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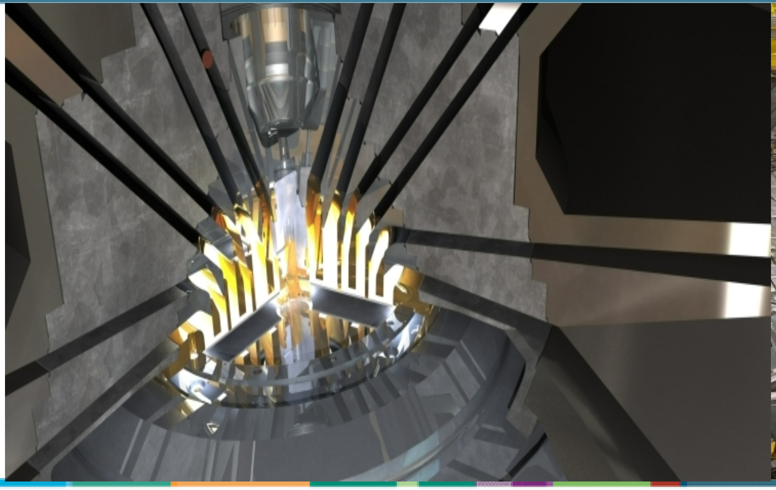
Sandia National Laboratories

The Saturn Accelerator Recapitalization Project



Bryan V. Oliver, P. Christenson, J. Douglass, C. Grabowski, B. Hutsel, M. Mazarakis, T. Pointon, M. Savage, D.Sirajuddin, K. Struve, and B. Ulmen

2021 IEEE International Pulsed Power Conference. Dec. 13, 2021

U.S. DEPARTMENT OF ENERGY NNSA

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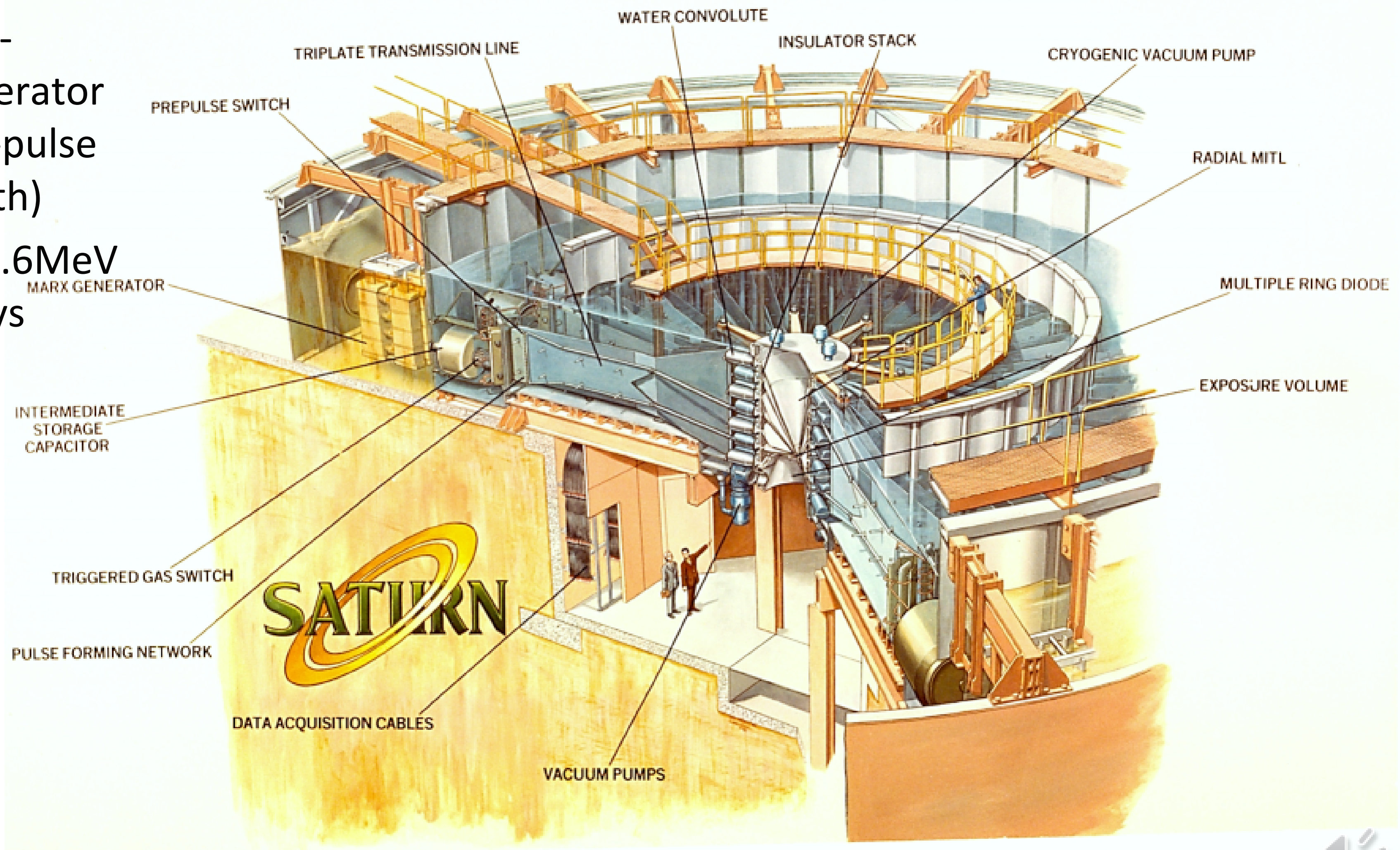
Saturn Pulsed Power Overview: A High Current Accelerator for X-ray Radiation Effects Science and Testing[1]

- Predecessor to ‘Z’
- Modular, high-power, variable-spectrum, pulsed-power accelerator (10 MA, 1.6 MeV,40 ns power-pulse and ~25ns radiation pulse width)
- High dose-rate generator for 1.6MeV endpoint bremsstrahlung x-rays



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

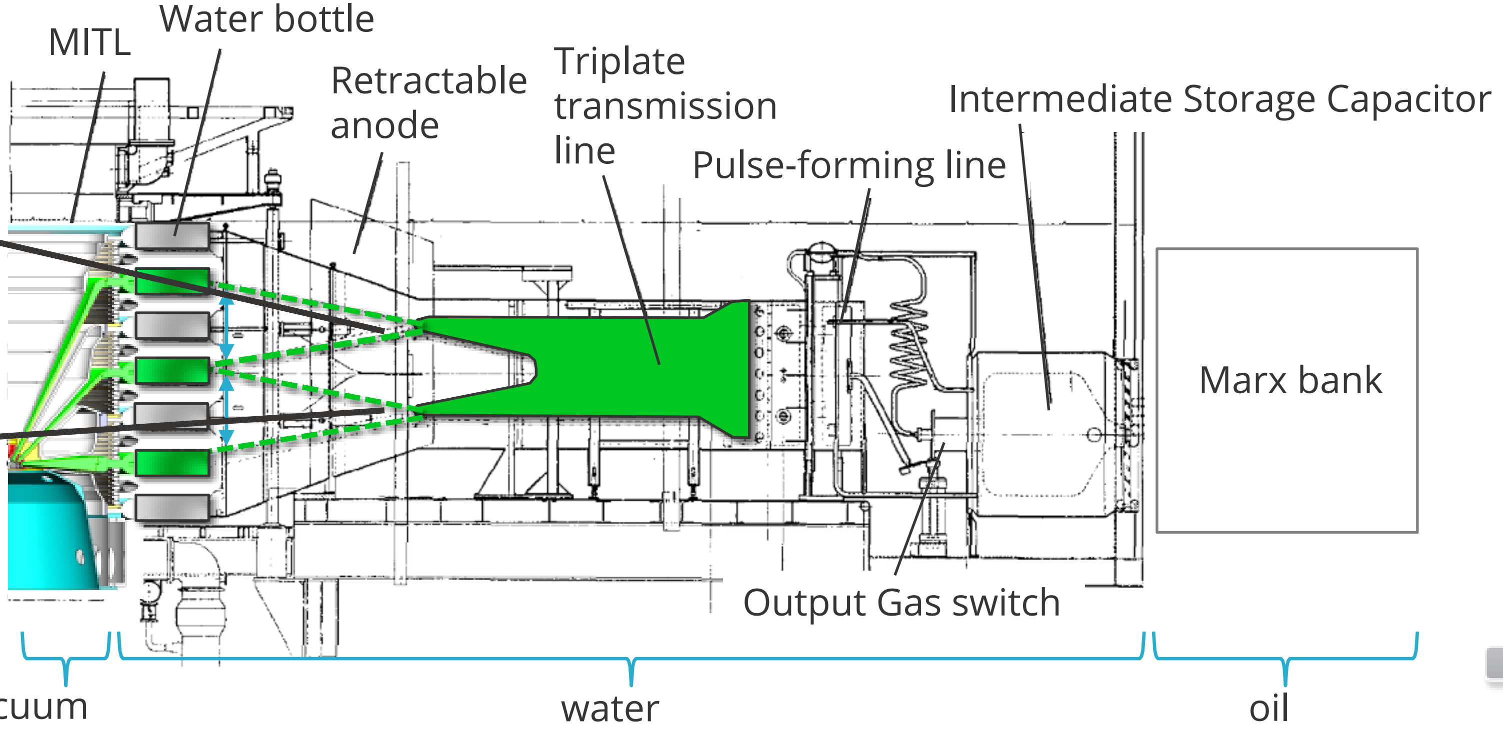
The Saturn Architecture

- 36-module, cylindrical geometry
  - ~40 kJ, 1 TW per module
  - ~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

Module

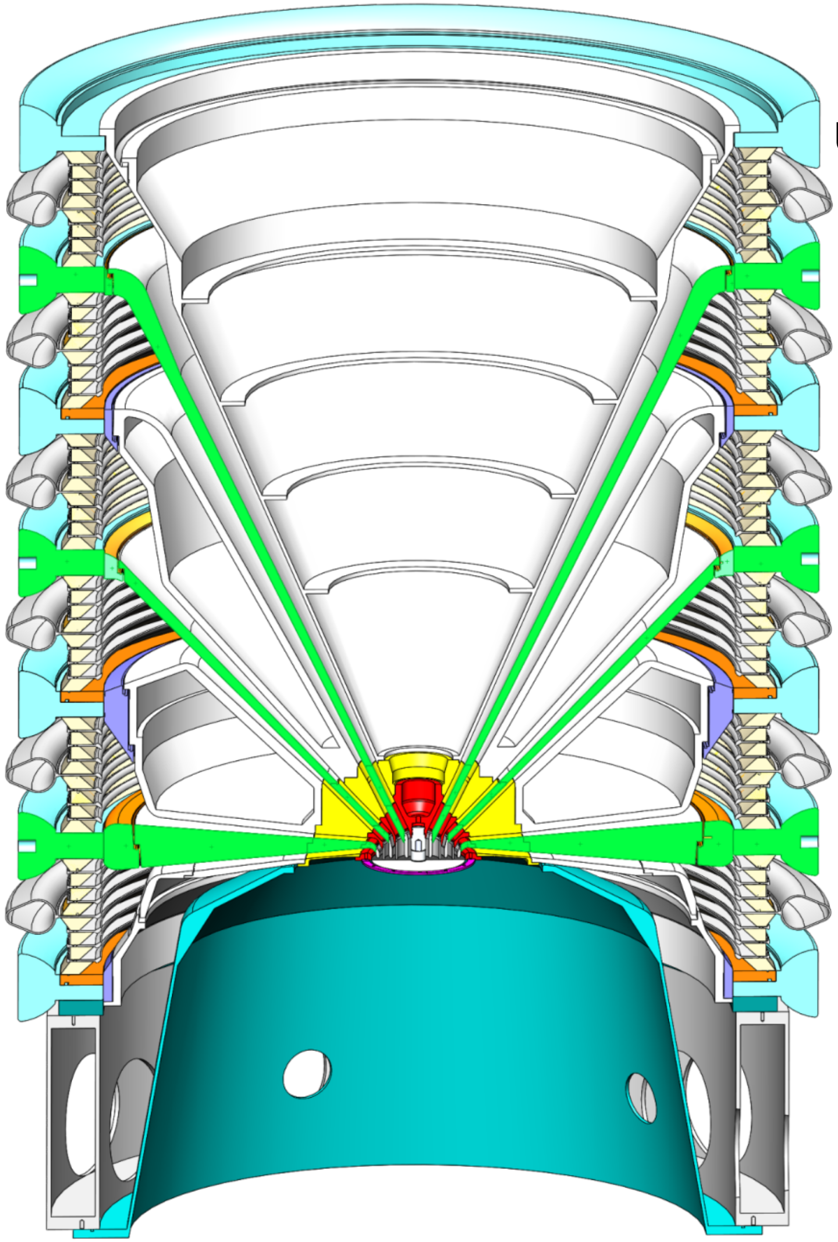
Upper rod connects to upper or middle cathode disk feed

Lower rod connects to lower or middle cathode disk feed



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

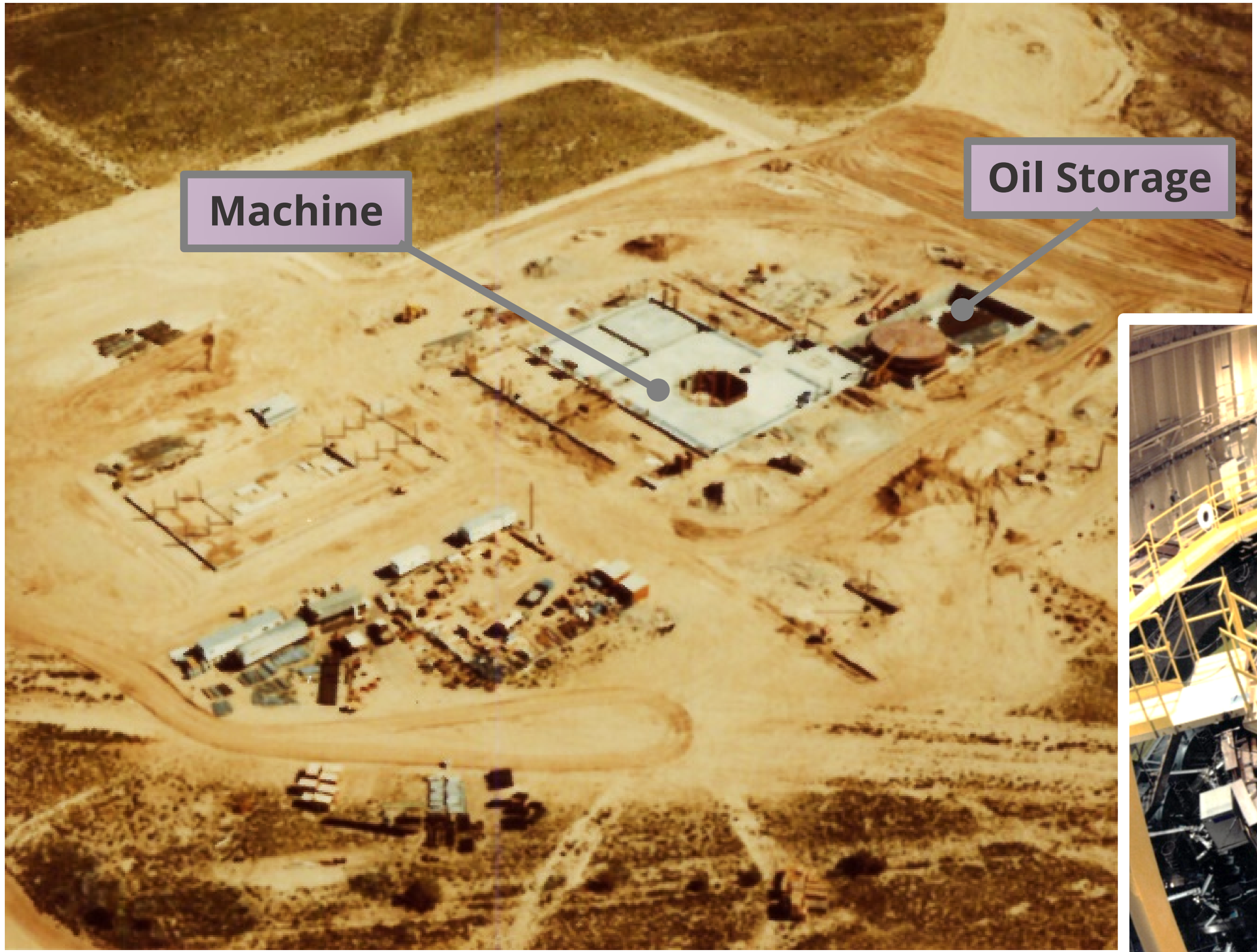
The Vacuum Stack, MITL and load region of the baseline configuration



- 3 nested conical triaxial lines, each making an anode-cathode-anode pair
- Bottom 2 lines are 2 Ω driven by 36 rods in azimuth
- Middle two lines are 3 Ω driven by 24 rods in azimuth
- Top two lines are 6 Ω driven by 12 rods in azimuth
- Each conical electrode is made in three sections
- Replacing relatively small hardware close to the axis allows a variety of loads to be fielded

Original Infrastructure is nearly 45 year old

The Particle Beam Fusion Accelerator (PBFA-1) was the predecessor for Saturn



↖1977

Ariel View of PBFA I Building & Infrastructure Under Construction

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PBFA-1 was converted to Saturn in 1987

↗1987

Team Photo Following PBFA I Conversion to Saturn

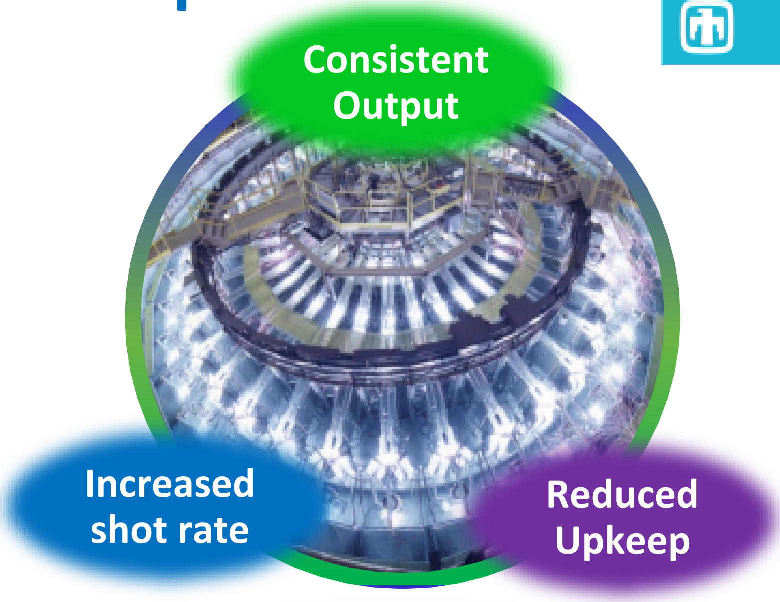
Bottom line…

- Issues
  - The facility is aged and operating in a run-to-failure mode with significant deferred maintenance
  - Present research and development in radiation sciences are stressing the capability
    - Insufficient shot frequency to cover requests
    - No time to address deferred maintenance
    - Shot to shot irreproducibility
  - Development of new platforms and future R&D cannot be realized

- **Maintenance and Refurbishment Assessment**
  - **~ 160 risk-prone scenarios are currently identified related to operations & infrastructure.**
  - **~ 40 are potential single point failures that would impact operations for more than a month.**

- Sandia (DOE/NNSA) is implementing an ~$49M investment to refurbish the facility. Activity will occur over 4-5 years.
- **Phase 1 activity (~ $30M investment) has begun and will continue to 2024, with 9 month downtime from Q3 2023 – Q2 2024.**

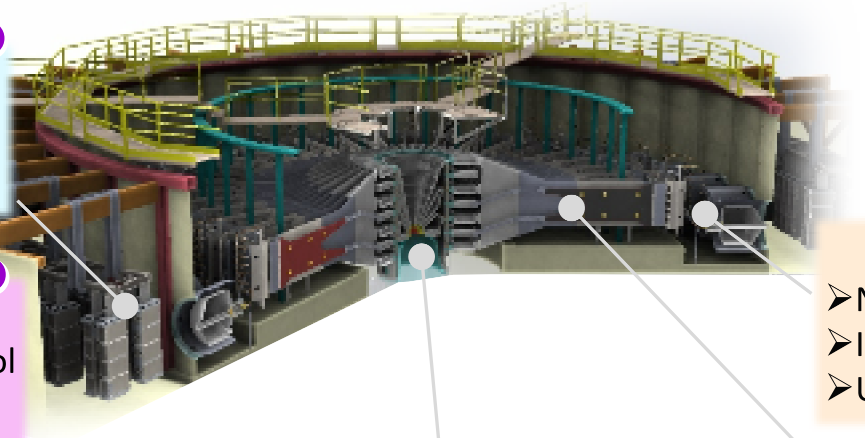
Saturn Recapitalization Project: Primary Objectives & Scope



❶ Provide Consistent Radiation Output
  Radiation output to ~ 10% shot-to-shot variation

❷ Increase Facility Shot Rate
  Enable consistent execution of one shot per 10-hour workday.

❸ Reduce Time Needed for Facility Upkeep
  Enable routine evaluation of machine performance.



Energy Storage Section: ❶❸
- Upgrade MTGs
- Laser Trigger MTGs
- Z-Based Operational & Safety Features

Technical Utility Systems: ❷❸
- Improve Water/Oil Fill & Drain Control
- Stainless Steel DI Water Piping
- SF6-Based Components Gas Isolation
- 24 VDC Water/Oil Actuators, Controls

Facility: ❷❸
- 8-Ton Crane
- MITL Fixtures Improvements
- Dry Compressed Air
- Paint High Bay
- Access Control System Enhancements

Stack/Vacuum Power Flow Section: ❶❷❸
- Improve MITL Alignment & Concentricity
- Design Hard-Set Diode
- Reduce Inductance
- Incorporate Stack Debubbling System
- Stainless Steel MITLs
- Stack & MITL Current/Voltage Monitors

Pulse Forming Section: ❶❷❸
- New Triggered Gas Switch
- Improve Gas Switch Trigger System
- Update Diagnostic Monitors

Transmission Section: ❶❷❸
- Addition of Water Diverters
- Stainless Steel Components
- Improve Connecting Rod Design

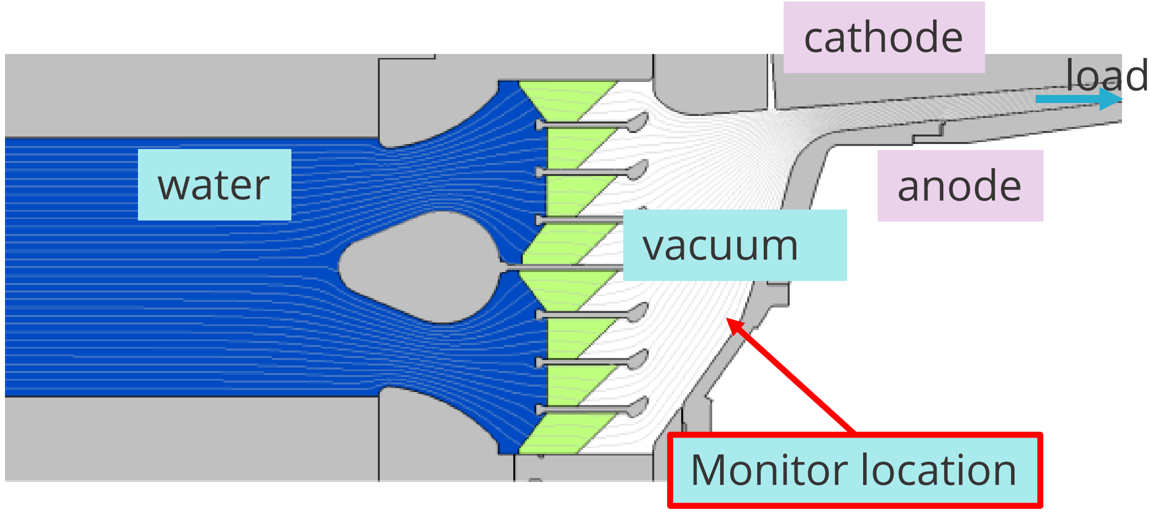
Data Acquisition System: ❶❸
- Repair/Upgrade Data Ports in Floor
- Fiber Optics Communications Capability
- Stack & MITL Monitors Infrastructure

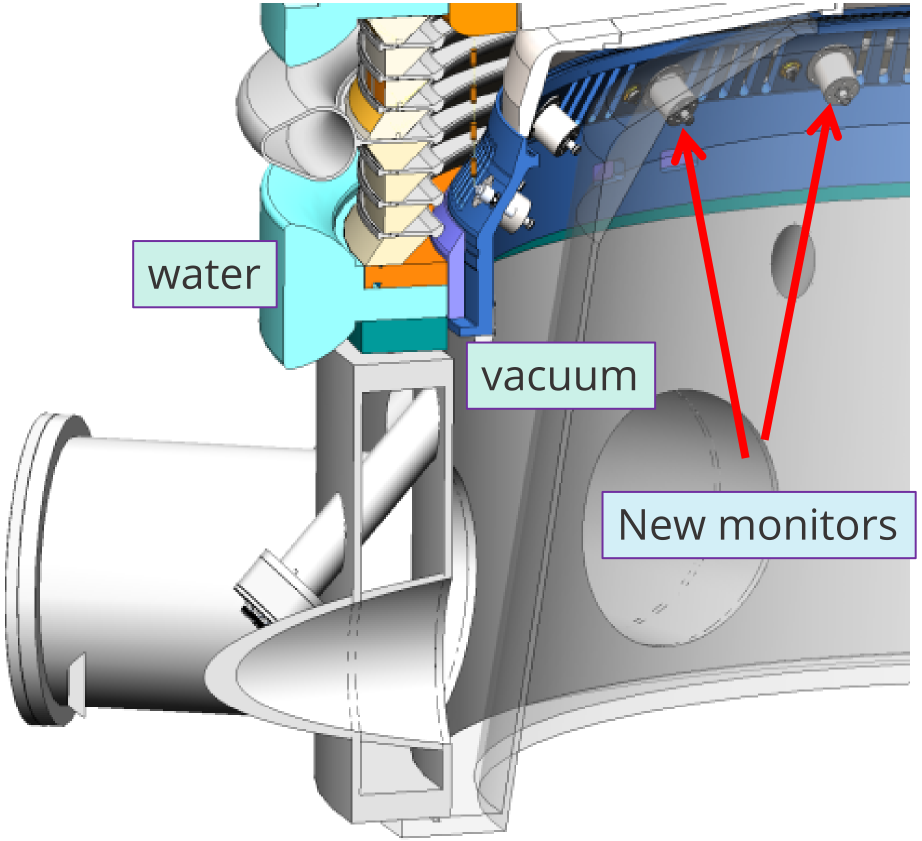
Dr. Mark Savage is the technical lead for the project

M. Savage et. al. "Technical goals of the Saturn recapitalization project", Oral 1O-D

Some Technical Activity Highlights

Developed and implemented I,V diagnostics to obtain accurate vacuum insulator voltage and forward wave





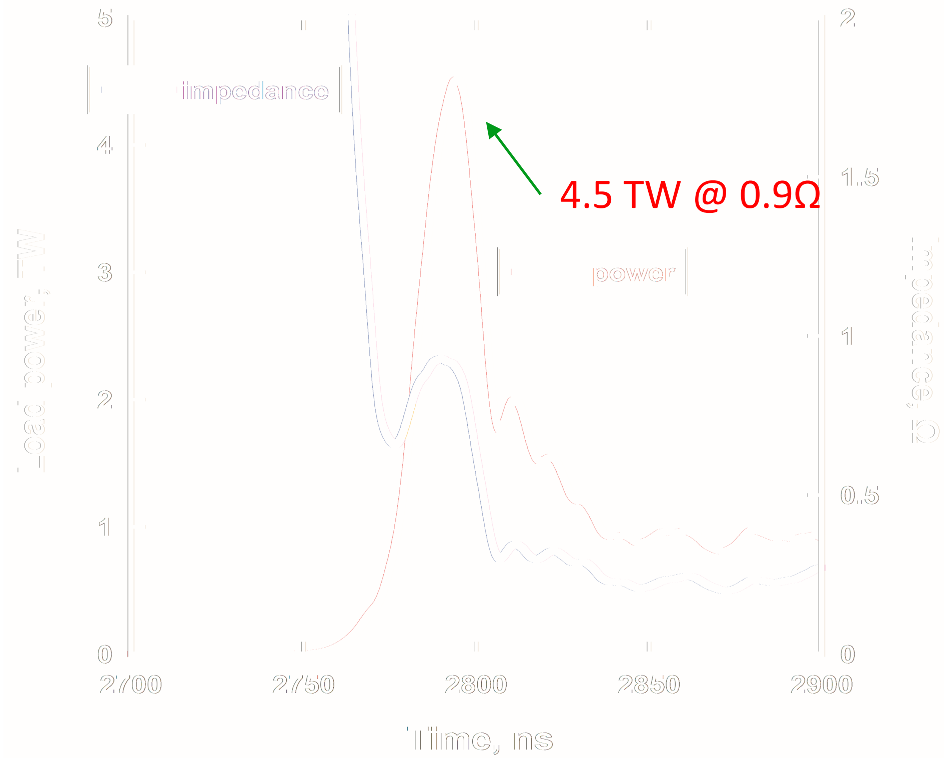
Vacuum MITL flare and monitor locations on lower level anode

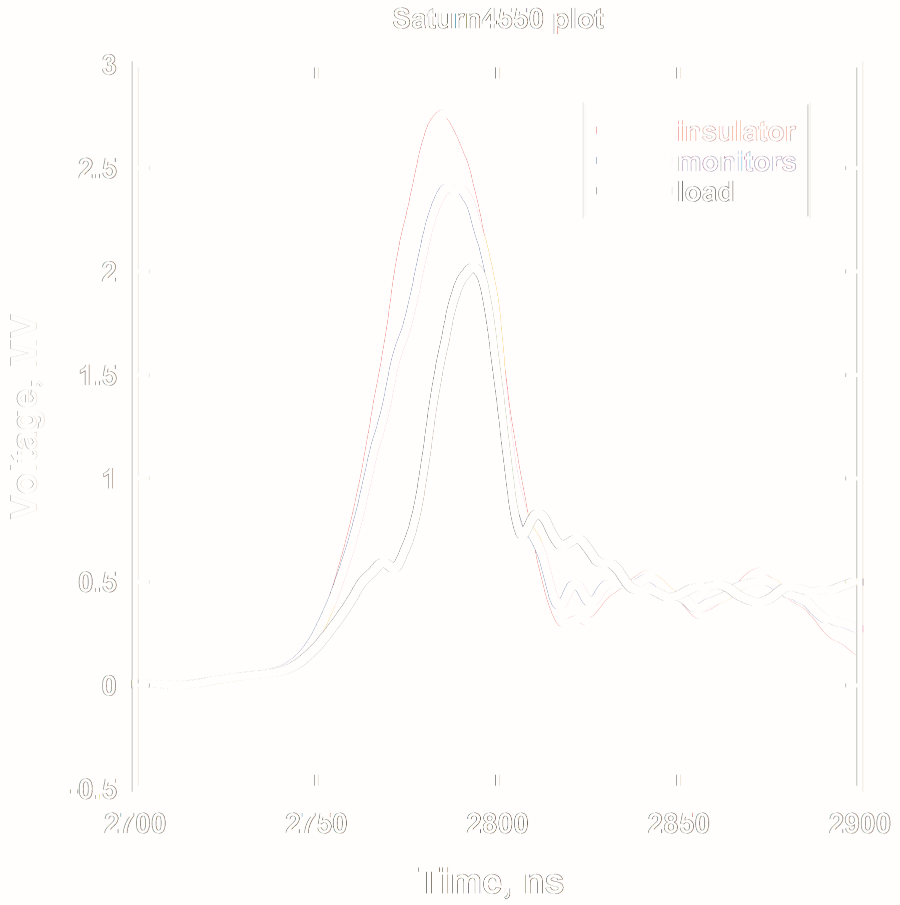
- **No stable location for monitors exists in the water just outside the insulator**
- **Voltage and current measurement at the same location**
- **Modified the lower level MITL flare to accommodate 18 voltage, current monitors in the highest power level of Saturn**
  - Current measurement in vacuum is relatively routine
  - Voltage measurement in vacuum requires attention to electron and plasma effects

M. Savage et. al. “Technical goals of the Saturn recapitalization project”, Oral 1O-D

I,V measurements inform stack and load characteristics

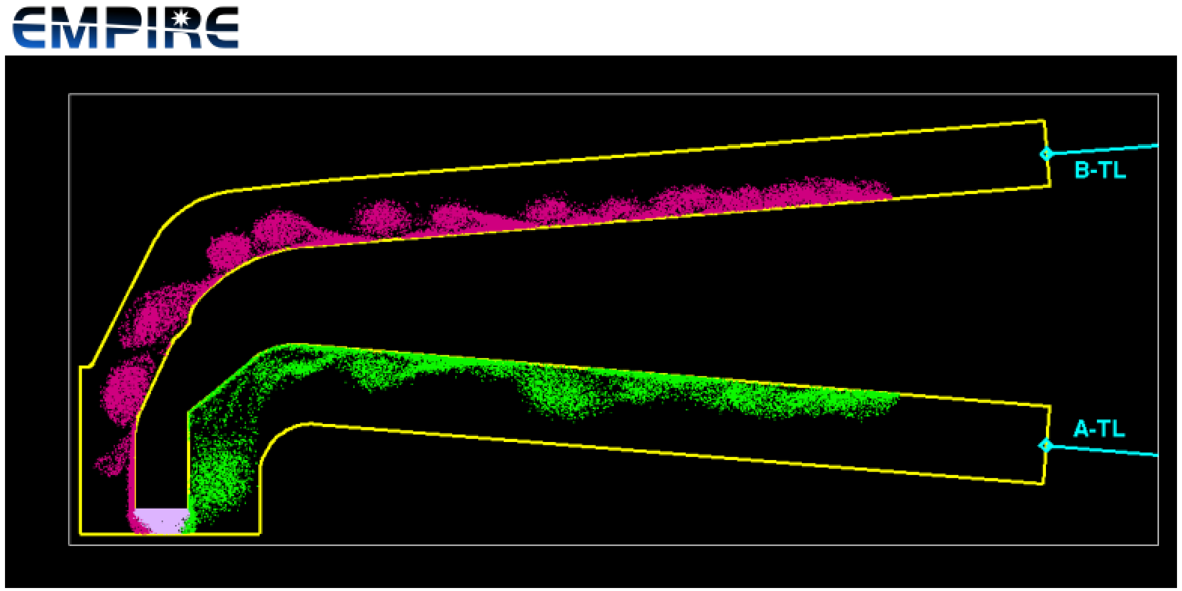
- Measurement corrected and translated to the insulator stack and load via TEM model
- Insulator stack peak voltage ~2.7 MV
- Power on the lower level ~ 4.5 TW and 0.9 Ohm.
  Translates to outer ring (lower two levels) diode power, impedance ~ 9 TW, 0.45 Ohm
- Observe impedance increase during power pulse rise.
  Expect increased diode inductance during beam pinch





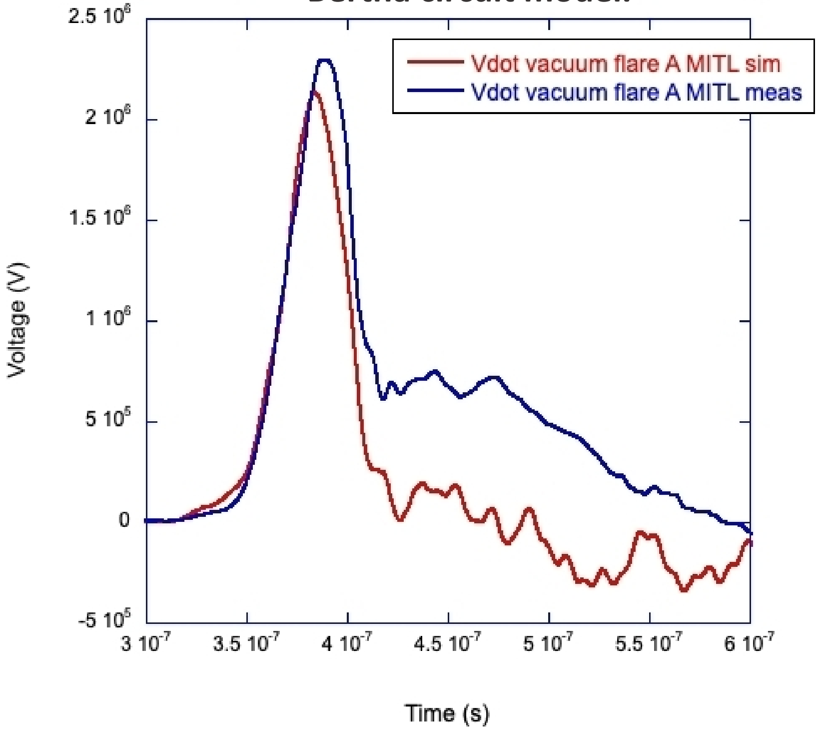
Circuit models and power-flow simulations are aiding MITL and diode design

- 3D circuit model uses a separate drive for each of the 36 lines that can be varied in time to investigate timing jitter effects. There is a separate model for each of the 3 cathode levels.
- 2D and 3D EM-PIC models using the EMPIRE code are being used to investigate Insulator stack stresses and MITL power-flow.



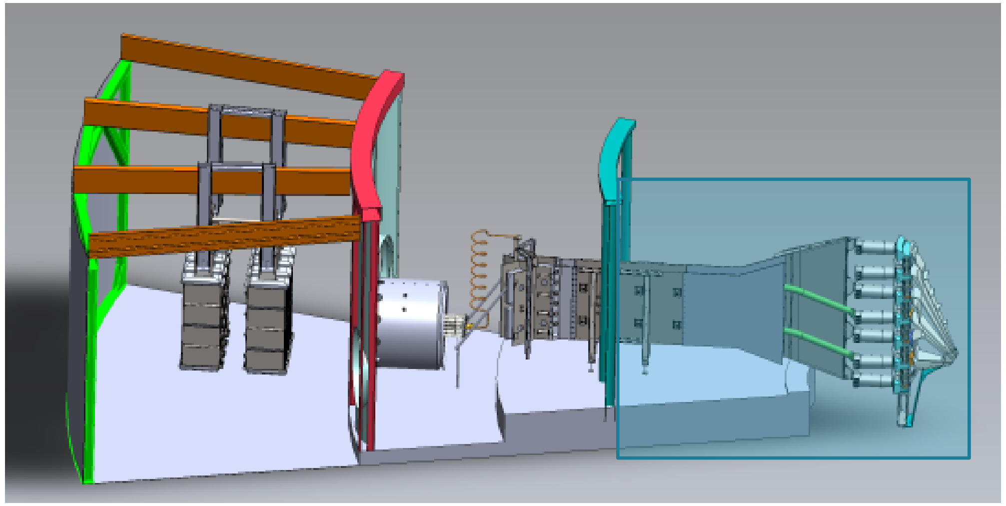
EMPIRE power-flow simulations of lower cathode (A,B levels) and diode.

Bertha circuit model.

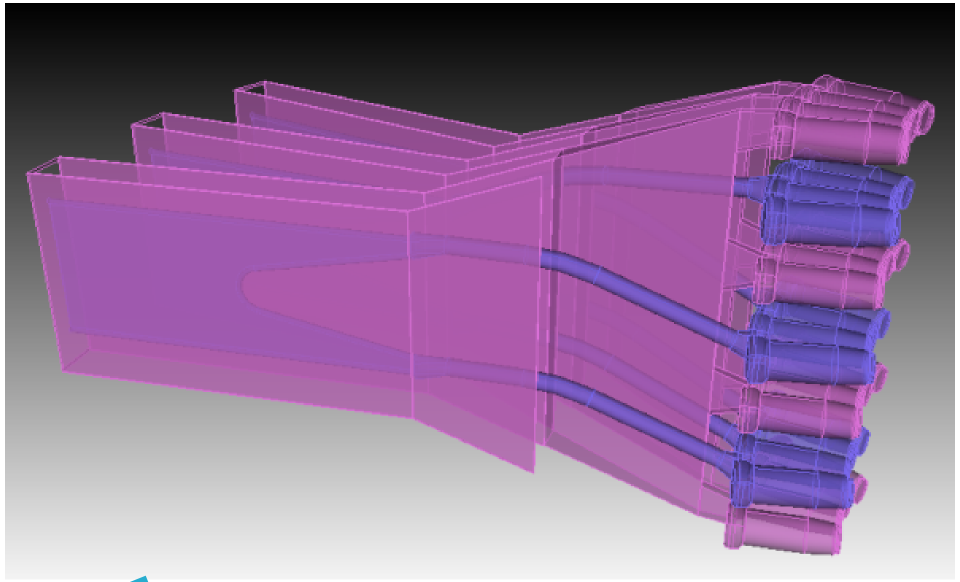


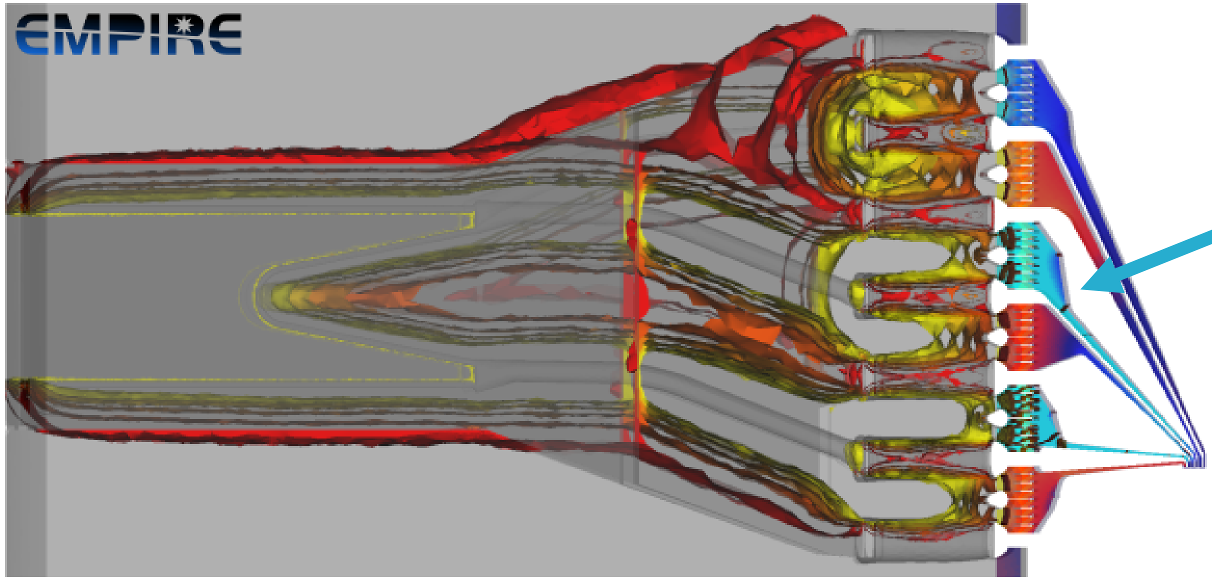
D. Surajuddin et al. "Power flow simulations of the Saturn accelerator using 1D multi-mode transmission line models", poster 1P
T. Pointon et. al. "Particle-in-cell simulations of the Saturn central vacuum section", poster 4P

3D EM model capture effects of drive and geometric asymmetries



CAD models truncated at tri-plate transmission line





Electric field contours

EM EMPIRE Simulations driven with symmetric, simultaneous waveforms at start of tri-plates show asynchronous drive of vacuum MITLs at different levels.

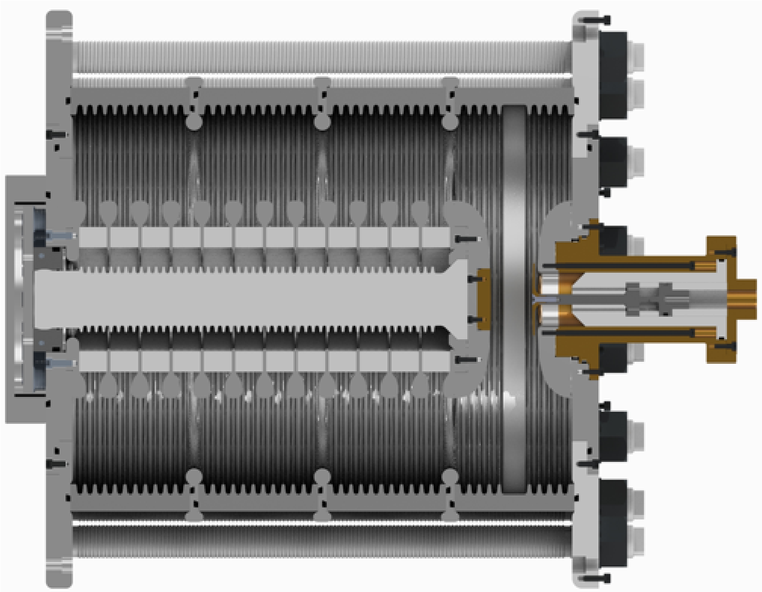
P. Christenson et. al. "3D electromagnetic simulations of the Saturn waterline through to the vacuum region", Poster 4D

A New output Gas Switch (D1) is designed and tested

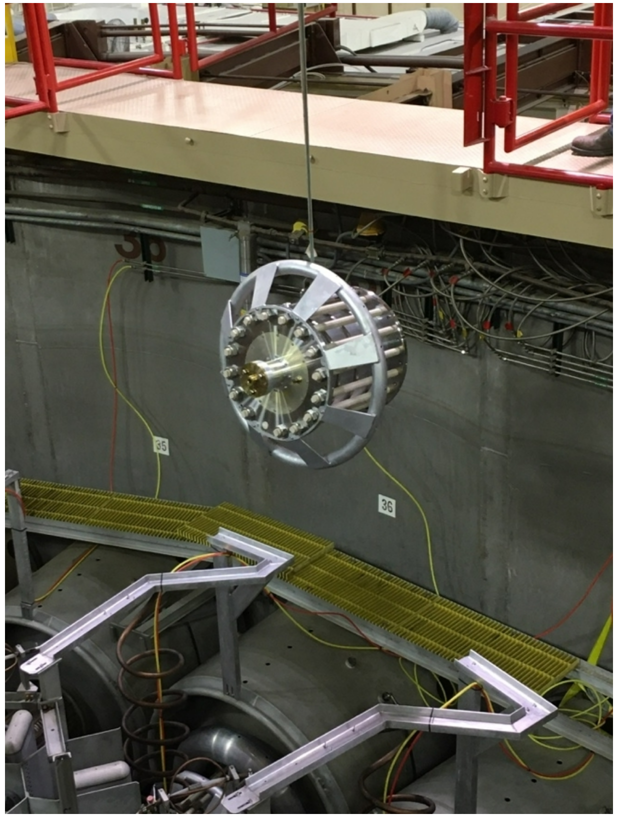
36 Saturn output gas switches

- immersed in the Saturn deionized water section
- pressurized with SF_6
- Tolerate >2.6 MV before closure
- Electrically triggered with a ~80 kV forward wave in high voltage cable

Saturn D1 Switch



New optical diagnostic
for timing fiducial



Requirements

- Improve jitter to ~ 4ns, 1s
- Reduce pre-fire rate
- Maintenance lifetime of ~200 shots
- Retain electrical triggering for simplicity, with option to laser-trigger if needed

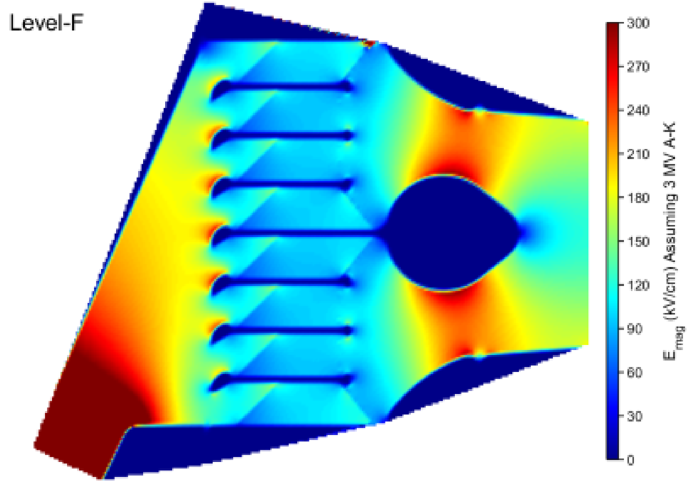
C. Grabowski et. al. “Characterization of a New 3-MV Gas Switch for Saturn”, Poster 3P
B. Ulmen et. al. “Optical measurement of the new Saturn gas switch as a timing fiducial”, Poster 3P

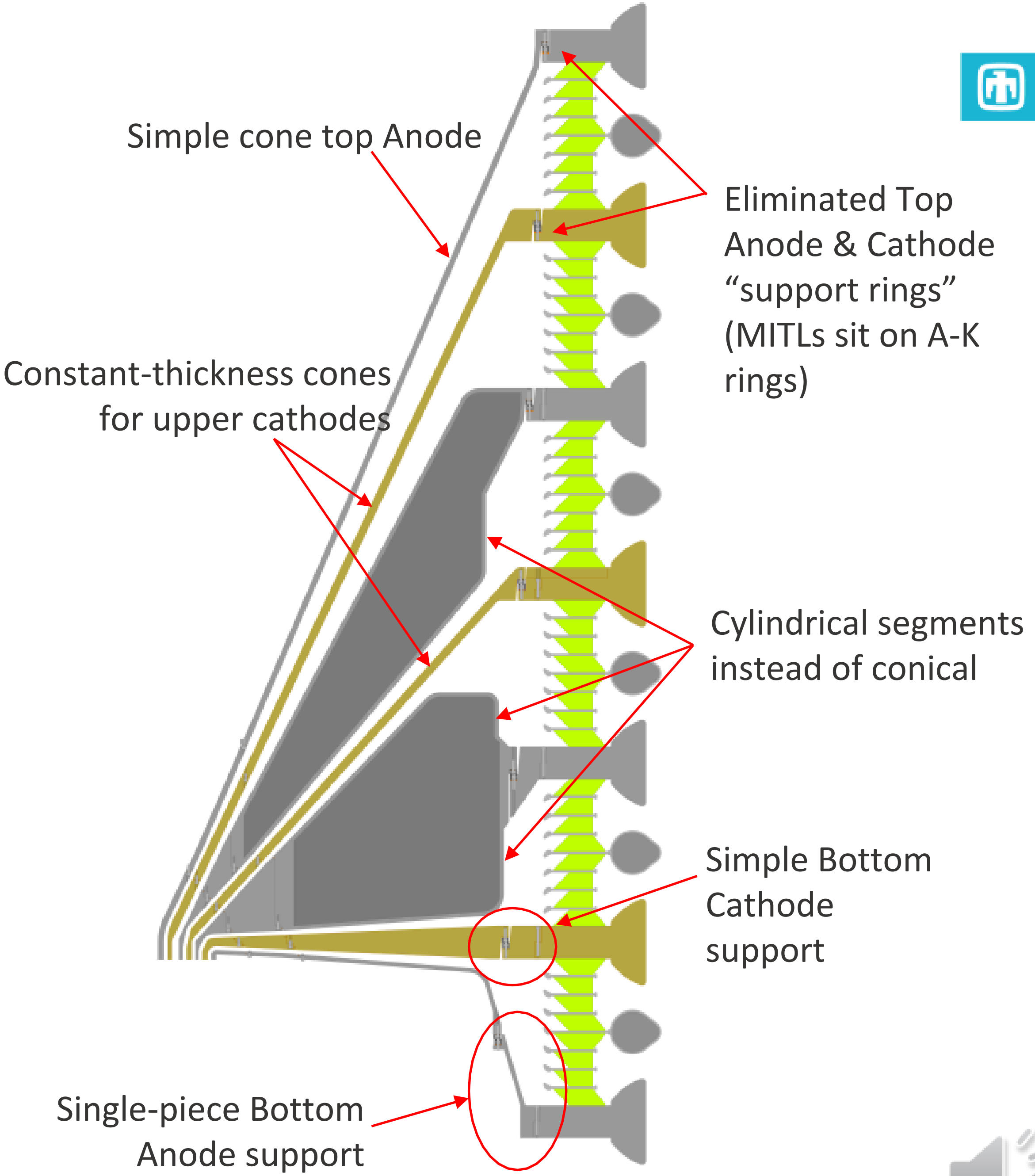
MITL and Insulator Stack upgrades

Design simplifications

- **All electrodes made of Stainless Steel (presently mix of SS and Al)**
- **Eliminated Cathode and Anode variable position support rings to better fix positions with flanged interfaces**
- **New-simplified electrode shapes, balancing inductance**
- **Peak E-field on insulator not to exceed 300 kV/cm**

Upper level E-field strength

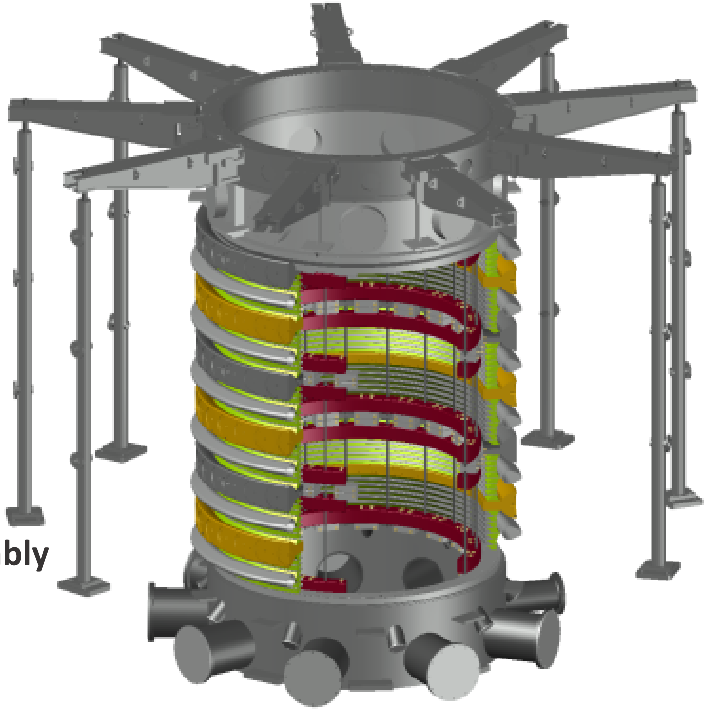




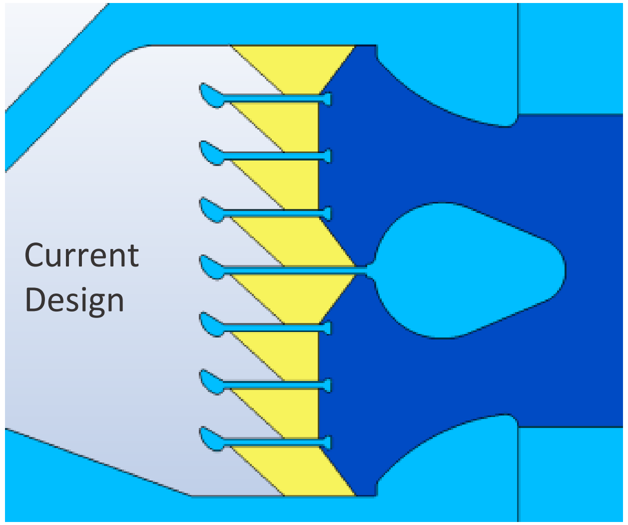
J. Douglass et. al. "Saturn MITL Design Update ", Oral 3O-A

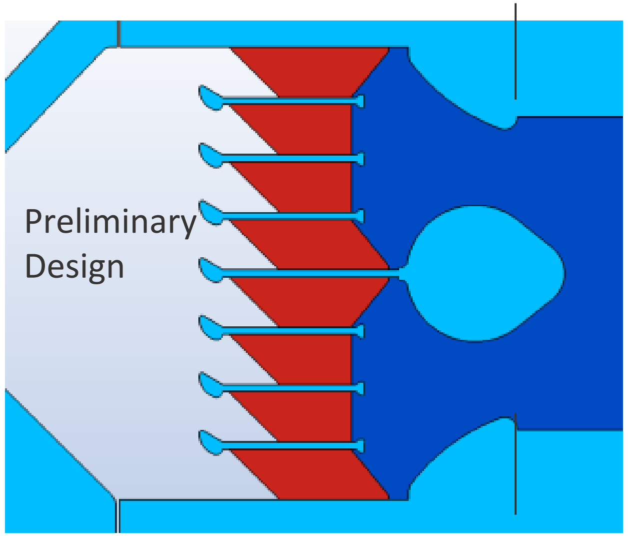
Insulator Stack geometry changes to support diagnostics and improve mechanical stability

- Increase the width of the insulator rings to provide mechanical stability and room for new voltage and current diagnostics.
- Minimize/eliminate any changes to the water section.
- Propose holding the OD of the AK rings constant, by shrinking the width of the water flare.



Insulator stack assembly

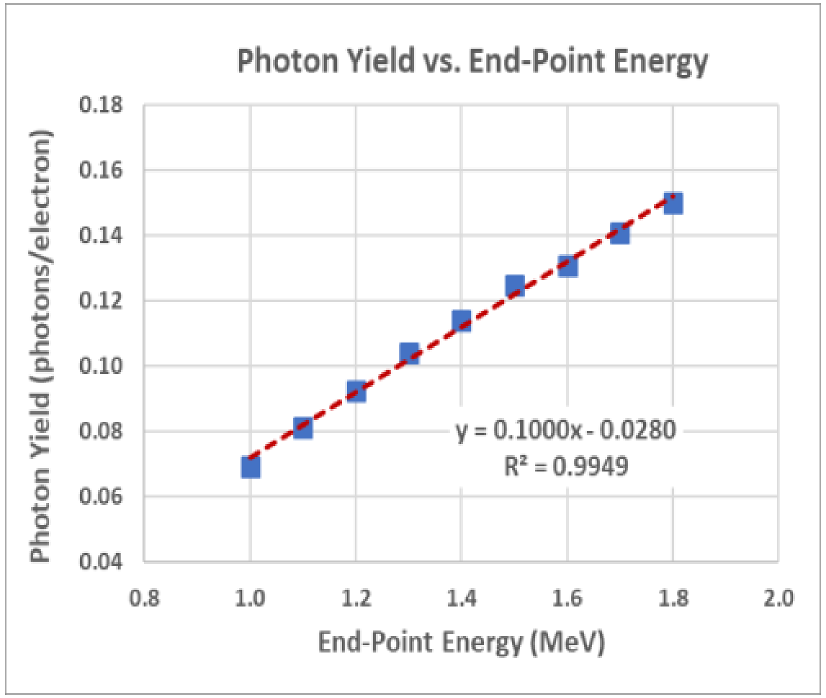


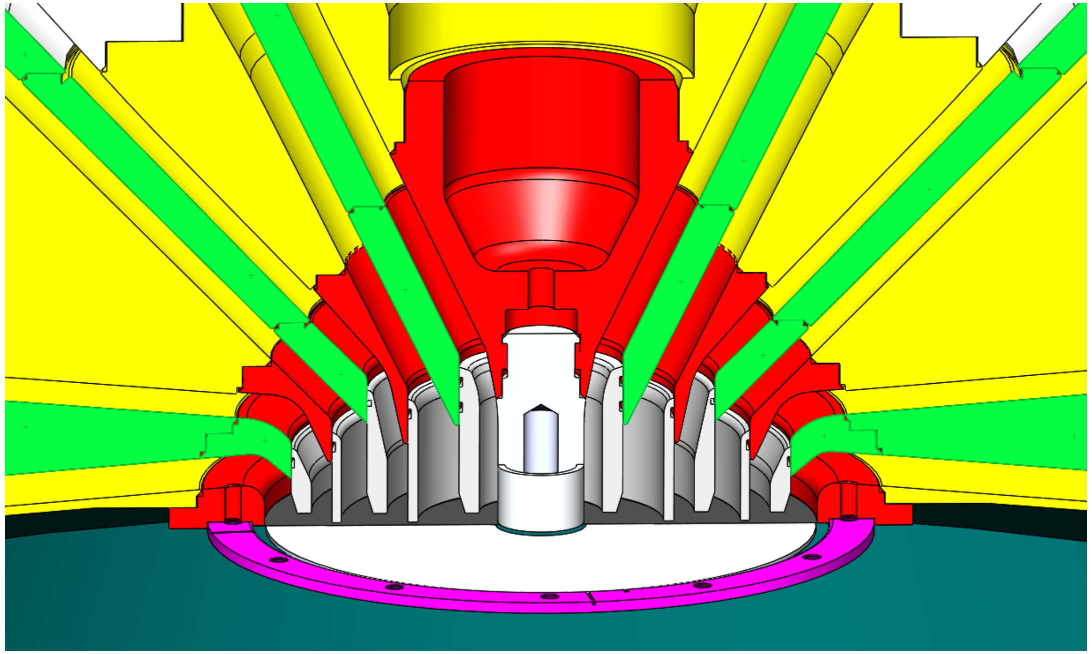


B. Hutsel et. al. “Saturn recapitalization project insulator stack design updates”, Oral 1O-D

Standard 3 ring diode – three nested annular diodes for low inductance, low impedance

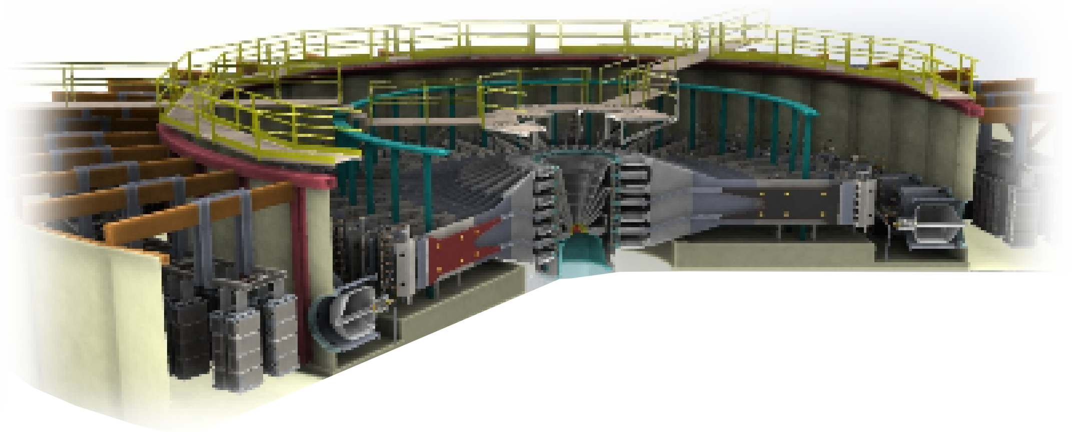
- Goal to limit shot-to-shot radiation output variation
- Dose varies ~ linearly with energy, dose-rate ~ linearly with power
- Diode is comprised of three nested annular triaxial diodes
- Want to operate near optimal impedance for each diode
- Ratio of radii ~ 3:2:1 to establish nearly equal current density per ring.
- At the diode, typically 10 MA, 1.6 MV (power weighted mean voltage), 22 ns fwhm radiation pulse





Summary:

- **Sandia is executing a multi year effort to refurbish and recapitalize major components of the Saturn Accelerator**
  - **Provide Consistent Radiation Output**
  - **Increase Facility Shot Rate**
  - **Reduce Time Needed for Facility Upkeep**
- **Phase 1 is concentrating on the vacuum section (diode, MITL, stack), high voltage output Gas Switch, as well as additional infrastructure (data acquisition, crane, oil/water)**
- **Phase 2 will concentrate on the energy storage system (Marx, Transmission, I-store)**



The Saturn Recap Project Team:

K. Austin, E. Breden, J. Cassidy, P. Christenson, J. Douglass, K. Dussart, B. Elbrecht, C. Grabowski, B. Hutsel, L. Jones, D. Kirschner, J. Lott, D. Lucero, M. Mazarakis, R. McKee, M. McLane, B. Oliver, A. Owen, T. Pointon, T. Renk, M. Savage, D. Sirajuddin, T. Smith, K. Struve, D. Tabor, J. Tunell, K. Vigil, B. Ulmen