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# Electron spectrometers for inelastic scattering from magnetic surface excitations

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**This paper compares the performance of two different designs for electron spectrometers to be used for inelastic scattering of spin-polarized electrons from surface magnons and Stoner excitations. The recently proposed combination of monochromators with 90° and 180° deflection angles ensures a maximum spin asymmetry signal while providing still a good quality of the monochromatic beam. Higher intensities, however, are obtained with the classical 146°/146° combination, which features a spin polarization longitudinal to the beam direction at the target. We present calculations for the monochromatic current for both combinations and argue that the use of the classical spectrometer type may be advantageous. Copyright © 2006 John Wiley & Sons, Ltd.**

**KEYWORDS:** electron spectrometers; inelastic scattering of electrons; magnons

## INTRODUCTION

Magnons or spin waves represent collective excitations of a magnetic solid. For a ferromagnetic crystal, each excitation quantum corresponds to a reversal of one spin. Since the spin reversal is distributed over the entire lattice, the energy required for the spin reversal goes asymptotically to zero in the long-wavelength limit and in the absence of an external field. The excitation energy increases quadratically with increasing wave-vector $k$. This dispersion property of a magnon is distinct from a Stoner excitation, which corresponds to a spin reversal of a single electron, i.e. to a transition from a spin-down band to a spin-up band. While magnon excitations in the bulk of a material are experimentally well investigated and theoretically understood, it is only lately that magnons localized at the surface of a solid became amenable to experimental studies.[1–4] Following an early suggestion of Gokhale *et al.*,[5] inelastic electron scattering was employed as means of detection of surface magnons in these experimental studies. The experimental progress is due to the construction of a novel type of electron spectrometer, which combines the production of an intense monochromatic beam from a spin-polarized photocathode with an orientation of the spin either strictly parallel or antiparallel to the magnetization of the sample, independent of the momentum transfer in the scattering process. To achieve that, the spin of the scattered electron must be oriented perpendicular to the scattering plane at the target, and therefore transverse to the beam direction. The photocathode emits electrons polarized longitudinal to the beam and the distribution of electron energies is between 200 and 300 meV. The use of these electrons therefore requires energy filtering as well as an electron deflection by a total deflection angle of 90°. We have shown in a previous publication[6] that this total deflection angle can be achieved by a combination of special 90° and 180° deflectors that are adapted versions of deflectors used for high-resolution electron spectroscopy of surface vibrations.[7] Despite the unconventional deflection angles, the special 90°/180° deflector combination features stigmatic focusing of the entrance slit onto the exit slit. In the dispersion plane, each of the deflectors focuses its image of the entrance slit onto the exit slit position. Perpendicular to the dispersion plane, the entrance slit of the 90° deflector is focused directly onto the exit slit of the 180° deflector, without an intermediate focus. Because of the stigmatic image, high monochromatic currents of polarized electrons could be produced. Even more importantly, the electron beam remained well defined, a necessary requirement for a high overall transmission of the electron spectrometer, as eventually an image of the entrance slit of the first energy selector on the exit slit of the last selector is required for optimum performance.

In the course of our studies, we have noticed that the described image deteriorates when the space charge of electrons is taken into account. While this is always the case, and is ultimately the reason for the current limit in the production of monochromatic electrons, it appeared that the deterioration of the beam quality in the 90° deflector was considerably larger than in our standard 146° deflectors. In this paper, we describe a systematic analysis of the effect of the space charge on the properties of the 90° deflector and calculate the monochromatic currents that can be obtained with the 90°/180° and the 146°/146° combinations. We find that the 146°/146° combination features a 7 times higher current. This higher current may more than compensate for the disadvantage of a non-perfect spin alignment.

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## TECHNICAL ASPECTS OF THE CALCULATION

Our electron optical calculations follow the principles described in Ref. 8. For the aberration-compensated deflector and a few more details on the calculation we refer to Ref. 6. We keep the dimensions of the deflectors as before.[6] Specifically, we use slits of width $s = 0.6$ mm and height $h = 6$ mm. The outer and inner radii of the deflectors are $r_o = 60.3$ mm and $r_i = 20.3$ mm, respectively. The slits are placed at a radial position of $r_0 = 33.5$ mm for the 146° and 180° deflectors and at $r_0 = 42$ mm for the 90° deflector. The energy spread of the cathode is assumed to be 300 meV and the entrance aperture angles are assumed to be ±4° perpendicular and parallel to the dispersion plane. The absolute results on the monochromatic current depend on these parameters. As we are interested in the comparison of two designs, we need not argue about their most appropriate choice at this point. The aberration-compensated electrostatic deflector features deflection plates which are curved orthogonal to the main deflection (= dispersion) plane, and an additional pair of cover plates parallel to the dispersion plane separated by a distance $H = 48$ mm (for figures of the design see Ref. 6). The potential applied to these cover planes controls the focal length. Stigmatic focusing is achieved only for a particular potential and a particular total deflection angle (146°) once the inner and outer radii are fixed.

The current provided by the combination of two monochromators is determined by the space-charge-induced aberrations of the electron trajectories. To calculate the effect of the space charge, we fill the deflector with a bundle of electrons equally distributed over the range of incident energies, the angular apertures and the positions in the entrance slit. These trajectories define the local distribution of the space charge in the deflector with the absolute value depending on the feeding current. The space-charge-induced potential is then calculated for a particular standard current by solving the Poisson equation numerically with the potentials set to zero on all electrodes. The actual potential distribution for a given potential distribution on the electrodes is then calculated from the solution of the Poisson equation multiplied with the actual feed current and the solutions of the Laplace equation for the independently variable electrodes, each multiplied with the actual potential on that electrode. Apparently, the method makes use of the linearity of the Laplace and Poisson equations. The method is equivalent to a first-order correction of the trajectories with respect to space-charge aberrations. For each potential distribution that corresponds to a particular feed current and a particular nominal pass energy, the program determines the optimum focusing potentials on the pair cover plates. The transmission of the deflector is then calculated with a bundle of 3000 trajectories, equally distributed over the slit and the angular aperture. The transmission as a function of the incident energy determines the energy resolution. The transmission of the second deflector is calculated with the trajectories of the electrons as they leave the first monochromator.

## RESULTS

Figure 1 shows the monochromatic current of the 90°/180° combination *versus* the feed current for a nominal pass energy of 4.12 eV. The energy width of the beam leaving the second deflector is about 30 meV (triangles). As seen from the figure, the monochromatic current saturates rather quickly (circles) because the energy spread of the beam leaving the first (90°) monochromator increases dramatically up to a point were all energy selection is lost. This loss of energy selection is due to the space-charge-induced aberrations in the monochromator. The energy spread of the beam leaving the second monochromator is not affected by the magnitude of the feed current into the second deflector. In other words, the second deflector operates without significant space-charge effects. The increased energy spread in the first monochromator was already noticed in Ref. 6. Fig. 2 displays the same quantities for a sequence of two 146° deflectors. The pass energy of the second deflector is set to 3 eV in order to obtain the same energy resolution of 30 meV as before. The first deflector operates as a retarding deflector at 3 times the pass energy of the second. For zero feed current, this retarding deflector has about the same energy resolution as the 90° deflector discussed before. Now the resolution deteriorates at much higher currents compared to the 90° deflector. Consequently, the monochromatic current leaving the second monochromator saturates at twice as high feed currents. The monochromatic current is about 7 times higher because of the better image quality. Figure 3 shows

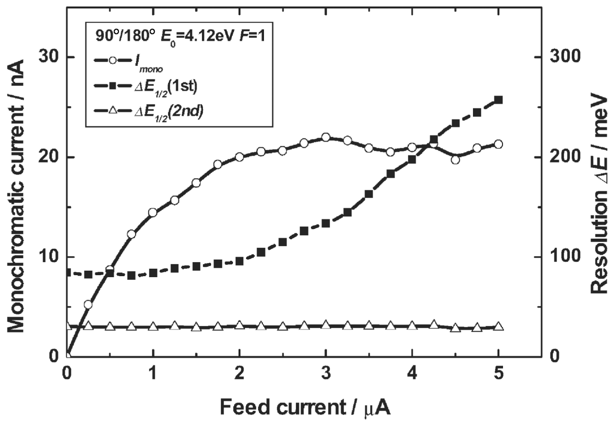


**Figure 1.** Monochromatic current and resolution for the 90°/180° combination.

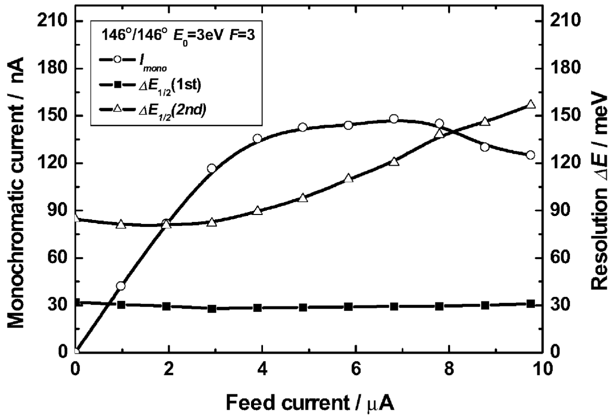


**Figure 2.** Monochromatic current and resolution for the 146°/146° combination with a retardation factor $F = 3$ for the first monochromator.

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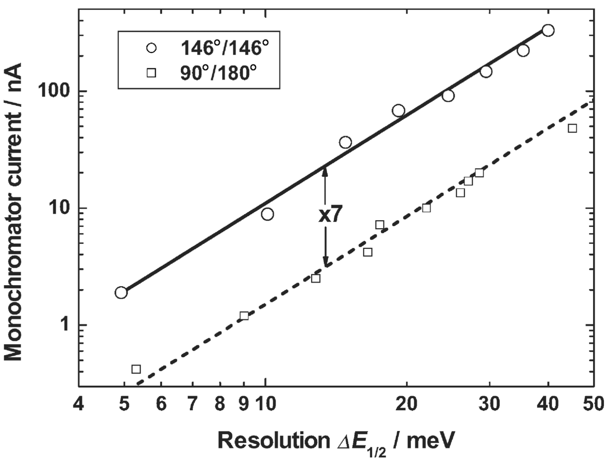


**Figure 3.** Monochromatic current *versus* resolution for the 90°/180° and the 146°/146° combinations. The 146°/146° combination delivers about 7 times higher currents for the same resolution.

a systematic comparison of the maximum currents *versus* the resolution obtained for the 146°/146° and the 90°/180° combinations.

## DISCUSSION

The substantially higher current makes the 146°/146° combination superior in all applications in which the spin-flip information is not needed. This may include even magnon excitations if the magnons have a sufficiently long lifetime so that they can be distinguished from other, for example, vibrational energy losses by their characteristic dispersion. In order to evaluate the merits of two devices when the spin-flip information is needed one has to consider the scattering geometry in the two cases with respect to the spin parameter (Fig. 4). For the 90°/180° combination one can have the spin of the incident electron perpendicular to the scattering plane (Fig. 4(a)). If the magnetization of the sample is likewise perpendicular to the scattering plane, one has the maximum possible asymmetry of the scattered intensity. The asymmetry $A$ is defined as

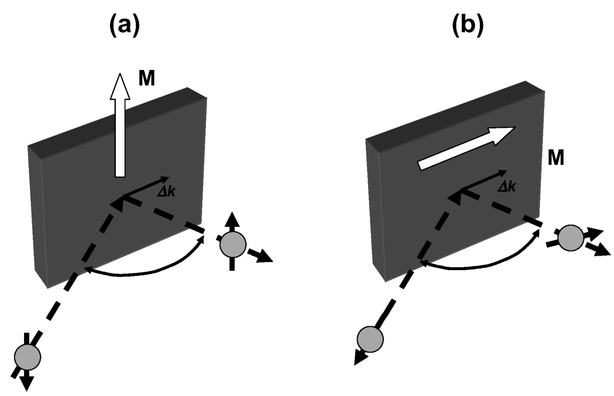


**Figure 4.** Geometries for spin-flip scattering. (a) transverse polarized beam, spin perpendicular to the scattering plane. (b) longitudinal polarization, the projection of the spin on the direction of the magnetization depends on the angle of incidence.

$$A = \frac{1}{P_0}\frac{I_{\uparrow\uparrow} - I_{\uparrow\downarrow}}{I_{\uparrow\uparrow} + I_{\uparrow\downarrow}} \quad (1)$$

where $I_{\uparrow\uparrow}$ and $I_{\uparrow\downarrow}$ are the intensities of the non-flip and flip processes and $P_0$ is the polarization of the beam with respect to the spin orientation of the magnetic excitation. The asymmetry is zero for excitations that are not associated with a spin flip. The asymmetry spectrum therefore reveals directly the magnetic nature of an elementary excitation. The advantage of the 90°/180° combination is that the orientation of the spin of the incident electron is independent of the angle of incidence. The polarization to be inserted in Eqn (1) is therefore the polarization provided by the photocathode. The 146°/146° combination with reverse curvature of the first and second monochromator preserves the longitudinal polarization of the beam emerging from the photocathode. To see an asymmetry the sample must be magnetized in the scattering plane. The effective polarization of the beam, which enters the asymmetry, is the initial polarization $P_0$ projected into the surface plane (Fig. 4(b)). Since the noise in the asymmetry spectrum is inversely proportional to the effective polarization, one should keep the angle of incidence close to grazing incidence for in-plane magnetization of the sample. Owing to the magneto-crystalline anisotropy, the easy axis may also be aligned parallel to the surface normal. Examples are hexagonal Co films with the $c$-axis perpendicular to the surface[9,10] and thin Fe films epitaxially grown on Cu(100).[11] In those cases, the longitudinal polarization is even an advantage, as spin waves would show no asymmetry signal if the polarization were oriented perpendicular to the scattering plane. Hence, the 146°/146° combination has a greater versatility with respect to the crystalline anisotropy of the samples to be investigated. In summary, we therefore tend to conclude that it is worthwhile exploring experimentally the possibilities of a spin-polarized spectrometer in the classical version of a 146°/146° combination.


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