Experimental investigation of two-phase metastable states at FAIR: need for laser-driven diagnostics

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in collaboration with

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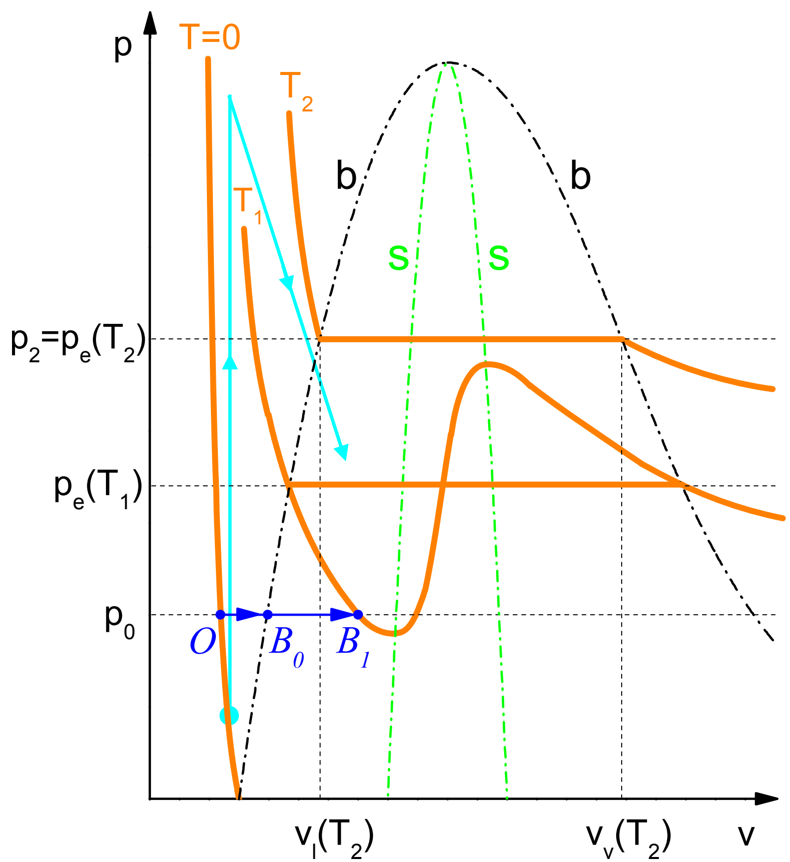
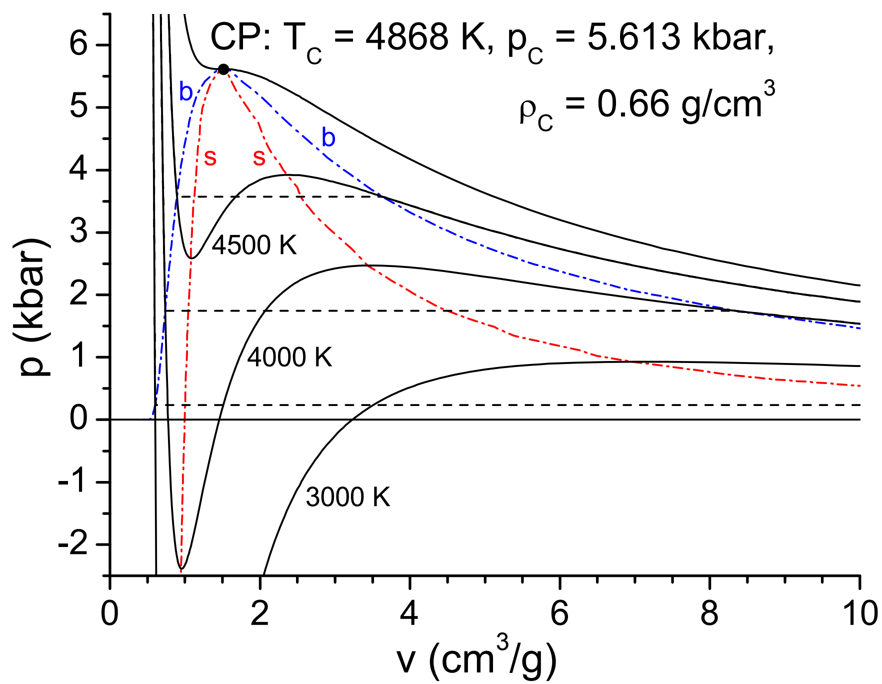
Formulation of the problem

Liquid-vapor phase equilibrium



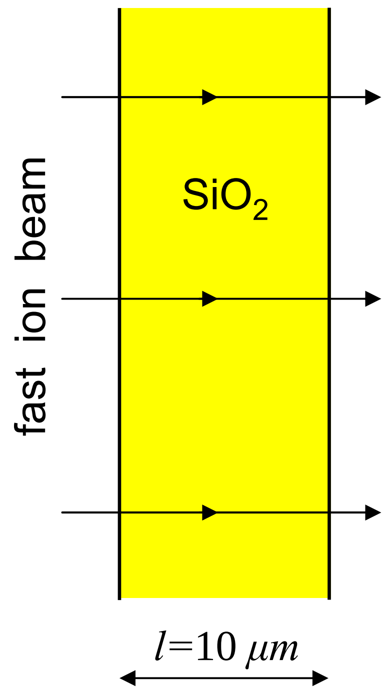
Realistic EOS of SiO_2 (S. Faik)



In the metastable region between the binodal (b) and spinodal (s) we have essentially a double-valued EOS !

Problem: **which of the two should one use in hydrodynamic simulations?**

Experiment: ion beam heated foil at FAIR



Quasi-static thermal expansion

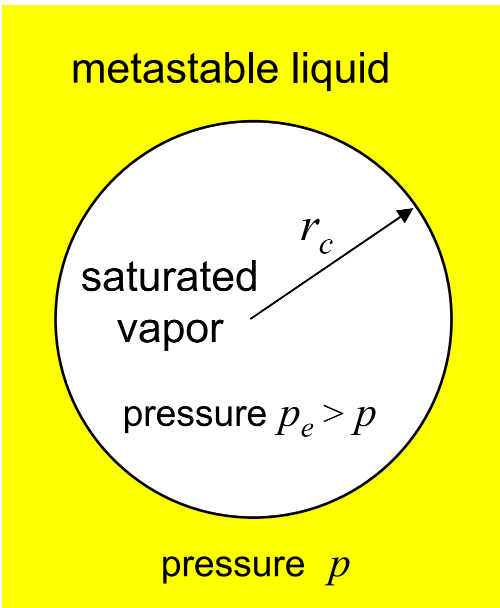
$t_{heating} \approx 10^{-7}$ sec

$t_{sonic} = l/c_s \approx 3\times10^{-9}$ sec

Quasi-uniform volumetric heating: $q = 10^{11}$ J g^{-1} s^{-1} (10 kJ/g in 100 ns)

Theory of homogeneous bubble nucleation

(V.P. Skripov "Metastable Liquids", Wiley, New York, 1974)



metastable liquid and saturated vapor in bubbles have the same temperature T

Bubbles with $r > r_c$ grow, with $r < r_c$ — collapse.

$$p_e = p + \frac{2\sigma}{r_c}, \qquad \sigma = \text{surface tension,}$$

$$W_c = \frac{4\pi}{3}\sigma r_c^2 = \frac{16\pi\sigma^3}{3(p_e - p)^2}$$

Rate of spontaneous bubble creation

$$J = N\left(\frac{3\sigma}{\pi m}\right)^{1/2} \exp\left(-\frac{W_c}{T}\right) \quad [\text{cm}^{-3}\text{s}^{-1}]$$

Mathematical derivation

Boiling is finished when, for given ρ and T, vapor occupies a fractional volume

$$\xi_v = \frac{\rho_l(T_2) - \rho}{\rho_l(T_2) - \rho_v(T_2)}, \qquad T_2 = T_2(\rho, T);$$

In a selected test volume V within a time interval dt $JV \cdot dt$ supercritical bubbles are born.

Boiling within volume V will be finished when

$$V\xi_v = V\int_0^t J(t')\left[V_c(t') + \int_{t'}^{t} \dot{V}_c(t', t'')\, dt''\right] dt'\,;$$

static boiling time:

$$t_b = \xi_v \left(JV_c\right)^{-1}$$

For large Gibbs numbers $G = W_c/T >> 1$ we can use an approximation

$$\int_0^t \Phi(t')\exp\left[-G(t')\right] dt' \approx \Phi(t)\cdot\exp\left[-G(t)\right]\cdot\int_{-\infty}^{0}\exp\left[-\tau\frac{dG}{dt}\right] d\tau =$$

$$= \Phi(t)\cdot\exp\left[-G(t)\right]\cdot\left[-\frac{dG}{dt}\right]^{-1}, \quad \text{where} \quad G(t') \approx G(t) + (t'-t)\frac{dG}{dt};$$

Proposed local criterion of explosive boiling

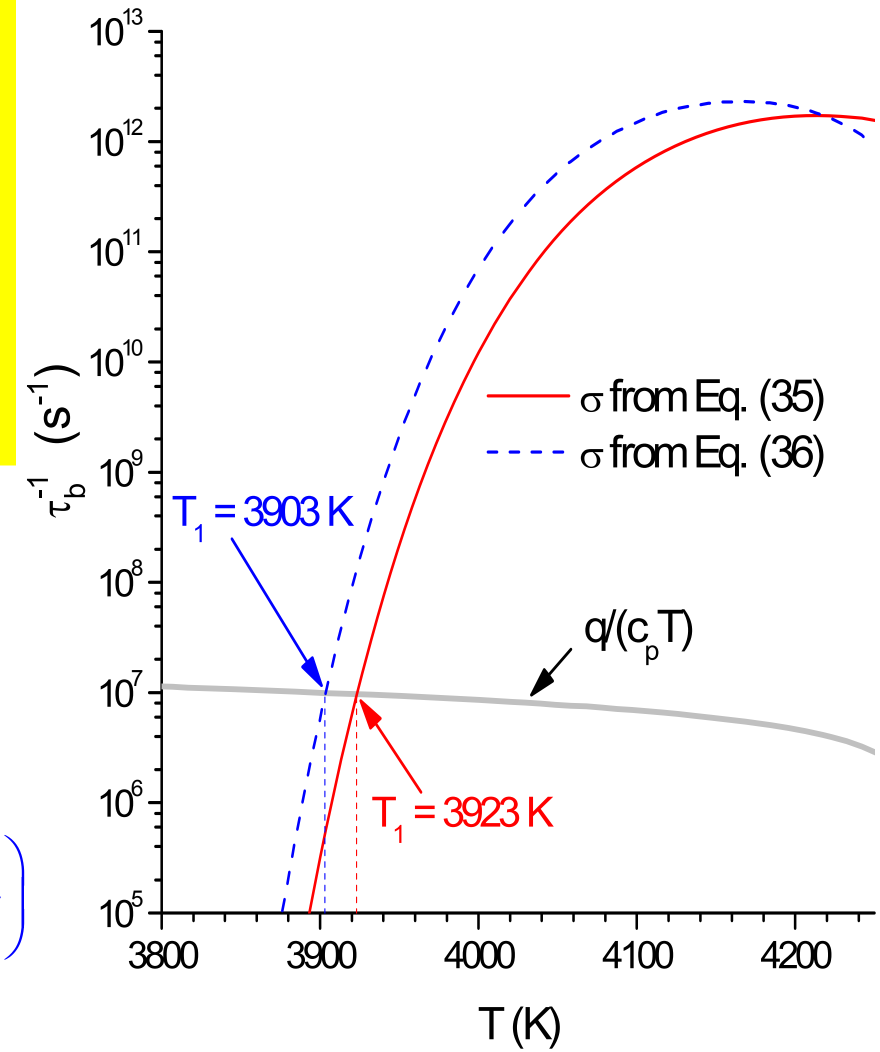
$$NV_c\left(\frac{3\sigma}{\pi m}\right)^{1/2}\left[\frac{d}{dt}\left(-\frac{W_c}{T}\right)\right]_{Lag}^{-1}\exp\left(-\frac{W_c}{T}\right)=\xi_v \quad \textbf{(1)}$$

$$V_c\equiv\frac{4\pi}{3}r_c^3,\qquad \xi_v\equiv\frac{\rho_l(T_2)-\rho}{\rho_l(T_2)-\rho_v(T_2)}$$

Alternative form for a particular case of uniform volumetric heating:

$$\tau_b^{-1}=\frac{d\ln T}{dt}=\frac{q}{c_pT}=\tau_h^{-1},\qquad \text{where}$$

$$\tau_b^{-1}\stackrel{\text{def}}{=}\frac{NV_c}{\xi_v}\left(\frac{3\sigma}{\pi m}\right)^{1/2}\left[T\frac{\partial}{\partial T}\left(-\frac{W_c}{T}\right)\right]_{Lag}^{-1}\exp\left(-\frac{W_c}{T}\right)$$

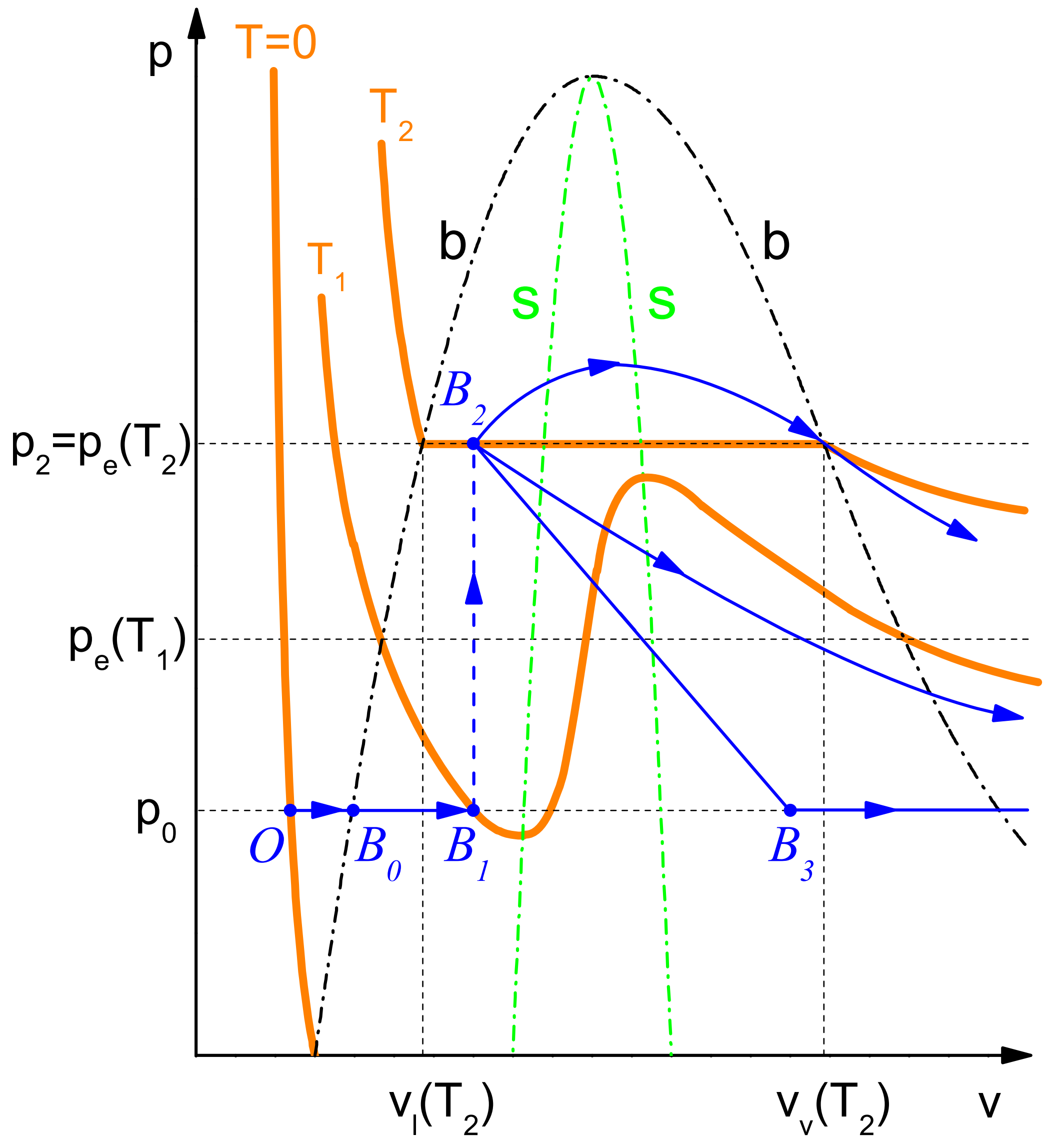


Our recipe for hydrodynamic simulations

- follow the metastable EOS branch until criterion (1) is fulfilled;
- make instantaneous irreversible transition to the equilibrium EOS at fixed density and specific internal energy:

$$\rho_1 = \rho_2, \quad \varepsilon_1 = \varepsilon_2 \quad \Rightarrow$$

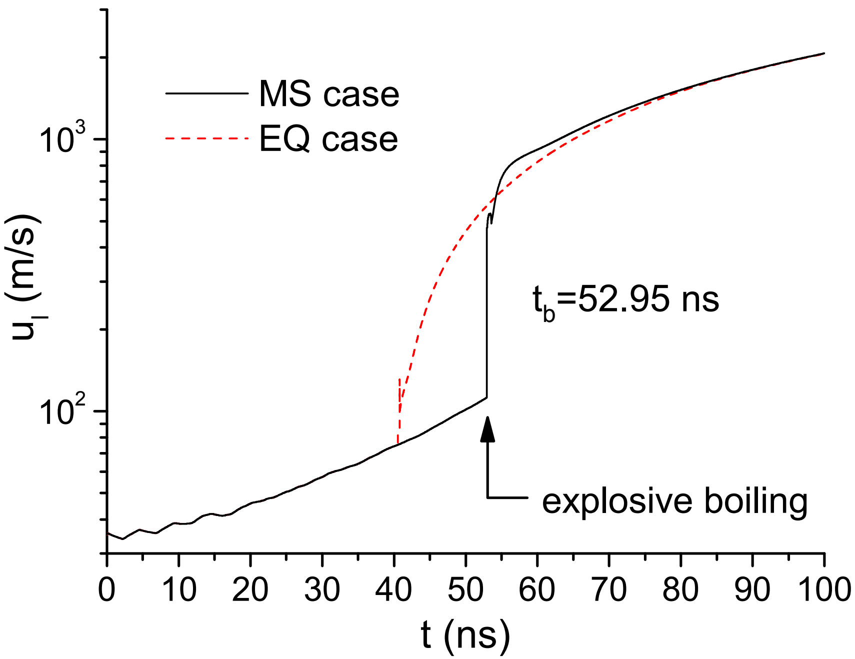
$$p_2 > p_1, \quad T_2 > T_1, \quad s_2 > s_1$$



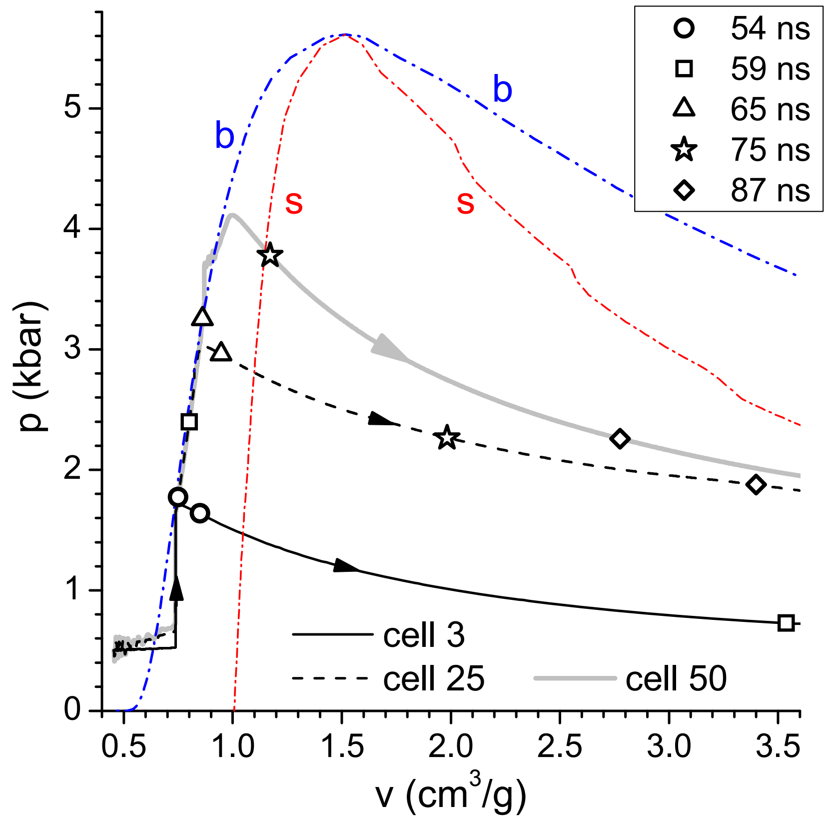
Application to an ion beam heated foil

SiO_2 foil, thickness l =10 µm, heating rate $q = 10^{11}$ J g^{-1} s^{-1} (FAIR)

Surface velocity



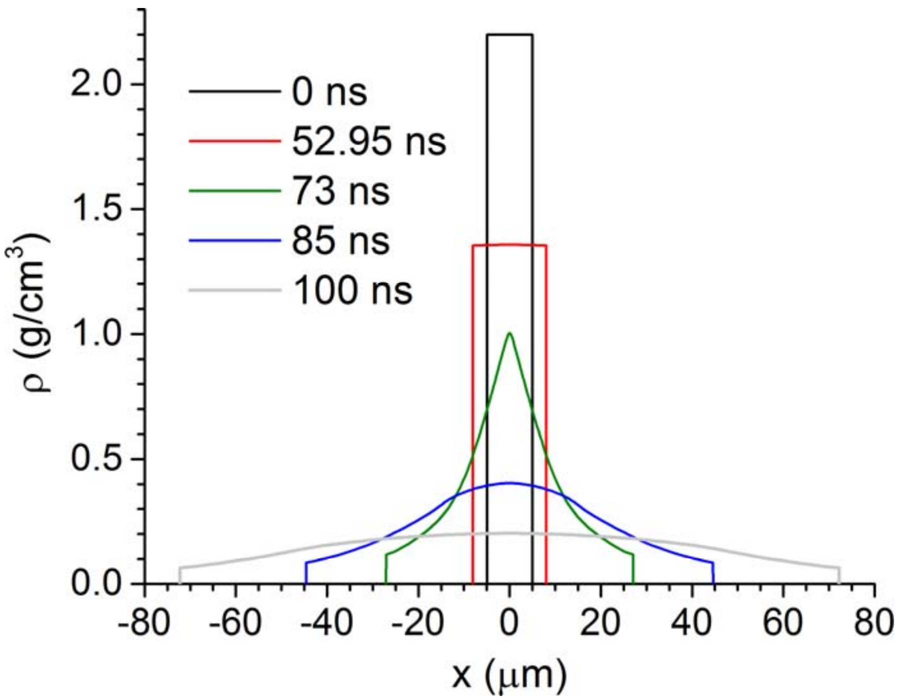
Phase-plane trajectories



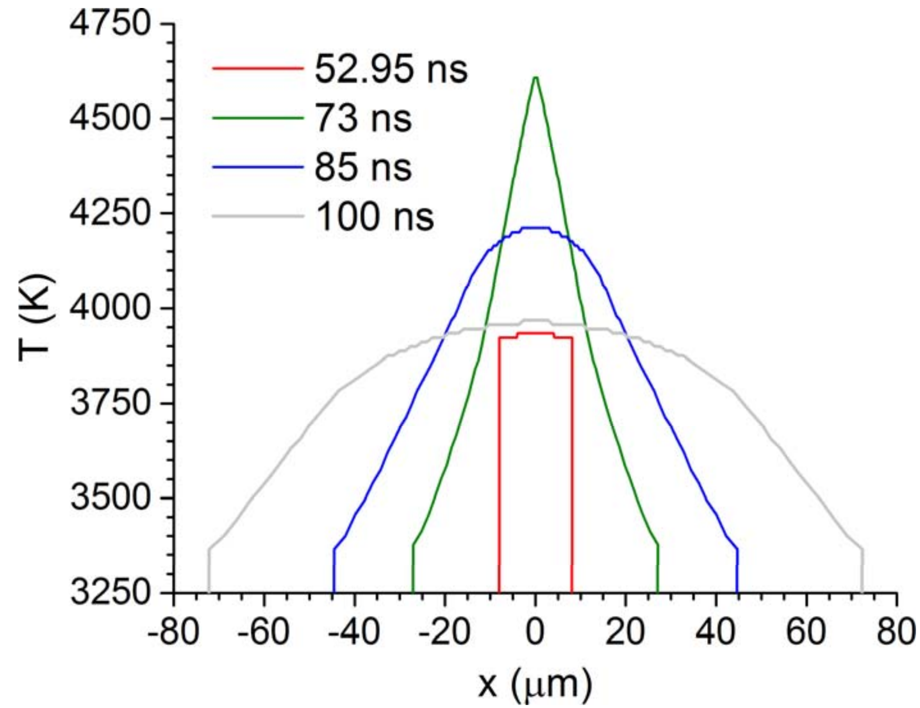
The center elements follow for about 20 ns the binodal (b) until the rarefaction wave arrives.

Application to an ion beam heated foil

Density evolution



Temperature evolution



Can density and temperature at the binodal (t_b=52.95 ns < t < 73 ns) be measured using laser-driven diagnostics?

Conclusion

- A solution to the double-valued EOS problem in the metastable region is proposed that stays within the purely hydro approach.

For ion-beam driven experiment at FAIR:

- Surface velocity measurement to detect the boiling time t_b.
- Density and temperature diagnostics at the binodal with few *μm* and ~*ns* resolution using laser-driven diagnostics?

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