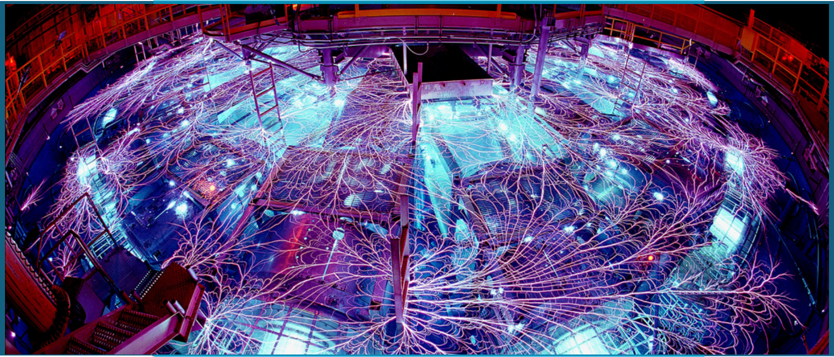
Sandia National Laboratories

SAND2020-13409C

Power flow simulations of the Z accelerator using EMPIRE



Presented by

David Sirajuddin[*], Matthew T. Bettencourt[*], Edward G. Phillips[*], Duncan McGregor[*], Nicholas Roberds[*], Nichelle Bennett[*], George R. Laity[*], David V. Rose[+] and Dale R. Welch[+]

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International Conference on Plasma Science (ICOPS)
Dec. 6, 2020

U.S. Department of Energy NNSA National Nuclear Security Administration

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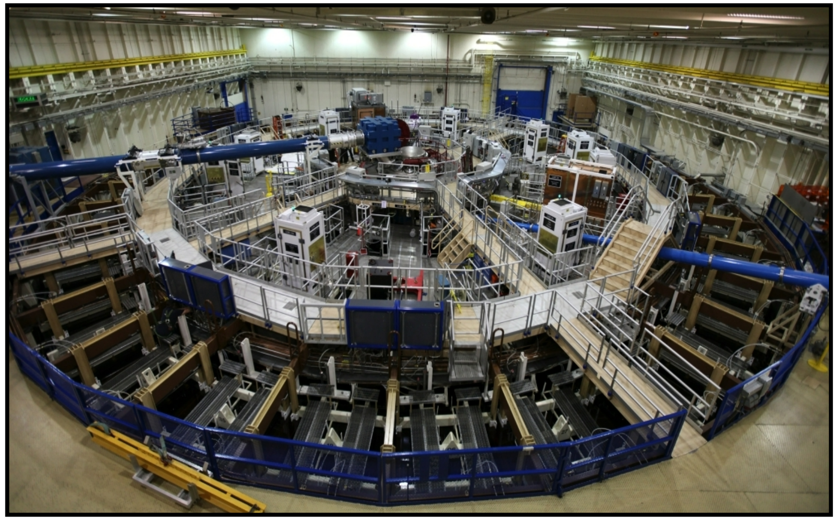
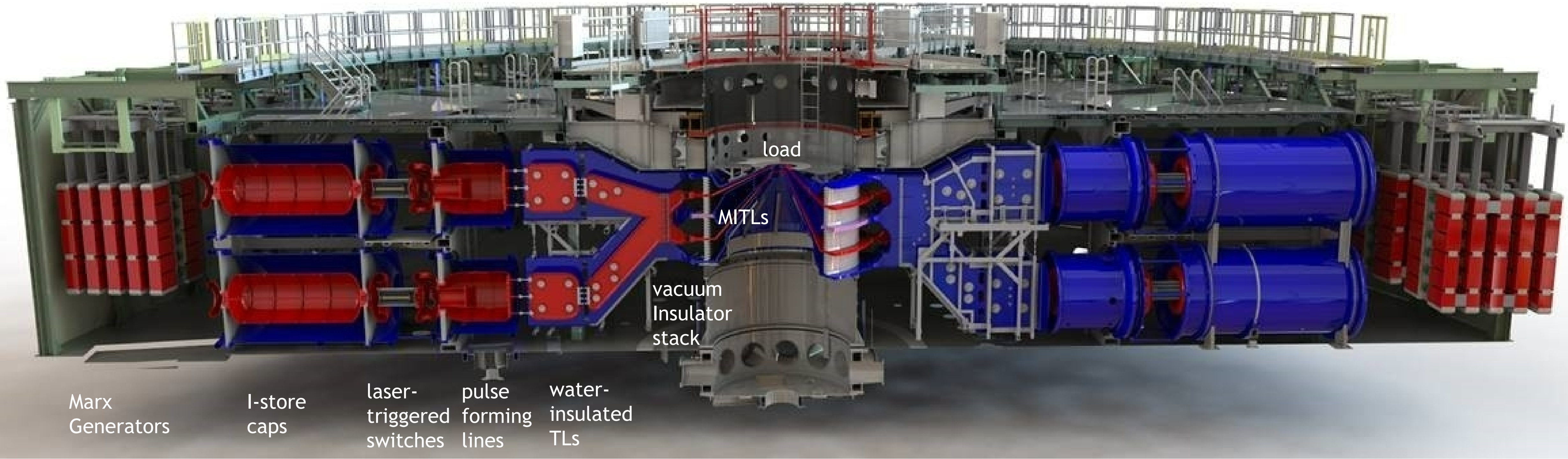
Outline

- System overview:
  - Z accelerator at Sandia
  - Modeling challenges
- Heterogeneous power flow model
- Simulation results
- Summary and future work
- Questions

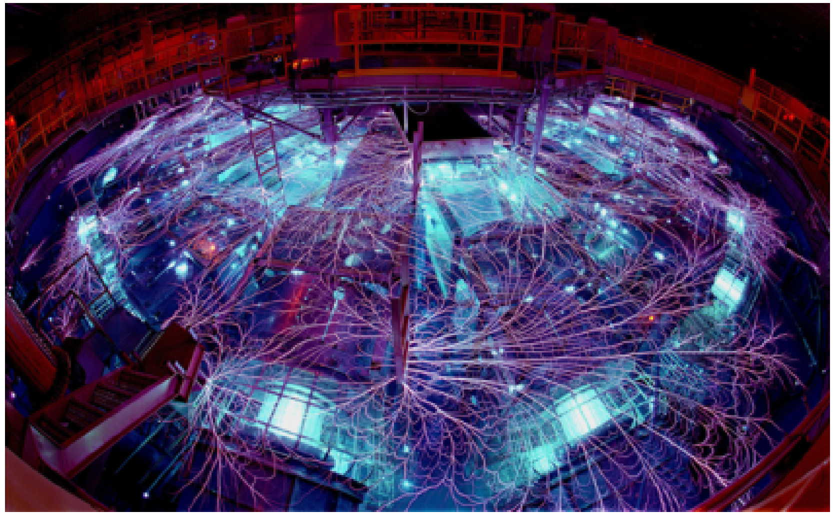
System overview: Z accelerator at Sandia



- Multi-purpose research device for high energy density (HED) physics
- <u>Storage</u>:
  - 36 Marxes = 2,160 caps
  - 95 kV, 20 MJ in ~ 3 min



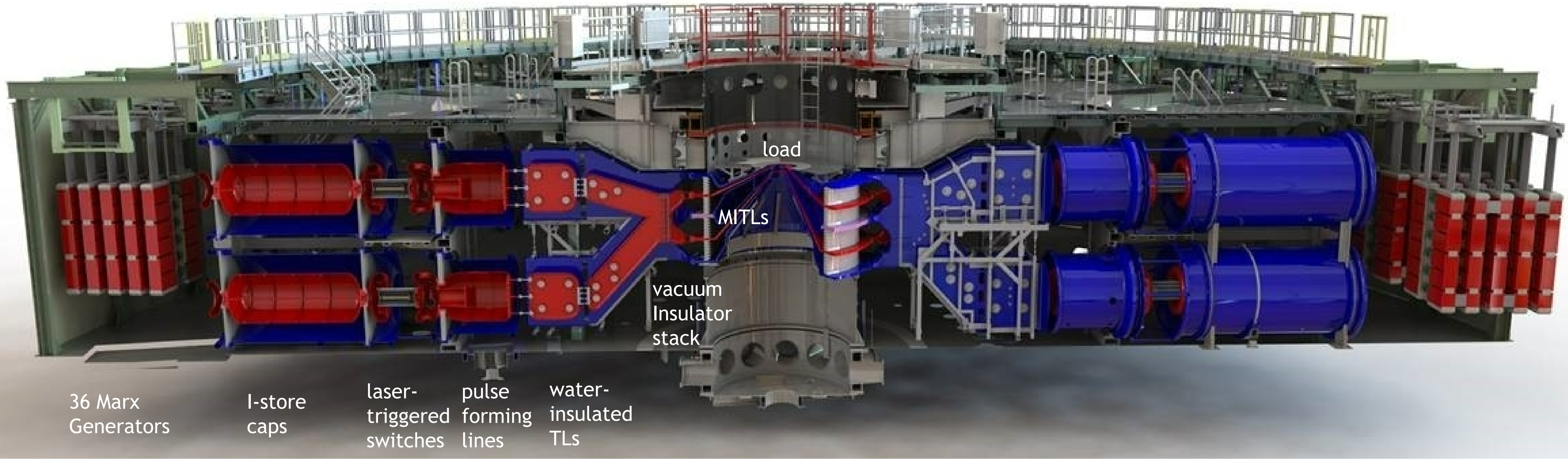
System overview: Z accelerator at Sandia



- Multi-purpose research device for high energy density (HED) physics

- 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



System overview: modeling challenges

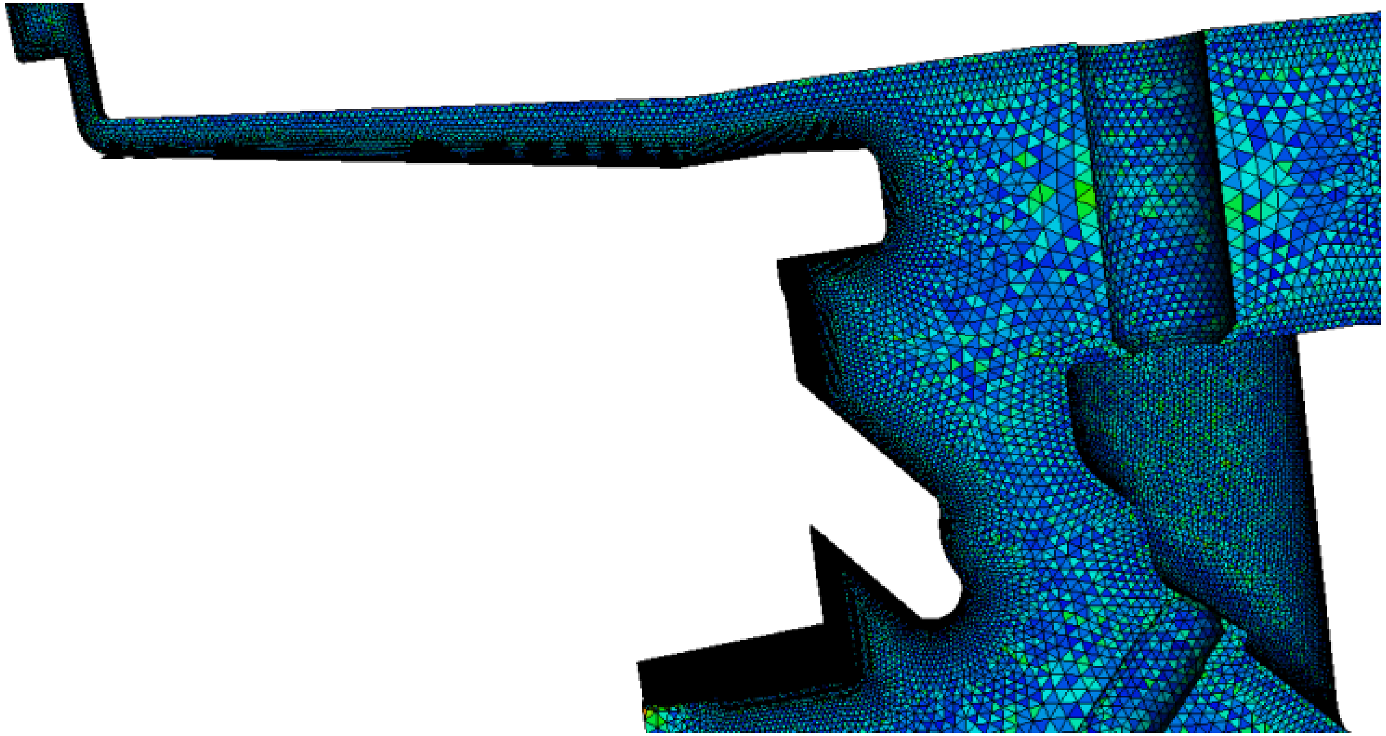
- Vastness of scales:
  - **time**: μs discharge time vs. THz electron cyclotron frequencies
  - **space**: meters-long transmission lines vs. micron electron gyroradii
  - **velocities**: thermal speeds (v/c ~ 10^{-6}) of desorbed neutrals vs. EM wave prop. (≤ c)
  - **densities**: ranging from near vacuum levels to greater than solid density

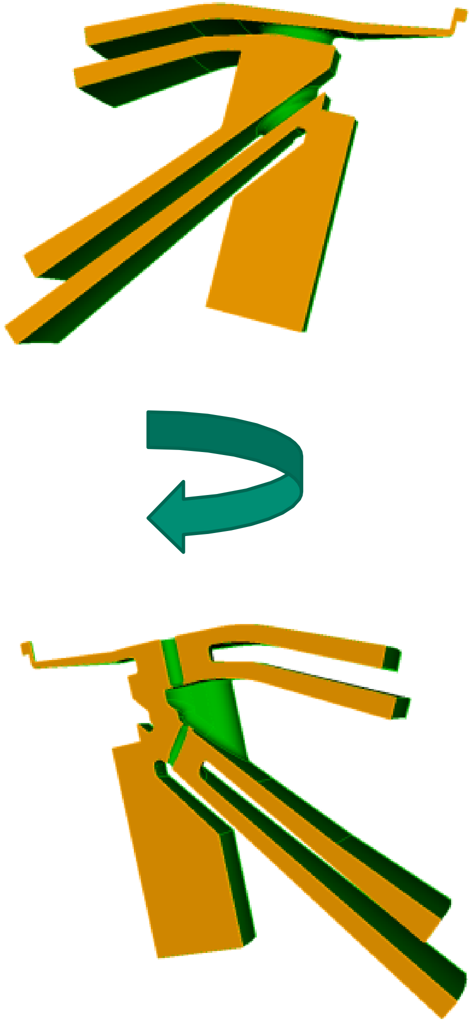
Underlying numerical methods introduce additional constraints

→ Modeling a large system is not tractable with homogeneous approaches

Required components for full physics heterogeneous model

- Electromagnetics described on complex geometries
- Symmetry boundary capabilities → reduced domain





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  - Particle creation:
    - Field-emitted electrons ~ 10^{14} cm^{-3} (SCL rate for > 200 kV/cm)
    - Desorption H_2O: $\frac{d\theta}{dt} = -k_0(T)\theta(t)e^{-E_d(1-\alpha\theta)/k_B T}$
    - Fragmentation: H_2O → $3e^- + 2H^+ + O^+$

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  - Heating: $\frac{\partial u}{\partial t} = Q(x,t) - \frac{\partial q}{\partial x}$ or analytical increment
    - Ohmic (magnetic diffusion) – $Q(x,t) = \eta(T)\left|\frac{1}{\mu_0}\left|\nabla \times \vec{B}\right|^2\right.$ where $\frac{\partial B_\parallel}{\partial t} = \frac{1}{\mu\sigma}\frac{\partial^2 B_\parallel}{\partial x^2} - \frac{1}{(\mu\sigma)^2}\frac{\partial(\mu\sigma)}{\partial x}\frac{\partial B_\parallel}{\partial x}$
    - Particle fluxes – $Q(x,t) = KE(x,t)$

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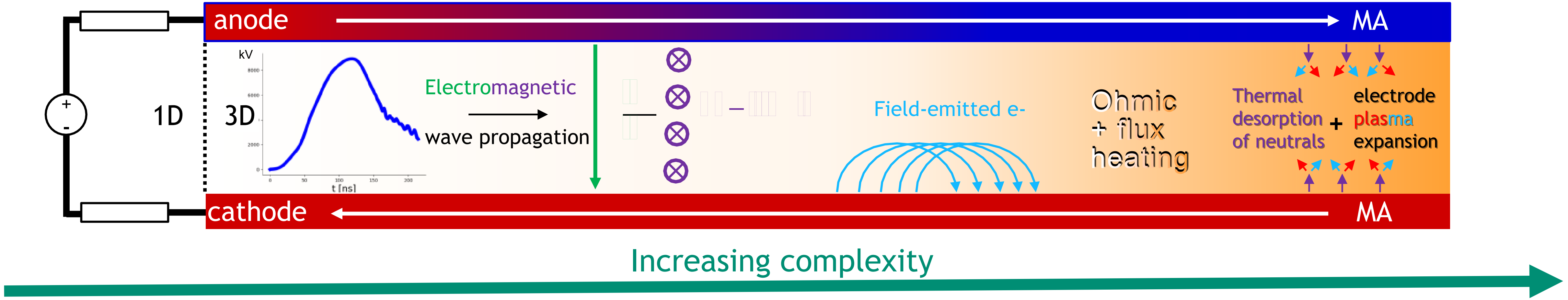
    - Particle fluxes – $Q(x,t) = KE(x,t)$
- Relativistic particle dynamics

Powerflow model building has advanced using an integrated approach where developing code capabilities are pushed through a pipeline of increasingly complex MITL systems

Models



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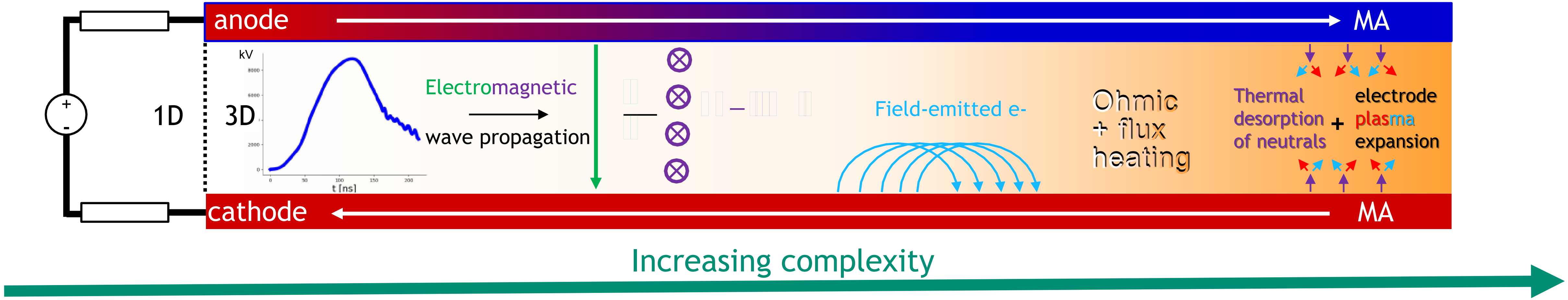
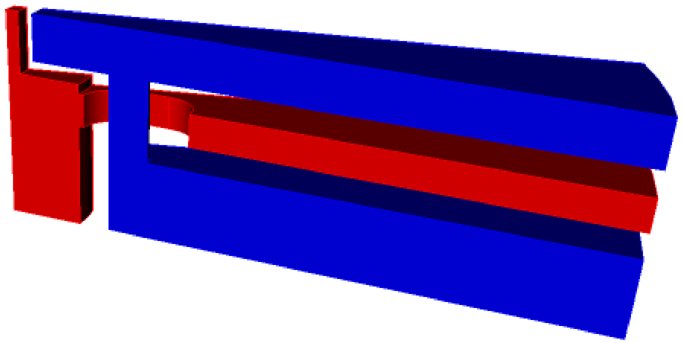
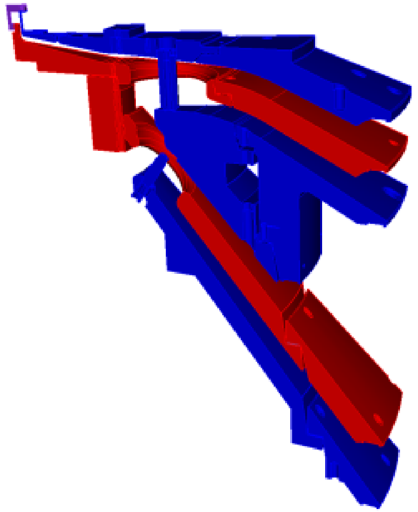


(3D) Half-o-lute



(3D) Powerflow 18a



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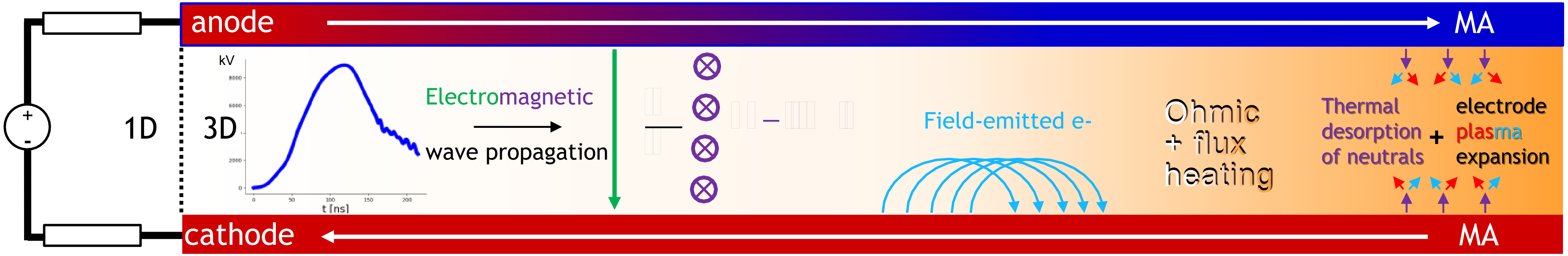
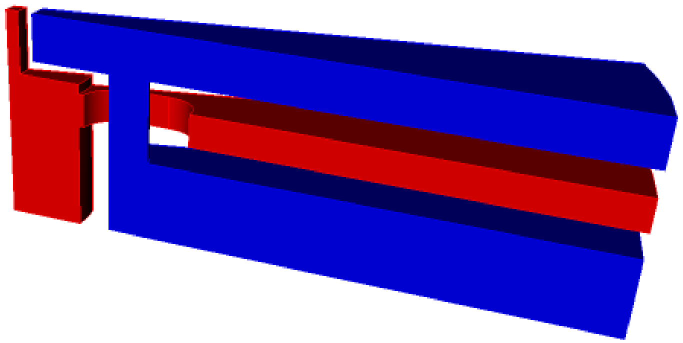


Increasing complexity

(3D) Half-o-lute



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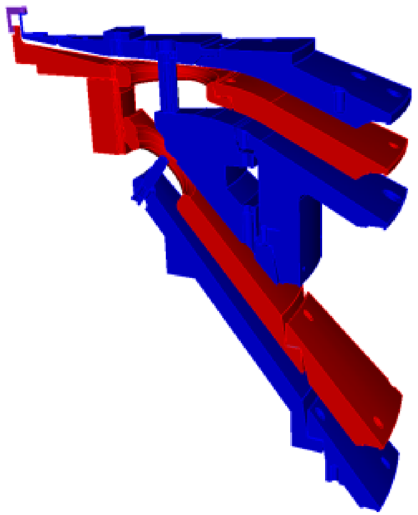
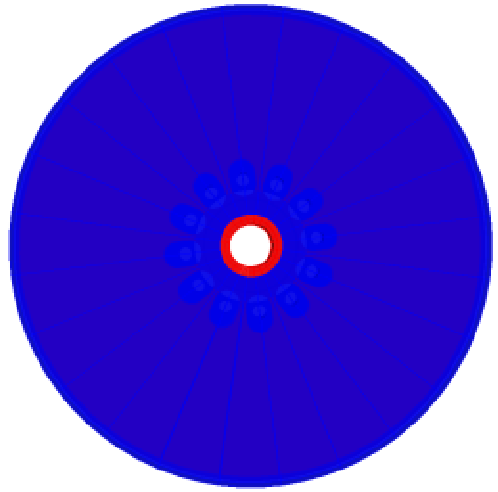
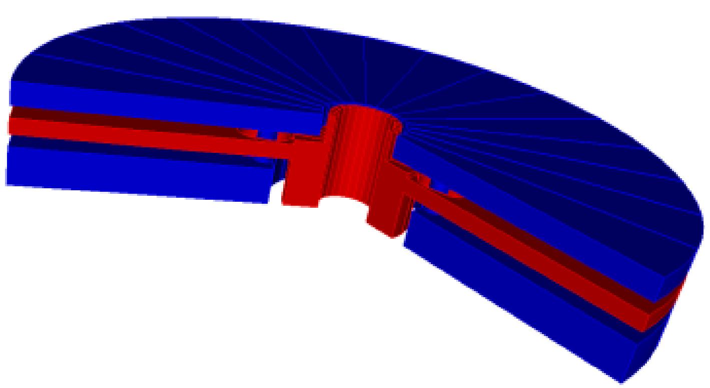


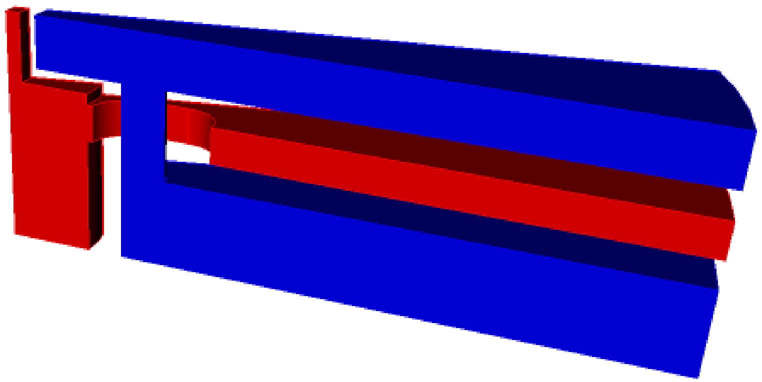
Half-o-lute model

Thanks to D. Welch, D.V. Rose
for CHICAGO simulation model

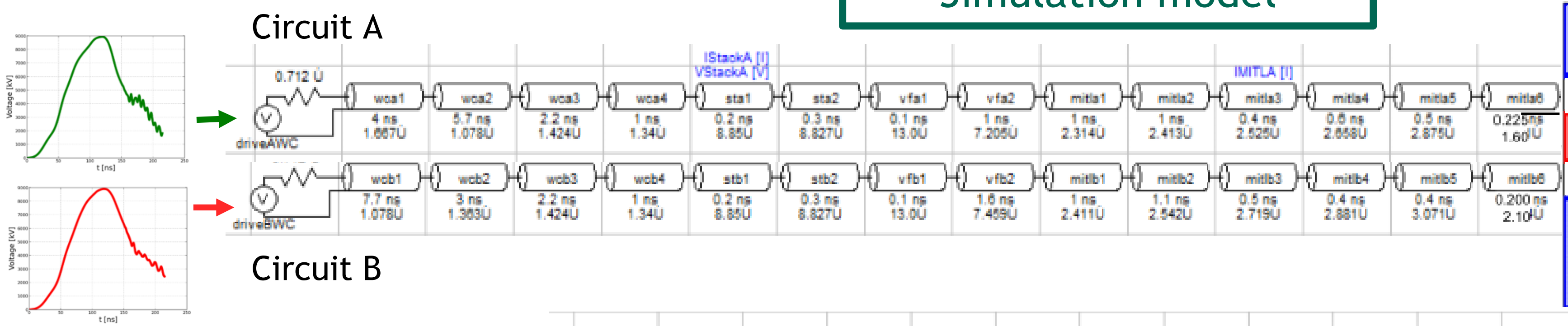
Hardware geometry

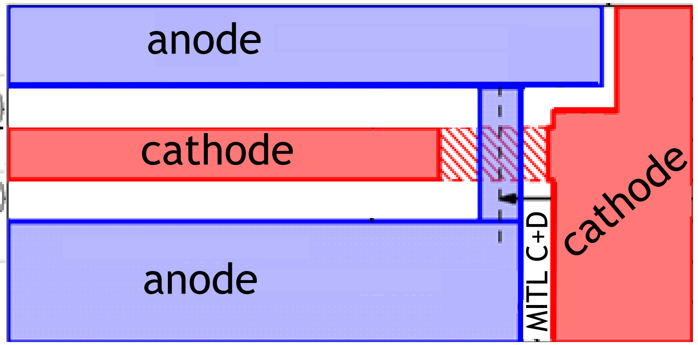


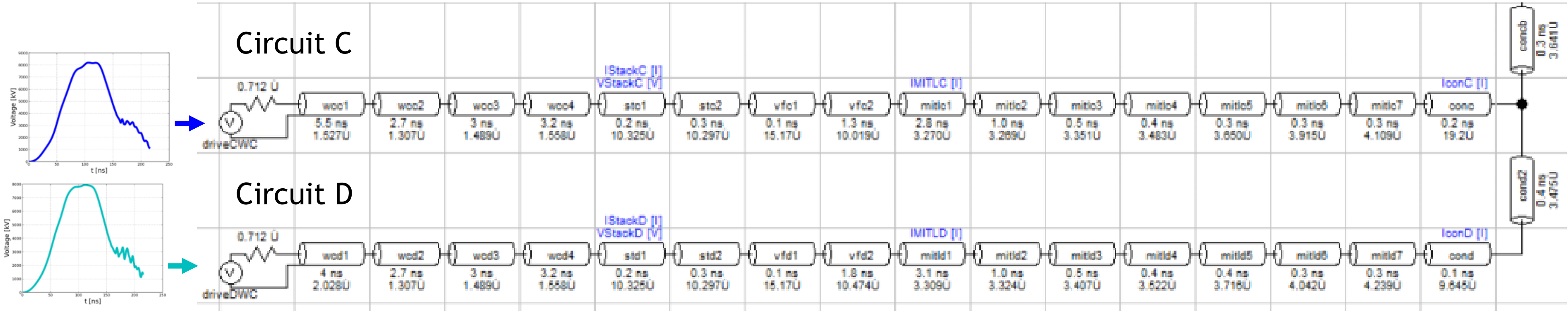




Simulation model



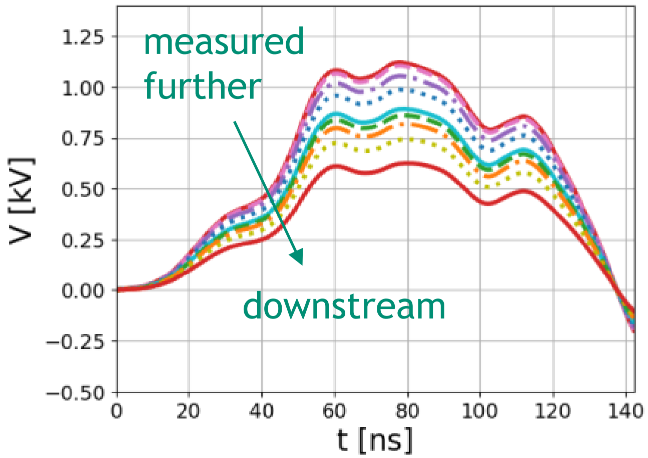


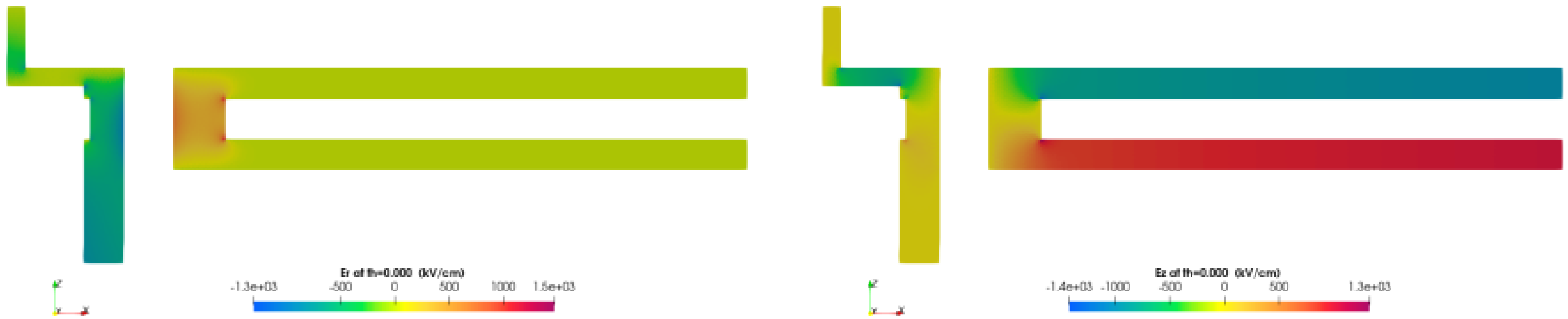


BERTHA circuit
work by B. Hutsel
et al.

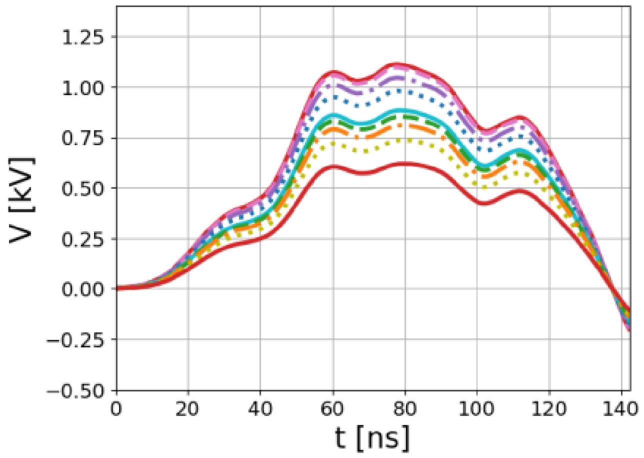
Half-o-lute code-comparison study: EMPIRE vs. CHICAGO – cold

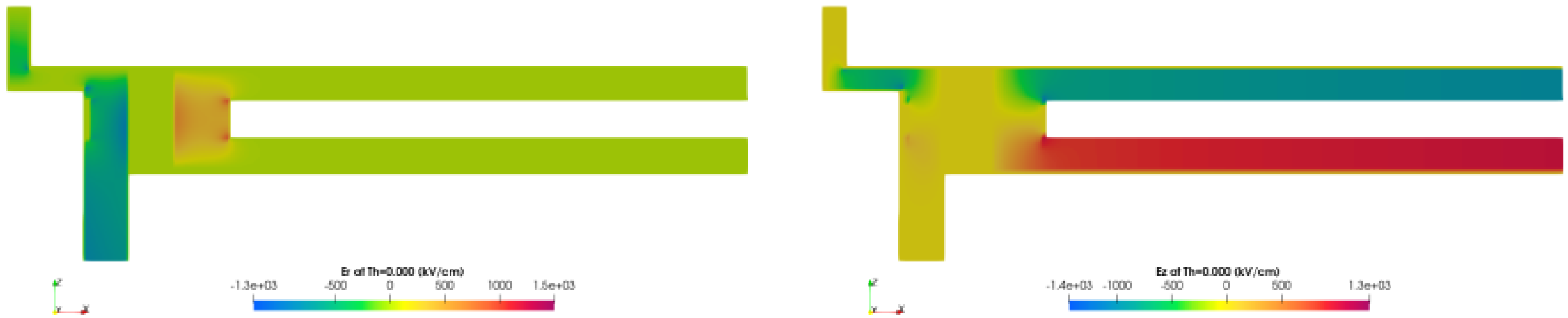
EMPIRE-PIC





CHICAGO-PIC





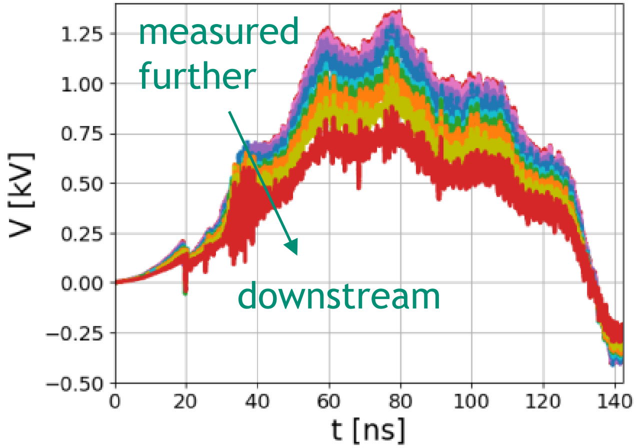
Voltages measured along MITL A → inner MITL

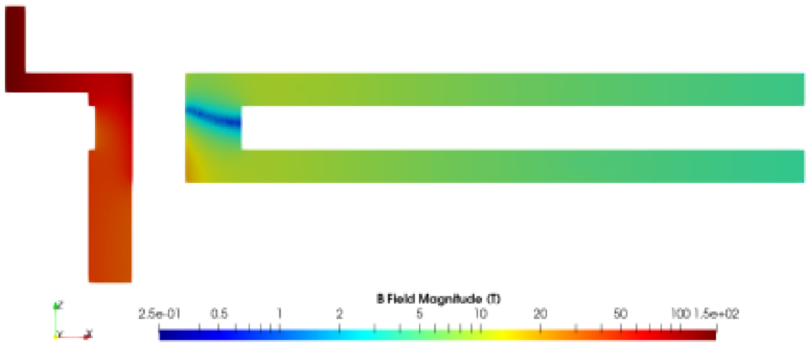
E_r at 110 ns

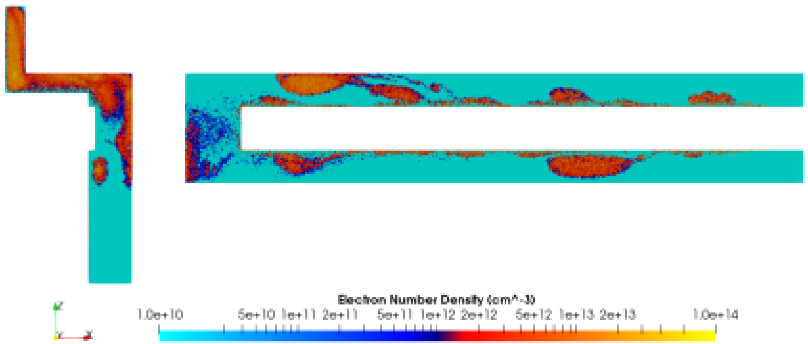
E_z at 110 ns

Half-o-lute code-comparison study: EMPIRE vs. CHICAGO – hot

EMPIRE-PIC







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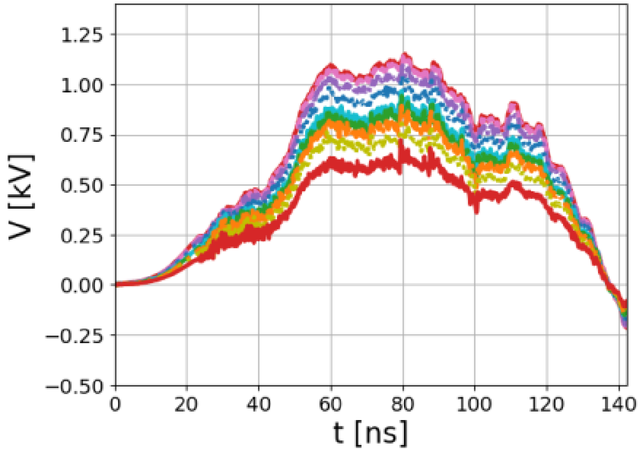
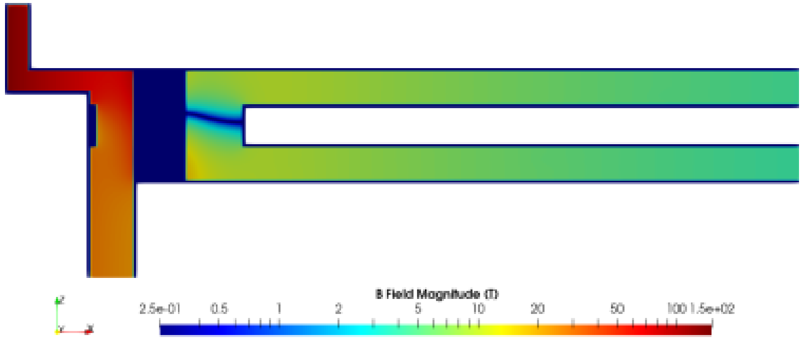
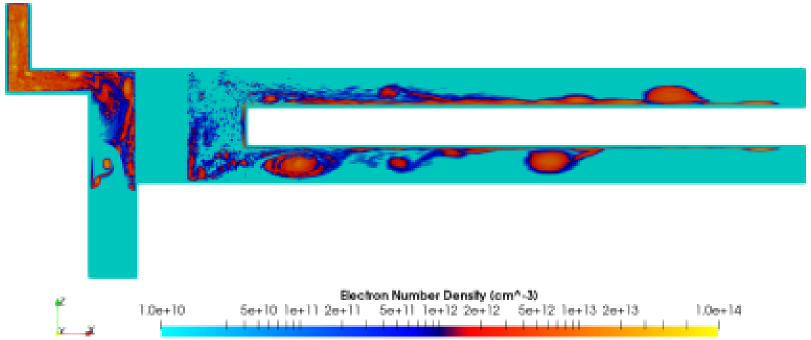






Voltages measured along MITL A → inner MITL

B field magnitude at 90 ns

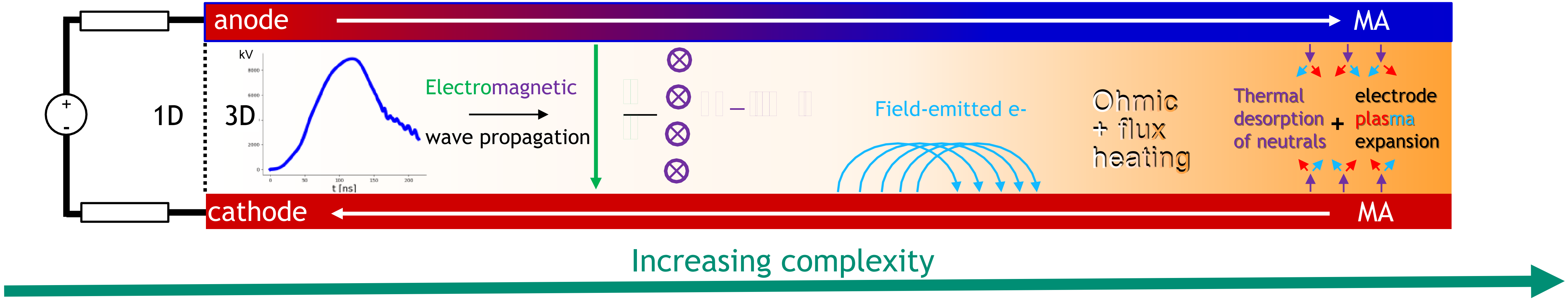
Electron density at 90 ns

Half-o-lute hot EMPIRE simulation: electron number density

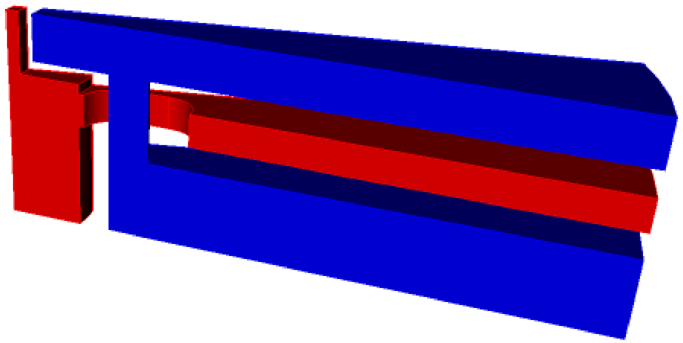
EMPIRE-PIC

Powerflow model building has advanced using an integrated approach where developing code capabilities are pushed through a pipeline of increasingly complex MITL systems

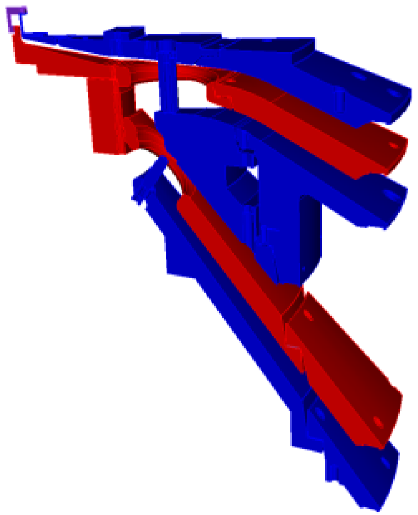
Models



(3D) Half-o-lute



(3D) Powerflow 18a



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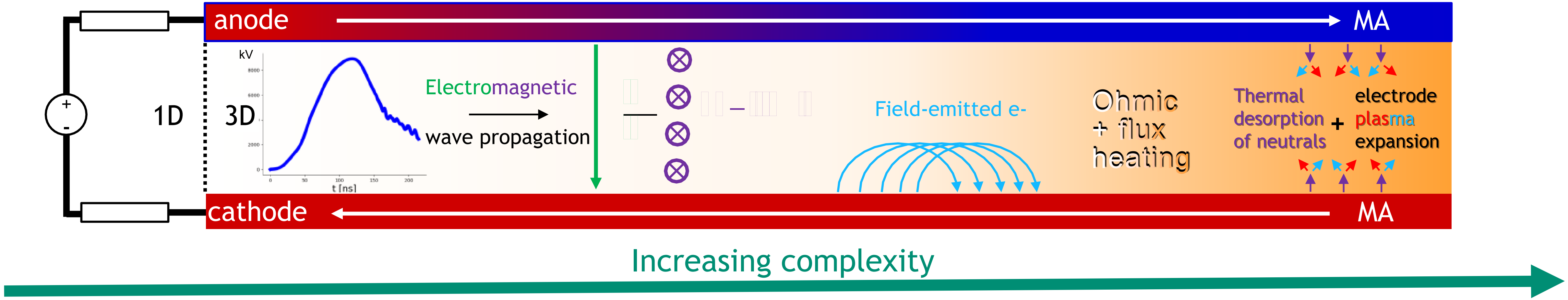

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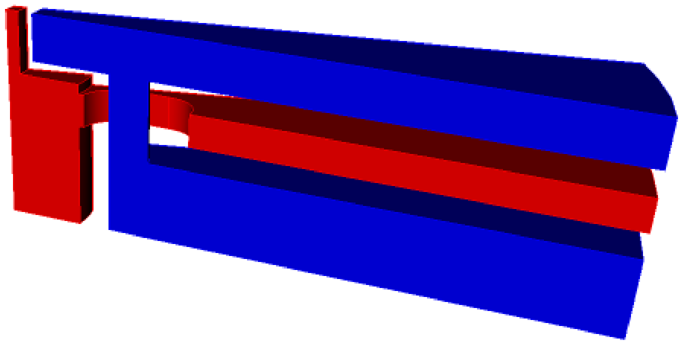

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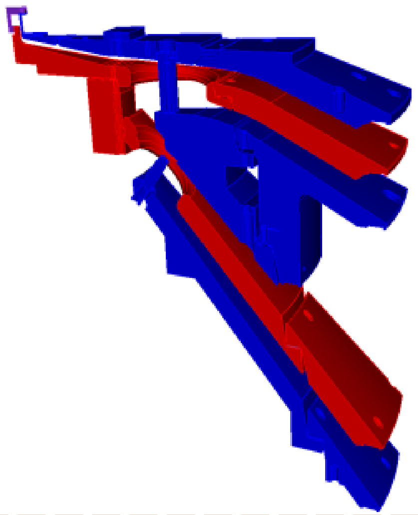
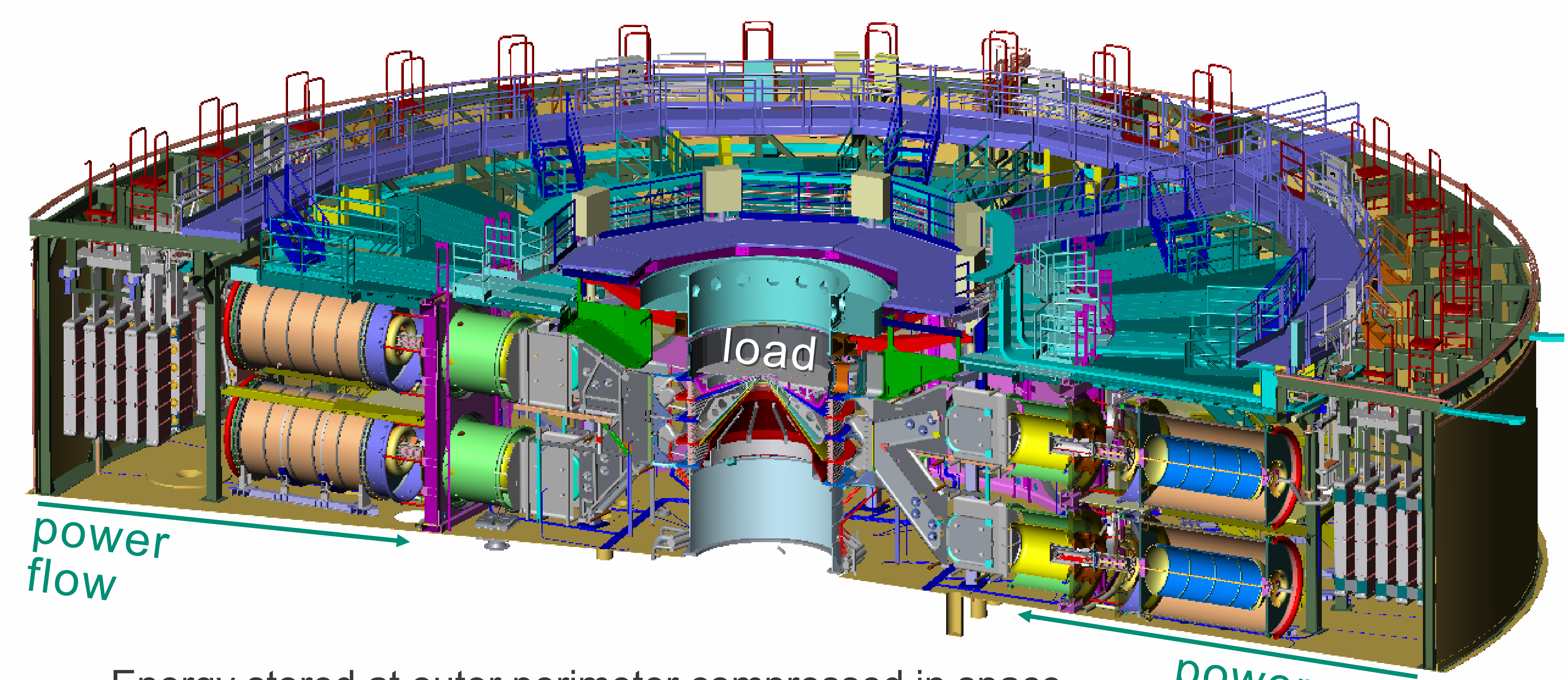


Powerflow 18a model setup: full problem domain

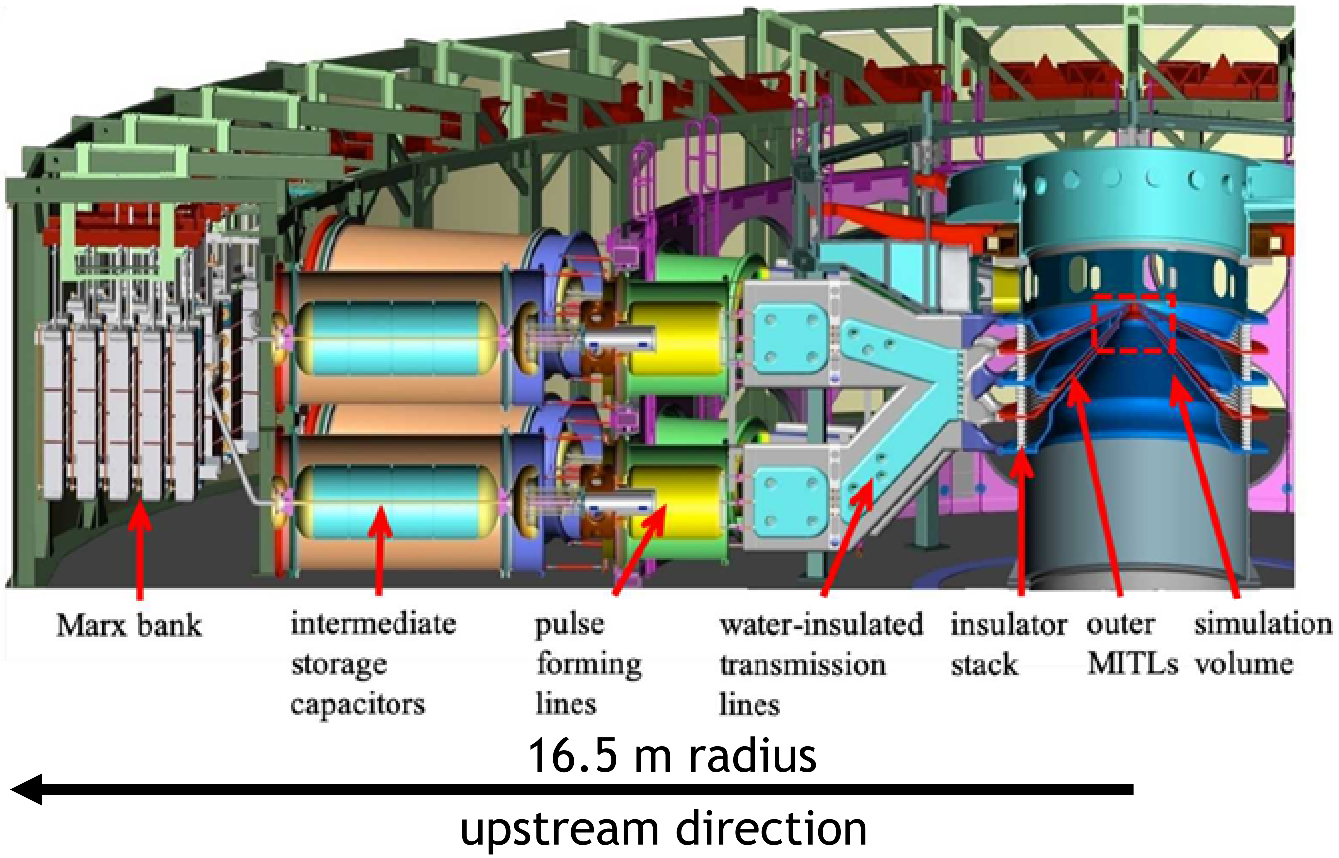


Energy stored at outer perimeter compressed in space and time

to deliver 26 MA peak within 100 ns at machine center (load)

Powerflow 18a model setup

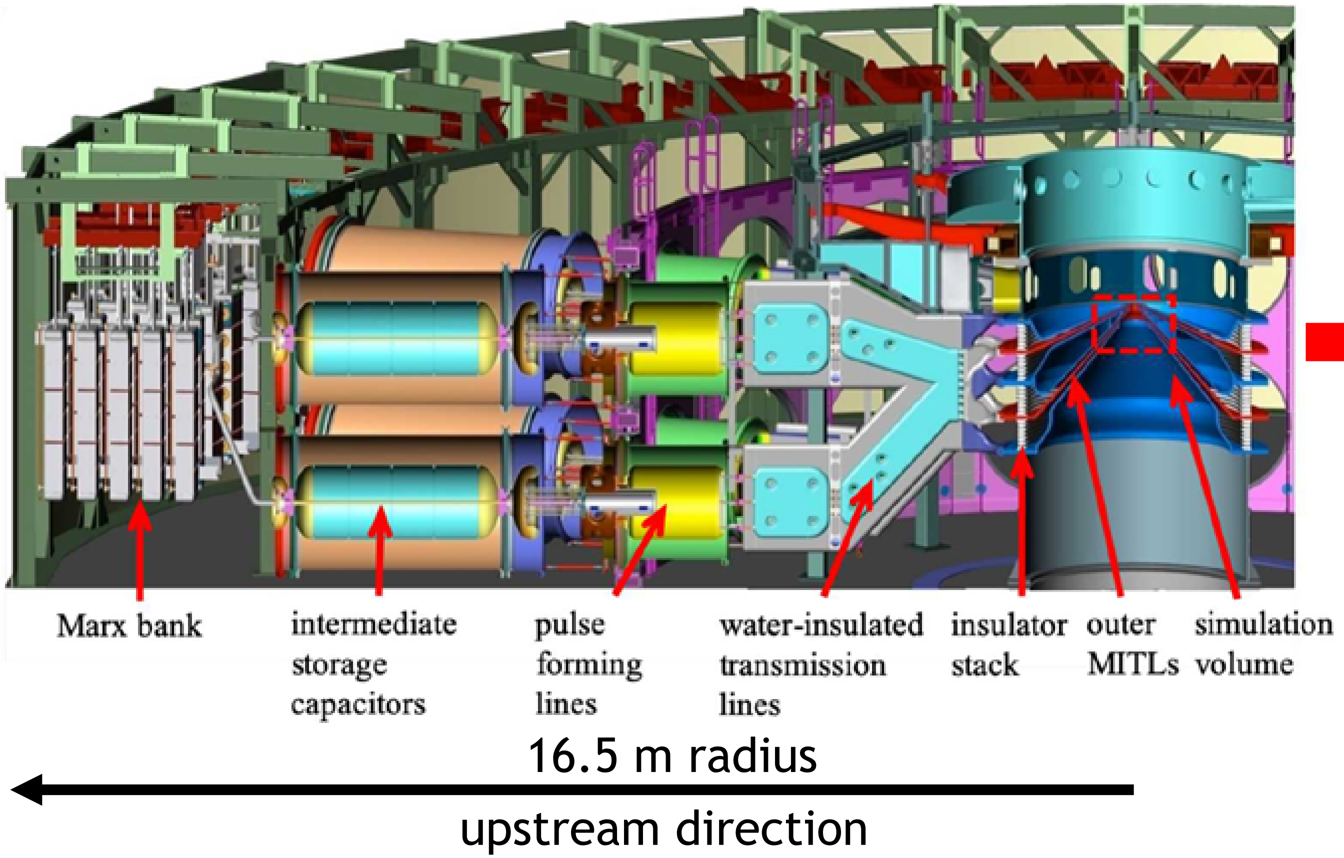
Figures: E. Waisman et al., Phys. Rev. ST Accel. Beams, Vol. 17, 120401, (2014)

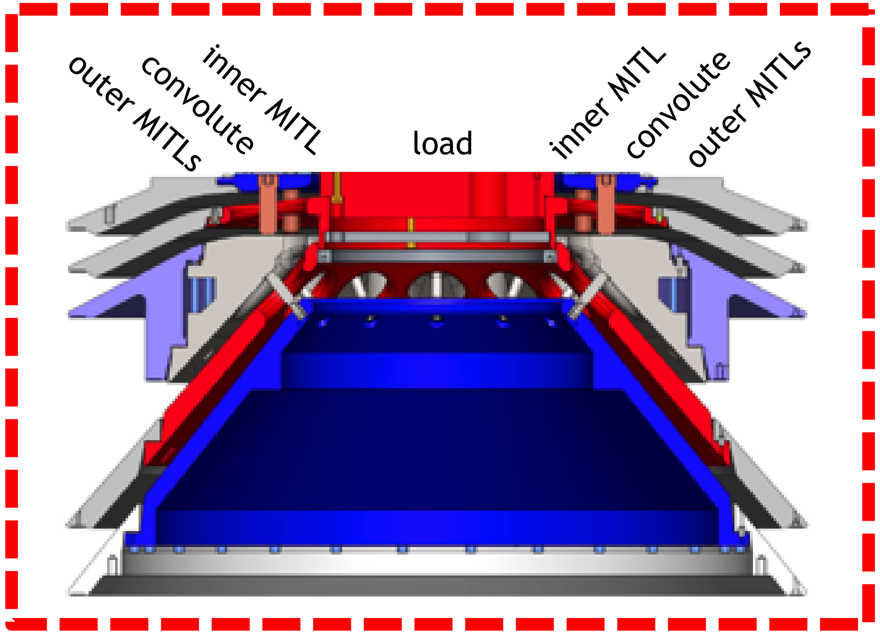


- Downstream: extreme conditions: 3D
  - $0 \leq |E| \leq 10^4$ kV/ cm
  - $0 \leq |B| \leq 300$ Tesla
  - electrode temperatures: $300 \leq T \leq T_{melt}$
  - particle creation, fragmentation, and more!
- Upstream: well-behaved conditions: 1D

Powerflow 18a model setup

Figures: E. Waisman et al., Phys. Rev. ST Accel. Beams, Vol. 17, 120401, (2014)

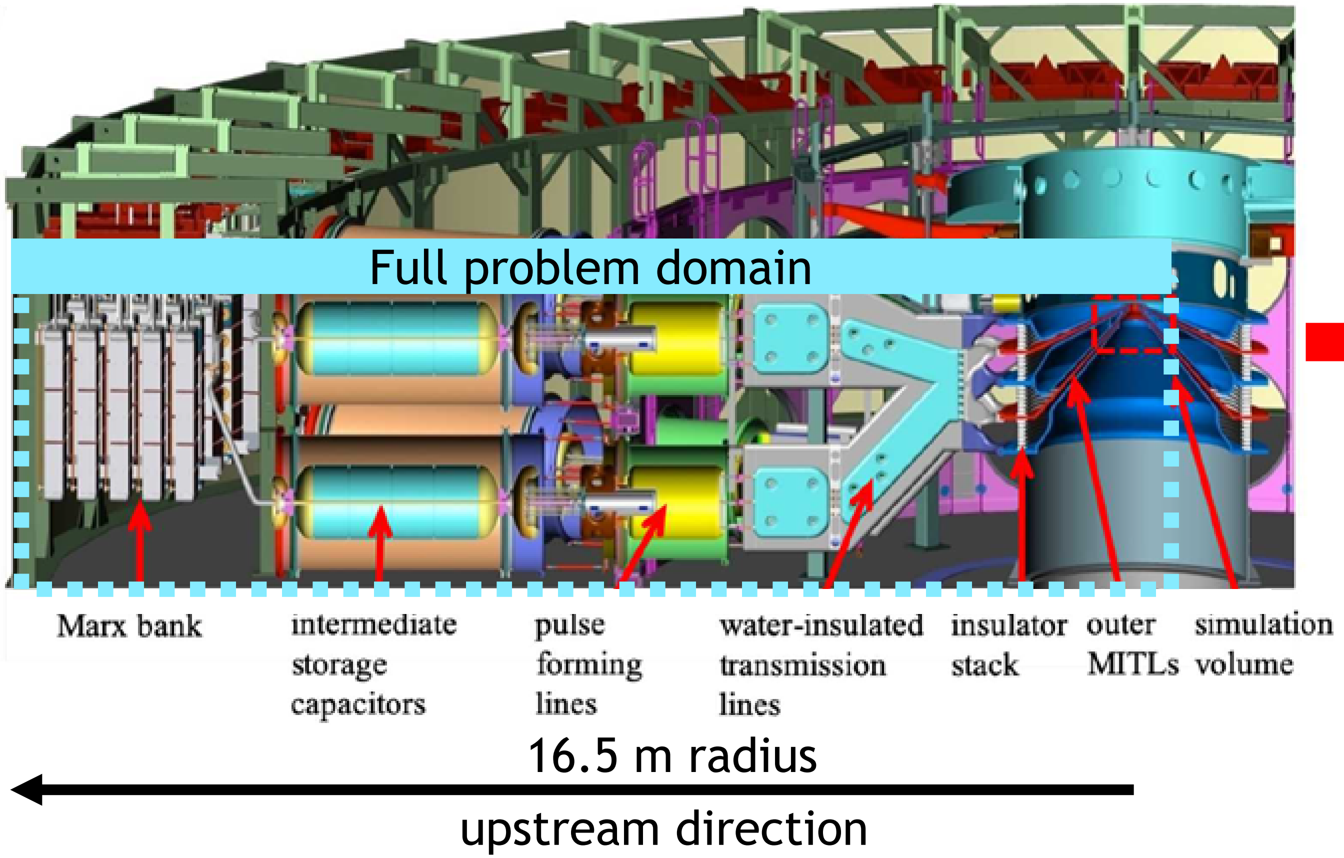


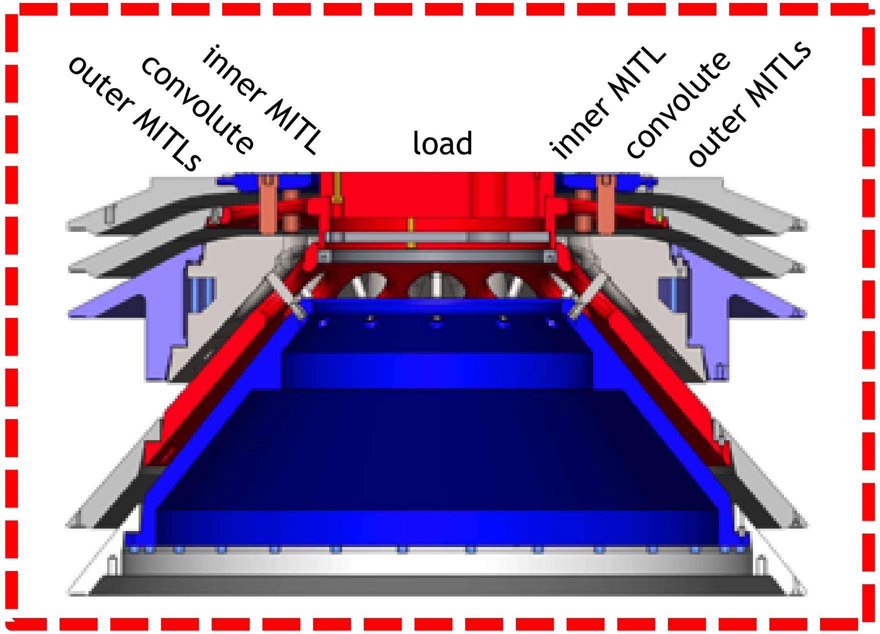


Region where 3D effects dominate

Powerflow 18a model setup

Figures: E. Waisman et al., Phys. Rev. ST Accel. Beams, Vol. 17, 120401, (2014)





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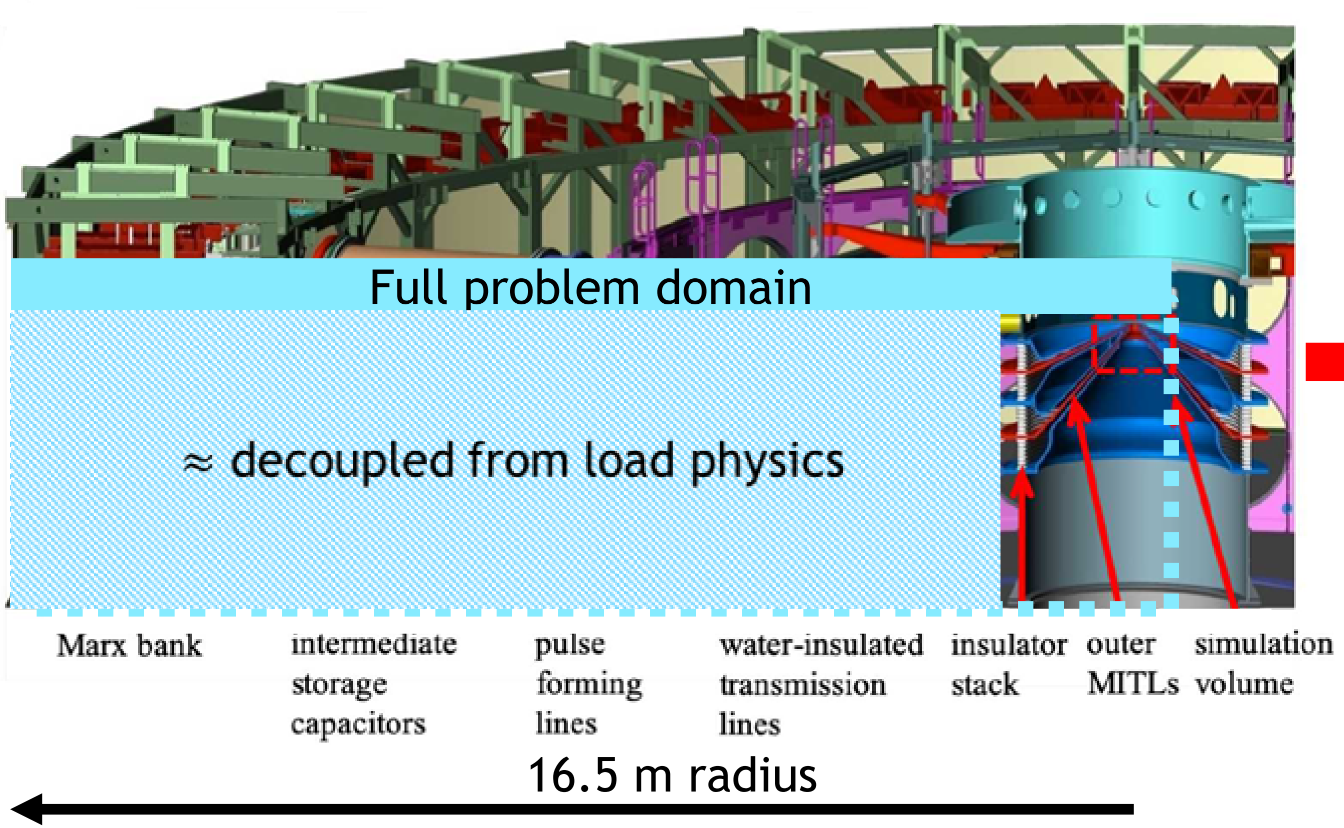
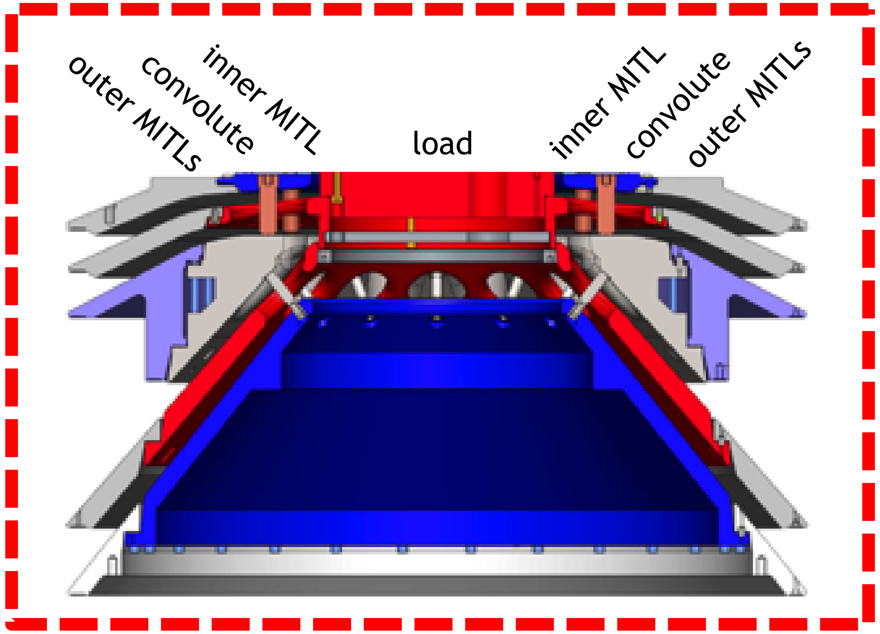
Powerflow 18a model setup





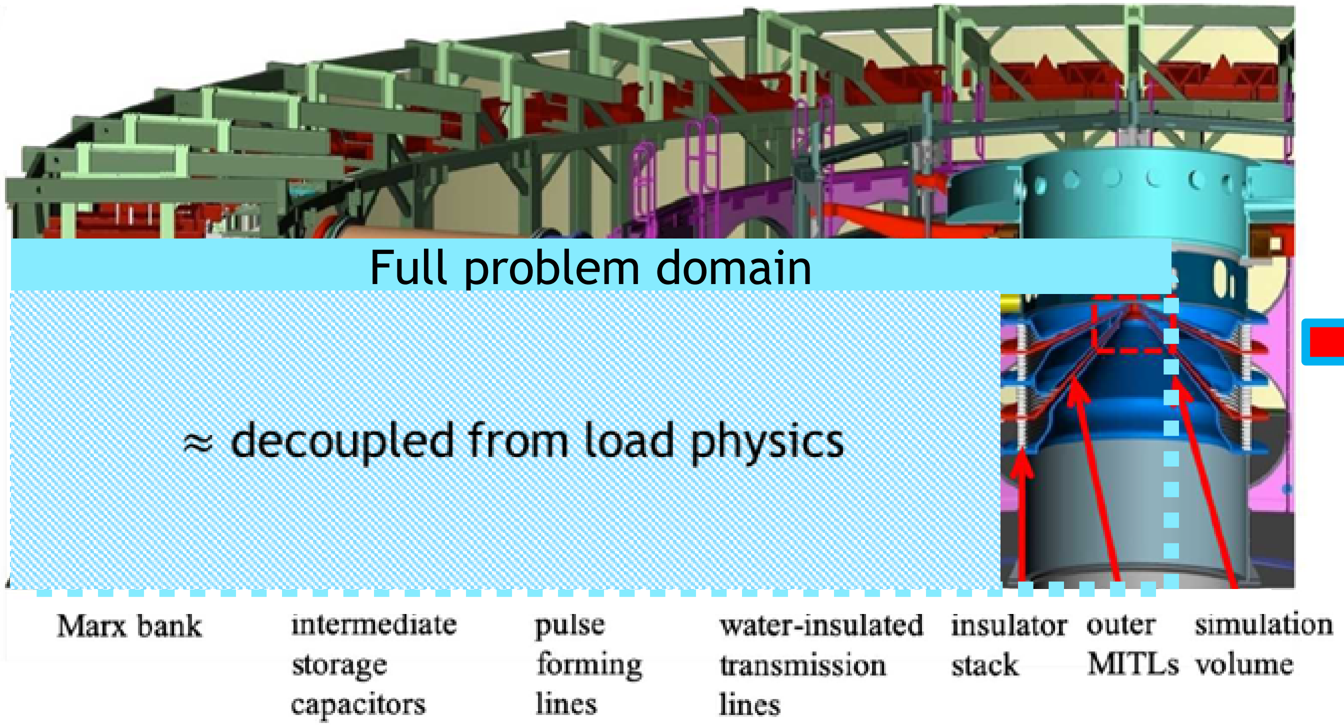
Region where 3D effects dominate

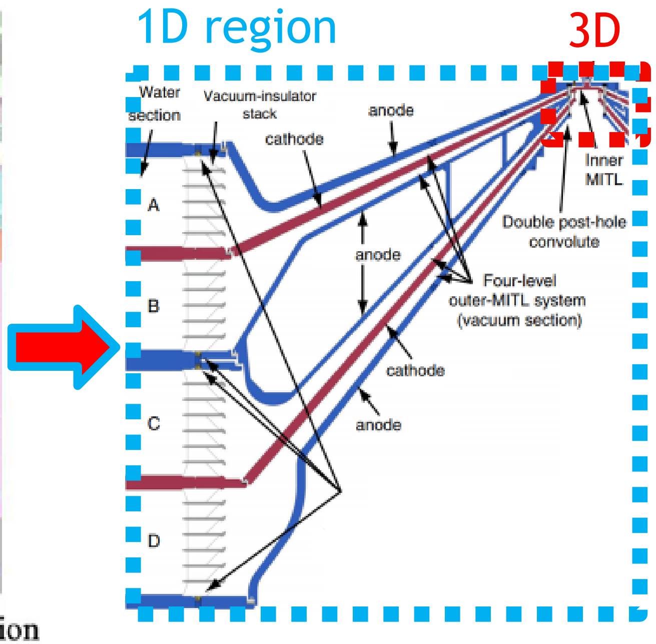
- Marx generators discharge time ≈ 1.5 µs
- EM roundtrip time ≈ 33 m

→ circuit upstream of water convolute decoupled from load physics

Powerflow 18a model setup

Figures: E. Waisman et al., Phys. Rev. ST Accel. Beams, Vol. 17, 120401, (2014)



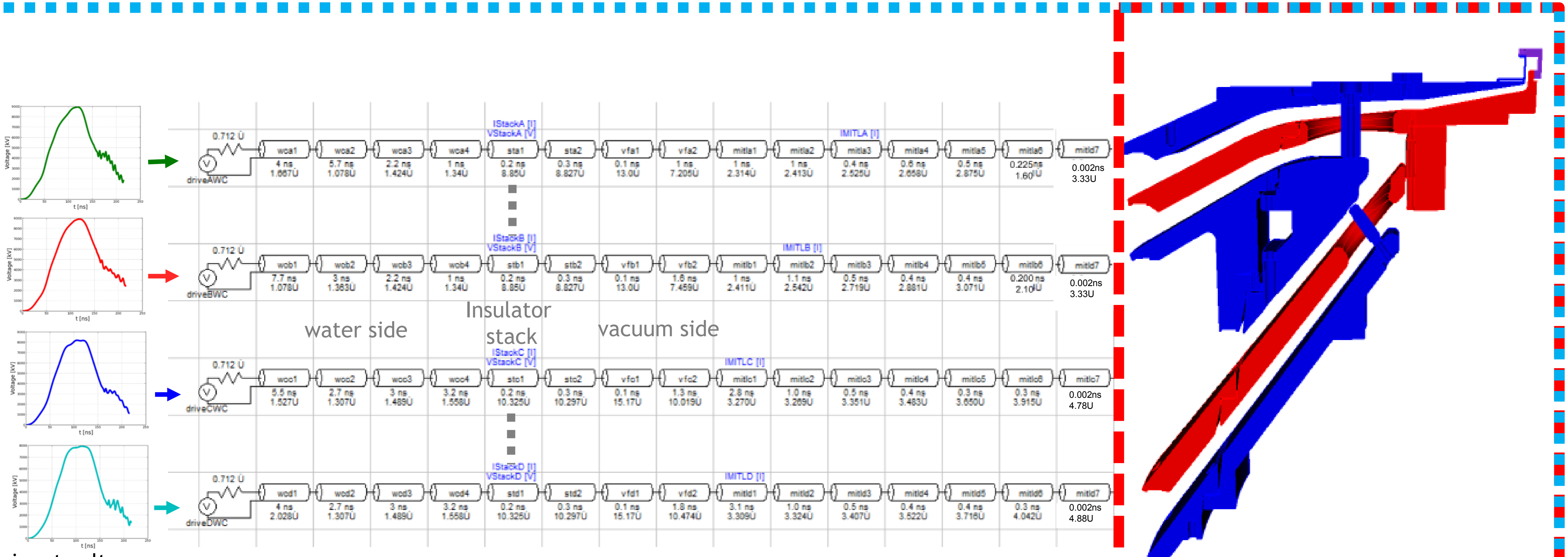


simulation model

Powerflow 18a model setup

1D region

3D

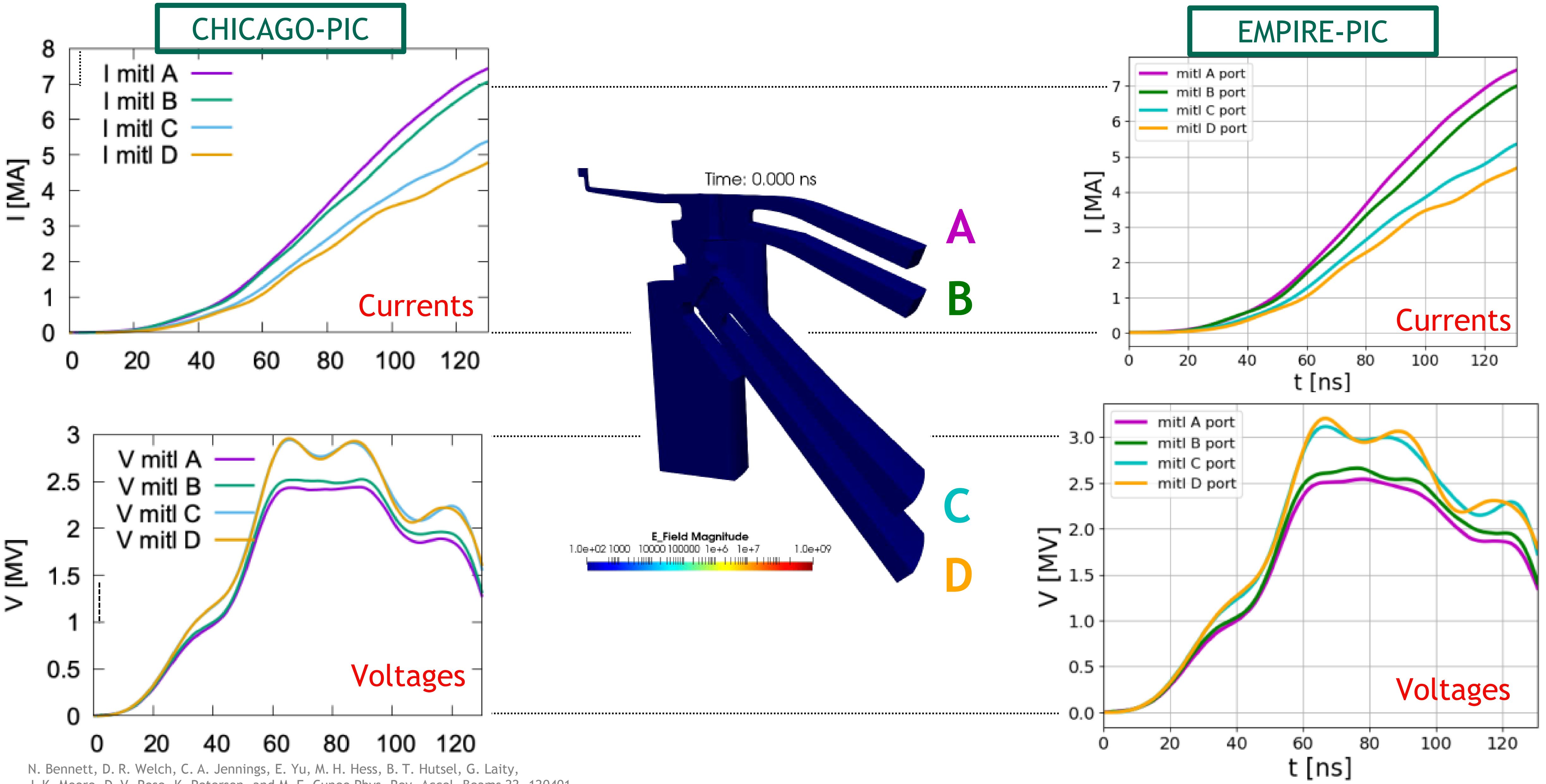


input voltages from full BERTHA Z circuit model

reduced BERTHA circuit (B. Hutsel et al.)

simulation model

Powerflow 18a code-comparison study: cold



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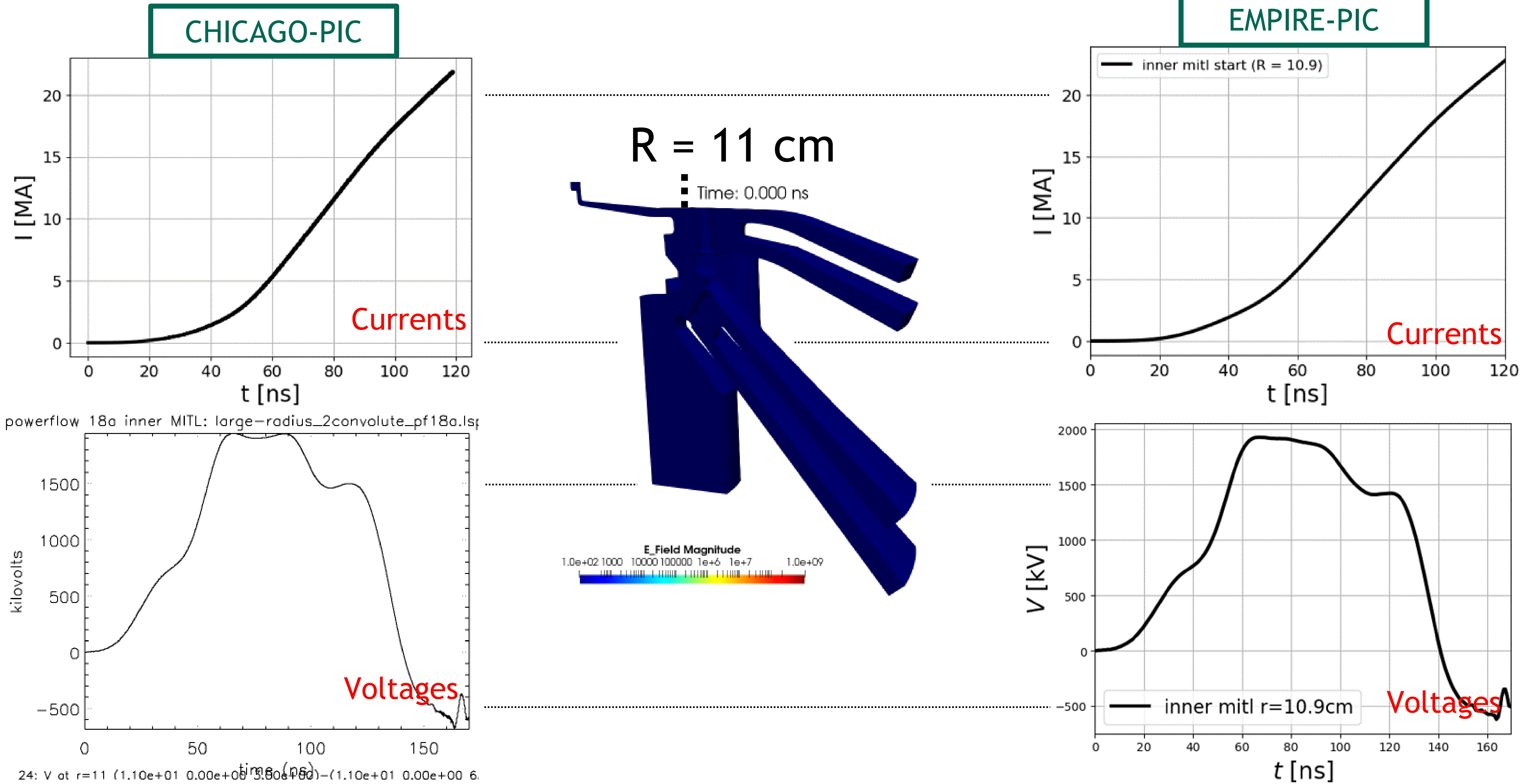
Powerflow 18a code-comparison study: cold



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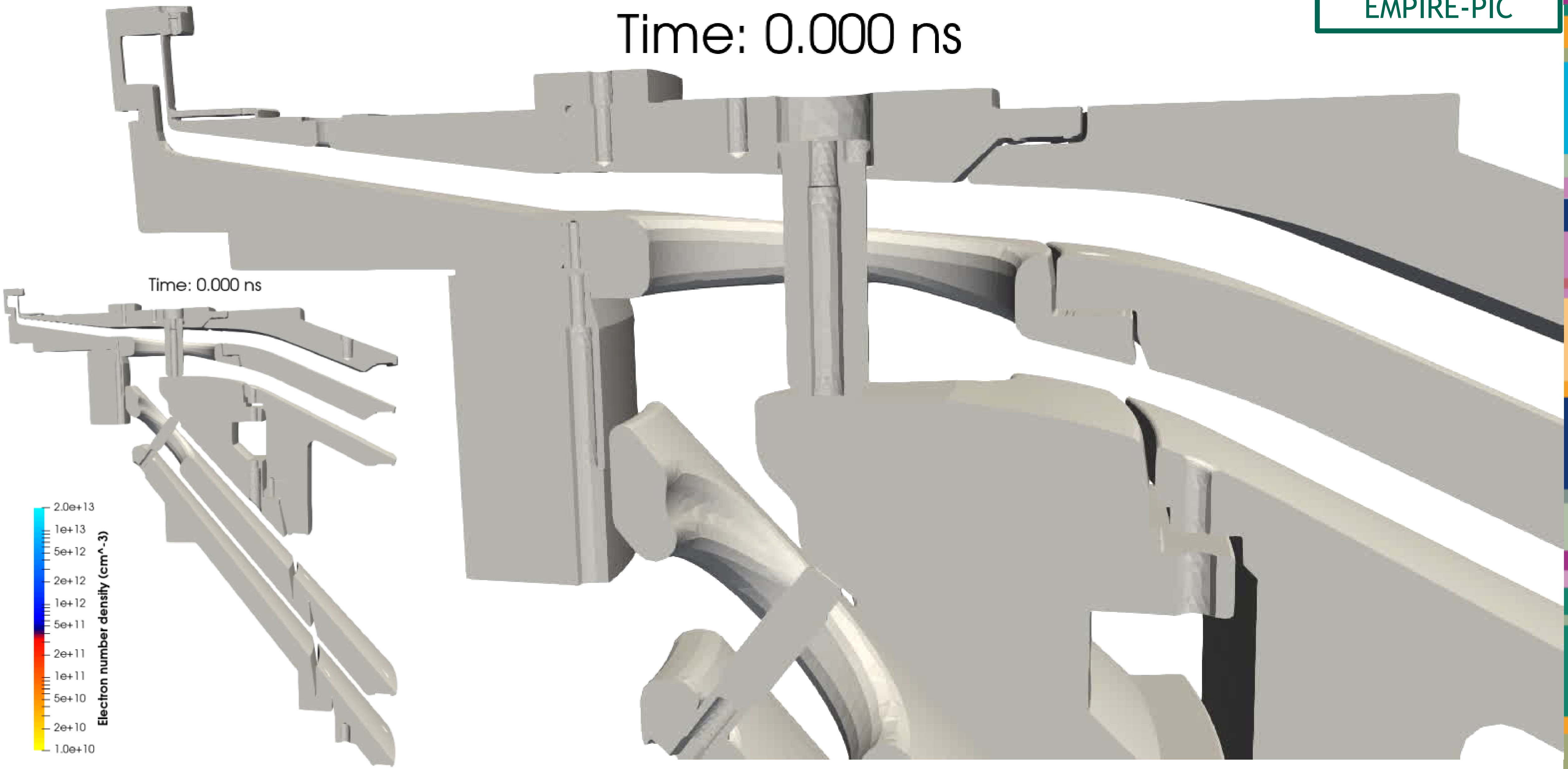
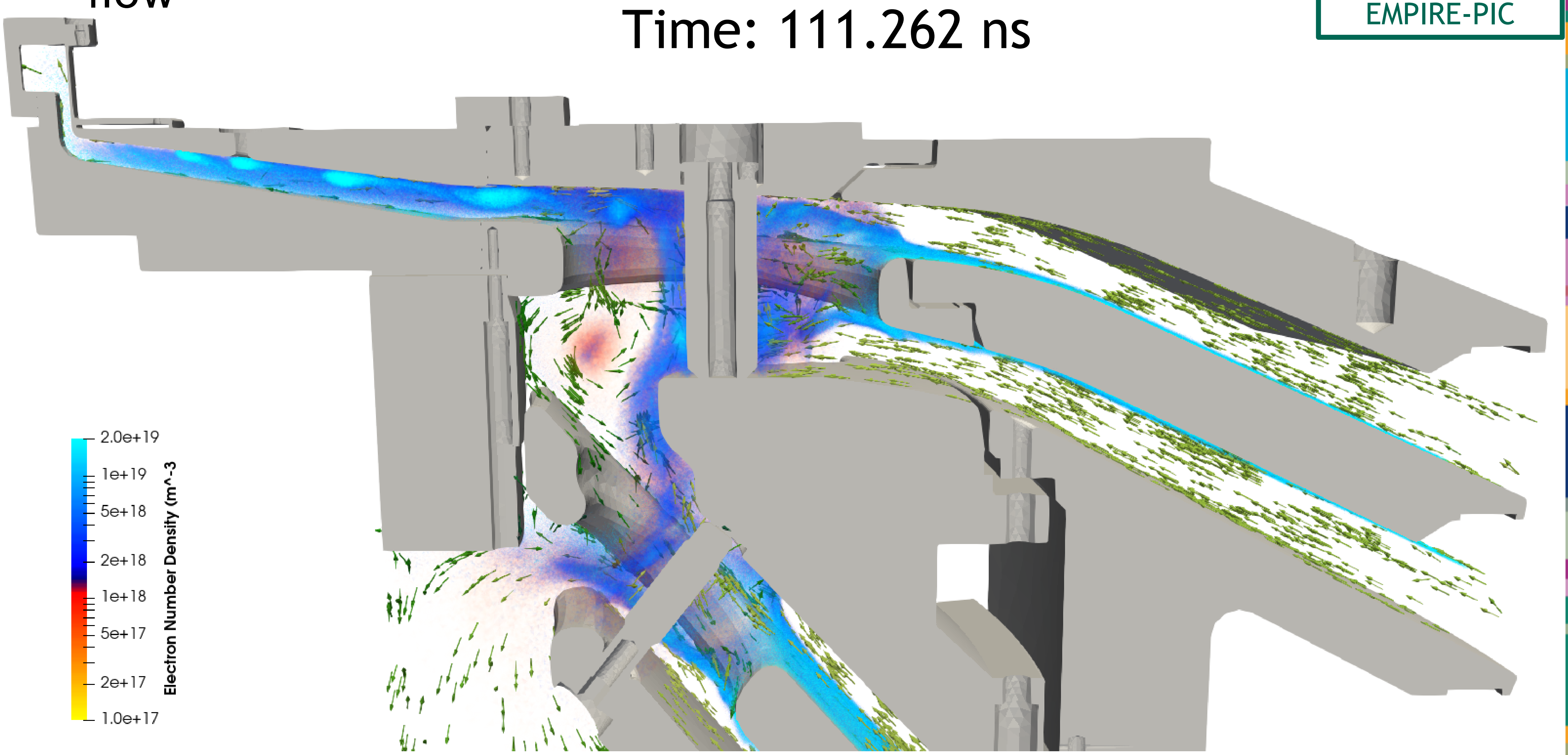
Powerflow 18a EMPIRE simulation: hot

EMPIRE-PIC



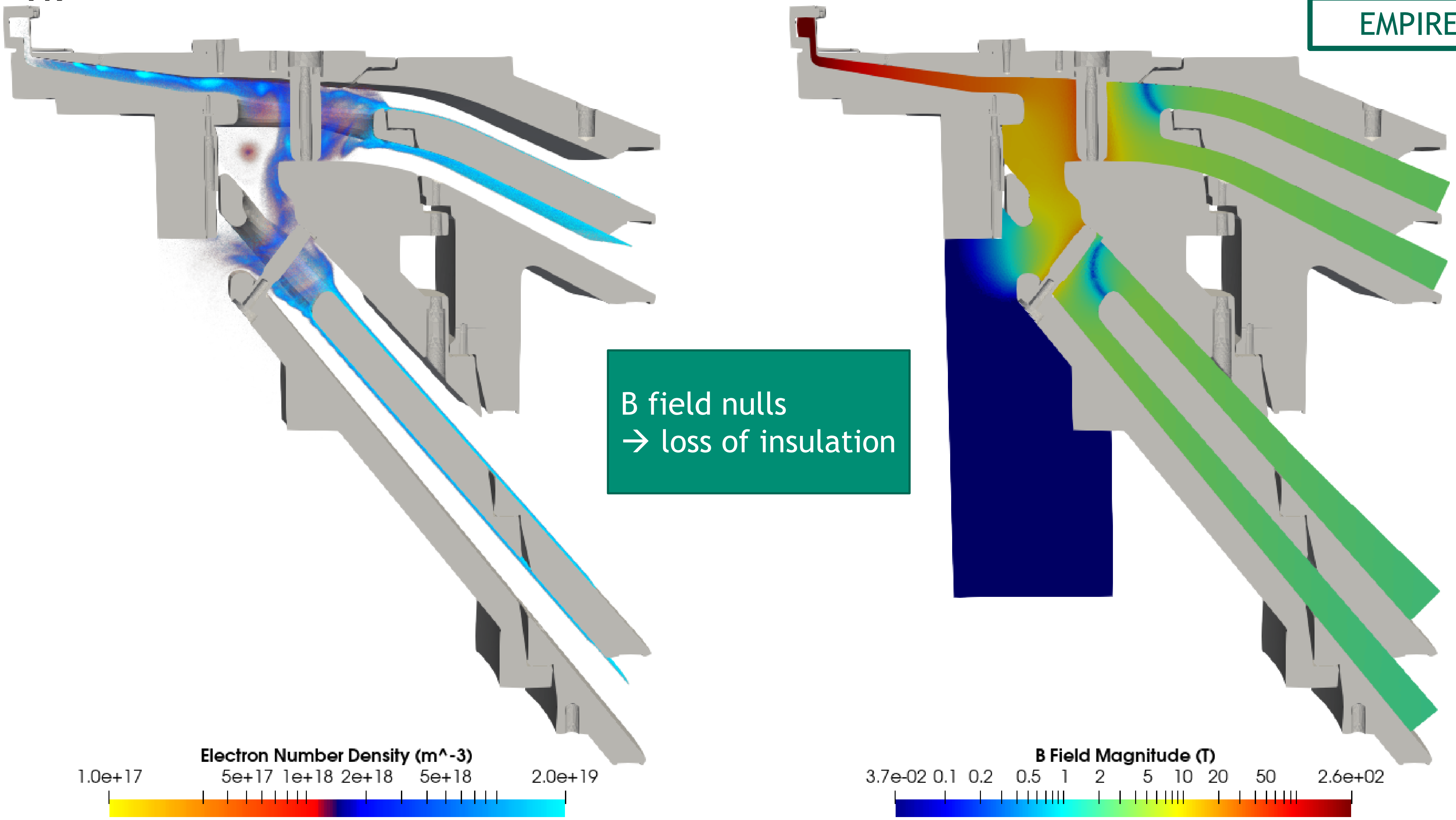
Powerflow 18a EMPIRE hot simulation: ExB vectors trace e⁻ flow

EMPIRE-PIC



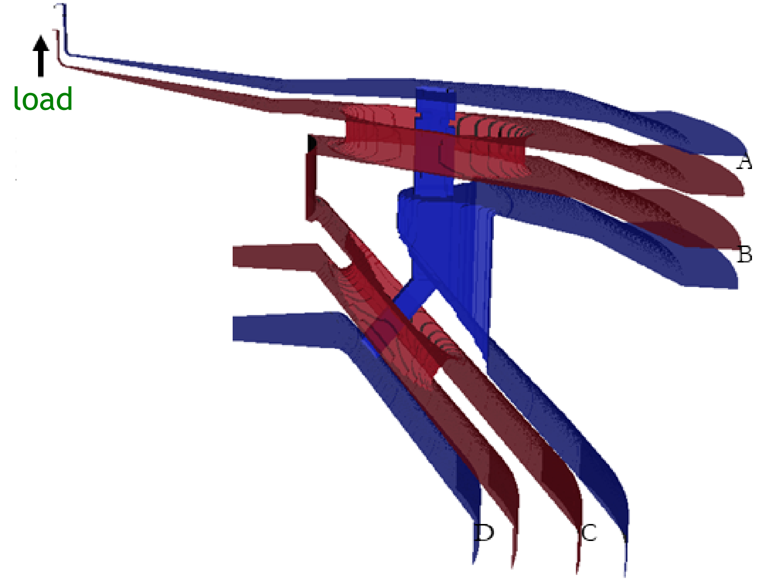
Powerflow 18a EMPIRE hot simulation: Time = 111.262 ns

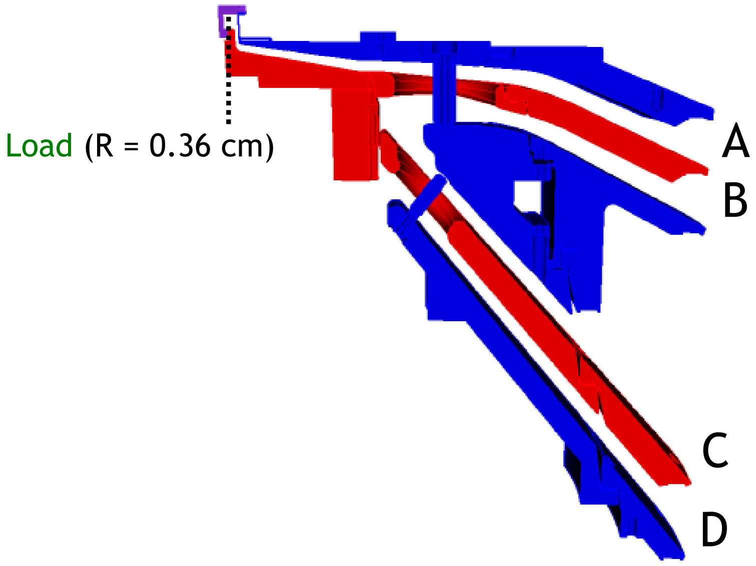
EMPIRE-PIC

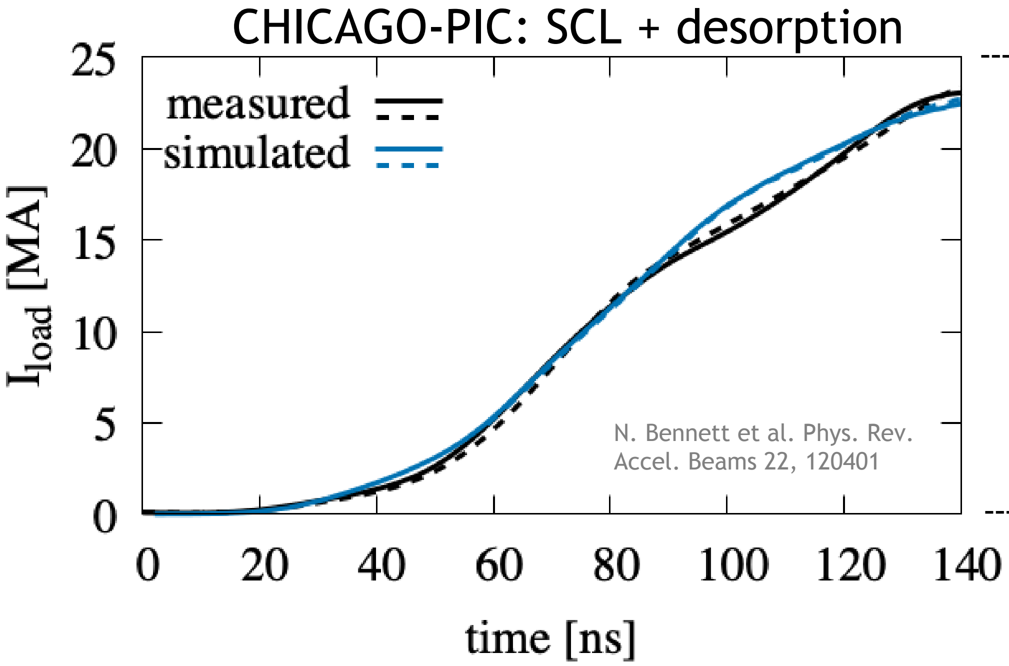


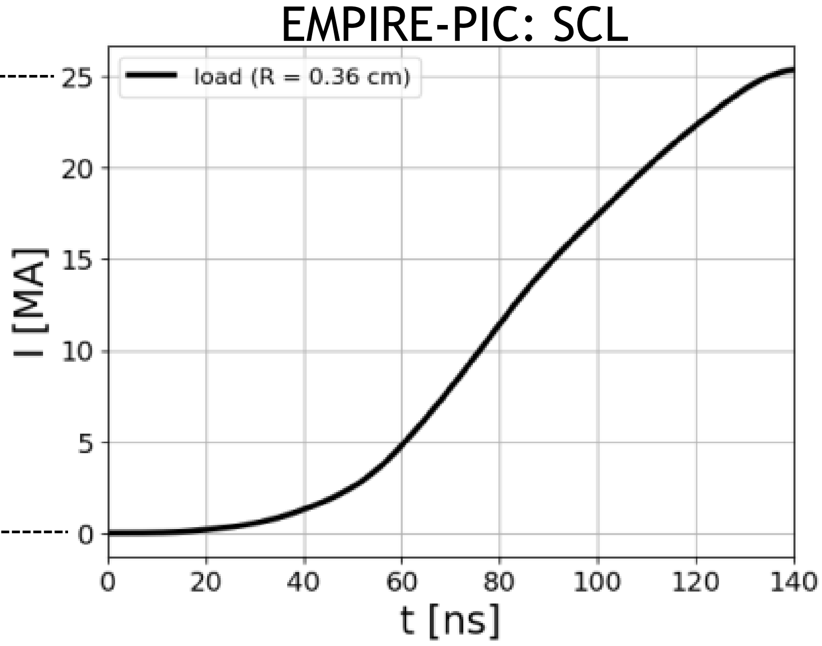
B field nulls
→ loss of insulation

Powerflow 18a (hot): CHICAGO vs. EMPIRE vs. probe measurements









Conclusions

- SNL's next-generation plasma simulation code, EMPIRE, is expanding to meet the challenges of power flow modeling.

- A 1D BERTHA circuit model has been successfully coupled to a 3D electromagnetic domain of the Z-convolute, demonstrating that the full device can be simulated at feasible cost.

- An EMPIRE power flow model incorporating EM wave propagation, space-charge limited emission with relativistic dynamics has:
  - ✓ Been benchmarked successfully against corresponding CHICAGO simulations.
  - ✓ Demonstrated good agreement with current data measured during the actual shots of this campaign.

- To achieve a full physics model, one more step = including thermal desorption → electrode plasma formation which introduces
  - Time step restrictions:
    - From plasma frequency (10^{16} cm^{-3}): $\Delta t < 0.05$ ps
    - From cyclotron frequency (300 T): $\Delta t < 0.01$ ps
  - Mesh resolution restrictions: 100 μm to resolve sheaths at *all* electrode surfaces.
  - Preliminary mesh revisions produce 93.75 μm elements at 2.6B elements, particle inventories approaching billions
    - Need: implicit time stepping, load balance, particle merge, and restart capability which are all emerging capabilities in EMPIRE

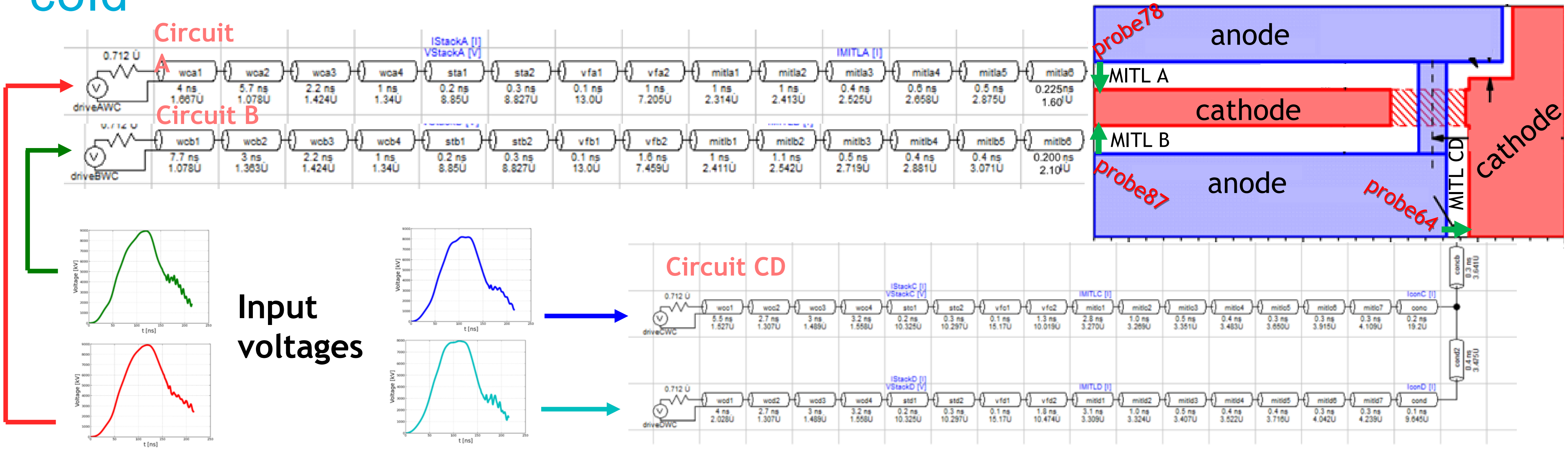
- Scaling studies on next-generation platforms (NGPs) and initial test runs on LLNL's sierra suggest a simulation turnover time of days is reachable for a full physics model

- Impacts:
  - Z power flow is a critical design criteria to understand, we have made significant steps towards demonstrating simulation simulations can be turned around fast enough to affect the design cycle of future Z shots.
  - As more confidence is gained in these models, EMPIRE power flow simulations will provide crucial design information, can, for next

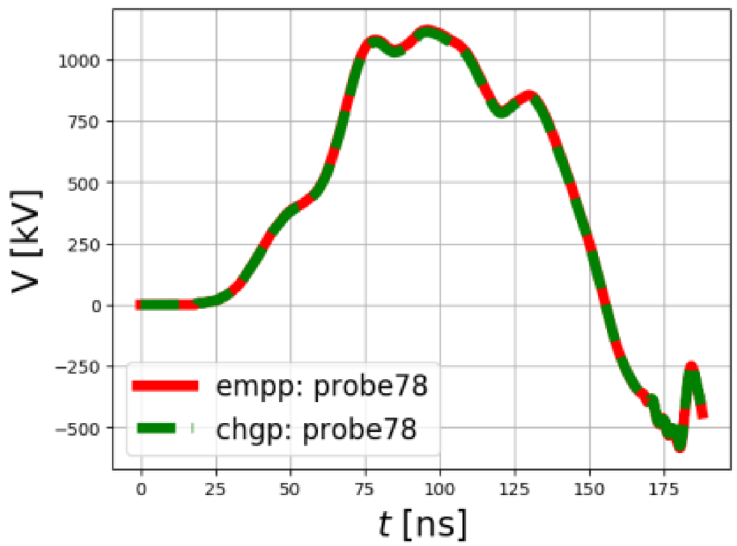
Thank you for your attention!
Questions?

Extras

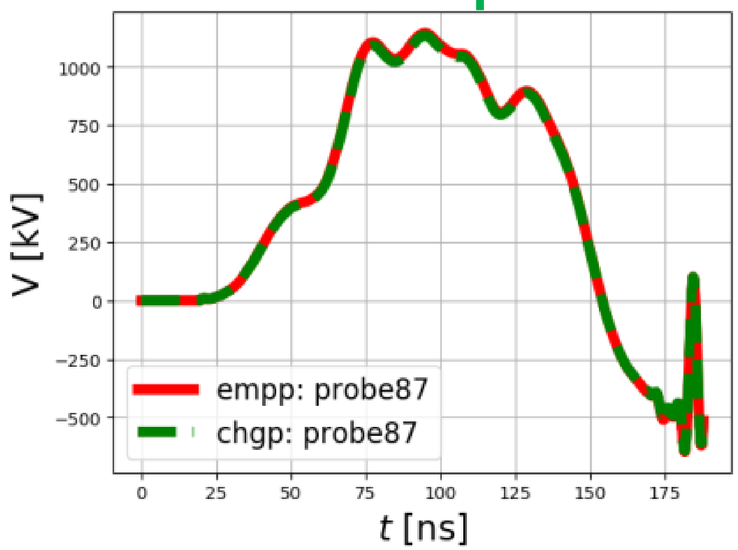
Half-o-lute EMPIRE vs. CHICAGO code-comparison study: cold



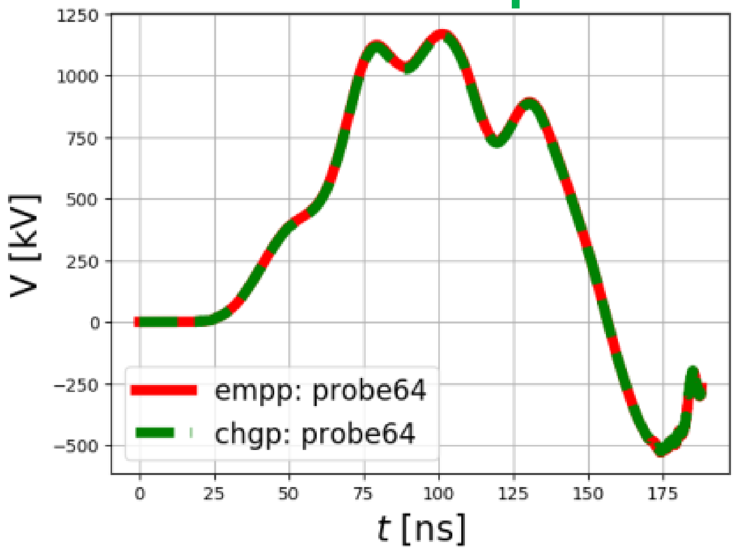
mitl A port



mitl B port



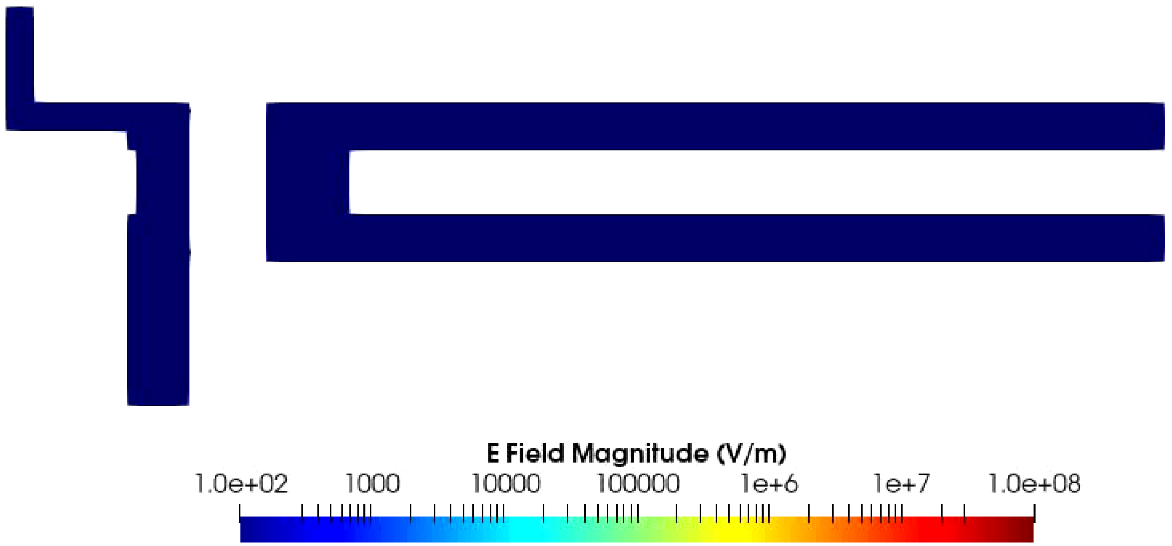
mitl CD port

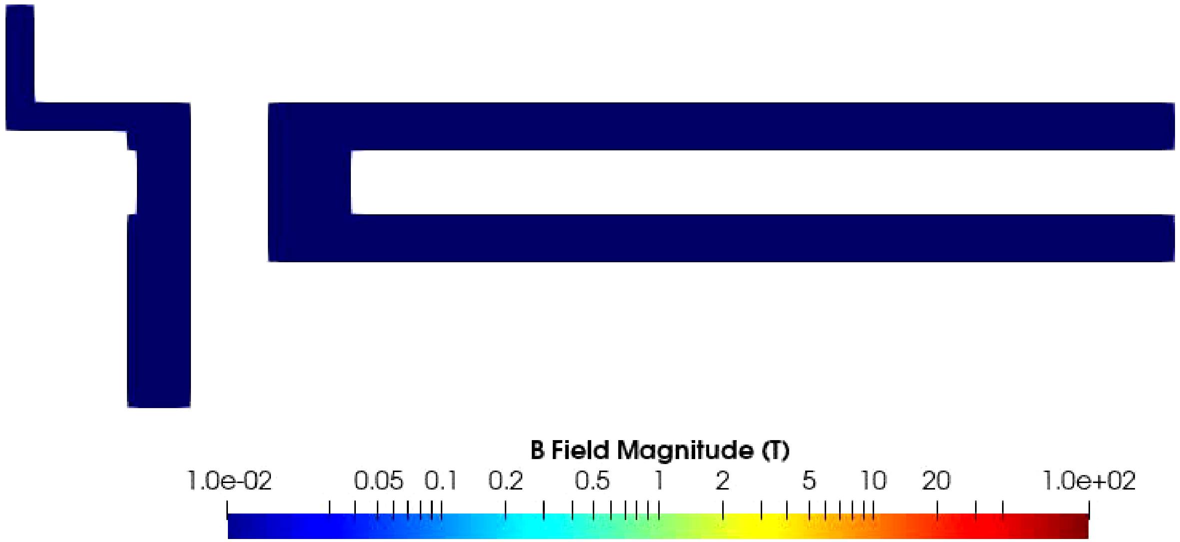


Half-o-lute cold EMPIRE simulation: EM fields

EMPIRE-PIC

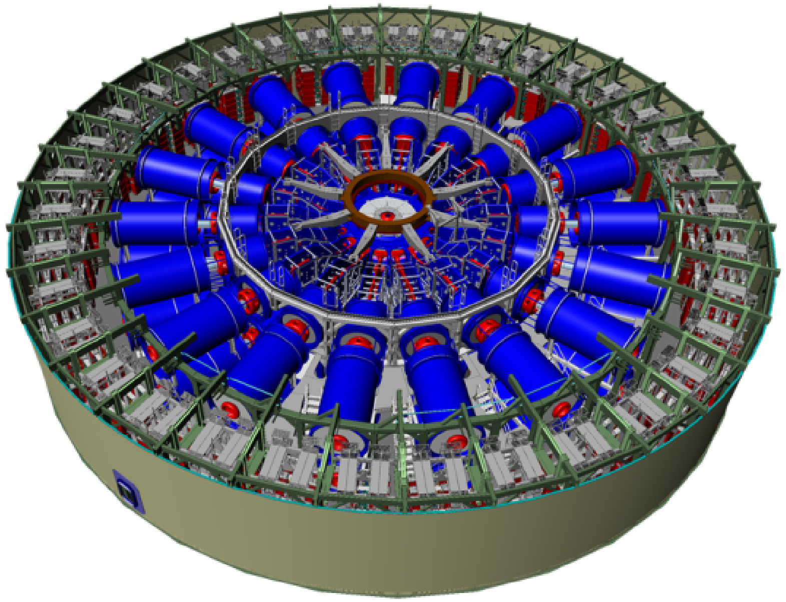
Time: 0.000 ns





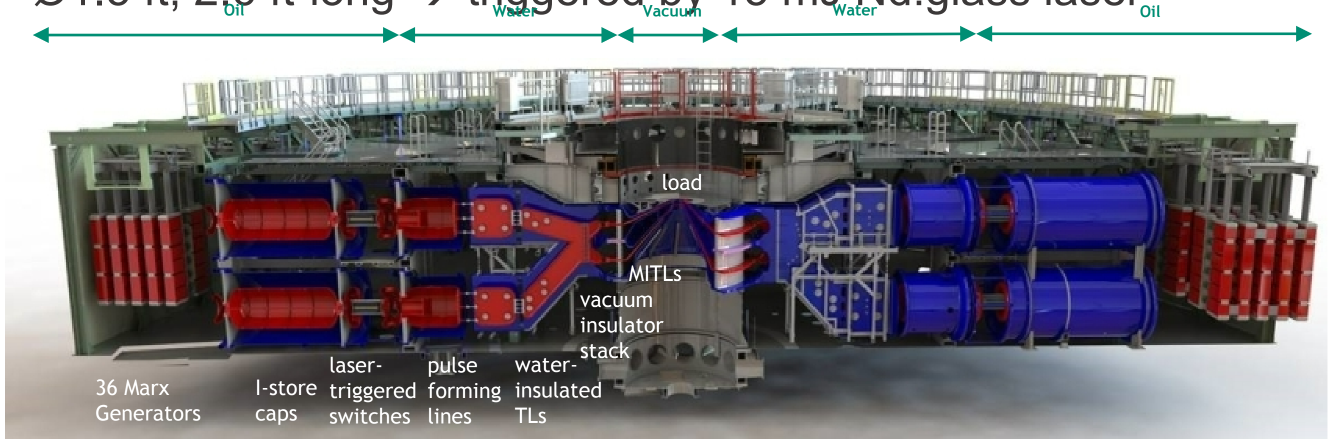
cross-sectional views at $\phi = 0$ degrees

System overview: Z accelerator at Sandia



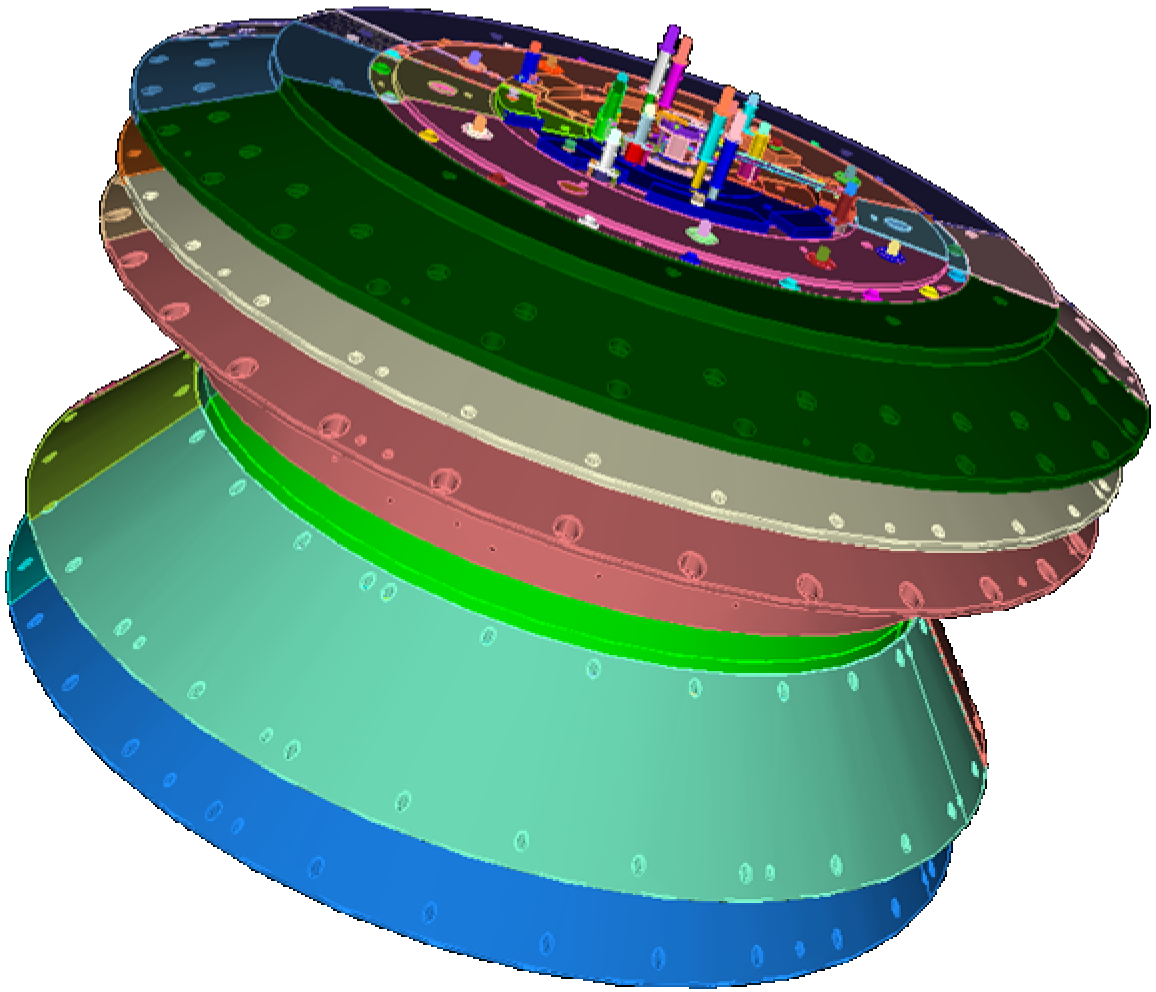
- <u>PFLs</u>:
  Ø5.5 ft, 4.5-ft long coaxial water cylinder → 700 kA at 200 ns rise
- <u>Outer MITLs</u>:
  - five nested 10-ton stainless steel cones
- Vacuum convolute → inner MITL → Load

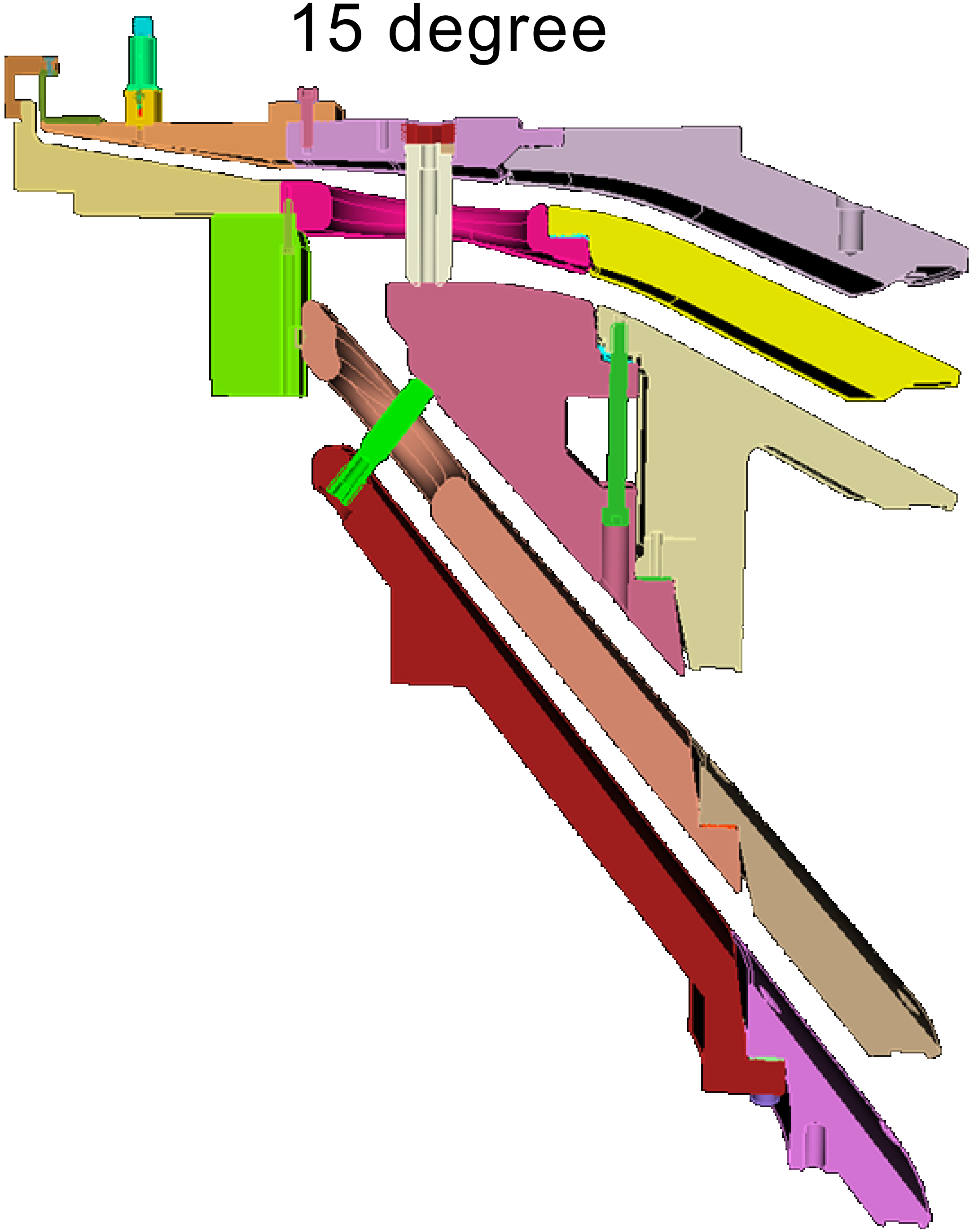
- <u>Marx generators:</u>
  - 36 Marxes housing sixty 2.6 uF capacitors each = 2,160 caps total
  - 20 MJ stored energy total
  - Charged to ~ 85 kV → 5.1 MV output voltage
  - Discharge time: 1.5 rise time to peak of 150 kA
- <u>I-store caps</u>
  Ø6.5 ft, 10-ft long water-filled cylinders charged to 5.1 MV → laser-triggered → peak current 600 kA in 500 ns rise
- <u>Laser-triggered gas switches</u>:
  Ø1.5 ft, 2.6 ft-long → triggered by 15 mJ Nd:glass laser



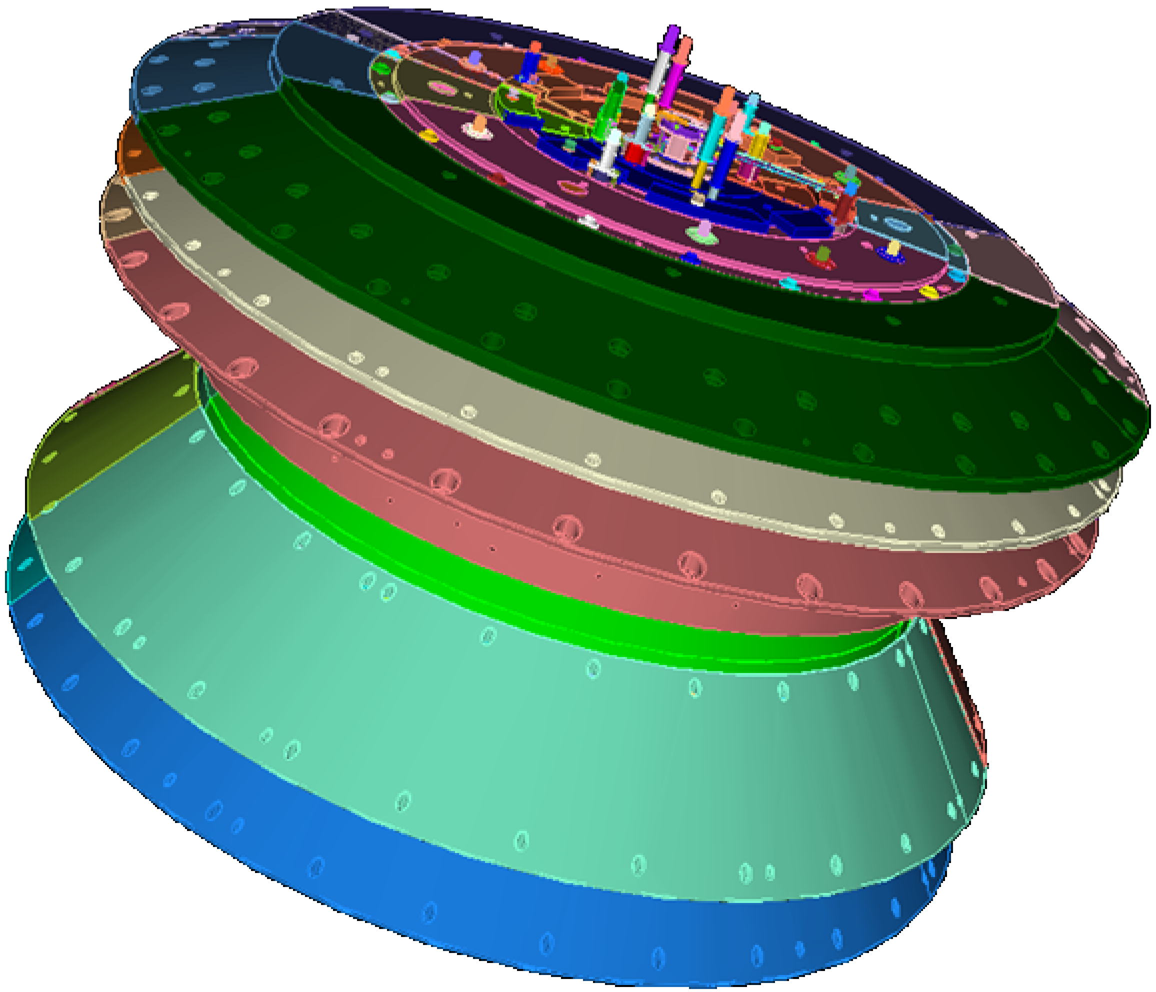
Component information: “How does the Z Machine Work? Sandia National Laboratories: Z Pulsed Power Facility: How Does the Z Machine Work?”. http://www.sandia.gov/z-machine/about_z/how-z-works.html. Accessed: 11/23/2020

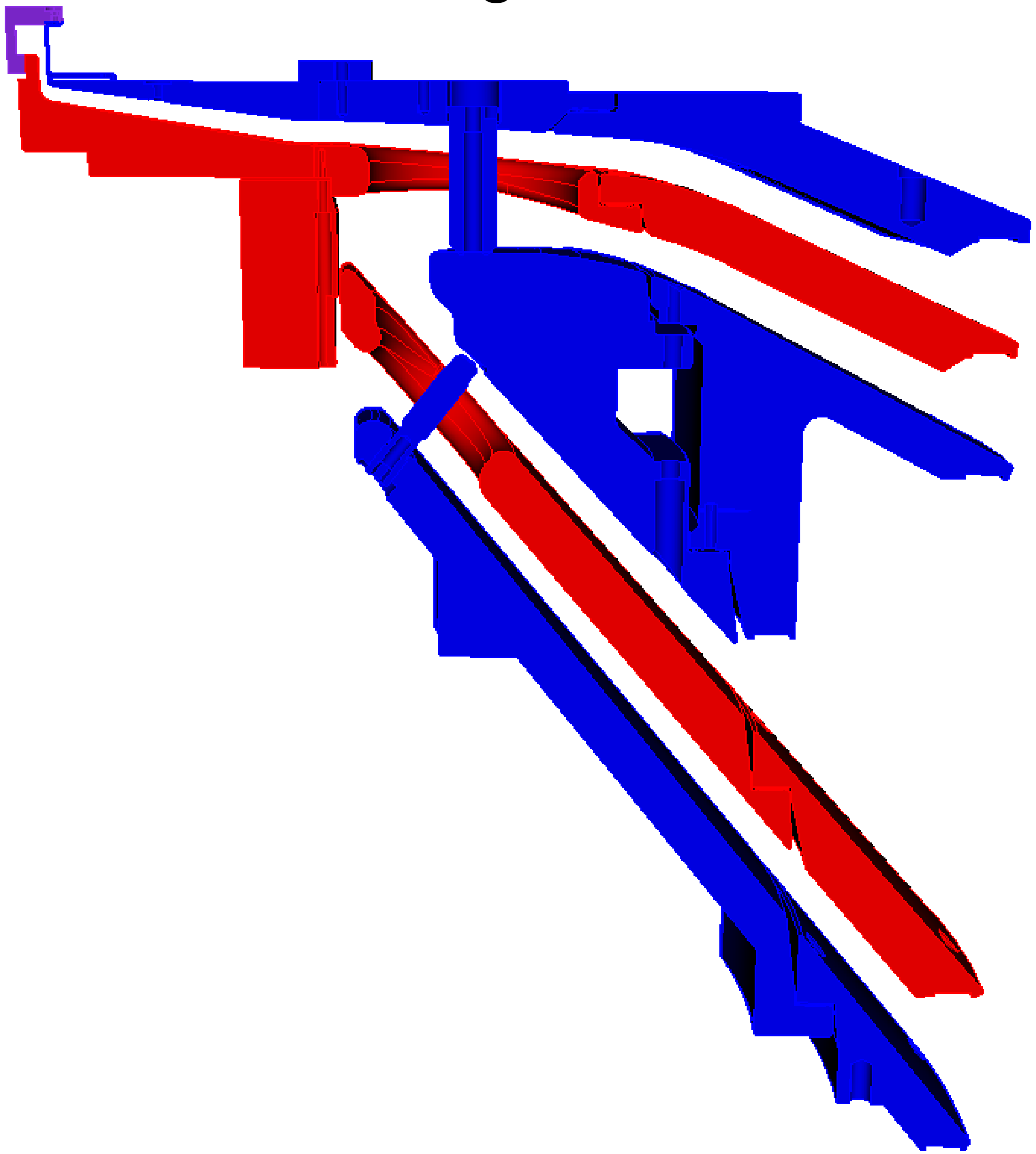
Powerflow18a hardware → 15 degree wedge



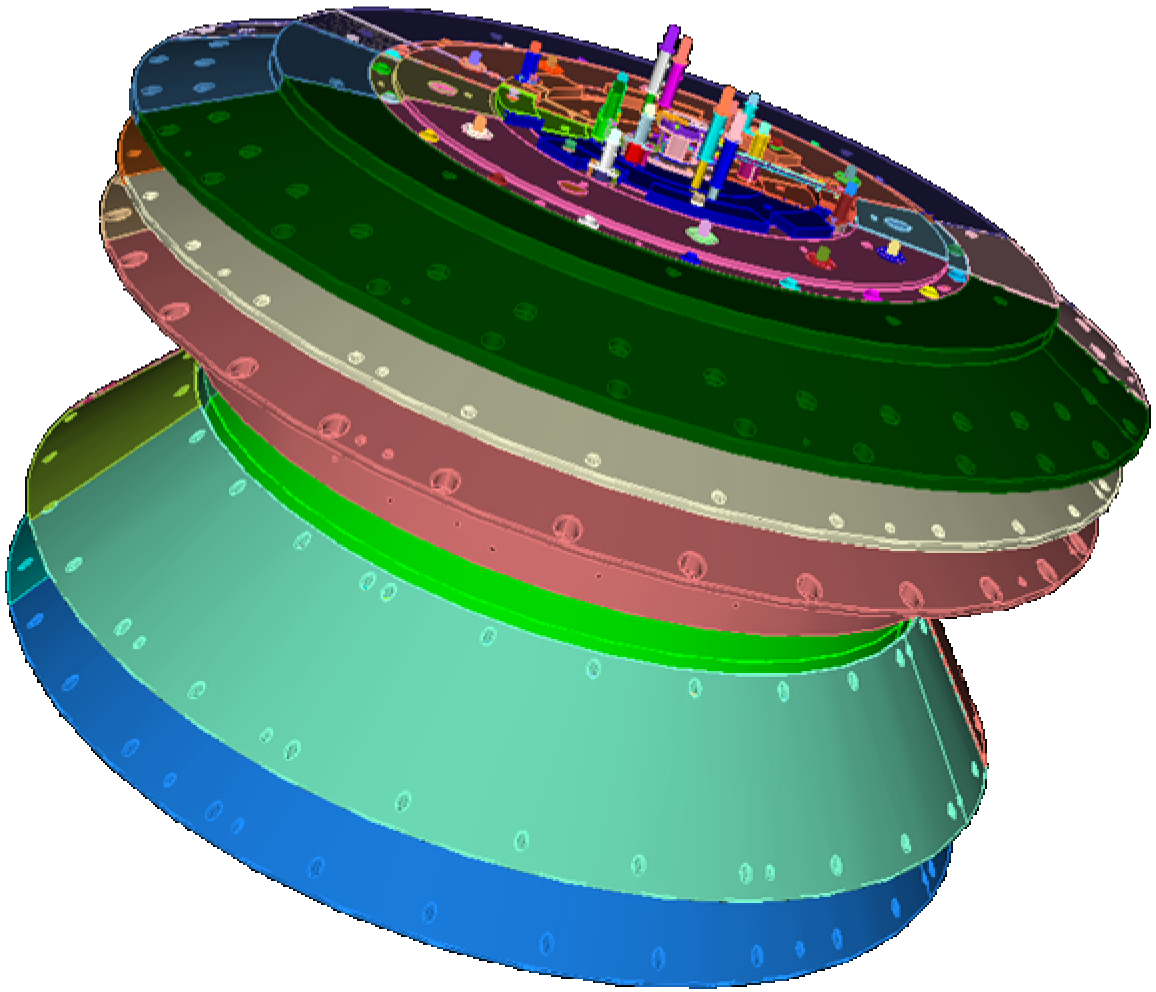


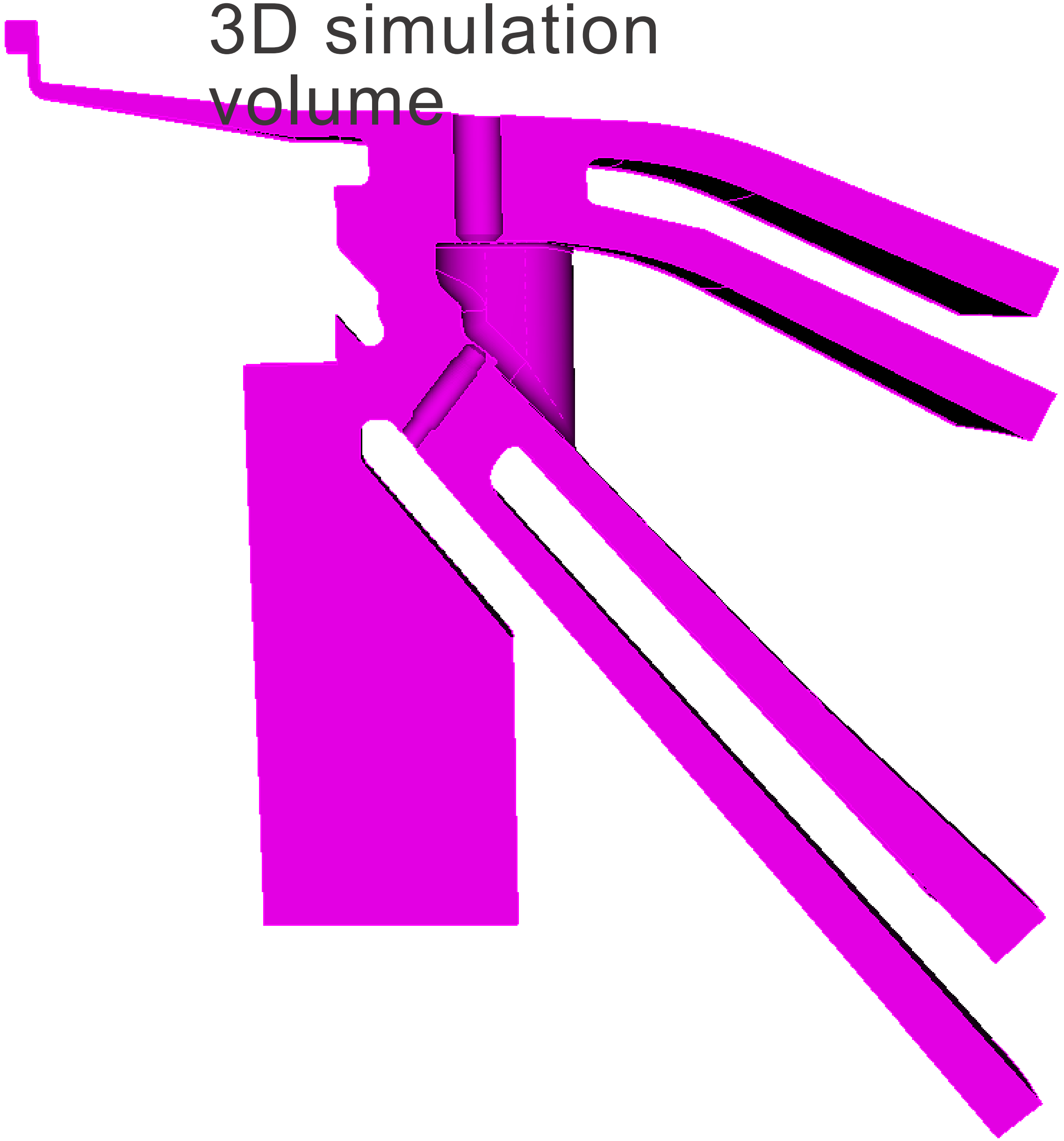
Powerflow18a hardware wedge → 15 degree



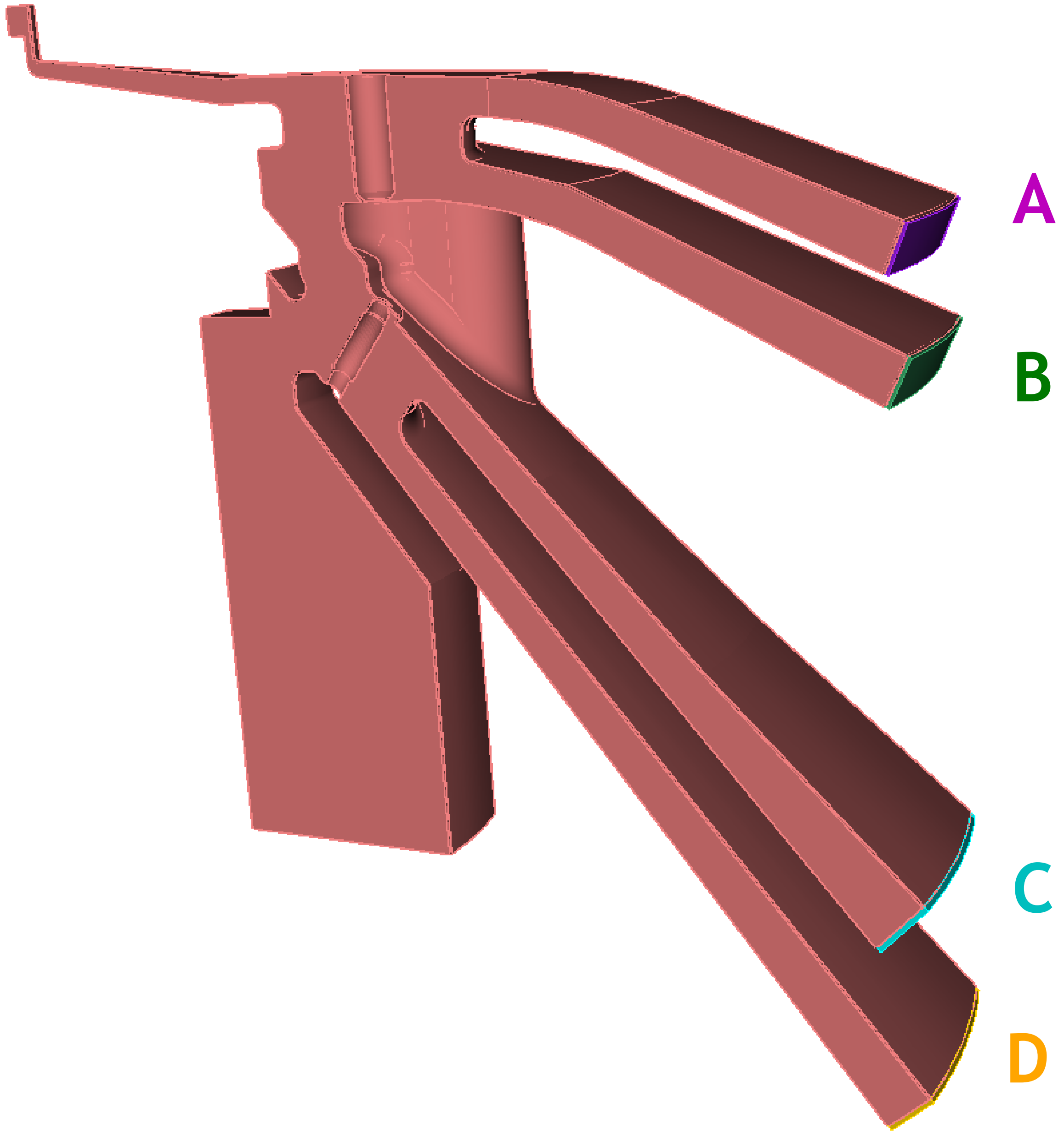


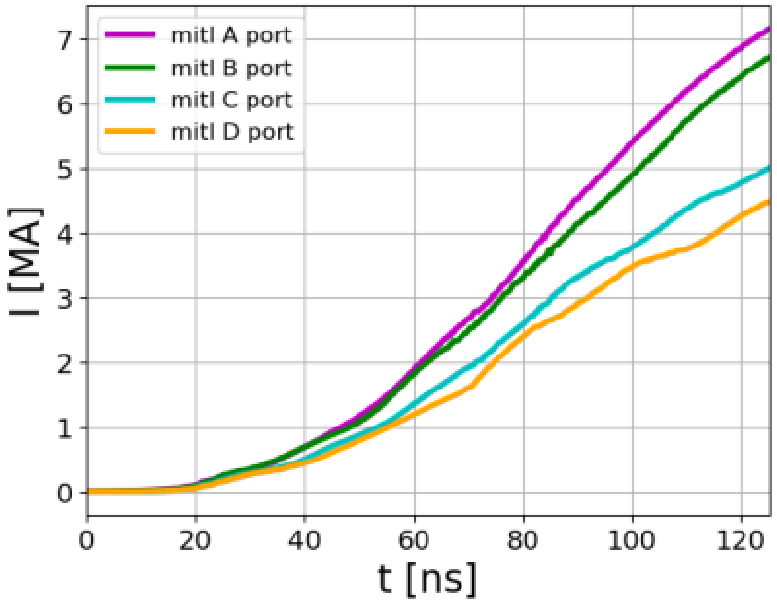
Powerflow18a hardware wedge → 15 degree 3D simulation volume

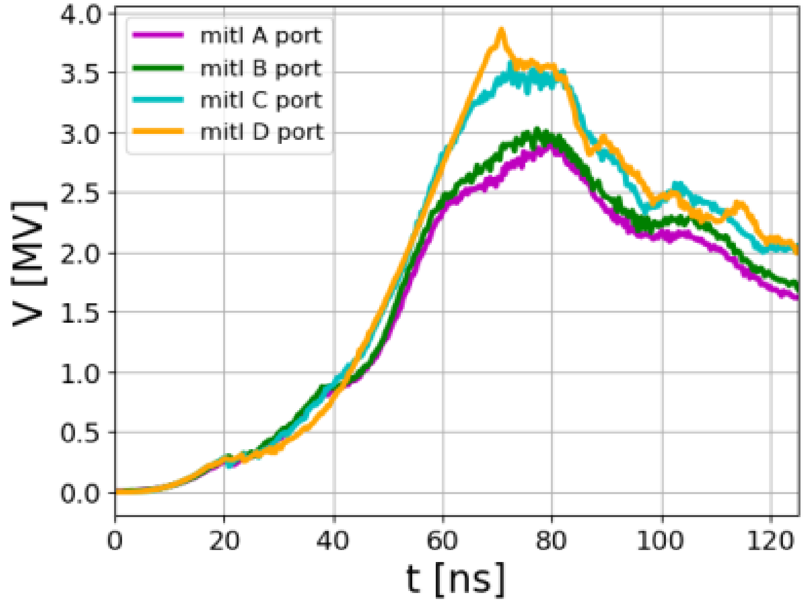




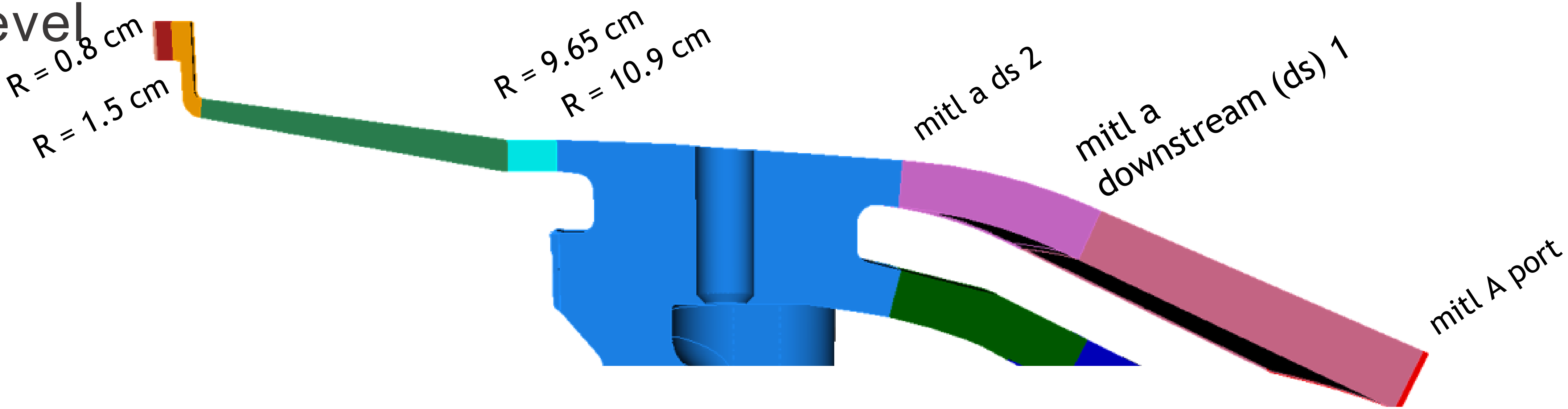
Powerflow 18a hot EMPIRE simulation: V and I at MITL

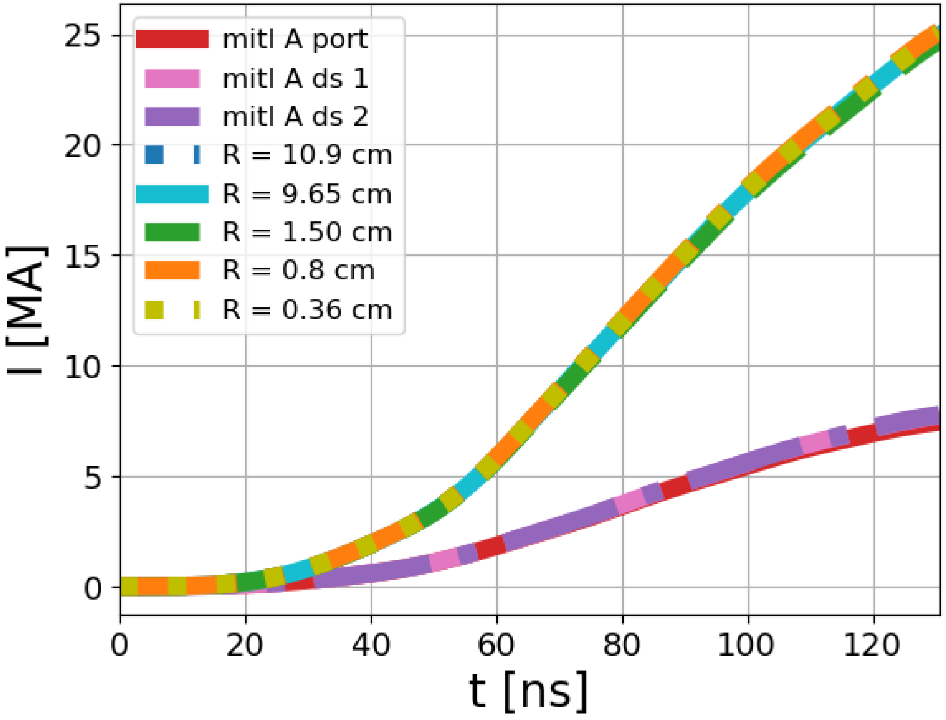


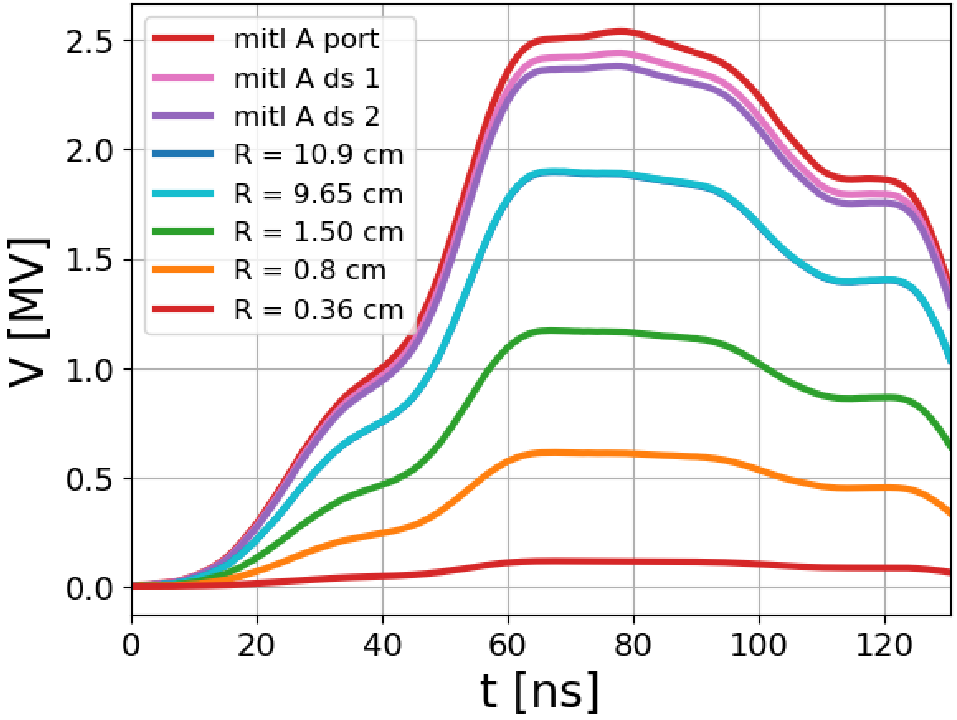




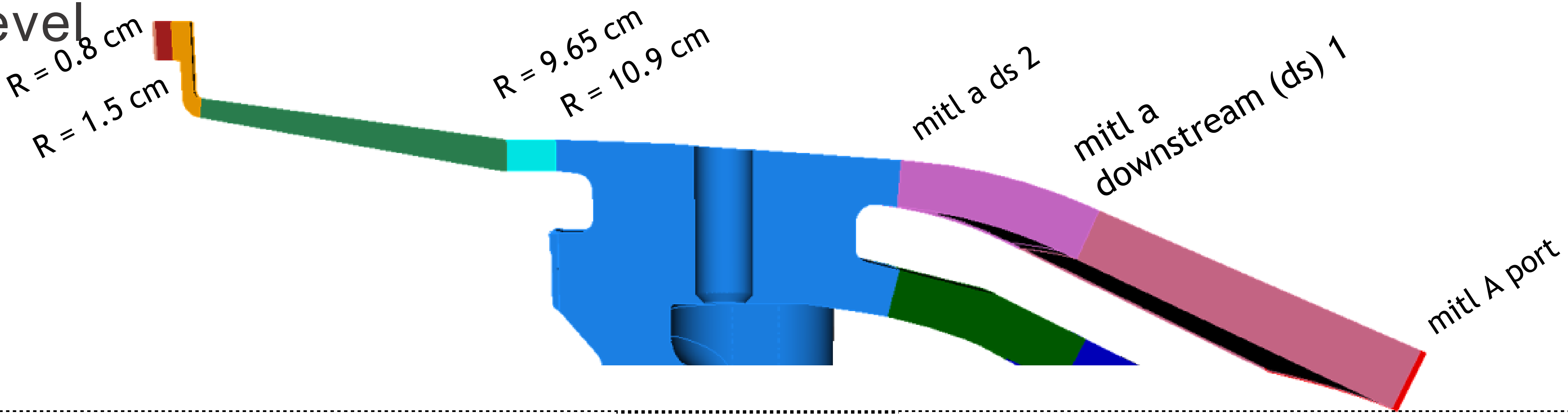
Powerflow 18a cold EMPIRE simulation: V and I along top level

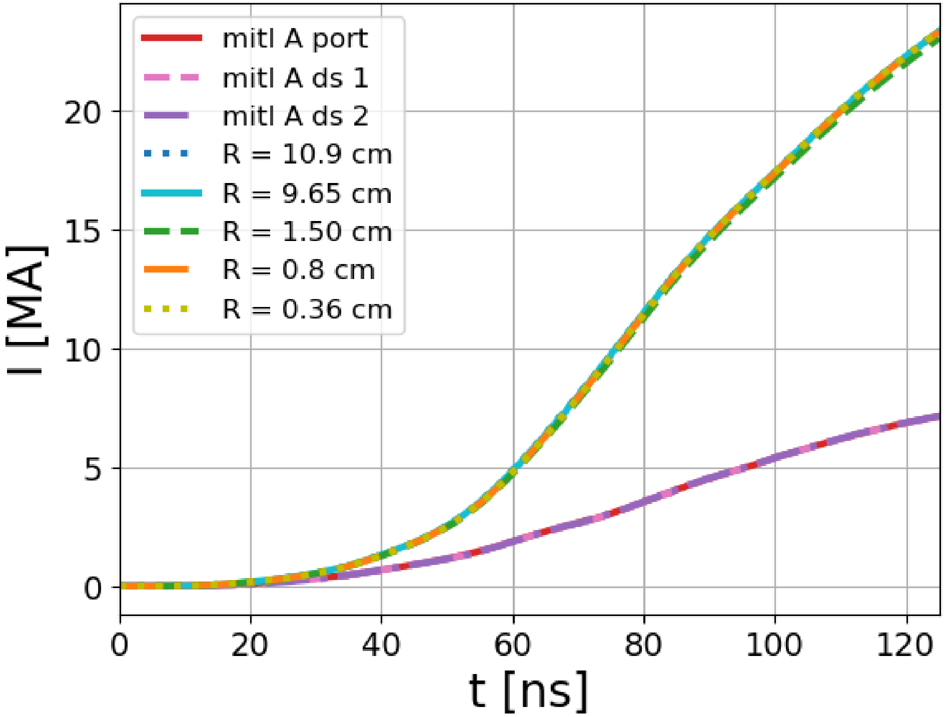


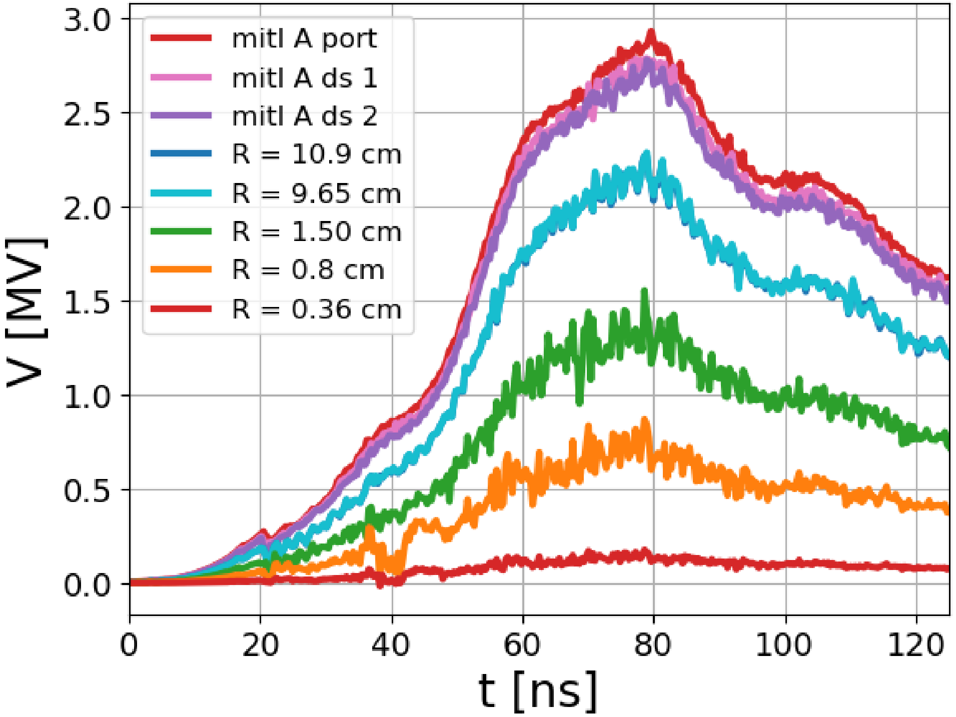




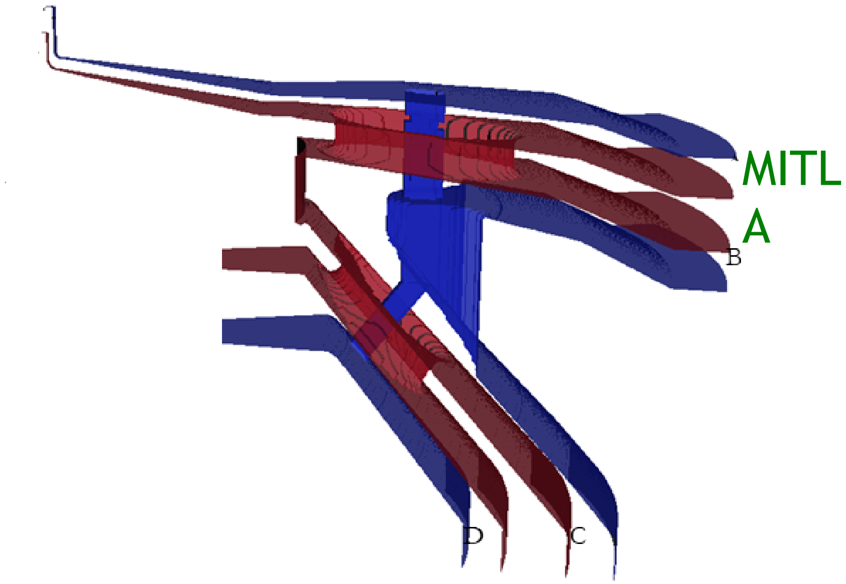
Powerflow 18a hot EMPIRE simulation: V and I along top level



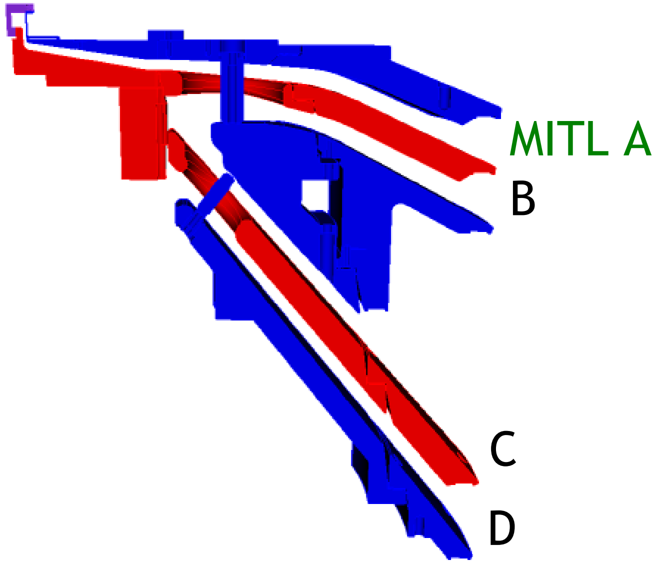




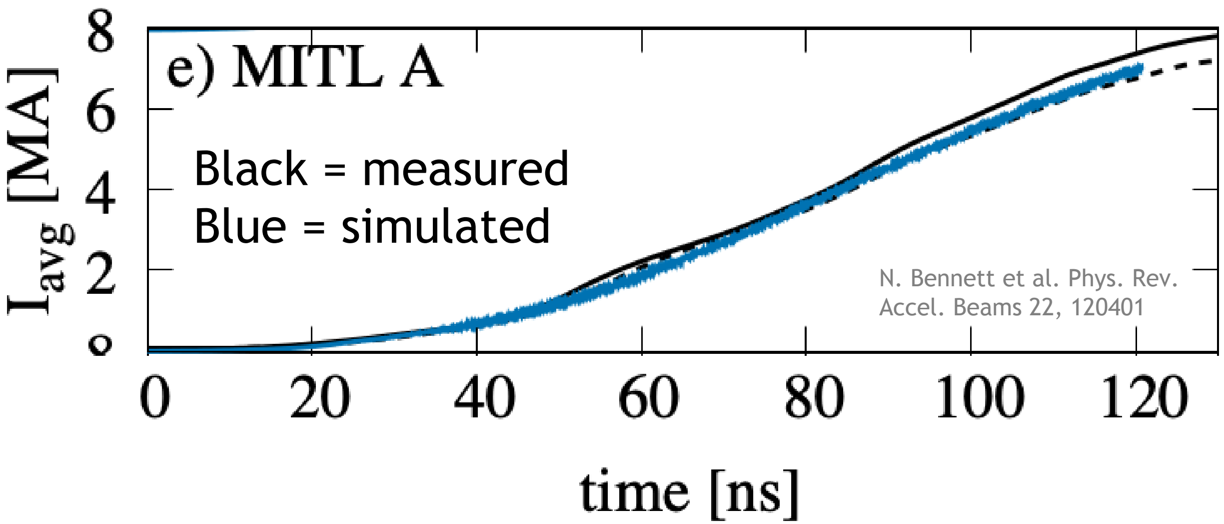
Powerflow 18a (hot): CHICAGO vs. EMPIRE MITL A current

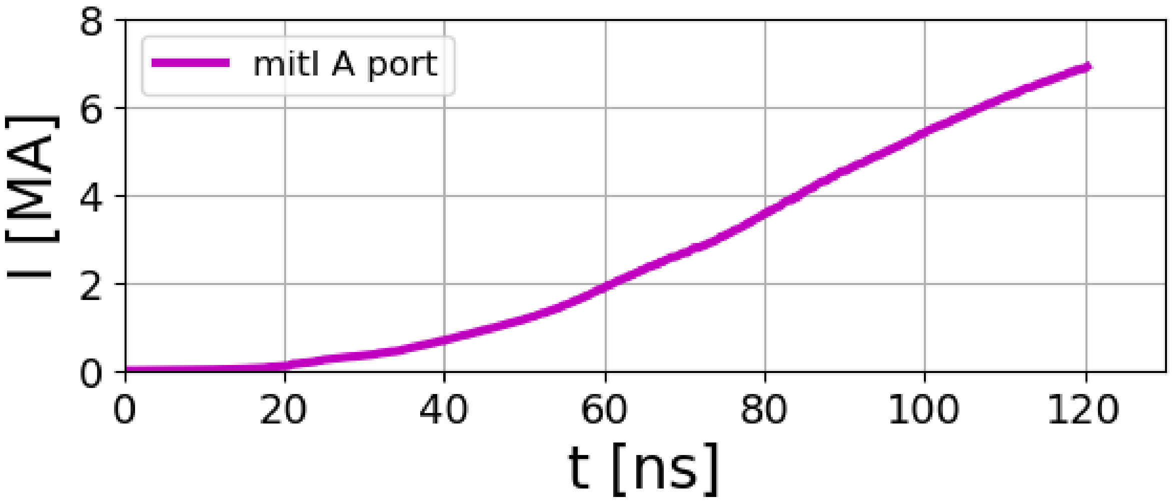


CHICAGO-PIC: SCL + desorption

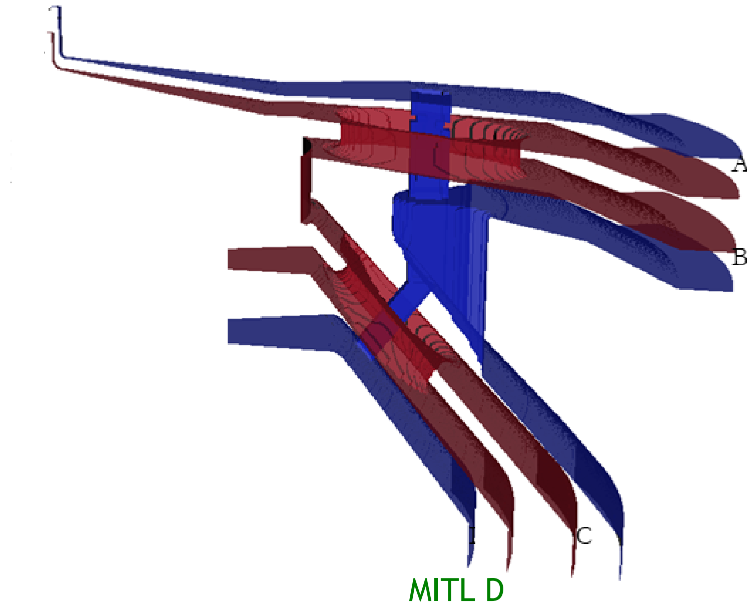


EMPIRE-PIC: SCL

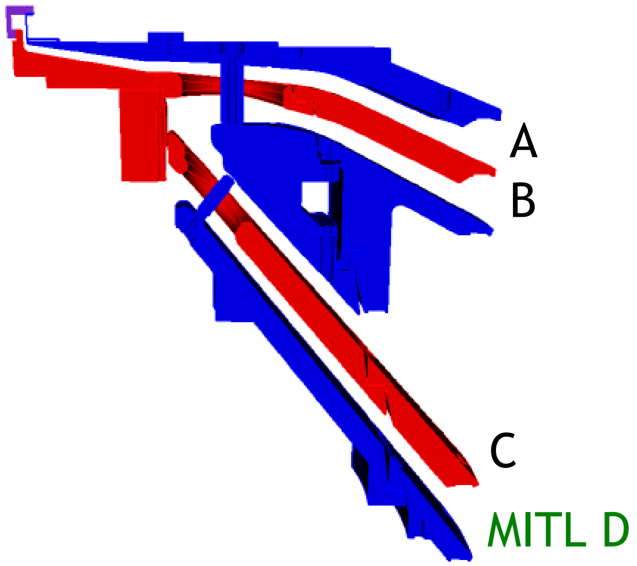




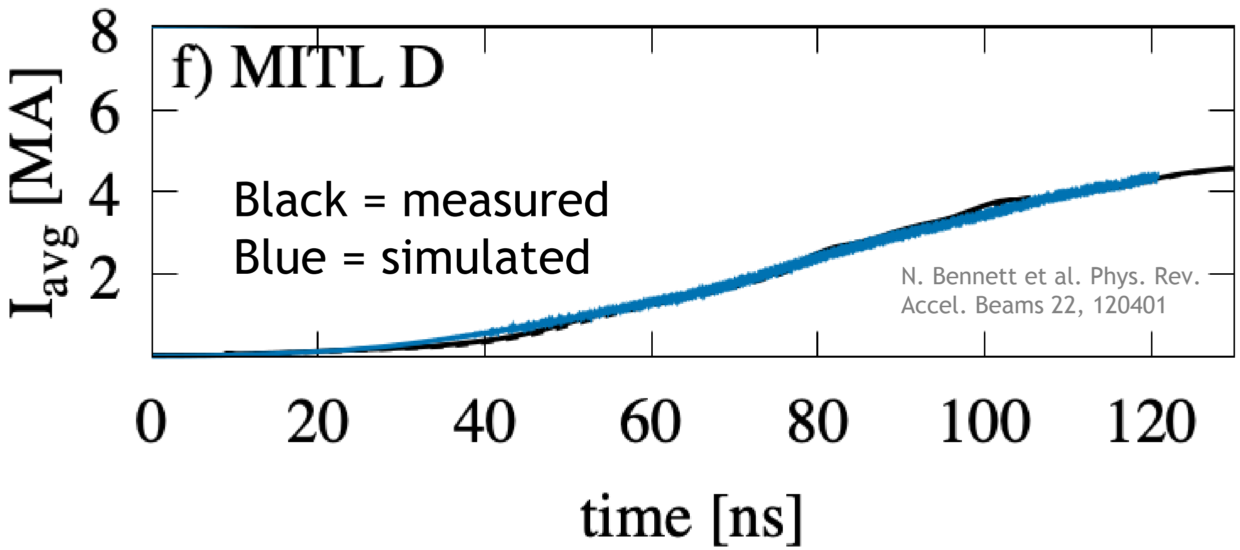
Powerflow 18a (hot): CHICAGO vs. EMPIRE MITL D current

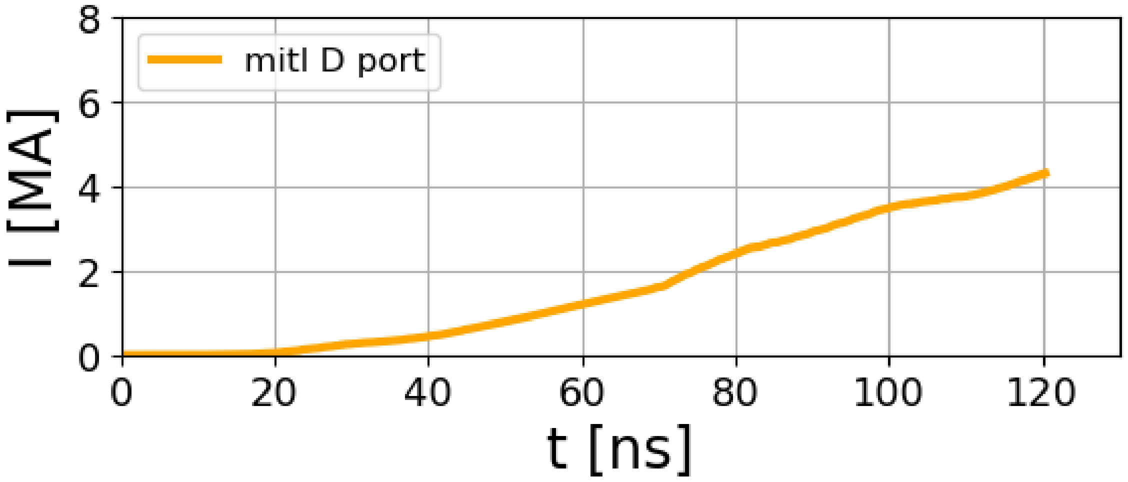


CHICAGO-PIC: SCL + desorption

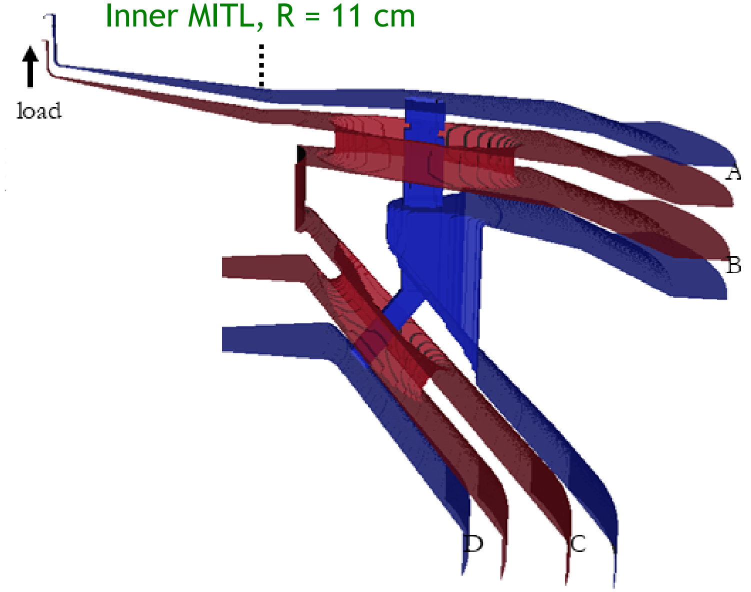


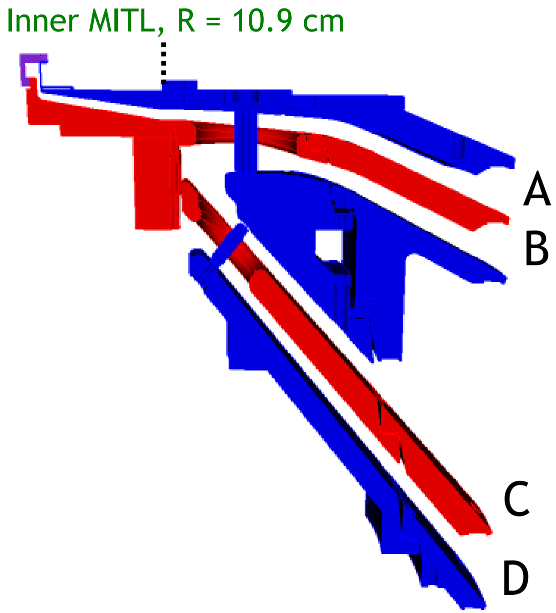
EMPIRE-PIC: SCL

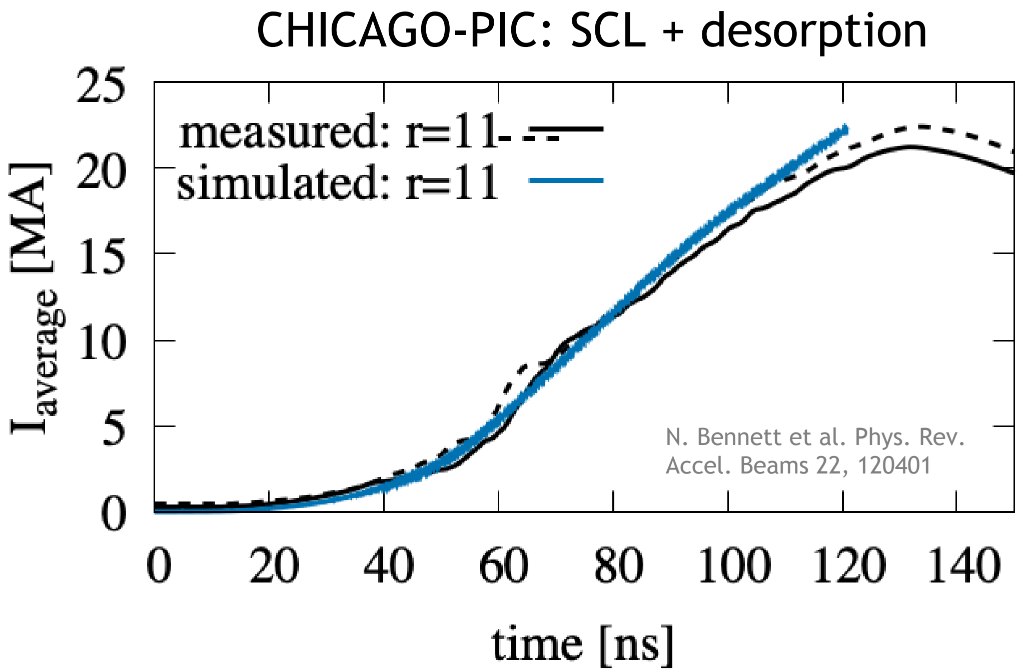


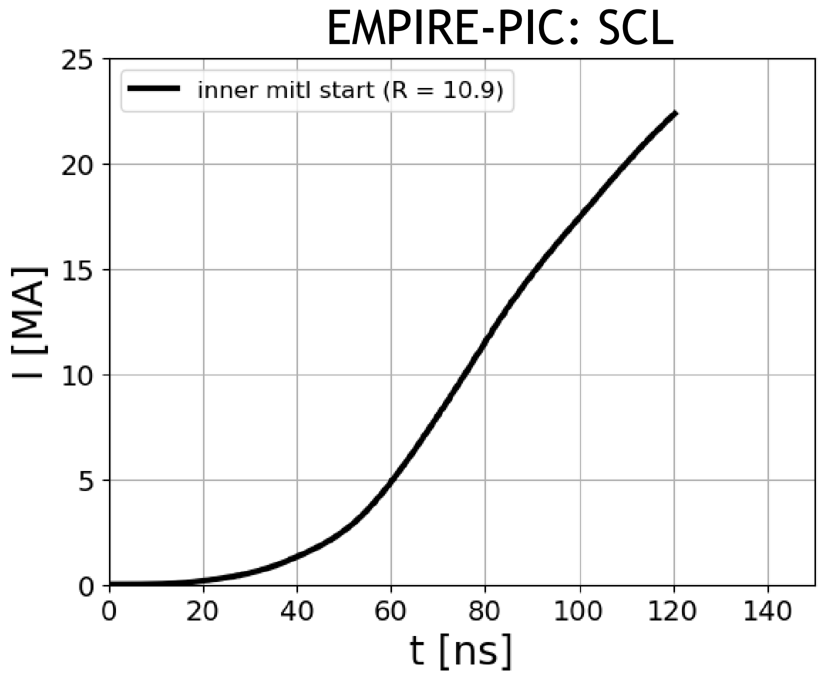


Powerflow 18a (hot): CHICAGO vs. EMPIRE inner MITL entrance current









Powerflow 18a hot EMPIRE simulation: EM fields

EMPIRE-PIC