# Earth's cooler core inferred from new resistance-heated diamond-anvil-cell experiments

The center core of the Earth is mainly composed of metallic iron. Since the liquid core coexists with the solid at the inner core boundary (ICB), the melting temperature of iron at ICB of 5100 km depth provides us an important constraint of the temperature of the Earth. Many researchers have conducted experiments to determine the melting temperature of the iron under high-pressure conditions corresponding to those at the ICB. A pioneering ultrahigh-pressure laser-heated diamond anvil cell (DAC) experiment performed by Boehler [1] showed the melting temperature of iron up to 200 GPa, in which melting was judged visually as the onset of convective motion. Extrapolation of Boehler's melting curve gives the melting point of iron to be 4850±200 K at 330 GPa corresponding to the pressure at ICB. The melting curve of iron has then been repeatedly examined by laser-heated DAC studies (e.g., Anzellini *et al.* [2]), but the results have been markedly different from each other. Anzellini and others found the melting point of iron to be 6230±500 K at 330 GPa by extrapolating their results from 200 GPa. These conflicting results are likely to be due to large spatial and temporal temperature variations, especially in the direction parallel to the compressional axis, in laser-heated DAC samples. Another source of the discrepancy may be the difference in the melting criterion employed in previous studies. Furthermore, the previous DAC experiments were carried out only up to 200 GPa and thus required long extrapolation to 330 GPa, which is another source of a large uncertainty. Here we employed internal-resistance-heated DAC techniques, which stabilize the sample temperature during heating compared with conventional laser heating [3]. Experiments were carried out up to 290 GPa and 5360 K, far beyond the pressure and temperature (*P*–*T*) rrange ever achieved in earlier internal-resistance-heated DAC studies (<100 GPa, <2000 K) (e.g., Komabayashi *et al.* [4]). The melting temperature of iron was determined on the basis of the change in the voltage–temperature relation to 290 GPa, close to the pressure at the ICB.

High-pressure melting experiments were conducted using an internal-resistance-heated DAC (Fig. 1). Pure iron foil with a thickness of 1 μm was fabricated with a focused ion beam system (FEI Versa 3D DualBeam); the central part of the foil was narrowed to locate a hot spot and generate temperature high enough to melt iron. The foil was loaded between the $Al_2O_3$ thermal insulation layers and connected to an electrode several millimeters away from the culet. After compression to a desired pressure, direct electrical current was applied to the iron foil for heating. Ramp rates were typically several hundred millivolts per second. One-dimensional temperature profiles were obtained parallel to the view given in Fig. 1 by a spectroradiometric method [5]. Synchrotron XRD measurements were conducted at SPring-8 **BL10XU** (Fig. 2) [5]. A monochromatic X-ray beam with a wavelength of 0.413–0.415 Å was collimated to 6 μm at full width of half maximum (FWHM) in runs performed below ~150 GPa and to 2 μm at higher pressures. Angle-dispersive XRD patterns were collected on a flat panel detector (PerkinElmer XRD 0822) with a typical exposure time of 1 sec.

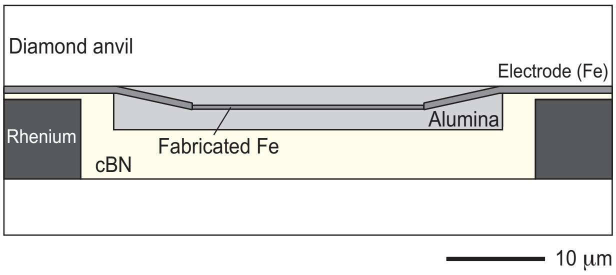


Fig. 1. Sample configurations for internal-resistance-heated DAC experiments.

We obtained the voltage–temperature relationship for the iron sample during heating by applying electricity. The sample temperature increased with increasing applied voltage; however, after reaching a certain temperature, the temperature started fluctuating. At the same time, we observed an anomaly in the voltage–resistance curve. In addition, the voltage–resistance relationship became no longer identical during the temperature increase and decrease (note the same voltage–resistance path during increasing and decreasing voltage unless such temperature fluctuation occurred at some point). Seventeen separate runs were performed between 6 and 290 GPa to determine the melting temperature of iron (Fig. 3) on the basis of the applied voltage–sample temperature relationship. In a run at around 90GPa, when we heated hcp Fe, the fcc phase appeared above 2770 K at 92 GPa, consistent with the result of an earlier experiments on the fcc–hcp boundary. The

XRD peaks corresponding to fcc then diminished with further temperature increase to 3030 K, coinciding with the onset of sample temperature fluctuation. After the high *P*–*T* experiment, we recovered this sample from the DAC and observed a clear melting texture in its cross section. The melting temperature of iron should therefore be 3030±150 K at 97 GPa. Even at higher pressures, we successfully observed the onset of fluctuation in the voltage–temperature relationship and obtained the melting point of iron to 290 GPa, which is well above the pressure range examined in previous DAC studies (< 200 GPa).

The melting point of pure iron, 5500±220 K at 330 GPa (Fig. 3), gives the upper limit for the temperature at ICB, since the liquid outer core includes light elements that depress the melting temperature. The combination of 2 wt% Si and 3.6 wt% O (or 0.7wt% H) indeed gives the least depression of the outer core liquidus temperature by 380(±170) K, although an Fe–Si–O liquid core is also unlikely [6]. Therefore, the ICB temperature should be lower than 5120±390 K. These values also give the upper bound for the temperature at core-mantle boundary (CMB) to be 3760±290K by employing the outer core density profile and the Grüneisen parameter $\gamma = 1.5$. It is certainly lower than the dry solidus temperature of ~4150 K for a pyrolitic/chondritic mantle at the CMB, consistent with the fact that the bottom of the mantle is presently not molten globally. The recent core energetics modeling by Hirose *et al.* [6] demonstrated that maintaining a geodynamo with 1 TW ohmic dissipation requires a core cooling rate of as low as 100 K/Gyr when we consider $SiO_2$ crystallization at the CMB. If the current CMB temperature is ≥4000K, the minimum core cooling rate of 100 K/Gyr leads to the global melting of the lowermost mantle at least 1.5 Gyr ago.

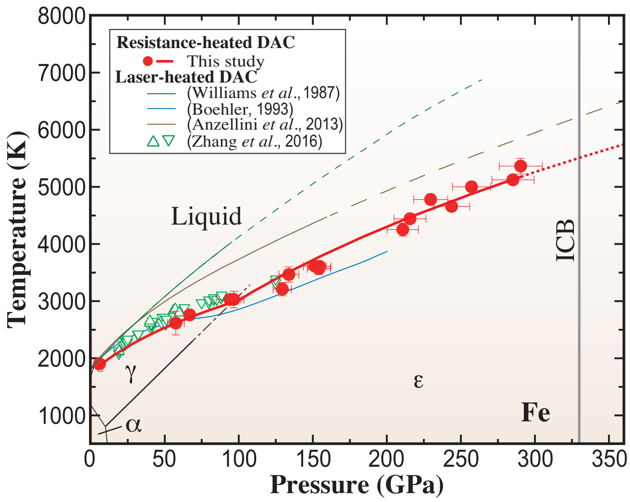


Fig. 3. Melting curve of iron at high pressure. Red closed circles are the onset of melting and the red line is the fitted melting curve (this study). Melting curves from previous reports are shown for comparison.

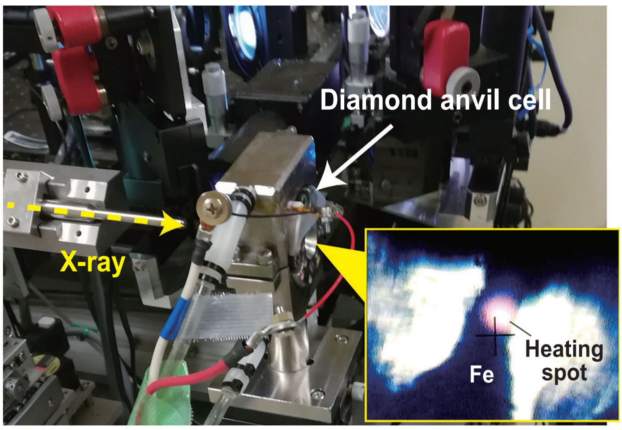


Fig. 2. Overview of the experimental setup at BL10XU, SPring-8. Inset shows an optical microscopy image during heating.

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## References

[1] R. Boehler: Nature **363** (1993) 534.
[2] S. Anzellini *et al.*: Science **340** (1993) 464.
[3] *R. Sinmyo, K. Hirose, Y. Ohishi: Earth Planet. Sci. Lett.* ***510*** *(2019) 45.*
[4] T. Komabayashi *et al.*: Phys. Chem. Miner. **39** (2012) 329.
[5] Y. Ohishi *et al.*: High Pres. Res. **28** (2008) 163.
[6] K. Hirose *et al.*: Nature **543** (2017) 99.