SAND2013-4355C

Optimized Radial-Transmission-Line Impedance Transformer for a Petawatt-Class Pulsed-Power Accelerator*

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June 17, 2013
Presented at the PPPS, San Francisco, CA

*Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the National Nuclear Security Administration under DE-AC04-94AL85000.

We are using 2 and 3D EM models to optimize the design of a petawatt-class pulse-power accelerator[1]

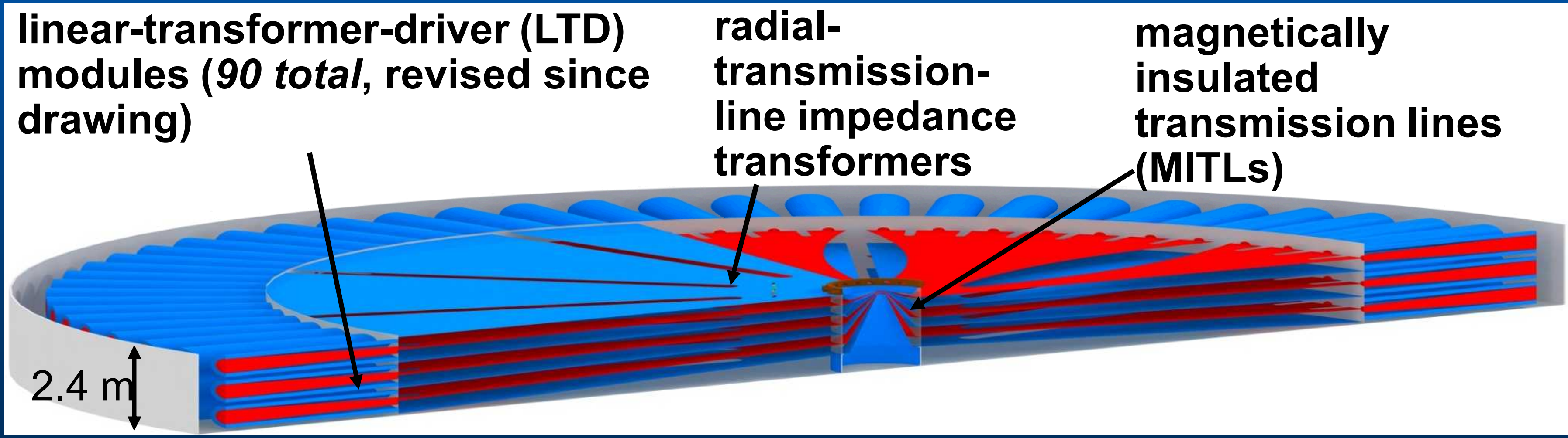
Z300 Design Parameters

$P_{\text{electrical}}$ = 350 TW

V = 8 MV

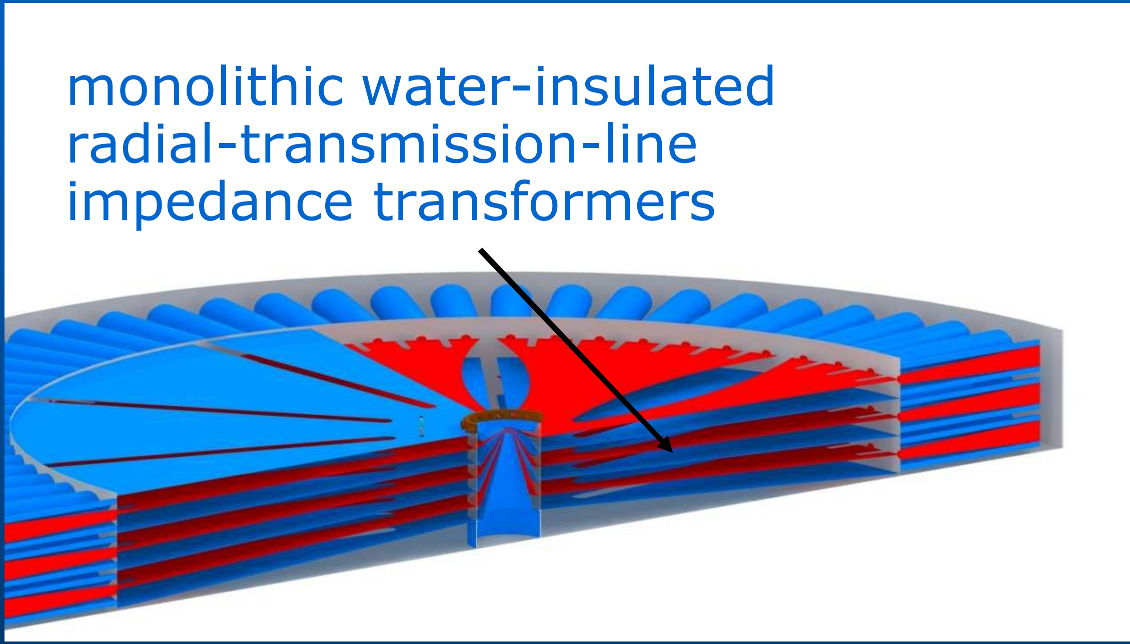
I = 45 MA

$\tau_{\text{implosion}}$ = 95 ns



[1] W. A. Stygar, M. E. Cuneo, D. I. Headley, H. C. Ives, R. J. Leeper, M. G. Mazarakis, C. L. Olson, J. L. Porter, T. C. Wagoner, and J. R. Woodworth, Phys. Rev. ST Accel. Beams 10, 030401 (2007).

Radial-Transmission-Line Impedance Transformers designed to provide required V, I to load.



$$Z(r) = A + Be^{m\alpha(R_{out}\Delta\theta_{out} - r\Delta\theta)}$$

- The input impedance is matched to the LTD system.
- The output impedance is matched to the MITL.
- Therefore, the inner and outer AK gap widths are fixed; *the gap tapers*.
- The radial impedance transition is controlled by azimuthal gaps in the cathode plates.
- An exponentially changing impedance has efficient voltage transformation/power transport.

The power-transport efficiency of an *exponential* transformer is readily calculated [1-3].

To keep the *fractional change in impedance per unit length* constant requires an *exponential* impedance profile:

$$\frac{1}{Z(r)}\frac{dZ(r)}{dr} \propto \text{constant} \longrightarrow Z(r) \propto \exp(\gamma r)$$

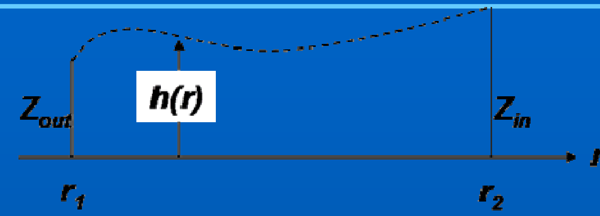
Assuming the power pulse has a dominant angular frequency ω and ratio of pulse to transit time $\Gamma \equiv 2\pi/3\omega\ /\ \tau << 1$, the power-transport efficiency of such a transformer is as follows:

$$\frac{P_{\text{out}}}{P_{\text{in}}} = \exp\left(\frac{-\left[\ln\left(Z_{\text{out}}/Z_{\text{in}}\right)\right]^2}{4\omega\tau_{\text{transformer}}}\right)$$

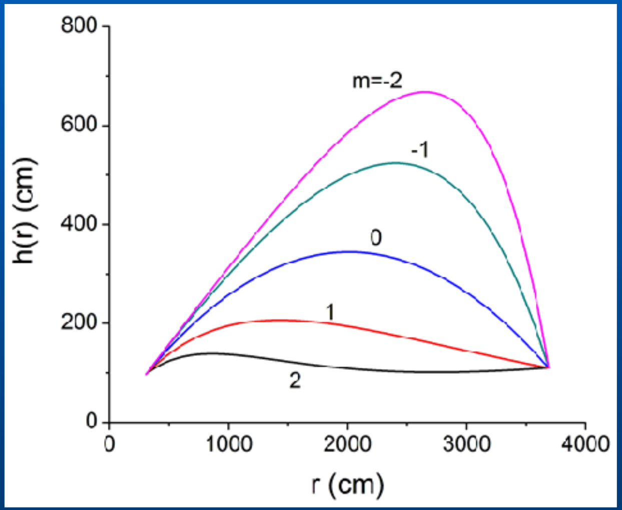
[1] W. A. Stygar et al., Phys. Rev. ST Accel. Beams 10, 030401 (2007).
[2] I. A. D. Lewis and F. H. Wells, *Millimicrosecond pulse techniques* (1959).
[3] D. R. Welch, et al., Phys. Rev. ST Accel. Beams **11**, 030401 (2008).

For Γ<<1, optimum Z(R) close to exponential in 2D LSP simulations [3]

Power transmission efficiencies of the Design I impedance transformer with various impedance profiles with LSP.



Profile Param (m)	1D Numerical Efficiency (%)	2D EM Sim Efficiency (%)
-2	69.1	**68.9**
-1	77.9	**76.9**
0	87.2	**87.4**
1	90.8	**90.5**
2	**88.4**	**86.7**



$$V_{in}(t) = \begin{cases} 0, & t \le 0 \\ V_0 \sin(\omega_0 t), & 0 \le t \le \dfrac{\pi}{\omega_0} \\ 0, & t \ge \dfrac{\pi}{\omega_0} \end{cases} ,$$

Parameters r_2 = 3688 cm, Z_{in} = 0.203 Ω, r_1 = 304.8 cm, and Z_{out} = 2.16 Ω, which give a one-way transit time τ = 1009 ns. *For* $\omega_0 = 1.4\times10^7\ s^{-1}$, $\Gamma \equiv 0.15$.

Radial-Transmission-Line Impedance Transformer: 3D Model of a Single Triplate

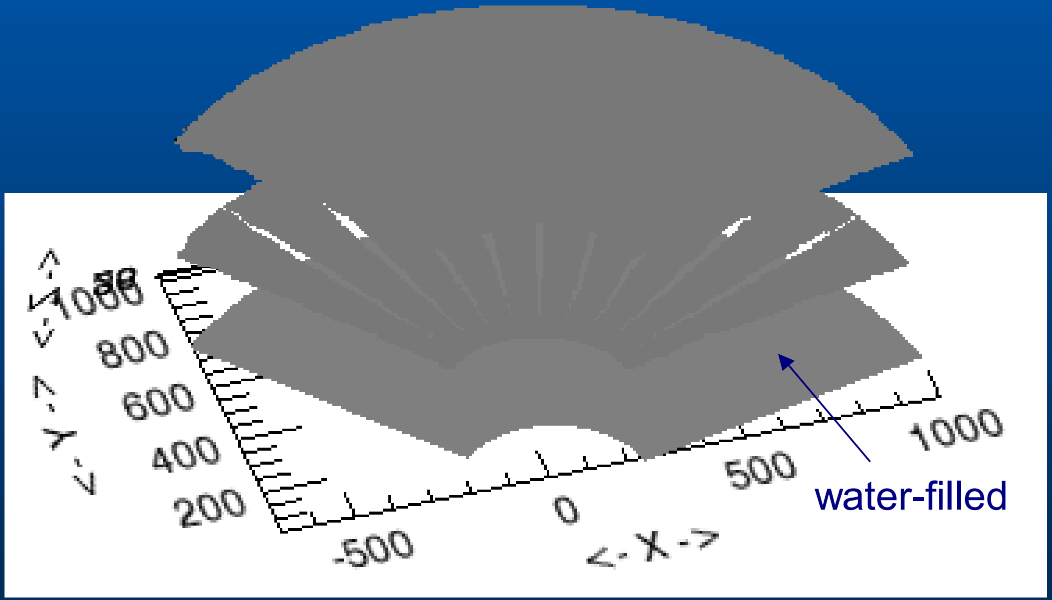
3D model includes 120° segment of a single triplate.

The cathode plate is formed with azimuthal gaps determined from the exponential Z(r) (m=1.0).

The azimuthal cuts allow for simple radial plate geometry and mitigate cross talk between LTD driver until very late in pulse.

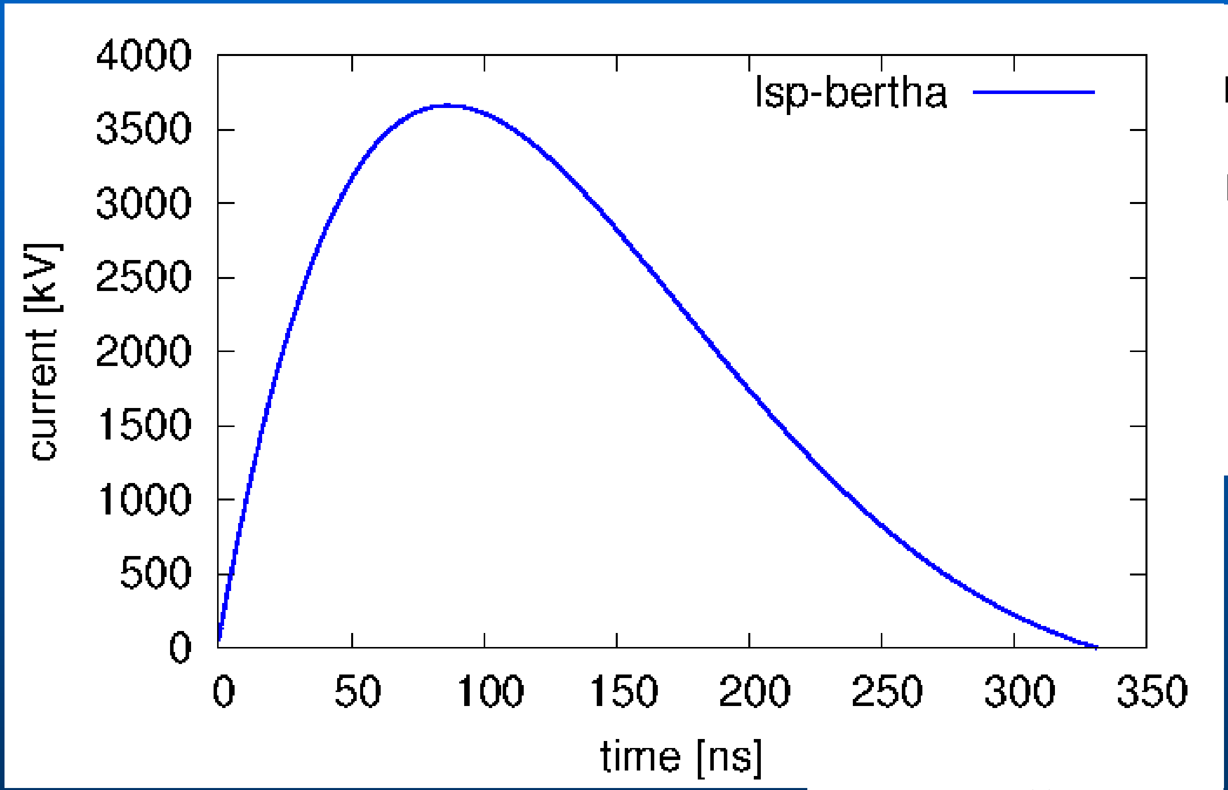
<u>radial transmission line parameters:</u>

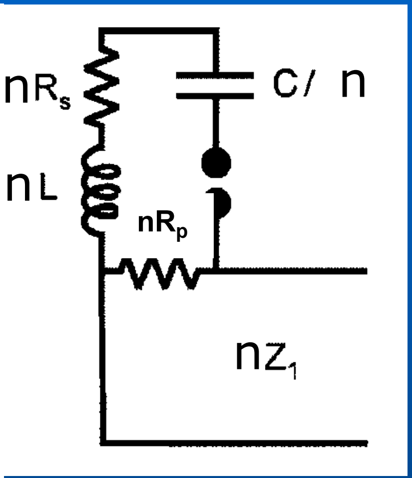
Z_{outer} = 0.1317
Z_{inner} = 0.48
AK gap Δz_{outer} = 38.5 cm
AK gap Δz_{inner} = 35.8 cm



LTD power fed by 1 or 10 simple circuits. More detailed circuit modeling is in progress.

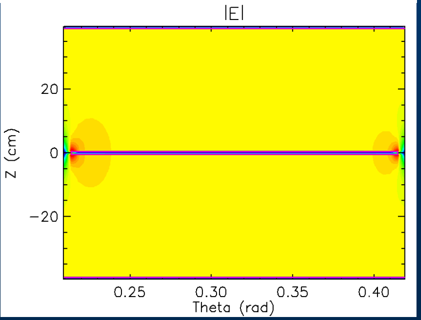
Simple Circuit Model represents each of 10 LTD Modules, enables assessment of coupling, timing, pulse shaping, etc.



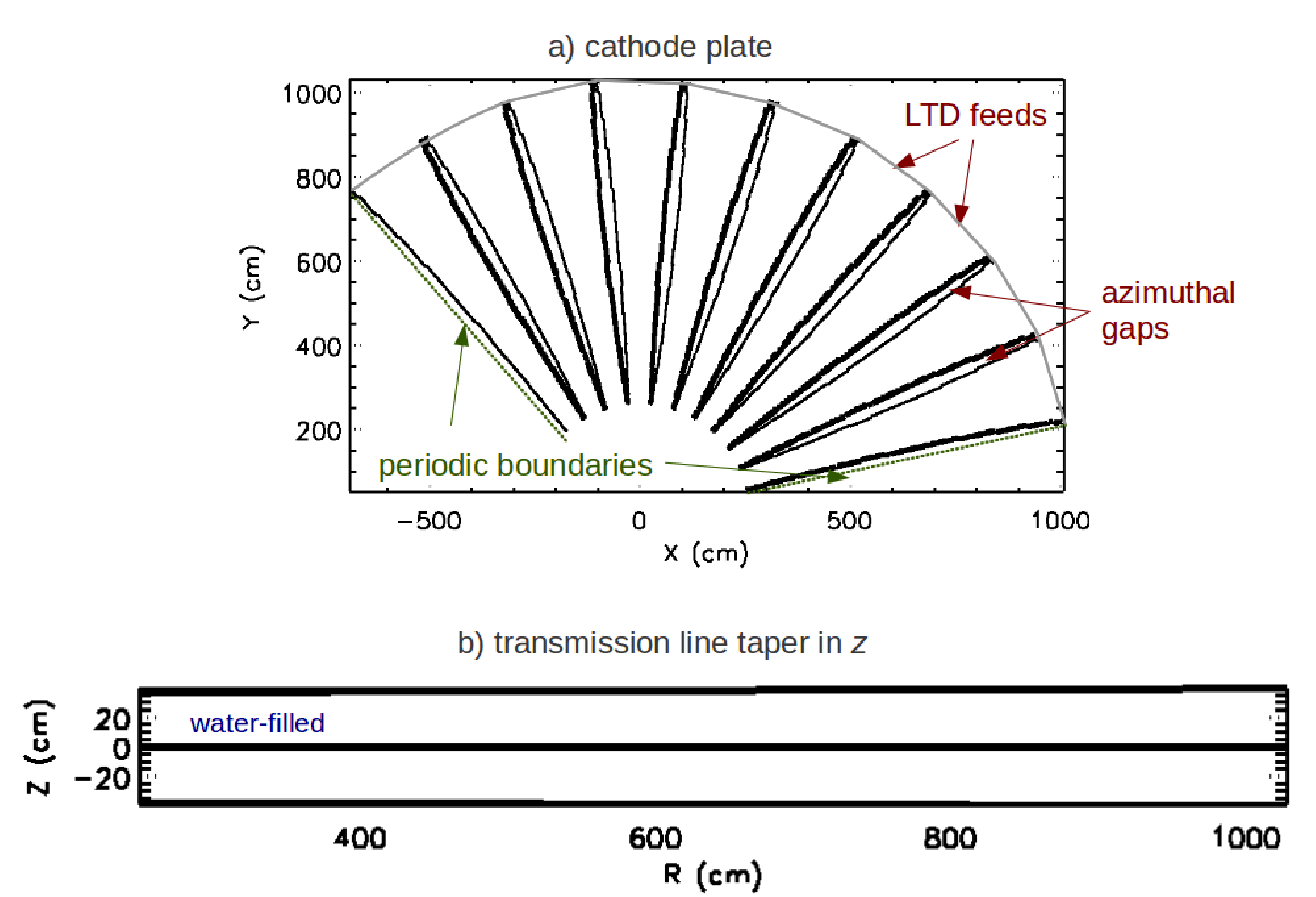


$n = 33$
$n^*R_s = 0.5445\ \Omega$
$n^*L = 247.5$ nH
$C/n = 24.24$ nF
$n^*R_p = 99\ \Omega$
$n^*V = 6600$ kV
$Z_{line} = 3.951\ \Omega$

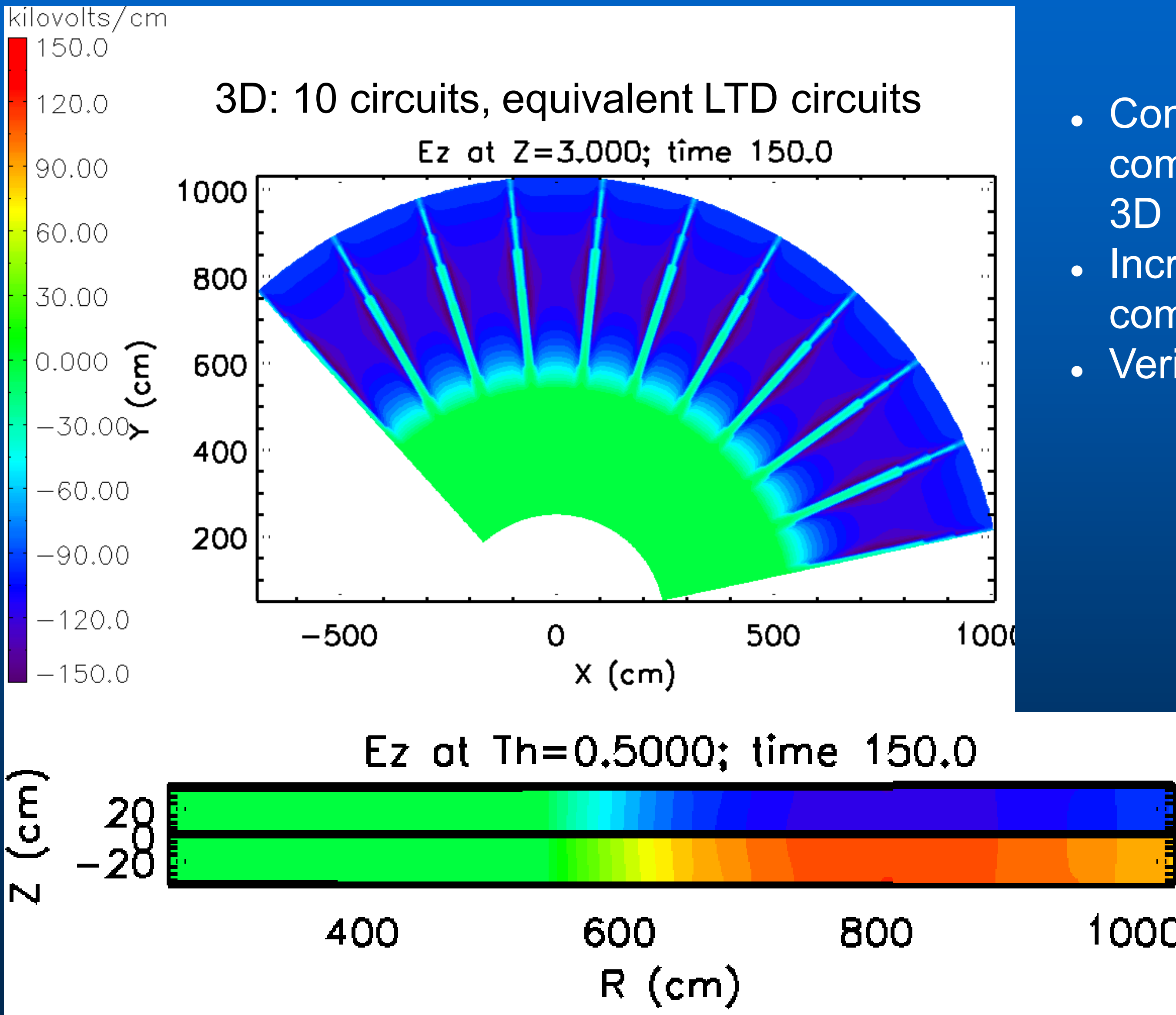
Current/voltage applied across single simulation LTD inlet



Exponential profile for tilted plate with azimuthal gaps.

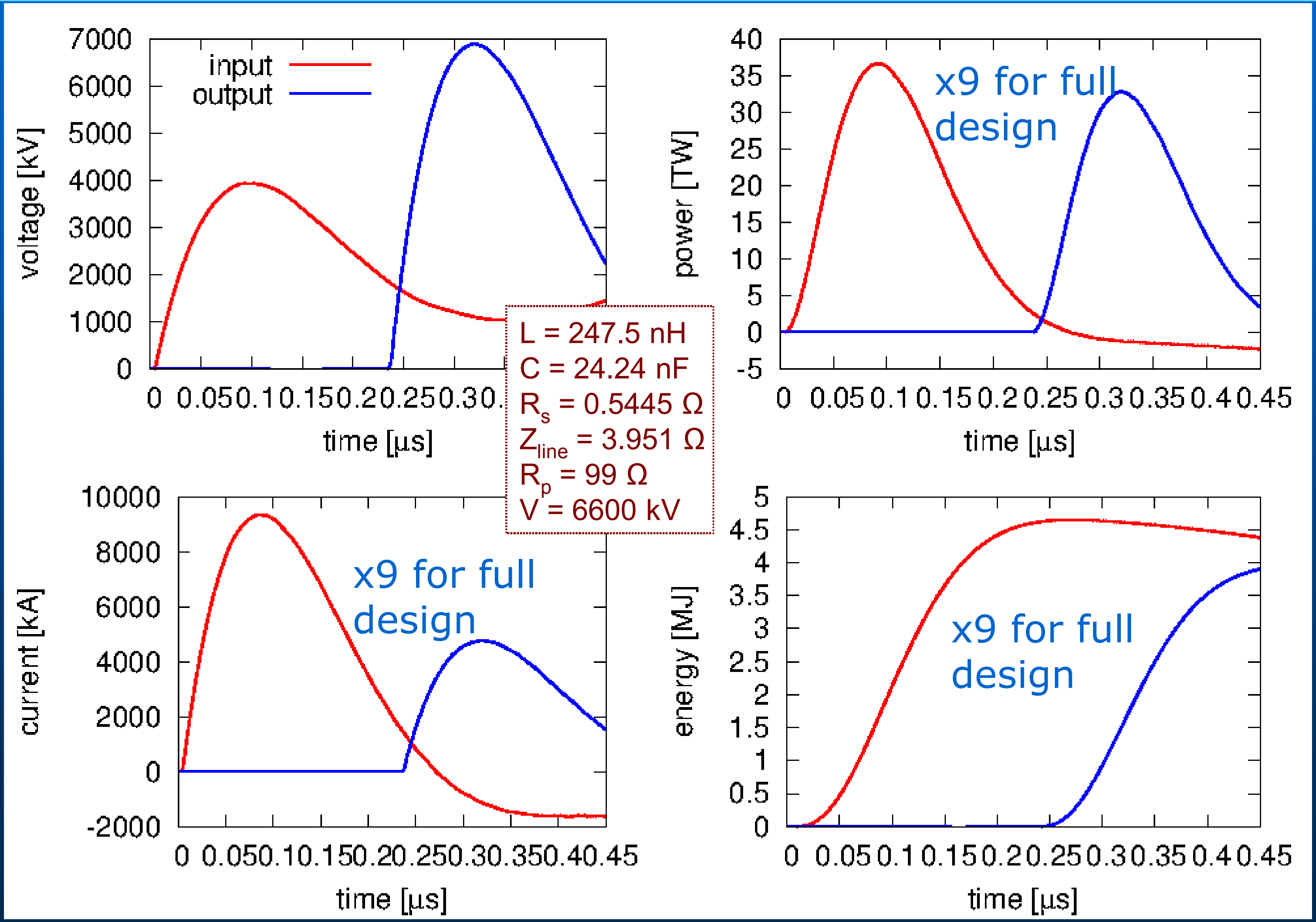


Snapshot of electric field after 150 ns for 3D simulation of a Single Triplate

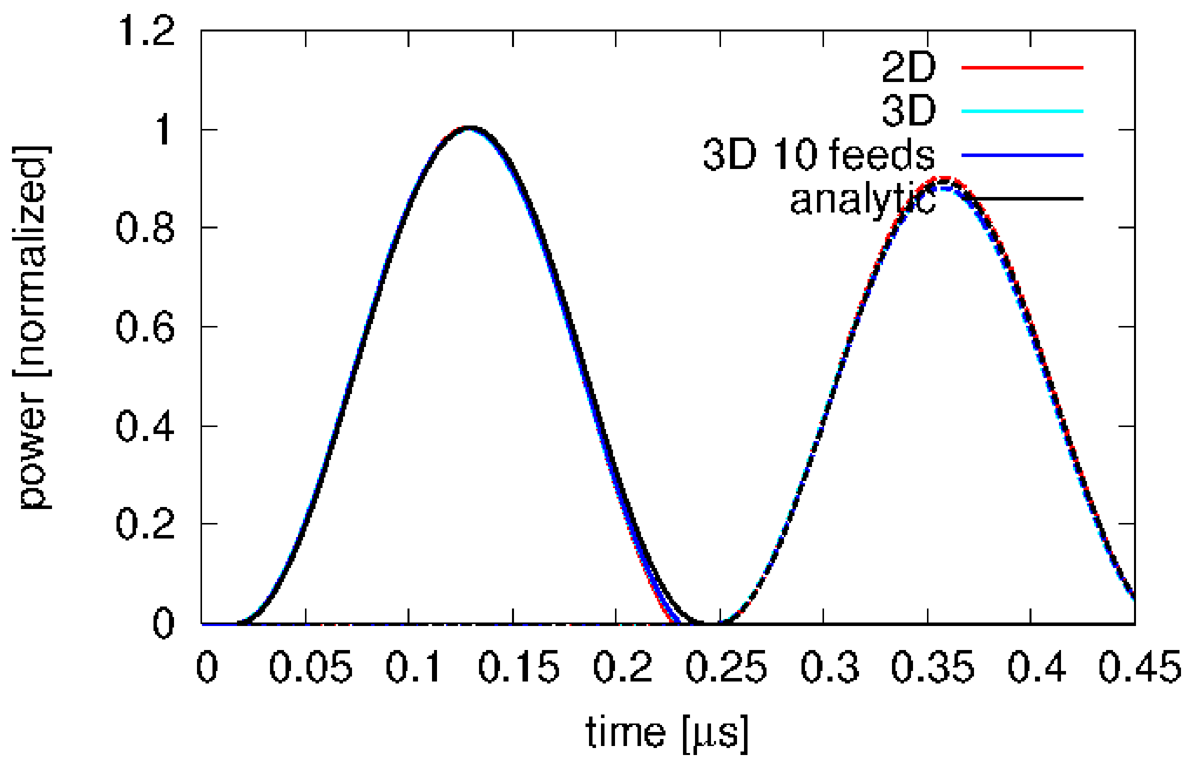


- Confirm model by comparing theory, 2D and 3D
- Incrementally add circuit complexity
- Verify efficiency

Simulation voltage, current, power and energy for 120° of Single Triplate Transformer 75% voltage gain at output



3D Power Transport compares nicely with theory.



$$V_{in}(t) = \begin{cases} 0, & t \le 0 \\ V_0 \sin(\omega_0 t), & 0 \le t \le \frac{\pi}{\omega_0} \\ 0, & t \ge \frac{\pi}{\omega_0}, \end{cases}$$

$$\begin{aligned} V_{in}(\omega) &= \int_0^{\pi/\omega_0} V_0 \sin(\omega_0 t) e^{i\omega t} dt \\ &= -V_0 \omega_0 \frac{e^{i\pi(\omega/\omega_0)} + 1}{\omega^2 - \omega_0^2}. \end{aligned}$$

$$V_t^{exp}(\omega) = \frac{e^{\alpha L/2}}{\cos(\gamma L) - ik\sin(\gamma L)/\gamma}$$

$$V_{out}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} V_{in}(\omega) V_t^{exp}(\omega) e^{-i\omega t} d\omega$$

3D Power transmission efficiency = 89.6% versus 90% for 2D, 90.4% theory.

We are assisting in the design of the next generation pulse-power accelerator using 3D simulation.

- With 1% agreement, theory, 2D and 3D calculations demonstrate good voltage transformation with high efficiency Exponential profile optimizes for short pulse limit.

Future Work

- We continue to upgrade model to include more detailed LTD circuit and load and calculate optimum Z profile.
- Impact of misfire and timing will be quantified.