

Generalized Scaling of Focal Temperature in Converging Shock Waves

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A scaling framework unifying the markedly different and independently studied cylindrical and spherical shock convergence is presented. For ionizing argon, we show that the focal temperature becomes invariant to shock symmetry and initial shock conditions when scaled by the prefocus shock Mach number, after accounting for pressure effects. The resulting collapsed focal temperature–Mach number relation is governed by the thermodynamics of argon, up to an equilibrium temperature of 35 000 K. Such a scaling enables both predictive estimation of focal temperatures over a wide range of initial conditions and, conversely, determination of the parameters required to achieve a target temperature in a given medium.

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Focusing of curved shock waves is among the most efficient mechanisms to generate high-energy densities in a medium. As the shock converges toward its focus, its strength is continuously and dramatically amplified, producing intense conditions upon focusing. Terapascal-scale pressures and temperatures reaching 10^4 – 10^5 K have been achieved by converging shock waves [1–3]. These high-energy densities find applications in inertial confinement fusion [4,5], medical therapies [6], materials research [7], and understanding phenomena such as stellar core collapse [8] and bubble collapse [9,10].

The dimensionality of the shock curvature strongly influences the dynamics of convergence and the strength and spatial extent of the intense conditions achieved upon focusing. Spherical shocks undergo stronger acceleration during convergence, generating very intense conditions at the focal point. Cylindrical shocks, because of the reduced dimensionality, generate relatively moderate conditions along the focal axis. Although less intense, cylindrical convergence offers optical access to the flow field perpendicular to the axis of convergence, allowing the tracing of the shock as it converges, focuses, and reflects [11–13]. Because of the striking differences in the nature of shock convergence and the distinct high-temperature regimes they produce, cylindrical and spherical convergence have traditionally been studied separately [14]. In this Letter, we present a scaling framework for ionizing argon that incorporates differences in shock geometry and initial pressure, collapsing the otherwise distinct focal

temperatures onto a single temperature–Mach number relation governed by the equation of state of argon. This relation enables estimation of the peak focal temperature from known initial conditions and, conversely, the selection of the initial Mach number, geometry, and initial pressure required to achieve a specified target temperature. We further present, with high spatial and temporal resolution, the evolution of focal temperature for cylindrical convergence, reaching $13\,500 \pm 500$ K, which in this approach of employing a shock tube is unaffected by the trailing expansion waves, inherent to laser- and pulsed-power-driven techniques [11–13,15].

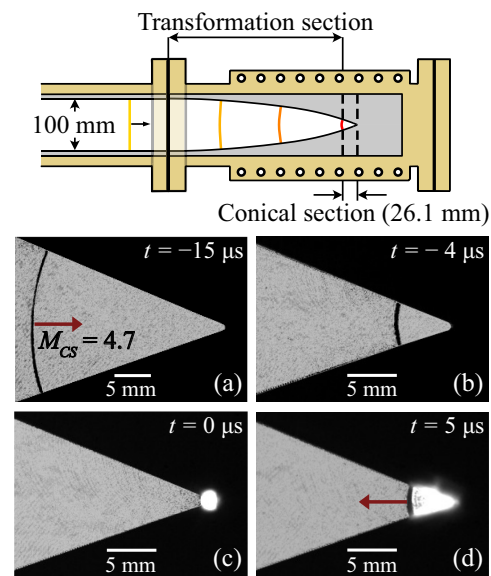


FIG. 1. Top: schematic of the shock tube test section used for generating cylindrical converging shocks. Bottom: background-subtracted shadowgraphs showing shock convergence and light emission during shock reflection.

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Shock convergence was investigated experimentally using a conventional shock tube (with a rectangular or circular cross section) equipped with a contoured insert that transformed an incoming planar shock into a sector of a cylindrical or spherical shock (Fig. 1). For cylindrical convergence, a 5.8-m-long shock tube with a rectangular cross section of 100×50 mm was used. The 1.1-m-long driver section was pressurized with helium to pressure P_4 (1.5–2.7 MPa), while the driven section was filled with argon at 295 K and pressure P_1 (10–12.1 kPa). The numbering of the flow states follows standard shock tube notation. Once the pressure ratio (P_4/P_1) corresponding to the desired shock Mach number was achieved, the shock was initiated using a fast-opening valve with an opening time of 2–3 ms [16]. Traced with pressure transducers, planar shocks with Mach number up to 4 were obtained, traveling toward the test section at the end of the driven section housing the contoured insert. The wall profile of the insert's transformation section was obtained by solving the Chester-Chisnell-Whitham relation [17] to smoothly transform the incoming planar shock into a cylindrical shock at its exit while avoiding Mach reflection (see Supplemental Material [18]). This is followed by a conical section where the shock radius decreases and the shock focuses at the vertex. This approach of producing curved shocks, investigated and employed in previous studies [2,16,19–23], offers the unique advantage of a curved shock traveling in undisturbed gas. Shadowgraphs of the flow were captured using a Shimadzu HPV-X2 high-speed camera operated at $2 - 10 \times 10^6$ frames per second, with an interframe time of 100–500 ns and an exposure time of 50–200 ns.

Figure 1 shows the convergence and reflection of the cylindrical shock. The shock begins converging from an initial radius $r_0 = 26.1$ mm with an initial Mach number $M_{CS} = 4.7 \pm 0.1$ [Fig. 1(a)]. As the shock converges toward the focus, it accelerates. For a perfect gas in the strong-shock limit, the shock motion approaches the Guderley self-similar solution [24]: $r(t)/r_0 = (-t/t_0)^\chi$, where $r(t)$ is the instantaneous shock radius. The convergence exponent χ depends on the specific heat ratio of the gas γ and the symmetry of convergence. For cylindrical convergence in a monatomic gas, χ approaches the asymptotic self-similar value of 0.815 62. In practice, however, the shock trajectory is not exactly self-similar over the entire convergence: Finite shock strength away from the focus [25] and real-gas effects modify the local convergence behavior. Since these departures act as higher-order corrections to the self-similar solution [25] and are gradual and monotonic, the trajectory remains well approximated by a Guderley-type relation. The corresponding χ can, therefore, be obtained from a least-squares fit of the Guderley-type relation to the observed trajectory. Based on experiments and real-gas computations, a higher value, $\chi = 0.8407 \pm 0.008$, was obtained for cylindrical convergence, corresponding to a weaker shock acceleration

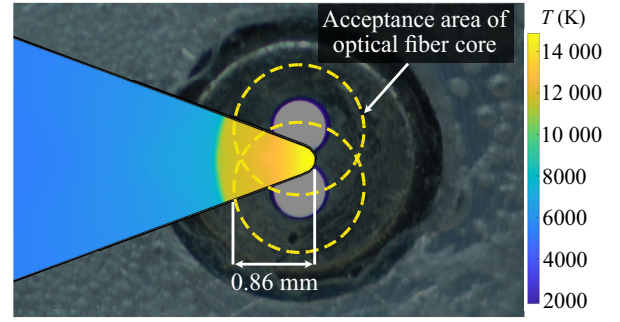


FIG. 2. Acquisition of emitted radiation by the optical fiber, showing that nonlocalized radiance measurement over the focus prevents measurement of the maximum temperature.

[16]. Upon focus and subsequent reflection of the shock, intense thermodynamic conditions cause substantial ionization of argon, resulting in light emission as seen in Figs. 1(c) and 1(d).

The peak focal temperature T_{focal} was measured spectroscopically from emission during shock focusing and the initial reflection. As shown in Fig. 2, the emitted radiation was acquired with a bifurcated optical fiber and transmitted simultaneously to a high-resolution echelle spectrometer and fast-response photomultiplier tubes (PMTs). Because of the UV window thickness and the numerical aperture of the fiber, the optical acceptance area extended to 0.86 mm upstream of the focal axis. Thus, the measured emission spectrum is not localized to the focal axis; rather, it results from emission by fluid elements at varying temperatures within the optical fiber acceptance area. The measured continuum spectrum follows a Planck distribution, with a Planck fit for $M_{CS} = 5.6 \pm 0.1$ and $P_1 = 12.1$ kPa yielding a radiance temperature of $13\,500 \pm 500$ K. To obtain the focal temperature evolution and ensure that the measured spectrum corresponded to the peak focal temperature, two-color pyrometry was performed using PMTs equipped with 220 and 405 nm bandpass filters, operated simultaneously with the spectrometer. The inset in Fig. 3 shows the temperature evolution and the spectrometer gate timing (width of 100 ns). After the initial rise, T_{focal} persisted for nearly 1 μs , during which the spectrum was acquired. For radiation to follow a Planck distribution, the gas must be in local thermodynamic equilibrium and be optically thick at the relevant wavelengths. Based on the flow field obtained from the numerical simulations described below, the electron density $n_e \approx 4 \times 10^{18} \text{ cm}^{-3}$ was estimated at a representative point 0.21 mm from the focal axis, well above the local thermodynamic equilibrium threshold $n_e \geq 3 \times 10^{16} \text{ cm}^{-3}$ [26–30]. The spectral absorption coefficient, calculated using the Opacity Library (OPLIB) tables from Los Alamos National Laboratory (LANL) [31] (accounting for bound-free photoionization, free-free bremsstrahlung, and bound-bound absorption), ranges from 0.577 cm^{-1} at a wavelength of $\lambda = 250$ nm to 4.171 cm^{-1} at $\lambda = 600$ nm. For a plasma length of 5 cm

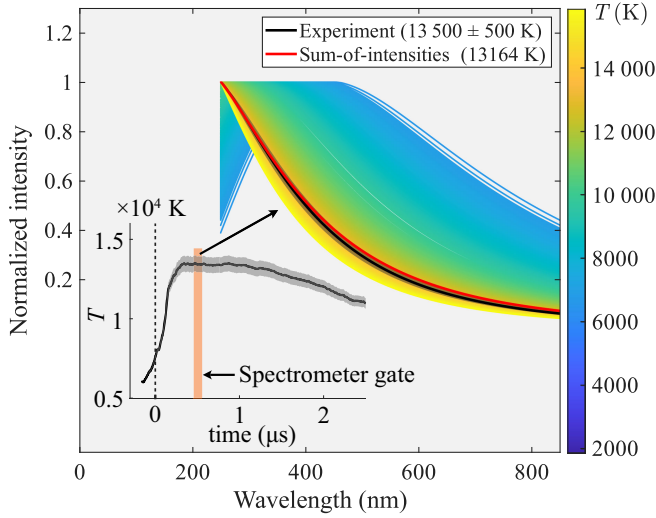


FIG. 3. Measured emission spectrum and reconstructed spectrum obtained by summing the blackbody contributions within the optical fiber acceptance area from the numerical temperature field. Inset: temporal evolution of T_{focal} measured using PMTs.

(the shock tube width), this results in an optical depth of $2.89 \leq \tau_\lambda \leq 20.96$, so that the emergent spectral intensity is $\approx 94\%$ of the local Planck function $B_\lambda(T)$, even at the wavelength where τ_λ is smallest. Moreover, the absence of discrete emission lines until $\approx 2 \mu\text{s}$ after the focusing instant is consistent with the large line-center absorption coefficients of the strongest Ar I transitions (97 cm^{-1} at $\lambda = 750.39 \text{ nm}$ and 111 cm^{-1} at $\lambda = 811.53 \text{ nm}$), further supporting optically thick, continuum-dominated emission.

Numerical simulations of the flow were performed to complement the experiments and to investigate shock convergence over a wider range of shock strengths than accessible in the present setup. Two-dimensional and axisymmetric, compressible, viscous, nonreacting Navier-Stokes equations were solved using the artificially upstream flux vector splitting–Roe (AUFSSR) scheme [32]. Temporal integration was carried out using a third-order accurate Runge-Kutta method. To account for high-temperature real-gas effects, the LANL SESAME 5173 equation of state (EOS) for argon [33] was employed. The sensitivity of the results to mesh refinement was assessed using three successively refined meshes with minimum cell sizes of 40, 20, and $10 \mu\text{m}$ near the focal point. T_{focal} , evaluated using the procedure described below, changed by 1.3% and 0.16% between successive refinements. All simulations were, therefore, performed on the $20 \mu\text{m}$ mesh, which comprised $\approx 2 \times 10^6$ cells. Additional details of the numerical methodology are provided in [16].

To replicate the inherently nonlocalized experimental measurements, the temperature from the computational flow field was obtained with a *virtual optical fiber* placed identically to the optical fiber in the experiments, having the same acceptance area. Figure 3 shows the spectral distribution of all sampled points within the acceptance

area of the virtual fiber, each at its local temperature. A resultant spectrum was constructed by summing the individual spectral intensities over the wavelength range and normalizing by the peak intensity. The sum-of-intensities distribution closely reproduces the measured emission spectrum, with a Planck fit resulting in T_{focal} of 13 164 K, consistent with the spectroscopically measured value of $13 500 \pm 500 \text{ K}$. Here, T_{focal} is the temporal maximum of the temperature inferred from the sum-of-intensities distribution. This value is lower than the maximum temperature of 18 800 K, which is reached near the focusing instant within $\approx 40 \mu\text{m}$ of the focal axis—a region that contributes only marginally to T_{focal} and is difficult to resolve experimentally.

With the measurement procedure established, we now quantify how T_{focal} scales with cylindrical shock strength. Because experiments with the conventional shock tube were limited to $M_{\text{CS}} < 6$, real-gas computations using the SESAME EOS for argon were employed to extend the range to $4.5 \leq M_{\text{CS}} \leq 12.6$ and assess pressure effects by varying $5 \leq P_1 \leq 25 \text{ kPa}$. Figure 4 shows the variation of T_{focal} with the initial cylindrical shock strength and P_1 . For comparison, previous spherical shock measurements [2], obtained using the same curved-shock generation approach in a circular shock tube, are also shown along with corresponding axisymmetric computations. For the same initial shock strength, spherical convergence results in substantially higher focal temperatures. The reasonable agreement between the computations and experiments for spherical convergence (especially at higher P_1) supports the applicability of the SESAME EOS at focal conditions relevant to the extended cylindrical convergence range. The distinct conical section geometries and resulting shock radii for the two configurations are illustrated in Fig. 5.

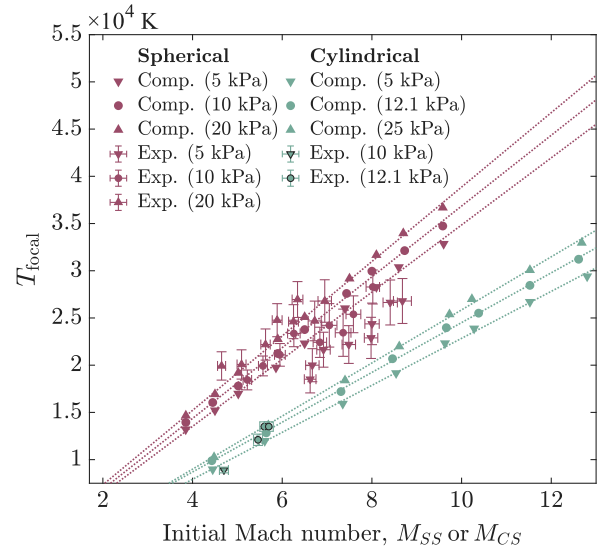


FIG. 4. Variation of T_{focal} with initial Mach number for spherical and cylindrical shock convergence in argon at different initial gas pressures P_1 .

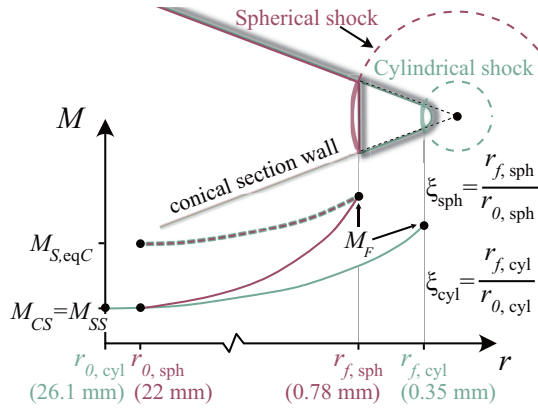


FIG. 5. Schematic illustrating geometric differences between cylindrical and spherical shock convergence and the mapping of spherical shock to an equivalent cylindrical shock.

The maximum temperatures and, thus, T_{focal} are attained during shock reflection after focusing (state 5 in standard shock-tube notation). The gas temperature within the optical fiber acceptance area (within 0.86 mm of the focal axis) behind the reflected shock can be expressed as

$$T_5 = \left(\frac{T_5}{T_2}\right) \left(\frac{T_2}{T_1}\right) T_1,$$

where, for the same fluid element, states 1 and 2 denote, respectively, the initial state and the state behind the converging shock. For the strong reflected shocks considered here, T_5/T_2 is nearly constant. Thus, T_{focal} is governed primarily by T_2 , which is set by the final (prefocus) Mach number M_F . Prior to the focusing instant, the gas in state 2 behind the converging shock is already sufficiently ionized, causing T_2/T_1 to scale as $f(M_F)$ rather than as $f(M_F^2)$, as would be the case for very strong shocks in an ideal gas, consistent with our computations and previous reports [34,35]. For the same initial shock strength, differences in convergence symmetry ($\chi_c = 0.8407 \pm 0.008$ for cylindrical and $\chi_s = 0.7654 \pm 0.0072$ for spherical) and in shock radii lead to markedly different M_F (Fig. 5) and, consequently, different T_{focal} .

A scaling for T_{focal} is developed that accounts for convergence dimensionality, initial and final shock radii, and pressure effects. To account for the geometrical differences in shock convergence, the spherical shock at its initial radius $r_{0,\text{sph}}$ and Mach number M_{SS} is mapped—using the Guderley-type relation—to an equivalent cylindrical shock with initial Mach number $M_{S,\text{eqC}}$, such that it reaches the same prefocus Mach number M_F at the same final shock radius $r_{f,\text{sph}}$:

$$M_{SS}(\xi_{\text{sph}})^{(\chi_s-1)/\chi_s} = M_{S,\text{eqC}}(\xi_{\text{sph}})^{(\chi_c-1)/\chi_c},$$

where $\xi_{\text{sph}} = (r_{f,\text{sph}}/r_{0,\text{sph}})$. Therefore,

$$M_{S,\text{eqC}} = M_{SS}(\xi_{\text{sph}})^{(\chi_s-1)/\chi_s \chi_c}. \quad (1)$$

Figure 4 shows that, for the same shock symmetry and initial shock strength, T_{focal} is higher for gas at higher P_1 . To explain this trend, we consider the thermodynamic state of the gas behind the reflected shock. Increasing P_1 leads to higher postreflection pressure P_5 and density ρ_5 . Since the gas behind the reflected shock is significantly ionized, variations in ρ_5 affect the degree of ionization and, consequently, the partitioning of energy between ionization and translational thermal energy. From the Saha equation, the first-stage degree of ionization $\alpha(\rho, T)$ decreases with increasing density [36]:

$$\frac{\alpha^2}{1-\alpha} \propto \frac{T^{3/2}}{\rho} \exp\left(-\frac{I_1^{\text{eff}}}{kT}\right), \quad (2)$$

where I_1^{eff} is the effective first ionization potential of the gas, including the reduction due to Coulomb interactions, and k is the Boltzmann constant. For the same shock strength, a higher ρ_5 shifts the equilibrium toward recombination, lowering α and thereby reducing the energy expended on ionization, which otherwise acts as an energy sink. Consequently, more energy remains available as translational thermal energy, thereby raising T_{focal} . To quantify the sensitivity of T_{focal} to P_1 , the functional dependence of temperature on pressure is derived from the Saha equation for first-stage ionization, resulting in $d \ln T / d \ln p = \beta$, where

$$\beta = \left(\frac{1}{2.5 + I_1^{\text{eff}}/kT}\right) \left(1 + \frac{2}{\alpha(1-\alpha^2)} \frac{d\alpha}{d \ln p}\right). \quad (3)$$

In the temperature range $10\,000 \text{ K} \leq T \leq 30\,000 \text{ K}$, where second-stage ionization is negligible, β varies between ≈ 0.1 and ≈ 0.05 . An optimal value of $\beta = 0.08$ is obtained for the computational results in this temperature range. The experimentally measured T_{focal} exhibit a stronger P_1 dependence. In addition to the thermodynamic effect of P_1 [Eq. (3)], the ionization relaxation length behind the converging shock front before focusing increases appreciably with lower P_1 [36–38]. A longer relaxation length (up to $\sim 1 \text{ mm}$ at lower M_F) makes gas compression during focusing less efficient, resulting in a lower T_{focal} upon reflection. These additional pressure effects, which are absent in computations, indicate a higher β value for the experimental measurements than the theoretical estimate [Eq. (3)]. The inset in Fig. 6 shows that β approaches the theoretical and computational value for measurements at higher P_1 , where the relaxation length is relatively short, supporting the argument above. For the full dataset, we find

$$\begin{aligned} T &\propto P_1^{0.08} \text{ for computations,} \\ T &\propto P_1^{0.20} \text{ for experiments.} \end{aligned} \quad (4)$$

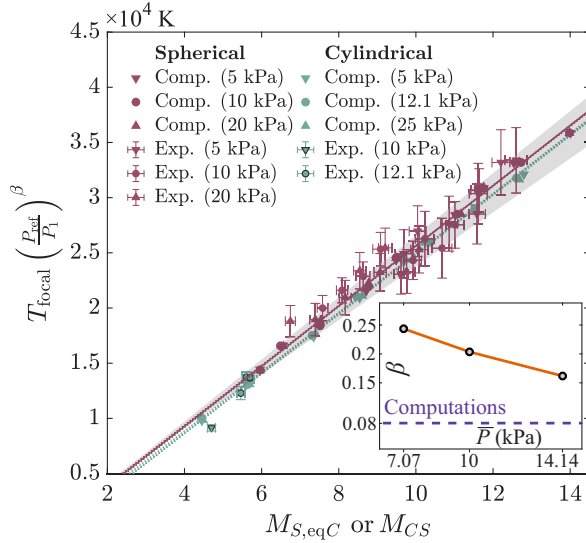


FIG. 6. Scaling of T_{focal} for cylindrical and spherical shock convergence, incorporating differences in convergence geometry and effects of initial pressure P_1 . Inset: reduced pressure sensitivity at higher P_1 due to shorter relaxation length behind the converging shock. $P_{\text{ref}} = 15$ kPa.

Figure 6 shows the result of mapping the spherical shock to an equivalent cylindrical shock [Eq. (1)] and correcting for pressure effects [Eq. (4)]. The collapse of T_{focal} from geometrically and thermodynamically diverse cases onto a single linear curve demonstrates that, once pressure effects are accounted for, the peak focal temperature is governed primarily by the prefocus shock state, characterized by the final Mach number M_F . This parameter represents the cumulative effects of convergence symmetry, the extent of focusing achieved, the development of instabilities inherent to curved shocks [39–42], and ionization behind the converging shock—all captured effectively through the convergence exponent χ . The pressure exponent β accounts for pressure effects on (i) the thermodynamic state of the ionized gas behind the converging and reflected shocks and (ii) the relaxation length behind the converging shock. Once these effects are incorporated through M_F and P_1^β , the peak focal temperature becomes invariant, revealing a unified scaling for shock focusing.

The applicability of the scaling was evaluated for a polygonal shock configuration, which offers improved stability during convergence. Using the initial shock parameters from the experimental study [43], the corresponding $M_{S,\text{eqC}}$ was determined from Eq. (1). The T_{focal} estimated from the scaling in Fig. 6 agrees with the reported measurements within the experimental uncertainty. The robustness of the scaling was further assessed for convergence geometries with shock-radius ratios ξ_x different from those in Fig. 5. The equivalent Mach number for arbitrary geometries (with corresponding M_{CS} and M_{SS}) is calculated as

$$M_{S,\text{eqC}} = \begin{cases} M_{SS}(\xi_{\text{sph}})^{(\chi_s - \chi_c)/\chi_s \chi_c} \left(\frac{\xi_x}{\xi_{\text{sph}}}\right)^{(\chi_s - 1)/\chi_s}, & \text{spherical,} \\ M_{CS} \left(\frac{\xi_x}{\xi_{\text{cyl}}}\right)^{(\chi_c - 1)/\chi_c}, & \text{cylindrical.} \end{cases} \quad (5)$$

For such cases, however, the estimated T_{focal} may deviate slightly from the measured value, since the emission acceptance area of the diagnostic relative to the focal point changes. For a fixed acceptance area, increasing r_f —or, equivalently, decreasing the acceptance area for fixed r_f —increases the effective magnification of the focal region, thereby increasing the relative weighting of the hotter core and, thus, yielding higher temperature estimates. Conversely, decreasing r_f or increasing the acceptance area yields lower temperature estimates.

In conclusion, this Letter establishes that, for ionizing argon up to equilibrium temperatures of 35 000 K, the focal temperature–Mach number relation collapses across different shock geometries and initial pressures when expressed in terms of the equivalent shock Mach number and corrected for pressure effects, with the resulting relation governed by the argon equation of state. Although demonstrated for argon, the underlying principles provide a basis for extension to other noble gases, with analogous focal temperature–Mach number relation governed by the respective equation of state. In practical terms, since shock convergence in different configurations and at different initial pressures maps to the same collapsed focal temperature–Mach number relation, a small but adequately spaced set of real-gas simulations or measurements—obtained using experimentally accessible geometries and initial pressures—is sufficient to efficiently characterize the focal temperature–Mach number relation for a given medium. The resulting medium-specific scaling is useful not only for forward prediction of focal conditions, but also for inverse design: It enables systematic selection of the shock configuration (geometry and Mach number) and initial pressure required to achieve a specified target temperature.

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Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency.

Data availability—The data that support the findings of this article are openly available [44].

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