

Theory and simulation of gap distance transitions in planar magnetically insulated transmission lines

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Magnetically insulated transmission lines (MITLs) are critical components for efficiently transporting power from pulsed power sources to a diverse range of loads, including magneto-inertial confinement fusion and radiation production. This study investigates the behavior of planar MITLs, taking into account the source voltage and source and load impedances, using two-dimensional theory and simulations. Self-limited behavior, where the MITL operating impedance (voltage divided by current) is insensitive to the value of load impedance, is extended to small-to-large gap distance MITL transitions. Load-limited behavior, in which the load impedance is below the self-limited impedance, causes the MITL operating impedance to adjust to match the load impedance and can be extended to describe large-to-small transitions. In both cases, the operating impedance of the larger MITL section changes to match the self-limited operating impedance of the smaller section. This behavior extends to multiple transitions and to both low and high impedance loads. Assuming equilibration occurs (pulse duration larger than MITL transit time), the entire MITL operating impedance becomes the self-limited impedance of the smallest-gap MITL section or the load impedance, whichever is lower.

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Introduction. Magnetic insulation, where strong magnetic fields prevent field emitted cathode electrons from being lost to the anode, is essential for efficiency in high energy density pulsed power systems [1,2]. While magnetic fields can be produced externally, such as in magnetrons [3,4], some designs generate self-magnetic insulation from electrode currents. Self-magnetically insulated devices include magnetically insulated line oscillators (MILOs) [5–8] and magnetically insulated transmission lines (MITLs) [9–11]. MITLs and MILOs are transmission lines (often planar, coaxial, conical), held under vacuum, designed to deliver power efficiently by using magnetic insulation to prevent electron losses. These devices are utilized in fusion research [12,13], high-power microwaves, and radiation production [14–17]. We use simple, planar systems with a source, MITL, and load to study variable-gap-distance MITLs, which could enable higher power delivery on devices such as Sandia’s Z machine [11,18]. To avoid confusion, we use the term “variable-gap” rather than “variable-impedance” because, as will be demonstrated, variable-gap MITLs become constant-impedance throughout after transients die out. Applications of this work extend

to variable-gap MILOs, where recent simulations have been conducted [19].

Simulation methods. Simulations were performed using Sandia National Laboratories’ Empire [20], employing electromagnetic, relativistic, particle-in-cell, and finite element methods. The simulation geometry is summarized in Fig. 1. The source voltage was supplied through a 1D source transmission line driven by the telegrapher’s equations, coupled to a 2D domain self-consistently [21], which allows the MITL to be driven by a time-dependent voltage. The 1D and 2D domains have modal coupling, which ensures the transverse electromagnetic (TEM) solution is continuous both ways [21]. Non-TEM modes from the 2D domain are dissipated by a first-order absorber, reducing artificial ringing [21]. The voltage ramps smoothly to a constant value sufficient to achieve self-magnetic insulation, leading to a quasiequilibrium state where transients have died out.

Originally, the load was a cathode tip with varying axial distance to a terminating anode, allowing load impedance modifications. For greater control of load impedance, a second 1D transmission line was used instead. The resistor shown in Fig. 1 reflects waves as expected when the impedances are not matched. By modeling the source and load as simple 1D transmission lines, the source and load inductances and impedances can be treated as fixed values (i.e., not varying due to electron flow). A constant-gap planar MITL is shown in Fig. 1 for clarity. Variable-gap

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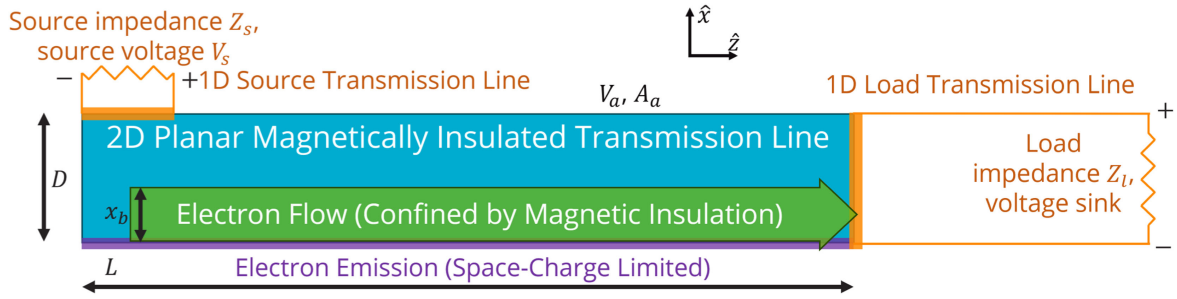


FIG. 1. Simulation schematic showing gap distance D , axial length L , anode voltage V_a , anode magnetic vector potential magnitude A_a , and electron flow height x_b for the constant-gap case. Source impedance Z_s , source voltage V_s , and load impedance Z_L are driven in one-dimensional (1D) transmission line models. The positive x direction $\hat{x}$ points from cathode to anode; the positive z direction $\hat{z}$ points from source-to-load and is the net direction of electron velocity.

cases keep a constant-gap section near the source and load, with the variable-gap transition section centered on the midpoint. The first gap distance D is always 10 cm, the same order-of-magnitude as the Z machine outer MITLs [22] and the HERMES-III MITL [1].

A discretization was chosen to allow 24 cells across the smallest gap with a time step size chosen so that a particle could not cross more than one cell in a single time step. Electrons were injected at the cathode at the space-charge limit, following theoretical assumptions [23] and experimental evidence [24]. Electrons reaching any boundaries were absorbed.

Theoretical methods. Brillouin flow theory [25] describes equilibrium electron flow along equipotential lines in an infinitely long MITL. The formulation of Lau *et al.* [23] is used throughout this Letter, which assumes a grounded cathode in both voltage V and magnetic vector potential $\vec{A}$. Symmetry means $\vec{A} = A_y \hat{y}$, so we drop vector notation and just use A [23]. Boundary conditions at the anode (subscript “a”) are V_a and A_a , cf. Fig. 1. An intermediate term χ_b is calculated as

$$\chi_b = \tanh^{-1} \left[\frac{(\bar{V}_a + 1)\bar{A}_a - \sqrt{\bar{A}_a^2 - \bar{V}_a^2 - 2\bar{V}_a}}{\bar{A}_a^2 + 1} \right] \quad (1)$$

with elementary charge e , electron mass m , dimensionless voltage $\bar{V}_a$

$$\bar{V}_a = (eV_a)/(mc^2), \quad (2)$$

and dimensionless vector potential $\bar{A}_a$

$$\bar{A}_a = (eA_a)/(mc). \quad (3)$$

The electron flow layer height x_b , or Brillouin hub height (hence, subscript “b”), is

$$x_b = D\chi_b/\kappa, \quad (4)$$

with gap distance D and divisor κ

$$\kappa = \frac{\bar{V}_a + 1 - \cosh(\chi_b) + \chi_b \sinh(\chi_b)}{\sinh(\chi_b)}. \quad (5)$$

The electrode current flowing in the cathode I_c is

$$I_c = \frac{mcw}{e\mu_0 D} \kappa. \quad (6)$$

Similarly, anode current I_a is

$$I_a = \frac{mcw}{e\mu_0 D} \kappa \cosh(\chi_b) \equiv I_c \cosh(\chi_b). \quad (7)$$

Finally, characteristic MITL operating impedance Z_{op} is

$$Z_{op} \equiv V_a/I_a \equiv V_a/(I_e + I_c) \quad (8)$$

with total electron flow current I_e . Note, by convention, all quantities are expressed as positive [23]. Varying A_a for constant V_a generates a curve of Z_{op} vs I_c .

By contrast, without electron flow, a planar transmission line has impedance Z_0

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \frac{D}{W} \quad (9)$$

with vacuum permeability μ_0 , vacuum permittivity ϵ_0 , and width (into the page) W . Empire [20] has a notional $W = 1$ m for two-dimensional simulations. For the 8, 10, and 12 cm gaps in this Letter, we obtain $Z_0 = 30.2, 37.7$, and $45.2 \, \Omega$, respectively.

These simulations are driven to quasiequilibrium, where transients have nearly dissipated. Thus, the time derivative in Faraday’s law vanishes and

$$\oint_{\partial\Sigma} \vec{E} \cdot d\vec{l} = 0 \quad (10)$$

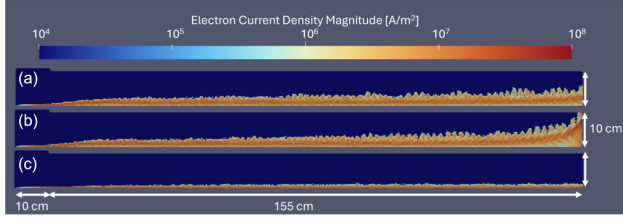


FIG. 2. Electron current density for a planar, 10 cm gap with voltage 10 MV. (a) Load impedance $Z_L = 37.7 \Omega$, source impedance $Z_s = 30 \Omega$; (b) $Z_L = 1000 \Omega$, $Z_s = 30 \Omega$; (c) $Z_L = 18 \Omega$, $Z_s = 18 \Omega$.

with closed loop $\partial\Sigma$ and vector element $d\vec{l}$ ensures V_a is uniform axially, since none of the geometries considered herein have steady-state electron losses to the anode. Similarly, Ampere's law,

$$\oint_C \vec{B} \cdot d\vec{l} = \iint_S \mu_0 \vec{J} \cdot d\vec{S} \quad (11)$$

with surface $\vec{S}$ ensures total current I_a is uniform axially. Any axial variations in electron current are exactly balanced by opposite variations in cathode current, so no sources or sinks of total current exist. Thus, we expect axially uniform operating impedance Z_{op} [Eq. (8)] after equilibration. This result also follows from wave reflection. If measured impedance discontinuities persisted after equilibration, forward- and backward-traveling waves would be partially reflected at discontinuities and the transmission line, by definition, would not be in quasiequilibrium condition. The quasiequilibrium state reached in simulation guarantees uniform operating impedance.

To quantify perturbations caused by geometric transitions, we first simulate constant-gap MITLs to establish baseline Z_{op} behaviors.

Constant-gap MITLs. Simulations of the 10 cm, 10 MV planar MITL electron flow with various load impedances Z_L are shown in Fig. 2. Since $Z_{op} < Z_0$, the source impedance Z_s was adjusted to match $Z_{op} = 30 \Omega$ (cf. Fig. 3) to yield 10 MV as the quasiequilibrium voltage. Deviations between theory and simulation I_c , seen clearly in the research of Ottinger and Schumer [26–28], are partially caused by axial ($\hat{z}$) variations in I_c caused by the input region where electron currents are low. Changing the diagnostic location in the simulation would change observed I_c . For consistency, throughout this Letter, the diagnostic location remains fixed at the midpoint of the relevant constant-gap section. Independent of diagnostic location, Z_{op} is constant through the entire MITL and is the focus of this Letter.

Though $Z_s = Z_{op} = 30 \Omega$ and $Z_L = 37.7 \Omega$, no wave reflection is evident. The physical mechanism is the localized high current density perturbation near the load, exaggerated in Fig. 2(b) by increasing Z_L to 1000 Ω .

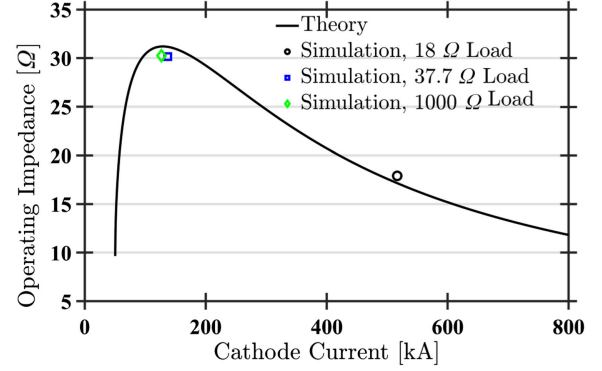


FIG. 3. Operating impedance Z_{op} vs cathode current I_c for a planar, 10 cm gap with voltage 10 MV. Source impedance 30 Ω for the 37.7 and 1000 Ω loads and 18 Ω for the 18 Ω load.

The perturbed flow patterns result in perfectly matched effective impedance from the perspective of the upstream MITL, perhaps acting as a current divider. Though further study is motivated by these results, this behavior has long been observed in experiment [1,29,30]. Unlike purely electromagnetic transmission lines, which equilibrate to the final load impedance, MITLs with no steady-state electron losses equilibrate to the lowest operating impedance. Indeed, without particles, a transmission line terminated by an open circuit equilibrates to a charged capacitor, whereas MITL electrons flow to the anode and yield a perfect impedance match to the MITL [29].

Conversely, lowering Z_L below $Z_{op} = 30 \Omega$ changes the operating point $Z_{op} = Z_L$ through the entire MITL. Figure 2(c) shows a far more tightly confined flow with $Z_{op} = Z_L = 18 \Omega$. To maintain 10 MV throughout, Z_s was also changed to 18 Ω , since $Z_s = 30 \Omega$ created a wave reflection with the MITL.

As load impedance increases, eventually the MITL reaches a consistent, “self-limited” Z_{op} [1,26,29,30]. The alternative descriptor “line-limited” is equivalent [26]. When Z_L is lower than self-limited Z_{op} , the MITL operates in the “load-limited” mode [1,26,29,30], and Z_{op} changes to match downstream impedance. This change in Z_{op} propagates upstream over time, a phenomenon called “retrapping” [31] since currents carried by electrons are subsequently carried by the cathode instead. Before retrapping, the MITL operates at the local, self-limited Z_{op} . Both self-limited and load-limited modes create perfect impedance matches between MITL and load due to local flow perturbations in the former case and changes in Z_{op} in the latter.

The variable-gap MITL simulations below demonstrate that small-to-large transitions result in self-limited behavior for the upstream MITL and large-to-small transitions in line-limited behavior upstream. Ultimately, this means variable-gap MITLs operate with constant operating impedance *everywhere* after retrapping propagates throughout.

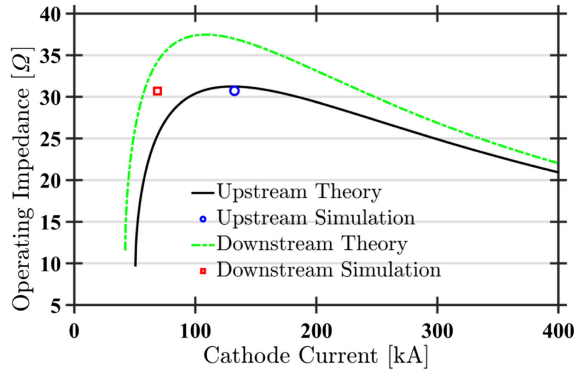


FIG. 4. Operating impedance Z_{op} vs cathode current I_c for a planar MITL transitioning from 10 cm (upstream) to 12 cm (downstream) over 1 m. Source impedance, 30 Ω ; load impedance, 37.7 Ω ; voltage, 10 MV.

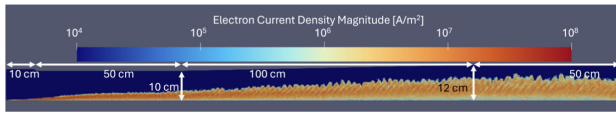


FIG. 5. Electron current density for a planar MITL transitioning from 10 cm (upstream) to 12 cm (downstream) over 1 m. Source impedance, 30 Ω ; load impedance, 37.7 Ω ; voltage, 10 MV.

Variable-gap MITLs. For small-to-large transitions, Fig. 4 shows that the small-gap section (10 cm gap) operates at approximately $Z_{op} = 30 \Omega$, just as with the self-limited constant-gap MITL. The large-gap section also operates at 30 Ω , though displaced from the theoretical curve horizontally and far from the local, self-limited point. Examining the current flow in Fig. 5, turbulent instabilities throughout the flow could explain deviations from theory, since theory assumes electrons move only downstream ($\hat{z}$) and travel in laminar layers. See the wave structure at the top of the electron flow in Figs. 2, 5, and 9 for visual evidence of turbulence. The small-gap section governs Z_{op} throughout. Just as with the self-limited, constant-gap MITL, no wave reflections remain in the MITL or load after quasiequilibrium is reached. Noise persisted with a relative standard deviation of 0.25% for voltage and anode current. Linear regressions calculated net drift of 0.01% during the ond half of simulated time. Over the same interval, electron current drifted 0.06%, commensurate with increased noise (1%–5% standard deviation). Accordingly, quasiequilibrium assumptions for integrated quantities, including operating impedance, are justified to well within 0.1%.

Figure 6 for a large-to-small transition shows the downstream (smaller gap) MITL has $Z_{op} = 24 \Omega$, the self-limited impedance for an 80% smaller gap. The current density plot in Fig. 7 shows a thin (superinsulated) layer of load-limited flow in the large-gap region, a smooth transition to self-limited flow in the small gap region, and a

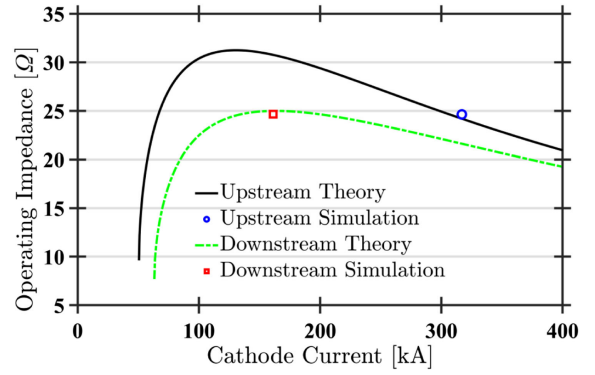


FIG. 6. Operating impedance Z_{op} vs cathode current I_c for a planar MITL transitioning from 10 cm (upstream) to 8 cm (downstream) over 1 m. Source impedance, 24 Ω ; load impedance, 37.7 Ω ; voltage, 10 MV.

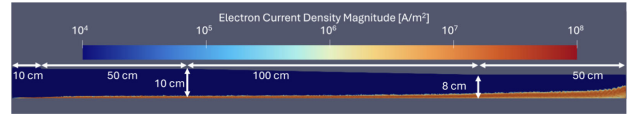


FIG. 7. Electron current density for a planar MITL transitioning from 10 cm (upstream) to 8 cm (downstream) over 1 m. Source impedance, 24 Ω ; load impedance, 37.7 Ω ; voltage, 10 MV.

local perturbation near the load due to the higher load impedance.

These behaviors are modular, holding true with multiple transitions. For any variable-gap system, given sufficient time to equilibrate to a quasiequilibrium condition (e.g., long enough pulse duration), operating impedance can be determined by first calculating the self-limited Z_{op} for each constant-gap section. No matter how geometric transitions are arranged, this evidence suggests the lowest Z_{op} (or load impedance Z_l , if smaller than all Z_{op}) anywhere in the MITL will become the Z_{op} throughout, unless electron

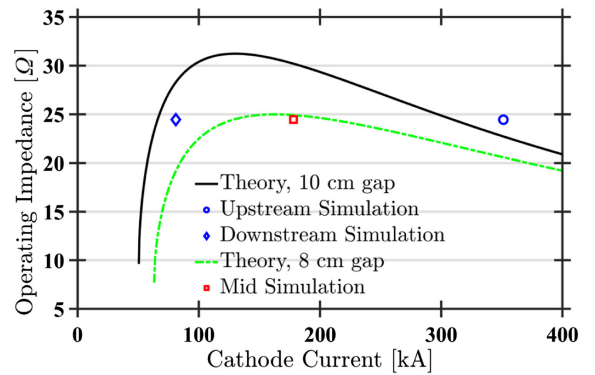


FIG. 8. Operating impedance Z_{op} vs cathode current I_c for a planar MITL transitioning from 10 cm (upstream) to 8 cm (mid) back to 10 cm (downstream) with 1 m transitions. Source impedance, 24 Ω ; load impedance, 37.7 Ω ; voltage, 10 MV.

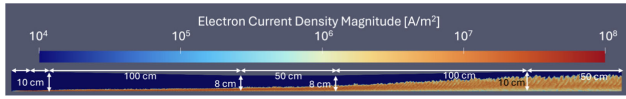


FIG. 9. Electron current density for a planar MITL with a 10 cm gap and an 8 cm gap region spanning the middle 50 cm of length, with 1 m transitions. Source impedance, 24 Ω ; load impedance, 37.7 Ω ; voltage, 10 MV.

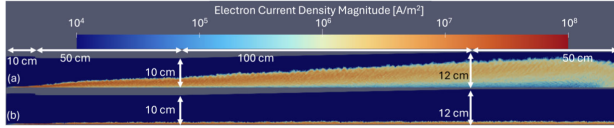


FIG. 10. Electron current density (a) before and (b) after wave reflection from load for a planar MITL transitioning from 10 cm (upstream) to 12 cm (downstream) abruptly. Source impedance, 18 Ω ; load impedance, 18 Ω ; voltage, 10 MV.

losses occur, which create a current divider, allowing different Z_{op} in different MITL sections.

Figures 8 and 9 show a large-small-large configuration. Despite significant deviations from theoretical assumptions for the upstream and downstream 10 cm sections shown in Fig. 8, the entire MITL reaches a Z_{op} corresponding to the 8 cm middle section. The lowest self-limited Z_{op} becomes Z_{op} for the entire MITL, seemingly independent of the number of different geometries. Future work will be required to assess whether different Z_{op} regions can exist after equilibration, perhaps due to continuous electron losses to the anode.

This modular nature extends to load impedance Z_l below all self-limited Z_{op} for the entire MITL. Figures 10(a) and 11(a) depict the moment just before retrapping propagates upstream for $Z_l = 18 \Omega$. Figures 10(b) and 11(b) show superinsulated flow with a thin electron flow layer after quasiequilibrium is reached, even with abrupt transitions in geometry.

Everywhere, $Z_{op} \equiv Z_l$, as shown in Fig. 12. When pulse durations are much longer than the source-load transit time of the MITL, allowing retrapping from the load to propagate throughout, this low Z_l case enables vastly simplified analysis and interpretation. So long as Z_l is lower than the self-limited Z_{op} everywhere in the MITL, the MITL operates at Z_l , regardless of the number of geometry changes provided that no electron losses occur after retrapping is complete.

Conclusion. This study examined constant- and variable-gap magnetically insulated transmission lines (MITLs). In each case, the operating impedance of the entire MITL changed to the lowest impedance among the load impedance and the self-limited operating impedance of each MITL section, where the self-limited condition corresponds

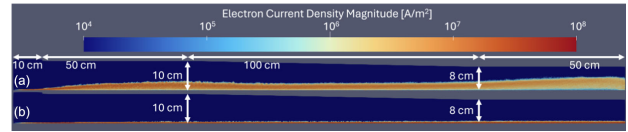


FIG. 11. Electron current density (a) before and (b) after wave reflection from load for a planar MITL transitioning from 10 cm (upstream) to 8 cm (downstream) abruptly. Source impedance, 18 Ω ; load impedance, 18 Ω ; voltage, 10 MV.

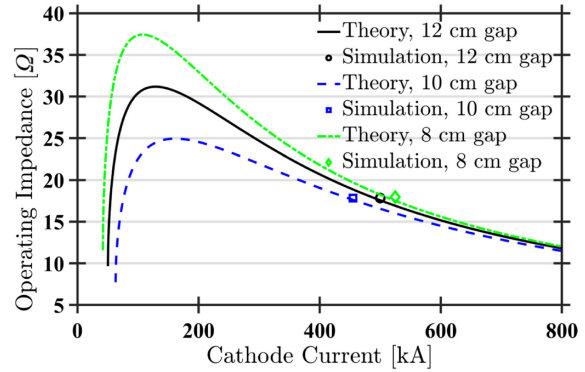


FIG. 12. Operating impedances Z_{op} for 10 to 8 cm and 10 to 12 cm MITLs with step transitions between sections and source impedance, 18 Ω ; load impedance, 18 Ω ; voltage, 10 MV. Data overlap for 10 cm MITL regions in both geometries.

to MITL operation in a constant-gap geometry with a large load impedance (even an open circuit load). Electron flow changes the operating impedance in each MITL section such that the variable-gap MITL has constant impedance everywhere. This effect propagates forward (toward the load) for small-to-large gap transitions and backward (toward the source) for large-to-small gap transitions. If an experimental pulse duration is longer than the source-to-load transit time, allowing equilibration to a quasiequilibrium condition, variable-gap MITLs will operate at a constant impedance throughout. Note that the effect of electron losses at quasiequilibrium was beyond the scope of this Letter and may enable variable-impedance behavior.

Future work is needed to understand the role of electron losses in MITL operating impedance. Additional study is needed to assess how these results can be applied to transient systems where the pulse duration is short compared to transit time.

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This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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