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Implementation and application of a simple radiation loss model for tamped volume ignition ICF targets

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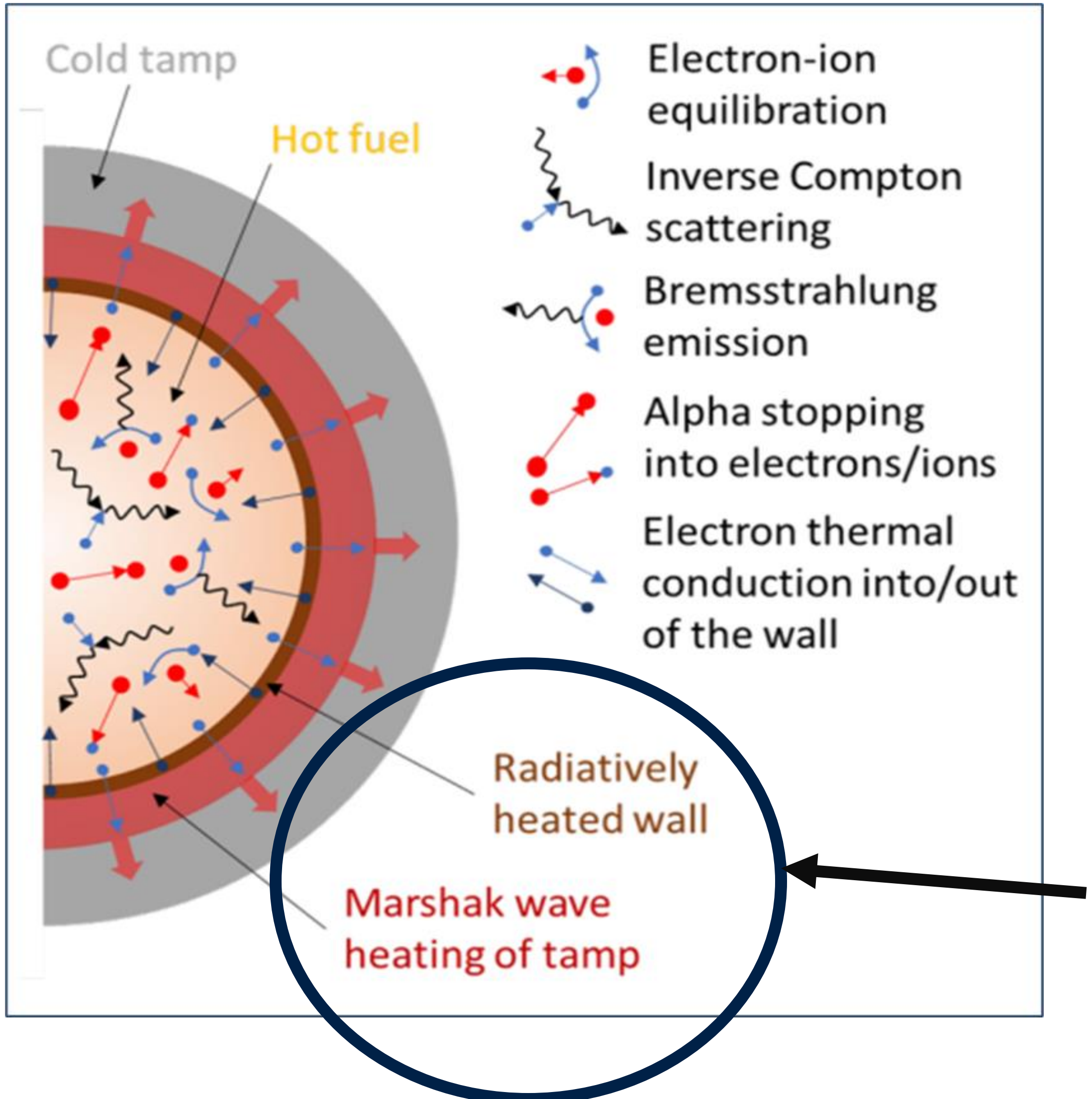
The advanced ignition model can quickly predict the dynamics of spherical volume ignition targets



- FLAIM is First Light's advanced ignition model used to model volume ignition targets
- It forms one part of FuSE – an end-to-end gain experiment modelling tool
- Uses the compression mechanisms of a spherical piston to drive the volume ignition capsule
- Three-temperature physics describing the interactions between the different components as illustrated on the left
- For more details, see: A. E. Saufi (PsM1A)
- This talk will focus on modelling the pusher-fuel interface

Self-similar solutions to the supersonic planar radiation diffusion equation can be determined

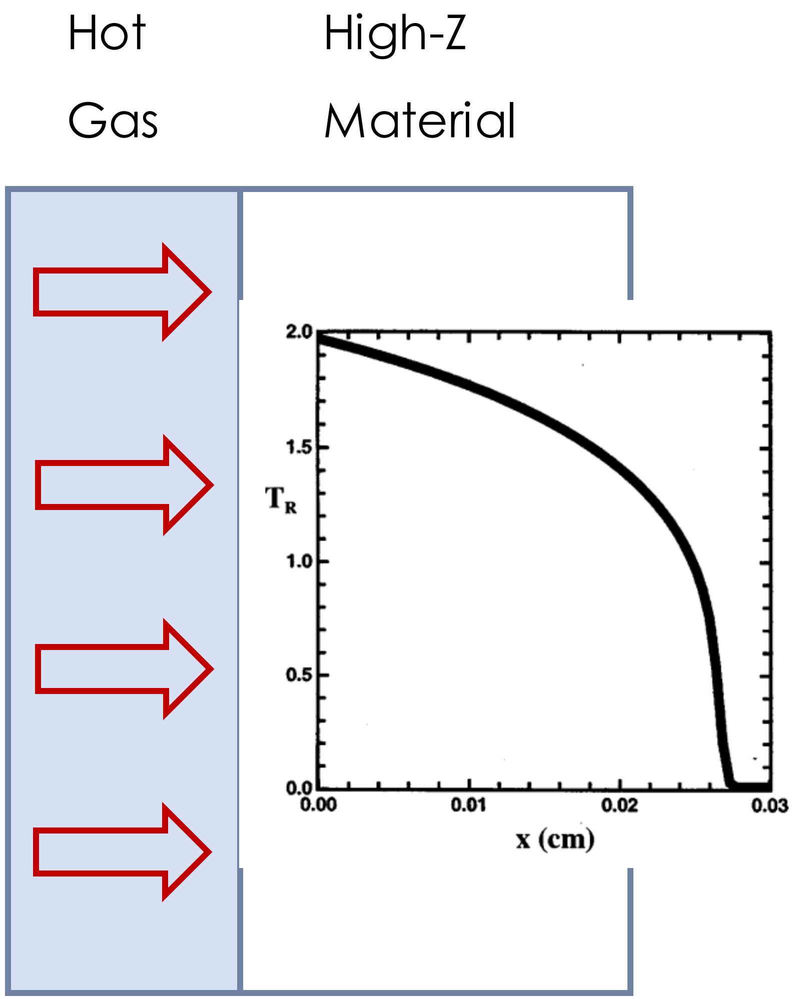
- Following Hammer & Rosen [1] analytical solutions
  - Assuming power-law description of the pusher material:

$$u = u_0 \left(\frac{T}{T_0}\right)^b \left(\frac{\rho}{\rho_0}\right)^m$$

$$\frac{1}{\chi} = \frac{1}{\chi_0}\left(\frac{T_0}{T}\right)^a \left(\frac{\rho_0}{\rho}\right)^l = \frac{1}{\kappa\rho}$$

- Starting with the radiation diffusion equation in 1D planar geometry:

$$\frac{du}{dt} = \frac{4}{3}\frac{d}{dx}\left[\frac{1}{\kappa\rho}\frac{d\sigma T^4}{dx}\right]$$



[1] J. Hammer and M. Rosen, Phys. Plasmas 10 (2003)

Inserting the analytic forms for material properties, a set of analytic solutions is derived

- The position of the Marshak wave in the high-Z metal is given by:

$$x_F^2 = \frac{2+\epsilon}{1-\epsilon}\, C\, \hat{H}^{-\epsilon} \int_0^t \hat{H}(t')\, dt'$$

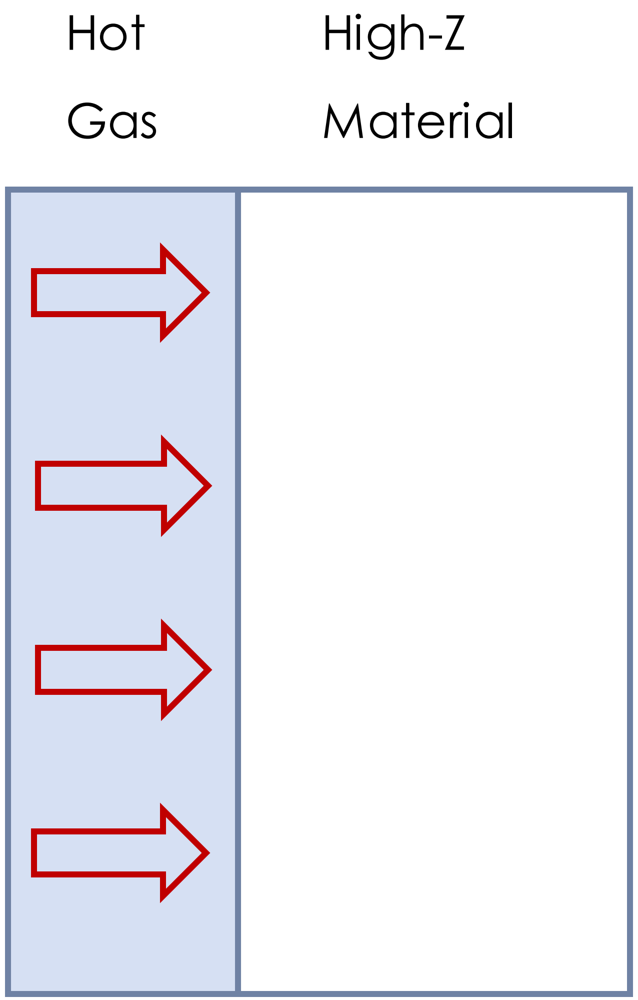
- And the radiative flux driving it is defined as:

$$F = u_0 \hat{\rho}^m (1-\epsilon) \frac{\partial}{\partial t}\left[x_F\, \hat{H}^{\epsilon}\right]$$

- Where the steepness parameter ϵ is defined with respect to the material properties:

$$\epsilon = \frac{b}{4-a}$$

- And the dimensionless temperature is $\hat{H} = \left(\frac{T_W}{T_0}\right)^{4-a}$



Rate equations can estimate the position and temperature of the Marshak wave in the high-Z pusher

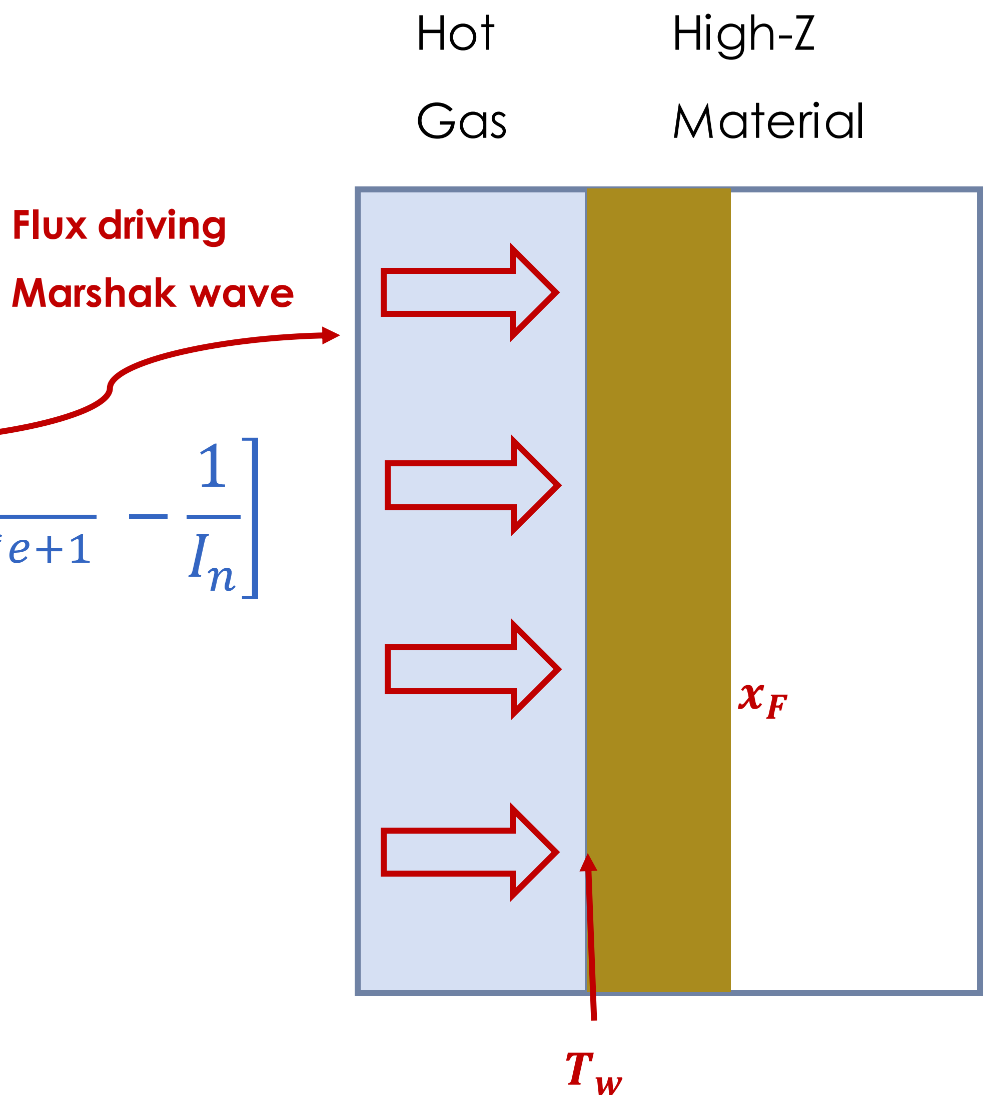
- The cumulative integral term is defined as:

$$\hat{I}_n = \int_0^t \hat{H}(t')dt' \rightarrow \hat{H} = \frac{d\hat{I}_n}{dt}$$

- Rate equations are thus derived as [2]:

$$\frac{d\hat{H}}{dt} = (4-a)\frac{T_W^{3-a}}{T_0^{4-a}}\frac{dT_W}{dt} = \frac{\hat{H}^2}{2}\left[\frac{2F}{u_0\rho^m(1-e)x_F\hat{H}^{e+1}} - \frac{1}{I_n}\right]$$

$$\frac{dx_F}{dt} = \frac{x_F\hat{H}}{2}\left[\frac{1}{I_n} - \frac{e}{\hat{H}^2}\frac{d\hat{H}}{dt}\right]$$

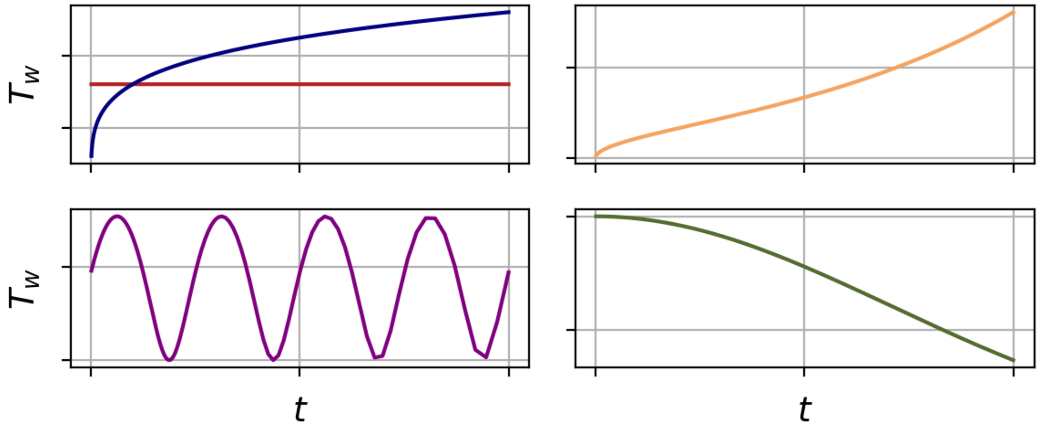


[2] E. Dodd et.al., Phys. Plasmas 27 (2020)

Model is verified against analytic tests and our in-house radiation-hydrodynamics code

Analytical verification:

- Analytic tests were derived by specifying a temperature profile and solving for the flux
- The expression for the flux is then inserted into the numerical solver



Comparison against B2:

- B2 is a multi-physics, 3D magneto-hydrodynamics code with multigroup radiation transport
- Comparison was set up using single-group radiative diffusion in 1D planar geometry with the power-law forms of the material properties as specified
- Driving boundary condition set using a radiative conduction model with the conductivity calculated from the opacity

Following this "recipe", different verification tests using set temperature profiles at the boundary are derived

- Power-law [2]:

$$T_w(t) = T_0 \left(\frac{t}{t_0}\right)^{\gamma}$$

- Exponential:

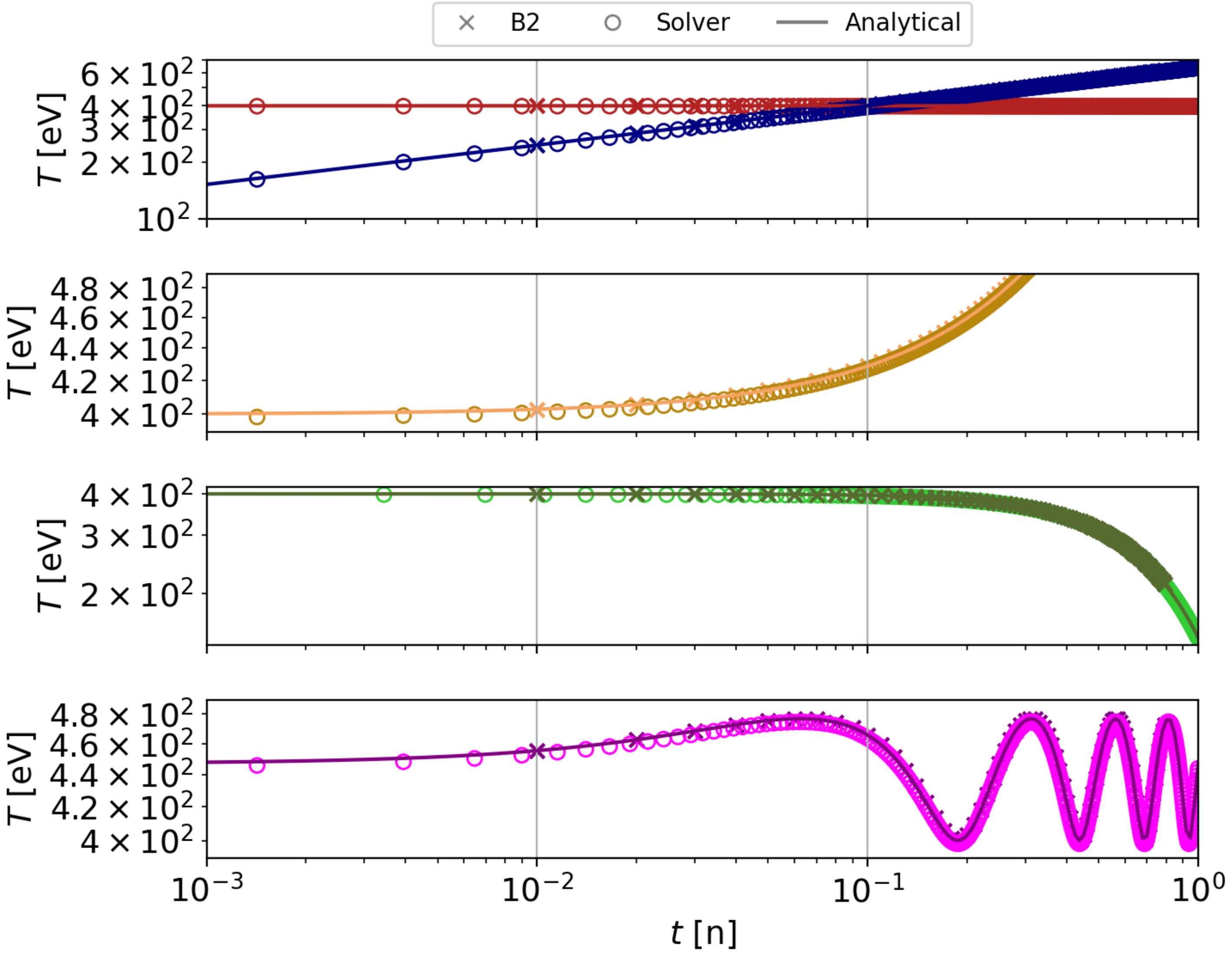
$$T_w(t) = T_0 \exp[2\gamma t]$$

- Gaussian:

$$T_{w(t)} = T_0 \exp[-\gamma^2 t^2]$$

- Sinusoidal:

$$T_w(t) = T_0[\sin(\gamma t) + 2]^{\frac{1}{4-a}}$$



[2] E. Dodd et.al., Phys. Plasmas 27 (2020)

Following this "recipe", a set of analytical verification tests is derived using different temperature profiles

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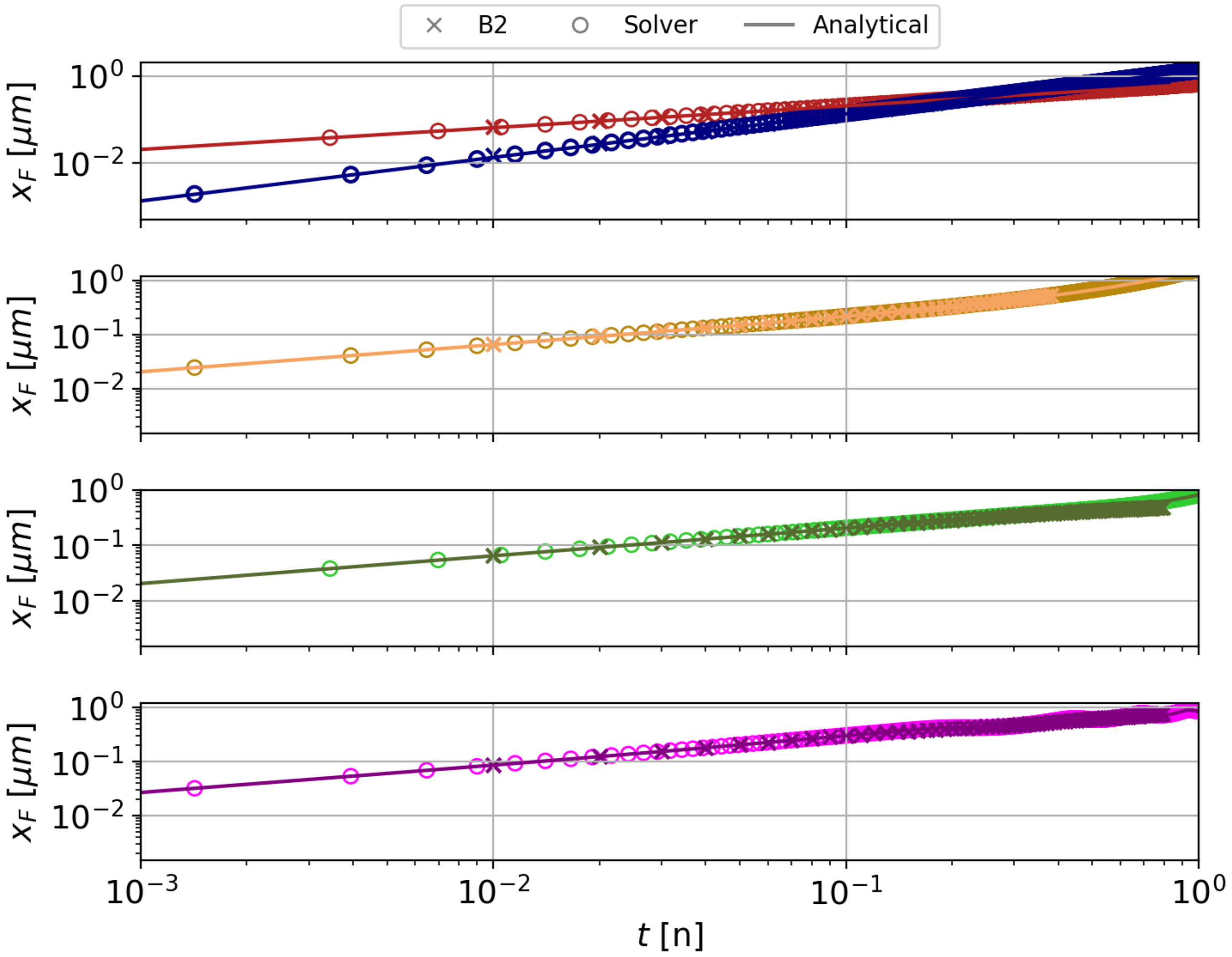

[2] E. Dodd et.al., Phys. Plasmas 27 (2020)

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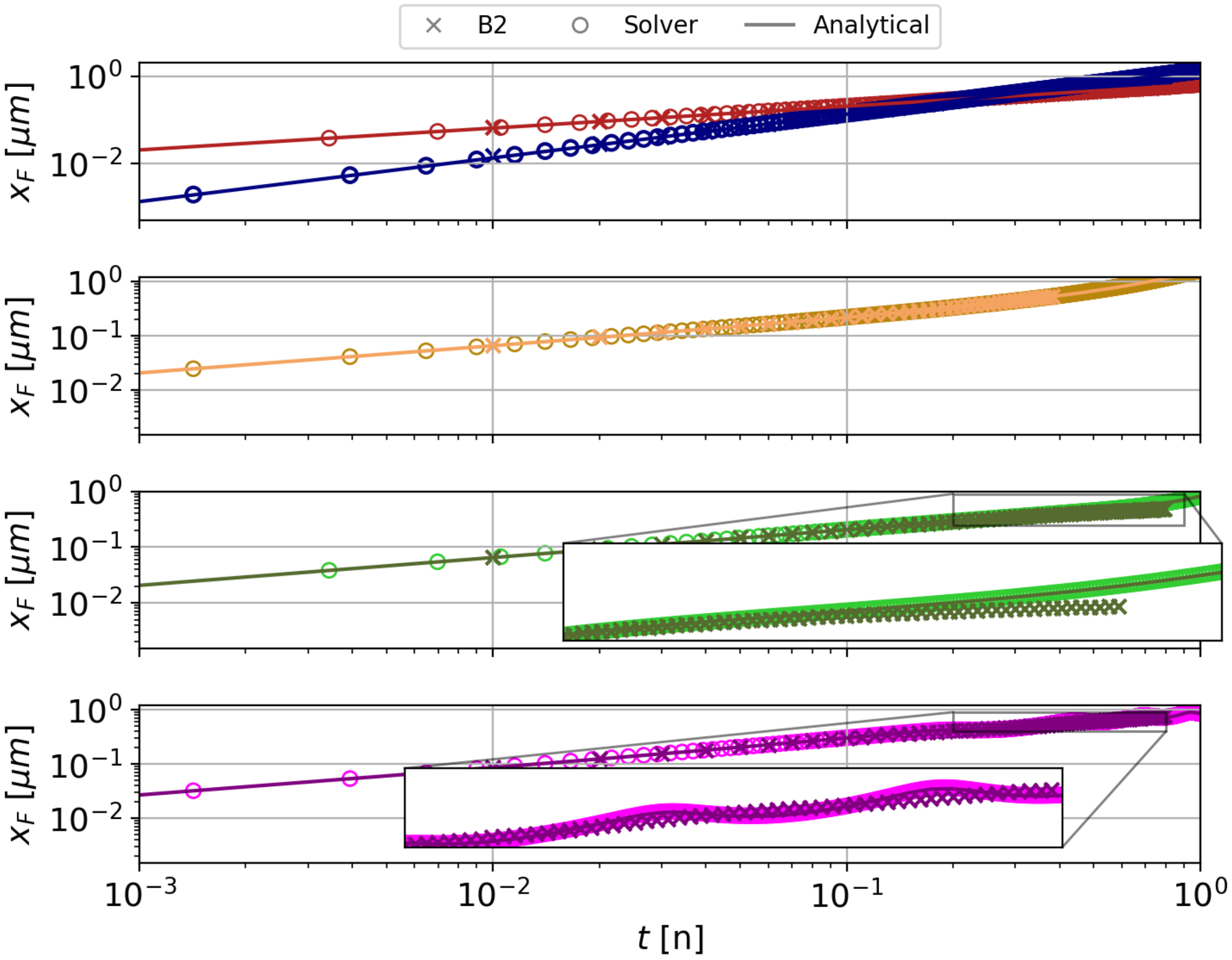


[2] E. Dodd et.al., Phys. Plasmas 27 (2020)

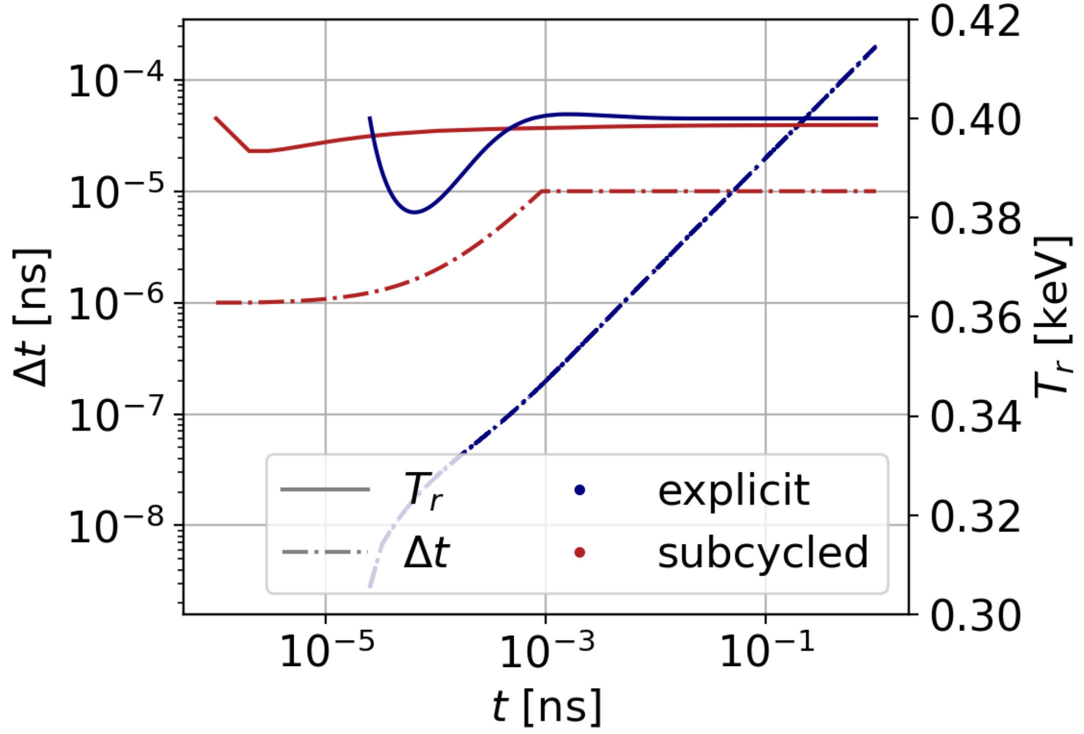
Initial conditions need to be fixed for the analytical test cases to be solved accurately

- The integral term leads to the equations has a singularity at $t = 0$

$$\hat{I}_n(t=0) = \int_0^{t=0} \hat{H}(t=0)\, dt'$$

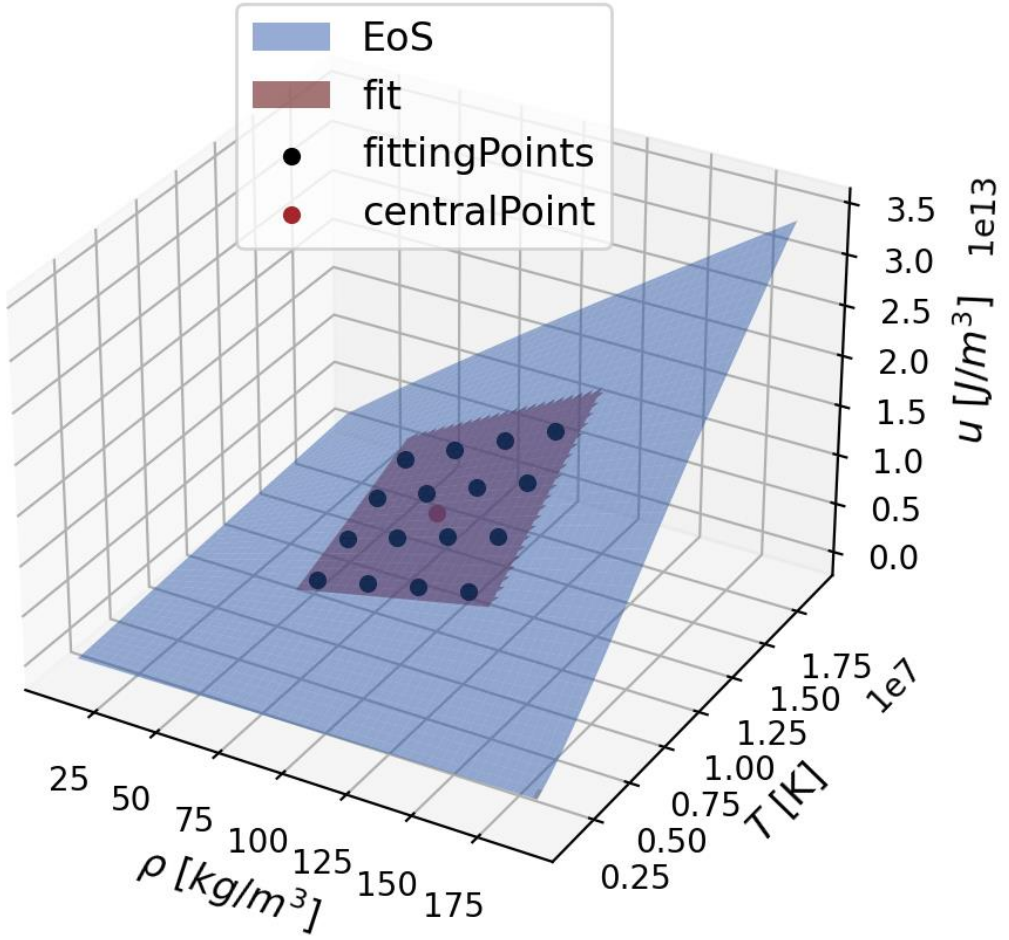
  - Since $\hat{H}(0) = 1$ by definition (as $T_w = T_0$), the integral term tends to zero and the $1/\hat{I}_n$ terms diverges
  - An approximation is made to avoid this initial singularity:

$$\hat{I}_n(0) = \int_0^{\Delta t_0} 1 \to \Delta t_0$$



- Choosing a small first time step Δt_0 and increasing it by a multiplier of 0.01 for each subsequent step ensures accurate results

Pusher material properties expressed in the form of a power-law requires surface fitting to a known EoS model



$$u = u_0 \left(\frac{T}{T_0}\right)^b \left(\frac{\rho}{\rho_0}\right)^m$$

$$\frac{1}{\chi} = \frac{1}{\chi_0} \left(\frac{T_0}{T}\right)^a \left(\frac{\rho_0}{\rho}\right)^l$$

- Least-square surface fitting calculator was developed to determine appropriate values for the coefficients from tabulated FEOS [3]
- Returns values for a, b, l and m
- Tool is flexible enough to fit for values over any region in space

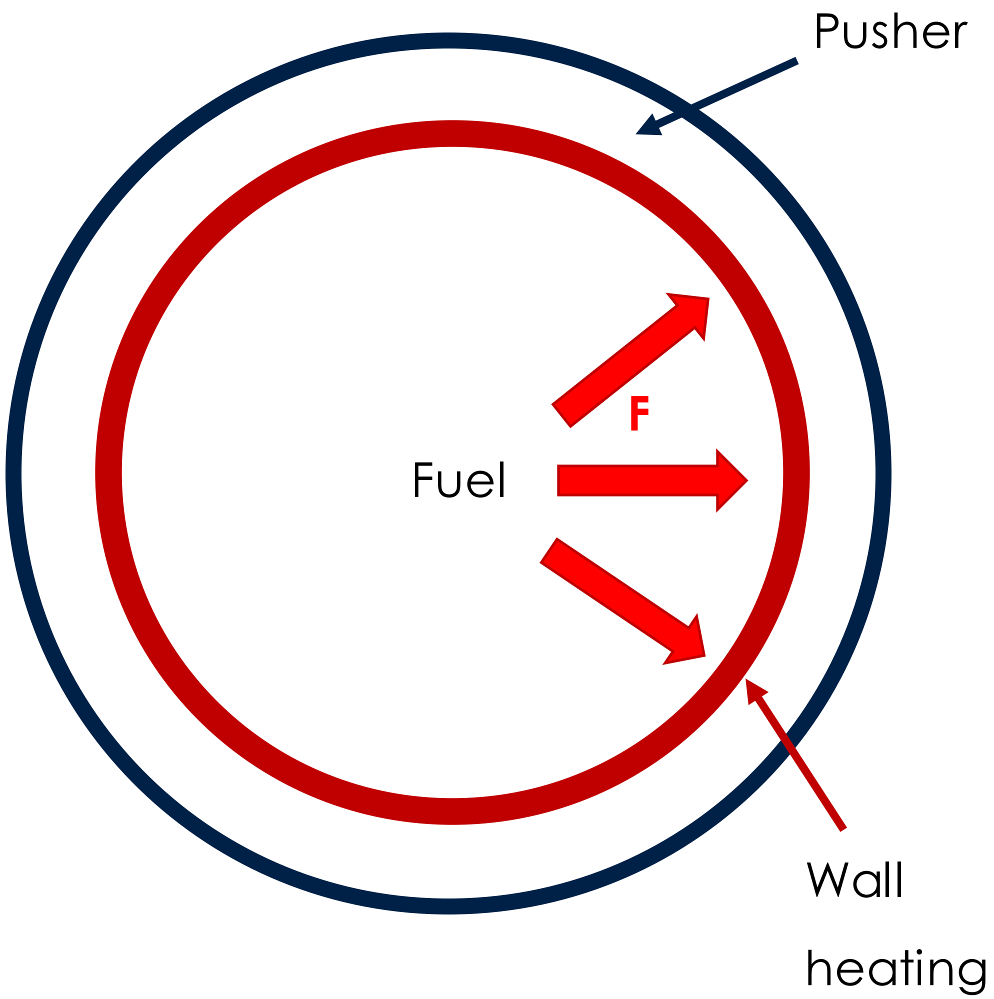
[3] S. Faik et.al., Comp. Phys. Commun. 227 (2018)

Loss model is coupled to the ignition model through the radiatively emitted flux from the fuel driving the Marshak wave

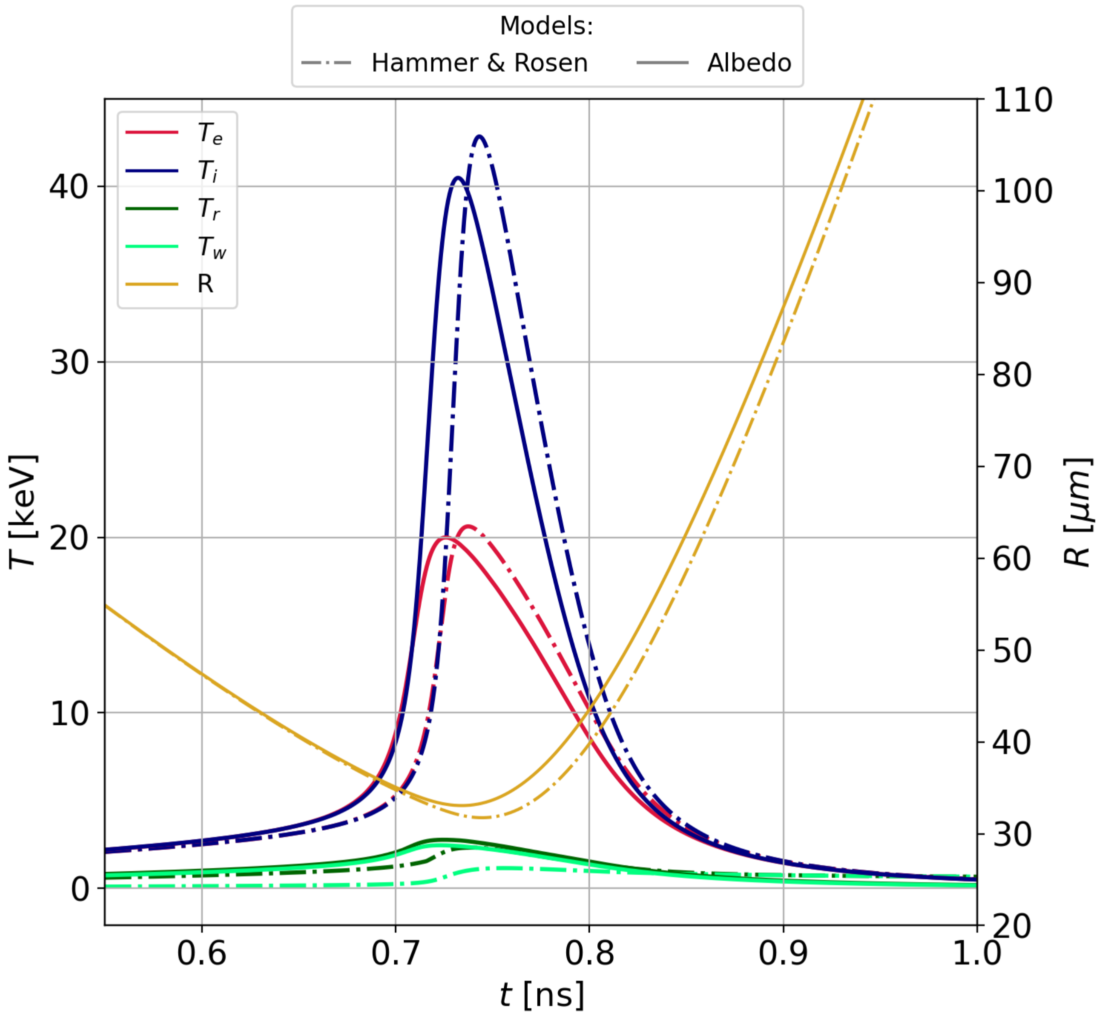
- Radiative flux emitted from the hot fuel drive the rate equations:

$$\frac{dU_R}{dt} = \left(\frac{U_R c}{4} - \sigma T_W^4\right)\frac{S}{V} = \boldsymbol{F}\,\frac{S}{V}$$

- Fuel radiation temperature and wall temperature are treated separately
- Operator splitting used to solve the different physical mechanisms
- Sub-cycled explicit forward Euler solver applied to the ODEs describing each physical process



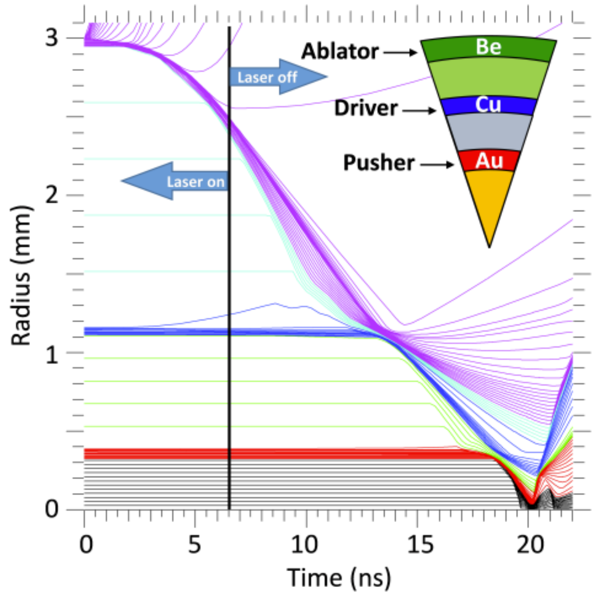
Different radiation loss models compared for a Revolver-like volume ignition target



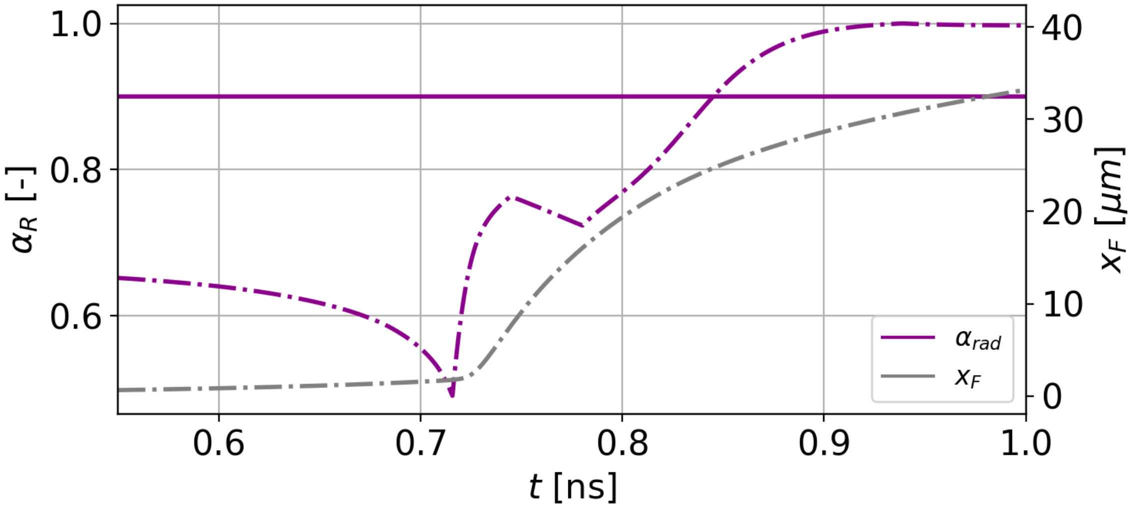
[5] C.-K. Huang et.al., Phys. Plasmas 24 (2017)

- Single shell volume ignition target
- Initial conditions:

$$R_0 = 326\mu m,$$
$$T_e = T_i = 380eV$$
$$T_R = 70eV$$
$$\delta_p = 54\ \mu m$$

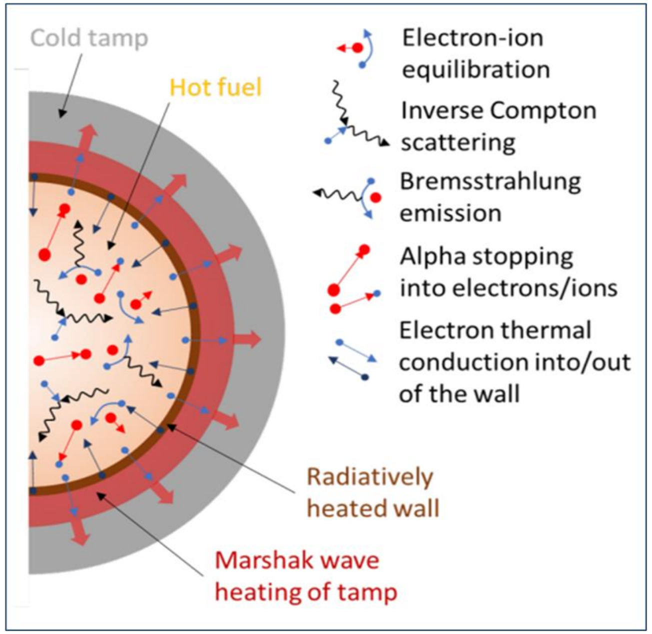


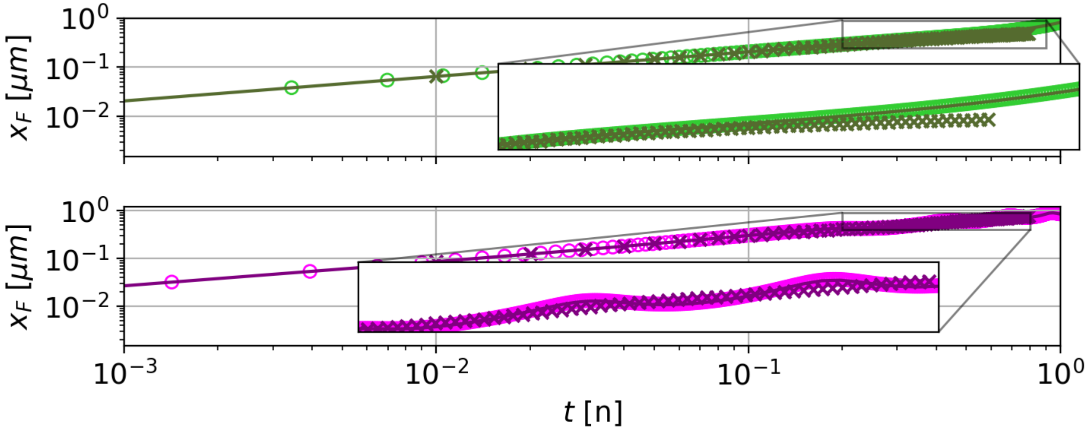
[4] K. Molvig et.al., PRL 116 (2016)



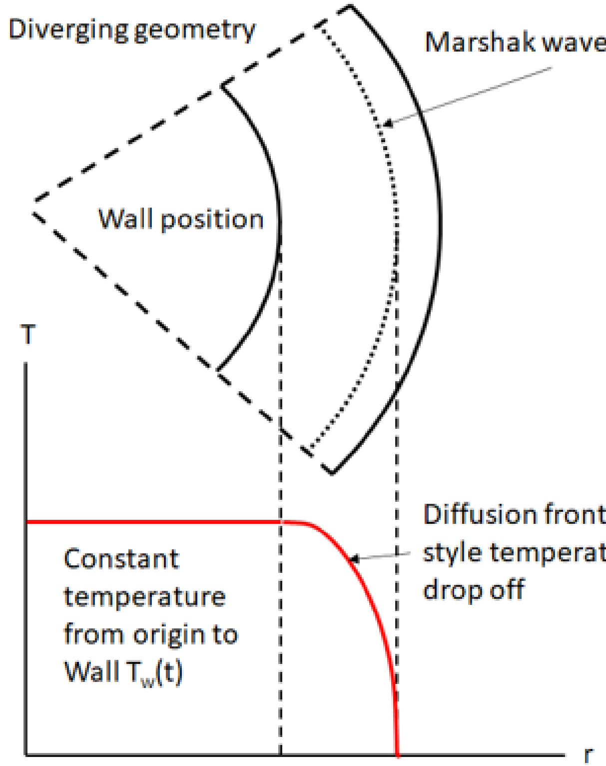
Summary

- We have presented a simple radiation loss model coupled to a full-physics volume ignition model
- Building on previously published work, this model can predict the evolution of a Marshak wave in the pusher material
- New verification tests implemented and compared against full radiation-hydrodynamics simulations
  - Unphysical behaviour is observed in the model where the heat front moves backwards or accelerates as the driving temperature decreases

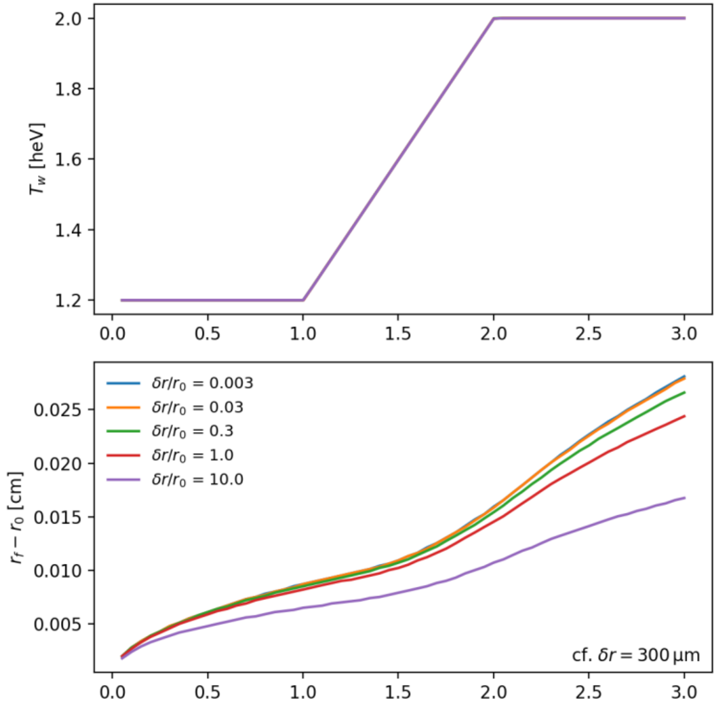




Future direction: accounting for spherical and 2D effects



- Quick scan of radiation loss in spherical capsules using B2 has shown the different behaviour of x_F
- We're working with Prof. Ryan McClarren (University of Notre-Dame) to look at the effect of spherical geometry on the radiation loss model
- 2D effects can be included using simple correction factors [6]



[6] A. Cohen et.al., Phys. Rev. Research (2020)

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Thank you for your attention
Please get in touch

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References

[1] J. Hammer and M. Rosen, Phys. Plasmas 10 (2003)

[2] E. Dodd et.al., Phys. Plasmas 27 (2020)

[3] S. Faik et.al., Comp. Phys. Commun. 227 (2018)

[4] K. Molvig et.al., PRL 116 (2016)

[5] C.-K. Huang et.al., Phys. Plasmas 24 (2017)

[6] A. Cohen et.al., Phys. Rev. Research (2020)

[7] R. Epstein, 64th Annual Meeting of the American Physical Society Division of Plasma Physics Spokane, WA, 17 – 21 October 2022