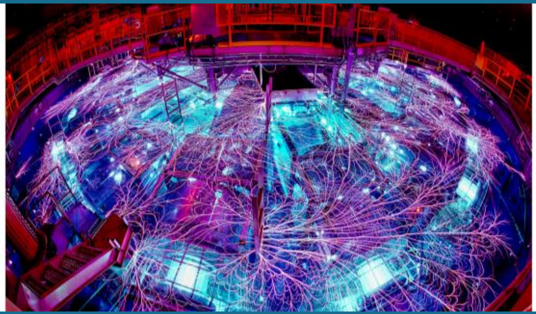
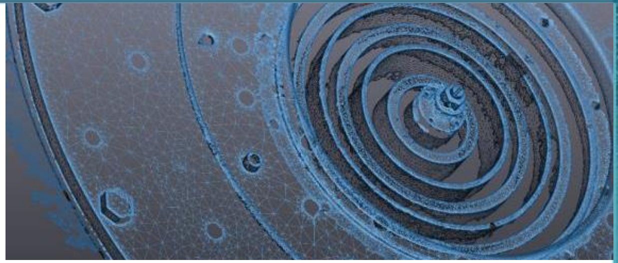
Power flow and vacuum breakdown in variable-impedance transmission lines under high self-magnetic fields





David Sirajuddin[a], Brian Hutsel[a], Troy Powell[a], Keith Cartwright[a], Adam Darr[a], Roman Shapovalov[b], Rick Spielman[b]

March 4, 2024

11th International Workshop on the Mechanisms of Vacuum Arcs (MeVArc 2024)

Tahoe City, CA USA

[a] Sandia National Laboratories, [b]University of Rochester Laboratory for Laser Energetics

Sandia National Laboratories

University of Rochester

ASAP — Assured Survivability and Agility with Pulsed Power

EMPIRE

U.S. Department of Energy

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Outline

- **Pulsed power at Sandia**
- **Subject of this talk**: Sandia National Laboratories' Z accelerator
- **The plasma simulation code: Empire**
- **Simulation model and results**
- **Towards NGPP: initial studies of variable-impedance MITLs**
- **Summary and conclusions**

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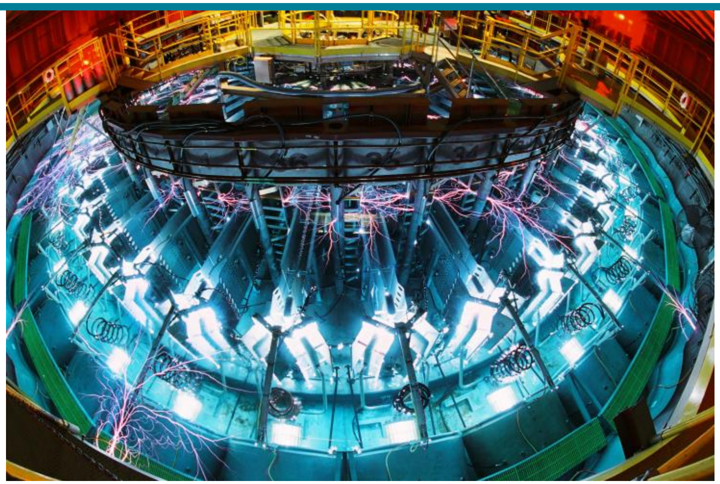
Pulsed Power at Sandia


Z


Saturn


HERMES-III

- Enabling "big science" research: HED physics, fusion, material EOS, opacities
- Delivering on national security: survivability testing
- The "big 3" pulsed-power workhorses at Sandia were built in the 1980s, largely based on experiments and empirical pulsed-power knowledge
- As we move towards next-generation pulsed power (NGPP), **there is significant programmatic interest to progress modeling capabilities** to enable predictive extrapolation into these new operating spaces (e.g. PW accelerators delivering > 60 MA) **and to vet new ideas for meeting design targets**

➢ variable (geometric) impedance is one such idea, we are assessing its viability to enable Z/NGPP

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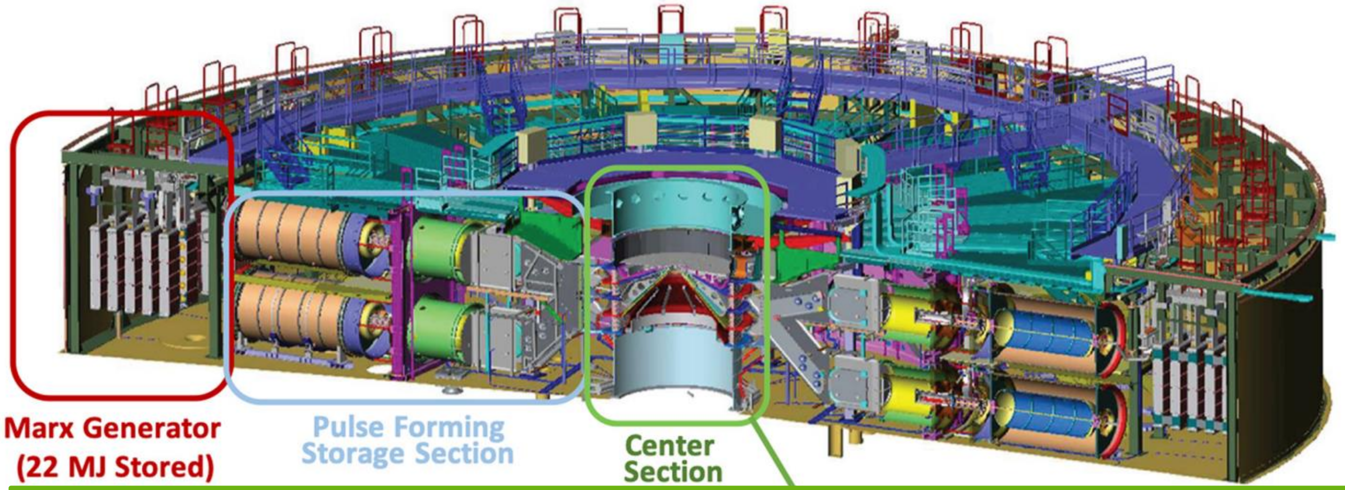
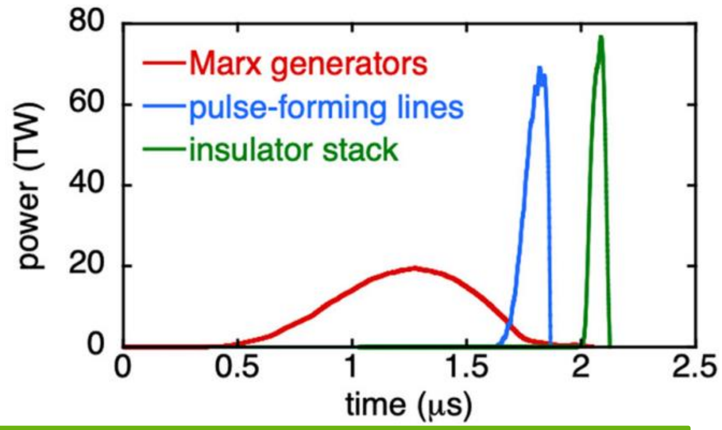
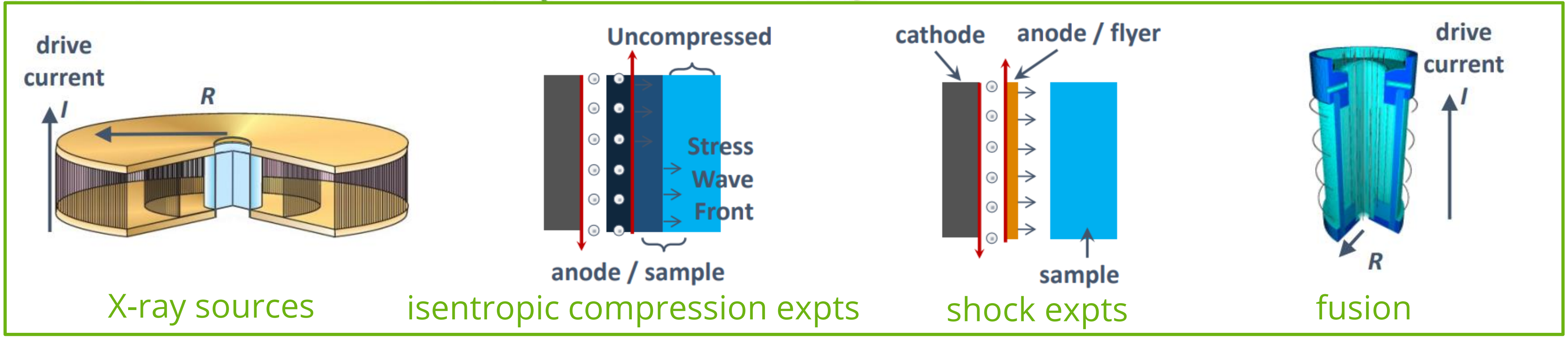
Storage
- 36 Marxes = 2,160 caps
- 95 kV, 20 MJ in ~ 3 min

Delivery to load
- 26 MA peak (80 TW)
- 100 ns rise time







Figures from D. Sinars et al. *Review of pulsed power-driven high energy density physics research on Z at Sandia.* Phys. Plasmas 27, 070501 (2020)

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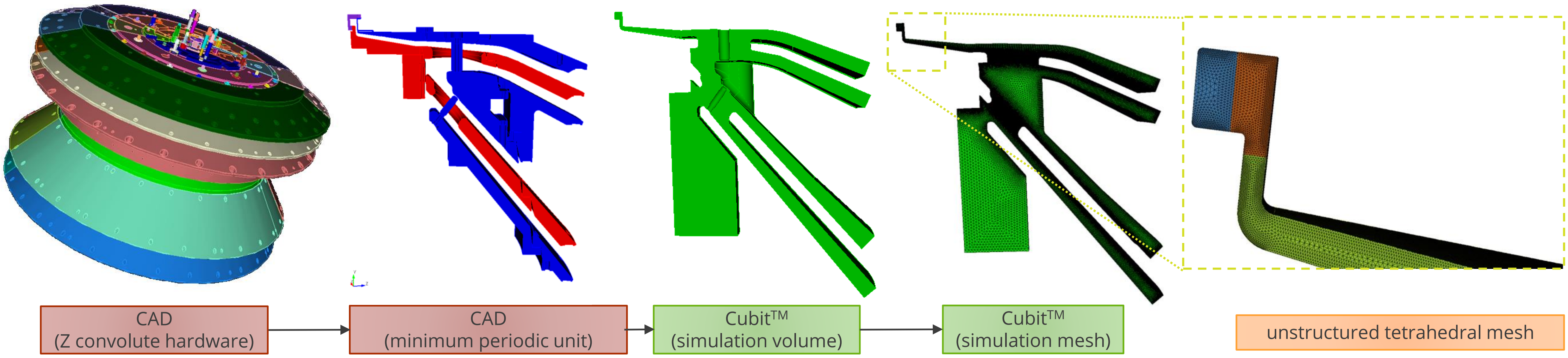

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  - particle-in-cell
  - fluid
  - hybrid

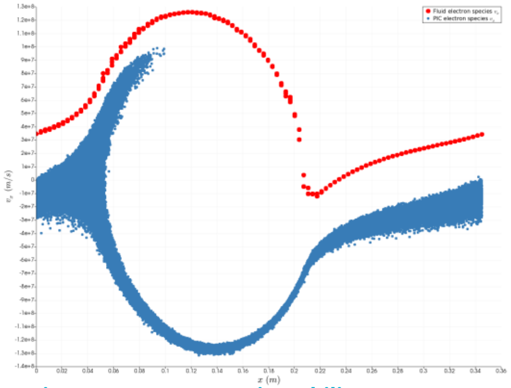
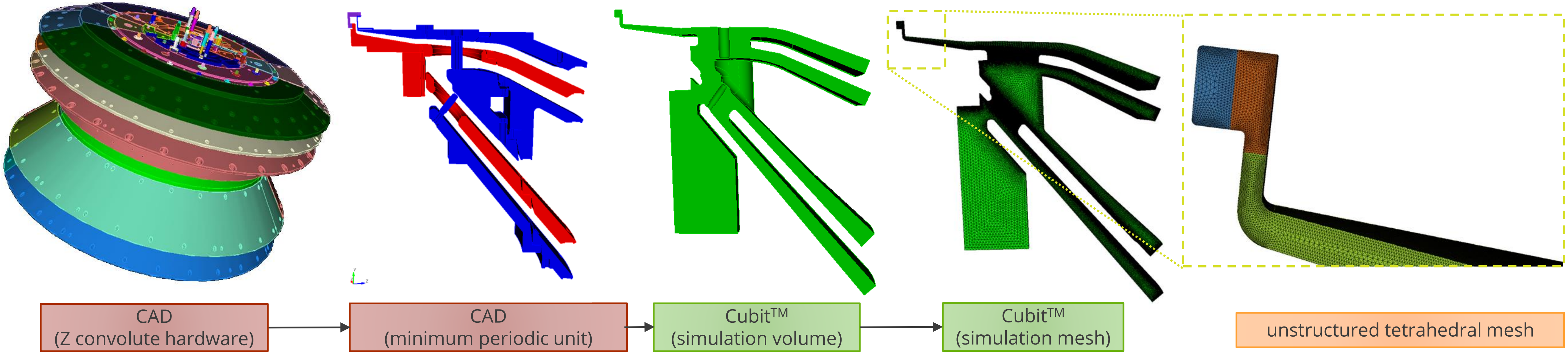


Figure 1: two-stream instability EMPIRE simulation[3] (hybrid) : PIC e^- (blue), fluid e^- (red)



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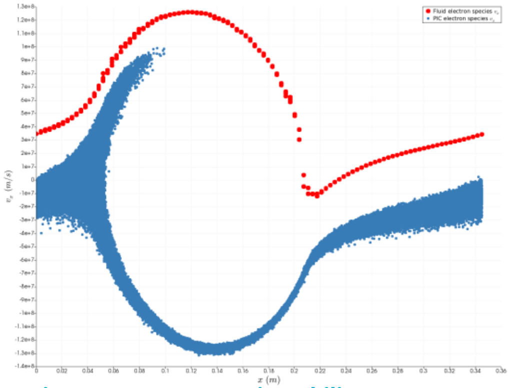

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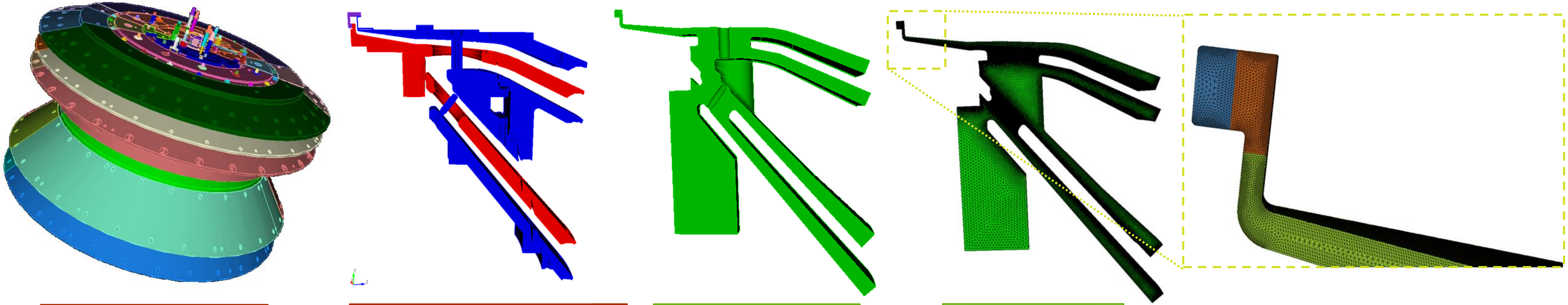

CAD (Z convolute hardware) → CAD (minimum periodic unit) → Cubit™ (simulation volume) → Cubit™ (simulation mesh)

unstructured tetrahedral mesh

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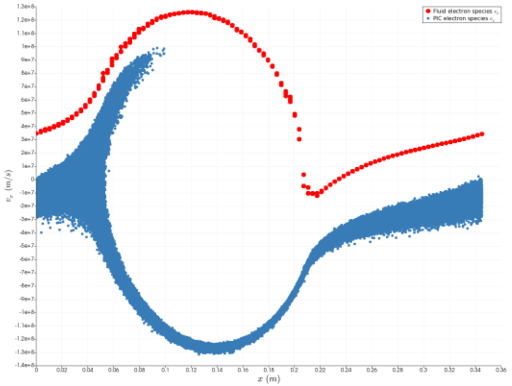
    - ❑ <u>*Soon*</u>: LANL Crossroads (ATS-3), LLNL El Capitan (ATS-4);
    - ❑ update: (Mar. 2023): Empire demonstrated on EAS3 system
  - Scaling demonstrated to 2048 nodes, 1.3B elems, 65.6B particles[1]



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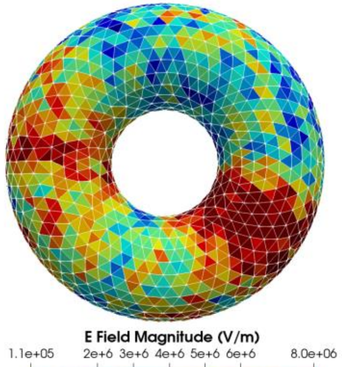

Figure 2: "Toroidal reference problem" used for EMPIRE performance monitoring at-scale

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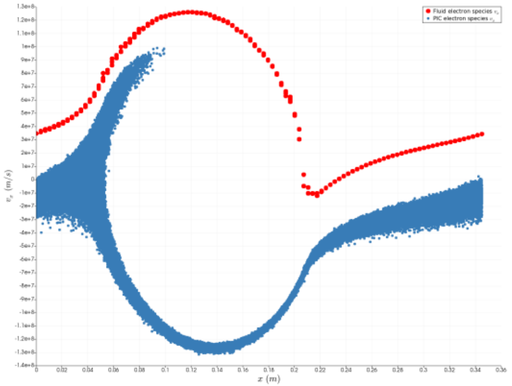
- Pulsed power sources are a major lab application ⇒ factors into code development priorities



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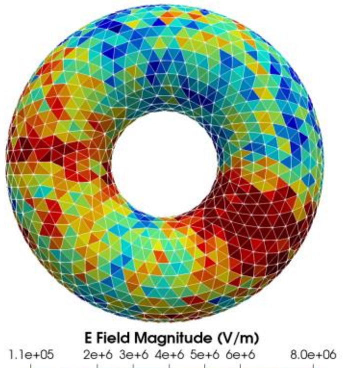

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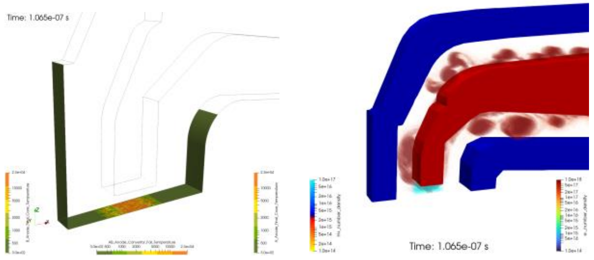

Figure 3: Saturn accelerator power flow conversion to electron beam generation

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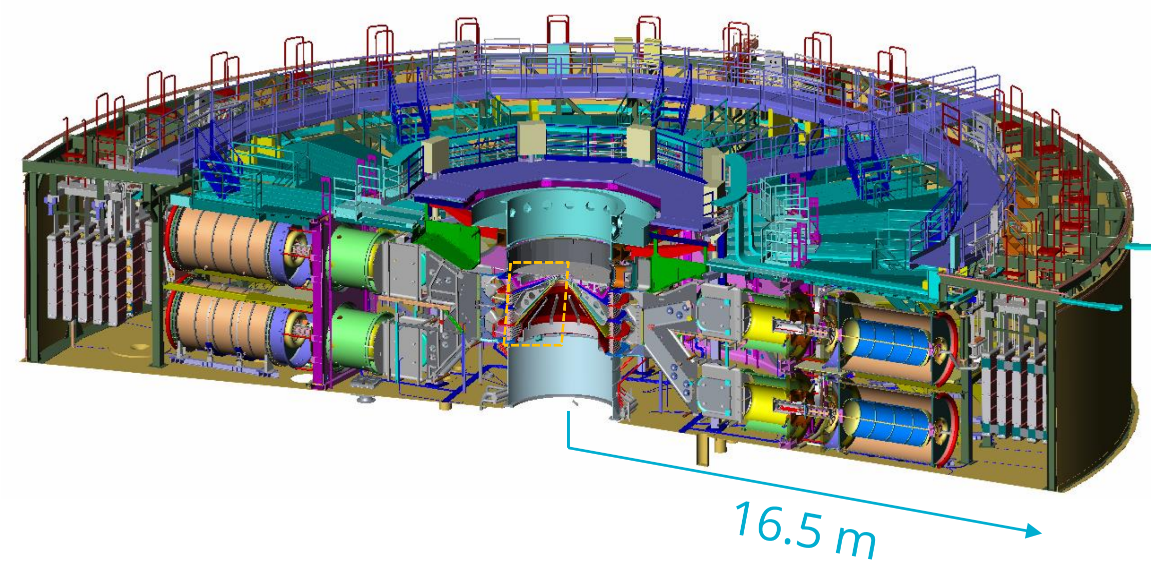
Computational challenges on Z: vastness of scales

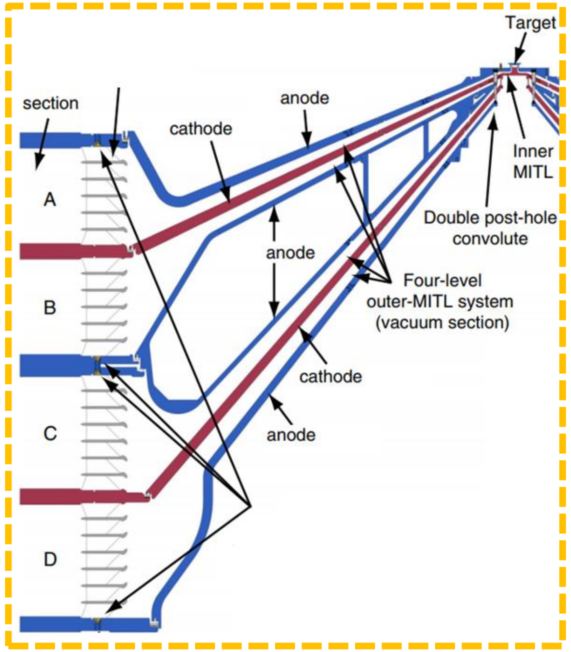
Power flow over system size



system size	(m)
pulse duration	(100 ns)
EM wave speeds in media	$(v/c \leq 1)$
near-vacuum	$(10^{-5}$ Torr)

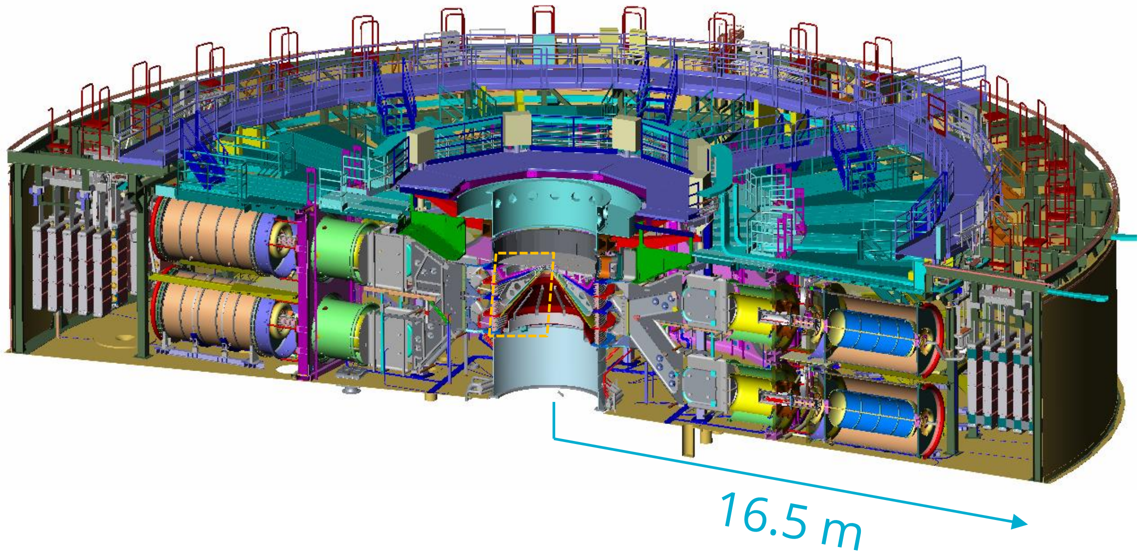
Computational challenges on Z: vastness of scales

Detailed MITL physics



vs.

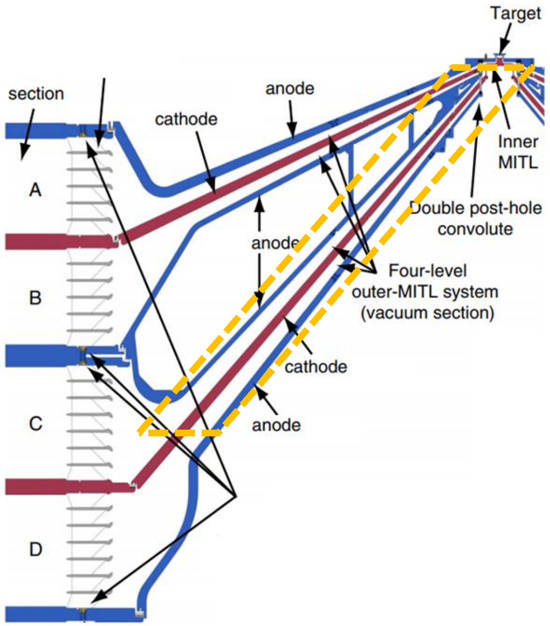
Power flow over system size



space:	Debye lengths	(μm)	vs.	system size	(m)
time:	electron freqs	(THz)	vs.	pulse duration	(100 ns)
velocities:	desorbed neutrals	($v/c \sim 10^{-6}$)	vs.	EM wave speeds in media	($v/c \leq 1$)
densities:	plasma densities	($\leq 10^{18}$ cm^{-3})	vs.	near-vacuum	(10^{-5} Torr)

Computational challenges on Z: multitude of processes

Detailed MITL physics



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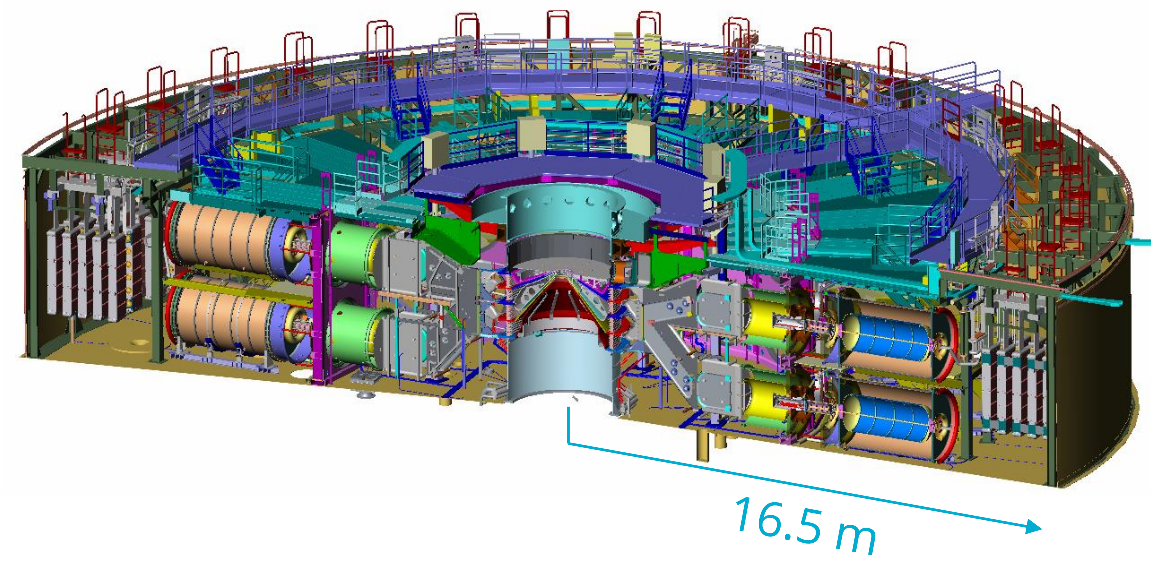

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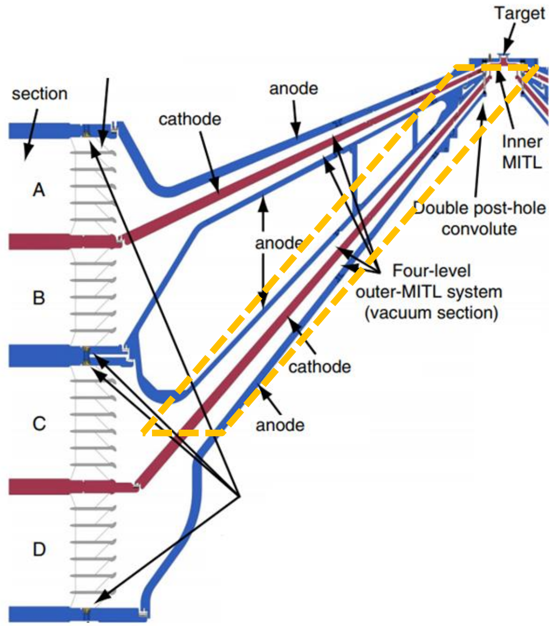

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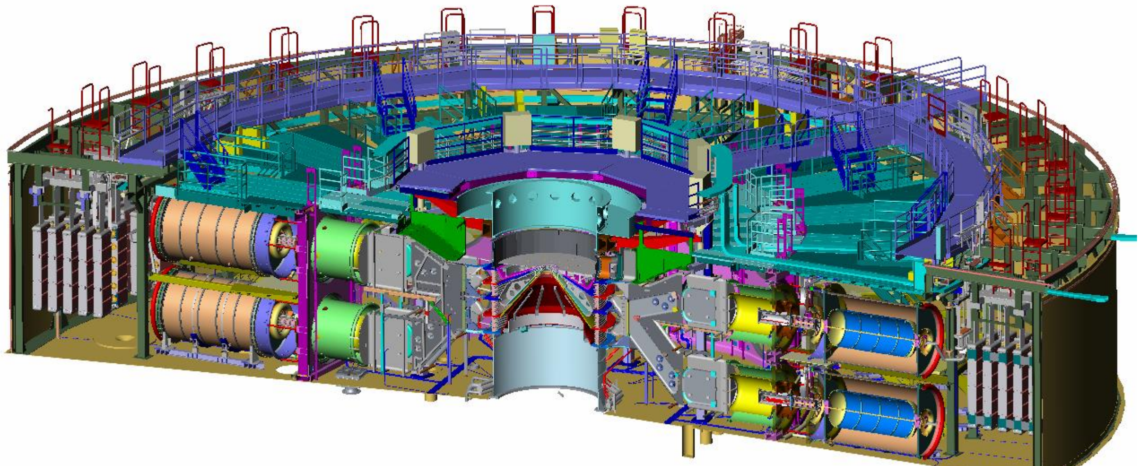
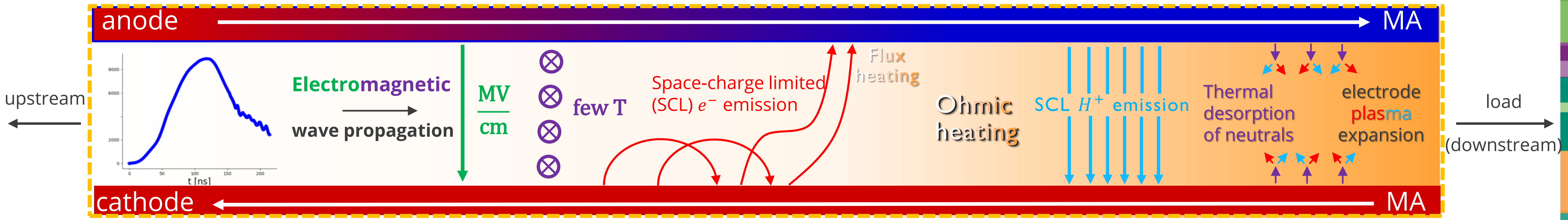


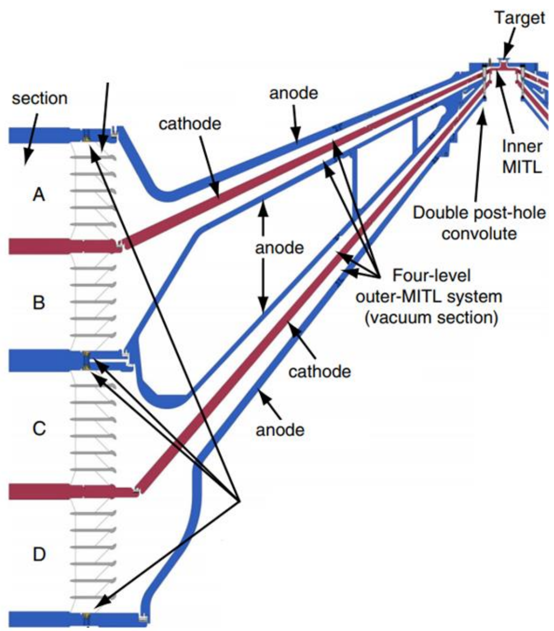


Most germane processes to correctly simulating pulsed power operation, i.e. a non-exhaustive list!

How can we simulate a meters-long system requiring micron resolution over 100 ns at 10^{-14}s timesteps?

Computational challenges on Z: vastness of scales

Detailed MITL physics



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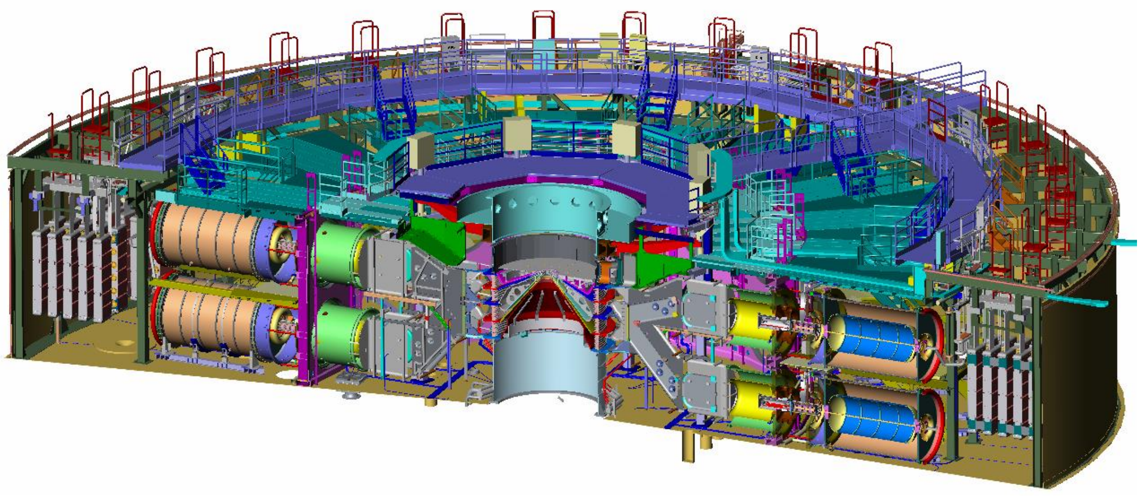

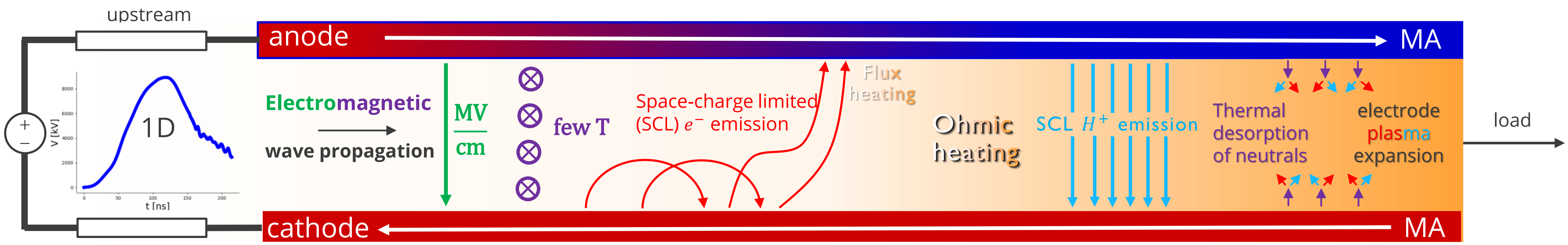

Solution: 1D-3D computational model – TEM wave propagation in 1D transmission line domains (meters) are coupled to a single 3D EM-PIC domain downstream (centimeters) simulating the details MITL physics

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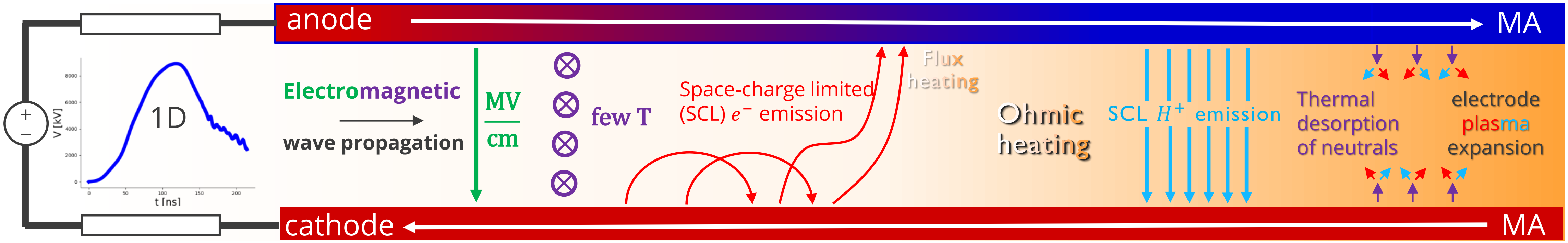

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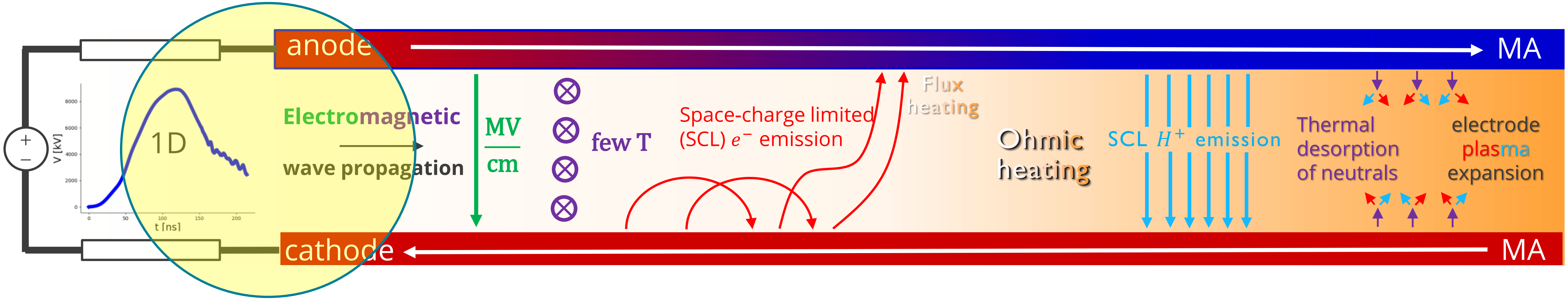

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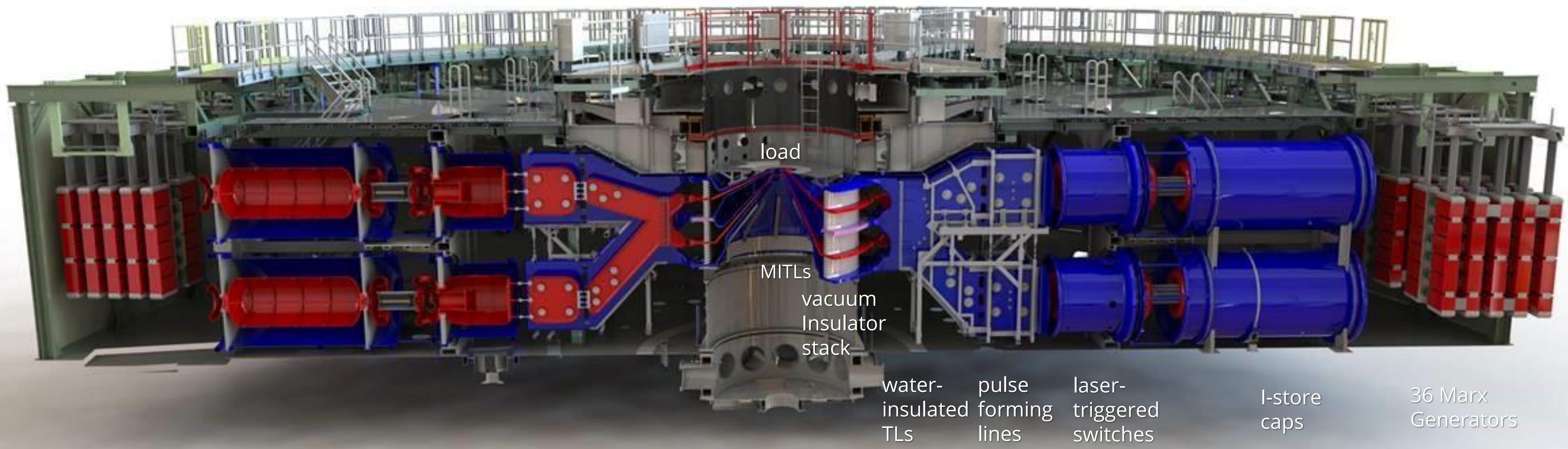
1D transmission line to 3D EM-PIC domain coupling

1. A 1D/2D full circuit model for Z was developed in BERTHA



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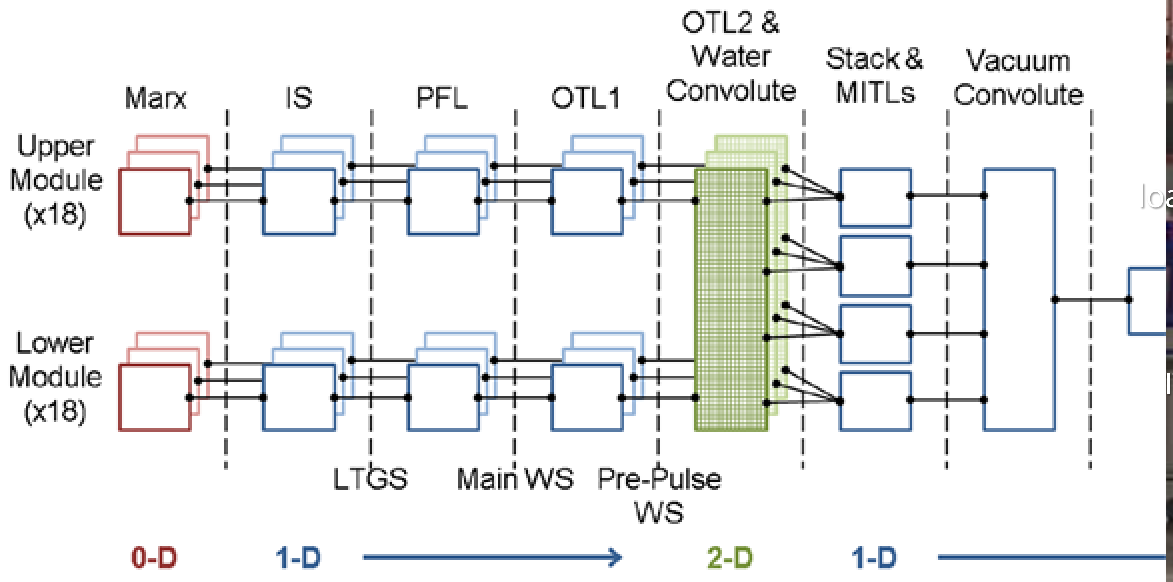
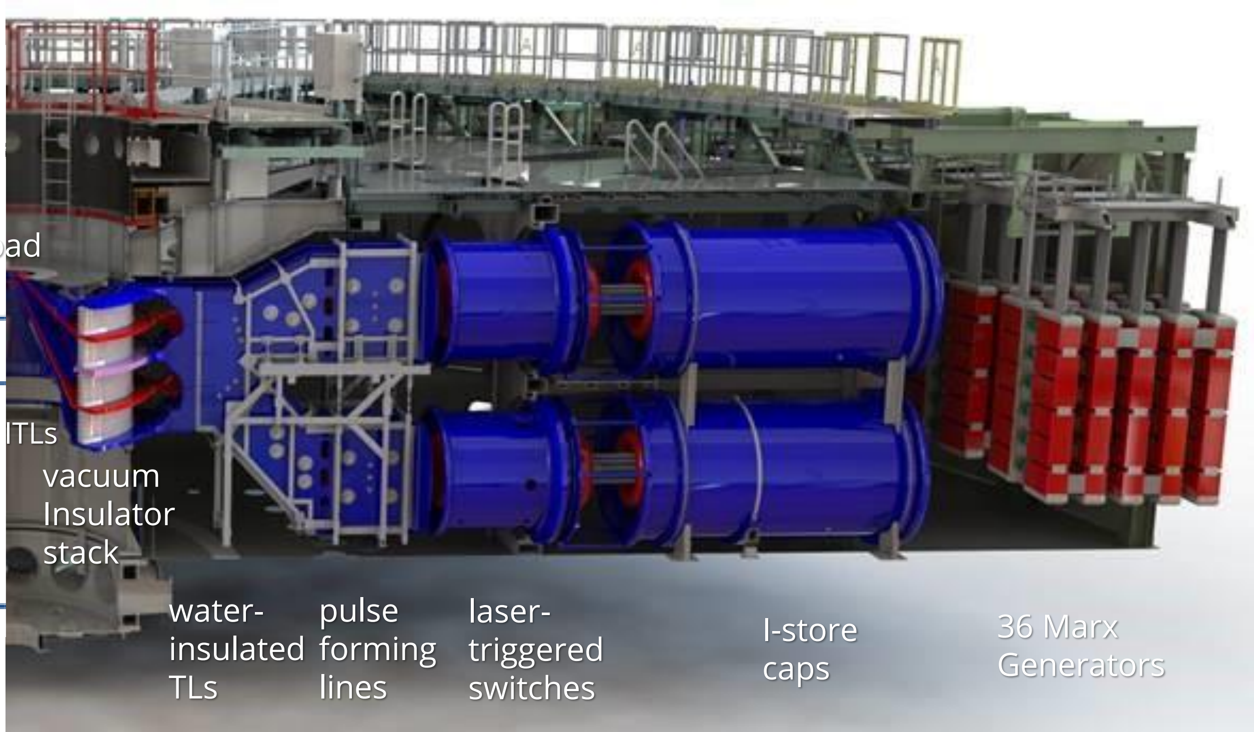
Full BERTHA circuit model



(Hutsel, B. T. Phys. Rev. Accel. Beams **21**, 030401)



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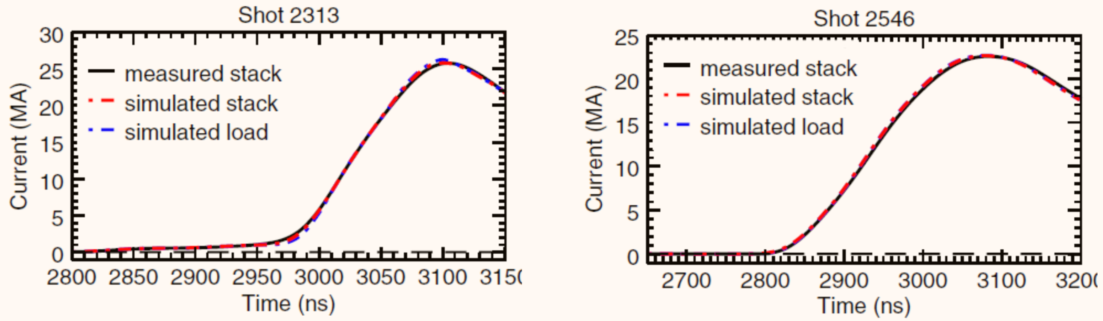
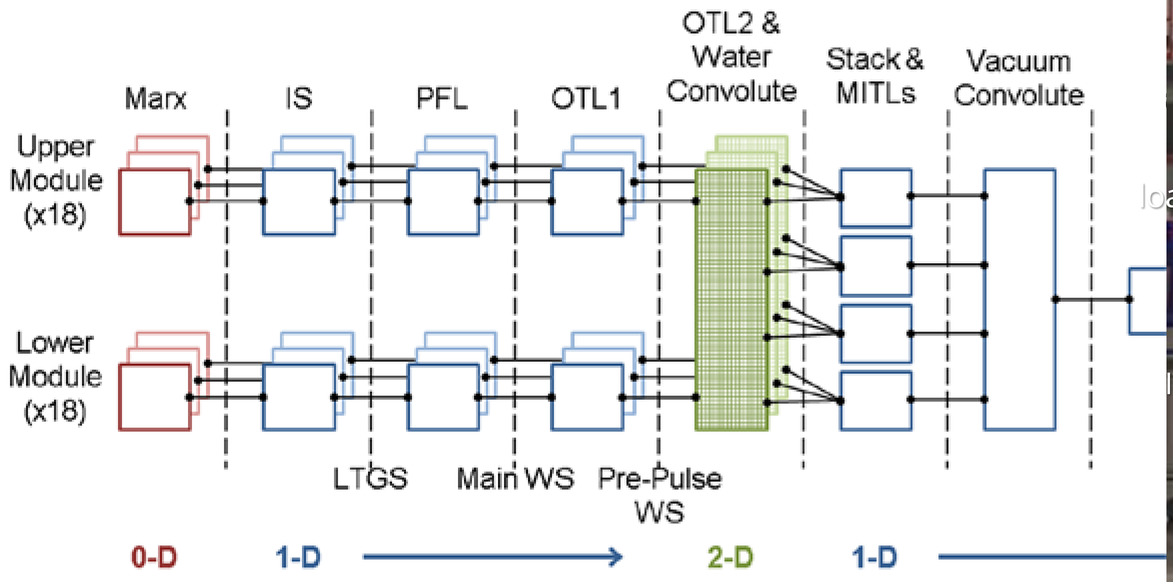


circuit model predictions agree with measurements for various shots

Full BERTHA circuit model



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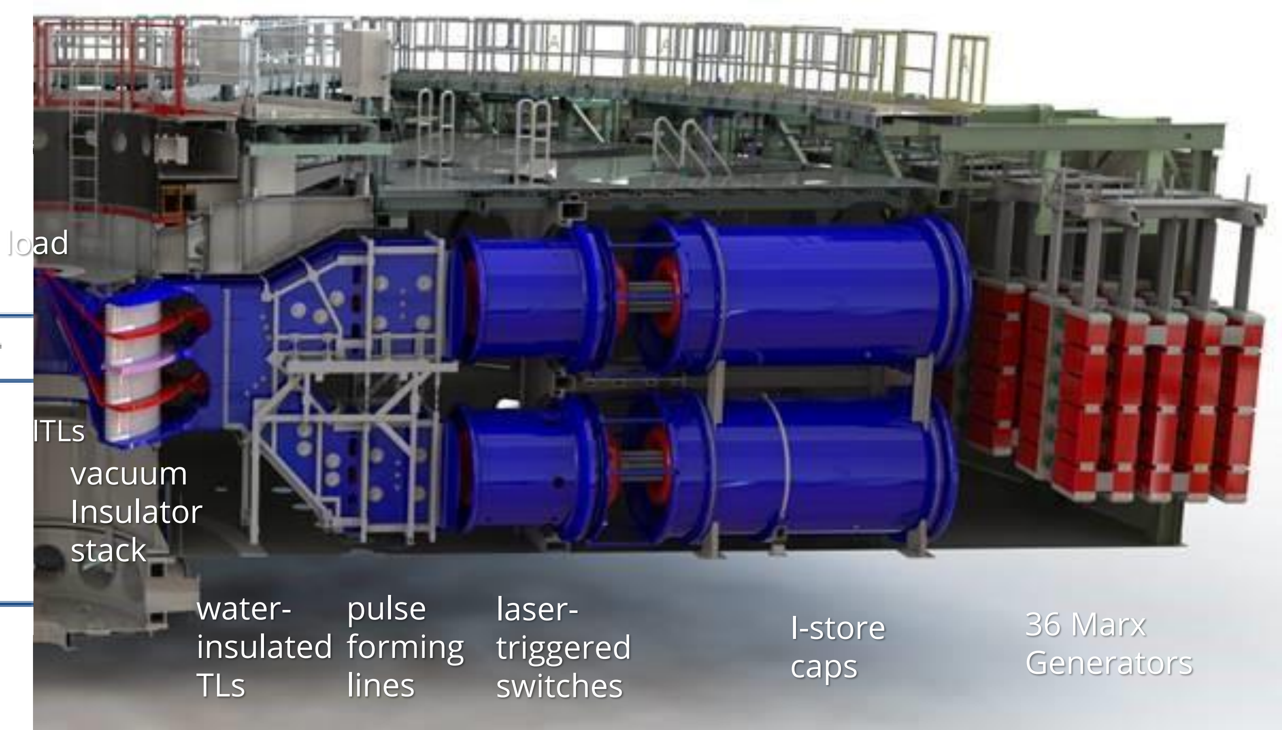

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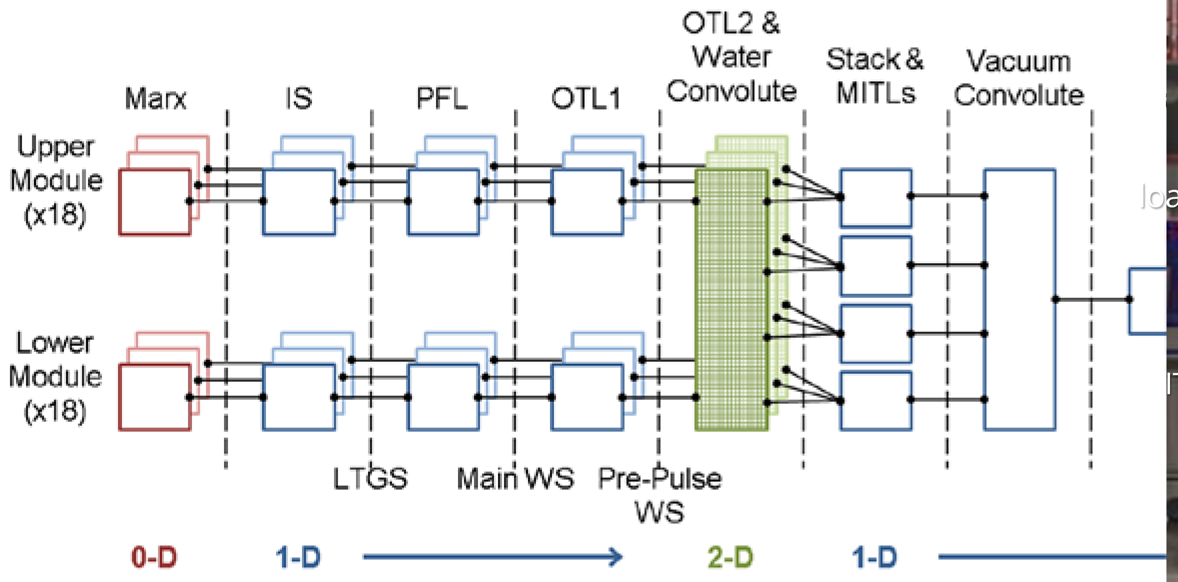
1D
Empire transmission lines



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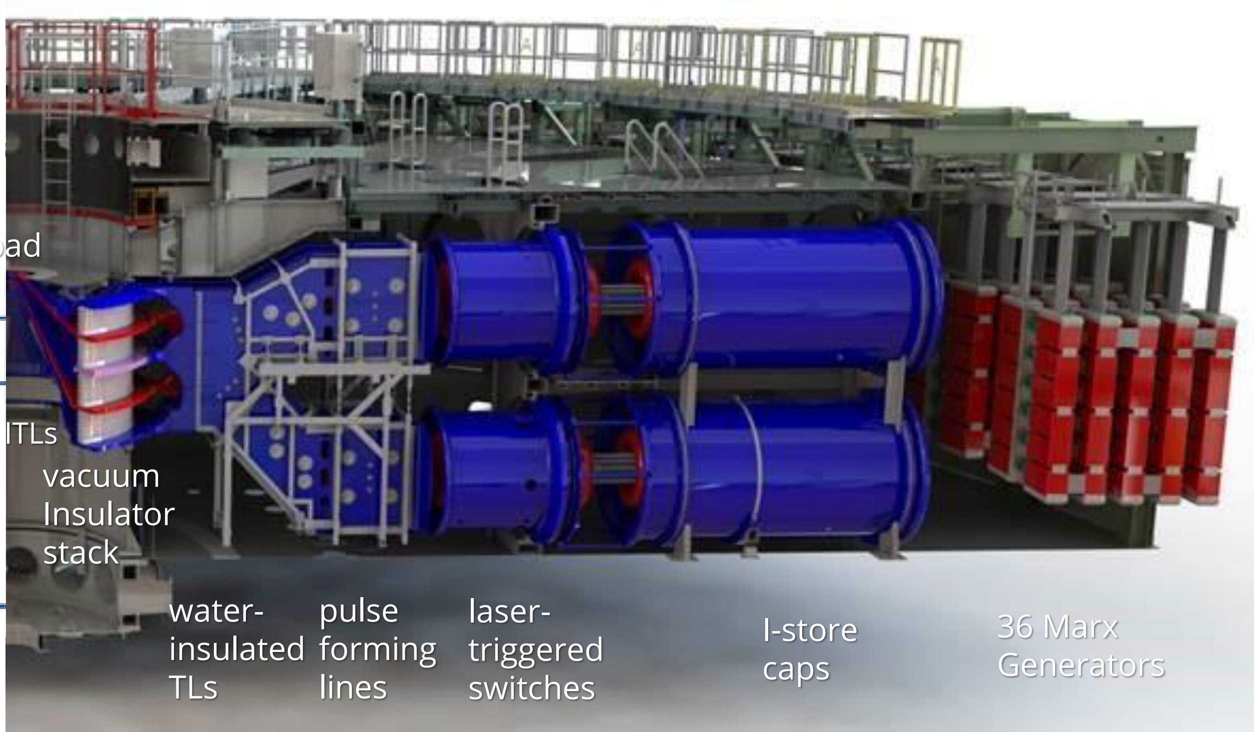

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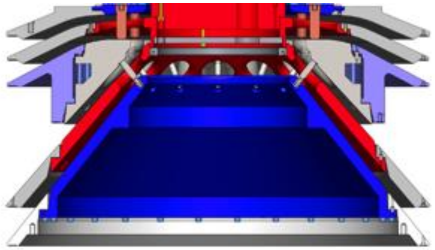
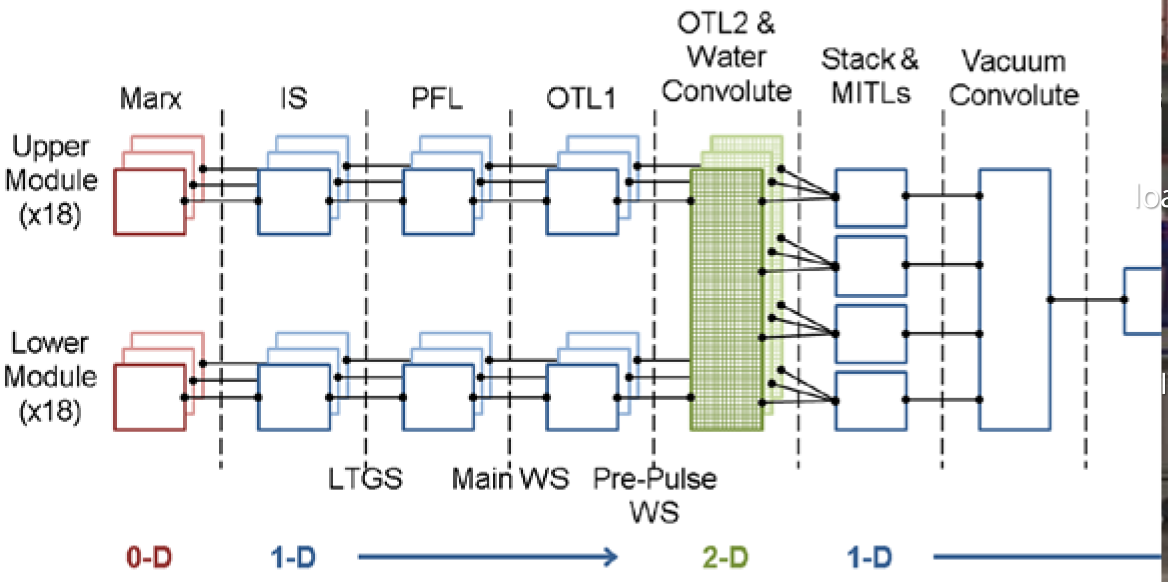


Fig: convolute hardware

Full BERTHA circuit model | 3D Empire EM-PIC | 1D Empire transmission lines



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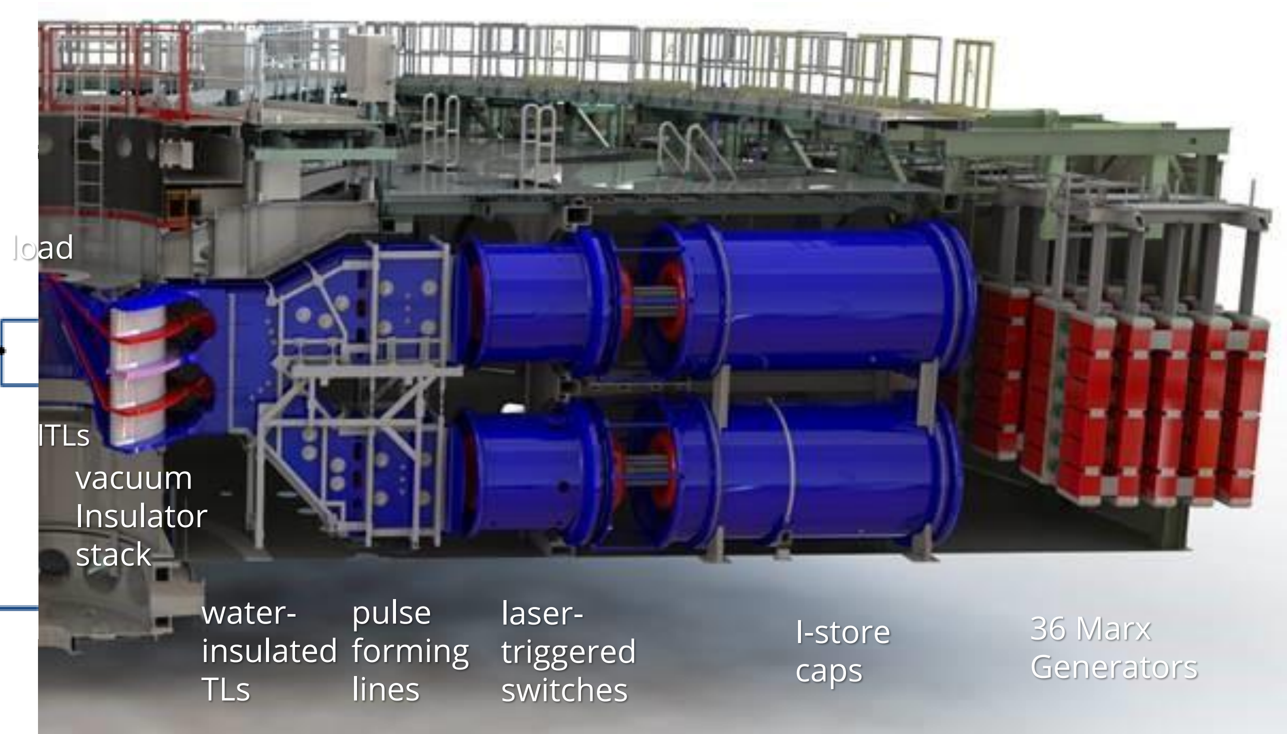

animation

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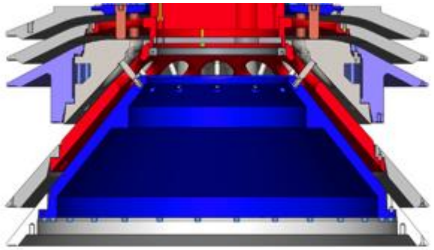
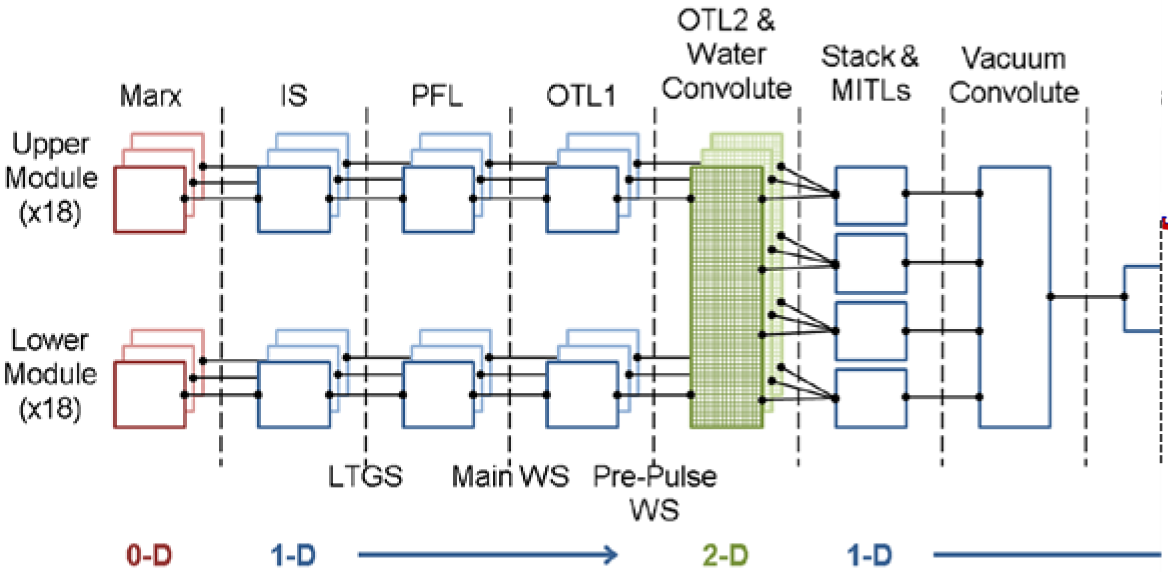
3. A 3D Empire EM-PIC domain was created from CAD

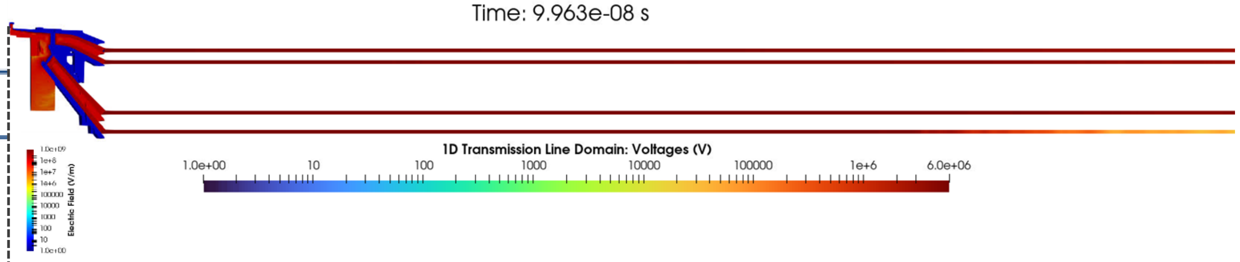


Full BERTHA circuit model

3D Empire EM-PIC

1D Empire transmission lines

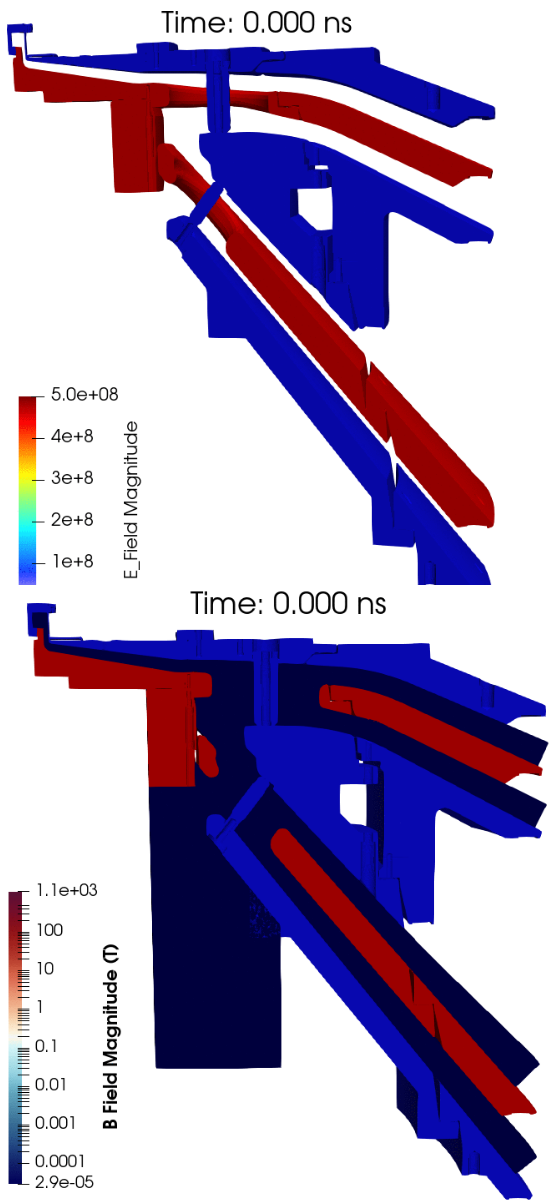


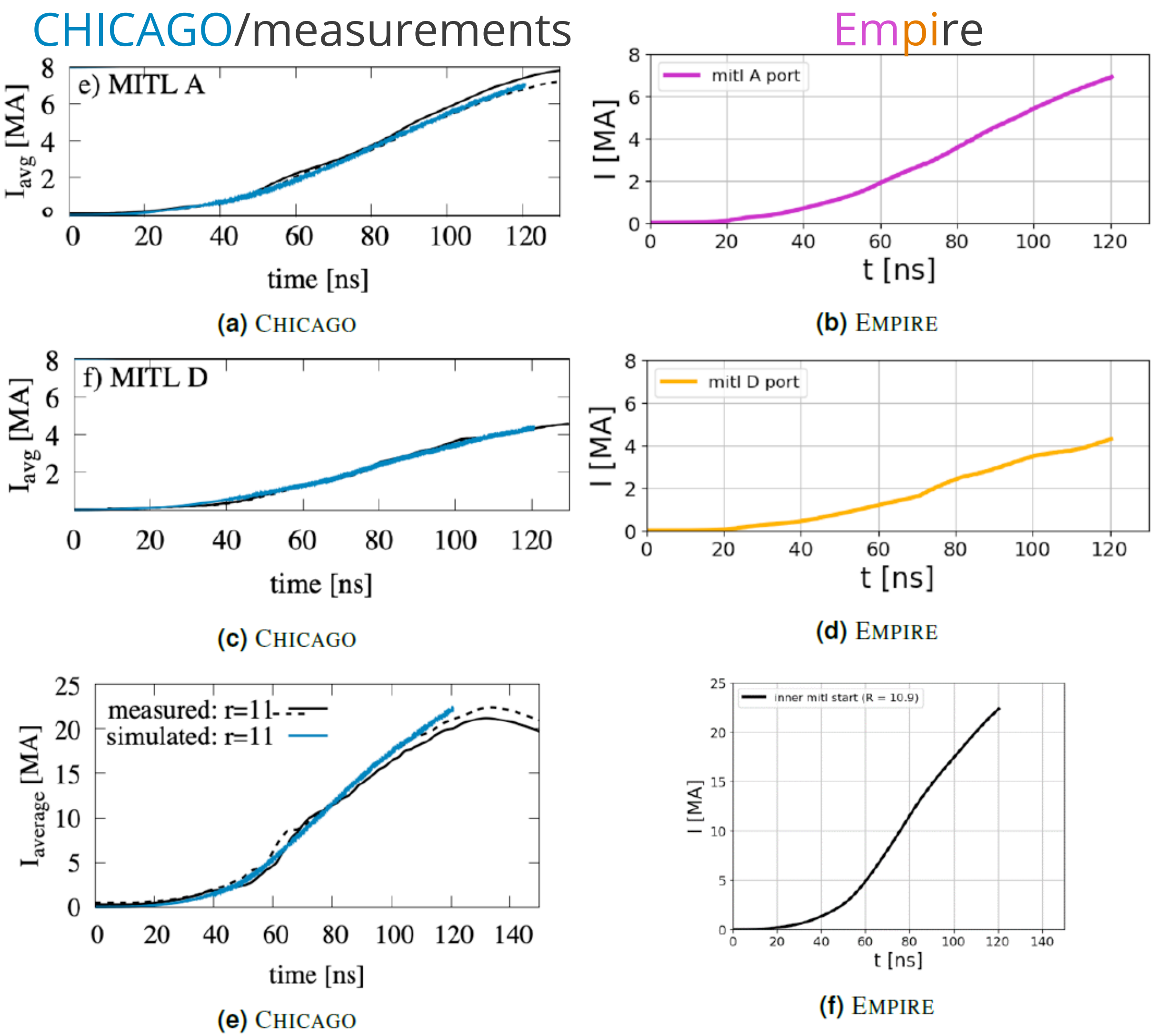


(Hutsel, B. T. Phys. Rev. Accel. Beams **21**, 030401)

1D TL-3D EM-PIC Empire model predicts currents in line with measurements

animation





Laity, George R. et al. Plasma Grand Challenge LDRD final report. SAND2021-0718. doi:10.2172/1813907.

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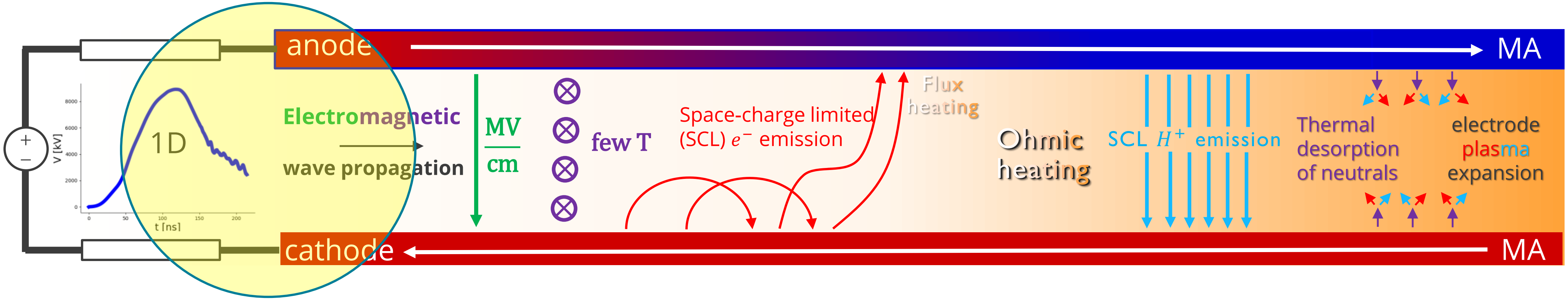

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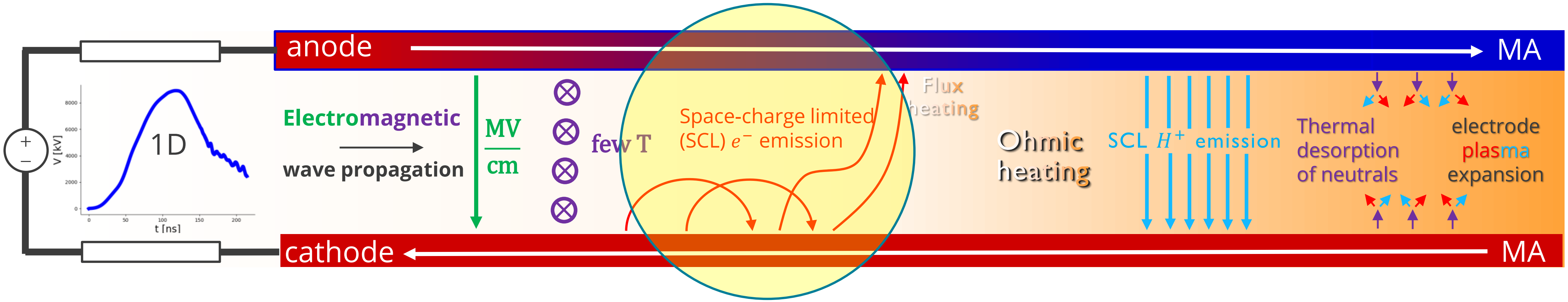

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Electron emission from cathodes

- In an extreme environment (e.g., Z/NGPP) the detailed story leading to electron emission is "awash", but its result is guaranteed

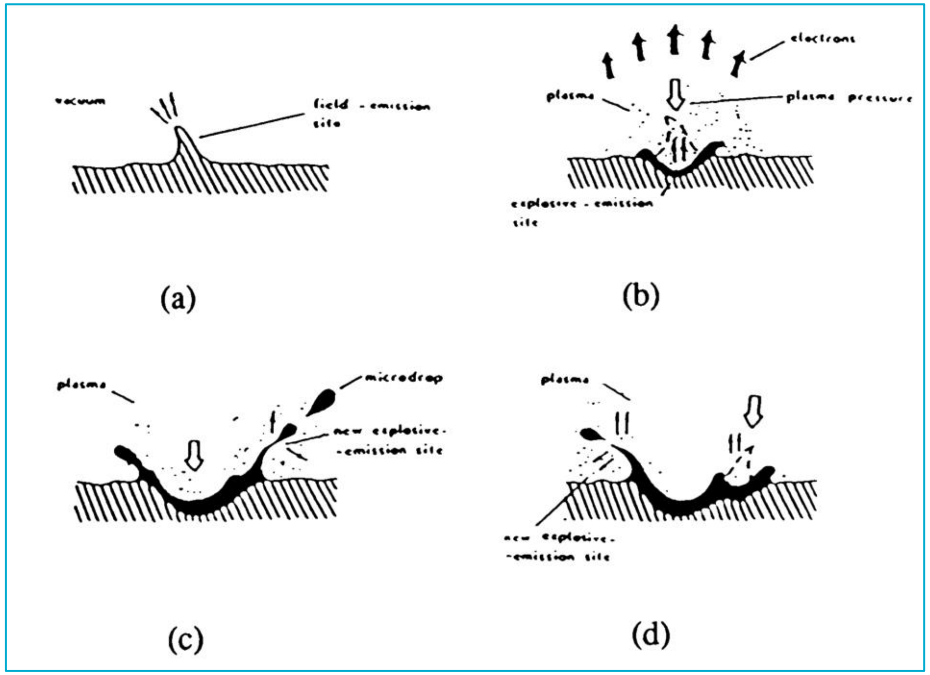


Figure from: G.A. Mesyats. *Pulsed Electrical Discharge in Vacuum*. 1989, p. 115

An applied electric field establishes "emission centers" (ECs) due to field enhancements at micro-protrusions

microamps is sufficient ηj^2 heating to violently ablate ("explode") material into the gap, splattering a remainder nearby, re-canvassing the landscape with new micro-protrusions and the process repeats, propagating to cover the cathode with thin film plasma

- Resolving a transition from E field (e.g. Fowler-Nordheim) to temperature field emission (e.g. Jensen, Richardson) or determining the correct field coupling therein is inconsequential in the context of a 100 ns pulse up to MV/cm → the cathode surface breaks down to plasma, making available a zero work function source of electrons from which emission is enabled up to its self-limiting maximum.

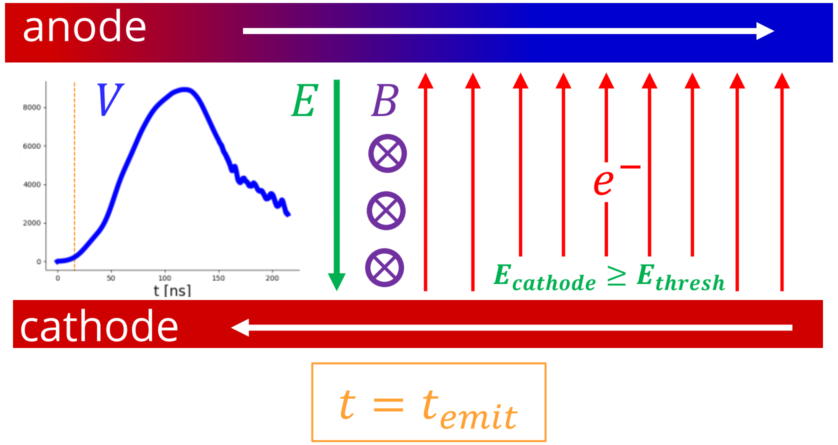
➢ Bottom line for modeling pulsed power: a basic SCL electron emission model suffices:

electrons are injected into the domain at the SCL rate from, typically $\boldsymbol{E}_{\text{cathode surface}} \cdot \hat{n} > 200$ kV/cm

How is Z still efficient given current loss mechanisms such as electron emission? Magnetic insulation

(Seminal work by Creedon (1975-1977), VanDevender, McDaniel, Mendel (1976 – 1982), NRL, …)

1. Electron emission condition



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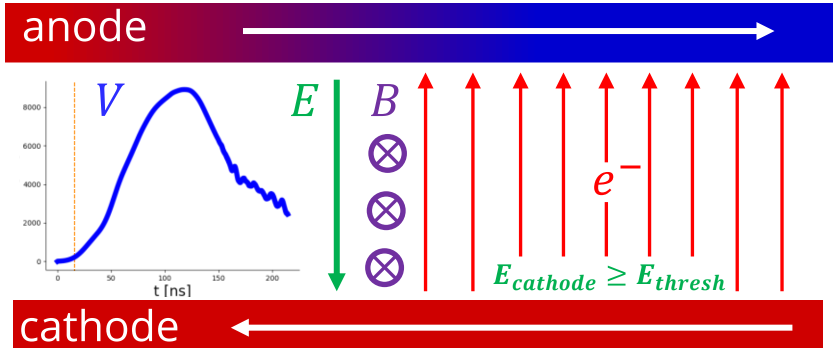
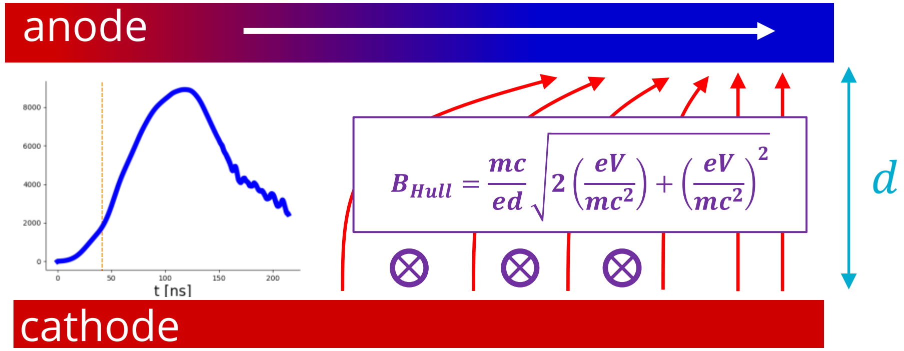


$t = t_{emit}$

2. Hull cutoff condition[1]



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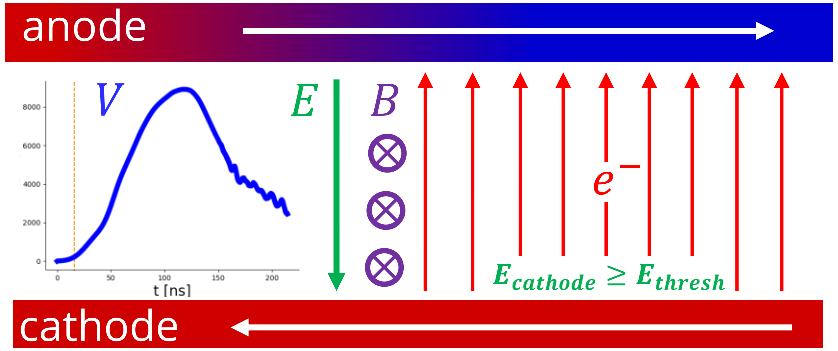

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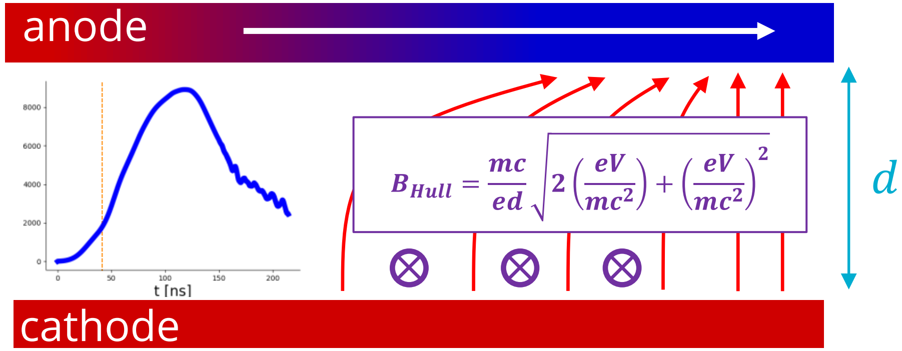
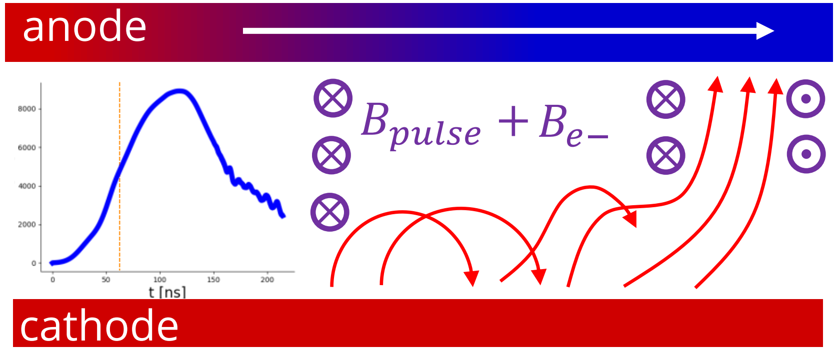


$t = t_{Hull}$

3. Loss front sets up insulation



$t = t_{setup}$

magnetic fields from the loss front reinforce flux upstream

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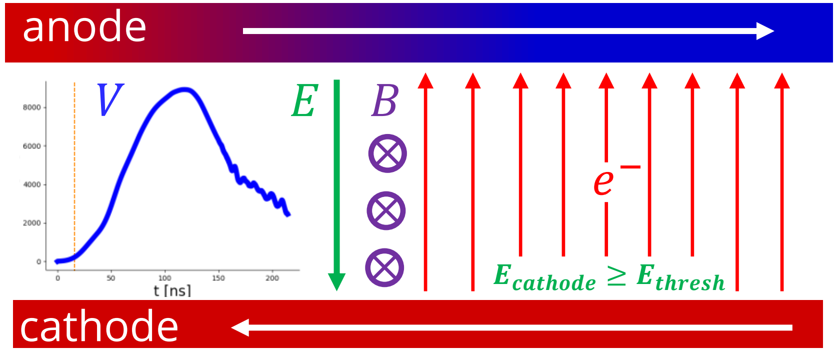

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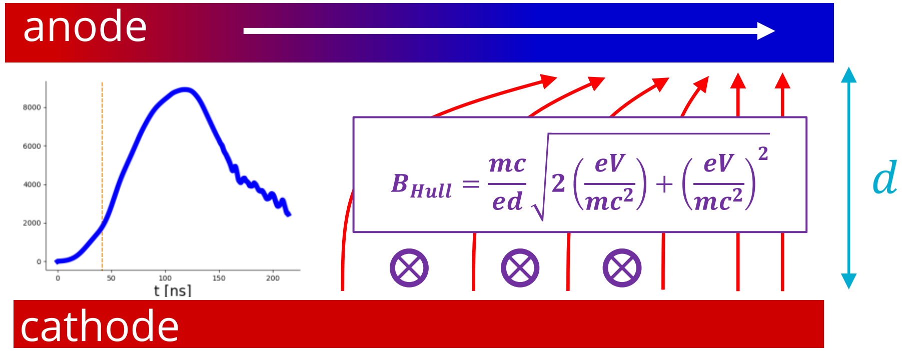

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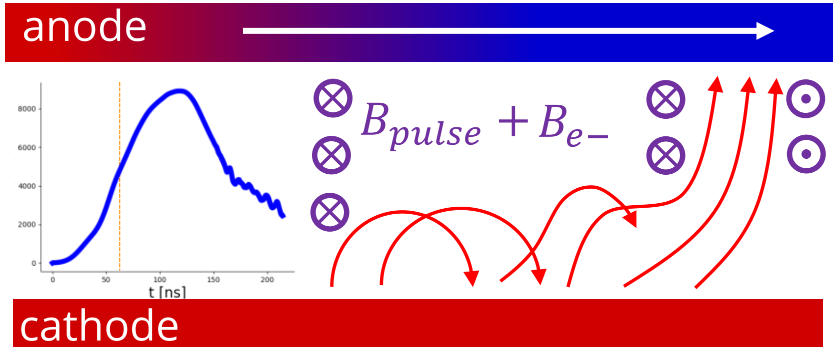
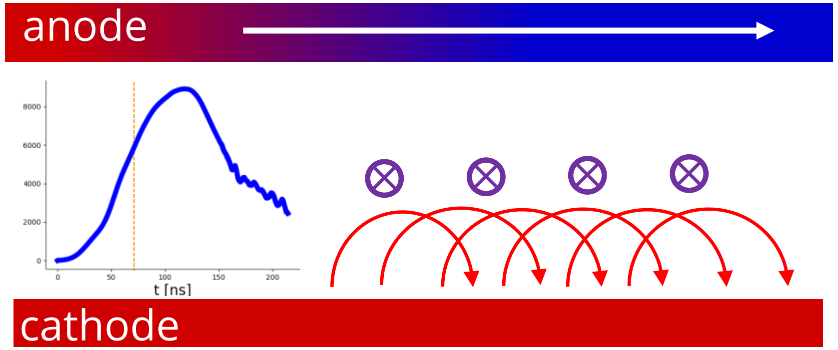


$t = t_{setup}$

magnetic fields from the loss front reinforce flux upstream

4. magnetically-insulated electron flow



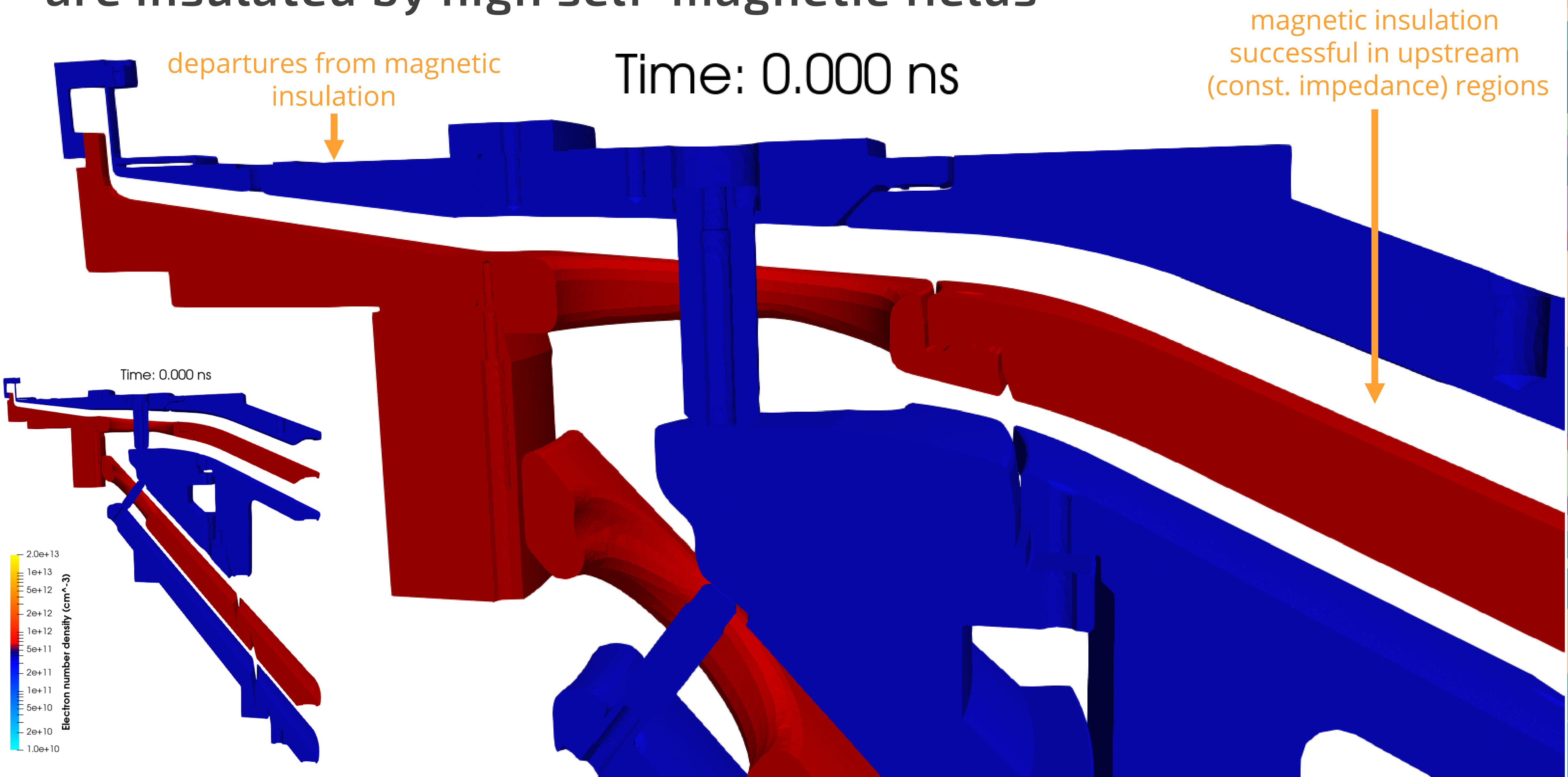
$t = t_{insul}$

The self-magnetic fields exceed the threshold for insulation "everywhere"

[1]Hull, A. W. Phys. Rev, vol. 18, pp. 31–57, Jul 1921.

cathode breakdown leads to electron emission up to the space-charge limit, but the majority of these electrons are insulated by high self-magnetic fields

animation



Electron vortex flow is typical in pulsed power accelerators: Diocotron instabilities

animation

Figure from Gilbert, C. “The Kelvin-Helmholtz Instability in Space.” CU Boulder, 2017.

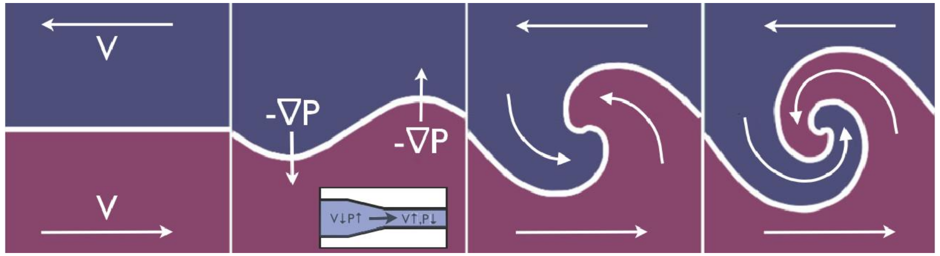
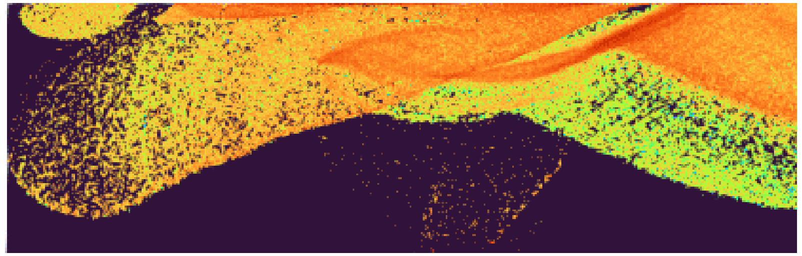
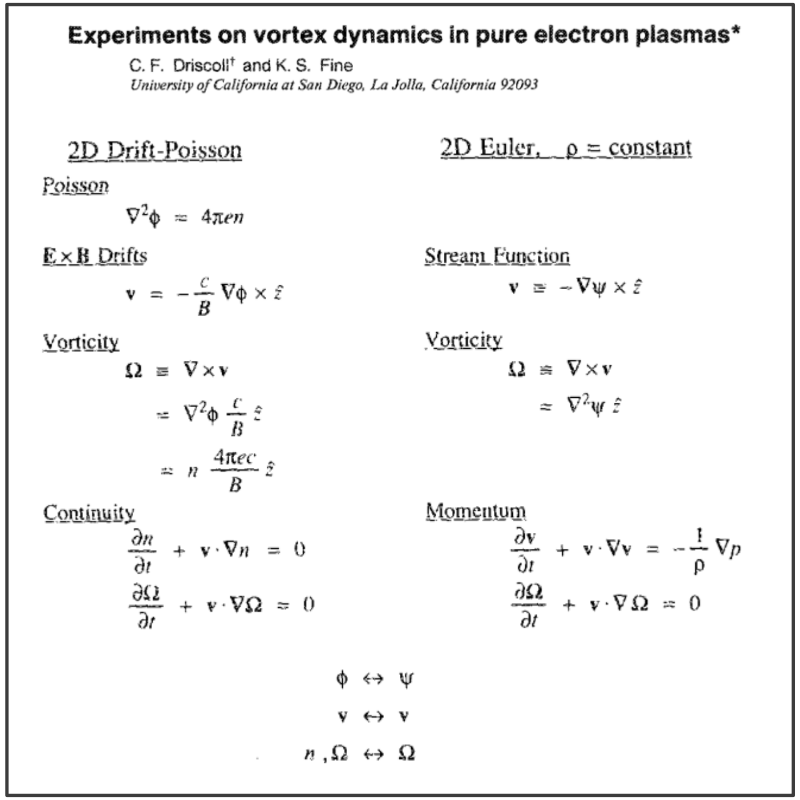


Figure: Empire simulation showing a Diocotron instability in insulated electron flows (shown: e- number density)



- “slipping stream instability” non-neutral charge sheets[1,2,3]
- seed perturbations can happen due to various (related) mechanisms: local E field deviations, impedance transitions
- completely analogous to Kelvin-Helmholtz instabilities in fluid dynamics (see right)



Experiments on vortex dynamics in pure electron plasmas*

C. F. Driscoll† and K. S. Fine

University of California at San Diego, La Jolla, California 92093

2D Drift-Poisson	2D Euler, ρ = constant
Poisson: $\nabla^2\phi = 4\pi en$	
E×B Drifts: $\mathbf{v} = -\frac{c}{B}\nabla\phi \times \hat{z}$	Stream Function: $\mathbf{v} = -\nabla\psi \times \hat{z}$
Vorticity: $\Omega = \nabla\times\mathbf{v} = \nabla^2\phi\,\frac{c}{B}\,\hat{z} = n\,\frac{4\pi ec}{B}\,\hat{z}$	Vorticity: $\Omega = \nabla\times\mathbf{v} = \nabla^2\psi\,\hat{z}$
Continuity: $\frac{\partial n}{\partial t} + \mathbf{v}\cdot\nabla n = 0$; $\frac{\partial\Omega}{\partial t} + \mathbf{v}\cdot\nabla\Omega = 0$	Momentum: $\frac{\partial\mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v} = -\frac{1}{\rho}\nabla p$; $\frac{\partial\Omega}{\partial t} + \mathbf{v}\cdot\nabla\Omega = 0$

$\phi \leftrightarrow \psi$

$\mathbf{v} \leftrightarrow \mathbf{v}$

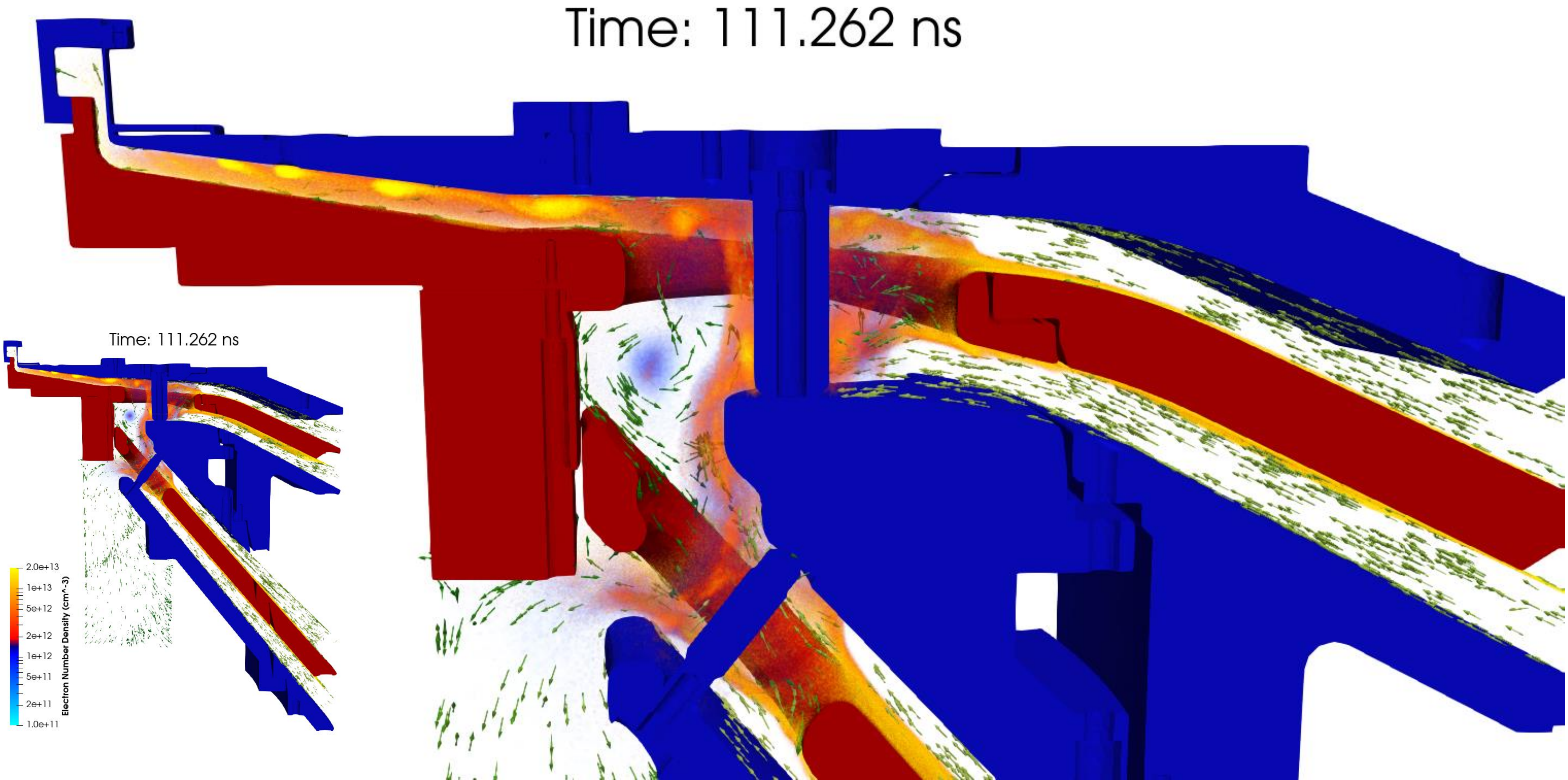
$n, \Omega \leftrightarrow \Omega$

Figure: dictionary showing the correspondence between Euler neutral fluid and plasma fluid equations

[1](seminal) O. Buneman; R. H. Levy; L. M. Linson. J. Appl. Phys. 37, 3203–3222 (1966). https://doi.org/10.1063/1.1703185
[2]C. F. Driscoll; K. S. Fine. Phys. Fluids B 2, 1359–1366 (1990) https://doi.org/10.1063/1.859556
[3]W. Knauer. J. Appl. Phys. 37, 602–611 (1966). https://doi.org/10.1063/1.1708223

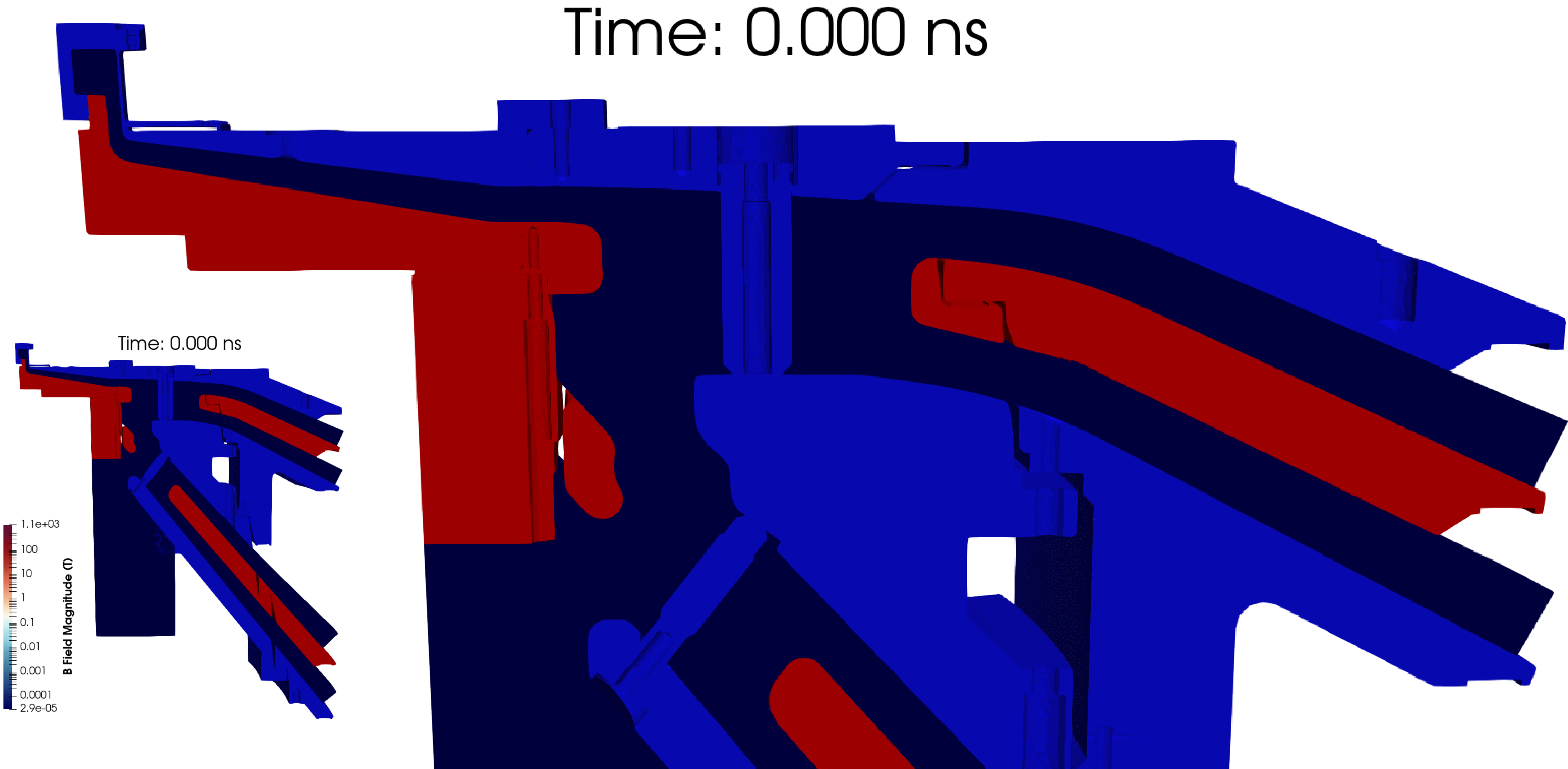
physics highlight: dominant transport is equilibrium flow

Equilibrium: $0 = -en_e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \rightarrow \boldsymbol{v}_\perp = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2}$ (same direction as power flow $\boldsymbol{S} = \boldsymbol{E} \times \boldsymbol{H}$)



Physics highlight: magnetic nulls in the convolute also contribute towards loss of insulation → lead to current losses to the anode "posts" in the convolute and result in ongoing particle flux heating

animation



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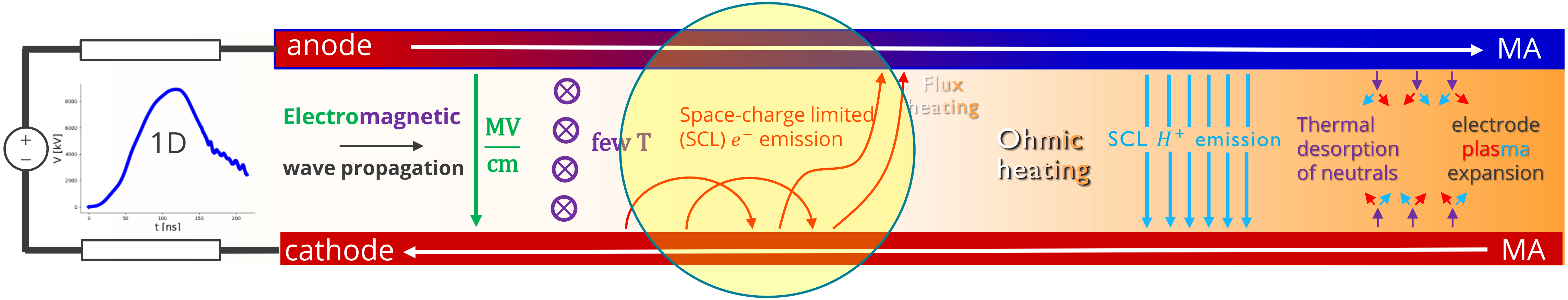

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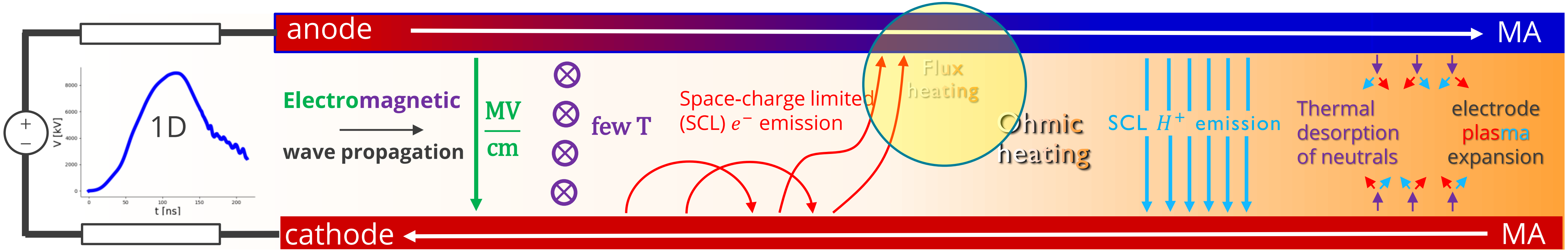

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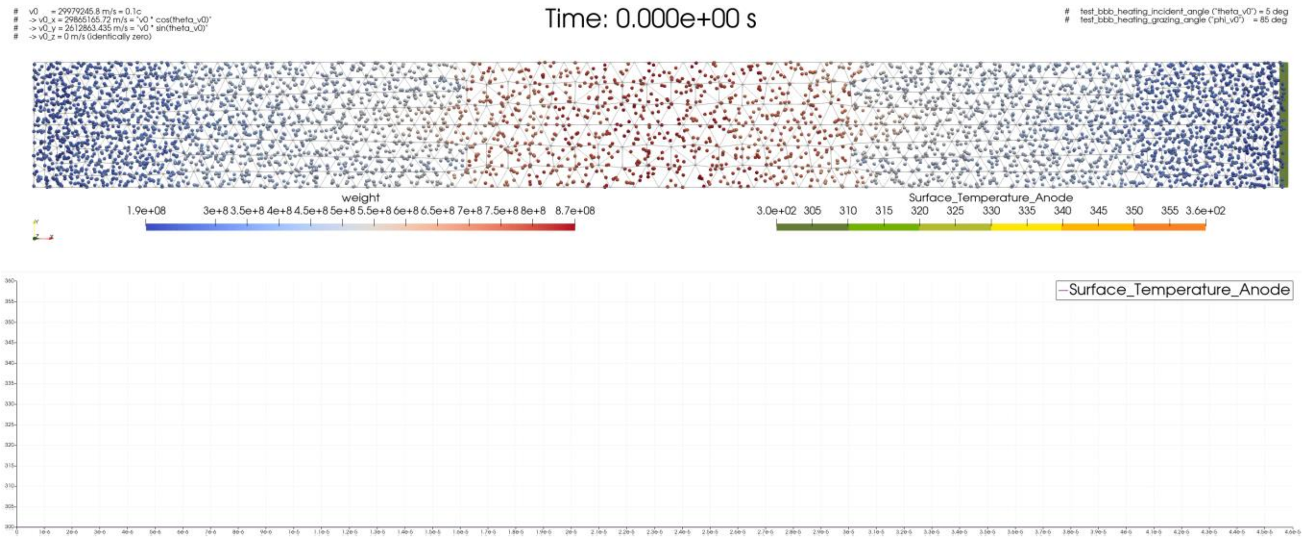
Electrode heating model

- 1D semi-infinite heat equation solve in “inside” direction (z) of material

$$\frac{\partial(c_v T)}{\partial t} = S(t,x) - \frac{\partial}{\partial x} k \frac{\partial T}{\partial x}$$

stainless steel

$$\sigma \approx 10^6 \text{ S/m}, \quad \frac{k}{c_v/(\sigma\mu)} \sim \frac{1}{350^2}$$



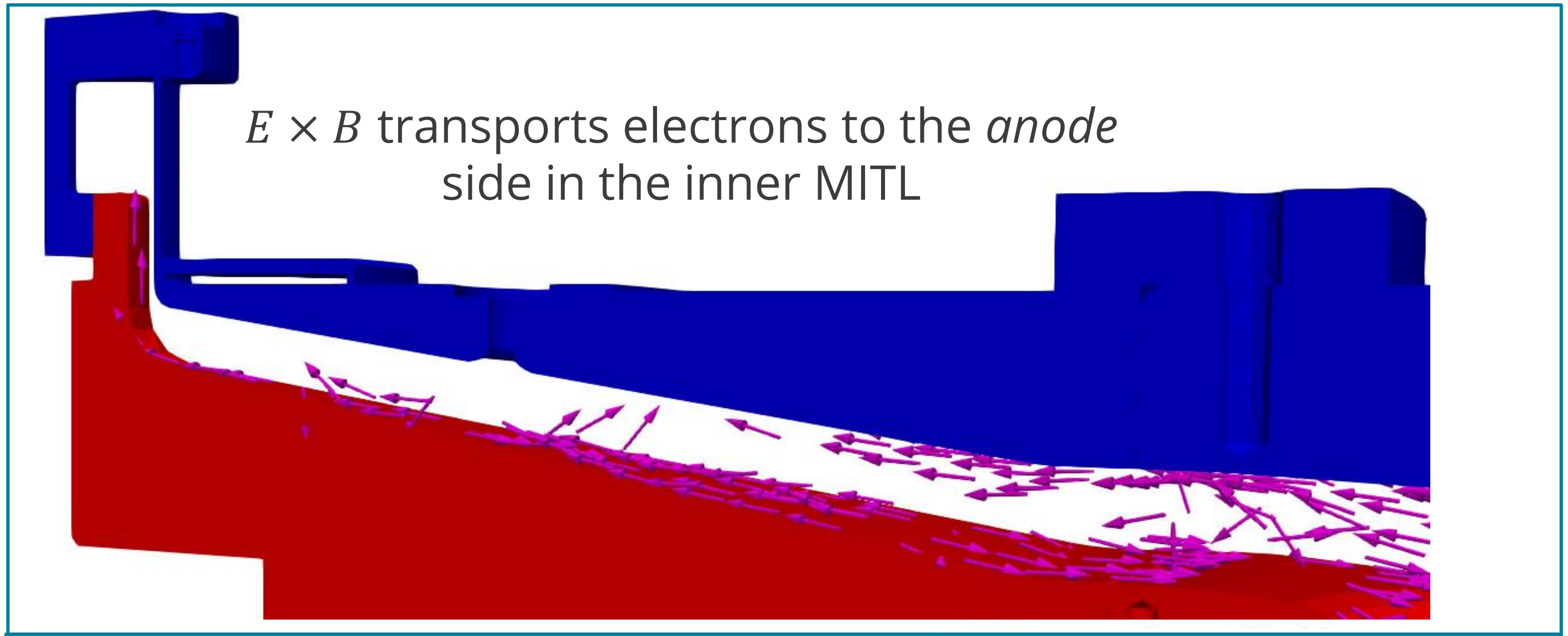
Particle impact heating

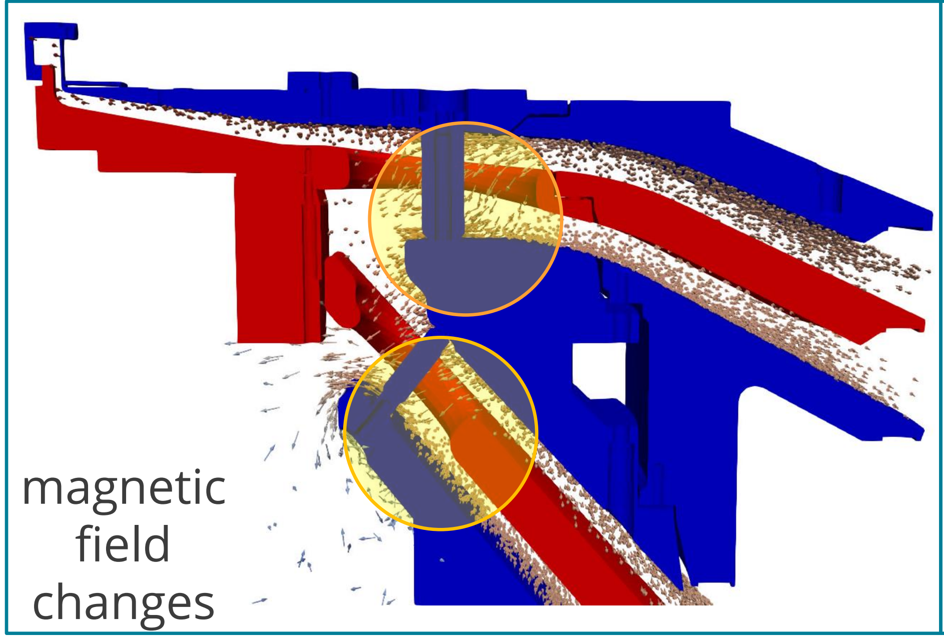
$$\boldsymbol{S_\Gamma(t,x)}$$

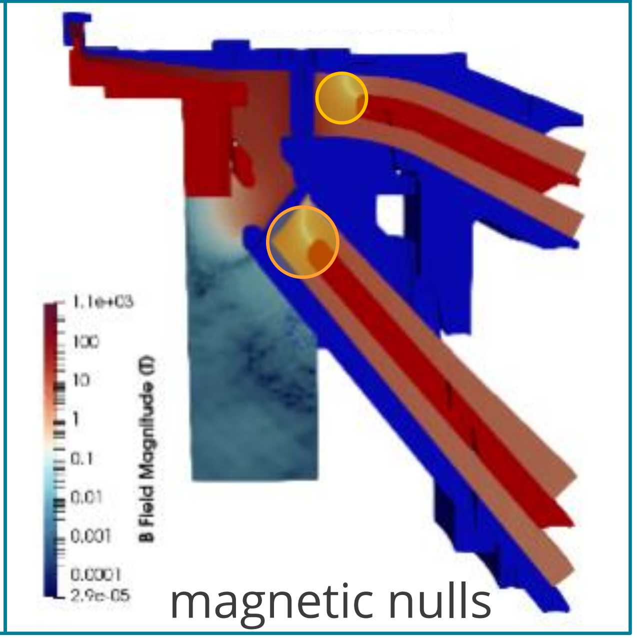
where the particle flux Γ deposits energy per cell along the depth x over each time step Δt using Bohr-Bethe-Bloch $\langle dE/dx \rangle$ stopping power model

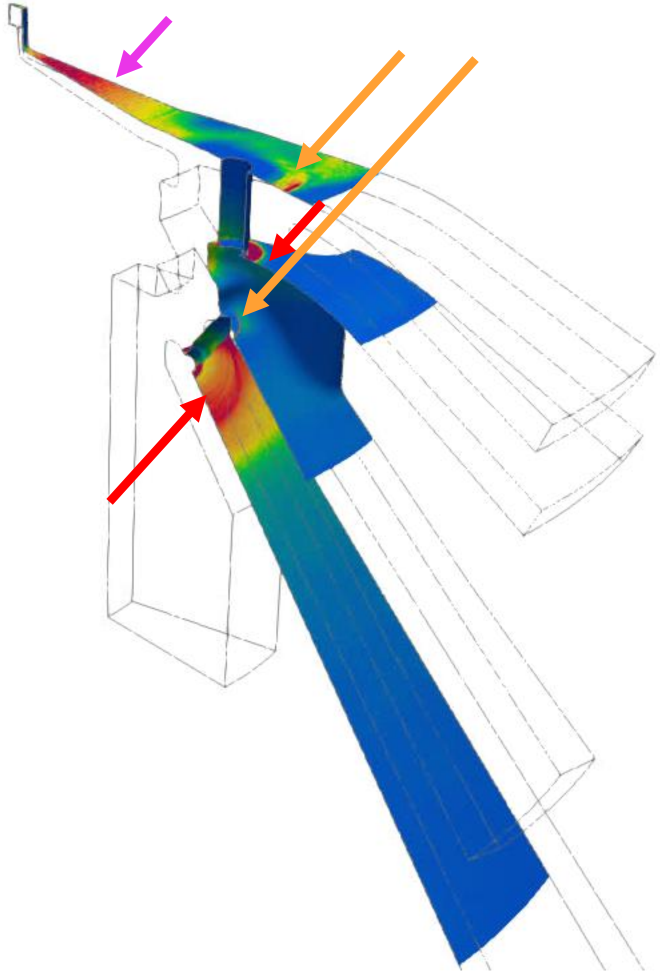
Empire includes an option for density effect corrections at the high energies using data from NIST ESTAR stopping power and range tables for electrons https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

Electron fluxes focus where magnetic nulls allow, wherever $E \times B$ takes them, and where the magnetic field changes



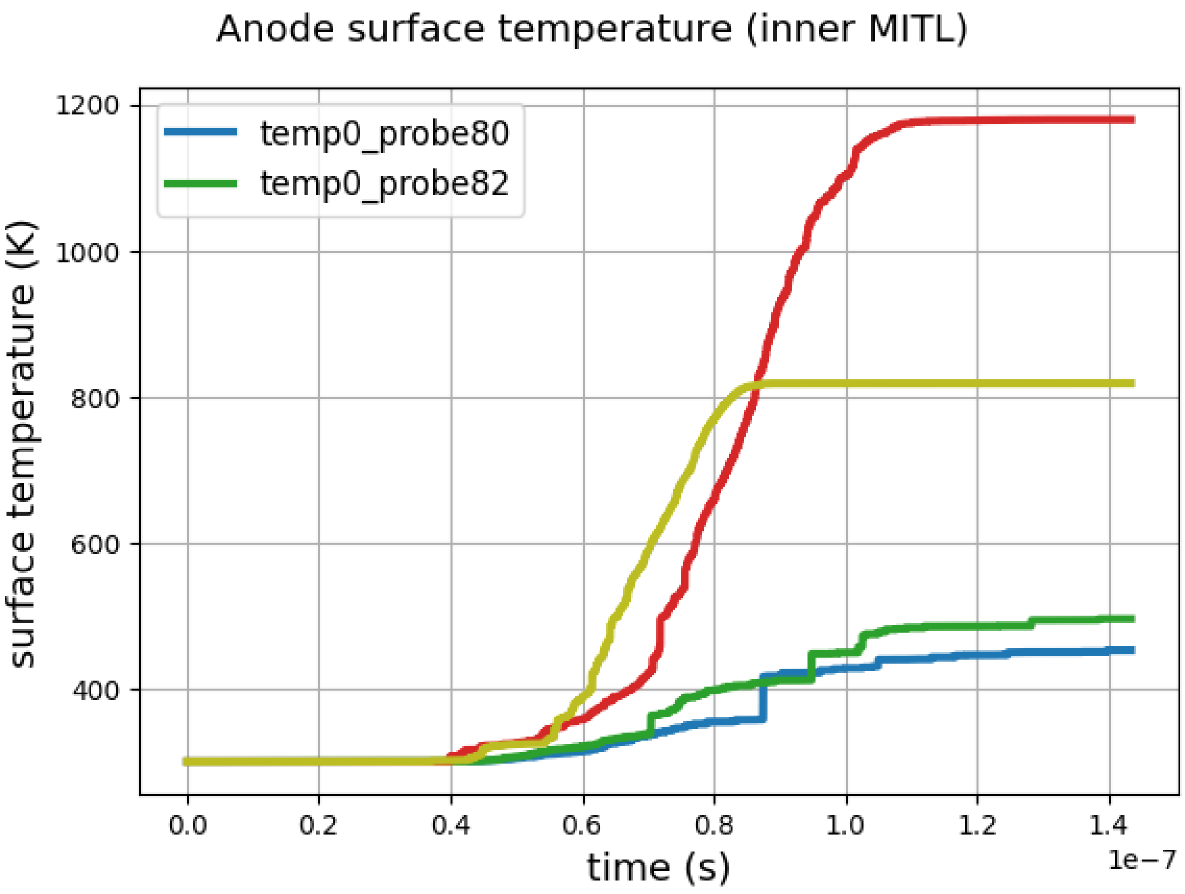


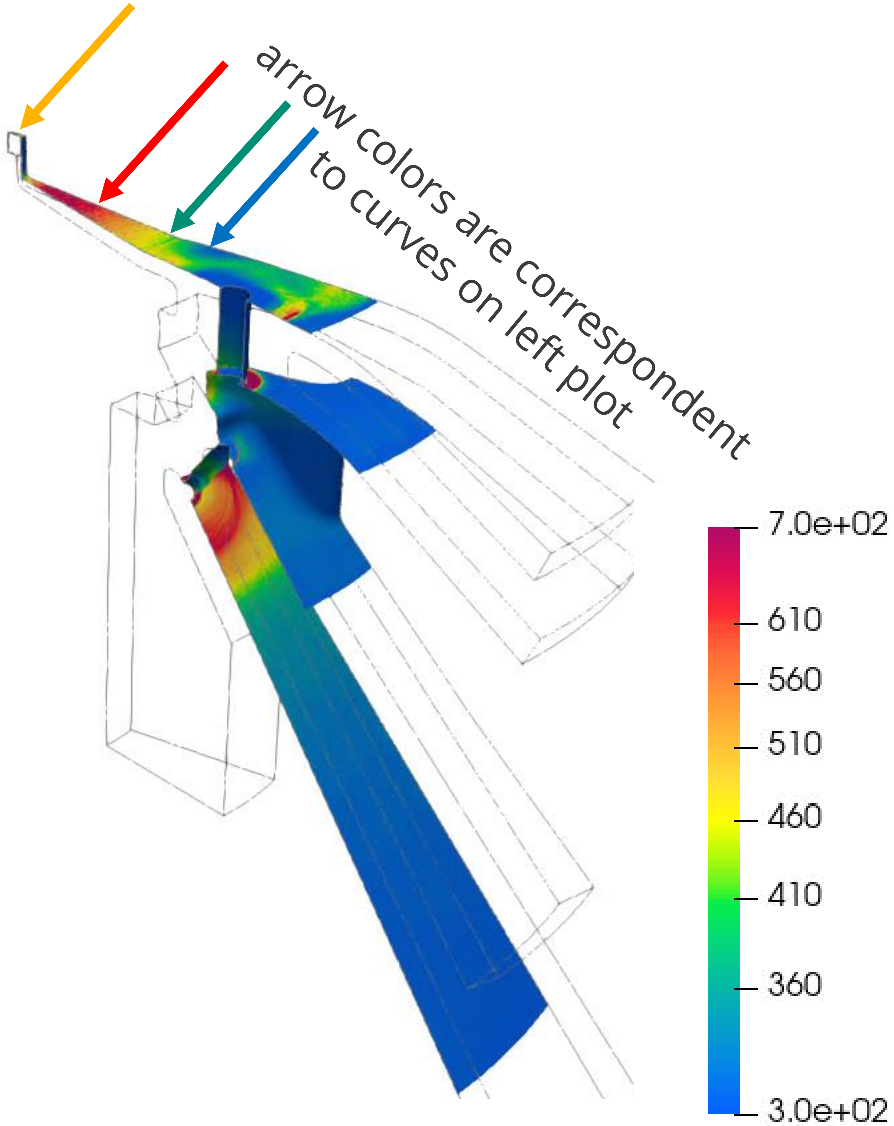




anode surface temperature

For SS304, we typically regard a $400°$ C temperature rise as the threshold for *anode breakdown**,





*Sanford, T. W. L. et al. Journal of Applied Physics 66, 10 (1989)

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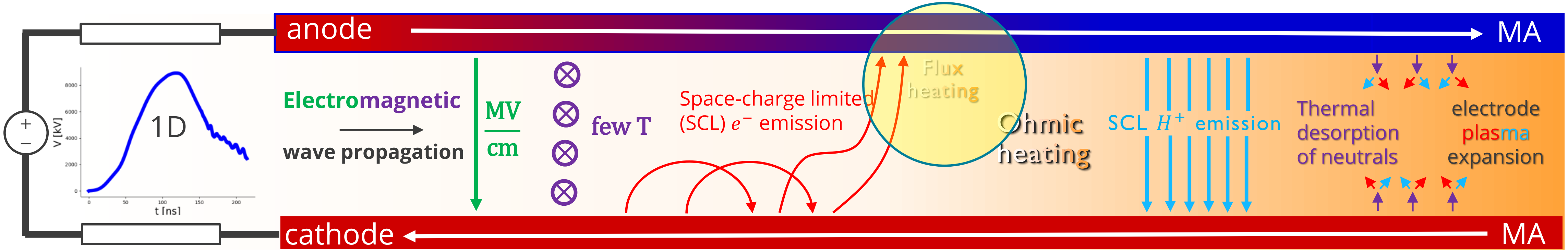

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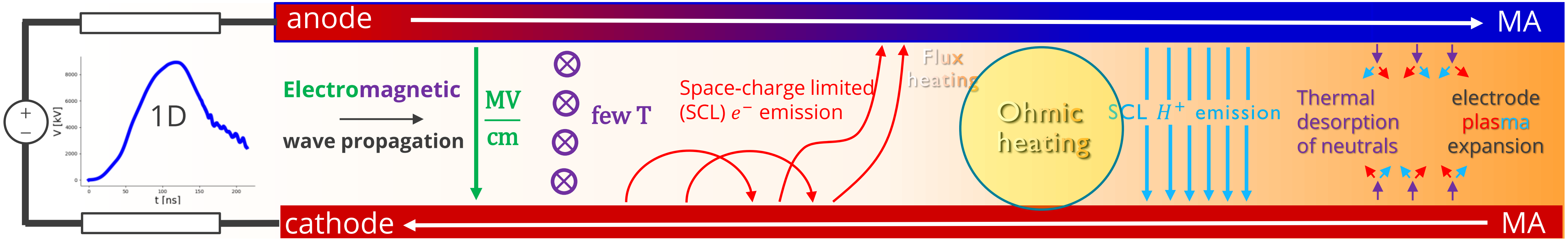

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Joule heating

$$S_B(t,x) = \frac{j^2(t,x)}{\sigma}$$

where this the eddy current j is induced from the magnetic field

$$\frac{\partial B_\parallel}{\partial z} = \frac{j}{\mu}$$

Ampere's law

penetrating a depth x

$$\frac{\partial B_\parallel}{\partial t} = \frac{1}{\mu\sigma}\frac{\partial^2 B_\parallel}{\partial x^2} - \frac{1}{(\mu\sigma)^2}\frac{\partial(\mu\sigma)}{\partial x}\frac{\partial B_\parallel}{\partial x}$$

Magnetic diffusion

- Magnetic fields approaching the load exceed 100 T → significant joule heating in the inner MITL
- Desorption flux of neutrals is strongly affected by surface temperature → affects electrode plasma formation and dynamics

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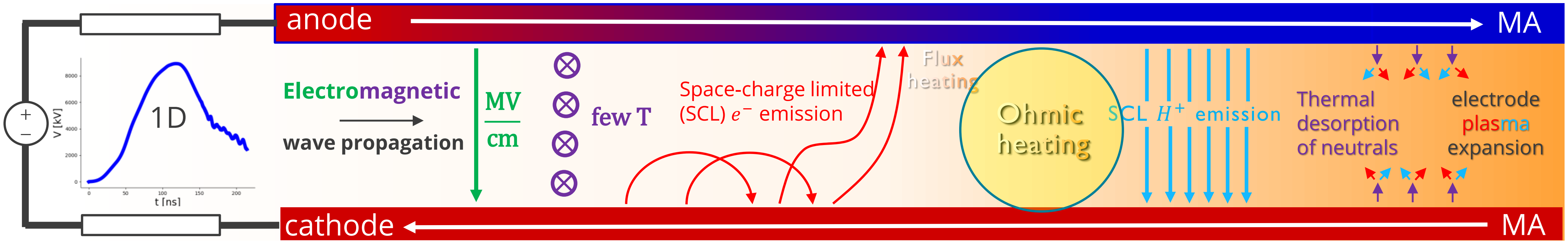

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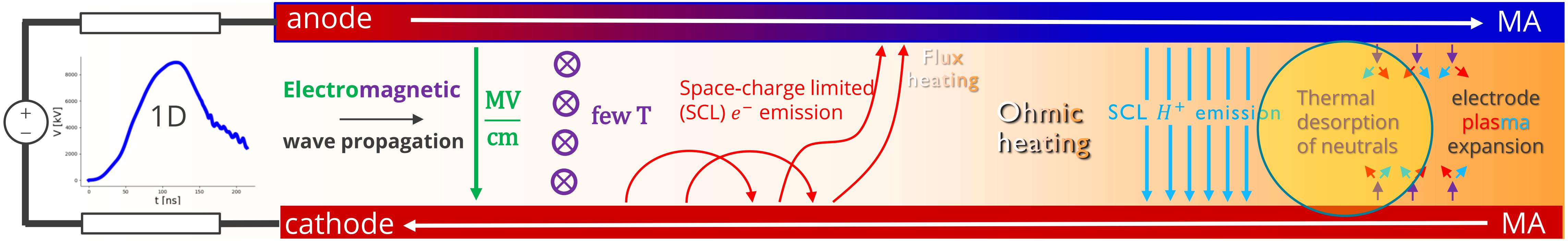

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Desorption of neutrals is highly complex: We use Polyani-Wigner flux model following a fitted Temkin isotherm is used to simulate Z-like desorption characteristics

animation

- General desorption flux:

$$\Gamma(\theta) = \nu[\theta(t)]^n \exp\left(\frac{-E_a(\theta(t))}{k_B T}\right)$$

(Polyani-Wigner)

$$\begin{cases} \dot{\theta} = -\Gamma \\ \theta = \dfrac{n(t)}{10^{19}\, m^{-2}} = [\text{monolayers}] \end{cases}$$

Rate depends on time-dependent surface coverage θ

  - Binding energy modeled by the Temkin isotherm: $E_a(\theta) = E_d\left(1 - \frac{\alpha}{f}\theta\right)$
    - shown in MD sims [1] to capture H_2O desorption characteristics in Fe_2O_3
  - We model ≈ 8 monolayers of H_2O

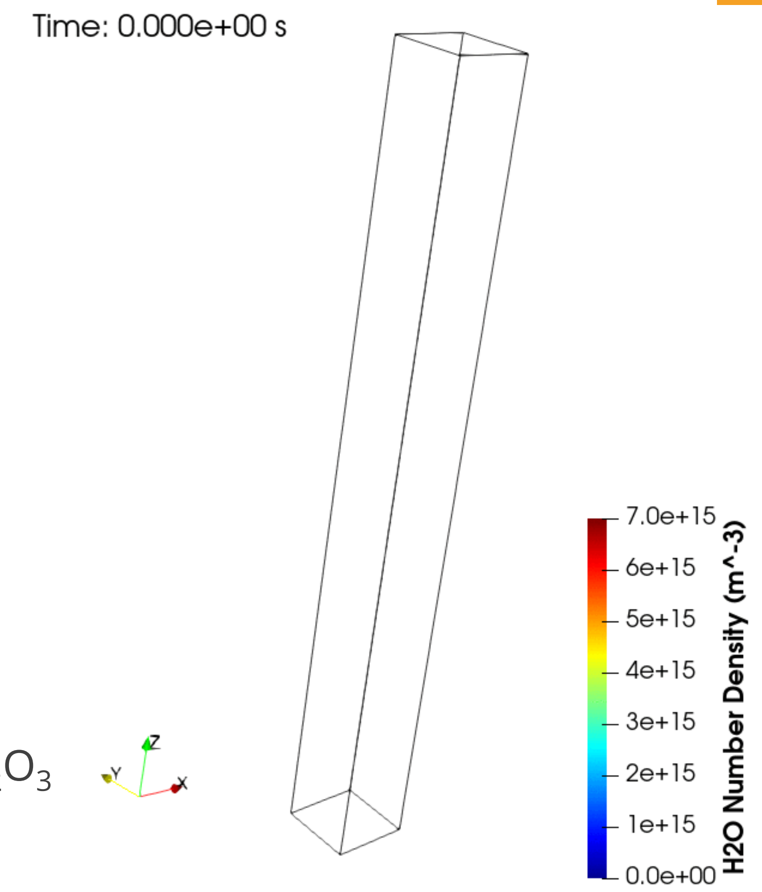

Figure: Simulated H_2O emission in a Z simulation less than a centimeter from the load; in the full simulation H2O breaks up into electrode plasmas with densities up to 10^{18} cm^{-3}

[1] J. M. D. Lane, K. Leung, et al., J. Phys. Condens. Matter 30, 465002 (2018).
[2] N. Bennett, D. R. Welch, et al. Phys. Rev. Accel. Beams **22**, 120401

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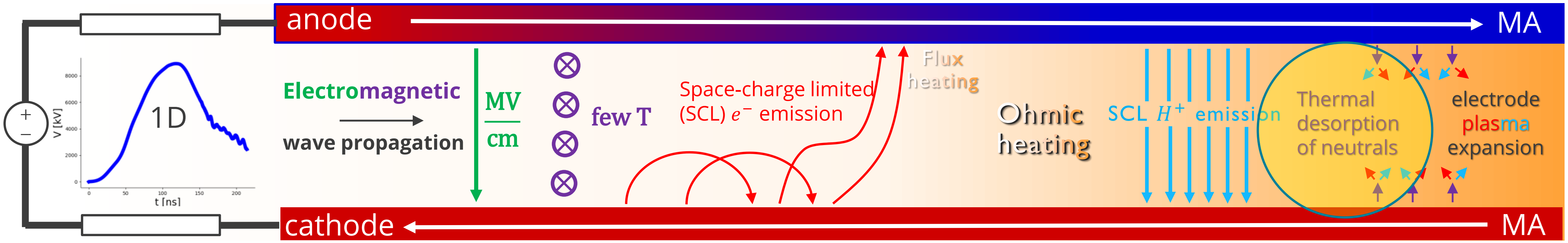

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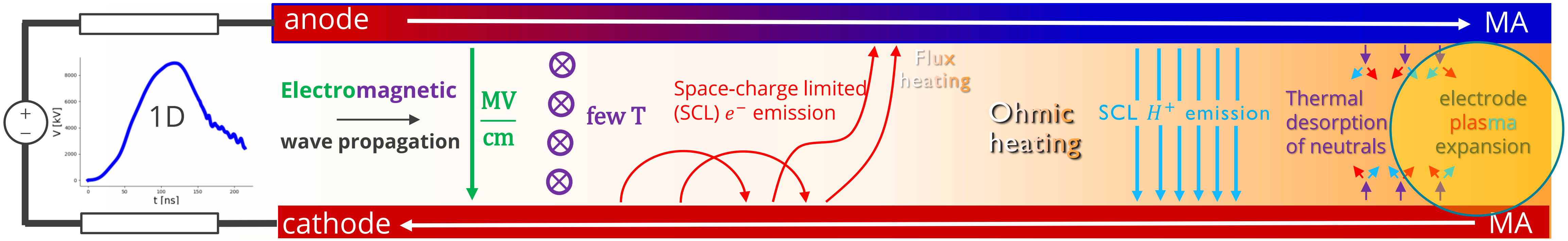

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electrode plasma modeling

automatic plasma model[1]

Streamlined model which breaks up H_2O in stages:

1. $H_2O \rightarrow H_2 + O$
2. $H_2 \rightarrow H + H$
3. $H \rightarrow H^+ + e^-$
4. $O \rightarrow O^+ + e^-$

Generates $H_2O \rightarrow 2H^+ + O^+ + 3e^-$ over a few cells from emitting surface

self-consistent plasma creation model[2]

Reaction type	Interaction	Heat of reaction (eV)	Reference
auto-fragmentation	$H_2O \rightarrow H_2 + O$		
ionization	$e + H \rightarrow 2e + H^+$	13.61	[8, 1]
ionization	$e + H_2 \rightarrow 2e + H_2^+$	15.43	[8, 1]
dissociation	$e + H_2^+ \rightarrow e + H + H^+$	7.317	[4, 1]
ionization	$e + O \rightarrow 2e + O^+$	562.878	[8, 1]
ionization	$H + H_2 \rightarrow e + H^+ + H_2$	20000	[1]
ionization	$H + H \rightarrow e + H^+ + H$	20000	[11, 1]
ionization	$H + H_2 \rightarrow e + H + H_2^+$	20000	[11, 1]
ionization	$H + H^+ \rightarrow e + 2H^+$	20000	[13, 1]
ionization	$H + H_2^+ \rightarrow e + H^+ + H_2^+$	20000	[10, 1]
ionization	$H^+ + H_2 \rightarrow e + H^+ + H_2^+$	20000	[11, 1]
charge exchange	$H + H_2^+ \rightarrow H^+ + H_2$	10	[6, 1]
charge exchange	$H + H^+ \rightarrow H^+ + H$	10	[6, 1]
charge exchange	$H_2 + H^+ \rightarrow H + H_2^+$	10	[6, 1]

As reported in Sirajuddin, D., Hamlin, N., Evstatiev, E., Hess, M., and Cartwright, K. *MRT 7365 Power flow physics and key physics phenomena: EMPIRE verification suite*. Technical Report. SAND2023-11146R.

DSMC collisions involving 14 most important interactions in these regimes

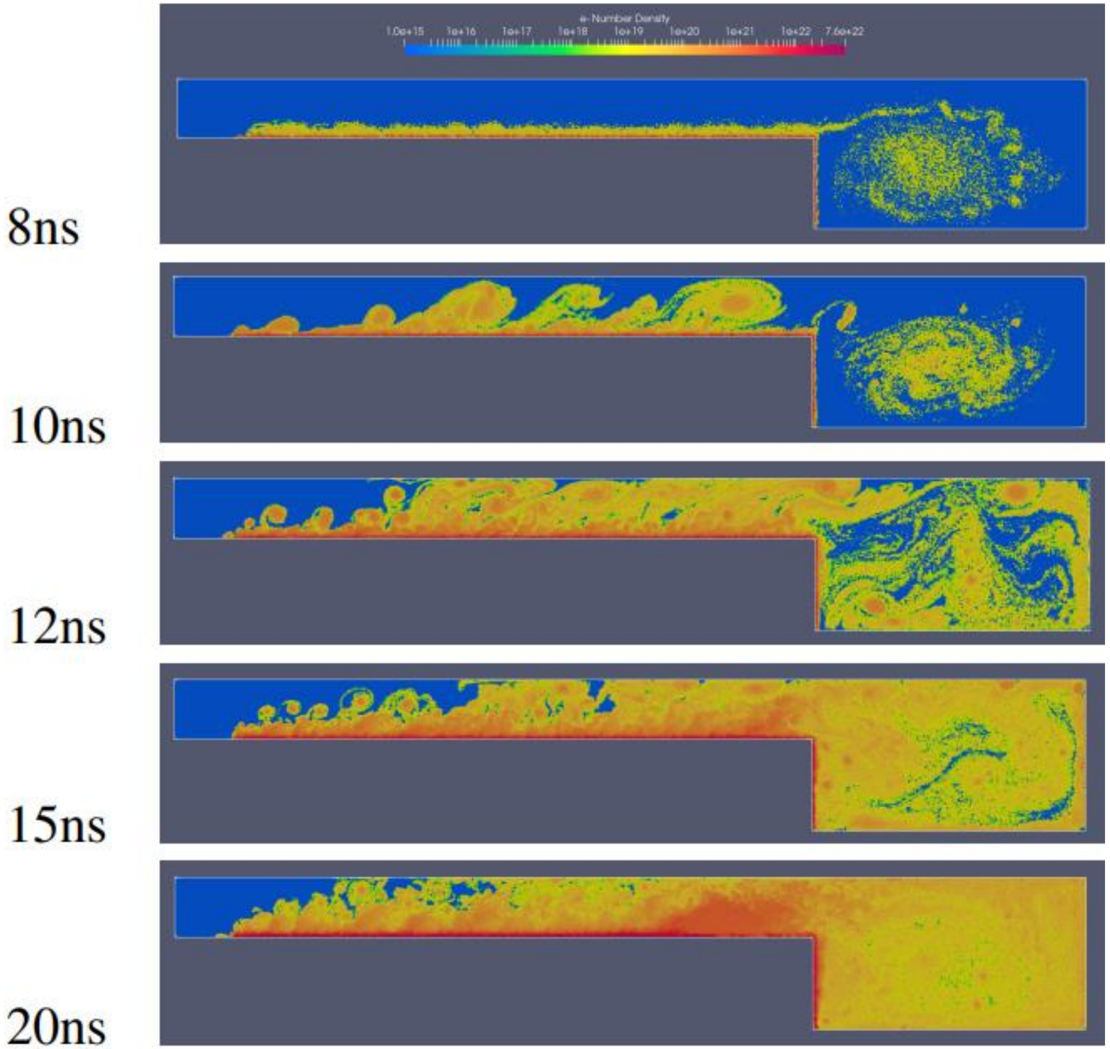
[1]N. Bennett, et al. Phys. Rev. Accel. Beams **22**, 120401

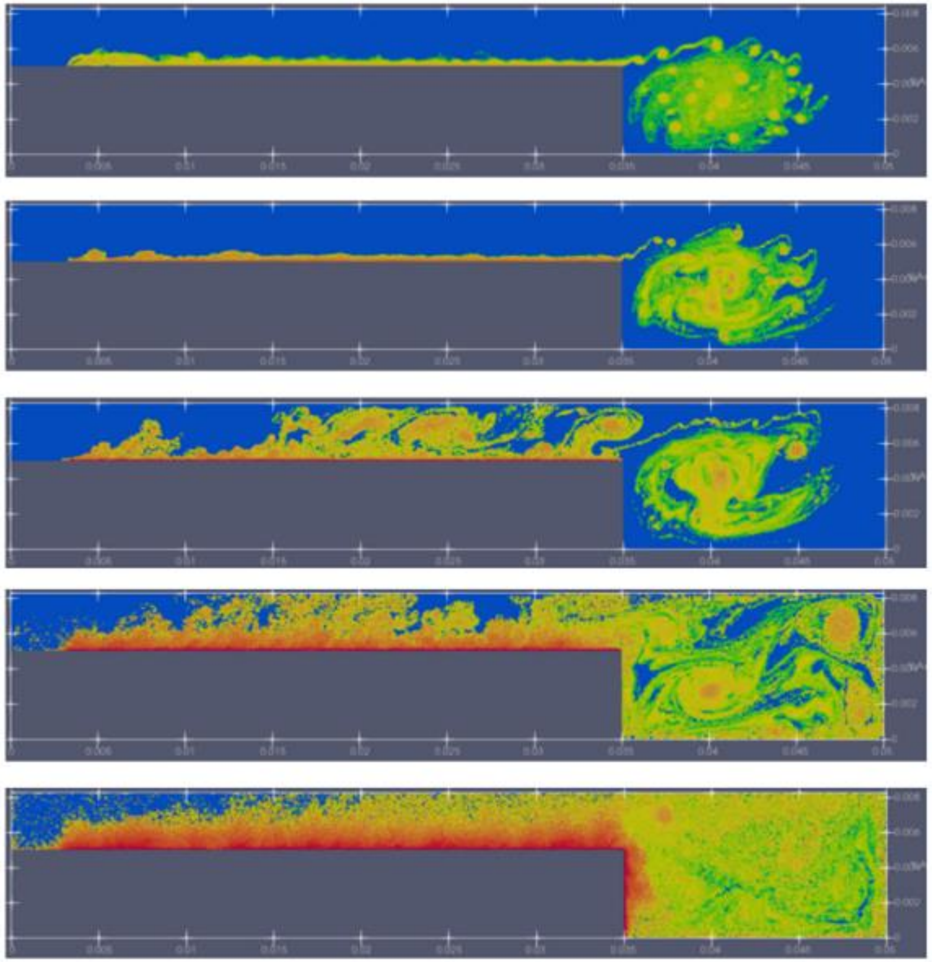
[2]N. Bennett, D. R. Welch, K. Cochrane, K. Leung, C. Thoma, M. E. Cuneo, and G. Frye-Mason. Phys. Rev. Accel. Beams 26, 040401

electrode plasma modeling

automatic plasma model

self-consistent plasma creation model





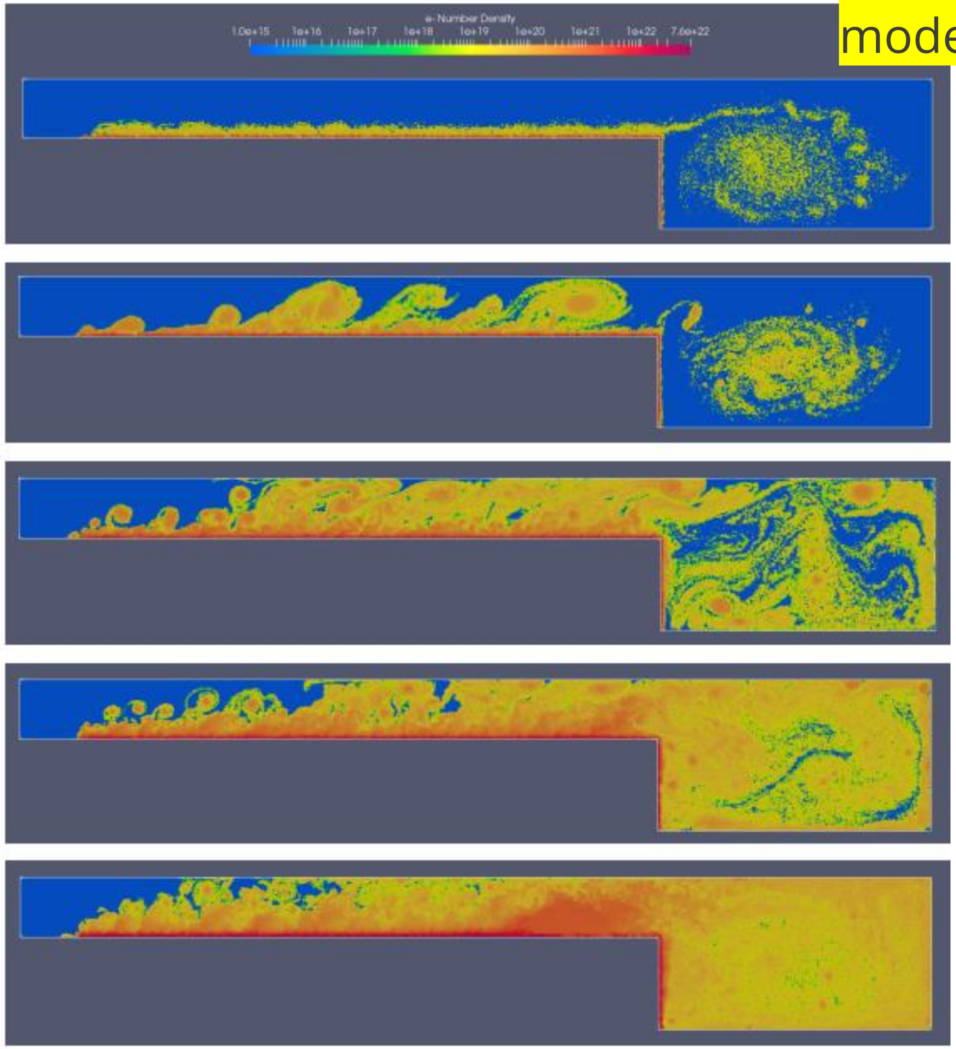
Simulations above by Nat Hamlin, Evstati Evstatiev, full report: Sirajuddin, D., Hamlin, N., Evstatiev, E., Hess, M., and Cartwright, K. *MRT 7365 Power flow physics and key physics phenomena: EMPIRE verification suite*. Technical Report. SAND2023-11146R.

electrode plasma modeling

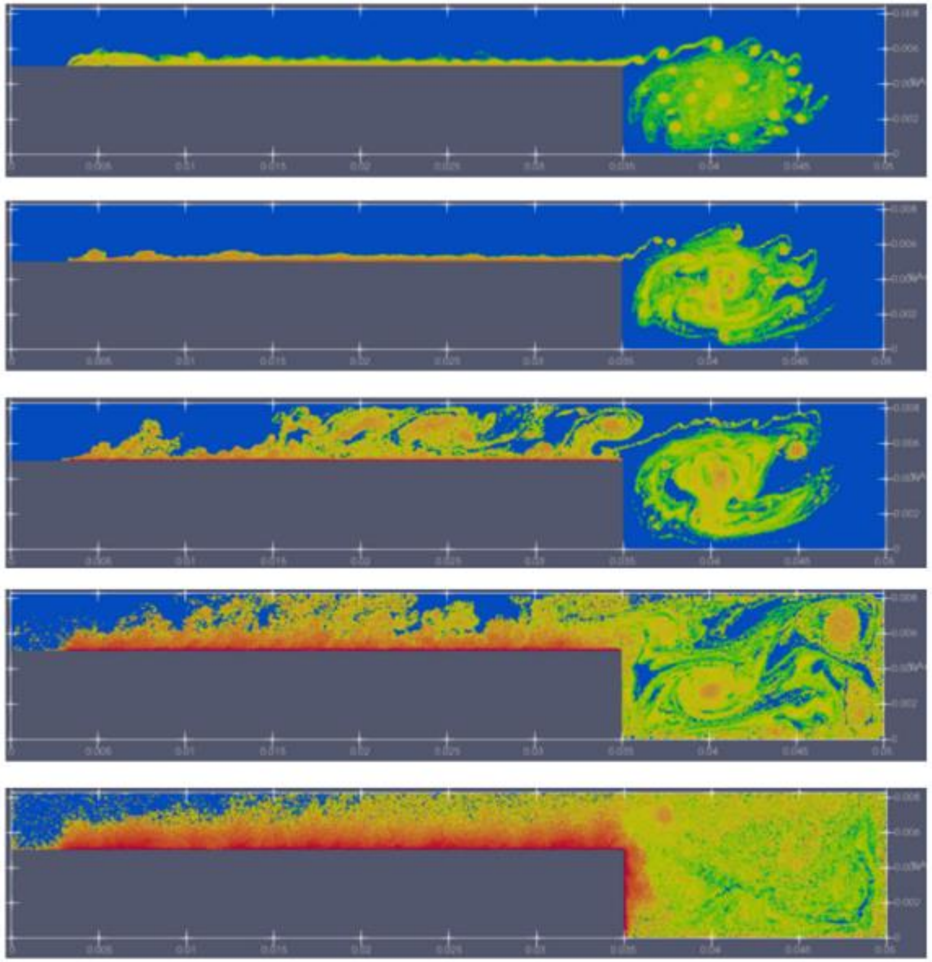
automatic plasma model | **self-consistent plasma creation model**

modeling highlight

8ns
10ns
12ns
15ns
20ns



2 ns "delay"



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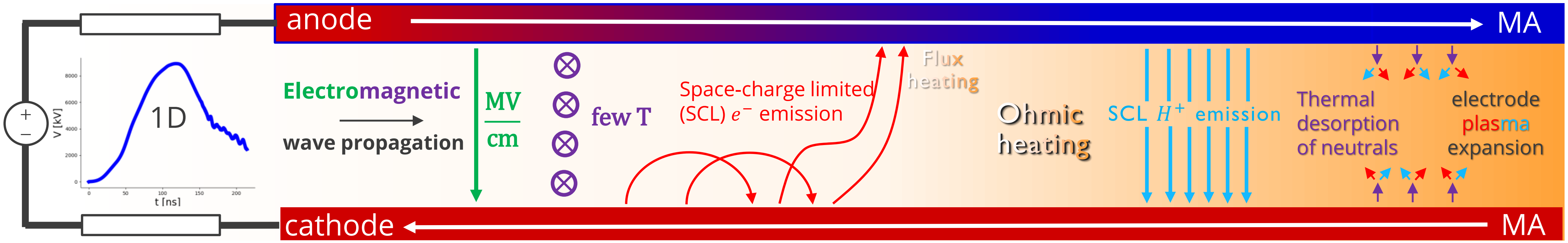
Outline

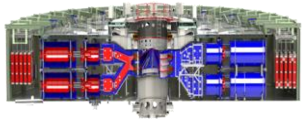
- **Pulsed power at Sandia**
- **Subject of this talk**: Sandia National Laboratories' Z accelerator
- **The plasma simulation code: Empire**
- **Simulation model and results**:



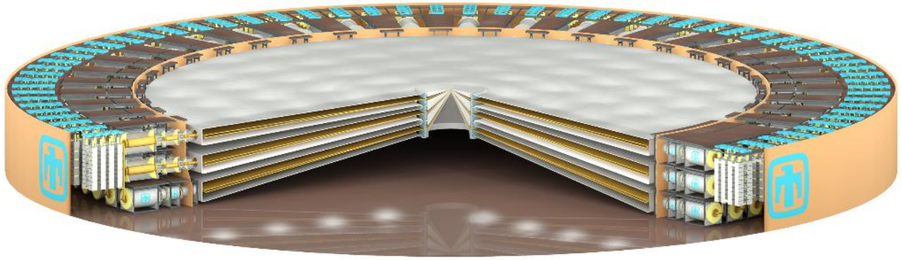
- **Towards NGPP: initial studies of variable-impedance MITLs**
- **Summary and conclusions**

Towards NGPP: variable impedance MITLs

- Existing pulsed power has been engineered using constant-impedance MITLs to minimize EM reflections and ensure high quality magnetic insulation of electron flows
- Using conventional guiding principles of pulsed-power engineering design, a next-generation pulsed power (NGPP) facility could be scaled up to deliver the required 2-3× power, but not without significant increases to total inductance, size, and cost
- Recent studies* have suggested there could be significant advantages using magnetically-insulated transmission lines (MITLs) with a variable geometric impedance
- **Fact**: *all* pulsed power machines are operated at a variable running impedance ($Z = V/I$) because of electron flows (and more)! This is not unfamiliar territory after all...
- **We are exploring variable-impedance MITLs in simulation as a means to minimize total inductance** and buy flexibility in NGPP designs, **using Z as a first “proof of concept” example**



Current Z Machine ~ 107 ft ∅



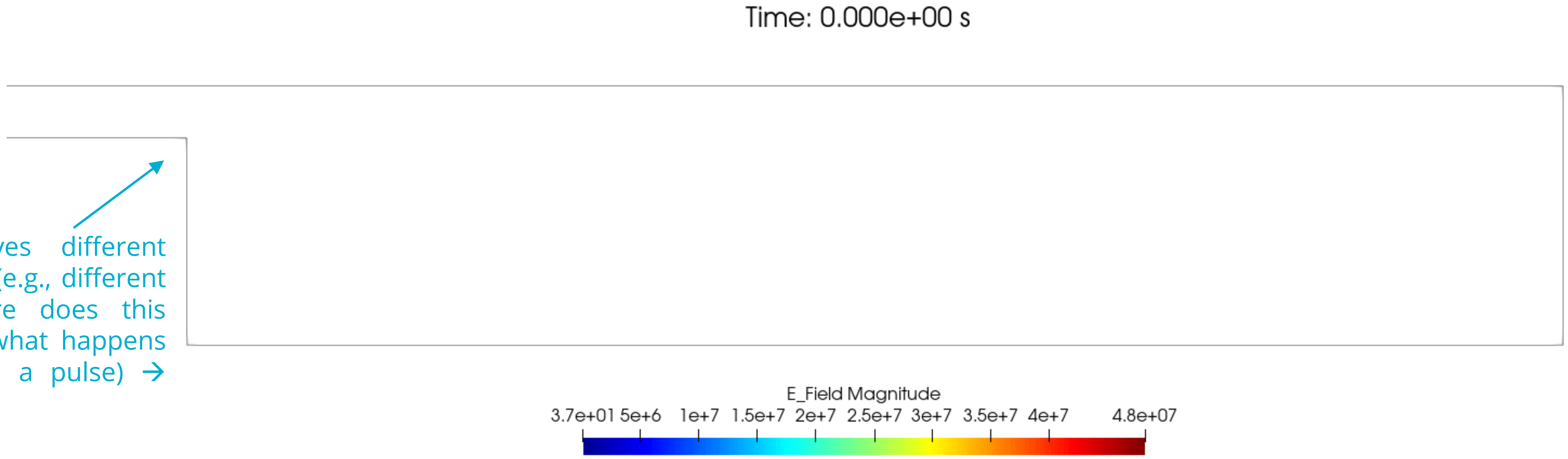
Potential concept of NGPP ~ 300 ft ∅ or more

- a pulse $\tau < 120$ ns is required
- from $I_{Z\ today} \sim 25$ MA to $I_{NGPP} \sim 50$ MA challenges our *inductance* L_{driver} *budget* $\left(\frac{dI}{dt} = \frac{V}{L}\right)$
- Minimizing L_{driver} required is of significant interest

*R. B. Spielman, "Pulsed-Power Innovations for Next-Generation, High-Current Drivers," in IEEE Transactions on Plasma Science, vol. 50, no. 9, pp. 2621-2627, Sept. 2022, doi: 10.1109/TPS.2022.3196188.

Discontinuities produce wave reflections, but we can smoothly transition between impedance mismatches

animation



equilibrium theory gives different solutions on either side (e.g., different e^- hub heights). Where does this difference actually go? what happens in non-equilibrium (e.g., a pulse) → need PIC simulations

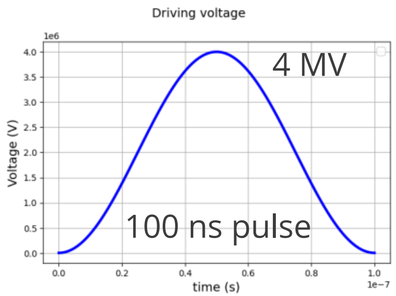
what about gradual impedance transitions? e,g., linear transition

installing a tapered impedance matching network

demonstrating reflected wave amplitudes are diminished

Shive, J. N. "AT&T Archives: Similiarities of Wave Behavior". https://www.youtube.com/watch?v=DovunOxlY1k

insulation in variable impedance MITLs



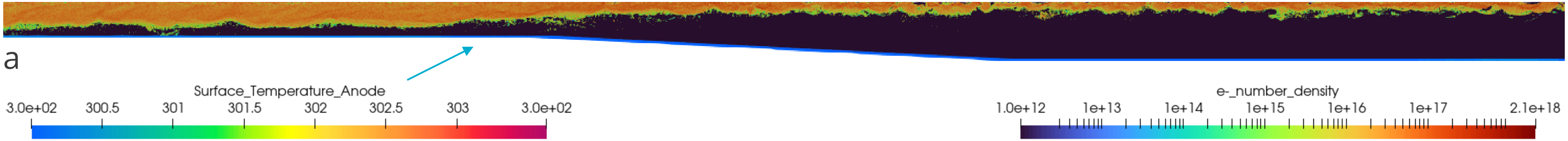
animation

sheath thickness increasing with electric field (decreasing gap)

Time: 5.003e-08 s

direction of power flow

k



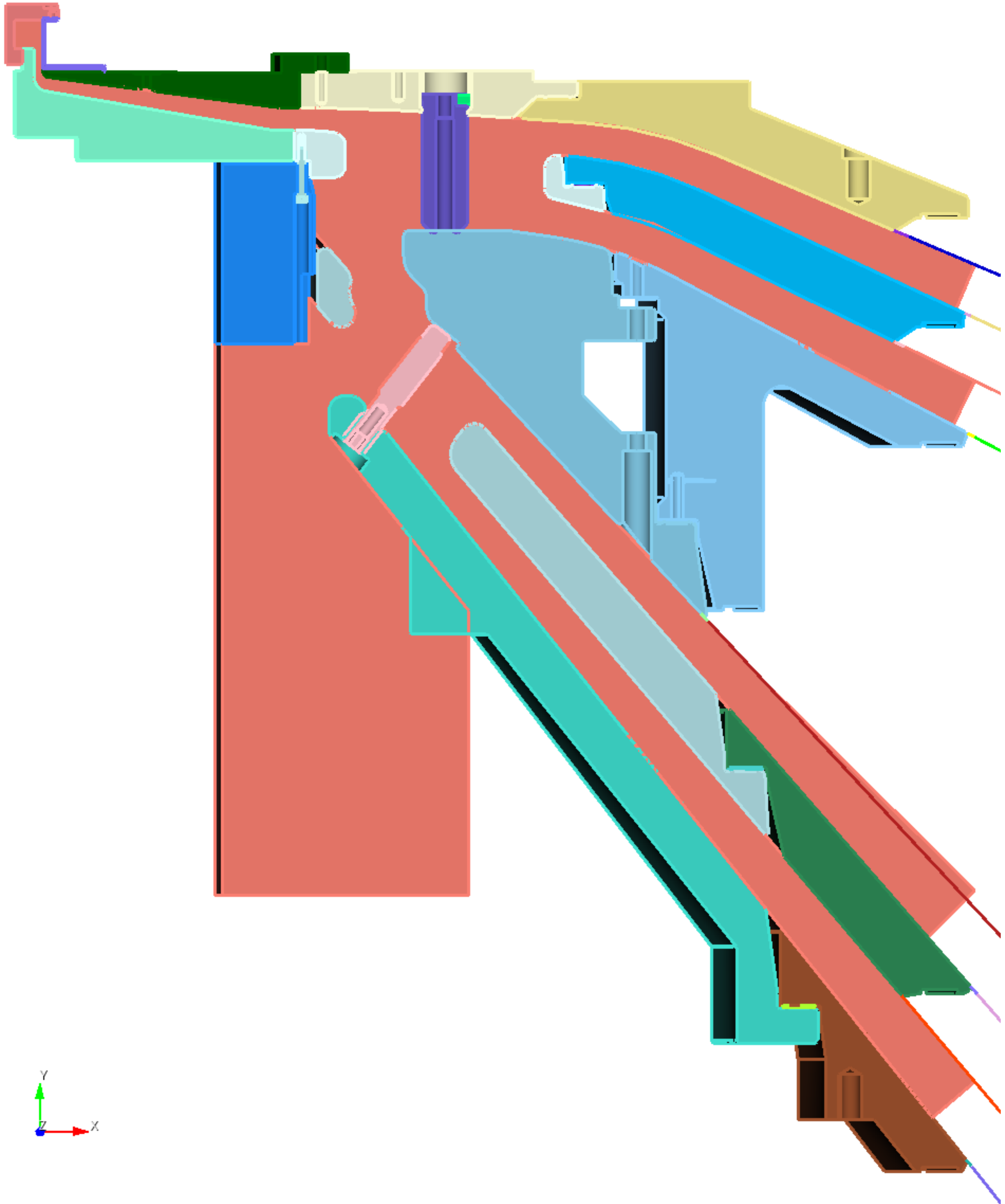
a

800 mm transition

- Reflected waves from impedance transition actually *helps* insulation upstream → "retrapping" waves
- In this case, the loss front does *not* heat the anode significantly (< 5° C)
  - sheath is successfully insulated soonafter
  - anode plasma formation is safely under the 400° C threshold

- In the real Z accelerator, the concerns for anode heating in the outer MITLs is not significant (remaining well below design requirements)

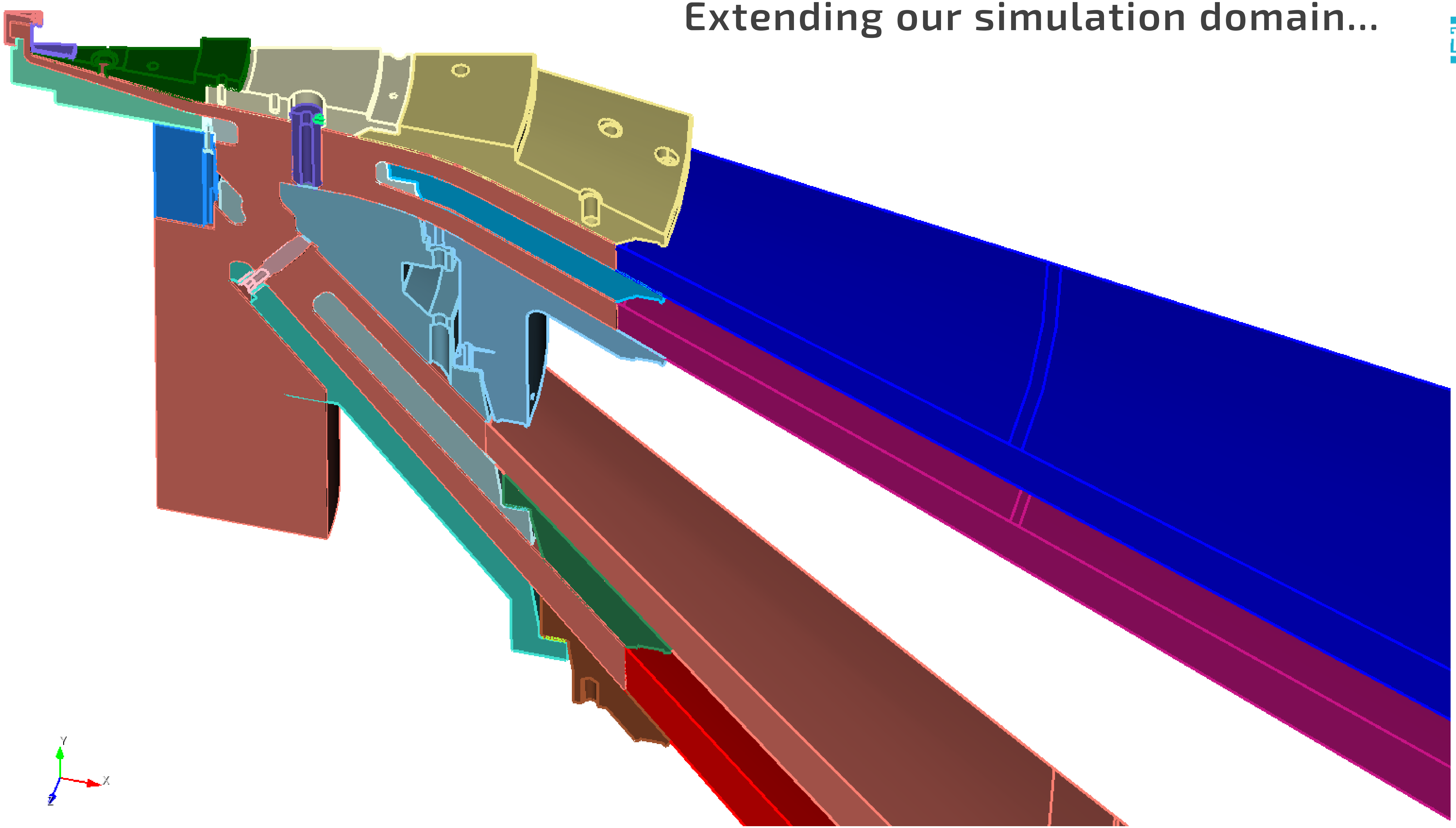
We can design a MITL that is "*safe everywhere*" by shrinking its outer gap and redistributing its current losses along the entire MITL. This MITL will have a lower total inductance.



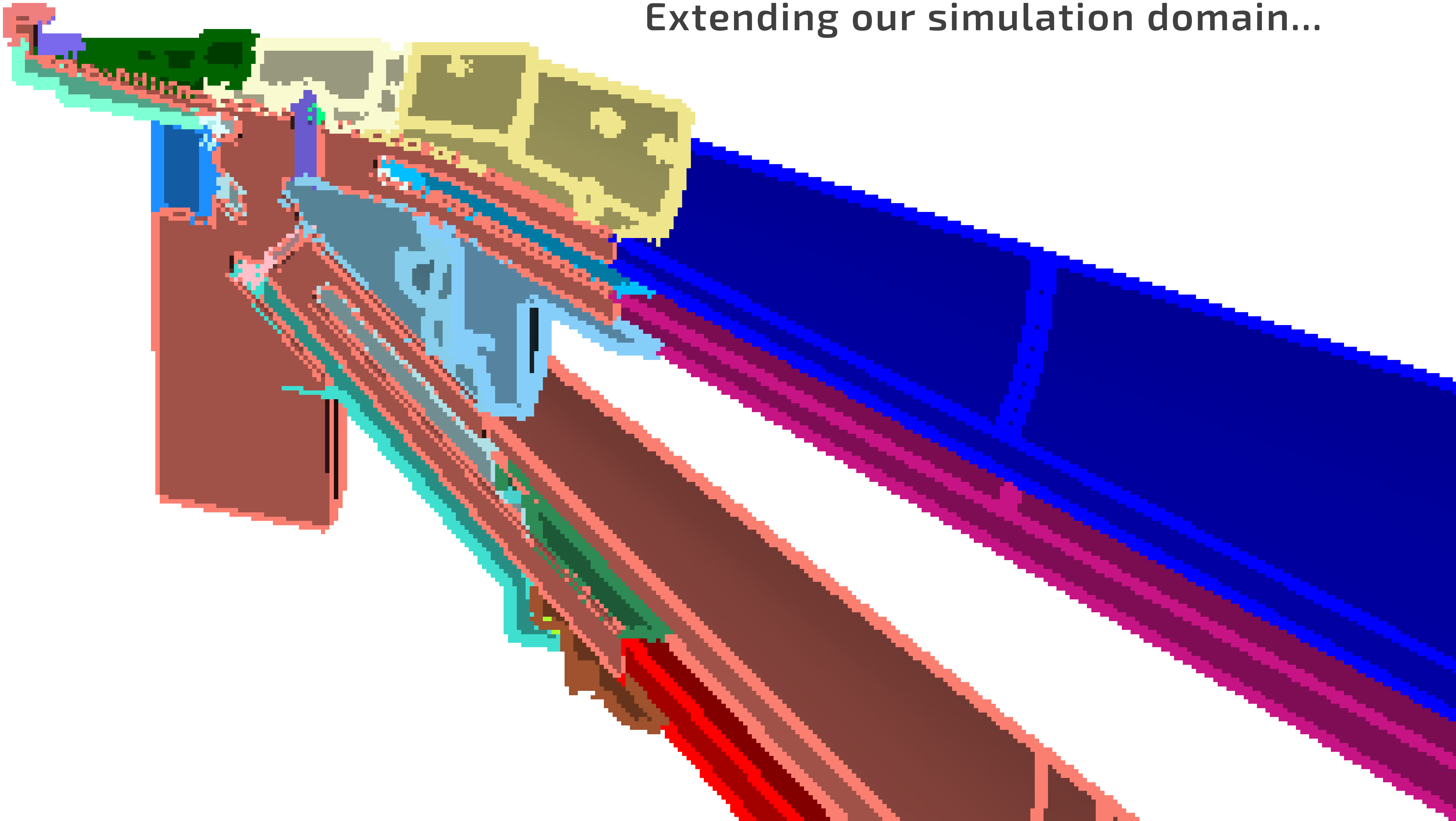
Determining the viability of using variable impedance MITLs on a real system like Z requires 3D EM-PIC power flow simulations of power flow *through the entire MITL*

→ need to extend our domain

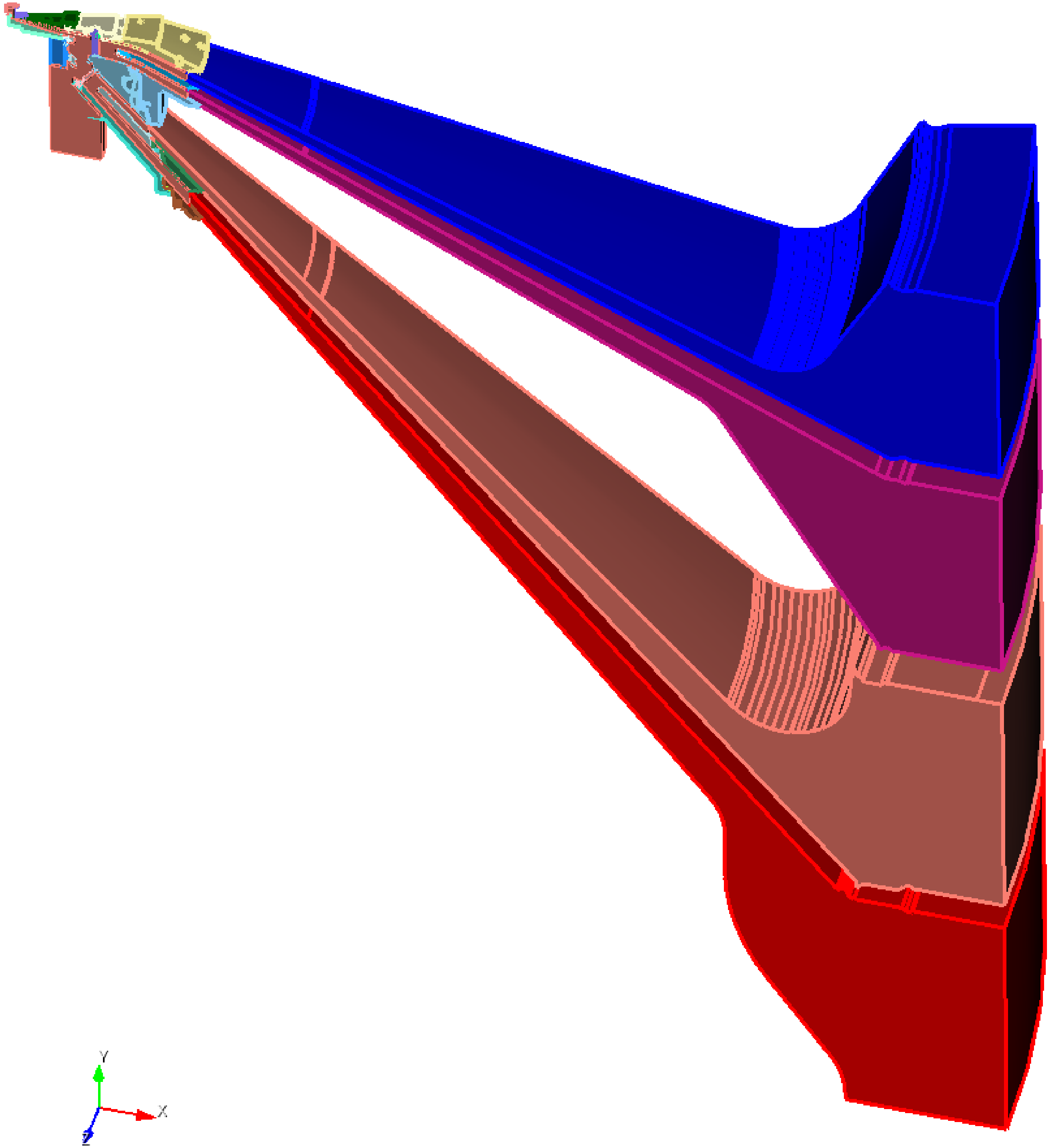
Extending our simulation domain...



Extending our simulation domain...



Extending geometry to examine entire MITLs

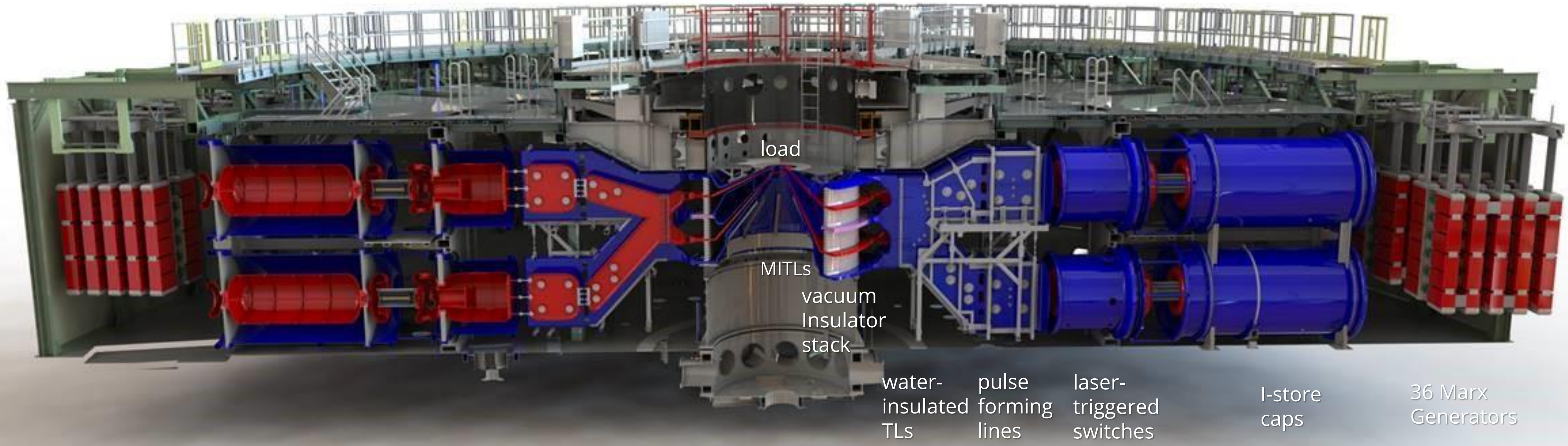


- This extended geometry has increased our simulation domain's radial extent ~30 cm out to 1.5 meters (insulator stack)
- nominally require ~ 250M element mesh
- **Scope**: sufficient to demonstrate one level benefits from a tailored geometric impedance profile ("proof of concept")

  → We choose to keep extension of level D (bottom)to reduce size and focus the problem

- Level D is the highest inductance line → will have biggest impact

Extended problem for variable impedance studies



Extended problem for variable impedance studies

1. A 1D/2D full circuit model for Z was developed in `BERTHA`
2. Equivalent 1D Empire transmission lines were defined based on 1
3. A 3D Empire EM-PIC domain was created from CAD

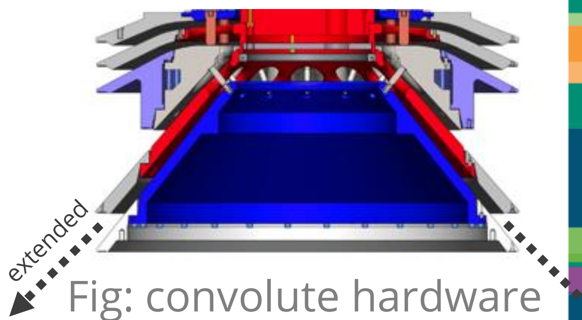
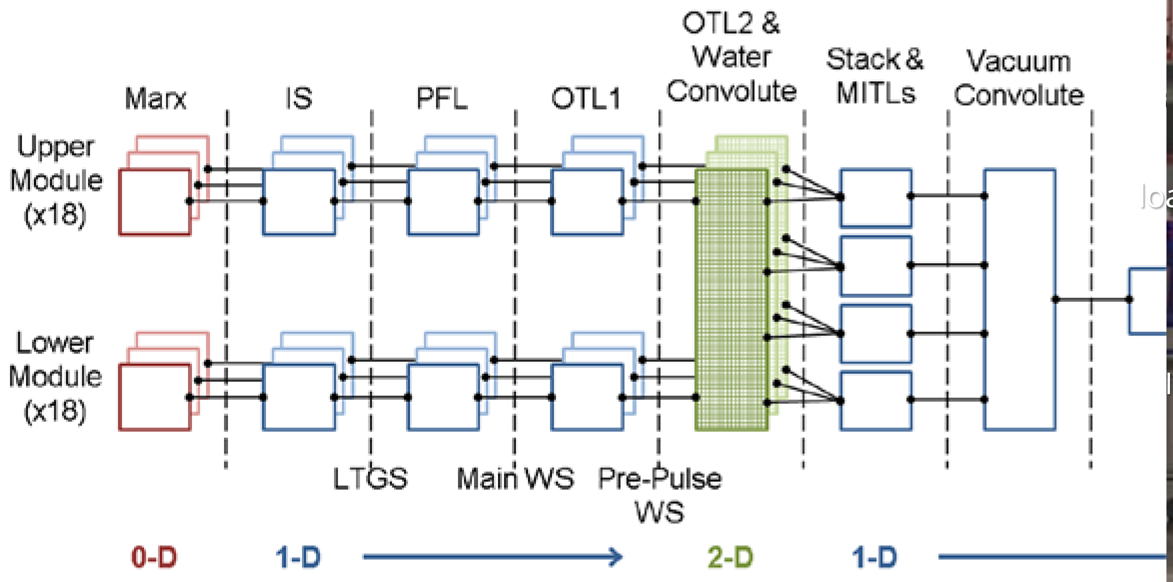


Fig: convolute hardware

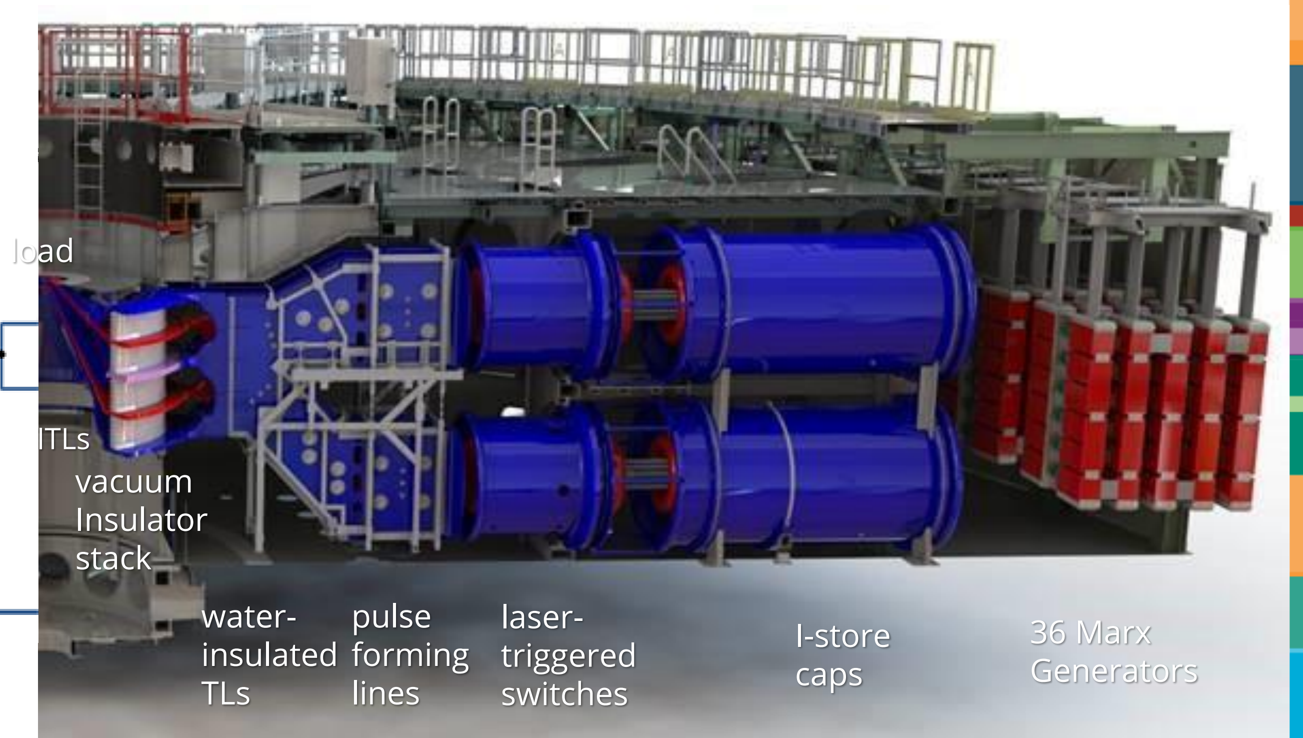
Full BERTHA circuit model

3D Empire EM-PIC

1D Empire transmission lines



(Hutsel, B. T. Phys. Rev. Accel. Beams **21**, 030401)



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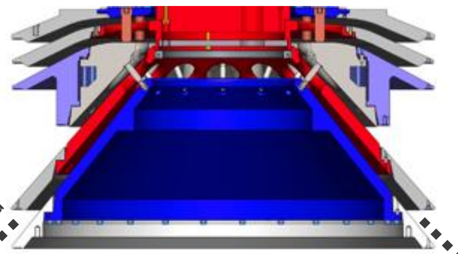

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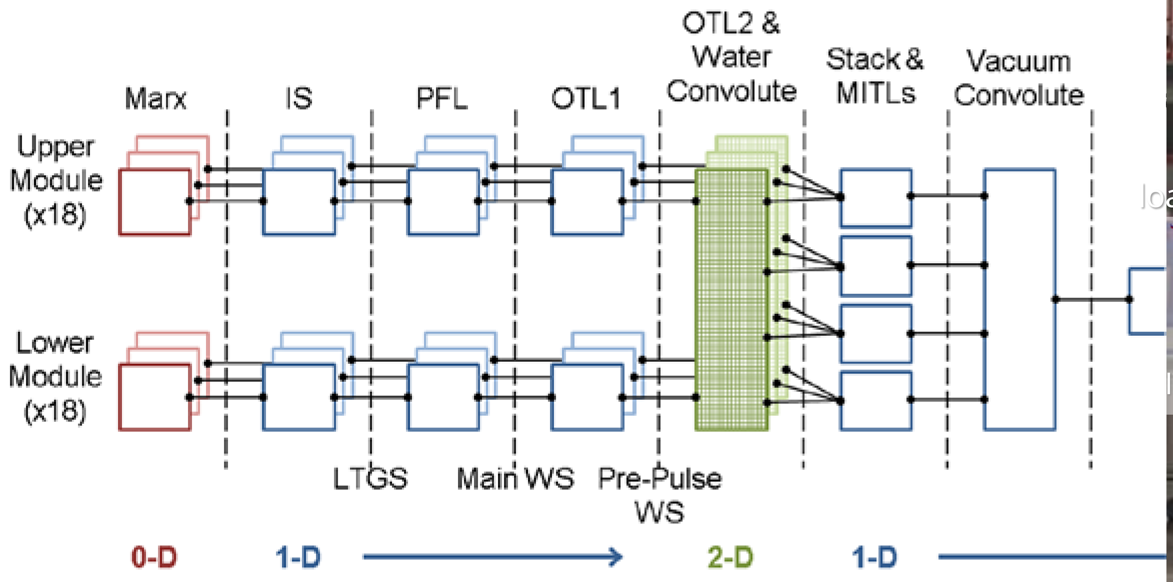

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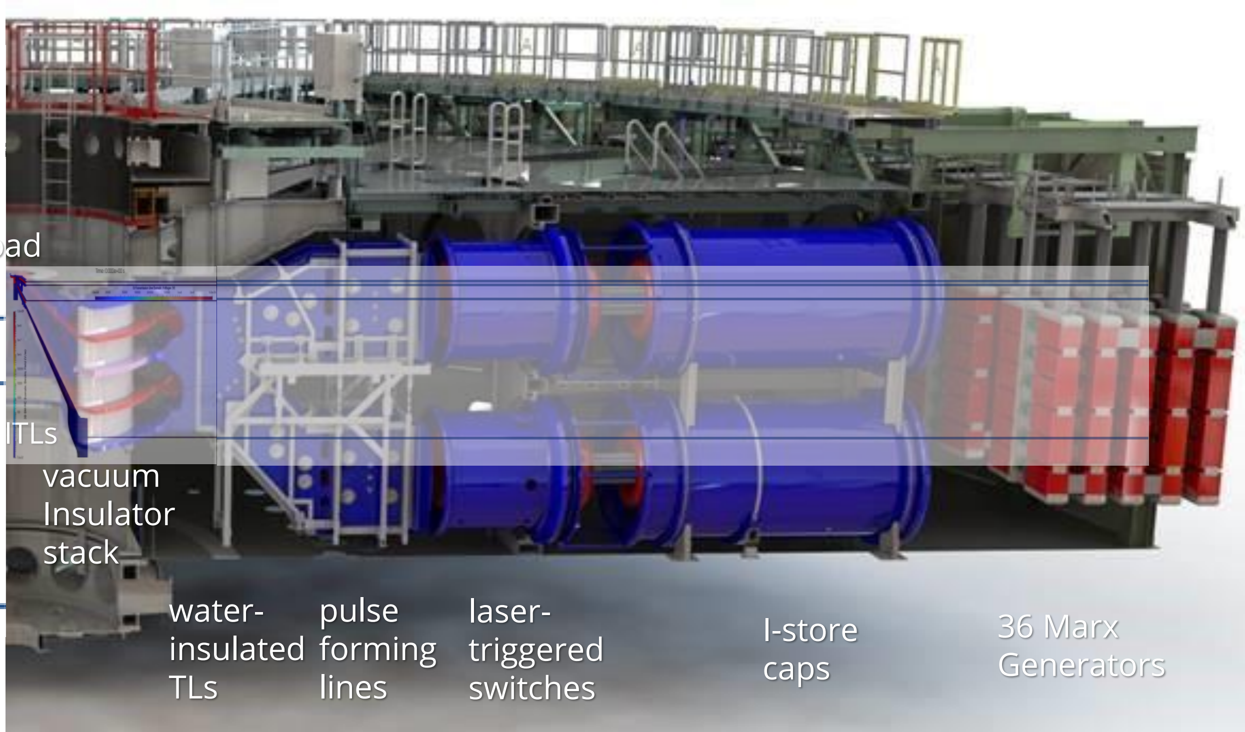
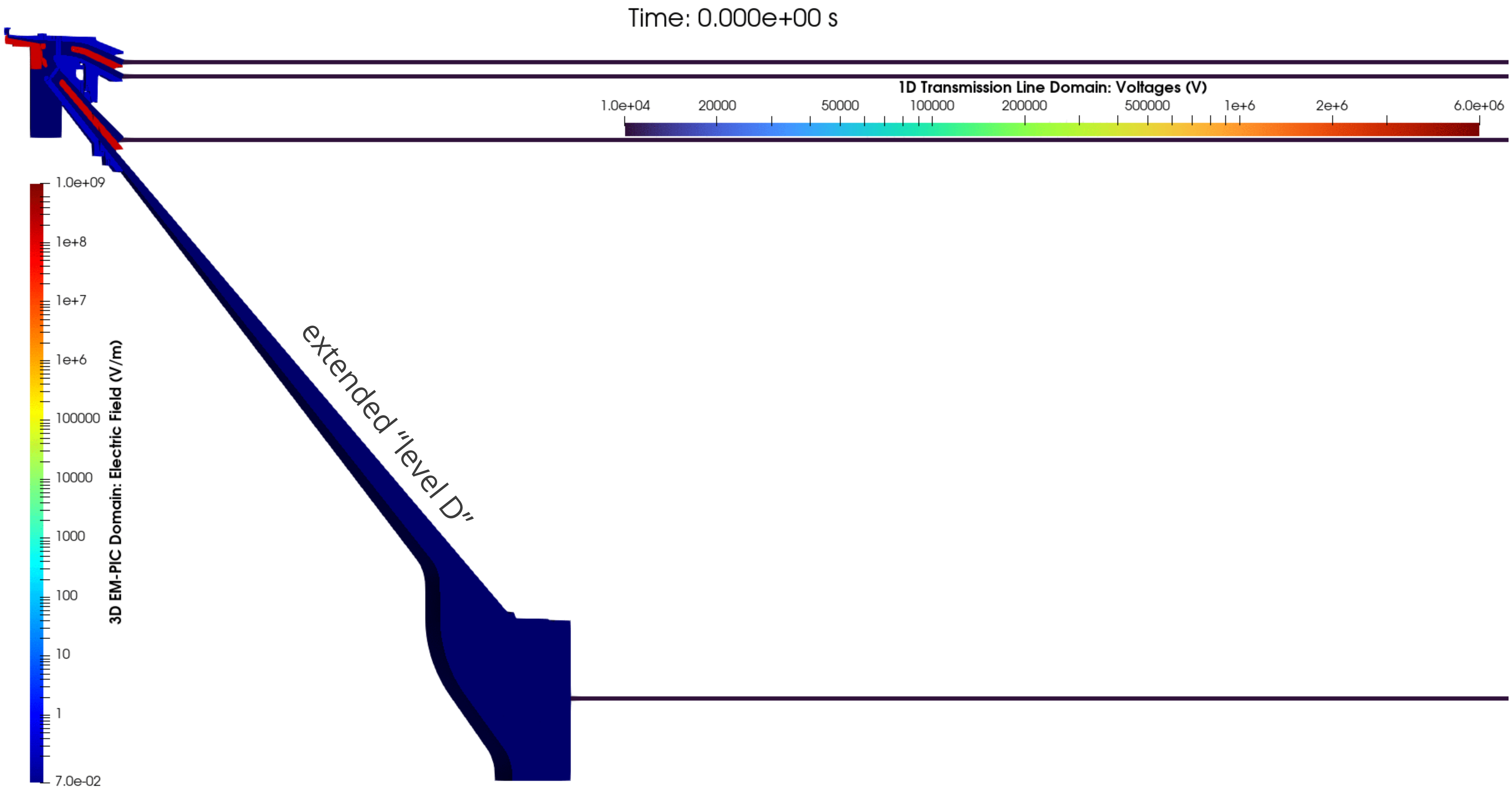


Z extended level D simulation setup



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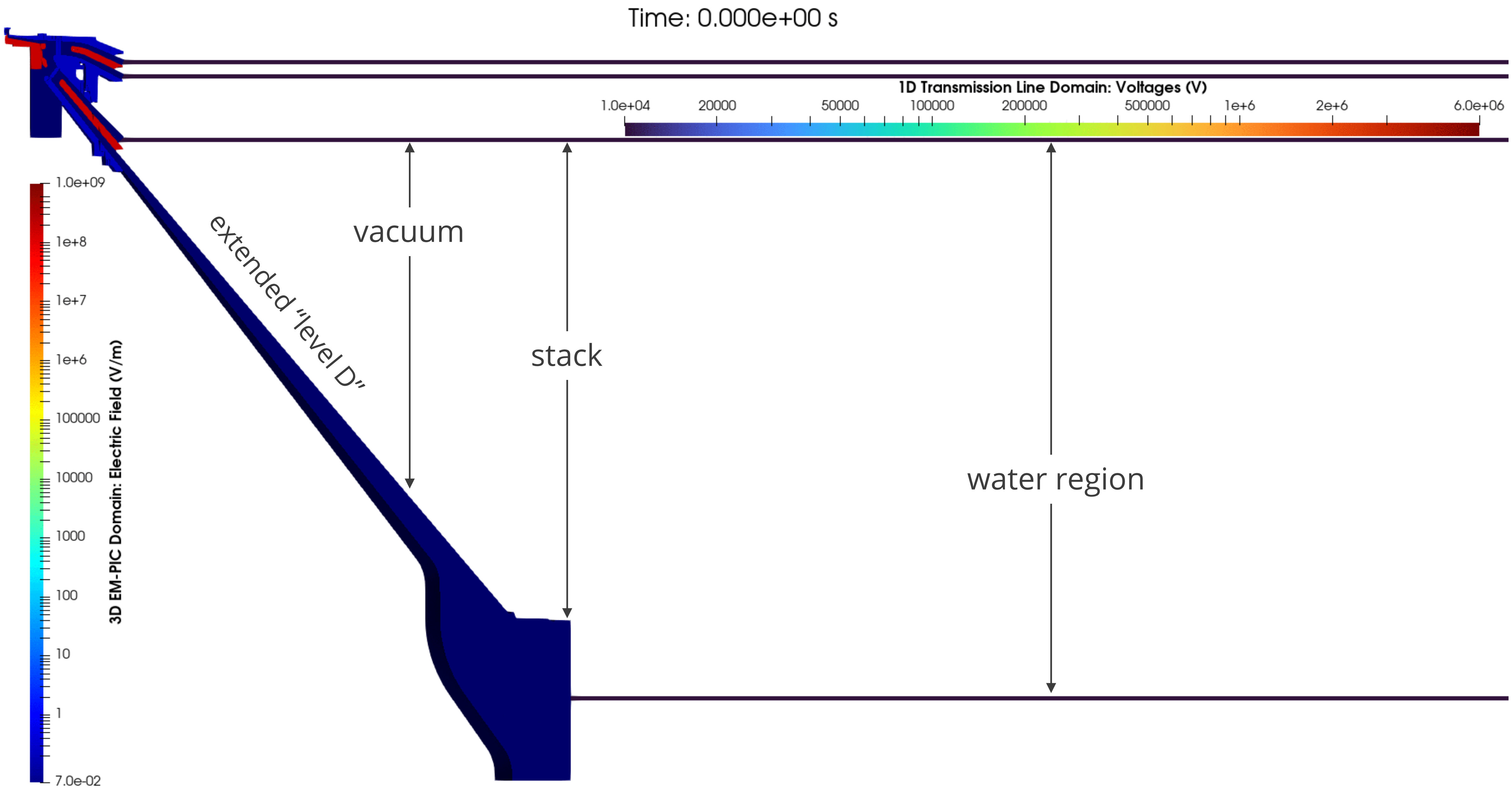
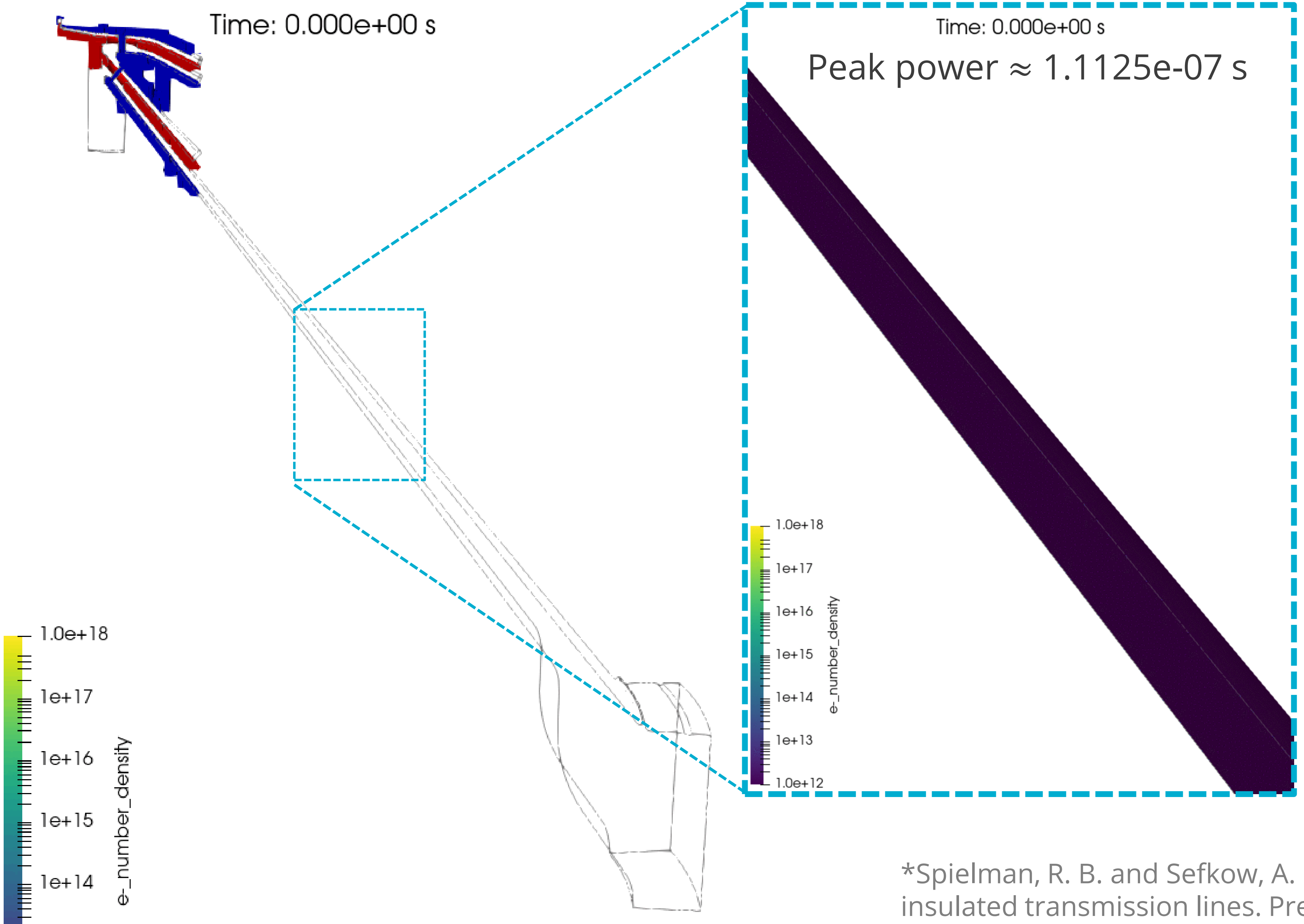


Electrons upstream are insulated *extremely well*



- The surface temperatures (not shown) in this extended region due to electron flux heating is ≤ 0.4° C
- According to our simulations, the outer MITLs in Z operate at 1000x below threshold for anode plasma
- → there is flexibility here from a pulsed-power engineering standpoint to tailor the impedance profiles
- circuit simulations* have shown this can actually *increase* the current delivered to the load
- <u>Next steps</u>: design optimized impedance profile using circuit simulations → simulate down-selected candidate in Empire

*Spielman, R. B. and Sefkow, A. Magnetic insulation and self magnetically insulated transmission lines. Presented at SNL. March 23, 2023.

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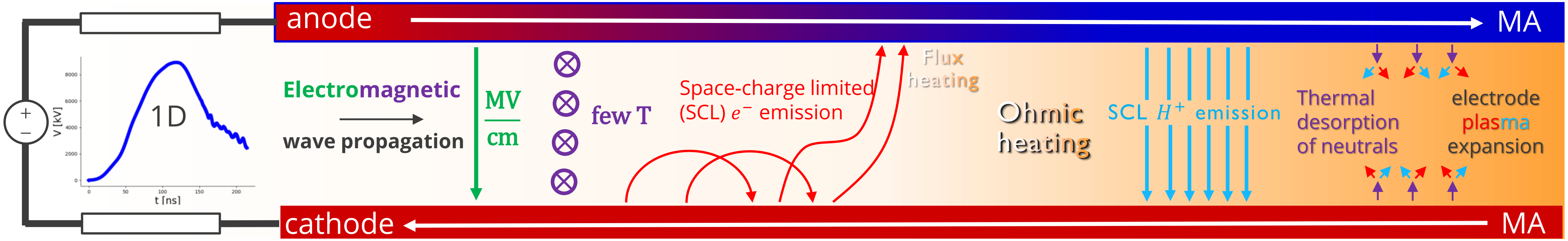


- **Towards NGPP: initial studies of variable-impedance MITLs**
- **Summary and conclusions**

Summary and conclusions

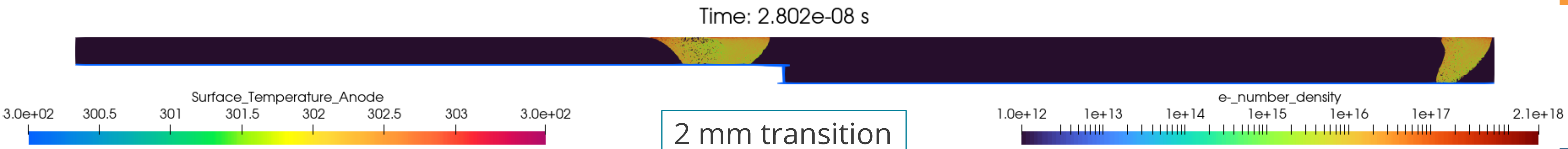
- Simulating pulsed power requires faithful modeling of a multitude of processes that develop in the vacuum transmission lines, high self-magnetic fields makes it even more challenging (e.g. time step restrictions due to cyclotron frequencies)
- To make the self-consistent problem feasible requires employing novel strategies to reduce the problem size (1D-3D coupling), the flexibility to focus resolution only where needed (unstructured meshes), and robust models to faithfully capture all the necessary physics. Even with the most judicious decisions, a performant simulation code with higher performance computing clusters is needed
- simulations shown here used 50 – 110M elements and up to 200 compute-nodes; however, the most expensive calculations only required < 16h of wall time
- We have developed a computational model for the Z accelerator, demonstrating successful machine-scale simulations using the Empire plasma simulation code. We are currently investigating (through simulation) what benefits variable (geometric) impedance can bring to this baseline (Z today)
- Ongoing work will more fully characterize operating performance of variable impedance MITLs so that any flexibility afforded therein (i.e., to minimize total drive inductance) can be maximally exploited in future pulsed power engineering to meet design objectives at reasonable cost and more reasonable size.

Thank you for your attention!

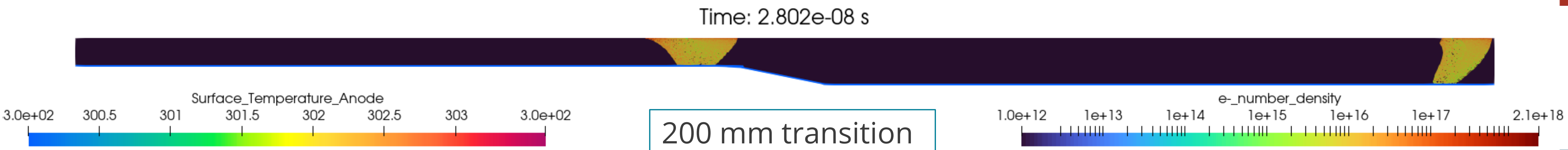
Questions?

extras

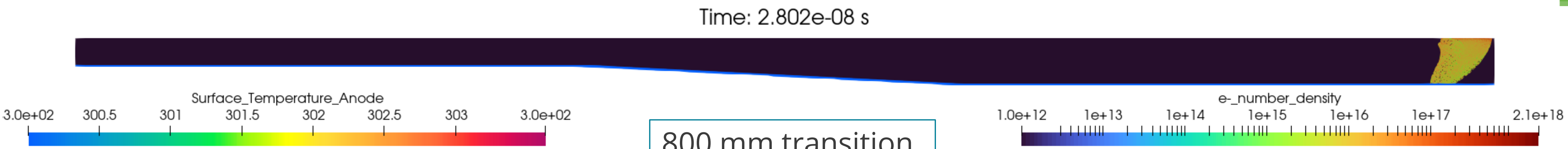
insulation in variable impedance MITLs



2 mm transition



200 mm transition



800 mm transition

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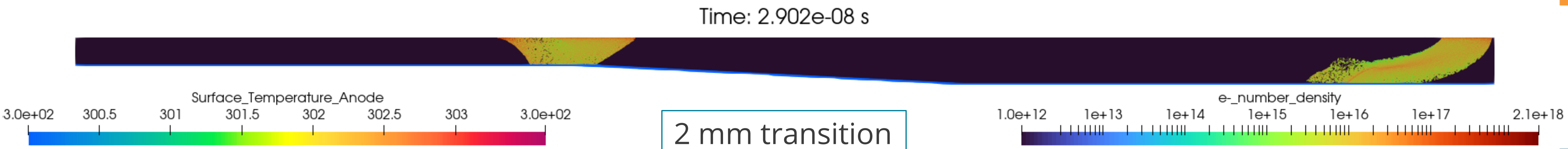

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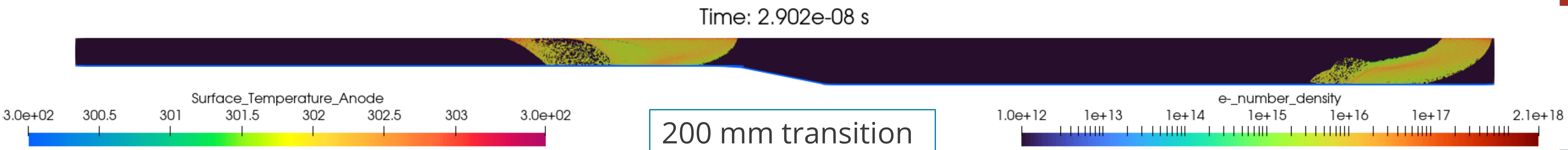

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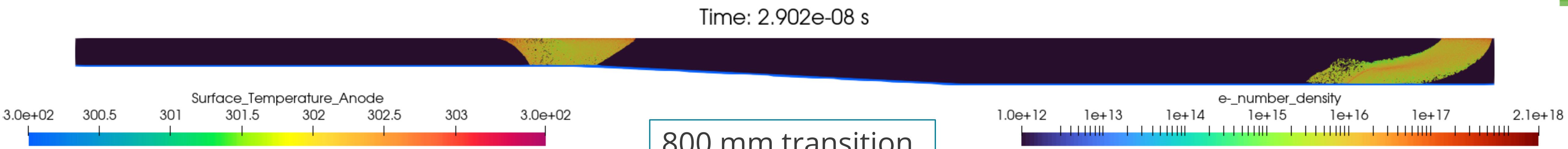

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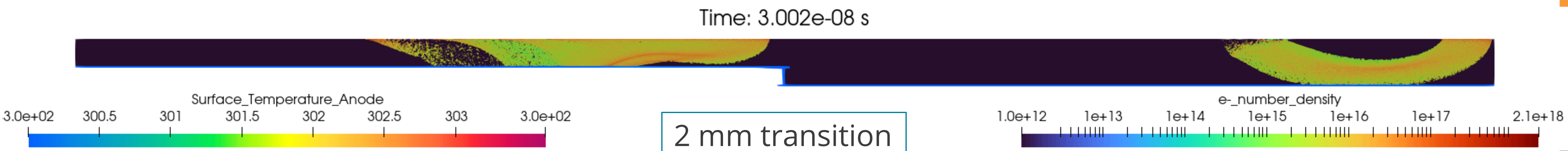

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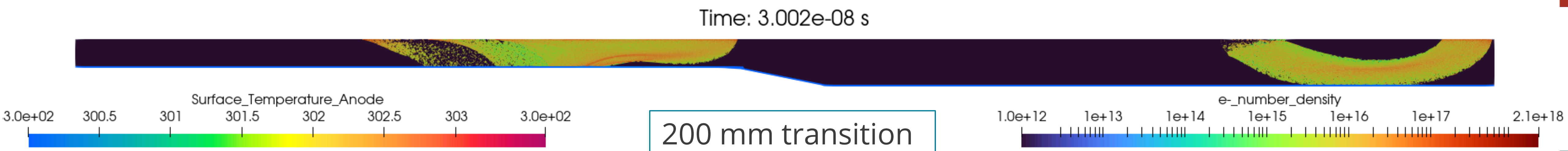

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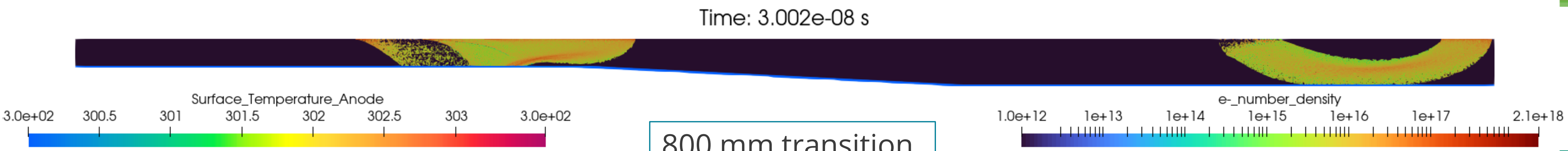

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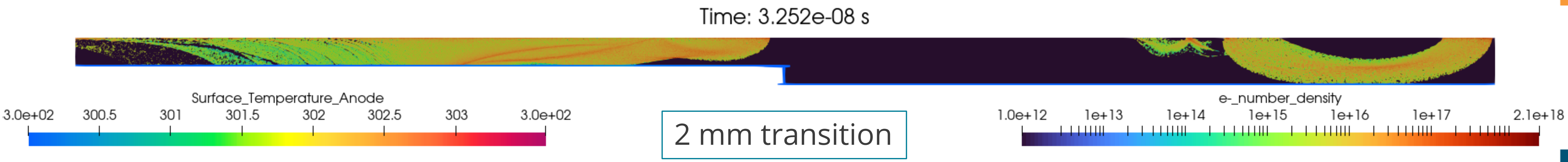

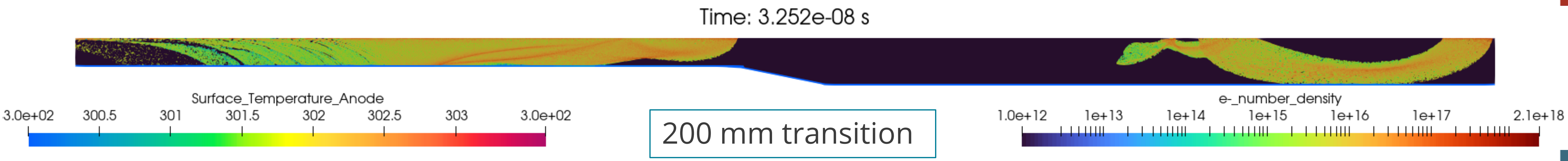

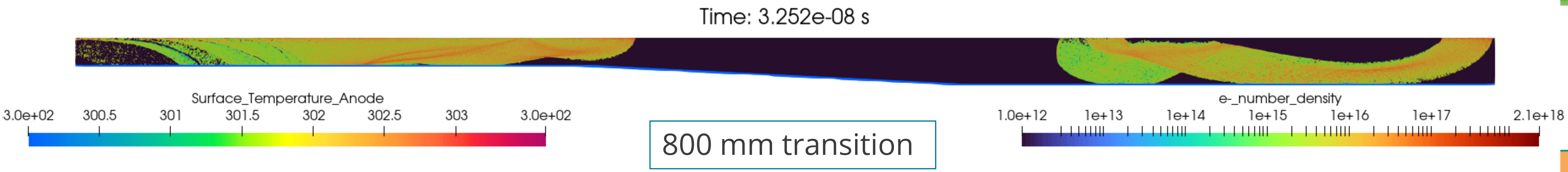

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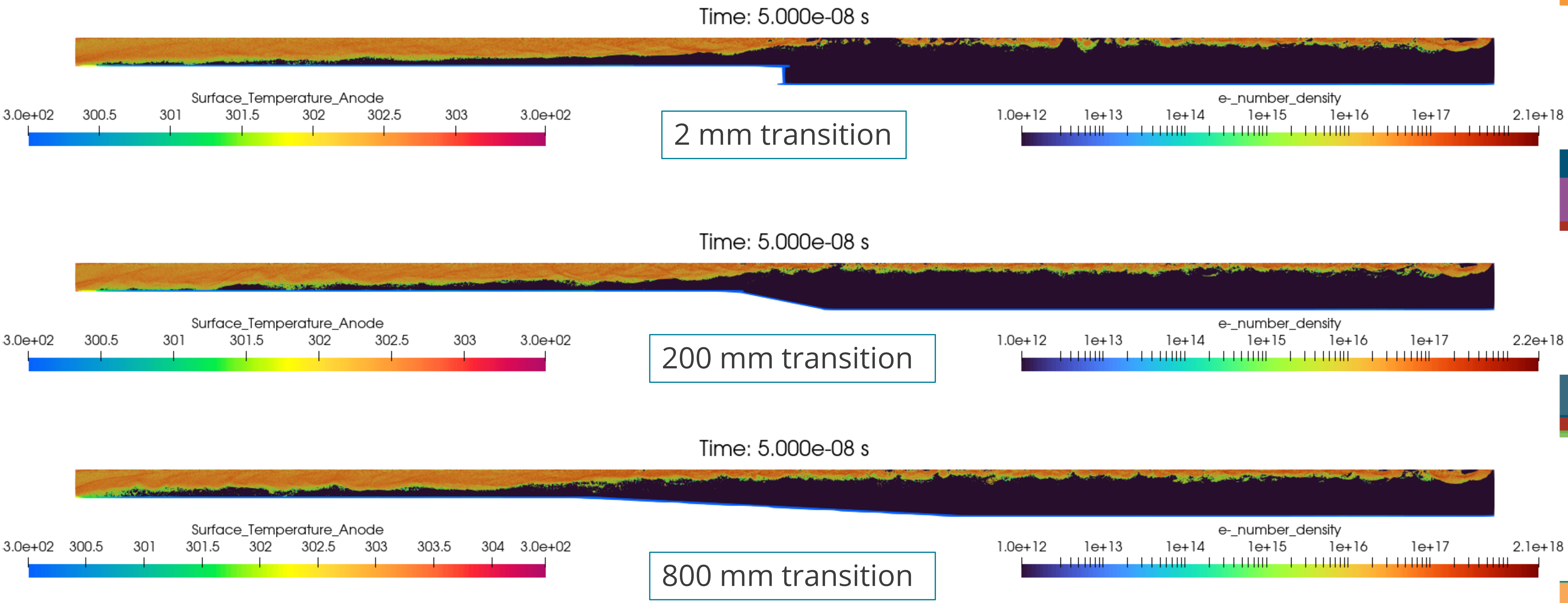

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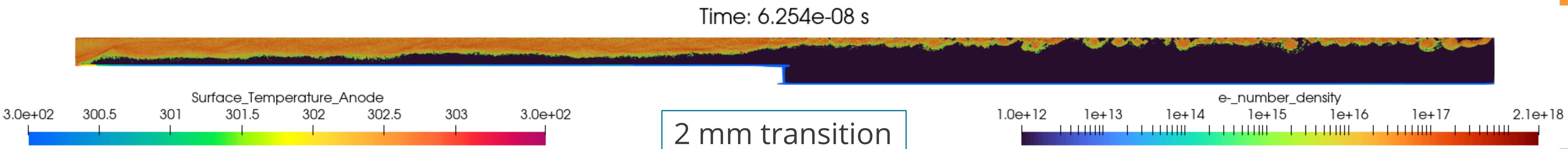

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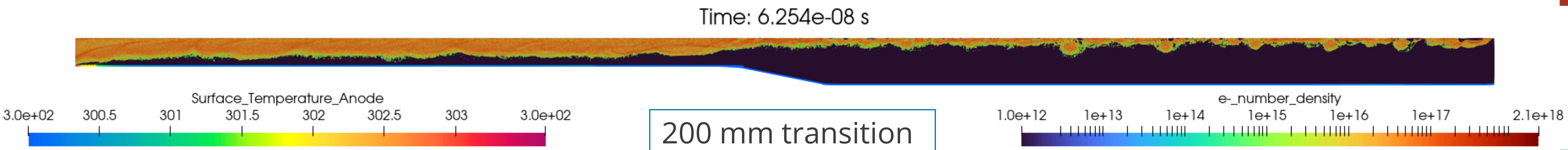

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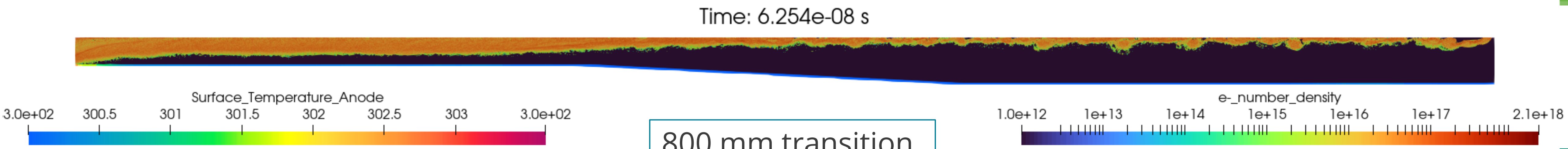

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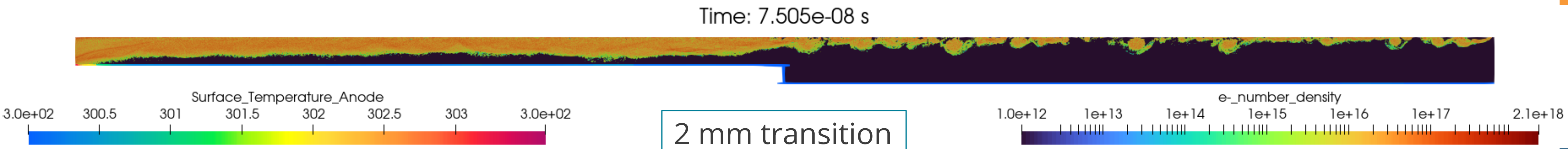

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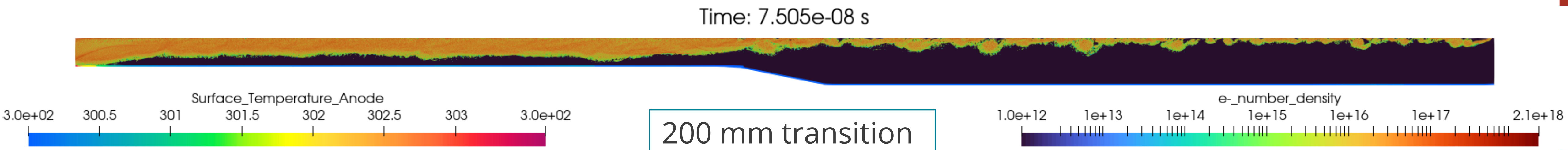

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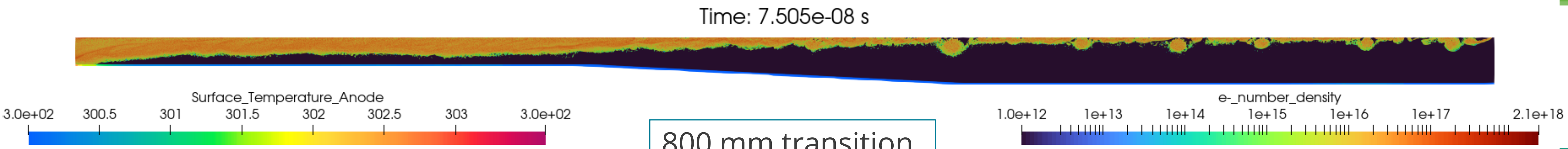

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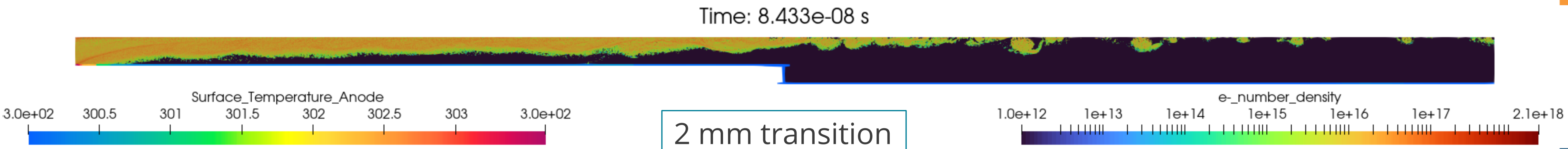

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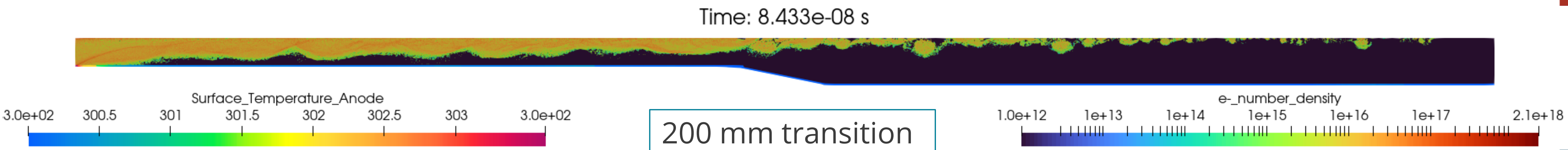

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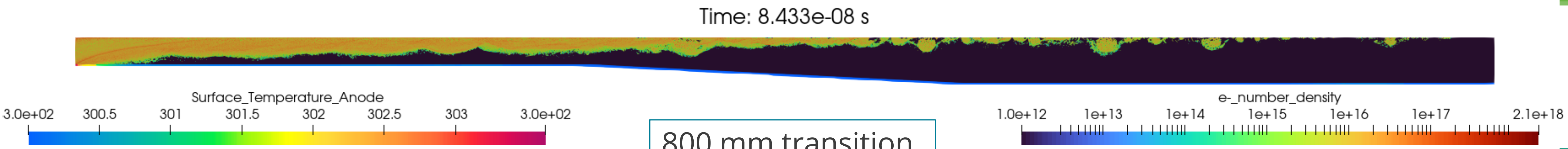

800 mm transition