International Journal of Mass Spectrometry xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Mass Spectrometry

journal homepage: www.elsevier.com/locate/ijms

A new design for imaging of fast energetic electrons

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ARTICLE INFO

Article history:
Received 20 December 2013
Received in revised form 12 February 2014
Accepted 17 February 2014
Available online xxx

Keywords:
Angular distribution
Photoemission
Photoelectron spectra
Strong-field excitation
Synchrotron radiation

ABSTRACT

We report on an essentially improved version of the classical Eppink–Parker velocity map imaging spectrometer design (Rev. Sci. Instrum. 68, 3477 (1997)). By adding electrostatic lenses with an opposite polarity to the extraction system we succeeded in extending the range of detection of energetic particles up to the keV regime at moderate (<20 kV) extraction voltage conditions. Simulations show that the electrostatic lens system acts in analogy to an achromatic lens in optics and leads to a reduction in the chromatic energy aberration. For comparison to other setups a transmission parameter of the extraction system is defined denoting the maximum kinetic energies of particles which can be analyzed. Detector size and spectrometer length only enter via geometry, that is the straight trajectories in the subsequent field-free particle drift. With respect to Eppink–Parker the energy range has been extended by a factor of 2.5. Moreover, particle trajectory simulations demonstrate that the energy resolution can be improved by about 20%. To test the performance, photoemission studies have been conducted to resolve above-threshold-ionization patterns from Xe atoms exposed to intense ultrashort laser pulses as well as single photon ionization of Ne atoms using tunable synchrotron radiation with photon energies up to 600 eV.

Introduction

The technique of Velocity Map Imaging (VMI) as introduced by Chandler and Houston [6] is a powerful and direct method to obtain a two-dimensional projection of the full particle momentum distribution. The kinetic energy and emission direction of the reaction products resulting from ionization, fragmentation, etc. are accessible in a single measurement. The widely spread Eppink–Parker setup Eppink and Parker [9] consists of a two-stage focusing electrostatic extraction and a position sensitive detector at some distance. The photoelectron trajectories leading to the momentum distribution on the detector can easily be calculated using ion trajectory simulations, e.g., SIMION8 [27]. Since its first use by Bakker et al. [1,2], the VMI-technique has found a wide range of applications in atomic and molecular physics [23,28,3] ranging up to the strong field regime [17,30], and aerosol physics [32] to only name a few. With photoelectrons, VMI spectrometers are applied to study low kinetic energies, i.e. in the range up to 60 eV [14,33]. Several modifications of the Eppink–Parker setup have been described in the literature [29,11,21,12]. However, only slight improvements were achieved with respect to an extension of the mapped energies and an improved momentum resolution. For example, Garcia et al. [11] introduced slits in the repeller in order to fit the instrument to their experimental requirements at a synchrotron beamline. There are two main drawbacks, which currently limit the utilization of the classical type of spectrometer to map the angular distribution of more energetic particles:

1 For guiding and focusing of energetic particles towards the position-sensitive detector the extraction voltage has to be substantially higher compared to the particle kinetic energy. Hence one has to deal with repeller voltages largely above 10.0 kV when trying to map keV ions/electrons. As a consequence at high gas load conditions special efforts have to be made to avoid discharges in the lens system.
2 Focusing on the detector can only be achieved within a narrow momentum range. For higher particle velocities, simulations show that the focus position substantially moves towards the extraction system. This results in a blurring of the signal on the position sensitive detector, hence a significant decrease in energy and angular resolution.

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http://dx.doi.org/10.1016/j.ijms.2014.02.009
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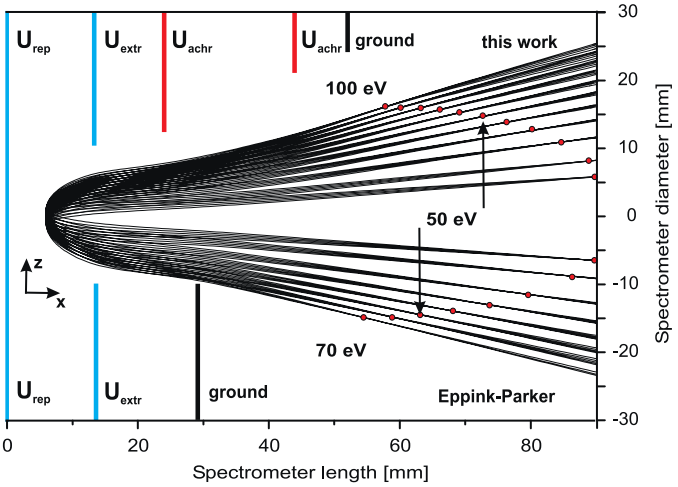

Fig. 1. Electron trajectories (E_{kin} = 5, 10–100 eV) released along a line (x = 6 mm, z = 0 ± 1 mm) parallel to the electrodes calculated for HEVMI (top) and Eppink–Parker (bottom). A repeller voltage of U_{rep} = −2 kV was used in the simulations. Clearly higher energy electrons are transmitted using the HEVMI setup. Red dots indicate the calculated focal point for different energies (arrows: E_{kin} = 50 eV). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

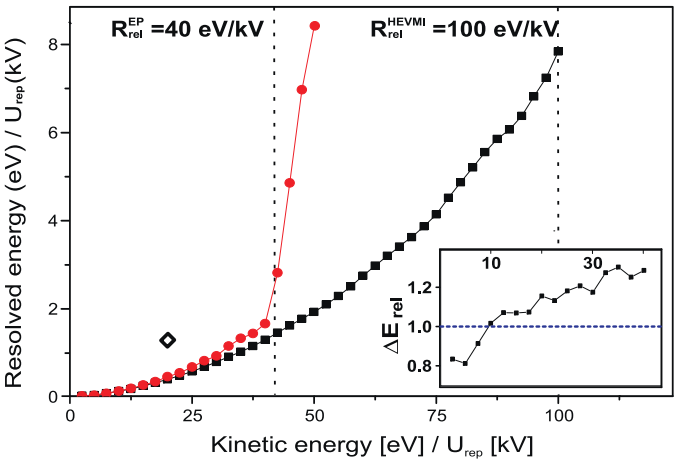

Fig. 2. Calculated energy resolution ΔE_{rel}=$\Delta E/E$=2$\Delta p/p$ (p denotes the electron momentum) of Eppink–Parker (EP) (○) compared to HEVMI (□) normalized to the repeller voltage U_{rep}. The transmission parameter R_{rel} is labeled for both setups. Above 40 eV/kV there is a distinct decrease in transmission as well as energy resolution using the EP setup. The simulations demonstrate that even near the HEVMI energy transmission limit of 100 eV/kV a value of $\Delta E_{rel} \approx 0.08$ can be achieved. Experimental resolution extracted from 2p line data shown in Fig. 5 but for an extended ionization region in z-direction resulting from the unfocused synchrotron X-ray beam. Inset: With respect to Eppink–Parker the simulations predict an improvement in ΔE_{rel} by about 20% for electrons faster than 10 eV/kV.

To the best of our knowledge, no effort has been dedicated to extend the operational range towards keV kinetic energies. Robust VMI technique can be, however, successfully utilized in experiments at X-ray free-electron lasers [19,20], where detection of high energy electrons including angular distribution might be desirable or in intense optical laser-matter interaction studies where the fast electrons provide informations about scattering at plasmons Passig et al. [22] or the ionic center [4].

In this contribution we present a High Energy Velocity Map Imaging (HEVMI) spectrometer, which is capable to map energetic particles. Moreover the design is characterized by an improved momentum resolution when compared to the classical setup. In the following we focus in our analysis on the imaging of energetic electrons.

Spectrometer design

Generally, the operational principle of the VMI spectrometer can be regarded as a projection of the expanding Newton spheres onto a 2D position sensitive detector, whereas the geometrical size is mainly determined by the electron time-of-flight through the spectrometer. Thus an extension of the energy range can be achieved by bringing electrons as fast as possible to the detector plane. Including the impact of the focusing field of the electrostatic lenses, the system has to be optimized to enable high energy electrons to pass through the spectrometer and ensure proper focusing.

To compare the transmission of the different setups, we conducted ion trajectory calculations and relate the maximum electron energies to the repeller voltage applied, i.e. R_{rel}. Eppink–Parker (EP) consists of a three electrodes setup [9] and allows electrons with maximum energy R_{rel}^{EP} = 40 eV/kV to pass through the spectrometer without colliding with the electrostatic lens system or being significantly disturbed by field distortions near electrode edges. With the new design electrons with energies up to R_{rel}^{HEVMI} = 100 eV/kV can still reach the detector. The 3D ion trajectory simulation package SIMION8 is used to design a compact HEVMI system. The total length of the spectrometer is reduced to 90 mm (from the repeller electrode to the detector plane) as shown in Fig. 1. Furthermore two positive equipotential electrodes are introduced. The extra electrodes form a concave electrostatic lens, which acts as an achromatic doublet. In optics such an element is known to compensate for chromatic aberrations. Here uncertainties in the focus length due to different electron kinetic energies are reduced. Electron trajectories are sketched to visualize the intrinsic aberrations of the electrostatic lens system, see Fig. 1. With the achromatic lens (top) the chromatic aberration is significantly reduced compared to Eppink–Parker (bottom) resulting in an improvement in the energy resolution ΔE_{rel} of e.g. 20% above 15 eV/ kV, see inset in Fig. 2. For convenience ΔE_{rel} is normalized to the potential applied at the repeller plate. At higher energies ΔE_{rel} increases (Fig. 2) giving a value of 0.16 at the transmission limit of 100 eV/ kV. We note, that two positive electrodes instead of a single one improves the resolution by more than 15%, e.g., from ΔE_{rel} = 4.2% to 4.9% at 500 eV. The calculations show that the resolution scales with $(\Delta z)^2$, see Fig. 1. Hence to attain the limit experimentally, the ionization region must be restricted to one micron in x and z-directions.

One can give a rule of thumb for the design of the HEVMI electrostatic lens system. First, the expansion of the Newton spheres for a system with mesh electrodes is simulated. This enables to neglect the rather complex influence of the focusing field on the electron trajectories. By tracing the electron pathways, this procedure gives fairly good values for the inner diameter of the electrode apertures. Next, one has to perform studies to optimize the focusing properties of the system by repeating the simulations now using gridless electrodes. For the present setup (Fig. 1) we find optimal voltage ratios of U_{rep}/U_{extr} = 1.55 and U_{rep}/U_{achr} = −1.5 leading to momentum focusing.

Experimental setup

The technical realization of the HEVMI setup is shown schematically in Fig. 3. Five cylindrical electrodes generate a non-uniform field, which guides the electrons through the spectrometer preserving the information about the 3D photoelectron momentum vector. An effusive gas injector (500 μm diameter pinhole) is integrated at the center of the repeller electrode. To test the HEVMI spectrometer at low and high energies light sources from a commercial Ti:Sapphire laser system and soft X-rays from the synchrotron radiation source DORIS are applied respectively. Briefly,

Please cite this article in press as: S. Skruszewicz, et al., Int. J. Mass Spectrom. (2014), http://dx.doi.org/10.1016/j.ijms.2014.02.009