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An Aberration Corrected Photoemission Electron Microscope at the Advanced Light Source

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Abstract. Design of a new aberration corrected Photoemission electron microscope PEEM3 at the Advanced Light Source is outlined. PEEM3 will be installed on an elliptically polarized undulator beamline and will be used for the study of complex materials at high spatial and spectral resolution. The critical components of PEEM3 are the electron mirror aberration corrector and aberration-free magnetic beam separator. The models to calculate the optical properties of the electron mirror are discussed. The goal of the PEEM3 project is to achieve the highest possible transmission of the system at resolutions comparable to our present PEEM2 system (50 nm) and to enable significantly higher resolution, albeit at the sacrifice of intensity. We have left open the possibility to add an energy filter at a later date, if it becomes necessary driven by scientific need to improve the resolution further.

INTRODUCTION

X-ray excited photoemission electron microscope (PEEM) combines the power of modern synchrotron radiation absorption spectroscopy with direct full imaging capability of PEEM. A conventional PEEM system consists of round lenses whose resolution is limited by spherical and chromatic aberration, and the spherical aberration coefficient Cs and the chromatic aberration coefficient Cc always being positive [1]. As a result aberrations can only be minimized by adjusting the geometry of the electrodes but not eliminated. These aberrations limit the ultimate resolution, defined by a 50% value of the Modulation Transfer Function to be typically 50 – 100 nm, for x-ray illumination and a 20 KV extraction field [2]. Aberrations must be compensated in order to remove their deleterious effects on the imaging properties of the microscope. An electron mirror can have aberration coefficients of opposite sign but equal magnitude with respect to those of electron round lens so that in principle, the aberrations can be canceled out and the resolution can be improved ultimately to the diffraction limit. A new X-ray PEEM with an electron mirror aberration corrector at the ALS has been designed (PEEM3) and the overall layout and correction scheme are described.

PEEM3 SYSTEM

An elliptically polarized undulator (EPU) at the straight sector 11 of the ALS will be used to produce linearly polarized light of arbitrary azimuth and left and right handed circularly polarized radiation with continuous change of ellipticity. A variable line space (VLS) plane grating monochromator beamline will provide soft x-ray in the spectral range from 100eV to 1500eV. A VLS design was chosen as it gives the opportunity to dynamically measure the photon energy, by active monitoring of the position of the zero order beam with respect to that of the monochromatic light defined by the exit slit. This is of crucial importance in minimizing noise in x-ray dichroism measurements. The system is designed to demagnify the source in the horizontal direction inside the exit arm of the monochromator, and then again after the exit slit by a K-B pair onto the sample, where we expect a 3 x 1 micron beam size to be achieved. This geometry was chosen to maximize the demagnification, but it also affords the opportunity to increase the beam size to 50 microns by defocusing the K-B mirrors by unbending.

PEEM3 uses an all-electric tetrode objective lens to optimize the performance for studying the magnetic surfaces and interfaces. This immersion objective lens accelerates the low energy secondary electrons emitted from the sample and forms a magnified intermediate image of the sample surface in front of a magnetic beam separator. Since the sample is part of the objective lens, the accelerating potential and working distance can be varied depending on the surface conditions of the sample. A field lens is located just in front of the entrance plane of the beam separator to have the field ray enter the beam separator parallel to the axis. Two electrostatic dodecapoles are put between the objective lens and the field lens and work as double-deflection system to align the electron angle and position separately, and to work as a stigmator.

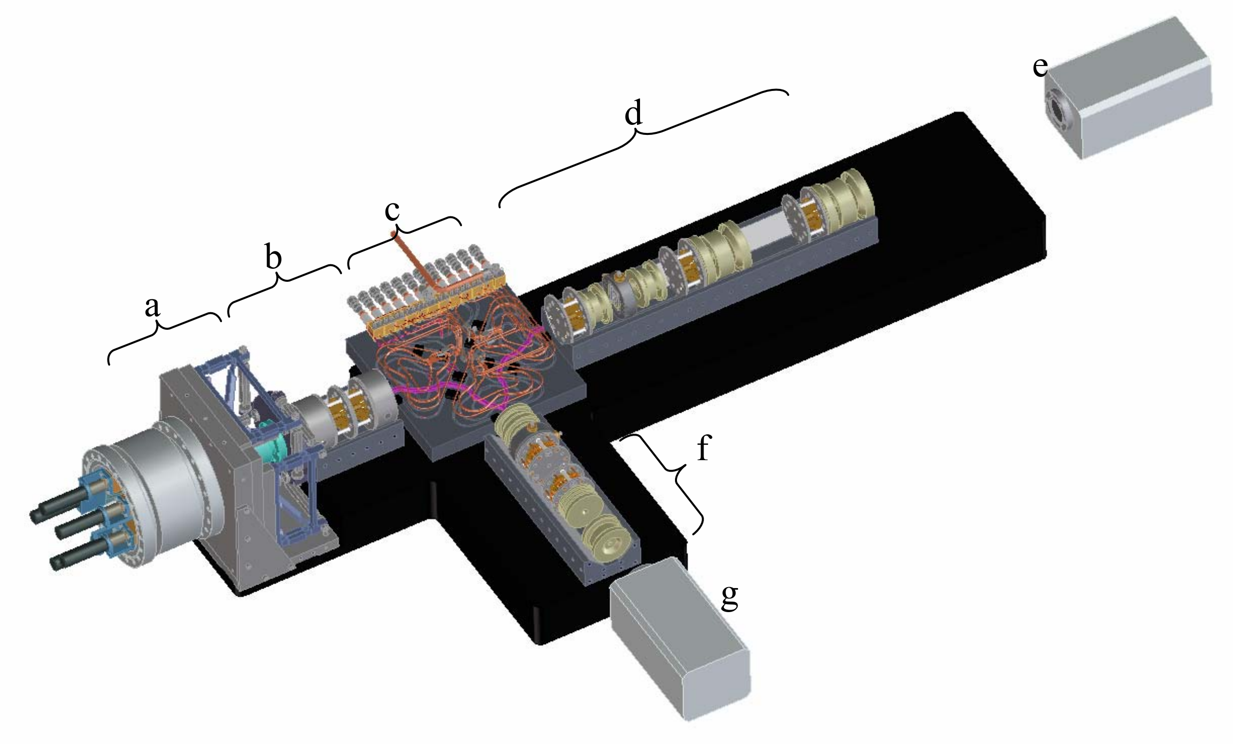

FIGURE 1. Schematic layout of an aberration corrected X-ray photoemission electron microscope at the ALS
a: sample manipulator, b: objective, c: beam separator, d: transfer and projector, e: Imaging CCD, f: mirror column
g: diagnostic CCD

The PEEM3 beam separator consists of two plane-parallel pole plates separated by a distance of 7mm and produces a magnetic dipole field to bend the electron beam by 90 degree [3]. By imposing double mirror symmetry conditions on the magnetic field, all the second-order geometrical aberrations are canceled. The imaging property of the beam separator is equivalent to that of a telescopic four round lens system. The object side focal plane of the first lens is transferred with unit magnification into the image side focal plane of the fourth lens.

The electron mirror has four rotationally symmetric electrodes and the reflecting electrode is of circular shape with a radius of 5.6mm [4]. The inner electrode is put at ground voltage, while the potentials of the other three electrodes give three free knobs to adjust focal length, chromatic aberration and spherical aberration of the mirror. In order to cancel coma generated by the mirror, the magnification of mirror is chosen to be -1 and a field lens is placed near the image plane to ensure that the linear optics is telescopic.

Due to the compact design of the magnetic beam separator, it is difficult to put a beam monitor within it. A projector lens and CCD detector are located behind the mirror, which is used as a diagnostic PEEM. This PEEM has similar resolution to our present PEEM2 system. It allows to independently test and optimize the first sector of the beam separator and to independently optimize the incoming and outgoing beam at the mirror. In the diagnostic mode, the mirror acts as an unipotential lens and the electron beam passes through a central hole with a diameter of 500 micron at the reflecting electrode.

The transfer optics and projection system are used to magnify the intermediate image of the object and source at the exit plane of magnetic separator onto the CCD detector without distortion. This behavior is achieved by removing the constraint of having a real object external to the followed lens. This column consists of four einzel lenses and has variable magnification. The first transfer lens is operated to give unit magnification and is used for enabling a suitable location for the back focal plane aperture.

A key aspect of the system is the mechanical layout. All components, the sample manipulator, the electron lenses, and the separator are all mounted on a common internal highly stable reference plate. This is required to achieve the stability we need over the course of experiments. Not only is good resolution needed for single images, but for multiple images over long time scales, either for example in pump-probe time resolved experiments, or for collecting a spectroscopic set of images. The separator is a source of several hundred watts of power, and so must be intensively water cooled. This is done through the use of hollow conductors through which flows high pressure water. Modeling shows that this, together with the insulation on the coil windings results in negligible heat transfer to the rest of the system. We believe that the mechanical linking of all components is essential for reliable and stable operation, and also ensures that we can have a highly effective magnetic shield for the system.

ABERRATION CORRECTOR

Two very different methods were developed to design the electron mirror for the PEEM3 microscope. The first uses an industry standard commercial code SIMION [5]. SIMION is an electrostatic and magnetic field modeling program which calculates the field using a finite difference method and traces the motion of electron using a fourth-order Range-Kutta integrator. The values of the spherical and chromatic aberration coefficients were extracted from the direct ray-trace. To do this, simulated electrons are fired into the mirror from a point source on the optical axis with different initial angles and energies, then the displacement at which each reflected electrons from the mirror crosses the optics axis are computed and recorded. The least square fits of the following forms

$$r_{sph} = \theta\Delta f + \theta^3 C_3 + \theta^5 C_5$$

$$r_{chr} = -\kappa\theta(C_c + \theta^2 C_{3c}) + \kappa^2 \theta C_{cc}$$

yield the coefficients of the dominant axial aberrations.

The second method uses charge density methods, in this case charged rings, to calculate the field distribution and differential algebra (DA) techniques to track the particle. The DA model approximates the exact solution of the equation of motion with a set of Taylor series of arbitrary but finite order expanded around a certain reference trajectory and gives Taylor maps. In principle, a DA technique can calculate numerically all aberration coefficients up to arbitrary order. The code for the DA model of the mirror is based on COSY INFINITY [6]. The equations of the motion using time as the independent variable was initially benchmarked against the standard equation of motion in COSY using a plane accelerating field, such that the trajectory equations are analytic, and the agreement of aberrations up to the fifth order was correct to 7 or more digits.

A test involving a mirror used an early test system used in SMART [7], for which we calculated the results using SIMION and COSY. Considering the fact that completely different field and optics models have been used for the mirror, the remarkable agreement shown here in Table 1 provides strong evidence to validate our design. A four electrode mirror has been found to effectively correct the spherical and chromatic aberrations from the objective lens for various operation modes of PEEM3.

Tab1e 1: Comparison of aberration coefficients of a diode mirror by different model

	Δf	C_c	C_3	C_5	C_{3c}	C_{cc}
SMART	$2x10^{-9}$ m	-9.8173m	-539.71m	-904640m	-3269.8m	-5.4317m
SIMION	$1.03\ x10^{-6}$m	-9.829m	-539.84 m	-913725 m	-3268.5m	-5.387m
COSY	$3.21x10^{-5}$ m	-9.9742m	-520.46m	-989923m	-4921.2m	-5.2229m

PEEM3 RESOLUTION

In our model to determine the resolution of PEEM3, the secondary electron distribution is used. We create a statistical ensemble of electrons with initial energy and angle spread and track the electron beam distribution weighted with the probability anywhere in the system. The resolution is defined as 68% in intensity of the point spread function. The effect of diffraction is calculated for each energy electron and summed up incoherently to yield a diffraction Airy pattern. The comparison of resolution versus transmission for PEEM2 and PEEM3 is shown in fig.2. Operating at 20kV and 2mm working distance, the point resolution for more than 90% transmission reaches 50nm with the mirror corrector, a significant reduction from that of 440nm without correction. The best resolution can be achieved is 5nm at 2% transmission, as opposed to 20nm at 1% transmission of PEEM2.

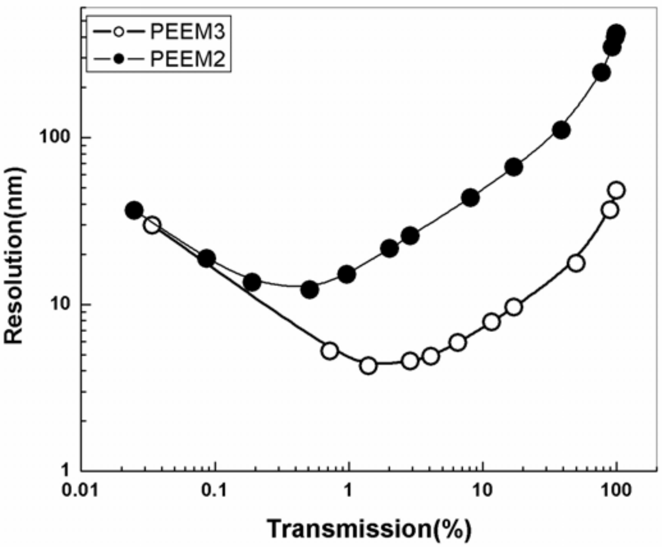

Figure 2. Comparison of resolution versus transmission of PEEM2 and PEEM3.

SUMMARY

The PEEM3 system should give a throughput around 50 x that of PEEM2 at 50 nm resolution, and should get to less than 10nm resolution in routine operation. We have designed the system to be flexible and upgradeable, with for example the possibility of adding an energy filter in due course, if required.

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