pulse results in fast Fermi-level bending due to carrier accumulation in the depletion layer. We revealed this mechanism by temperature-dependent pump-probe measurements with picosecond time resolution (*20*). As shown in Figure 4B, the radiation was produced from a bulk highly oriented pyrolytic graphite (HOPG) excited by femtosecond laser pulses at 800 nm. By varying the incident angle of the pumping laser and applying an external bias, it was confirmed that the photocarriers driven by the built-in field within the first few carbon atomic layers were responsible for the THz generation (*21*).

The THz vibrational modes in biomolecules are very sensitive to molecular configuration and conformation. We used THz-TDS measurements to investigate the absorption and dispersion of polycrystalline α- and γ-glycine in the spectral region of 0.5 THz–3.0 THz (*22*). On the other hand, biomolecular reactions in a physiological condition are very important in many biological and medical studies, but quite difficult to detect. After overcoming the issue of water absorption using our highly sensitive THz-TDS system, we successfully observed the molecular reactions in aqueous solutions of anticancer drug oxaliplatin with λ-DNA and M-DNA extracted from mouse liver. As shown in Figure 4C, the half-life of the reaction was about 4.0 h for λ-DNA and 12.9 h for M-DNA, which can be attributed to their differences in strand length, composition, and sequence of nucleic acids (*23*).

References

1. B. Y. Cheng *et al.*, *Acta Phys. Sin.* 3, 861 (1994).
2. J. X. Fu, R. J. Liu, Z. Y. Li, *Appl. Phys. Lett.* **97**, 041112 (2010).
3. L. Lu, Z. Wang, arXiv:1611.01998.
4. L. Lu, J. D. Joannopoulos, M. Soljačić, *Nat. Phys.* **12**, 626–629 (2016).
5. Q. H. Yan *et al.*, *Nat. Phys.* (2016), www.nature.com/articles/s41567-017-0041-4.
6. S. Cao *et al.*, *Sci. Rep.* **5**, 8041 (2015).
7. S. Cao *et al.*, *Nano Res.* **9**, 306–316 (2016).
8. J. Tang, W. Geng, X. Xu, *Sci. Rep.* **5**, 9252 (2015).
9. Y. Sun *et al.*, *ACS Photonics* **4**, 369–377 (2017).
10. Y. Zhao *et al.*, *Opt. Express* **23**, 9211–9220 (2015).
11. K. J. Jin *et al.*, *Adv. Mater.* **21**, 4636–4640 (2009).
12. Y. Q. Feng *et al.*, *Sci. Rep.* **6**, 22382 (2016).
13. K. J. Jin *et al.*, *Phys. Rev. B* **71**, 184428 (2005).
14. A. Q. Jiang *et al.*, *Adv. Mater.* **23**, 1277–1281 (2011).
15. C. Wang *et al.*, *Appl. Phys. Lett.* **98**, 192901 (2011).
16. C. Ge *et al.*, *ACS Appl. Mater. Interfaces* **8**, 34590 (2016).
17. K. J. Jin *et al.*, *Appl. Phys. Lett.* **91**, 081906 (2007).
18. J. Xing *et al.*, *Opt. Lett.* **34**, 1675–1677 (2009).
19. L. Wang, in *Encyclopedia of Modern Optics*, vol. 5, G. Steel, B. D. Guenther, Eds. (Elsevier, New York, 2004), pp. 163–168.
20. Y. L. Shi *et al.*, *Appl. Phys. Lett.* **88**, 161109 (2006).
21. T. Ye *et al.*, *Sci. Rep.* **6**, 22798 (2016).
22. Y. L. Shi, L. Wang, *J. Phys. D* **38**, 3741–3745 (2005).
23. X. J. Wu *et al.*, *Ap pl. Phys. Lett.* **101**, 033704 (2012).

Ultrafast intense laser technology and physics

Yutong Li, Zhiyi Wei*, Bingbing Wang, and Jie Zhang*

The pursuit of ultrashort laser pulses and ultraintense laser power has attracted interest from a wide range of disciplines since the creation of lasers. The invention of chirped pulse amplification (CPA) technology and the discovery of Kerr-lens mode locking (KLM) for the titanium (Ti) sapphire laser in 1985 and 1991, respectively, have enabled us to generate ultrahigh intensity laser pulses at tabletop scale. With remarkable progress in recent years, peak power up to several petawatts (PW) has been reported, and pulse durations of shorter than 50 attoseconds have been demonstrated, which not only provide unprecedented extreme conditions for exploring emerging physics and phenomena, but also open a new era for revealing the ultrafast dynamics of electrons. Since the National Research Institute of Physics, Academia Sinica, was founded in 1928, optics has been studied as one of the main disciplines, and considerable achievements in laser science and technology have been made in the past 90 years. Inheriting these developments and innovations in optical physics,the Institute of Physics (IOP), Chinese Academy of Sciences, has been working toward ultrafast lasers and intense laser–matter interactions since 1997. Until now, only carrier-envelope phase (CEP)-controlled few-cycle lasers have been capable of realizing low-noise frequency comb generation and attosecond laser pulses; however, intense laser power—up to 1.16 PW—has now been generated from the in-house Ti-sapphire laser facility [XL-III (eXtreme Light)]. These laser systems have provided an experimental platform for research on laser-driven particle acceleration, novel laser-driven X-ray and THz radiation sources, laboratory astrophysics, fundamental physical processes relevant to advanced nuclear fusion concepts, long-distance propagation of femtosecond (fs) laser pulses in air (*1, 2*), and ultrarelativistic laser–matter interactions. Below, we briefly review some previously published results.

CEP control of few-cycle femtosecond lasers

It has been challenging work generating the shortest laser pulse. By using chirped mirrors to compensate for dispersion, we have generated 6-fs pulses from an in-house Ti-sapphire laser oscillator (*3*). An ultrabroad saddle-shaped spectrum was designed to enable superior results in CEP measurements, based on the difference fre-

Key Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences/Beijing National Laboratory for Condensed Matter Physics, Beijing, China
*Corresponding authors: zywei@iphy.ac.cn (Z.W.), jzhang@iphy.ac.cn (J.Z.)

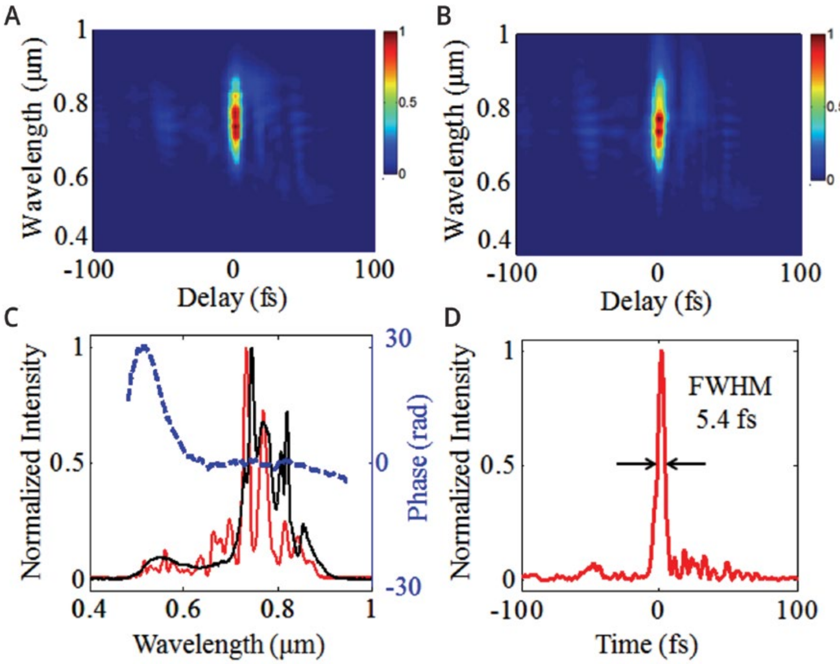

FIGURE 1. Frequency-resolved optical gating (FROG) characterization of a 5.4-fs pulse compressed from the supercontinuum.

quency generation (DFG) scheme—CEP frequencies with signal-to-noise ratios of up to 58 dB have been obtained. By locking the CEP and laser repetition rate to a microwave reference, we established an optical frequency comb with low noise (*4*).

The development of CPA technology has also attracted wide interest for its ability to compress intense laser pulses to a few cycles and stably lock the CEP. For this purpose, we injected a 30-fs laser pulse from a CPA Ti-sapphire laser (Femtopower Pro) into a hollow fiber to broaden the spectrum. Following a set of chirped mirrors that compensate for the dispersions, laser pulses as short as 3.8 fs with 0.5 mJ of energy were generated at a repetition rate of 1 kHz, corresponding to about 1.5 optical cycles. More recently, we replaced the hollow fiber with a set of thin silica plates to broaden the spectrum—transmittance of up to 85% was demonstrated in comparison with the 50% transmittance in the hollow fiber scheme—and the laser pulses were compressed to 5.4 fs with 0.68 mJ of energy, corresponding to a peak power higher than 0.1 terawatts (TW) (*5*). Figure 1 shows frequency-resolved optical gating (FROG) traces that characterize the pulse. The CEP could be continuously locked within a 75.2-mrad root mean square (RMS) for many hours.

Generation of isolated attosecond laser pulses

With the intense femtosecond laser–gas interaction, high-order harmonic generation (HHG) occurs on the attosecond timescale in the extreme ultraviolet (XUV) range. Since the first measurement of attosecond laser pulses by Drescher *et al*. (*6*), numerous studies on attosecond physics have been performed throughout the world. To generate isolated attosecond laser pulses for applications in condensed matter physics, we used the aforementioned CEP-controlled 5-fs CPA laser to induce interactions with noble gases, such as neon (Ne) and argon (Ar)—HHG events with discrete and continuous distributions were measured. By accurately controlling the CEP of the driving laser, we observed the arrowlike HHG spectrum—corresponding to the long and short trajectories of the ionized electrons (Figure 2)—for the first time; the contribution to HHG spectra can be easily recognized, which agrees well with the full quantum explanation (*7*).

To further measure the pulse duration of the HHG, we recorded the photoelectron energy spectrum with a time-of-flight detector. By scanning the delay between the attosecond XUV and femtosecond infrared (IR) pulses, the fringe-resolved streaking spectrogram was obtained, as shown in Figure 3. The pulse duration and phase can be retrieved from the spectrogram by FROG for complete reconstruction of attosecond bursts (FROG-CRAB), which showed attosecond laser pulses as short as 160 as, centered at a photon energy of 82 eV (*8*).

Amplification of the femtosecond laser to 1.16 PW with a high contrast ratio

To generate femtosecond laser pulses for even higher-energy laser–matter interactions, we developed a series of Ti-sapphire lasers with improved regenerative and multipass schemes based on CPA technology. For laser–matter interaction experiments at petawatt level, a contrast ratio of higher than 10^{10} in the temporal domain is required, to avoid preplasma formation before the arrival of the main pulse. Defined as the ratio of main laser intensity to background intensity, the contrast has been greatly enhanced by 5 or 6 orders of magnitude with some novel techniques. To generate ultraintense femtosecond laser pulses with high contrast from our XL-III facility, we proposed a new scheme that combines a doubled CPA system and a femtosecond noncollinear optical-parametric amplifier (NOPA)—its schematic diagram is shown in Figure 4; a sub-10 fs in-house Ti-sapphire oscillator was used as the seeding source. After amplification by a two-stage NOPA, which was pumped by the laser pulse from the CPA I, a 26-μJ signal with a contrast ratio of 10^{10} was obtained at a central wavelength of 800 nm. Seeding the high contrast signal into the CPA II and suppressing the parasitic lasing with a special liquid material surrounding the Ti-sapphire crystal, a 32.3-J laser pulse with a duration of 27.9 fs—corresponding to a peak power of 1.16 PW—was measured using a commercial FROG device (*9*). To our knowledge, this is the first laser pulse of larger than 1 PW from a Ti-sapphire laser facility.

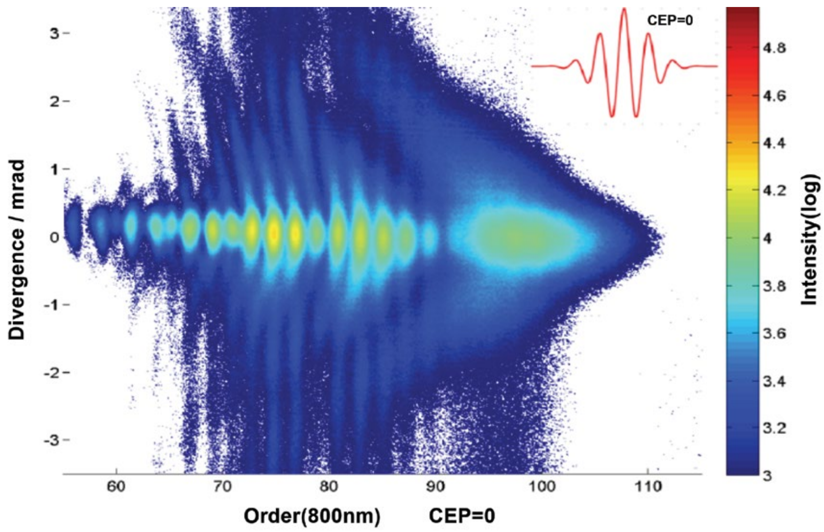

FIGURE 2. Arrowlike high-order harmonic generation (HHG) spectrum.

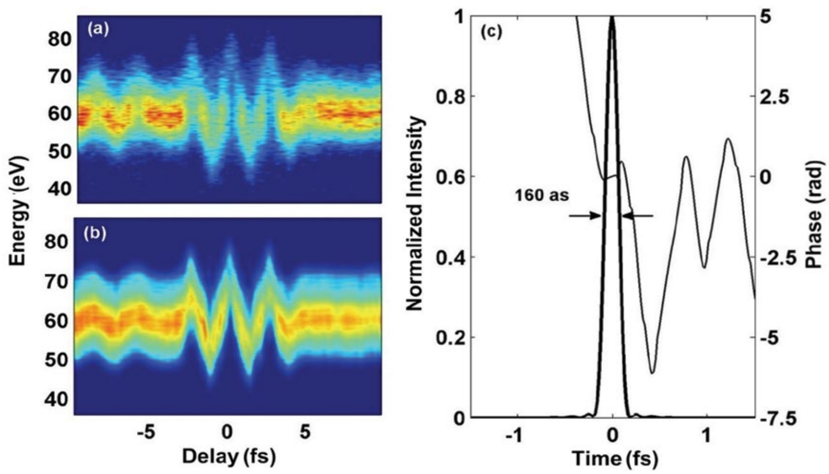

FIGURE 3. Fringe-resolved streaking spectrogram.

Generation and transport of intense laser–produced energetic (fast) electrons

The generation and transport of fast electrons are fundamental physical processes that are important for applications such as fast ignition (FI) of inertial confined fusion. We have comprehensively studied the physics of fast electrons within laser durations ranging from femtoseconds to picoseconds, and intensities ranging from 10^{16} W/cm^2 to 10^{20} W/cm^2. We demonstrated a stable, collimated fast electron beam along the target surface in intense laser interactions with planar solid foils at large incident angles (Figure 5)—the confinement being due to the surface quasistatic electromagnetic fields (*10*). The effects of laser polarization on emission direction of fast electrons from solid targets have been identified (*11*). For the first time, we observed the directional emission of fast electrons from water plasma (*12*). A two-dimensional Fokker–Planck code was developed, and we found that the well-known Spitzer–Harm model is no longer held under field strength, which prompted us to propose a new theoretical model (*13*). We have demonstrated bulk ion acceleration in low-density foam targets with the electrostatic fields induced by the fast electron transport among the multiple lamellae inside the foam (*14*). A key issue with the FI scheme is enhancing the heating efficiency of high-intensity lasers; for this purpose, we proposed a magnetically assisted FI scheme (*15*), which could enhance efficiency by up to 14% with an external magnetic field of 20 megagauss (MG).

Laser-driven novel radiation sources

Hard X-ray sources based on femtosecond laser–driven plasmas have numerous interesting applications owing to their ultrashort duration and small sizes. Using high-contrast laser–cluster target interactions, we have generated quasi-monoenergetic hard X-ray radiation with a peak brightness of 10^{21} photons/(s mm^2 mrad^2). We further proposed a new oscillation injection scheme and obtained a high yield of 5×10^8 photons with a peak brilliance of 10^{23} photons/(s mm^2 mrad^2)/[0.1% bandwidth (BW)] in a corresponding experiment (*16, 17*). In view of the big challenge of intense THz radiation generation, we have extended plasma radiation to the THz regime; THz sources stronger than hundreds of μJ were generated with intense lasers. A linear mode conversion mechanism was proposed, and it was demonstrated through picosecond laser interactions with large-scale inhomogeneous plasmas (*18, 19*). In addition, we demonstrated coherent THz radiation from a foil due to transition radiation of the laser-produced electron beams (Figure 6); the THz radiation energy (of up to 400 μJ) is comparable to that from linear accelerators (*20*).

Laboratory astrophysics

The extreme conditions created by high-power lasers

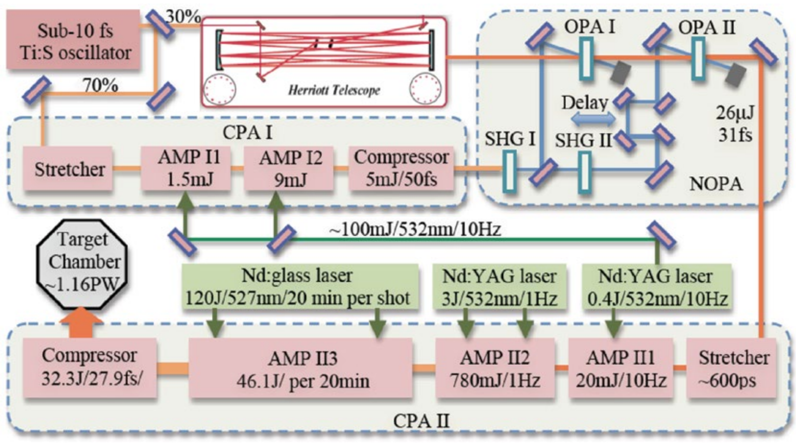

FIGURE 4. Schematic setup of the XL-III (eXtreme Light) facility. AMP, amplifier; CPA, chirped pulse amplifier; OPA, optical parametric amplifier; SHG, second harmonic generation.

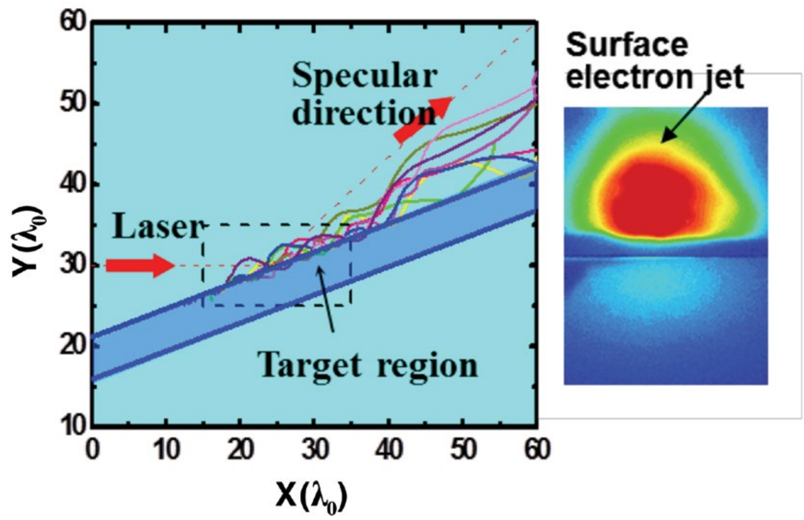

FIGURE 5. Fast electron beam emission along the surface of a target irradiated by intense laser pulses.

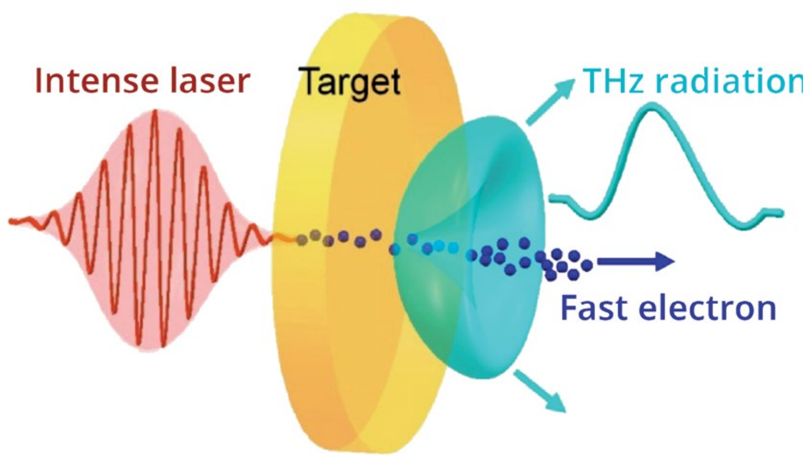

FIGURE 6. Schematic diagram illustrating THz generation via coherent transition radiation from the rear surface of a foil target.

can be used to simulate astronomical phenomena and processes. Magnetic reconnection (MR) is important in many astrophysical phenomena, such as solar flares. We reconstructed MR outflows and the loop-top X-ray source in solar flares at the laboratory. The electron-diffusion regions (EDR) in MR were resolved, and electron acceleration was observed (*21, 22*). Collisionless shock waves, responsible for the generation of high-energy cosmic rays, were demonstrated with two counterstreaming laser-produced plasmas (*23*). By heating a simple open-ended coil with a high-power laser, a 200-T pulsed strong magnetic field was generated (*24*). Herbig–Haro (HH) objects associated with newly born stars are of great interest in astrophysics. We generated a laser-produced supersonic jet deflected by 55 degrees when colliding with a nearby orthogonal side flow, which well represented the jet deflection in the HH object (*25*).

Strong-field atomic and molecular physics

We revealed the effect of a static electric field on HHG in research on strong-field atomic and molecular physics in 1998 (*26*). Since then, we have focused on the dynamic processes of intense laser–matter interaction, including the excitation, ionization, and emission of atoms and molecules in intense laser fields. We have been long-engaged in developing the frequency-domain theory of the recollision processes in intense laser fields. In contrast with conventional time-domain theory, there are many advantages offered by frequency-domain theory. For example, all dynamic processes can be decoupled into two steps: (1) above threshold ionization (ATI) and (2) laser-assisted collision (LAC) or laser-assisted recombination (LAR), so that one can investigate separately the roles of these subprocesses; additionally, all recollision processes—including HHG, high-order ATI (HATI), and nonsequential double ionization (NSDI) (*27*)—can be solved under a unified theoretical frame, where the relationships among all these processes can be conveniently studied. Progress has also been made on numerical approaches for solving the time-dependent Schrodinger equation based on the Hylleraas and B-spline methods. For the first time, we found the CEP effect in the laser-driven atomic bound–bound transition for a long laser pulse containing tens of laser cycles (*28*).

Perspectives

Studies of ultrashort intense laser–matter interactions have been performed worldwide during the past decades. In the future, we will concentrate on demonstrating some important applications for laser-driven radiation sources. The Synergetic Extreme Condition User Facility (SECUF) will be built in five years in Beijing; there we will build ultrafast radiation and electron beamlines for studying the dynamics of many disciplines, including condensed matter, biology, and chemistry.

References

1. T. T. Xi, X. Lu, J. Zhang, *Phys. Rev. Lett.* **96**, 025003 (2006).
2. X. Lu *et al.*, *Sci. Rep.* **5**, 15515 (2015).
3. Y. Y. Zhao, P. Wang, W. Zhang, J. R. Tian, Z. Y. Wei, *Sci. China Ser. G* **50**, 261–266 (2007).
4. W. Zhang, H. Han, Y. Zhao, Q. Du, Z. Wei, *Opt. Express* **17**, 6059–6067 (2009).
5. P. He *et al.*, *Opt. Lett*. **42**, 474–477 (2017).
6. M. Drescher *et al.*, *Science* **291**, 1923–1927 (2001).
7. P. Ye *et al.*, *Phys. Rev. Lett.* **113**, 073601 (2014).
8. M. J. Zhan *et al.*, *Chin. Phys. Lett.* **30**, 093201 (2013).
9. Z. Wang *et al.*, *Opt. Lett.* **36**, 3194–3196 (2011).
10. Y. T. Li *et al.*, *Phys. Rev. Lett.* **96**, 165003 (2006).
11. L. M. Chen *et al.*, *Phys. Rev. Lett.* **87**, 225001 (2001).
12. Y. T. Li *et al.*, *Phys. Rev. Lett.* **90**, 165002 (2003).
13. S. M. Weng *et al.*, *Phys. Rev. Lett.* **100**, 185001 (2008).
14. Y. T. Li *et al.*, *Phys. Rev. E* **72**, 066404 (2005).
15. W. M. Wang, P. Gibbon, Z. M. Sheng, Y. T. Li, *Phys. Rev. Lett.* **114**, 015001 (2015).
16. L. M. Chen *et al.*, *Phys. Rev. Lett.* **104**, 215004 (2010).
17. W. Yan *et al.*, *Proc. Nat. Acad. Sci. U.S.A.* **111**, 5825–5830 (2014).
18. Z. M. Sheng, K. Mima, J. Zhang, H. Sanuki, *Phys. Rev. Lett.* **94**, 095003 (2005).
19. G. Q. Liao *et al.*, *Phys. Rev. Lett.* **114**, 255001 (2015).
20. G. Q. Liao *et al.*, *Phys. Rev. Lett.* **116**, 205003 (2016).
21. J. Zhong *et al.*, *Nat. Phys.* **6**, 984–987 (2010).
22. Q. L. Dong *et al.*, *Phys. Rev. Lett.* **108**, 215001 (2012).
23. X. Liu *et al.*, *New J. Phys.* **13**, 093001 (2011).
24. B. J. Zhu *et al.*, *Appl. Phys. Lett.* **107**, 261903 (2015).
25. D. Yuan *et al.*, *Astrophys. J.* **815**, 46 (2015).
26. B. Wang, X. Li, P. Fu, *J. Phys. B* **31**, 1961–1972 (1998).
27. B. Wang, Y. Guo, J. Chen, Z. C. Yan, P. Fu, *Phys. Rev. A* **85**, 023402 (2012).

Research on magnetism and magnetic materials

Young Sun*, Fangwei Wang, Xiufeng Han, Zhaohua Cheng, Fengxia Hu, Wenhong Wang, Jianwang Cai, and Baogen Shen

The Institute of Physics (IOP) has a long history of research on magnetism and magnetic materials, beginning in 1934, when Ruwei Shi began studying magnetism at the Institute of Physics of the Academia Sinica. In 1950, a magnetism research group was established within the Institute of Applied Physics at the Chinese Academy of Sciences (CAS). This group was expanded to form a magnetism laboratory in 1959, and later developed into the CAS Open Laboratory of Magnetism in 1987. Finally, it became the State Key Laboratory of Magnetism (SKLM) in 1995. Historically, the magnetism laboratory at IOP has been regarded as the national center for magnetism studies. It has educated many young researchers who later found staff and faculty positions at various universities and institutions around China. At present, SKLM consists of seven research groups (M01–M07) that cover diverse research topics ranging from traditional magnetic materials to frontiers in modern magnetism (Figure 1).

Magnetic functional materials

Since the 1960s, the exploration of advanced rare-earth permanent magnets has had a traditional research direction. The magnetism laboratory has been accumulating data on permanent magnets for many years, achieving fruitful results in this field, including the successful fabrication of new melt-spun Nd-Fe-B permanent magnets with a single-phase hard magnetic behavior, the first synthesis of $Sm_2(Fe,Ga)_{17}C_y/\alpha$-Fe nanocomposites, and the confirmation of the origin of enhanced remanence in $Sm_2Fe_{17-x}M_xC_y$ nanopermanent magnets. The discovery of SmFeGaC permanent magnets is believed to have opened a new research direction for permanent magnets. Related works have won the first prize for Science and Technology in Beijing, and the second prize for Natural Sciences at the Chinese Academy of Sciences. In 1985, some faculty members of the magnetism laboratory founded the Beijing Zhong Ke San Huan Hi-Tech Company, based on previous achievements in the field of permanent magnets. After more than 30 years of rapid development, it is now among the top three permanent magnet companies in the world.

The refrigeration technique based on the magnetocaloric effect (MCE) has obvious advantages over the conventional gas-compression technique in

State Key Laboratory of Magnetism, Institute of Physics, Chinese Academy of Sciences
*Corresponding author: youngsun@iphy.ac.cn