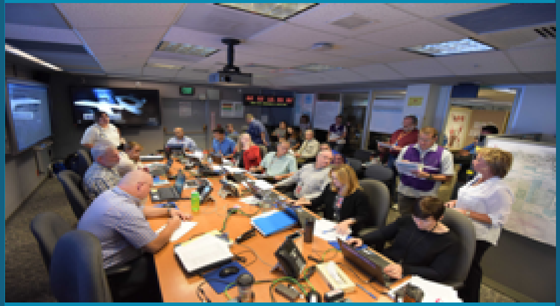
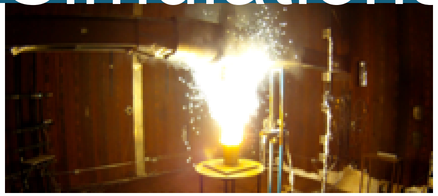
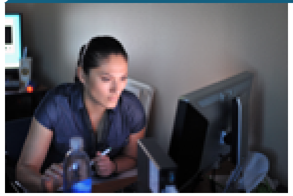
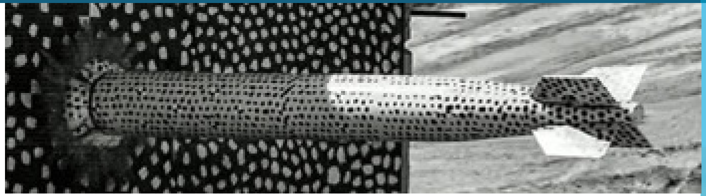
SAND2021-9804C

Effects of Vacuum Impedance Changes on MITL Flow using 3D Electromagnetic PIC Simulations









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Outline

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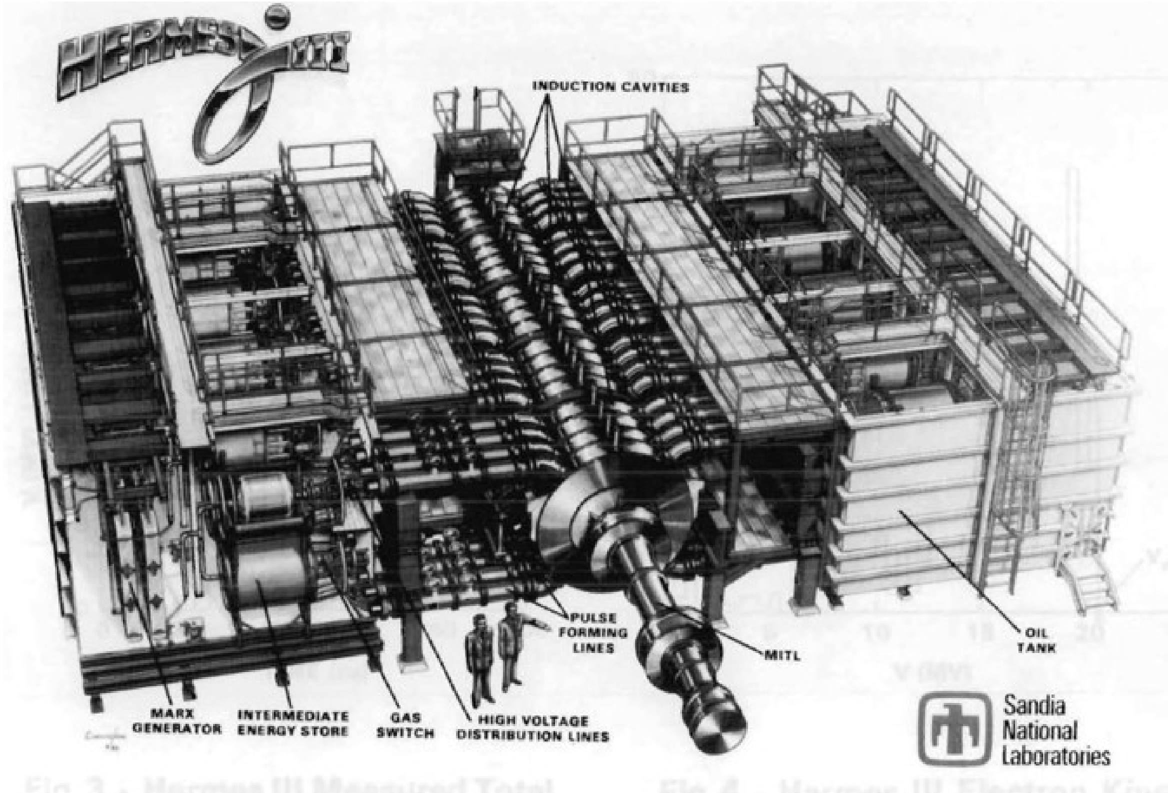
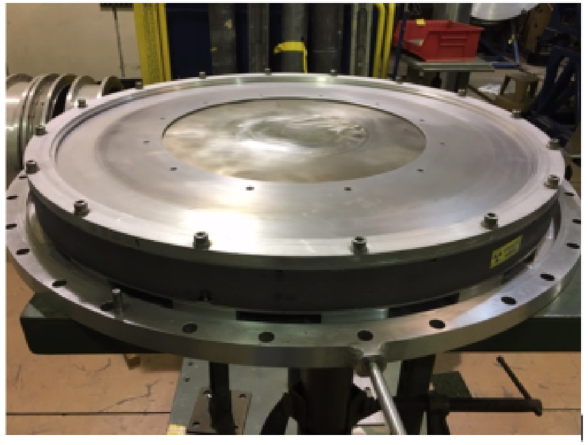
- Analysis of simulated MITL sheath flow

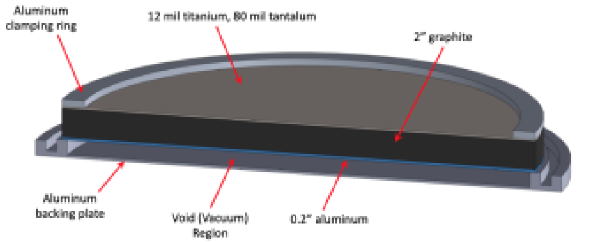
Conclusions and Future Work

HERMES-III Background

HERMES-III Background







Nominally an 18MV, 550kA coaxial accelerator
Uses Inductive Voltage Adders (IVAs) to combine Marx pulses
This requires a floating cathode
Can operate in bremsstrahlung mode or an ion-diode mode (reverse pola

MITL Basics (Planar Example)

SCL emission once breakdown threshold is reached

Electromagnetic pressure balance yields approximation of MITL voltage

$P_E = \varepsilon_0 E^2/2$ [ref 1] $P_B = B^2/2\mu_0$ [ref 2]

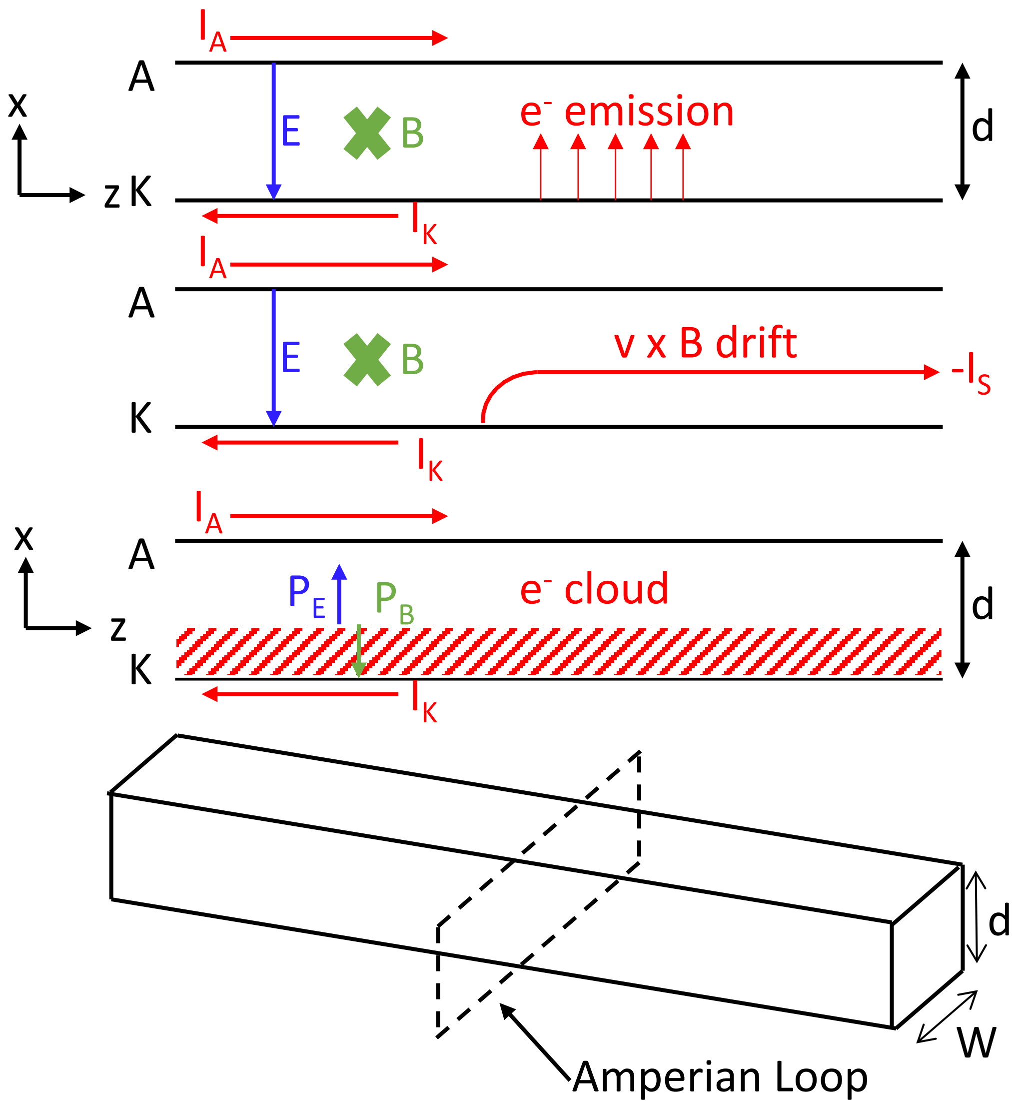
$$\frac{B_A^2}{2\mu_0} - \frac{\epsilon_0 E_A^2}{2} = \frac{B_K^2}{2\mu_0} - \frac{\epsilon_0 E_K^2}{2}$$

$$E_A = c\sqrt{B_A^2 - B_K^2} \qquad \mu_0 I = BW$$

$$V = E_A \cdot d = c\mu_0 \frac{d}{W}\sqrt{I_A^2 - I_K^2} \qquad c\mu_0 \frac{d}{W} = Z_0$$

[ref 3]

$$V = Z_0\sqrt{I_A^2 - I_K^2}$$



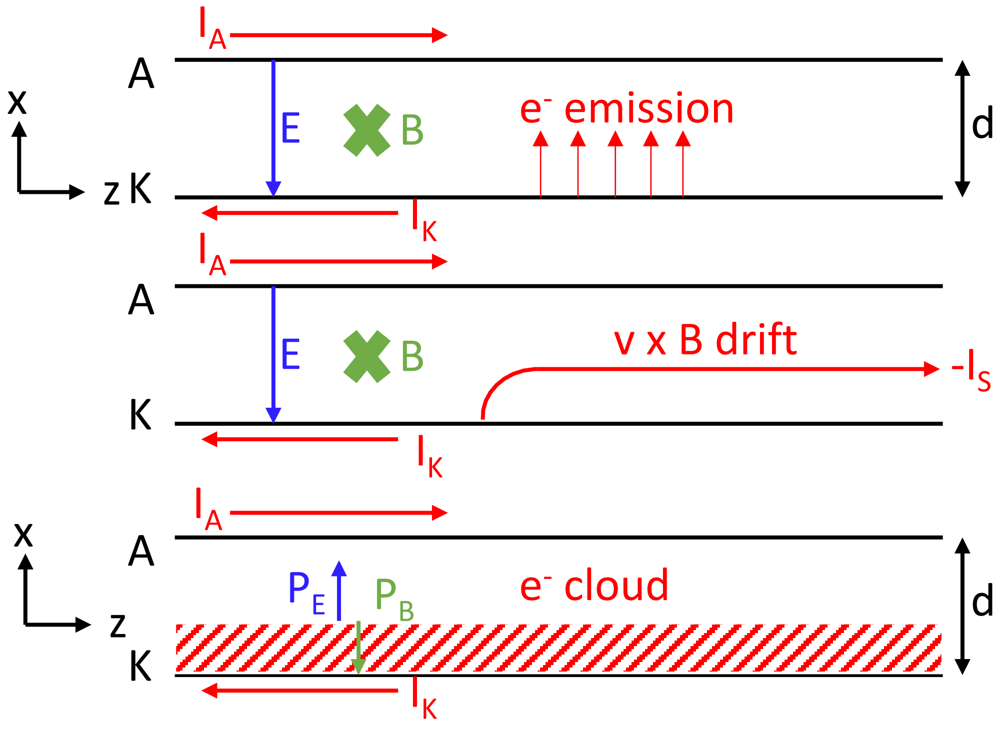
[1] – Griffiths, David J. *Introduction to Electrodynamics*. Upper Saddle River, N.J: Prentice Hall, 1999.
[2] – Chen, Francis F., *Introduction to Plasma Physics and Controlled Fusion.* N.Y.: Plenum Press, 1984.
[3] – Pozar, David M., *Microwave Engineering.* N.J.: Wiley, 1998

MITL Voltage Calculation

Without space charge correction: $V = Z_0\sqrt{I_A^2 - I_K^2}$

$$Z_f = \frac{V}{\sqrt{I_A^2 - I_K^2}}$$

Miller [4]: $V = Z_0\sqrt{I_A^2 - I_K^2} - \frac{mc^2}{2e}\frac{I_A^2 - I_K^2}{I_K^2}$



Ottinger [5]:

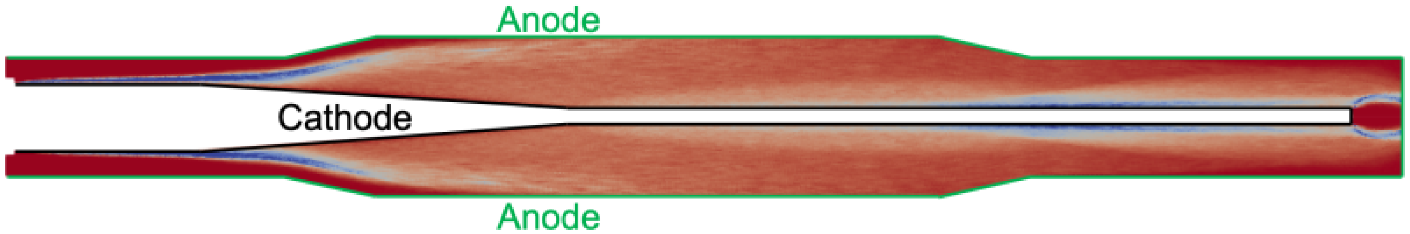
$$V = Z_0\sqrt{I_A^2 - I_K^2} - \frac{mc^2}{e}\frac{Z_0 I_A - \left[Z_0^2 I_A^2 - \left(Z_0(I_A^2 - I_K^2) + \frac{4T_m d^2/\epsilon_0}{Z_0(I_A^2 - I_K^2)}\right)\right]^{1/2}}{\left[Z_0^2 I_A^2 - \left(Z_0(I_A^2 - I_K^2) + \frac{4T_m d^2/\epsilon_0}{Z_0(I_A^2 - I_K^2)}\right)\right]^{1/2}}$$

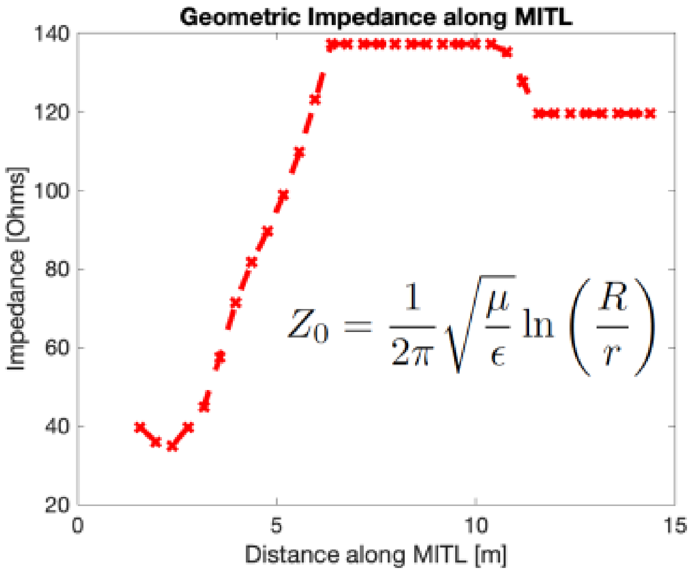
$$T_m = 0, \quad \Rightarrow \quad V = Z_0\sqrt{I_A^2 - I_K^2} - \frac{mc^2}{e}\frac{I_A - I_K}{I_K}$$

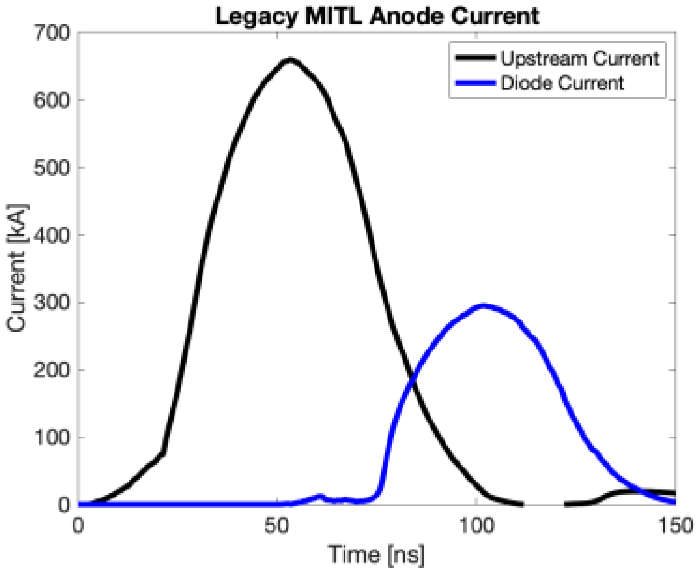
[4] – Miller, P. A., Mendel, C. W., "Analytic model of Applied-B ion diode impedance behavior" (Appendix A), Journal of Applied Physics, 61, 529. 1987.
[5] – Ottinger, P. F., Schumer, J. W., Hinshelwood, D. D., and Allen, R. J., “Generalized Model for Magnetically Insulated Transmission Line Flow”. IEEE Transactions on Plasma Science, Vol 36, No. 5. October, 2008.

Legacy Extended MITL Configuration

- Courtyard used to test large articles
- Extended MITL transports power through indoor test cell into courtyard
- Anode and cathode radii varied dramatically
- Impedance more than tripled in the first few meters
- Sheath flow would lift off of cathode and short into anode.
- Current lost was roughly half of pulse magnitude







Redesigned Configuration

Constant Impedance Design

Design focused on maintaining the ratio of R/r

$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu}{\epsilon}}\ln\left(\frac{R}{r}\right)$$

Engineering problem: cantilevered floating cathode

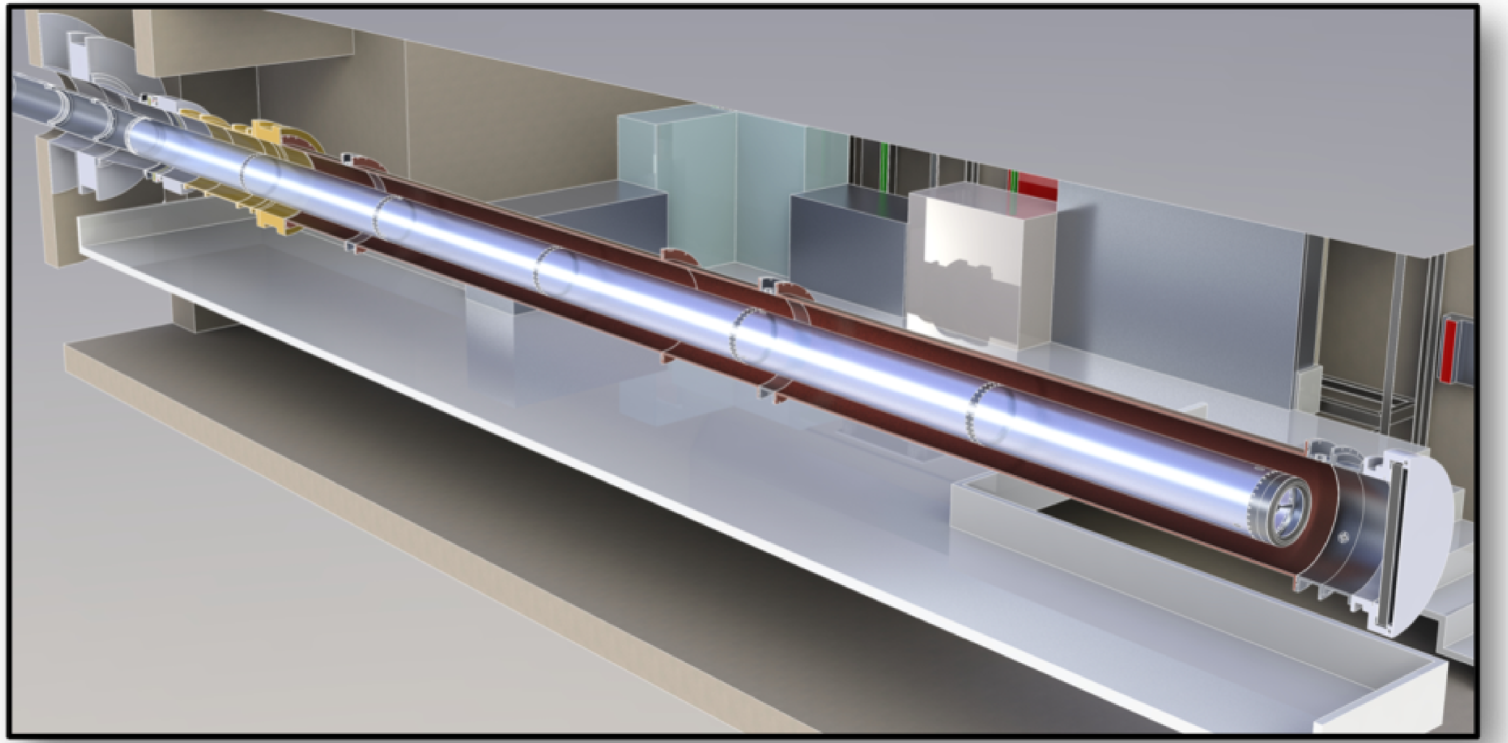
Engineering solution: Thin “nacho cheese can” cathode with clocking rings every few meters

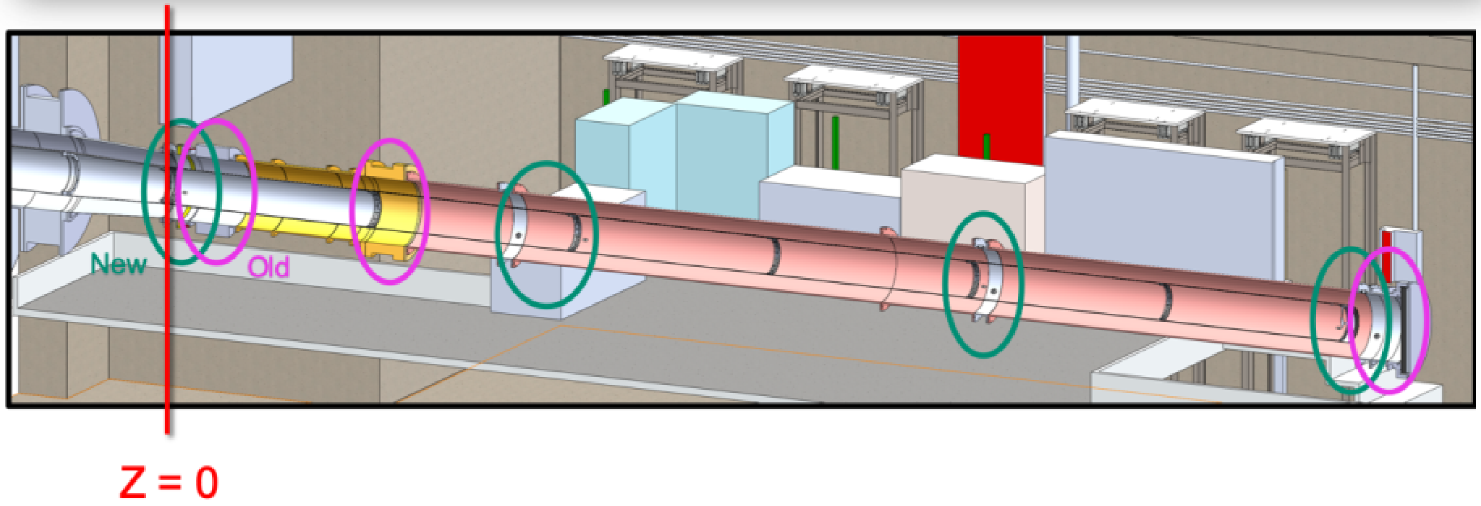
Deflection at diode was typically fractions of an inch

Addition of several cathode B-dot sensors

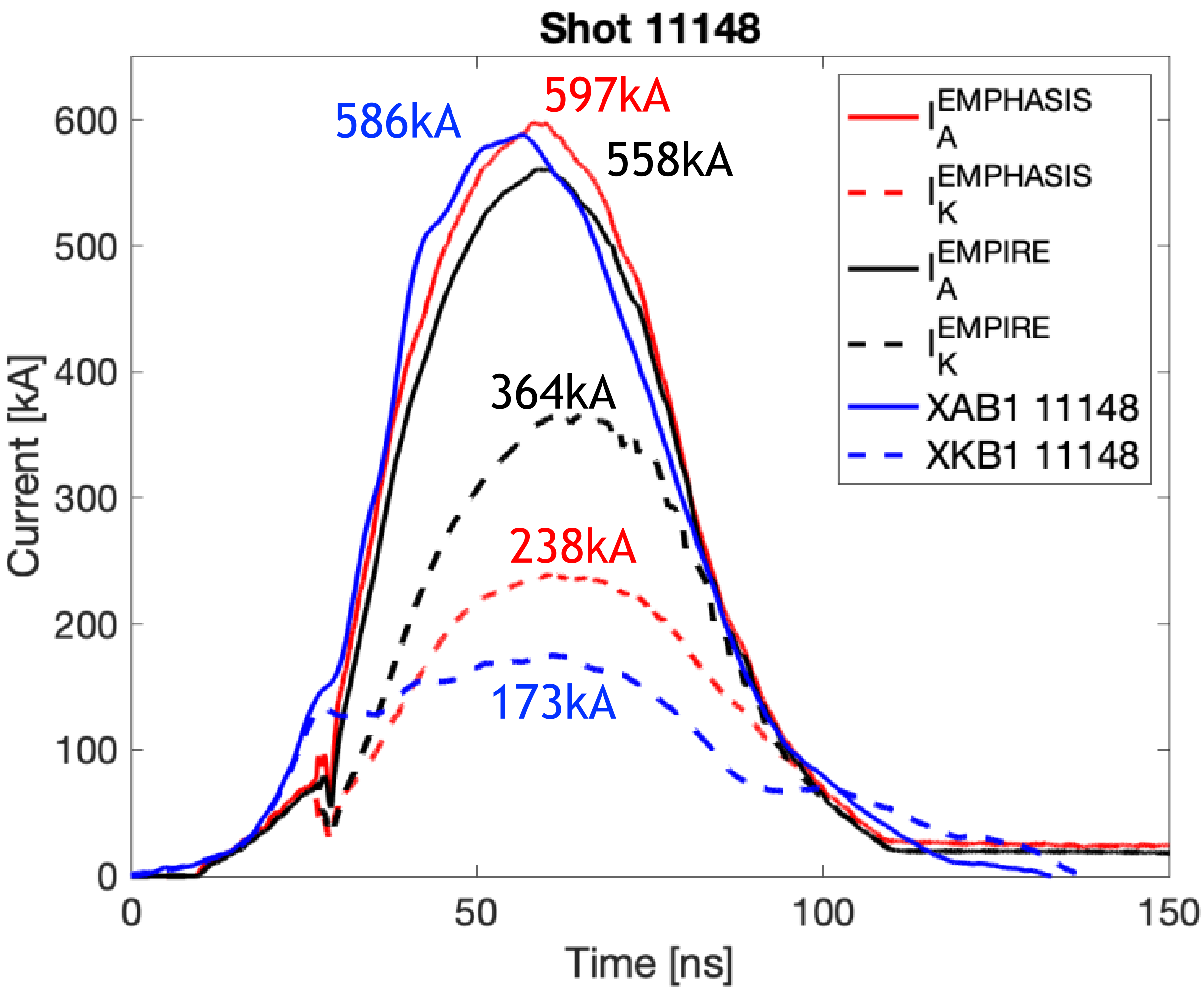
Simulations performed in both EMPHASIS and EMPIRE

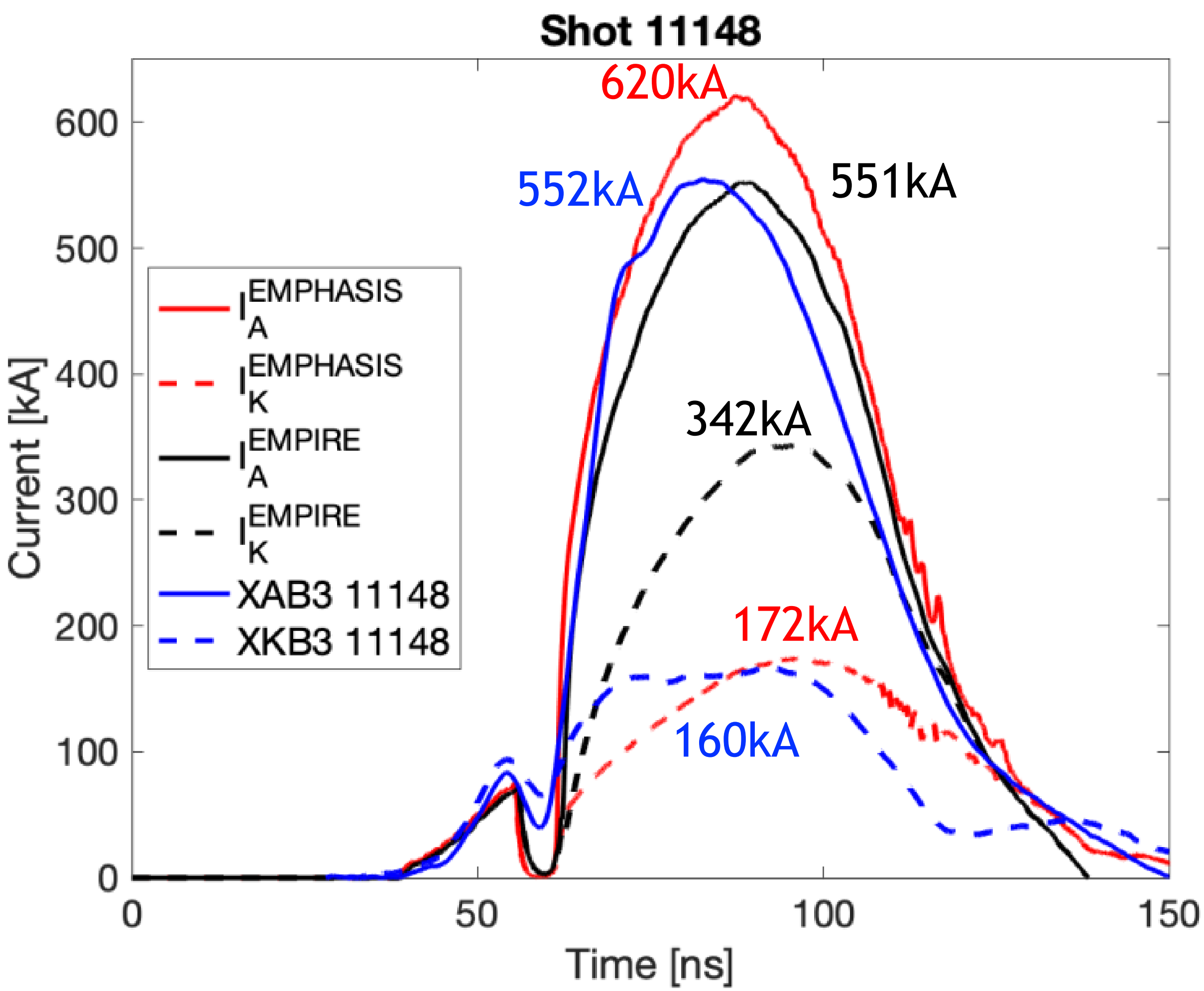
- EMPHASIS: Legacy PIC code developed at Sandia National Laboratories
- EMPIRE: PIC-Fluid-Hybrid code in development at Sandia National Laboratories



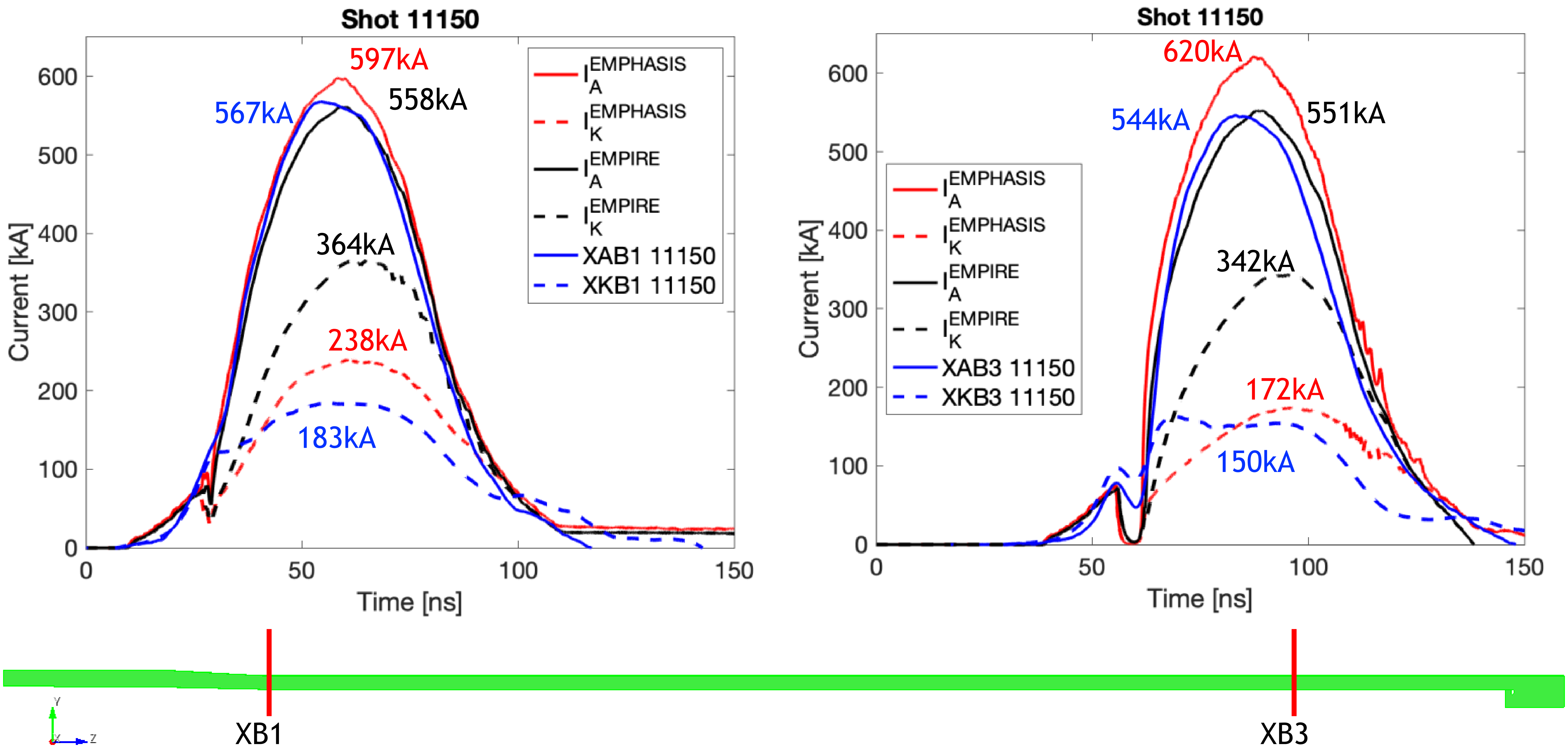


Simulation and Shot 11148

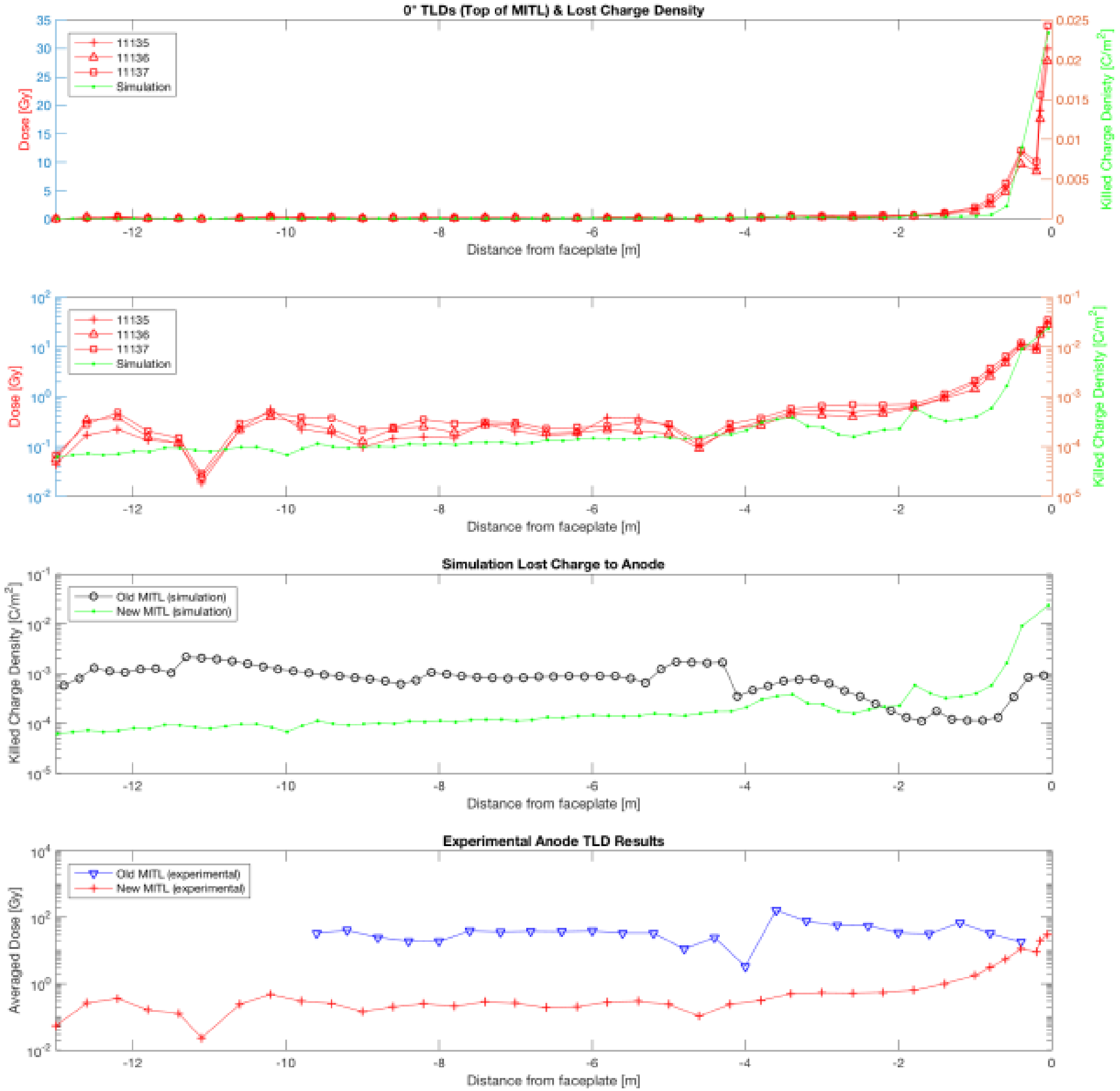


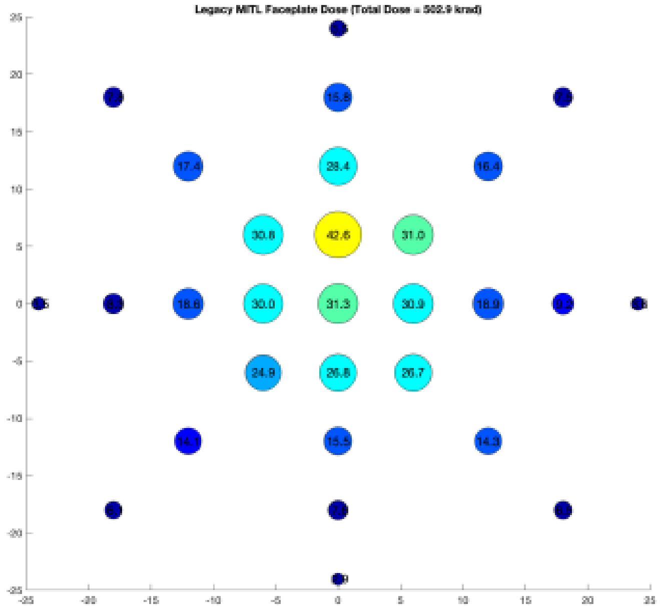


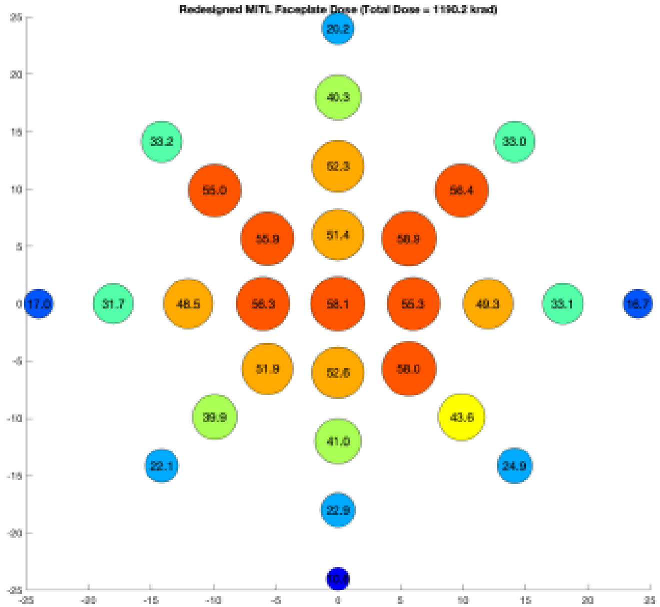
Simulation and Shot 11150



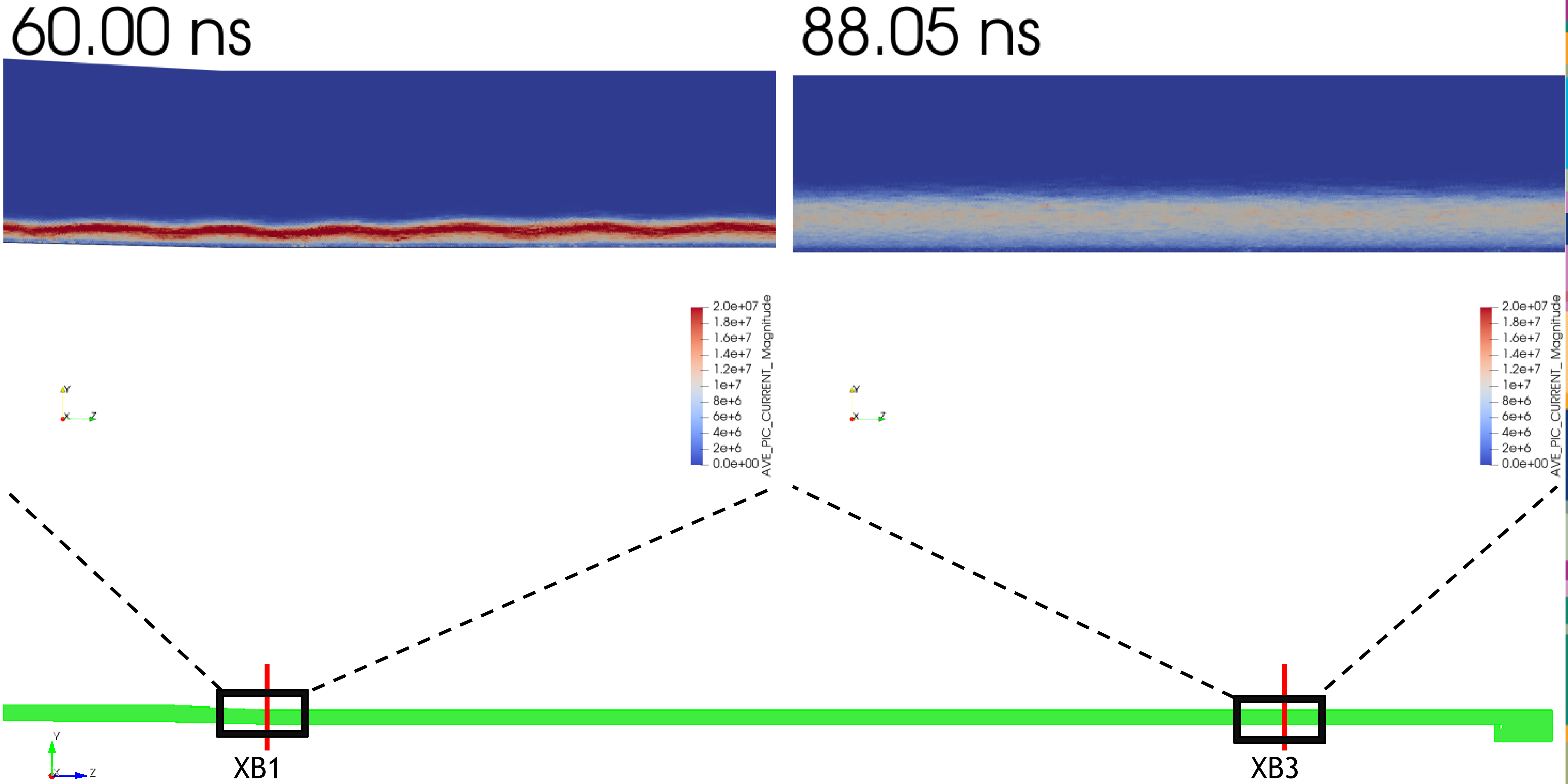
TLD Qualification of MITL Performance



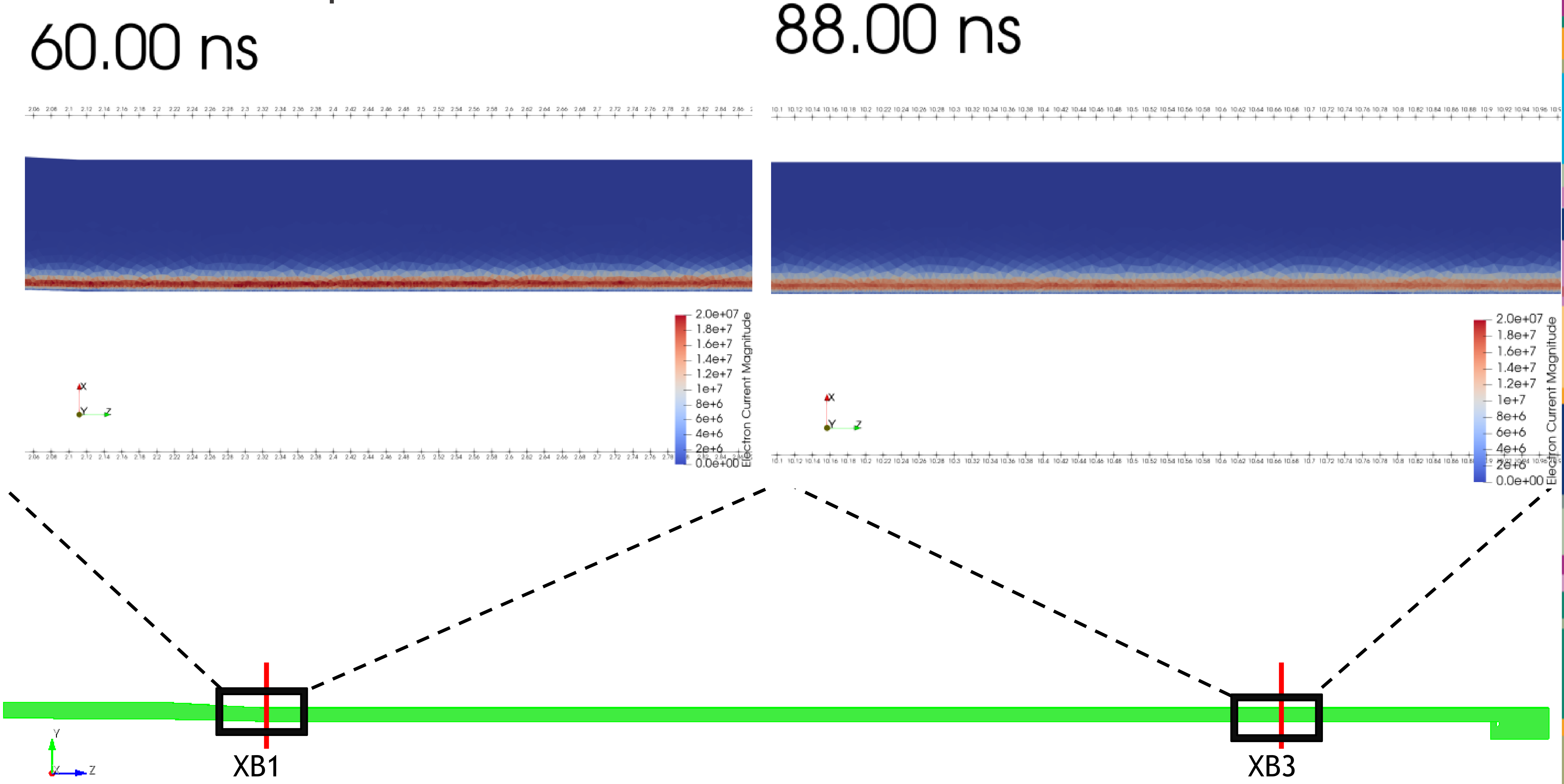




Sheath Expansion: EMPHASIS



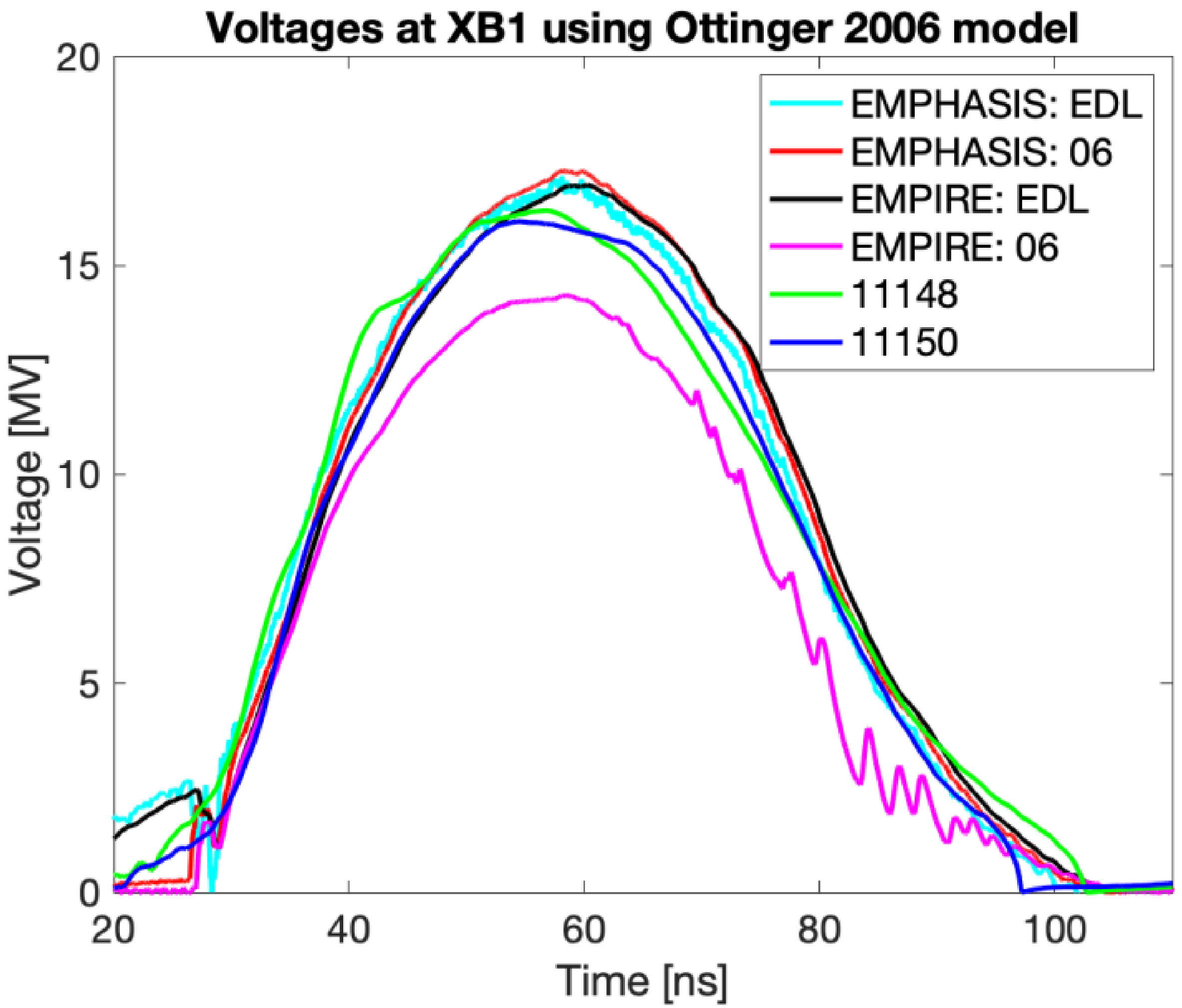
Sheath Expansion: EMPIRE

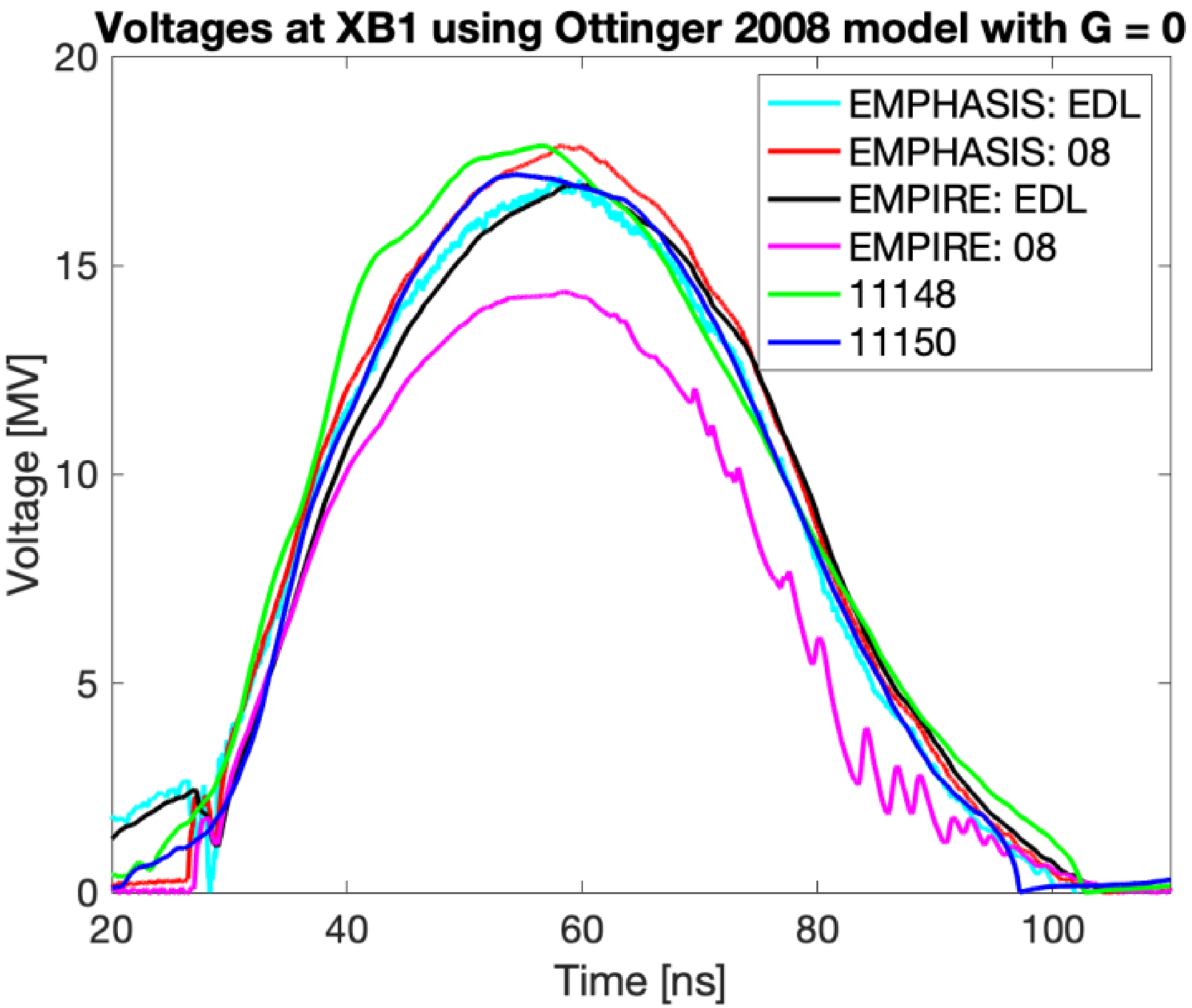


Voltage Calculation (Sensor Station 1)

[6]: $$V = Z_0\sqrt{I_A^2 - I_K^2} - \frac{gmc^2}{2e}\frac{I_A^2 - I_K^2}{I_K^2}$$

$$V = Z_0\sqrt{I_A^2 - I_K^2} - \frac{mc^2}{e}\frac{I_A - I_K}{I_K}$$



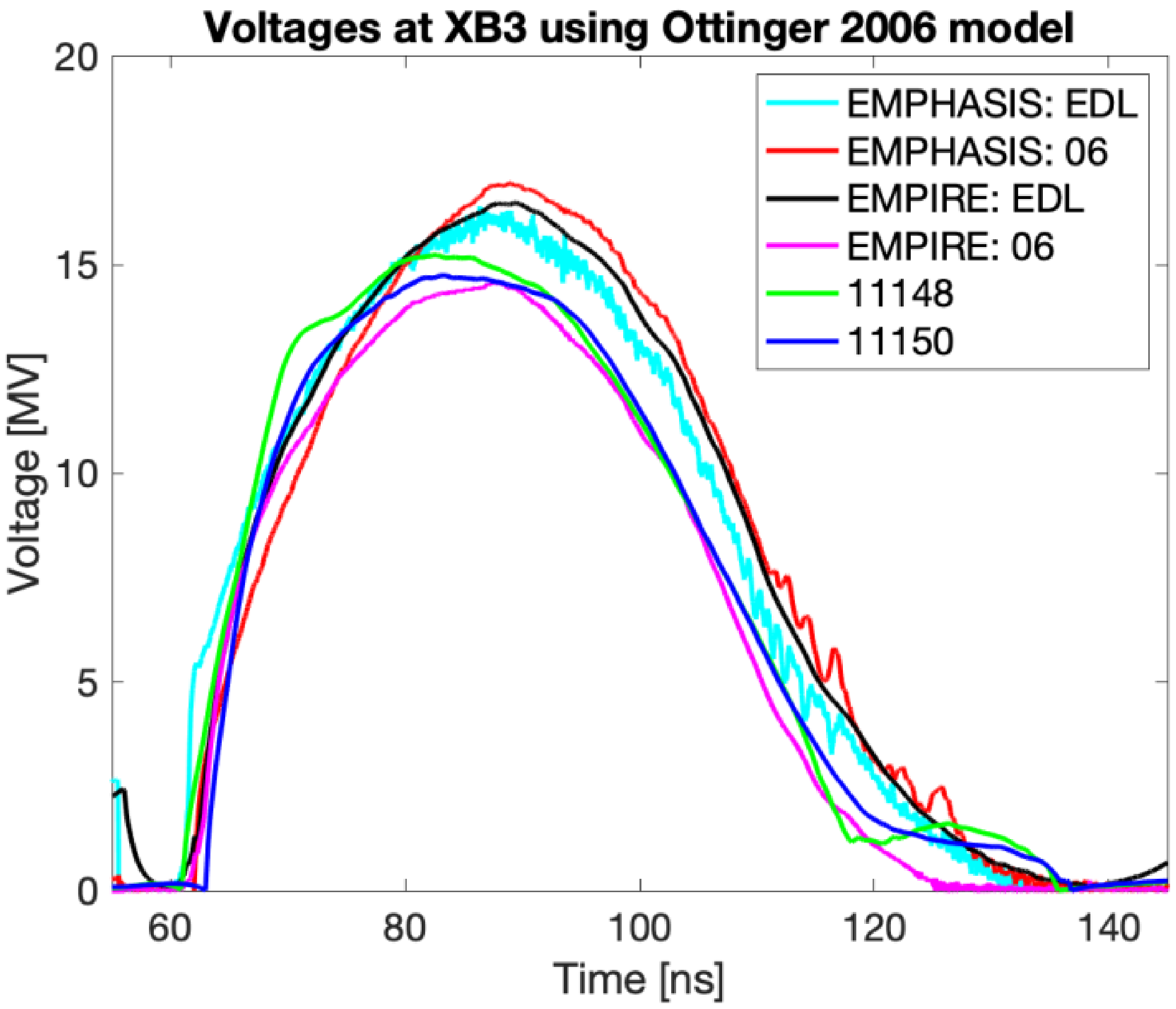


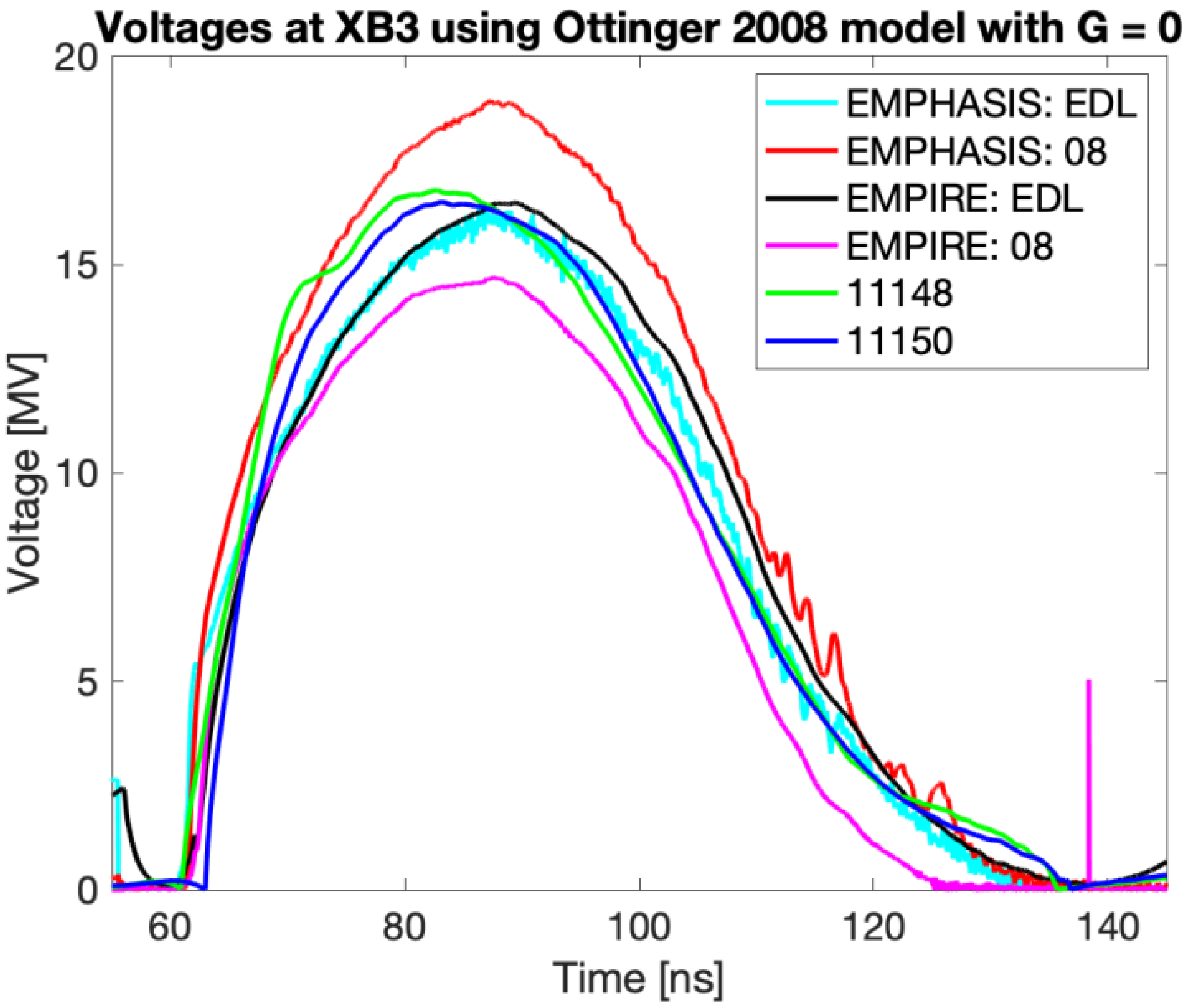
[6] – Ottinger, P. F., and Schumer, J. W., "Rescaling of Equilibrium Magnetically Insulated Flow Theory Based on Results from Particle-In-Cell Simulations". Physics of Plasmas 13, 063109. 2006.

Voltage Calculation (Sensor Station 3)

$$V = Z_0\sqrt{I_A^2 - I_K^2} - \frac{gmc^2}{2e}\frac{I_A^2 - I_K^2}{I_K^2}$$

$$V = Z_0\sqrt{I_A^2 - I_K^2} - \frac{mc^2}{e}\frac{I_A - I_K}{I_K}$$



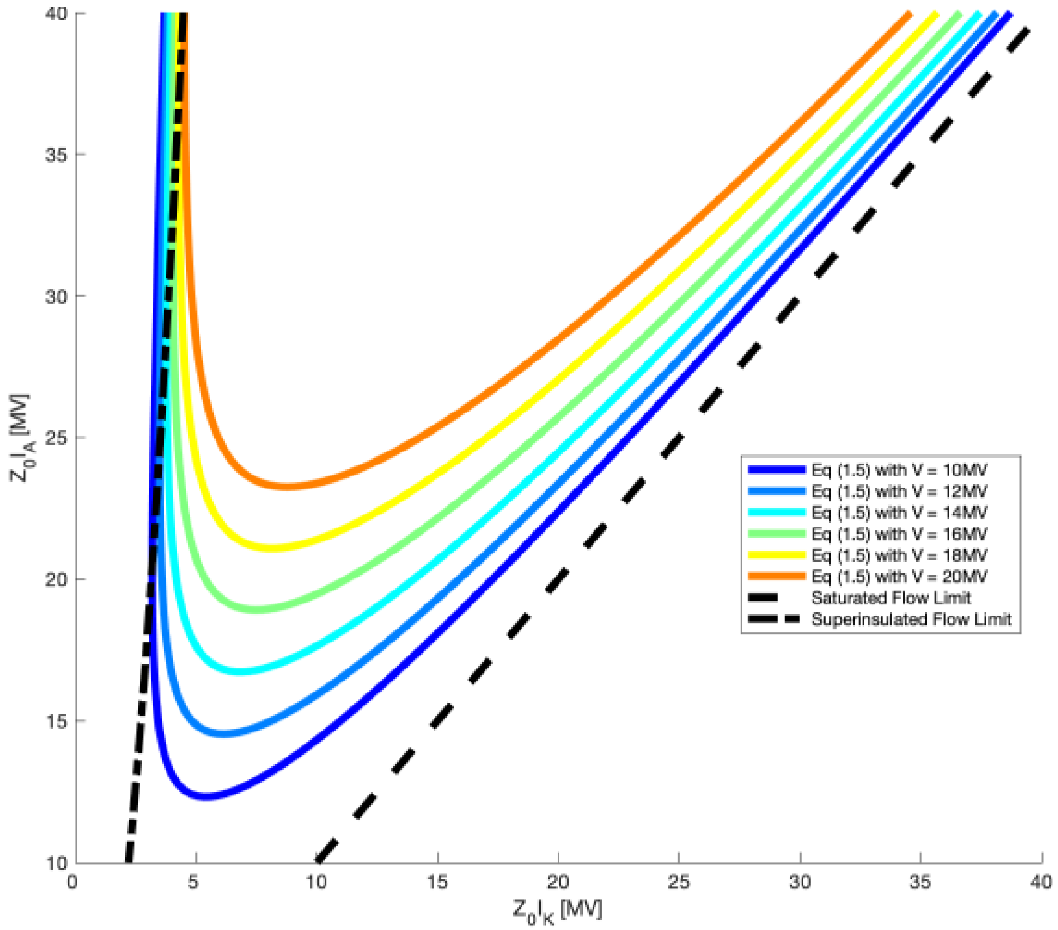


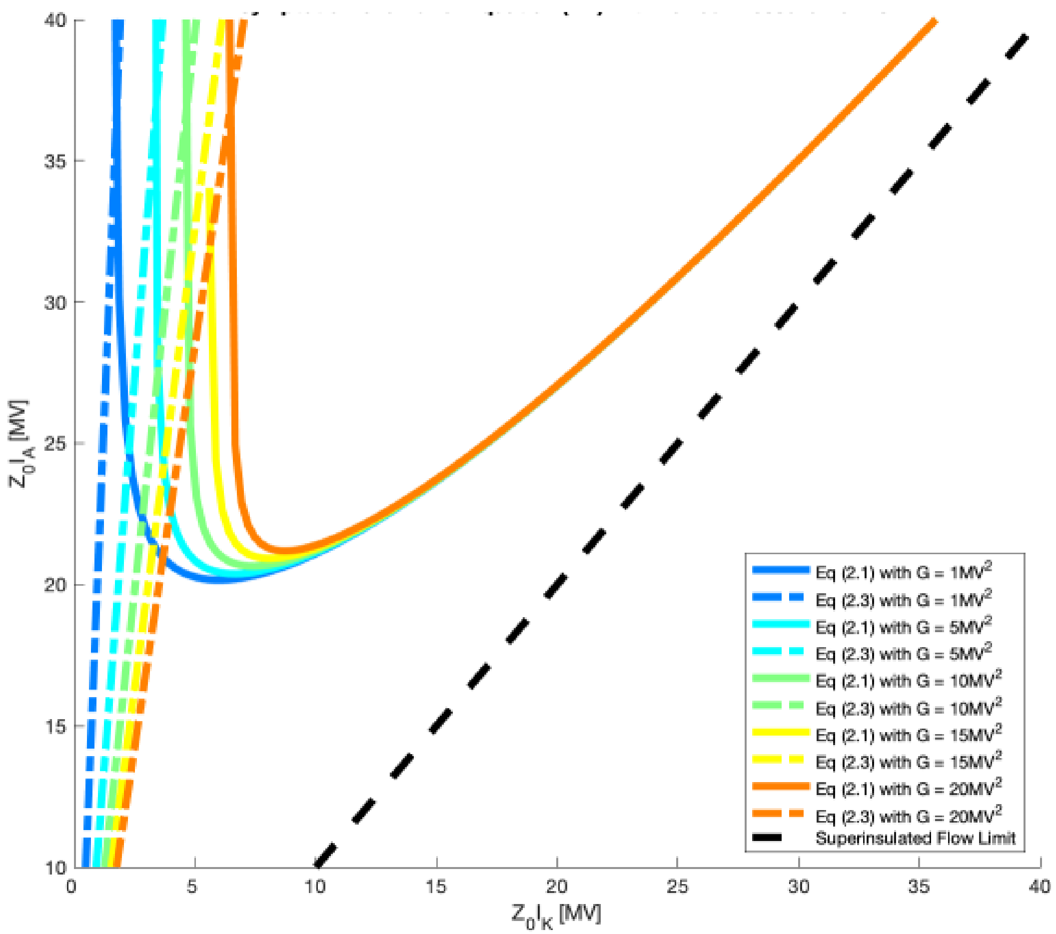
Voltage Calculation (Fingerprint Plots)

$$V = Z_0\sqrt{I_A^2 - I_K^2} - \frac{mc^2}{2e}\,\frac{I_A^2 - I_K^2}{I_K^2}$$

$$V_{Ott(08)} = Z_0\sqrt{I_A^2 - I_K^2} - \frac{mc^2}{e}\,\frac{Z_0 I_A - \left[Z_0^2 I_A^2 - \left(Z_0\sqrt{I_A^2 - I_K^2} + \frac{4T_m d^2/\varepsilon_0}{Z_0\sqrt{I_A^2 - I_K^2}}\right)^2\right]^{1/2}}{\left[Z_0^2 I_A^2 - \left(Z_0\sqrt{I_A^2 - I_K^2} + \frac{4T_m d^2/\varepsilon_0}{Z_0\sqrt{I_A^2 - I_K^2}}\right)^2\right]^{1/2}}$$

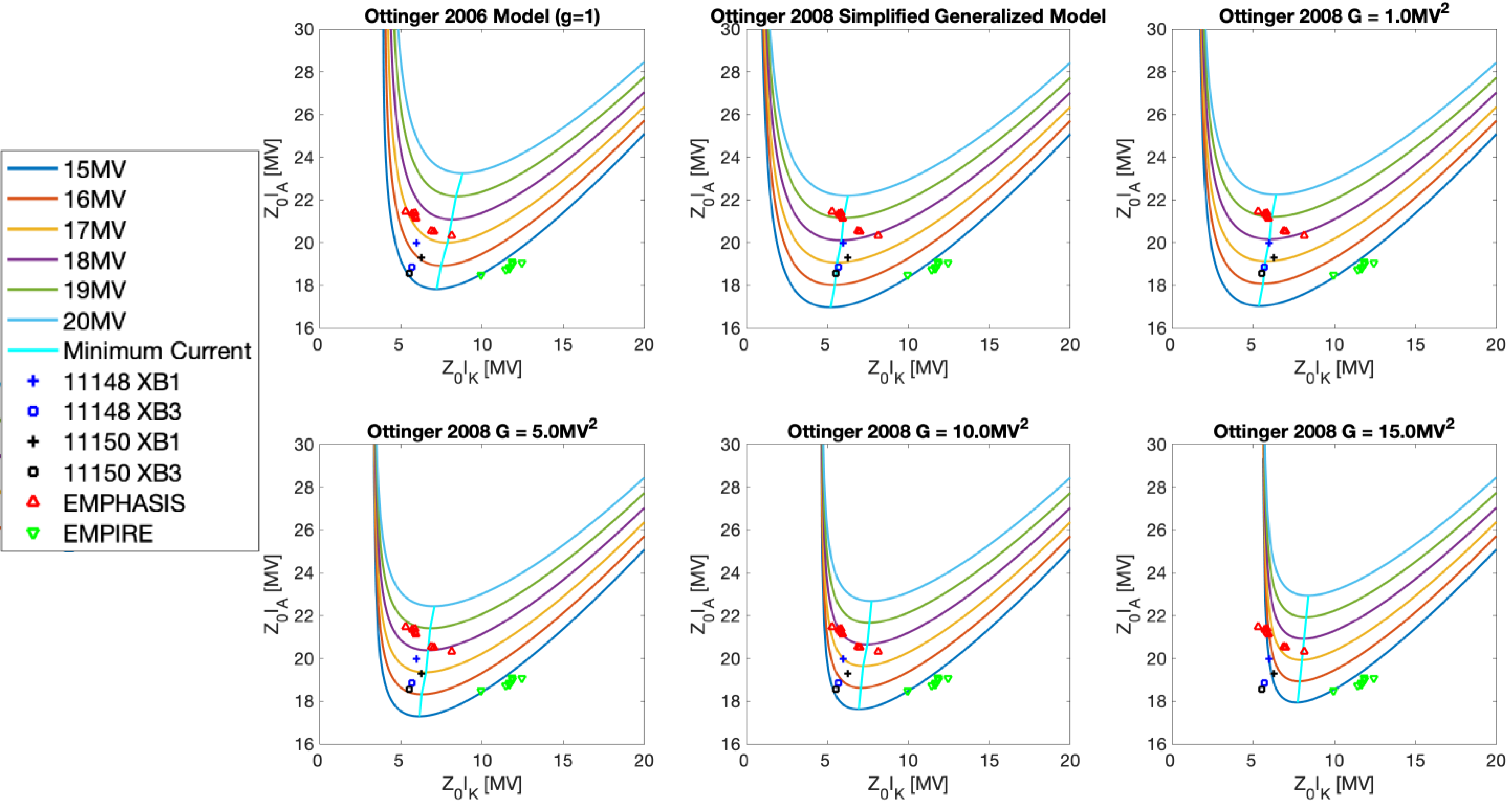
$$G \equiv 4T_m d^2/\epsilon_0$$





Voltage Calculation (Fingerprint Plots)

$$G \equiv 4T_m d^2/\epsilon_0$$



A look at electron pressure

$$G \equiv 4T_m d^2/\epsilon_0$$

T_m = KT * n_{max}
KT = 100eV

$$\frac{\partial T}{\partial x} = \rho(E - v_z B)$$

G = 5.3×10^{17} MV^2
G = 1.8×10^{17} MV^2

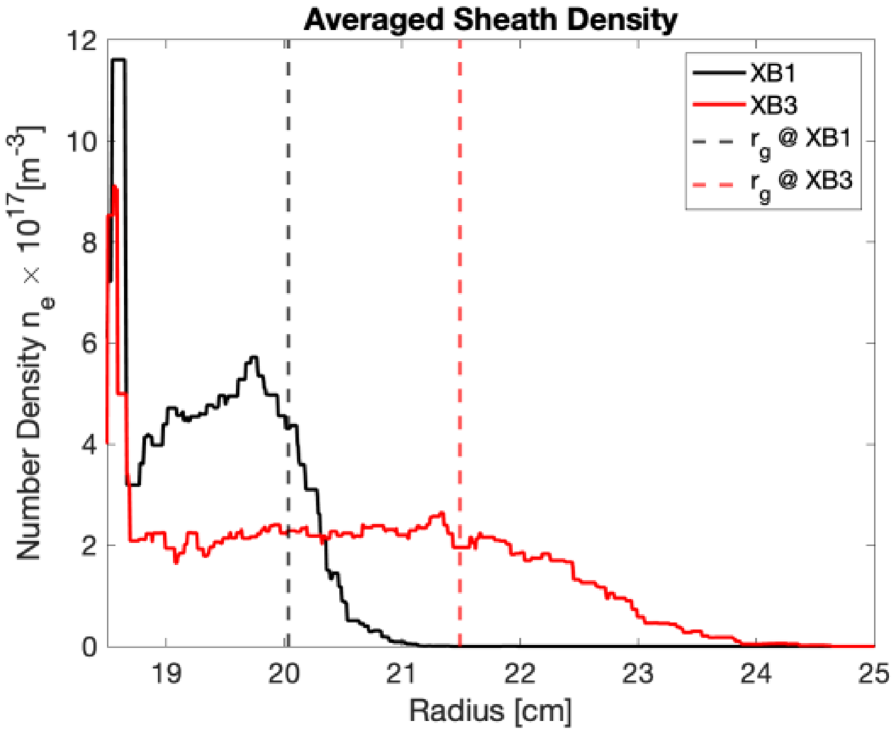
??

Suppose T_m = KT * ρ_{max}

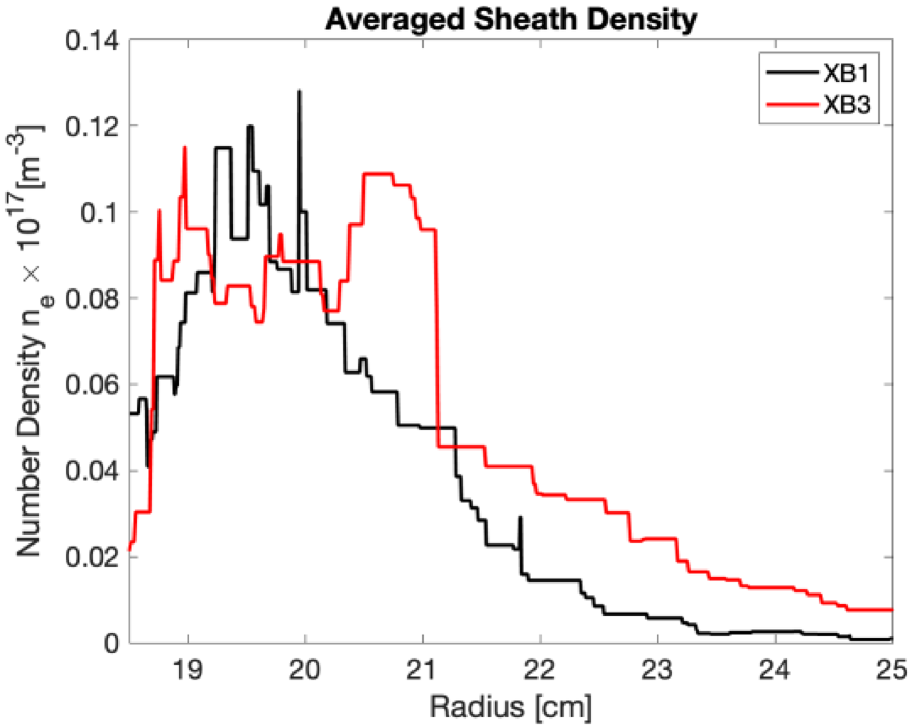
G = 0.022 MV^2
G = 0.0072 MV^2

More believable…

EMPHASIS



EMPIRE



Conclusions and Future Work

Maintaining constant geometric impedance in the MITL transports power much more effectively.

EMPHASIS: Overpredicts both sheath and anode currents

- Due to Dirichlet voltage boundary condition

EMPIRE: Underestimates sheath current overall

- Using TLBC gives better agreement

Ottinger’s simplified model yields decent approximations for voltages

More work needs to be done to understand the sheath parameters in simulation

A better TLBC will be implemented in EMPIRE in the future (but not for EMPHASIS)