International Journal of Mass Spectrometry 406 (2016) 55–61

Contents lists available at ScienceDirect

International Journal of Mass Spectrometry

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

An aplanatic-lens velocity map imaging spectrometer with improved kinetic energy resolution for photoions

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ARTICLE INFO

Article history:
Received 9 April 2016
Received in revised form 8 June 2016
Accepted 13 June 2016
Available online 15 June 2016

ABSTRACT

We propose a new method to improve the energy resolution of photoions with an aplanatic velocity map imaging spectrometer. Building on the traditional VMI spectrometer with three aperture electrodes, we apply a stepped voltage on the extractor electrode of the spectrometer to reduce the spherical aberration effect of the electrostatic lens. This stepped voltage acts as a diverging electrostatic lens in ion optics. A combination of the converging electrostatic lens and the subsequent diverging electrostatic lens constitutes an aplanatic electrostatic lens. With precisely controlling the moment of the voltage, we suppress the spherical aberration effect induced by the converging electrostatic lens in the traditional VMI spectrometer. Both simulated and experimental results demonstrate that the energy resolution is significantly improved using this aplanatic-lens VMI spectrometer.

1. Introduction

Atoms and molecules exposed to strong laser fields will lead to many interesting strong-field phenomena such as above-threshold ionization [1], tunnel ionization [2,3], sequential or nonsequential double ionization [4–6], high-order harmonic generation [7,8] and molecular dissociation [9,10]. All of those phenomena can be used to retrieve the atomic and molecular information and dynamics [11,12]. Velocity map imaging (VMI) technique [13], developed by Eppink and Parker in 1997, is powerful in investigating the underlying dynamics of the dissociation, ionization and molecular collisions [14–16]. Experimentally, the VMI technique has been widely used in photoelectron holography [17–19], electron wavepacket interference [20,21], molecular orbital imaging [22,23], etc. In a typical velocity map imaging setup, the products resulting from the dissociation or the ionization processes are focused onto a two dimensional detector with an electrostatic lens configuration. In general, the detector consists of dual micro-channel plates, a phosphor screen, and a CCD camera. A 2D image is recorded on the detector, where the radial of the image is proportional to particle velocity and the intensity distribution around the azimuth is indicative of the angular distribution. In a linearly polarized laser field, the 3D initial velocity distribution of the generated particles is cylindrically symmetric. With some retrieval algorithms [24–26], the 3D initial velocity distribution can be reconstructed from the 2D raw image.

The energy resolution of the VMI setup stands as a crucial parameter for accurately imaging the atomic and molecular dynamics. A high kinetic energy (KE) resolution will provide an unambiguous image for strong-field atomic and molecular process, which is especially vital for some fine structures in the energy spectrum. For instance, the multiphoton ionization of some atoms and molecules shows some resonant peaks which are very close to each other in the photoelectron KE spectra [27–29]. In addition, Stark splitting also induces some fine structures in the photoelectron KE spectra [30,31].

In VMI spectrometers, with the electrostatic lens, the ions or electrons which origin from different positions with the same initial velocity vector are mapped to the same point in the focal plane. Thus the resolution of the ion imaging technique was dramatically enhanced. Since the use of the VMI, many works has been reported with high resolution [34–36]. A KE resolution as good as 0.38% has been reported by Maurice H. M. Janssen et al. in 2005 [35]. However, the aberration effect of the electrode lens in VMI has a crucial effect on the resolution of the image [37]. This effect is also found in imaging techniques using ion/electron optics, such as the spherical aberration effect in transmission electron microscopy (TEM) [32] and ultracold ion source [33]. The spherical aberration effect in VMI

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http://dx.doi.org/10.1016/j.ijms.2016.06.006
1387-3806/

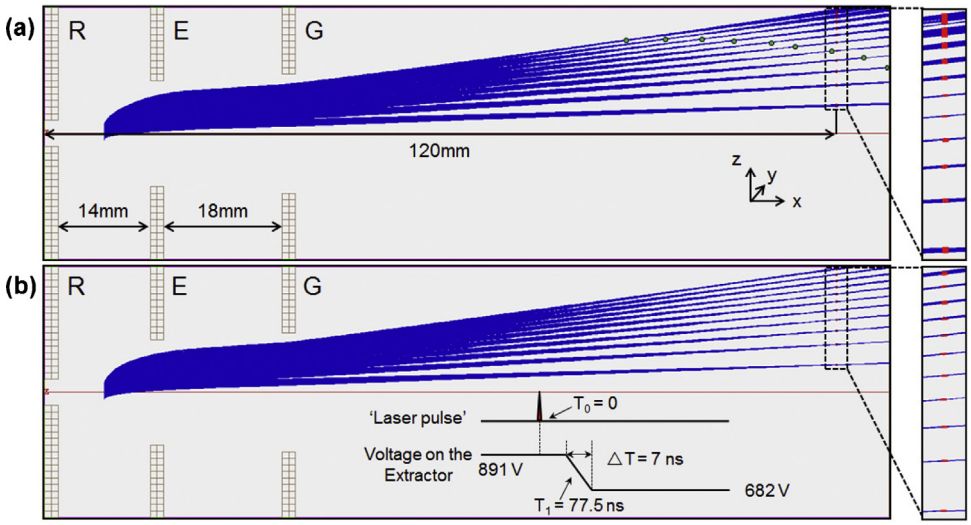

Fig. 1. Cross-sections of the traditional VMI spectrometer and the AL-VMI spectrometer. Blue lines are the trajectory of the ions. The red spots are the intersection points of the particles' trajectories with the detector. The green points are focuses of the ions, noting that the focuses (green points) in the bottom drawing are not shown for overlapping with the detector. In the two imaging spectrometers, the distances between the detector and the repeller electrode are identical. The two right panels show the enlarged view of the spots on the detectors. The electrodes' setups, which can be found in the figure, of the two imaging spectrometers are same as each other. R = repeller, E = extractor and G = grounded electrode. (a) Cross-section of the traditional VMI spectrometer. (b) Cross-section of the AL-VMI spectrometer. The inset is the voltage that we applied on the extractor and its timing match with the laser pulse in the AL-VMI spectrometer. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

manifests itself as the particles with different KE reaching a velocity focus at different positions along the time-of-flight direction. This effect leads to a "v" shaped dispersion [38] of the KE resolution, i.e., the resolution for ions with low KE and high KE is worse than that with the medium KE.

In recent years, several methods are proposed to improve the resolution of the spectrometer [39–41]. S. Skruszewicz et al. have designed a high energy VMI, in which two electrodes are added into the traditional VMI spectrometer [39]. The two additional electrodes act as another two concave electrostatic lenses. With the two additional electrostatic lenses, the ions/electrons can be squeezed further to the spectrometer axis thus increasing the KE measurement range of the spectrometer. This design could also improve the resolution of the photoelectrons. Another design called thick-lens VMI was proposed by N.G. Kling et al., who extends the applied electric field using 11 electrodes to form a thick electrostatic lens [41]. This permits measurements of the charged particles with higher KE while achieving a good resolution over a wide range of KE. However, this spectrometer consists by up to 11 electrodes, which is complicated for construction and adjustment. In this article, we introduce a much simpler method to improve the KE resolution of the ion images. On the basis of the configuration of the traditional VMI, we apply a stepped voltage on the extractor electrode to avoid the spherical aberration effect of the electrostatic lens. This stepped voltage acts as a diverging electrostatic lens. The intrinsic converging electrostatic lens and the subsequent diverging electrostatic lens constitute an aplanatic electrostatic lens. Through careful modelling and measurements of the ion images, we demonstrate the energy resolution can be significantly improved using this aplanatic lens VMI (AL-VMI). This paper is organized as follows. In Section 2, we investigate the performance of the AL-VMI spectrometer by simulation. The experimental implementation of the AL-VMI spectrometer is shown in Section 3. The discussion and conclusion of this paper are given in Section 4.

2. Simulations

We first show a typical VMI setup in Fig. 1(a). The spectrometer of the VMI consists of three plates with aperture electrodes. The distance between the repeller (R) electrode and the extractor (E) electrode is 14 mm, between the extractor electrode and the ground (G) electrode is 18 mm, and between the repeller electrode and the detector plane is 120 mm. The interaction region of the "laser" and the "molecular beam" is located in the middle of the electrodes R and E. The "laser" is linearly polarized along the *z*-axis and propagates along the *y*-axis. The ions' trajectories in the VMI spectrometer can be simulated using SIMION v. 8.0 [42]. The blue curves in Fig. 1(a) are the ions' trajectories with different KE. Here we have assumed that the size of the interaction region along the *y*-axis is 1.0 mm, and the size along the *x*-axis, which corresponds to the minimum beam waist of the "laser", is 10.0 μm. The initial KE ranges from 0.5 eV to 10.5 eV with an interval of 1 eV. This KE range of the ions is common in a typical VMI experiment. The initial velocity of the ions is along the *z* axis. A voltage of +740.5 V is applied on the repeller electrode and a voltage of +565 V on the extractor electrode. The focuses of the ion beams for different energies are labeled with green spots in Fig. 1(a). From Fig. 1(a), it can be clearly seen that the ions with high KE are focused earlier than that with low KE. In fact, this phenomenon is induced by the spherical aberration effect of the electrostatic lens. In the VMI spectrometer, ions with high KE fly through the edge of the electrostatic lens, while ions with low KE fly through the center of the electrostatic lens. Due to the spherical aberration effect, the ions with high KE flying away from the central line will be focused earlier than that with low KE flying near the central line. Generally, the detector plane is placed near the focus point of ions with the medium KE. Thus, on the detector plane, one can see that the width of the mapped ion distribution (labeled with red spots in Fig. 1) is minimum for ions with medium KE and it becomes very large for ions with low KE or high KE, i.e., the resolution for ions with low KE and high KE is worse than that with the medium KE. In short, the KE resolution of the VMI spectrometer decreases because of the spherical aberration effect.

To reduce the influence of the spherical aberration, we apply a stepped voltage on the extractor electrode instead of constant voltage for the traditional VMI. A similar method has been successfully used in transmission electron microscopy (TEM) [43] and ultracold ion source [33] to reduce the spherical aberration effect. Using