Development and Performance of Ultra-High Energy Resolution Dreamline Beamline at SSRF

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Abstract

The ultrahigh-energy-resolution soft X-ray beamline, "Dreamline," at the Shanghai Synchrotron Radiation Facility (SSRF), has been successfully constructed and is now fully operational for conducting angle-resolved photoemission spectroscopy (ARPES) and photoelectron emission microscopy (PEEM) experiments. Both branches of the beamline utilize a sophisticated plane-grating monochromator equipped with four variable-line-spacing gratings, enabling it to span an energy range of 20–2000 eV. The beam spot size at the ARPES endstation is H:60 m×V:30 m, while the vertical size is a crucial factor in determining the energy resolution of the beam, which is influenced by the exit slit. Notably, the energy resolution at the ARPES sample positions has been measured to be an 17.2 meV at 867.1 eV, setting a new benchmark for the highest resolution capability within this energy range among similar international facilities. Furthermore, under the 4σ opening of the white light slit, the full energy range flux of double undulator exceeds 1012 photons per second per 0.01% bandwidth (phs/s/0.01%BW) below 800 eV when selecting the appropriate grating, while the flux across the full energy range remains above 1011 phs/s/0.01%BW.

Full Text

Preamble

Development and Performance of Ultra-High Energy Resolution Dreamline Beamline at SSRF∗

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The ultrahigh-energy-resolution soft X-ray beamline, "Dreamline," at the Shanghai Synchrotron Radiation Facility (SSRF), has been successfully constructed and is now fully operational for conducting angle-resolved photoemission spectroscopy (ARPES) and photoelectron emission microscopy (PEEM) experiments. Both branches of the beamline utilize a sophisticated plane-grating monochromator equipped with four variable-line-spacing gratings, enabling it to span an energy range of 20–2000 eV. The beam spot size at the ARPES endstation is H:60μm×V:30μm, while the vertical size is a crucial factor in determining the energy resolution of the beam, which is influenced by the exit slit. Notably, the energy resolution at the ARPES sample positions has been measured to be 17.2 meV at 867.1 eV, setting a new benchmark for the highest resolution capability within this energy range among similar international facilities. Furthermore, under the 4σ opening of the white light slit, the full energy range flux of double undulator exceeds 10^{12} photons per second per 0.01% bandwidth (phs/s/0.01%BW) below 800 eV when selecting the appropriate grating, while the flux across the full energy range remains above 10^{11} phs/s/0.01%BW.

Keywords: Synchrotron radiation, Beamline, High resolution, Monochromator, SSRF

Introduction

Quantum materials, such as superconductors,[?] topological materials,[?] heavy fermion systems,[?] and magnetic materials,[?, ?] have emerged as a significant research frontier due to their exotic quantum properties and revolutionary technological potential. Understanding these materials demands multidimensional characterization, where band structure analysis—revealing the distribution and motion state of electrons—is crucial for understanding the physical properties of these materials.[?] This analysis establishes quantitative connections between microscopic electronic behavior (e.g., electron correlations, spin-orbit coupling) and macroscopic properties, including electron-pairing in superconductors,[?, ?] surface-protected topological effects,[?] magnetically ordered configurations,[?] and scintillator detector materials,[?] among others. Notably, strong correlations and competing interactions in these systems often defy conventional theoretical descriptions, necessitating experimental techniques capable of resolving subtle electronic structures with both spatial and energy precision. Photoemission spectroscopy serves as a pivotal direct experimental tool in this endeavor. It probes the electronic band structure directly in momentum space and has been central to the discovery and understanding of quantum materials, from strongly correlated states to those with nontrivial topology. Over the past two decades, dramatic improvements in resolution and its expansion into the space, time, and spin domains, combined with advances in synthesizing novel materials and applying nonthermal tuning in situ, have unlocked new dimensions for studying all quantum materials, enabling profound scientific contributions to contemporary research.[?]

Two photoelectron-based spectroscopies, angle-resolved photoemission spectroscopy (ARPES)[?] and photoemission electron microscopy (PEEM)[?] are essential tools for studying quantum materials. ARPES enables direct momentum-space visualization of band structures through high-energy/angle-resolution spectroscopy, offering unprecedented insights into Cooper pair formation mechanisms in superconductors,[?] spin polarization in spintronic materials,[?] Fermi surface topology in topological insulators,[?] and strong electron correlation in diluted semiconductors.[?] Notably, for conventional ARPES using vacuum ultraviolet (VUV) light, the escape depth of photoelectrons in solids is limited to just a few angstroms,[?] making it ideal for probing surface-dominated systems like quasi-2D materials (cuprate and iron-based high-temperature superconductors, etc.). Complementarily, PEEM integrates spectroscopic data with nanoscale imaging,[?] allowing real-time mapping of surface state dynamics and interface effects—critical for understanding spintronic materials.

While VUV-ARPES/PEEM dominate surface-sensitive studies, bulk property characterization requires deeper probing depths. Soft X-ray-based ARPES overcomes this limitation through synchrotron radiation excitation, achieving penetration depths exceeding nanometers compared to traditional VUV ARPES.[?] However, soft X-ray ARPES faces challenges in achieving high resolution, not only because of higher photon energy, but also due to reduction of beam flux and cross-section normally in this energy range compared with VUV. For example, the optimal energy resolution at the ADRESS beamline[?] is only 30 meV at 900 eV.

To meet the demand for high energy resolution in the soft X-ray region for band structure studies, a soft X-ray beamline, "Dreamline," has been designed[?] and constructed at the Shanghai Synchrotron Radiation Facility (SSRF). It operates in the 20-2000 eV energy range with a record energy resolution of 17.2 meV at 867 eV, setting a new benchmark for the highest resolution capability within this energy range among similar international facilities. Furthermore, under the 4σ opening of the white light slit, the full energy range flux of double undulator exceeds 10^{12} photons per second per 0.01% bandwidth (phs/s/0.01%BW) below 800 eV when selecting the appropriate grating, while the flux across the full energy range remains above 10^{11} phs/s/0.01%BW. The beam spot size at the ARPES endstation is H:60µm×V:30µm, while the vertical size is a crucial factor in determining the energy resolution of the beam, which is influenced by the exit slit.

The Dreamline beamline uniquely combines synchrotron advantages (with insertion device)—high brightness, wide tunability, and polarization control—with advanced real/momentum space detection systems. This state-of-the-art facility has enabled groundbreaking discoveries, including the experimental observation of Weyl fermions in TaAs,[?] three-component fermions in MoP,[?] unconventional chiral fermions in CoSi,[?] spin splitting in an antiferromagnet,[?] and several other notable user accomplishments.[?, ?] Its design has catalyzed multidisciplinary collaborations, producing several high-impact publications since commissioning in 2015.[?, ?]

II. Beamline Optical Architecture

SSRF is China's first 3rd-generation synchrotron, which boasts an electron energy of 3.5 GeV and a low emittance of 3.9 nm rad.[?] The Dreamline, developed with the aim of providing an ultra-high-resolution beamline, bridges the VUV and soft X-ray regimes (20-2000 eV) through an innovative pair of APPLE II-type elliptically polarized undulators (EPU) (where EPU148 is used for 20-300 eV and EPU58 for 200-2000 eV). This dual-source configuration ensures continuous coverage with strategic overlap (200-300 eV), enabling seamless transitions between surface-state probing (with low photon energy) and bulk property analysis capabilities (with high photon energy), based on the penetration depth study result of electrons in solids. Notably, the undulators support dynamic polarization switching among linear horizontal/vertical and left/right circular polarizations, facilitating orbital symmetry studies through selection rule analysis in the process of photoemission—critical for complex multi-orbital behavior inherent in quantum materials, such as iron-based superconductors.[?]

The optical design of the beamline has been optimized specifically for the ARPES branch, as it represents one of the most demanding experimental needs. The beamline optical layout (Fig. 1a [Figure 1: see original paper]) prioritizes high-energy resolution through minimized non-planar components upstream of the exit slit. A plane mirror (M1) with 1.2° incidence angle serves dual purposes: heat load management via integrated water cooling and harmonic suppression. The angle of incidence on M1 was carefully selected, striking a delicate balance between ensuring high reflectivity at high photon energies and filtering the power transmitted to downstream optical components. To mitigate the potential impact of the significant absorbed power, which can reach a maximum of 1500W, an integrated water-cooling system has been implemented for M1.

The primary element of the beamline is a vertically dispersing variable-line-spacing plane-grating monochromator (VLS-PGM)[?], which is also capable of achieving vertical beam focusing towards the exit slits. The VLS-PGM is equipped with four holographically ruled gratings: a low energy resolution grating (LEG), a middle energy resolution grating (MEG), a high energy resolution grating (HEG), and a very high resolution energy grating (VEG) with center grooving line densities of 400 L/mm, 800 L/mm, 1200 L/mm, and 3600 L/mm, respectively. These gratings cover overlapping energy ranges for flexible resolution-light intensity trade-offs.

A pre-mirror (M2) with dual Au/Ni coatings optimizes reflectivity across energies, while its single-axis rotation mechanism ensures precise grating alignment. For this purpose, the pre-mirror undergoes a combination of translation and rotation to ensure the grating is illuminated at the correct angle of incidence, maintaining the beam's focus at the exit slit. This simultaneous translation and rotation are efficiently achieved through a single rotation mechanism.[?] For the two distinct reflective coatings Au and Ni (arranged side-by-side), the Ni coating is used with the LEG and MEG, while the Au coating is reserved for the HEG and VEG, optimizing performance across different energy ranges.

At the downstream side of the PGM, the beamline splits into two branches for ARPES and PEEM. They operate in a time-shared mode, achieved by switching the plane mirror Mb. Two Kirkpatrick-Baez (KB) systems[?] then direct beams to ARPES and PEEM endstations (Fig. 1b). For ARPES, elliptical cylindrical mirrors M3/M4 refocus the beam vertically/horizontally after monochromatization. The PEEM branch employs parallel optics through KB mirrors M3b/M4b, maintaining spatial integrity for nanoscale imaging. All optical components incorporate active thermal stabilization to counteract thermal deformation, ensuring sub-μm beam stability critical for high-resolution measurements.

The performance of a state-of-the-art ARPES system hinges critically on energy and angular resolutions, which are directly determined by optical design and motion/thermal stability treatment. To achieve the high energy resolution goal of Dreamline, the beamline integrates several key innovations: (1) Online thermal deformation correction mitigates mirror distortions caused by high-power loads, improving energy resolution performance; (2) Hybrid focusing geometry combines vertical dispersion with horizontal refocusing capabilities, enhancing angular resolution precision; and (3) Advanced optical alignment protocols enable seamless integration of beam steering, stability control, and calibration procedures. These systematic optimizations collectively establish a new benchmark for resolving subtle electronic structures in quantum materials, as demonstrated by the beamline's experimental achievements in complex material studies.

III. Optimized Beamline for High Energy Resolution

To achieve the ultra-high resolution of the Dreamline, various aspects were considered during the design and construction of the beamline, including reducing system aberrations, correcting thermal deformation through Cff optimization of the monochromator, controlling the temperature stability of the monochromator, and minimizing monochromator vibrations.

3.1 Reducing System Aberrations to Improve Beamline Resolution

The energy resolution of the beamline is primarily determined by the following five key factors: the characteristics of the light source, the size of the exit slit, the meridional surface error of the grating, the meridional surface error of the plane mirror, and the aberrations of the entire optical system, as specifically expressed by Equation 1:

$$\Delta E_{\text{beamline}} = \sqrt{\Delta E_{\text{light}}^2 + \Delta E_{\text{pm}}^2 + \Delta E_{\text{grating}}^2 + \Delta E_{\text{slit}}^2 + \Delta E_{\text{aberration}}^2}$$

Among the factors influencing the energy resolution of the beamline, the energy broadening of the light source (ΔE_{light}) is primarily determined by intrinsic parameters such as the source emittance. The contributions from the plane mirror (ΔE_{pm}) and the monochromator grating ($\Delta E_{\text{grating}}$) depend on the surface fabrication accuracy of the optical components. Specifically, the surface error of the plane mirror is 0.2 µrad, while that of the grating ranges from 0.1 to 0.2 µrad. The energy broadening contribution from the exit slit (ΔE_{slit}) is of the same order of magnitude as that of the light source. Notably, since the aberration of the plane mirror is zero, the resolution of the entire beamline is mainly determined by the aberration characteristics of the monochromator grating. It is particularly important to emphasize that the impact of aberrations on resolution exhibits spatial dependence, with its influence significantly increasing as the beam deviates further from the center of the mirror surface.

To achieve high energy resolution in the beamline, effectively suppressing optical aberrations is crucial. In the design of the Dreamline beamline, an innovative single focusing element scheme—namely, the VLS grating of the monochromator—was adopted as the sole optical element upstream of the exit slit. By precisely optimizing the geometric parameters of the VLS grating, the system aberrations can be reduced to near-zero levels. Specifically, at a specific optimized energy point (e.g., 1000 eV), the third-order aberration coefficient (F_{30}) and the fourth-order aberration coefficient (F_{40}) can both be nullified by appropriately selecting the VLS grating parameters b_3 and b_4.[?] Although F_{30} and F_{40} are not zero at non-optimized energy points, their values remain extremely low—down to -5.60×10^{-14} and 4.2×10^{-13} respectively at 1 keV—ensuring high-resolution performance across the entire working energy range.

3.2 Thermal Deformation Correction to Improve Beamline Energy Resolution

Synchrotron radiation undulator sources are characterized by high energy density and broad spectrum properties. The upstream optical elements of the monochromator, due to absorbing a significant amount of heat, undergo thermal deformation, which severely affects the performance of the beamline. Below, we analyze how the thermal deformation, approximated as convex mirrors for M1 and M2, impacts the focusing conditions of the variable line spacing grating in the monochromator.

Since M1 is vertically mounted and the monochromator's plane mirror M2 is horizontally mounted, the thermal deformation in the meridional direction of M1 and the sagittal direction of M2 mainly affects the horizontal focusing, with no significant impact on the energy resolution. Based on theoretical simulation results,[?] the thermal deformation on the surface of the M1 plane mirror, which uses microchannel internal water cooling, can be equivalently considered as a convex mirror with a curvature radius of 2.9×10^5 m. This deformation increases the horizontal divergence angle of the light source, leading to an approximately 0.5% increase in the object distance of the KB mirror. This change can be corrected by adjusting the grazing incidence angle of the KB mirror.

Through ANSYS numerical simulations combined with SHADOW tracing analysis, it was found that the thermal deformation in the sagittal direction of M1 can be approximated as a cylindrical mirror, and its impact on energy resolution is negligible. For the monochromator's plane mirror M2, which also uses microchannel internal water cooling, the thermal deformation equivalent curvature radius is 6000 m. This deformation alters the object distance of the grating, affecting the focusing conditions at the exit slit and leading to a decrease in energy resolution. To address this issue, this study employs a VLS grating with non-parallel light incidence for vertical beam focusing, optimizing the C_{ff} value to adjust the focus point. Simulation results show that when the C_{ff} value is increased from 7 to 7.363,[?] the beamline's energy resolution significantly improves, effectively compensating for the performance degradation caused by thermal deformation. Ultimately, the optimal performance indicators for beamline spot size and resolution were achieved, with the experimental station measuring a best resolution of over 50000 at 1000 eV.

This research provides an effective solution for compensating thermal deformation in synchrotron radiation beamlines, offering significant theoretical and practical implications for enhancing beamline performance.

3.3 Impact of Temperature Fluctuations on Beamline Energy Resolution

Theoretical analysis of the effect of temperature fluctuations on monochromator performance indicates that changes in ambient temperature cause a relative height difference between the front and rear support legs of the monochromator, leading to a rotation of the entire monochromator and ultimately resulting in beam energy drift. Since the temperature change process is relatively slow, this effect primarily manifests as a systematic shift in energy values, without significantly affecting the energy resolution. The structural parameters of the Dreamline monochromator are as follows: overall height of the monochromator $H = 1.3$ m, the distance between the front and rear support legs $L = 1$ m, and the support material is stainless steel (linear thermal expansion coefficient $\alpha = 1.5 \times 10^{-5}$ K^{-1}).

When there is a temperature difference $\Delta T = 0.1$ K between the front and rear support legs, the rotation angle θ can be calculated using the following Equation 2:

$$\theta \approx \arctan(\alpha \cdot \Delta T \cdot H/L) = \arctan(1.5 \times 10^{-5} \times 0.1 \times 1.3) = 1.95 \times 10^{-6} \text{ rad}$$

This minute rotation angle will cause a change in the beam path, leading to a systematic drift in energy values. In practical operation, it is necessary to establish a temperature monitoring system and develop corresponding compensation algorithms to eliminate the interference of temperature fluctuations on experimental results.

For a 3600 L/mm VEG grating, when ambient temperature fluctuations cause a temperature difference of 0.1 K, it results in an energy drift of 35.8 meV at 1000 eV. This value exceeds the system's resolution at 1000 eV (20 meV), making it a non-negligible source of systematic error. To effectively address this issue, this study proposes a material optimization solution: replacing the stainless steel support material of the monochromator with granite, which has superior thermal stability ($\alpha = 0.3 \times 10^{-5}$ K^{-1}). Theoretical calculations after material optimization show that under the same temperature difference condition ($\Delta T = 0.1$ K), the energy drift caused by granite supports is reduced to 7.2 meV at 1000 eV, which is below the system's energy resolution and meets experimental requirements. Based on these research results, by constructing a constant-temperature enclosure to control the temperature difference between the front and rear support legs within 0.1 K, combined with an active temperature control system, the impact of temperature fluctuations on system performance is further reduced.

This optimization solution not only effectively resolves the energy drift issue but also provides important references for the thermal stability design of high-precision grating systems. Through the synergistic effect of material optimization and temperature control, the system can maintain an energy resolution better than 20 meV at 1000 eV, meeting the requirements for precision experimental measurements.

3.4 Impact of Vibration on Beamline Energy Resolution

The vibration level of the SSRF foundation is 0.2 µm (RMS). Under the most unfavorable conditions, a vertical relative displacement of 0.4 µm may occur between the front and rear support legs of the monochromator, resulting in an angular change of $\delta = 0.4$ µm / 1 m = 0.4 µrad. By analogy with the calculation method for the effect of temperature on energy drift, we systematically analyzed the relative energy drift caused by vibration, with detailed results shown in Table S1 (supporting information).

The vibration effect is most significant for the VEG grating, causing a reduction in energy resolution of approximately 10,000 at 1000 eV, while the performance changes for other types of gratings are relatively smaller. It should be noted that the above calculations are based on the most extreme estimation, assuming a maximum vertical relative displacement of 0.4 µm between the front and rear support legs of the monochromator. In reality, due to the correlation between the vibrations of the front and rear support legs, the actual vertical relative displacement should be smaller than this theoretical value. Nevertheless, to ensure optimal energy resolution, an independent foundation was designed for the monochromator system in the construction of the Dreamline beamline, effectively isolating environmental vibrations. The foundation uses granite material with a low thermal expansion coefficient, simultaneously reducing the impact of temperature fluctuations and vibrations. This improvement scheme provides reliable technical support for enhancing beamline resolution.

IV. Beamline Performance

The performance of the beamline including energy resolution, photon flux, energy range, and spot size at sample position is thoroughly evaluated with the suitable exit slit aperture.

4.1 Energy Resolution Measured by Beamline Ionization Chamber

The primary factors influencing the energy resolution within a beamline can be classified into five key components: the dimensions of the light source, the geometry of the exit slit, the meridional profile accuracy of the grating, the meridional profile precision of the plane mirror, and the overall aberrations along the optical path. Notably, the aberrations introduced by the plane mirror in a grating monochromator are negligible, with the primary source of aberrations stemming exclusively from the grating. Through meticulous calculations, it has been determined that the effect of these aberrations on the energy resolution is minimal and can therefore be disregarded.

In the realm of grating systems, the most crucial determinant of energy resolution is the size of the light source, closely followed by the influence of the exit slit (particularly in low-energy gratings, or LEGs, and medium-energy gratings, or MEGs) and the error in the grating's profile.

To precisely evaluate the beamline resolution, an ionization chamber was strategically positioned downstream of the exit slit, serving as the cornerstone for measuring the inner shell excitation spectra of standard gases, as expressed in our previous report.[?] This chamber consists of a vacuum cavity, a leak valve equipped with a gas inlet, an MCP (Microchannel Plate) detector, and a nuclear electronics system (ORTEC 584/996) which is responsible for amplifying and counting ion pulses. A key advantage of this setup is its capability to perform measurements under extremely low working pressures, thereby significantly reducing the influence of collision broadening on the results.

In our experimental endeavors, we recorded spectra at a gas pressure of 1×10^{-6} Torr, using a white slit aperture with dimensions of 400 µm × 1000 µm, and an exit slit aperture varying from 20 µm to 250 µm. The observed spectrum peak displayed a distinct Voigt profile, which is fundamentally a convolution of a Lorentzian-broadened peak, indicative of natural lifetime broadening with a linewidth of ΔL, and the beamline's instrumental resolution, modeled as a Gaussian function characterized by a width of ΔG. By using the known Lorentz broadening of the intrinsic Ne gas absorption, specifically $\Delta E_{\text{Ne-K}} = 250$ meV, as a benchmark, we were able to deduce ΔG as a reliable indicator of the beamline's energy resolution.[?]

The core excitations in gas-phase Ne near the Ne-K threshold have been investigated using MCP measurements in an ionization chamber equipped with a 3600 L/mm grating. The Ne K absorption-edge transition to the Rydberg levels $1s \rightarrow 3p$ at $hv = 867.1$ eV was observed in Figure 3a [Figure 3: see original paper], in order to characterize the energy resolution. The peak was simulated using a Voigt profile, assuming a Lorentzian linewidth of $L = 250$ meV, with a Gaussian width of $\Delta G = 80$ meV deconvolved from the beamline resolution. This yields a resolving power ($E/\Delta E$) of 10839, corresponding to an energy resolution (ΔE) of 80 meV, under the condition of an 80 µm exit slit. Figure 3b presents the $1s - 3p$ core-excitation resonances of gas-phase Ne recorded using various exit slit apertures. The theoretical value of the beamline resolution was obtained via SHADOW ray-tracing, as previously reported in our work. Unfortunately, as the exit slit size decreases, the intrinsic $1s \rightarrow 3p$ peak width approaches the value of the Lorentzian linewidth, leading to significant errors in the Voigt fitting. When the exit slit is smaller than 80 µm, an unambiguous fit of the $1s - 3p$ resonance at 867.1 eV using a Lorentzian line convolved with a Gaussian profile becomes challenging, with fitting uncertainty coming close to the profile width. Consequently, it becomes unreliable to determine the ultimate resolution as evident in Figure 3b by the further deviation of measured resolving power from theoretical prediction.

4.2 Energy Resolution by ARPES

Given the inaccuracy of the Voigt fitting method for measuring the absorption spectrum of rare gases through an ionization chamber in determining the energy resolution of the beamline in the ultra-high regime, we have opted to use an ARPES experimental station through measuring the Fermi distribution function, which subsequently allows us to accurately assess high resolution. For energy resolution purposes, the comprehensive resolution of the ARPES system can be mathematically expressed in Equation 3[**?**]:

$$\Delta E_{\text{total}} = \sqrt{\Delta E_{\text{light}}^2 + \Delta E_{\text{noise}}^2 + \Delta E_{\text{analyzer}}^2 + \Delta E_{\text{other}}^2 + \Delta E_T^2}$$

ΔE_{light} denotes the energy broadening inherent to the light source. In the case of a helium lamp, this broadening is exceptionally narrow, measuring less than 1 meV. Conversely, for synchrotron radiation light, the extent of energy broadening is predominantly governed by various factors, notably including the undulator light source and the grating. As a general rule, an increase in photon energy is accompanied by a corresponding increase in the broadening.

$\Delta E_{\text{analyzer}}$ signifies the energy resolution capability of the ARPES analyzer. This resolution is primarily influenced by three key factors: the pass energy (E_p), the width of the analyzer's slit, and its acceptance angle. As a general rule, reducing either the pass energy, the slit width, or the acceptance angle results in an enhancement of the analyzer's resolution. However, this is achieved at the cost of a decreased photocurrent intensity passing through the slit within a given time frame, ultimately leading to a weaker signal. Consequently, to optimize the signal-to-noise ratio in experiments, a delicate balance must be found between maximizing resolution and ensuring sufficient photocurrent intensity, thereby selecting a configuration that provides the best overall performance.

ΔE_{noise} represents the broadening caused by noise, which should be minimized as much as possible. For this purpose, the equipment should be properly grounded and vibrations should be reduced.

ΔE_{other} represents the broadening caused by a variety of factors, including spot jitter, spatial magnetic fields, and charge effects, all of which should be minimized as much as possible. As a practical example, maintaining various optical components at stable temperatures and pressures serves to effectively prevent spot jitter.

ΔE_T embodies the broadening effect attributable to temperature variations. In pursuit of ultra-high energy resolution, experiments are typically conducted under exceedingly low temperatures, aiming to mitigate the impact of temperature broadening and thereby enhance the precision of the measurements.

The first four factors can be collectively designated as the instrumental resolution, ΔE_{system}, of the ARPES experimental system. The total and instrumental resolutions of the actual system are characterized by measuring the characteristic width of the Fermi edge of gold or copper. In the case of the Fermi distribution function, there is no discernible peak-shaped structure, and thus the half-height width cannot be adopted as the characteristic width through a Gaussian distribution fit. Instead, the energy range corresponding to a Fermi distribution value from 0.9 to 0.1 of its maximum is typically taken as the characteristic width. Based on this definition, we have:

$$f(E_1) = \frac{1}{e^{(E_1 - E_F)/(k_B T)} + 1} = 0.9$$
$$f(E_2) = \frac{1}{e^{(E_2 - E_F)/(k_B T)} + 1} = 0.1$$

The characteristic width can be expressed in Equation 6:

$$\Delta E_{\text{fit}} = 2 \ln 9 \cdot k_B T$$

Herein, ΔE_{fit} denotes the fitted characteristic width, while k_B represents the Boltzmann constant, and T signifies the sample temperature. As clearly demonstrated by the previously mentioned equation, the characteristic width of the Fermi function exhibits a linear dependence on temperature.

By applying the Fermi distribution function to fit the Energy Distribution Curve (EDC) of the sample, we can ascertain the fitted temperature, T_{fit}. Subsequently, the aforementioned equation is applied to compute the characteristic width, ΔE_{fit}, of the Fermi distribution function, which acts as a measure of the system's total measurement resolution. To isolate the instrument resolution, the characteristic width is then adjusted by subtracting the intrinsic width of the Fermi distribution function at the experimental temperature. The instrument's resolution can then be approximated using Equation 7:

$$\Delta E_{\text{system}} = \sqrt{\Delta E_{\text{fit}}^2 - \Delta E_T^2}$$

To determine the energy resolution of a synchrotron radiation beamline, it is essential to employ the helium lamp integrated within the ARPES system as a standard for measuring its ultimate resolution. Under identical experimental conditions, we compare the resolutions attained through measurements utilizing both the helium lamp and synchrotron radiation. Given the negligible energy broadening of the helium lamp, which is merely 0.4 meV at 21.2 eV, its contribution to broadening can be disregarded. Thus, the disparity between the two measurements is solely attributable to the energy broadening of the synchrotron radiation, which consequently represents the resolution of the synchrotron radiation beamline.

$$\Delta E_{\text{beam}} = \sqrt{\Delta E_{\text{total(beam)}}^2 - \Delta E_{\text{total(He)}}^2}$$

For resolution calculation of the synchrotron beamline, we can use a monochromator grating (3600 L/mm) to generate 867 eV synchrotron radiation. Measurement of the copper surface Fermi edge yielded a system resolution of 31.5 meV (encompassing beamline + analyzer broadening), while helium lamp measurements gave a system resolution of 26.4 meV (helium source + analyzer broadening). By conducting ARPES testing on Cu with a helium lamp as the light source, under the conditions of a 13K temperature and a 0.3 mm analyzer slit setting, the Fermi edge of the Cu surface was measured, yielding an analyzer resolution of 26.4 meV. Therefore, based on Equation 8, the resolution of the Dreamline beamline specifically is determined to be 17.2 meV, corresponding to an energy resolving power of 50,400 at 867 eV.

Fig. 3 [Figure 3: see original paper]. The resolution test results for the Dreamline are presented as follows: (a) By measuring the Fermi edge of the Cu surface using a helium lamp as the light source, under the conditions of a temperature of 13K and an analyzer slit setting of 0.3mm, the analyzer resolution was determined to be 26.4 meV. (b) Utilizing 867 eV synchrotron radiation to measure the Fermi edge of the Cu surface, the beamline resolution was calculated to be 17.2 meV. The resolving power was derived as 867/0.0172, resulting in a value of 50,400@867eV.

Fig. 4 [Figure 4: see original paper]. The resolution test results for the Dreamline are presented as follows: (a) By measuring the Fermi edge of the Cu surface using a helium lamp as the light source, under the conditions of a temperature of 13K and an analyzer slit setting of 0.3mm, the analyzer resolution was determined to be 26.4 meV. (b) Utilizing 867 eV synchrotron radiation to measure the Fermi edge of the Cu surface, the beamline resolution was calculated to be 17.2 meV. The resolving power was derived as 867/0.0172, resulting in a value of 50,400@867eV.

4.3 Photon Flux Measurement

The photon flux at the anticipated sample position was determined using an AXUV100G photodiode, whose photocurrent, induced by the incident beam, is linearly proportional to the flux. The photon flux can be calculated based on the photoelectric conversion efficiency of the photodiode, as outlined in Equation 9[**?**, **?**]:

$$\text{Flux} = \frac{I \times 3.66 \times 250}{e \times I_{\text{BC}} \times \Delta E_{\text{beam}} \times 10000}$$

Where I is the photocurrent (A) recorded by the photodiode at the sample position, e is the electron charge of 1.6×10^{-19} C, E_{beam} refers to the energy broadening (in eV) at the gas absorption edge, and I_{BC} stands for the ring current (mA) during flux measurement. Since the beamline flux is inherently linked to both the beamline bandwidth and the energy value, the flux measurement corresponds to an experimental condition of a 0.01% bandwidth. The beamline bandwidth is adjustable via the monochromator slit size, while energy calibration is achieved using a gas ionization chamber. Through rigorous testing, the Dreamline beamline has demonstrated the capability to perform full-energy-range flux measurements under a 4σ opening of the white light slit for the double undulator. This includes measurements utilizing corresponding gratings under varying light polarization conditions (LH for horizontal polarization and C for circular polarization). By selecting the appropriate grating, this beamline can guarantee a flux exceeding 10^{12} phs/s/0.01%BW below 800 eV and a flux exceeding 10^{11} phs/s/0.01%BW across the entire energy range (20-2000 eV).

4.4 Beam Spot Sizes at the ARPES Sample

An X-ray beam position monitor (BPM) system is installed at the ARPES endstation and is ready to measure the spot sizes at any time. This system comprises a bottom-mounted manipulator in the main chamber, configured with a 100 mm tungsten wire and a YAG:Ce scintillator, as well as an AXUV100G photodiode mounted downstream. The YAG:Ce scintillator is used to locate the X-ray beam position, while the photodiode measures the photon intensity of the direct soft X-ray beam.

The BPM is driven by stepper motors to scan across the beam spot at the intended sample position, resulting in a step change in the intensity of the photocurrent before and after shading. To obtain the spot profile in the horizontal or vertical direction, the step signal of the recorded photocurrent is differentiated (first derivative), and the spot size is derived from its full width at half maximum (FWHM) value. In our measurements, these scans were performed at approximately 100 eV, using a white slit aperture of 1000 μm × 3000 μm and an exit slit aperture of 50 μm. The measured beam spot size at the ARPES end-station is H:60μm×V:30μm (see supporting information Fig. S1). The vertical size of the beam spot at the sample is a crucial factor in determining the energy resolution of the beam, which is influenced by the exit slit. The measured spot size in the vertical direction with varying exit sizes is shown in Fig. 5c, which is in accordance with the theoretical values.

Fig. 5 [Figure 5: see original paper]. Beam spot size measurements at the ARPES sample position. Derived spot sizes are presented along with the calculated and theoretical values of spot size in the vertical direction for different exit slit apertures, respectively. All measurements were carried out at 100 eV using varying exit slit apertures.

V. Applications to Materials

The coexistence of a near Fermi Energy (E_F) flat band and a Van Hove singularity in a two-phase superconductor was meticulously investigated using ARPES with high quantum behavior in these materials.[**?**]

VI. Summary

The construction of the ultra-high energy resolution soft X-ray beamline at SSRF marks a significant innovation in synchrotron instrumentation, featuring a dual-EPU design for unprecedented 20-2000 eV energy coverage and a novel plane-grating monochromator with four VLS gratings. This breakthrough system achieves a record resolving power of 50,400 at 867.1 eV through high-line-density gratings and integrated thermal correction capabilities—surpassing conventional monochromator performance. Comprehensive flux measurements utilizing the Dreamline beamline demonstrate exceptional operational value: below 800 eV, selected gratings deliver $>10^{12}$ photons/s/0.01%BW, while maintaining $>10^{11}$ photons/s/0.01%BW across the full energy spectrum under variable polarization conditions. These capabilities substantially exceed comparable flux benchmarks reported for similar facilities (e.g., Diamond Light Source I05, BESSY II UE112-PGM) while matching their energy ranges. The combined strengths of ultra-high energy resolution, exceptional flux intensity, and wide spectral coverage establish this beamline as an essential tool for quantum materials research, enabling fundamental discoveries in electronic structure and correlated phenomena.

VII. Bibliography

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