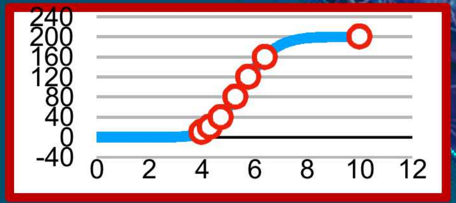
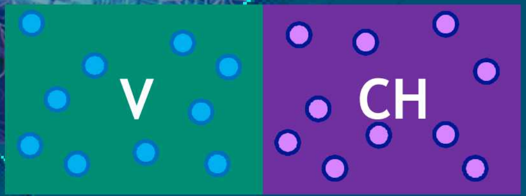
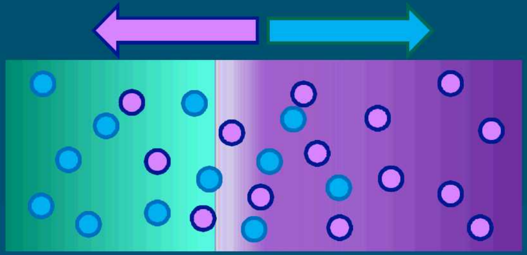
SAND2019-9432C

Experimental Validation of Dense Plasma Transport Models using the Z-Machine







PRESENTED BY

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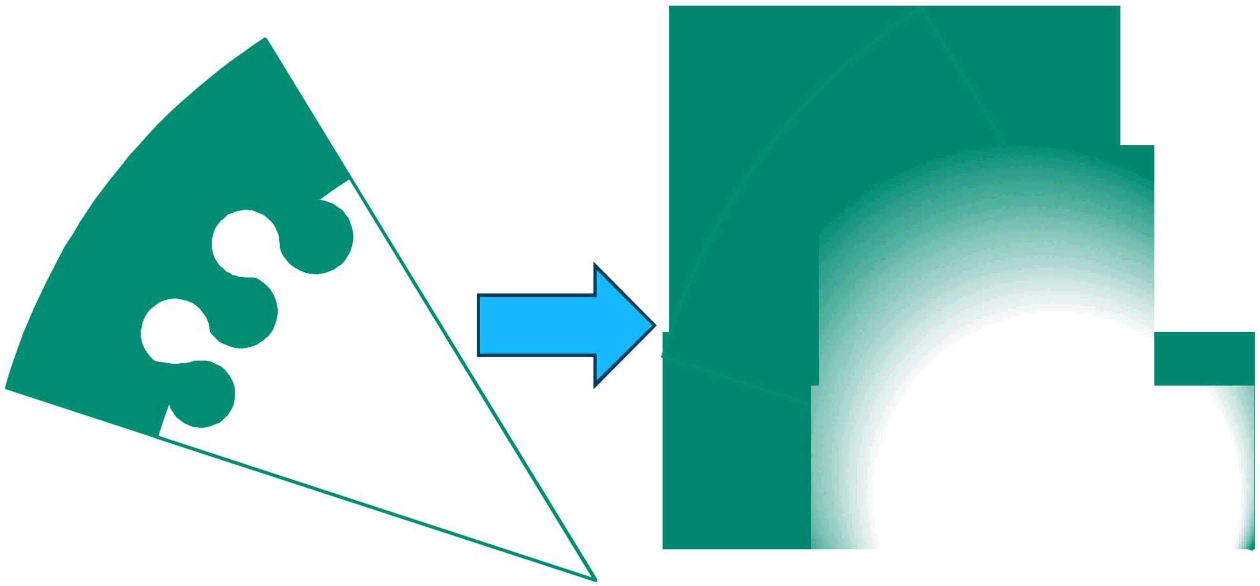
This project has been a large interdisciplinary effort

- Diagnostic Development
  - E.C. Harding, M. Schollmeier, G.P. Loisel, S.B. Hansen
- Sample Development
  - S.B. Hansen, P.J. Christenson, P.F. Knapp, T. Mattsson
- Target Fabrication
  - Haibo Huang, Reny Paguio, Brian Stahl
  - *General Atomics, La Jolla, CA*
- Modeling and Source Development
  - R. Vesey, P. J. Christenson, T. Mattsson, K. Beckwith, C. Kopenhafer, L. Stanek, R. Clay III, M. Murillo
- Multi-species BGK theory and code development
  - J. Haack (LANL), L. Stanton (SJSU), M. Murillo (MSU) and C. Hauck (ORNL)

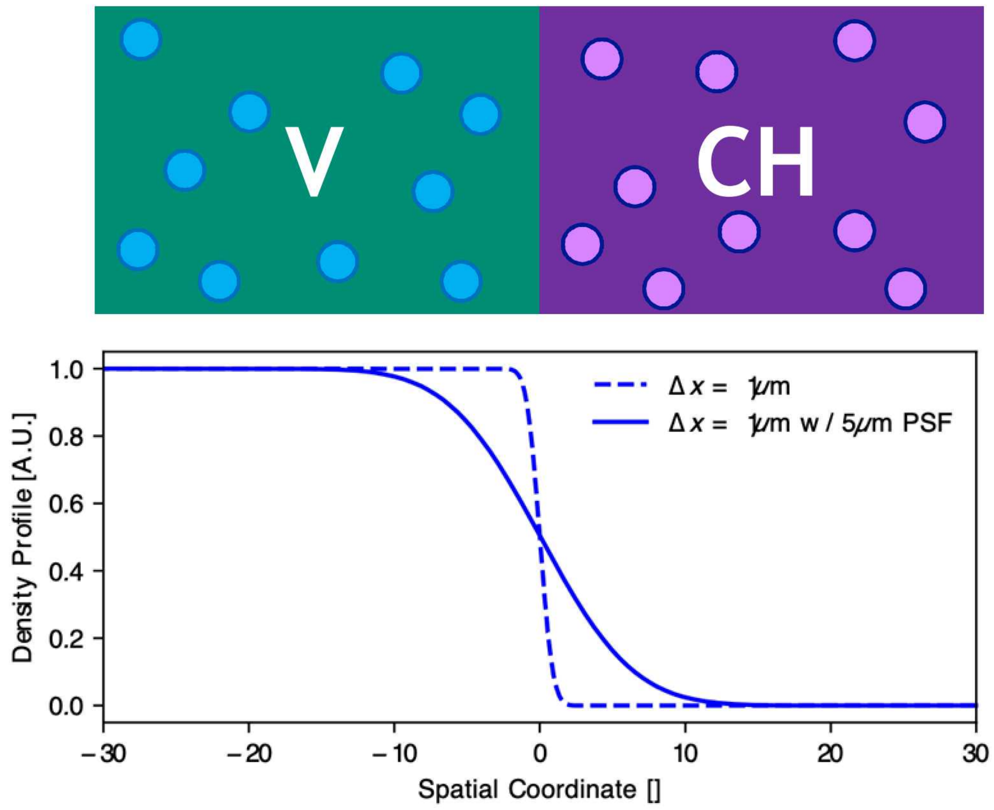
Understanding material transport across an interface is fundamentally tied to our understanding of mix

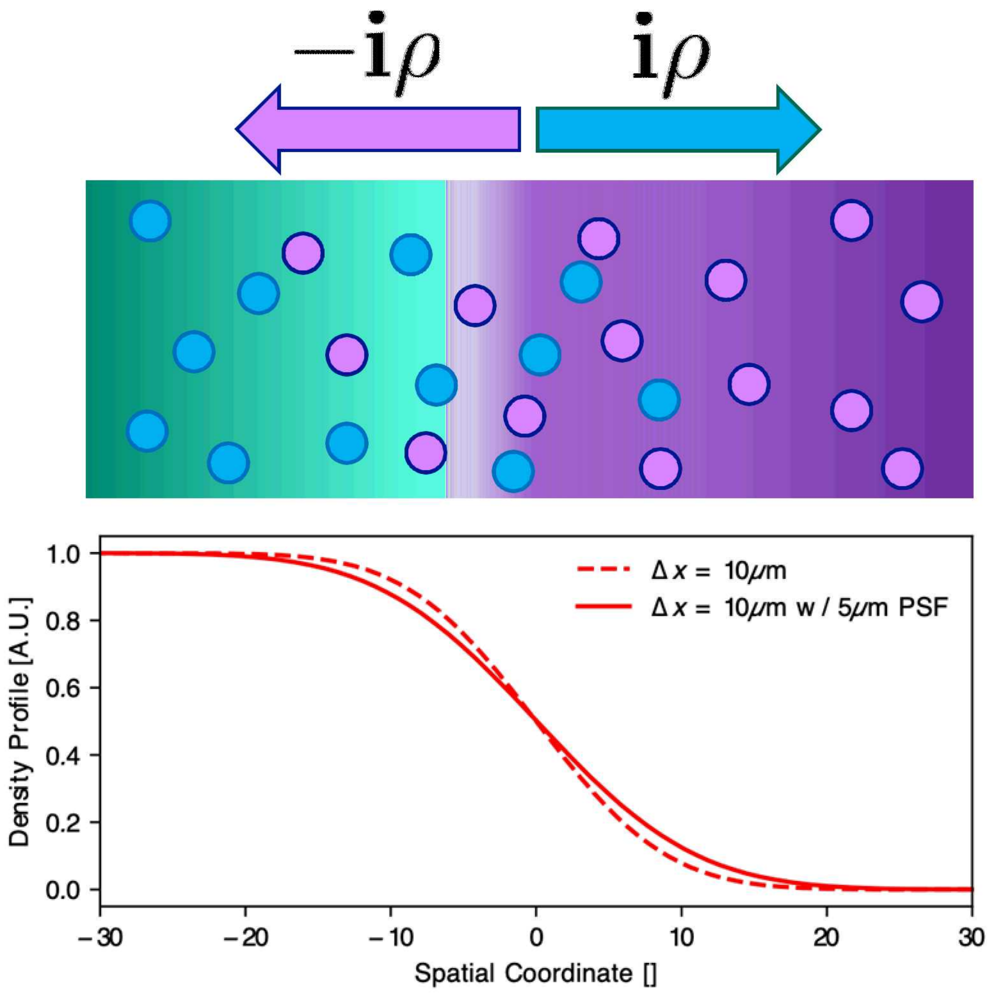


- In addition to distorting the hotspot shape and introducing vorticity, perturbations will
  - increase the surface area available for transport processes
  - decrease the scale length over which transport needs to operate to mix a volume
- Unfortunately fluid models don't account for transport processes well, particularly in strongly coupled plasmas

- How does an interface go from perturbed to mixed
- Is it just hydrodynamic stirring/turbulence?
- What role does diffusion play?

We want to measure the “blurring” of an interface between a strongly coupled mid-Z element and a low Z material





Plasma Transport Sample and Diagnostic Concept

Half moon sample allows transmission to be obtained from the attenuation

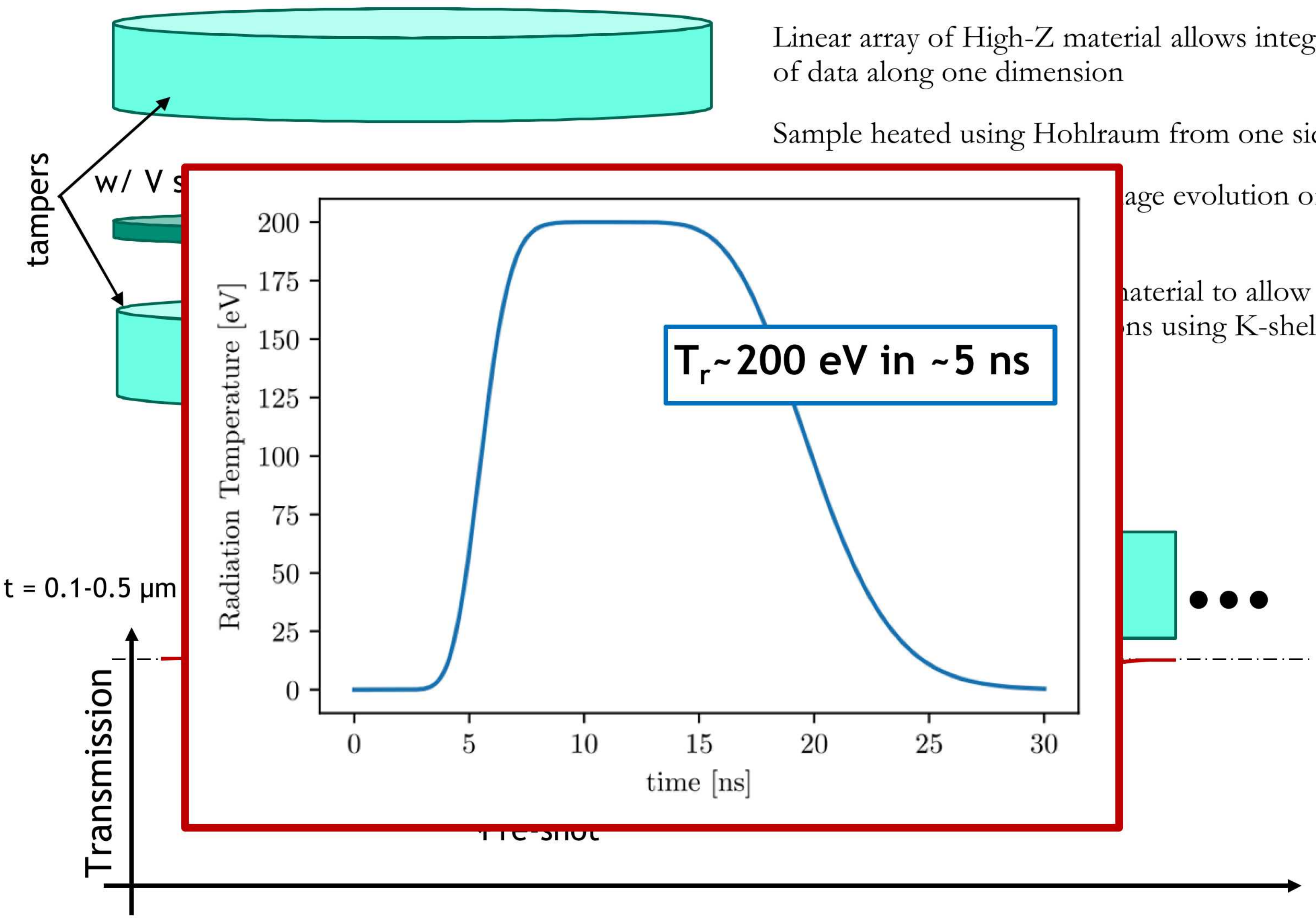
Linear array of High-Z material allows integration of data along one dimension

Sample heated using Hohlraum from one side

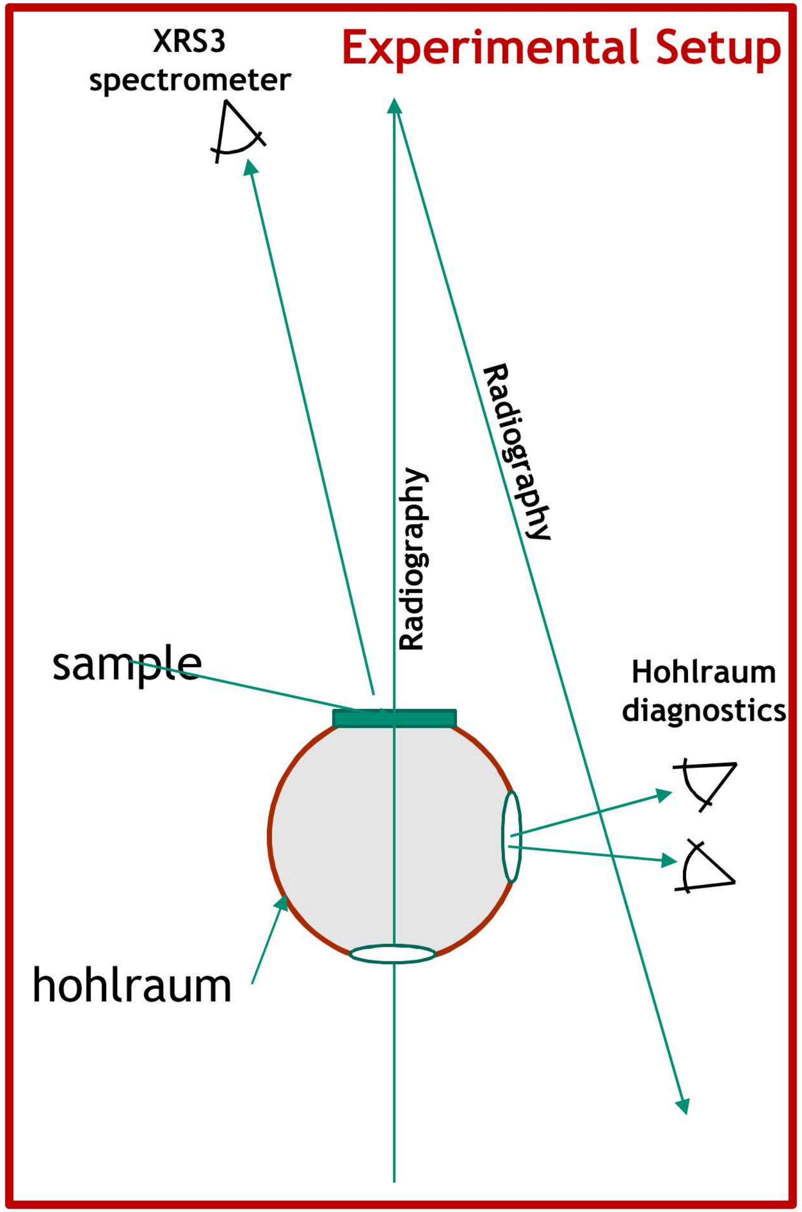
age evolution of high

aterial to allow
ns using K-shell

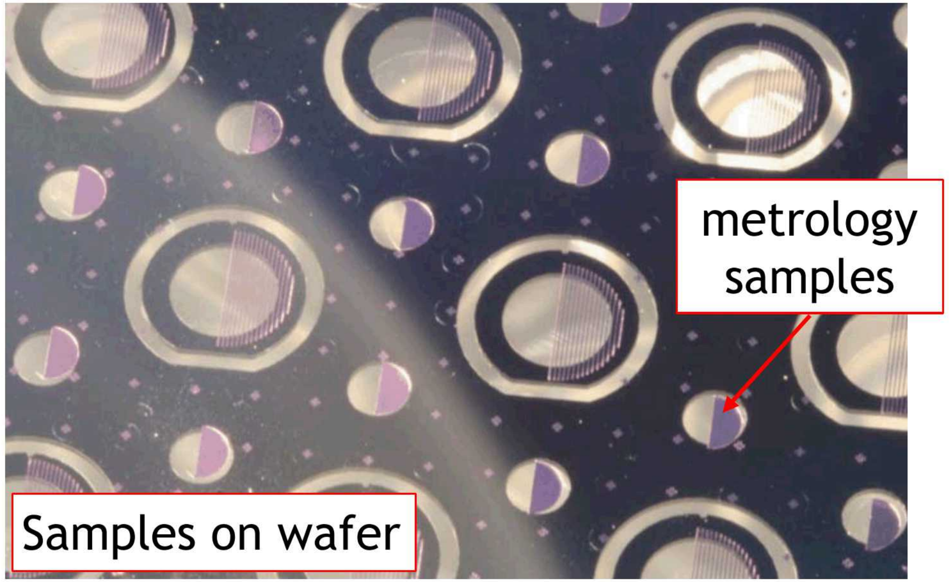
Conceptual Sample

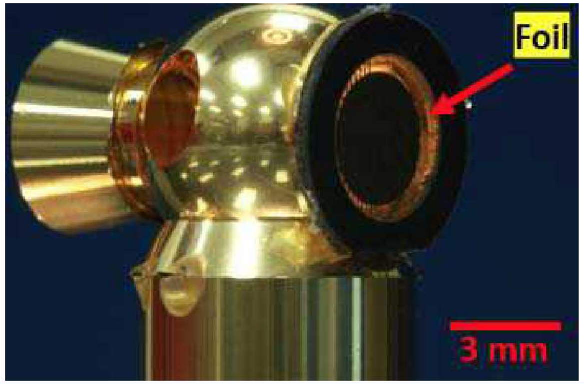


Experimental Setup

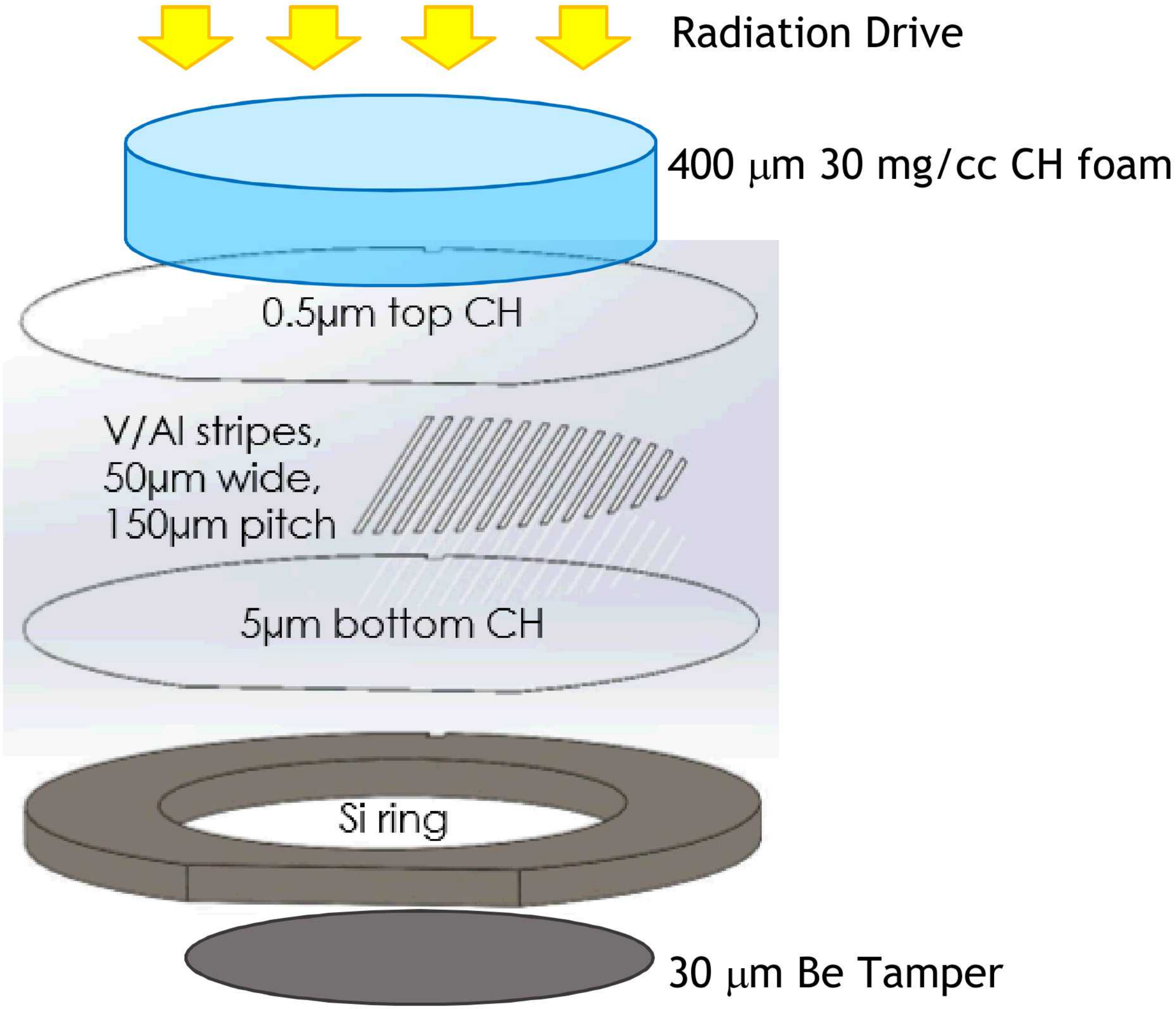


Fabrication of the sample required significant R&D by general atomics





Sample on hohlraum w/ Be tamper attached

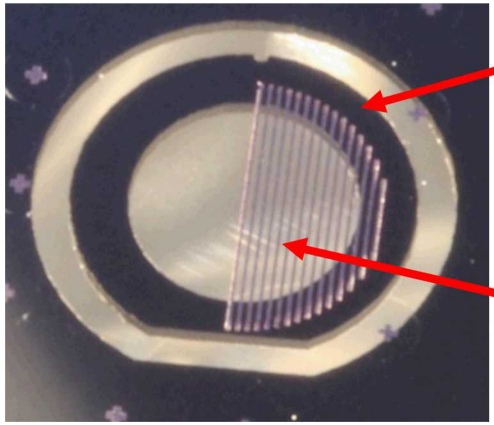


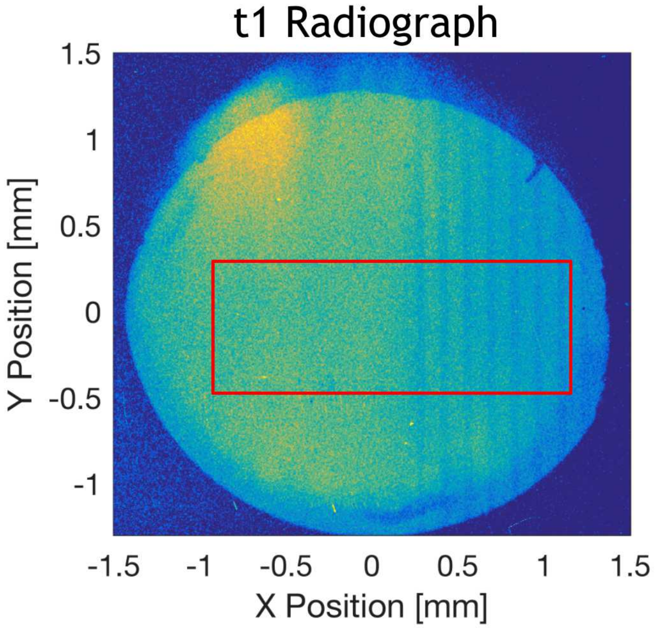
- Requirement of sharp interface led to use of lithographic technique
- Significant effort in metrology for areal density, mixture properties, and edge widths

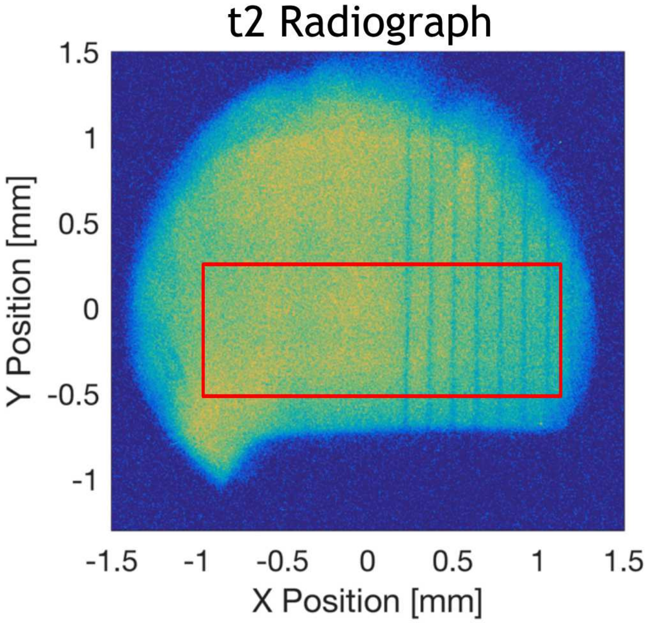
Material provided by Haibo Huang, General Atomics

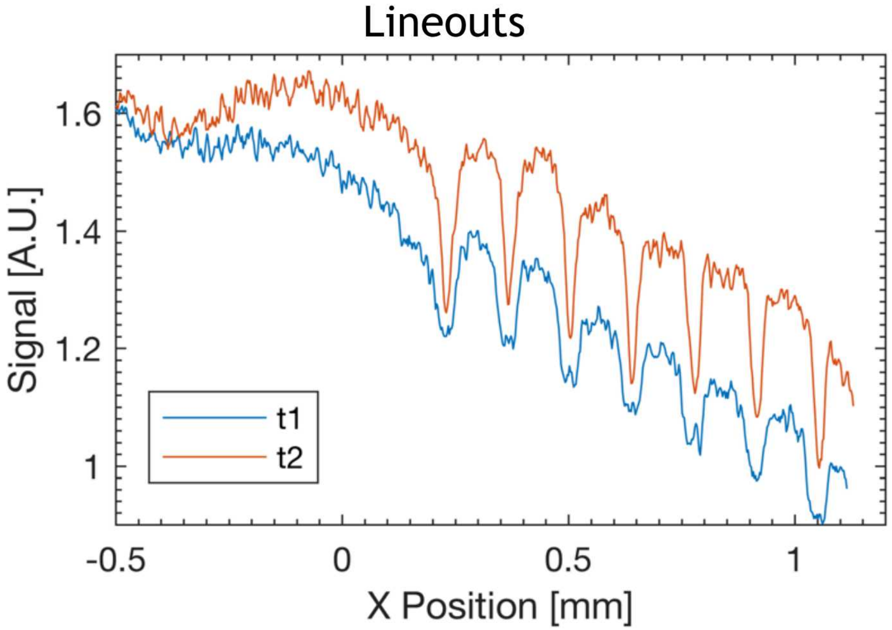
First plasma transport experiments have been executed on Z demonstrating the feasibility of the proposed measurement

- Executed two experiments in March testing x-ray heating and diagnostics performance
- Demonstrated good contrast of the sample in the radiographs on shot z3220 (6.1 keV backlighter with detector placed at closer focal position)





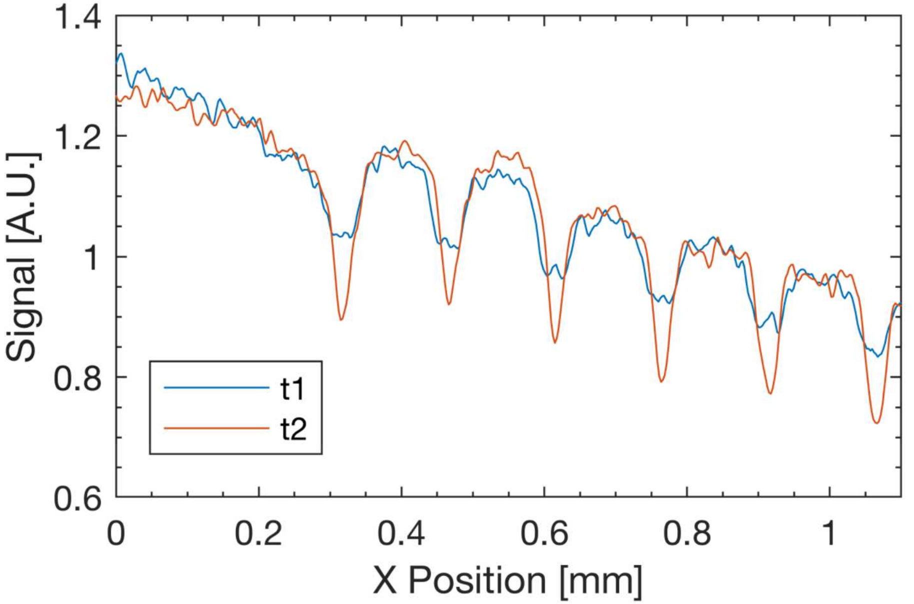


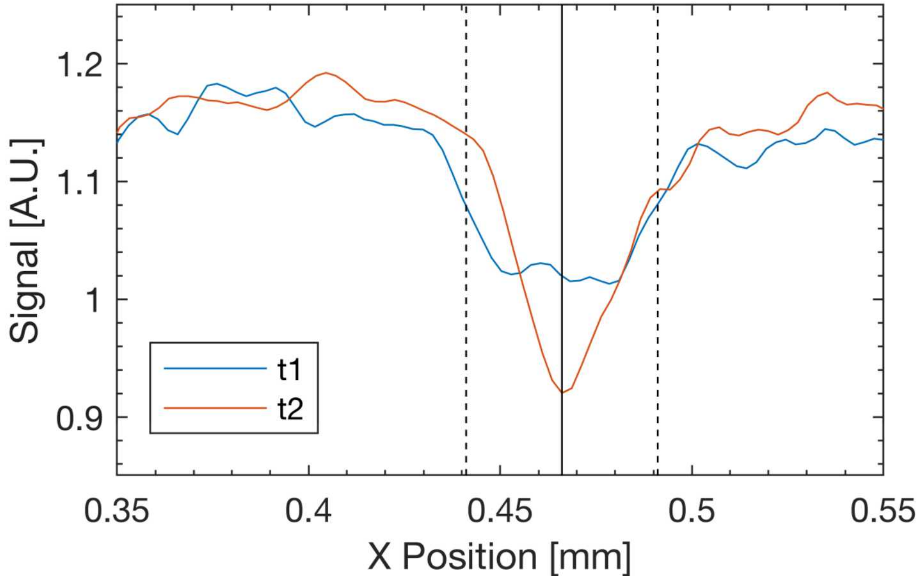


A closer look at the experimental data

There is a clearly visible difference between the two frames

- The V strips appear to get "squeezed"
- There is a substantial absorption difference (hohlraum emission makes it difficult to assess this)
- The width of the strips is approximately correct, though the resolution is not as good as anticipated





Boltzmann Equation for HED Plasma Transport

Direct integration of equations of motion:

- *Too* expensive for timescales & length scales of interest for plasma transport experiments

Dense plasmas: strongly collisional and near equilibrium:

- Adopt a *multi-species* Boltzmann model to provide *kinetic* description of plasma transport

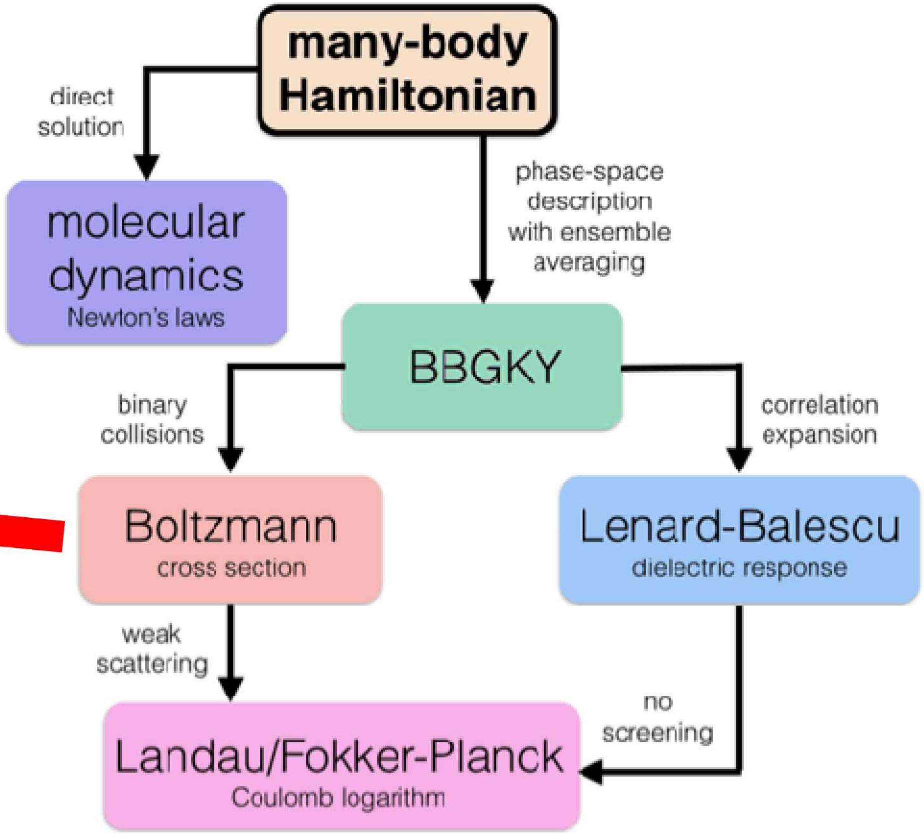
$$\frac{\partial f_i}{\partial t} + \mathbf{c}\cdot\nabla_{\mathbf{x}} f_i + \mathbf{a}_i\cdot\nabla_{\mathbf{c}} f_i = Q_i[\mathbf{f}], \quad i \in \mathcal{S}.$$

Collision operator is criti

$$Q_i[\mathbf{f}] = \sum_{j \in \mathcal{S}} Q_{ij}[f_i, f_j],$$

$$Q_{ij}[f_i, f_j] = \int \left(f_i(\mathbf{c}')f_j(\mathbf{c}_*') - f_i(\mathbf{c})f_j(\mathbf{c}_*)\right) g\sigma_{ij}\, d\Omega\, d\mathbf{c}_*.$$

- Has to guarantee conservation of mass, momentum and energy and that the entropy is constant to increasing (*H*-theorem)



Stanton & Murillo (2016): Fig.1
Relevant Structure of Kinetic Theory
[for transport in HED Plasmas]

BGK Collision Operator for HED Plasma Transport

Dense plasmas: strongly collisional and near equilibrium:

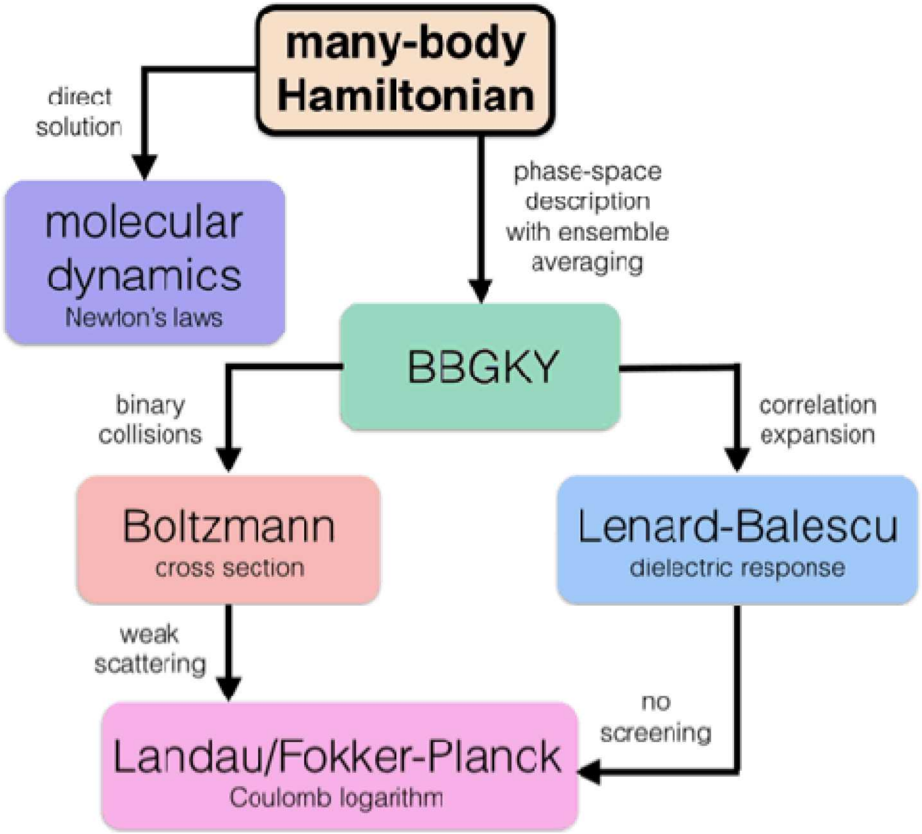
- Expand collision operator about equilibrium: BGK-like approach (Haack et al., 2017a)
- Replace Boltzmann collision operator with a relaxation operator that (Haack et al., 2017a):
  - Conserves particle number, momentum and energy
  - Satisfies the *H*-theorem

$$Q_i[\mathbf{f}] = \sum_{j} Q_{ij}[f_i, f_j], \quad Q_{ij}^{\mathrm{BGK}} = \nu_{ij}(\mathbf{c})(\mathcal{M}_{ij} - f_i),$$

$$\mathcal{M}_{ij}[f_i, f_j] = n_i \left(\frac{m_i}{2\pi T_{ij}}\right)^{3/2} \exp\left[-\frac{m_i(\mathbf{c} - \mathbf{v}_{ij})^2}{2T_{ij}}\right],$$

$$\mathbf{v}_{ij} = \frac{\rho_i \nu_{ij} \mathbf{v}_i + \rho_j \nu_{ji} \mathbf{v}_j}{\rho_i \nu_{ij} + \rho_j \nu_{ji}}, \quad T_{ij} = \frac{n_i \nu_{ij} T_i + n_j \nu_{ji} T_j}{n_i \nu_{ij} + n_j \nu_{ji}} + \frac{\rho_i \nu_{ij}(v_i^2 - v_{ij}^2) + \rho_j \nu_{ji}(v_j^2 - v_{ij}^2)}{3(n_i \nu_{ij} + n_j \nu_{ji})},$$

  - Cross distribution depends on single species density, mass and cross velocity, temperatures and interspecies collisions rates
    - **Unknown: how to compute collision rates?**



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Collision Rates for HED Plasma Transport

Dense plasmas: strongly collisional and near equilibrium:

- Expand collision operator about equilibrium: BGK-like approach (Haack et al., 2017a)
- BGK collision operator has the form:

$$Q_{ij}^{BGK} = \nu_{ij}(\mathbf{c})(\mathcal{M}_{ij} - f_i), \qquad \nu_{ij}(\mathbf{c}) = \int \mathcal{M}_{ji}(\mathbf{c}) g \sigma_{ij} \, d\Omega d\mathbf{c}_*$$

- Issues:
  - Analytic form *only* known for Maxwell molecules
  - Integral here is singular for (e.g.) Coulomb potentials
- Compare momentum, temperature relaxation rates for Boltzman vs. BGK collision operators:

$$\frac{\partial}{\partial t}(\mathbf{v}_j - \mathbf{v}_i)\Big|_{Boltz} = -\alpha_{ij}\left[\left(\frac{\rho_i + \rho_j}{\rho_i \rho_j}\right)\frac{m_i + m_j}{2}\right](\mathbf{v}_j - \mathbf{v}_i), \qquad \frac{\partial}{\partial t}(T_j - T_i)\Big|_{Boltz} = -\alpha_{ij}\left[\left(\frac{n_i + n_j}{n_i n_j}\right)(T_j - T_i) + \frac{(\mathbf{v}_j - \mathbf{v}_i)^2}{3}\left(\frac{\rho_j - \rho_i}{n_i n_j}\right)\right],$$

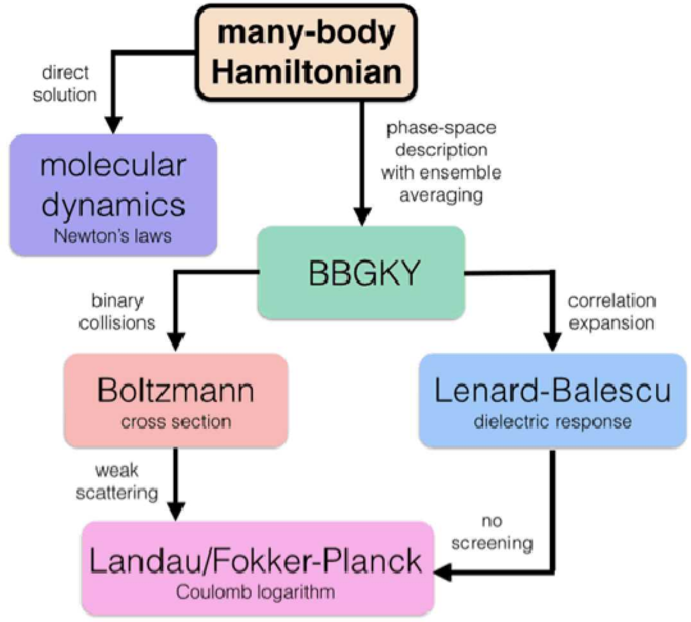
$$\frac{\partial}{\partial t}(\mathbf{v}_j - \mathbf{v}_i)\Big|_{BGK} = \nu_{ji}(\mathbf{v}_{ji} - \mathbf{v}_j) - \nu_{ij}(\mathbf{v}_{ij} - \mathbf{v}_i), \qquad \frac{\partial}{\partial t}(T_j - T_i)\Big|_{BGK} = \nu_{ji}\left((T_{ji} - T_j) + \frac{m_j}{3}(\mathbf{v}_{ji} - \mathbf{v}_j)^2\right) - \nu_{ij}\left((T_{ij} - T_i) + \frac{m_i}{3}(\mathbf{v}_{ij} - \mathbf{v}_i)^2\right).$$

  - Hard to satisfy both simultaneously. Instead satisfy either *momentum relaxation* or *temperature relaxation*.
- Utilize *generalized Coulomb logarithm* from Stanton & Murillo (2016) to compute collision cross-sections

$$\nu_{ij}^{M} = \frac{1}{\rho_i}\frac{128\pi^2 n_i n_j (m_i m_j)^{3/2}(Z_i Z_j e^2)^2}{3(2\pi)^{3/2}\mu_{ij}(m_j T_i + m_i T_j)^{3/2}} K_{11}(\gamma$$

$$\nu_{ij}^{T} = \frac{1}{n_i}\frac{256\pi^2 n_i n_j (m_i m_j)^{1/2}(Z_i Z_j e^2)^2}{3(2\pi)^{3/2}(m_i T_j + m_j T_i)^{3/2}} K_{11}(\gamma_{ij}$$

$$K_{11}(\gamma) = \begin{cases} -\frac{1}{4}\log\left(\sum_{k=1}^{5} a_k \gamma^k\right), & \gamma < 1 \\ \frac{b_0 + b_1 \log\gamma + b_2 \log^2\gamma}{1 + b_3\gamma + b_4\gamma}, & \gamma > 1. \end{cases}$$



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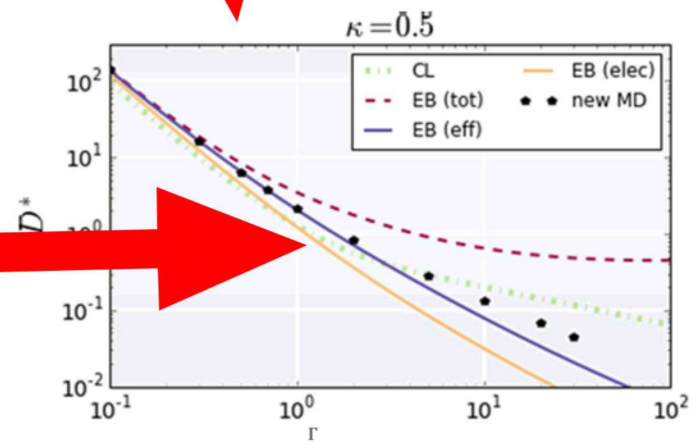
Stanton & Murillo (2016): Fig.10
Dimensionless self-diffusion coefficient computed using screened interaction



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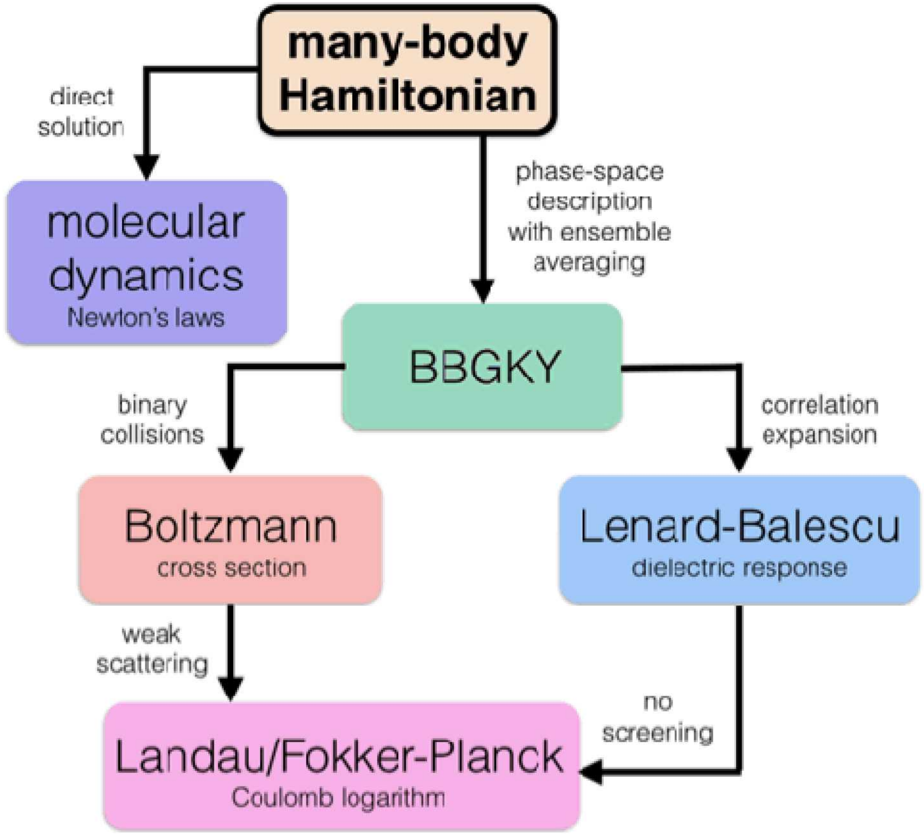
- Hydrodynamics found from taking moments over distribution function:

$$n_i = \int f_i d\mathbf{c}, \quad \rho_i = m_i n_i, \quad \mathbf{v}_i = \frac{1}{\rho}\int m_i \mathbf{c} f_i d\mathbf{c},$$

  - Mass conservation: $\frac{\partial \rho_i}{\partial t} + \nabla_{\mathbf{x}}\cdot(\rho_i \mathbf{v}) + \nabla_{\mathbf{x}}\cdot(\rho_i \mathbf{V}_i) = 0,$
  - Momentum conservation: $\frac{\partial(\rho\mathbf{v})}{\partial t} + \nabla_{\mathbf{x}}\cdot(\rho\mathbf{v}\otimes\mathbf{v}) + \nabla_{\mathbf{x}}\cdot\mathbf{P} = \sum_i \rho_i\mathbf{a}_i,$
  - Energy conservation: $\frac{3}{2}\left(\frac{\partial(nT)}{\partial t}+\nabla_{\mathbf{x}}\cdot(nT\mathbf{v})\right)+\nabla_{\mathbf{x}}\cdot\mathbf{q}+\mathbf{P}:\nabla_{\mathbf{x}}\mathbf{v} = \sum_i \rho_i \mathbf{V}_i\cdot\mathbf{a}_i,$
- Closures:

$$\mathbf{V}_i = \frac{1}{n_i}\int \mathbf{C} f_i d\mathbf{c} = \mathbf{v}_i - \mathbf{v}. \quad \mathbf{P} = \sum_{i\in\mathcal{S}}\int m_i \mathbf{C}\otimes\mathbf{C} f_i d\mathbf{c} = \sum_{i\in\mathcal{S}}\mathbf{P}_i. \quad \mathbf{q} = \sum_{i\in\mathcal{S}}\int \frac{m_i}{2} C^2 \mathbf{C} f_i d\mathbf{c} = \sum_{i\in\mathcal{S}}\mathbf{q}_i.$$



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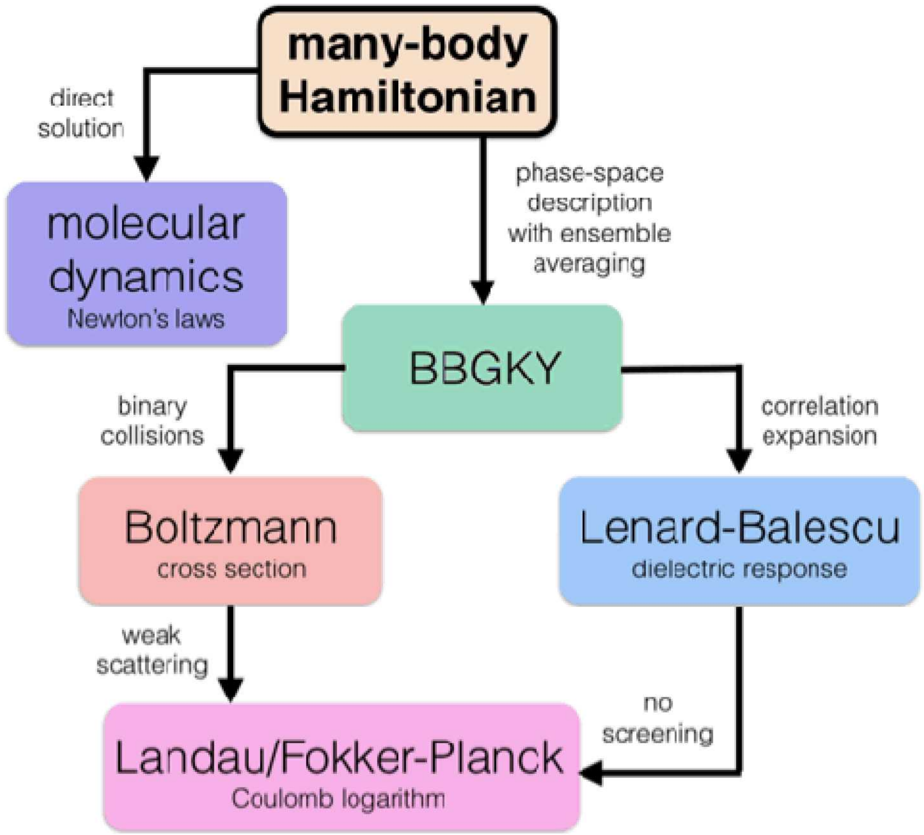
  - Mass conservation: $$\frac{\partial \rho_i}{\partial t} + \nabla_{\mathbf{x}} \cdot (\rho_i \mathbf{v}) + \nabla_{\mathbf{x}} \cdot (\rho_i \mathbf{V}_i) = 0,$$
  - Momentum conservation: $$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla_{\mathbf{x}} \cdot (\rho \mathbf{v} \otimes \mathbf{v}) + \nabla_{\mathbf{x}} \cdot \mathsf{P} = \sum_i \rho_i \mathbf{a}_i,$$
  - Energy conservation: $$\frac{3}{2}\left(\frac{\partial (nT)}{\partial t} + \nabla_{\mathbf{x}} \cdot (nT\mathbf{v})\right) + \nabla_{\mathbf{x}} \cdot \mathbf{q} + \mathsf{P} : \nabla_{\mathbf{x}} \mathbf{v} = \sum_i \rho_i \mathbf{V}_i \cdot \mathbf{a}_i,$$
- Closures:

$$\mathsf{P} = pT - \eta[(\nabla \mathbf{v} + (\nabla \mathbf{v})^T] - 2/3(\nabla \cdot \mathbf{v})\mathsf{I}]$$

$$\mathbf{d}_i = \nabla x_i + (x_i - y_i)\nabla \log p + \frac{\rho_i}{p}\left(\frac{Z_i e}{m_i} - \sum_j y_j \frac{Z_j e}{m_j}\right)\mathbf{E}.$$

$$\mathbf{V}_i = \sum_j D_{ij} \mathbf{d}_j. \quad \mathbf{q} = -K \nabla T + \frac{5T}{2} \sum_i n_i \mathbf{V}_i$$



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BGK Theory *Predicts Non-Fluid-like* Plasma Transport at CHO-DT Interface

Haack et al. (2017b):

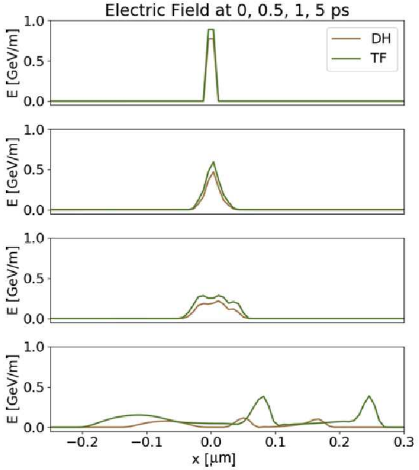
- Utilize multi-species Vlasov-Poisson-BGK system to study plasma transport at CHO-DT interface
- Electric field computed as:

$$-\frac{1}{4\pi}\nabla_x^2\phi = \sum_i Z_i e n \qquad \mathbf{E} = -\nabla_\mathbf{x}\phi,$$

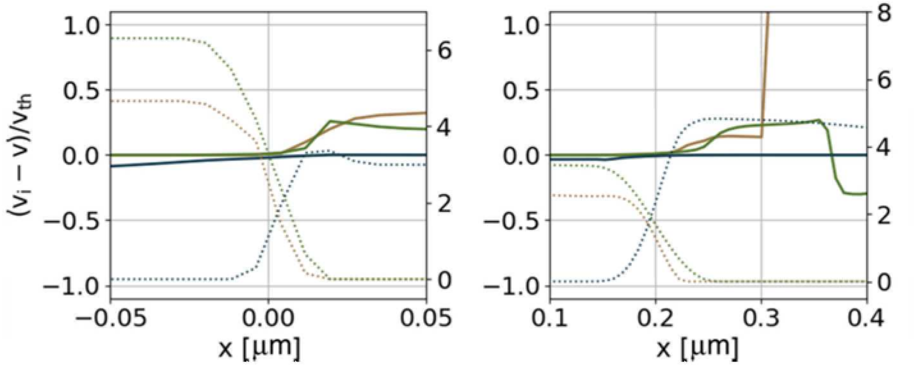
- Thomas-Fermi electron model: strong electric fields form at interface (~GeV/m).

$$n_e = \frac{2(2\pi m_e T_e)^{3/2}}{(2\pi\hbar)^3}\mathcal{F}_{1/2}[(e\phi+\mu)/T_e].$$

- Hydrogen can separate from the plastic and mix into the fuel (also dependent on the electron heating model).
- Ion diffusion velocities sufficiently large c.f. ion thermal speed to invalidate assumptions used in deriving Navier-Stokes-like fluid equations from VBGK-system
  - Predictions made with hydrodynamic models should be falsifiable



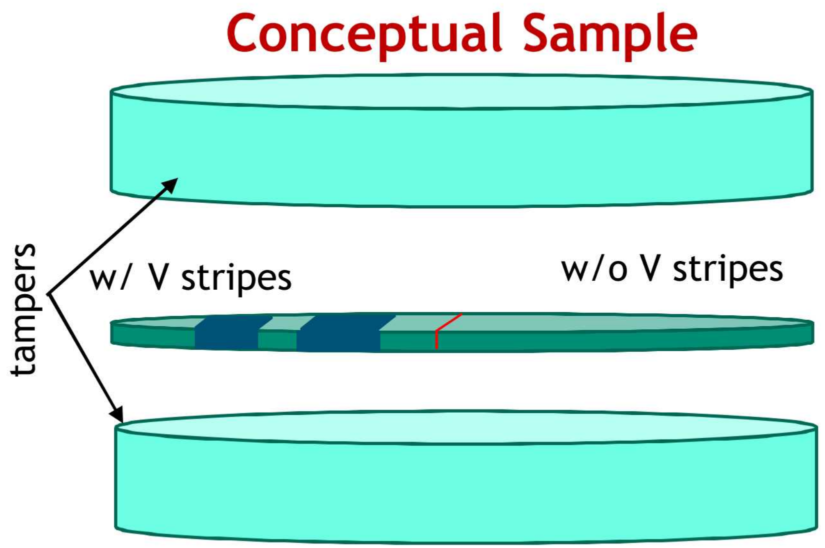
Haack et al. (2017b): Fig. 3. (left); Interfacial electric fields for CHO-DT interface computed using Debye-Huckel & Thomas-Fermi models. These electric fields drive the evolution of hydrogen at the interface

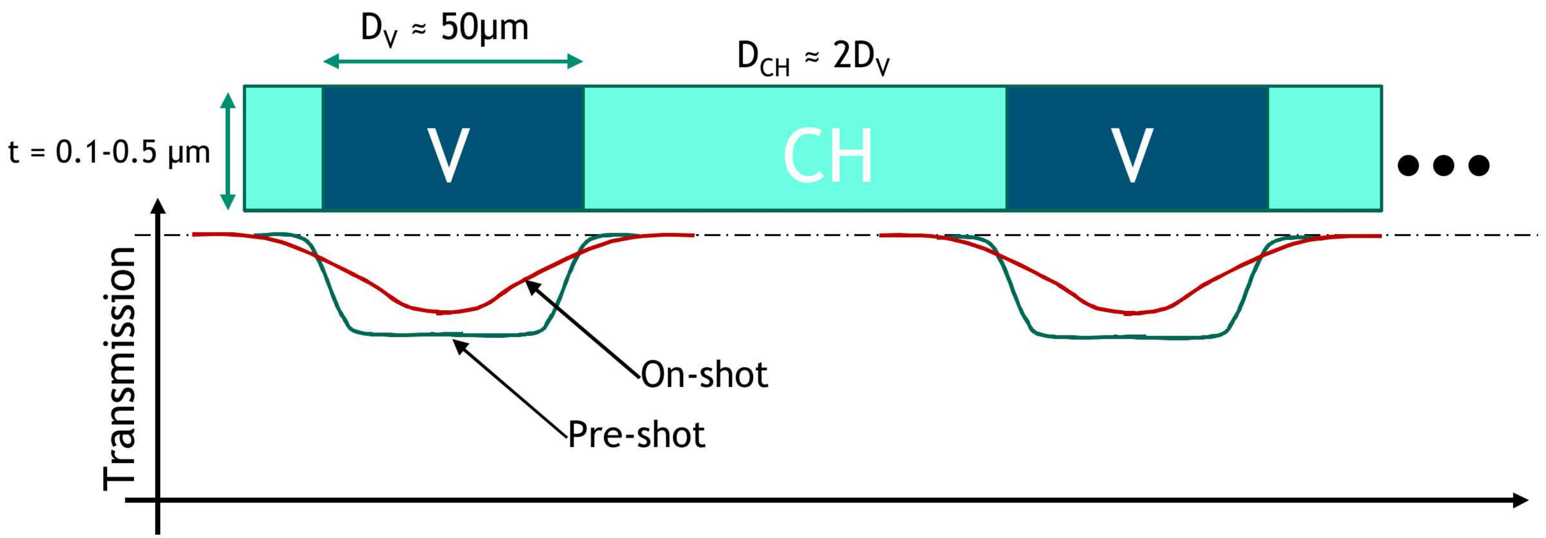


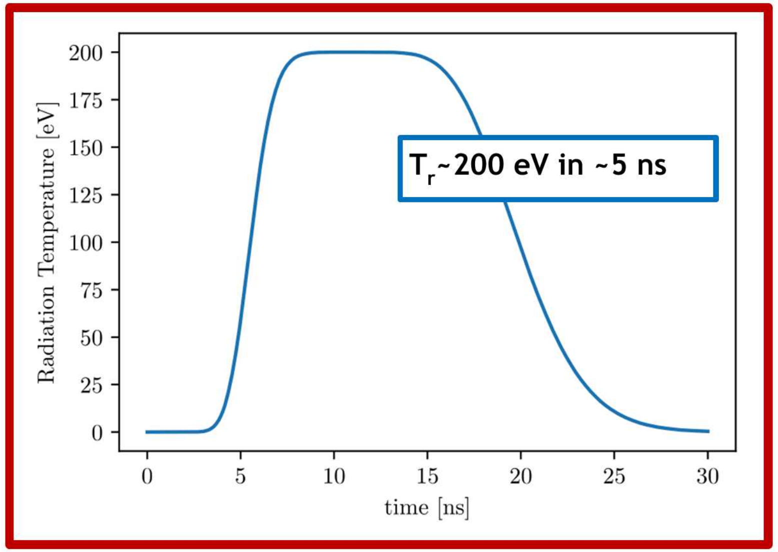
Haack et al. (2017b): Fig. 5. (above); Number densities (10-22/cc, dotted lines) and diffusion velocities (solid lines) for H (green), C (brown) and D (black) at 500fs (left) and 10 ps (right). Note the separation between the C,H distributions at the interface and that the H has diffusion velocities ~ thermal velocity

Plasma Transport Sample and Diagnostic Concept

- Utilize electrostatic multi-species kinetic code to study plasma transport at CHO-V/Al interface
  - 1d periodic setup (simulate 1 bar V/Al, 1 bar CH)
  - Thomas-Fermi Average Atom model for ionization state
  - Fermi-Dirac statistics for electrons
  - Momentum relaxation model for ion-ion collisions
- Simulation setup: replace DT-mix with V at 90% solid density with 10% Al doping
  - Ions initialized at 10eV
  - Assume radiation and electrons are in temperature equilibrium:
    - Ramp electrons from 10eV to 200eV
    - At experimental densities, electrons exhibit quantum effects *below* 10eV, therefore start simulations at 10eV (4ns)







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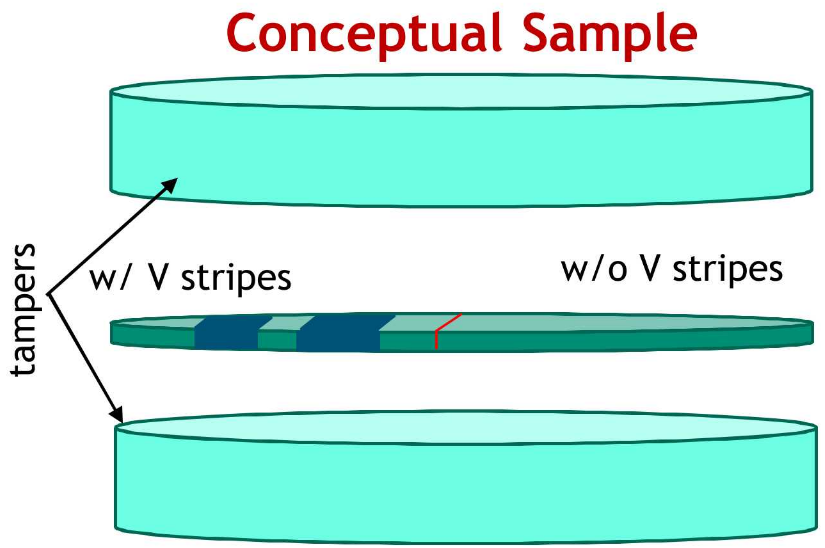
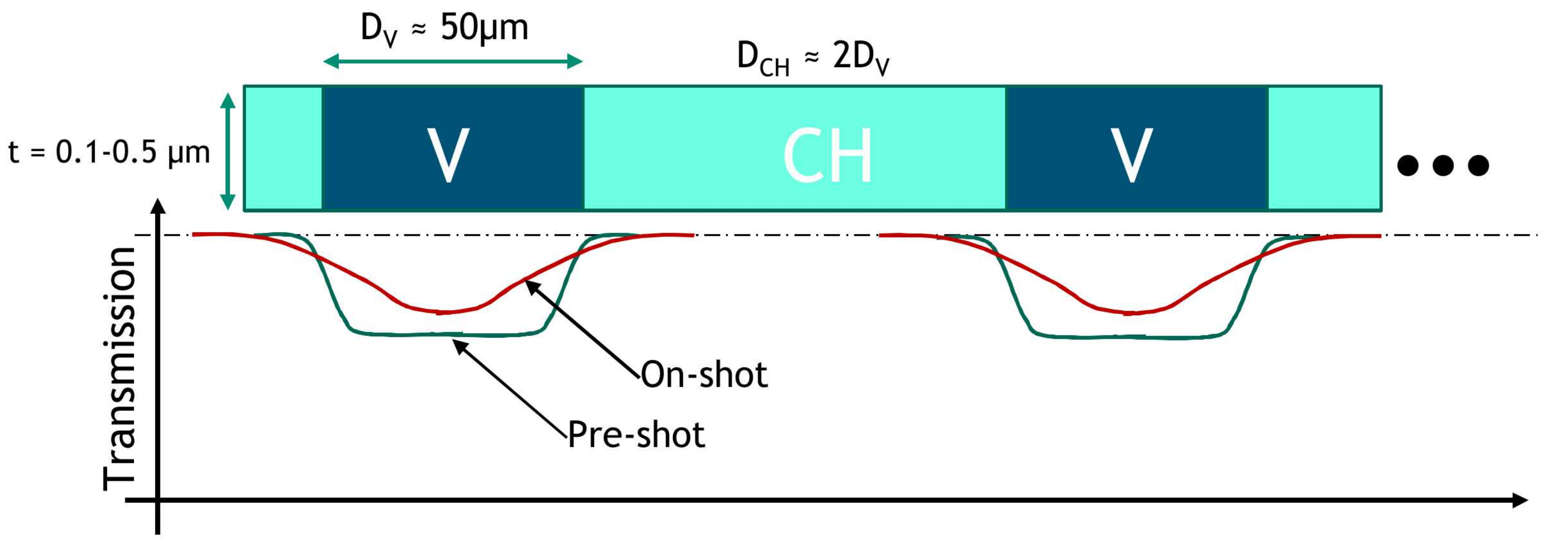
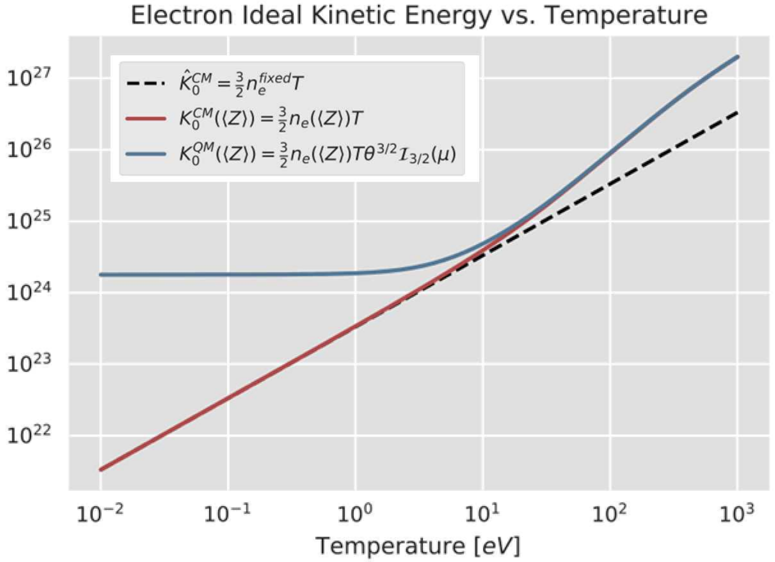
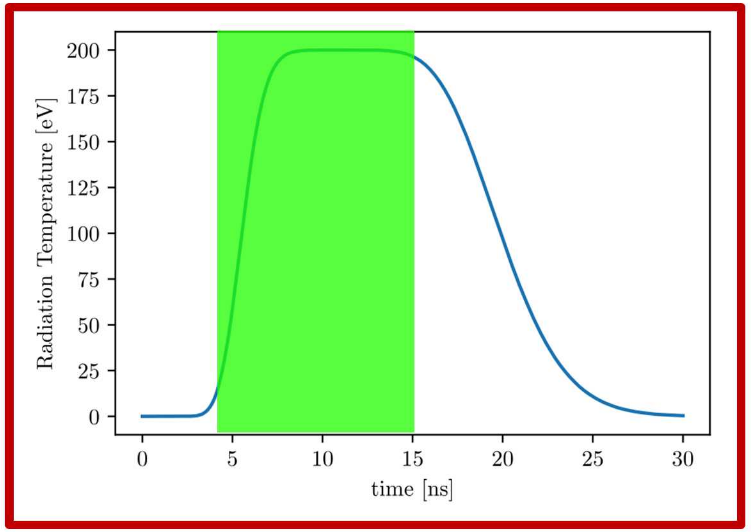






Kinetic Modeling of V/CH Interface: Electrons in Thermal Equilibrium with Radiation



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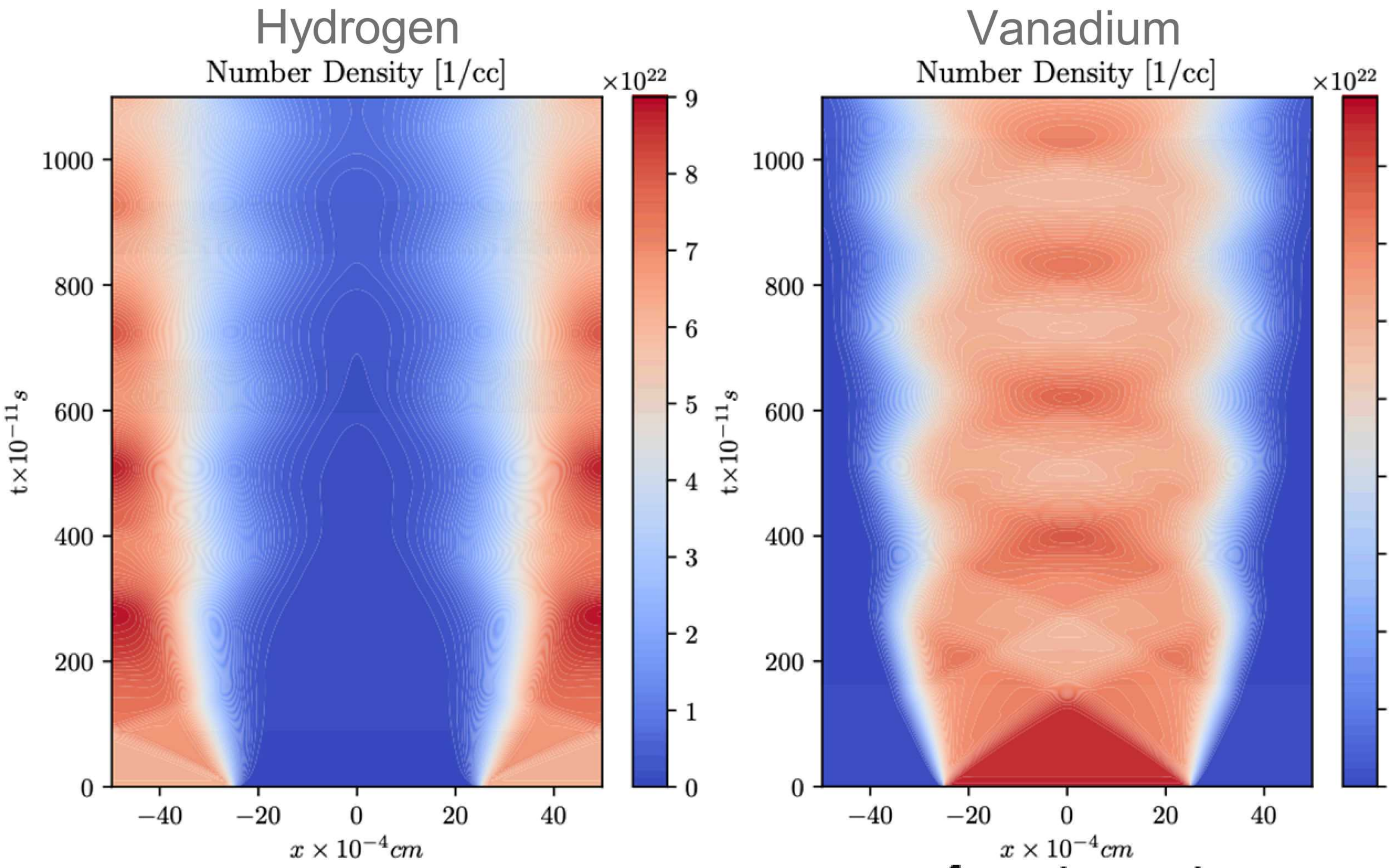
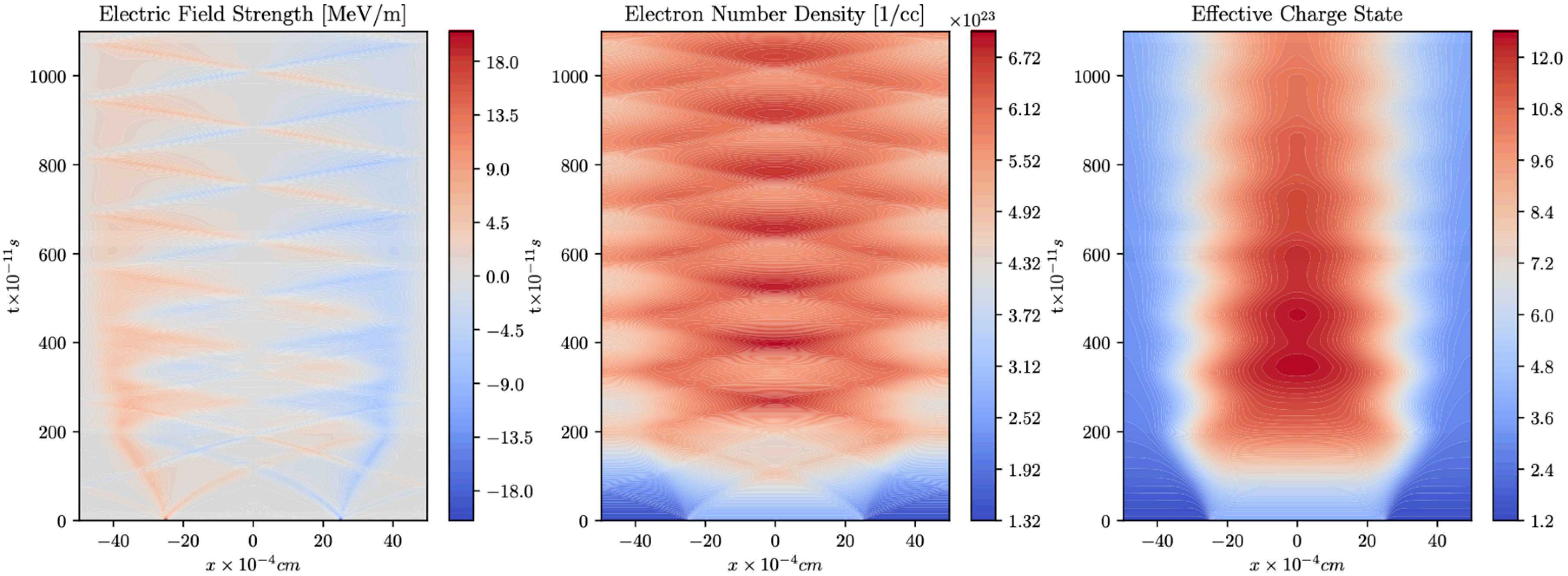
  - Assume radiation and electrons are in temperature equilibrium:
    - Ramp electrons from 10eV to 200eV



$$\nu_{ij}^M = \frac{1}{\rho_i}\frac{128\pi^2 n_i n_j (m_i m_j)^{3/2}(Z_i Z_j e^2)^2}{3(2\pi)^{3/2}\mu_{ij}(m_j T_i + m_i T_j)^{3/2}} K_{11}(\gamma_{ij}),$$

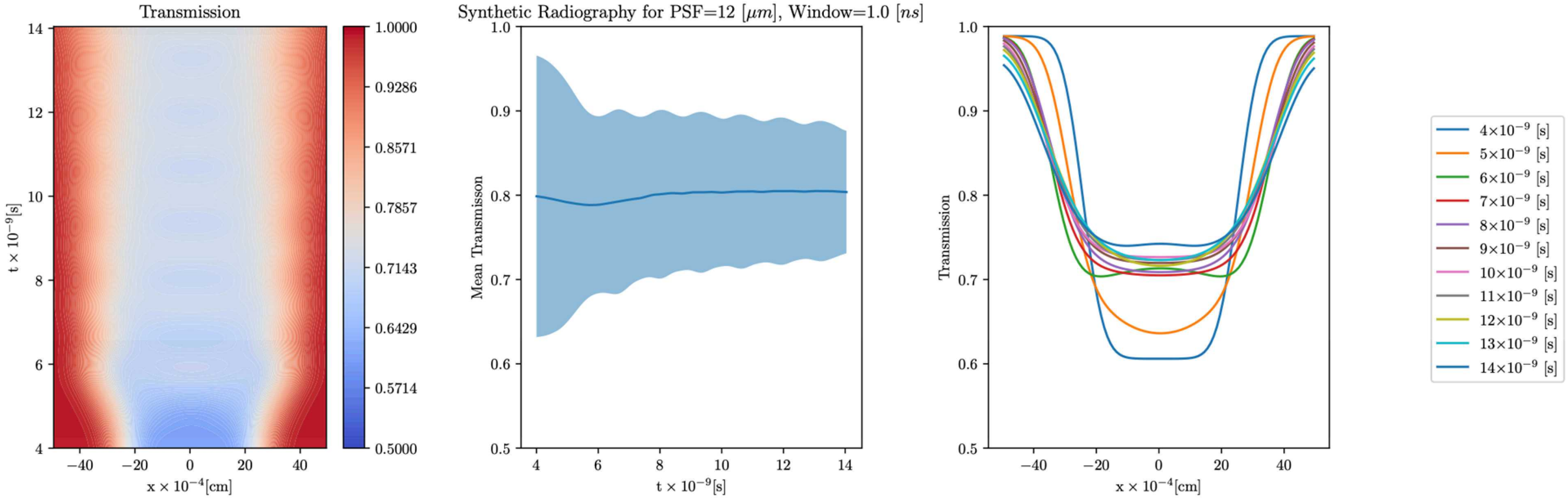
$$K_{11}(\gamma) = \begin{cases} -\frac{1}{4}\log\left(\sum_{k=1}^{5} a_k \gamma^k\right), & \gamma < 1 \\ \frac{b_0 + b_1 \log\gamma + b_2 \log^2\gamma}{1 + b_3\gamma + b_4\gamma}, & \gamma > 1. \end{cases}$$

Kinetic Modeling of V/CH Interface: Electrostatic Fields



- Simulation setup: replace DT-mix with V at 90% solid density with 10% Al doping
  - Thomas-Fermi Average Atom model for ionization state; Fermi-Dirac statistics for electrons
  - Momentum relaxation model for ion-ion collisions
  - Ions initialized at 10eV; ramp electrons from 10eV to 200eV over 5ns
- Observe strong electric fields that spread into plasma with time:
  - Electrons rapidly spread through the sample
  - Complex variability patterns in both the electric field and the electrons

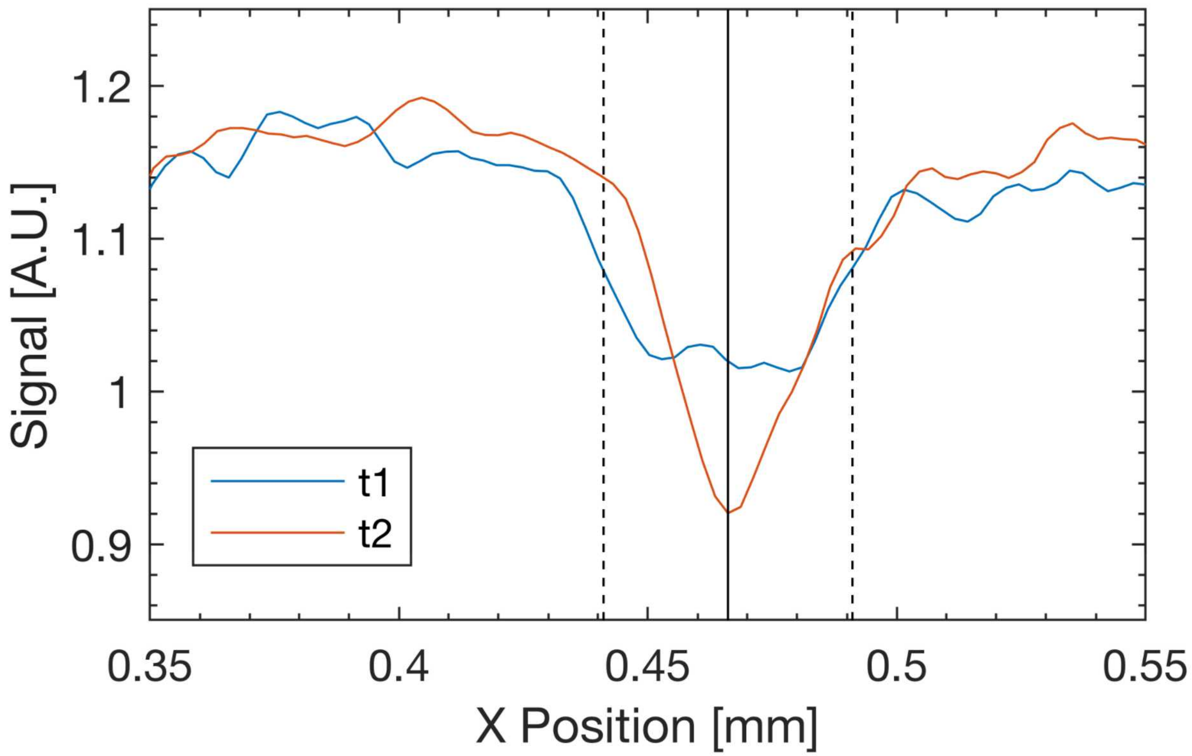
Kinetic Modeling of V/CH Interface: Synthetic Radiography

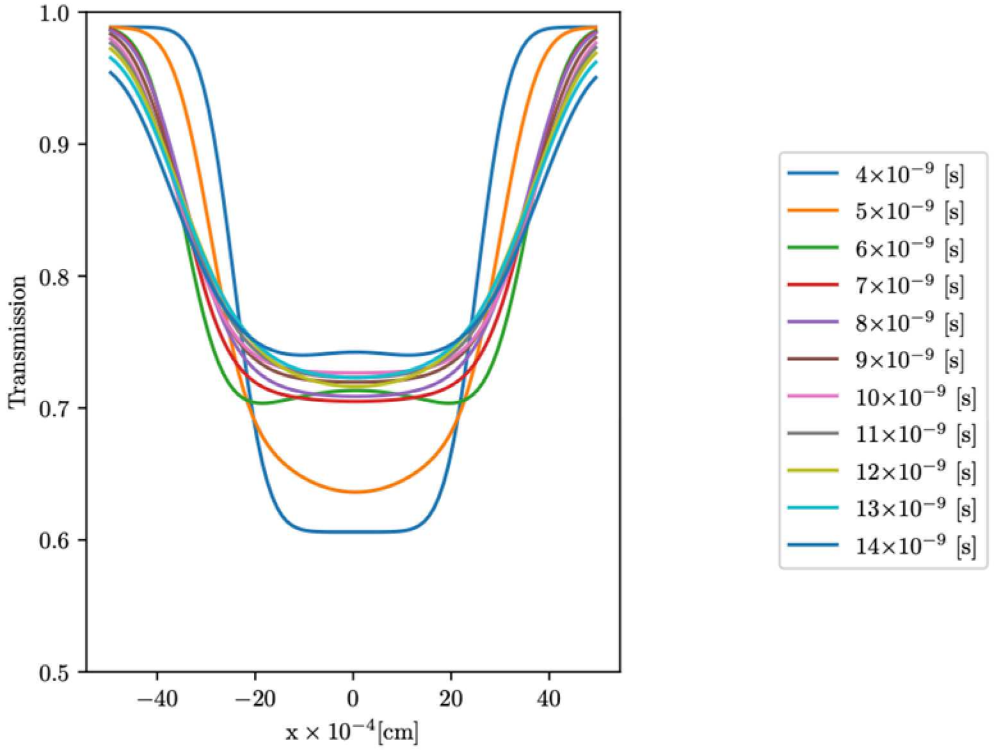


- Simulation setup: replace DT-mix with V at 90% solid density with 10% Al doping
  - Thomas-Fermi Average Atom model for ionization state; Fermi-Dirac statistics for electrons
  - Momentum relaxation model for ion-ion collisions
  - Ions initialized at 10eV; ramp electrons from 10eV

- Claire Kopenhafer (MSU; Summer 2019 CSGF Practicum) developed synthetic radiography tools based on YT:
  - Enables comparison of sample evolution to experimental data
  - Mean transmission imprinted with variability pattern associated with electric field
  - Vanadium *broadens* and ratio between 'trough' and wings decreases

Kinetic Modeling of V/CH Interface: Synthetic Radiography





- Simulation setup: replace DT-mix with V at 90% solid density with 10% Al doping
  - Thomas-Fermi Average Atom model for ionization state; Fermi-Dirac statistics for electrons
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  - Ions initialized at 10eV; ramp electrons from 10eV

- Claire Kopenhafer (MSU; Summer 2019 CSGF Practicum) developed synthetic radiography tools based on YT:
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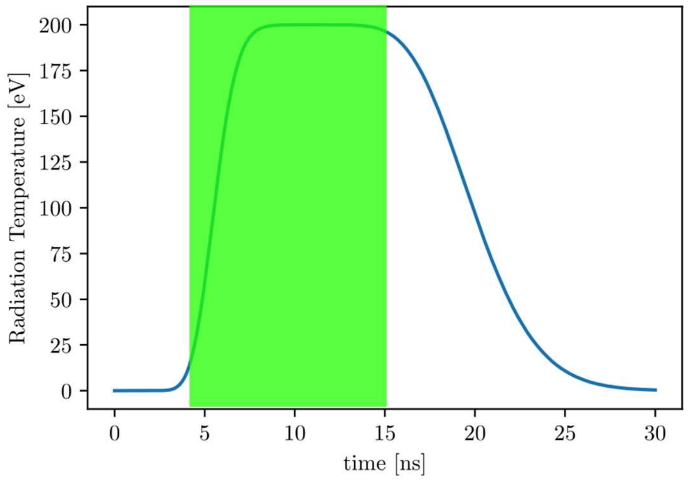
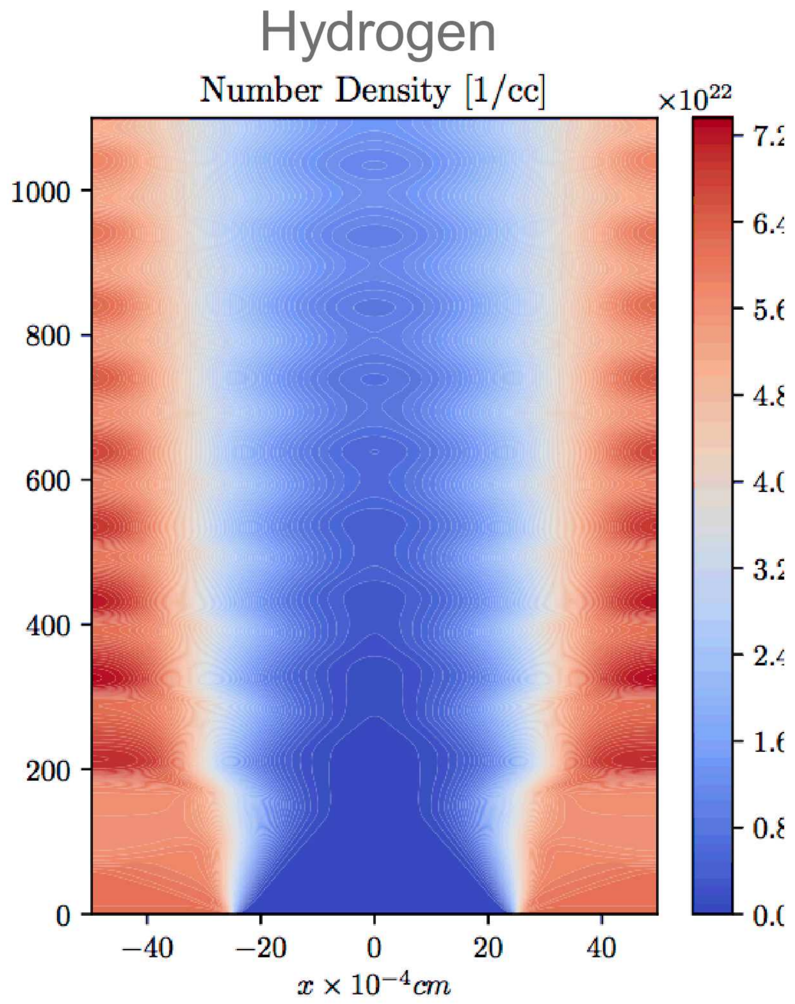
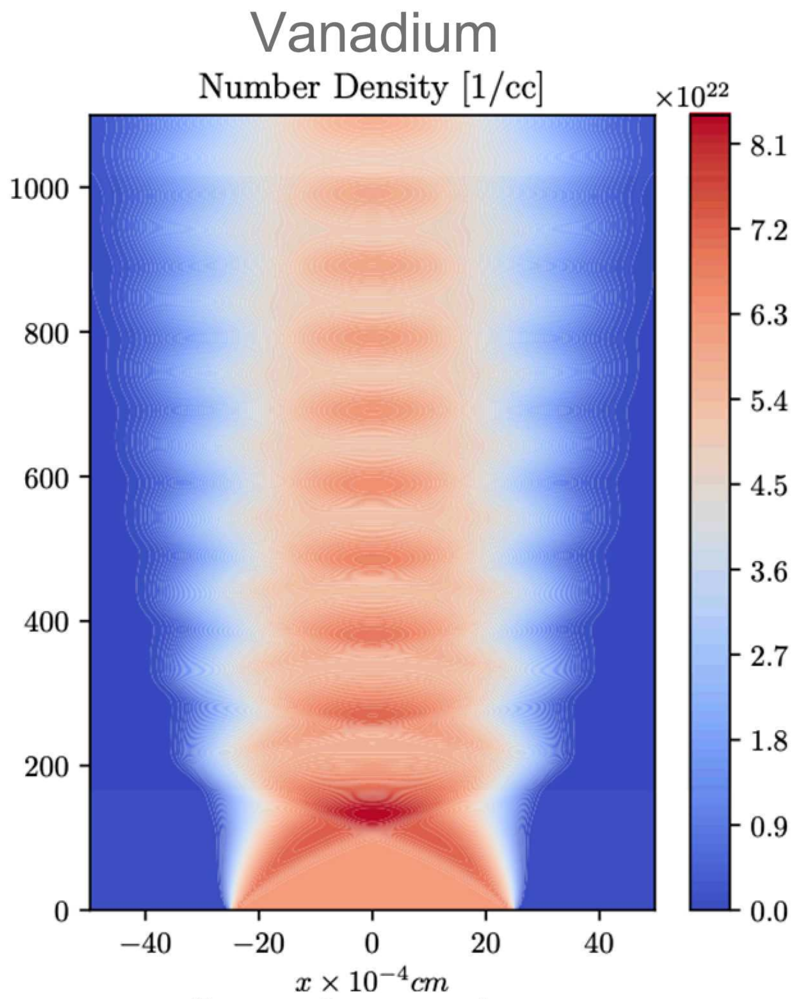
Kinetic Modeling of V/CH Interface: Changing the Collision Model



- Utilize electrostatic multi-species kinetic code to study plasma transport at CHO-V/Al interface
  - Thomas-Fermi Average Atom model for ionization state
  - Fermi-Dirac statistics for electrons
  - Temperature relaxation model for ion-ion collisions
- Simulation setup: replace DT-mix with V at 90% solid density with 10% Al doping
  - Ions initialized at 10eV
  - Assume radiation and electrons are in temperature equilibrium:
    - Ramp electrons from 10eV to 200eV





$$v_{ij}^T = \frac{1}{n_i}\frac{256\pi^2 n_i n_j (m_i m_j)^{1/2}(Z_i Z_j e^2)^2}{3(2\pi)^{3/2}(m_i T_j + m_j T_i)^{3/2}} K_{11}(\gamma_{ij}),$$

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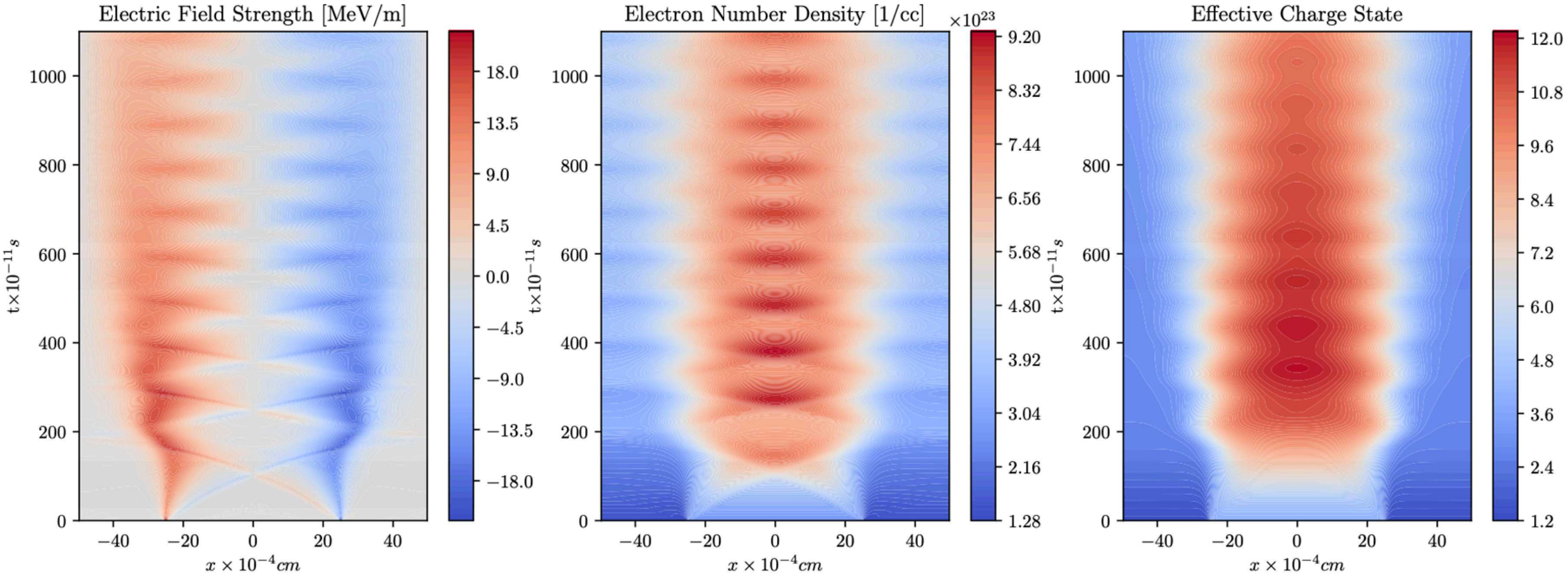
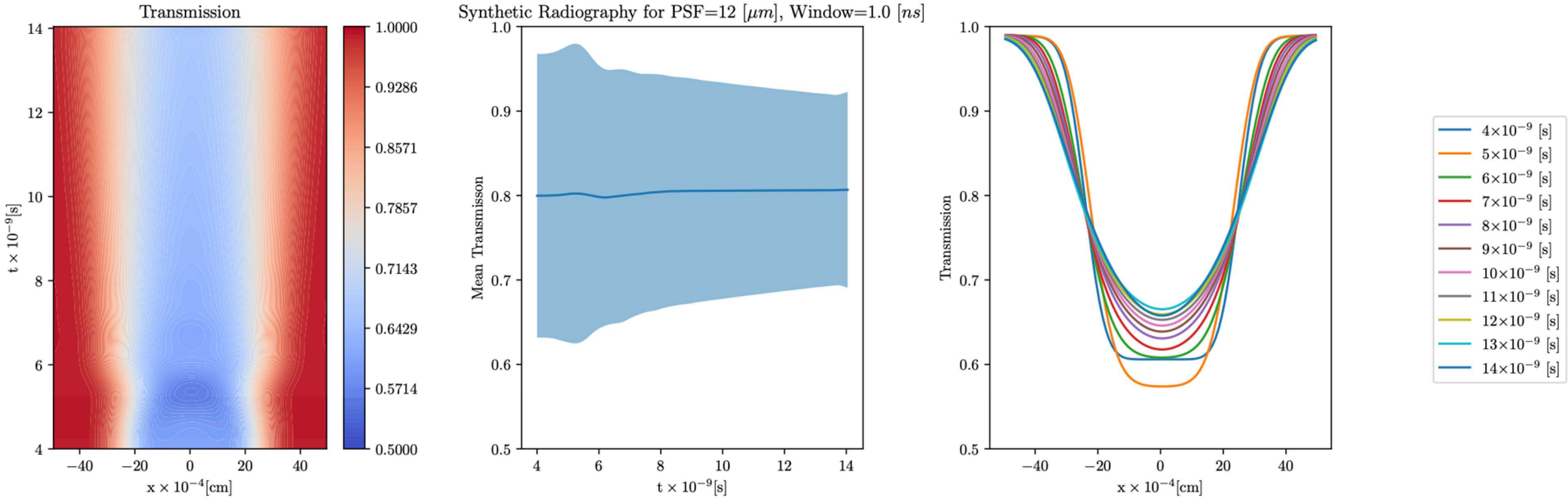
Kinetic Modeling of V/CH Interface: Electrostatic Fields



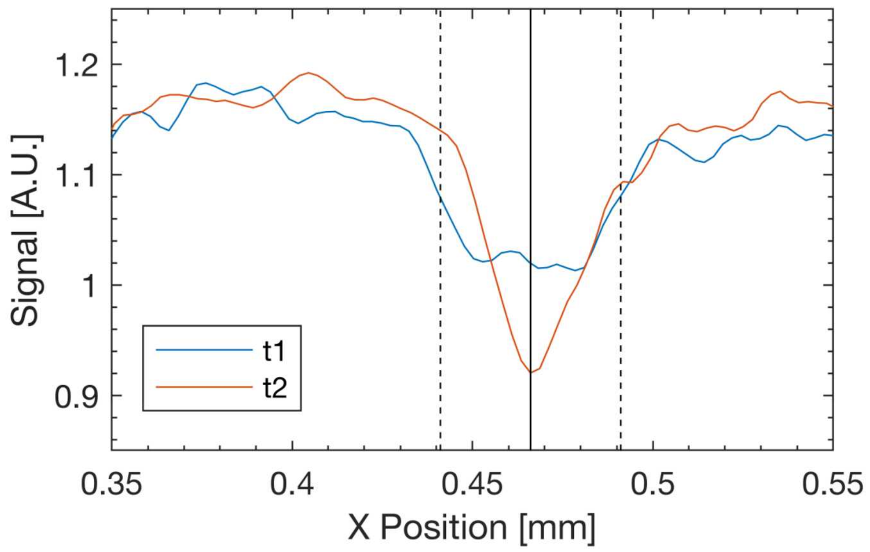
- Simulation setup: replace DT-mix with V at 90% solid density with 10% Al doping
  - Thomas-Fermi Average Atom model for ionization state; Fermi-Dirac statistics for electrons
  - Temperature relaxation model for ion-ion collisions
  - Ions initialized at 10eV; ramp electrons from 10eV to 200eV over 5ns
- Similar to CHO-DT case, observe strong electric fields that spread into plasma with time
  - Electrons remain confined within the Vanadium strip
  - Electric fields ~*2x* stronger in plastic than in previous case

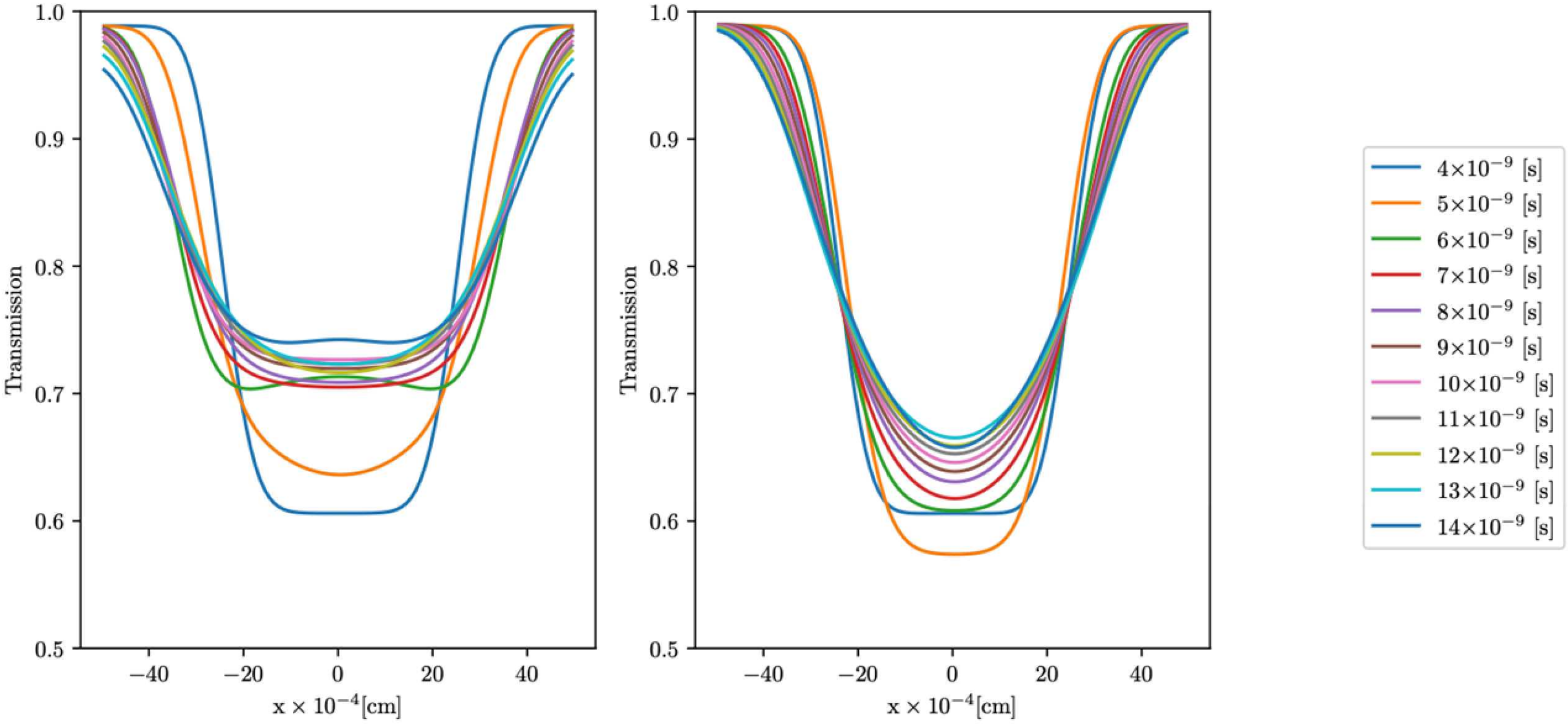
Kinetic Modeling of V/CH Interface: Synthetic Radiography



- Simulation setup: replace DT-mix with V at 90% solid density with 10% Al doping
  - Thomas-Fermi Average Atom model for ionization state; Fermi-Dirac statistics for electrons
  - Temperature relaxation model for ion-ion collisions
  - Ions initialized at 10eV; ramp electrons from 10eV to 200eV over 5ns
- Claire Kopenhafer (MSU; Summer 2019 CSGF Practicum) developed synthetic radiography tools based on YT:
  - Significantly reduced variability in mean transmission
  - Transmission profile distinct from previous case, but still broadens and flattens

Kinetic Modeling of V/CH Interface: Synthetic Radiography

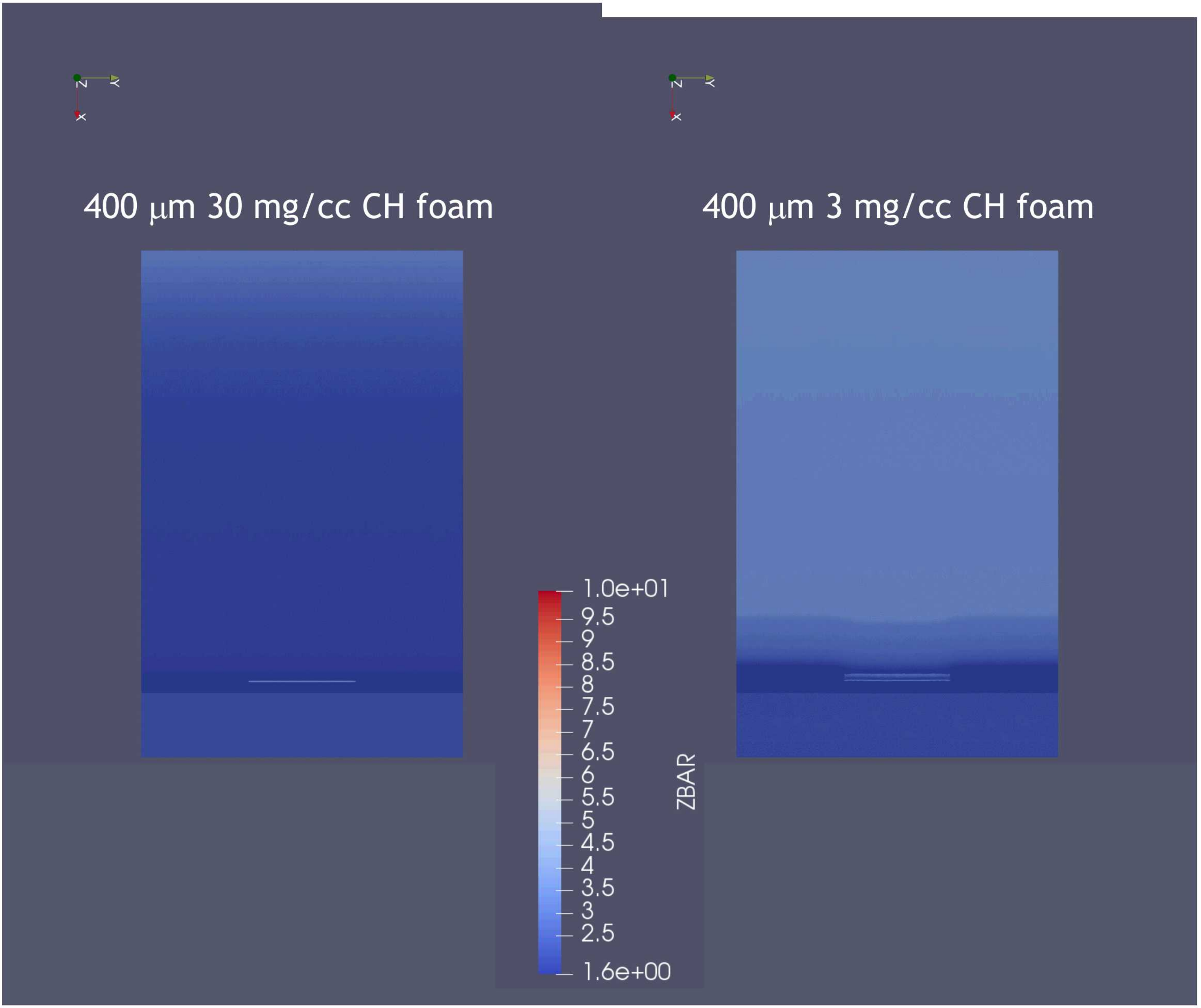


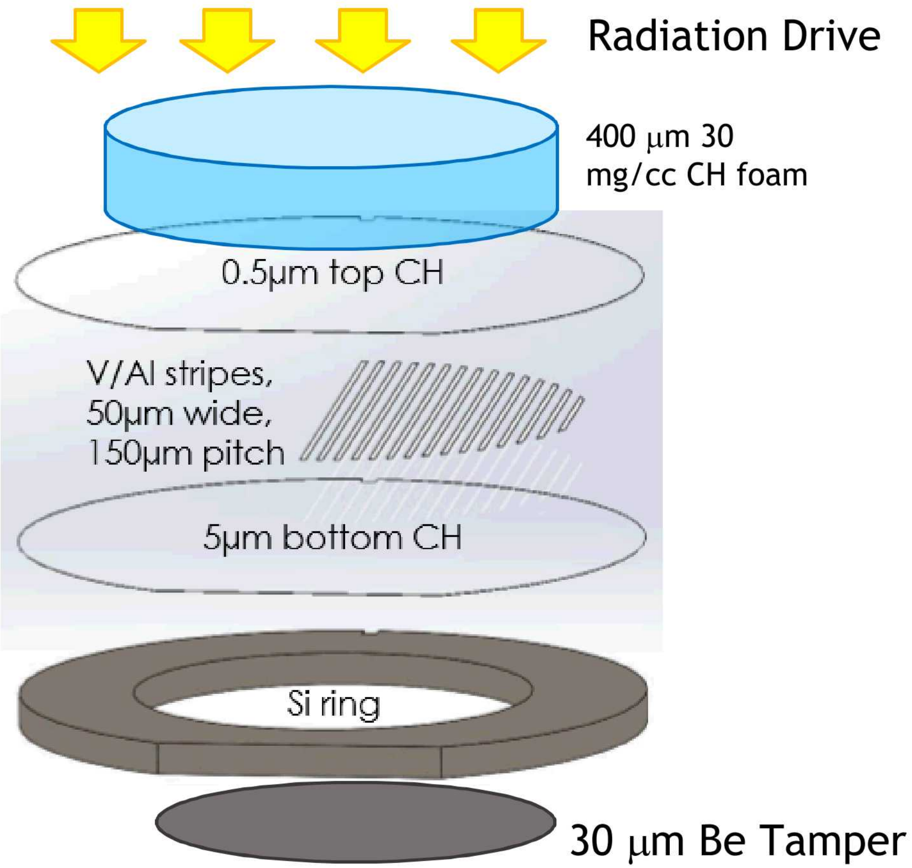


- Simulation setup: replace DT-mix with V at 90% solid density with 10% Al doping
  - Thomas-Fermi Average Atom model for ionization state; Fermi-Dirac statistics for electrons
  - Temperature relaxation model for ion-ion collisions
  - Ions initialized at 10eV; ramp electrons from 10eV to 200eV over 5ns

- Claire Kopenhafer (MSU; Summer 2019 CSGF Practicum) developed synthetic radiography tools based on YT:
  - Distinct differences between transmission profiles for two collision models
  - Distinguishable at experimental resolution
  - Neither case resembles experimental data at qualitative level

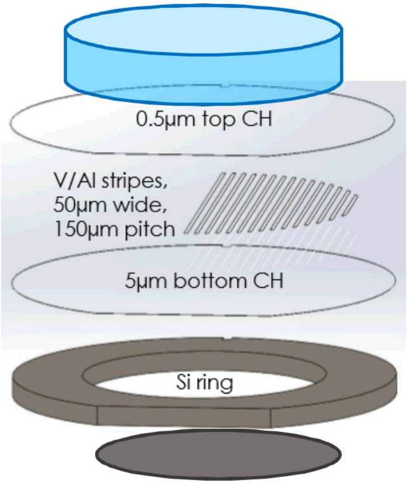
Radiation Hydrodynamics: How fast are we heating anyway?

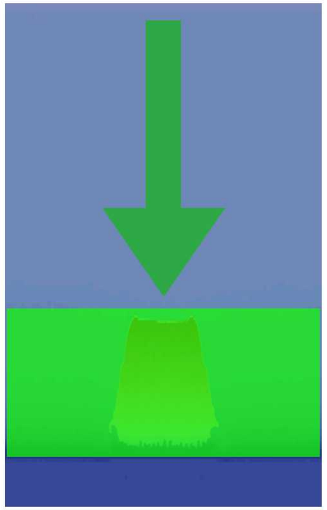




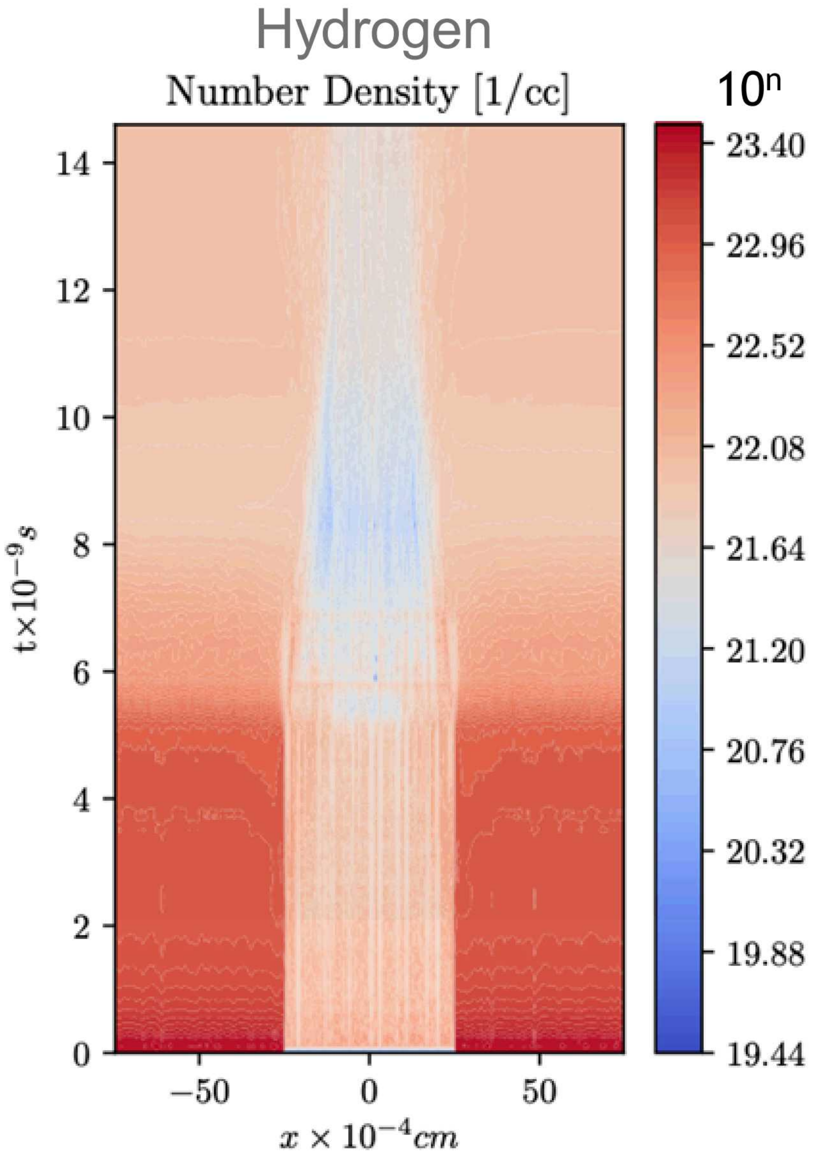
- ALEGRA Radiation hydrodynamics calculations conducted at experimental conditions reveal sensitive to CH foam properties
  - Foam optical depth at experimental densities sufficient to prevent sample from heating
  - Radiation shock at late times drives instability on sample surfaces
  - Lowering effective optical depth of foam allows sample to heat *but* exhibits significant expansion

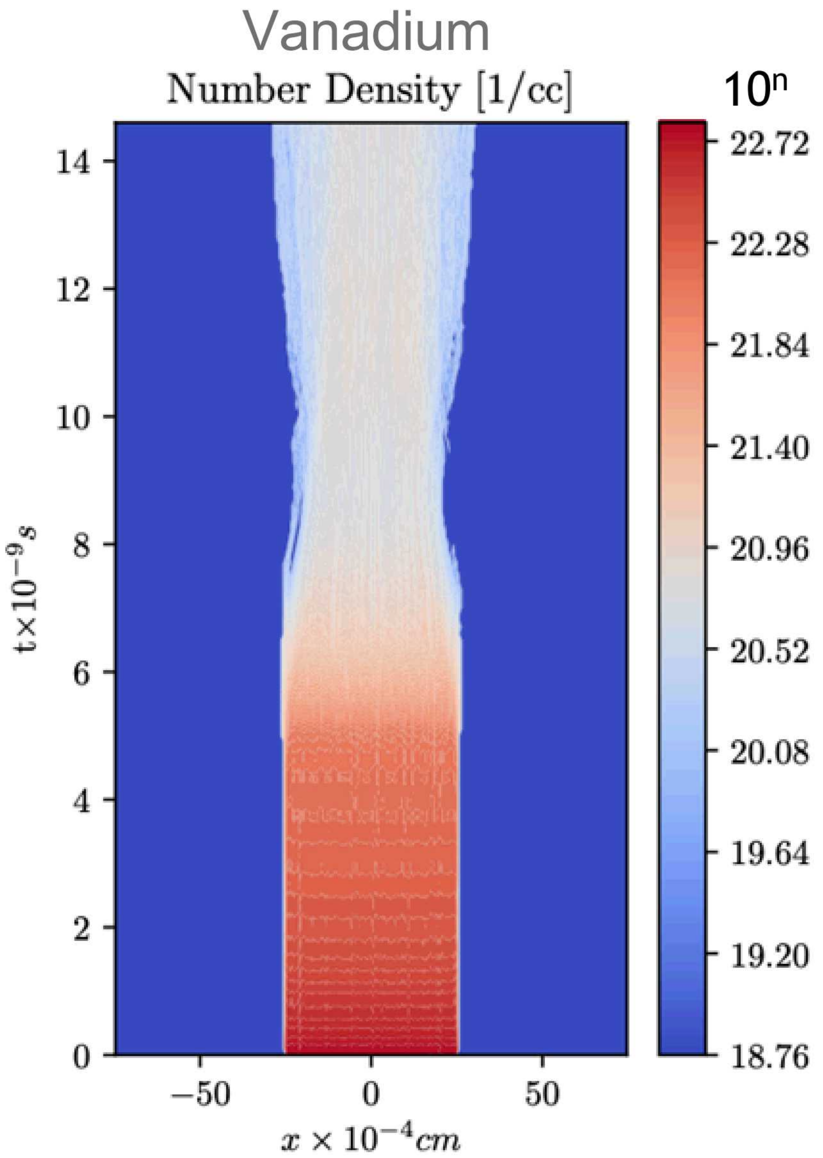
Radiation Hydrodynamics: How fast are we heating anyway?



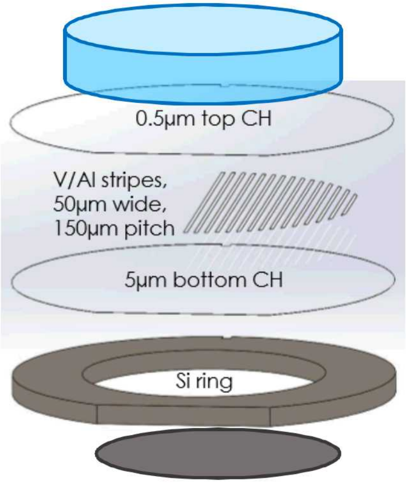


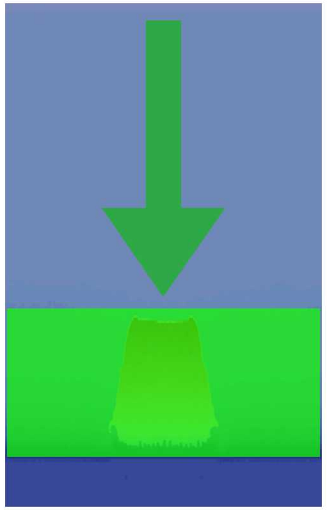
- Analyze time evolution of sample by integrating simulation along radiation path, over region adjacent to Vanadium
  - Focus attention on low density foam case
  - Plastic appears to compress Vanadium in the 8-10ns window



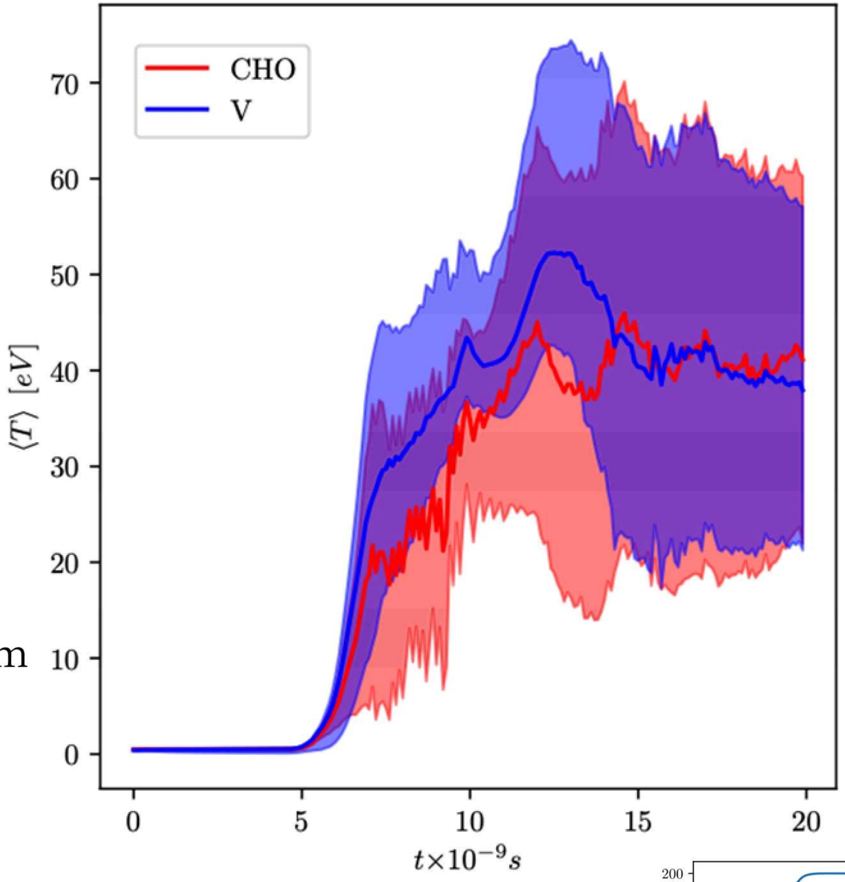


Radiation Hydrodynamics: How fast are we heating anyway?

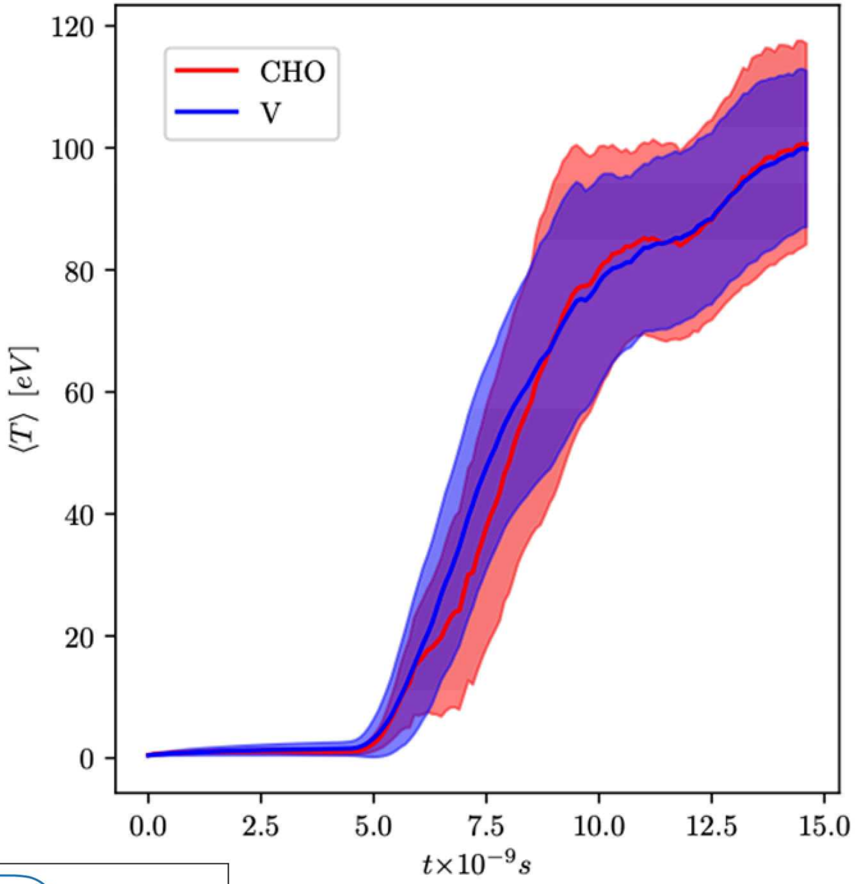




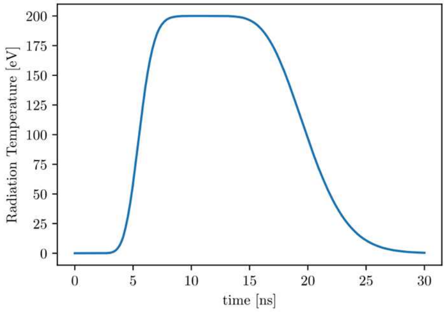
400 μm 30 mg/cc CH foam



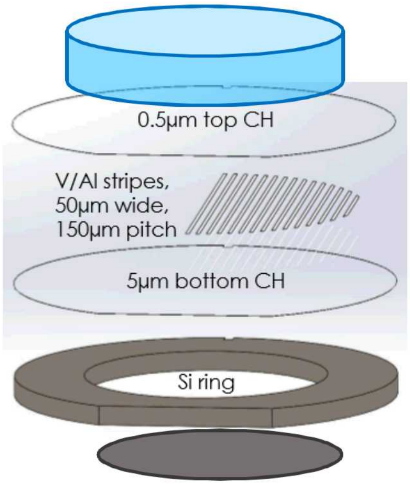
400 μm 3 mg/cc CH foam

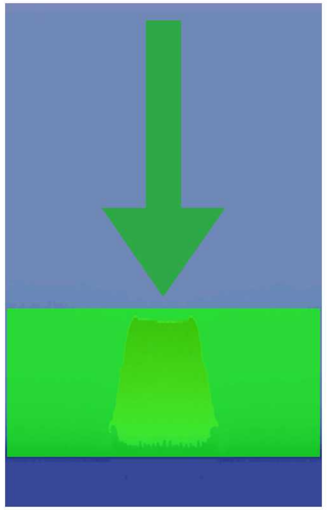


- Analyze time evolution of sample by integrating simulation along radiation path, over region adjacent to Vanadium
  - Heating strongly dependent on effective optical depth of foam
  - Foam @30 mg/cc: V & plastic only heat to 40eV
  - Foam @3 mg/cc: V & plastic heat to 80eV by 10ns and 100eV by 15ns
  - Impacts ionization state achieved

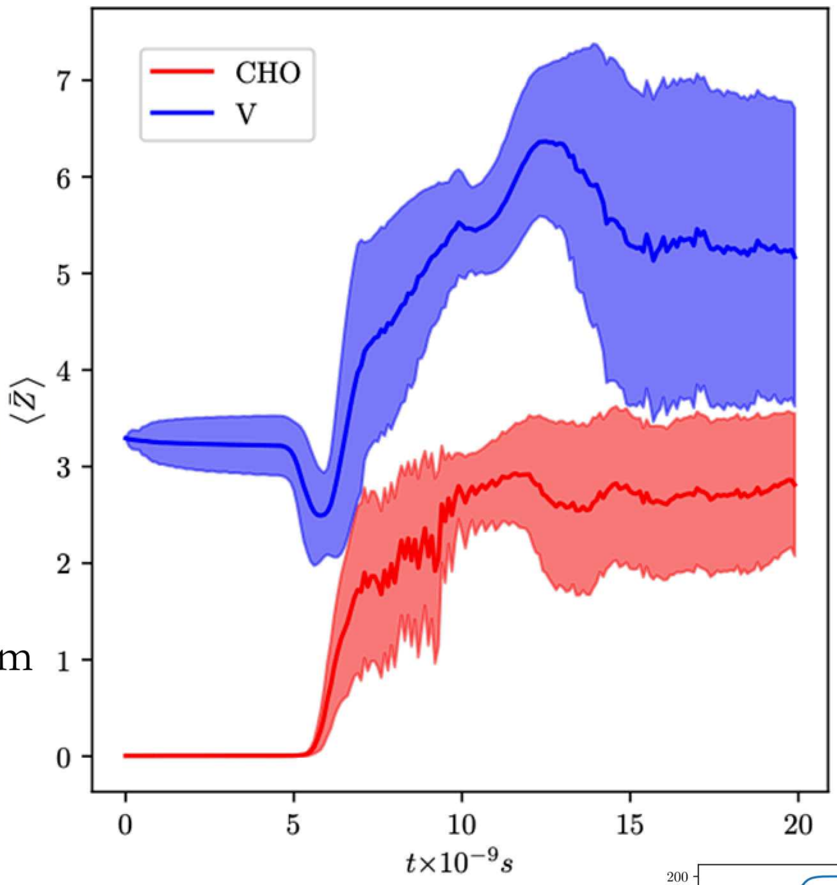


Radiation Hydrodynamics: How fast are we heating anyway?





400 μm 30 mg/cc CH foam



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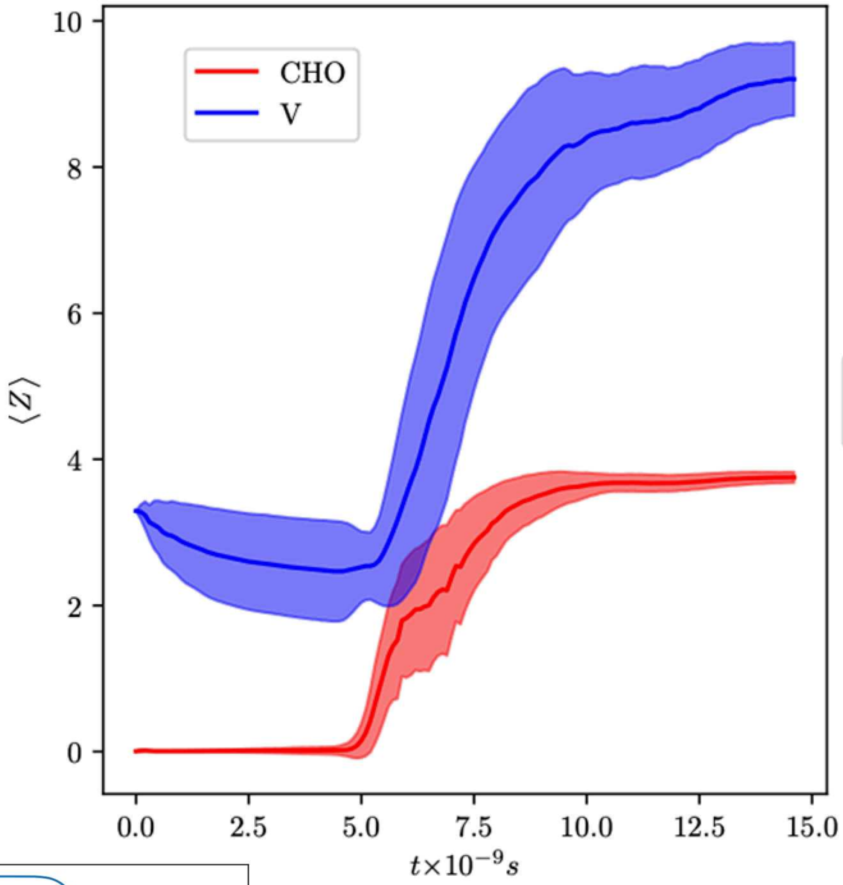

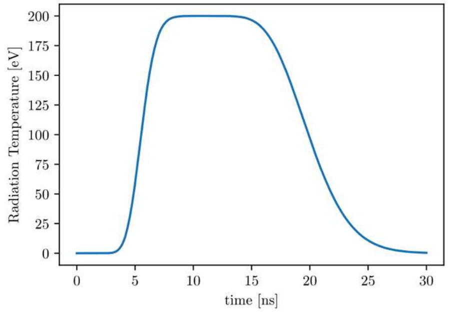

- Analyze time evolution of sample by integrating simulation along radiation path, over region adjacent to Vanadium
  - Heating strongly dependent on effective optical depth of foam
  - Foam @30 mg/cc: V & plastic only heat to 40eV
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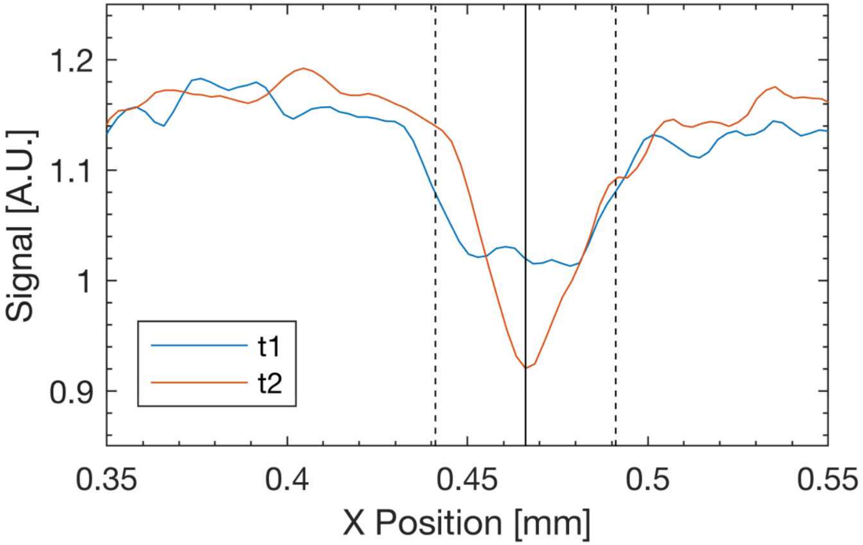
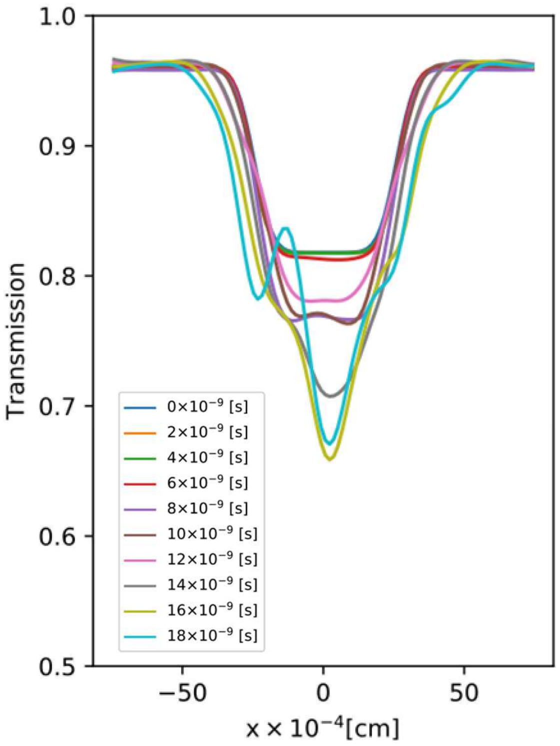
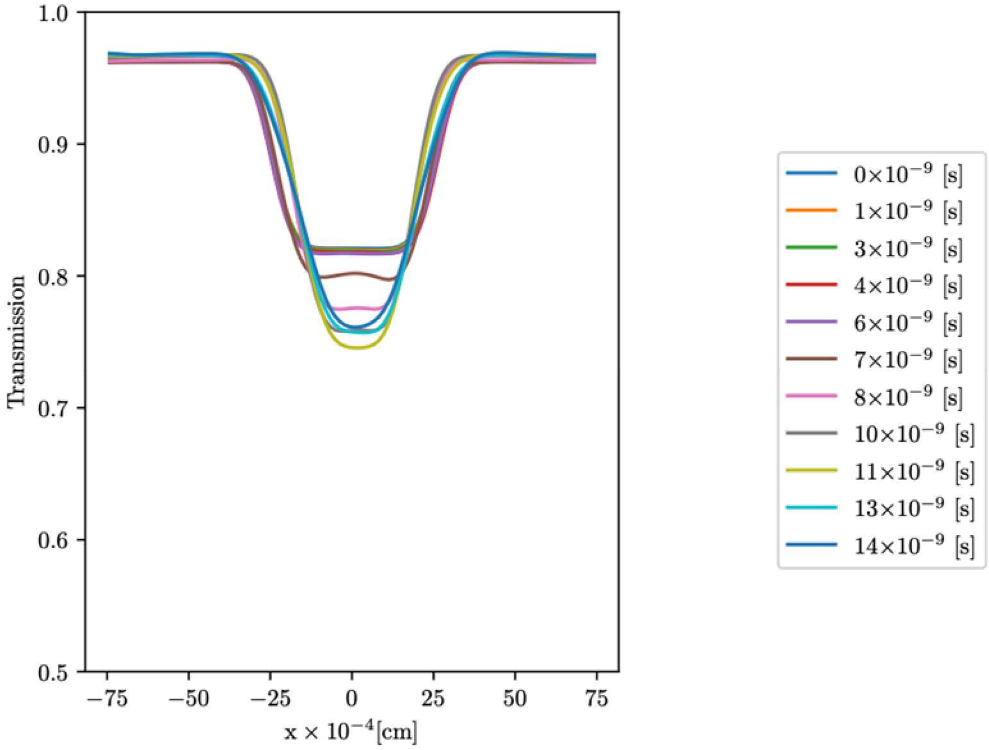
  - Impacts ionization state achieved

Kinetic Modeling of V/CH Interface: Synthetic Radiography

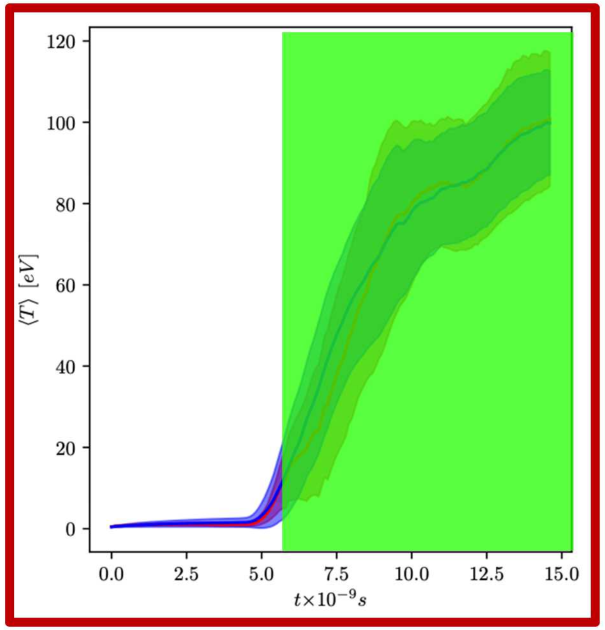




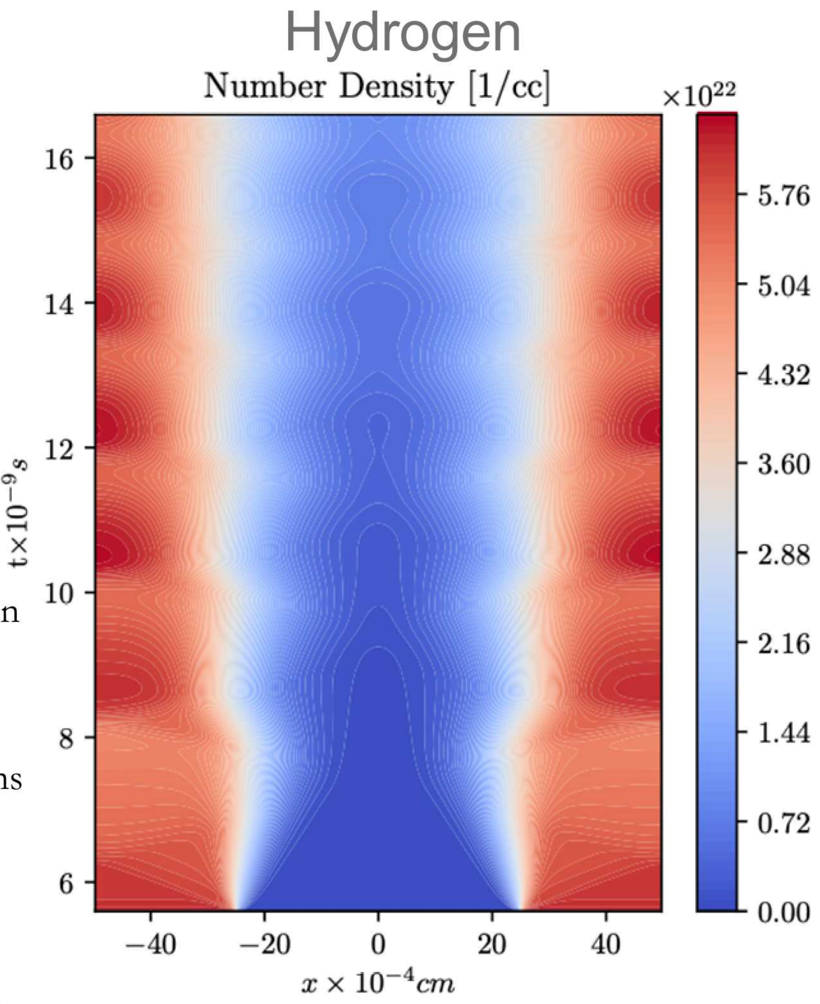


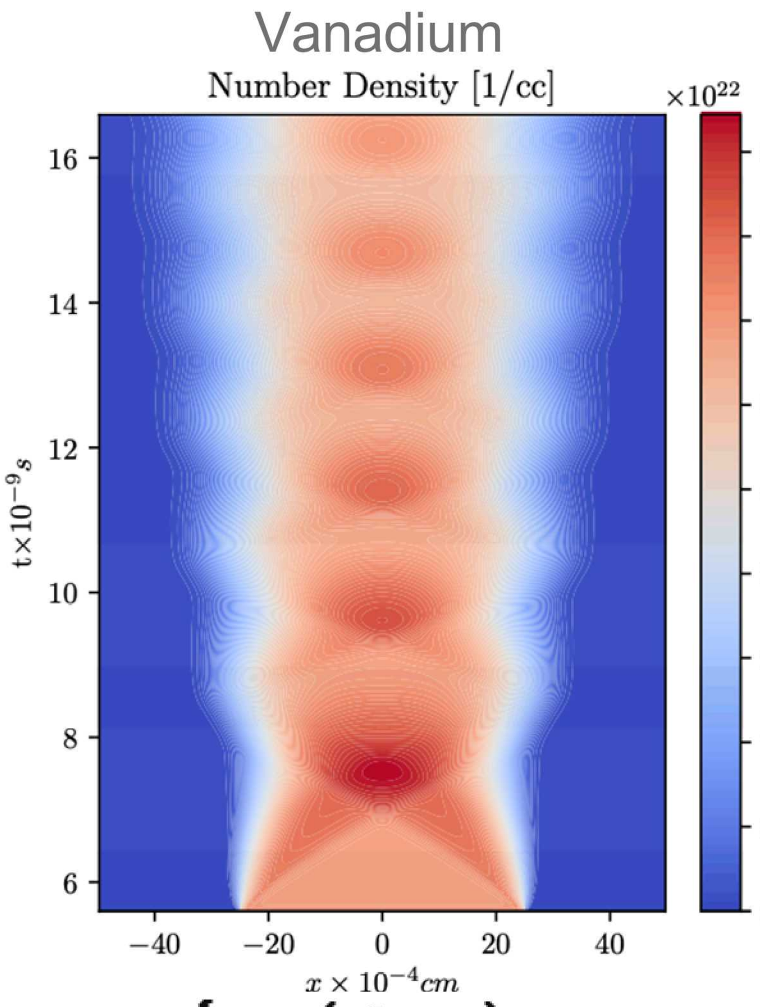
- Heating strongly dependent on effective optical depth of foam
  - Impacts transmission profiles derived for synthetic radiography
- YT-based synthetic radiography tools allow ALEGRA data to be reduced in *same* framework as kinetic data:
  - Foam @30 mg/cc: transmission profile *broadens* and *deepens;* late time asymmetries emerge
  - Foam @3 mg/cc: transmission profile profile *narrows* and *deepens*; remains symmetric
- Conclusion: we're doing an experiment with foam, so we're doing an experiment on the foam

Kinetic Modeling of V/CH Interface: Changing the Heating Rate



- Utilize electrostatic multi-species kinetic code to study plasma transport at CHO-V/Al interface
  - Thomas-Fermi Average Atom model for ionization state
  - Fermi-Dirac statistics for electrons
  - Temperature relaxation model for ion-ion collisions
- Simulation setup: replace DT-mix with V at 90% solid density with 10% Al doping
  - Ions initialized at 10eV
  - Electrons follow temperature profile derived from 3 mg/cc radiation hydrodynamics calculations





$$\nu_{ij}^T = \frac{1}{n_i} \frac{256\pi^2 n_i n_j (m_i m_j)^{1/2} (Z_i Z_j e^2)^2}{3(2\pi)^{3/2} (m_i T_j + m_j T_i)^{3/2}} K_{11}(\gamma_{ij}),$$

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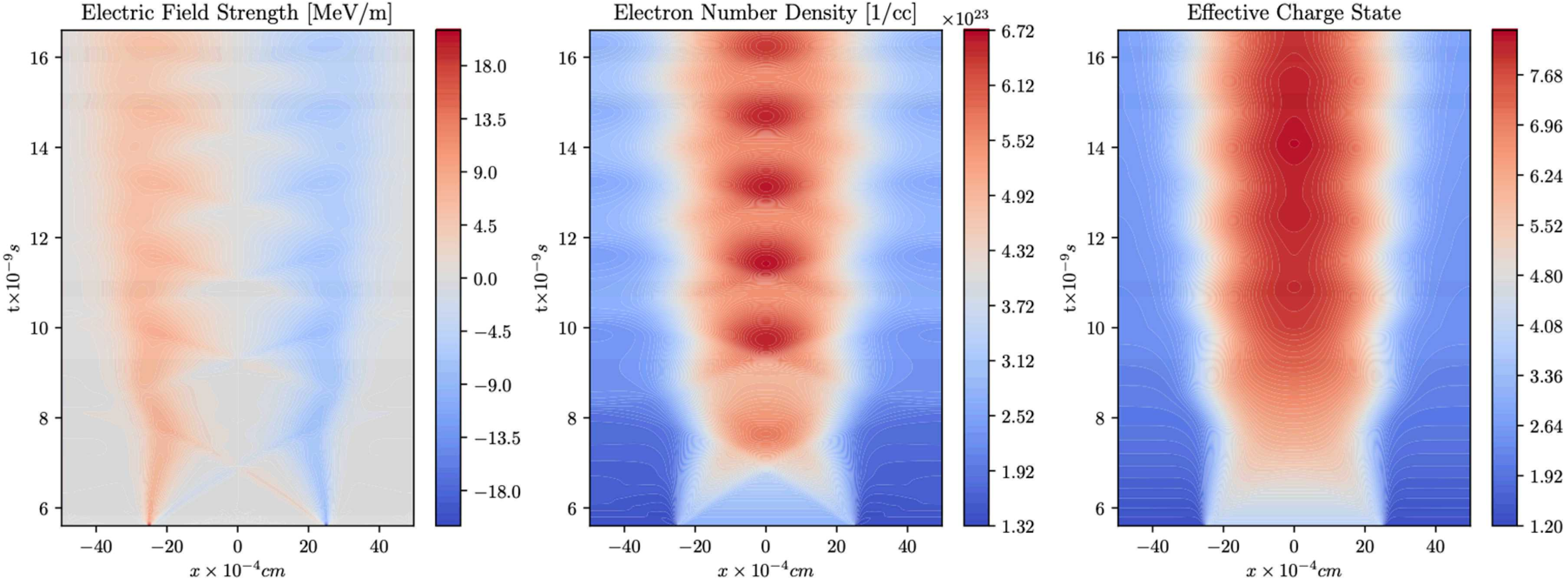
Kinetic Modeling of V/CH Interface: Electrostatic Fields

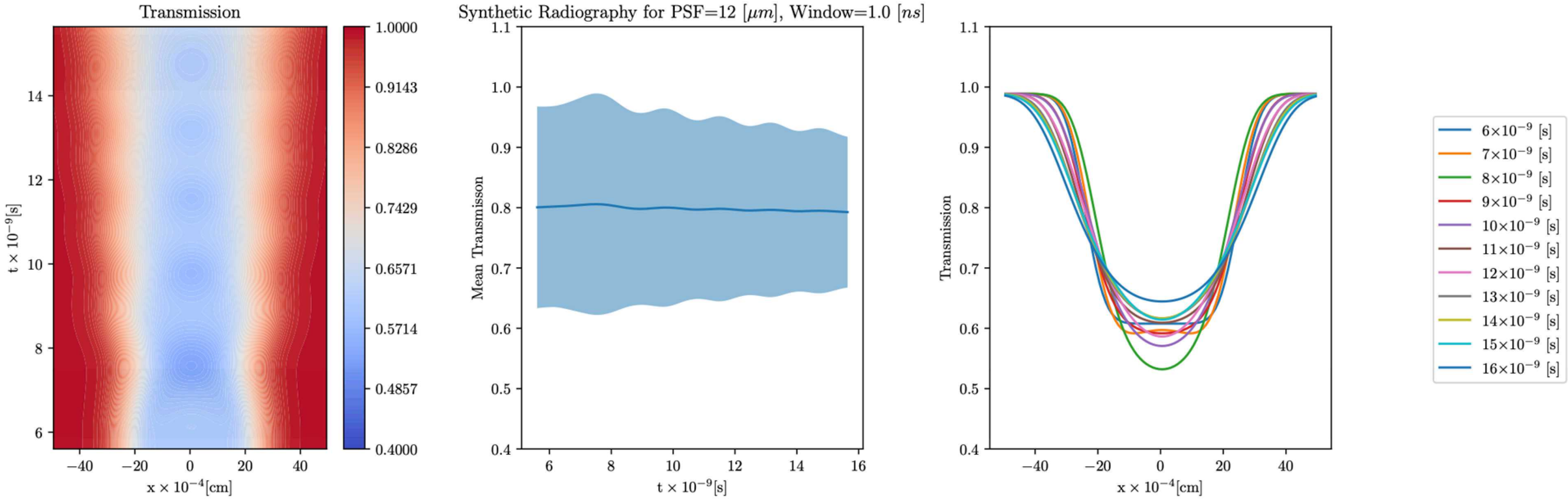


- Utilize electrostatic multi-species kinetic code to study plasma transport at CHO-V/Al interface
  - Thomas-Fermi Average Atom model for ionization state; Fermi-Dirac statistics for electrons
  - Temperature relaxation model for ion-ion collisions
- Simulation setup: V @90% solid density, 10% Al doping
  - Ions initialized at 10eV

- Electrons temperature derived from 3 mg/cc rad hydro

- Electric field & electron evolution is qualitatively the same as before:
  - Electrons remain confined within the Vanadium strip
  - Electric fields *~9x* weaker c.f. heating to *200eV*

Kinetic Modeling of V/CH Interface: Synthetic Radiography



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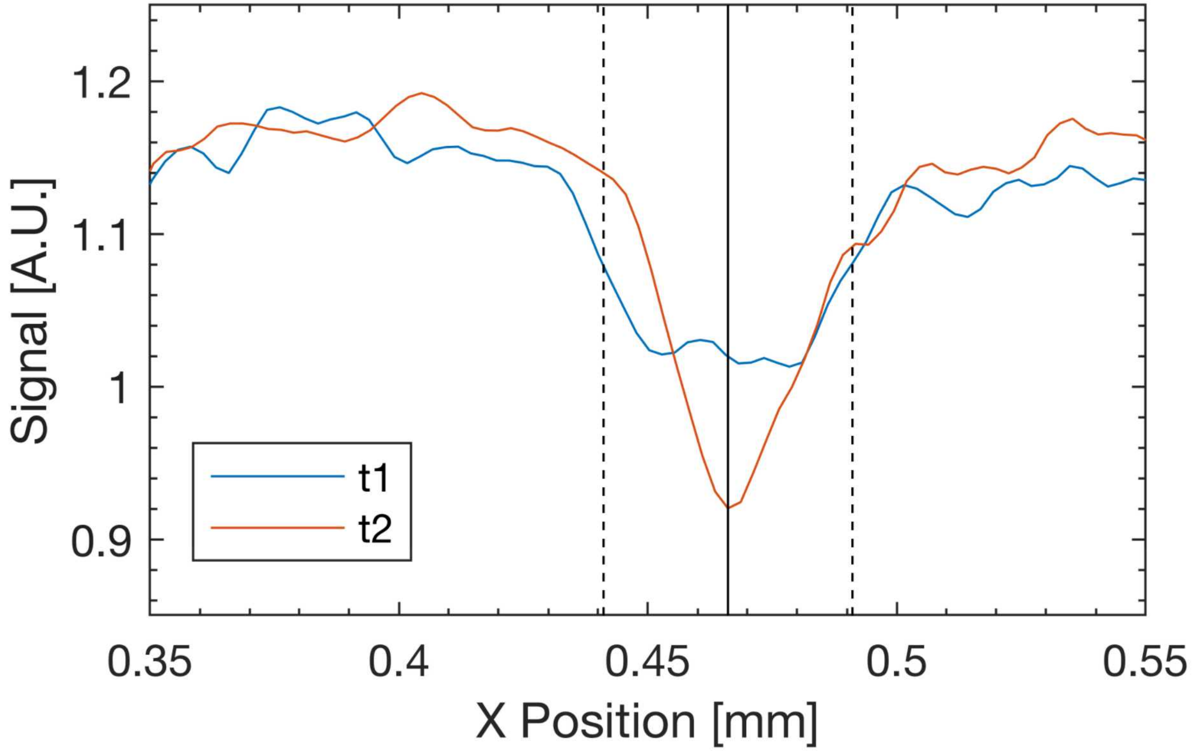
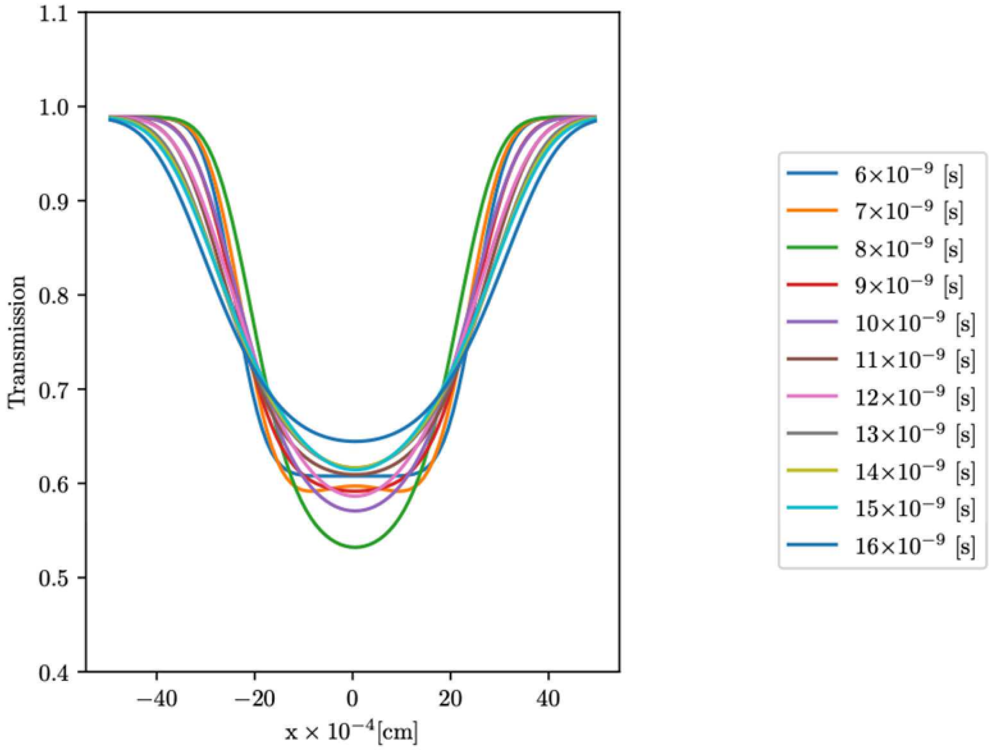
  - Temperature relaxation model for ion-ion collisions
- Simulation setup: V @90% solid density, 10% Al doping
  - Ions initialized at 10eV
  - Electrons temperature derived from 3 mg/cc rad hydro
- Synthetic radiography:
  - Transmission profile deepens and narrows prior to 8ns
  - After 8ns, profile becomes shallower and widens:
    - Indicates electric field induced transport important at *later* times

Radiation Hydrodynamics: Synthetic Radiography





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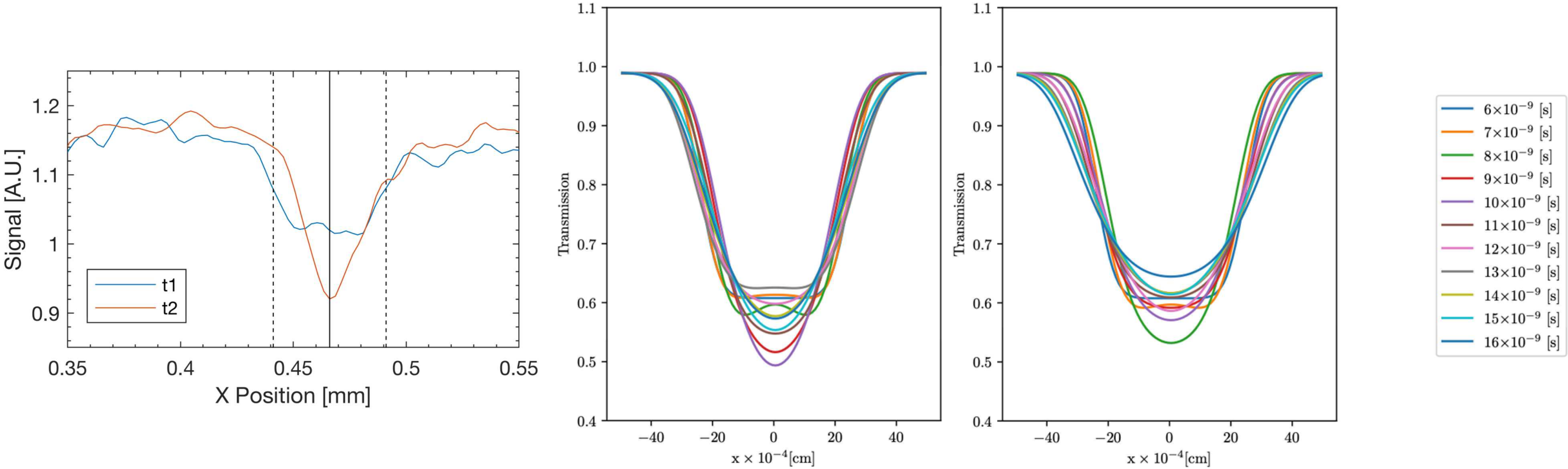
Kinetic Modeling of V/CH Interface: Synthetic Radiography



- Utilize electrostatic multi-species kinetic code to study plasma transport at CHO-V/Al interface
  - Thomas-Fermi Average Atom model for ionization state; Fermi-Dirac statistics for electrons
  - Temperature relaxation model for ion-ion collisions
- Simulation setup: V @90% solid density, 10% Al doping
  - Ions initialized at 10eV
  - Electrons temperature derived from 3 mg/cc rad hydro

- Synthetic radiography:
  - Re-run calculation *without* electric field
  - Transmission profile deepens and narrows prior to 10ns
  - After 10ns, profile becomes shallower but *remains* narrow:
    - Late time behavior crucial for diagnosing diffusion

Conclusions & References

Z-Machine provides a unique capability to study plasma transport

- Initial series of experiments have examined diffusion of a Vanadium/Plastic interface
- Radiographs from these experiments become *narrower* and *deeper* later in the experiment
- Modeling is challenging: broad range of timescales and temperatures

Idealized kinetic models:

- Heating the interface (200eV over 10ns, electrons in equilibrium with radiation) leads to generation of electric fields that penetrate into bulk material
- Significant dependence on collision model (momentum vs. temperature relaxation)
- Synthetic radiography tools indicate that kinetic models of interface are associated with transmission profiles that become *broader* and *shallower* as material heats

Radiation hydrodynamic calculations:

- Heating of Vanadium/Plastic interface is strongly influenced by the effective optical depth of the foam
  - Foam @experimental densities results causes Vanadium/Plastic to heat to ~40eV, exhibits strong turbulent mixing
  - Foam @10x *lower* densities results in Vanadium/Plastic to heat to ~100eV, exhibits reduced levels of turbulent mix
  - Synthetic radiography for low density foam case is *qualitatively* consistent with experimental data

Kinetic models w/radiation hydrodynamic-derived heating:

- Qualitative match to experimental behavior; indicates improved understanding of foam opacity is critical.
- Influence of electric fields emerges at late times (>10ns): careful control of experimental radiography timing is critical.
- Differences in diffusive transport models *can*, in principle, be distinguished with current experimental capabilities.
  - Need to quantify uncertainties in opacity models, ionization states, transport models in order make *quantitative* comparisons to experiment

References:

- VPBGK code available at: https://github.com/lanl/Multi-BGK
- Stanton & Murillo (2016): 10.1103/PhysRevE.93.043203
- Haack et al. (2017a): 10.1007/s10955-017-1824-9
- Haack et al. (2017b): 10.1103/PhysRevE.96.063310