北京应用物理与计算数学研究所
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秘密★长期

A multi-component hydrodynamic plasma model for resolving mesoscopic disequilibria

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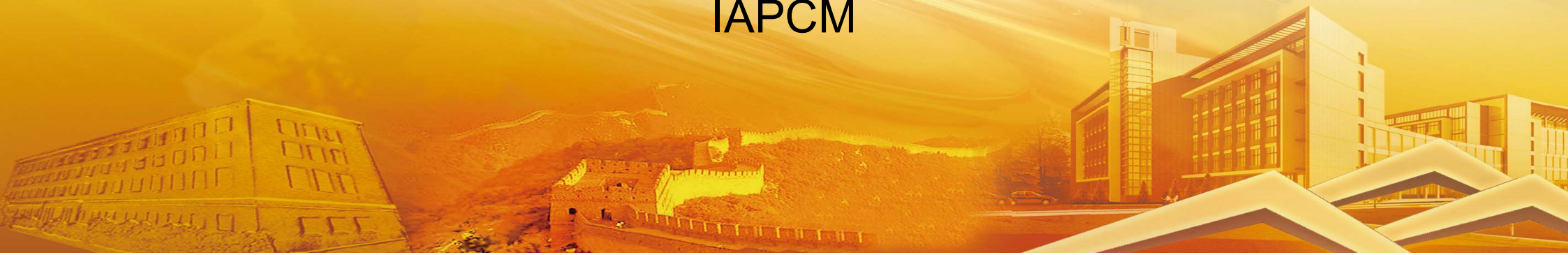
IAPCM



Outline

I. Motivation

II. Model formulation

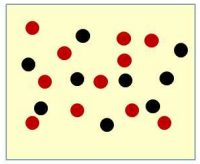
III. Verification and validation

IV. Application

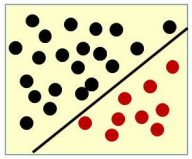
V. Conclusion

I Motivation

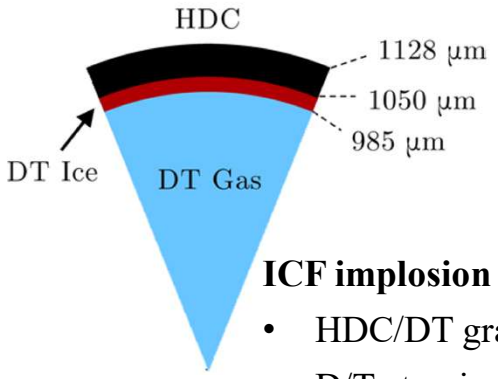
◆ **Multi-material and nonlinear hydrodynamic instability and mixing is significant to ICF**



Atomic mix

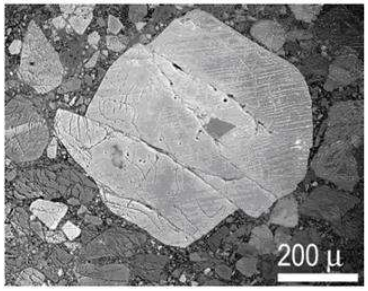


Grain mix



ICF implosion

- HDC/DT grain→atomic
- D/T atomic



High explosive

- HMX/Void grain mix
- Reactant/product atomic mix

◆ **Temperature~keV plasma transport（viscosity/mass diffusion）impact mix development** [1,2]

Diffusion（velocity disequilibrium）is a dominant mixing mechanism in gas-filled capsule

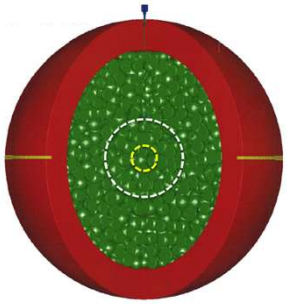
[1] A.B. Zylstra, PRE, 2018. [2] Vold E, POP, 2022.

I Motivation

◆ **The ion temperature separation affects mixing development and fusion reaction**

Grain mix

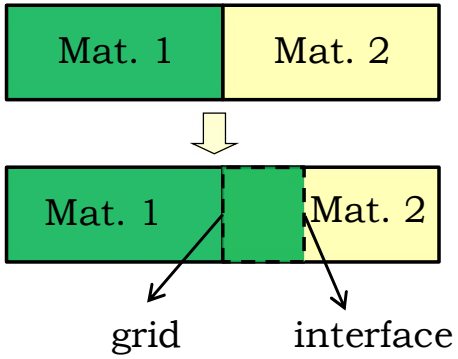
MARBLE exp[1]

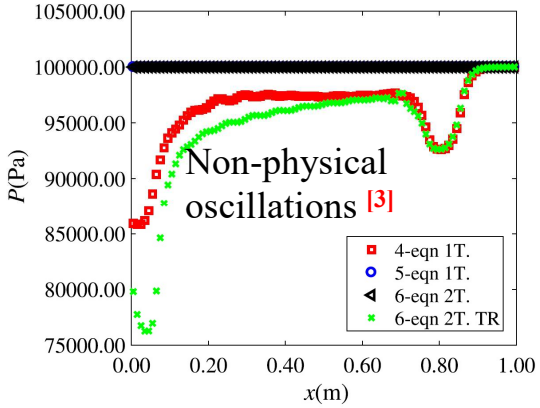


Atomic：reaction in ion temperature diseq.

- **OMEGA：** D^3He exp. [2]
- **SG：** Obtained evidence for temperaure separation betweem **D-ion T-ion**（~4keV）

◆ **In Eulerian framework ion-temp. equilibrium causes non-physical oscillation at material interface**





[1] Haines B.M., et al., NC, 2020. [2] Rinderknecht H.G., et al., PRL, 2015. [3] **Zhang C.**, et al., JCP, 2022.

Ⅰ Motivation

- **Traditional ICF codes（xRAGE/HYDRA/LARED-S etc.）rely on one-fluid equilibrium hydrodynamic equations**
- **Equilibrium models fail to capture mechanical/thermal disequilibrium between different ion species**

I Motivation

Traditional models

Baer-Nunziato model not applicable

- Only grain mix
- Ion-electron equilibrium

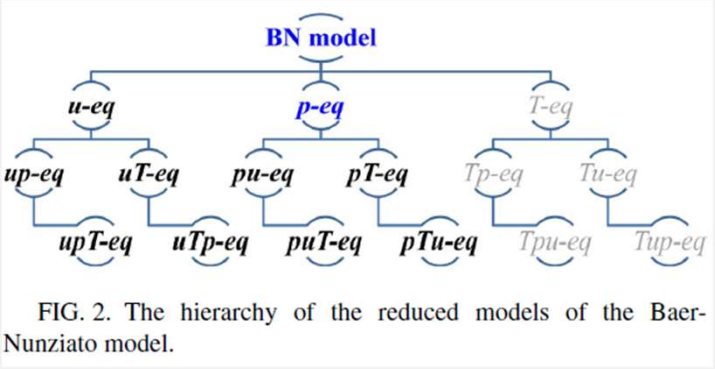


FIG. 2. The hierarchy of the reduced models of the Baer-Nunziato model.

Two-fluid model not applicable

- Only atomic mix

New model

Muti-component disequilibrium model

Requirements:

I. Physical components

Viscosity, heat conduction, ion-electron temp. diseq., ion-ion mechanical/thermal diseq.

II. 1st & 2nd law of thermodynamics

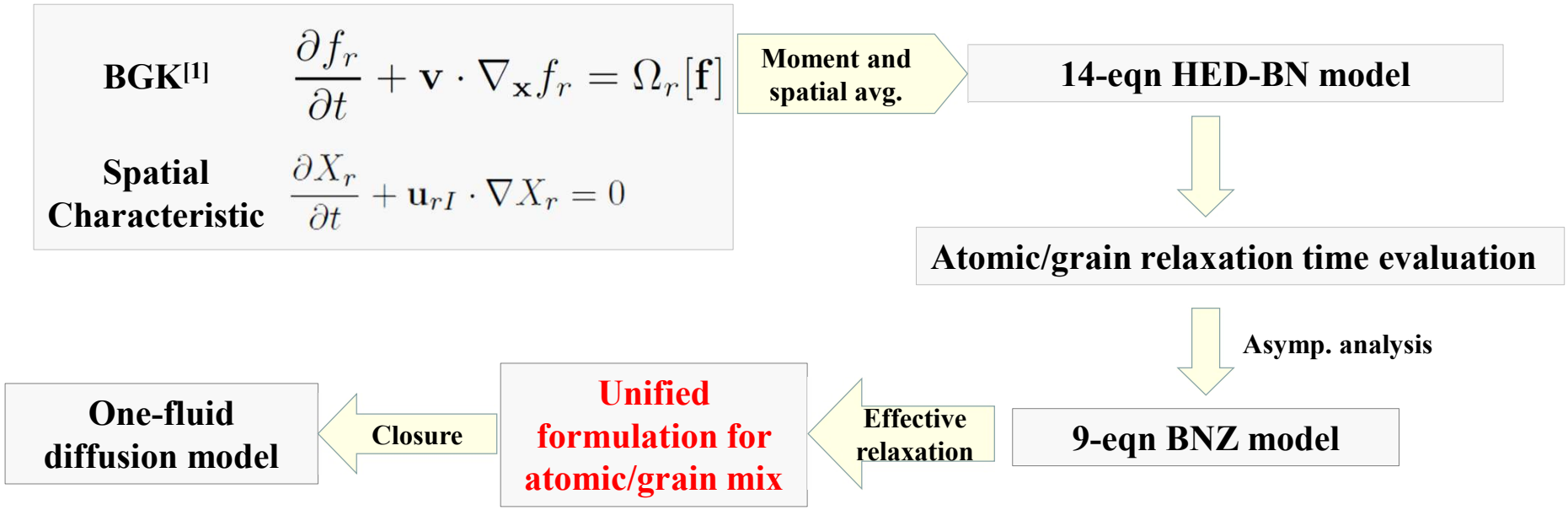
III. Reduction to classical models

IV. Unified formulation for atomic and grain mix

[1] M.R. Baer, J.W. Nunziato, 1986. [2]Braginskii S. I., Reviews of Plasma Physics, 1965.

II Model formulation

We obtain the HED-BN model by means of moment- and spatial- averaging of the BGK model. The 14-eqn HED-BN model is then reduced by asymptotic analysis with some relaxation times as perturbation parameter. The reduced models can deal with velocity/temperature diseq. between ion-electron and different ion species.



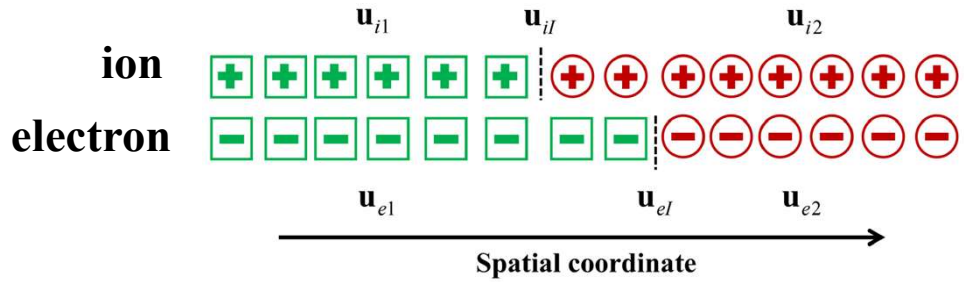
[1] J.R. Haack, et al., JSP, 2017.

II Model formulation

☐ **Key step 1：derivation of the HED-BN model by moment- and spatial- averaging of the BGK model.**

$$\frac{\partial f_r}{\partial t} + \mathbf{v}\cdot\nabla_{\mathbf{x}} f_r = \Omega_r[\mathbf{f}]$$

***r* = *lk*，*l* :ion/electron，*k*:component index**



$$\Omega_{lk} = \Omega_{lk,lk} + \sum_{j=k,k'} X_{l'j}\Omega_{lj,l'j} + X_{lk'}\Omega_{lk,lk'} + \mathbf{n}\cdot\nabla X_{lk'}\Omega^{A}_{lk,lk'}$$

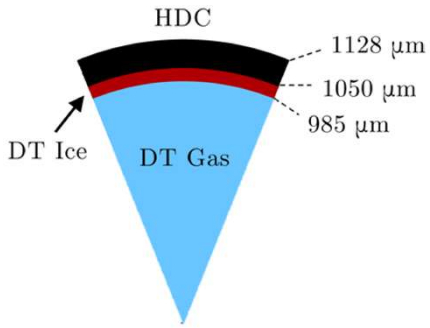
Same comp.	Same comp.	diff. comp.	diff. comp.
ion-ion	ion-elec	ion-ion	ion-ion
elec-elec		elec-elec	elec-elec
		Volume col.	Surface col.
		(atomic mix)	(grain mix)

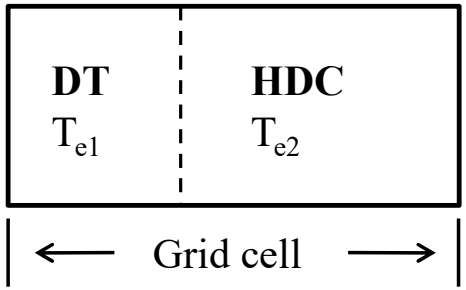
II Model formulation

☐ **Key step 1：derivation of the HED-BN model by moment- and spatial- averaging of the BGK model.**

Why do we need two electron temperatures?

- For describing sub-grid temperature distribution
- Maintain neutrality





II Model formulation

Key step 1：derivation of the HED-BN model by moment- and spatial- averaging of the BGK model.

Mass balance

$$\frac{\partial \alpha_{lk}\rho_{lk}}{\partial t} + \nabla\cdot(\alpha_{lk}\rho_{lk}\mathbf{u}_{lk}) = 0$$

Momentum balance

$$\frac{\partial \alpha_{lk}\rho_{lk}\mathbf{u}_{lk}}{\partial t} + \nabla\cdot(\alpha_{lk}\rho_{lk}\mathbf{u}_{lk}\mathbf{u}_{lk}) + \nabla(\alpha_{lk}p_{lk}) + \nabla\cdot\left(\alpha_k\overline{\overline{\Pi}}_{lk}\right) =$$
$$\mathbf{R}_{lk} + p_{lI}\nabla\alpha_{lk} + \overline{\overline{\Pi}}_{lI}\cdot\nabla\alpha_{lk} + \mathbf{M}_{l,kk'}$$

Energy balance

$$\frac{\partial \alpha_{lk}\rho_{lk}E_{lk}}{\partial t} + \nabla\cdot(\alpha_{lk}\rho_{lk}E_{lk}\mathbf{u}_{lk} + \alpha_{lk}p_{lk}\mathbf{u}_{lk}) + \nabla\cdot\left(\alpha_{lk}\overline{\overline{\Pi}}_{lk}\cdot\mathbf{u}_{lk}\right) + \nabla\cdot(\alpha_{kl}\mathbf{q}_{lk}) =$$
$$Q_{lk} + \mathbf{R}_{lk}\cdot\mathbf{u}_{lk} + p_{lI}\mathbf{u}_{lI}\nabla\alpha_{lk} + \mathbf{u}_{lI}\cdot\left(\overline{\overline{\Pi}}_{lI}\cdot\nabla\alpha_{lk}\right) + \mathbf{q}_{lI}\cdot\nabla\alpha_k - \tilde{p}_{lI}\mathcal{P}_{l,kk'} + \tilde{\mathbf{u}}_{lI}\cdot\mathbf{M}_{l,kk'} + \mathcal{Z}_{l,kk'}$$

Volume fraction

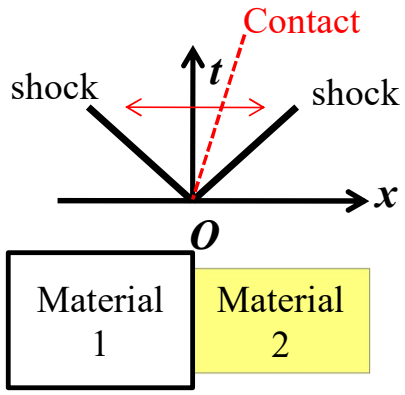
$$\frac{\partial \alpha_{lk}}{\partial t} + \mathbf{u}_{lI}\nabla\alpha_{lk} = \mathcal{P}_{l,kk'}$$

- **Grain mix between different materials**
- **14 equations**

II Model formulation

- **Key step 2：Evaluate ICF mechanical/thermal relaxation times and determine the perturbation parameter for asymptotic analysis.**

For grain mix evaluate with continuum mechanics



For atomic mix evaluate with coulomb collision

- **Relaxation rate of mean velocities（Braginskii,1965）**

$$\nu_{k/k'} = \frac{n_{k'} m_{kk'}}{m_k} \frac{4\sqrt{2\pi}\Lambda_{kk'} Z_k Z_{k'} e^4}{3\sqrt{m_{kk'}}(k_B T)^{3/2}}$$

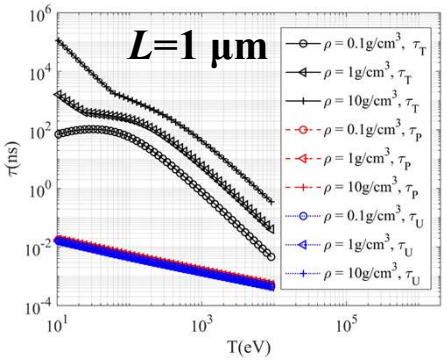
- **Relaxation rate of temperatures（Huba,2014）**

$$\nu^T_{k/k'} = 1.8 \times 10^{-19} \frac{(m_k m_{k'})^{1/2} Z_k^2 Z_{k'}^2 n_{k'} \Lambda_{kk'}}{(m_k T_{k'} + m_{k'} T_k)^{3/2}}$$

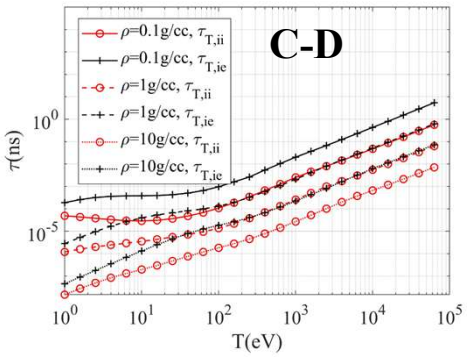
- **Mechanical relax. time (density, wave speed, grain size)**
- **Temperature relax. time (density, heat conuctivity, grain size)**

II Model formulation

Key step 2：Evaluate ICF mechanical/thermal relaxation times and determine the perturbation parameter for asymptotic analysis.



- **Relax times in grain mix: thermal >> mechanical(velocity, pressure)**
  （L=1μm, T<1keV, ~ 3 orders）



- **Ion-elec. and ion-ion temperature relax time maybe of the same order**
  1keV, 0.1g/cc, τ_{ie}/τ_{ii}=8（CD） τ_{ie}/τ_{ii}=3（AlD）

$$\frac{\partial \mathbf{V}}{\partial t} = -\left(\frac{m_e n_e}{m_i n_i \tau_e} + \frac{1}{\tau_e}\right)\mathbf{V} \qquad \frac{\partial \delta T}{\partial t} = -2\left(\frac{m_e n_e}{m_i n_i \tau_e} + \frac{m_e}{m_i \tau_e}\right)\delta T$$

- **elec-ion relaxation times : mean velocity << temperature**

◆ **Perturbations: mechanical relaxation time in grain mix, ion-elec. mean velocity relaxation time in atomic mix**

II Model formulation

- **Key step 3： By asymptotic analysis of the 14-eqn HED-BN model，one obtains the following approximations**

◆ **At the material interface, electron pressure relaxation rate >> ion pressure relaxation rate**

$$O\left(\frac{\mu_p^{e1/e2}}{\mu_p^{i1/i2}}\right) \sim O\left(\sqrt{\frac{\rho_{ik}}{\rho_{ek}}}\right)$$

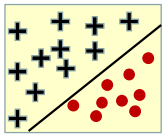
◆ **Ion-electron momentum exchange is reduced to be a gradient term from a relaxation term**

$$\alpha_k \mathbf{R}_{ik} \approx -\nabla \cdot \left(\alpha_{ik} \overline{\overline{P}}_{ek}\right) + \overline{\overline{P}}_{eI} \cdot \nabla\left(\alpha_{ik}\right) + \mathbf{M}_{ek}$$

◆ **The volume fraction equations for ions and electrons are reduced to be the same equation**

II Model formulation

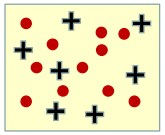
- **Key step 4： By introducing an effective pressure relaxation to the atomic mix， we obtain a unified formulation for both grain and atomic mix**
- **The effective unified model can be reduced to the classical two-fluid model**



Grain mix

Volume fraction $\alpha_r = \frac{1}{V}\int_V X_r \mathrm{d}V$

Pressure relaxation → variation of α_r



Atomic mix

Volume fraction undefined → Pressure fraction α_k^*

Pressure relaxation undefined → Effective pressure relaxation

$$\frac{\partial p_{lk}^*}{\partial t} = \zeta_{lk}^* \left(p_{lk'}^* - p_{lk}^*\right), \quad \sum_k \zeta_{lk}^* \to \infty$$

II Model formulation

Key step 5： Reduce multi-velocity to sing-velocity model with closure relation

- **Neglect second-order terms of diffusion velocity $\mathbf{w}_k$**
- **Close $\mathbf{w}_k$ with the Fick's law**

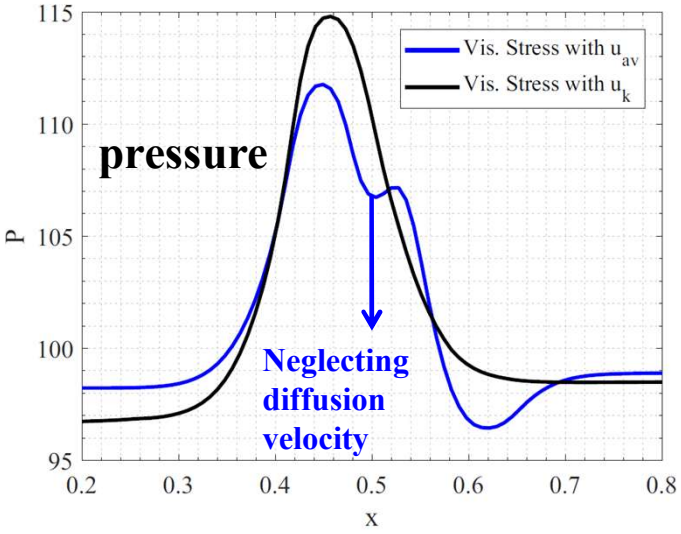
Grain mix $\mathcal{O}\left(|\mathbf{w}_k|^2\right) \sim \mathcal{O}(\tau_u^2)$

Atomic mix $\mathcal{O}\left(|\mathbf{w}_k|^2\right) \sim \mathcal{O}(\mathrm{Kn}^2)$

◆ **Diffusion velocity makes a non-negligible contribution to mixture momentum equation (especially for compressible flows)**

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{u}\boldsymbol{u} - \sum \alpha_k \overline{\overline{T}}_{ak} \right) = \sum \nabla \cdot (\alpha_k \overline{\overline{T}}_{wk})$$

◆ **Neglecting the diffusion velocity contribution violates 2nd law**



[1] A.W Cook, POF, 2009. [2] **Zhang C.,** PRE, 2023.

II Model formulation

Different levels of relaxations lead to a hierarchy of disequilibrium models

Model	Ion eqns	Elec. eqns	Assumptions	Wave speeds
Nine-eqn	7	2	Ions in full diseq.	$u_1, u_1, u_2, u_2, u_I,$ $u_1 \pm a_1,$ $u_2 \pm a_2,$ $a_k^2 = a_{ik}^2 + (a'_{ek})^2$
Eight-eqn	6	2	+ Ion velocities eq.	u(6 times), $u \pm \sqrt{y_1 a_1^2 + y_2 a_2^2}$
Six-eqn	5	1	+ Ion/elec. mechanical eq.	u(4 times), $u \pm \sqrt{\frac{1}{\rho(\alpha_1/A_1+\alpha_2/A_2)}},$ $A_k = \rho_k \left(a_{ik}^2 + (a'_{ek})^2\right)$
Five-eqn	4	1	+ Ion/elec. mechanical and thermal eq.	u(3 times), $u \pm \sqrt{\gamma_i p_i/\rho + a_e^2},$ $\gamma_i = \frac{\sum y_k C_{vik}(\gamma_{ik}-1)}{\sum y_k C_{vik}} + 1$
Four-eqn	3	1	+ Ion/elec. mechanical, thermal and compressibility eq.	$u, u, u \pm \sqrt{a_i^2 + (a'_e)^2}$

◆ **Hyperbolic, disequilibrium, thermodynamically compatible, reduction to classical models**

[1] **Zhang C.**, et al., JCP, 2022. [2] **Zhang C.**, et al., JCP, 2023. [3] **Zhang C.**, et al., PRE, 2023. [4] **Zhang C.**, arXiv 2408.15531.

II Model formulation : examples

BNZ (Baer-Nunziato-Zeldovich) model

$$\frac{\partial \alpha_k \rho_{ik}}{\partial t} + \nabla \cdot (\alpha_k \rho_{ik} \mathbf{u}_k) = 0$$

$$\frac{\partial \alpha_k \rho_{ik} \mathbf{u}_k}{\partial t} + \nabla \cdot (\alpha_k \rho_{ik} \mathbf{u}_k \mathbf{u}_k) + \nabla \cdot \left(\alpha_k \overline{\overline{P}}_{ik} + \alpha_k \overline{\overline{P}}_e \right) = \overline{\overline{P}}_{iI} \cdot \nabla \alpha_k + \mathbf{M}_{ik}$$

$$\frac{\partial \alpha_k \rho_{ik} E_{ik}}{\partial t} + \nabla \cdot (\alpha_k \rho_{ik} E_{ik} \mathbf{u}_k) + \nabla \cdot \left(\alpha_k \overline{\overline{P}}_{ik} \cdot \mathbf{u}_k \right) + \nabla \cdot (\alpha_{kl} \mathbf{q}_{ik}) =$$

$$\alpha_k Q_{ik} + \mathbf{u}_{iI} \cdot \left(\overline{\overline{P}}_{iI} \cdot \nabla \alpha_k \right) + \mathbf{q}_{iI} \cdot \nabla \alpha_k - \tilde{p}_{iI} \mathcal{P}_{ik} + \tilde{\mathbf{u}}_I \cdot \mathbf{M}_{ik} + \mathcal{Z}_{ik}$$

$$\frac{\partial \alpha_k \rho_{ik} \varepsilon'_{ek}}{\partial t} + \nabla \cdot (\alpha_k \rho_{ik} \varepsilon'_{ek} \mathbf{u}_k) + \left(\alpha_k \overline{\overline{P}}_{ek} \cdot \nabla \right) \cdot \mathbf{u}_k + \nabla \cdot (\alpha_k \mathbf{q}_{ek}) =$$

$$\alpha_{lk} Q^{\varepsilon}_{ek} + (\mathbf{u}_{iI} - \mathbf{u}_k) \cdot \left(\overline{\overline{P}}_{eI} \cdot \nabla \alpha_k \right) + \mathbf{q}_{eI} \cdot \nabla \alpha_k - \tilde{p}_{eI} \mathcal{P}_{ik} + (\tilde{\mathbf{u}}_I - \mathbf{u}_k) \cdot \mathbf{M}_{ek} + \mathcal{Z}_{lk}$$

$$\frac{\partial \alpha_k}{\partial t} + \mathbf{u}_I \cdot \nabla \alpha_k = \mathcal{P}_k$$

- **Reduce to Baer-Nunziato model if neglect electron**
- **Reduce to Zeldovich model for single fluid**
- **Repects 2nd law**

9 equations, 2 velocities, 4 pressures, 4 temperatures

II Model formulation : examples

8-eqn model

$$\frac{\partial \alpha_k \rho_{ik}}{\partial t} + \nabla \cdot (\alpha_k \rho_{ik} \mathbf{u}) = -\nabla \cdot (\alpha_k \rho_{ik} \mathbf{w}_k),$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left(\rho \mathbf{u}\mathbf{u} + \sum \alpha_k \overline{\overline{P}}_{ak} \right) = -\nabla \cdot \left(\sum \alpha_k \overline{\overline{P}}_{wk} \right),$$

$$\frac{\partial \alpha_k \rho_{ik} \varepsilon_{ik}}{\partial t} + \nabla \cdot (\alpha_k \rho_{ik} \varepsilon_{ik} \mathbf{u}) + \alpha_k p_{ik} \nabla \cdot \mathbf{u} = -p_{iI} \mathcal{P}_{ik} - \nabla \cdot (\alpha_k \rho_{ik} \varepsilon_{ik} \mathbf{w}_k) - \alpha_k p_{ik} \nabla \cdot \mathbf{w}_k + \mathcal{G}_{ik},$$

$$\frac{\partial \alpha_k \rho_{ek} \varepsilon'_{ek}}{\partial t} + \nabla \cdot (\alpha_k \rho_{ik} \varepsilon'_{ek} \mathbf{u}) + \alpha_k p_{ek} \nabla \cdot \mathbf{u} = -p_{eI} \mathcal{P}_{ek} - \nabla \cdot (\alpha_k \rho_{ik} \varepsilon'_{ek} \mathbf{w}_k) - \alpha_k p_{ek} \nabla \cdot \mathbf{w}_k + \mathcal{G}_{ek},$$

$$\frac{\partial \alpha_k}{\partial t} + \mathbf{u} \cdot \nabla \alpha_k = \mathcal{P}_k.$$

8 equations, 1 velocities,
4 pressures, 4 temperatures

5-eqn model

$$\frac{\partial \alpha_k \rho_{ik}}{\partial t} + \nabla \cdot (\alpha_k \rho_{ik} \mathbf{u}) = -\nabla \cdot (\alpha_k \rho_{ik} \mathbf{w}_k),$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left(\rho \mathbf{u}\mathbf{u} + \sum \alpha_k \overline{\overline{P}}_{ak} \right) = \nabla \cdot \left(\sum \alpha_k \overline{\overline{P}}_{wk} \right),$$

$$\frac{\partial \rho \varepsilon_i}{\partial t} + \nabla \cdot (\rho \varepsilon_i \mathbf{u}) + p_i \nabla \cdot \mathbf{u} = -\nabla \cdot \left(\sum \alpha_k \rho_{ik} \varepsilon_{ik} \mathbf{w}_k \right) - \sum \alpha_k p_{ik} \nabla \cdot \mathbf{w}_k + \mathcal{G}_i,$$

$$\frac{\partial \rho \varepsilon'_e}{\partial t} + \nabla \cdot (\rho \varepsilon'_e \mathbf{u}) + p_e \nabla \cdot \mathbf{u} = -\nabla \cdot \left(\sum \alpha_k \rho_{ik} \varepsilon'_{ek} \mathbf{w}_k \right) - \sum \alpha_k p_{ek} \nabla \cdot \mathbf{w}_k + \mathcal{G}_e.$$

5 equations, 1 velocities,
2 pressures, 2 temperatures

II Model formulation : numerical methods

- **The proposed model is a hyperbolic-parabolic-relaxation system solved by the fractional step method**

Hyperbolic

- 5th order Spatial reconstruction MLP
- Free of spurious oscillations
- Volume fraction positivity（N≥3）
- Interface-sharpening

Parabolic

- **Explicit** method LIM

(V.T. Zhukov, Mat. Model. 22 (2010).)

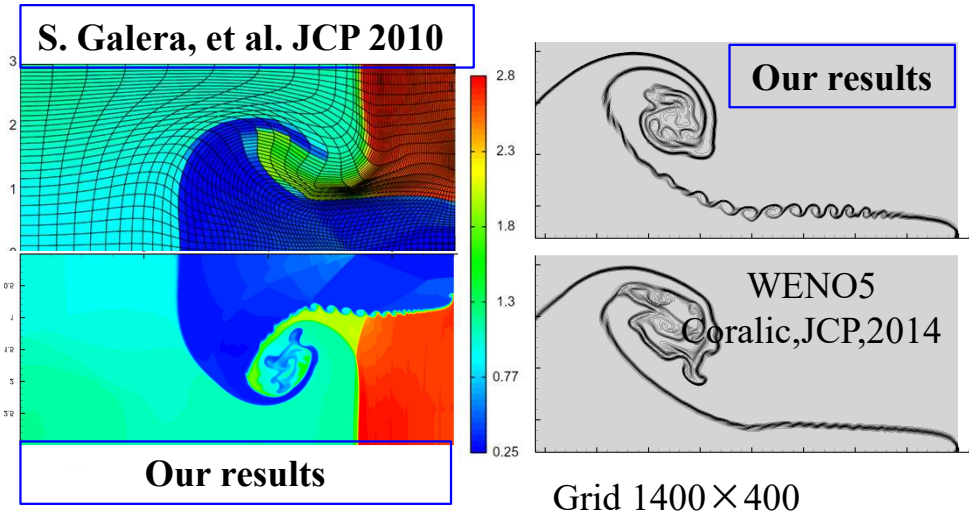
Relaxation

- Efficient fixed-point iteration

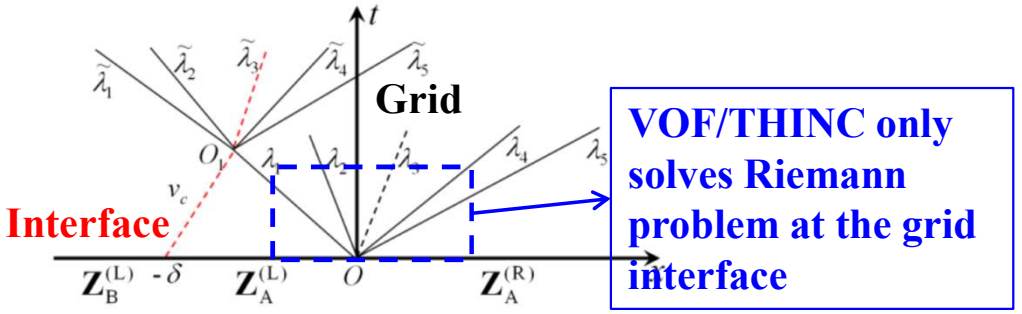
1. **Zhang C.,** et al, JCP, 2022; **Zhang C.,** et al, JCP, 2023.
2. Menshov I., **Zhang C.,** 2021, WCCM-ECCOMAS.
3. **Zhang C.,** et al., J. Sci. Comput., 83(31) (2020) .
4. **Zhang C.,** et al., Comput. & Fluids. 236(2022)105311.

III Model verification and validation

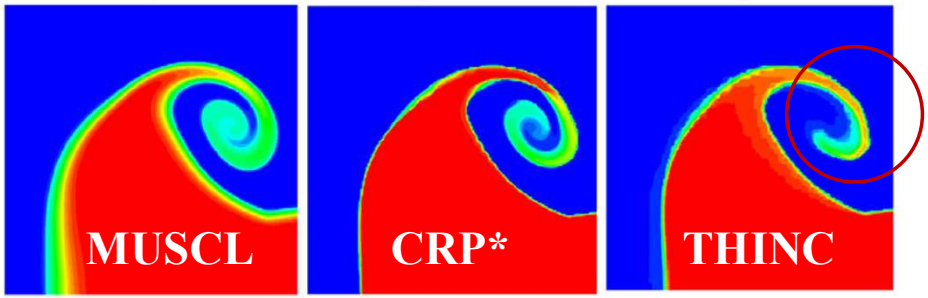
☐ Hydrodynamic part



Better resolution than WENO



Our method solves the entire Composite Riemann problem [1,2]

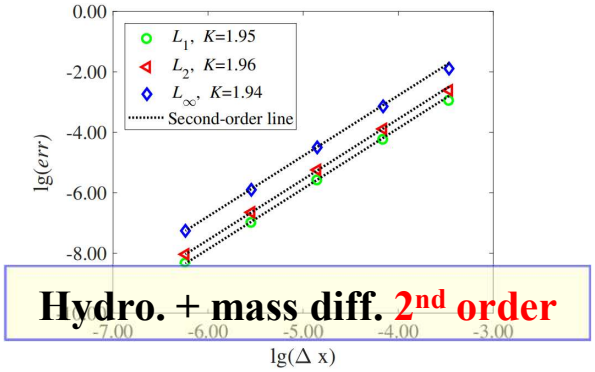


Better resolution than THINC

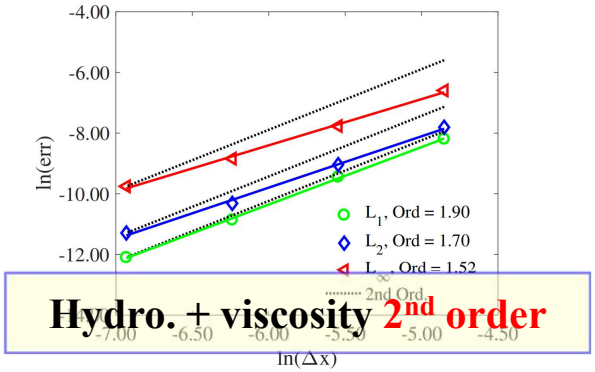
[1] Menshov I., Zhang C., 2021, WCCM-ECCOMAS.
[2] Zhang C., Menshov I., 2019, AMC

III Model verification and validation

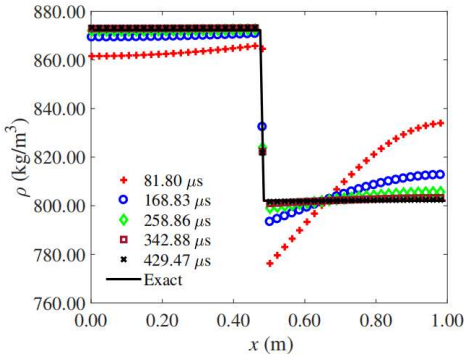
- **Heat conduction, mass diffusion, viscosity, and LIM efficiency**



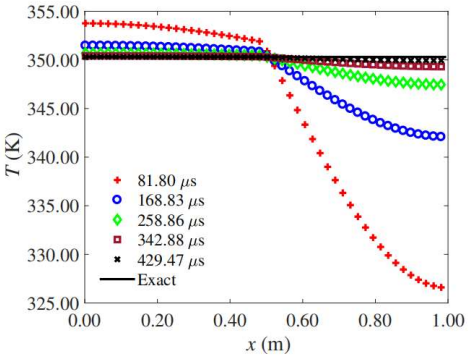
Hydro. + mass diff. 2nd order



Hydro. + viscosity 2nd order

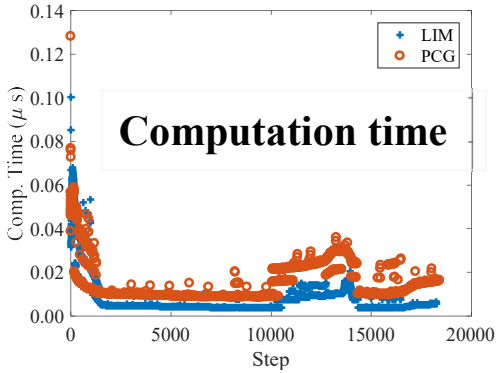


(a) Density



(b) Temperature

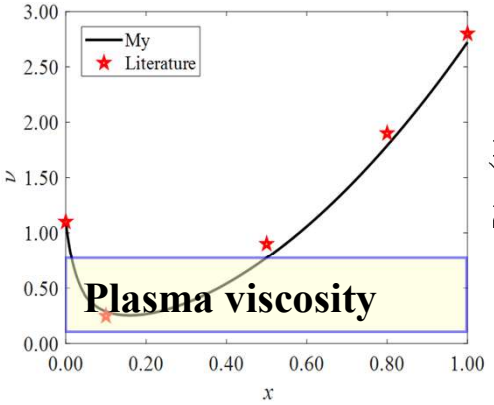
Multi-material heat conduction part achieves convergence



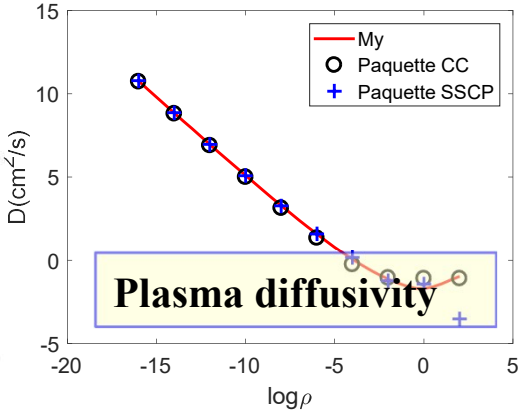
For electron heat conduction computation time of LIM is 50% of that of PCG

III Model verification and validation

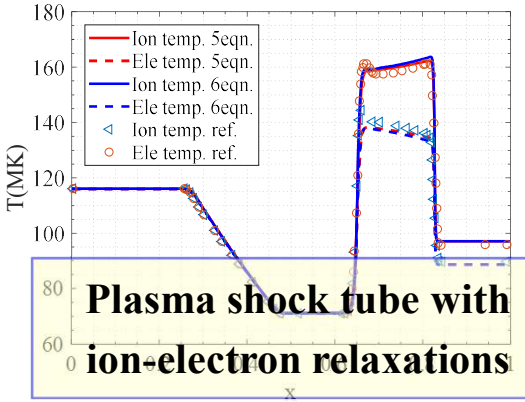
Transport parameters



Plasma viscosity



Plasma diffusivity



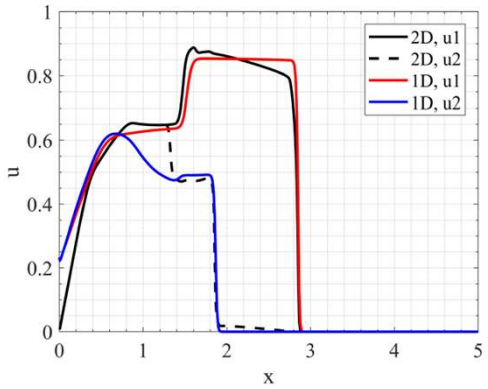
Plasma shock tube with ion-electron relaxations

2D

Material 1 $\rho = 1$, $p = 1$	$\rho = 0.125$, $p = 0.1$ ***Material 1***
	$\rho = 1$, $p = 0.1$ ***Material 2***

1D

$\rho_1 = 1$, $\rho_2 = 0.125$, $p_1 = p_2 = 1$, $\alpha_1 = 1\text{-}10^{-3}$	$\rho_1 = 0.125$, $\rho_2 = 1$, $p_1 = p_2 = 0.1$, $\alpha_1 = 0.5$

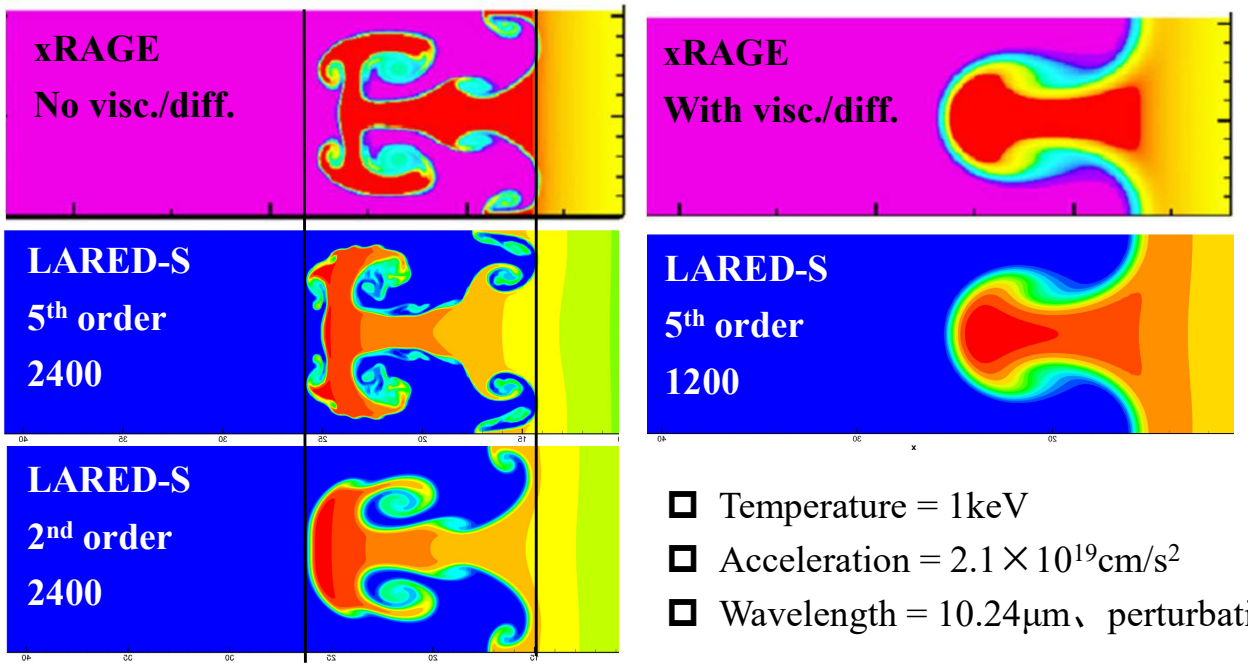


The disequilibrium model well captures the velocity disequilibrium

[1] Sangam, et al., JCP, 444 (2021) 110565. [2] Clérouin, et al. EPL, 89(1998). [3]Paquette, et al. Astrophys. J. Suppl. Ser., 61 (1986).

III Model verification and validation

☐ RTI at ICF deceleration stage



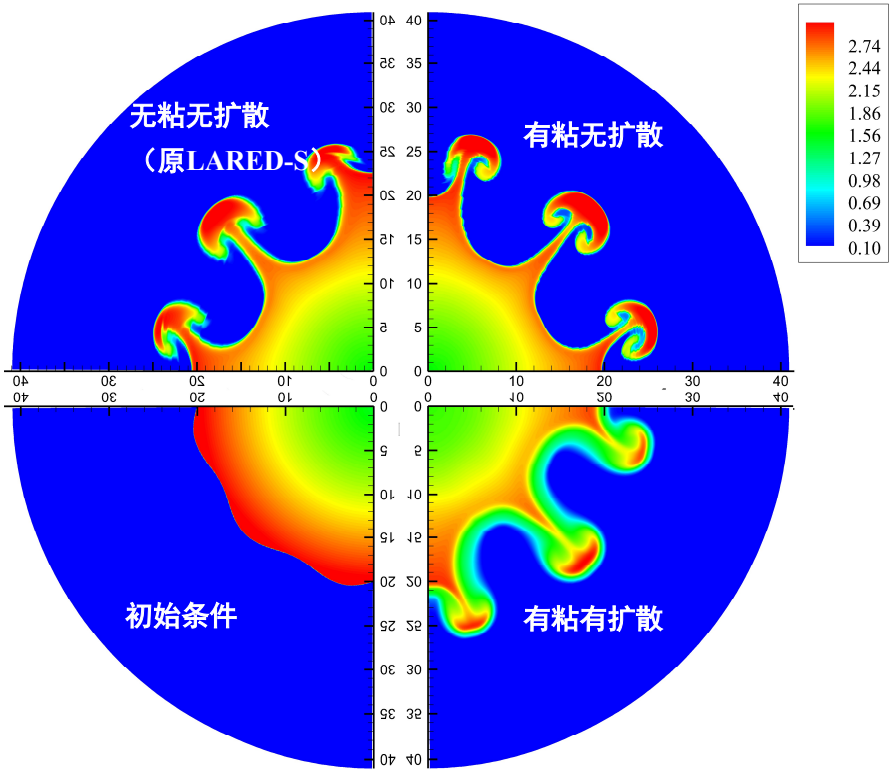
◆ **Our results agree well with the xRAGE code**

- ☐ Temperature = 1keV
- ☐ Acceleration = $2.1 \times 10^{19} cm/s^2$
- ☐ Wavelength = 10.24μm、perturbation = 3%

[1] Vold E., et al., POP, 2021.

III Model verification and validation

- **Numerical results in spherical geometry**



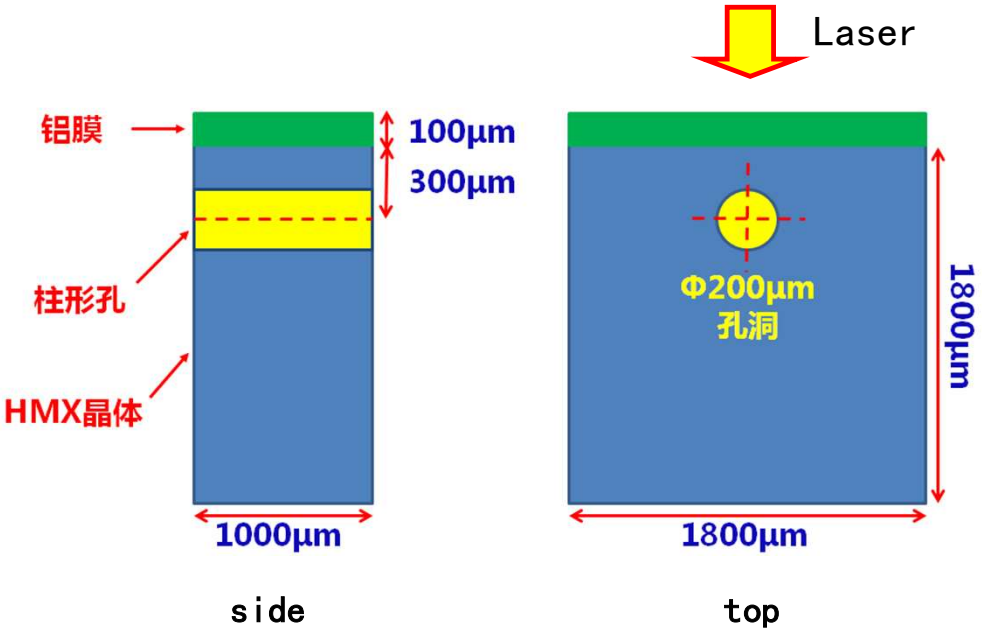
◆ **The plasma diffusion affects the RTI development (characteristic wavelength = 10μm)**

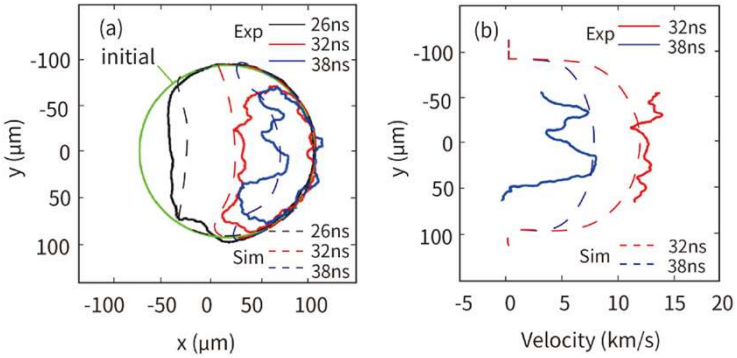
RT growth rate（Vold E., POP2020）

$$\omega = \left[\left(\frac{Agk}{(1+bkL_D)} + ((\gamma + aD)k^2)^2\right)^{1/2} - (\gamma + aD)k^2\right]$$

III Model verification and validation

- **The simulation results agree with exp. results for the laser-ablation of HMX target**





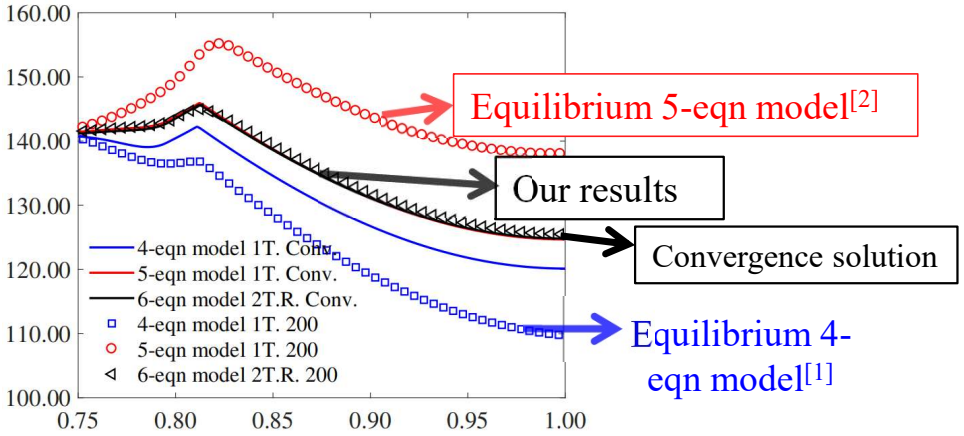
Void interface **Interface velocity**

Cao Z., Chu G., Ma X., et al. Visualizing pore collapse in explosive using X-ray picosecond tracking imaging, PRL, under review.

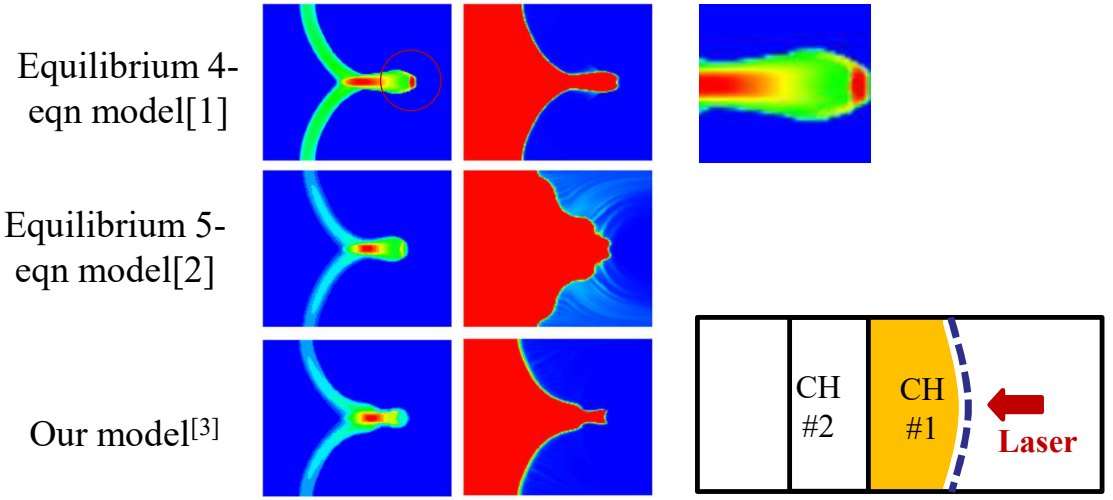
III Model verification and validation

☐ Our disequilibrium model has numerical advantage over traditional one-fluid model

✓ Advantage1 : faster convergence



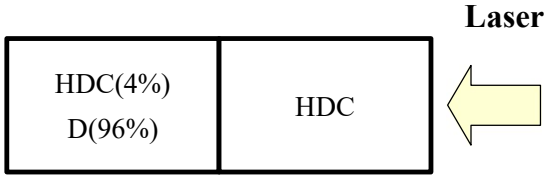
✓ Advantage1 : free of oscillation



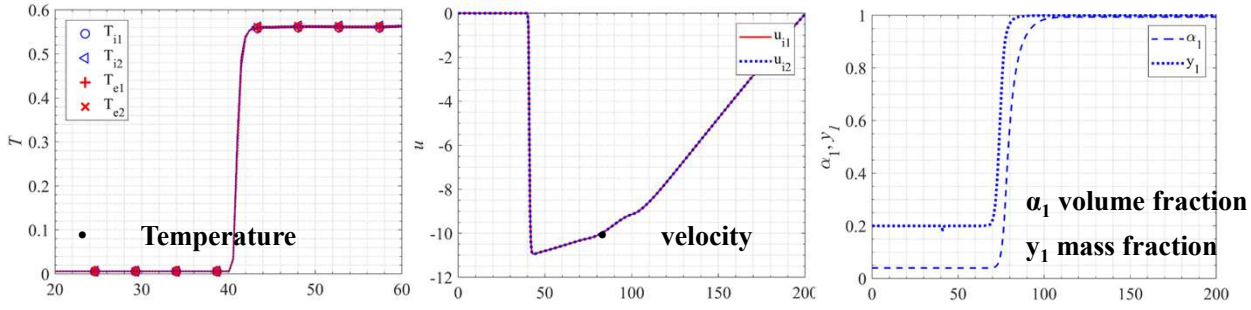
[1] Lemartelot S., Int J Multiphas Flow, 2014. [2] Beig S.A., JCP, 2015. [3] **Zhang C.**, et al., JCP, 2022.

IV Application (1): disequilibria in grain mix

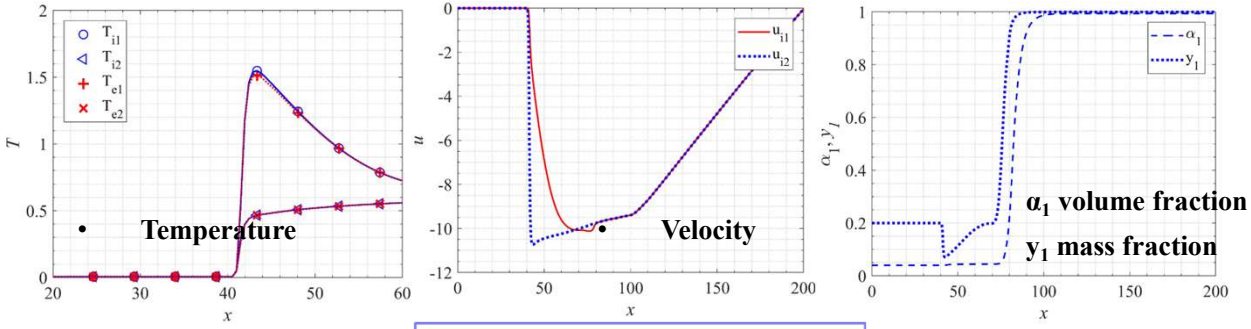
- **Ablation shock hits the grain mixture（Characteristic length = 10μm， temperature separation = 1MK， velocity separation = 10km/s）**



- **BNZ model**
- **HDC/D in grain mix**
- **Component separation after shock**



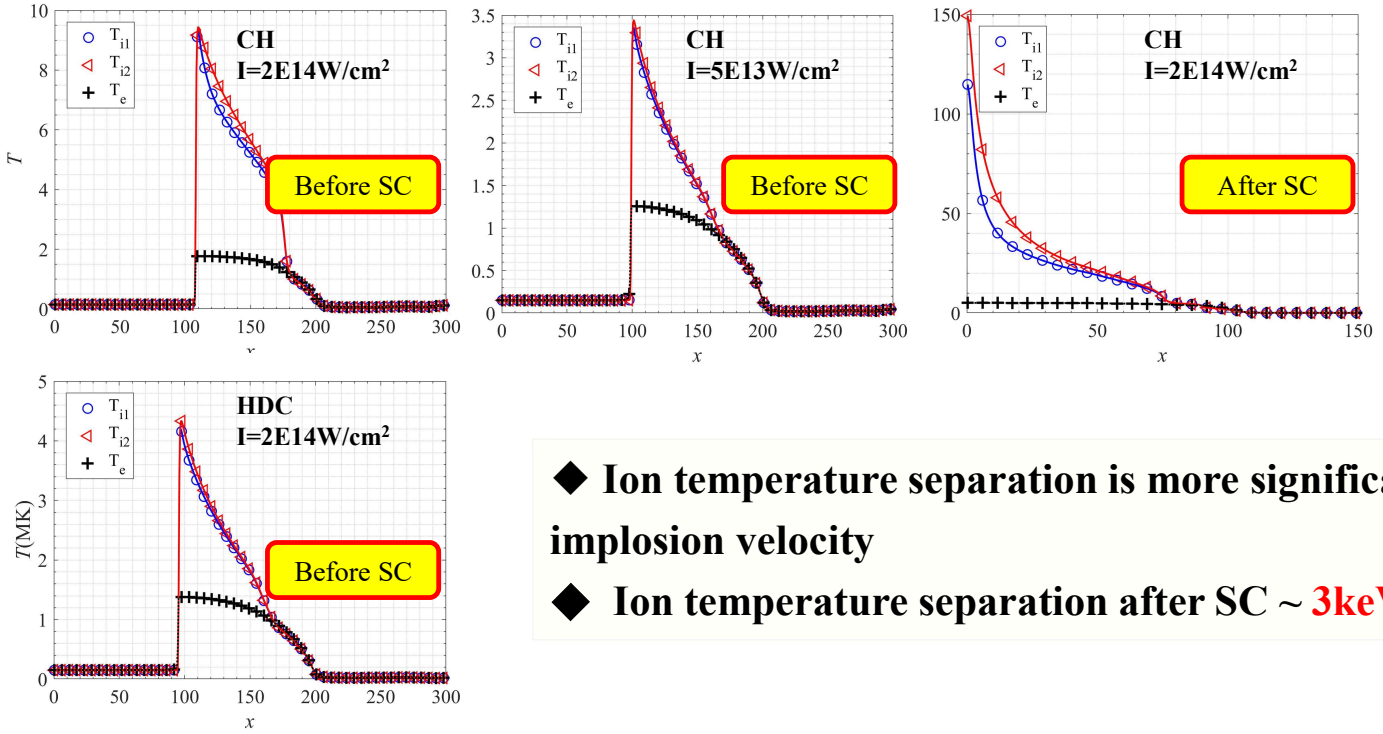
Characteristic length = 0.1μm



Characteristic length = 10μm

IV Application (2): disequilibria in atomic mix

- **Our model resolves temperatures of different ion species and electrons in atomic mix of ICF**



SC = shock convergence

T relax. time $\tau_T \sim \frac{T^{3/2}}{Z^4}$

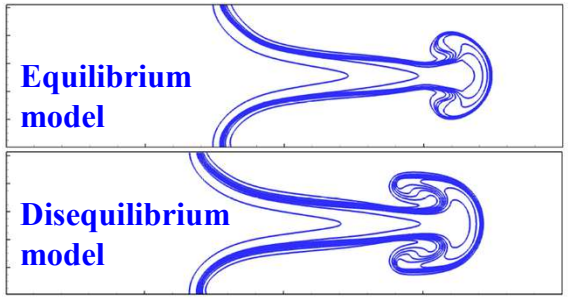
Implosion time $\tau_{\mathrm{imp}} = \frac{l}{u}$

◆ **Ion temperature separation is more significant for high laser power and implosion velocity**

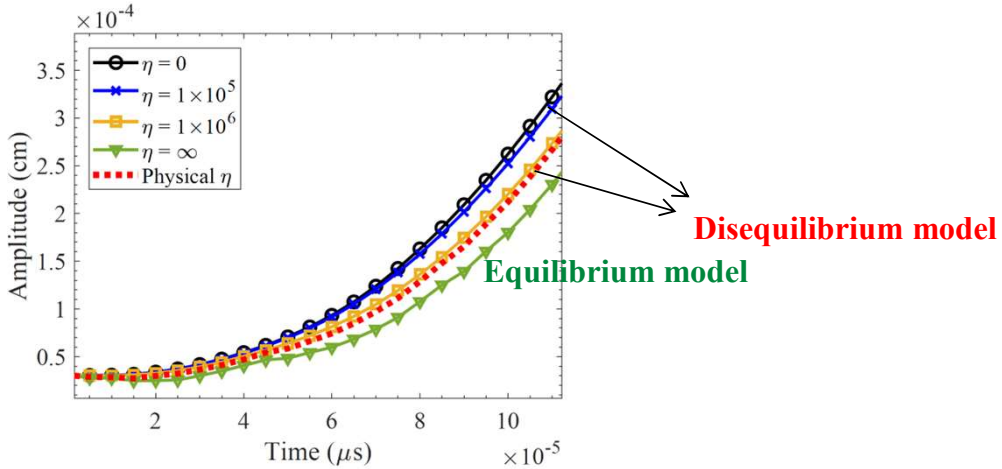
◆ **Ion temperature separation after SC ~ 3keV**

IV Application (3): Effect of temperature relax. on RTI

- Temperature relaxation slows down the development of RTI
- Using one-fluid model may underestimate perturbation development



Interface



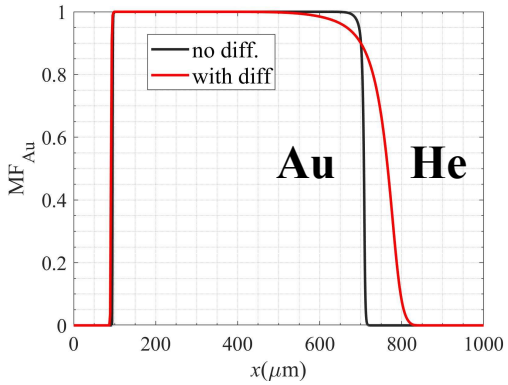
The perturbation growth under different relaxation rates η

- Temperature relaxation alters the acceleration at the interface

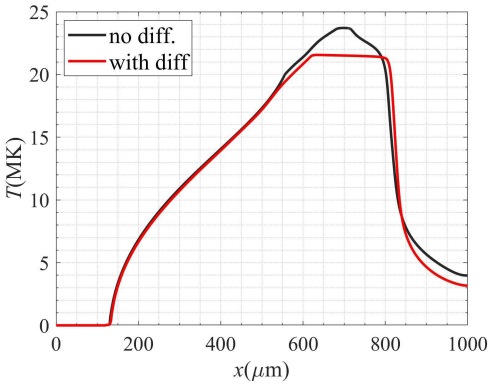
Zhang C., Wang L., PRE,108(2023)045108.

IV Application (4): Interpenetration mix in hohlraum

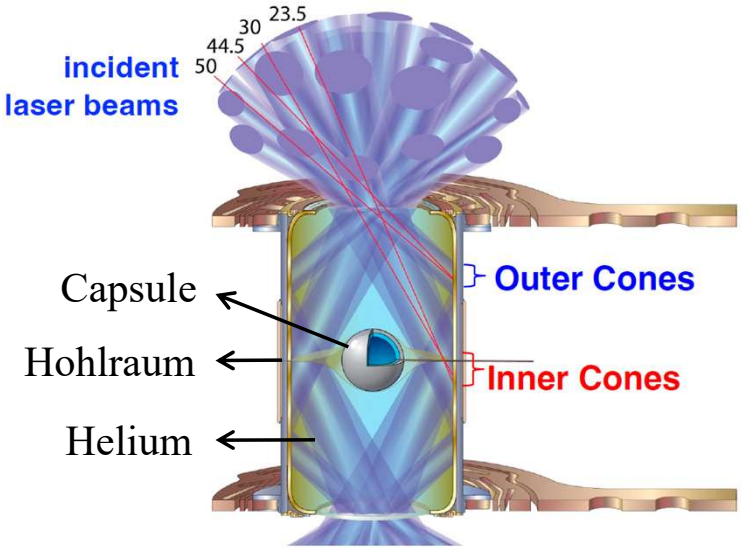
- **The laser-ablated Au bubble and Helium interpenetration due to velocity disequilibrium. The resulting mix zone is as long as 300μm, leading to energy loss.**



Au mass fraction



Temperature



ICF indirect drive

Conclusion

◆ **We have proposed a multi-component disequilibrium model**

- **It resolves temperatures and velocities of different ion/electron species**
- **It has a unified formulation for atomic/grain mix**
- **It has numerical advantages in convergence and is free of spurious oscillations**

The model has been used to evaluate the disequilibria in atomic/grain mix of ICF

- **The temperature separation between ion species is as large as 3keV after shock convergence**
- **Temperature relaxation slows down RTI development**
- **Velocity disequilibrium causes serious inter-penetration mixing between Au and He in hohlraum (~300μm)**