Recent Results with the 6GHz Flat-*B* ECR Ion Source at ORNL-HRIBF*

Y. Liu[1;1)] Y. Kawai[2] G. D. Alton[1]

1 (Oak Ridge National Laboratory, Oak Ridge, TN 37831-6368, USA)
2 (AccSys Technology, Pleasanton, CA 94566, USA)

Abstract Experimental studies were conducted to characterize and improve the performance of the flat-*B* ECR ion source. The emittance of the source was investigated for the first time. The output beam currents of high-charge-states of Ar (q >8) were nearly doubled by increasing the plasma electrode aperture from 4mm to 6mm in diameter. To investigate possible enhancements with broadband microwave radiation, a "white" Gaussian noise generator was employed with a TWT amplifier to generate microwave radiation with a bandwidth of ∼200MHz. The performance of the flat-*B* ECR ion source was found to be much better with narrow bandwidth radiation when the source was operated in the flat-*B* region. However, the ion beam intensities and charge state distributions were improved with the broadband radiation when the source was tuned off the flat-*B* region.

Key words ECR ion source, flat-*B* configuration, multi-charged ions, broadband microwave, emittance

1 Introduction

The all-permanent, 6GHz ECR ion source at the Holifield Radioactive Ion Beam Facility (HRIBF), Oak Ridge National Laboratory (ORNL) was constructed with its axial magnetic field in either conventional parabolic or central flat (flat-*B*) profiles[1]. In the flat-*B* configuration the central magnet field is nearly constant over a region of ∼2cm to form a large ECR volume on axis that is in resonance with single frequency microwave radiation[2]. The source can be operated in either configuration for direct comparison of the performances of volume and surface ECR modes. A detailed description of the source and its performances can be found elsewhere[1, 3, 4]. It has been demonstrated that the volume ECR mode produces higher charge-states and higher intensities within a particular charge-state than does the surface ECR mode[3]. However, much work remains to bring the flat-*B* source performance to levels competitive with existing sources. In recent studies, we investigated different plasma electrode apertures, broadband microwave radiation, biased disk, and plasma potential measurement with Langmuir probes. The effects of plasma electrode aperture and broadband radiation are reported in this article. ECR ion sources are playing an ever-increasing role in the production of high intensity beams of multiply charged ions for accelerator based nuclear and particle-physics experiments. It is important to have a measure of the quality of such beams in terms of their ability to be transported over long distances or to be focused into small spot sizes. With a newly installed emittance measurement system at the HRIBF, the emittance of the flat-*B* ECR ion source was investigated for the first time. The emittance system and the preliminary

Received 20 April 2007
* Supported by the U.S. Department of Energy under contract DE-AC05-00OR22725 with UT-Battelle, LLC
1) E-mail: liuy@ornl.gov

emittance results are also briefly reported here.

2 Plasma electrode aperture

The flat-B ECR ion source was initially operated with a 4mm plasma electrode aperture. To increase the output of the source, the aperture was increased to 6mm. Fig. 1 presents the Ar ion intensities and the best distributions of high-charge-state ions obtained with the 6mm aperture as compared to the 4mm aperture under similar source operation conditions (Fig. 1(a)) and when the source parameters were optimized separately for each aperture (Fig. 1(b)). The data shown in Fig. 1(a) were obtained with low rf power of 37.6W (f=6.158GHz) for 6mm aperture and 42.7W (f=6.155GHz) for 4mm aperture at similar gas pressures. As seen, the beam intensities of all charge states were nearly doubled as the aperture was increased from 4mm to 6mm. When rf power and other source parameters were optimized for high charge states, the best Ar^{8+} intensity increased from 25μA to 30μA while the intensities of higher charge states ($q>9$) were more than a factor of 2 higher with the 6mm aperture. The rf power needed for peak source output was also higher with 6mm aperture. The difference in optimal rf power between 6mm and 4mm aperture can be clearly seen in the Ar^{8+} intensity versus rf power as illustrated in Fig. 2. The 6GHz flat-B source was initially powered with a Klystron amplifier. A traveling wave tube amplifier (TWTA) was recently utilized. Also shown in Fig. 2 is Ar^{8+} intensity versus microwave power from the Klystron when the source was operated with a 4mm plasma electrode aperture. As noted, the source output was peaked at much lower rf power from the TWTA than the Klystron; further increasing the TWTA output resulted in lower ion beam intensities. However, for the same plasma electrode aperture higher Ar^{8+} currents could be obtained with the Klystron at much higher rf power. Similar results have been reported by Celona et al[5]. The enhanced source performance with TWTA at lower rf power was attributed to the relatively larger frequency bandwidth in TWTA output than that of the Klystron – the ECR zone induced in the source with TWTA was a finite volume instead of a thin surface, consequently, microwave power could be more efficiently absorbed and more electrons could be heated to higher energies. These results indicate that a proper broadband microwave radiation could improve the performance of ECR ion sources, as discussed in the next section.

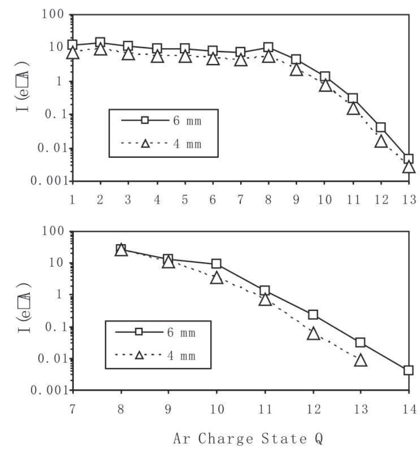

Fig. 1. Comparisons of Ar charge state distributions obtained with 6mm and 4mm apertures (a) under similar operation conditions and (b) with source parameters optimized for each aperture.

Although the output of the flat-B ECR ion source was increased with a 6mm plasma electrode aperture, the capability of the source for generating highly charge ions is still limited. It could be mainly attributed to 1) low effective plasma confinement (the last closed constant-B field is at 3.3kG) and 2) too small RF chamber for effective rf injection. To further improve the source performance, better plasma confinement and improved rf injection system may be necessary.

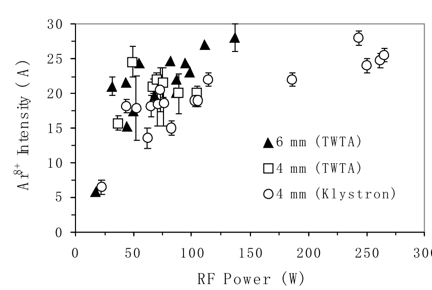

Fig. 2. Ar^{8+} intensity versus rf power from a TWTA and a Klystron with 6mm and 4mm plasma electrode apertures.

3 Broadband microwave radiation

Injecting multiple discrete frequency microwave radiation into conventional-B geometry ECR ion sources has proven to enhance the performances of these sources by forming multiple ECR zones in the sources[6—9]. It was also suggested that broadband microwave radiation could be a more effective alternative for increasing the physical sizes of the ECR zone within these sources[10]. To investigate this alternative, a broadband microwave system consisting of a noise generator, an external local oscillator, and a TWTA has been developed at the HRIBF[11]. The noise generator generates additive white Gaussian noise (AWGN) with a bandwidth of 200MHz as shown in Fig. 3, which are sent to the TWTA for amplification. The amplified broadband radiation is then injected into the ECR ion source. The central frequency of the broadband radiation is tunable via the external local oscillator from 5.85 to 6.65GHz[12].

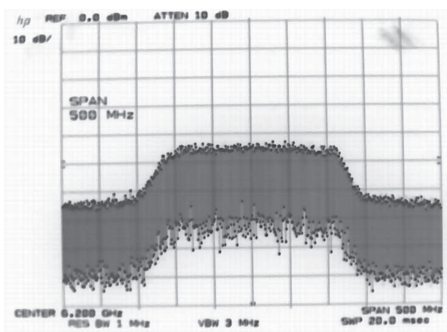

Fig. 3. rf spectrum of the noise generator output operating at a central frequency of 6.2GHz.

The broadband microwave was first used to power the flat-B ECR ion source and the source performance with the 200MHz broadband radiation was compared with that of narrow bandwidth radiation (single frequency) from the TWTA without the noise generator. All the comparative measurements were made using Ar gas and the source parameters were optimised for Ar^{8+}. Of special interest was the source performance as a function of the microwave frequency. As shown in Fig. 4, the source performance was much better with single frequency microwave than the broadband microwave at frequencies <6.3GHz, which corresponded to the resonant frequencies of the flat region of the magnetic field. When the frequency was increased above 6.3GHz, off resonance from the flat field region, the source performance dropped significantly with single frequency microwave. This behaviour is a further proof that volume ECR could out perform surface configuration, as we have previously reported[3]. In contrast to single frequency operation, the source performance was improved in the non-flat region when the broadband was used, suggesting that broadband radiation could enhance the performances of conventional minimum-B ion sources. The first experimental results with the noise generator to inject a 200MHz bandwidth microwave radiation into a conventional minimum-B, 6.4GHz ECR ion source reported enhancement for $Ar^{9+\rightarrow 11+}$ by factors >2 with broadband microwave radiation over those powered with narrow bandwidth radiation[13]. However, comparing volume ECR with the broadband method, the results also indicate that the former is better than the latter, provided that all other parameters are the same.

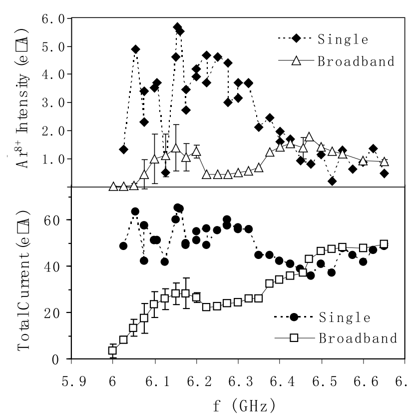

Fig. 4. (a) Ar^{8+} intensities and (b) total ion beam intensities (measured prior to magnetic analysis) as a function of microwave frequency with single frequency and broadband radiation.

4 Emittance measurements

ECR ion sources are known to have relatively large emittances due to large transverse energy spread in ions, high axial magnetic fields in the extraction region, and space-charge-effects. Improving the emittance of ECR ion sources is essential for their applications. A new emittance measurement system was recently installed at the off-line ion source test facility of HRIBF for ion source characterization. It is comprised of two identical step-motor driven “slit-harp” units for determining the transverse emittance of an ion beam in x (horizontal) and y (vertical) directions, respectively. Each emittance unit consists of an electrically insulated slit aperture, positioned 0.4m in front of a detector array which is made up of 32 electrically isolated tungsten strips. The current striking each of the detectors is used to determine the differential angular divergence of the ion beamlet passing through the slit aperture at a given x or y position. The angular resolution of the device is ± 1.14mrad. The slit-detector unit is mounted on a common support base which is driven by a 1.8° stepping motor with a linear resolution of 0.015mm for accurate linear motion and position determination. By stepping the slit-detector unit across the ion beam and recording the angular distribution at each position, the ion distribution as a function of the position and angular divergence is obtained. The emittance measurements were fully automatic and computer controlled.

The emittance system can be placed before or after the mass analyzing magnet to measure the emittances of total ion beams or mass selected beams. Either information is important to ion source development. In the present study, it was installed before the mass analysis magnet, about 0.3m behind the object point of the bending magnet, for determining the emittance of the total ion beams extracted from the ion source. The only optical element between the source and the emittance device was a 3” inner diameter einzel lens. Preliminary emittance measurements were conducted for the flat-B ECR source with a 6mm plasma electrode aperture and a simple single-gap extraction system. However, at the time of the study the y-unit was not completed, thus, only the transverse emittances in the horizontal direction were measured. Fig. 6 shows a typical $x-x$’ emittance pattern observed and the corresponding emittance contours for 10%—90% of total ion beam intensity. For emittance measurements the source parameters were optimized for high charge states and the position of the extraction electrode and the einzel lens voltages were optimized for maximum Ar^{8+} intensity extracted from the source. The plasma electrode was located about 3cm away from the apex of the axial magnetic field. The optimal extraction electrode position was found to be about 2.3cm from the plasma electrode. In all measurements, similar S-shaped patterns as shown were observed, indicating large aberrational effects experienced by the ion beam or unmatched extraction conditions. Such distorted emittance patterns were indeed predicted by simulations for the cases when the plasma electrode was not located at the apex of the magnetic field[14]. As noted, the wings in the emittance pattern are not symmetric, which also suggests that the source was perhaps mounted slightly off axis.

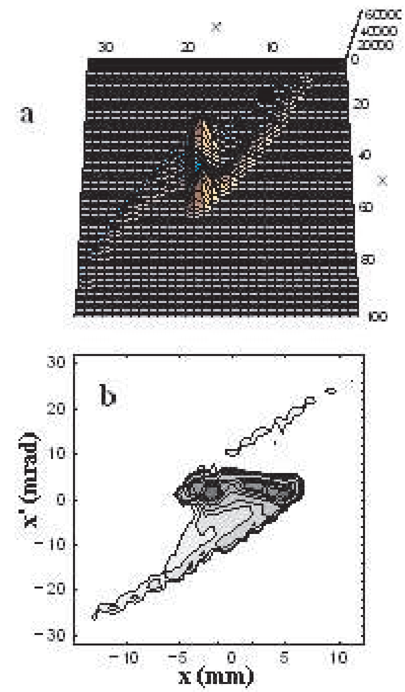

Fig. 5. Measured emittance data and the calculated emittance contours for 10%—90% of the total ion beam current.

Room-mean-square (rms) emittances and fractional emittances corresponding to 10%—90% of the total ion currents were evaluated from measured emittance data. The rms emittance was calculated as

$$\varepsilon_{\rm rms} = \sqrt{<x^2><x'^2> - <xx'>^2}\ , \tag{1}$$

where $<x^2>$, $<x'^2>$ and $<xx'>$ are the second moments of the beam distribution in the (x, x')

plane. For fractional emittances the emittance contours which contain 10%—90 % of the total beam were calculated by performing a Simpson's rule integration over the emittance data iteratively in increments of 10% to an accuracy of 0.1%. The area within a particular contour is the emittance for that particular beam fraction. The resulting rms and 90% beam emittances for three different total currents extracted from the flat-B source at 20kV are listed in Table 1 (in units of π·mm·mrad). The 90% emittance was given as the area of the 90% beam contour divided by π. These emittance values are relatively small compared to those of other ECR ion sources. However, they clearly show a trend to increase with increasing ion current, which may be attributed to space-charge effects. Emittances of higher ion currents were not measured due to signal saturation (the gain levels of the emittance device were later modified).

Table 1. rms and 90% contour beam emittance.

rf/W	f/GHz	I/eμA	rms	90%
17.7	6.085	64	25.8±0.10	71.4±0.52
40	6.158	91	31.1±0.26	86.6±0.93
42	6.159	102	32.57	88.15

Further systematic measurements are necessary to completely characterize the emittance of the flat-B ECR ion source. However, the results obtained already show that the simple one-gap extraction system will not provide low-aberration beams. Improved extraction system, such as the accel-accel system originally designed for this source[14], will be investigated.

References

1 LIU Y, Alton G D, Reed C A et al. Rev. of Sci. Intrum., 1998, **69**: 1311

2 Alton G D, Smithe D N. Rev. Sci. Instrum., 1994, **65**: 775

3 LIU Y, Alton G D, Bilheux H et al. Proc. 16th International Conf. on ECR Ion Sources, ed. M. Leitner, AIP, 2005, **CP749**: 191

4 LIU Y, Meyer F M, Cole J M. Proc. 16th International Conf. on ECR Ion Sources, ed. M. Leitner, AIP, 2005, **CP749**: 187

5 Celona L, Gammino S, Ciavola G et al. Proc. 16th International Conf. on ECR Ion Sources, ed. M. Leitner, AIP, 2005, **CP749**: 99

6 XIE Z Q, Lyneis C M. Rev. Sci. Instrum., 1995, **66**: 4218

7 Alton G D, Meyer F M, LIU Y et al. Rev. Sci. Instrum., 1998, **69**: 2305

8 Vondrasek R et al. 16th Int. Workshop on ECR Ion Sources, Berkeley, California, September, 2004. 31

9 Vondrasek R, Scott R, Pardo P et al. Proc. 16th International Conf. on ECR Ion Sources, ed. M. Leitner, AIP, 2005, **CP749**: 31

10 Alton G D, Kawai Y, LIU Y et al. Proc. 16th International Conf. on ECR Ion Sources, ed. M. Leitner, AIP, 2005, **CP749**: 103

11 Kawai Y, Alton G D, LIU Y. Proc. 2005 Particle Accelerator Conference, 1529

12 The Model UFX9850 white-noise generator is a product of Noise/Com, Inc. Parsippany, NJ 07054

13 Alton G D, Kawai Y, LIU Y et al. HEP & NP, 2007, **31**(Suppl. Ⅰ): 128 (in Chinese)
(Alton G D, Kawai Y, LIU Y et al. 高能物理与核物理, 2007, **31**(Suppl. Ⅰ): 128)

14 Hassina N. Bilheux, Ph.D. thesis, Université de Versailles Saint-Quentin-en-Yvelines, France (2003)