operating assembled in a de-ionized water insulated voltage adder. Special care is being taken to clean by filtration, remove dissolved and free water, and de-aerate the oil of the cavities. Similar treatment is effectuated on the water of the voltage adder in addition to deionization and bubble removal. To that effect two continuously operating water and oil re-circulating systems were designed and built. One of the most important LTD driver applications (IFE) will require tens of thousands of shots without interruption. Presently, we are operating two modified cavities with more robust components and specially designed for water insulation "O" rings and grooves. Lifetime experiments of the voltage adder will be done with a matched liquid resistor load. If the modifications are proved successful, similar changes will be implemented in the remaining eight cavities. Our goal is to have the LTD Mykonos X voltage adder operating with all ten cavities as soon as possible in a water insulated mode.

1. Introduction

Sandia in collaboration with the High Current Electronic Institute (HCEI) in Tomsk, Russia has developed new, fast, high-current, high-voltage induction accelerators based on the Linear Transformer Driver (LTD) technology [1-2]. LTD based drivers are currently considered for many applications including x-ray radiography, very high current Z-pinch drivers, isentropic compression drivers, and Z-pinch IFE (Inertial Fusion Energy). LTD is a new method for constructing high-current, high-voltage induction pulsed accelerators. The salient feature of the approach is switching and inductively adding the pulses at low voltage straight out of the capacitors through low inductance transfer and ferromagnetic core isolation. The pulse forming capacitors and switches are enclosed inside the accelerating cavity. In a standard configuration all the capacitors have the same value and the output pulse has sinusoidal shape. In most recent work [3] it was demonstrated that the shape of the pulse can be changed according to the application requirements by mixing capacitors of different capacitance in a pre-described fashion. Thus it is possible to obtain square shaped pulses, trapezoidal pulses, etc. High currents can be achieved by feeding each cavity core with many capacitors connected in parallel in a circular or square array. High voltage is obtained by inductively adding the output voltage of many cavities in series. Most importantly the LTD drivers has been experimentally demonstrated that can be multi-pulsed at up to 0.09Hz [4,5]. This makes LTD the driver of choice for Inertial Fusion Energy (IFE) where the required repetition rate is estimated to be 0.1 Hz [4,5,6].

We have prepared a new LTD laboratory, named Mykonos, to house our 10, 1-MA, 100-kV LTD cavities constructed and received from the HCEI in Tomsk, Russia. Presently, we have assembled and are testing in the Mykonos laboratory a two 1-MA LTD cavity, water insulated voltage adder with a liquid resistor load (Mykonos II). This is the first induction voltage ever constructed and operated with a water-filled coaxial transmission line. Following the successful commissioning of Mykonos II to up 95 kV charging, we are currently implementing a substantial number of modification to the cavity hardware in order to make them more water and water bubble proof. Those modes were deemed necessary following the lesson learned during commissioning.

In section **2** we describe the 1-MA, 100-kV LTD cavity and present single cavity results with matched resistive load. In section **3** we present the Mykonos II, two-1-MA LTD cavity water insulated voltage adder and the resistive load design. We also elaborate on the advantages and disadvantages of using deionized water as a voltage adder insulator. In section **4** we describe the up-to-date experimental results and compare them with the SCREAMER [7] circuit code numerical simulations. In section **5** we present in detail the modifications currently being implemented on the original HCEI constructed cavities. The final section **6** summarizes our Mykonos II experimental results, give the status of the 1MV, 1MA, MYKONOS X water insulated voltage adder and present future plans.

2. Fast, 100 ns, 1-MA LTD cavity

The LTD cavities enclose the entire pulse-forming network that generates the output pulse. This pulse is applied across the insulator that separates the anode and cathode output electrodes (A-K gap) of the cavity.

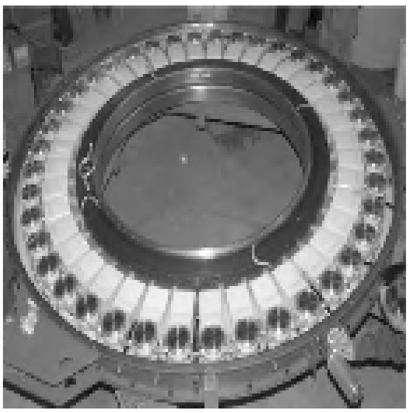
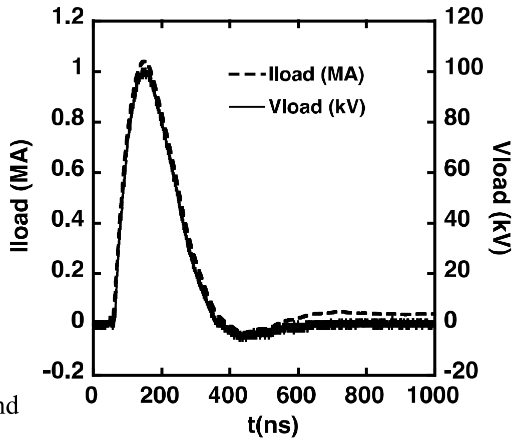


Fig.1. The 1-MA LTD cavity top lid and plastic insulator removed.

The cavity shape is similar to a flattened doughnut with the axial A-K gap at the center of the inside cylindrical surface [8]. In Fig. 1 we present the 1-MA LTD cavity. The top metal cover and the plastic insulator that insulates the charged parts from the cavity top wall are removed. Fig. 2 presents the output voltage and current on a matched load.



and

Fig. 2. Current and voltage output of the 1-MA LTD cavity with ~ 0.1 Ω resistive load.

The cavity contains two circular arrays of 40 double-ended capacitors, 40-nF, 15-nH each especially developed for our LTD program. The bottom array is separated from the top by a ~1 cm plastic insulator plate. The top capacitors can be charged up to + 100-kV maximum charge and the bottom ones up to -100kV. Each pair of positively and negatively charged capacitors is connected in series through an individual gas switch. We call this subsection a brick. Therefore each cavity encloses 40 bricks.

3. Mykonos II, two 1-MA LTD cavity water insulated voltage adder

Our ten 1-MA LTD cavities were originally designed and built to run in a vacuum or Magnetic Insulated Transmission Line (MITL) voltage adder configuration. However, later we decided to use de-ionized water as voltage adder insulator. There are a number of physics advantages in utilizing water insulation. Namely:

1. All the current flows on the surface of the transmission line conductors.
2. There is no sheath current erosion and resulting pulse shortening**.**
3. The transmission line can be terminated with high impedance loads without losing ~1/3 of the total current on the walls, causing substantial wall erosion.

4. The water lengthens the transit time from cavity to cavity by a factor of 9.
5. The later is very important for output pulse shaping by staggering the trigger of the different cavities in the same voltage adder voltage adder [9].
6. Many voltage adders can be connected in parallel to a common transmission line without loosing magnetic insulation (magnetic nulls).

However, we must acknowledge certain engineering disadvantages with the use of water. A number of them are;

1. For high voltage adders of 6 MV and higher the water vacuum interface near the load can present some difficulties.
2. The presence of air bubbles in an enclosed water system may cause arcing
3. The de-ionized water can corrode metal surfaces and degrade the water voltage holding strength.
4. Extremely high forces (60,000 lb or 28,000 kg) are required to compress the cavity "o" rings in order to make them oil and water tight. We do not have here the advantage of the atmospheric pressure to compress the cavities.
5. With water the voltage adder becomes heavier.
6. Requires water filtration, de-ionizing, re-circulating, and de-bubbling systems.
7. Requires lengthier maintenance service.
8. Fill first the voltage adder with water and then fill the cavities with oil otherwise water enter into the cavities.

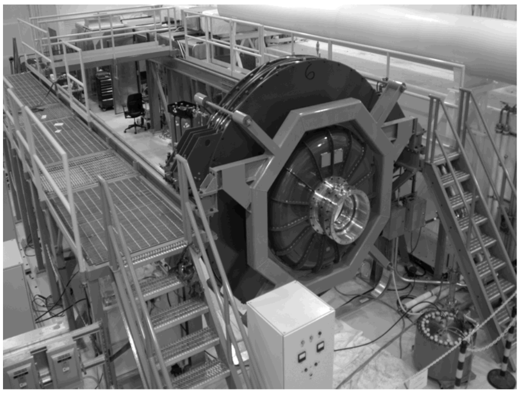


Fig. 3. The Mykonos II LTD, two 1-MA cavity voltage adder. The rail system can accommodate 20 LTD cavities.

Special care has been taken to address most of the disadvantages. The slant angle of the plastic A-K gap insulator was reduced from 45^0 to 4^0. The stainless steel surfaces of the cavity exposed to the de-ionized water and the cathode stalk were passivated to avoid corrosion and water resistance degradation.

A 6.35-mm diameter channel was drilled on the top side of the A-K gap cathode electrode connecting to the outside of each cavity in order to facilitate the removal of bubbles possibly formed at the A-K gap triple points. The channel is fitted with the same diameter plastic tube that extends all the way to the outside top of the cavity. The cavities are hung vertically from the rails as shown in Fig. 3. A small water reservoir is connected at the upper end of the tube which can be pumped if necessary to further force the bubbles to exit the A-K gap region (Fig. 4-5).

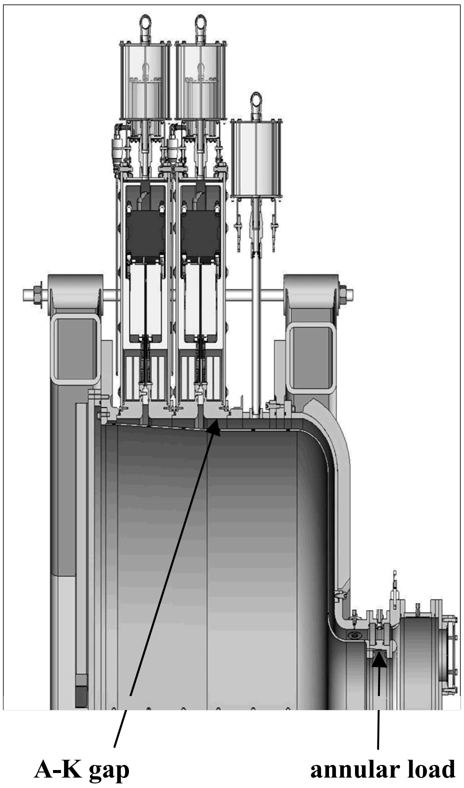


Fig.4. Schematic diagram (side section) of 2 cavities stacked together in a voltage adder configuration. Only the upper half above the axis of the cavity is shown

4. Experimental results and comparison with simulations

Mykonos II performed as expected. We have fired up to now 3,600 shots between 50 and 95kV in a rep rate mode. Conservatively we fire every 40 seconds. Our first goal was to condition the cavity switches. To that effect we fired in rep rate mode 100 shots per charging voltage in steps of 5kV. The pressure for every setting was the minimum possible without any pre-fire during the 100 shot series. The results are presented in Fig. 6 in absolute pressure units together with a similar work done at HCEI.

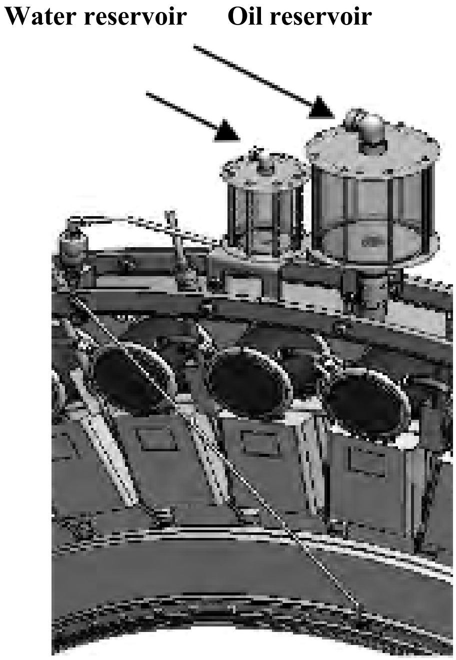


Fig. 5. Schematic diagram of a 1-MA LTD cavity section modified in order to operate in a water insulated voltage adder configuration. The de-bubbling plastic tube is shown going from the bottom right to the left top and connects with the water reservoir.

The Tomsk results are somewhat more conservative than the Sandia results.

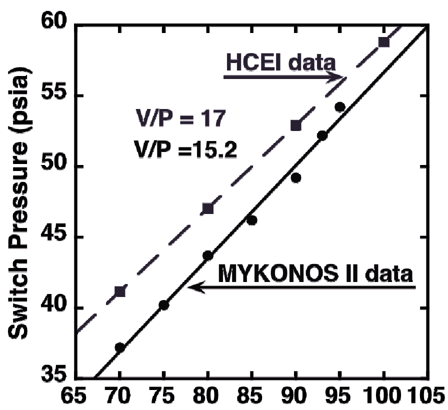


Fig. 6 Mykonos II switch conditioning results (absolute pressures scale).

Figure 7 present the same as Fig. 6 results but in gauge relative pressure scale. In this representation the Tomsk and Sandia results appear to be very closer together.

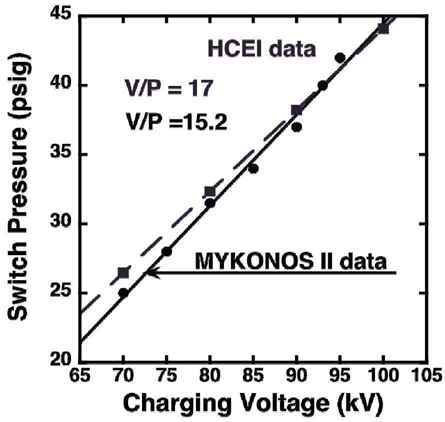


Fig. 7. Same as Fig. 6 results but in gauge relative pressure scale.

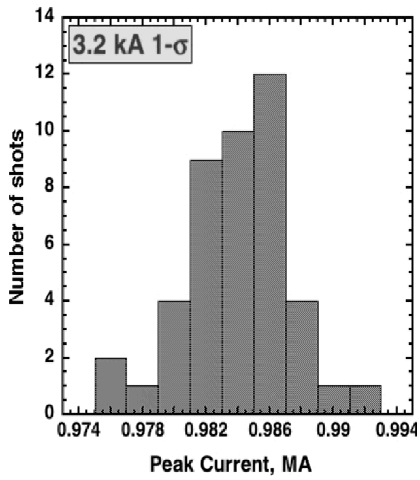


Fig. 8. Time jitter at 95kV charging. Sixty shots were fired in repetition rate mode (every 40 sec.).

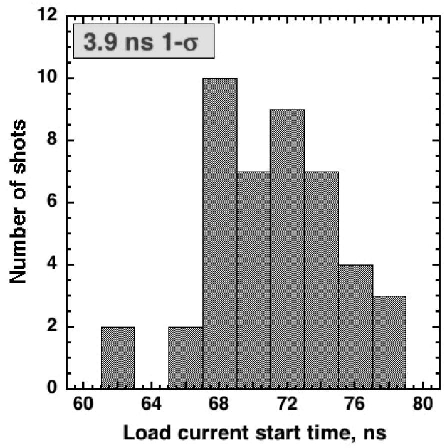


Fig. 9. Statistics of the peak current spread for

95 kV charging. The peak current spread was 3.9ns (1-σ).

Figures 8 and 9 present statistics of the 95-kV shots. Although the operating pressure was not yet optimized for minimum FWHM, the time jitter (4 ns,) and peak current spread are reasonable (3.2 kA).

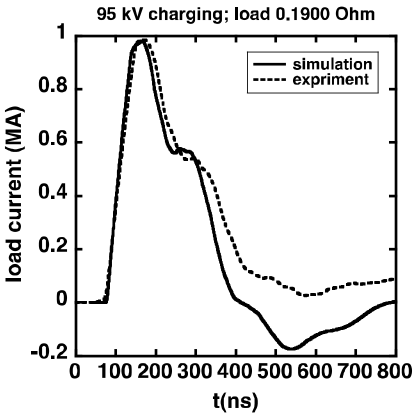


Fig. 10. Comparison of the load current at 95-kV charging with circuit code simulation results.

Figure 10 compares a typical 95-kV output current pulse at the load with SCREAMER simulations [8]. The results up to the peak of the current agree quite well with the simulation. However, at the fall of the pulse the two traces deviate from each other. We believe that this is due to the difficulty of precisely simulating with SCREAMER the impedance and inductance variation of the curved transmission line connecting the load to the last LTD cavity (Fig. 4).

At 80-kV charging we performed pulse-shaping experiments by staggering the firing of the cavities as a whole and also each cavity quadrant separately. The results successfully demonstrated the capability of our MYKONOS to alter the temporal history of the output pulse [9].

5. Summary of the 1-MA LTD modifications.

Currently we are implementing a number of modifications into the original 1-MA cavity hardware. These modifications are based on our experience and lessons learned while operating LTD I, LTD II, and Mykonos II and hopefully will make the cavity operation more reliable and robust. In addition to the changes made to make the cavities capable of operating assembled in a water insulated voltage adder, the following modifications are currently implemented:

1. Modify the cavity A-K electrodes. Fill existing bolt-holes and replace them with new ones on a perfect circumference. Make new “ O” ring **grooves** to shield water from seeping into the cavity (Fig. 11).
2. Disassemble and modify the HCEI switches and replace the Legris gas feed-throughs with Swageloks (Fig, 12).
3. Replace the two-piece polycarbonate/ polyethylene middle A-K gap insulator with a monolithic polyurethane insulator (Fig.13).
4. Replace the polyethylene insulators at the top and bottom of the cavities with polyurethane ones (Fig. 14).
5. Use the thickest available Tygon tubing to build the charge and trigger resistors.
6. Manufacture a thicker steel top cover with azimuthal slots for bolt clocking instead of the original compression ring (Fig.15).
7. Install continuous oil recirculation and dual filtration system to keep the particulate content of the oil below 200 particulates per cubic centimeter.

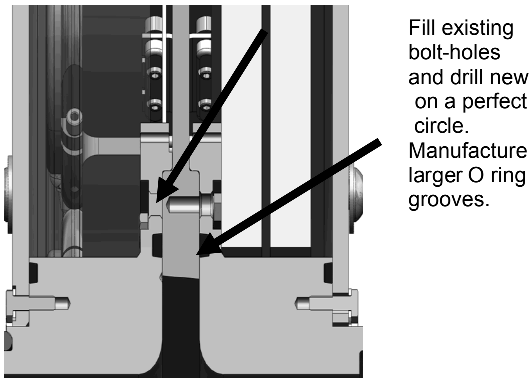


Fig. 11, Section of the LTD cavity including the A-K gap. The arrows show the modifications implemented on the anode and cathode electrodes.

Fig. 12. New gas lines feeding the two switches with Swaglock fittings.

Two cavities are already reassembled with those new components and are currently under evaluation.
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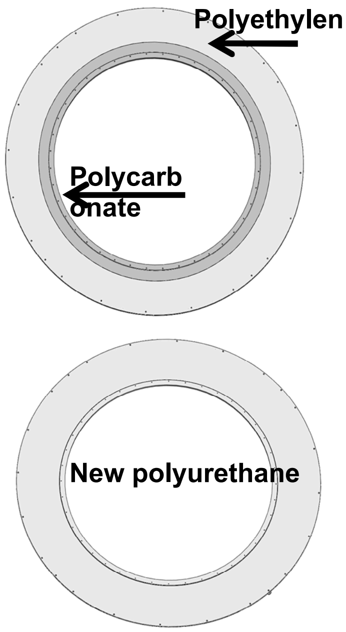

Fig. 13. Old a new plastic water/oil interface.
The new one is a monolithic polyurethane insulator

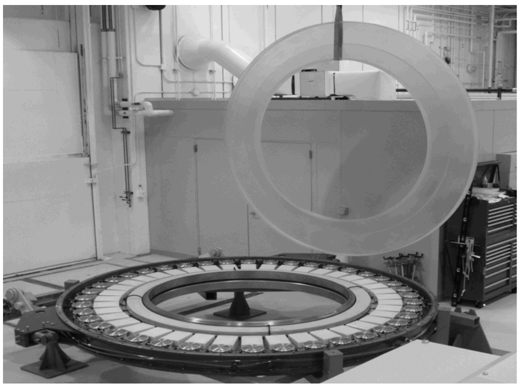

Fig. 14. The new polyurethane insulating cover is in the process of being placed on the top array of the capacitors and switches.

6. Summary .

While the remaining 8 cavities are being modified, we are testing a shorter version of a two modified cavity voltage adder (Mykonos II). The voltage adder is de-ionized water insulated and is terminated with a liquid salt solution resistive load. We have fired close to 3,600 shots with the unmodified cavity voltage adder in rep rate mode, conditioning the switches up to 95 kV charging and performing pulse-shaping experiments [10].

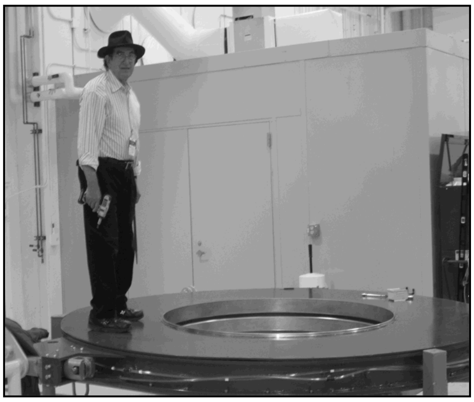

Fig. 15. A thicker and stronger steel top cover capable of withstanding the weight of one of the co-authors was manufactured with azimuthal slots for bolt clocking instead of the original O ring compression ring.

The current, voltage, power, and energy transmitted into the load is as calculated, and the output pulse shapes are in good agreement with simulations.
Our future plans are first to evaluate the modified cavities' performance up to 100kV charging and then proceed in assembling the Mykonos X voltage adder with all 10 modified cavities. Pulse shaping and vacuum power flow experiments are planned for both Mykonos II and Mykonos X.

8. Acknowledgments

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