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SANDIA-HIGH CURRENT ELECTRONIC INSTITUTE (HCEI) COLLABORATION IN FAST LTD DEVELOPMENT*

Following the impressive operational success of the first slow (~1 microsecond) LTD in Gramat, France, that was invented, designed and built by the team at HCEI headed by Boris Kovalchuk [1, 2], Dillon McDaniel of Sandia asked the inventors if they could apply this technology for the production of fast ~100 ns pulses. The inventors accepted the challenge, and a number of communications [3] were exchanged between Sandia and HCEI on how the fast LTDs could be used for this research. The first published theoretical analytical study of such fast LTDs was presented in the 1999 Pulsed Power Conference in Monterey, California by M. G. Mazarakis *et al.,* [4]. This paper attracted a lot of interest in the pulsed power community, resulting in a large number of requests for copies. Following that, a strong collaboration started between Sandia and HCEI that culminated in the production of 10 of the largest to-date 1 MA, 1 GW fast LTD cavities which compose now the MYKONOS voltage adders at Sandia.The different stages of the fast LTD development through the years and the up-to-date accomplishments will be presented. Although this technology has mushroomed around the globe, this paper will concentrate solely in the Sandia-HCEI collaboration.

Keywords: LTD generator, LRC-circuit, Z-pinch drivers

Introduction

Sandia National Laboratories, during the last 15 years, is working very closely with the High Current Electronic Institute in Tomsk, Russia, and in particular with the Pulsed Power Department headed by Professor and Academician Boris Kovalchuk to develop, test, and improve the fast LTD technology.

The idea to develop a very fast LTD stage came up during a joint meeting between Sandia and HCEI in 1998 in the Centre d'Etude de Grammat, France with the occasion of constructing and commissioning the French SPHINGS accelerator [1, 2]. SPHINGS is the first Z-pinch driver ever built introducing the LTD technology. Each LTD stage has only two large capacitance capacitors, and consequently the generated output pulse is relatively long and of the order of 1-2 microsecond. The shortcoming of the device was the long output pulse. Microsecond pulses could give plenty of time for the Raleigh-Taylor instabilities to develop, grow, and disrupt the imploding liner or wire array. A faster pulse, ~100ns, would have been much more desirable for Z-pinch drivers. That was the reason for Dillon McDaniel from Sandia National Laboratories to suggest to Boris Kuvalchuk and Sasha Kim from HCEI the option of a much faster LTD structure. Sasha Kim [3] proposed the idea of assembling a number of identical sections (today called bricks) consisting of two small capacitors connected in series with an individual switch, positioning them evenly around the axis of a circular cavity, connecting them in parallel to a common load and triggering them simultaneously. Following the meeting in Grammat, a number of communications (unfortunately unpublished) were exchanged between Sandia and HCEI on how the fast LTDs could be designed, built, and used for a fast Z-pinch assembly. Boris Kuvalchuk liked Sasha Kim's idea and quickly designed and built with the assistance of Sasha Kim an intermediate pulse length LTD (450 ns) utilizing 20, 170nF capacitors available in Ukraine (at that time low capacitance capacitors of 40 nF or less at 100 kV were not available in Russia). The stage was not circular but rectangular, and the basic similarity with our present LTD stages was the connection in parallel of a number of capacitors to a common load through an inductive core. This work was presented by Sasha Kim [5] in the 1999 Pulsed Power Conference in Monterey, California.

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The first published theoretical analytical study of 100 ns fast LTD stages the way we know them today was presented independently by Michael Mazarakis [3] in the same 1999 Pulsed Power Conference in Monterey, California. It appears that 1999 was the year of fast LTD cavities the way we know them

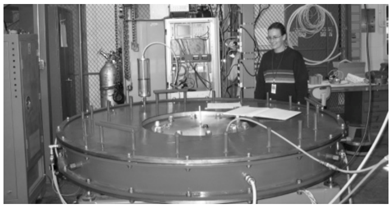


Fig.1. LTD I cavity at Sandia laboratory.

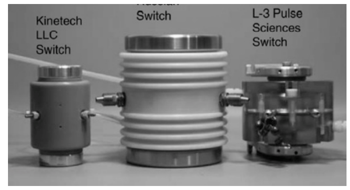


Fig. 2. Kinetech and L-3 switches compared with the HCEI switch.

today! Those two seminal works were the beginning of a strong Sandia and HCEI collaboration on fast LTDs that continues uninterrupted for the last 15 years.

It should be emphasized that presently Sandia has a very aggressive fast LTD developmental program and considers LTD (the technology initiated at HCEI) as the technology of choice for our future isentropic material studies (ICE), Z-pinch, and radiographic drivers.

To date we have completed the experimental evaluation in both single and rep-rated modes of four (LTD I, LTD II, and LTD III, LTD IV) [6] 2-m in diameter cavities producing currents to a matched load between 500 -800-kA and one ~125 kA LTDR radiographic cavity[7]. We have studied the performance of five 1-MA, 3-meters in diameter LTD cavities individually and in vacuum insulated voltage adder configuration with both resistive and vacuum electron diode loads [8, 11], we have successfully completed the evaluation of a two 1-MA cavity voltage adder with deionized water insulation (MYKONOS II) [8], and we are currently starting the tests of a five deionized water insulated cavity voltage adder (MYKONOS V) in the MYKONOS laboratory. A total of 10 MYKONOS cavities were built in HCEI and transported to Sandia. A large chartered Russian plane flew them together with auxiliary equipment directly from Tomsk to Albuquerque, New Mexico, USA. In the first tests with the five 1-MA cavity voltage adder performed in HCEI in Tomsk, the cathode stalk was overmatched to the cavities' impedance and was vacuum insulated. The ultimate goal of the present work with the 1-MA cavities in Sandia is to evaluate their performance and the power flow transmission efficiency combined into a de-ionized water insulated voltage adder configured module. The remaining five cavities are in storage awaiting the output of the MYKONOS V tests. If the tests are successful, a 10 cavity 1-MA module will be assembled (MYKONOS X). This module could be considered as a building block for future larger high current and high voltage accelerators replacing and doubling the current of the presently successfully operating Z accelerator [9]. The LTD I (Fig.1) and LTD II were built as well in HCEI and tested in Sandia. A vacuum insulated, seven LTDR 125-kA cavity voltage adder was also built in HCEI and shipped to Sandia [7]. This device, completed with 14 more cavities by Sandia, is currently operating successfully with large area diode; rod pinch, and Self Magnetic Pinch (SMP) diode loads for radiographic applications [10]. The LTD III is practically the same as LTD II but had L-3 corporation switches, while the LTD IV has Kinetech switches and 80 nF capacitors.

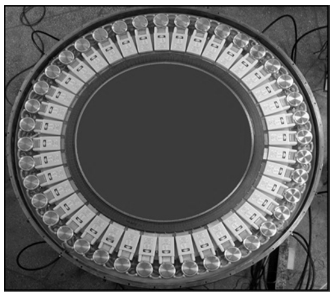
A substantial effort was dedicated in Sandia to develop new low inductance, low jitter, higher current switches for LTD. Figure 1 compares the HCEI switch with Kinetech and L-3 switches. The LTD III cavity was equipped with L-3 switches that could bring the load current up to 700 kA or even higher. LTD IV with Kinetech switches and 80 nF capacitors is currently under investigation.. It should be pointed out that all 21 LDTR cavities contain now 10 L-3 switches each with a very satisfactory performance.

The presently utilized five 1-MA MYKONOS cavities have the original HCEI switches and incorporate a substantial number of modifications necessitated mainly by the utilization of water as insulating medium. These modifications are described in detail in references [12].

Most recently a breakthrough in the LTD cavity design was proposed by Sasha Kim of HCEI and built in collaboration with Sandia: the Square Pulse LTD with 3rd and 5th harmonics [13,14]. This idea revolutionizes the LTD principle and opens the door to many applications since now not only can we make a square pulse but also change the rise time and the pulse shape (trapezoidal pulse shapes). A second prototype cavity with 3rd and 5th harmonics (the first prototype cavity included only the fundamental and 3rd harmonic) is presently under construction in HCEI by Sasha Kim and coworkers.

In the following sections we briefly describe the design and results of the different types of fast high current LTD cavities tested individually; we describe the experimental work done in Tomsk HCEI with a five 1-MA cavity vacuum insulated voltage adder connected both to a vacuum electron diode and a resistive load; we present experimental results of the water insulated MYKONOS II voltage adder with a resistive load; we present results of the 7 and 21 cavity radiographic voltage adder; and finally we describe the Square Pulse LTD idea and present one cavity prototype with 3rd harmonic.

High current fast LTD cavity designs



1-MA MYKONOS cavity **LTD I and LTD II** **LTD R**

Fig. 3. Three different size cavities built in HCEI for Sandia labs

Fig.3 we present three different size of LTD cavities. The top metal cover and the plastic insulator that insulates the charged parts from the cavity top wall are removed in order to show the cavity interior network of switches and capacitors. Cavities LTD I, LTD II, LTD III, IV, 1-MA MYKONOS, and LTD R can in principle be charged to ±100-kV. However, LTD I had a 5-cm smaller outer diameter than LTD II and could not be charged above ±85kV.

All the cavities contain two circular arrays of small capacitors. In Figure 3 only the top array is seen. 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 negatively and positively charged capacitors is connected in series with a separate switch positioned vertically and capable of holding 200-kV DC potential difference. This basic unit, named “brick”, composed of two capacitors and one switc h connected in series, defines the rise-time, current and period of the cavity output pulse.

All types of constructed cavities have the same axial length of ~ 22cm. The 1 -MA MYKONOS, cavity is the largest (3m in diameter), while the LTD I, LTD II, LTD III, and LTD IV cavities have a smaller diameter and are approximately equal to 2m. The LTDR cavity is even smaller (~1.5 m), having only 10 bricks. Cavities LTD I, LTD II and III have 20 bricks, while the 1-MA cavity contains 40 bricks.

Most of the LTD cavities were operated at single as well as rep-rated modes.

The research results with the LTD I cavity are presented in detail in reference [5]; Figures 4, 5, and 6 present some of the results, especially the great reproducibility of the output pulses (Fig.4), the switch self-brake curve (Fig, 5) and the very law switch jitter (Fig.6). We fired 13,000 shots at rep-rate up to 5 shots per minute without experiencing any component overheating or problems with the switches, the capacitors, and t he supporting automated systems. Finally during the 13,000 shots, following the determination of the switch optimum operating pressure, not switch pre-fires were recorded.

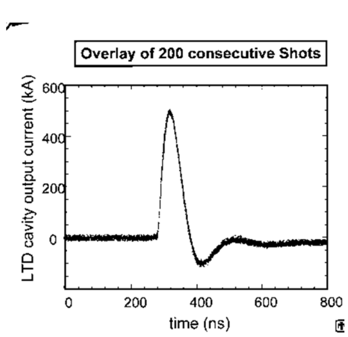


Fig.4. LTD I, overlay of 300 shot current pulses.

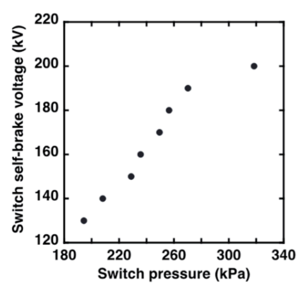


Fig. 5. LTD II self-brake curve

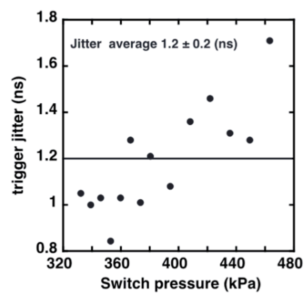


Fig. 6. LTD II switch trigger jitter

The experimental work with the LTD II cavity had different goals. In addition to firing a large number of shots for component longevity verification at ± 100kV charging, the cavity performance for different switch pressures was studied. Namely the switch pressure was varied from 53psia (= 366 kPa) to 67psia (=463 kPa) in steps of 2psia (~ 14kPa) (Fig. 5). For each pressure setting 1000 shots were fired at ± 100-kV charging. The 1-MA MYKONOS cavities were tested at HCEI with various loads and performed equally well. Fig. 8 shows the output voltage and current on a match 0.1 resistive load.

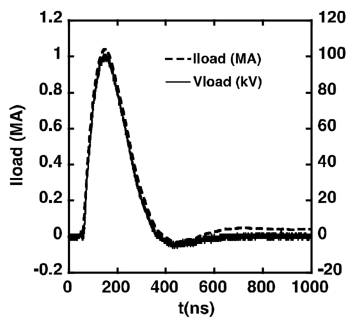


Fig. 7. 1-MA MYKONOS cavity load current and voltage.

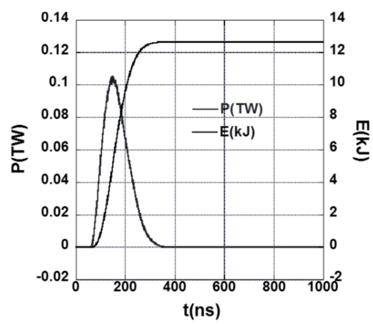


Fig. 8. 1-MA MYKONOS cavity load power and energy

Experimental tests with a radiographic LTDR cavity with resistive load have shown some voltage oscillations (Fig. 9). The oscillations had a frequency of 70 MHz and tended to grow in amplitude with increasing charge voltage. The source of oscilations had been identified as due to stray capacitance in the output of the cavity [7].

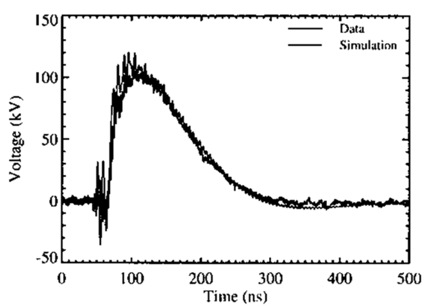


Fig. 9. Comparison of experimental data and simulation of a single LTDR cavity.

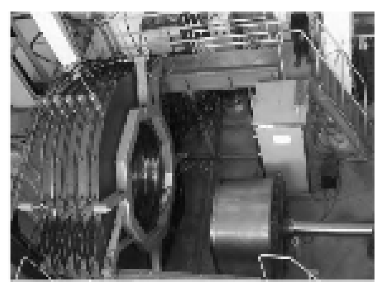
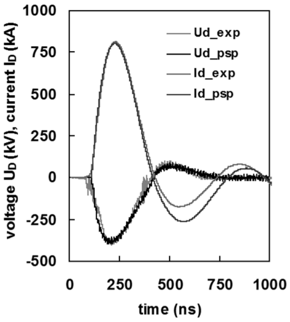


Fig. 10. Five 1-MA LTD Mykonos voltage adder With the cathode stalk outside.

LTD inductive voltage adder experiments

(Fig. 9). The first five cavities were assembled in a voltage adder configuration before being shipped to Sandia. The coaxial transmission line of the voltage adder was vacuum insulated and connected both to a electron vacuum diode (Fig.10) and to a resistive load. Fig. 11 shows five 1-MA LTD cavity voltage adder results compared with numerical simulations. The diode voltage for clarity is inverted. The simulations were done for charge voltage ± 90kV.

The ten 1-MA cavities were originally designed and built to run in a vacuum or Magnetic Insulated Transmission Line (MITL) voltage adder configuration. However, by the time we received them from Tomsk we decided to use de-ionized water as voltage adder insulator. Our motivation was to test the advantages of water insulation as compared to MITL approach.The results were as expected and in full agreement with simulations (Fig. 13). A five cavity de-ionized water voltage adder is recently completed and power transmission tests have recently begun.



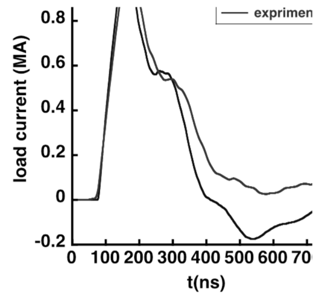
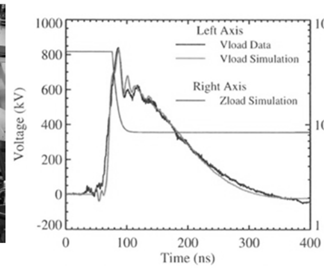


Fig. 11. Five cavity voltage adder results

Fig. 12. The MYKONOS II Laboratory

Fig.13. MYKONOS II results.



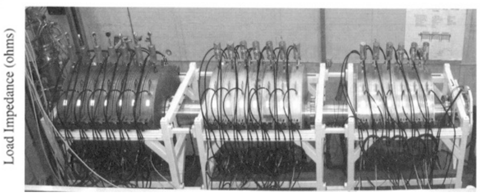
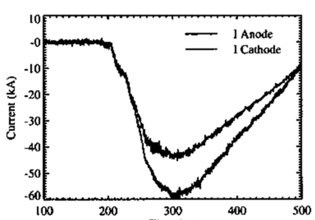


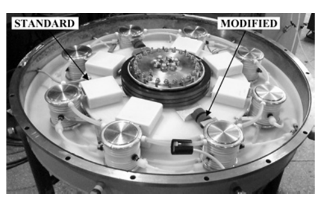
Fig. 14. First seven LTDR cavity, HCEI built, voltage adder.

Fig. 15. Seven cavity output on a largr area diode.

Fig. 16. The 21 LTDR Ursa Minor

A 1-MV LTDR voltage adder (Fig. 14) was built at HCEI and tested in Sandia National Laboratories with a large area diode. The output volage on the diode load, compared with numerical simulationsis, is presented in Fig. 15. The oscillations observed with the single cavity, although reduced, still persist. The seven LTDR cavities built in HCEI were completed with 14 more built in Sandia to make Ursa Minor. It is routinely operating with large area electron diodes and also with radiographic diode loads like rod pinch and Self Magnetic Pinch (SMP) [11] diodes. Fig. 17 presents MITL anode and cathode current measured after the last voltage adder cavity with a large adea diode load.





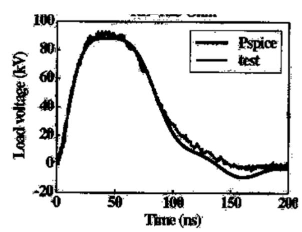


Fig. 17. The Ursa Minor MITL Anode (60 kA) and cathode (40 kA)

Fig. 18. Square pulse LTD with 3rd harmonic.

Fig.19. Load voltage output with third harmoni

The idea of the Square Pulse LTD is based on the Fourier Theorem, which states that any waveform can be reproduced by the superposition of a series of sine and cosine waves. In particular, the constant function *f(x)* at $0 \le x \le \pi$ defined as $f(x) = \frac{\pi}{4}$ can be reproduced by a series of sine functions. If we keep only the fundamental and the third harmonic approximation we can come quite close in reproducing a square pulse. Fig. 19 is the output pulse from a cavity containing four bricks with 8nF capacitors and two bricks of two 1.7 nF capacitors connected in series at each side of the brick. By adding a 5th harmonic at the right proportion as described in reference [14,15] we can produce a pulse much more approaching to square and with faster rise time (Fig. 20)

Conclusion

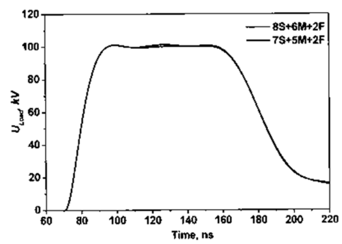


Fig. 20. Square pulse with different ratios of 1st 3rd and 5th harmonics.

During the last 15 years the Sandia - HCEI collaboration was very fruitful. It advanced the LTD technology in technological maturity and into a very high standarsd of reliability and performance. New devices based on LTD keep coming up every year. In Sandia we project that all our future pulsed power drivers will be based on LTDs. We foorsee that LTD will eventually replace practically all the Marx generators. We have developed already many conceptual designs for future LTD driver for Z pinch, ICE, IFE, and radiography that the limiting space of the present report does not allow us to describe. Those last fiteen years were the most exciting years for innovative pulsed power science and electrophyscs, achievements.

`REFERENCES

1. B. M. Kovalchuk, V. A. Vizir, A, A, Kim, *et al.*//Russ. Phys. J. **40,**1142 (1997).
2. F. Lassalle, A. Loyen, *et al.* // Status on the Sphinx machine based on the 1 microsecond LTD technology, in Proceedings of the the the 16th IEEE International Pulsed Power Conference, Edited by I. Schamiloglu and F. Peterkin (IEEE, NJ, 2007) p. 217.
3. A. A. Kim // Private communication, 1998.
4. M. G. Mazarakis, and R. B. Spielman // A compact, high-voltage e-beam pulser, in Proceedings of the 12th IEEE International Pulsed Power Conference, Edited by C. Stalling and H. Kirbie (IEEE, NJ, 1999) p. 412.
5. A. A. Kim, B. M. Kovalchuk, *et al.* // 0.75 - MA , 400-ns rise time LTD stage, in Proceedings of the 12th IEEE International Pulsed Power Conference, Edited by C. Stalling and H. Kirbie (IEEE, NJ, 1999) p. 955.
6. M. G. Mazarakis, W. E. Fowler, A, Kim, *et al.*// High current, 0.5 MA, fast, 100ns, linear transformer driver experiments, Phys. Rev. ST Accel.Beams **12**, 050401 (2009) p. 050401-1
7. J. Leckbee, S. Cordova, *et al.* // Testing of a 1-MV linear transformer driver (LTD) for radiographic applications, in Proceedings of the 17th IEEE International Pulsed Power Conference, Edited by F. Peterkin and R.Curry (IEEE, NJ, 2009) p. 156.
8. M. G. Mazarakis, M. J. Savage, *et al.* // Experimental validation of the first 1-MA water-insulated MYKONOS LTD voltage adder, in Proceedings of the 18th IEEE International Pulsed Power Conference, Edited by R. Curry and B. V. Oliver (IEEE, NJ, 2011) p. 625.
9. W. A. Stygar, W. E. Fowler, *et al.* // Architecture of petawatt-class z-pinch accelerators, Phys. Rev. ST Accel.Beams **10**, 030401 (2007) p. 030401-1.
10. J. Leckbee, S. Cordova, *et al.* // Linear Transformer Driver (LTD) research for radiographic applications, in Proceedings of 18th IEEE International Pulsed Power Conference, Edited by R. Curry and B. V. Oliver (IEEE, NJ, 2009) p. 614.
11. A. A. Kim, M. G. Mazarakis, *et al.* // Development and tests of fast 1-MA linear transformer driver stages, Phys. Rev. ST Accel.Beams **12**, 050402 (2009) p. 050402-1.
12. M. G. Mazarakis, A. A. Kim, et al. // PLENARY talk in Proceedings of the 17th Internationl Symposium on High-Current Electronics, HCEI, Tomsk 2012. To be published
13. A. A. Kim, M. G. Mazarakis, *et al.*// Square Pulse LTD, in Proceedings of the 18th IEEE International Pulsed Power Conference, Edited by R. Curry and B. V. Oliver (IEEE, NJ, 2011) p. 917.
14. A. A. Kim, M. G. Mazarakis, *et al.*// Square pulse LTD with 5th harmonic bricks, in Proceedings of the 19th IEEE International Pulsed Power Conference, Edited by B. V. Oliver, M. Crawford and J. Verboncoeur (IEEE, NJ, 2013) p. 1354.

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