Recent 28GHz Results with VENUS*

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Abstract The next generation, superconducting ECR ion source VENUS (Versatile ECR ion source for NUclear Science) has operated with 28GHz since 2004, and has produced world record ion beam intensities. The VENUS project is focused on two main objectives. First, for the 88-Inch Cyclotron, VENUS will serve as the third injector source boosting both the energy and intensity of beams available from the facility. Secondly, VENUS also serves as the prototype injector source for a high intensity heavy ion beam driver linac for a next generation radioactive ion beam facility, where the goal is to produce intense beams of medium to low charge states ions such as 240eμA of Xe^{20+} or 250eμA of $U^{28+\mathrm{to}34+}$. These high intensity ion beam requirements present a challenge for the beam transport system since the total currents extracted from the ECR ion source reach several mA. Therefore in parallel to ion beam developments, we are also enhancing our ion beam diagnostics devices and are conducting an extensive ion beam simulation effort to improve the understanding of the ion beam transport from the VENUS ECR ion source. The paper will give an overview of recent experiments with the VENUS ECR ion source. Since the last ECR ion source workshop in Berkeley in 2004, we have installed a new plasma chamber, which includes X-ray shielding. This enables us to operate the source reliably at high power 28GHz operation. With this new chamber several high intensity beams (such as 2.4mA of O^{6+}, 600eμA of O^{7+}, 1mA of Ar^{9+}, etc.) have been produced. In addition, we have started the development of high intensity uranium beams. For example, 200eμA of U^{33+} and U^{34+} have been produced so far. In respect to high charge state ions, 1eμA of Ar^{18+}, 133eμA of Ar^{16+}, and 4.9eμA of U^{47+} have been measured. In addition, ion beam profile measurements are presented with, and without the sextupole magnetic field energized. These experimental results are being compared with simulations using the WARP code.

Key words VENUS ECR ion source, superconducting ECR, uranium beams

1 Introduction

The next generation of heavy ion accelerators (proposed or under construction) require a great variety of high charge state ion beams with up to an order of magnitude higher intensity than currently demonstrated with conventional Electron Cyclotron Resonance (ECR) ion sources[1]. Therefore, next generation superconducting sources are being developed which have the potential to achieve this necessary performance enhancement. The first, and currently the most advanced, next generation source in operation is the fully superconducting ECR ion source VENUS at Lawrence Berkeley National Laboratory[2]. One of the key technological advances of VENUS has been the use of liquid metal filled bladders in between the superconducting magnet coils for clamping, which enables VENUS to operate at optimum magnetic confinement fields for 28GHz operation. This technique has opened the possibility for

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Received 20 April 2007

* Supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Physics Division of the U.S. Department of Energy under Contract DE AC03-76SF00098

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even higher field superconducting sources, and it is now used in several next generation sources under construction. Since 2004 28GHz has been routinely used as primary heating frequency for the VENUS ECR ion source. The operation experience with the superconducting magnets has been very good. The coils have not experienced a quench for normal operation since the ion source commissioning was started in 2002 and are routinely run 10% above design currents. In addition, ion beam current densities extracted from VENUS for metals and gases have demonstrated that the high intensities required for the next generation injector are feasible.

As tuning experience is gained and more power is injected into the plasma, the ion beam intensities are still increasing and the performance limits of VENUS have not been reached yet. With this dramatic increase in performance, the total extracted ion beams can reach tens of mA and are highly space charge dominated. This makes the design of the beam transport system more challenging for the next generation sources. The simulation of the beam extraction and transport from ECR ion sources is complex, and the development of accurate models and enhanced beam diagnostics to support this development has become an important field for ECR ion sources development.

2 Beam experiments with VENUS

During the 28GHz commissioning, VENUS was tested with oxygen and xenon. More extensive tests were done with Bi since its mass is close to uranium and was used as an initial indicator of the source's capability to produce 10 particle μA of uranium[2]. Recently, extensive tests were performed with argon and uranium, which are further described in sections 2.1 and 2.2. Table 1 shows some of the results and compares intensities with other sources for reference.

Table 1. Commissioning results for VENUS in comparison with other high performance ECRIS.

f/GHz		VENUS[2]	SERSE[3]	GTS[4]	SECRAL[5]
		28 or 18+ 28	28	18	18GHz
^{16}O	6^{+}	2850		1950	2300
	7^{+}	600			810
^{40}Ar	12^{+}	860		380	510
	13^{+}	720*			
	14^{+}	514		174	270
	16^{+}	133		50	73
	17^{+}	14		4.2	8.5
	18^{+}	1			
^{129}Xe	25^{+}		216	244	
	26^{+}	290		228	410
	27^{+}	270		168	306
	28^{+}	222		120	
	29^{+}	168		*	
	30^{+}	116	100	60	101
	31^{+}	67		40	68
	34^{+}	15		8	21
^{209}Bi	25^{+}	243			
	29^{+}	245			
	30^{+}	225			
	31^{+}	203			
	41^{+}	15			
	49^{+}	1.0			

* C^{4+} contamination less than 5eμA

2.1 Argon results

One of the requirements for the Spiral II injector is the production of 1emA of Ar^{12+} from the injector ion source[6]. To test the capability of a VENUS type source to meet these intensity requirements, the source was tuned for medium and high charge state argon ion beam production. Fig. 1 shows the dependence of the Ar^{12+} and Ar^{14+} ion beam currents on power when both the flow of the oxygen mixing gas and the argon gas are held constant. The Ar^{12+} current intensity levels of as more power is coupled into the plasma and the charge state distribution (CSD) shifts to higher charge states. The charge state distribution peak moves from Ar^{12+} to Ar^{14+}. To keep the charge state distribution peaked on Ar^{12+} while increasing the microwave power argon gas has to be added. This is shown in Fig. 2 in which the dependence of the Ar^{12+} current on microwave power is graphed for different gas flow values. For reference the injection pressure measured outside the plasma chamber is stated for the different curves. For the single data point (blue circle) the gas flow for the oxygen mixing and the argon feed gas were adjusted to optimize the source for Ar^{12+} production at this power level. As shown in Figs. 1 and 2, no saturation of beam current with power is observed. This is not surprising since the power density coupled to the plasma is relatively modest. An important goal for the near future will be to couple the maximum available power of 10kW 28GHz and 2kW of 18GHz into the plasma to continue to push the envelope of the VENUS performance.

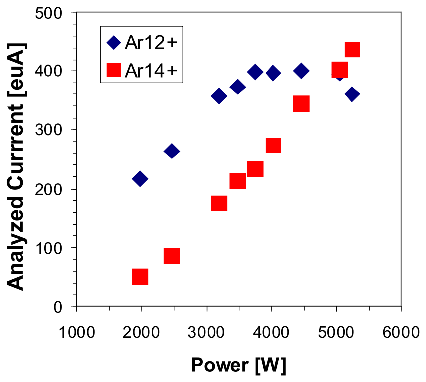

Fig. 1. Dependence of Ar^{12+} and Ar^{14+} on the coupled microwave power when both, the oxygen mixing gas and the argon gas flow are held constant. As more power is coupled into the plasma the CSD shifts to higher charge states.

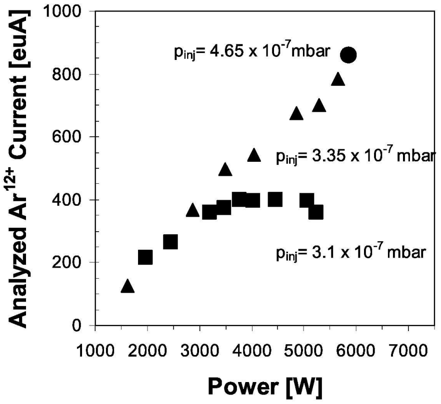

Fig. 2. Dependence of the Ar^{12+} output on microwave power for 3 different argon and oxygen gas flows.

Figure 3 shows a spectrum with the source optimized on Ar^{12+}. A total microwave power of 5.8kW (640W/liter) is coupled to the plasma. The total extracted beam current is 7.3emA at an extraction voltage of 22kV. The total beam transmission into the Faraday Cup is better than 80% for this spectrum. As an example for a high charge state spectrum, Fig. 4 shows a spectrum where VENUS was optimized for Ar^{16+}. Both spectra shown were taken at similar magnetic confinement fields; however the overall gas flow was reduced to peak at higher charge states.

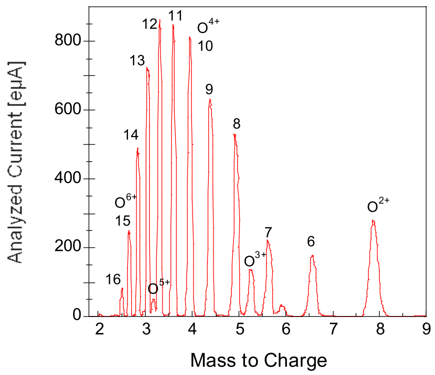

Fig. 3. CSD for a high intensity Ar^{12+} beam, a total microwave power of 5.8kW was used.

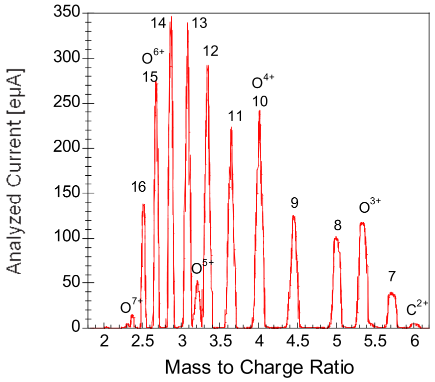

Fig. 4. CSD peaked for higher charge states, a total microwave power of 3.4kW was used.

2.2 Uranium beams

As prototype injection source for a next generation radioactive ion beam facility, the primary goal for VENUS is the production of 8 particle μA of any medium charge state between U^{29+}and U^{35+} (electrical currents between 230 and 280eμA). While the ion beam intensities extracted for Bi indicate that this goal is achievable, the production of uranium beams is much more challenging, because of the chemical properties of uranium and the high temperature required to produce enough vapour as feeding material for the plasma. In addition, chemical reactions are more likely at higher temperatures, which can compromise the reliability of the oven.

There are several possible materials to produce uranium vapour. It can be produced either from pure uranium or uranium compounds. Pure uranium melts at 1250℃ and can be contained in pure Yttria crucibles and tungsten ovens, but is chemically very reactive. In addition, its vapour pressure can be reduced by oxide layers that can form even in the high vacuum environment of an ECR ion source[7]. Pure uranium has not been tested yet at LBNL. Another possibility is the use of uranium compounds. The most promising ones are URe_2, UN, and UO_2. URe_2 has the highest vapour pressure of these three compounds and was successfully used for uranium beams at LBNL before[8]. The required temperature for URe_2 is typically between 1700 (high charge states) to 2000℃ (medium charge sates) for the VENUS oven geometry. Its melting point is around 1950℃. On the other hand, UO_2 has a vapor pressure of 10^{-2}mbar at 2050℃[9], therefore requiring temperatures between 2100 and 2300℃ for the VENUS oven. If the oven can sustain these high temperatures, it would probably be the ideal compound for several reasons. It sublimes and has a very high melting point of 2820℃[9]. It is chemically stable and easy to handle. In addition, its oxygen is an ideal mixing gas for the plasma. UN has a similar vapor pressure as UO_2, but nitrogen is not a good mixing gas. The following data presented were obtained using URe_2 compounds. It was tested first, since it has the lowest temperature requirements. Parrallel tests with UO_2 have been started in the LBNL ECR ion source using a W oven. These preliminary experiments were promising in terms of intensity, stability, and reliability. Therefore, UO_2 it will be tested in VENUS in the near future.

To achieve the high temperatures required, an axial ovens using W, Ta or Re heating elements were developed for VENUS[10]. The metal is either directly loaded into the oven or placed into a ceramic crucible. Extensive off-line oven tests coupled with finite element thermal analysis have been conducted to optimize the existing oven design and to evaluate its performance at high temperature. Off-line oven performance tests have shown that the oven assembly can reliably run at furnace temperatures above 2300℃ for W and Re ovens. However, when the oven is used in VENUS, the oven experiences a strong $I\times B$ force in the high axial magnetic field of the injection solenoid. To prevent bending of the hot oven crucible under the magnetic force, the heater current flow must be either parallel to the magnetic field for a DC heater or an AC heater supply must be used. Both options are currently being pursued.

2.2.1 High intensity uranium results

Figure 5 shows a high intensity ion beam spectrum of a uranium beam optimized for medium charge states. Over 200eμA were achieved in the charge states 33^+ and 34^+ at an oven temperature of approximately 2000℃. This is a factor of 9 higher than the previous U record beam extracted from the AECR-U at LBNL. For these tests URe_2 was placed directly in the crucibles. When URe_2 starts to melt at a temperature around 1950℃ in the oven, the electrical resistance of the oven decreases, which reduces the oven temperature. This limits the maximum temperature of the oven to temperatures below the melting point, thereby limiting the achievable vapour pressure and the maximum uranium current density. To achieve stable operation above the melting point, the liquid URe_2 compound needs to be decoupled from the heating element and must be placed into a ceramic crucible. For this purpose, URe_2 loaded into a pure Yttria crucible has been successfully tested in the LBNL ECR and will be tested in VENUS next.

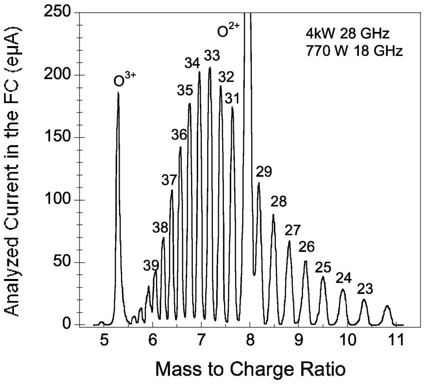

Fig. 5. Uranium CSD distribution for a high intensity medium charge state tune optimised for 33 to 34^+.

2.2.2 Uranium high charge state production

Recently, VENUS ion beams have been injected into the 88-Inch Cyclotron. As a third injector source for the 88-Inch Cyclotron, the goal is the production of 5eμA of U^{46+}. Therefore, VENUS was also tested for high charge state uranium production.

Figure 6(a) shows the best high charge state spectrum to date. From the oven standpoint high charge state production is by far easier, since the optimum vapor pressure requires an oven temperature well below the melting point of the URe_2 compound. The full spectrum (shown in Fig. 6(b)) is dominated by the oxygen mixing gas. The oxygen CSD is only minimal affected by the heavy metal. Over 550eμA of O^{7+} were produced even when the source was optimized on U^{47+}.

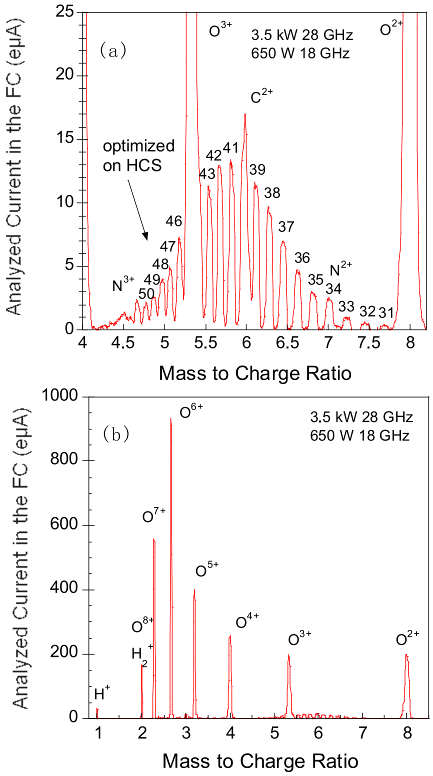

Fig. 6. (a) High CSD for Uranium beam; (b) CSD of the oxygen mixing gas of this tune.

3 Ion beam transport: simulations and experimental results

Over the last two years, the three-dimensional, particle-in-cell code WARP[11, 12] has been enhanced to allow end-to-end beam dynamics simulations of the VENUS beam transport system from the extraction region, through a mass-analyzing magnet, to a two-axis emittance scanner[13]. Recently, a plasma sheath extraction model has been added in order to simulate the extraction and transport of ion beams from the superconducting ECR ion source VENUS[14]. The WARP code is ideally suited to simulate ECR ion source transport systems since it can handle large particle numbers, multiple species, applied and self fields, and has a powerful PYTHON programming shell that allows the user to easily customize the simulation. The addition of an axially symmetric sheath extraction model for multi species plasmas allows for the simulation of the entire VENUS beam line including the extraction region.

To benchmark the code against experimental measurements, a beam profile monitor (beam harp) was installed after the extraction region about 80cm downstream of the extraction aperture. The beam can be focused with the extraction solenoid (Glaser) lens onto the beam profile monitor. The harp scanner consist of 62, 0.1mm diameter wires contained within a 5.0cm square window, with half of the wires running parallel to the vertical and half parallel to the horizontal direction. The wire spacing is 1mm near the center of the harp window and 2mm at the outer edges. The experimentally measured beam profiles were compared with simulated ones for He^+ beams, since this is the simplest beams system. Two modes of source operation were employed for these tests. In addition to the normal operating mode where both confining solenoids and sextupoles are energized, a second mode of operation was used in which the sextupoles were turned off. In this case, the plasma confinement is provided solely by the solenoidal field and is axially symmetric. As expected, a symmetric beam in both the x- and y-directions is measured at the beam harp. As an example, Fig. 7 shows one of the beam profiles obtained for a particular Glaser magnet setting. The red curve is the experimental measured data for the horizontal direction; the blue curve is the simulated beam profile using the WARP code. As can be seen in Fig. 7, the size of the simulated beam compares very well with the size of the experimentally measured beams.

With the confining sextupoles energized, the beam profile measurements show distinct asymmetry (see Fig. 8(a) for the horizontal and 8(b) for the vertical beam). This asymmetry is a product of the triangular plasma distribution from which the beam is extracted, resulting in a triangular beam shape. This result is consistent with previously observed triangular beam structures on a tantalum viewing screen[13, 14]. To simulate this asymmetric beam in WARP a triangular beam distribution at the plasma aperture is used. As the sheath extraction component of WARP is not yet capable of self-consistently simulating asymmetric plasmas, an approximation is used based on the symmetric extraction simulation of the first 22cm of beam transport. After a self-consistent extraction solution has been obtained, a homogenous, triangular distribution of particles is moved through the solved, symmetric potential mesh using an initial orientation based on experimental plasma marks on the extraction electrodes. This triangular distribution is then used for the remainder of the simulation using the transverse field solver, which more appropriately treats the beam asymmetry. As can be seen in the plots of Fig. 8, this simple approximation reproduces the size and shape of measured harp distributions reasonably well, but we are currently working on a more realistic model for the initial extraction conditions.

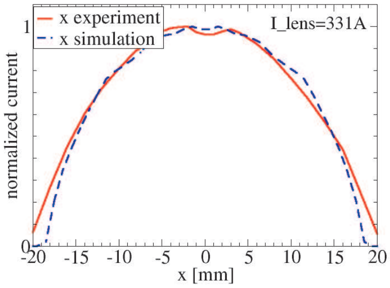

Fig. 7. An experimental and simulated harp profile is plotted for a 600μA He$^+$ beam extracted from VENUS with sextupole fields off.

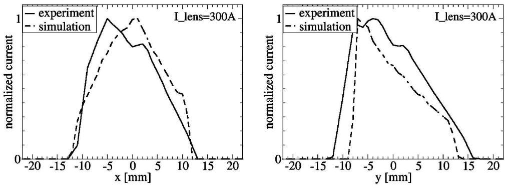

Fig. 8. Comparison between experimentally measured and simulated beam profiles in the a) horizontal directions and b) for the vertical direction. The beam asymmetry can be clearly seen.

In order to compare the simulated beam with phase space current density measurements taken with emittance scanners located after the analyzing dipole, both the axially symmetric and the asymmetric simulated beams are tracked through the three dimensional field of the analyzing dipole. Fig. 9 shows such a comparison for a symmetric beam (sextupoles off) and Fig. 10 for an asymmetric beam (standard ECR fields) for the horizontal phase space.

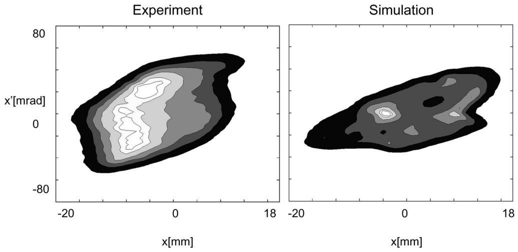

Fig. 9. Experimental (left) and simulated (right) horizontal phase space current density plots for with source sextupole currents off.

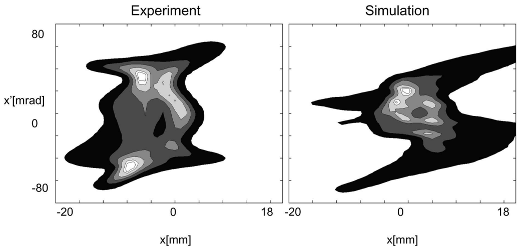

Fig. 10. Experimental (left) and simulated (right) horizontal phase space current density plots with source sextupole currents on.

In both cases the beam size and maximum divergence are in fairly good agreement, but both the phase space tilt and current density distribution show difference, which will be further investigated. In particular, beam simulations with high statistics will be important to reduce artificial density variations in the simulated beam.

4 Acknowledgments

The authors also whish to thank to Dave Grote for his support using the WARP code, the technical crew of the 88-Inch Cyclotron for its support of the beam development, and Timothy Loew for the thermal analyses of the VENUS high temperature oven.

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