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Next generation ECR ion sources: First results of the superconducting 28 GHz ECRIS – VENUS

D. Leitner *, C.M. Lyneis, S.R. Abbott, D. Collins, R.D. Dwinell, M.L. Galloway, M. Leitner, D.S. Todd

Lawrence Berkeley National Laboratory, 1 Cyclotron Road, MS 88R0192, Berkeley, CA 94720, USA

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Abstract

VENUS (Versatile ECR ion source for NUclear Science) is a next generation superconducting ECR ion source, designed to produce high current, high charge state ions for the 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory. VENUS also serves as the prototype ion source for the RIA (rare isotope accelerator) front end. The goal of the VENUS ECR ion source project as the RIA R&D injector is the production of 200 eμA of U^{30+}, a high current medium charge state beam. On the other hand, as an injector ion source for the 88-Inch Cyclotron the design objective is the production of 5 eμA of U^{48+}, a low current, very high charge state beam. To achieve those ambitious goals, the VENUS ECR ion source has been designed for optimum operation at 28 GHz. The nominal design fields of the axial magnets are 4 T at injection and 3 T at extraction; the nominal radial design field strength at the plasma chamber wall is 2 T, making VENUS currently the world's most powerful ECR plasma confinement structure. Recently, the six year project has made significant progress. In June 2002, the first plasma was ignited at 18 GHz. During 2003, the VENUS ECR ion source was commissioned at 18 GHz, while preparations for 28 GHz operation were being conducted. In May 2004 28 GHz microwave power has been coupled into the VENUS ECR ion source for the first time. Preliminary performance-tests with oxygen, xenon and bismuth at 18 GHz and 28 GHz have shown promising results. Intensities close to or exceeding the RIA requirements have been produced for those few test beams. The paper will briefly describe the design of the VENUS source and its beam analyzing system. Results at 18 GHz and 28 GHz including first emittance measurements will be described.

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Keywords: High charge state ECR ion source; ECRIS; Plasma ion source; Radioactive ion beams; Ionization efficiency

* Corresponding author. Tel.: +1 510 486 7814; fax: +1 510 486 7983.
E-mail address: dleitner@lbl.gov (D. Leitner).

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1. Introduction

ECR (electron cyclotron resonance) ion sources are widely used for the production of high quality multiply charged ion beams for accelerators, atomic physics research and industrial applications. The development and refinement of ECR ion sources over the last three decades has provided remarkable improvements in their performance. For example in 1980, Micromafios produced 20 eμA of Ar^{8+} and 10 eμA of Ar^{9+} [1]. 23 years later in 2003 the RIKEN 18 GHz source produced 2000 eμA of Ar^{8+} and 1000 eμA of Ar^{9+} [2]. These remarkable improvements were made possible by advances in permanent magnet strengths, and ECR design technology.

The main driving components for improving the performance of ECR ion sources were formulated in Geller's famous ECR scaling laws, predicting that higher magnetic fields and higher frequencies will increase the performance of ECR ion sources [3]. Following these guidelines, several high performance ECR ion sources like CAPRICE [4], AECR-U [5], RIKEN 18 GHz [6], and ECR4 [7] have been built and are in use at heavy ion accelerator laboratories around the world.

Driven by the increasing demand for higher performance ECR ion sources, third generation ECR ion sources are now emerging. Traditional designs are utilizing increased permanent magnet strength, like the PHOENIX [8] source or the GTS ECR [9] ion source. In addition, several hybrid sources using superconducting solenoid fields and permanent magnet hexapole are being developed [6,10, 11].

Recently, with advances in superconducting magnet technology, the next generation of high field superconducting sources is emerging: the first one of these is the superconducting source SERSE [12].

Additional projects to build third generation superconducting ECR ion sources, such as GYRO-SERSE in Catania [13] and SECRAL in Lanzhou [14] are underway or in planning stages. The most advanced third generation superconducting source now in operation is the VENUS ECR ion source, which is described in more detail in this paper.

2. The VENUS ECR ion source

Fig. 1 shows the mechanical layout of the VENUS ECR ion source. The mechanical design has been optimized for maximum ion source performance as well as easy serviceability for operational use. Up to three off-axis wave guides and two high temperature ovens [15] can be inserted from the injection tank. Several innovative mechanical design solutions were incorporated to accommodate the physics and engineering requirements. The plasma chamber is made out of aluminum due to its favorable secondary electron emission properties and its resistance to plasma etching. It has been designed to handle up to 15 kW of microwave power. The mechanical design is described in more detail in [16,17].

The design and development of the superconducting magnets are described in [16,18]. The sextupole coils are wound around a pole with iron in the center, which enhances the peak field by about 10%. The superconducting sextupole coils experience strong forces in the axial field of the solenoids. Therefore, a new clamping scheme utilizing liquid metal filled bladders was developed to prevent any movement of the energized coils. The sextupole can be operated at 2.4 T (110% of its design field) with the solenoids operating at their design fields, 4 T at injection and 3 T at extraction respectively.

The cryogenic system for VENUS operates at 4.2 K with three cryocoolers each providing up to 45 W of cooling power at 50 K and 1.5 W at 4 K in a closed loop mode without further helium transfers. In addition, provisions for a fourth cryocooler have been added to the cryostat. During the 18 GHz commissioning phase, a novel heat exchanger for the cryocoolers was developed, which efficiently couples the cryocoolers to the LHe reservoir [19]. The present system provides up to 2 W of cooling power to remove heat generated by bremsstrahlung, which is produced by the plasma electrons and deposited in the cryostat. However, the preliminary 28 GHz tests showed that improved X-ray shielding will be necessary to run VENUS at full capacity of the 10 kW 28 GHz gyrotron power supply.

The low energy ion beam transport system consists of a movable accel-decel extraction system

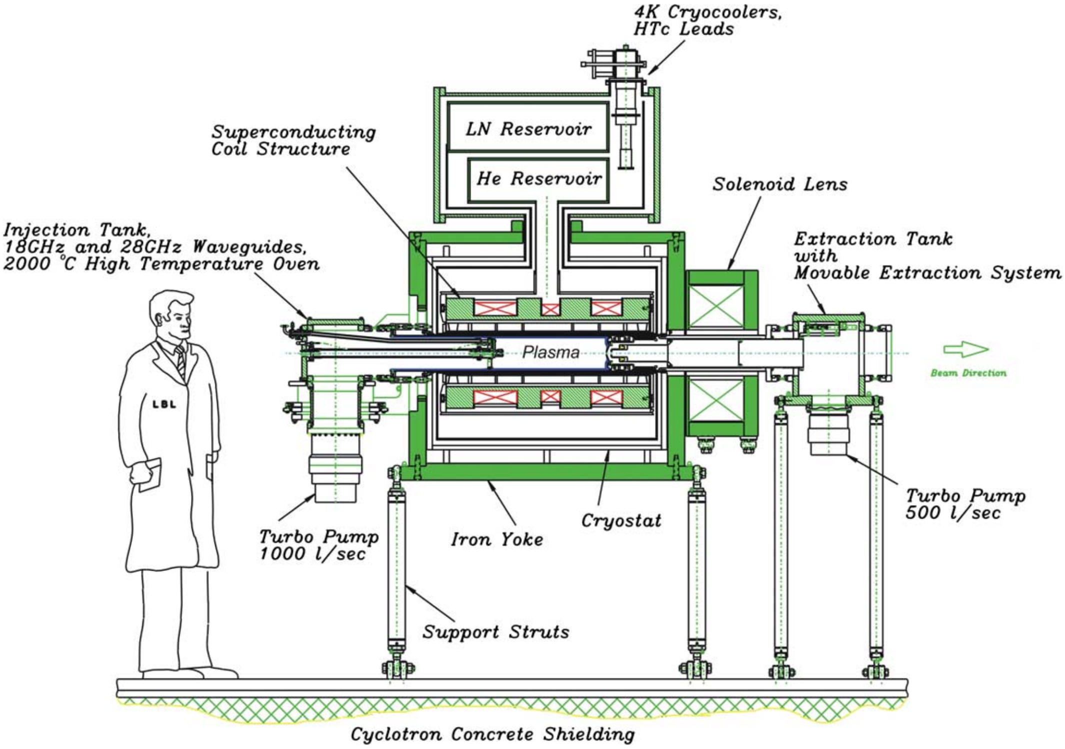

Fig. 1. Mechanical layout of the VENUS ion source and cryogenic systems.

(operating at up to 30 kV extraction voltage), and a large gap, 90° double focusing analyzing magnet [20]. The beam transport system was designed for high current, high charge state extraction. Therefore, to minimize beam blow up due to space charge, the extracted ion beam is directly matched into the analyzing magnet. After the mass analyzing section, a two-axis emittance scanner has been installed. Emittance measurements results are described in Section 5.

3. The microwave system

The VENUS ECR ion source plasma can be heated with 2 kW of 18 GHz power and/or up to 10 kW of 28 GHz power. A 'traditional' microwave set-up is used for the 18 GHz microwave power. The 18 GHz system consists of an 18 GHz solid state oscillator, an 18 GHz klystron amplifier, a quartz HV break and a quartz vacuum window. The 28 GHz power is provided by a VIA-301 Heatwave™ gyrotron system that is able to deliver 100 W to 10 kW continuous wave (CW) RF output at 28 GHz [21]. The RF output level is smoothly controllable throughout this entire range. The power can be set and maintained to within 10 W at the higher power end of the power range and to within 30 W at the lower power end of the power range. The gyrotron may be operated locally via its front panel or remotely via either RS-232 and/or Ethernet connections. Through the RS-232 the forward power, the reflected power, the interlock status and critical operating parameters are transmitted and tied into the VENUS PLC (Programmable Logic Control) control system.

The microwave components for 10 kW, 28 GHz operation are significantly different from those systems using lower frequency, lower power klystron amplifiers. The 28 GHz system propagates the microwave in an over-moded circular wave guide

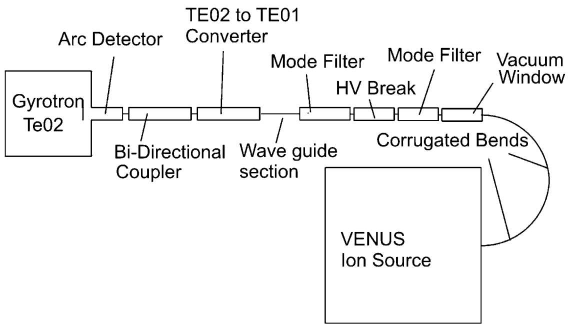

Fig. 2. Schematic layout of the VENUS 28 GHz microwave system.

system in the TE_{01} mode. This mode has low attenuation but requires specialized bends, mode filters, and other microwave components to prevent the propagation of unwanted modes. The schematic of the microwave layout is shown in Fig. 2.

4. Commissioning results at 18 and 28 GHz

The VENUS source was tested briefly with various gases at 18 GHz and 28 GHz in order to be able to compare VENUS to other high performance sources. But more extensive measurements have been performed using bismuth for the rare isotope accelerator (RIA) ion beam development program. Bismuth was chosen since its mass is close to uranium. Therefore, the extraction, and ion beam transport characteristics are very similar. However, bismuth is less reactive than uranium, not radioactive, and evaporates at modest temperatures. Furthermore, it has only one isotope and provides a clean spectrum for systematic emittance measurements.

Table 1 states the initial performance of VENUS at 18 GHz and preliminary results at 28 GHz for oxygen, xenon, and bismuth. For

Table 1
Preliminary commissioning results of VENUS at 18 GHz and 28 GHz in comparison with three other high performance ECR ion sources, the double frequency heated AECR-U [5] and the 18 GHz ECR ion source GTS [9] and SERSE 28 GHz [22]

		VENUS		AECR-U	GTS	SERSE	SERSE
f (GHz)		18	28	10 + 14	18	14 + 18	28
^{16}O	6^+	1100	1200	840*	1950	540	
	7^+	324	>360	360*		225	
Xe	20^+	164	320		310	135	380
	27^+	84	120	30	168	78	
Bi	24^+		243				
	25^+	160	243	70			
	27^+	150.0		75			
	28^+	128.0	240	60			
	29^+	115.0	245	55			
	30^+	102.0	225	57			
	31^+	86.0	203	48			
	32^+	60.0	165	41			
	33^+	43.0		32			
	34^+	34.0		25			
	36^+	26.0		16			
	37^+	23.0		11.9			
	38^+	20.0		9.4			
	41^+	11	15	4.4			
	43^+	5.4	11.5	3.0			
	44^+	4.5	7.7	2.2			
	46^+		3.6	1.2			
	47^+		2.4	0.90			
	48^+		1.4	0.60			
	49^+		1.0	0.25			
	50^+		0.5	0.15			

comparison, the published data from other high performance ion sources are included.

The 18 GHz commissioning was carried out in 2002 and 2003 while preparations for the 28 GHz operation were underway. During this commissioning period, a number of improvements were made to the cryostat system, the 18 GHz microwave system, and the magnet power supply control system [23,24]. Following these improvements, VENUS is now operational at the full capacity of the 2 kW, 18 GHz klystron. The operation experience has been excellent in terms of stability, reproducibility, and reliability.

However, since VENUS has a large plasma volume of about 9 l, the maximum microwave power density available for VENUS is only .22 kW/l at 2 kW. At this power density, VENUS cannot reach its performance peak at 18 GHz. In comparison, the power density used in the AECR-U at peak performance is 1.7 kW/l in double frequency mode and about 1 kW/l in single frequency mode [5]. With the installation of the 10 kW 28 GHz gyrotron in May 2004, the maximum power level available is 10 kW, which would provide a power density of 1.1 kW/l. In the early tests, the maximum power injected has been 4.5 kW. Fig. 3 shows the analyzed current dependency to the microwave power coupled into the plasma for a few sample ion beams. The almost linear increase in current for all the ions with rf power shows that 4.5 kW is well below the saturation point.

If the sextupole and mirror fields are held constant, the most sensitive tuning parameters for the VENUS ion source are the axial minimum field, the pressure in the plasma chamber and the biased disk voltage. All of these parameters are coupled to some degree. One example of such a dependency is shown in Fig. 4. The Xe^{20+} current is plotted in dependence of the center solenoid coil current while all other tuning parameters were held constant. The center coil is polarized opposite to the injection and the extraction solenoid coils. It is used to tune the minimum field of the axial mirror. The 12 A increase in center coil current shown in Fig. 4 represents a decrease of approximately 20% in absolute center field strength. At the same time, the plasma chamber pressure changes opposite to the Xe^{20+} ion current. The increase in pressure indicates that the plasma pumping is reduced as the center field increases, suggesting that the heating efficiency (or rf power coupled to the plasma) is reduced decreasing ion source performance.

Fig. 5 displays three charge state distribution (CSD) spectra as the source tune is shifted from low (a), to medium (b) and high charge state pro-

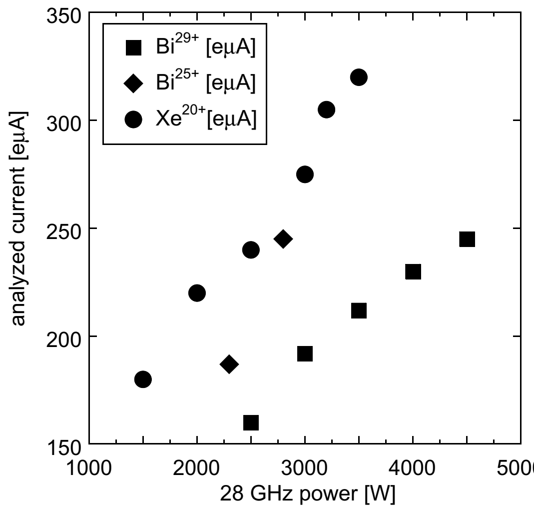

Fig. 3. Dependence of the extracted current for several ions to the coupled 28 GHz microwave power.

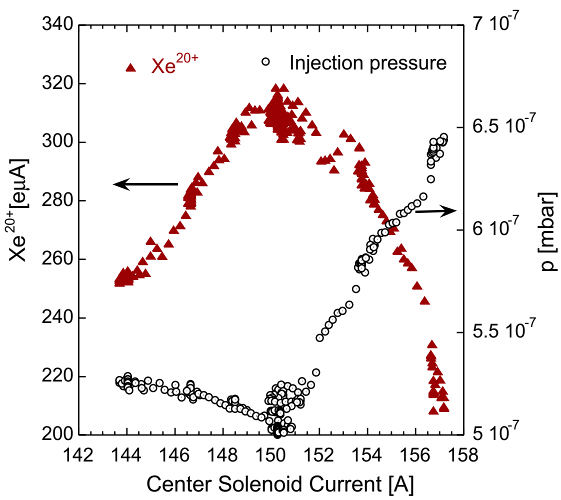

Fig. 4. Dependence of the analyzed Xe^{20+} current to the center coil.

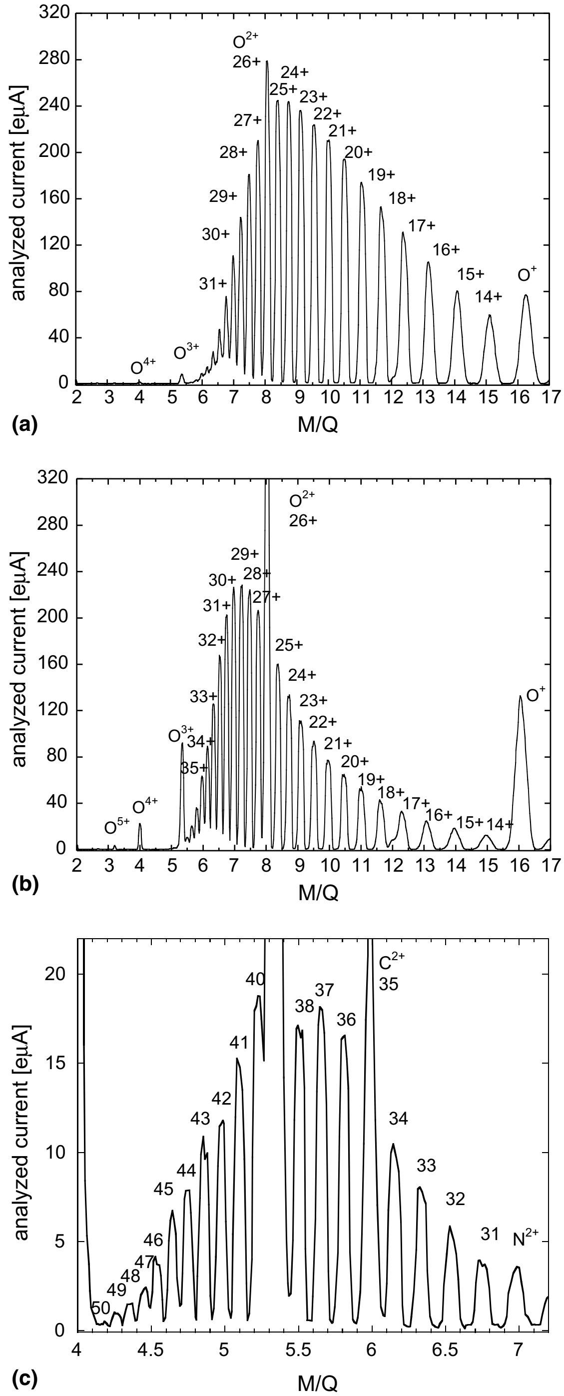

Fig. 5. Analyzed Bi current for an ion source tune at 28 GHz optimized for low (a), medium (b), and high (c) charge states. Note the different current scales in the spectrum (c).

duction (c). The low to medium charge states are relevant for RIA, the high charge states with an M/Q lower than 5 are of interest to the 88-Inch Cyclotron. The CSD-peak was shifted from 24+ to 37+ between spectrum (a) and (c). In the latter spectrum, the lower Bi charge states disappear. These wide shifts in the CSD distribution become possible since VENUS has a strong plasma confinement, which allows reaching several different charge state distribution equilibriums.

The ratio of support (mixing) gas ions to bismuth ions can be used to shift the charge state distribution. To illustrate this fact, the spectrum (c) is plotted again in Fig. 6. By comparing the spectra Figs. 5(a), (b) and 6, it can be seen that the oxygen support gas spectrum emerges from the bismuth spectrum as the Bi charge state distribution is shifted to higher charge states. If the source is tuned for the low charge Bi states, the high charge states of oxygen completely disappear from the charge state distribution (see Fig. 5(a) and (b)). As the source is tuned for Bi^{41+}, the support (mixing gas) dominates the spectrum, and the oxygen spectrum peaks again on the He like ion O^{6+} (see Fig. 6). The same rf power and very similar confinement fields were used to obtain Figs. 5(b) and 6. However, the bismuth and the oxygen flux were reduced lowering the plasma chamber pressure about 12%. In addition, the bias voltage was lowered from 100 V to 36 V. This 'gas mixing' effect is well known and used in ECR ion sources as well as EBIS/EBIT sources [25].

5. Emittance measurements

Two main contributions to the ion beam emittance have to be considered for an ECR ion source extraction system: (1) the ion beam transverse temperature, and (2) the induced beam rotation (angular momentum) due to the decreasing axial magnetic field in the extraction region. Considering that the ions in an ECR plasma are relatively cold with temperatures in the order of 1 eV or less, the emittance contribution due to the magnetic field becomes the dominant factor for most modern ECR ion sources [26]. Assuming a uniform plasma density distribution across the plasma

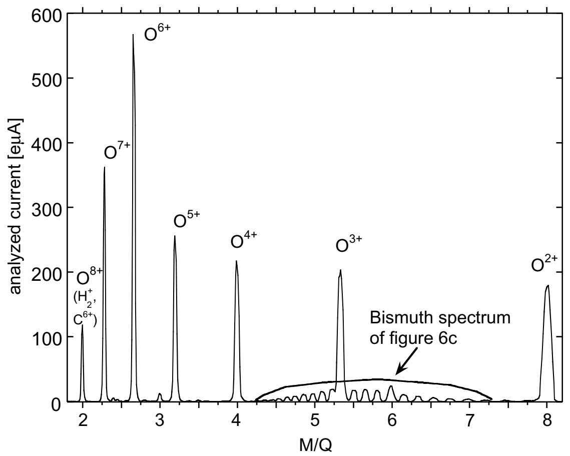

Fig. 6. Oxygen charge state distribution from the Bi spectrum of (c).

outlet hole, the emittance due to beam rotation induced by the decreasing magnetic field in the vicinity of the extractor can be described by Busch's theorem (assuming $\varepsilon^{100\%} = 5 \cdot \varepsilon^{\mathrm{rms}}$, a waterbag distribution)

$$\varepsilon_{\mathrm{MAG}}^{xx'\text{-rms-norm}} = 0.032 r^2 B_0 \frac{1}{M/Q}, \qquad (1)$$

where ε is the normalized $x - x'$ rms emittance in $\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$, r is the plasma outlet hole radius in mm, B_0 is the axial magnetic field strength at the extractor in T, and M/Q is the dimensionless ratio of ion mass in amu to ion charge state [26]. Following this dependence, the emittance should decrease with ion mass and increase with charge state for a charge state distribution. However, the experimental results do not show this behaviour.

Preliminary emittance measurements were performed for bismuth ion from Bi^{23+} to Bi^{41+} using 18 GHz heating and for Bi^{29+} and Bi^{31+} using 28 GHz. The results are plotted in Fig. 7. For the ion beam transport the main difference between the two heating frequencies is the extraction mirror fields, which were 1.2 T for 18 GHz and 2.1 T for 28 GHz. The minimum theoretical emittance values using those field values and the VENUS extraction hole radius of 4 mm are also plotted in Fig. 7. It can be clearly seen that the measured emittance does not follow the predicted

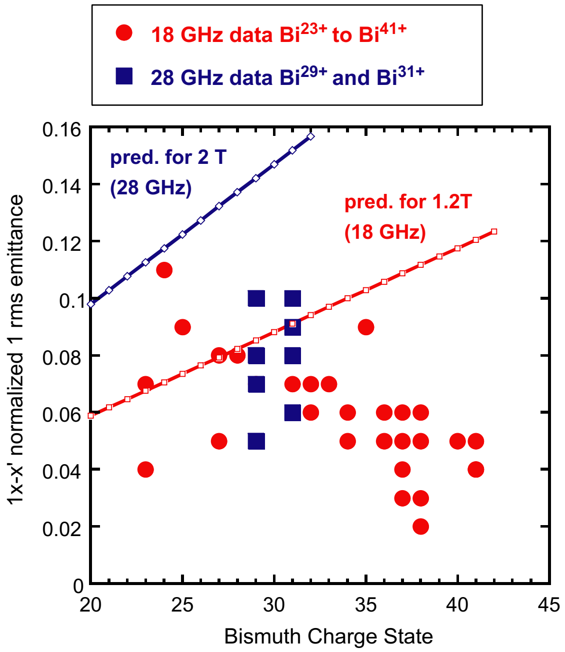

Fig. 7. Dependence of the emittance value from the ion charge state for bismuth for the 18 GHz heated plasma and the 28 GHz heated plasma. In addition, the predicted emittance dependence from the magnetic field is also shown.

dependence. On the contrary, the higher the charge state the lower the measured emittance value. Similar results have been previously measured on different ECR ion sources [27,28]. These results are consistent with a possible model that the highly charged ions are trapped closer to the axis and therefore would be extracted from a virtual extraction hole that is smaller than the real extraction hole decreasing the measured effect of the magnetic field on the emittance [27,28].

6. Summary

During the last two years significant progress has been made on the VENUS project, which began in 1997. In 2003, the successful commissioning at 18 GHz marked a major milestone. At initial 18 GHz operation intense high charge state beams such as 1100 eμA of O^{6+}, 160 eμA of Bi^{25+} and 11 eμA of Bi^{41+} have been extracted easily.

The first 28 GHz plasma was ignited in May 2004. Preliminary results have been summarized in this paper. Relevant to the RIA project, 320 eμ of Xe^{20+} and 245 eμA of Bi^{29+} have been extracted so far, which is well above the RIA requirements. Preliminary emittance measurements have been performed for high intensity Bi ion beams at RIA relevant intensities and the emittances meet the RIA specifications [29]. With respect to the 88-Inch Cyclotron operation, 15 eμA of Bi^{41+} and 120 eμA Xe^{27+} (have been produced, which is about four times the intensity now available from the AECR-U. Plans to connect the VENUS source to the 88-Inch Cyclotron are in progress.

During the next year we are planning to continue the commissioning at 28 GHz power levels of up to 10 kW.

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