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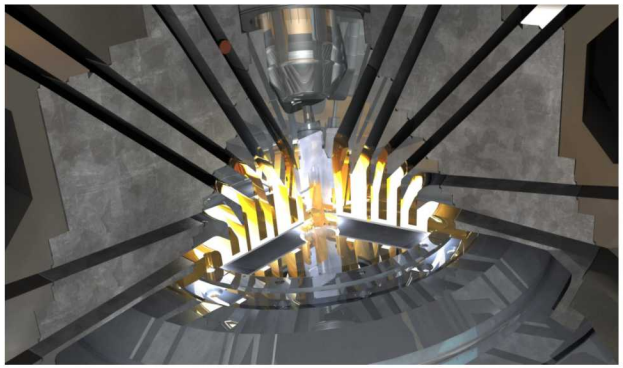

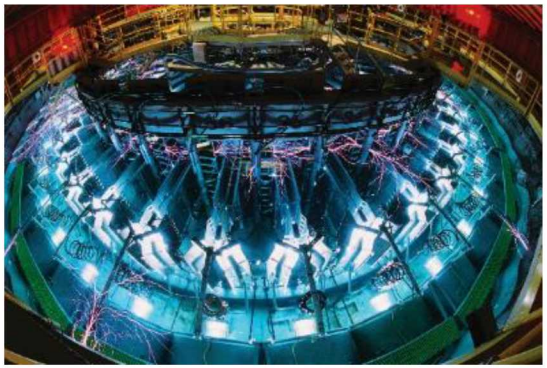

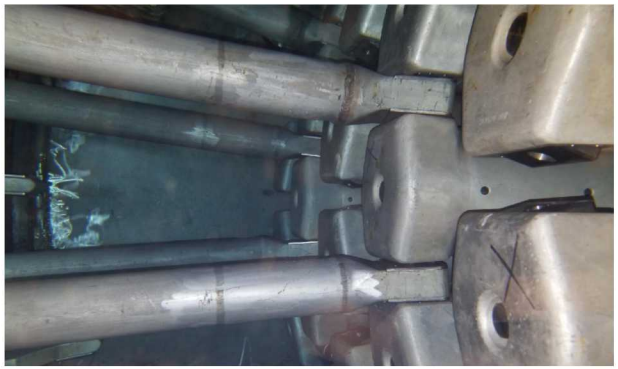

Estimates of Saturn Radiation Output Scaling versus Machine Design Parameters

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U.S. DEPARTMENT OF ENERGY

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NNSA National Nuclear Security Administration

16th International Conference on Megagauss Field Generation and Related Topics

What I will talk about

- Quick review of what Saturn is and what are its capabilities
- What we are planning to do with the machine
- Some estimates on how radiation output can scale with various design parameters

The Saturn Accelerator

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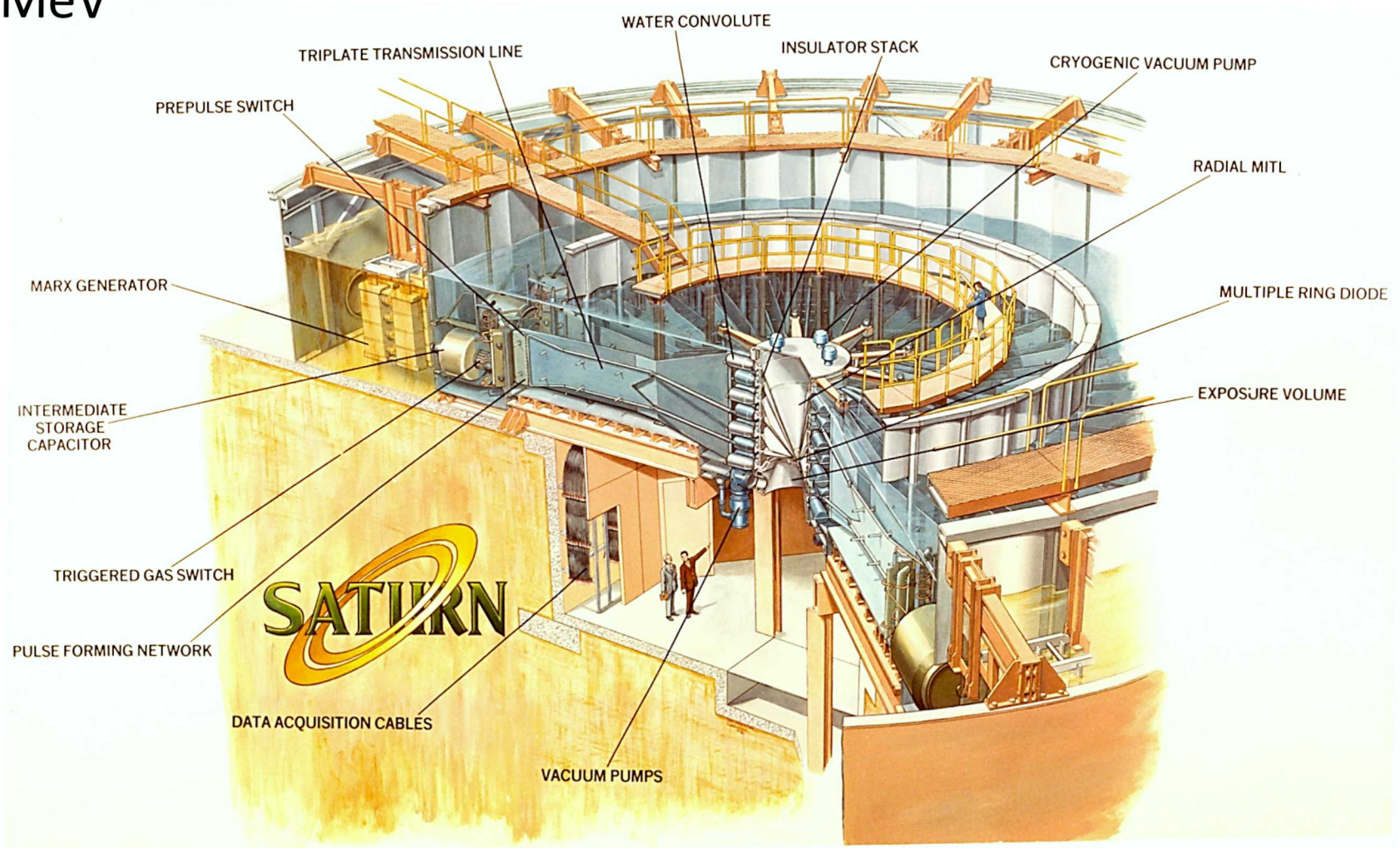
- Saturn is a short-pulse (~ 40 ns FWHM) x-ray generator capable of delivering up 10 MA into a bremsstrahlung diode to yield up 5 x 10^12 rad/s (Si) per shot at an energy of 1 to 2 MeV.
- It was built in the 1980's as a rebuild of the PBFA I accelerator
- Has been a reliable scientific tool since its first shot in 1987 as a driver for both radiation sources and z-pinch plasmas

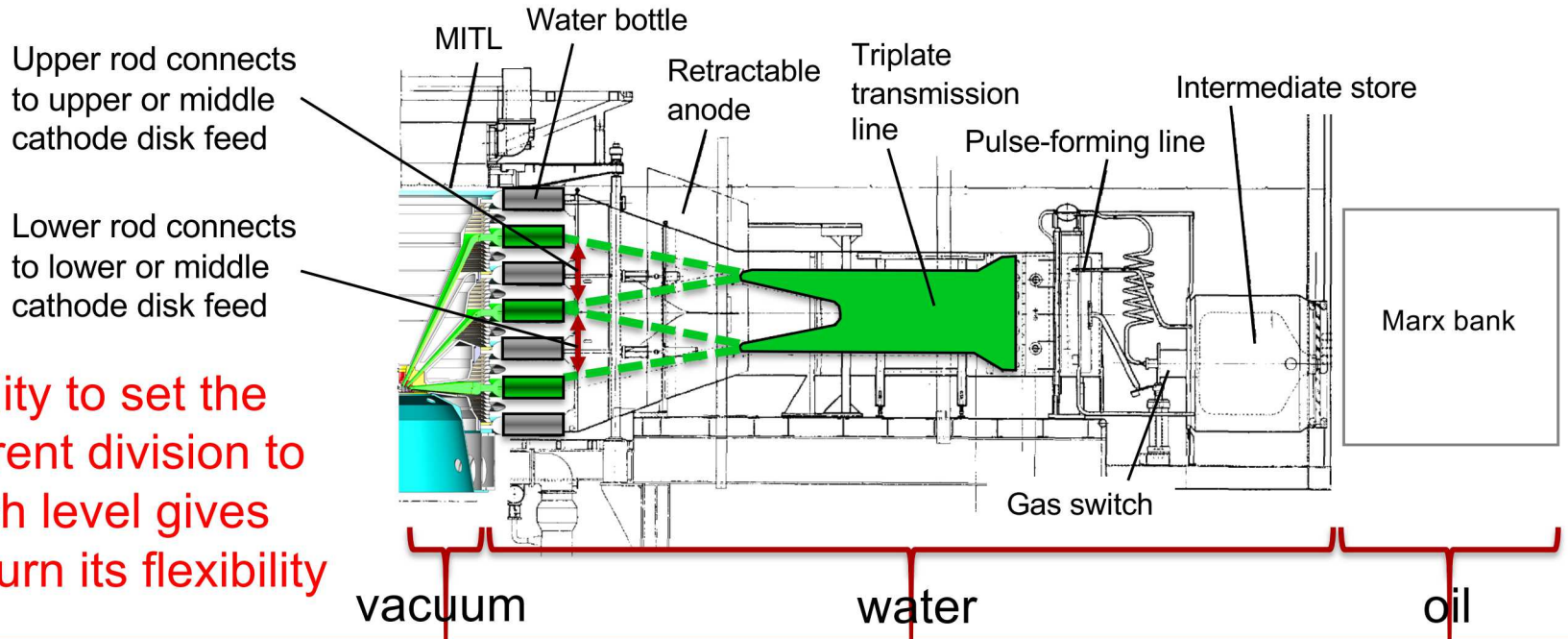
Saturn has thirty-six Marx banks and water PFLs that drive 3 "independent" Bremsstrahlung radiation loads

Nominally 10 MA, 1.6 MV, 40 ns power pulse, 5×10^{12} rad/s (Si) at 1 MeV



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

Rods connect the water transmission lines to the bottles at the stack

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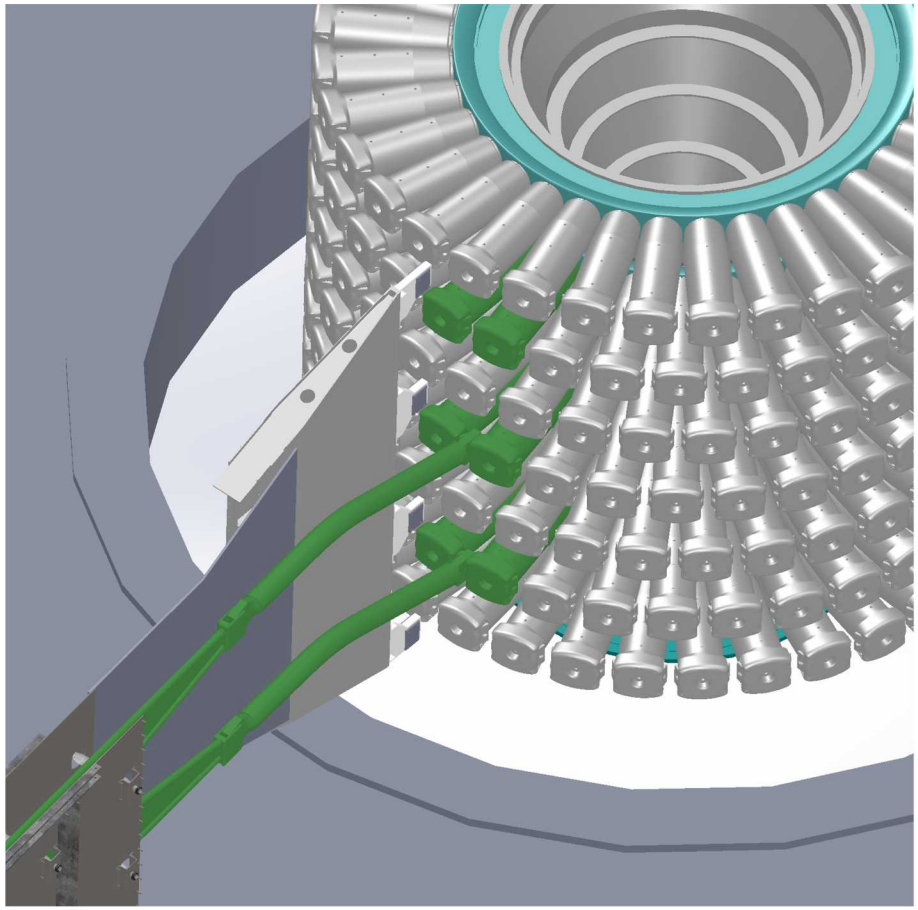
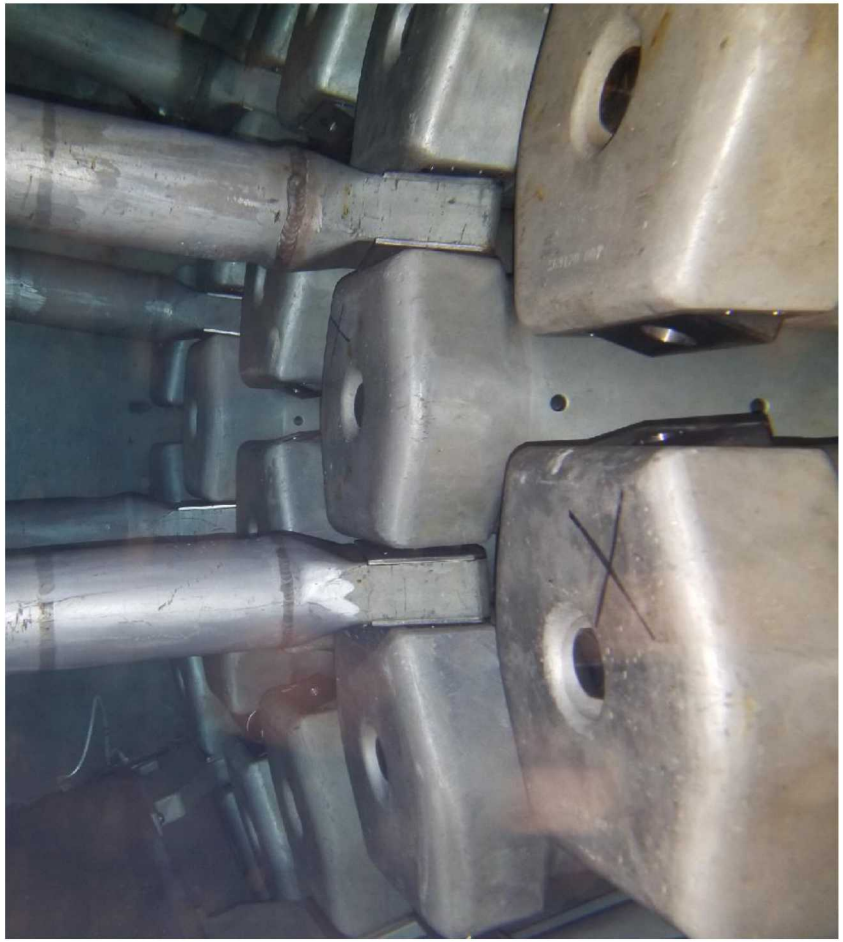
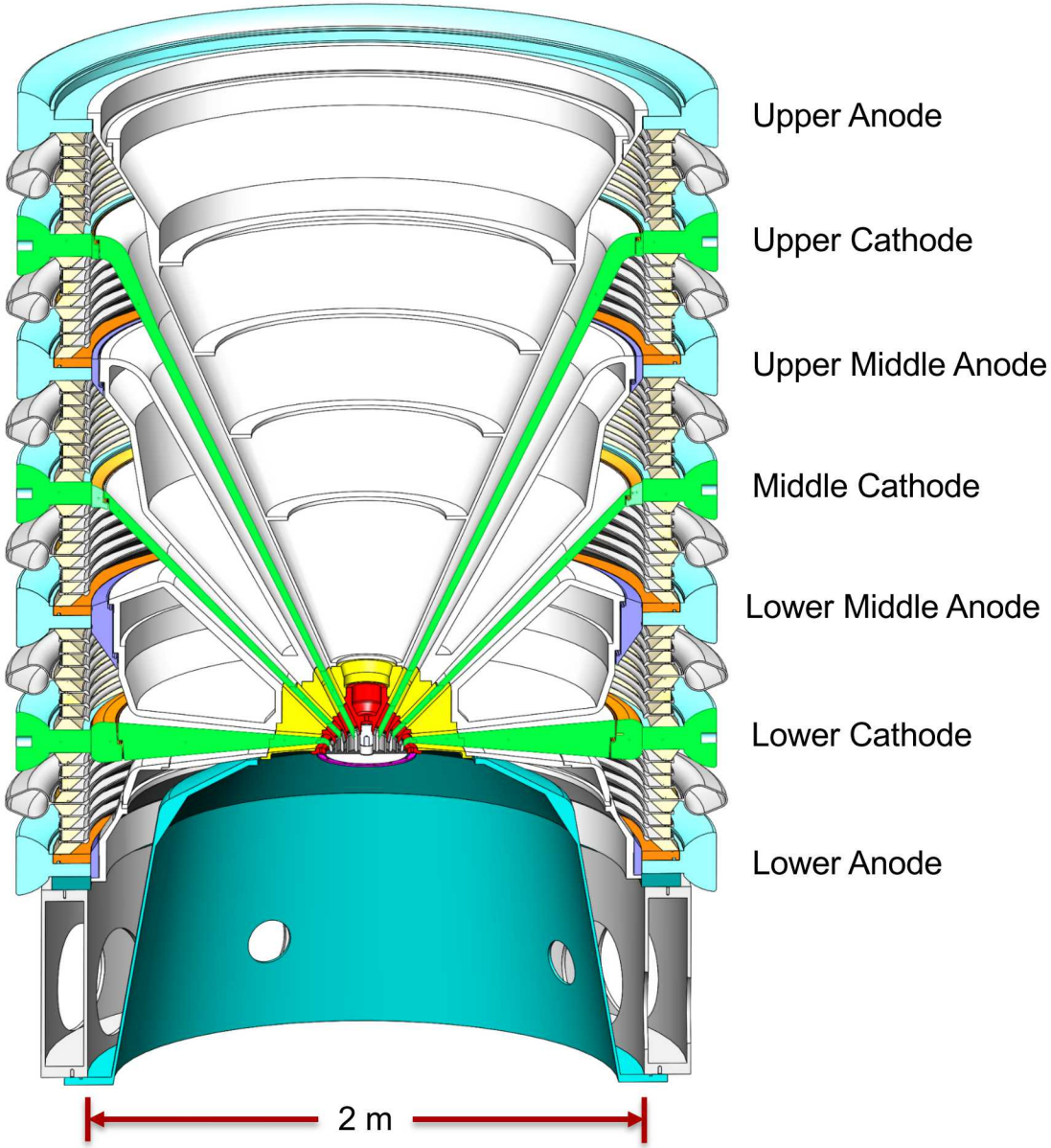




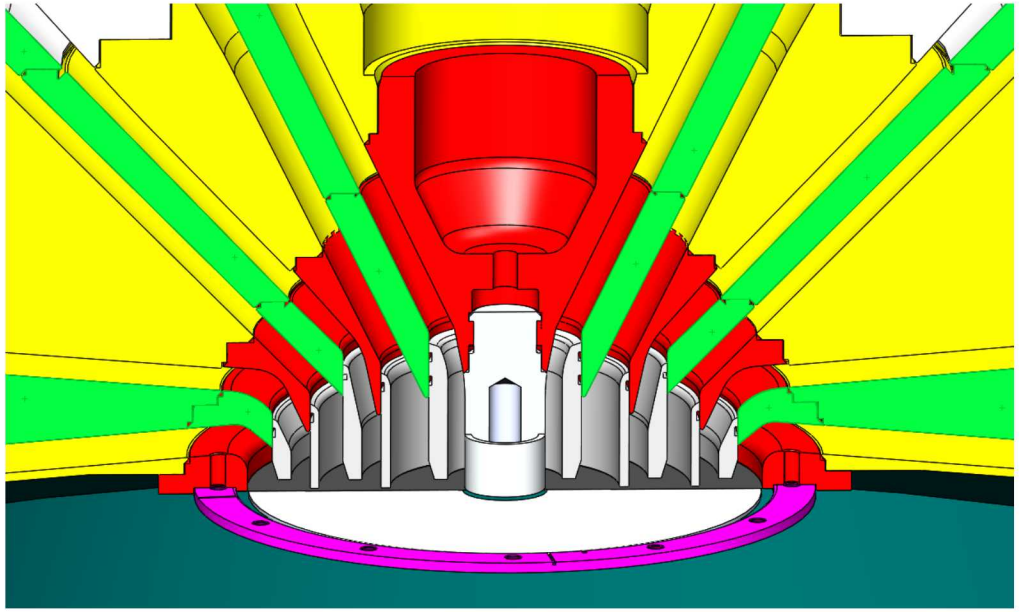
Vacuum Stack, MITLs, and Load Region

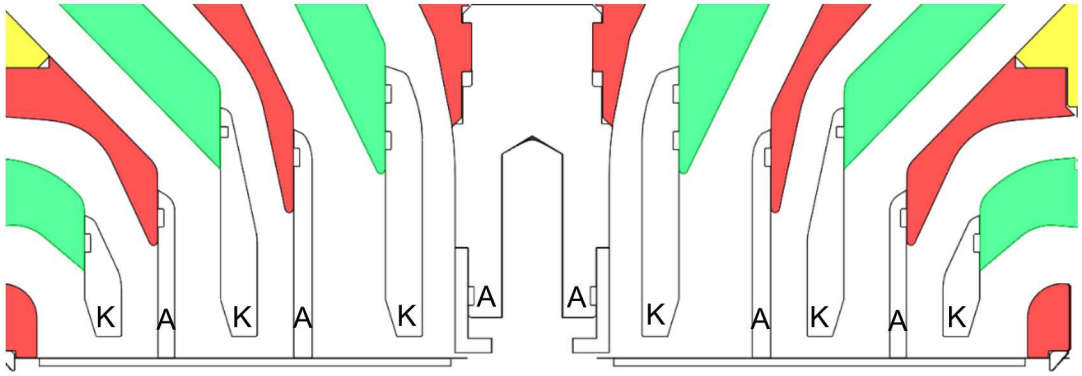


- 3 nested conical triaxial lines
- Bottom 2 lines are 2 Ω driven by 36 rods
- Middle two lines are 3 Ω driven by 24 rods
- Top two lines are 6 Ω driven by 12 rods
- Each conical electrode is made in three sections
- Replacing relatively small hardware close to the axis allows a variety of loads to be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

We need to rebuild/upgrade Saturn

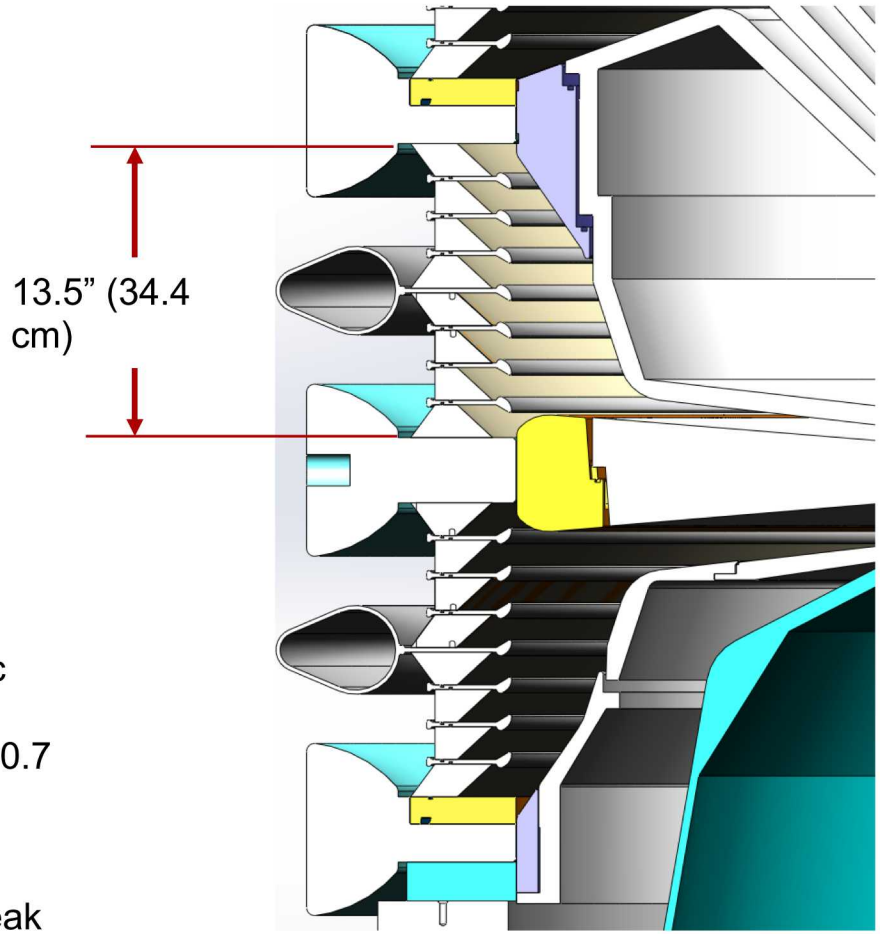
Over-riding requirement is to maintain existing capability

- The machine is 30 years old. Components are wearing out. We need to rebuild and replace many.
- We need to increase reproducibility and reliability
- Better/more diagnostics at stack and in vacuum
- We need to improve data collection and handling
  - Improved timing, delays
  - Cable compensation for fast signals
- Is feasible we want to double radiation output at the same or lower endpoint energy (1 MV)

Components that need attention:

- Rimfire gas switch (in oil or water?)
- Trigger for the rimfire gas switch
  - Upgrade existing electrical trigger
  - Or, implement laser triggering
- Water/Vacuum insulator stack
  - Too conservative, too much inductance
  - Mechanical wear and tolerance
- Connections to the vacuum lines (water bottles)
- Intermediate store water capacitor
- Mechanical alignment of water switches
- Water line impedance
- Lower impedance diode

A & B Stack Dimensions



Total height – 7 x grading ring height = plastic height

34.4 cm - 7 x 0.526 cm = 30.7 cm (12”)

For a peak voltage of 2.0 MV, the average peak field is

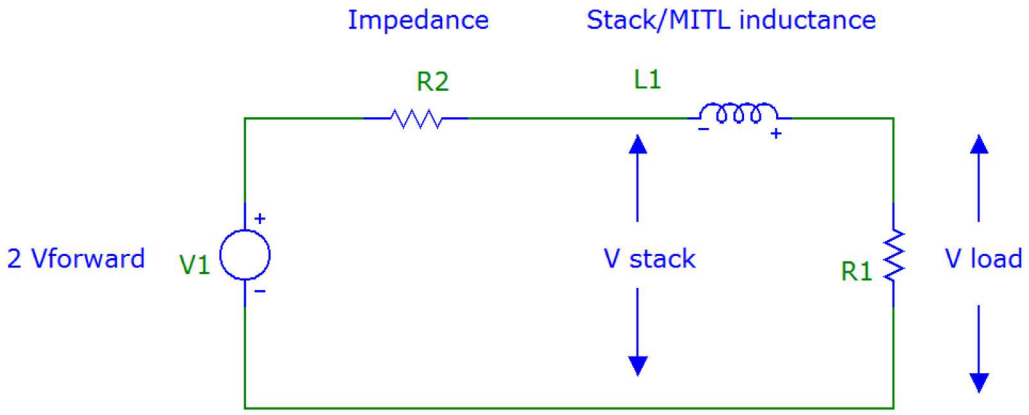
2000 kV / 30.7 cm = 65 kV/cm

Potential upgrade options

- Same water-line architecture
  - Minor changes, refurbish existing components
  - Design changes to better access unused Marx bank energy
- Fast Marx design that could eliminate need for gas switch
- Magnetic switching to replace water switching
- Others?

Much can be learned from simple scaling calculations using a sine-squared drive pulse

- Represent the machine as an LRC circuit with a resistive load
  - Inductance primarily the stack and MITLs
  - Consider the load as a fixed small resistance (0.1 Ohm)
- Estimate radiation scaling as current x diode voltage^2.7
- Look at effects of voltage, current, inductance



2.0 MV sine-squared drive, FWHM 25 ns

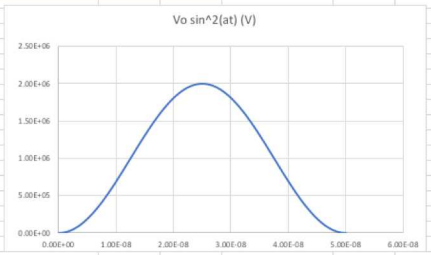
A & B MITLS only

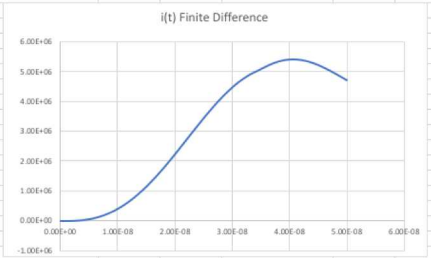
36 8-Ohm rods

Double-exponential diode resistance

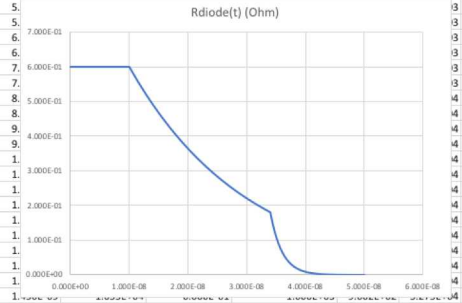
Current solved with a 50 ps timestep

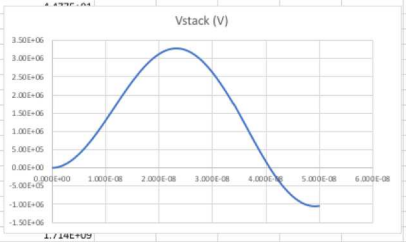
Input Parameters			Derived Parameters		
Vo =	2.00E+06	Volts			
Z oneline =	8	Ohm	Zmachine =	2.222E-01	Ohm
T half =	2.50E-08	sec	a =	6.283E+07	rad/sec
n lines to diode =	36				
L stack & MITLs =	9.70E-09	Henries			
Initial diode resistance =	0.6	Ohm			
Time constant 1, exp decay =	2.00E-08	sec			
Tstart, exp decay =	1.00E-08	sec			
Time constant 2, exp decay =	2.00E-09	sec	delta T =	5.000E-11	sec
T peak radiation =	3.40E-08	sec	R at Tpeak =	1.807E-01	

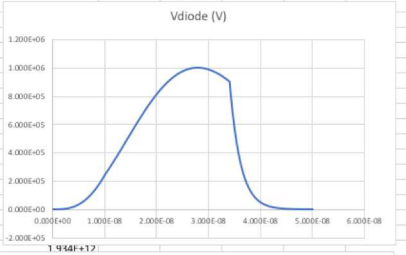


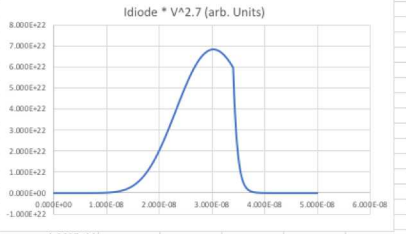


Index	t (sec)	Vo sin^2(at) (V)	Rdiode(t) (Ohm)	i(t) Finite Difference	Vdiode (V)	Vstack (V)	Idiode V^2.7 (arb. Units)
0	0.000E+00	0.000E+00	6.000E-01	0.000E+00	0.000E+00	0	0.000E+00
1	5.000E-11	1.974E+01	6.000E-01	0.000E+00	0.000E+00	3.948E+01	0.000E+00
2	1.000E-10	7.896E+01	6.000E-01	4.070E-01	2.442E-01	1.578E+02	9.046E-03
3	1.500E-10	1.776E+02	6.000E-01	1.625E+00	9.747E-01	3.549E+02	1.516E+00
4	2.000E-10	3.158E+02	6.000E-01	4.056E+00	2.434E+00	6.307E+02	
5	2.500E-10	4.934E+02	6.000E-01	8.102E+00	4.861E+00	9.851E+02	
6	3.000E-10	7.105E+02	6.000E-01	1.416E+01	8.497E+00	1.418E+03	
7	3.500E-10	9.671E+02	6.000E-01	2.263E+01	1.358E+01	1.929E+03	
8	4.000E-10	1.263E+03	6.000E-01	3.391E+01	2.035E+01	2.519E+03	
9	4.500E-10	1.598E+03	6.000E-01	4.839E+01	2.903E+01	3.186E+03	
10	5.						
11	5.						
12	6.						
13	6.						
14	7.						
15	7.						
16	8.						
17	8.						
18	9.						
19	9.						
20	1.						
21	1.						
22	1.						
23	1.						
24	1.						
25	1.						
26	1.						
27	1.						
28	1.						
29	1.						
30	1.500E-09	1.771E+04	6.000E-01	1.770E+03	1.062E+03	3.503E+04	
31	1.550E-09	1.891E+04	6.000E-01	1.951E+03	1.170E+03	3.739E+04	
32	1.600E-09	2.014E+04	6.000E-01	2.143E+03	1.286E+03	3.981E+04	
33	1.650E-09	2.142E+04	6.000E-01	2.348E+03	1.409E+03	4.232E+04	
34	1.700E-09	2.273E+04	6.000E-01	2.565E+03	1.539E+03	4.489E+04	
35	1.750E-09	2.408E+04	6.000E-01	2.795E+03	1.677E+03	4.755E+04	
36	1.800E-09	2.547E+04	6.000E-01	3.038E+03	1.823E+03	5.027E+04	
37	1.850E-09	2.690E+04	6.000E-01	3.294E+03	1.976E+03	5.307E+04	
38	1.900E-09	2.837E+04	6.000E-01	3.564E+03	2.139E+03	5.594E+04	
39	1.950E-09	2.987E+04	6.000E-01	3.849E+03	2.309E+03	5.889E+04	
40	2.000E-09	3.142E+04	6.000E-01	4.148E+03	2.489E+03	6.191E+04	
41	2.050E-09	3.300E+04	6.000E-01	4.461E+03	2.677E+03	6.501E+04	
42	2.100E-09	3.462E+04	6.000E-01	4.790E+03	2.874E+03	6.817E+04	
43	2.150E-09	3.628E+04	6.000E-01	5.135E+03	3.081E+03	7.141E+04	
44	2.200E-09	3.797E+04	6.000E-01	5.495E+03	3.297E+03	7.472E+04	
45	2.250E-09	3.971E+04	6.000E-01	5.871E+03	3.523E+03	7.811E+04	
46	2.300E-09	4.148E+04	6.000E-01	6.264E+03	3.758E+03	8.156E+04	
47	2.350E-09	4.329E+04	6.000E-01	6.673E+03	4.004E+03	8.509E+04	
48	2.400E-09	4.514E+04	6.000E-01	7.100E+03	4.260E+03	8.869E+04	
49	2.450E-09	4.702E+04	6.000E-01	7.544E+03	4.526E+03	9.236E+04	
50	2.500E-09	4.894E+04	6.000E-01	8.005E+03	4.803E+03	9.611E+04	
51	2.550E-09	5.090E+04	6.000E-01	8.485E+03	5.091E+03	9.992E+04	
52	2.600E-09	5.290E+04	6.000E-01	8.983E+03	5.390E+03	1.038E+05	1.068E+14
53	2.650E-09	5.494E+04	6.000E-01	9.499E+03	5.700E+03	1.078E+05	1.314E+14
54	2.700E-09	5.701E+04	6.000E-01	1.004E+04	6.021E+03	1.118E+05	1.609E+14
55	2.750E-09	5.912E+04	6.000E-01	1.059E+04	6.354E+03	1.159E+05	1.964E+14
56	2.800E-09	6.127E+04	6.000E-01	1.116E+04	6.699E+03	1.201E+05	2.388E+14
57	2.850E-09	6.345E+04	6.000E-01	1.176E+04	7.055E+03	1.243E+05	2.893E+14
58	2.900E-09	6.567E+04	6.000E-01	1.237E+04	7.424E+03	1.286E+05	3.493E+14
59	2.950E-09	6.793E+04	6.000E-01	1.301E+04	7.805E+03	1.330E+05	4.203E+14
60	3.000E-09	7.022E+04	6.000E-01	1.366E+04	8.198E+03	1.374E+05	5.041E+14
61	3.050E-09	7.255E+04	6.000E-01	1.434E+04	8.604E+03	1.419E+05	6.028E+14
62	3.100E-09	7.492E+04	6.000E-01	1.504E+04	9.023E+03	1.465E+05	7.187E+14
63	3.150E-09	7.733E+04	6.000E-01	1.576E+04	9.454E+03	1.512E+05	8.544E+14
64	3.200E-09	7.977E+04	6.000E-01	1.650E+04	9.899E+03	1.559E+05	1.013E+15
65	3.250E-09	8.225E+04	6.000E-01	1.726E+04	1.036E+04	1.607E+05	1.197E+15
66	3.300E-09	8.476E+04	6.000E-01	1.805E+04	1.083E+04	1.655E+05	1.412E+15
67	3.350E-09	8.731E+04	6.000E-01	1.886E+04	1.131E+04	1.704E+05	1.660E+15
68	3.400E-09	8.989E+04	6.000E-01	1.969E+04	1.181E+04	1.754E+05	1.948E+15

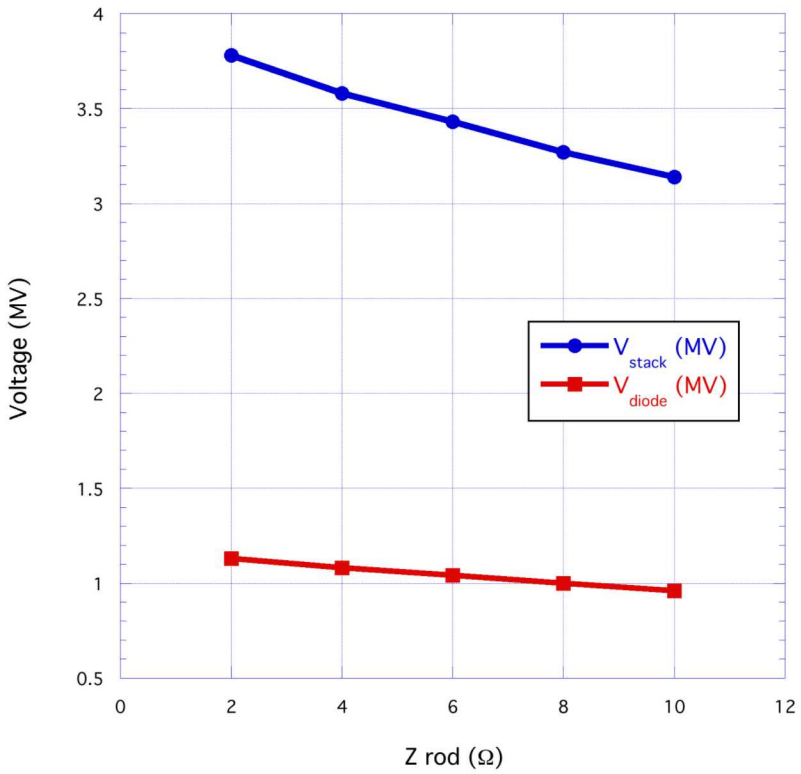


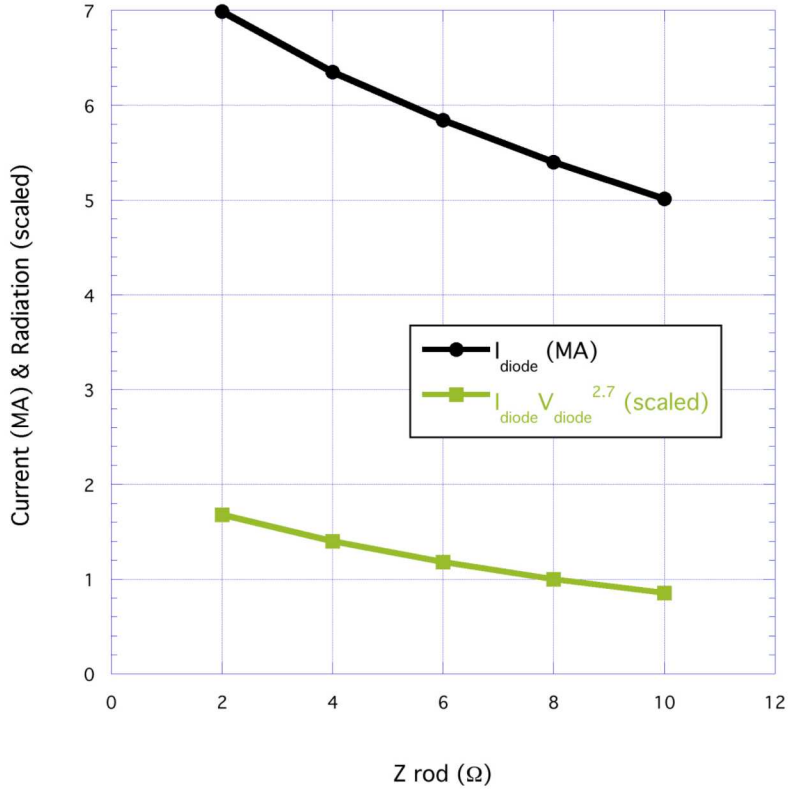






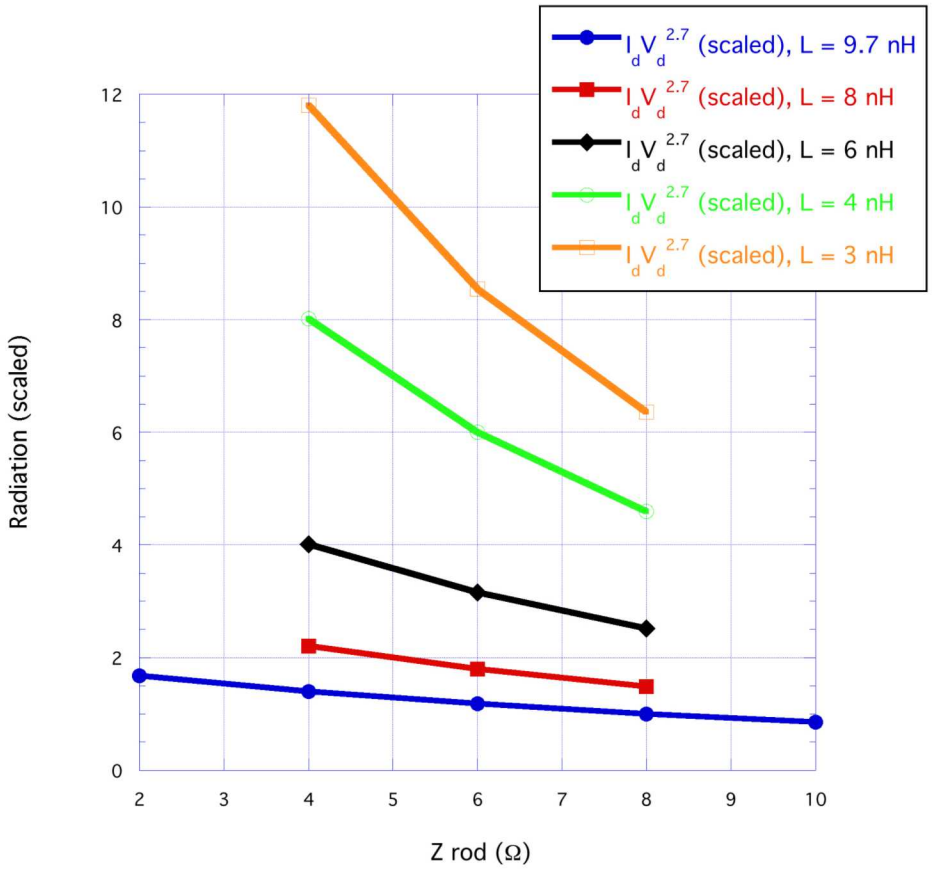
Scaling of the existing configuration with rod impedance
Peak voltage, current, and radiation vs. Z rod

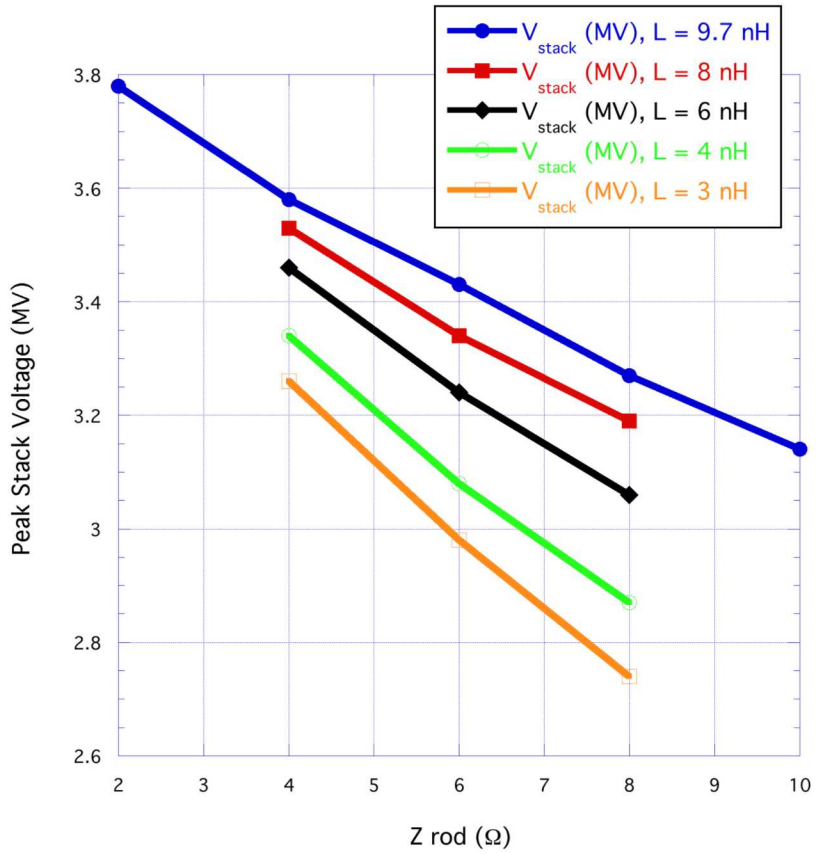




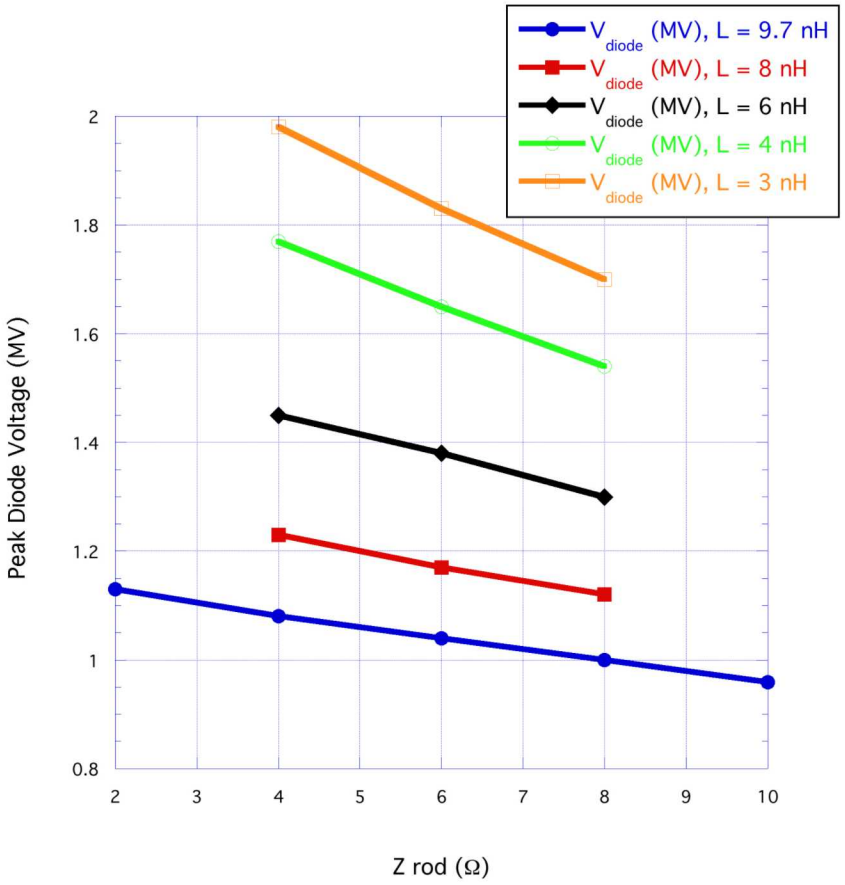
Radiation yield scaled to configuration with 8 Ohm rods with 9.7 nH A&B Stack & MITL inductance

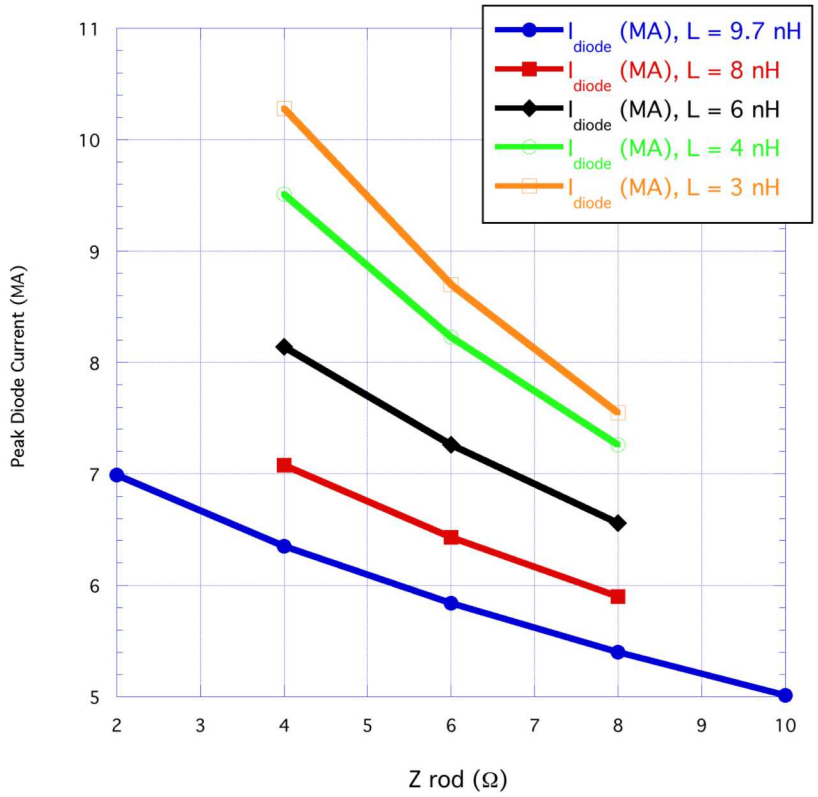
Radiation & Stack Voltage vs L and Z





Diode Voltage & Current vs. L and Z





Observations from the scaling study

- Stack voltage relatively insensitive to L and Z, but
  - Decreases with decreasing L
  - Increases with decreasing Z
  - Linear with V_o
- Current very sensitive to L and Z
- Rad output proportional to current to the 3.7 power since diode voltage = I R_{diode}

Conclusions

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- We are still in the position of deciding how much to change for the rebuild of Saturn.
- Redesign and rebuild of the gas switches already started, but major design changes of other components yet to be decided.
- Options are available for both increasing reliability as well as performance.
- Most likely approach will be to rebuild Saturn using the existing water-line architecture with improvements to some components and functions, and seeking to use more energy from the Marx bank.