SAND2016-8949C

# Warm X-ray Source Development on the Saturn Accelerator

B. V. Oliver, V. Harper-Slaboszewicz, K. Struve, B. Ulmen
Sandia National Laboratories
Albuquerque, NM

***Abstract*— There is a continuing long-term need to develop high fluence, short pulse (~40 ns) warm x-ray sources with photon energies in the ~100 keV range for electronics and materials testing. The Saturn high current accelerator at Sandia National Laboratories has been used extensively for driving high current (8 MA, 0.3-1.7 MeV) electron beam bremsstrahlung diodes for such testing. The primary diode fielded on Saturn is comprised of three concentric cylindrical cathode rings and a thin anode disk. The anode is separated from the ring cathodes by a small (0.5 cm) vacuum gap and acts both as the return current path for the emitted electrons and as a bremsstrahlung x-ray converter. In order to both increase x-ray fluence while simultaneously lowering the spectral energy of the x-rays we have been conducting research on new diode geometries. We will present advances in reflex triode development and the fielding of a multi-rod-pinch diode configuration and discuss the potential advantages of these sources over our standard 3-ring diode.***

***Keywords—Saturn accelerator; pulsed power; reflex triode; multi rod-pinch diode***

## I. INTRODUCTION

The Saturn accelerator is a low impedance, very high current pulsed power driver [1]. It has been a workhorse for x-ray environment testing and experimentation since it began service in 1987. The current and voltage at peak are nominally 10 MA and 1.6 MV with a power pulse lasting 40 ns. The machine is axially symmetric with 36 parallel lines converging on a central vacuum stack, with each line providing about 50 kJ of forward-going power to the stack.

## II. SATURN PULSED POWER

Each line on Saturn (Fig. 1) begins with a Marx bank storing 150 kJ at 2.7 MV. Upon triggering, the capacitor bank discharges into a 19 nF intermediate store water capacitor until a gas switch is electrically triggered. The energy flows into two parallel 2 Ω transmission lines until the voltage reaches approximately 2.3 MV at which point 20 parallel water switches self-break, transfering the power into the output 2 Ω section of the pulse forming line (PFL). This discharges through a prepulse suppression rail gap into the vertical triplate transmission line. This 3 m long, 2 Ω line tapers to 4 Ω and terminates in two 8 Ω rods. Each rod connects to an 0.5 Ω radial disk feed formed by 36 adjacent "water bottles" attached to each electrode ring of the central vacuum stack.

Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

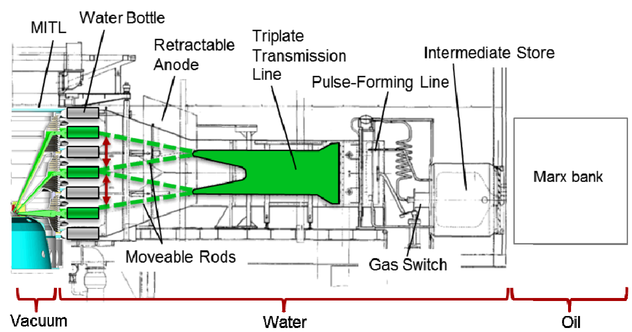


Fig. 1. Schematic of a single power flow line showing the energy storage, pulse compression and power flow sections of the machine. Each of the rods (dotted lines) can be attached to one of two cathode rings.

The disc feed is 18.6 ns long, so the vacuum section is transit time isolated from remainder of the water section. Inside the vacuum stack (Fig. 2), seven nested conical anodes and cathodes form six magnetically insulated transmission lines (MITLs) that converge to the load. The design impedance of the top two MITLs is 6 Ω, the middle two MITLs is 3 Ω, and the bottom two MITLs is 2 Ω. These parallel MITLs provide a reduced impedance to allow high currents at low voltage.

Saturn is a very flexible current driver because rods in the water section can be moved to distribute the current to a desired ratio between the upper, middle and lower cathodes. Up to 36 of the total 72 rods can be connected to each cathode ring. This has allowed a large variety of loads to be fielded, most recently x-ray sources based on a reflex triode and a multi rod-pinch diode.

## III. BASELINE BREMSSTRAHLUNG DIODE

The standard x-ray source utilized on Saturn is a bremsstrahlung diode consisting of three nested triaxial diodes. The baseline pulsed power configuration for this source is to drive the bottom cathode with 36 rods, the middle cathode with 24 rods, and the top cathode with 12 rods. The intent is to achieve an even distribution of linear current density on the cathode rings, which have a ratio of radii of 3:2:1 from outer to inner. The gaps on the MITLs are set to achieve balanced impedances to support this current distribution.

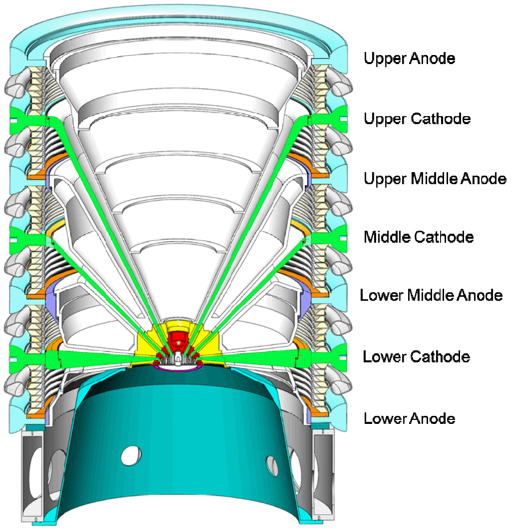


Fig. 2. Saturn vacuum stack showing the MITL configuration of the baseline bremsstrahlung diode. The MITLs have several sections indicated by the white, yellow and red colored hardware.

The MITLs are joined from three bolted sections with compressed current contacts. This makes servicing the MITLs easier as well as allowing for changes to load power flow with only minimal hardware changes. Fig. 3 shows the hardware configuration of the 3-ring bremsstrahlung diode. The only hardware that requires replacement after each shot are the anode and cathode tips shown in white, the tantalum converter, and the aluminum beam stop.

The compact geometry and high radiation dose rate make fielding current and voltage diagnostics within the diode impossible, so evaluation of diode performance must rely on other diagnostics. One diagnostic particularly useful for characterizing the performance of x-ray sources on Saturn is a fast framing camera which indirectly images the x-ray source region using a fast scintillator and an 8-frame segmented, gated image intensifier read out using a single large format CCD camera [3]. The maximum frame rate of the camera is 500 MHz with zero interframe time. This allows evaluation of the relative timing and intensity of the radiation produced by each of the three rings, which in turn can be used to evaluate the relative current and voltage.

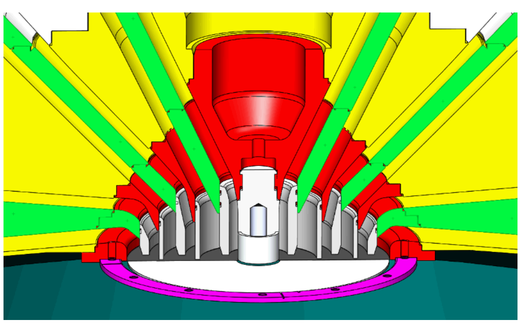

Fig. 3. A sectioned view of Saturn's baseline 3-ring bremsstrahlung diode x-ray source. The cathodes are shown in green. The tip hardware replaced for each shot is shown in white.

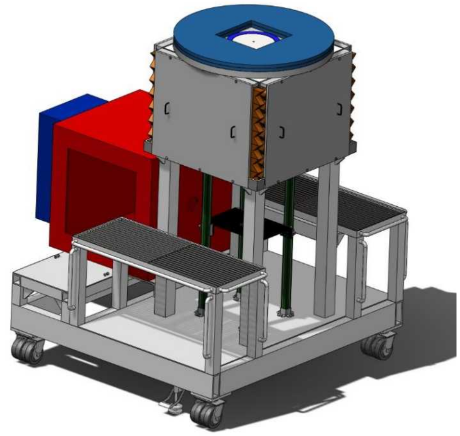

Fig. 4. Saturn fast framing camera showing the entrance pinhole, the radiation shielding of the optical path, and the screen box containing the imaging system.

### A. *Operating parameters*

The operating parameters of this load are deduced from the currents measured in the vacuum section on the lower anode and upper anode, and the voltages measured in the radial disc feed in the water section on the corresponding lines. The voltage is time-shifted and inductively corrected using the current signal to give the voltage and current at the current monitor, which is close to the load. Based on this approach, near peak power, the operating impedance of the outer diode is about 0.25 Ω and the inner diode is about 0.6 Ω, significantly undermatched to the MITLs.

## IV. Reflex Triode Development

The bremsstrahlung spectrum produced by the baseline 3-ring diode has the majority of its energy content at high energies. Warm x-ray sources are desirable for many applications and this has spurred the development of the reflex triode, which produces a bremsstrahlung spectrum of much lower endpoint energy with relatively higher warm x-ray spectral content.

The reflex triode consists of a thin radiator foil anode between a pair of cathodes shown conceptually in Fig. 5. Electrons emitting from the cathodes make multiple passes through the foil, converting their energy into bremsstrahlung x-rays. The design allows for a larger fraction of low energy photons to escape the converter.

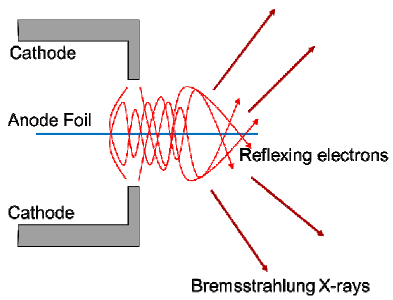


Fig. 5. Conceptual diagram of a reflex triode.

*A. Positive polarity power flow*

In order to operate a reflex triode on Saturn, the machine must operate in positive polarity. Normally, the anodes are grounded through the water section and the cathodes transmit the negative polarity power pulse to the diode. For a reflex triode however, the anodes must be driven positive relative to the grounded cathodes. This is not straightforward on Saturn; the Marx bank cannot be charged positive without significant reconfiguration.

The solution is to use the large dimensions of the machine, the relatively long time scales of the forward going power pulse to transit time isolate the anodes from the water section ground. The upper and lower anodes are removed, and the upper and lower cathodes are connected directly to machine ground creating a large ballast inductor (~250 nH). The power pulse sees this large inductance and that drives the voltage on the anodes positive during the time that power pulse takes to go out to the water section and reflect. The positive polarity on the two anodes in turn drives the center cathode to ground.

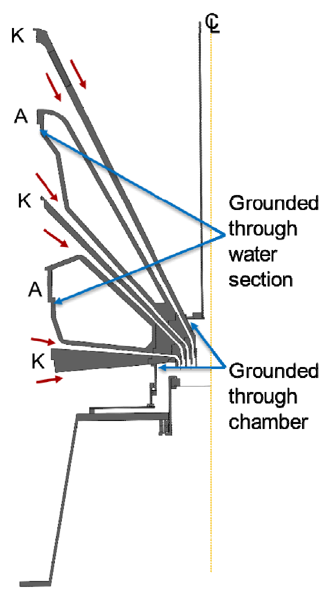


Fig. 6. Section slice of the MITLs for positive polarity configuration on Saturn used for the reflex triode.

This configuration was conceptually validated by models before being implemented on the machine. For short pulses, this mode does result in reduction in available current to the load by about one third since the power on two of the six transmission lines reflects back to the water section. This power is considered lost since the radiation pulse has ended by the time it comes back to the load.

*B. LANTERN source*

The Large Area Nested Triode with Electron Reflexing eNhancement source is an implementation of the reflex triode on Saturn consisting of two nested cylindrical reflex triodes. The anode foils are wrapped around the anode tips and hang down through a gap in the cathodes. This is shown in detail in Fig. 7.

There are several advantages to this configuration on Saturn. First, the hardware is not significantly different than the standard 3-ring bremsstrahlung diode. Only minor modifications were made to the innermost section of the MITL meaning that power flow to the tips will be similar. The 13 µm tantalum foil is conveniently available in strips which are easy wrapped around the anode tips. Additionally, the cylindrical geometry has a low susceptibility to premature shorting of the AK gaps. The framing camera image of this source (Fig. 9) shows that even late in the pulse both foils continue to radiate symmetrically.

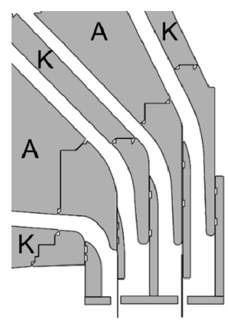


Fig. 7. Diagram of LANTERN showing the configuration of anodes and cathodes and the reflexing foils. This is a zoomed in portion of Fig. 6.

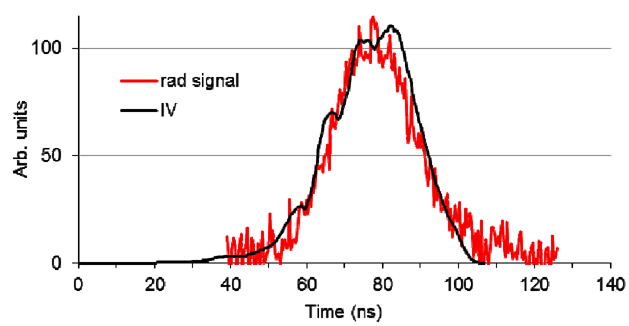


Fig. 8. The LANTERN source produces a radiation pulse that closely tracks the power source with a FWHM of approximately 28 ns.

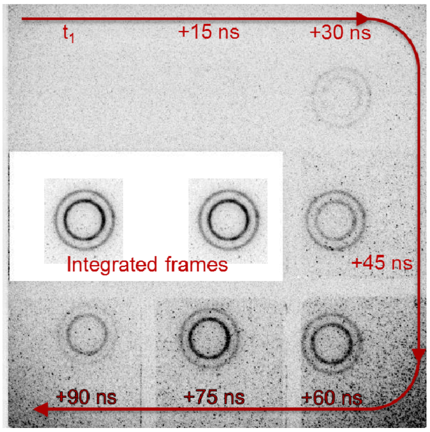


Fig. 9. Framing camera image of nested cylindrical reflex triode radiation source.

## V. Multi Rod-Pinch Diode Development

While the reflex triode performs well, there are several drivers that lead toward the development of another type of source, a massively parallel rod pinch array. The two big drivers for the new source are enhancing the warm x-ray yield and increasing the areal density. On the operational side, it is highly desirable to reduce the mechanical complexity and reduce refurbishment requirements of the hardware. This allows for reduced labor and faster machine turn-around times.

Building a higher flux warm x-ray source presents an immediate physics challenge, because the efficiency of bremsstrahlung sources goes down as electron energy goes down. Because the bremsstrahlung flux scales with the current, the key to increasing x-ray output is increasing the areal current density of the source. However, the current density of cylindrical intense electron beams across a vacuum gap is limited by pinching of the electrons in the self-magnetic field of the beam,

$$I_c = \alpha \left[\frac{2\pi m_e c}{e\mu_0}\right]\frac{R_c}{d}(\gamma_0^2 - 1)^{1/2}$$

where d is the gap, $R_c$ is the cathode radius, and α is an empirical correction factor (~1.4) [4]. Experience shows that there are practical limits to the minimum gap, and as a result, for a given electron energy there is a maximum current per unit length that can be transported across the gap. In order to obtain a higher bremsstrahlung flux at a given electron energy, it is necessary to put more pinch length in the field of view of the test region. Saturn's baseline bremsstrahlung diode uses three concentric rings to increase this pinch length. However, increasing the number of rings introduces mechanical complexity, increasing the machine turn-around time. An alternate approach that we explored is a closely packed array of small aspect ratio rod pinches.

### *A. Initial testing on URSA Minor*

The initial testing of the multi rod-pinch was performed using components of the Ursa Minor accelerator. The experiments used five LTD cavities and the central stalk to examine the pinch behavior of small aspect ratio rod pinches using solid tungsten rods of varying radius: 0.635 cm, 0.95 cm, and 1.27 cm [5]. It was noted that the rods sustained very little damage, and could be reused.

The next set of experiments constructed 4 rod and 10 rod, close-packed arrays of anode radius of 0.635 cm and cathode radius 1.27 cm [6]. The voltage and current were approximately 300 kV, 45 kA/rod on the 4 rod array and 150 kV, 15 kA/rod on the 10 rod array. No problems were found with current penetration to the center of the array and the pinch behavior between the two arrays was qualitatively similar. The pinch traveled out to the end of the rods in all cases. Pinhole imaging showed that the initial pinch is asymmetric in the A-K gap. The pinch symmetrizes as it moves toward the tip. These experiments gave confidence that the current would penetrate uniformly into the larger array planned for Saturn and that the Saturn pulsed power parameters would be sufficient to see pinching at the tips.

### *B. Diode simulation*

Early simulation of the flow in a rod pinch array showed that the coupling of the magnetic fields produced by the multiple diodes would result in some current asymmetry around each rod. The result would be increased current density on the side of the rod toward the center of the array and reduced current density toward the edge of the array. In addition, the simulations showed the formation of magnetic nulls between the rods. Based on these simulation results, the cathode geometry was modified to confine electron emission to the desired area and to increase isolation between the rods. This modified geometry was implemented in all of the multi-rod experiments.

The small-scale multi-rod experiments using Ursa Minor showed the expected asymmetry around each rod, with increased current density on the side toward the array axis. However, they also showed that the pinch would symmetrize as it moved toward the tip of the rod.

An early concern in the development of the multi-rod array was that the current would not penetrate to the center of the array, however the simulations showed that the current on the center rods was virtually identical to that on the edge rods. Additionally, the small-scale experiments showed that the currents on all the rods were the same, to within the accuracy of the measurements.

### *C. Experiments on Saturn*

Obtaining the required pulsed power drive on Saturn was a concern. The multi-rod-pinch array is most naturally driven by a single anode and cathode line, operated in positive polarity. However, the post-hole convolute developed to drive z-pinch sources on Saturn is at too small a radius to drive the multi-rod-pinch array. In addition, it operated in negative polarity. To obtain the required drive on Saturn, the pulsed power is configured for positive polarity operation with the lower cathode grounded through the chamber and the lower middle anode driving the anode plate. To avoid damaging the accelerator, these experiments were conducted with only some of the Marx generators charged, so the unpowered lines could absorb the reflected power from the mismatched load.

The multi-rod-pinch array deployed on Saturn consists of 51, 0.635 cm radius tungsten anode rods bolted to a stainless steel plate (Fig. 10). The stainless steel cathode plate has 1.27 cm radius apertures giving a nominal radial A-K gap of 0.32 cm. The accuracy of the gaps after installation in the machine was found to be 0.32 ± 0.005 cm. The voltage and current design values for 12 lines are 200 kV and 33 kA/rod; for 18 lines they are 400 kV and 50 kA/rod.

### *D. Saturn experimental results*

Several observations from the Ursa Minor experiments were confirmed on the Saturn experiments. The anode and cathode hardware was reusable, with only slight damage to the anode rods and debris deposition on the cathode plate. Based on the appearance of similar damage to all anode rods and the uniformity of the framing camera image (shown in Fig. 11), the current penetration to the center of the array was generally uniform. The rod damage was greater on the side facing the axis of the array than on the side facing away from the axis.

Unlike the Ursa Minor experiments, the current did not pinch to the end of the rods, and appeared to be confined mostly to the region under the cathodes. This was a surprise, since the rod currents and voltages were designed to be similar to the Ursa Minor configuration. The reason for this failure to pinch is not known at this time. Limited data were collected on the Saturn experiments. The current monitors on the cathode feed plate failed, so the current reaching the diode area was not measured. Although there was no indication of a localized loss of current in the feed, it is possible the current reaching the array was substantially less than the design value. In addition, the Ursa Minor experiments used a longer current pulse of nominally 150 ns, while the Saturn current pulse was only 30 ns. It is possible that the pulse was not long enough to allow pinching to the end of the rod.

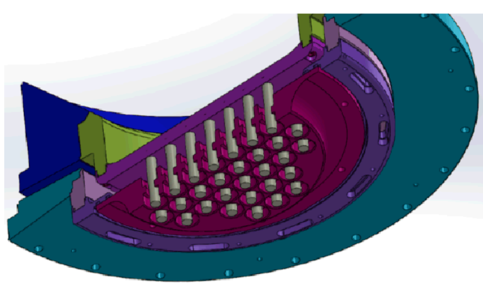

Fig. 10. Sectioned 3-D model of the Saturn multi rod-pinch experiment hardware.

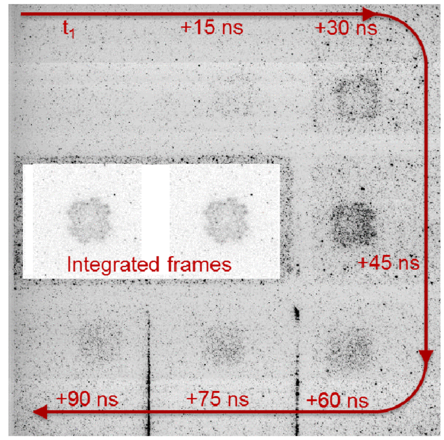


Fig. 11. Framing camera image of Saturn multi-rod-pinch radiation source showing good current penetration to the center of the array.

## VI. Conclusion

Saturn is a very flexible pulsed power driver for short pulse bremsstrahlung radiation sources. It can be configured to drive up to half of the power to any of three cathode levels. By not charging some of the Marx generators, it can be operated at reduced power without having to adjust any switches. With some loss of power, it can be configured to operate in positive polarity without the use of a posthole convolute. It can be operated in short pulse (30 ns) or long pulse (110 ns) modes. With the implementation of “combo rods”, two rods connected to a single water bottle, it will be possible to drive all of the power to a single cathode without the use of a vacuum convolute.

Saturn’s flexibility has been exploited to drive a variety of bremsstrahlung radiation sources requiring different pulsed power configurations, including nested ring diodes, nested cylindrical reflex triodes, and a large multi-rod-pinch array. It is anticipated that Saturn will continue to be adapted to drive other radiation loads in the future.

# Acknowledgment


We acknowledge input from B. Weber and others at the Naval Research Laboratory, Washington D.C. on the reflex triode implementation on Saturn. We also acknowledge the excellent LSP simulation work performed by Voss Scientific, LLC, Albuquerque, NM.


# References


[1] D.D. Bloomquist, R. W. Stinnett, D. H. McDaniel, J. R. Lee, A. W. Sharpe, J. A. Halbleib, L. G. Schlitt, P. W. Spence, and P. Corcoran. "Saturn, a large area X-ray simulation accelerator." In Proc. 6th IEEE Pulsed Power Conference, Arlington, VA, p. 310. 1987.

[2] J.D. Boyes, J.S. Cap, G.M. Douglas, T.L. Franklin, J.M. Hart, H.C. Ives, S.J. Robischon, B.L. Smith, W.O. Stoppkotte, and D.M. VanDeValde. “Engineering Design of the Saturn Accelerator” .In Proc. 6th IEEE Pulsed Power Conference, Arlington, VA, 1987.

[3] G. W. Smith, D. S. George, D. Harrison, S. Hill, R. J. Hohlfelder, V. Harper-Slaboszewicz, R. R. Gallegos, M. B. Ingle and P. Simpson, "Ultrafast imaging of nanosecond pulse x-ray simulators", Proc. SPIE 7126, 28th International Congress on High-Speed Imaging and Photonics, 712603 (February 10, 2009).

[4] Swanekamp, S. B., Commisso, R. J., Cooperstein, G., Ottinger, P. F., & Schumer, J. W. (2000). Particle-in-cell simulations of high-power cylindrical electron beam diodes. *Physics of Plasmas (1994-present)*, *7*(12), 5214-5222.

[5] V. J. Harper-Slaboszewicz, J. Leckbee, P. W. Lake, and A. L. McCourt. 2014. "Effect of Rod Material on the Impedance Behavior of Small Aspect Ratio Rod Pinches." IEEE Transactions on Plasma Science, 42(9), 2207-2212, (2014).

[6] V. J. Harper-Slaboszewicz, J. Leckbee, N. Bennett, E.A. Madrid, D. V. Rose, C. Thoma, D. R. Welch, P.W. Lake, and A.L. McCourt, ."Parallel Operation of Multiple Closely Spaced Small Aspect Ratio Rod Pinches". IEEE Transactions on Plasma Science, 43(1), 422-432 (2015).