COMPARISON OF THE PERFORMANCE OF THE UPGRADED Z WITH CIRCUIT PREDICTIONS

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Abstract

Since the completion of the ZR upgrade of the Z accelerator at the Sandia National Laboratories in the fall of 2007, many shots have been taken on the accelerator, and there has been much opportunity to compare circuit-code predictions of the performance of the machine with actual measurements. We therefore show comparisons of measurements, and describe a full-circuit, 36-line Bertha circuit model of the machine. The model has been used for both short-pulse and long-pulse (tailored pulse) modes of operation. We also present the as-built circuit parameters of the machine and indicate how these were derived. We discuss enhancements to the circuit model that include 2D effects in the water lines, but show that these have little effect on the fidelity of the simulations. Finally, we discuss how further improvements can be made to handle azimuthal coupling of the multiple lines at the vacuum insulator stack.

I. INTRODUCTION

The Pulsed Power Sciences Center at Sandia National Laboratory recently completed a refurbishment project of the Z accelerator. [1] ZR (the refurbished Z accelerator) is the world's largest pulse power accelerator of its kind and is primarily used as a driver for z-pinch inertial confinement fusion experiments (ICF), isentropic compression experiments (ICE), and other high energy density physics related work. Prior to the refurbishment, a transmission line circuit model of Z was created to predict voltages and currents in the accelerator [2]. With the completion of the refurbishment it was necessary to upgrade the model to include as-built parameters of the new components. A drawing of ZR is given in Fig. 1.

In this paper we describe the upgraded transmission line circuit model for ZR. In section II we describe how the circuit parameters were obtained using both 2D and 3D electrostatic field solvers, and describe the resulting circuit model. In section III we discuss 2D transmission line modeling for the non-symmetric components, and indicate how this is implemented in the circuit code. In section IV we present both 1D and 2D transmission line simulations for ZR shot 1780 (which had an inductive, short-ciruit load), and compare with data taken from the shot. In section V we summarize our results and offer suggestions for improvement and future development.

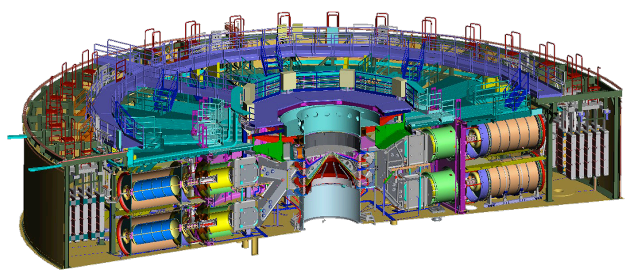

Fig. 1. Cut-away drawing of the 33-m diameter ZR accelerator.

II. ELECTROSTATIC MODELING

ZR generates a large current (20 to 30 MA) that is delivered to various experimental loads. For ICF experiments with a z-pinch load, the desired pulse is 26 MA or higher with a rise time of about 100 ns. These pulses are formed in pulse power lines that consist of a combination of capacitors, transmission lines, and switches. ZR has 36 pulse-power lines grouped in pairs (one on top of another creating 18 pairs) that feed into a center section containing the experimental load. The pulse is generated in each line by discharging a Marx capacitor bank containing sixty 2.6 μF capacitors charged between 60-100 kV. When discharged current flows into a 23 nF intermediate storage capacitor (IS). At this point the rise time of the pulse is roughly 1.5 μs. Charge accumulates in the IS until a laser triggered gas switch (LTGS) triggers the line to synchronize it with the other 36 lines so that all pulses arrive at the load simultaneously. The pulse then flows into a pulse forming line (PFL), a water switch

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14. ABSTRACT
Since the completion of the ZR upgrade of the Z accelerator at the Sandia National Laboratories in the fall of 2007, many shots have been taken on the accelerator, and there has been much opportunity to compare circuitcode predictions of the performance of the machine with actual measurements. We therefore show comparisons of measurements, and describe a full-circuit, 36-line Bertha circuit model of the machine. The model has been used for both short-pulse and long-pulse (tailored pulse) modes of operation. We also present the as-built circuit parameters of the machine and indicate how these were derived. We discuss enhancements to the circuit model that include 2D effects in the water lines, but show that these have little effect on the fidelity of the simulations. Finally, we discuss how further improvements can be made to handle azimuthal coupling of the multiple lines at the vacuum insulator stack.

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(WS), a first output transmission line (OTL1), a pre-pulse water switch (PPWS), and then a second output transmission line (OTL2) where upper and lower lines are combined. The output of the vertical OTL2s connect through water convolutes (WC) to four horizontal disk transmission lines at the vacuum insulator stack. The combined effect of the switches, capacitors, and transmission lines reduces the rise time of the pulse to roughly 100 ns. Passing through the stack, current flows in vacuum through four magnetically insulated transmission lines (MITLs) that are connected in parallel with a post-hole convolute (PHC) near the center of the machine. The resulting current is the sum of the outputs of all 36 lines, and is delivered to the load through a short disk and coaxial MITL. A cross sectional image of one of the 18 pulse power line pairs feeding into the stack is given in Fig. 2.

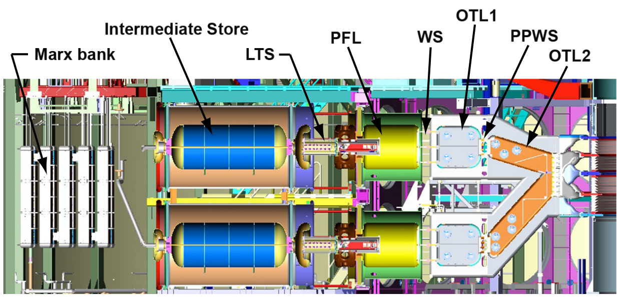


Fig. 2. Cross-sectional view of two-line pair of ZR pulsed power lines.

Before a transmission line circuit-code model of ZR can be implemented the characteristic impedance and resistive loss for each circuit component must determined. This is done by dividing each component into smaller segments, and determining the characteristic impedance Z_0 for each segment. These calculations were done with the 2D Electro and 3D Coulomb electrostatic field solvers. [3]

The process for determining Z_0 is to use the electrostatic solver to calculate the capacitance C of each segment, and to estimate the propagation time Δt through that segment. The propagation time is found by measuring the length of the central voltage contour, and dividing by the propagation velocity in that component. Alternatively, one can calculate the inductance L of that segment with a magnetic field solver, and use both the capacitance and inductance to determine Z_0. The relationship between these parameters is given by:

$$Z_0 = \frac{L}{\Delta t} = \frac{\Delta t}{C} = \sqrt{\frac{L}{C}} \qquad (1)$$

Thus, Z_0 can be found from either the inductance or capacitance of a segment. The following tables (1 through 11) and figures (3 through 7) give values so derived and show some of the unique geometries of the machine. These values were then used to construct a 36-line, full-circuit Bertha [4] model of ZR.

Table 1. Marx bank parameters for ZR shot 1780.

Charge Voltage:	82.00	kV
Marx Capacitance:	43.30	nF
Marx Inductance:	13500.00	nH
Marx Resistance	3.00	Ω
Resistance to Ground	567.00	Ω
Inductance to I-Store Up:	2000.00	nH
Inductance to I-Store Down:	1175.00	nH

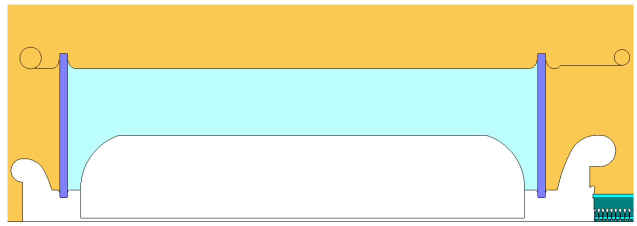


Fig. 3. Intermediate store configuration for the capacitance calculation with Electro. Yellow regions are transformer oil, light blue is water, dark blue polyurethane insulators, and white regions are the conductors.

Table 2. Intermediate store parameters.

	C (F)	Length (m)	Dielectric	Δt (ns)	Z (Ω)	L (H)	R (Ω)
1	5.92E-11	2.37E-01	oil	1.17	19.82	2.32E-08	
2	9.69E-12	5.60E-02	poly	0.37	38.53	1.44E-08	
3	1.95E-09	3.35E-01	water	9.99	5.13	5.12E-08	2.06E+04
4	2.44E-09	2.86E-01	water	8.53	3.50	2.99E-08	1.65E+04
5	1.96E-09	2.48E-01	water	7.40	3.77	2.79E-08	2.05E+04
6	3.26E-09	4.14E-01	water	12.35	3.79	4.68E-08	1.23E+04
7	3.26E-09	4.14E-01	water	12.35	3.79	4.68E-08	1.23E+04
8	3.26E-09	4.14E-01	water	12.35	3.79	4.68E-08	1.23E+04
9	2.21E-09	2.80E-01	water	8.35	3.77	3.15E-08	1.82E+04
10	2.70E-09	3.18E-01	water	9.49	3.52	3.33E-08	1.49E+04
11	1.93E-09	3.34E-01	water	9.96	5.16	5.14E-08	2.08E+04
12	9.69E-12	5.70E-02	poly	0.38	39.22	1.49E-08	
13	1.32E-10	2.83E-01	oil	1.40	10.63	1.49E-08	
Total length (ns)		9.41E+01		Dielectric	ε_r	ρ	
Total length (m)		3.68E+00		oil	2.2		
	Total C (F)	2.32E-08		polyurethane	4.0		
	Total L (H)	4.33E-07		water	80.0	5.66	MΩ-cm
	Total R (Ω)	1.75E+03					

Table 3. Parameters for the LTS.

	C (F)	Δx (m)	Dielectric	Δt (ns)	Z (Ω)	L (H)
1	3.52E-13	0.03	gas	0.010	284.1	2.84E-08
2	6.61E-13	0.03	gas	0.010	151.5	1.52E-08
3	9.85E-13	0.03	gas	0.010	101.6	1.02E-08
4	2.09E-12	0.03	gas	0.010	48.0	4.80E-09
5	1.71E-12	0.03	gas	0.010	58.6	5.86E-09
6	2.16E-13	0.03	gas	0.010	462.8	4.63E-08
7	2.63E-13	0.03	gas	0.010	381.3	3.82E-08
8	3.07E-13	0.03	gas	0.010	326.5	3.27E-08
9	3.44E-13	0.03	gas	0.010	290.7	2.91E-08
10	3.74E-13	0.03	gas	0.010	267.8	2.68E-08
11	3.99E-13	0.03	gas	0.010	250.9	2.51E-08
12	4.18E-13	0.03	gas	0.010	239.5	2.40E-08
13	4.24E-13	0.03	gas	0.010	236.0	2.36E-08
14	4.20E-13	0.03	gas	0.010	238.3	2.39E-08
15	4.03E-13	0.03	gas	0.010	248.3	2.49E-08
16	3.74E-13	0.03	gas	0.010	267.8	2.68E-08
17	3.34E-13	0.03	gas	0.010	299.8	3.00E-08
18	2.75E-13	0.03	gas	0.010	363.9	3.64E-08
19	2.09E-12	0.03	gas	0.010	48.0	4.80E-09
20	1.39E-12	0.03	gas	0.010	71.8	7.19E-09
21	6.47E-13	0.03	gas	0.010	154.8	1.55E-08
22	9.68E-12	0.05	gas	0.017	36.9	6.28E-09
Total Length (ns)		2.27		R open	1.00E+04	Ω
Total Length (m)		0.68		R closed	1.10	Ω
Total C (F)		2.42E-11		τ	1.65	ns
Total L (H)		4.86E-07		Switch Time	1210.00	ns

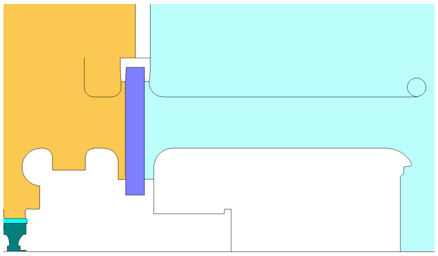


Fig. 4. PFL configuration for the Electro calculation. Same color scheme as previous figure.

Table 4. Parameters for the PFL.

	C (F)	Δx (m)	Dielectric	Δt (ns)	Z (Ω)	L (H)	R (Ω)
1	2.19E-11	0.117	oil	0.58	26.48	1.53E-08	
2	1.55E-10	0.77	oil	3.81	24.52	9.34E-08	
3	3.26E-11	0.178	oil	0.88	27.00	2.38E-08	
4	4.57E-11	0.219	oil	1.08	23.71	2.57E-08	
5	2.47E-11	0.101	poly	0.67	27.26	1.84E-08	
6	1.00E-10	0.051	water	1.52	15.22	2.32E-08	1.42E+05
7	1.41E-09	0.102	water	3.04	2.16	6.57E-09	1.01E+04
8	1.56E-09	0.135	water	4.03	2.59	1.04E-08	9.12E+03
9	2.76E-09	0.25	water	7.46	2.70	2.02E-08	5.14E+03
10	2.76E-09	0.25	water	7.46	2.70	2.02E-08	5.14E+03
11	2.25E-09	0.202	water	6.03	2.67	1.61E-08	6.30E+03
12	2.32E-09	0.202	water	6.03	2.60	1.57E-08	6.12E+03
13	1.50E-09	0.119	water	3.55	2.37	8.42E-09	9.49E+03
14	2.95E-09	0.127	water	3.79	1.29	4.87E-09	4.82E+03
Total	49.928	ns		Dielectric	ε_r	ρ	
Total	2.823	m		Oil	2.2		
Total	1.788E-08	F		Polyurethane	4		
Total	3.021E-07	H		Water	80	2.00	MΩ-cm
Total	806.635	Ω					

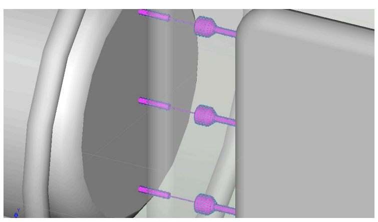


Fig. 5. Water switches between the PFL and OTL1.

Table 5. Water switch parameters.

	L (H)	Δx (m)	Dielectric	Δt (ns)	Z (Ω)	C (F)
1	1.80E-08	0.146	water	4.36	4.13	9.49E-10
2	3.36E-08	0.12	water	3.58	9.39	2.62E-09
3	2.82E-08	0.165	water	4.92	5.73	1.16E-09
Total Length (ns)		12.86		R open (Ω)	1000	
	Total C (F)	4.73E-09		R closed (Ω)	0.1	
	Parallel C (F)	7.42E-10		τ (ns)	9	
	Total L (H)	7.98E-08				

Table 6. Parameters for the OTL1.

	C (F)	Δx (m)	Dielectric	Δt (ns)	Z (Ω)	L (H)	R (Ω)
1	6.07E-10	0.077	water	2.30	3.79	8.70E-09	23410.65
2	6.76E-10	0.077	water	2.30	3.40	7.80E-09	20991.11
3	1.93E-09	0.21	water	6.27	3.25	2.03E-08	7360.25
4	1.93E-09	0.21	water	6.27	3.25	2.03E-08	7360.25
5	1.15E-09	0.12	water	3.58	3.12	1.12E-08	12380.26
6	1.15E-09	0.12	water	3.58	3.12	1.12E-08	12380.26
7	8.45E-10	0.1	water	2.98	3.53	1.05E-08	16811.67
8	6.70E-10	0.1	water	2.98	4.45	1.33E-08	21198.36
9	4.95E-10	0.1	water	2.98	6.03	1.80E-08	28682.51
Total Length (ns)		33.24		ρ (MΩ-cm)	2.00		
	Total C (F)	9.45E-09					
	Total L (H)	1.21E-07					
	Total R (Ω)	1.50E+03					

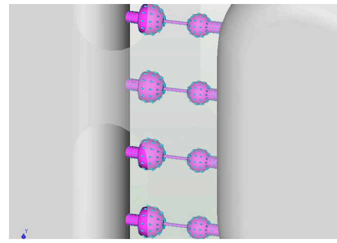


Fig. 6. Pre-pulse water switches between the OTL1 and OTL2 transmission lines.

Table 7. Parameters for the pre-pulse water switches.

	L (H)	Δx (m)	Dielectric	Δt (ns)	Z (Ω)	C (F)
1	6.36E-09	0.0619	water	1.85	11.75	1.57E-01
2	5.88E-09	0.0403	water	1.20	7.07	1.70E-01
3	5.47E-09	0.0518	water	1.55	8.46	1.83E-01
Total Length (ns)		4.60		R open (Ω)	1000	
	Total C (F)	5.10E-01		R closed (Ω)	0.1	
	Parallel C (F)	1.20E-09		τ (ns)	2	
	Total L (H)	4.33E-08				

Table 8. The 1D model of the upper arm of the OTL2.

	C (F)	Δx (m)	Dielectric	Δt (ns)	Z (Ω)	L (H)	R (Ω)
1	7.18E-10	0.154	water	4.60	6.40	2.94E-08	1.98E+04
2	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
3	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
4	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
5	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
6	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
7	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
8	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
9	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
10	7.42E-10	0.159	water	4.75	6.40	3.01E-08	1.91E+04
11	7.42E-10	0.159	water	4.75	6.40	3.01E-08	1.91E+04
Total Length (ns)		46.10		ρ (MΩ-cm)	2.00		
	Total C (F)	7.20E-09		Total R (Ω)	1.97E+03		
	Total L (H)	2.94E-07					

Table 9. The 1D model of the lower arm of the OTL2.

	C (F)	Δx (m)	Dielectric	Δt (ns)	Z (Ω)	L (H)	R (Ω)
1	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
2	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
3	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
4	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
5	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
6	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
7	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
8	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
9	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
10	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
11	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
12	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
13	6.25E-10	0.134	water	4.00	6.40	2.56E-08	2.27E+04
14	6.88E-10	0.148	water	4.40	6.40	2.82E-08	2.07E+04
15	5.86E-10	0.126	water	3.75	6.40	2.40E-08	2.42E+04
16	5.86E-10	0.126	water	3.75	6.40	2.40E-08	2.42E+04
Total Length (ns)		63.90		ρ (MΩ-cm)	2.00		
	Total C (F)	9.99E-09		Total R (Ω)	1.42E+03		
	Total L (H)	4.09E-07					

Table 10. The 1D model of the mixer section, the short section where the two arms of the OTL2 are joined.

	C (F)	Δx (m)	Dielectric	Δt (ns)	Z (Ω)	L (H)	R (Ω)
1	1.29E-09	0.178	water	5.30	4.10	2.17E-08	1.10E+04
2	1.29E-09	0.178	water	5.30	4.10	2.17E-08	1.10E+04
Total Length (ns)		10.60		ρ (MΩ-cm)	2.00		
	Total C (F)	2.58E-09		Total R (Ω)	5.50E+03		
	Total L (H)	4.34E-08					

Table 11. Parameters of the water convolute and the four MITLs, A (upper most), B, C, and D (lowest).

	A		B		C		D	
	Δt (ns)	Z (Ω)	Δt (ns)	Z (Ω)	Δt (ns)	Z (Ω)	Δt (ns)	Z (Ω)
Water convolute	12.45	0.705	12.45	0.705	12.13	0.837	12.13	0.837
	5.26	0.73	5.26	0.73	4.65	0.859	4.65	0.859
Stack and MITLs	1.350	1.21	1.350	1.21	1.350	1.44	1.350	1.44
	5.890	1.41	5.890	1.41	5.890	1.66	5.890	1.66
	0.227	8.65	0.227	8.65	0.227	10.12	0.227	10.12
	0.329	9.07	0.329	9.06	0.329	10.60	0.329	10.60
	0.518	11.90	0.850	11.33	0.365	17.90	0.607	14.53
	0.484	5.36	0.834	4.86	0.476	12.40	0.608	9.76
	1.380	2.33	1.110	2.41	0.471	4.90	0.463	8.92
	0.998	2.46	1.000	2.55	3.560	3.28	0.345	6.93
	1.010	2.70	1.000	2.80	1.000	3.39	3.810	3.30
	0.498	3.08	0.502	3.19	0.508	3.62	1.000	3.45
	0.504	3.97	0.506	4.05	0.504	4.26	0.508	3.73
							0.500	4.37

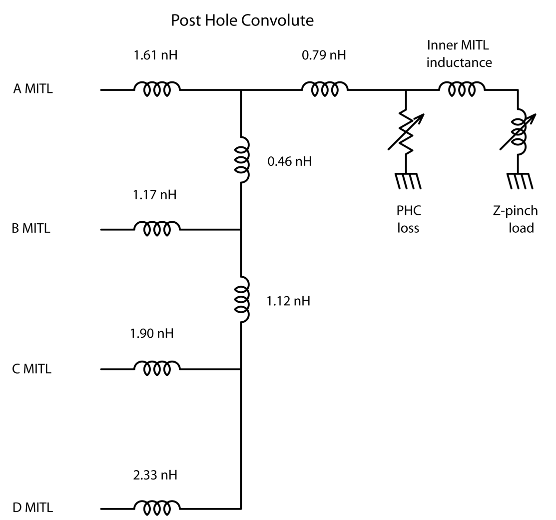


Fig. 7. Post-hole convolute and load region configuration.

III. 2D MODELING

Due to the non-symmetric geometries of some of the components on ZR, it is apparent that a 1D transmission-line model may not be sufficient for all components and 2D models may be needed. In particular, it may be necessary to use 2D modeling of the OTL2 to correctly simulate its effects. An approach of implementing a 2D model is based largely on the Transmission Line Matrix (TLM) method developed by P.B. Johns and W.J.R. Hoefer [5,6,7]. With this technique a two dimensional cross-sectional area is represented by set of a nodes each containing series inductance, and capacitance and resistance to ground. A diagram of a TLM node is shown in fig. 8, and its Bertha implementation in fig. 9.

With the TLM transmission line element implemented in Bertha, a 2D mesh of the entire OTL2 was made by joining hundreds of TLM circuit elements to fill the OTL2 geometry. The total capacitance and resistance of the OTL2 were calculated using Electro, and were divided among the individual elements. This gave a total resistance of 128 Ω and a capacitance of 19.31 nF. The distance across each element was calculated to be 5.62 cm or 1.67 ns. An illustration of the mesh configuration is given in Figs. 10 and 11.

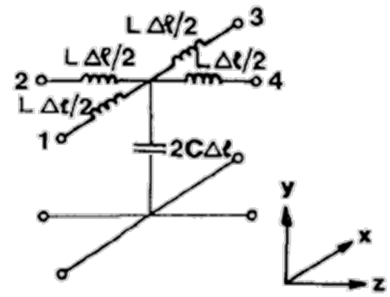


Fig. 8. Transmission line matrix (TLM) node [7].

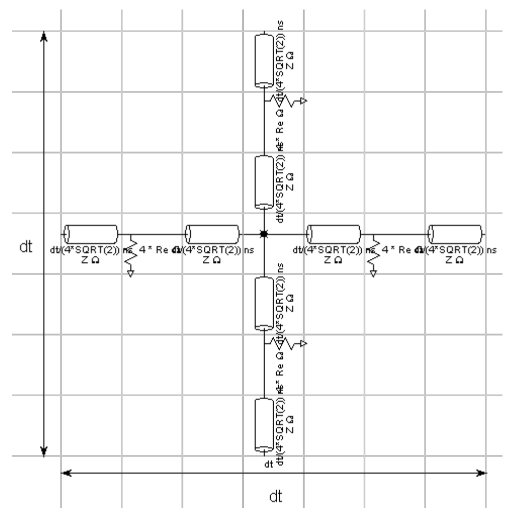


Fig. 9. Bertha implementation of a TLM node that includes resistive loss to ground.

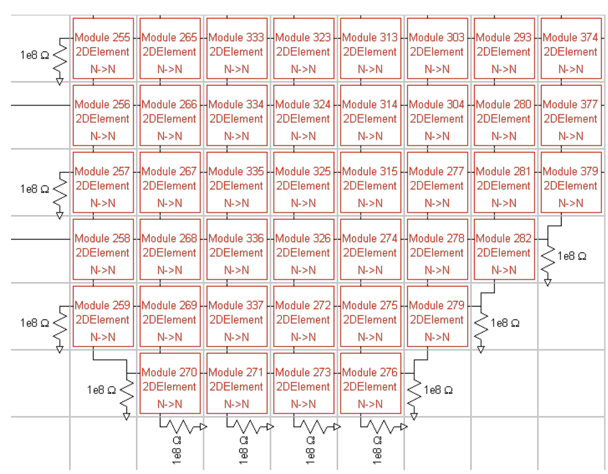


Fig. 10. Lower end of a 2D mesh of the lower arm of OTL2. Each square represents the 2D circuit shown in the previous figure.

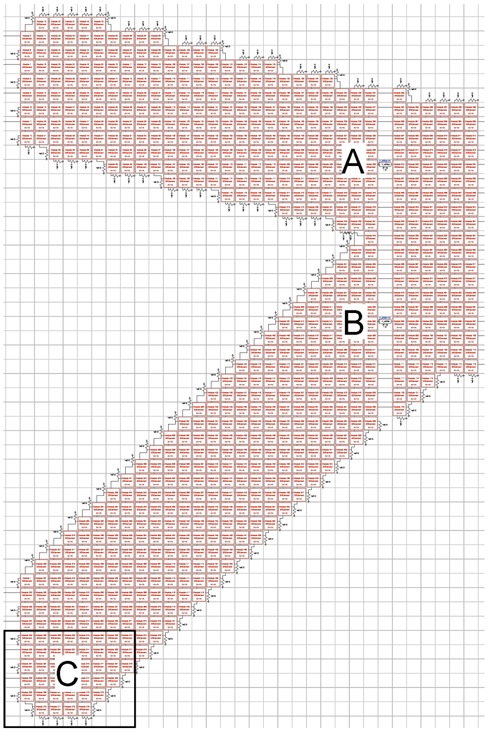


Fig. 11. Full 2D circuit of OTL2. The region C is shown in the previous figure, and regions A and B are the junctions of the upper and lower lines to the mixer.

IV. ZR BERTHA MODEL

Using the circuit parameters given above, a model was built to simulate ZR for a standard z-pinch shot. Bertha modules were made for the various components and connected to replicate a pair of pulse power lines as shown in Fig. 11. Parameters for the upper and lower lines vary slightly to account for different line lengths.

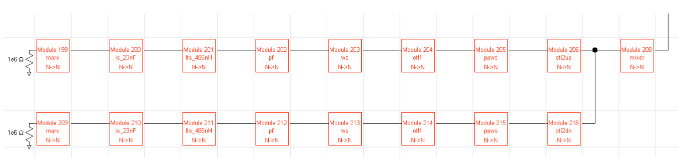
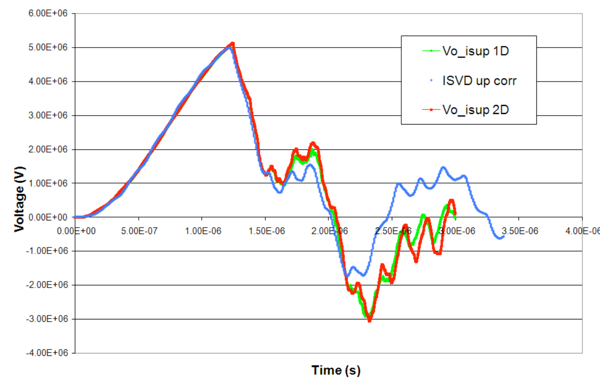


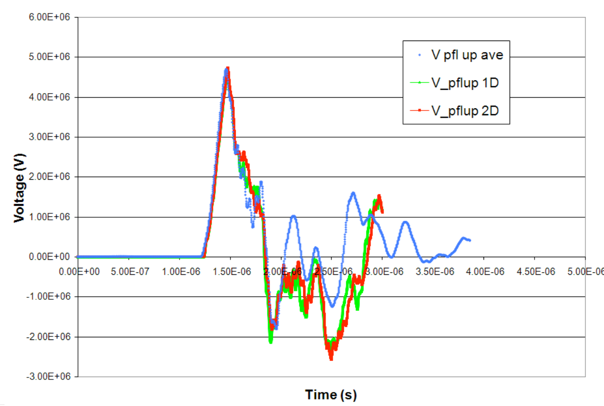
Fig. 11. Pair of pulse power modules in the Bertha circuit.

A complete model of ZR was created by connecting 18 pairs of lines to a 1D model of the center section and load. The resulting complete Bertha model of ZR is too large to show here. The full Bertha model of ZR, including the 2D mesh for the OTL2, contains over 100,000 transmission line elements and requires approximately one hour and 30 minutes to run on an Intel Dual Core machine running at 3.32 GHz. A version with a 1D model of the OTL2 has only 3600 transmission line elements, and runs in a few minutes.

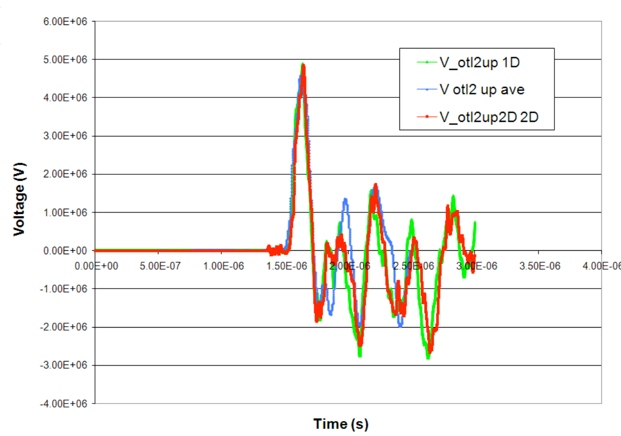
Fig. 12 contains voltage and current plots for several components that compare the Bertha simulations for both the 1D and 2D OTL2 models, with the measured values for shot 1780. As can be seen, the 2D model does not significantly improve the accuracy of the simulation. But, despite the difficulty involved in specifying parameters for so many components, the results of the model are generally in good agreement with measurements.



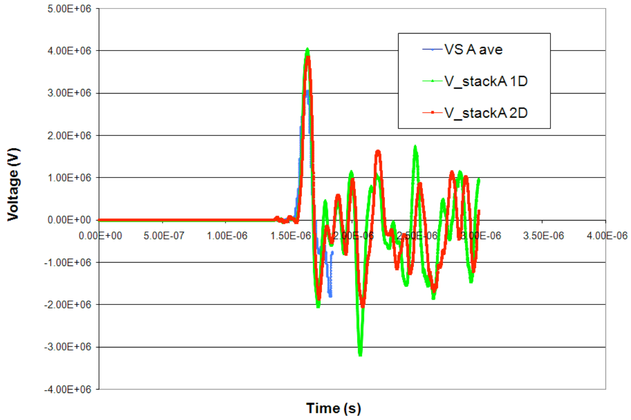
(a) Intermediate store voltage. Blue trace is measured, and green (1D) and red (2D) traces are simulations.



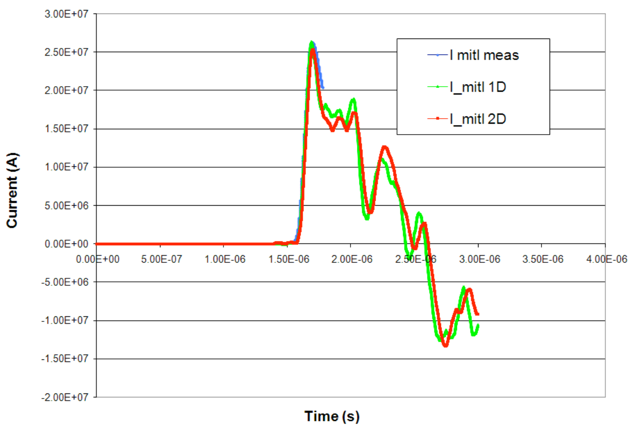
(b) Pulse-forming line voltage, same color convention.



(c) Output transmission line 2 voltage.



(d) Voltage at stack level A (upper-most level.)



(e) Current measured in the MITL.

Fig. 12. Comparison of measured voltage and current at several locations within ZR for shot 1780.

V. SUMMARY

Generally the Bertha model of ZR provides good agreement with measured voltages and currents. While there is some variance between the simulated and measured voltages and currents, the capacitive and inductance circuit parameters obtained from the electrostatic field solvers are close enough to give a reasonable characterization of the machine. While circuit parameters for some of the rotationally symmetric geometries (IS, LTS, PFL), and non-rotationally symmetric geometries (WS, OTL1, PPWS, OTL2) are readily obtained using 2D and 3D electromagnetic field solvers, circuit parameters for the switches that connect components in the pulse-forming section are not easily determined. Parameters for the center section components (water convolutes, insulator rings, MITLs, and post-hole convolute) were obtained from either hand calculation of 2D cross-sections or from 3D PIC-code simulations.[8]

We find through the process of running multiple simulations that the match to some of the smaller details in the waveform can be significantly altered by small changes in just a few parameters, some of which are not well characterized. Among the variables that can cause large variations with only small changes are: the inductance of the line from the Marx to the IS, the resistivity of the water in the IS, the switch time of the LTS, the rise time of the LTS, the switch time and closing rate of the WS and PPWS, the inductance of the water convolutes, and the impedance of the matching section between the OTL2, water convolutes and MITLs.

We also note that the 2D OTL2 model does not significantly improve the circuit simulations of ZR. But a potential improvement is to model the center section as four levels of a 2D mesh. In the latest model, all 18 pulse-power pairs connect at one point through one equivalent water convolute, rather than at azimuthally-separated positions around the vacuum insulator stack. The stack and MITLs, which are over 3 m in diameter, are treated as 1D transmission lines. But lines entering on opposite sides of the machine can provide significant delays that lead to pulse broadening. This effect is now not included in the circuit model but is likely important for tailored pulse shape shots where the various lines are fired at different times. But work is now being done to add a 2D model of this section to account for these delays.

VI. REFERENCES

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