FIRST RESULTS FOR THE 28 GHZ OPERATION OF THE SUPERCONDUCTING ECR ION SOURCE VENUS

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Abstract

Commissioning of the superconducting ECR ion source, VENUS, at 28 GHz began in May 2004. In its first four months of operation at this frequency, it has produced a number of intense heavy ion high charge state beams such as 320 eμA of Xe^{20+} and 240 eμA of both Bi^{25+} and Bi^{29+}. The intensities of these beams meet or exceed the requirements for the RIA driver linac ion source. Emittance measurements on bismuth also fall within the acceptance for the proposed accelerator. VENUS has also produced very high charge states beams including 11 eμA of Bi^{43+} and 1 eμA of Bi^{49+} that can be used for the 88-Inch Cyclotron. In the paper, we describe the performance of VENUS at 18 and 28 GHz, the design and operation of the 28 GHz gyrotron, measurements of the bremstrahlung heating of the cryogenic system and plans for further development.

INTRODUCTION

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 200eμA 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 5eμA of U^{48+}, a low current, very high charge state beam.

To meet those goals, the VENUS ECR ion source has been designed for operation at 28 GHz and meets the guidelines for the optimum axial and radial magnetic fields at this frequency [1]. The maximum magnetic fields are 4T at injection and 3T at extraction and 2.4 T at the plasma chamber wall, which makes VENUS the most powerful ECR plasma confinement structure to date. This allows it to take advantage of the frequency scaling law proposed by Geller [2], which predicts that beam intensities should scale with the square of the microwave frequency,

In May 2004, 28 GHz microwave power from a new gyrotron was coupled into the VENUS ECR ion source for the first time. This followed two years of commissioning at 18 GHz. The results of both the 18 and 28 GHz operation are very encouraging, but are also still preliminary since more time is needed to explore the wide range of operating parameters available with VENUS.

THE VENUS ECR ION SOURCE

Figure 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. The plasma chamber is made out of aluminum, which has favorable secondary electron emission properties and is resistance to plasma etching. The mechanical design is described in more detail in [3,4]. The design and development of the superconducting magnets are described in [3,5]. The low energy ion beam transport system consists of a movable accel-decel extraction system (operating at up to 30 kV extraction voltage), and a large gap, 90-degree double focusing analyzing magnet [6].

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 4.2 K in a closed loop mode. During the 18 GHz commissioning phase, a new heat exchanger for the cryocoolers was developed, which efficiently couples the cryocoolers to the liquid helium reservoir [7]. The present system provides a total of 5 W of cooling power at 4.3 K, with 3 W going to cooling the cryostat and 2 W available to remove bremstrahlung heating.

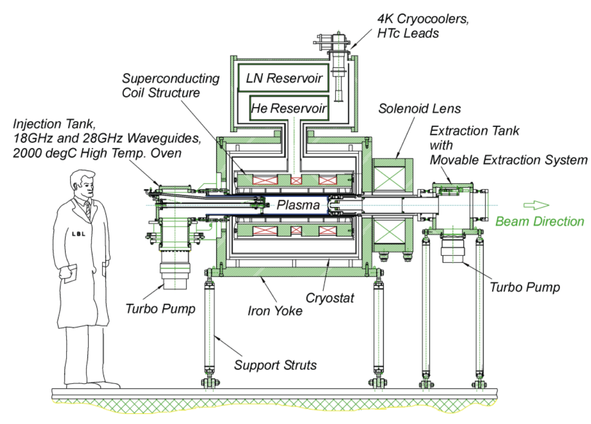

Figure 1: Mechanical layout of the VENUS ion source and cryogenic systems

The VENUS ECR ion source plasma can be heated with 2 kW of microwave power from an 18 GHz klystron and/or with 10 kW from a 28 GHz gyrotron. The 28 GHz power is provided by a VIA-301 Heatwave^{TM} gyrotron system that is able to deliver 100 watts to 10 kW continuous wave (CW) RF output at 28 GHz [8]. The microwave components for 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 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.

COMMISSIONING RESULTS AT 18 AND 28 GHZ

The VENUS source has been tested briefly at 18 GHz and 28 GHz with various gases. More extensive measurements were done with bismuth since its mass is close to uranium, which is of great interest for the Rare Isotope Accelerator (RIA). 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: Initial results of VENUS at 28 GHz and 18 GHz in comparison the double frequency heated AECR-U.

f(GHz)		*VENUS* *28*	*VENUS* *18*	*AECR-U* *10+14*
^{16}O	6^+	1200	1100	840
	7^+	>360	324	360
Xe	20^+	320	164	
	27^+	120	84	30
Bi	24^+	243		
	25^+	243	160	70
	29^+	245	115.0	55
	30^+	225	102.0	57
	31^+	203	86.0	48
	32^+	165	60.0	41
	41^+	15	11	4.4
	43^+	11.5	5.4	3.0
	46^+	3.6		1.2
	49^+	1.0		0.25
	50^+	0.5		0.15

The initial performance of VENUS at 18 and 28 GHz for oxygen, xenon, and bismuth is given in Table 1. For comparison, the data from the AECR-U, which operates with double frequency heating at 10 and 14 GHz, are included. The results should be viewed as preliminary for two reasons. First, at 18 GHz the tests were done with a maximum of 2 kW of microwave power. VENUS has a large plasma chamber with a volume of about 9 liters so the maximum power density available was only .22 kW/liter in comparison to the AECR-U where 1.7 kW/liter can be used. Similarly, at 28 GHz the maximum power injected so far was 4.5 kW and most of the measurements were done with substantially less power. Figure 2 illustrates the dependence of the extracted currents in VENUS versus microwave power, which indicates that it is far from the saturation point. Second, VENUS remains in the early stages of its development and only a limited range of parameters have been explored so far. Even with these caveats, Table 1 shows that, particularly for bismuth, operation with VENUS at 28 GHz produces significantly more intense beams than the 14 GHz AECR-U.

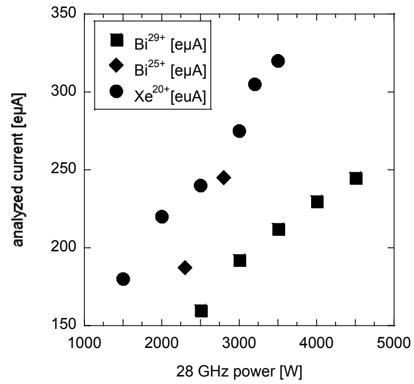

Figure 2: Dependence of the extracted current for several ions to the coupled 28 GHz microwave power.

Figure 3 shows the charge state distribution (CSD) for bismuth tuned to maximize the intensity of Bi^{29+}. The CSD can be shifted to peak on a wide range of charge states such as Bi^{25+} (250eμA), Bi^{29+} (245eμA) and Bi^{41+} (15 eμA) by adjusting the gas-mixing ratio between oxygen and bismuth and other source parameters.

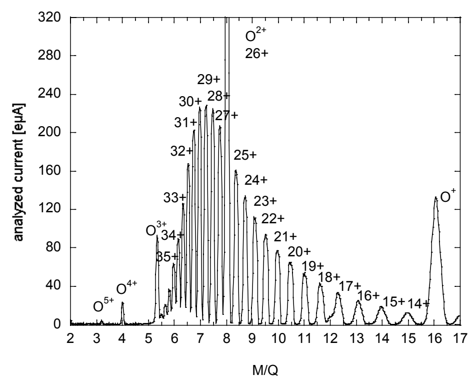

Figure 3: Analyzed Bi current for an ion source tune at 28 GHz optimized for maximum Bi^{29+}.

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 1 rms horizontal emittance values for these beams were less than 0.12 pi mm mrad, which is within the acceptance of the proposed RIA driver linac. In addition, the data showed a systematic trend for lower emittance values for higher charge state beams.[9] This was previously observed on the AECR-U and it supports a model where the high charge state ions are concentrated on axis rather than uniformly distributed across the extraction hole. [10]

Bremstrahlung produced by the hot plasma electrons colliding with the plasma walls are particularly troublesome for superconducting ECR ion sources. The high energy bremstrahlung that go through the radial plasma and cryostat walls cause an additional cryogenic heat load [11] and localized heating in the superconducting coils that may lead to quenches [12]. Generally, higher frequency sources produce higher x-ray fluxes although the precise scaling has not been measured.

Model calculations of electron cyclotron resonance-heated plasmas predict that the mean energy of the hot electrons increases approximately linearly with frequency [13].

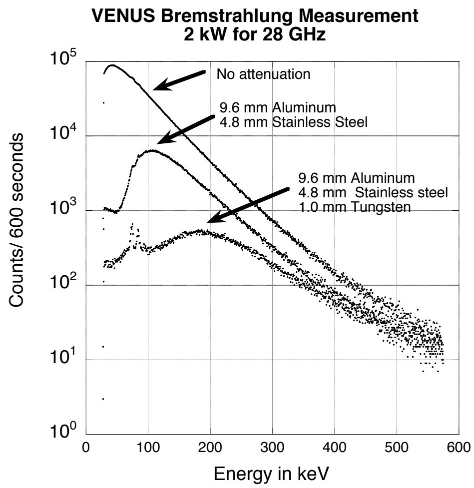

Figure 5: Axial bremstrahlung measured for 2 kW of 28 GHz microwave power.

The VENUS cryostat has several calibrated carbon glass resistors are located in the cryostat and on the cold heads of the cryocoolers. The temperatures can be measured about 5 mK and the response of the system to an additional heat load has been calibrated by using a small heater located at liquid helium temperature. The results at 18 GHz showed that the heat loading was sensitive to the tuning of the source and was on the order of 150 mW per kW of microwave power [14]. Measurements at 28 GHz, however, show that the bremstrahlung heating rate is higher and on the order of 1 W per kW of microwave power.

The bremstrahlung spectra at 28 GHz were measured using a 12.5 cm thick heavy met collimator and germanium detector located on the straight-through port of the analyzing magnet. While it would have been preferable to measure the radial bremstrahlung flux, the thick iron yoke surrounding VENUS makes this difficult. Figure 5 shows the axial bremstrahlung spectrum with no attenuation, with sheets of aluminum and stainless steel to simulate the VENUS plasma chamber and cryostat wall and with an additional 1 mm thick sheet of tungsten. The relative energy in each spectrum was calculated and the addition of 1 mm of tungsten reduced the transmitted energy by a factor of 4.5.

The polyester high voltage insulation for the plasma chamber was recently removed and found to be discolored due to x-ray damage at the location along the plasma flutes were there is a minimum in the magnetic field. This indicates that the hot electrons are being lost radially in localized regions along the plasma flutes.

For these reasons, we are designing a new plasma chamber that will provide additional shielding to reduce the bremstrahlung loading in the cryostat and in the superconducting coils. The present aluminum chamber is only 4 mm thick at the plasma flutes. Two mm of a high density, high z material such as tungsten, tantalum or gold will reduce the heating by a factor of 20, which would reduce the 28 GHz the heating rate to about 50 mW per kW of microwave power or 500 mW at 10 kW. Since without shielding VENUS has operated at 4.5 kW without bremstrahlung induced quenches, the new shielding should also provide sufficient protection for this issue.

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