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Emittance characterization of a hot-cavity laser ion source at Holifield Radioactive Ion Beam Facility

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The first investigation of the transverse emittance of a hot-cavity laser ion source based on all-solid-state Ti:sapphire lasers is presented. The emittances of 65Cu ion beams generated by three-photon resonant ionization are measured and compared with that of the 69Ga and 39K ion beams resulting from surface ionization in the same ion source. A self-consistent unbiased elliptical exclusion method is adapted for noise reduction and emittance analysis. Typical values of the rms and 90% fractional emittances of the Cu ion beams at 20 keV energy are found to be about 2 and 8 π mm mrad, respectively, for the ion currents of 2–40 nA investigated. The emittances of the laser-produced Cu ion beams are smaller than those of the surface-ionized Ga and K ion beams. © 2009 American Institute of Physics. [DOI: 10.1063/1.3184343]

I. INTRODUCTION

Many of the fundamentally important reactions in nuclear physics and nuclear astrophysics are now being studied with radioactive ion beams (RIBs). The quality of RIBs extracted from the ion source is of vital importance to precision nuclear physics measurements. The efficiency to transport the beams from the ion source to the associated experiments, and the ability to suppress isobar contaminants by mass separators, are dependent on the quality of the ion beams. Emittance is the figure of merit widely utilized to characterize the quality of ion beams. It is used, for example, to determine the compatibility of an ion beam with a given beam transport system, the mass resolution of a mass separator, and the ion optics design of the experimental apparatus. Thus, the knowledge of precise emittance values of the ion source is necessary for many experiments.

Resonant ionization laser ion sources (RILISs) are playing an increasing role in providing isobarically pure RIBs for the frontier research.1–4 In a RILIS, a particular isotope can be selectively ionized by laser radiation via stepwise atomic resonant excitations followed by ionization in the last transition. The resonant ionization process is highly selective and is applicable to the majority of the elements in the periodic table.5,6 Today, a RILIS is being used, e.g., for more than 50% of the RIB experiments at the ISOLDE facility, CERN.7,8 Several other RIB facilities around the world are implementing or developing RILISs for their research programs.9 Despite the increasing importance of RILISs in generating RIBs for nuclear physics research and the fact that these ion sources have been the subject of many investigations related to such applications, there are few measurements of their emittance. The present investigation was motivated by this deficiency.

A hot-cavity RILIS based on all-solid-state Ti:sapphire lasers is under development at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory. Ion beams of stable isotopes of Sn, Ge, Ni, and Cu have been generated with the source by three-step resonant photoionizations.10,11 We report the first emittance characterization of the hot-cavity RILIS. The emittance of laser-produced Cu ion beams as well as surface-ionized Ga and K ion beams were measured for comparison. In Sec. II, we give the description of the laser ion source. The experimental apparatus and emittance measurement method are described in Secs. III and IV, respectively, and the algorithms for evaluating the beam emittance from the experimental data are given in Sec. V. It will be seen that effective noise exclusion is important for accurate emittance evaluation. In Sec. VI, we discuss the noise reduction methods and the procedure for data processing and emittance evaluation. The experimental and analysis results are presented in Sec. VII.

II. DESCRIPTION OF THE LASER ION SOURCE

The hot-cavity laser ion source used in this study consisted of a hot-cavity surface ionization ion source and a system of three tunable Ti:sapphire lasers. A schematic drawing of the ion source is shown in Fig. 1. The main element of this source was a tubular cavity made of a 30 mm long Ta tube of 3 mm inner diameter and 1 mm wall thickness. The cavity was connected to a target material reservoir via a Ta transfer tube of 8.5 mm inner diameter and 0.508 mm wall thickness. The length of the transfer tube is typically about 100 mm. Both the cavity and the transfer tube were resistively heated to high temperatures, while the target reservoir was heated radiatively by a separate resistive heater. To ob-
tain atomic species, solid samples were evaporated in the heated reservoir and the gaseous materials then effused through the transfer tube into the cavity. The atomic species of interest were ionized by the laser radiation entering into the cavity from the right through the extraction electrode and the ions were then extracted. The temperature of the cavity was typically 1600–2000 °C, sufficiently high for decomposing the molecular species, if present, into atomic components and for reducing the wall sticking time of the atomic species of interest, while maintaining relatively low probability for surface ionization of unwanted species. More details on the ion source can be found in Ref. 10.

The three Ti:sapphire lasers were developed and built at the University of Mainz. They were pumped by a single Q-switched Nd:YAG laser at 532 nm with 60 W of total pump power at 10 kHz repetition rate. Accordingly, the Ti:sapphire laser outputs were pulsed at 10 kHz, with a pulse width of about 30 ns. In order to suppress decay losses in stepwise resonant excitation, each Ti:sapphire laser was actively Q-switched using an internal Pockels cell so that the three lasers could be synchronized to within 5 ns. The fundamental output of the Ti:sapphire lasers was tunable between 700–960 nm with spectral linewidth of 1–3 GHz, which was suitable for resonant excitation and ionization of atomic species at high temperatures. Using higher harmonics of the fundamental Ti:sapphire laser output, tunable laser radiation between 200–480 nm could be obtained. The corresponding harmonic generation units for frequency-doubling, -tripling, and -quadrupling were also provided by the University of Mainz. Typical laser power available in this study was ~2 W in the fundamental, ~200 mW in frequency doubled, and ~40 mW in both the frequency tripled and quadrupled outputs. A more detailed description of the laser system can also be found in Refs. 12 and 13.

III. EXPERIMENTAL SETUP

The experiment was conducted at the HRIBF off-line Ion Source Test Facility 2 (ISTF-2), a schematic of which is shown in Fig. 2. The hot-cavity ion source was mounted on an ion source test stand at 20 kV. Ions extracted from the source were accelerated to 20 keV energy and focused by means of an Einzel lens into a double-focusing 90° dipole magnet for mass analysis. After mass separation, the ion beam was directed into an emittance measurement device located ~30 cm behind the image plane of the dipole magnet and ~6 m from the ion source. The intensity of the ion beam was monitored before and after mass analysis by insertion of remotely actuated Faraday cups, which were located immediately behind variable slit-type apertures positioned at the object and image planes of the mass analysis system.

Laser beams from the three Ti:sapphire lasers entered the beam line under vacuum through a view port located on the dipole magnet chamber. The laser beams traveled toward the ion source in the opposite direction of the ion beam and were focused from a distance of about 4 m into the tubular cavity.

The emittance of the ion beams of stable Cu isotopes produced by resonant laser ionization in the hot-cavity ion source was investigated. In preparation for this investigation at HRIBF, spectroscopic studies had been performed at the University of Mainz to identify different three-photon ionization schemes for Cu. Two of the schemes were successfully reproduced at HRIBF with the hot-cavity laser ion source and used to generate Cu ion beams. The Cu ion beam intensities available for emittance characterization were 2–40 nA. Details of the ionization schemes used and the spectroscopic studies on resonant ionization of Cu will be reported elsewhere. It should be noted that frequency quadrupled Ti:sapphire laser light was required for the first excitation step in Cu and that this study was the first time that frequency quadrupling of the Ti:sapphire lasers was used in a laser ion source application.

The hot-cavity ion source design employed here is widely used in positive surface ionization sources.14–16 During this study, ions of low ionization potential elements produced by surface ionization in the hot-cavity laser ion source were also observed. The surface ions included Na, K, Ca, Ga, and Sn, which came from impurities in the sample materials or the construction materials of the ion source assembly. A comparative study of the emittance of the laser and
surface-ionized ion beams provides valuable information on ion generation, confinement, and transport in the ion source. Therefore, the emittances of surface-ionized $^{69}$Ga and $^{39}$K ion beams, obtained under the same ion source operating conditions as for the laser-produced beams, were also measured. Ga and K surface-ionized beams were chosen for the comparative study because their mass and beam intensities were close to that of Cu. The Cu ions were solely produced by laser radiation. No surface-ionized Cu ions were observed. All measurements were conducted at 20 keV ion beam energy.

IV. METHOD OF EMITTANCE MEASUREMENT

The emittance measurement apparatus consisted of two identical stepping-motor driven slit-detector devices for determining the transverse emittance of an ion beam in $x$ and $y$ directions, respectively. It was a commercial unit constructed based on the slit-harp method for emittance measurement. The principle of this method is illustrated in Fig. 3. Each unit had an electrically insulated slit aperture, positioned 40 cm in front of a detector array which was made up of 32 tungsten strips that were equally spaced and parallel to the slit. The slit aperture was 0.1 mm wide and 40 mm long, while the detector strips were 0.508 mm wide and 50 mm long, separated by 0.406 mm wide ceramic insulators. The differential angle between two adjacent detectors was approximately $\Delta \theta = 2.285 \text{ mrad}$, and the detector plate positions to suppress the secondary electrons. Permanent magnets were mounted at the slit aperture and detector plate positions to suppress the secondary electrons. The magnitude of the magnetic field within the gap of the magnets was designed to be larger than 250 G and the magnetic field was oriented such that secondary electrons could not be emitted during ion current monitoring.

V. COMPUTATION OF EMITTANCE

The measured emittance data are two-dimensional arrays of beam intensities $I(x_i, x'_i)$ and $I(y_j, y'_j)$, where $x_i$ is the $i$th slit position and $x'_i$ the angular position of the $j$th ($i=1–32$) detector with respect to the z axis in the $x$-direction. The same definitions apply to $y_j$ and $y'_j$. Since the differential angle between two adjacent detectors is approximately $\Delta \theta = 2.285 \text{ mrad}$, the $j$th detector is at an angle of $x'_j = j \Delta \theta$ and $y'_j = j \Delta \theta$. The measured transverse space, $(x,x')$ or $(y,y')$, is the so called trace space. If the areas occupied by the beam in the $xx'$ and $yy'$ trace spaces are $A_{xx'}$ and $A_{yy'}$, respectively, the transverse emittances are given as $\varepsilon_{x'} = A_{xx'}/\pi$ and $\varepsilon_{y'} = A_{yy'}/\pi$. In this report we use the convention to include the symbol $\pi$ in the units, that is, $\text{mm mrad}$, and the emittances quoted are non-normalized emittances of the ion beams at 20 keV beam energy.

The algorithms for evaluating beam emittance in the $xx'$-plane are described below. The same algorithms and formulas, with $x$ replaced with $y$ and $x'$ replaced with $y'$, hold for the emittance in the $yy'$-plane.

A. rms emittance

The rms emittance is defined as

$$\varepsilon_{\text{rms}} = \sqrt{\langle x^2 \rangle (x'^2) - (xx')^2},$$  \hspace{1cm} (1)

where $\langle x^2 \rangle$, $\langle x'^2 \rangle$, and $\langle xx' \rangle$ are the second order statistic moments of the beam distribution in the two-dimensional trace space $(x,x')$. A similar equation holds for the $(y,y')$ space, which can be treated fully analogously. The rms emittance of the ion beam is calculated from the measured two-dimensional beam intensity array using Eq. (1), where the second moments of the beam distribution in the $xx'$-plane, $\langle x^2 \rangle$, $\langle x'^2 \rangle$, and $\langle xx' \rangle$, are determined as the following:

$$\langle x^2 \rangle = \frac{\sum_{i=1}^{N} \sum_{j=1}^{32} (x_i-x)^2 I(x_i, x'_j)}{I_{\text{tot}}},$$

$$\langle x'^2 \rangle = \frac{\sum_{i=1}^{N} \sum_{j=1}^{32} (x'_i-x')^2 I(x_i, x'_j)}{I_{\text{tot}}},$$

$$\langle xx' \rangle = \frac{\sum_{i=1}^{N} \sum_{j=1}^{32} (x_i-x)(x'_i-x') I(x_i, x'_j)}{I_{\text{tot}}},$$

where $I_{\text{tot}}$ is the total intensity.
\[
\langle x'^2 \rangle = \frac{\sum_{j=1}^{N} \sum_{i=1}^{32} (x'_j - x'_i)^2 I(x_i, x'_j)}{I_{\text{tot}}},
\]
(3)
\[
\langle xx' \rangle = \frac{\sum_{j=1}^{N} \sum_{i=1}^{32} (x_i - x'_j)(x'_i - x'_j)I(x_i, x'_j)}{I_{\text{tot}}},
\]
(4)
where \( N \) is the total number of selected slit positions across the ion beam in the \( x \)-direction and \( I_{\text{tot}} \) is the total ion current detected at the detector plane and is given by summing the ion currents on all 32 detectors and over all slit positions
\[
I_{\text{tot}} = \sum_{i=1}^{N} \sum_{j=1}^{32} I(x_i, x'_j),
\]
(5)
and \((x_c, x'_c)\) is the centroid of the ion beam distribution
\[
x_c = \frac{\sum_{i=1}^{N} \sum_{j=1}^{32} x_i I(x_i, x'_j)}{I_{\text{tot}}},
\]
(6)
\[
x'_c = \frac{\sum_{j=1}^{N} \sum_{i=1}^{32} x'_i I(x_i, x'_j)}{I_{\text{tot}}},
\]
(7)
A real beam with arbitrary phase space distribution is often represented by an equivalent ellipse of area \( \pi \sigma_{\text{rms}} \)
\[
\gamma_T x'^2 + 2 \alpha_T xx' + \beta_T x'^2 = \sigma_{\text{rms}}^2, \quad \text{with} \quad \beta_T \gamma_T - \alpha_T^2 = 1.
\]
(8)
The coefficients are the so-called Twiss or Courant–Snyder parameters given by
\[
\beta_T = \frac{\langle x'^2 \rangle}{\sigma_{\text{rms}}}, \quad \gamma_T = \frac{\langle xx' \rangle}{\sigma_{\text{rms}}}, \quad \text{and} \quad \alpha_T = -\frac{\langle x'^2 \rangle}{\sigma_{\text{rms}}}.\]
(9)
This is an imaginary perfect beam which has a homogeneous distribution within a hard-edged elliptical contour, and which has the same second moments and total intensity as the given beam. When the rms emittance and two of the Twiss parameters are known, the orientation and aspect ratio of the equivalent ellipse can be determined.

### B. Fractional emittance

In many cases, the outermost ions of an ion beam may extend far away from the core of the beam as a result of, for example, scattering processes. Those ions usually contribute to a very small fraction of the beam but could make the apparent geometric beam emittance significantly large. Therefore, another convention in the characterization of ion beams is to quote the emittance for a given fraction of the total beam. To obtain the fractional emittance, equal-intensity contours containing 10%–90% of the total ion beam are calculated in increments of 10%. The area within each contour divided by \( \pi \) is taken as the fractional emittance for the particular beam fraction. The contours are determined by iteratively excluding the data points with the lowest intensities and then performing a Simpson’s rule integration over the remaining data until a predefined fraction of the total integrated intensity is retained. The full set of the remaining data points outlines an area, within which all the data points have \( I(x_i, x'_j) \) values exceeding threshold intensity; while the exterior has all the points for which \( I(x_i, x'_j) \) is less than the threshold. The area divided by \( \pi \) then gives the emittance for the fraction of the beam enclosed and the outline of the area is the corresponding fractional emittance contour. In this report, the 90% fractional emittance is quoted for the beam emittance, which omits all low intensity data points with an integrated contribution of 10% of the total ion beam current.

### C. Beam profile

The projected one-dimensional beam profile in the \( x \)- or \( y \)-direction can also be derived from the measured emittance data. Summing the ion currents on all 32 strips at a slit position \( x_i \) gives the intensity of the beamlet \( I(x_i) \) passing through the slit
\[
I(x_i) = \sum_{j=1}^{32} I(x_i, x'_j).
\]
(10)
The listing of the beamlet intensities \( I(x_i) \) versus \( x_i \), \( i=1 \) to \( N \), thus depicts the projected beam intensity profile in the \( x \)-direction. The beam profile in the \( y \)-direction, \( I(y_i) \), is obtained in similar way.

### VI. DATA PROCESSING

Noise exclusion is essential for accurate emittance evaluation as the derived emittance value, especially the rms emittance, is very sensitive to the influence of noise in emittance data. In this study, the available ion beam currents were on the order of 2–40 nA. For such low beam intensities the amplifier-integrator circuits were operated with a gain of 1000, at which the background noise was also enhanced significantly. At first, the measured data are subjected to background subtraction by the use of the signal-free background data taken without the ion beam present but under similar operation conditions as the actual beam-on measurements.

As described above, the signals from the 32 detectors were sent to 32 individual amplifier-integrator circuits. Even though these circuit boards were made identical, small variations in the baseline values of the integrator outputs were unavoidable. When the amplifier-integrator circuits were operated at high gains, such variations became pronounced for relatively small signals. Moreover, the baselines of the detector channels were found to drift independently during the measurements. Thus, a characteristic feature of the emittance data is that the baseline level is different for each individual detector. To correctly remove the background noise, the baseline of each detector channel in the emittance data is subtracted individually using the background data taken for the corresponding detector, instead of a mean value for all the detectors.

### A. The self-consistent, unbiased elliptical exclusion (SCUBEEx) method

Very often, there remains substantial background noise in the data even after baseline subtraction, as seen in the regions off the peak in the three-dimensional (3D) display [Fig. 4(a)] or the equal-intensity contour plot [Fig. 4(b)] for a typical set of baseline-corrected emittance data. It is clear that further noise exclusion is necessary before extraction of emittance information. Removing the remaining noise could be highly subjective to personal preference and biased considerations. Stockli et al.\(^{24,25}\) have reported a SCUBEEx method, which provides a self-consistent, unbiased elliptical exclusion method to remove the remaining noise.
method for automatic data reduction and rms emittance calculation. Briefly, it is a procedure in which successively smaller exclusion ellipses are applied around the centroid of the measured beam intensity distribution. Any data points falling outside of the ellipse are assumed to be background noise and the mean value of all the outside data points is subtracted from each data point within the ellipse. As the ellipse becomes smaller, the corresponding rms emittance value decreases as more noise is excluded, and may eventually reach a plateau when most of the background noise is excluded while the real beam is intact. The boundary of the real beam is identified by the onset of the sharp drop in the rms emittance value as the ellipse is further reduced to truncate the beam. The rms emittance is then determined by taking the mean of the values in the plateau region.

We have utilized the SCUBEEx method for further data reduction and emittance evaluation but in a slightly different way. Since the background level has been subtracted from the emittance data, only the elliptical exclusion steps are performed. An example of noise reduction by the modified SCUBEEx method is presented in Fig. 5, where the emittance data shown in Fig. 4 are compared after noise exclusion using a 200 and 50 mm mrad exclusion ellipse, respectively. As noted, the noise is substantially removed with the 50 mm mrad ellipse while the actual beam is still intact. It demonstrates that SCUBEEx is an effective tool for automatic and fast noise reduction.

The fractional emittance is not as prone to small background noise as the rms emittance since the data points contained in a certain fractional emittance are determined by their intensities alone. However, for the emittance data taken with ion beam currents of less than 20 nA, the SCUBEEx method is found to be very useful and often necessary for the evaluation of the fractional emittances. Therefore, we also adopted the modified SCUBEEx process for fractional emittance evaluation.

FIG. 4. (a) 3D display and (b) equal-intensity contour plot of typical emittance data after baseline subtraction.

FIG. 5. 3D displays of the emittance data shown in Fig. 4 after noise reduction with an exclusion ellipse of (a) 200 and (b) 50 mm/mrad, respectively. The area inside the exclusion ellipse is shown in darker color.

FIG. 6. Comparison of beam distributions in x'x space (a) without and (b) with interpolated data points.
B. Data interpolation

The measured emittance data show that the ion beams, both laser-produced and surface-ionized, exhibit rather small angular distributions. In most cases not more than three detectors were struck by the beamlet passing through the slit aperture at each slit position. This indicates that the angular resolution of the emittance device was limited and may lead to underestimation of the beam emittance. Moreover, errors in determining the emittances, especially the fractional emittance, would be very large due to too few data points in \( \frac{x}{H} \) or \( \frac{y}{H} \)-distributions. To improve the accuracy of emittance evaluation, additional data points between two successive detectors are added by interpolation using a cubic spline fit. On the other hand, there is no need to interpolate the data in the \( x \)- and \( y \)-directions as the slit steps were sufficiently fine. Therefore, interpolation is only used to reconstruct the \( x' \) and \( y' \) angular distributions. For all the emittance analyses reported here, four interpolated data points are added between two successive \( x' \) or \( y' \) data points. The interpolation is performed on the data after background subtraction. A comparison of the equal-intensity contour plots in \( xx' \) trace space for the low intensity (<5 nA) \( ^{63}\)Cu and \( ^{69}\)Ga ion beams, measured under identical ion source operating and mass separation conditions, in equal-intensity emittance contour plots after data processing (baseline subtraction and interpolation) and noise elimination with selected exclusion ellipses. The spikes seen in the contour plot of the Cu ion beam in the \( yy' \) trace space are noise points that are too close to the beam to be removed by an exclusion ellipse without cutting the real beam. The positive inclination of the emittance patterns in \( xx' \) trace space corresponds to a diverging beam in the horizontal plane at the location of the emittance device, while the negative inclination of the emittance patterns in the \( yy' \) trace space indicates a converging beam in the vertical direction. This difference may be attributed to a slightly stronger focusing of the ion beams by the dipole magnet in the horizontal direction than in the vertical direction.

As expected, with the interpolated data points, uncertainties in calculating the fractional emittance have been significantly reduced and the fractional contours can be calculated to an accuracy of 0.1%. Both rms and 90% fractional emittances derived with interpolated data are, on the average, about 20% larger than those without interpolation.

VII. RESULTS AND DISCUSSION

Figure 7 shows typical emittance data in \( xx' \) and \( yy' \) trace spaces for the low intensity (<5 nA) \( ^{63}\)Cu and \( ^{69}\)Ga ion beams, measured under identical ion source operating and mass separation conditions, in equal-intensity emittance contour plots after data processing (baseline subtraction and interpolation) and noise elimination with selected exclusion ellipses. The spikes seen in the contour plot of the Cu ion beam in the \( yy' \) trace space are noise points that are too close to the beam to be removed by an exclusion ellipse without cutting the real beam. The positive inclination of the emittance patterns in \( xx' \) trace space corresponds to a diverging beam in the horizontal plane at the location of the emittance device, while the negative inclination of the emittance patterns in the \( yy' \) trace space indicates a converging beam in the vertical direction. This difference may be attributed to a slightly stronger focusing of the ion beams by the dipole magnet in the horizontal direction than in the vertical direction.

Although the emittance plots of the Cu and Ga ion beams look similar in shape, there are noticeable differences between them. The differences can also be seen clearly in the one-dimensional beam profiles obtained using Eq. (10), which are shown in Fig. 8 together with Gaussian fit curves and the full width at half maximum (FWHM) given by the Gaussian fitting. The Cu ion beam exhibits almost perfect Gaussian distribution in both \( x \)- and \( y \)-directions [Figs. 8(a) and 8(b)], suggesting that the Cu ions were produced by the laser beams in confined locations and were well thermalized having a Maxwell velocity distribution in the transverse...
phase space (and probably also in the longitudinal space, which was not explicitly probed in this study). On the other hand, the beam profiles of the surface-ionized Ga ions clearly deviated from a Gaussian distribution [Figs. 8(c) and 8(d)]. Although the calculated FWHM values of these profiles cannot be compared directly because of different focusing of the beams, these data show that the size of the low intensity Cu ion beams in each transverse dimension was small. The typical FWHM at the waist could be around 2 mm.

Figure 9 shows the SCUBEEx analyses for the $xx'$ and $yy'$ emittances of low intensity ($\leq$5 nA) laser-produced $^{63}$Cu and surface-ionized $^{69}$Ga ion beams. The data presented are the averaged SCUBEEx results of several experimental measurements for both Cu and Ga ion beams obtained on the
same day and under identical ion source operation and mass separation conditions. Only the plateau regions of the SCUBEEx curves are shown. The Cu ion beam currents available for the comparative study were between 2–4 nA, slightly less than that of the Ga ions. Consequently, the emittance data for Cu had larger noise and the corresponding SCUBEEx curves are more scattered and exhibit shorter and less flat plateaus than those of the Ga beams. However, it is clear that for all the measurements both the rms and 90% fractional emittances of the Cu ion beams converge to lower plateau values than those of the Ga beams, in both $xx'$ and $yy'$ trace spaces. The results indicate that the laser-produced Cu ion beams have smaller emittances than the surface-ionized Ga ion beams. The explanation for this could be that the Cu ions were created by laser beams within a narrow volume along the axis in the ion source, which was defined by the overlapping of the three laser beams. The Ga ions were produced from extended surfaces of a much larger volume and possibly of larger temperature differences. The possibility that the surface-ionized Ga ions had larger spatial and angular distributions and were less thermalized than the laser ionized Cu ions is consistent with the observation that the Ga beam profiles in $x$ and $y$ directions deviate from Gaussian distributions.

The emittance patterns of the surface-ionized K ions are found different from those of both Cu laser ions and Ga surface-ions. Figure 10 shows the contour plots, and beam profiles of a 6.5 nA $^{39}$K ion beam in the $x$- and $y$-directions. The K ion distributions are significantly distorted in both $xx'$ and $yy'$ trace spaces and the beam profiles exhibit multipeak structures, strongly deviating from the Gaussian distribution. Weak S-shaped features can also be noticed in the contour plots, indicating the presence of aberration effects experienced by the K ions.

Figure 11 compares the SCUBEEx results for the 6.5 nA $^{39}$K ion beam and the $^{63}$Cu ion beam of 25 nA, for which the emittance data were measured under the same ion source operating conditions. No space charge effects are expected at these beam currents as evidenced by the fact that the emittance values for the 25 nA Cu beam are similar to those of lower intensities (Fig. 9). Note the emittances obtained for the K beams are considerably larger than that of the laser-produced Cu beams as well as that of the surface-ionized Ga beams. This is in part due to the fact that K ions are lighter in mass and thus are expected to have larger thermal velocities and angular distributions than Ga and Cu ions at the same hot-cavity temperatures. Furthermore, the ionization potential of K (4.3407 eV) is smaller than that of Ga (5.9993 eV). Therefore, surface ionization of K is much easier and may take place at more extended and cooler surfaces than that of Ga, which could result in off-axis ions and thus larger beam sizes and angular distributions. All these facts are thought to contribute to the distorted emittance patterns and larger beam emittances for the K ions. Figure 10 also shows that the K ion beam was divergent at the emittance meter location in both horizontal and vertical directions, while the Cu and Ga beams were convergent in the vertical direction. This is due to slightly different Einzel lens voltages for the K beams, as the Einzel lens voltage was optimized for each beam individually. It was observed that a small change in the Einzel lens voltage would change the focus position of the ion.

![FIG. 10. Typical emittance contour plots (upper) and beam profiles (lower) obtained for surface-ionized $^{39}$K ion beams in $x$ (left) and $y$ (right) direction. The ion beam currents were about 6.5 nA.](image-url)
beams, and thus the orientation of the emittance ellipse measured, but did not significantly affect the beam emittance value.

Table I summarizes the evaluated non-normalized rms and 90% fractional emittance values for the laser ionized $^{63}$Cu and the surface-ionized $^{69}$Ga and $^{39}$K ion beams at 20 keV beam energy. The results listed are the mean values of the SCUBEEx analyses of more than ten measurements for Cu (beam currents: 2–40 nA) and three to four measurements for both Ga and K (beam currents: 3–7 nA). The errors on these values are the calculated pooled standard deviations.

It is seen from the table that the laser ion beam emittances are on the order of 2.5 and 8 mm mrad for rms and 90% fractional emittances, respectively, slightly smaller than that of the surface-ionized Ga beams and considerably smaller than that of the K beams. No measurable aberration effects are observed in the measured emittance data and there is no significant change in the beam emittance versus beam intensity for the Cu laser ions.

It is noticed in Table I that the value of the horizontal emittance ($xx$ trace space) is slightly larger than that of the vertical emittance ($yy$ trace space) for each individual ion beam. Although the differences are within the uncertainties of the emittance values, the trend may not be coincidental but rather reflects the influence of the mass analyzing magnet—the longitudinal energy spread in the ion beam contributes to a larger horizontal emittance due to the magnetic dispersion. In order to quantitatively verify this hypothesis, the ion trajectories, beam envelopes, and phase space ellipses of the ion beams within the experimental apparatus were simulated using the TRACE-3D (Ref. 26) code. As expected, the simulations confirm that an initial energy spread would cause an increase in the horizontal emittance but not in the vertical emittance. However, an initial energy spread of 10 eV is needed for about 5% increase in the horizontal emittance and up to 20 eV is needed for a 10% increase. These energy spreads are certainly too large for the hot-cavity ion source but could result from small instabilities in the acceleration and Einzel lens voltages. Unfortunately, we could not measure the energy spread of the ion beams during these investigations. Nevertheless, the simulation results show the order of magnitude and trend of the influence of the longitudinal energy spread on the transverse emittances.

### VIII. CONCLUSION

The transverse emittance of the $^{63}$Cu ion beams produced by three-photon resonant ionization using Ti:sapphire lasers in a hot-cavity laser ion source has been measured using the slit-harp method. In order to obtain useful and realistic emittance values, various noise reduction methods have been used in data processing and emittance analysis. The SCUBEEx method is found to be an effective tool for automatic and fast noise reduction and can significantly reduce the errors introduced by noise and other artifacts.

The estimated rms and 90% fractional emittances of the Cu ion beams are on the order of 2 and 8 mm mrad, respectively, in both $xx'$ and $yy'$ trace spaces, for the ion cur-

**TABLE I. Estimated emittance values in π mm mrad for 20 keV $^{63}$Cu, $^{69}$Ga, and $^{39}$K ion beams.**

<table>
<thead>
<tr>
<th>Ion beam</th>
<th>rms $\epsilon_x$</th>
<th>rms $\epsilon_y$</th>
<th>90% $\epsilon_x$</th>
<th>90% $\epsilon_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{63}$Cu</td>
<td>2.2 ± 0.4</td>
<td>2.2 ± 0.5</td>
<td>7.6 ± 0.6</td>
<td>7.3 ± 0.8</td>
</tr>
<tr>
<td>$^{69}$Ga</td>
<td>3.2 ± 0.4</td>
<td>2.8 ± 0.4</td>
<td>11.7 ± 0.6</td>
<td>10.3 ± 0.5</td>
</tr>
<tr>
<td>$^{39}$K</td>
<td>5.1 ± 0.4</td>
<td>4.7 ± 0.4</td>
<td>17.9 ± 0.6</td>
<td>17.3 ± 0.6</td>
</tr>
</tbody>
</table>
rants of 2–40 nA investigated. These values are smaller than that of the Ga beams and significantly smaller than that of the K beams produced by surface-ionization in the same source under similar operating conditions. Comparisons of the emittances of these beams indicate that the laser ionized Cu ions were produced within a well localized, small volume along the axis and were well thermalized in the ion source, while the surface-ionized Ga and K ions were created with spatial and angular distributions larger than that of the Cu ions.

The results of this study also show that the emittance of the laser ion source is considerably smaller than the emittances of other types of ion sources that are used at HRIBF and have been investigated with the same emittance apparatus. For example, at 20 keV beam energy, the 90% fractional emittance is on the order of 60, 80, and 25 μm mrad for the HRIBF sputter ion source,\(^{27}\) electron cyclotron resonance ion source,\(^ {28}\) and electron beam plasma ion source, respectively, demonstrating that besides better selectivity, RILISs can also provide better beam quality.

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27 Trace 3D is developed and distributed by the Los Alamos National Laboratories Accelerator Code Group.
