

# Diamond precipitation dynamics from hydrocarbons at icy planet interior conditions

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The pressure and temperature conditions at which precipitation of diamond occurs from hydrocarbon mixtures is important for modelling the interior dynamics of icy planets. However, there is substantial disagreement from laboratory experiments, with those using dynamic compression techniques finding much more extreme conditions are required than in static compression. Here we report the time-resolved observation of diamond formation from statically compressed polystyrene,  $(C_8H_8)_n$ , heated using the 4.5 MHz X-ray pulse trains at the European X-ray Free Electron Laser facility. Diamond formation is observed above 2,500 K from 19 GPa to 27 GPa, conditions representative of Uranus's and Neptune's shallow interiors, on 30  $\mu$ s to 40  $\mu$ s timescales. This is much slower than may be observed during the  $\sim$ 10 ns duration of typical dynamic compression experiments, revealing reaction kinetics to be the reason for the discrepancy. Reduced pressure and temperature conditions for diamond formation has implications for icy planetary interiors, where diamond subduction leads to heating and could drive convection in the conductive ice layer that has a role in their magnetic fields.

Hydrocarbons are found in a variety of astrophysical locations, including in icy planets and moons<sup>1–3</sup>. In many of these environments, such as the interiors of icy planets and during impact events, hydrocarbon-rich matter is subjected to extremes of pressure and

temperature that can induce chemical reactions<sup>4–9</sup>. In the atmospheres of Uranus and Neptune, carbon is observed at many times solar abundance and hydrocarbons have been predicted to be abundant within them<sup>1,2</sup>.

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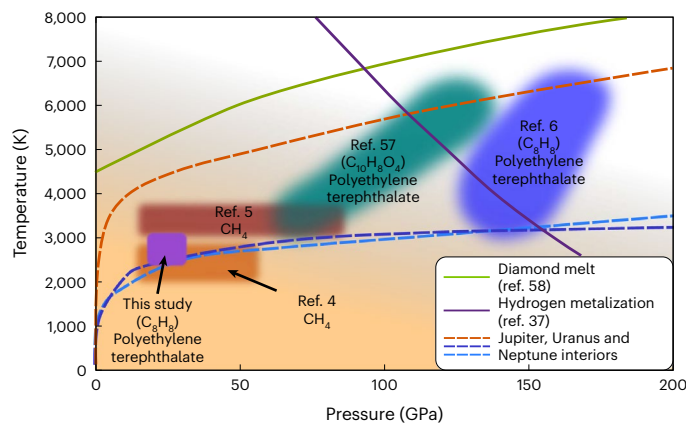
At high-pressure high-temperature conditions, both experimental and theoretical studies have found that methane ( $\text{CH}_4$ ) is converted to more complex hydrocarbons and hydrogen above a few gigapascals and 1,200 K (refs. 4, 5, 7–11). In addition, ethane ( $\text{C}_2\text{H}_6$ ) is found to form both  $\text{CH}_4$  and heavier hydrocarbons at similar conditions<sup>9</sup>. In the carbon–hydrogen system, the lifetimes of molecular C–C and C–H bonds have been predicted to become short at high temperature and pressure<sup>7</sup>, with the result that hydrocarbon molecules become very short lived and the system is better viewed as a mixture of carbon and hydrogen atoms than as persistent molecules. At the high-pressure high-temperature conditions that occur within icy planets, the carbon and hydrogen demix, and the fate of hydrocarbons deep in them is conversion to diamond and a hydrogen-rich phase<sup>4–7</sup>.

Within icy planets, diamond formed from such reactions is denser than the surrounding ices and will sink deeper into the planet due to gravity, providing an additional source of heating that can affect their evolution and internal dynamics<sup>4,6,12</sup>. In our Solar System, Neptune has higher luminosity than Uranus, pointing at an internal energy source<sup>1,2,13</sup>, which could arise from the diamond formation and sedimentation. Beyond the Solar System, many exoplanets have been discovered with densities matching icy planets and intermediate sizes between Earth and Neptune<sup>14</sup> where hydrocarbon demixing may be an important process. The conditions at which diamond precipitation occurs dictates the depth at which the diamond forms and the size and age of an exoplanet, where this process will play a role in planetary dynamics.

Despite the importance of this reaction, the pressure and temperature required are subject to large disagreement in the literature, in particular between studies using dynamic or static compression techniques. Optical laser-heated diamond-anvil-cell (DAC) studies on  $\text{CH}_4$  find diamond formation above 10 GPa and 2,000 K to 3,000 K (refs. 4, 5), while a study using laser-driven shocks in polystyrene found diamond formation only above 140 GPa and 4,000 K (ref. 6). The conditions determined for diamond formation in different experimental studies are summarized in Fig. 1.

A suggested origin of this discrepancy is reactions with the metallic coupler typically used to absorb the heating laser in optical laser-heated DAC studies<sup>6</sup>. Previous DAC studies used platinum<sup>4,5</sup>, which can react with hydrogen to produce platinum hydride<sup>15</sup> with the result that the reaction is changed from hydrocarbon  $\rightarrow$  diamond + hydrogen to hydrocarbon + platinum  $\rightarrow$  diamond + platinum hydride. The formation of metal hydrides changes the thermodynamics of the reactions and is known to promote other reactions in hydrocarbons under pressure<sup>16</sup>. Catalytic effects from the metallic coupler have also been suggested to play a role<sup>10</sup>, although catalysts can only change reaction rates and not the overall thermodynamic favourability. It should be noted that not all laser-heated DAC studies used a coupler. Various alkanes heated directly with a  $\text{CO}_2$  laser showed diamond formation between 10 GPa and 20 GPa (ref. 17) and, similarly, heated polyethylene formed diamond at 2,500 K between 10 GPa and 30 GPa (ref. 18). Effects arising from the presence of the diamond surface of the anvils are unlikely in studies using couplers, including this one, as the heated region is separated from the anvil surface by colder material (Extended Data Fig. 1). Previous DAC studies have investigated only samples quenched to ambient temperature after heating, however, and no static compression experiment has observed diamond formation from hydrocarbons in situ at high temperature.

Another difference is the choice of sample. However, hydrocarbons are known to undergo reactions to form mixtures of species at pressure and temperature conditions below those at which demixing to diamond and a hydrogen-rich phase occur<sup>4,5,7–10</sup>. The precursor therefore determines the ratio of carbon to hydrogen. DAC studies on diamond formation from optical laser-heated hydrocarbons all find the temperature required for diamond formation to be in the region of 2,000 K to 2,500 K regardless of the initial hydrocarbon<sup>4,5,17,18</sup>.



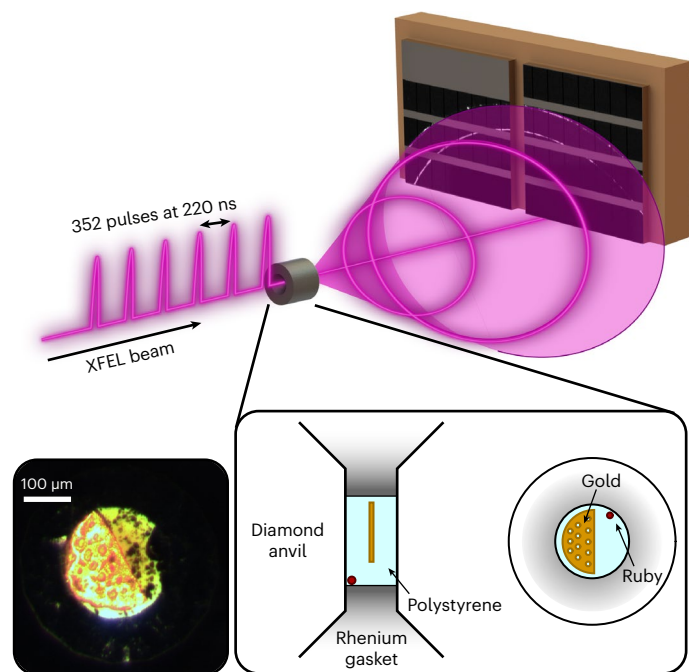
**Fig. 1 | State diagram of hydrocarbons at high pressure and temperature.**

The diagram shows the differing conditions found to be required for diamond formation, as well as selected phase transitions (solid lines) and planetary interiors (dashed). Studies using static compression (orange area<sup>4</sup> and red area<sup>5</sup>) observe diamond formation at lower pressure and temperature than shock experiments (blue area<sup>6</sup>), which observe it only at conditions corresponding to those where hydrogen is metallic<sup>37</sup>. The results presented here confirm that diamond formation can occur at conditions found in the shallow interiors of Uranus<sup>1</sup> and Neptune<sup>2</sup>, including at lower estimates of the temperature conditions. The conditions for diamond formation in shocked polyethylene terephthalate,  $(\text{C}_{10}\text{H}_8\text{O}_4)_n$  (green area<sup>57</sup>), the diamond melt curve<sup>58</sup> and Jupiter's isentrope<sup>39</sup> are also shown.

Studies on  $\text{CH}_4$  and  $\text{C}_2\text{H}_6$  find the formation of new compounds<sup>8–10</sup>, which can be either heavier or lighter<sup>9</sup>, in samples quenched from lower temperatures before diamond formation. This is consistent with the results of ref. 7, which used computational methods to simulate hydrocarbons at high pressure and temperature and found that the C–C and C–H bonds become short lived and that the concept of individual molecules as long-lived entities breaks down. One could therefore conjecture that, once in this state, the initial material dictates the C:H ratio based on its stoichiometry, but as the initial bonds will have broken before diamond formation, its starting chemical structure is less important. It is worth noting that the disagreement between static and shock compression studies persists in shocked polyethylene, which shows no diamond formation corresponding to conditions where it is observed statically<sup>19</sup>.

Perhaps the largest difference between the measurements of the laser-heated DAC and shock compression studies is the timescale of the physical processes, which can differ by more than ten orders of magnitude. The duration between shock compression and the probe is of the order of 10 ns (refs. 6, 19, 20), while laser-heated hydrocarbon studies in diamond cells have taken place on timescales of seconds to minutes<sup>4,5,18</sup>. Computer molecular dynamics simulations typically study reaction processes on even shorter timescales in the subnanosecond range<sup>7,10</sup>. Given that diamond formation in hydrocarbons is partly diffusion controlled, an implied rate dependence in diamond precipitation could explain differences between dynamic and static experimental observations. A dependence on timescale for diamond formation and corresponding material properties, such as equations of state, would have major implications for diverse scenarios ranging from inertial confinement fusion<sup>21,22</sup> to formation of natural impact microdiamonds<sup>23</sup>.

Here we investigate the effect of time on diamond formation in statically compressed X-ray free-electron laser (XFEL)-heated polystyrene. To avoid unwanted reactions, we use a gold coupler that forms no known hydrides or carbides. Heating occurs via a series of <50 fs high-intensity X-ray pulses at 4.5 MHz (ref. 24), which also probe the state of the sample via powder X-ray diffraction<sup>25,26</sup>. In this way,



**Fig. 2 | Experimental set-up.** The set-up includes a 4.5 MHz X-ray pulse train acting as pump and probe on the sample compressed in a DAC with diffracted X-rays incident on an eight-module AGIPD 500k. The enlargement shows the DAC loading configuration with the perforated gold coupler embedded in polystyrene. Inset: a micrograph of the sample before the experiment.

we recover the evolution of the system in the time domain on a time-scale between 220 ns and 77  $\mu$ s, which is intermediate between shock and traditional laser-heated DAC experiments. In doing so, we characterize demixing kinetics at extreme conditions, which offers insight into the process and resolves the discrepancy between previous static and dynamic compression experiments.

## Results

Polystyrene film was compressed in DACs and heated using an XFEL beam absorbed by a perforated 5- $\mu$ m-thick gold foil coupler embedded in the sample. The experimental set-up is shown in Fig. 2. The temperature was measured via spectrally resolved streaked optical pyrometry (SOP) with a time window of 97.4  $\mu$ s, which encompasses the full 352 pulses in the XFEL pulse train<sup>27</sup>. SOP is a surface measurement and, as hydrocarbons darken when heated in DACs<sup>4,5,8,9,18</sup>, it measures the temperature of the opaque envelope of the heated sample due to the large increase in emissivity during reaction<sup>28,29</sup>.

Thermal measurements were complemented by diffraction from the gold coupler, which constrains its temperature via the thermal equation of state of gold<sup>30</sup>. The gold equation of state gives systematically cooler temperatures, which is expected due to differences in the temporal structure of the measurements, and is subject to 300 K to 500 K uncertainty arising from the choice of equation of state, temperature gradients and thermal pressure. The upper temperature measurable by the equation of state of gold is also limited by its melting point, about 2,200 K to 2,500 K for the pressures in this study<sup>31,32</sup>. In addition to experimental measurements, the thermal evolution of the sample was investigated using finite element analysis (FEA). The simulations indicate  $\pm 200$  K thermal gradients across the  $\sim 10$ - $\mu$ m-diameter hole in the gold coupler. Time-resolved data are presented in Fig. 3. Additional discussions of the experiment are presented in Methods.

Diamond formation was determined by the emergence of the diamond {111} peak in the X-ray diffraction patterns and was observed in polystyrene that was X-ray heated above 2,500 K in a pressure range

of 19 GPa to 27 GPa. Diamond formation was not observed at lower temperatures (Extended Data Fig. 2) and diamond took at least 30  $\mu$ s to form when this temperature was exceeded (Extended Data Figs. 3 and 4). Heating for a shorter duration using a truncated pulse train (reaching 3,400(300) K for 15  $\mu$ s) did not result in diamond formation, confirming the requirement for sustained heating at these pressures.

The diamond {111} peak is well suited to determine the presence of diamond as the diamond anvils are single crystals with the (100) axis aligned with the compression axis (and the XFEL beam), so that the {111} peaks of the anvils are not observed on the detector. Other diamond peaks fall outside the  $q$  range accessible in this experiment ( $q = 1.29\text{--}4.47 \text{ \AA}^{-1}$ ), where  $q$  is the momentum transfer. At early times, around 30  $\mu$ s, the diamond peak is weak and requires summation over multiple integrated frames to be observed above the background. At around 40  $\mu$ s, larger diamond grains start to materialize, as evident from the distinct diffraction spots in the raw patterns (Extended Data Fig. 5). In addition to the time-resolved observation of the emergence of this peak during heating, it was also observed in the quenched sample using the highly attenuated XFEL beam. Diamond is also observed in the Raman spectrum of the recovered parts of the heated sample after removal from the DAC.

Figure 4 compares the X-ray diffraction patterns of the sample at various stages during heating. At early times, no diffraction from diamond is observed, while after 40  $\mu$ s there is a clear diamond {111} peak in the integrated patterns collected from individual pulses. Diamond diffraction is also observed from the cooled sample using a subsequent highly attenuated X-ray pulse train.

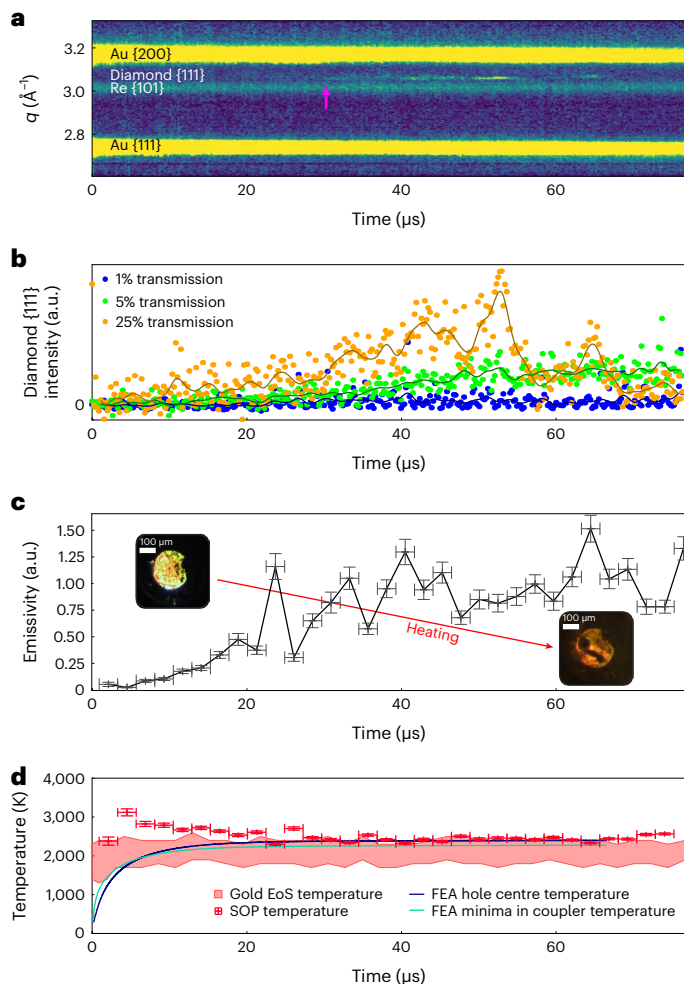
Raman spectra of the decompressed sample after removal from the diamond cell are shown in Fig. 5. The first-order Raman peak of diamond is clearly observed, offering additional confirmation that diamond formation occurred at high-pressure high-temperature conditions. Adjacent polystyrene that was subjected only to pressure but not heated does not show this peak. Removal of the sample from the DAC is necessary to observe this peak due to the strong Raman signal from the diamond anvils.

## Discussion

The results offer time-resolved insight into the dynamics of carbon-hydrogen demixing at extreme conditions and resolves the disagreement between previous laser-heated DAC and laser-driven shock experiments. We observe diamond to form from polystyrene between 19 GPa and 27 GPa, but only after it is held above 2,500 K for 30  $\mu$ s to 40  $\mu$ s. Initially, summing multiple integrated frames is required to get clear diffraction from the diamond {111} peak above background, and isolated spots from individual crystallites are not observed in the raw diffraction patterns. This implies that the diamond forms a powder initially. At later times, diamond diffraction is observed in single integrated frames (Fig. 4b), with visible spots of higher intensity at the diamond {111} scattering angle (Extended Data Fig. 5), implying a larger fraction of diamond and larger crystals at later times. The intensity arising from the emergence of the diamond {111} peak over three runs is shown in Fig. 3b. Low pulse energies from the run with 1% absorber transmission results in negligible heating and no detectable diamond formation. Both 5% and 25% beam power resulted in heating and the emergence of diffraction signal from diamond after  $\sim 30$   $\mu$ s.

In the high-power runs at late times, the diamond signal is observed to fluctuate. This is attributed to the increased size of the diamond crystallites at later times resulting in larger fluctuations in the diffraction signal as they move and rotate within the molten region and so only intermittently fulfil the Bragg conditions. Extended Data Fig. 1 shows a thermal cross-section of the sample based on FEA simulation; owing to thermal gradients, the fluid hydrocarbon region is larger than the hotspot where diamond formation occurs, allowing for migration and rotation of the diamond crystallites. They can then move out of Bragg conditions or away from the  $\sim 10$   $\mu$ m coupler hole where the hotspot is





**Fig. 3 | Time-resolved data from a run starting at 20 GPa with average pulse energy of 71  $\mu\text{J}$ .** The initial XFEL pulse occurs at time 0. **a**, Integrated diffraction patterns from the AGIPD detector as a function of time in the region of interest, background subtracted and normalized to the beam-intensity monitoring diode. Yellow shades correspond to higher intensity. The pink arrow indicates the onset of observable diamond signal. **b**, Intensity of the diamond peak as a function of time for different X-ray absorber transmissions. The 25% transmission is the same run as the other panels in this figure. Lines are smoothed by a 15-pulse-wide Hamming window. **c**, Emissivity increases during the run. Insets: photos showing the sample before and after heating. **d**, Temperature as a function of time. Bars show fitted temperatures from SOP with a 2.4- $\mu\text{s}$ -bin width and the error shown is the fitting error; in addition to this there is  $\pm 200$  K from thermal gradients. The red region is temperature from the equation of state (EoS) of the gold coupler<sup>30</sup>, and blue and green lines are temperatures modelled using FEA. Temporal error bars represent the time bin of the SOP. Emissivity and temperature error bars represent one-half standard deviation confidence and are derived from the fitting uncertainty of a Planck function to the spectrographic data and statistical analysis of these data<sup>27</sup>.

centred and that is probed by the XFEL beam. Diamond is more absorbing to X-rays than the surrounding liquid hydrogen-rich phase, and the XFEL beam is (approximately) Gaussian in intensity. Therefore the region of a diamond crystal closest to the beam centre is most heated. This may generate a force pushing it away from beam centre.

Our data enable the observation of reaction pathways unavailable previously. They agree with static experiments concerning the reaction product but, in addition, they provide insight into the transformation in the time domain. The unique capabilities of XFEL heating allow for the use of a gold coupler that couples poorly to infrared heating lasers. There are no known compounds of gold with hydrogen or carbon

so reaction with the coupler is not expected or observed, avoiding potential issues with previous laser-heated DAC studies. It has been previously proposed<sup>6</sup> that loss of molecular hydrogen from samples in traditional DAC experiments<sup>5</sup> could explain the observed difference between shock and static studies; however, this argument is speculative, as is its relevance for planetary interiors where molecular hydrogen loss to the atmosphere is likely<sup>33</sup>. Our experiments operate on a considerably shorter timescale than traditional DAC experiments, which limits the time available for hydrogen diffusion. In addition, the barrier of cold polystyrene that encapsulates the heated region (Extended Data Fig. 1) will further reduce hydrogen losses. This suggests an alternative reason for the discrepancy between studies using dynamic and static compression.

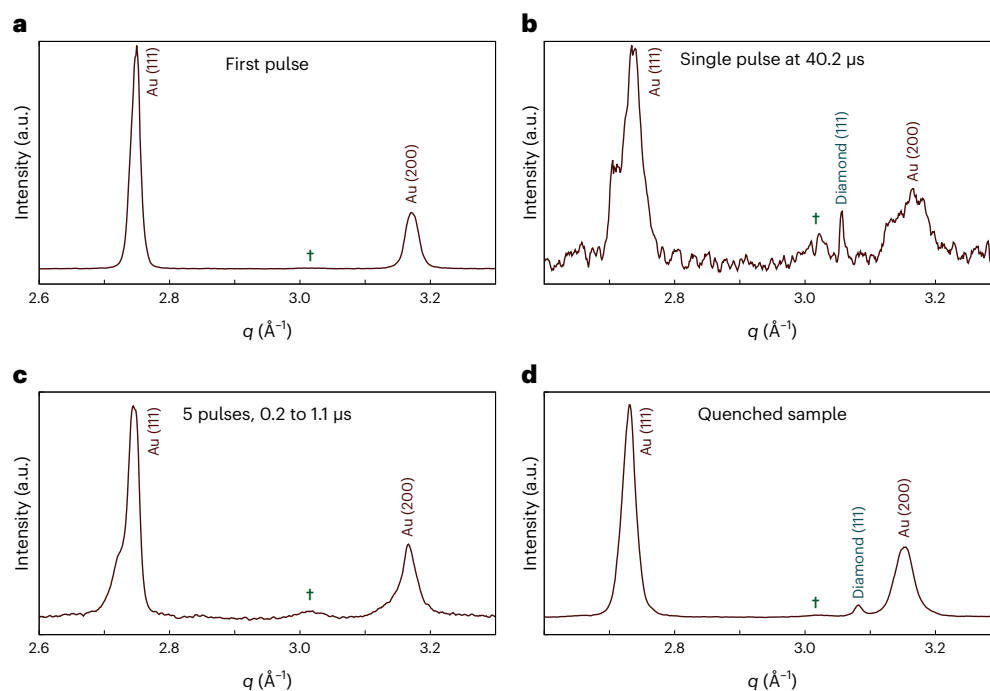
Instead, the disagreement appears to arise from the kinetics of the diamond formation mechanism. Laser-shock compression studies typically probe timescales in the region of 10 ns, which is three orders of magnitude shorter than is required for diamond formation at lower pressures observed in this study. The formation of diamond from the high-pressure high-temperature mixture of carbon and hydrogen implies demixing. At shorter times, or lower temperatures, the sample darkens, consistent with the formation of complex hydrocarbons previously observed<sup>4,5,8,9</sup> and calculated<sup>7,10</sup>. These are amorphous and not readily detected using X-ray diffraction.

The results of previous studies have suggested that the timescale of diamond formation is dictated by the stability of the carbon–hydrogen fluid from which it precipitates. Dynamic compression studies observe rapid diamond formation at conditions where hydrogen is metallic<sup>6,29,34–37</sup> and have inferred the presence of metallic hydrogen in the shocked material<sup>38</sup>. Carbon is not predicted to metallize up to much higher pressures<sup>39</sup>, and we speculate that the greatly decreased timescale of diamond formation in conditions where hydrogen is metallic could arise from the expulsion of non-metallic carbon from the metallic hydrogen.

Compared with a previous shock experiment<sup>6</sup>, the lower pressure and temperature required for diamond formation at longer, microsecond, timescales has implications for the interior dynamics of icy planets. These are known to contain  $\text{CH}_4$  in their atmospheres, and many models propose small-molecule ( $\text{H}_2\text{O}$ ,  $\text{CH}_4$ ,  $\text{NH}_3$ ) ‘ice’ mantles surrounding a rocky core<sup>1,2</sup>. The formation of diamond within the mantles is proposed as a source of internal heating from phase separation of the carbon and hydrogen and subsequent gravitational heating from sedimentation of the denser diamond. However, more recent models of their interior conditions (Fig. 1) suggest that the temperatures required for diamond formation in shock studies may be reached only near the cores of the local icy planets.

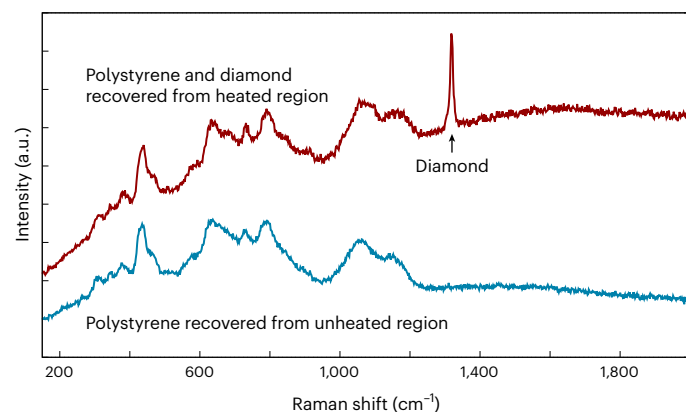
The conditions at which diamond formation is observed in this study occur within the shallow interiors of both Uranus and Neptune, pointing to other reasons for the differences in their luminosity<sup>13</sup>. The shallower diamond formation depth leads to greater potential heating as the diamond will subduct further. Our results place diamond formation above the proposed superionic ice layer<sup>40–42</sup>. Diamond-rich subduction plumes resulting from demixing can thus occur in the electrically conductive ices, where they can contribute to the convective flow and dynamo activity that is believed to be responsible for the complex multipolar magnetic fields of the ice giants<sup>42–46</sup>.

The lower pressure and temperature conditions also relax constraints on the size of the astronomical body in which hydrocarbons would form diamonds. While 10 GPa is higher pressure than occurs in any moons in our Solar System, many exoplanets have been discovered with sizes between Earth and Neptune and densities consistent with icy compositions<sup>14</sup>. These so-called mini-Neptunes make up one of the largest groups of exoplanets discovered and, being both plentiful and composed substantially of water, are of wide interest. The generation of diamonds within them could drive geodynamics, and have potential effects on their atmospheric composition and planetary evolution<sup>14,47</sup>.



**Fig. 4 | Integrated X-ray diffraction patterns in the region of interest from a run starting at 19 GPa.** There are no observable peaks at other  $q$  within the angular range of the detector. **a**, First pulse showing unheated and unreacted sample. **b**, Pulse 183, 40.2  $\mu$ s after the first pulse, showing clear diffraction from the diamond {111} at  $q = 3.056 \text{ \AA}^{-1}$ . **c**, Sum of pulses 2 to 6 showing no diamond

at early times. **d**, Diffraction from the quenched sample at 16 GPa shows a clear diamond {111} peak at  $q = 3.086 \text{ \AA}^{-1}$ . The increase in  $q$  from **b** to **d** is due to lattice contraction on cooling. The broad peak marked with a dagger is the rhenium {101} reflection from the DAC gasket.



**Fig. 5 | Raman spectra of the sample after removal from the DAC.** Previously pressurized but unheated material is in blue and material from the heated spot is shown in red. Note the sharp diamond Raman peak present in only the material that was previously heated to 2,500 K.

In conclusion, we have observed diamond formation on 30  $\mu$ s timescales from polystyrene at 19 GPa to 27 GPa above 2,500 K in XFEL-heated DAC experiments. This avoids potential problems with previous optical laser-heated DAC studies and shows the discrepancy in diamond formation conditions determined in static and shock compression to be due to the markedly differing experimental timescales. This implies significant differences in chemical alteration, diamond formation and equation of state for dynamic loading of CH-bearing materials on different timescales, such as between nanosecond-laser and microsecond-impact compression experiments, and geophysical events on longer timescales. The conditions determined are consistent with diamond formation in both Uranus and Neptune at shallow depth,

such that diamond precipitation may have a considerable evolutionary or present role in planetary dynamics. It also allows for diamond formation in much smaller icy bodies, which are observed to be a common class of exoplanet.

## Methods

Polystyrene film was compressed using a DAC equipped with Boehler Almax geometry anvils with 400  $\mu$ m culets and a rhenium gasket preindented to 60  $\mu$ m thickness. A schematic of the loading is shown in Fig. 2. Two layers of polystyrene were loaded sandwiching a perforated 5  $\mu$ m gold foil coupler, with a small ruby sphere included for pressure determination<sup>48</sup>. In addition, a flake of amorphous boron was included as a laser coupler and can be seen as the powdery material in the micrograph of the sample in Fig. 2. This was not used, and is spatially separate from the gold so played no part in the experiment.

The polystyrene acts as the sample, pressure medium and insulation. In XFEL-heated DAC samples, it is necessary to provide a thermal barrier between the strongly absorbing coupler and diamonds to prevent anvil failure and maintain heat in the sample<sup>25,26</sup>. The gold coupler was laser cut<sup>49</sup> with approximately 10  $\mu$ m perforations spaced at 20  $\mu$ m. These are sized such that the edges of the XFEL beam will be absorbed and heat the gold, while the centre of the beam probes the heated sample. The hole spacing is adequate to minimize heating of adjacent holes. Gold was chosen as it has no known compounds with hydrogen or carbon and its diffraction peaks do not coincide with those of diamond, but it is high  $Z$  so effectively absorbs the X-rays.

Samples were prescreened at PETRA III beamline P02.2 using 0.4845  $\text{\AA}$  radiation collected on a Perkin Elmer XRD 1621 large-area detector<sup>50</sup>. This confirmed the polystyrene to be non-crystalline with the only observable diffraction peaks arising from the gold coupler. The pressure obtained from the equation of state<sup>30</sup> of the gold coupler was 25(1) GPa. Integrated diffraction patterns from the prescreening are shown in Supplementary Figs. 1 and 2.

The XFEL pump–probe experiment was performed at the High Energy Density instrument of the European XFEL<sup>25</sup> using 0.6965 Å (17.8 keV) radiation delivered in <50 fs pulses. Pulse trains consisted of up to 352 X-ray pulses delivered at 4.5 MHz for an inter-pulse spacing of 220 ns. The beam was focused using compound refractive lenses to a nominal 8 μm full-width at half-maximum spot. The diffraction pattern from each pulse was individually collected on the large-area adaptive gain integrating pixel detector (AGIPD) detector<sup>51,52</sup> with pixel size of 200 μm at a distance of 390 mm covering an angular range of 8.2° to 26.0° (corresponding to  $q = 1.29\text{--}4.06 \text{ \AA}^{-1}$ ;  $d\text{-spacing} = 1.55\text{--}4.87 \text{ \AA}$ ). By collecting individual diffraction patterns from each pulse, we effectively probe the state obtained from the previous heating pulse and perform the heating for the next measurement in each pulse. This leads to an initial step-wise temperature increase that rapidly saturates<sup>25,26</sup>.

Figure 4 shows integrated X-ray diffraction patterns taken at the XFEL before, during and after heating. As well as the peaks from the gold coupler and the diamond formed, there is a broad peak at around  $q = 3.02 \text{ \AA}^{-1}$ , which is the {101} reflection from the rhenium gasket. This arises from low-intensity fringes that extend significantly beyond the focused section of the XFEL beam hitting the gasket and is observed in all XFEL shots. The {101} reflection is the strongest of rhenium<sup>53</sup>, and no other peaks from the gasket are observable. It is not observed in the prescreening data from PETRA III (Supplementary Figs. 1 and 2) as this beam passes through a pinhole. A pinhole was not used with the XFEL beam due to spatial fluctuations between the pulses. Additional data are presented in Supplementary Figs. 3 and 4 and Supplementary Table 1.

The total energy per pulse was controlled using absorbers. The full pulse energy was 306(23) μJ measured by the beam-intensity monitoring diode, which is calibrated using an absolutely calibrated X-ray gas monitor<sup>54</sup>, the pulse energies for the run presented in Fig. 3 are shown in Supplementary Fig. 5. Higher transmissions (≥5%) cause measurable heating of the gold coupler and corresponding changes in the sample. Very low transmissions (0.5% to 1%) caused negligible heating and were used to probe the quenched sample after the high-temperature pump–probe experiment. A new coupler hole was used for each pump–probe experiment, such that each heating X-ray pulse train was incident on fresh material and any transformations can be ascribed to it alone. The starting pressure for a run was determined from the positions of the gold peaks in the first pulse that probes the unheated material. This varied between runs due to pressure gradients across the DAC sample and the cell relaxing to lower pressure over the course of the experiment. The load on the cell was not adjusted during the experiment. In addition to the transmission, the energy absorbed, and hence degree of heating, depends on the geometry of the hole in the coupler and the beam pointing. For this reason, higher-transmission runs usually yielded higher temperatures, but not universally.

Raman spectra were taken of the sample after removal from the DAC using a 514 nm argon-ion excitation laser in a micro-Raman system. Due to the localized heating, the Raman spectrum of the heated region includes signal from unheated material that was further from the coupler. Raman spectra of the material in the DAC was not obtained as the anvils cracked when the XFEL beam intensity was increased to 50%.

Temperature was measured from the upstream side of the DAC using SOP<sup>27,29</sup> with a time window of 97.4 μs, covering the duration of the heating. The field of view is 50 μm, although SOP is most sensitive to the hottest part of this area so effectively measures the temperature of the hotspot. Temperature and emissivity are both fitted as free parameters in a series of time steps across the streak image via a Planck distribution between 575 nm and 800 nm (Supplementary Figs. 6–8). In XFEL-heated DACs, temperature increases rapidly over the first few pulses before saturating<sup>26</sup>. The arrival of the first XFEL pulse coincides with the start of the initial rise in thermal emission (Fig. 3). The emissivity of both gold and the unheated polystyrene is very low and the intensity of the black-body radiation increases over the first 10 μs along with other changes

in the sample. The emissivity shown in Fig. 3 is normalized to plateau near 1, which is probably close to the real emissivity due to the black state of the sample produced by heating. This darkening and change in emissivity is probably due to initial reactions before diamond formation. The uncertainties in emissivity are assessed from a combination of fitting error and variations between two runs using the same beam transmission (25%), which are shown in Supplementary Fig. 9. It is noted that SOP is a surface probe and, as the polystyrene is darkened after heating, it is possible that some material close to the coupler reaches higher temperature but is obscured by opaque material further from the coupler. Extended Data Fig. 1 shows a thermal cross-section of the sample based on FEA simulation, which illustrates this.

The thermal equation of state of the gold coupler<sup>30</sup> offers a complementary temperature probe based on thermal expansion of the lattice. Temperature gradients in the coupler smear the diffraction peaks to lower  $q$  due to lattice expansion. The difficulty in fitting the peak, combined with possible thermal pressure<sup>26,55</sup>, results in a much larger uncertainty, typically ~400 K, in the temperature measured by the gold coupler than by the SOP. This uncertainty arises from the choice of equation of state, fitting of the diffraction peak, which has a skewed shape from thermal gradients, and possible thermal pressure. The upper bound on temperature is obtained by assuming 3 GPa of thermal pressure<sup>26,55</sup> and fitting the low- $q$  edge of the gold peaks. The lower bounds assumes thermal pressure fully relaxes during the 220 ns between pulses. Positions assigned to the low- $q$  edge of this peak are shown in Supplementary Fig. 10.

Figure 3 shows the temperature obtained from the gold equation of state to be systematically lower than that determined via SOP. This is expected as the sample is heated in very short bursts by the XFEL pulses with cooling between them, so the temperature has a saw-tooth profile<sup>25,26</sup>. The SOP is most sensitive at highest temperature where emission is brightest, while the XFEL pulse probes the sample at the coolest point on each period. In addition to the temporal differences, there are also spatial differences in the techniques. SOP is a surface probe, while X-ray diffraction probes the bulk. Further data and fits from the SOP are presented in the Supplementary Section IV. The temperatures quoted are those determined by SOP. The temperature measurable using diffraction from the gold coupler is limited by the melting point of gold, about 2,200 K to 2,500 K for the pressures in this study<sup>31,32</sup>.

The thermal evolution of the sample was modelled using FEA simulation of the first 300 pulses. FEA simulations were performed in two-dimensional geometry with rotation symmetry around the XFEL beam and coupler hole, with thermal transport both parallel and perpendicular to the beam<sup>26,56</sup>. The results are shown in Fig. 3d, with further results presented in the Supplementary Section VI. The model parameters are presented in Supplementary Table 2. Sample heating is introduced mainly by the repeated direct heating of the coupler by the beam edges and gradual indirect heating of the sample cavity (Extended Data Fig. 1 and Supplementary Fig. 11). FEA temperatures agree well with experimental observations, reaching a stable temperature of 2,500 K within ~10 μs (~50 pulses) due to balance of cooling and heating rates<sup>26</sup>. The sample is observed to reach this temperature at shorter times than the model predicts, which we attribute to initial misalignment between the sample hole and XFEL beam such that the first pulse is not perfectly centred on the hole and so deposits more energy into the coupler, followed by rapid migration of hot gold<sup>56</sup> away from the beam. The stronger gold diffraction from the initial pulse compared with subsequent pulses supports this interpretation (Supplementary Fig. 4), suggesting the hole rapidly reformed around the beam on initial heating leading to improved model agreement on longer timescales.

## Data availability

The datasets used during the current study are available from the corresponding author on reasonable request.



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## Author contributions

All authors were involved in experimental planning. M.F., E.B., M.B., R.J.H., C.S., H.-P.L., Z.K. and A.F.G. coordinated the experiment. M.F. prepared the samples. H.-P.L., J.D.M., L.M.A., S.K. and B.M. performed the prescreening at P02.2 at PETRA III. M.F., C.S., C.B., H.-P.L., Z.K., S.N., J.D.H., C.P., E.E., R.S.M., S.C., O.B.B., M.J.D. and A.F.G. conducted the experiment. T.L., S.S., C.S. and J.S.-D. operated the AGIPD detector. R.R., S.H.G. and A.F.G. advised. M.F., R.S.M., O.B.B., R.J.H., Z.K., C.P., E.E. and A.F.G. analysed the data. M.F. and R.S.M. wrote the paper.

## Competing interests

The authors declare no competing interests.

## Additional information

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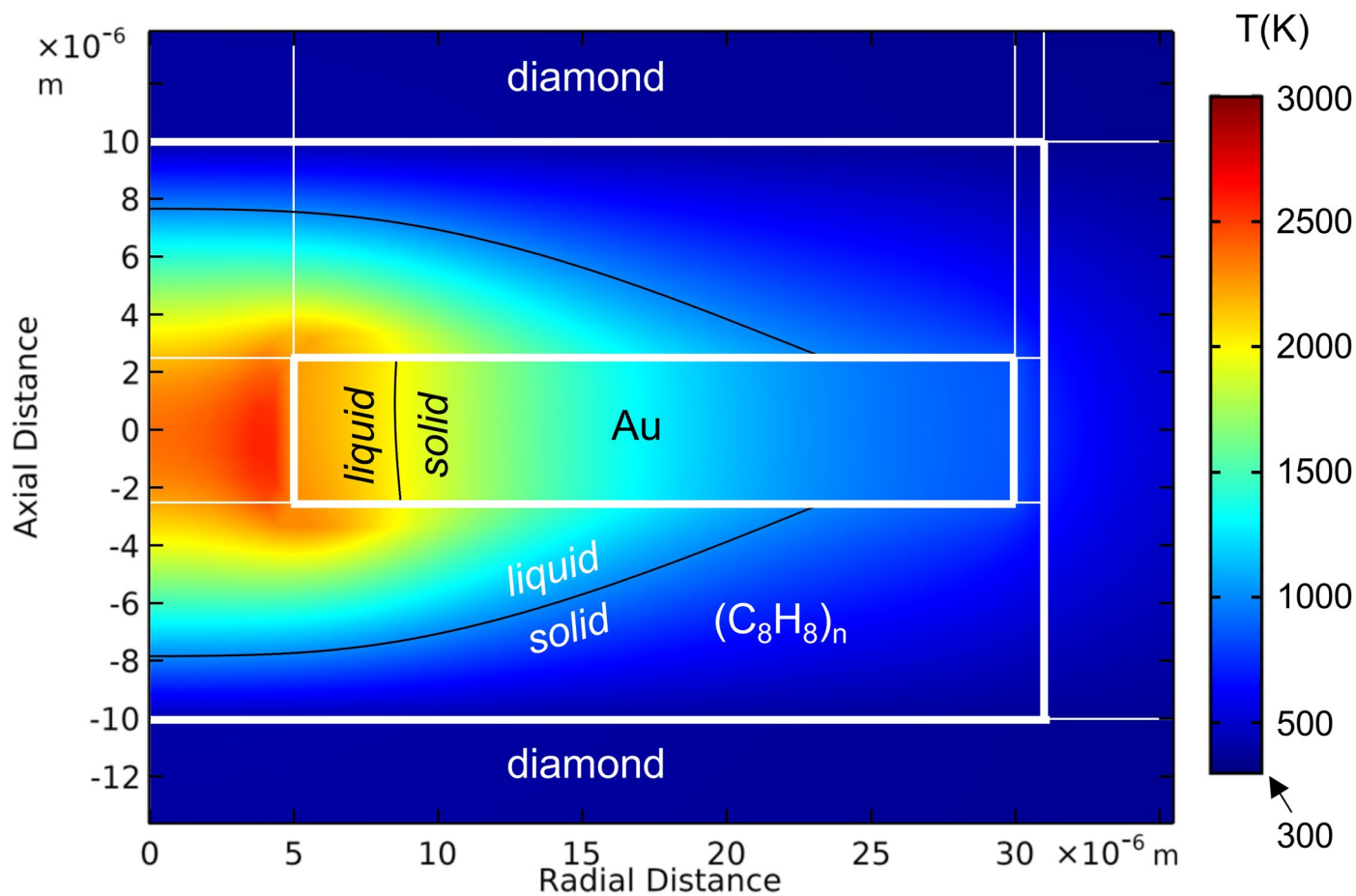
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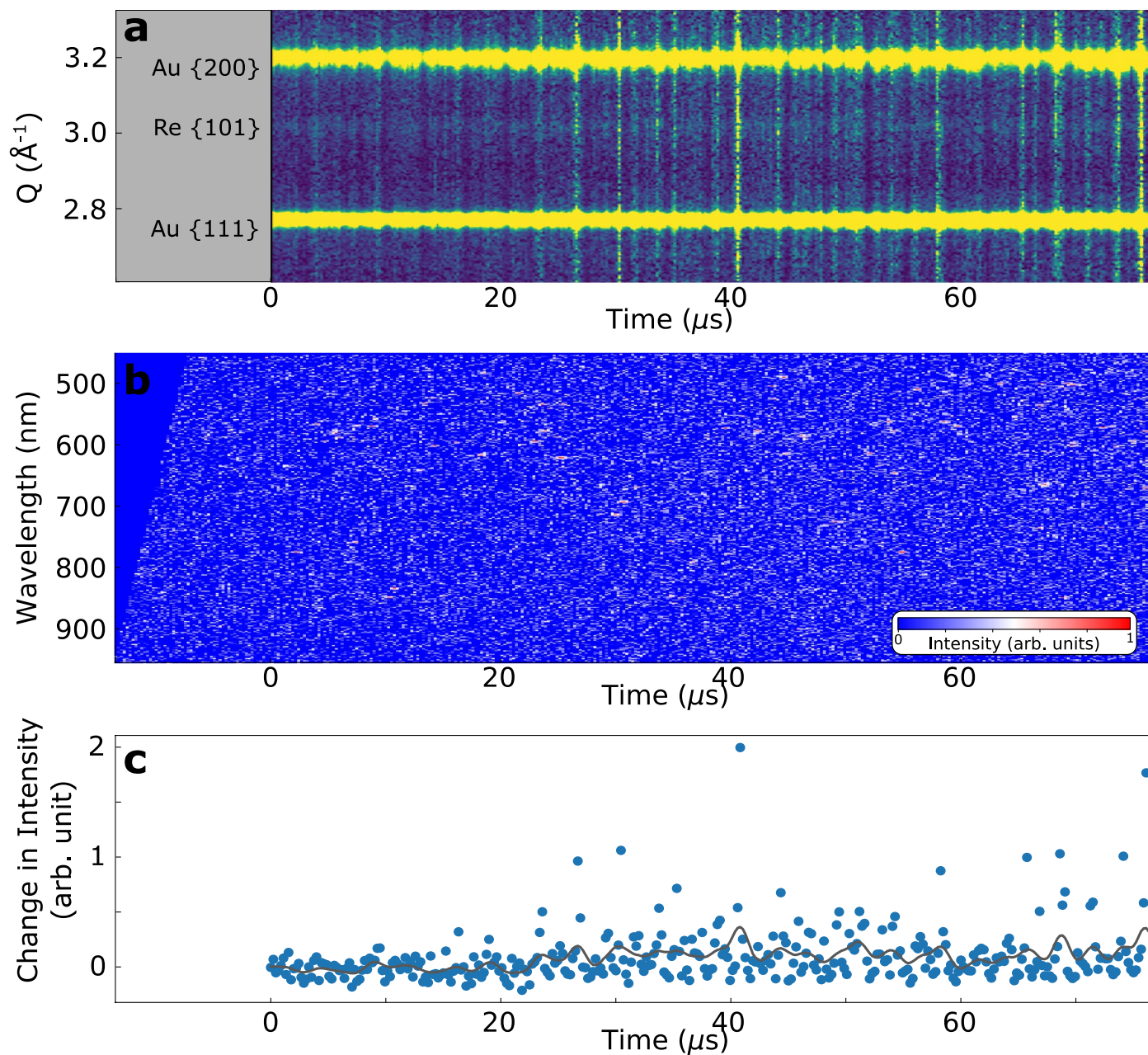
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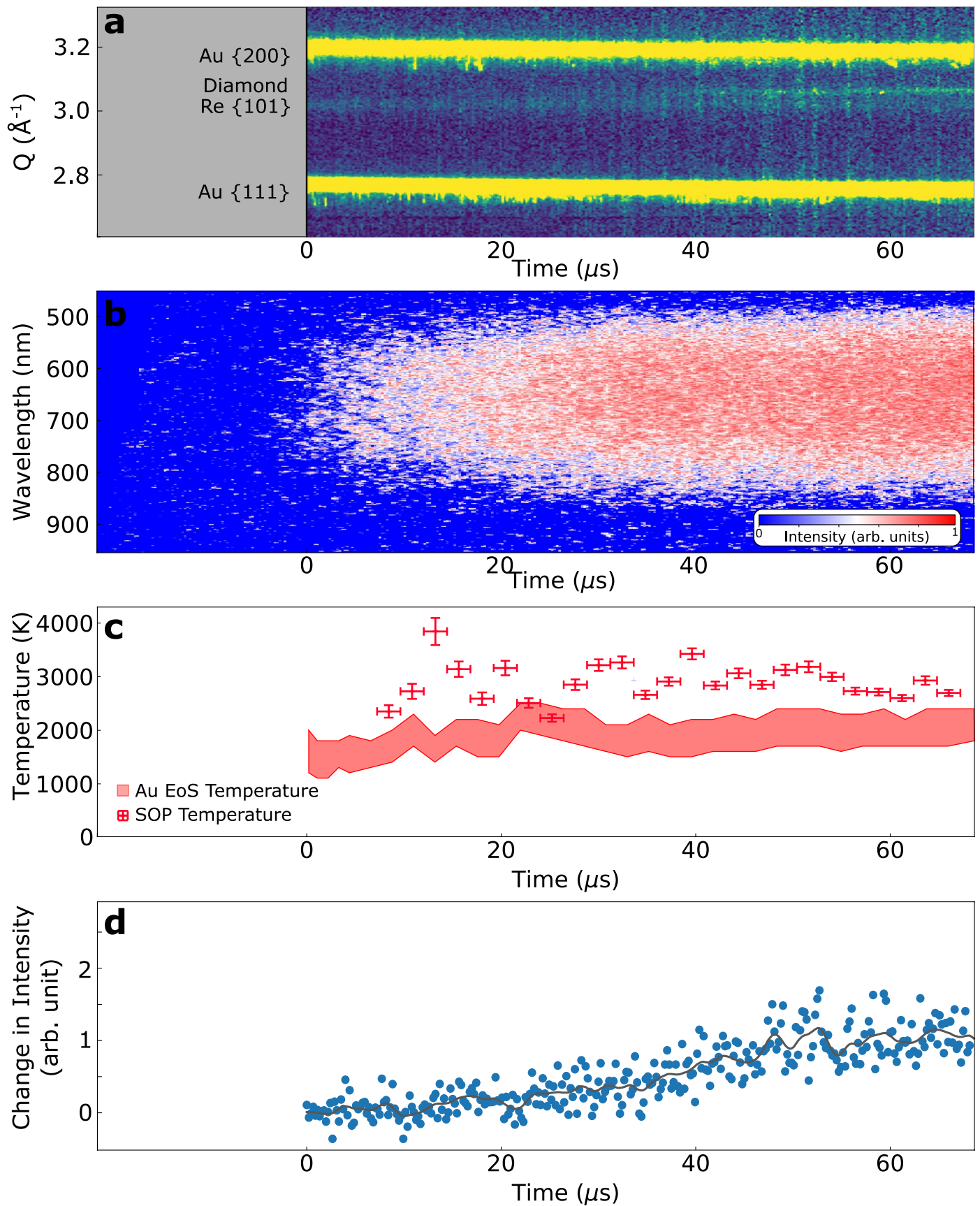
**Extended Data Fig. 1 | FEA Model of Sample Temperature.** FEA model (cylindrical section) of sample temperature at the time of XFEL probing at  $30 \mu\text{s}$  in Fig. 3d. Bold white lines indicate boundaries between DAC components; light white lines indicate additional boundaries required by the analysis; XFEL radiation is from below<sup>26</sup>. Black lines indicate solid-liquid boundaries, with the melting point of Au taken to be  $2350 \text{ K}$ <sup>31,32</sup> and the melting point of polystyrene

taken to be  $1000 \text{ K}$  (representing a likely minimum bound, considering an ambient melting point of  $510 \text{ K}$  and steep rise with pressure). The model shows high temperatures are localized near the coupler hole, with cold material surrounding the hotspot, including several microns of cold and solid polystyrene separating the sample from the diamond anvils and significantly more separating the hot sample from the gasket.



**Extended Data Fig. 2 | Time resolved data from a run with 1% beam power.** No thermal emission or diamond is observed. **a:** XRD in region of interest, vertical stripes are artifacts from diode normalization. **b:** SOP spectrogram showing no

emission. **c:** Time evolution of intensity at  $q$  where diamond is expected shows no diamond formation, the line is smoothed with 15 pulse wide Hamming window. Time 0 is estimated first arrival of X-rays based on other runs.

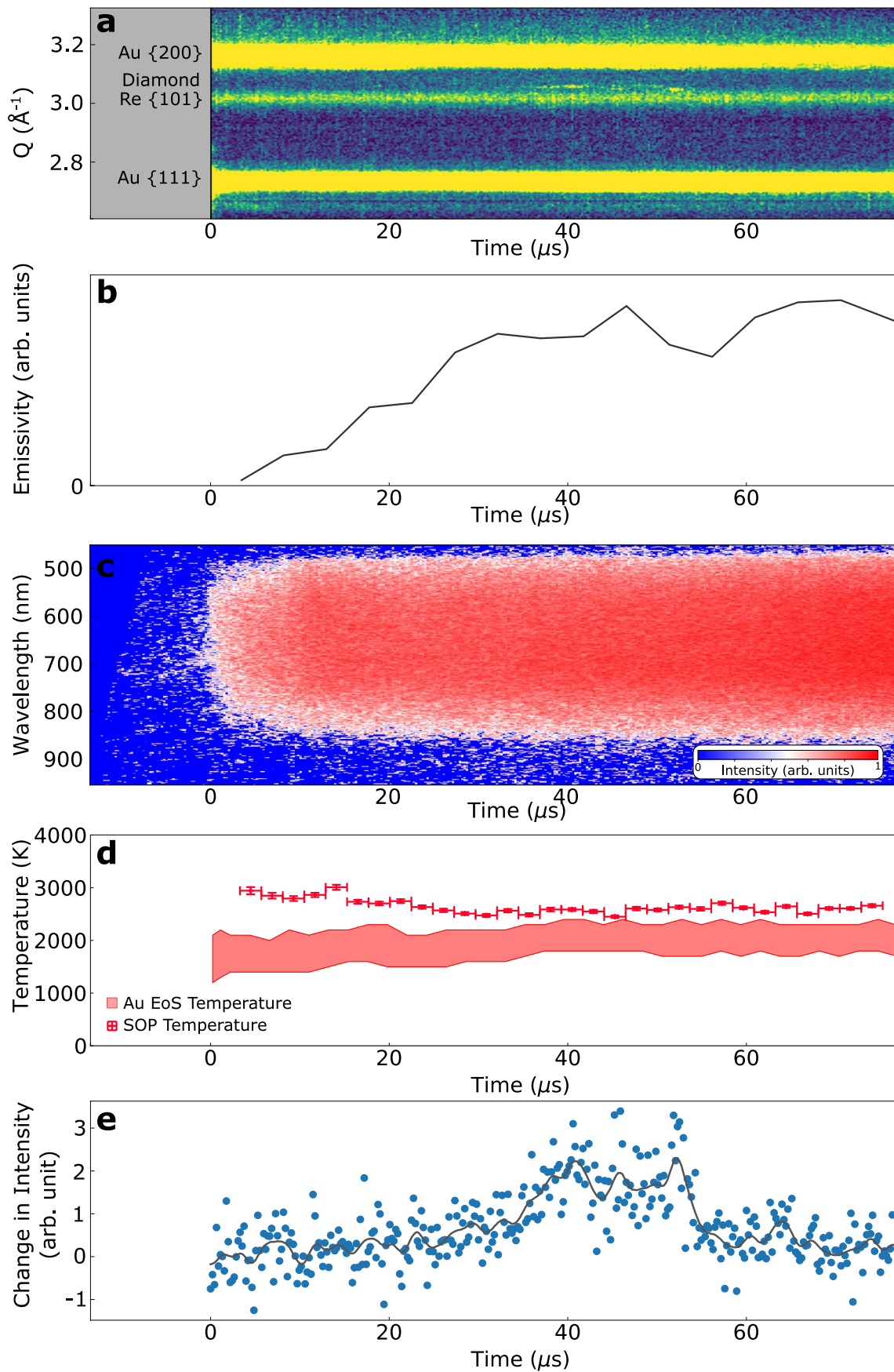


Extended Data Fig. 3 | See next page for caption.



**Extended Data Fig. 3 | Time resolved data from a run with 5% beam power.** Thermal emission and diamond formation are observed. **a:** XRD in region of interest normalized to beam intensity monitoring diode. The diamond 111 reflection is visible after 40  $\mu$ s. **b:** SOP spectrogram. **c:** Temperature from SOP fitting and equation of state of gold<sup>30</sup>. **d:** Time evolution of diamond peak intensity, line is smoothed with 15 pulse wide Hamming window. Time

0 corresponds to first X-ray pulse based on rising edge of thermal emission. Temporal error bars represent the time bin of the SOP, temperature error bars represent one-half standard deviation confidence and are derived from the fitting uncertainty of a Planck function to the spectrographic data and statistical analysis of these data<sup>27</sup>.

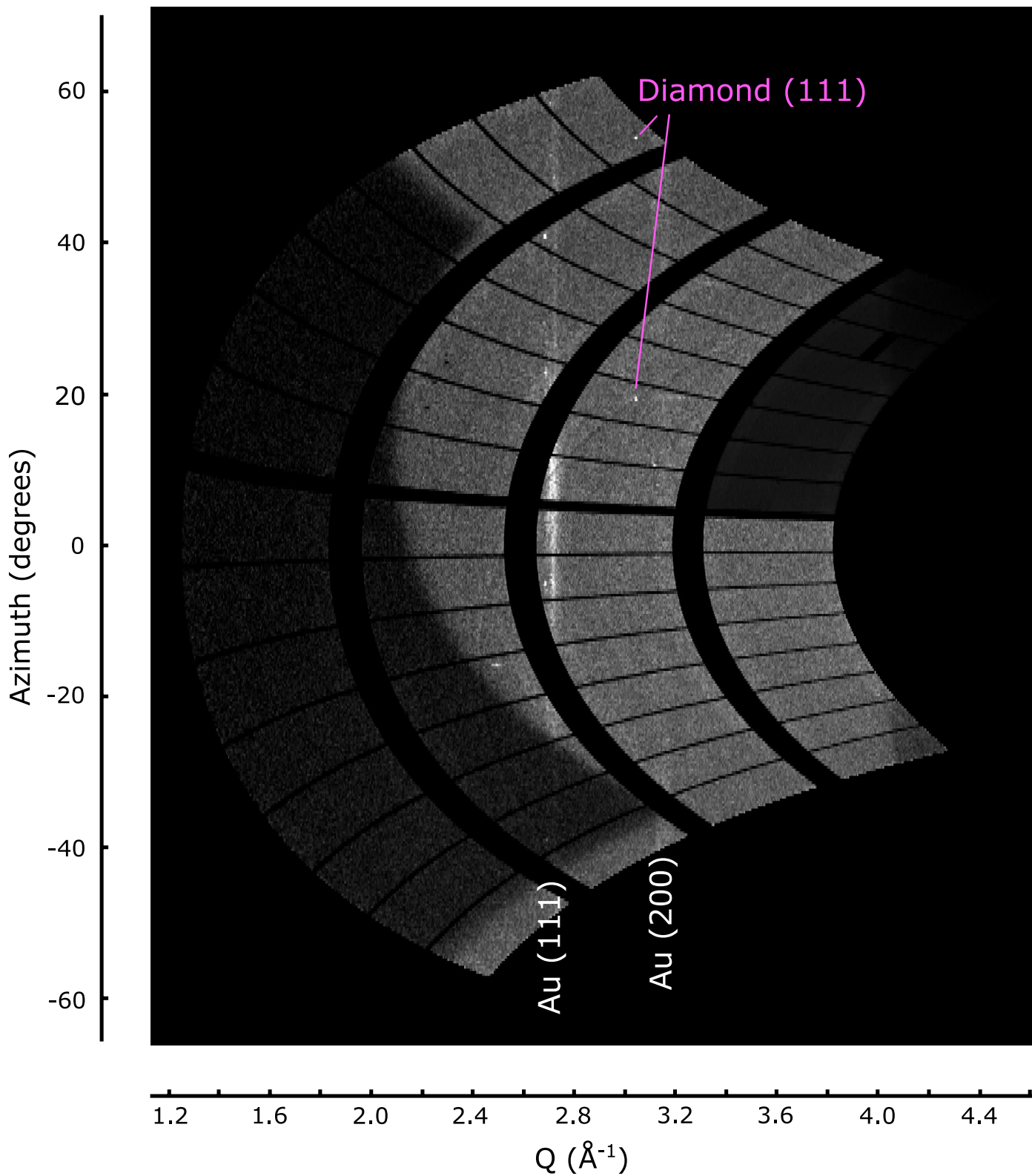


Extended Data Fig. 4 | See next page for caption.

**Extended Data Fig. 4 | Time resolved data from a run with 25% beam power.** This is a different run than is presented in Fig. 3, but shows similar temperatures and diamond formation. **a:** XRD in region of interest normalized to beam intensity monitoring diode. The diamond {111} reflection is visible after 35  $\mu$ s. **b:** Emissivity as a function of time. **c:** SOP spectrogram. **d:** Temperature from SOP fitting and equation of state of gold<sup>30</sup>. **e:** Time evolution of diamond

peak intensity, line is smoothed with 15 pulse wide Hamming window. Time 0 corresponds to first X-ray pulse based on rising edge of thermal emission. Temporal error bars represent the time bin of the SOP, temperature error bars represent one-half standard deviation confidence and are derived from the fitting uncertainty of a Planck function to the spectrographic data and statistical analysis of these data<sup>27</sup>.





**Extended Data Fig. 5 | Unintegrated Diffraction Image.** Raw diffraction pattern from a single XFEL pulse taken  $40.2 \mu\text{s}$  into a run starting at 19 GPa. The SOP temperature is 2540(30) K. The integrated pattern is shown in Fig. 4b.  $\lambda = 0.6965 \text{\AA}$ . Lighter shades correspond to higher signal, brightness and contrast

$Q$  ( $\text{\AA}^{-1}$ )

are optimized for visibility. The pattern is azimuthally unwrapped such that vertical lines are at constant  $q$  (also known as 'caked'). The shadow at low  $q$  is from the mirror used to observe the sample, the dark panel (top right) was faulty and masked when integrating the diffraction patterns.