Infrared Microspectroscopy Beamline BL06B at SSRF

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Abstract

The infrared microspectroscopy beamline (BL06B) is a phase II beamline project at the Shanghai Synchrotron Radiation Facility (SSRF). The construction and optical alignment of BL06B were completed by the end of 2020. By 2021, it became accessible to users. The synchrotron radiation infrared (SRIR) source included edge radiation (ER) and bending-magnet radiation (BMR). The extracted angles in the horizontal and vertical directions were 40 and 20 mrad, respectively. The photon flux, spectral resolution, and focused spot size were measured at the BL06B end station, and the experimental results were consistent with theoretical calculations. SRIR light has a small divergence angle, high brightness, and a wide wavelength range. As a source of IR microscopy, it can easily focus on a diffraction-limited spatial resolution with a high signal-to-noise ratio (SNR). The BL06B end station can be applied in a wide range of research fields, including materials, chemistry, biology, geophysics, and pharmacology.

Full Text

Preamble

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Abstract: The infrared microspectroscopy beamline (BL06B) is a phase II beamline project at the Shanghai Synchrotron Radiation Facility (SSRF). Construction and optical alignment of BL06B were completed by the end of 2020, and it became accessible to users in 2021. The synchrotron radiation infrared

(SRIR) source comprises edge radiation (ER) and bending-magnet radiation (BMR), with extracted angles of 40 mrad in the horizontal direction and 20 mrad in the vertical direction. Photon flux, spectral resolution, and focused spot size were measured at the BL06B endstation, with experimental results consistent with theoretical calculations. SRIR light features a small divergence angle, high brightness, and broad wavelength range. As a source for IR microscopy, it can readily achieve diffraction-limited spatial resolution with high signal-to-noise ratio (SNR). The BL06B endstation supports research across diverse fields including materials science, chemistry, biology, geophysics, and pharmacology.

Keywords: Synchrotron radiation, Infrared beamline, Infrared microspectroscopy

1. Introduction

IR spectroscopy is a powerful analytical technique because numerous characteristic absorption bands in the IR region correspond to molecular structures, enabling broad applications across many fields. Synchrotron radiation infrared (SRIR) sources are 100–1000 times brighter than conventional sources and offer advantages such as small divergence angle, high collimation, and wide wavelength range [1,2]. When SRIR serves as the source for an IR microscope, the spatial resolution approaches the optical diffraction limit, allowing observation of sample fine structures at the micron scale. Recently, advanced SRIR sources and detectors have created new experimental opportunities and widespread applications for scientists [3-13].

Over the past two decades, numerous SRIR beamlines have been constructed at third-generation synchrotron radiation facilities worldwide [14-17]. The Shanghai Synchrotron Radiation Facility (SSRF) is a third-generation light source operating at 3.5 GeV with a beam current of 240 mA, covering a spectral range from far-infrared to hard X-ray regions [18,19]. Currently, more than 20 beamlines are operational at SSRF. The Dynamic Line (D-line) of the Shanghai Light Source is a phase II beamline project comprising two beamlines and three experimental endstations. One beamline is the IR beamline BL06B based on a bending magnet source, while the other is the energy-dispersive X-ray absorption spectroscopy (ED-XAS) beamline BL05U based on an undulator source. The overall goal of the D-line is to couple X-ray and IR light at the same point on the experimental sample, enabling simultaneous detection of dynamic processes in molecular, atomic, and electronic structures. ED-XAS and IR spectroscopy provide complementary methods for examining different energy-level structures of samples. In addition to combined experiments, the two endstations can also conduct independent studies.

The IR beamline BL06B is a branch of the D-line. Construction was completed by the end of 2020, and commissioning and user access began in 2021. The BL06B experimental endstation is optimized for mid-infrared and far-infrared regions, equipped with a Fourier transform infrared (FTIR) spectrometer, IR microscope, and scanning near-field optical microscope (SNOM). The spatial resolution of SRIR microscopy approaches the theoretical diffraction limit, enabling detection of fine structures in the micron region. With IR SNOM, spatial resolution is determined by the curvature radius of the AFM tip, achieving better than 50 nm. Furthermore, the IR endstation supports applications across materials science, chemistry, biology, geophysics, pharmacology, and cultural heritage research.

This study introduces the optical layout and endstation of the IR beamline BL06B at SSRF, presents the experimental equipment and methods, and describes commissioning results including photon flux, spectral resolution, focused spot size, and initial user achievements.

2.1 Light source

SSRF is a third-generation synchrotron radiation source with an energy of 3.5 GeV and maximum current of 300 mA. In recent years, top-up mode operation has provided users with a stable beam current of 240 mA. The IR branch of the D-line is located at BL06B of SSRF. SSRF advantages include low emittance and excellent electron beam stability. However, bending magnet extraction ports limit the vertical extraction angle. Edge radiation (ER) is concentrated closer to the beamline axis and exhibits less brightness degradation from spherical aberrations and additional aperture restrictions, making ER advantageous as a bright SRIR source [20]. Both ER and bending-magnet radiation (BMR) are extracted from the storage ring as IR sources for BL06B, with an extracted solid angle of 40 mrad (−15 to 25 mrad) in the horizontal direction and 20 mrad (−10 to 10 mrad) in the vertical direction.

2.2 Extraction mirror M1

The first plane mirror, M1 (extraction mirror), is located 1.806 m from the light source and reflects the infrared beam. High-energy photons emitted from the source are absorbed by M1, creating an excessively high thermal load from intense X-ray and UV radiation. The total thermal load reaches 3000 W, with a maximum power density of 205 W/mm^2 at the mirror surface. Without treatment, the extraction mirror would heat to very high temperatures and suffer significant distortion. This heat load can be removed by cutting a slot in extraction mirror M1 while only slightly affecting infrared photon flux. A 3.0 mm slot provides an appropriate size, with detailed descriptions and calculations provided in Reference 1.

M1 dimensions are 140 mm × 70 mm × 20 mm (L×W×H), with a slot length of 110 mm. The mirror substrate is Glidcop coated with a ~200-nm aluminum layer. A photon mask is placed in front of M1, and the mirror is indirectly water-cooled.

2.3 Beamline optics

An optical schematic of the IR beamline BL06B layout is shown in Fig. 1 [Figure 1: see original paper]. The beamline includes 17 mirrors and slits, CVD diamond windows, beam position monitors (BPM), and other equipment. Detailed mirror parameters are listed in Table 1 . Optical alignment of the IR beamline is challenging due to its complex optical path.

Fig. 1 Optical layout of the SRIR beamline BL06B at SSRF.

The M1 plane mirror is located 1.806 m from the light source and features a central 3.0 mm-wide slot to avoid overheating from intense X-rays and UV light. After horizontal reflection by the extraction mirror, the IR beam is deflected by 90° and incident on the second plane mirror, M2, via the radiation protection wall. The distance between M2 and M1 is approximately 2.2 m. The IR beam reflected by M2 is redirected from a horizontal 90° angle to a vertical orientation before striking the first toroidal mirror, T1. T1 focuses the IR beam onto the CVD diamond window, which is wedge-shaped to prevent multiple reflections. The window exhibits transparency in the infrared region with an effective diameter of 22 mm, effectively separating the ultra-high vacuum (UHV) section of the beamline from the downstream high vacuum (HV) section.

Toroidal mirror T2, placed behind the CVD diamond window with the same parameters as T1, corrects the aberration of T1. T1 has a compression ratio (object distance to image distance ratio) of 2.4, compressing the far-IR spot size on the CVD diamond window and improving far-IR transmission efficiency. This reduces IR intensity loss due to the effective size limitation of the diamond window.

An adjustable slit at the T2 focal point limits beam size and blocks stray light. The slit adjustment range is 0–50 mm with submillimeter accuracy. The front surface of the slit blade can serve as a visible-light target, and a CCD camera can observe the position and shape of the T2 focused spot.

Plane mirror M4 is a switching mirror that controls the IR beam direction. When inserted into the optical path, M4 reflects the IR beam to plane mirror M5b. A pair of toroidal mirrors, T3b and T4b, shape a square spot. The IR beam is focused and reflected by an optical matching system comprising M7b, T5b, and M8b, finally incident on the FTIR spectrometer of the combined endstation BL05U.

When M4 is removed, the IR beam enters the IR experimental endstation BL06B. Plane mirror M6a selects whether the IR beam enters the FTIR spectrometer or SNOM. T3a and T4a are off-axis parabolic mirrors. The IR beam is collimated by T3a and incident onto the SNOM system, or focused by T4a and incident onto the FTIR spectrometer of the BL06B endstation.

Table 1 Parameters of the mirrors Mirror Distance to source Para.

Coating Dimensions Toroidal Diamond Edge(0.5) Toroidal Toroidal Toroidal

(Rt×Rs)mm2 (L×W) mm2 3794$×18973794×1897*FocallengthFocallength*2409×26543431×2654140×70150×2
Focal length

2.4 Simulation

The photon flux of the main optical elements is calculated using SRW software, as shown in Figure 2 [Figure 2: see original paper]. The figure shows photon flux at the SRIR source, M1, diamond window, and entrance of the FTIR spectrometer. Theoretical calculations consider many factors, including dimensions of all optical components, M1 slot size, 2% loss per reflection, and 60% transmission efficiency of the CVD diamond window. Total losses along the entire IR beamline are considered, and the photon flux at the FTIR spectrometer entrance is predicted to be 3.3×10^{13} phs/s/0.1% B.W. @ 4200 cm^{-1} (2.38 m, 300 mA) via theoretical calculation. 2.38 mm 100 mm 200 mm Source Window Spectrometer Optics Fig. 2 Photon flux at different optical elements, as calculated by SRW.

3.1 Key instrument

The main equipment at the BL06B endstation is a Bruker VERTEX 80v FTIR spectrometer and Hyperion 3000 IR microscope, as shown in Fig 3 [Figure 3: see original paper]. The high-resolution FTIR spectrometer is equipped with Si, KBr, and CaF_2 beam splitters, DTGS (with KBr/PE window), MCT, InGaAs, and Si-bolometer detectors, covering a spectral range of 10–10000 cm^{-1}. Various accessories are available, including attenuated total reflection (ATR), automatic sample changer, combined transmission, and specular reflection unit (11° incidence angle). The Bruker IR microscope is equipped with 4× visible objective, 15× and 36× IR/visible objectives, grazing angle incidence IR (GIR) objective, ATR objective, diamond anvil cell, mid-infrared polarizer, and MCT detector (600–10000 cm^{-1}). The 15× IR/visible objective lens has a working distance of 24 mm, suitable for in situ experimental cells. The SRIR source's small size, high collimation, and high brightness enable easy focusing to the optical diffraction limit. The SNR of SRIR is two to three orders of magnitude higher than that of a globar source when using aperture sizes below $15\times15 m^{2}$ with the IR microscope.

The IR SNOM (Bruker nano IR3) is also installed, as shown in Figure 4 [Figure 4: see original paper], along with a QCL laser covering 908–1668 cm^{-1}. The SNOM device combined with the QCL laser operates in two modes: atomic force microscopy IR (AFM-IR) mode and SNOM mode with an MCT detector (600–10000 cm^{-1}). This technique enables nanoanalysis of samples using mid-IR spectroscopy with resolution beyond the diffraction limit [21-22]. AFM-IR spectroscopy is a powerful technique that uses an AFF tip to directly detect samples. IR absorption by the sample generates a thermal expansion effect when the IR laser is focused on the sample, causing the AFM cantilever to oscillate with amplitude proportional to the sample's IR absorption.

AFM-IR technology exhibits broad application prospects, particularly for samples with high thermal expansion coefficients such as soft materials and biological samples. The spatial resolution of experimental measurements is related to the AFM tip's radius of curvature, achieving better than 50 nm. Therefore, AFM-IR identifies chemical composition at the nanoscale and is primarily used for spectral measurements at specified positions and imaging at fixed wavenumbers.

SNOM technology has played an increasingly important role in investigating nanoscale properties and structures of various materials. The basic principle of scattering-type SNOM (s-SNOM) is that an illuminated AFM tip forms an enhanced light field that serves as a scattering source. The near field is modified by a nearby sample, yielding the sample's optical properties. The spatial resolution is better than 50 nm and independent of the incident light wavelength. Since the scattered near-field signal from the AFM tip is extremely weak, effective extraction of near-field information is a key challenge.

Fig. 3 IR spectrometer and microscope (VERTEX 80v and Hyperion 3000, Bruker)
Fig. 4 Scanning near-field optical microscope (NanoIR3, Bruker)

3.2 In-situ Accessory

Several in situ sample cells are available for the IR spectrometer and microscope: (1) Oxford low-temperature instrument: a dry, compact cryostat providing optical access to temperature-controlled samples in vacuum, with temperature variation from room temperature to 4 K. (2) High-temperature high-pressure (HTHP) cell: the sample is placed in a central sample post-heater mount, enabling measurements from room temperature to 800 °C under vacuum conditions, with pressure variation from vacuum (0.003 Torr) to 1000 psi for all in situ reaction studies. (3) HTHP Diffuse Reflectance Accessory: solid powder samples are placed in a heatable sampling cup within a controllable chamber, enabling diffuse reflectance measurements from room temperature to 800 °C and pressures from vacuum (0.001 Torr) to 500 psi. (4) Linkam Temperature Controlled stage (THMS600) for the IR microscope with a temperature range of −196 °C to 600 °C.

3.3 Experimental methods

(1) IR spectroscopy: transmission, reflection, ATR, and diffuse reflection methods obtain chemical composition and structural information of samples. (2) IR microspectroscopy: transmission, reflection, ATR, and GIR methods obtain spatial distribution and components of samples with spatial resolution approaching the optical diffraction limit. (3) Nano-IR spectroscopy and imaging: AFM-IR and SNOM technologies developed using SNOM devices combined with a QCL laser achieve experimental spatial resolution better than 50 nm in both methods.

4. First commissioning results

At the end of 2020, several performance parameters of the BL06B station were measured, including spectral range, spectral resolution, focused spot size (IR microscope), and photon flux at the spectrometer entrance.

After aligning the SRIR beamline optical path, photon flux was measured at the spectrometer entrance. The parallel SRIR beam passed through an optical filter (NB-2380-052 nm, Spectrogon Corporation) and was focused by a parabolic mirror onto a calibrated Si diode (G12183-030K, Hamamatsu, Inc.). Photocurrent was measured using a picoammeter, and photon flux was derived through a series of formulas. The measured photon flux was 3.2×10^{13} phs/s/0.1% B.W @ 4200 cm^{-1} for a 300 mA injection current, with measurement and calculation details provided in Reference 2. This experimental result shows excellent consistency with the theoretical prediction of 3.3×10^{13} phs/s/0.1% B.W. at 4200 cm^{-1} (300 mA) from SRW software calculations, as shown in Figure 2.

Fig. 5 [Figure 5: see original paper] Three-dimensional intensity distribution obtained using a pinhole (5 m diameter).

The focused spot size of the IR microscope was measured using a 5 m diameter pinhole, the SRIR source, and a pair of 36× objectives. An MCT detector was used in the 600–10000 cm^{-1} spectral range. Two-dimensional mapping of the SRIR spot was performed using OPUS software with the following parameters: 4 cm^{-1} spectral resolution, 16 scans, and 2 m step size in both X and Y directions. The three-dimensional intensity distribution of the SRIR beam at 1000 cm^{-1} is shown in Figure 5, with intensity distributions extracted along horizontal (H) and vertical (V) directions at 1000 cm^{-1}. The corresponding full width value is 24 m, which closely matches the theoretical optical diffraction limit of 24.4 m calculated by formula 1.22 λ / NA (NA=0.5). The SRIR beam allows more light into smaller pinholes than is possible with conventional globar sources, demonstrating the advantages of high collimation and brightness for microspectroscopy.

The IR spectrometer's spectral resolution was measured with the SRIR source introduced into the Bruker VERTEX 80v spectrometer using a KBr beam splitter and MCT detector. CO gas sealed in a gas cell served as the test sample, yielding an absorbance spectrum in the mid-infrared region with an absorption peak FWHM of 0.07 cm^{-1}.

Performance parameters of the IR beamline endstation are summarized in Table 2 . The spectral range covers 10–10000 cm^{-1} for the IR spectrometer, with spectral resolution better than 0.1 cm^{-1}. Photon flux at the spectrometer entrance is 3.2×10^{13} phs/s/0.1% B.W @ 4200 cm^{-1} @ 300 mA. For the IR microscope, the spectral range is 600–10000 cm^{-1} (detector-limited), and the focused spot diameter is ~24 m at 1000 cm^{-1} using the 36× objective, achieving diffraction-limited spatial resolution.

Table 2. Performance of the IR microspectroscopy endstation

Spectral range: 10 cm^{-1}–10000 cm^{-1} (Spectrometer), 600 cm^{-1}–10000 cm^{-1} (Microscope)
Spectral resolution: 0.1 cm^{-1}
Photon flux (spectrometer entrance): 3.2$×10^{13}$ phs/s/0.1% b.w. @ 4200 cm^{-1} @ 300 mA
Focused spot size: ~24 m @ 1000 cm^{-1} (Full Width)

5. First user achievements

SRIR microspectroscopy is a powerful technique for examining IR spectra and mapping samples with diffraction-limited spatial resolution. The BL06B endstation has been widely used across various research fields.

In chemical science, J. M. Yuan et al. established a superfast pathway for zeolite with nano-channels [23]. Adsorption configurations and diffusion processes of different long-chain alkanes in various zeolite channels were directly measured via SRIR microspectroscopy, providing direct experimental evidence for theoretical simulations. Diffusion experiments revealed that diffusion trends and pore size effects for short- and long-chain alkanes showed completely opposite results in zeolites. SRIR experiments also verified deformation differences between long-chain molecules in different pore sizes. Mingbin Gao et al. conducted in situ high-temperature transmission IR microscopic mapping [24], directly capturing the ratio of low-carbon to long-chain olefins in different zeolite topologies during methanol-to-olefin conversion via SRIR mapping. This study proposed a quantitative model of shape-selective catalysis and explained its mechanism during zeolite framework catalysis using SRIR information. Hu et al. completed an in situ high-temperature FTIR experiment [25], incorporating isolated Co-motifs into the MFI zeolite framework using pure silicon. The position, structure, and microenvironment of Co atoms were revealed through their unique catalytic effect on propane dehydrogenation (PDH). The in situ high-temperature FTIR experiment at the BL06B endstation demonstrated that the H element of the active center $\{(\ SiO)_2Co(HO{-}Si\ )_2\}$ participates in the dehydrogenation process, verifying the proposed reaction mechanism.

In materials science, Gao et al. developed silk protein ion elastomers through casting solution and high-humidity induction technology [26]. SRIR microspectroscopy characterized the silk fibroin ion elastomers, determining protein secondary structure by integrating the characteristic amide I peak of silk fibroin. After three days of high-humidity treatment, the β-sheet structure was only ~20%. This method effectively solves material hardening problems, as high-humidity treatment as a mild and controllable induction method significantly improves the tensile strength of silk protein-ion elastomers. Zhang et al. examined the structure and mechanical stability of porous MOF materials using in situ high-pressure SRIR microspectroscopy with a diamond anvil cell [27], developing MOFs with high mechanical stability for industrial applications. The source of mechanical stability in porous materials was clarified, enabling controllable synthesis of MOF materials with specific mechanical stability.

In environmental science, Zhiqiang Shi et al. studied functional group quantification analysis of aquatic green algae [28]. SRIR microspectroscopy characterized the toxic effects of Cd on Cosmarium sp. cells in vivo, conducting mapping and functional group quantification of biological macromolecules within single algal cells. Results showed that heavy metals inhibit biosynthesis of biological macromolecules such as carbohydrates, proteins, and lipids in algal cells. Correlation analysis and principal component analysis revealed good correlation between (C-OH)/Amide II and algal cell biochemical parameters, indicating that carbohydrate changes in algal cells can serve as biomarkers for heavy metal toxicity effects on single-cell microalgae.

In biomedical science, Shanshan Guo et al. used the BL06B endstation to examine SRIR spectra and component distributions of pathological tissues [29]. SRIR spectra effectively revealed lipid, protein, and nucleic acid characteristics of breast tumors and normal tissues, complementing X-ray phase-sensitive microtomography (XPCT) data and identifying tumor markers in complex biomolecules. Average infrared spectra of breast tumors at different stages showed differences in characteristic peaks of lipids, proteins, and nucleic acids, demonstrating that SRIR mapping and spectral technologies are effective tools for identifying cancerous tissues. Wang et al. measured single cells from mouse pancreatic islets using SRIR spectroscopy [30], obtaining original absorption spectra from 200 cells. Pancreatic islet cells were subdivided into five main groups with quantitatively determined proportions using PCA and other analytical methods, demonstrating that single-cell infrared spectra provide valuable complementary techniques for describing cellular heterogeneity within pancreatic islets.

6. Summary and conclusion

This study introduced the IR beamline BL06B at SSRF, described its optical layout, and presented experimental equipment and methods. Performance parameters of the BL06B endstation were measured, including focused spot size (IR microscope), spectral resolution, and photon flux at the spectrometer entrance. Results showed good agreement between measured photon flux and theoretical calculations, with the SRIR microscope achieving diffraction-limited spatial resolution. With high spatial resolution, several SRIR applications have been completed by users, and primary achievements were described. Using IR SNOM, nano-analysis of samples by mid-IR spectroscopy can be achieved with spatial resolution of tens of nanometers. The IR endstation supports application research across materials science, chemistry, biology, geophysics, and pharmacology.

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References

1. T. Ji, Y. J. Tong, H. C. Zhu et al., The status of the first infrared beamline at Shanghai Synchrotron Radiation Facility. Nucl. Instrum. Meth. A, 788, 116–121 (2015). Doi: 10.1016/j.nima.2015.03.080

2. Z. Y. Zhang, M. Chen, Y. J. Tong et al., Performance of the infrared microspectroscopy station at SSRF. Infrared. Phys. Techn. 67, 521-5250 (2014). Doi: 10.1016/j.infrared.

3. Y. D. Wang, X. L. Li, J. Hu et al, Synchrotron infrared spectral regions as signatures for foodborne bacterial typing, Nucl. Sci. Tech., 30, 25 (2019). Doi: 10.1007/s41365-019-0554-x

4. J. F. Liu, S. Wang, R. J. Yang et al., Bio-inspired graphene oxide-amino acid cross-linked framework membrane trigger high water permeance and high metal ions rejection, J. Membr. Sci., 659, 120745 (2022). Doi: 10.1016/j.memsci.2022.120745

5. Y. Wang, J. Ren, Z. C. Lv et al., Direct functionalization of natural silks through continuous force-reeling technique, Chem. Eng. J., 435, 134901 (2022). Doi: 10.1016/j.cej.2022.

6. J. Qian, X. Gao, Y. D. Wang et al., Synchrotron Infrared Microspectroscopy for Stem Cell Research, Int. J. Mol. Sci., 23, 9878 (2022). Doi: 10.3390/ijms23179878

7. W. W. Zhang, S. Yang, R. X. Peng et al., Hierarchically non-uniform structures determine the hydro-actuated bending deformation of camel hair, Cell Rep. Phys. Sci., 3, 100793 (2022). Doi: 10.1016/j.xcrp.2022.100793

8. S. S. Guo, G. X. Wei, W. Q. Chen et al., Fast and Deep Diagnosis Using Blood-Based ATR-FTIR Spectroscopy for Digestive Tract Cancers, Biomolecules, 12, 1815 (2022). Doi: 10.3390/biom12121815

9. L. L. Wang, H. Y. Du, H. C. Xu et al., Insights into phenanthrene attenuation by hydroxyl radicals from reduced iron-bearing mineral oxygenation, J. Hazard. Mater., 439, 129658 (2022). Doi: 10.1016/j.jhazmat.2022.129658

10. J. Qian, Y. D. Wang, X. L. Li et al., Hydrogel microenvironment contributes to chemical-induced differentiation of mesenchymal stem cells: single-cell infrared microspectroscopy characterization, Anal. Bioanal.

Chem., 415, 3305 (2023). Doi: 10.1007/s00216-023-04746-z

11. T. T. Zuo, M. Xie, M. L. Yan et al., In situ analysis of acupuncture protecting dopaminergic neurons from lipid peroxidative damage in mice of Parkinson's disease, Cell Proliferat., 55, e13213 (2022). Doi: 10.1111/cpr.13213

12. C. X. Huang, J. Xu, J. Li et al., Hydrogen peroxide responsive covalent cyclodextrin framework for targeted therapy of inflammatory bowel disease, Carbohyd. Polym., 285, 119252 (2022). Doi: 10.1016/j.carbpol.2022.119252

13. C. Chen, Q. Shi, M. Z. Li et al., Engineering an enthesis-like graft for rotator cuff repair: An approach to fabricate highly biomimetic scaffold capable of zone-specifically releasing stem cell differentiation inducers, Bioact. Mater., 16, 451 (2022). Doi: 10.1016/j.bioactmat.

14. I. Yousef, S. Lefrancois, T. Moreno et al., Simulation and design of an infrared beamline for SESAME (Synchrotron-light for Experimental Science and Applications in the Middle East), Nucl. Instrum. Methods Phys. Res. A, 673, 73 (2012). Doi: 10.1016/j.nima.2011.12.012

15. X. J. Zhou, H. C. Zhu, J. J. Zhong et al, New status of the infrared beamlines at SSRF, Nucl. Sci. Tech., 30, 182 (2019). Doi: 10.1007/s41365-019-0696-x

16. D. Creagh, J. Mckinlay, P. Dumas, The design of the infrared beamline at the Australian synchrotron, The design of the infrared beamline at the Australian synchrotron, Vib. Spectrosc., 41, 213 (2006). Doi: 10.1016/j.vibspec.2006.02.009

17. P. Roy, M. Rouzieres, Z. M. Qi et al., The AILES Infrared Beamline on the third generation Synchrotron Radiation Facility SOLEIL, Infrared Phys. Techn., 49, 139 (2006). Doi: 10.1016/j.infrared.2006.01.015

18. H. J. Xu, Z. T. Zhao, Current status and progresses of SSRF project, Nucl. Sci. Tech., 19, 1 (2008). Doi: 10.1016/S1001-8042(08)60013-5

19. J. H. He and Z. T. Zhao, Shanghai synchrotron radiation facility, Natl. Sci. Rew., 1, 171 (2014). Doi: 10.1093/nsr/nwt039

20. R. A. Bosch, Computed flux and brightness of infrared edge and synchrotron radiation, Nucl. Instrum. Meth. A, 454, 497 (2000). Doi: 10.1016/S0168-9002(00)00476-9

21. D. Perez-Guaita, K. Kochan, M. Batty al., Multispectral Atomic Force

Microscopy-Infrared Nano-Imaging of Malaria Infected Red Blood Cells, Anal. Chem., 90, 3140 (2018). Doi: 10.1021/acs.analchem.7b04318

22. G. B. Dai, Z. B. Yang, G. S. Geng et al., Signal detection techiniques for scattering-type scanning near-field optical microscopy, Appl. Spectrosc. Rev., 53, 806 (2018). Doi: 10.1080/

23. J. M. Yuan, M. B. Gao, Z. Q. Liu et al., Hyperloop-like diffusion of long-chainmolecules under confinement, Nat. Commun., 14, 1735 (2023). Doi: 10.1038/s41467-023-37455-3

24. M. B. Gao, H. Li, J. Y. Yu et al., Quantitative principle of shape-selective catalysis for a rational screening of zeolites for methanol-to-hydrocarbons, AIChE J., 68, e17881 (2022). Doi: 10.1002/aic.17881

25. Z. P. Hu, G. Q. Qin, J. F. Han et al., Atomic Insight into the Local Structure and Microenvironment of Isolated Co-Motifs in MFI Zeolite Frameworks for Propane Dehydrogenation, J. Am. Chem. Soc., 144, 12127 (2022). Doi: 10.1021/jacs.2c02636

26. L. T. Cao, C. Ye, H. Zhang et al., An Artificial Motion and Tactile Receptor Constructed by Hyperelastic Double Physically Cross-Linked Silk Fibroin Ionoelastomer, Adv. Funct. Mater., 33, 2301404 (2023). Doi: 10.1002/adfm.202301404

27. Z. Y. Zhang, G. X. Qin, X. M. Li et al., Enhanced Mechanical Stability and Proton Conductivity Performance from the Dense Mn(II)-Metal-Organic Framework to Porous Mn(II)−Fe(III)-Metal−Organic Framework, Inorg. Chem., 61, 15166 (2022). Doi: 10.1021/acs.inorgchem.2c02357

28. Z. Q. Shi, M. J. Guo, H. Y. Du et al., Investigation of cytotoxic cadmium in aquatic green algae by synchrotron radiation-based Fourier transform infrared spectroscopy: Role of dissolved organic matter, Total Environ., (2023). Doi: 10.1016/j.scitotenv.2023.161870

29. S. S. Guo, J. S. Xiu, L. N. Kong et al., Micro-tomographic and infrared spectral data mining for breast cancer diagnosis, Opt. Laser. Eng., 160, 107305 (2023). Doi: 10.1016/j.optlaseng.

30. Y. D. Wang, Y. Gao, X. L. Li et al., Single-cell infrared phenomics identifies cell heterogeneity of individual pancreatic islets in mouse model, Analytica Chimica Acta, 1258, 341185 (2023). Doi: 10.1016/j.aca.2023.341185

Note: Figure translations are in progress. See original paper for figures.