# Enhancing the Performances of Conventional $B$-Geometry ECR Ion Sources with Broadband Microwave Radiation*

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**Abstract** As clearly demonstrated at several laboratories, the performances of electron-cyclotron resonance (ECR) ion sources can be enhanced by increasing the physical sizes (volumes) of embedded ECR zones. Enlarged ECR zones have been achieved by engineering the central magnetic field region of these sources so they are uniformly-distributed “volumes” in resonance with single-frequency rf power. Alternatively, the number of ECR surfaces in conventional minimum-$B$ geometry sources can be increased by heating their plasmas with multiple, discrete frequency microwave radiation. Broadband rf power offers a simple, low cost and arguably more effective means for increasing the physical sizes of the ECR zones within the latter source type. In this article, theoretical arguments are made in support of the volume effect and the charge-state enhancing effects of broadband microwave radiation (bandwidth: 200MHz) plasma heating are demonstrated by comparing the high-charge-states of Ar ion beams, produced by powering a conventional minimum-$B$ geometry, 6.4GHz ECR ion source, equipped with a biased disk, with those produced by conventional bandwidth (bandwidth: ~1.5MHz) radiation.

**Key words** ECR ion source, ECR volume-effect, ECR zone size, broadband ECR plasma heating

## 1 Introduction

High-energy, heavy-ion accelerator-based nuclear physics and nuclear-astrophysics research facilities rely heavily on the availability of high-charge-state ion beams as effective means for increasing energies while reducing facility costs since the final energies of heavy ion beams increase linearly with charge-state, $q$, in electrostatic and linear rf acceleration devices and as $q^2$, in cyclical rf acceleration devices, such as the cyclotron or synchrotron. The electron cyclotron resonance (ECR) ion source is arguably the best choice of existing sources for the generation of cw beams of highly-charged ions.

During the past decade and a half, remarkable progress has been made in the advancement of the technologies of the ECR ion source, due in large-part to an enhanced understanding of the mechanisms underlying complex ion formation and factors that limit ion production. Advanced sources have been utilized for the past few decades with great success as viable sources of a wide variety of high-charge-state ion beams at high-energy, heavy-ion accelerator-based research facilities for nuclear physics and nuclear-astrophysics research. The charge-state-distributions in these sources are affected, under optimum vacuum conditions, by the electron population and energy distribution, means for introducing electrons, their efficient acceleration and confinement. The efficiency of ECR acceleration depends on the sizes and locations

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of the ECR zones in relation to the launch direction and modal character of the injected rf power.

As reviewed in Ref. [1], the technology of the ECR source has slowly but steadily advanced principally through: improvements in plasma confinement; improvements in vacuum quality; supplementing their plasma-discharges with cold electrons; and use of the gas mixing effect. The ECR-zones, in conventional minimum-$B$ geometry ECR ion sources, powered with narrow-bandwidth microwave radiation, are thin volumes which are small in relation to their total plasma volumes. Therefore, the probability for acceleration of electrons that arrive in the ECR zone in phase with the electric field vector of the electromagnetic wave is lower than possible in extended volume ECR zones. Therefore, it is reasonable to believe that the performances of conventional minimum-B ECR ion sources can be improved by increasing their respective resonance volumes, as suggested in Refs. [2—6]. Due to the fact that absorption of RF power depends on sizes of embedded ECR zones, sources with larger ECR zones have the ability to absorb more ECR power and consequently, the ability to accelerate larger populations of electrons to higher energies-desirable attributes for producing high-intensity, high-charge-state ion beams. The importance of ECR zone size on the performances of ECR ion sources has been clearly demonstrated by tailoring the central magnetic field so that it forms a large resonant volume[7—9] (spatial domain) and by increasing the number of discrete frequencies used to power conventional minimum-$B$ geometry sources[10—13]. However, in practice the number of discrete frequencies and consequently, the number of resonance zones embedded in the plasma, is limited by the number of rectangular waveguide injection ports or the number of signal generator input ports in the multi-channel combiner used to inject individual frequencies into the source[12, 13].

As predicted in Refs. [4—6], broadband sources of rf power offer cost effective, simple to operate and, arguably, more effective alternatives for increasing the physical sizes of ECR zones in conventional minimum-$B$ geometry (frequency-domain) sources. The present article provides evidence of the viability of the broad bandwidth technique for enhancing the performances of convention-$B$ geometry sources by comparing the charge-state distributions and intensities extracted from a conventional minimum-$B$ geometry, 6.4GHz ECR ion source[14], equipped with a biased disk, when operated with traveling-wave-tube (TWT) amplified microwave signals generated, respectively, from an additive “white-noise” generator (WGN) (bandwidth: ~200MHz)[15]) and a conventional local oscillator (LO) generator (bandwidth: ~1.5MHz). A block diagram for the WNG injection system is shown in Fig. 1.

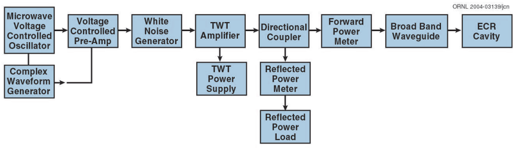
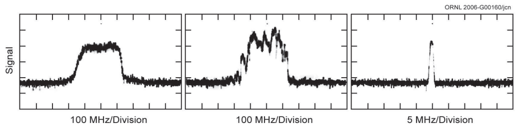


Fig. 1. Schematic block diagram of the WNG injection system.

## 2 Experimental arrangement and procedures

All experiments were performed with the JYFL 6.4GHz conventional minimum-$B$ geometry ECR ion source (Fig. 1)[14] at the University of Jyväskylä using Ar as the feed gas. The performances of the source were compared when operated with either narrow bandwidth radiation, produced in a conventional local oscillator or with broad bandwidth microwave radiation from a white noise generator[15], under the same neutral gas pressure and input power conditions. The carrier signal from the local oscillator (LO, bandwidth: ~1.5MHz) was fed directly into the traveling wave tube amplifier (TWTA) for the narrow bandwidth experiments. For the broadband experiments, the signal from the LO was fed into a white-noise generator producing and output signal with bandwidth: 200MHz FWHM, equally distributed about the central frequency of the LO (6.4GHz) signal.

All measurements were carried out at the same microwave power level (200W), determined by subtracting the reflected power from the forward power of the TWTA. Ion beam intensities were monitored in an electron suppressed Faraday cup located after magnetic mass analysis. Neutral gas pressures were measured at the injection end of the source without igniting the plasma. Power injected into- and reflected from- the plasma chamber was monitored at the TWTA. Fig. 2 displays typical WNG and LO generated rf spectra, as monitored with the biased disk when used as an antenna, positioned at the injection end of the plasma chamber, after amplification by the TWTA.



(a) (b) (c)

Fig. 2. (a) WNG prior to injection and (b) WN after injection, as monitored with the biased disk as an antenna; (c) LO spectra prior to injection.

As noted in Fig. 2(b), the broadband rf signal, recorded from the biased disk, is no longer uniformly distributed, as compared to the distribution monitored at output of the TWTA, due to impedance mismatch of certain frequencies in the distribution, resulting in reflection of ~20% of the injected power. For narrow bandwidth operation (Fig. 2(c)), ~6% of the LO signal was reflected without change in shape after amplification and injection into the plasma chamber.

Plasma potentials were measured with an instrument described in Ref. [16] for both modes of operation. The biased disk was operated at a voltage of $\sim -210$V, determined to optimize $Ar^{11+}$ beam intensities. A high-purity Ge detector was used to monitor un-collimated X-ray emission along the radial direction of the source.

## 3 Experimental results

The reproducibility of all data derived in these experiments was $< \pm 10\%$. Fig. 3 displays $Ar^{11+}$ beam intensity versus pressure, produced with TWTA amplified signals from the WNG and LO, with 0V and $-210$V respectively applied to the biased disk.

The intensities of high-charge-state ions (e.g., $Ar^{9+,}$ $Ar^{10+}$ and $Ar^{11+}$) are found to increase in resonant-like manner at a pressure of $\sim 2.6\times10^{-5}$ Pa and precipitously fall at lower pressures. The observed resonant-like plasma density dependent effects cannot be readily explained in terms of electron heating/microwave absorption processes nor can be attributed to any of the principal atomic physics processes which dictate the equilibrium composition of the charge-state distribution. As noted in Fig. 3, the affect of broadband radiation on the high-charge-states of $Ar^{q+}$ (e.g., $Ar^{9+}$ and higher) is clear (factors $> 2$). The fact that the biased disk voltage does not affect the observed trend suggests that the physical processes underlying the beneficial effects of these techniques (broadband heating and biased disk) on the production of high-charge-state ions are different. The voltage applied to the biased disk apparently affects the loss rate of cold electron population increasing the electron density of the plasma while broadband microwave radiation affects the electron heating process.

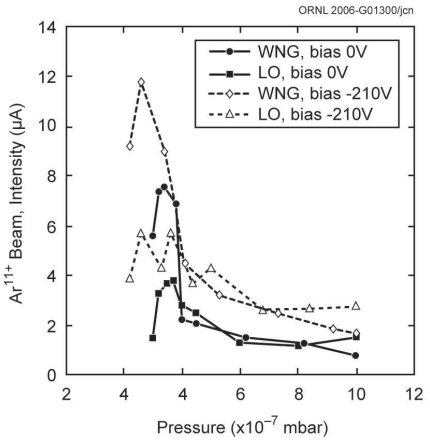


Fig. 3. $Ar^{11+}$ beam intensity versus pressure produced with signals from the WNG and LO microwave generators, as measured at the injection end of the source. Disk bias voltage: (a) 0V; (b) $-210$V.

Figures 4(a) and 4(b) respectively display intensity and WNG/LO intensity ratio versus charge-state taken at a pressure of $\sim 2.6\times10^{-5}$Pa (neutral density, $n_0 \cong 6.28\times10^{9}/\text{cm}^3$ at 300K) for $Ar^{q+}$ beams produced with TWTA amplified signals from the WNG and LO with 0V and $-211$V applied to the biased disk. In each case, the source was optimized for the production of $Ar^{11+}$ ion beams. As noted, the intensity ratio increases with increasing charge-state with and without biased disk voltage. As is found for multiple discrete frequency modes of operation[4—6], broadband radiation does not enhance the production of low and intermediate charge-states (i.e., charge states <Ar$^{8+}$), presumably, because these states serve to populate higher charge-states.

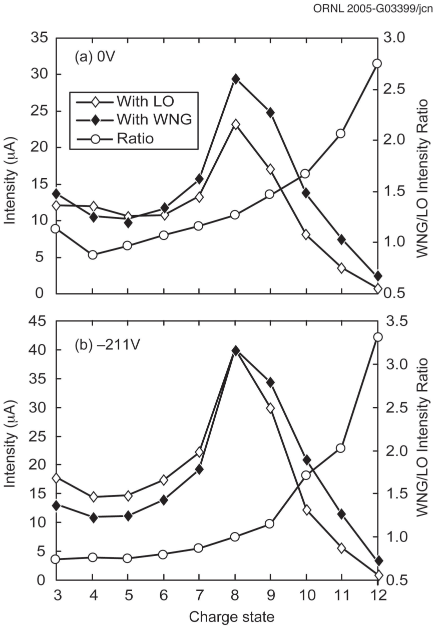


Fig. 4. Intensity versus charge-state for Ar$^{q+}$ ions produced with signals from the WNG and LO microwave generators and WNG/LO Ar ion beam intensity ratio versus charge-state. (a) Biased disk voltage: 0V; Pressure: 3.4×10$^{-5}$Pa; (b) biased disk voltage: −211V, Pressure: 2.6×10$^{-5}$Pa.

Plasma potential and normalized X-ray count rate as functions of the neutral gas pressure are presented, respectively, in Fig. 5 for both modes of operation. (Data in Fig. 5 were taken without biased disk voltage.) As noted, the total X-ray count (Fig. 5(a)) and plasma potential (Fig. 5(b)) suddenly dip at approximately the same pressure, seemingly in correlation with the abrupt increase in intensity versus pressure observed for high-charge-state ion beams (Fig. 3). The physical processes underlying this behavior are unknown. No significant differences between plasma potentials or X-ray count rates were observed for the two modes of operation. This is reasonable because, the plasma potential and X-ray count rate are separately related to charged particle losses determined by the minimum-$B$ magnetic field configuration, identical for both modes of operation. The X-ray count rate is a direct measure of the electron loss rate while the plasma potential is affected by the balance between the loss rates of electrons and ions (including the source drain current)[16].

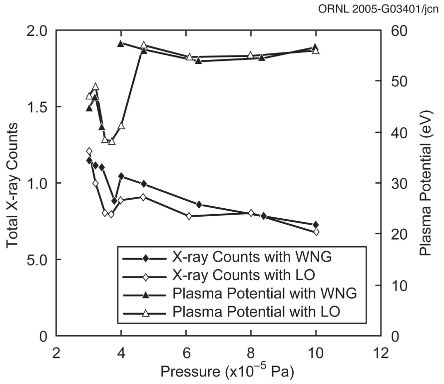


Fig. 5. (a) Total X-ray count versus pressure, as integrated over the complete range covered by the X-ray detector; (b) plasma potential versus pressure.

## 4 Discussion and conclusions

In conclusion, the broadband rf scheme described in this report offers a simple, effective and low-cost alternative for increasing the sizes of ECR zones in conventional minimum-$B$ geometry sources, and consequently, a means for enhancing the high-charge-state capabilities of these sources, over independently powered narrow bandwidth, multiple discrete frequency schemes. In the present experiments, the net input rf power was limited to 200W for both the WNG and LO injection schemes because of power induced out-gassing effects which lead to exacerbated charge-exchange interactions, thereby, precluding evaluation of the ultimate capability of the WNG technique. In absence of power related out-gassing induced charge-exchange or saturation effects, beam intensities generated by use of the WNG are expected to further increase approximately by the ratio of the WNG to LO bandwidths, at the same power density. The potential of the broadband technique for enhancing high-charge-states beam intensities over conventional means at equivalent power densities is illustrated in

Fig. 4 where the ratio of WN/LO generated high-charge-state beams is seen to continually increase with charge-state, with or without voltage applied to the biased disk, even under much lower power-density operating conditions. The causes of the anomalous effects in intensity, X-ray count and plasma potential versus pressure density data cannot be explained in terms of known atomic physics or electron heating/microwave absorption processes and therefore, remain unresolved.

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