Road to X-ray science beyond 100 Tesla

Conventionally, in the research of condensed matter physics, the magnetic field of a few tesla is used as a valuable tool to reveal properties of materials by directly acting on magnetic moments, such as electron spin, orbital motion, and nuclear spins, in a perturbative manner. Using high magnetic fields beyond 10 T, various phase transitions, not only magnetic phase transitions in spin systems but also electronic phases such as superconductivity, charge density wave, multiferroic phase, and metal-insulator transitions, can be induced. This reminds us of the fact that electron spins play crucial roles in the formation of not only magnetic phases but also electronic phases.

On the other hand, condensed matter physics beyond 100 T remains a frontier. It is still unknown what happens to condensed matter when placed under magnetic fields well exceeding 100 T. There are two reasons. One is that the magnetic field is so large that the effects are considered *nonperturbative* in many ways. Hence, theoretical predictions are difficult. The other reason is that, experimentally, producing a magnetic field beyond 100 T requires an uncommon technique called destructive pulse magnets (DPMs). With DPMs, the explosion of coils, pulse durations of a few microseconds, and very large instruments are unavoidable. Currently, a few systems have been installed in large facilities around the world. This situation prevents the casual investigation of material properties above 100 T.

We have made efforts to cultivate the frontiers beyond 100 T and have started to discover marked changes in lattice structures induced at ultrahigh magnetic fields. At the Institute for Solid State Physics, University of Tokyo, we generated 1200 T using the newly developed system based on the electromagnetic flux compression technique in 2018 [1]. Furthermore, we developed techniques to measure the properties of materials such as magnetization, electric conductivity, and magnetostriction [2]. Using those techniques, we revealed exotic phase transitions possibly involving large lattice changes, such as the ferromagnetic phase transition of solid oxygen [3], the metal-insulator transition of VO_2 [4], and possible excitonic phases in $LaCoO_3$ [5,6]. All these findings are based on the measurements of the macroscopic properties of materials. To obtain concrete evidence that we have altered the lattice structures using magnetic fields, we regard complementary microscopic measurements such as X-ray diffraction and spectroscopy measurements to be essential. However, our magnetic field generators are very large and therefore not transportable.

In the present study [7], we devise a new instrument called Portable INtense Kyokugenjiba (PINK-01), as shown in Figs. 1(a-c) and Figs. 2(a-c). PINK-01 is a portable DPM system with a weight of less than 1 ton that is capable of generating pulsed high magnetic fields by the single-turn coil technique. The maximum magnetic field is 77 T in a room temperature bore of 2.5 mm diameter, which is the world's highest field obtained with a portable system. Owing to its portability, we transported PINK-01 to the X-ray free electron laser (XFEL) facility SACLA. At SACLA **BL3**, we carried out the first X-ray diffraction (XRD) experiment at 77 T with XFEL, PINK-01, and a sample of perovskite manganite, $Bi_{0.5}Ca_{0.5}MnO_3$ (BCMO), that shows the charge-ordered phase.

As shown in Figs. 3(a-c), we were successful in observing the lattice changes in the sample of BCMO

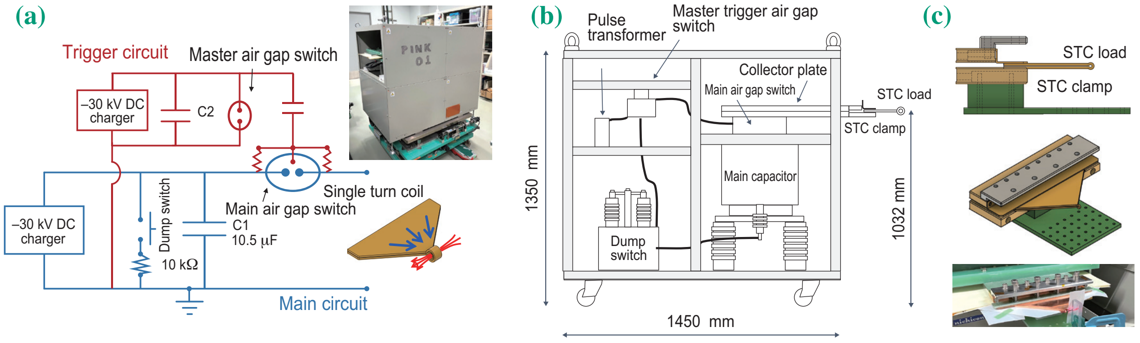

Fig. 1. **(a)** Electric circuit, **(b)** side view of the discharge unit, and **(c)** views of the single-turn coil clamps of PINK-01.

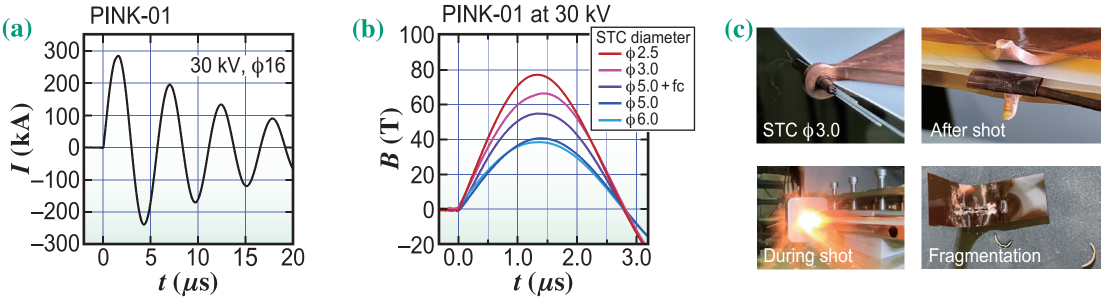

Fig. 2. Waveforms of **(a)** discharged current and **(b)** generated magnetic fields, and **(c)** views of the single-turn coil before, during, and after discharge, obtained using PINK-01.

by using X-rays. The lattice change is considered to be due to the magnetic-field-induced melting of the charge-ordered phase. The result is evidence that we are now capable of the microscopic measurement of materials at high magnetic fields of 77 T, which opens a door to a new era of material science at ultrahigh magnetic fields with microscopic measurements.

As future directions, we are now working on two things. One is the development of a low-temperature environment by means of a small original handmade He flow cryostat to realize XFEL experiments at low temperatures and high magnetic fields. The cryostat must be as small as ϕ4.0 mm including the vacuum shield. The other is the development of PINK-02 with the aim of generating magnetic fields of 100 T and beyond. Armed with such equipment, we play to attempt the structural analysis of the θ phase of solid oxygen, the spin-state crystallization of spin crossover cobaltites, and the valence-induced structural transition of Eu compounds, for starters. As a further goal, we hope to expand our targets to chemistry, biology, plasmas, and quantum vacuums.

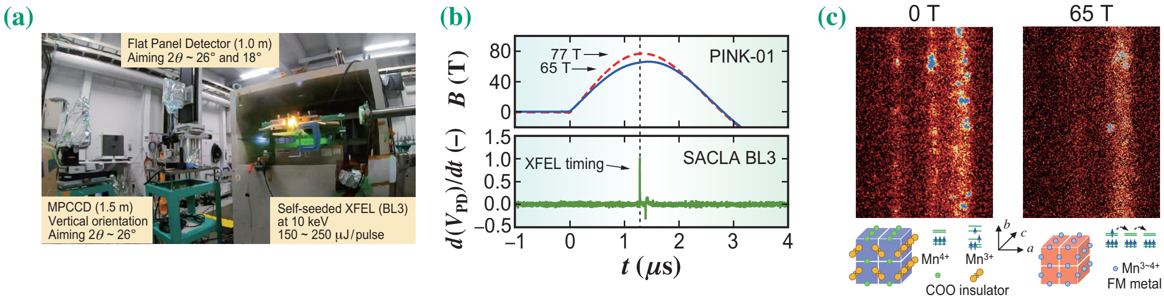

Fig. 3. **(a)** Photograph of PINK-01 in experimental hutch 2 at SACLA BL03 during the simultaneous discharge of magnetic field and XFEL pulses. A flat panel detector and an MPCCD are used as detectors. **(b)** The magnetic field and XFEL timing are well synchronized. **(c)** Part of the Debye-Scherrer rings from BCMO before and during the magnetic field pulse up to 65 T. The marked lattice change is apparent.

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