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Voltage optimization of a 4-element injection lens on a hemispherical spectrograph with virtual entry aperture

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ABSTRACT

We present simulation results for a biased paracentric hemispherical deflector analyzer equipped with a 4-element input lens and a position sensitive detector used in our zero-degree Auger projectile spectroscopy apparatus. Calculations of electron trajectories traversing the lens and analyzer fields were performed and cross checked using both boundary-element and finite-difference methods. The two middle lens electrode voltages were varied as free parameters, while various criteria were used to select their optimal values in an effort to obtain improved energy resolution.

1. Introduction

Accelerator-based atomic physics can now be investigated in Greece through the APAPES project [1] experimental setup with a newly operational innovative electron spectroscopy apparatus [2] composed of a paracentric hemispherical deflector analyzer (HDA) [3–7] equipped with a 4-element injection lens and a 2-D position sensitive detector (PSD) to be used for zero-degree Auger projectile spectroscopy (ZAPS) of ion–atom collisions [6,8,9].

In order to improve our experimental techniques on recording Auger electron energy spectra we also searched in *simulation* for the optimal lens voltages that would allow us to reach the highest energy resolution in our ZAPS [7,8] experimental setup. In this ZAPS apparatus, the electrons are measured in the direction of the beam (zero degrees) and therefore the physical size of the HDA entry aperture must be large (6 mm) to allow the uninhibited passage of the *ion beam* itself, which goes straight through the lens and HDA exiting from a hole in the back of the HDA and eventually stopped in a faraday cup used for ion beam normalization. Thus, the lens system plays a particularly important role in regulating the electron energy resolution of the analyzer since it defines the size of the much smaller *virtual* HDA entry aperture [10], which goes into the energy resolution formula. The values of the lens voltage combination, V_{L4} and V_{L5}, (see Fig. 1) and their relation to the size of the beam spot on the PSD, form families of elliptical-like contours [11], and have been investigated for different pre-retardation factors, $F = E_{s0}/E_0$, where E_{s0} is the electron source energy and E_0, is the pass energy ($F = 1$ for no pre-retardation, and $F > 1$ when $E_s < E_{s0}$). The relation between beam spot size and energy resolution was evaluated by means of computer simulations of electron trajectories flying through the entire spectrometer including the injection lens system.

The lens optimization was carried out by simulations using the SIMION 8.1 charge particle optics software package [12]. SIMION solved the Laplace equation in the lens and the HDA for the simulated experimental setup utilizing the finite difference method. Simple initial electron distributions were flown through the lens, HDA and all the way through to the PSD. The two lens voltages V_{L4} and V_{L5} were varied as free parameters while various criteria were used to select the optimal voltage combinations including PSD beam spot size minimization, lens magnification and beam angle minimization at the lens image plane and others in an effort to obtain improved energy resolution. The size of the resulting beam spot along the dispersion direction at the PSD, x_{span} was recorded for each electron distribution. The simulations were carried out for various

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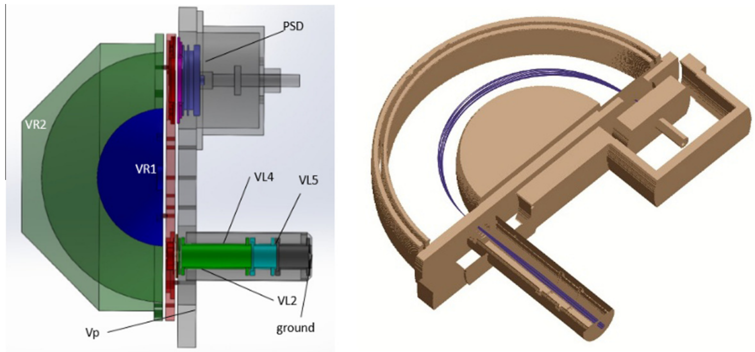

Fig. 1. (Left) Schematic representation of the spectrograph consisting of an injection lens, the HDA and the PSD. All the important electrode elements are shown. Each color represents a different voltage. V_{L4} and V_{L5} are the voltages on the corresponding lens electrodes varied in the simulations. The plate voltage V_p is responsible for the final electron deceleration. (Right) SIMION 3-D cropped image showing electron trajectories in the lens and HDA. Electron trajectories are started at the target ion–atom collision region about 288 mm away (not shown). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
List of simulation parameters for minimum x_{span} values obtained in SIMION for $F = 1$, 4 and 8. Also included are corresponding values of the beam width, y_{span} in the non-dispersive direction (y-axis) and the positions of the focal (z_f) and image (z_i) planes with the corresponding linear magnification M_L. The lens entry marks the position of $z = 0$.

F	V_{L4} (V)	V_{L5} (V)	SIMION determined quantities				
			x_{span} (mm)	y_{span} (mm)	z_f (mm)	z_i (mm)	$\lvert M_L \rvert$
1	−570	550	0.443	0.456	−143.8	−163.3	0.245
4	−570	625	0.679	0.738	−138.1	−160.0	0.387
8	−840	−510	0.904	0.999	−133.2	−157.9	0.512

lens pre-retardation factors F. The validity of the SIMION results were finally cross-checked with the boundary-element method (BEM) [13] and good agreement was invariably found.

The lens voltages obtained from simulations in this way will be soon tested on the actual experimental apparatus with the expectation that they will provide further improved energy resolution compared to the previously empirically found lens voltages [7].

2. Experimental setup

The APAPES experimental station is at the 5 MV Tandem Van de Graaff accelerator of the Institute of Nuclear and Particle Physics (INPP), located at the National Center for Scientific Research (NCSR) “Demokritos” in Athens. The description of the new beam line has been given elsewhere [2]. In Fig. 1 (left), assembly drawings of the HDA including 4-element injection lens and PSD in SolidWorks 3D [14] were used to prepare accurate geometry input data for the SIMION program using so called “geometry” files. Fig. 1

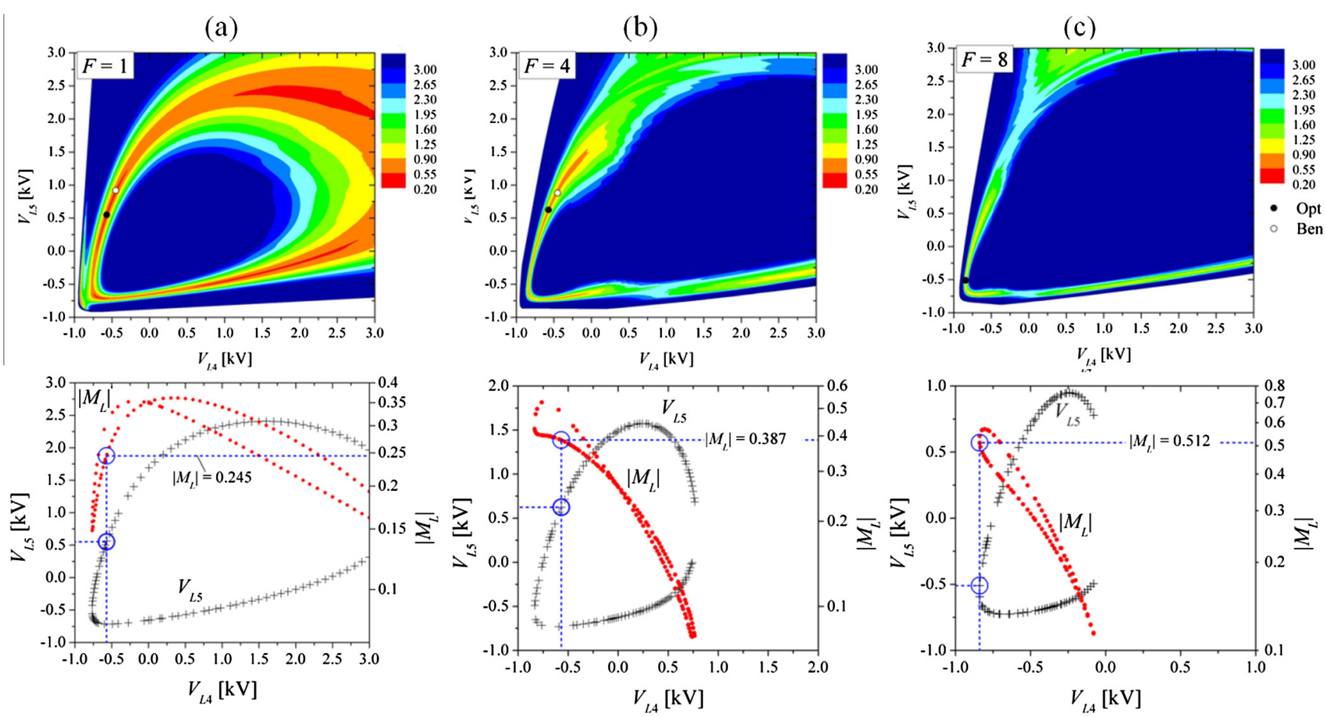

Fig. 2. Simulation results for (a) $F = 1$, (b) $F = 4$ and (c) $F = 8$. (Top) 2-D contour plots of the beam trace width x_{span} (in mm) as functions of V_{L4} and V_{L4} lens voltages. The optimal values of V_{L4} and V_{L5} are listed in Table 1 and shown as black dots, while older empirically found values are shown as white dots. (Bottom) Lens voltages V_{L4} and V_{L5} interdependence illustrated for the zoom-lens mode is plotted as black crosses. The corresponding linear magnification $|M_L|$ (refer to the logarithmic scale to the right) with respect to V_{L4} is also plotted as red dots. The open blue circles show the optimal working points (V_{L4}, V_{L5}, $|M_L|$) listed in Table 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

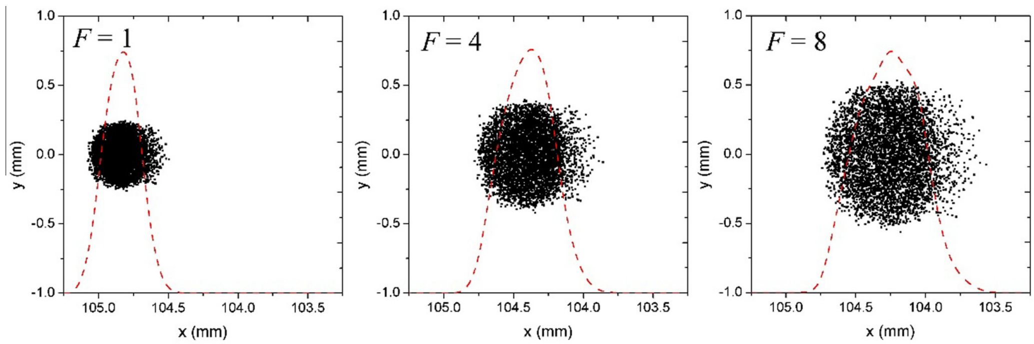

Fig. 3. Calculated spot size on the detector plane (xy-plane) of the PSD at the exit of the HDA for $F = 1$, 4 and 8. Normalized line profiles resulting from the vertical projections of the electron distributions along the dispersion direction (x-axis) are also shown from which the value of the FWHM could be determined.

(right) shows an example of simulated trajectories in the analyzer system for 1 keV pass energy and $F = 1$.

3. Simulation results

The geometry files used for the simulations in SIMION 8.1 utilized surface enhancement with a grid unit (gu) density of 0.254 mm/gu to ensure the highest accuracy conditions for the simulated apparatus. Electrode voltages for each of the four elements of the injection lens and the HDA itself as well as the initial conditions of the electron beam were controlled independently in SIMION by the use of Lua programming. The entire voltage space of both V_{L4} and V_{L5} lens voltages was scanned in steps of $\Delta V = 5$ V, while x_{span} was recorded for each combination. In our simulation, minimum values of x_{span} were found to be related to HDA optimal energy resolution as also expected from basic theory.

Simulations results are plotted in Fig. 2 (top) as 2-D contours of x_{span} versus V_{L4} and V_{L5} for $E_{s0} = 1$ keV and $F = 1$, 4 and 8. The optimal V_{L4} and V_{L5} voltage sets are displayed as black dots, while empirically discovered lens voltages using Auger lines produced in ion–atom collisions and previously used are also displayed as white dots and seen to also lie along the same contours. In Fig. 2 (bottom), we display the relationship between V_{L4} and V_{L5} and the variation of the linear magnification $|M_L|$ with V_{L4}, when the object z_0 and image z_i plane positions are held fixed (typically referred to as *zoom-lens curves*) [15].

In all cases the object plane position was set at $z_0 = +288.47$ mm while the image plane position is $z_i = -163.3$ mm for $F = 1$, $z_i = -160.0$ mm for $F = 4$ and $z_i = -157.9$ mm for $F = 8$, respectively. The lens entry is at $z = 0$, with the z-axis decreasing in the direction of the electron path. The lens itself has a total length of 149 mm. The detector is placed at a distance h = 17.56 mm from the HDA exit plane. The linear magnification at the optimal working points is also shown in red in Fig. 2 (bottom) and listed in Table 1.

In Table 1 we list the combinations of V_{L4} and V_{L5} voltages for $F = 1$, 4 and 8 that gave the minimum beam trace widths x_{span} together with the values of other important lens parameters.

In Fig. 3, the calculated exit spot sizes are shown on the detector plane (xy-plane) for each of the F values listed in Table 1. The size of the spot is seen to increase with F as the lens linear magnification also increases in agreement with the Helmholtz–Lagrange law that sets the ultimate limits on the energy resolution [10].

4. Summary and conclusions

Electron trajectories were simulated in the biased paracentric HDA [with 4-element injection lens and 2-dimensional position sensitive detector (PSD)] modeling existing apparatus. Optimal lens voltages were found by minimizing the measured simulated beam widths on the PSD plane leading to optimal energy resolution. We expect this approach to be helpful to experimenters in determining the lens voltages for best energy resolution, which can be done in simulation with substantial savings in overall effort. In addition, once such a simulation has been setup and tested, it can also be used beneficially by students as a learning tool to increase understanding of the experimental apparatus under optimal resolution conditions.

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