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Power flow simulations of the Saturn accelerator using 1D multi-mode transmission line models

David Sirajuddin, Duncan A. McGregor, Edward G. Phillips, Peggy Christenson, Kenneth W. Struve, Timothy D. Pointon, Keith Cartwright, Ben Ulmen, Kevin Austin, Jonathan Douglass, Mark Savage, Brian Hutsel

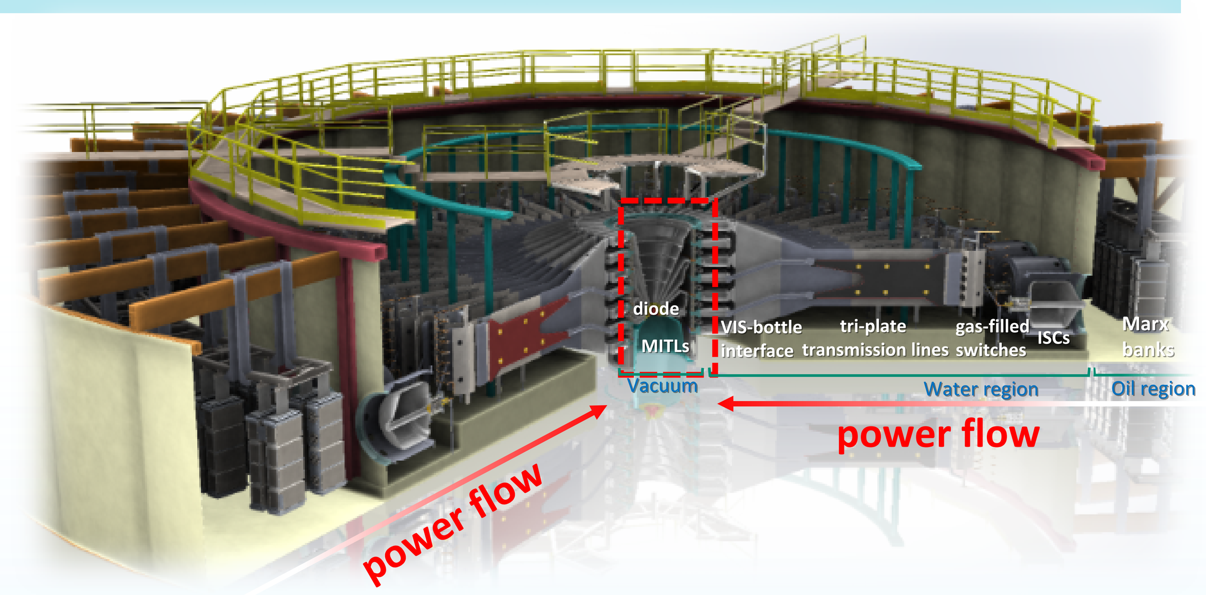
Motivation

Deviations from ideal transverse electromagnetic (TEM) wave propagation arise in pulsed-power machine from:

- *small asymmetries*: corners, holes, gaps
- *large asymmetries*: convolutes
- *nonlinear mechanisms*: electron/ion emission, plasma formation, gap closure, electrode melt
- *drive mechanisms*: pulse shaping, machine jitter

Ideal power coupling from line to load requires transverse electromagnetic (TEM) waves to reach the load. This poster investigates the operating behavior of the Saturn accelerator under transverse magnetic (TM) wave drive to assess the extent to which higher order modes developing in an originally TEM wave affect this design target.

The Saturn accelerator



36 Marx banks (~ 40 kJ per module) drive a 3-ring diode near the machine center R ~ 2 to 12 cm of Saturn to produce intense X-ray output

Electron beam generation:

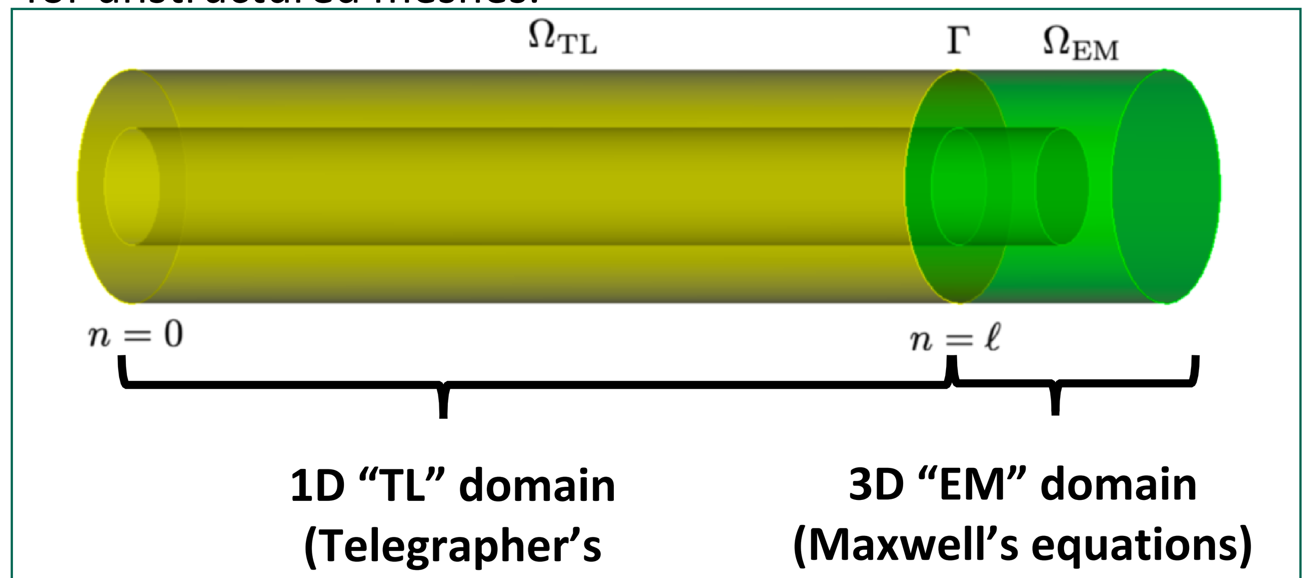
- 8 to 10 MA
- 1.5 MeV
- 25 ns

X-ray generation:

- 100 keV to 1.5 MeV
- 5 to 40 krad Si

1D multi-mode transmission line models

In previous work [1], we introduced a method for coupling the most general electromagnetic (EM) model for the 3D Maxwell equations with the 1D TEM Telegrapher's equations for unstructured meshes.



In this poster, we present recent results extending this coupling to support 1D multi-mode TM wave propagation.

1D-3D TM mode coupling verification

3D TM_1 wave

- amplitude, $V_0 = 990$ V
- frequency, $f_{TM,1} = 40$ GHz
- domain length = $2 \cdot \frac{2\pi}{k_{TM,1}}$
- initial conditions: $\boldsymbol{E}, \boldsymbol{B}$
- wave drive: Dirichlet E field $E_z(t), E_y(t)$ at $z = 0$

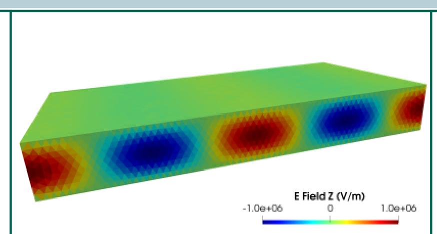


Figure 1: initial condition in direction of propagation, $E_z \neq 0$

Full 3D EM convergence

- 3D cell size, $h = 1\ \mathrm{mm} \cdot \frac{1}{r}$
- time step, $\Delta t = \frac{1}{20 \cdot f_{TM,1}} \cdot \frac{1}{r}$
- refine, $r = 1.0, 1.5, 2.0, 2.5$

→ *expectation*: $O(h + \Delta t^2)$

Cell size (m)	PPC z	PPP c	E_z error	E_z rate	E_y error	E_y rate	B_x error	B_x rate
1.00E-03	16.2	8.5	2.89E-02	--	4.89E-02	--	4.19E-02	--
6.67E-04	24.3	12.7	1.52E-02	1.57	2.59E-02	1.56	2.46E-02	1.31
5.00E-04	32.5	16.9	1.02E-02	1.4	1.82E-02	1.22	1.80E-02	1.07
4.00E-04	40.6	21.1	7.72E-03	[illegible]	[illegible]	1.15	1.41E-02	1.09

1D-3D TM_1 wave

- same $V_0, f_{TM,1}, k_{TM,1}$
- 1D+3D length = $2 \cdot \frac{2\pi}{k_{TM,1}}$
- 3D initial conditions: $\boldsymbol{E}, \boldsymbol{B}$
- 1D initial conditions: I, V_n, V_t
- 1D wave drive: TL voltage $V_t(t)$ at $n = 0$

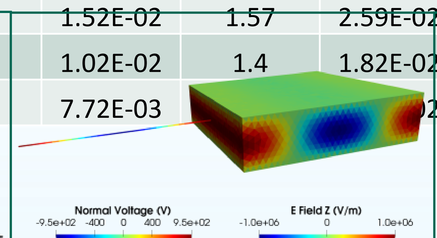


Figure 2: initial conditions in direction of propagation, $V_n, E_z \neq 0$

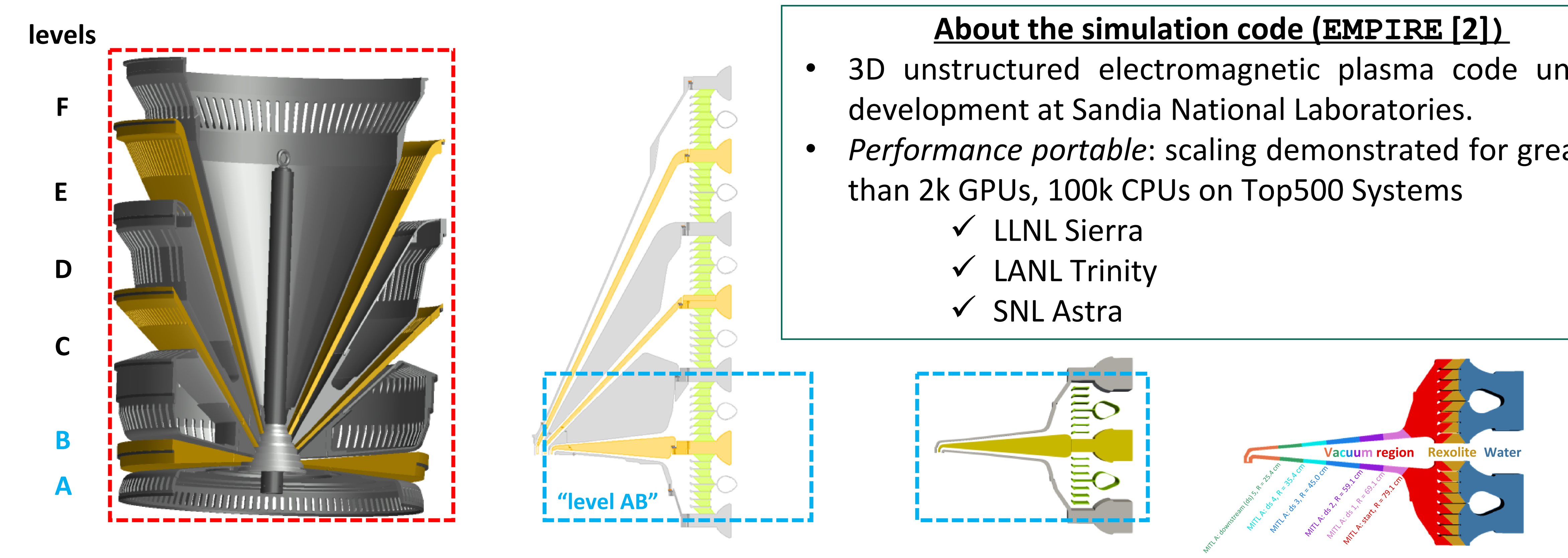
1D-3D EM convergence

- 3D cell size, $h = 1\ \mathrm{mm} \cdot \frac{1}{r}$
- 1D cell size, $\Delta n = 1\ \mathrm{mm} \cdot \frac{1}{r}$
- time step, $\Delta t = \frac{1}{20 \cdot f_{TM,1}} \cdot \frac{1}{r}$
- refine, $r = 1.0, 1.5, 2.0, 2.5$

→ *expectation:* $O(h + \Delta t^2 + \Delta n^2 + k_{TM,1}^2 h)$

Cell size (m)	PPP z	PPP c	E_z error	E_z rate	E_y error	E_y rate	B_x error	B_x rate
1.00E-03	16.2	8.5	3.15E-02	--	5.96E-02	--	4.73E-02	--
6.67E-04	24.3	12.7	1.41E-02	1.98	2.88E-02	1.79	2.58E-02	1.5
5.00E-04	32.5	16.9	9.86E-03	1.24	1.93E-02	1.4	1.85E-02	1.16
4.00E-04	40.6	21.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

3D EM Saturn simulation



Full hardware rendering | Full hardware cross-section | level AB hardware | level AB simulation volume

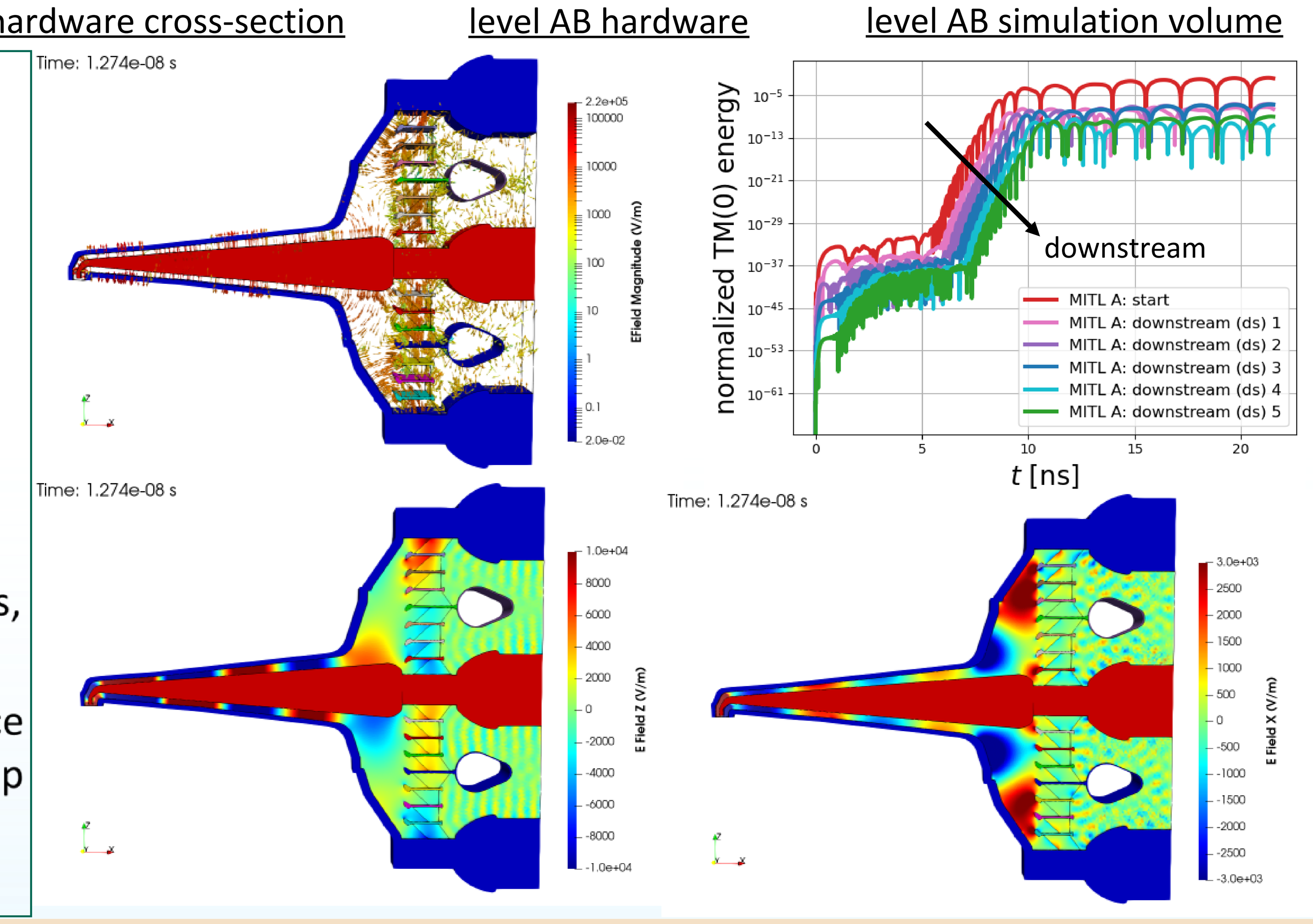
About the simulation code (EMPIRE [2])

- 3D unstructured electromagnetic plasma code under development at Sandia National Laboratories.
- *Performance portable*: scaling demonstrated for greater than 2k GPUs, 100k CPUs on Top500 Systems
  - ✓ LLNL Sierra
  - ✓ LANL Trinity
  - ✓ SNL Astra

About the simulation

- three 3D electromagnetic blocks:
  - water : $\epsilon_r = 80$
  - Rexolite®: $\epsilon_r = 2.53$
  - vacuum : $\epsilon_r = 1$
- 5 degree wedge (7.64M elements)
- 1D transmission line coupling, 990V sinusoidal TM wave drive
- 5.5 wall-hours 1632 Intel Cascade Lake cores / 34 nodes, 12 OpenMP threads per node
- Traveling TM wave components evanesce downstream as the narrowing gap approaches TM mode cutoff conditions

→ ***in gap*: TEM ~ 10 × TM amplitude**



Conclusions

- We have extended our coupling method of 1D transmission line to 3D electromagnetic domains to support TM multi-mode waves and verified our implementation in the SNL plasma simulation code, EMPIRE.
- The 1D-3D coupling was leveraged to investigate higher order TM mode drive in level AB of the Saturn accelerator
- *Next steps*: TM perturbations of full TEM Saturn wave drive for jitter sensitivity studies, including more physics (e.g. particles, heating)

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References

[1] D. A. McGregor, et al. *Variational, stable, and self-consistent coupling of 3D electromagnetics to 1D transmission lines in the time domain*, J. Comput. Phys. (2021, accepted)
[2] M. T. Bettencourt, et al. *EMPIRE-PIC: A Performance Portable Unstructured Particle-in-Cell Code*. Comm. in Comput. Phys. *30* (**4**). 1232-1268. (Aug. 2021)

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