Practical Circuit Models and Simulations using Transmission Lines

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Outline

- Introduction and Background
- Transmission line algorithm
- 0-D, 2-D, 3-D models
- Pulse power models
- Conclusion

Introduction

This talk is about circuit modeling as practiced at Pulse Sciences, Inc. over the past ~30 years

- Since my introduction to pulse power in 1983
- Used for our part of many systems
  - **High power accelerators**: Proto 2, Saturn, Z, and ZR (Sandia), Decade PRS (DTRA), Phoenix (NSWC)
  - **Induction Voltage Adders**: Hermes 3, RITS (Sandia), CYGNUS (LANL), Hydrus (AWE)
  - **Linear accelerators**: Rex, DARHT 1, DARHT 2, (LANL), AIRIX (CEA), SLIA (NSWC), FXR (LLNL)
  - **High power lasers**: NIKE (NRL)
- Capability developed ad hoc over time
  - Largely as means to produce hardware designs

  [Typical of much pulse power technology development]

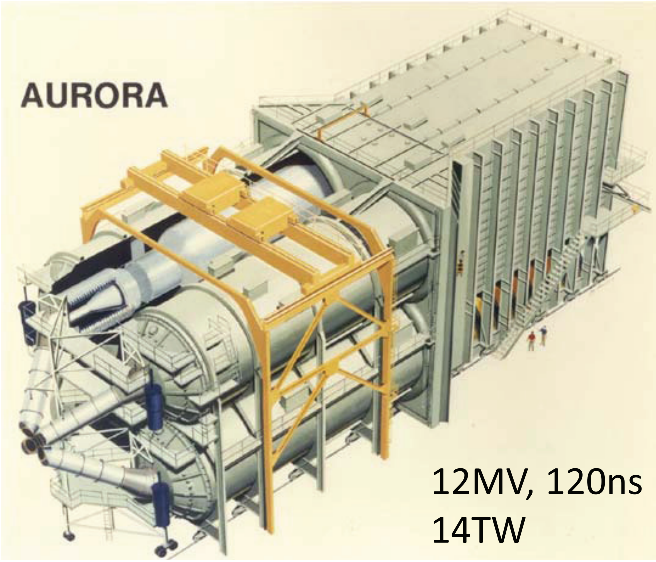
Computer simulations of pulse power circuits are now standard practice

- Essential tools for:
  - System design and performance prediction
  - Component design
  - “Post-diction” - post shot simulation to understand how a system behaved
  - Development of better models
  - Operation – pre-shot machine configuration

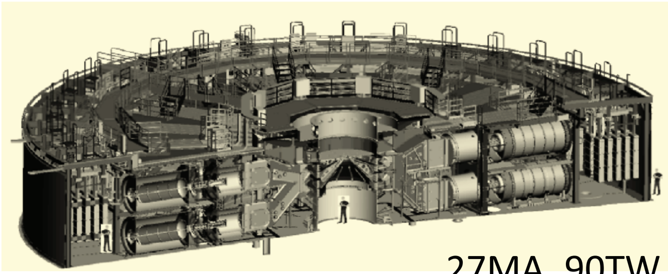
But this was not always the case …

Background

- A lot of pulse power was designed and built with out the aid of any computer simulations
  - For example, Aurora- designed in 1969, completed in 1972
  - Analytic circuit calculations
  - Prototype hardware iterations
  - No circuit or diode simulations
- Computer simulations for pulsed power developed as the IT revolution unfolded
  - Mainframe simulations through the 1970s
  - “Personal computer” starting in the late 1970s
- Computer simulations have changed pulse power design
  - Lower risk designs
  - More complex systems
  - Precision pulse shape predictions
  - Deeper understanding of pulse power machines



Refurbished Z



27MA, 90TW

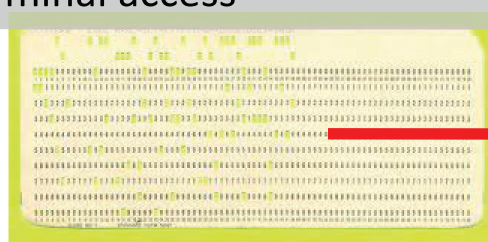
Mainframe computer simulations in the 1970s and early 1980s

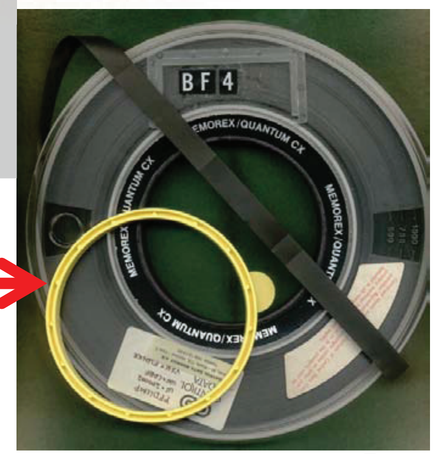
- Many pulse power simulations used existing network analysis codes such as SCEPTRE and NET-2
- At PSI we primarily used SCEPTRE
  - Originally developed in the 1960s to study transient radiation effects in military electronics
  - Explicit integration and predictor-corrector solution algorithms
  - Infamous for very time consuming solutions when time steps shrank to maintain numerical stability
  - e.g. nano-second → femto-second time steps when switches closed
  - One advantage of SCEPTRE was the ability to compile and link in custom models written in FORTRAN
    - e.g. switch and diode models

Mainframe computers in early 1980s

CDC CYBER 7600	
Introduced:	1969
Price:	US $5.1M
Processing Power:	36Mflop Peak 60-bit words
Processors:	9 Central Units 15 Peripheral Units @36.4MHz
RAM:	64k word SCM 512k word LCM
Electrical Power:	64kW SCM 512kW LCM

Punch cards were being replaced by magnetic tape and CRT terminal access





Other mainframes (LANL):
Cray 1 (1976)
Cray XMP, 713Mflop (1985)

Using remote mainframe computers was very cumbersome

- Accessed by teletype terminal through telephone phone lines
  - Acoustic couplers connected to modems
  - Data transfer at 300 baud (with a good connection)
- Expensive computing time was limited
- Job priority cost extra on shared computers
- Printed simulation results were typically delivered by mail
  - Reams of line printer output
  - Primitive computer graphics led to making graph paper plots by hand

Teletype terminal and Telephone line modem with Acoustic coupler

Advent of microcomputers brought a plethora of "homegrown" codes

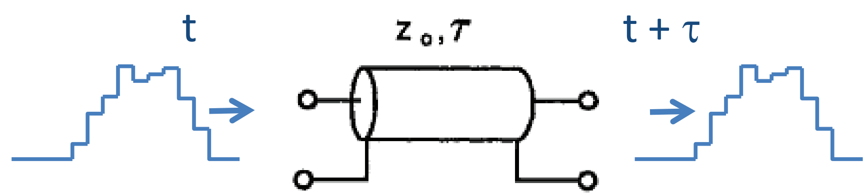
- Microcomputers were first used at PSI as terminals to remote mainframes
  - Pre- and post-processing digital data
  - Initially hampered by 300 baud modems
- Then as platforms for homegrown code
  - Very limited number of commercial applications
  - Very limited capability required efficient algorithms
  - Differential equation circuit solvers
  - Transmission line based circuit solvers
  - By the early 1980s: TLCODE at PSI, T-LINES at HDL, SCREAMER at SNLA, BERTHA at NRL, PSPICE (commercial)

Osborne 1	
Introduced:	April 1981
Price:	US $1,795
Weight:	24.5 pounds
CPU:	Zilog Z80 @ 4.0 MHz
RAM:	64K RAM
Display:	built-in 5" monitor
	53 X 24 text
Ports:	parallel / IEEE-488
	modem / serial port
Storage:	dual 5-1/4 inch, 91K drives
OS:	CP/M

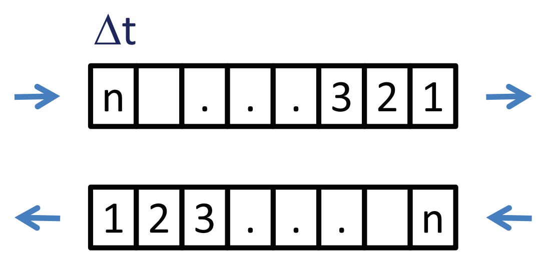
Hayes SmartModem	
Computer operated	
Introduced:	1981
Speed:	300 bits per second

Transmission line code basics

• A uniform, lossless transmission line is defined by its impedance Z_0 and its transit time τ
• Waveforms approximated by a series of step pulses

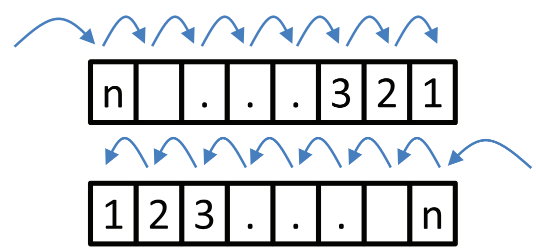


• Forward and reverse traveling waves are stored in separate memory arrays
- One array element per simulation time step Δt
- Arrays store future open circuit voltages



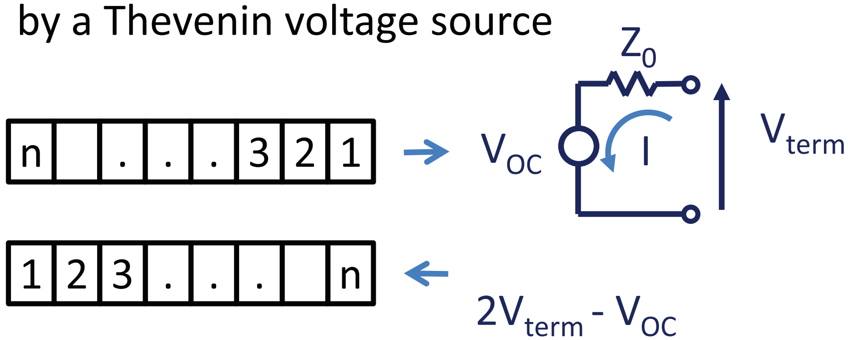
Open circuit voltage arrays

Simulation time is advanced by shifting the open circuit arrays



Transmission line connections

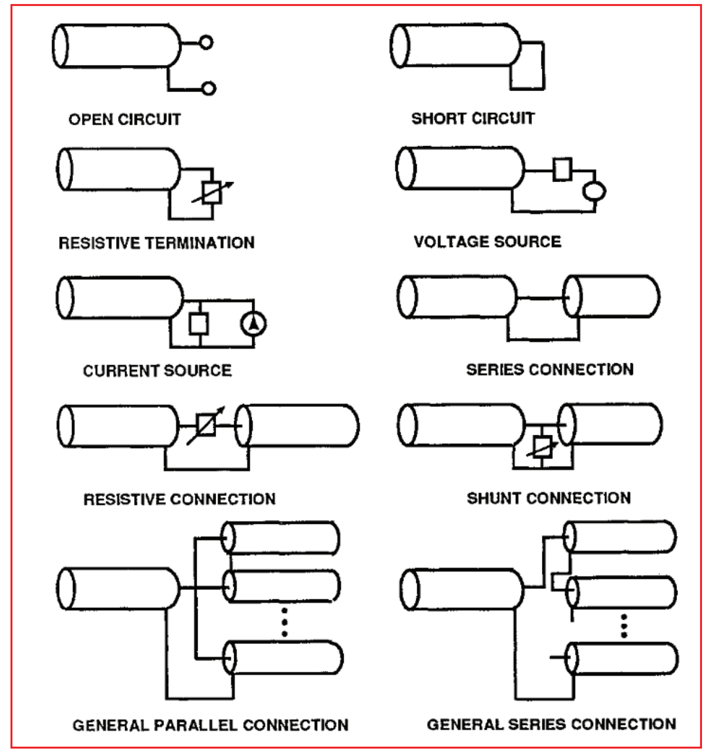
Each end of a transmission line is modeled by a Thevenin voltage source



TL connections are solved at each time step

- Purely algebraic
- Kirchhoff's laws
- Numerically stable
- Solve quickly
- Ends isolated by at least one time step

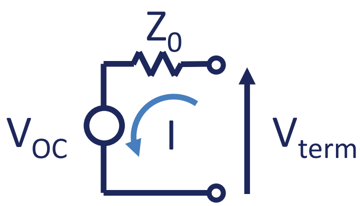
Wavelet entering a line is determine by the difference between $2V_{term}$ and V_{OC}

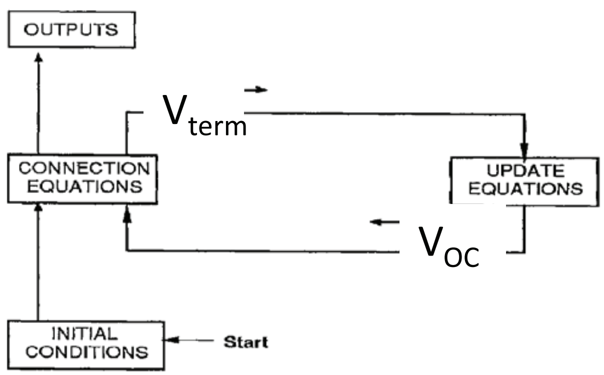


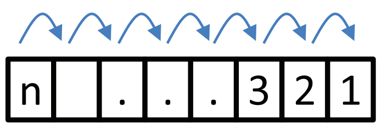
Circuit topology is unrestricted

- n-way connections
- loops

TL circuits were a perfect fit for early microcomputers







Advance the time
$t + \Delta t$

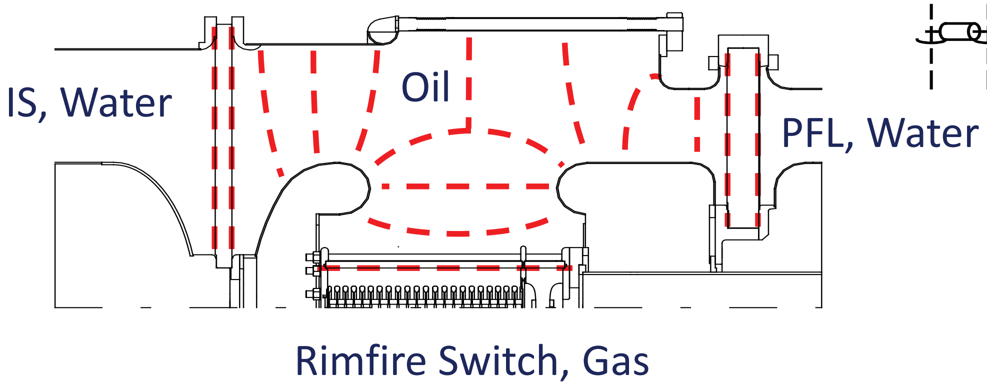
- Simple TL algorithm was easy to implement in FORTRAN by casual computer programmers
- Practical circuits for design iterations typically solved ~ 1 minute
- Larger circuit simulations pushed that limit for special cases - runs taking between 1 hour and 1 week to solve

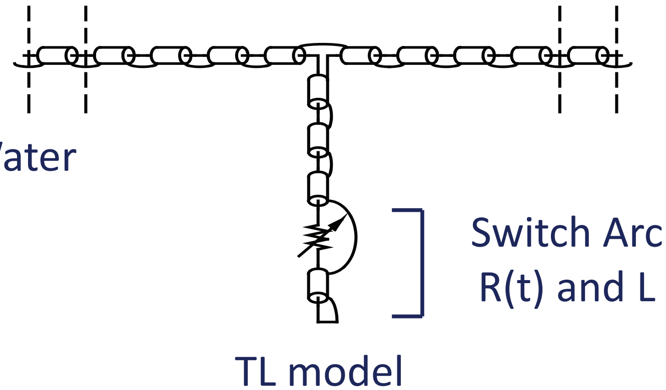
TL simulation benchmarks in 1989 on 10MHz, 286 processor:

- < 1 minute for comparable circuits run with SCEPTRE on mainframes
- ½ to 1/10 the time of SPICE simulations

Transmission lines are natural for modeling high voltage pulse power components

- Fast rise-times are comparable to or smaller than hardware transit times
- Some regions are obvious
  - Transmission line elements model one spatial dimension (1-D)
  - represented by its transit time τ
  - Example: straight coaxial section of a pulse forming line
- More complex regions require knowledge of field structure, capacitance, and inductance
  - L and C are preserved in each region
  - Example: laser triggered gas switch region in ZR (coaxial)



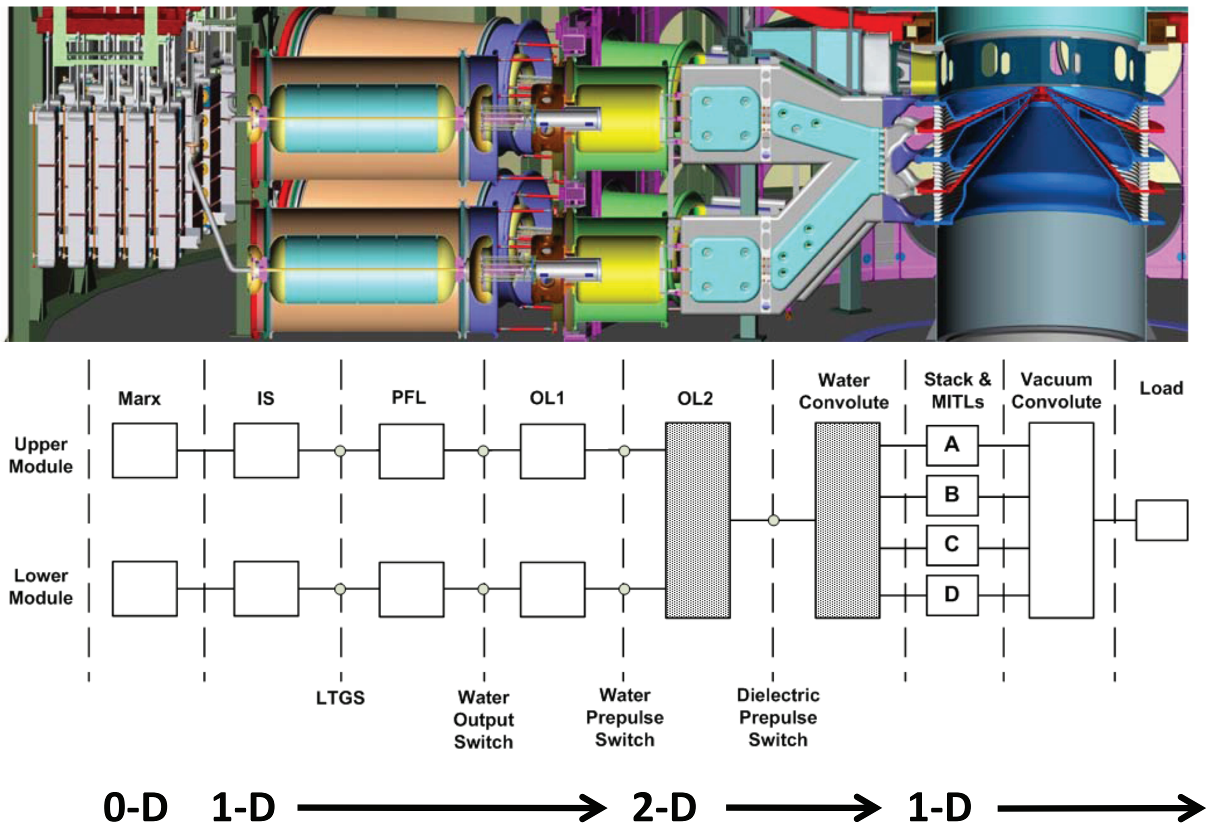


TL solvers also provide 0-D, 2-D, and 3-D modeling capability using 1-D elements

- 0-D "lumped" C or L approximated by short transit time elements
  - All TLs have both L and C
  - No such thing as a pure capacitor or pure inductor anyway (or massless rope, or frictionless pulleys!)
- 2-D and 3-D modeled by networks of 1-D TL elements
  - Networks have both transmission line and L-C ladder properties
  - Geometric I/O is challenging
  - Practicality demands circuits that use the lowest dimension required to accurately model a given pulse and hardware

Complex 3-D geometries can often be modeled with 1-D elements

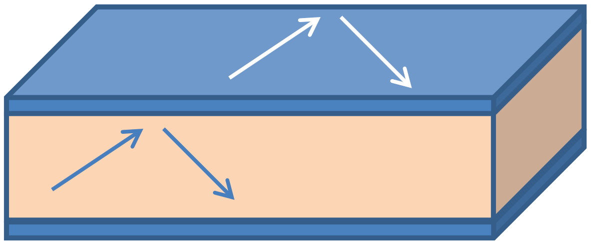
Common TL element facilitates use of mixed dimensions within one model

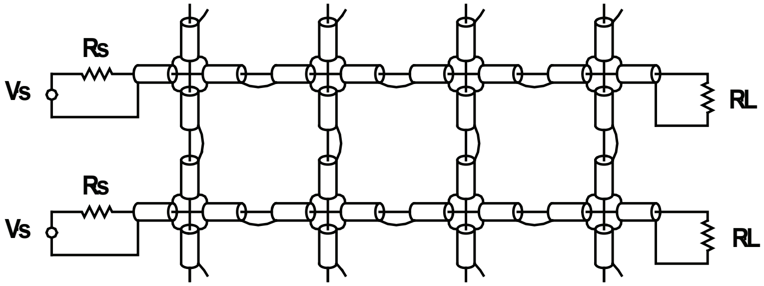


- Accurately models coupling within a circuit
- Avoids practical problems when separate codes used for each region
- Multi-dimensional circuit models proven to be essential for many machines

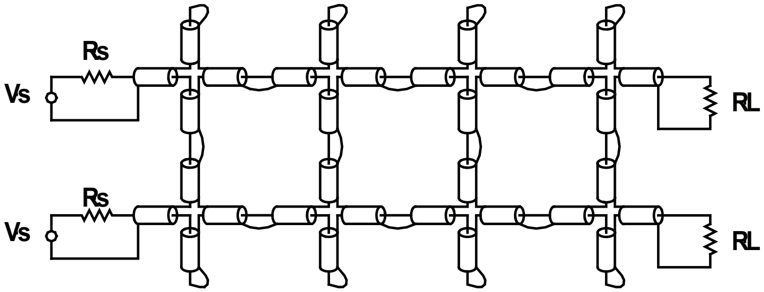
2-D TL Models

- Technique developed at PSI ~25 years ago
- Typical 2-D orthogonal mesh
  - Edges defined by physical geometry
  - four-way connection at intersections
    - Parallel TLs model 2-D magnetic field
      - e.g. current spreading on parallel plates
    - Series TLs model 2-D electric field
      - e.g. waves through dielectric between conductors
      - Slab or coax symmetry
  - Boundary conditions imposed on fringes of mesh
  - Resistors in intersections model dielectric conductivity (not shown)
  - Mesh behaves like LC ladder, not simple T-lines





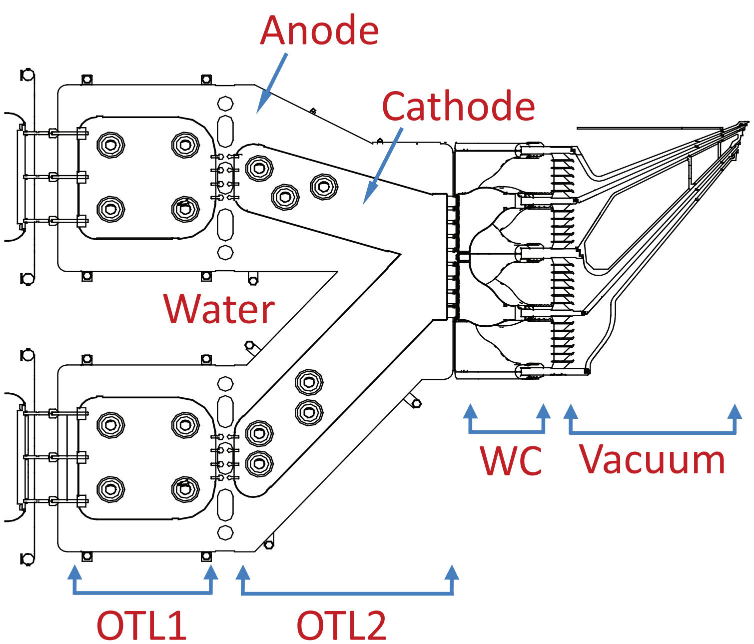
4-way parallel junctions

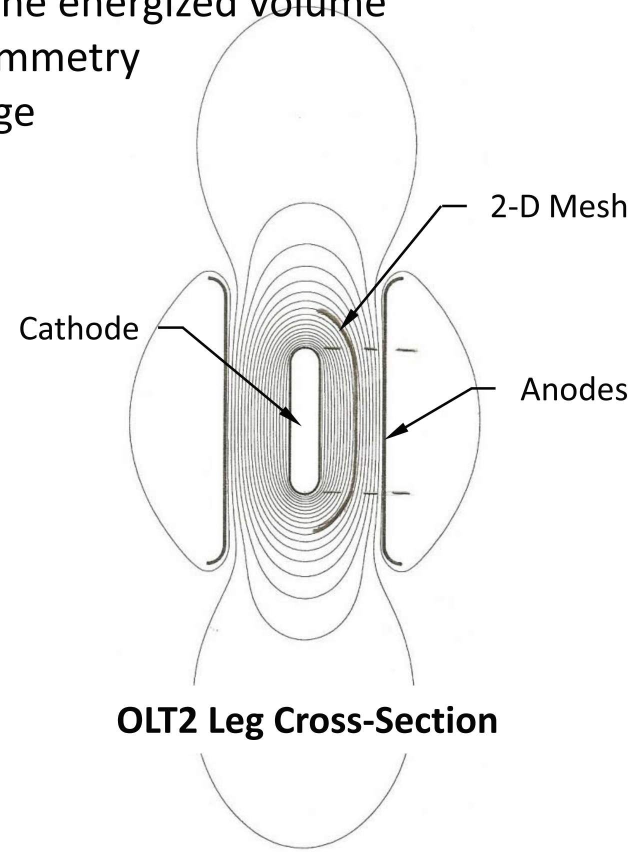


4-way series junctions

2-D TL model of ZR's Output Line 2

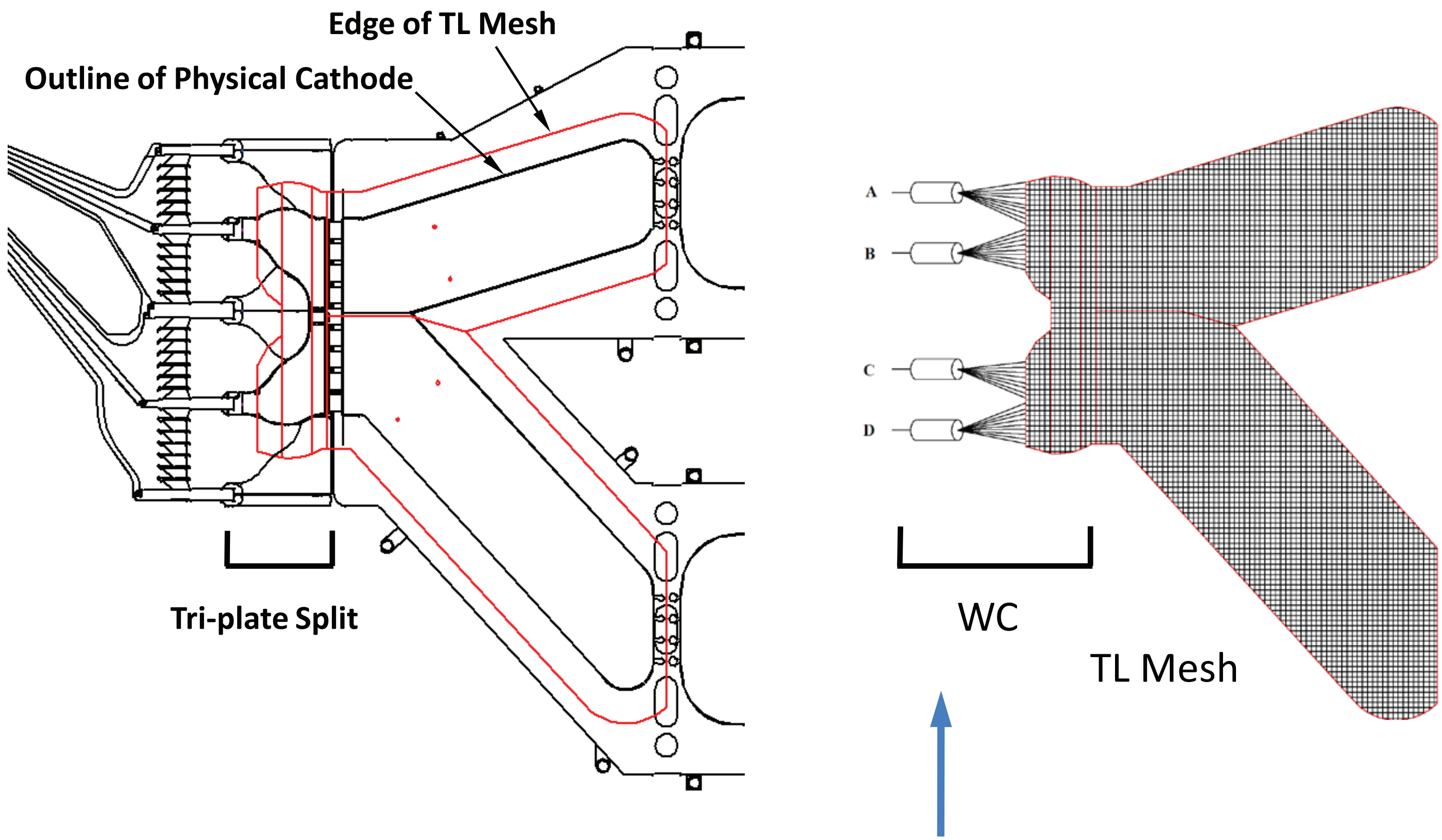
- Water filled vertical tri-plate geometry
  - ~26ns (legs) and ~43ns (mixing region) edge to edge transit times
  - ~25ns rise time and ~100ns length voltage pulse
  - Transverse modes excited by angles and timing difference between upper and lower pulse lines
- The extent of the 2-D mesh is determined by the energized volume
- Mesh impedance is halved to model mirror symmetry
- Edge of mesh extends beyond the cathode edge





OLT2 Leg Cross-Section

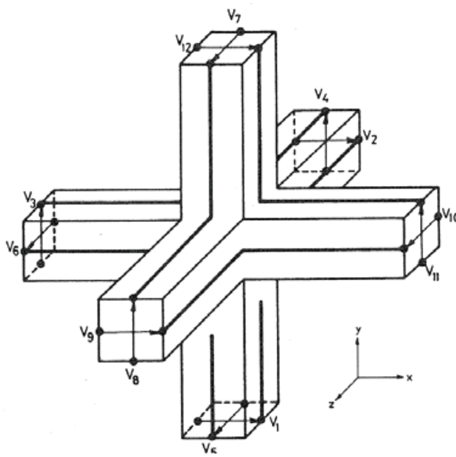
2-D TL Mesh that models ZR's OTL2



Note: 1-D lines were used after triplate split
- Balance of WC 3-D geometry
- Vacuum stack regions
- Conical MITLs

3-D TL Models

- 3-D E&M can also be modeled with an orthogonal mesh of transmission lines
  - 12 transmission lines connect at each junction
    - Two TLs in each principal direction – one for each component of the electric field
  - Mesh behaves like a combination of TLs and L-C network depending on the propagation direction characteristics
  - Very large number of TLs typical
- Code I-O is much more difficult than 2-D
  - Boundary conditions, wave inputs, visualization
- Used at PSI for simple geometries – e.g. NIKE PFL bend
- More practical to make equivalent electrical models
  - From scaled analog models
  - or 3-D computer simulations



Symmetrical condensed 3-D node, after Johns at Univ. Nottingham. Copyright 1987 IEEE.

Connection solved via 12 x 12 scattering matrix.

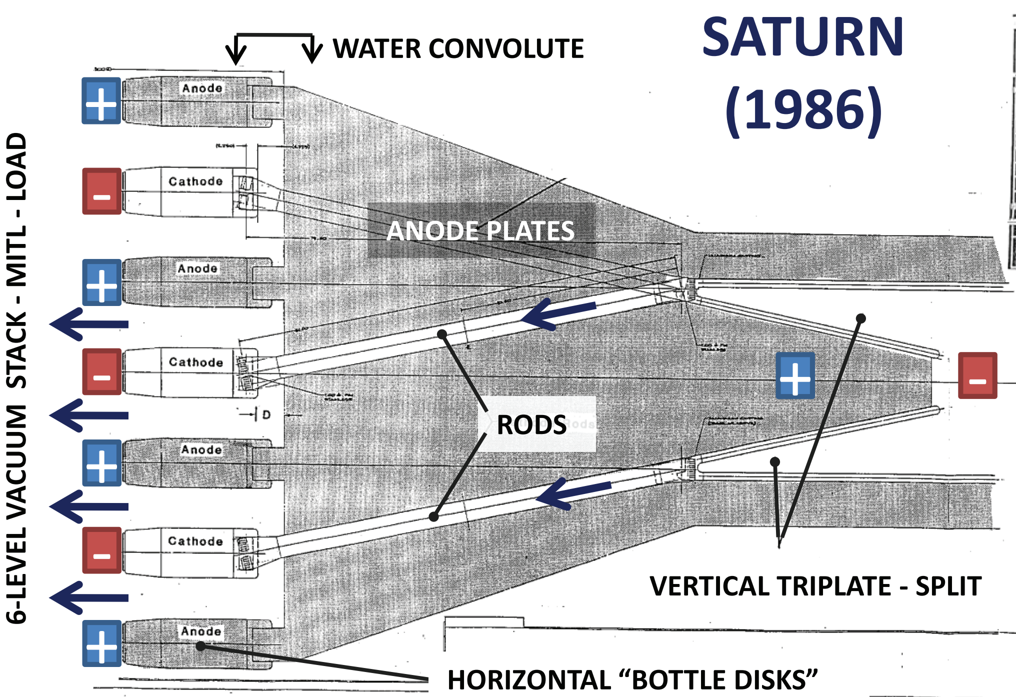
Connection cannot be represented by a lumped element circuit.

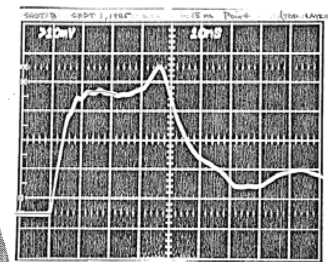
Equivalent circuit models unfolded from pulsing scaled analog models

Scaled models were used at PSI to create equivalent models for complex 3-D geometries

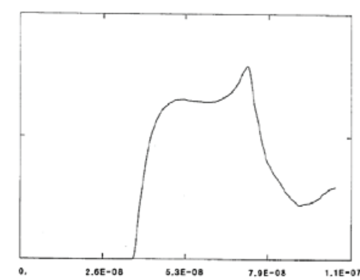
- Water convolutes of PROTO-2 and SATURN
- Pulse shaping stubs of APEX study

- Models pulsed in swimming pool
- Equivalent circuit models derived by unfolding TDR measurements
- Results used in full system circuit models

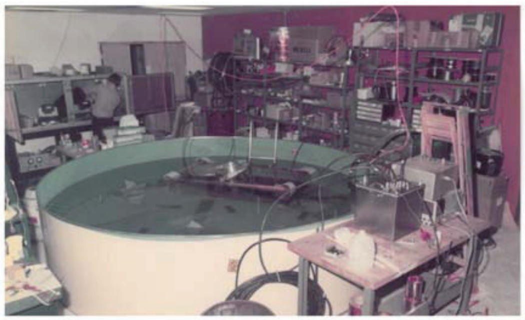




TDR at rods



TL equivalent



Swimming Pool Facility

Equivalent TL models are now created by matching 3-D E&M simulations

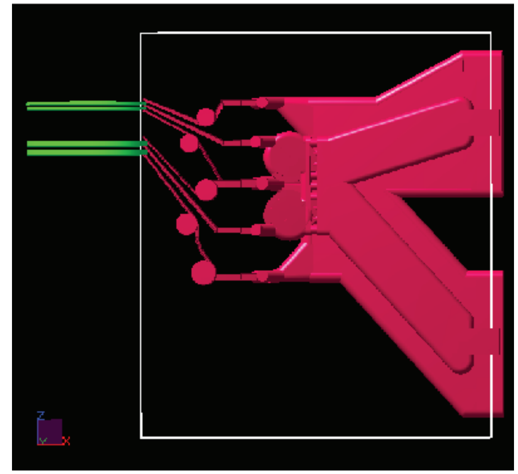
Equivalent models derived from 3-D simulations

- IVA cavities of RITS and Hydrus
- Water convolute of ZR
- More and better probes
- Match both reflections and throughput with TLs

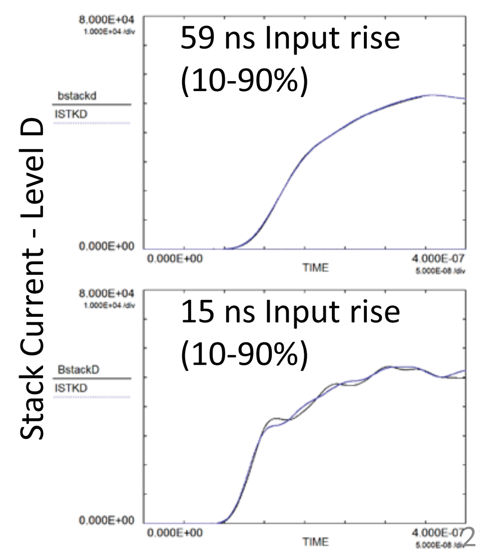
Example – ZR's OTL2 and Water Convolute

- Models for identical geometries were created in TL and 3-D LSP
  - OTL2 + WC + vacuum stub geometry
  - Isolated difficult WC region
  - Equivalent 1-D WC elements derived
- TL model validated for several drive conditions
  - Step pulse input (1-cos leading edge)
  - 10 to 100 ns times to peak
  - Upper + lower, upper only, lower only
  - Non-uniform voltages and currents matched for equivalent probe positions

- Simple 1-D TL model for OTL2 failed to match coupling between upper and lower legs



LSP compared to TL equivalent



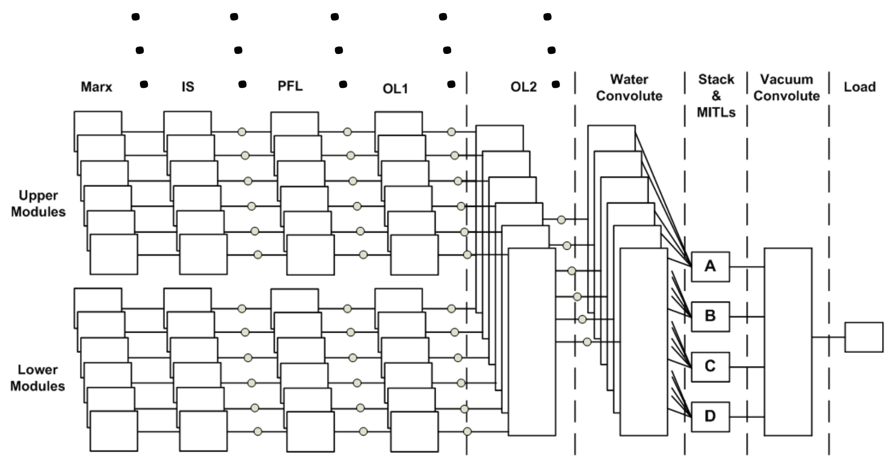
Practical circuit run times are still ~ 1 minute

Runtimes useful for iterative processes have remained fairly constant over past 30 years

- e.g. design, machine configuration for pulse shape, etc
- model size and complexity growth proportional to increased computer performance, memory, storage

Example – ZR's full circuit for pulse shaped material response shots

- Intel® Xeon® CPU at 2.67GHz (TL)
  - 23,000 time step (2.3μs) simulation: 70 seconds
- Open MPI running on 7 of an 8 core Xeon Linux 3.3GHz workstation (BERTHA)
  - 20,000 time step (2.0μs) simulation: 30 seconds
  - will try genetic algorithm to automatically determine machine configurations



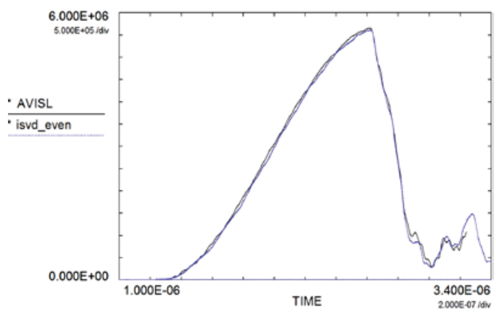
Full ZR Model

- 36 pulse line modules
- 18 2-D OTL2 and WC
- 61,000 TL elements
- 26,000 resistor elements
  - passive loss
  - active switches
  - active vacuum region loss

TL circuit model of ZR reproduces many of the measured waveform features

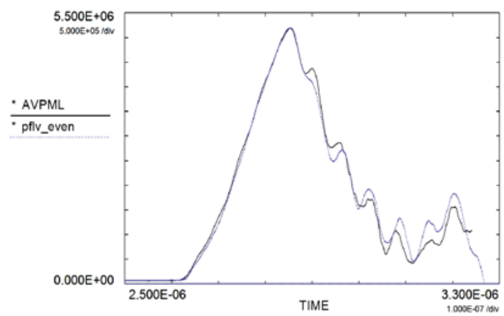
Z-pinch Load – synchronous pulse lines

Intermediate Store Voltage



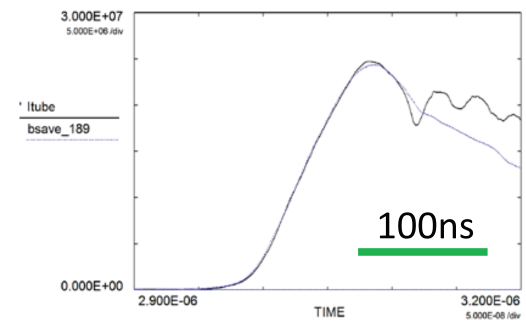
Shot 1896

PFL Voltage



Shot 1896

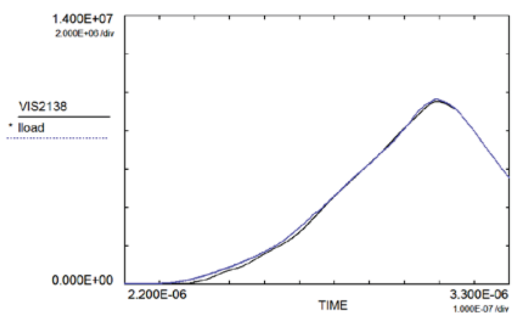
Total Stack Current



Shot 1896

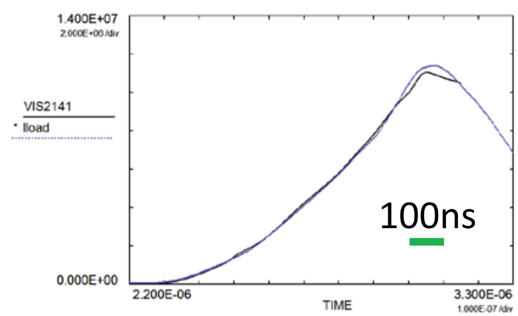
Material Response Load – pulse lines staggered over ~500ns

Load Current



Shot 2138

Load Current



Shot 2141

- Simulated load current compared to unfold from VISAR data
  - L(t) unfolded from VISAR and 2-D MHD simulations
  - Matched switch times

TL Simulation (black)
ZR Shot Data (blue)

Access to source code facilitated use of special pulse power circuit elements

- “Homegrown” pulse power codes persisted after commercial circuit solvers became available for “personal computers”
  - Primarily because pulse power modeling requires special elements
  - And to be practical, those models required access to source code
    - Only a few lines of FORTRAN become extremely elaborate models when using standard PSPICE elements
- Model development typically occurs only as needed
- Models shared with other pulse power codes for joint projects
- Specialized pulse power circuit codes today include TLCODE at L-3 (formerly PSI), SCREAMER at Sandia, BERTHA at NRL

Elements and features developed especially for pulse power circuits

- **Switch elements**: R(t) and recently R(V,t,gap) [this conference]
- **Diode and load elements**: Child-Langmuir including plasma closure, rod-pinch, gas-puff and wire z-pinch, exploding wires
- **Magnetic core loss**: I(V,t) [Schlitt at PPC2005]
- **Vacuum power flow loss**: including under-insulated and insulated MITL with plasma gap closure, resistive wall
- **Automatic 2-D mesh generation** for three symmetries and numerous connection and plotting routines
- Limited **3-D** capability
- Connection algorithm to **drive large physics codes** directly (e.g. MHD, PIC)

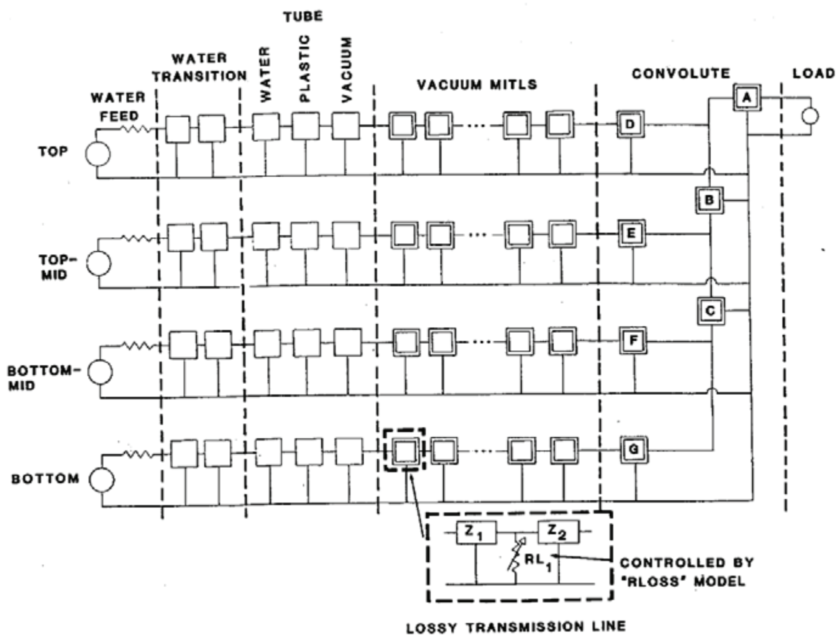
Many of these models have been presented at past conferences and in a number of publications

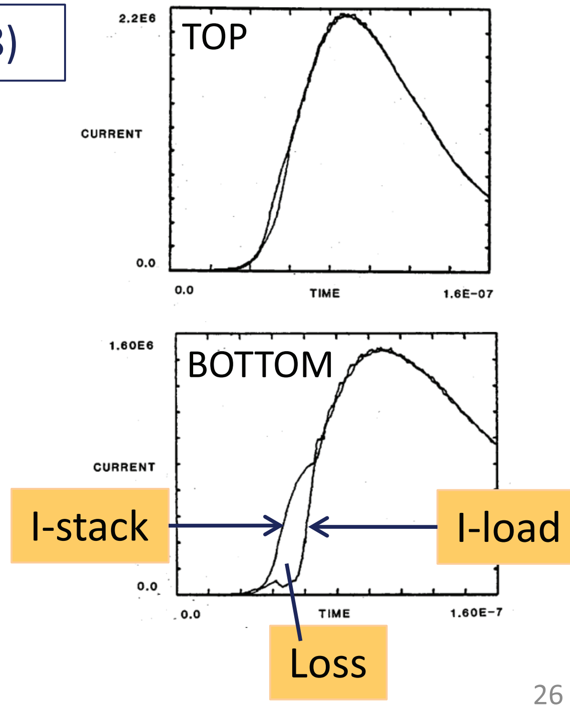
MITL loss model

MITL loss modeled using Sandia's RLOSS model

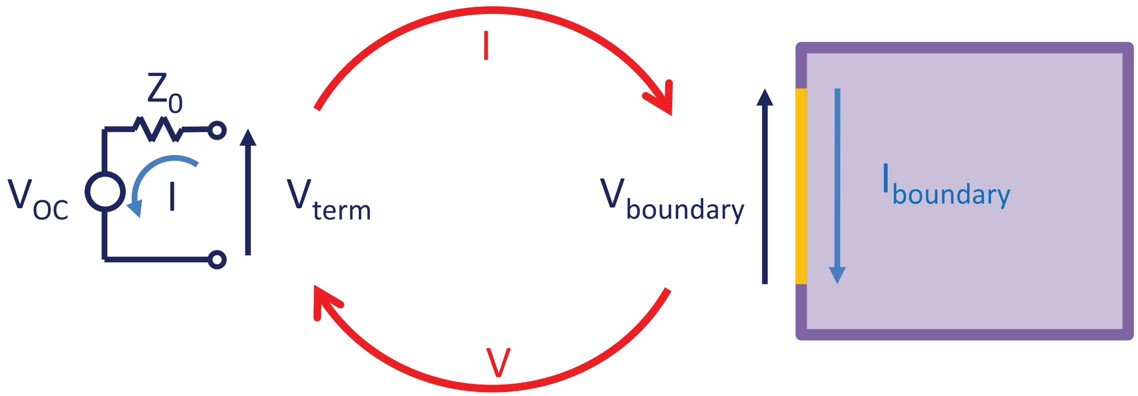
- Conical MITL modeled by short TL segments
- Losses shunted in variable resistor
- Pressure balance theory determines insulation based on local V and I
- Magnitude is fraction of Child-Langmuir current in segment area
- Model extended to model gap closure and insulated flow lost in vacuum convolute (SATURN, Z, ZR)

Example - Proto2 puff diode design simulations (1988)





Coupling TL to physics codes



Coupling full circuit models to large physics codes is often required for accurate simulations

- Coupling to a TL based model can be simple (TL - MACH2, 1999)
  - TL circuit sets the terminal-boundary current using the net boundary voltage calculated by the physics code
  - Simulation times kept in sync by advancing TL time when

    physics time $\geq$ TL time + Δt_{TL}

    ($\Delta t_{physics}$ usually varies and is less than Δt_{TL})
  - Voltage distribution on physics boundary depends on physical geometry

Conclusion

- Pulse power simulation capability has grown greatly over the past 30 years
  - Spurred in part by the advent of the microcomputer in late 1970s - early 1980s
  - Access to source code allowed development of models tailored to pulse power
- Transmission line element based circuits
  - Fast, numerically stable, algebraic junction equations
  - Unrestricted topology, including 2-D and 3-D structures
  - Natural, accurate, and practical way to simulate pulse power systems
  - Becoming a standard within many organizations
- Circuit simulations are now an essential component of pulse power design, operation, and development
  - Lower risk designs
  - More complex systems
  - Precision pulse shape predictions
  - Deeper understanding of pulse power machines