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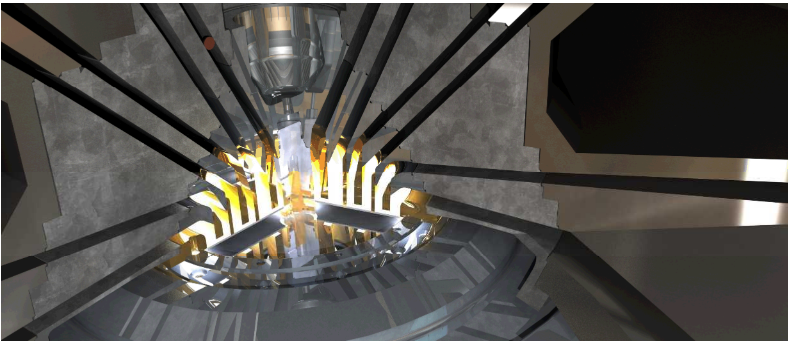

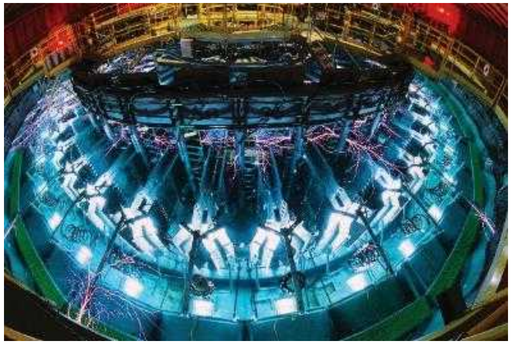

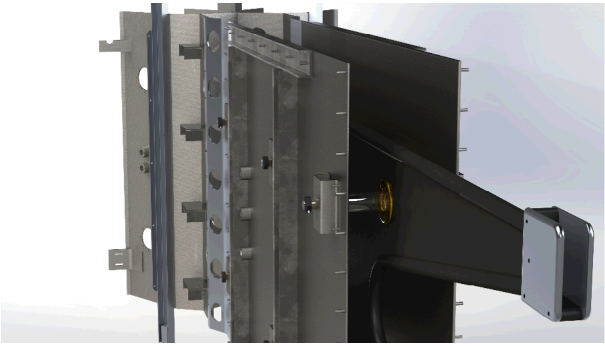

Warm X-ray Source Development on the Saturn Accelerator

Bryan V. Oliver, V. Harper-Slaboszewicz, K. Struve, and B. Ulmen

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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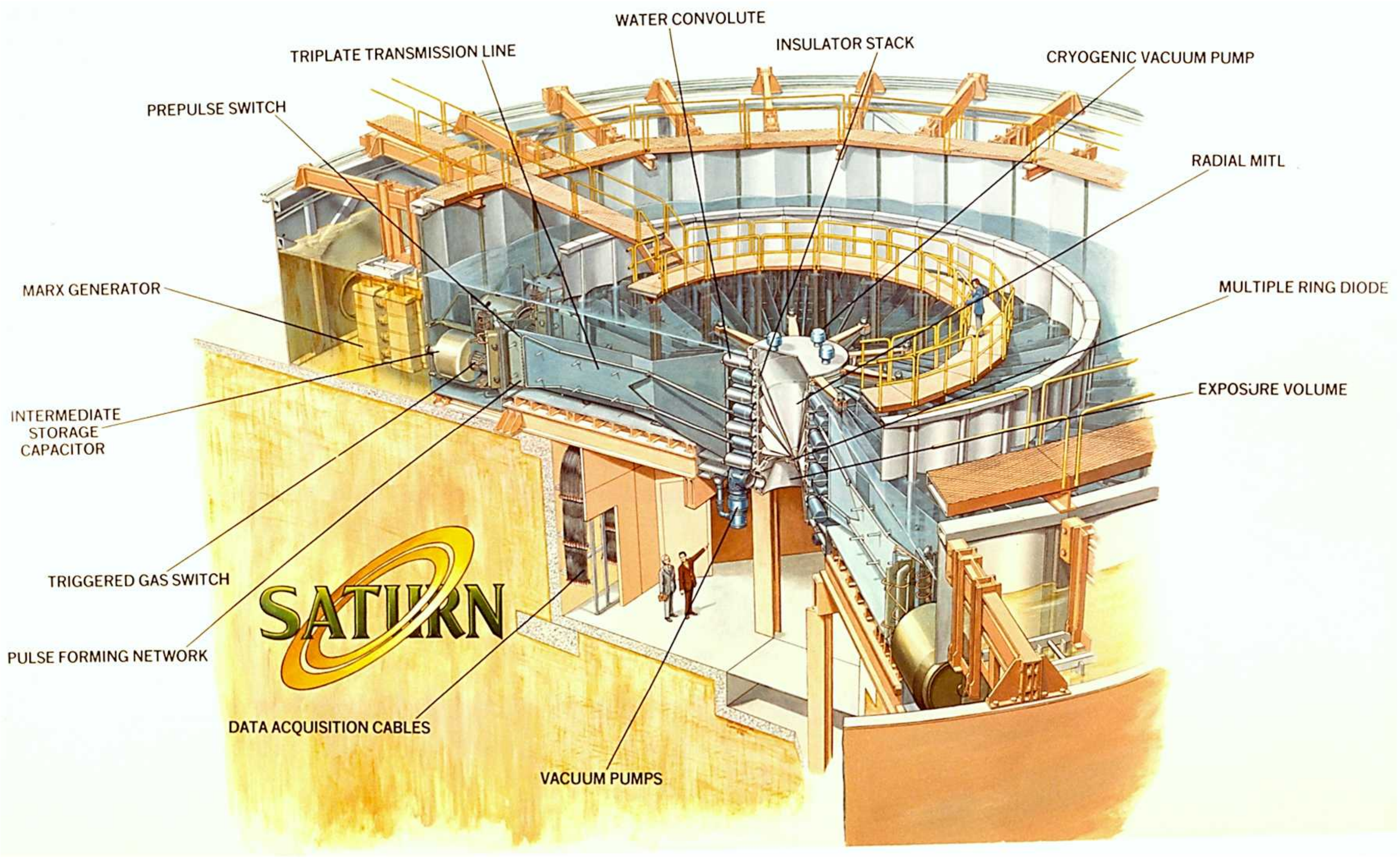
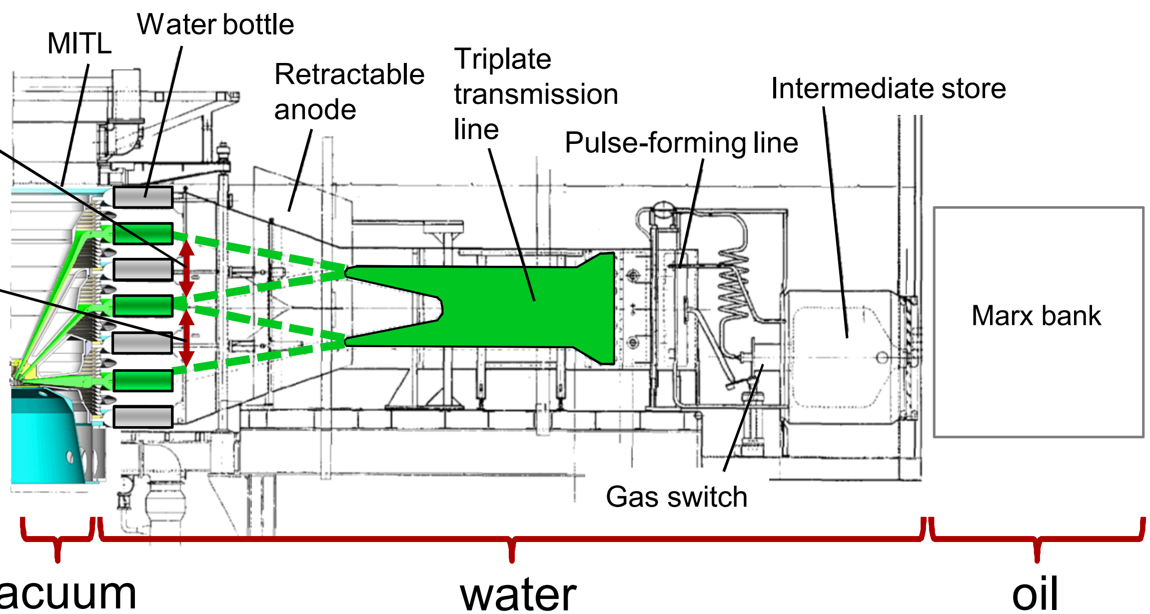
Saturn Overview

- Saturn is a low impedance very high current short pulse driver
- Nominally 10 MA, 1.6 MV, 40 ns power pulse



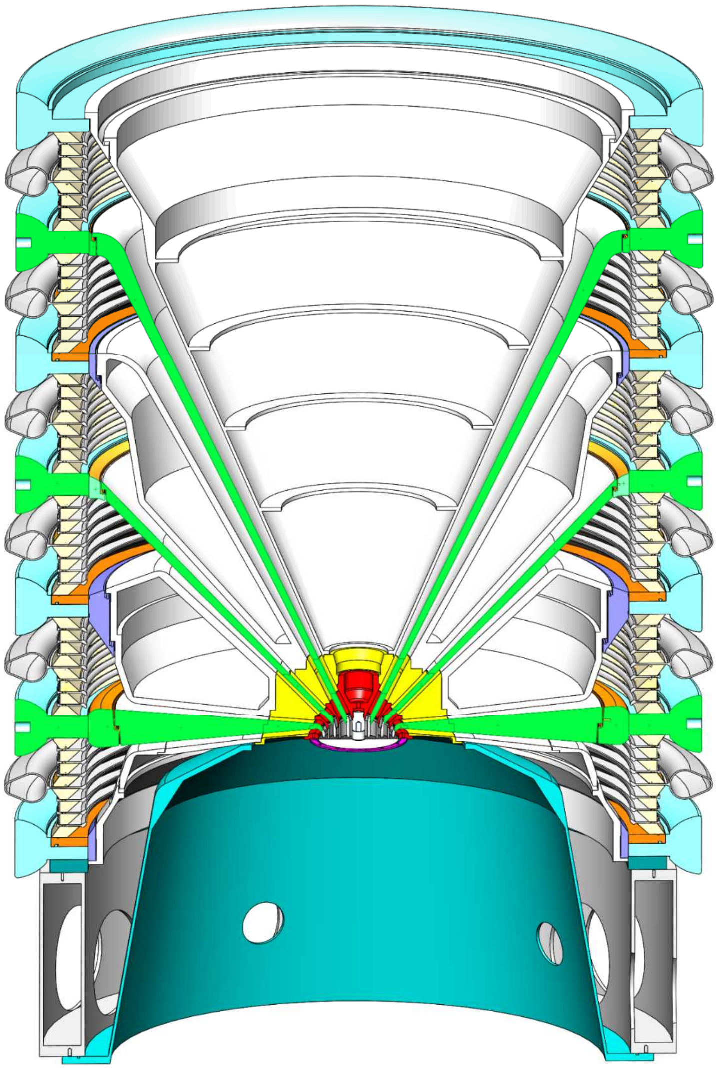
Saturn pulsed power

- Each one of 36 vertical triplate lines
  - 50 kJ forward-going energy
  - ~2 MV at beginning of TL
  - 40 ns FWHM power pulse
  - Nominally 2 Ω
  - Anode is grounded, cathode is pulsed negative
- Water convolute connects lines to vacuum stack
  - Each line is connected to two 8 Ω rods
  - Each rod connects to ½ Ω radial cathode disk feed in water
  - Up to 36 rods (half machine) can be connected to each level



Ability to set the current division to each level gives Saturn its flexibility

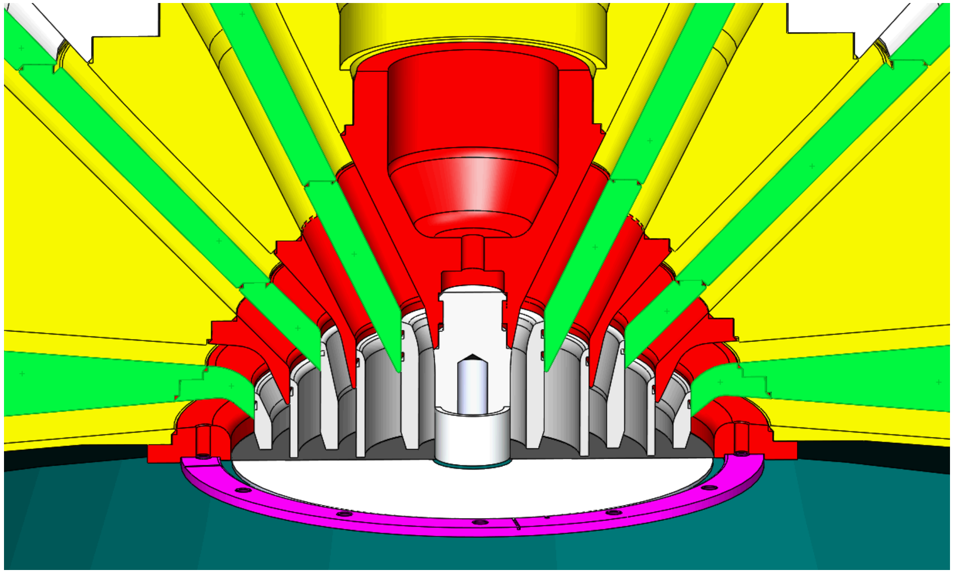
The Vacuum Stack and load region of the baseline configuration

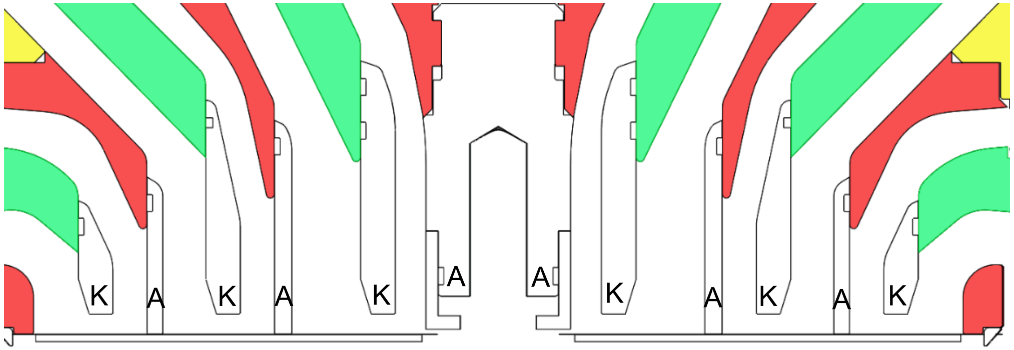


- 3 nested conical triaxial lines
- Bottom 2 lines are 2 Ω driven by 36 rods
- Middle two lines are 3 Ω driven by 24 rods
- Top two lines are 6 Ω driven by 12 rods
- Each conical electrode in made in three sections
- Replacing relatively small hardware close to the axis allows a variety of loads to be fielded
- The upper and lower anodes are not vacuum barriers. The vacuum barrier is separate

Standard diode on Saturn – three nested annular diodes for low inductance

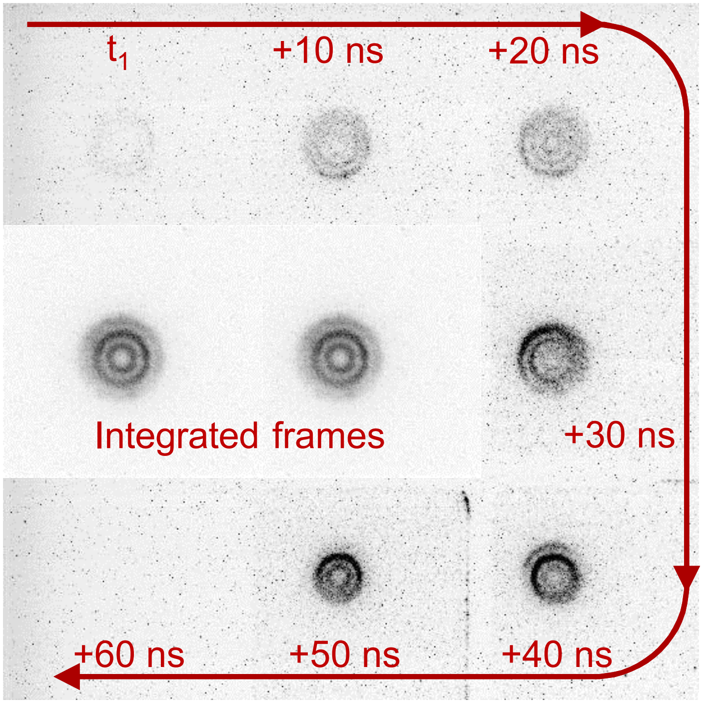
- Three nested annular triaxial diodes
- Ratio of radii 3:2:1
- Equal widths so ratio of areas 3:2:1
- Impedances balanced so have equal current density on each annular cathode
- At the diode, get 10 MA, 1.6 MV (power weighted mean voltage), 20 ns radiation pulse
- This has been the workhorse



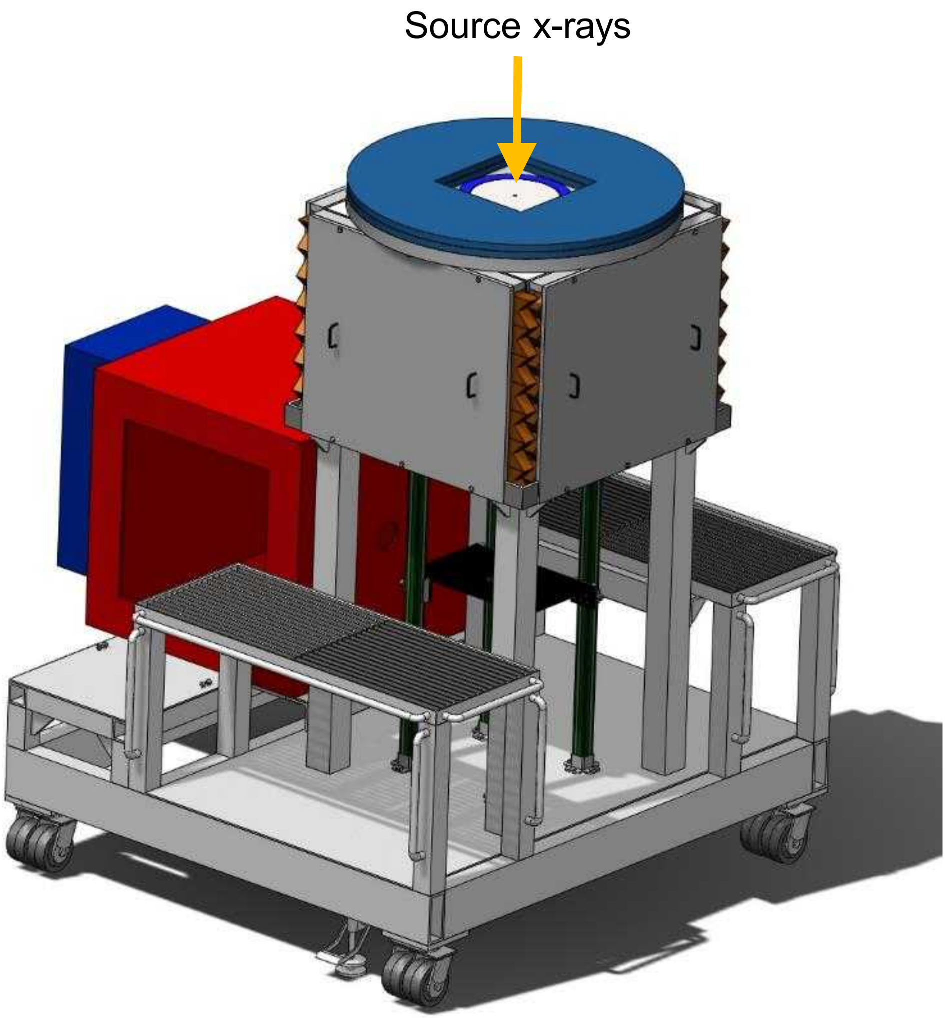


Aluminum tip hardware shown in white replaced after each shot

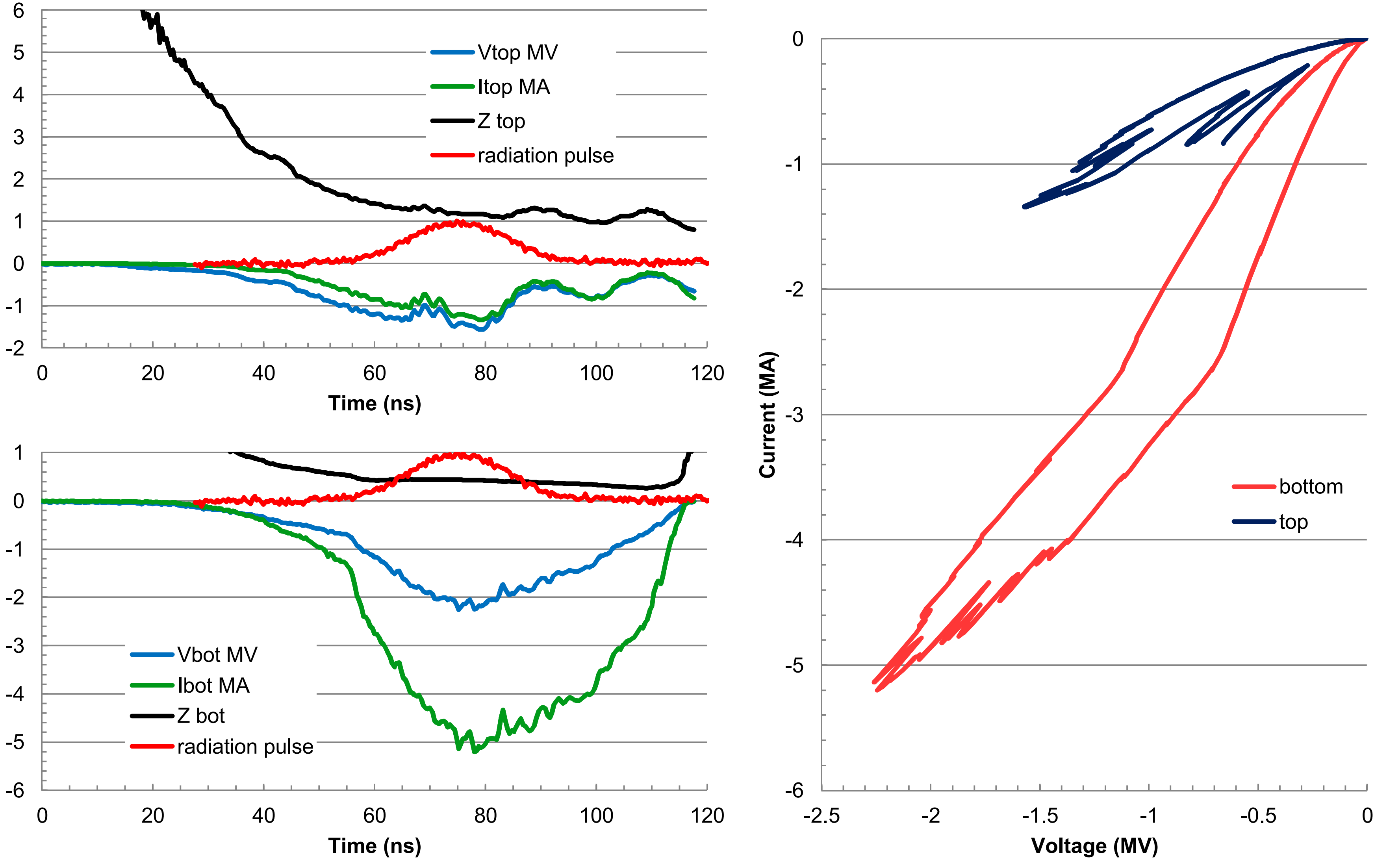
Fast framing camera provides insight into diode dynamics



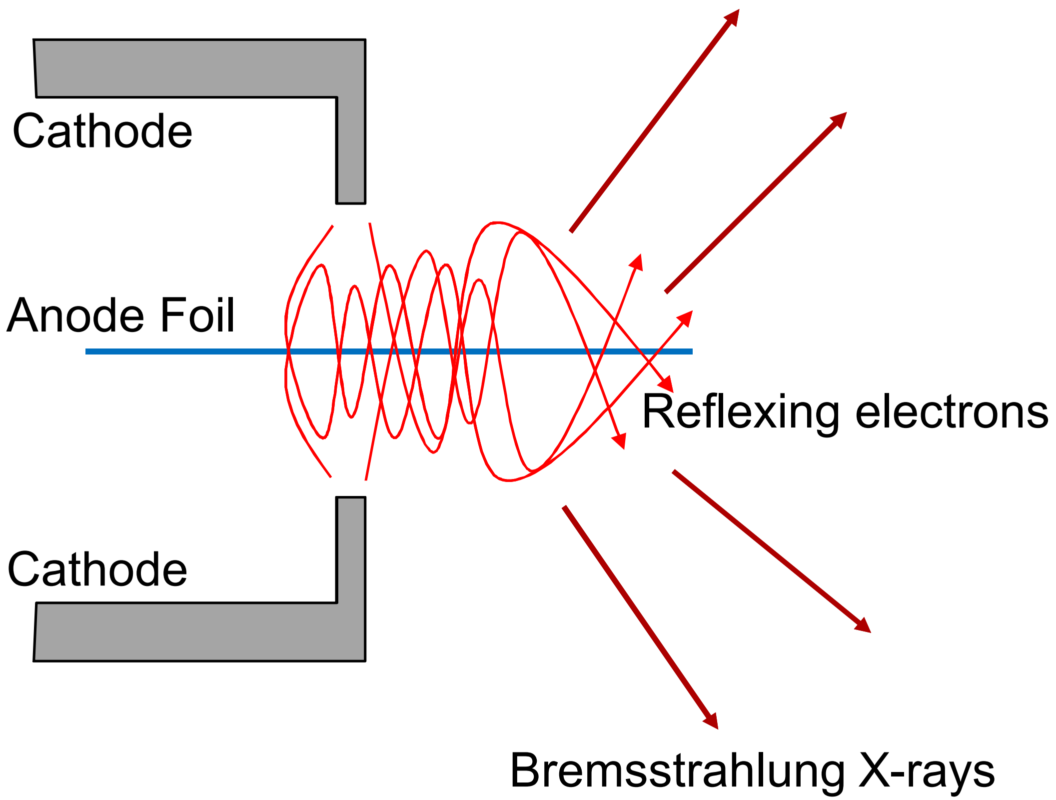
- Intensified visible framing camera
- Images fast scintillator
- 8 independently triggered frames
- Frame width down to 2 ns
- Can be light limited – does not use 8-way splitter



Operating characteristics of the standard Saturn diode

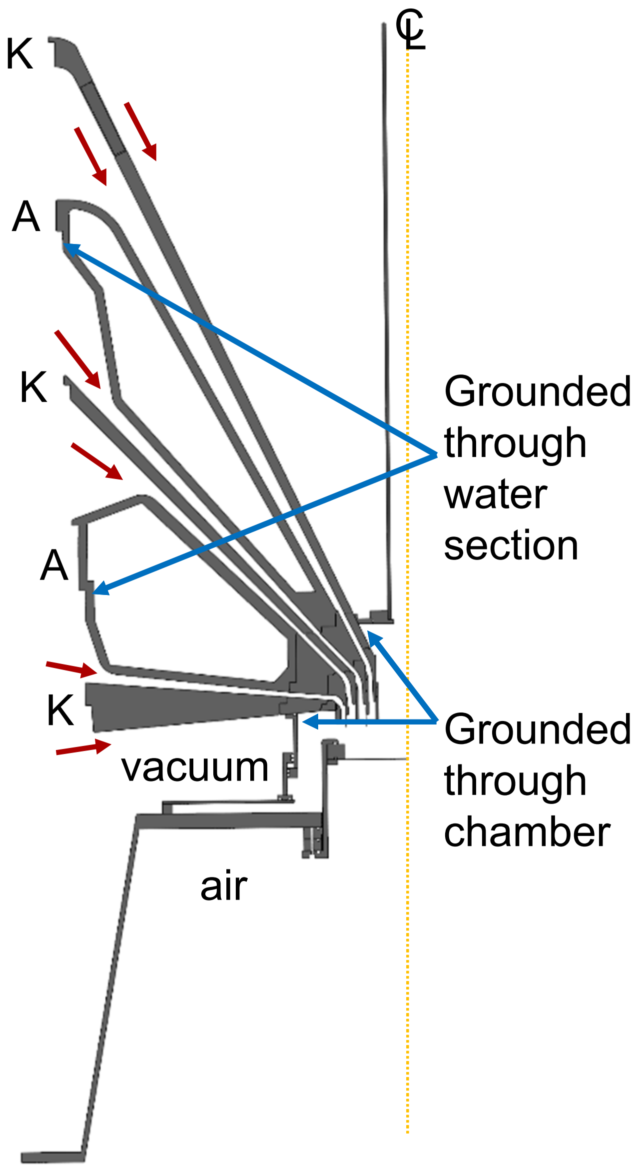


Next generation Saturn warm x-ray sources utilize reflexing triodes



- The thin anode of a reflexing diode allows more warm x-rays to escape compared to standard diodes
- Electrons emitted from the cathode tips are repelled by opposite tip
- Anode thickness is chosen such that the electrons make multiple passes through the foil
- To use this type of source need to operate in positive polarity

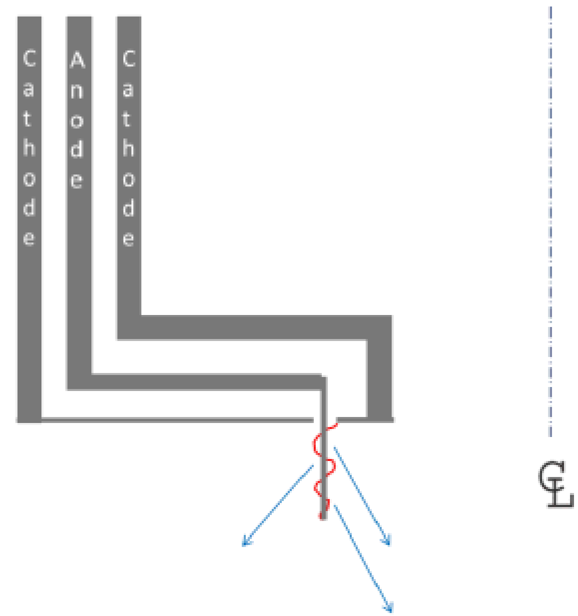
Positive Polarity Power Flow on Saturn



- Inverting the polarity of Saturn power flow by reversing charge voltage is not straightforward so use an alternate approach
- Power flowing on the outside of the upper and lower cathodes flows to ground through the chamber acting as a ballast inductor
- The power pulse down the two outer MITLs drives the two anodes positive
- The anodes are transit time isolated from ground through the water section
- The power pulse on the central two MITLs in turn drives the center cathode to ground
- This conceptual model validated by simulations
- Positive polarity mode (for short pulses) results in a reduction of current to the load by ~1/3

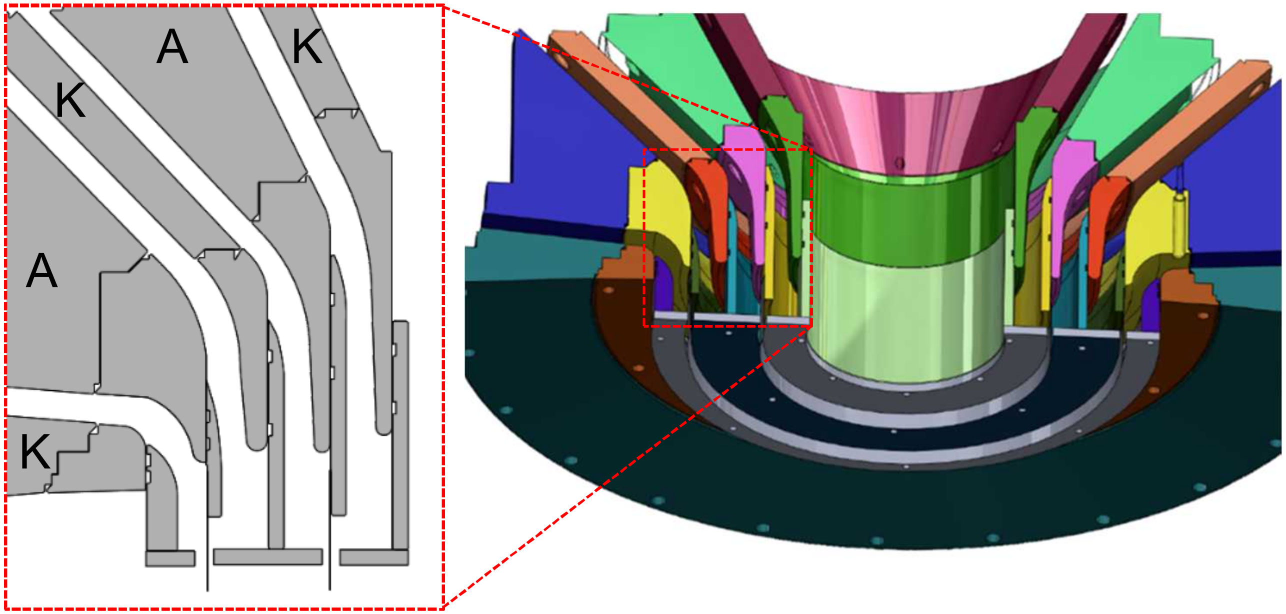
Cylindrical geometry reflex triode has several advantages

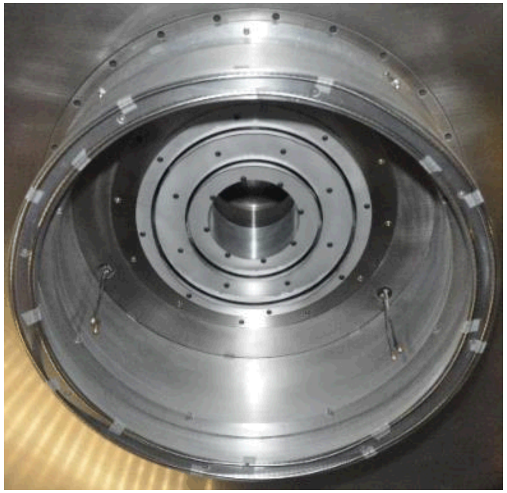
- Hardware is not very different than standard bremsstrahlung source
- Thin (13 μm) Tantalum foil is conveniently available in thin strips
- Cylindrical geometry appears to be less susceptible to premature shorting of the A-K gap than planar geometry
- Compatible with a nested geometry to reduce load impedance



B.V. Weber, R.J. Commisso, D.D. Hinshelwood, G. Phipps, S.J. Stephanakis, S. B. Swanekamp, "New reflex triode configuration for improved moderate-energy x-ray production", 2011 Abstracts IEEE International Conference on Plasma Science, http://dx.doi.org/10.1109/PLASMA.2011.5993077

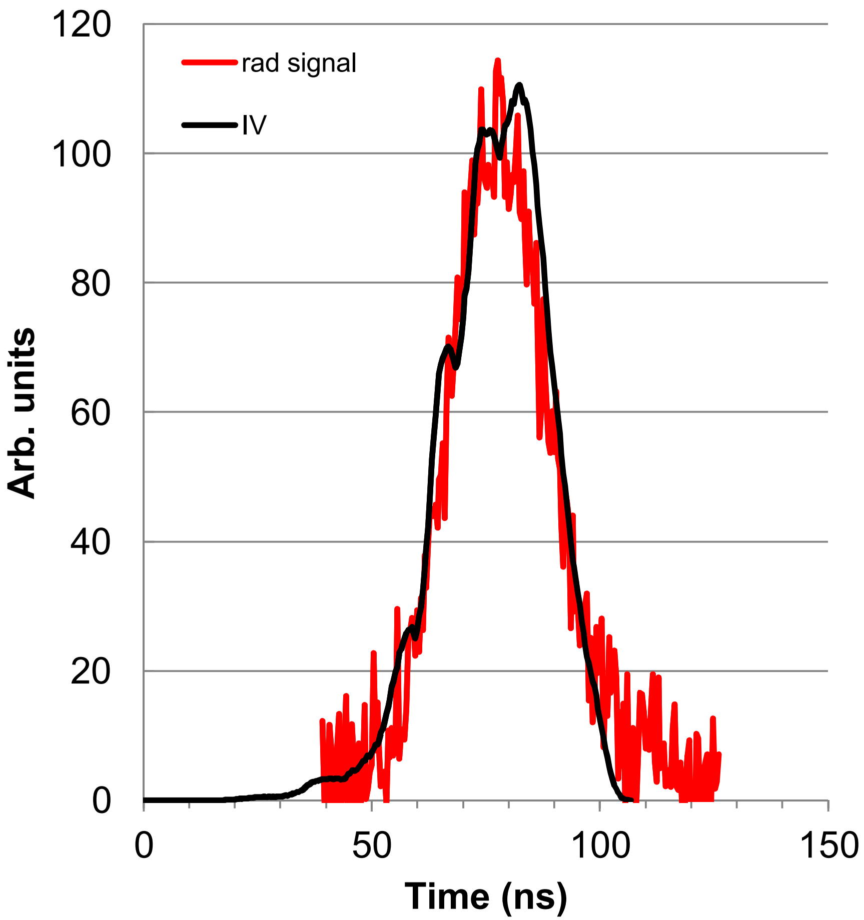
Large Area Nested Reflex Triode (LANRT)



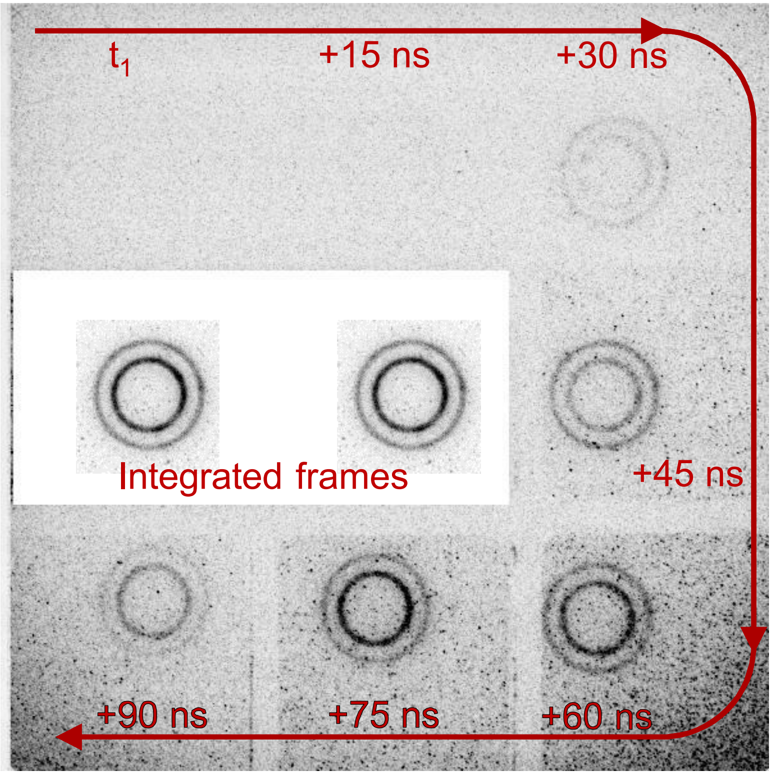


- Machine is put into positive polarity by grounding the top and bottom cathodes through a large inductance (~250 nH)
- Design in collaboration with B. Weber et al., Naval Research Laboratory, Washington, D.C.

LANRT Characteristics



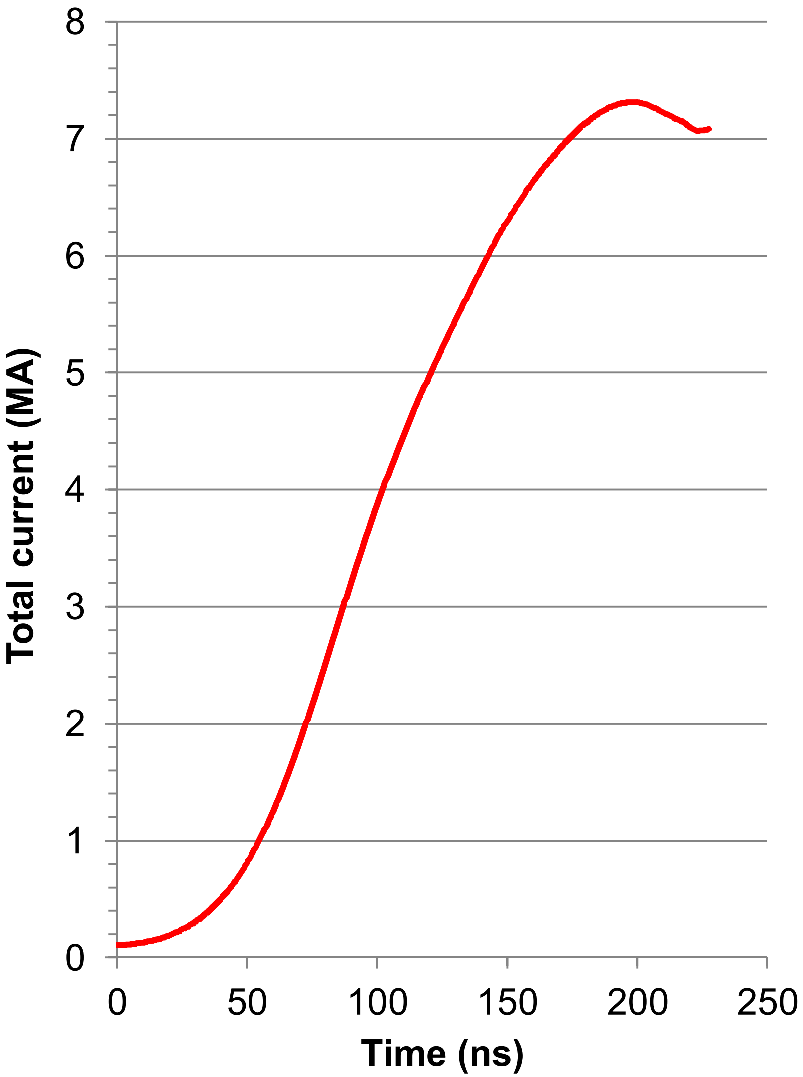
~28 ns FWHM
Closely tracks power pulse



No evidence of shorting of the diode even late in time with 3 mm AK gap

Possible next step for Saturn reflex triodes

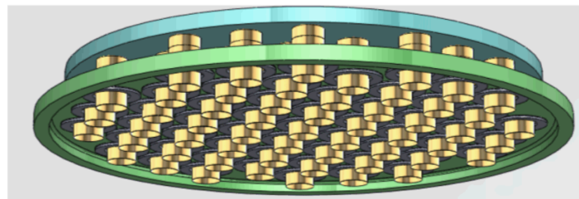
- One option is long pulse operation
  - Present method for positive polarity loses ~1/3 machine current because of 18.6 ns one way transit time in the radial disk feed
  - Operating in long pulse mode would allow this current to get to the diode
  - Long pulse has only been used for z-pinch loads to date
  - Current coupling should be better for bremsstrahlung diode loads



What is the next step after nested cylindrical reflex triodes for generation of warm x-rays on high current drivers? This is one approach

Reduce mechanical complexity

Increase areal current density



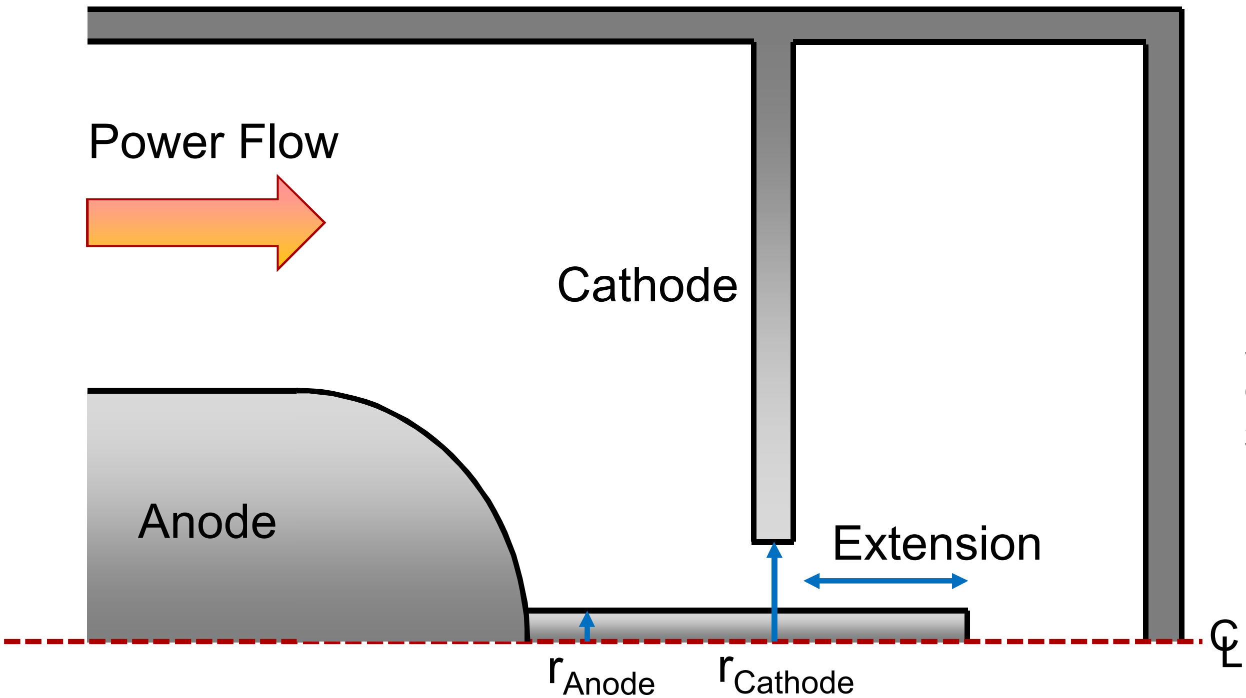
Massively parallel rod pinch array

- Monolithic construction
- Reusable stainless and tungsten hardware
- Closely coupled rod pinches
- Operate at low impedance
- Reduced debris

Reduce refurbishment or replacement of hardware between shots

Enhance warm x-ray yield

Rod pinches have been extensively studied for radiography applications



R. A. Mahaffey, J. Golden, Shyke A. Goldstein, G. Cooperstein, App. Phys. Lett. 33, 795 (1978)

- Radiation in reflection enhances warm x-ray output
- Positive polarity operation required
- For radiography, high impedance, large aspect ratio rod pinches are used
- For our application, low impedance, low aspect ratio, thick rods

Why use a massively parallel rod pinch array?

- We would like to build higher flux warm x-ray sources *But*
- The efficiency of bremsstrahlung sources goes down as the electron energy goes down
- The current density of intense electron beams across a vacuum gap is limited by pinching of the electrons in the self-magnetic field of the beam

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

- There are practical limits to the minimum gap d that can be used in these sources

For a given electron energy there is a maximum current per unit pinch length that can be transported across the gap, so

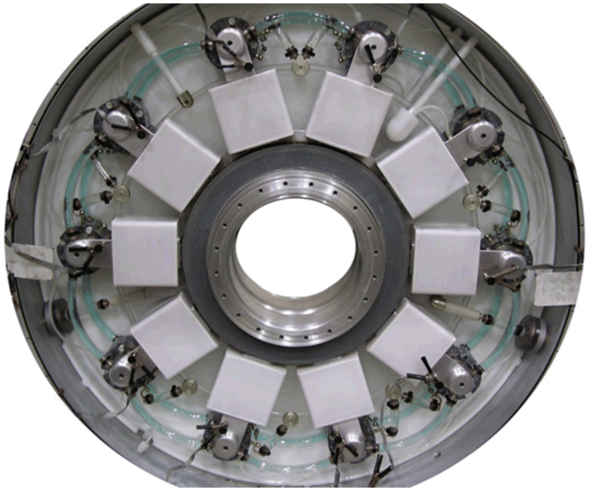
To obtain a higher bremsstrahlung flux at a given electron energy, it is necessary to put more pinch length in the field of view of the test region

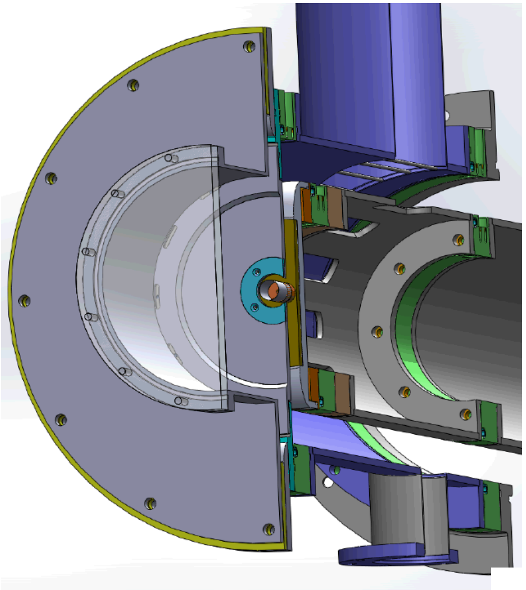
- Multiple concentric ring diodes as on Saturn become mechanically complex as the number of rings increases
- Closely packed rod pinches are an alternate approach

Characterize behavior of small aspect ratio rod pinches

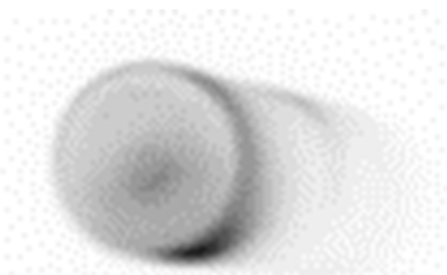
- Early experiments used 5 cavities and the central stalk from Ursa Minor as the pulsed power driver

One LTD cavity of Ursa Minor

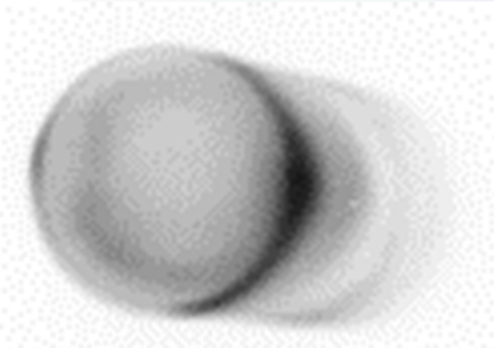




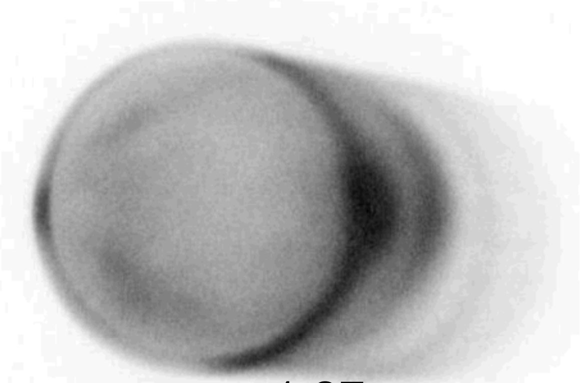
- Pinch dwells on edge of tip
- Impedance as expected
  - gap closure 1–2 cm/μs
- Anode rods and cathodes reusable
- Light rod damage provides indication of pinch behavior



r_{anode} 0.635 cm
$r_{cathode}$ 1.6 cm

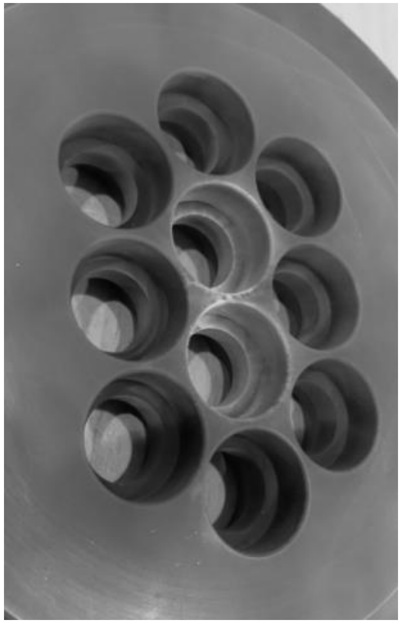


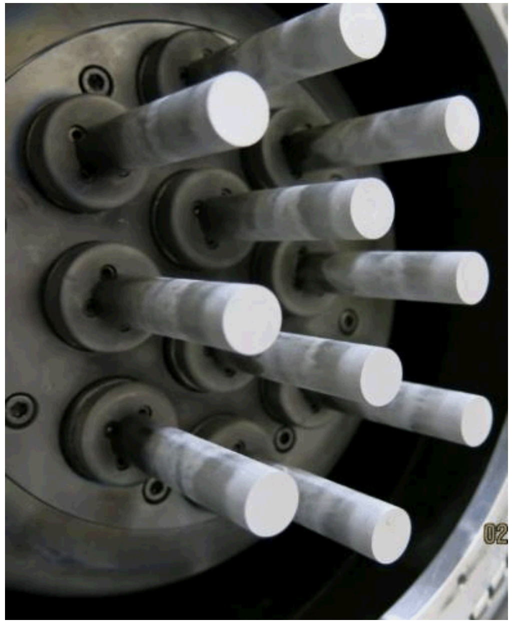
r_{anode} 0.95 cm
$r_{cathode}$ 1.6 cm

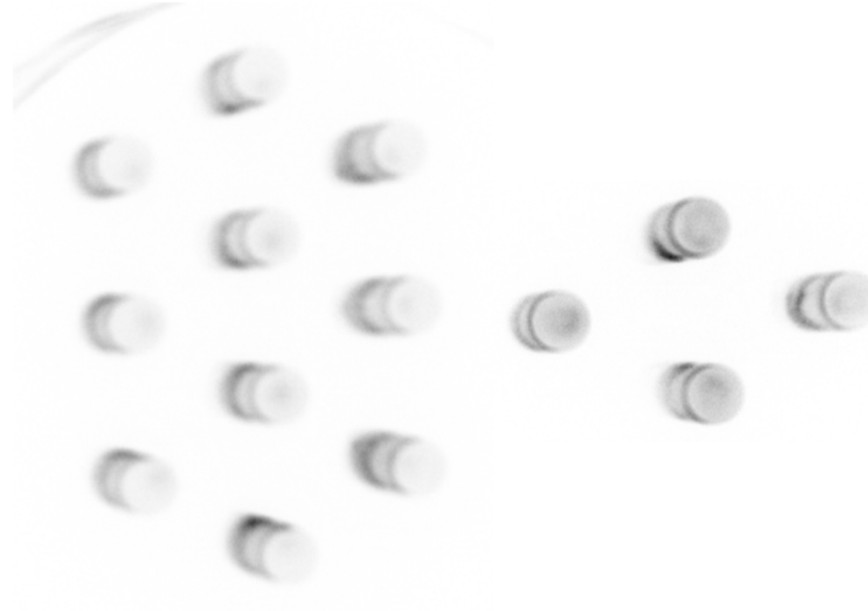


r_{anode} 1.27 cm
$r_{cathode}$ 1.6 cm

Evaluate performance of small closely coupled small aspect ratio rod pinch arrays



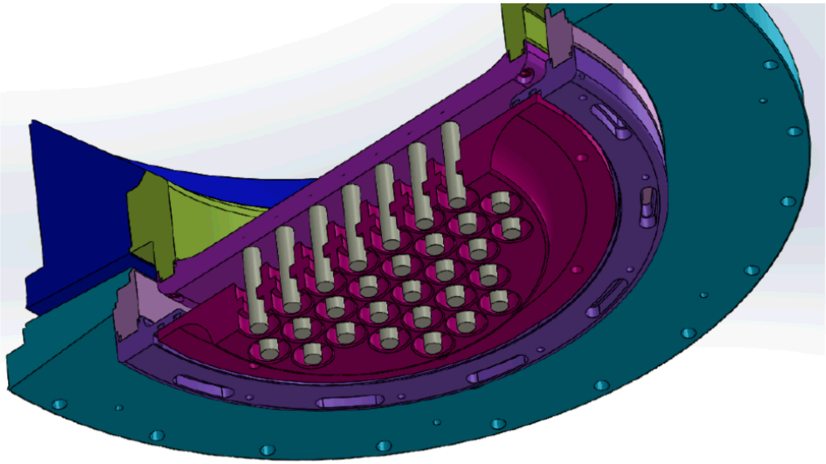




- Same Ursa Minor driver , 15 kA rod current, ~150 kV
- r_a .635 cm, r_c 1.27 cm
- Hardware reusable
- No evidence of problems with current penetration to center of array
- Some bias of pinch toward center of array, pinch goes to end of rod on all rods
  - Light anode damage indicates pinch symmetric under cathode, biased toward center of array as sweeps to the tip, then symmetrizes near tip
- Pinch behavior qualitatively similar on 4 rod shot at 45 kA rod current, 300 kV

Massively parallel rod pinch array on Saturn

- 51 solid W anode rods r_a .635 cm
- Stainless steel cathode plate r_c 1.27 cm
- Nominal radial gap 3.2 mm
- Radial gap on all rods measured to 3.2 ± 0.05 mm
- Design values for 12 lines
  - 200 kV
  - 33 kA/rod
- Design values for 18 lines
  - 400 kV
  - 50 kA/rod
- Saturn pulsed power configuration
  - Positive polarity so lower cathode grounded
  - Lower cathode drives cathode plate
  - Lower center anode drives anode plate



First Saturn shot

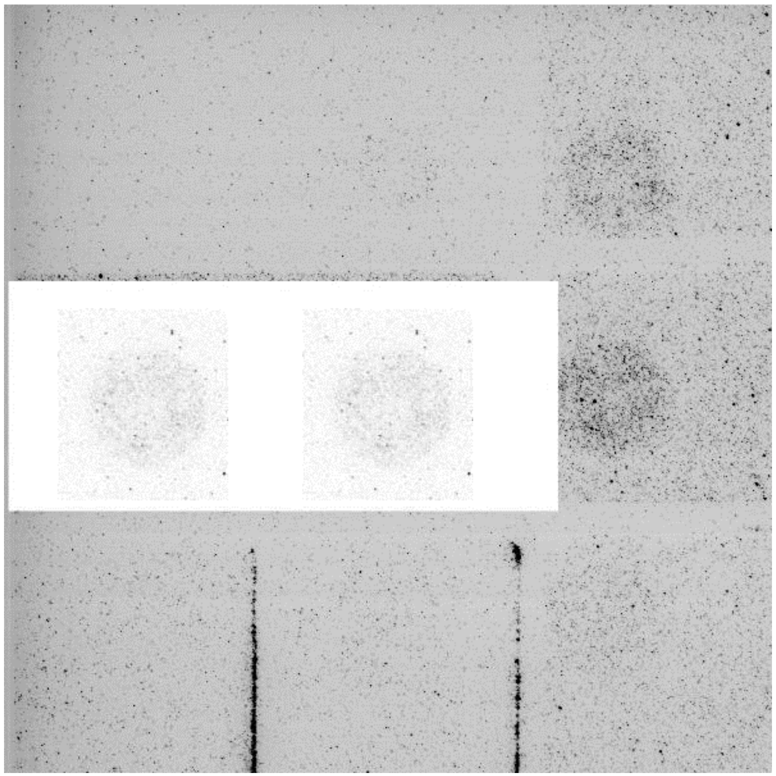
- 12 lines, 51 rods
- Peak current 1 MA, 20 kA/rod
- Light rod damage is primary diagnostic
- Based on rod damage, electron flow started under the top and bottom edges of the cathode on each rod, with more flow on the side toward the center of the array
- In a few cases the pinch traveled toward the tip, but did not reach the tip
- Based on the damage, current division among the rods is approximately equal

Second Saturn shot

- 18 lines, 51 rods
- Estimated peak current 1.5 MA, 30 kA/rod
- Pinch behavior qualitatively similar
- Near center of array some pinching onto tip
- In many cases pinch reached the side of the tip facing the center of the array
- Based on the damage, current division among the rods is approximately equal

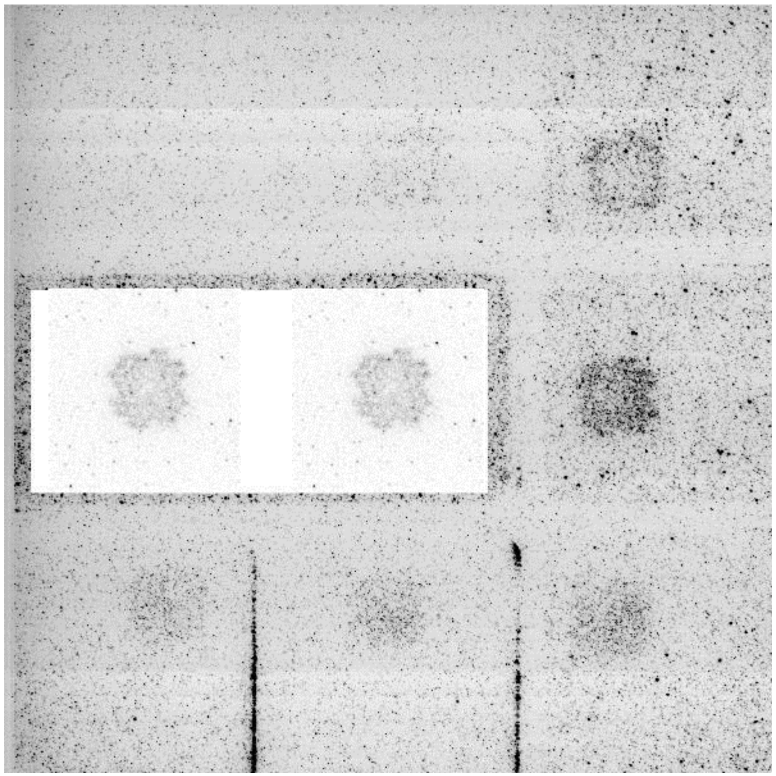
Framing camera images confirm current penetration to center of array

First shot



15 ns frames

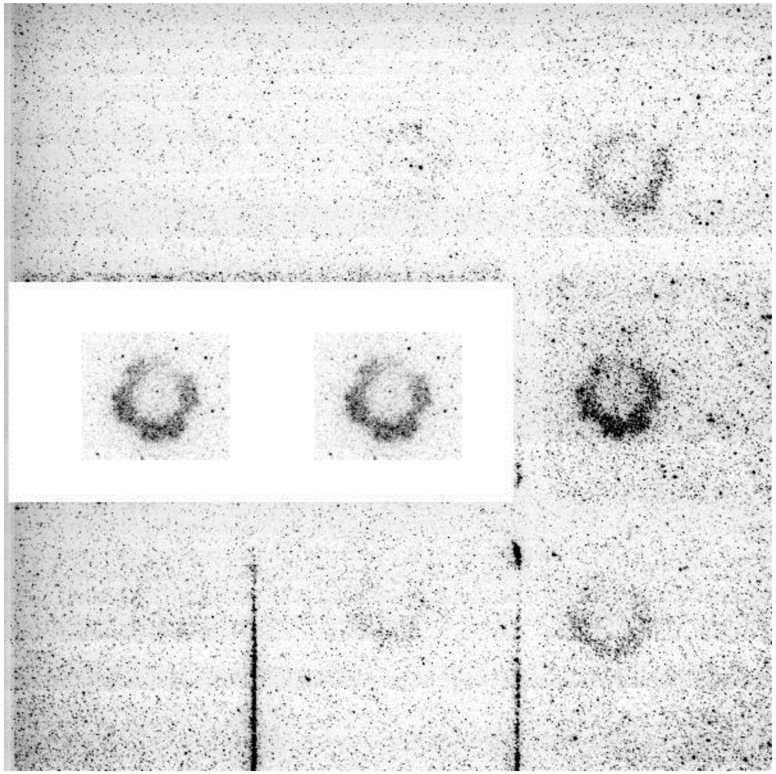
Second shot



15 ns frames

Third Saturn shot – remove central 19 rods

- 18 lines, 32 rods, estimated peak current 1.5 MA, 50 kA/rod
- Some pinching onto tip
- Based on the damage, current division among the rods is approximately equal
- No significant improvement in radiation performance

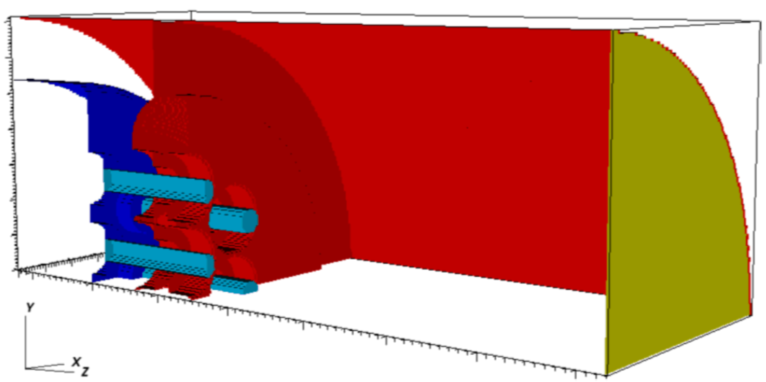


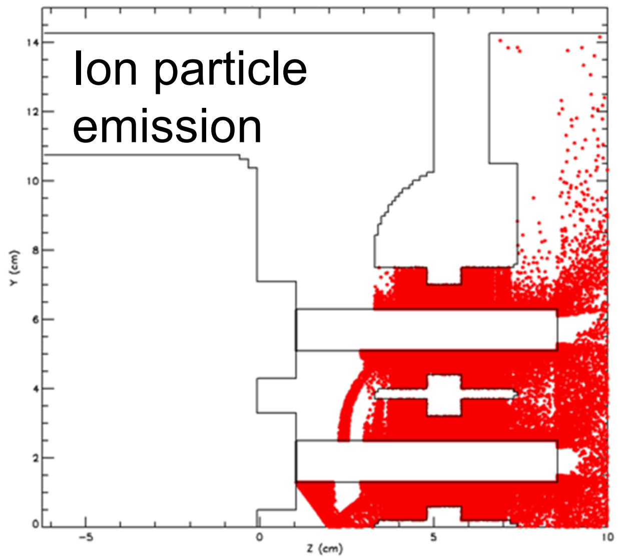
15 ns frames

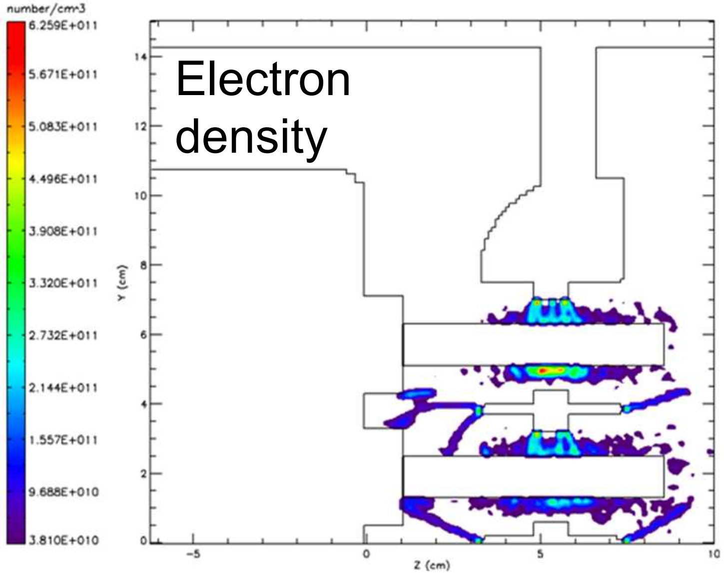
Rod Pinch Simulations

- Large Scale Plasma (LSP) simulations of the Ursa Minor, 10 rod experiment
- Looked at field asymmetries, pinch behavior, rod-to-rod interactions
- Results agreed with experiment, showed relatively uniform distribution of current to the rods

Simulation geometry







Next steps with multi rod pinch array

- Improve pulsed power drive
  - Use “combo rods” to take both outputs of the water triplate transmission lines to the bottom cathode
- Enhance pinching toward tip
  - Longer dwell time – operate Saturn in long pulse mode
  - Rod shaping
  - Increased isolation – deeper wells in cathode?
- First step is detailed simulations of rod pinch array

Investigation of New 3-D Clam Shell MITL for Improved Power Flow

Purpose

Combine the power from Saturn's 36 modules into a single radial disk feed without magnetic-null losses, invert the voltage polarity, and drive large-area ion diode.

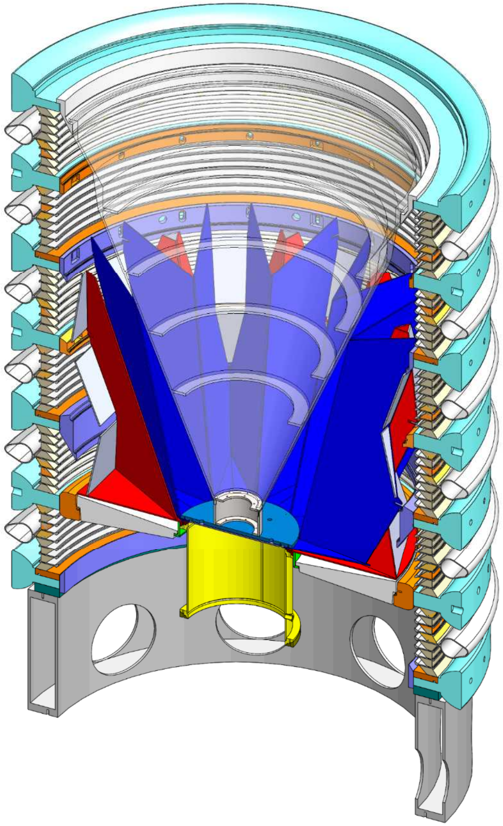
Advantages

The CSMITL combines the power at large radius – low losses compared to standard Saturn MITLs.

Large-area ion diode is new capability for thermo-mechanical shock response testing.

Plan

Fabrication nearly completed. Testing planned on Saturn in March 2017.



Vandevender et. al. "Requirements for self-magnetically insulated transmission lines," Phys. Rev. Accel. Beams, 18, 030401 (2015).
Vandevender et. al. "New self-magnetically insulated connection of multilevel accelerators to a common load," Phys. Rev. Accel. Beams, 18, 030403 (2015).

Future development of warm x-ray sources on Saturn

Sandia National Laboratories

- Saturn is a very flexible large short pulse driver for radiation sources
  - 10 MA
  - 2 MV
  - 40 ns (normal) or 140 ns (long pulse) power pulse
  - 3 cathodes, up to ½ drive power on any one of these cathodes
    - With "combo rods" potentially put full drive power on single cathode
  - Negative (full power) or positive (½ power for short pulse) polarity
- Improved physics understanding of radiation source mechanisms warrants revisiting other potential radiation source mechanisms

Acknowledgements

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Thanks to Andy Biller for providing some nice looking images

Voss Scientific, LLC for Large Scale Plasma (LSP) code simulations