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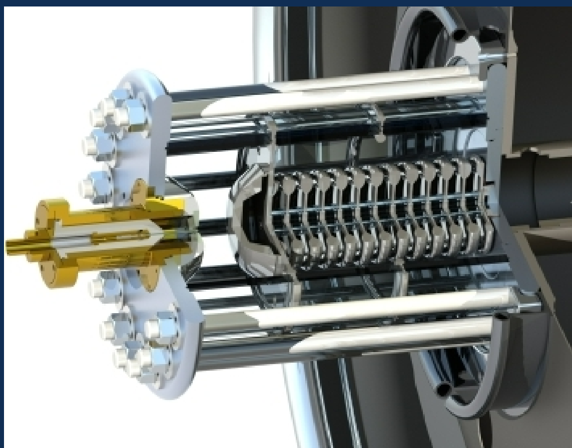

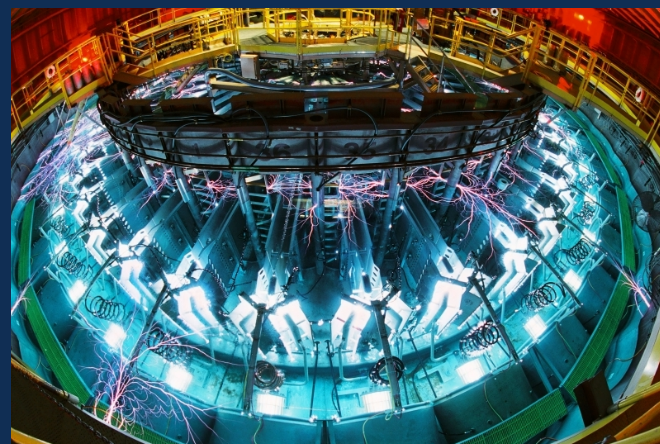

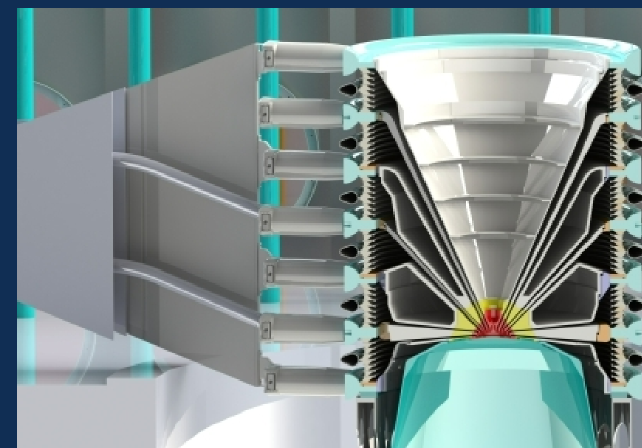

Saturn Pulsed-Power Considerations

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17 December 2018

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Bottom line: we have identified areas for improvement

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- **Pulsed power success will be gauged by Saturn *demonstrably* delivering 10 MA at 1.6 MV to a standard bremsstrahlung load *reliably and with margin***
- **Load performance success will be gauged by setting the load gap to within <10% of nominal under vacuum, and achieving consistent radiation output**
- **Operational success will be gauged by reduced setup and maintenance time**

Saturn was converted from PBFA-I in 1987

- **PBFA-I was an ion beam driver for ICF research, delivering ~36 TW forward-going power and ~14 MA total to a proton beam diode**
- **With Saturn, the 36 separate vacuum insulators and magnetically insulated transmission lines were replaced by a single axially-symmetric assembly**

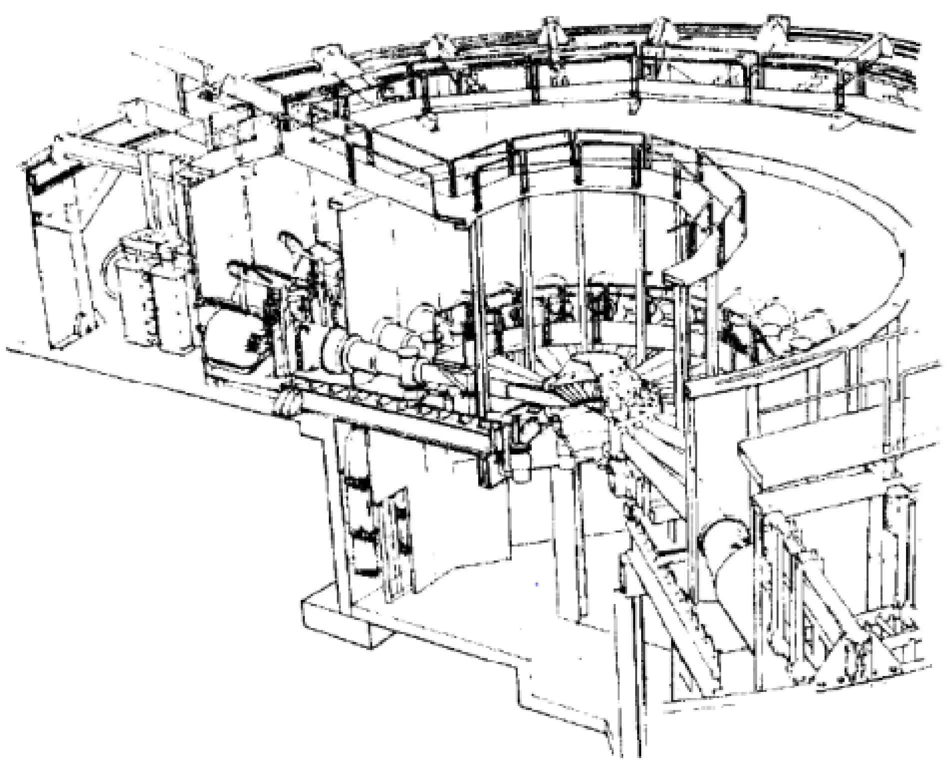
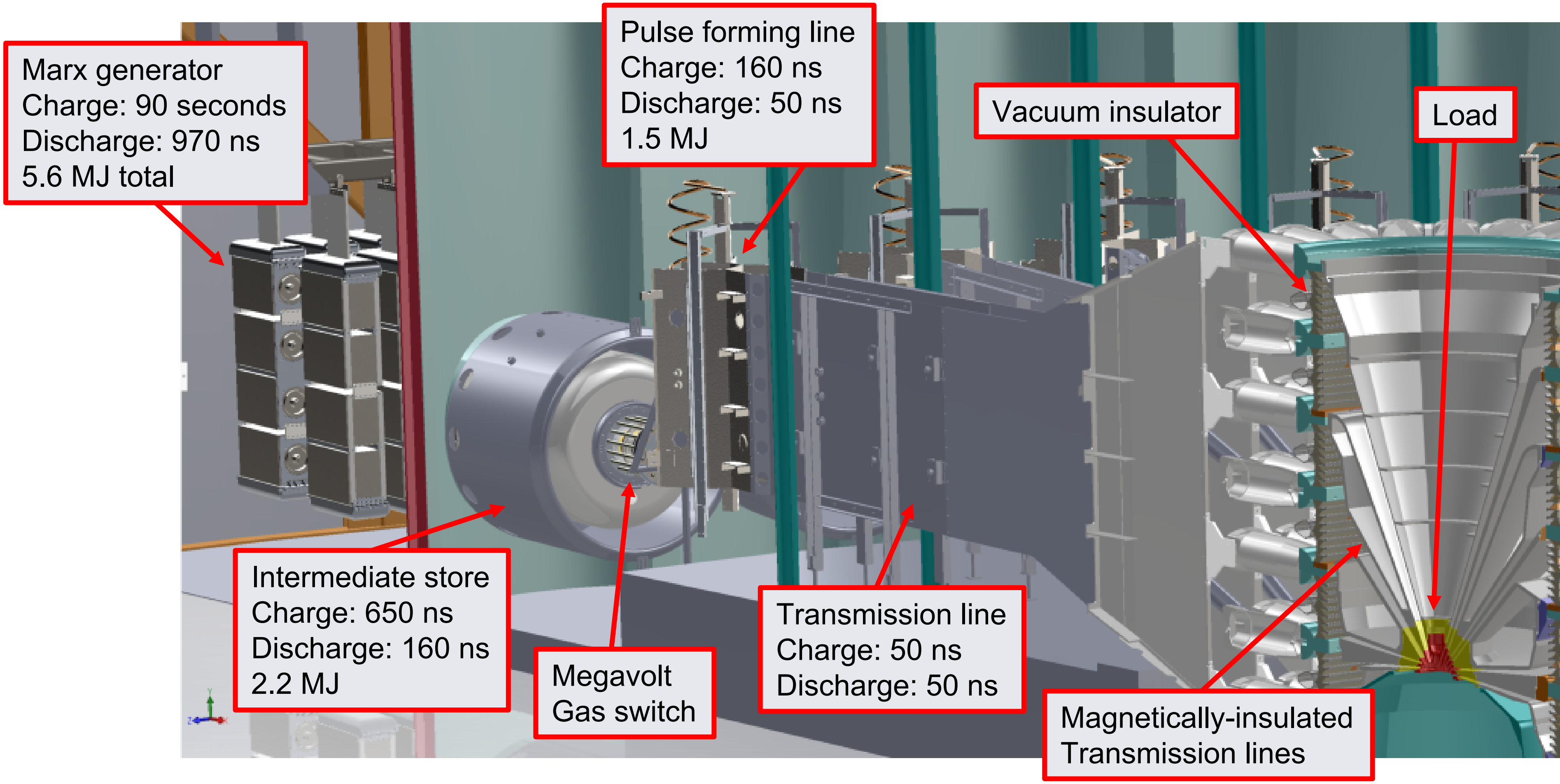


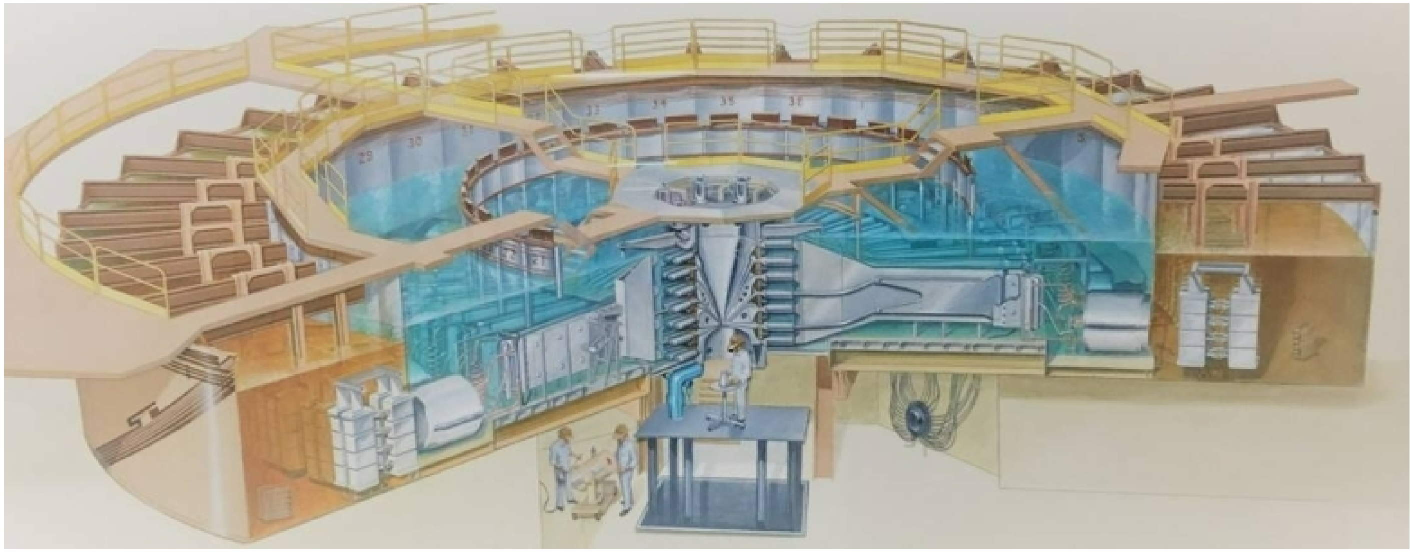
Figure 1. PBFA-I.

Saturn Pulsed Power: 1987-today



Saturn has all the basics:

- **Adequate Marx energy**
- **Adequate space in the oil and water sections**
- **Infrastructure for a large facility**



We can judiciously apply advances in pulsed power and other fields since Saturn was designed

High-level goals for Saturn work

- ***Improve reproducibility and reliability***
  - **Improve components (e.g., gas switch) to better utilize energy and reduce pulse variations**
  - **Improve load region power flow (control power flow gaps in vacuum)**
  - **Improve current contacts and alignment accuracy**
- ***Increase shot rate***
  - **Reduce overall electrical stress and damage**
- ***Improve operational efficiency***
  - **Employ known operational advances from Z and elsewhere (e.g., Marx troubleshooting)**
  - **Improve data quality to aid troubleshooting and predict failures**
- ***Improve source uniformity and increase area***
  - **MITL changes not to preclude larger area, more uniform source**
- ***Lower radiation endpoint***
  - **Not to preclude load region changes (alternate diode technology)**

The rules

- **Maintain Saturn's ability to deliver 10 MA at 1.6 MV and 20 ns radiation FWHM, with margin**
- **Minimize sources of variability (dominated by the load, but present throughout)**
- **Improve pulsed power precision and temporal accuracy**
- **Effectively use available energy (minimize stored energy)**
- ***No pulsed power testbed apart from Saturn itself***
- **Simplified operations and minimized maintenance**
- **Add power flow diagnostics and improve data quality**

Saturn pulsed power

- Energy storage section
  - Trigger system
  - Marxes
- Pulse forming system
  - Intermediate store capacitors
  - Electrically-triggered megavolt gas switches
  - Pulse-forming lines
  - Water switches
  - Transmission line
- Vacuum insulator and magnetically insulated transmission lines
- Load

The Saturn Marxes use reliable components

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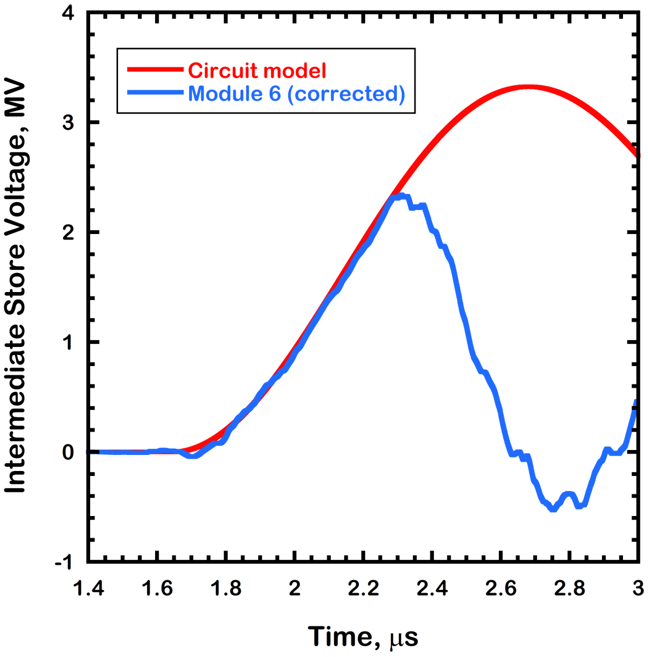
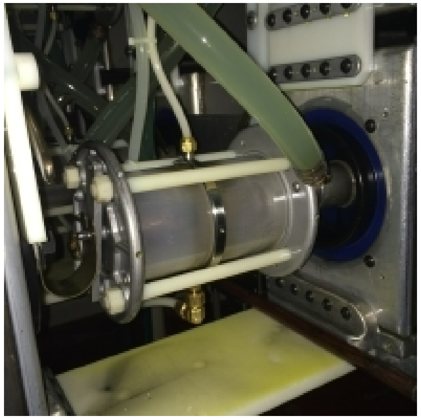
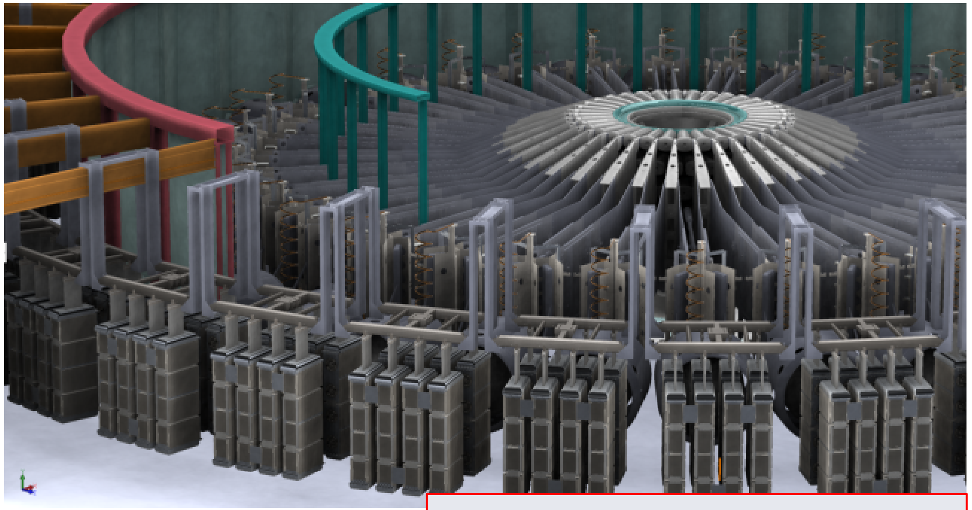
- **150 kJ each, 2.7 MV open-circuit**
  - **~6 µH, 42 nF**
- **32 each 1.35 µF paper/foil capacitors (1152 total) ca. 1986 Solid charge resistors**
- **T508-AX switches (used in Z and several other large machines)**





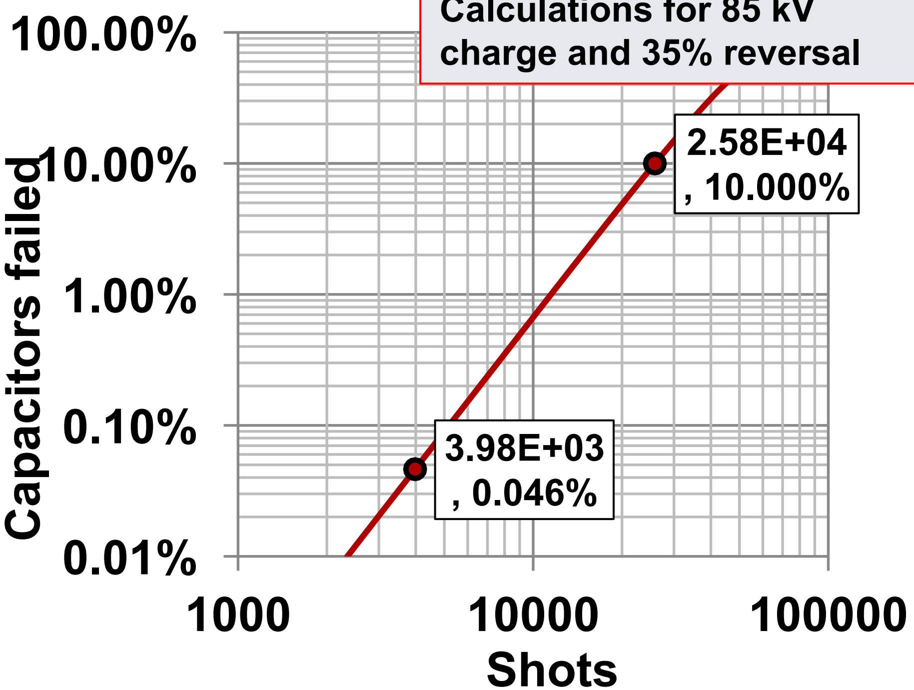
Replacing the Saturn Marx capacitors ($10M) appears unnecessary



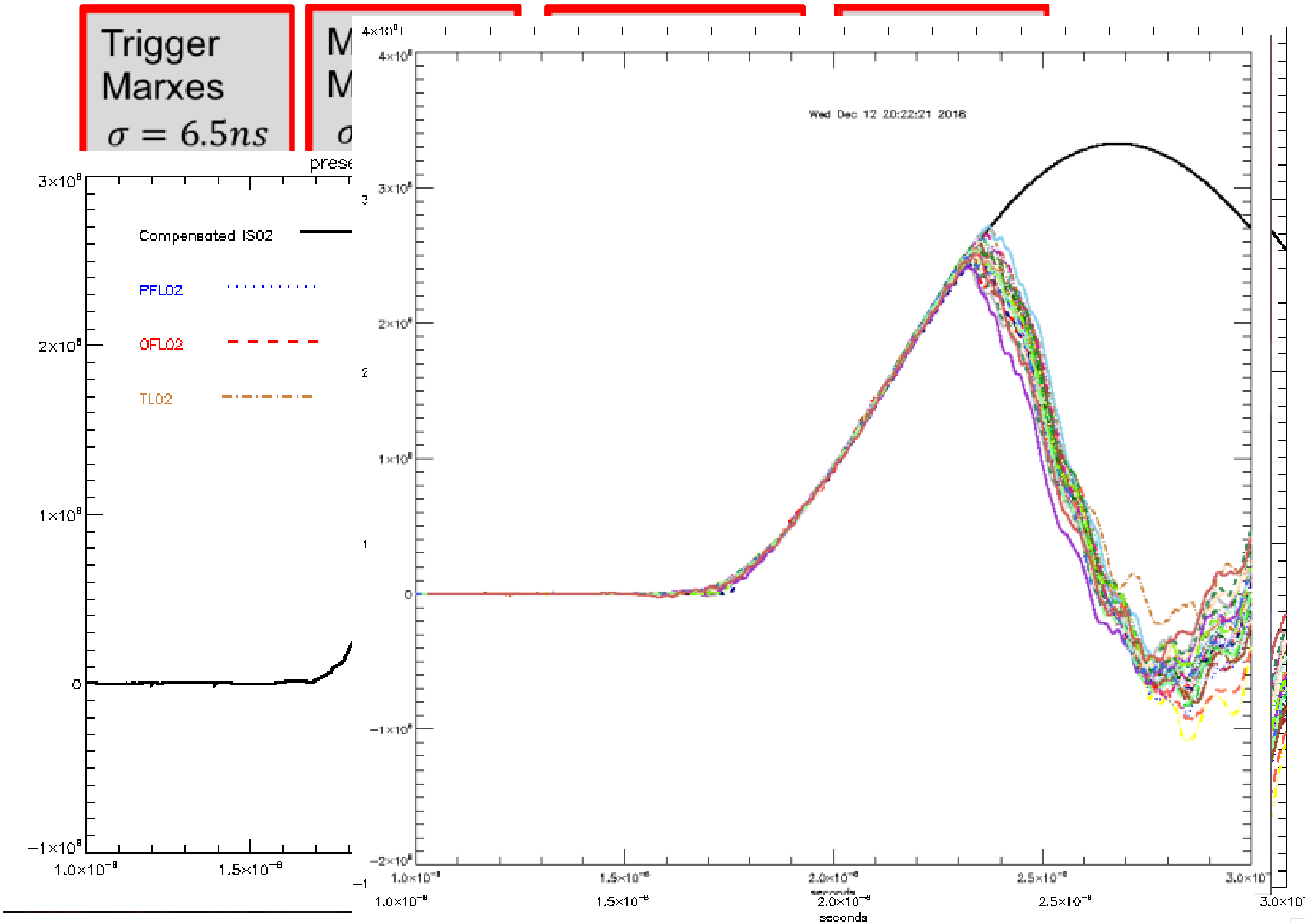
- Modeling paper/foil capacitors is well-understood
- Calculations benchmarked to Sandia's capacitor testing program for ZR
- Infant mortality rates comparable to that of ZR observed

Capacitor wear-out rate expected: ~1 failure/800 shots

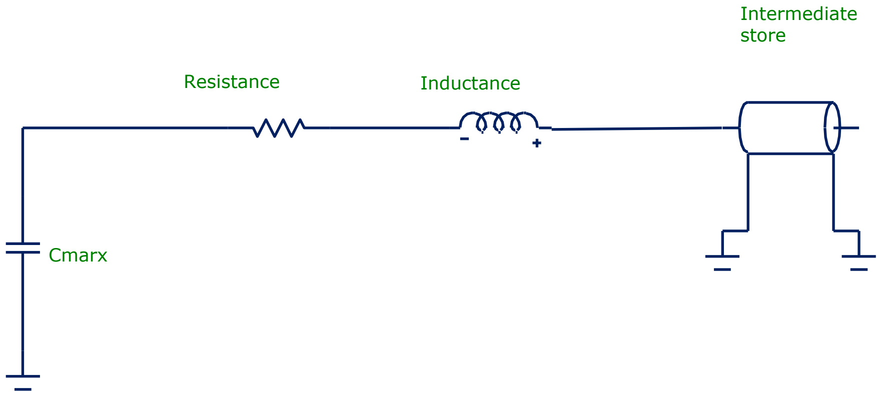
Calculations for 85 kV charge and 35% reversal

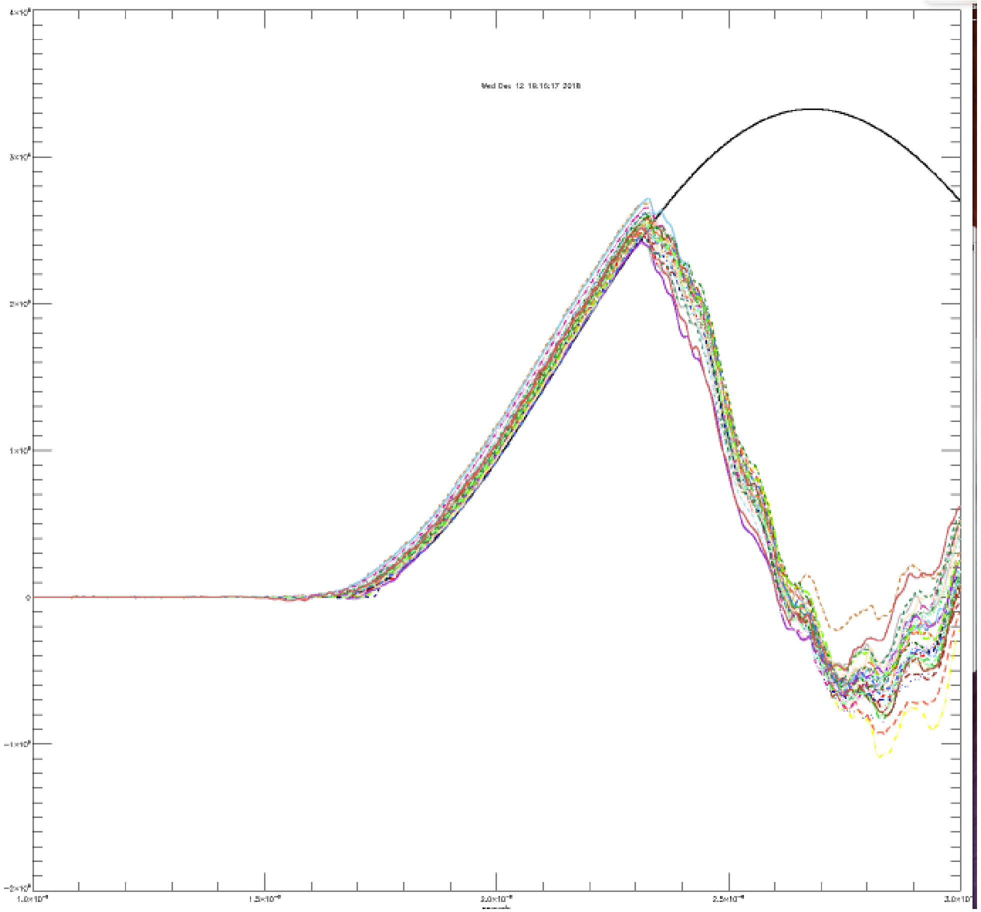


Overall timing data for a Saturn experiment



Marx jitter causes gas switch voltage variations

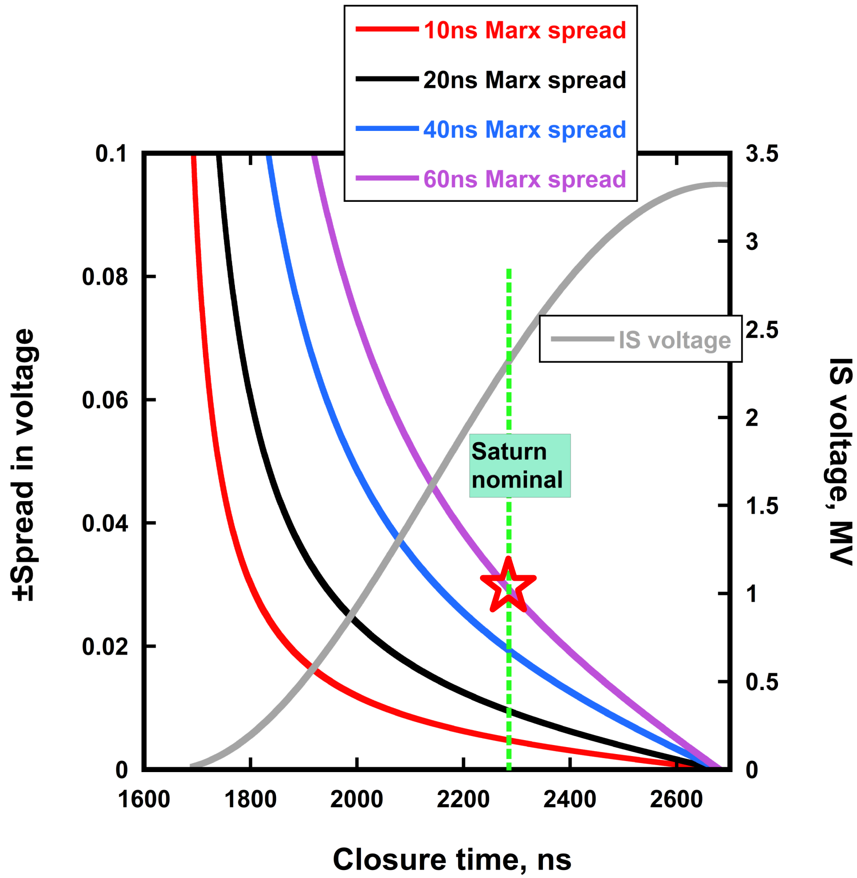




What Marx jitter is acceptable?

$$\epsilon = \frac{V_{is}(t+\Delta t) - V_{is}(t-\Delta t)}{V_{is}(t)}$$

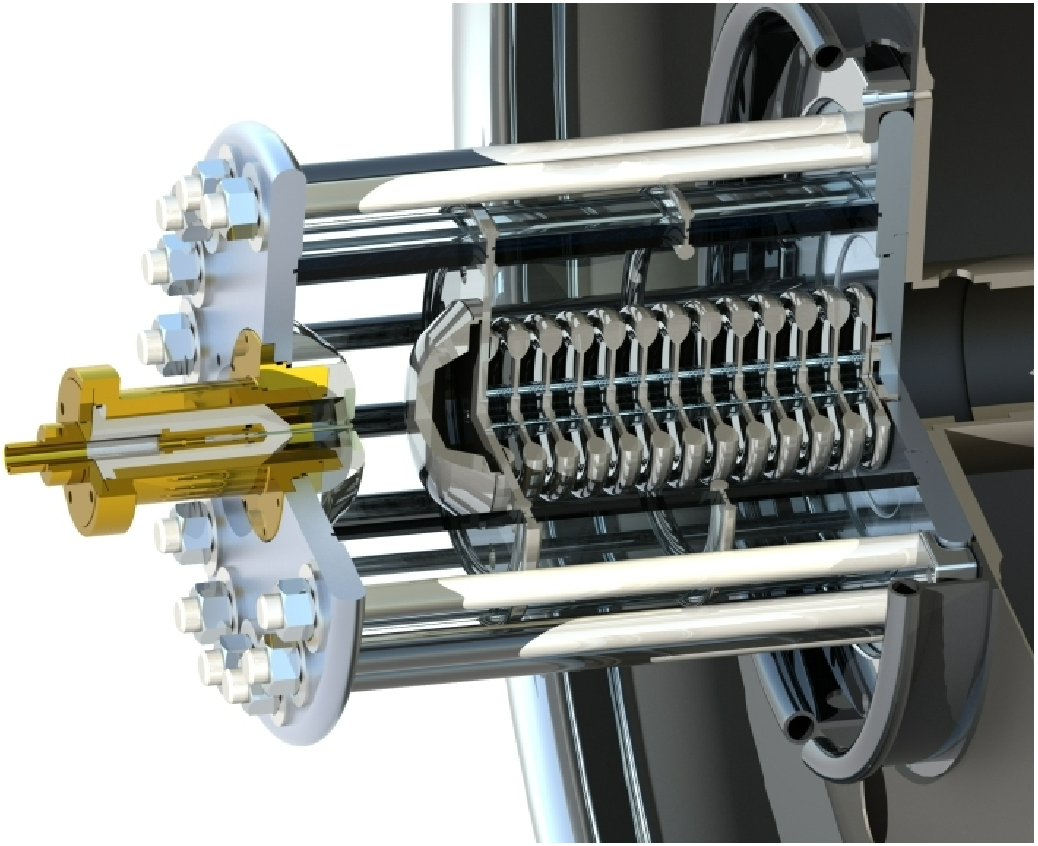
- **The gas switches are relatively sensitive to voltage changes**
  - **Presently operating with ±3% variation which is significant**
- **With 20ns Marx spread and later trigger, switch voltage variations would be < ±1%**
  - **By triggering the gas switches later, the main Marx charge voltage can be reduced**



Higher voltage MTGs would allow more reliable Marx operation and less Marx jitter

Module timing is critical, and largely determined by the gas switch

- The 36 SF_6-insulated switches are electrically triggered with a ~70 kV pulse from a single generator
- The trigatron design may not be optimal for a high-current switch
- Saturn does not need pulse-shaping



Water switch jitter is not a concern for Saturn

- Charlie Martin/Tom Martin empirical formula predicts ~3 ns one-sigma for the water switches on Saturn
- This equation typically over-predicts Z water switch jitter
- Presently the water switch jitter is driven by intermediate -store voltage variations (from Marx jitter)

$$Jitter_{1-\sigma} \cong 0.0028\tau_{charge-ns} d_{cm}$$

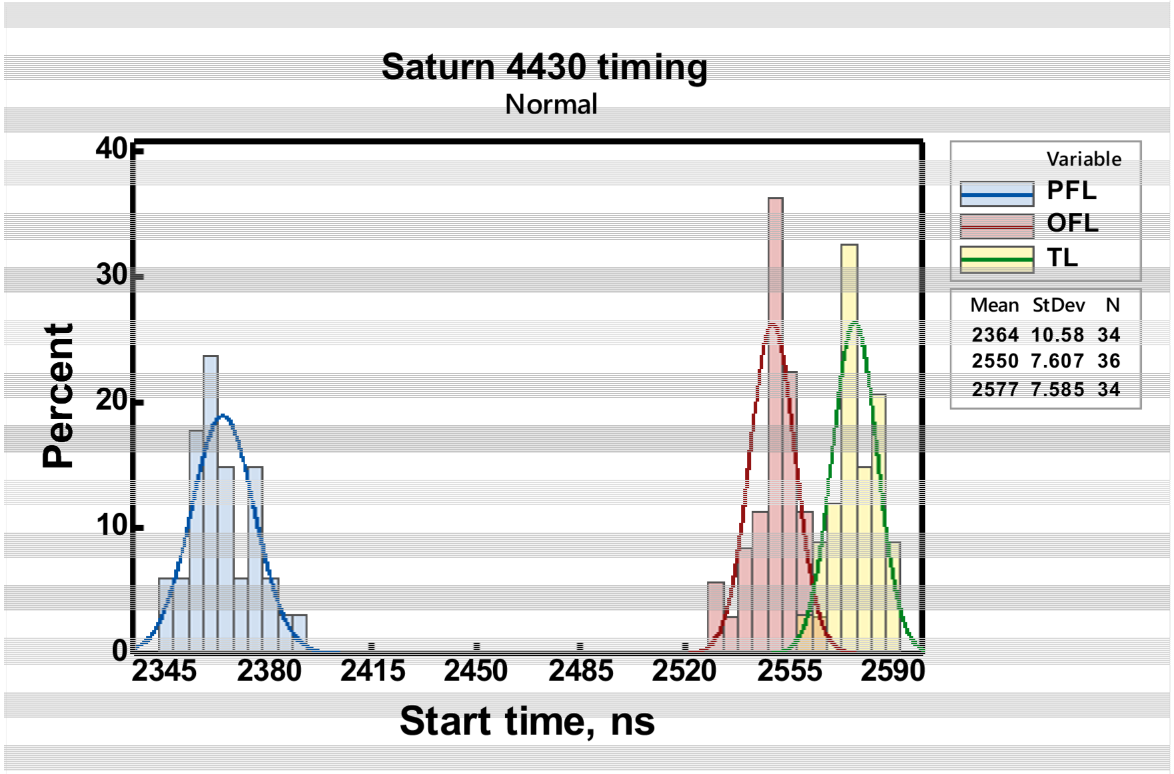
Descriptive Statistics: t_pfl_4387, t_ofl_4387

Statistics

Variable	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	m
t_pfl_4387	36	0	2366.5	1.33	7.96	2336.7	2364.1	2366.2	2370.7	2386.1
t_ofl_4387	36	0	2539.7	1.19	7.15	2529.6	2532.9	2539.2	2543.5	2555.7

Typical forward-wave one-sigma is 7.5 ns, and 18 ns FWHM

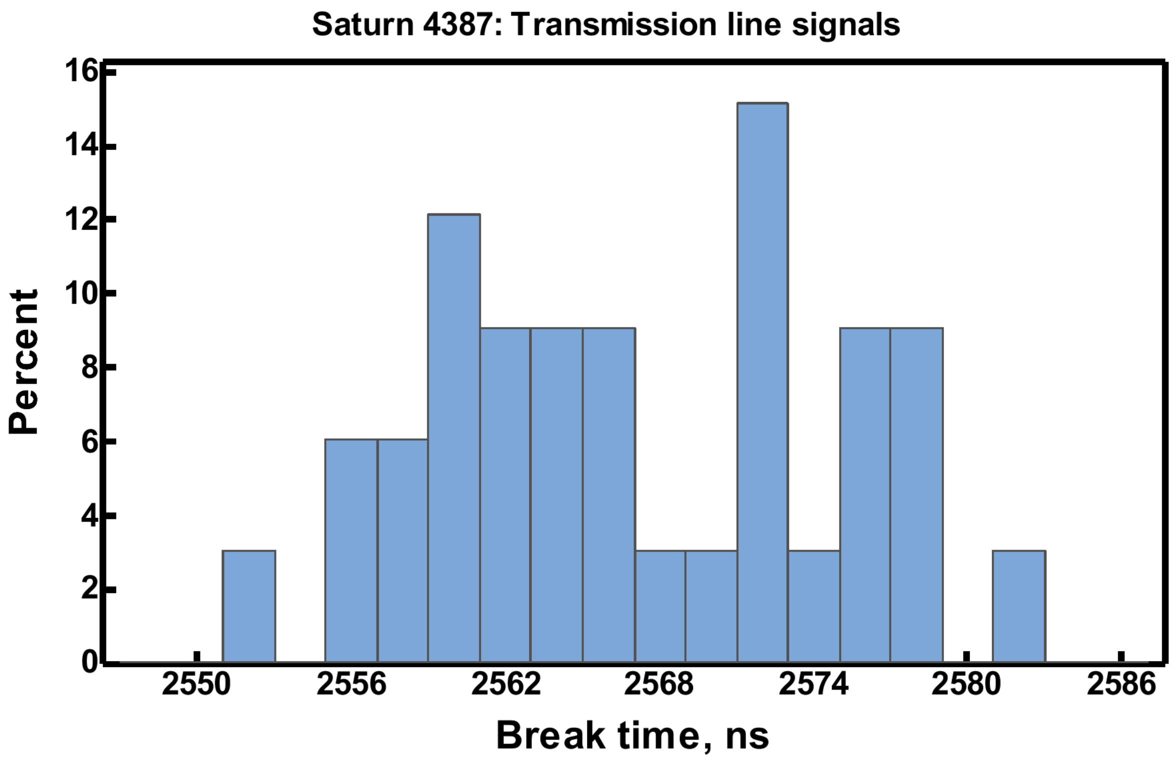
- The gas switch largely determines the machine jitter
- The gas switch timing (evidenced in PFL timing) could be bi-modal, indicating weak triggering



The jitter after the water switches is actually *less* than the jitter before the water switches

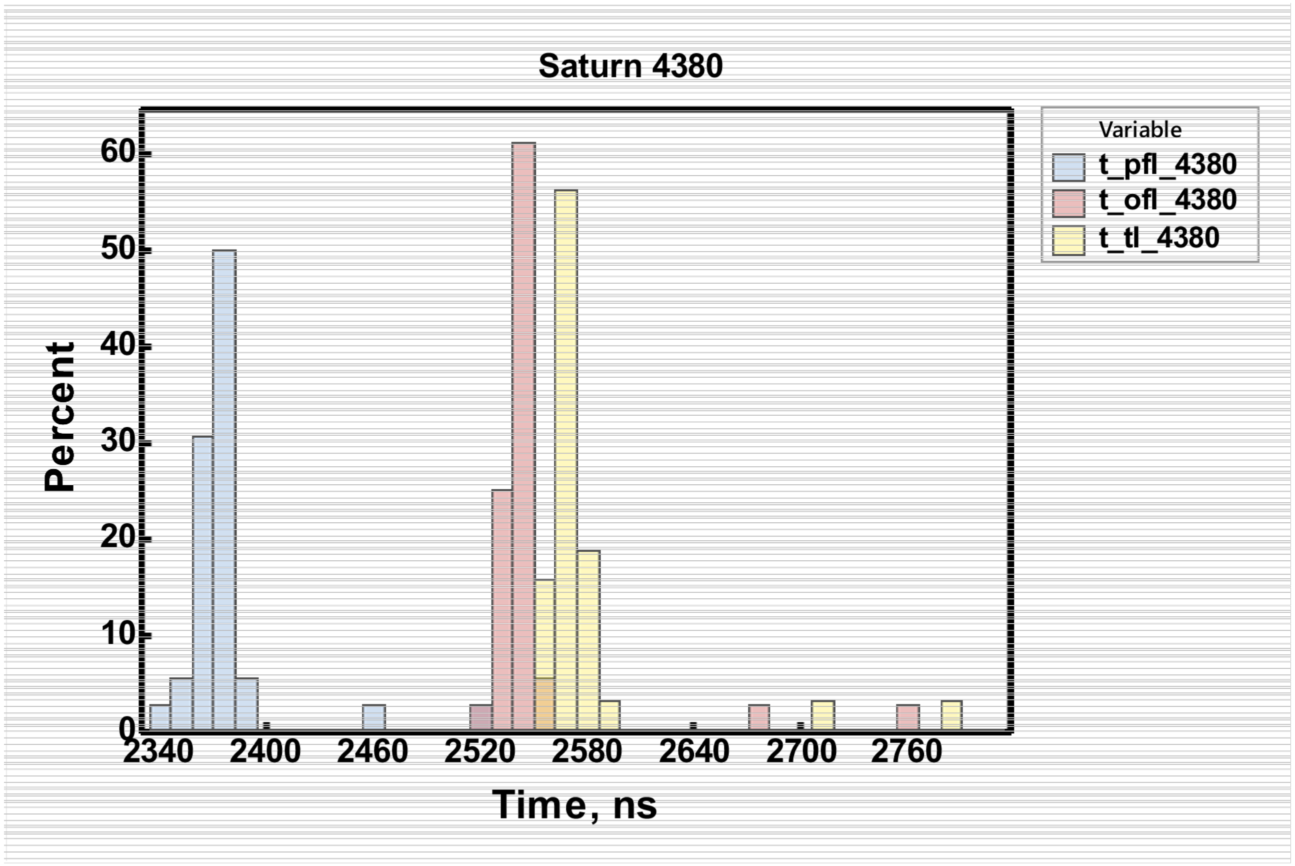
Final machine spread is typically 30-35 ns

Low-impedance bremsstrahlung energy coupling is sensitive to pre-pulse and module spread



Late or missing modules happens, and will reduce dose

- **Power is reduced ~6% $(35/36)^2$, and dose rate will be reduced more than 5% for a single late module**



What inter-module timing variation is acceptable?

- **Module spread reduces the peak power at the load, reducing voltage**
  - **The impedance seen by each module decreases with module spread**
- **Gap closure results in lower effective load impedance for larger module spread**
- **We probably don't want to allocate the entire dose variation budget to module timing spread**

Proto-II: A single late module (of eight) reduced the dose and dose rate by half

$$\dot{D} \approx IV^{\alpha} = PV^{\alpha-1} = \frac{Z_{load}P^2}{V^{3-\alpha}}$$

If power is inversely related to the module timing variations:

$$P = \frac{P_0}{\sqrt{1 + \left[\frac{3.55\sigma}{\tau_0}\right]^2}}$$

$_0 = 35$ ( )

If $\alpha \cong 2$ and $I \approx constant$

$$\dot{D} \approx P^2 = \frac{P_0}{1+\left[\frac{3.55\sigma}{\tau_0}\right]^2}$$

$$\sigma_{module} \leq \frac{\tau_0}{3.55}\sqrt{\frac{\Delta}{1-\Delta}}$$

To keep dose within 5%
$(\Delta = .05)$: $\sigma < 3.4\ ns$

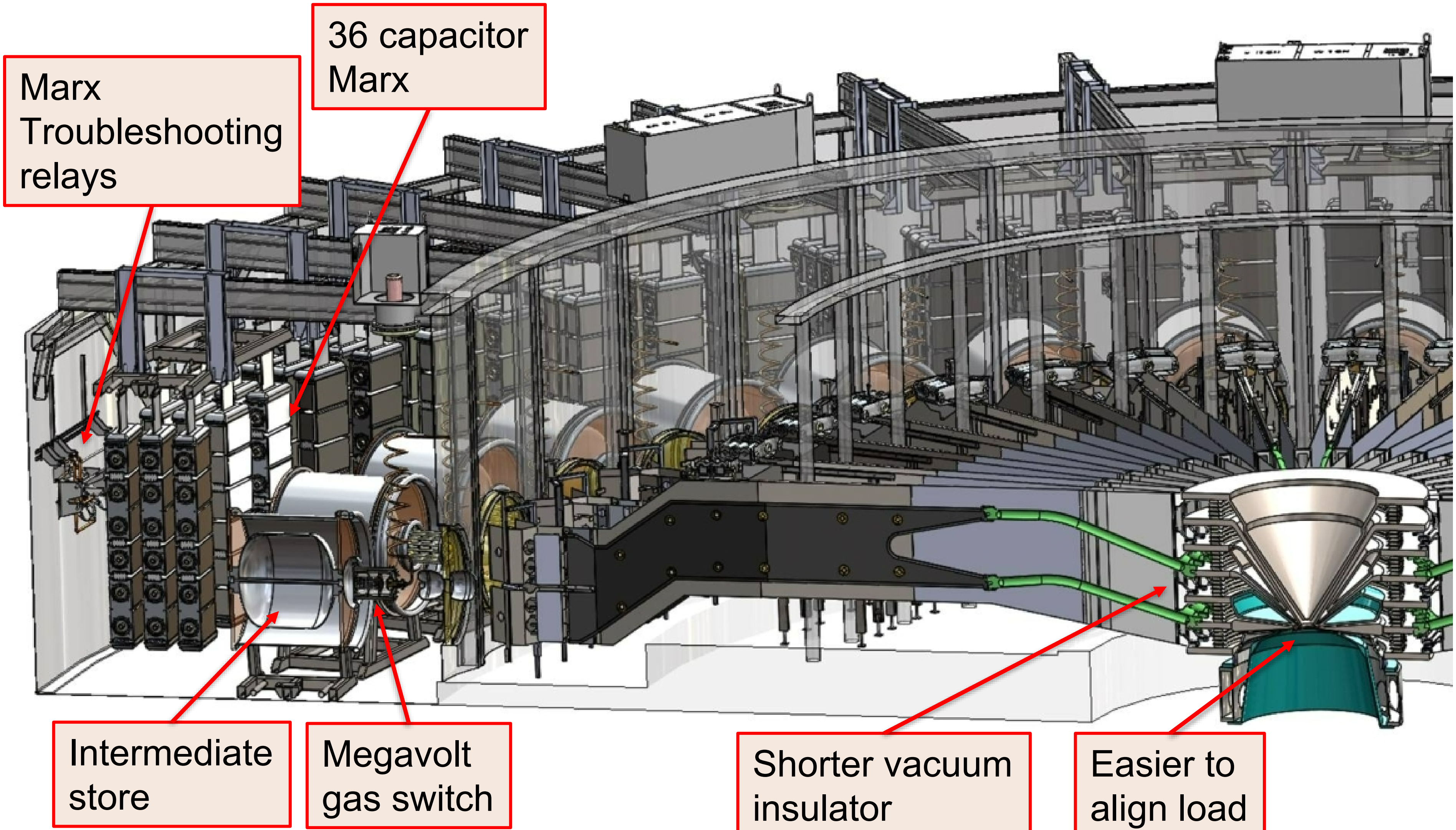
There are many possible improvements, but we'll focus on three being considered

A. **Redesign the vacuum insulator stack, magnetically-insulated transmission lines, and load**
   - Expedite machine loading while improving load-gap precision
   - Optimize MITLs for power flow

B. **Improve switching precision throughout the machine**
   - Affects load performance, overall timing, and pulse repeatability

C. **Move the megavolt gas switch into the oil tank**
   - Improves switch reliability and could reduce nominal charge voltage required

If we did everything, Saturn might look like this:



Possible change number one:
Replace vacuum insulator and magnetically insulated transmission lines

Modernize vacuum insulator stack and MITLs

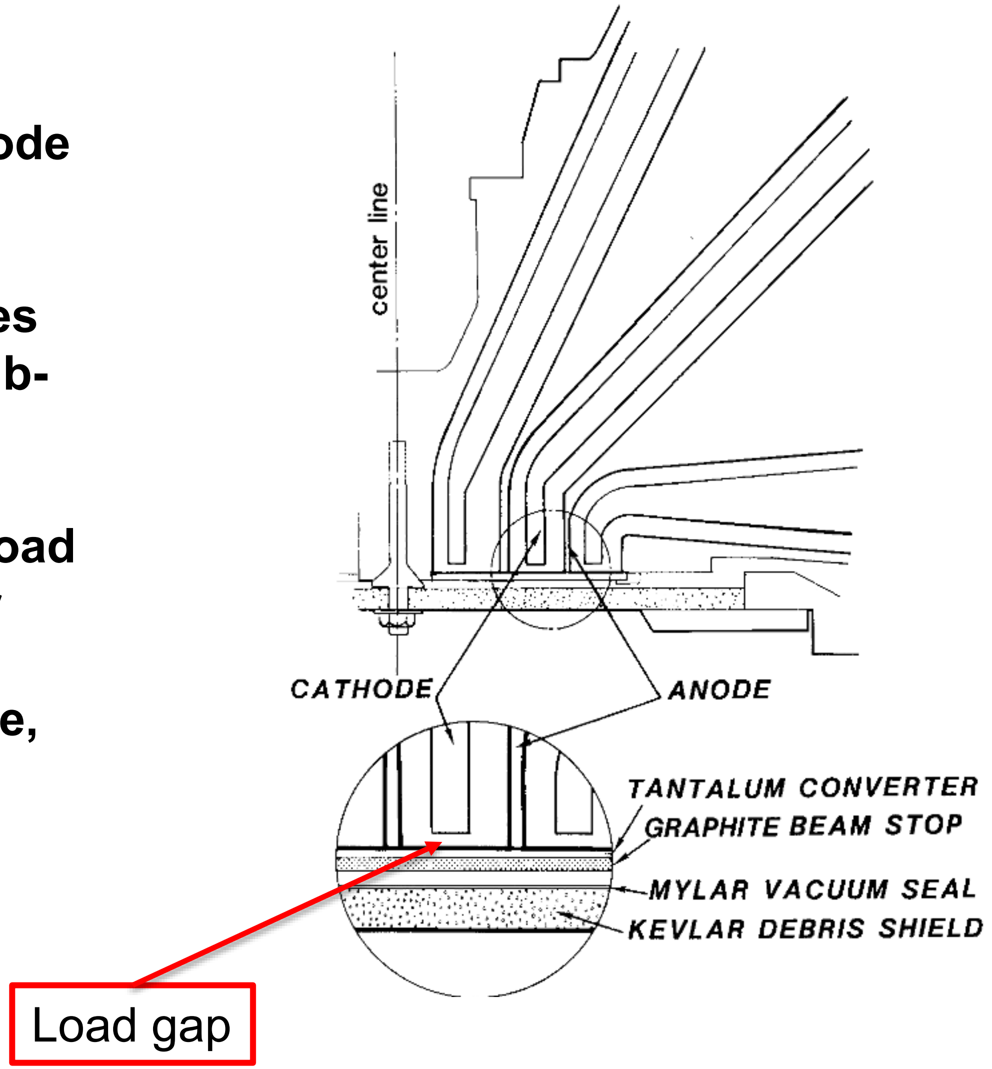
- **Load alignment and gap-setting require significant improvement, for both shot rate and load performance**
- **Present vacuum insulator assembly has no usable voltage or current diagnostics**
- **The vacuum insulator is (conservatively) designed for higher voltage than necessary**
- **Present insulator design is basically incompatible with automatic water-side de-bubbling**
- **Present system uses un-trapped diffusion pumps which backstream oil onto the load surfaces**

Reasons to change the insulator stack and MITLs

- MITL positioning techniques developed at Z are more effective
  - Affects shot rate, load performance
- Reduce vacuum inductance
  - Improves operating margin and electrical efficiency
  - Vacuum inductance limits the driver response to collapsing load impedance
- Reduce area of stack and MITLs to be cleaned between shots
  - Improves shot rate
- Allow stack de-bubbling without diving
  - Improves safety and saves time
- Monitoring machine and load performance
  - Crucial to understanding load and machine behavior

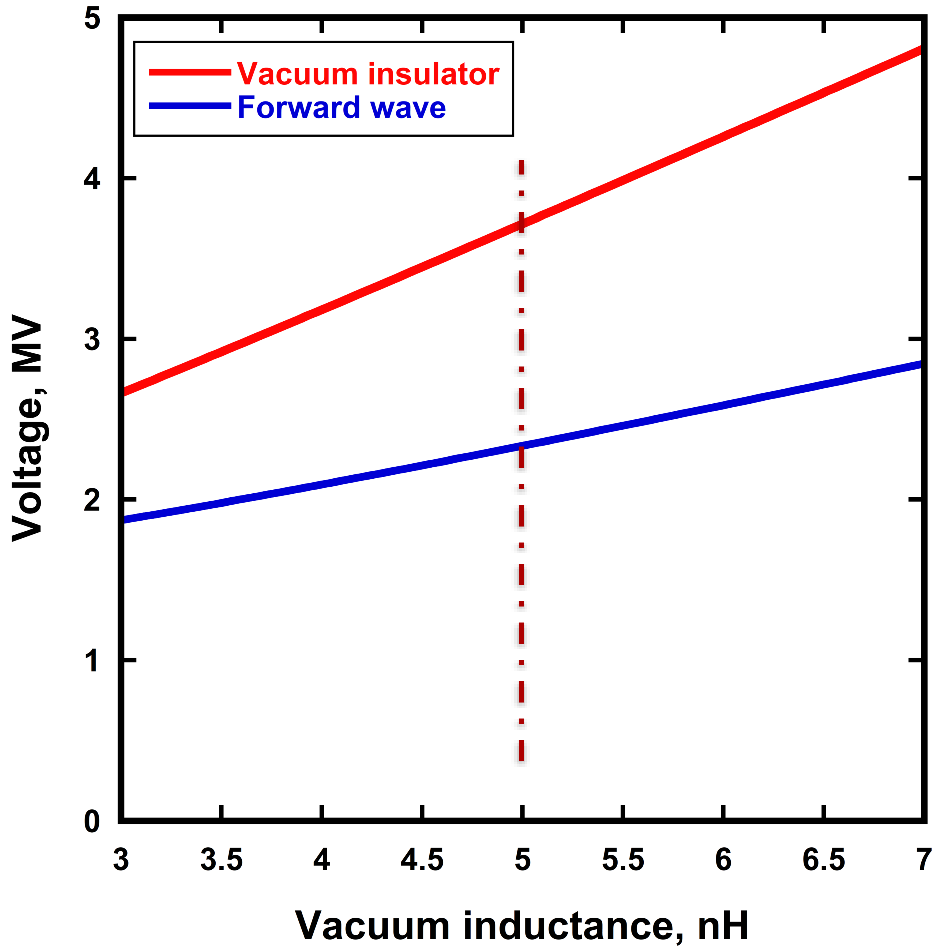
The triaxial bremsstrahlung diode is efficient but sensitive to gap

- For relativistic voltages, the diode impedance is basically proportional to gap
- High-current, low voltage diodes require small gaps (~4 mm); sub-mm accuracy is required for consistency
- The 50k lbf axial atmospheric load causes shifting in the insulator assembly during pump-down
- Increased rigidity, with accurate, consistent measuring and adjusting capability is required



MITL inductance largely determines insulator voltage

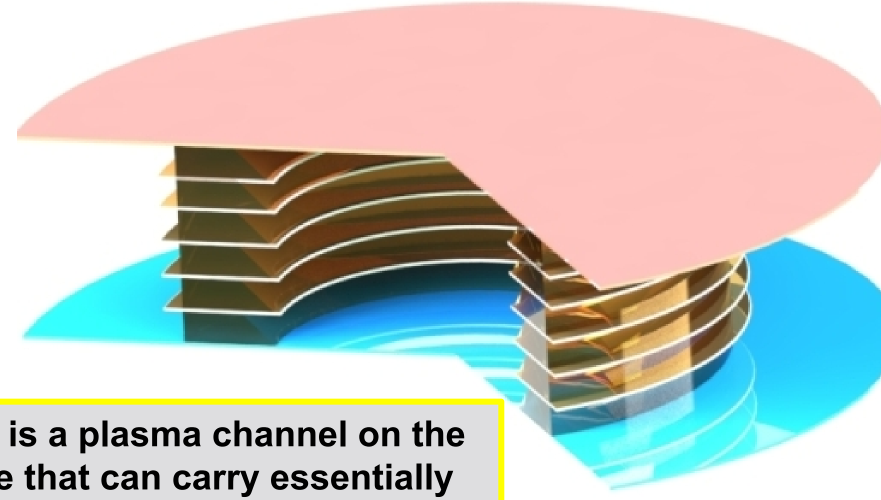
- This ignores load gap closure which reduces peak voltage somewhat
- Saturn today ~5 nH effective



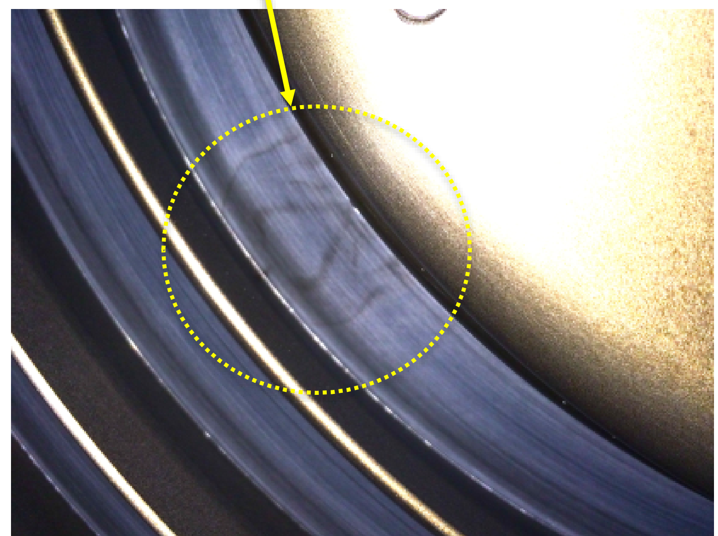
12.5 MA@1.6 MV load voltage 35 ns electrical FWHM

The solid-vacuum interface is the critical part of the power flow chain

- **Typically the insulator design should be well-matched to the actual requirements**
- **The probability of vacuum flashover depends strongly on the applied electric field (voltage)**
- **While reliability improves with insulator length, there are disadvantages**
  - **Added inductance in vacuum**
  - **Taller insulators are harder to grade well**
  - **More area to clean**
  - **Less stable mechanically**



"Flashover" is a plasma channel on the solid surface that can carry essentially unlimited current

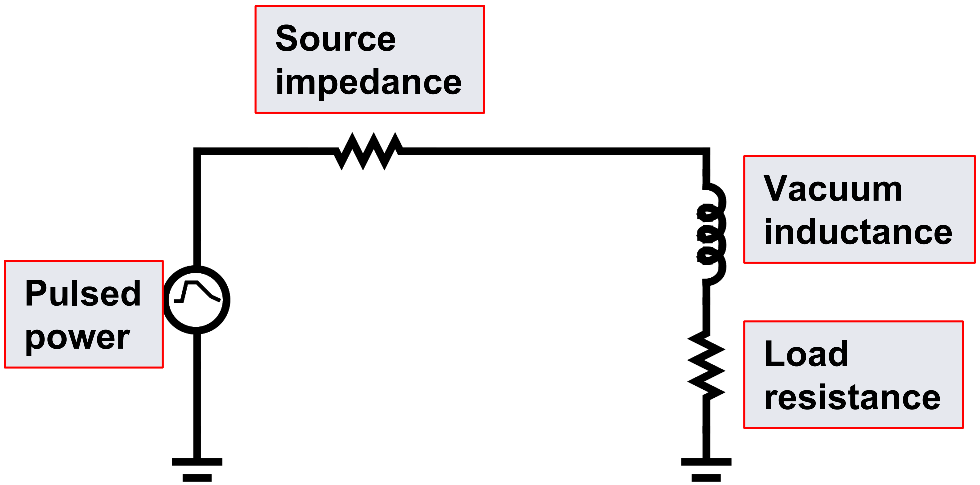


We use a simplified model to scan parameters

- Set peak load current and peak load voltage
- Assume sine-squared temporal profile (typically 45 ns FWHM to achieve 25 ns radiation)
- The load is what matters, so calculate from there outward

Saturn is short-pulse and inductance-dominated

- Because of the short pulse length, only a small part of the Saturn system is needed for simplified calculations- the load can't "see" past the bottles
- The source impedance (water lines outside the insulator), load impedance, and the MITL inductance are key



$$2.2\,\frac{L}{R} \approx 53\ ns \text{ presently}$$

Basic circuit calculations

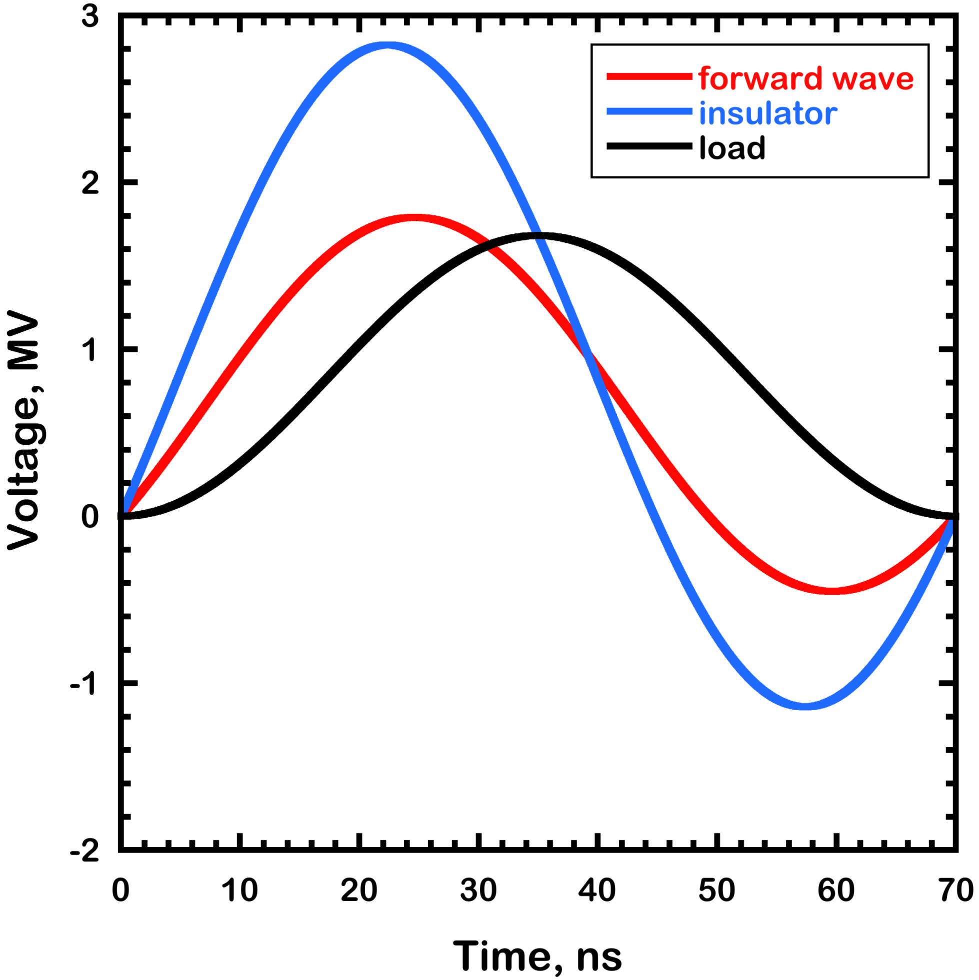
- Prescribe load voltage, current, vacuum inductance, source impedance, and sin^2 pulse width ($\sim sin^4$ radiation pulse)
- Extrapolate upstream to find the vacuum insulator voltage and required forward-wave

$$V_{insulator} = V_{load} + \frac{L_{vacuum}}{R_{load}} V'_{load}$$

$$V_{forward} = V_{insulator} + \frac{Z_{source}}{R_{load}} V_{load}$$

Reverse model calculation example

- **1.6 MV and 10 MA load parameters, 4 nH vacuum, 35 ns electrical FWHM**
- **The forward wave is close to the load voltage**
- **The insulator voltage is higher due to MITL inductance**
- **For a short pulse, the drive voltage must *reverse* to pull magnetic energy from the MITLs (on Saturn, gap closure does this)**



Vacuum insulators have been studied extensively

- There are multiple formulations that derive an empirical fit to data for flashover probability
- All formulations are strong functions of applied field
- Saturn was originally designed to JCM criteria

$$p = \frac{1}{2}\left[\frac{E}{\gamma_{JCM}} t_{eff}^{1/6} A^{.1}\right]^{10}$$

JCM 1960s

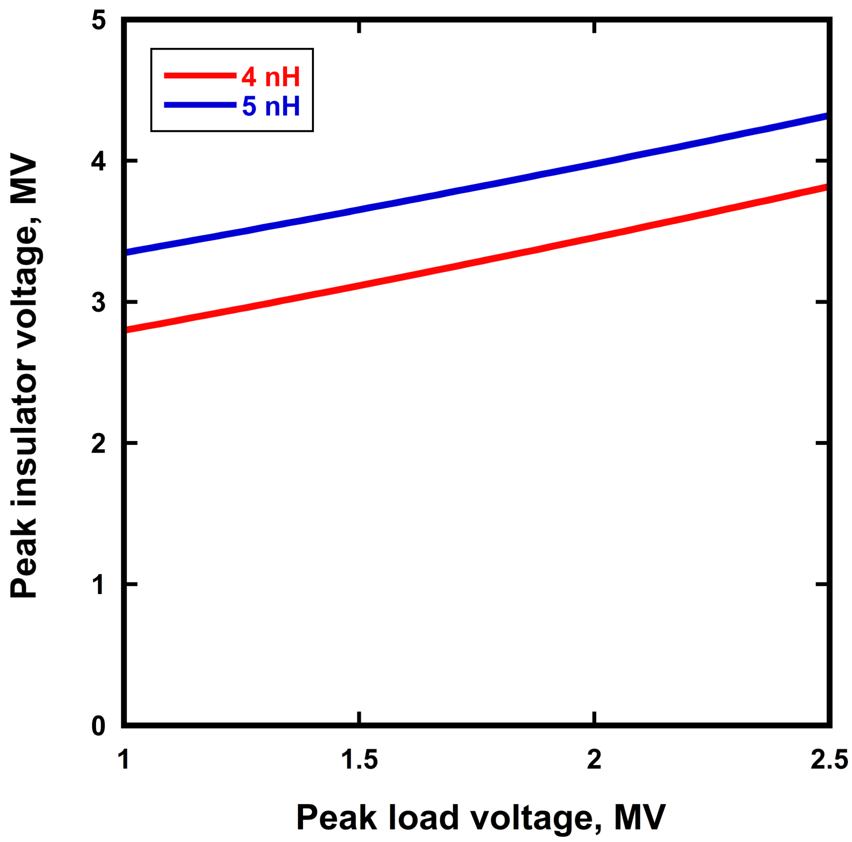
Insulator reliability depends upon insulator size, electric field, and stress duration

$$p = 1 - exp\left[-\left(\frac{E}{\gamma_{SM}}\right)^{10} t_{eff} \frac{Cln(2)}{\left(exp\left(\frac{.024}{d}\right)\right)^{10}}\right]$$

Stygar 2004

We predict acceptable vacuum insulator flashover probabilities for the short stack

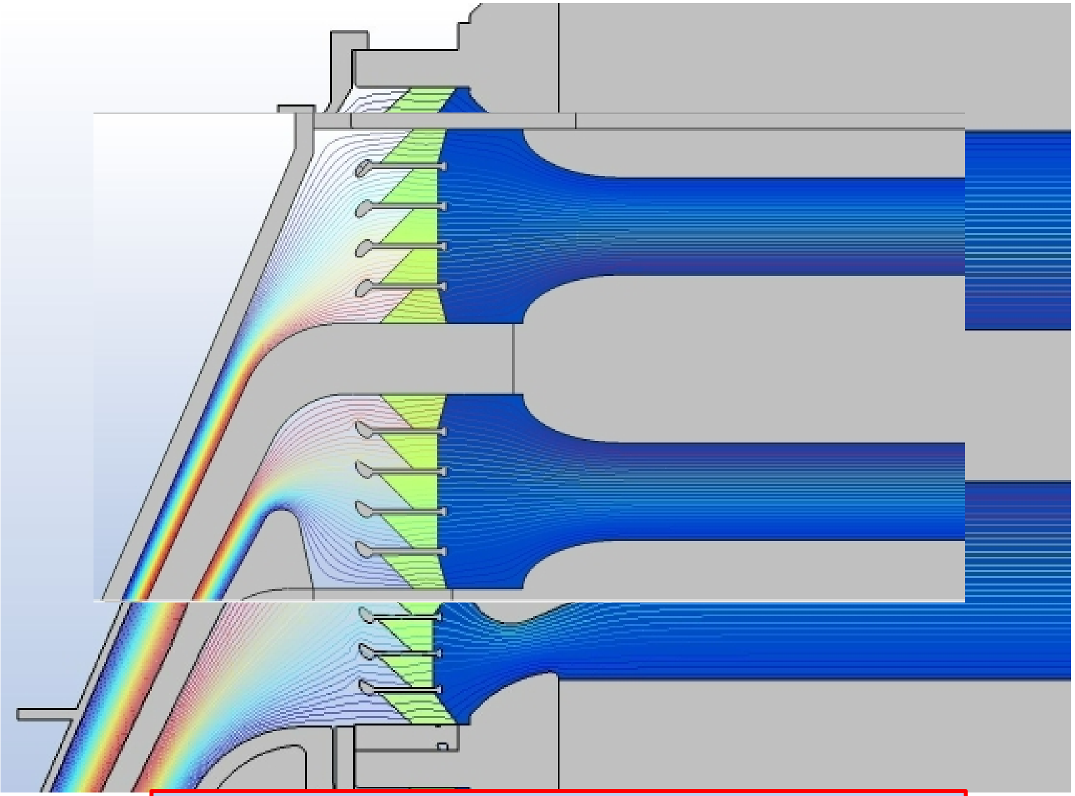
- Voltage for 12.5 MA, 25 ns FWHM radiation pulse at 1.6 MV load voltage
  - Present insulator- (5 nH, 3.7 MV, 121 kV/cm): calculated flashover probability 4.6×10^{-11}
  - Shorter insulator- (4 nH, 3.2 MV, 157 kV/cm) calculated flashover probability: 4.4×10^{-2}
- Shorter insulator at 10 MA calculated flashover probability: 6.8×10^{-3}



Tie to data: ZR routine operation ~1% flashover rate at 152 kV/cm; 1.8% flashover probability calculated

Why do we think a shorter insulator is viable?

- **The Saturn insulator was prescribed to tolerate 4MV with a conservative analysis (and was acrylic)**
- **Saturn is not capable of applying this voltage to the insulator, nor is there a need to do so**
- **More recent calculations, and data from Z indicate that higher field is acceptable**
  - **Azimuthal EM transit-time for a large insulator improves hold-off (Saturn azimuthal transit time is 57 ns)**
  - **Multi-level insulators are able to tolerate higher field (interrupted avalanche)**



This design is graded to within 3.5%

Possible change number two:
Improve pulsed power accuracy and efficiency

Improve Saturn switching accuracy and pulsed power efficiency

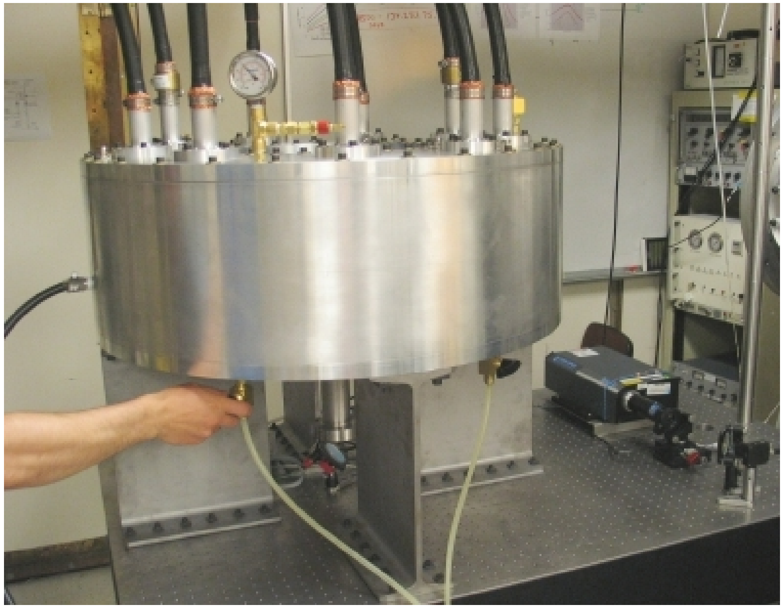
- Apply additional precision to charge voltages throughout the system
- Reduce Marx temporal jitter
- Improve the triggered megavolt gas switches for lower temporal jitter and reduced mis-fire rate
- Optimize the switching times for more efficient operation
- Improve the water-switched pulse-forming lines for more stable performance and reduced higher-order modes

Reasons for improving timing accuracy and reliability

- X-ray output is a strong function of electrical power-module spread reduces power and slows the rise time
  - Slower rise time causes more variability in load behavior
  - Reduce Marx spread to make the gas switch voltage more uniform
  - Develop improved gas switches, studying multiple triggering approaches
- Optimize machine timing for desired output with minimal energy
  - For example- more optimal timing would allow the same output as achieved today at 85 kV Marx charge, with only 70 kV charge

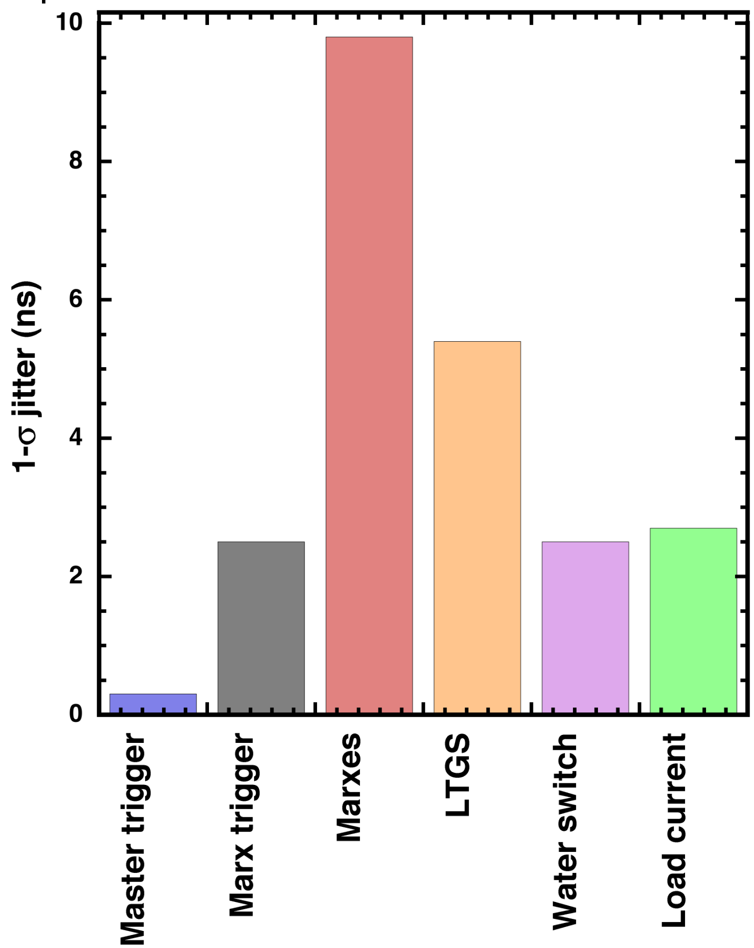
Tools to reduce module jitter

- **Higher-voltage trigger Marxes**
- **Review Marx triggering scheme and pressure calculations**
  - **Develop Z-like shot configuration spreadsheet**
- **Develop improved megavolt gas switches**
  - **Lower electrical stress**
  - **Improved trigger mechanism (trigatron, V/n, laser), considering operational requirements**
- **Implement state-of-the-art trigger generators for Marxes and gas switches**
- **Calibrate and evaluate all charging systems**



The temporal precision needed for Saturn is done at Z every day

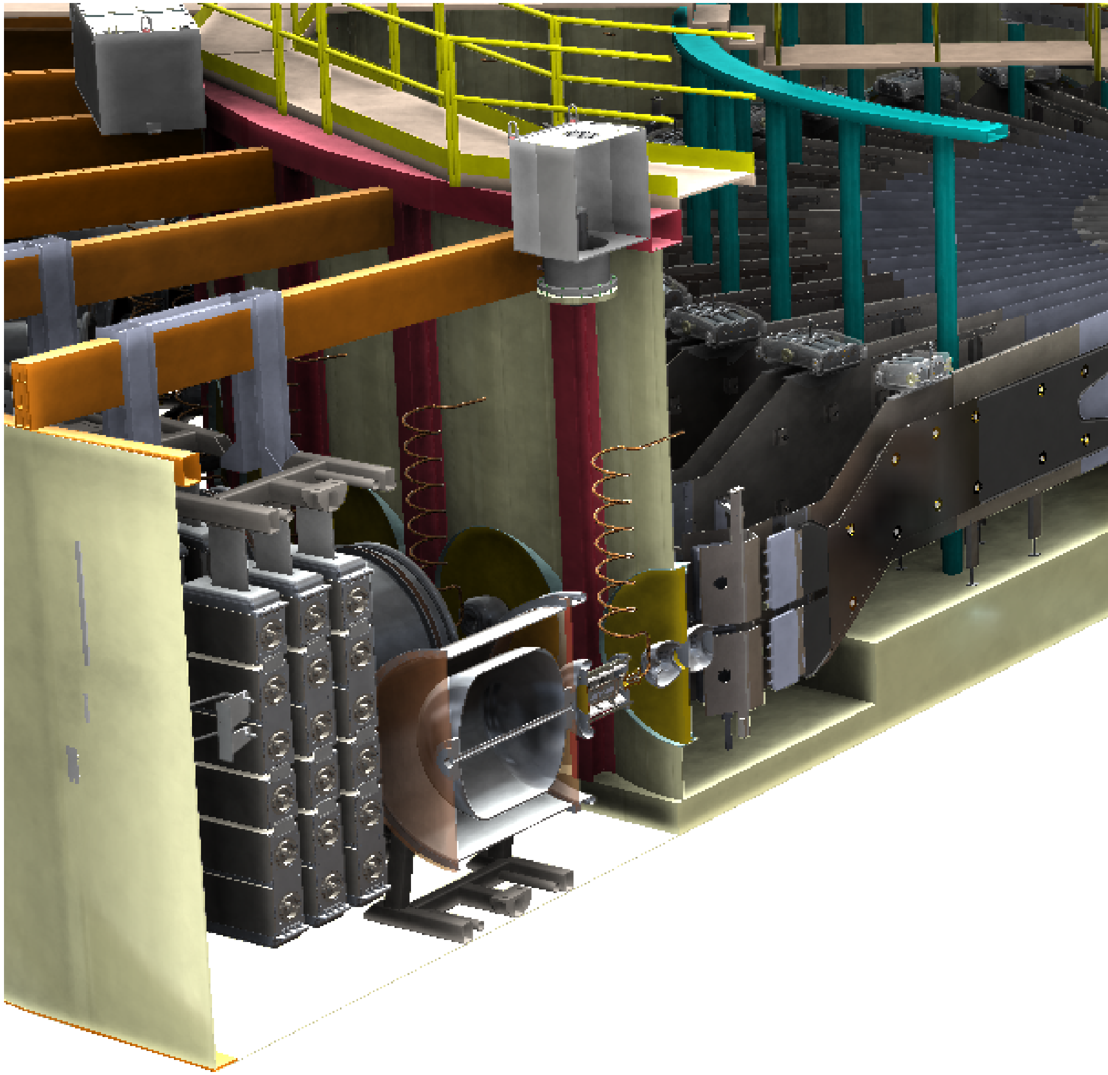
- **No part of the Z machine has a 1-σ jitter greater than 10 ns**
- **The Z system is operated at low pre-fire probability**
- **Reliability is always a major focus**



Possible change number three:
Reconfigure the energy storage system

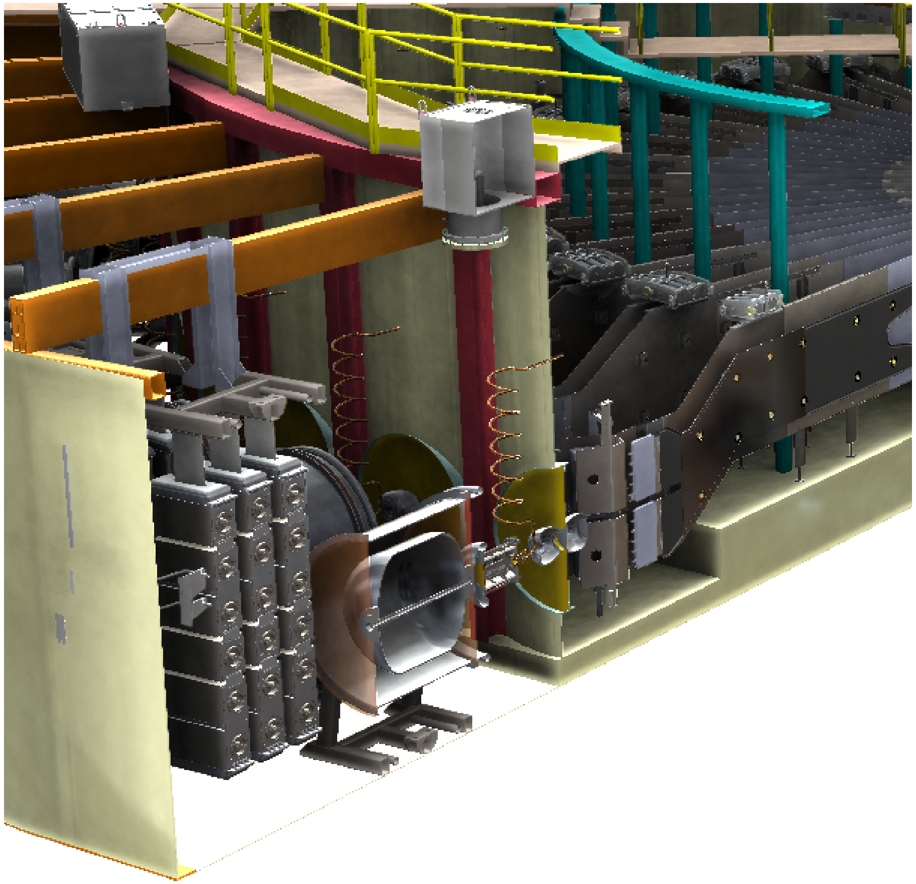
Move the intermediate store capacitors and megavolt gas switches into the oil tank

- The gas switch *may* benefit from oil immersion
- For the gas switch to be in oil, the intermediate store capacitor and electrical trigger inductor will also be in oil
- The space available makes a 6-column, 6-row Marx more attractive than the present 8-column, 4-row Marx



Reasons for moving the gas switch into the oil tank

- Because of the disparate EM wave velocities in plastic and water, there is an increased tangential field on the switch housing in water
- An oil-immersed electrically triggered switch would have lower shunt losses to the trigger inductor
- The trigger inductor would be damaged less from late-time arcing if in oil
- Freed space in water could allow minor pulse-forming improvements



Many other ideas are under consideration for Saturn pulsed power

- **Implement the laser-triggered primary trigger generator and replace the spider**
  - **Improve trigger system accuracy and reliability**
- **Redesign the nine Marx trigger generators for increased output voltage**
  - **Increased output voltage (800 kV vs 600 kV) reduces main Marx jitter and allows higher Marx reliability**
  - **MTGs in isolated oil volumes allows consistently higher oil quality**
  - **Implement ZR MTG trigger circuit improvements**
- **Add automatic shorting levers to the 36 main Marxes**
  - **Adds redundant personnel safety**
- **Implement ZR’s Marx troubleshooting relay system (allows disconnecting a Marx remotely)**
  - **Reduces time to locate a shorted Marx from many hours to a few minutes**
  - **Eliminates personnel hazards of disconnecting Marxes manually**

Conclusions

- Saturn is an impressive and unmatched facility, even after 30 years
- Some reasonable improvements could make it better
- We have identified three major upgrades to evaluate
  - Replace the vacuum insulator and MITLs, and re-engineer the load region
  - Update the megavolt gas switching and trigger systems
  - Re-locate the megavolt gas switch into the oil tank
- There are numerous other diagnostic and utility improvements that can be made at low risk