First Results of the Superconducting ECR Ion Source Venus with 28 GHz

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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 magnetic confinement configuration consists of three superconducting axial coils and six superconducting radial coils in a sextupole configuration. The nominal design fields of the axial magnets are 4T at injection and 3T at extraction; the nominal radial design field strength at the plasma chamber wall is 2T, making VENUS the world most powerful ECR plasma confinement structure. From the beginning, VENUS has been designed for optimum operation at 28 GHz with high power (10 kW).

In 2003 the VENUS ECR ion source was commissioned at 18 GHz, while preparations for 28 GHz operation were being conducted. During this commissioning phase with 18 GHz, tests with various gases and metals have been performed with up to 2000 W RF power. At the initial commissioning tests at 18 GHz, 1100 eμA of O^{6+}, 160 eμA of Xe^{20+}, 160 eμA of Bi25+ and 100 eμA of Bi^{30+} and 11 eμA of Bi^{41+} were produced.

In May 2004 the 28 GHz microwave power has been coupled into the VENUS ECR ion source. At initial operation more than 320 eμA of Xe^{20+} (twice the amount extracted at 18 GHz), 240 eμA of Bi^{24+} and Bi^{25+}, and 245 eμA of Bi^{29+} were extracted. The paper briefly describes the design of the VENUS source, the 28 GHz microwave system and its beam analyzing system. First results at 28 GHz including emittance measurements are presented.

I. INTRODUCTION

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 achieve those ambitious goals, the VENUS ECR ion source has been designed for optimum operation at 28 GHz.

The Venus ECR ion source project was started in 1997 with the development of the superconducting structure and cryostat which was completed in 2001. At the last ECR ions source workshop in June 2002 at the University of Jyvaskyla, the first plasma ignition using 18 GHz microwave was reported. The source was commissioned with 18 GHz in 2003 and in 2004 28 GHz was coupled for the first time. Table 1 summarizes the major milestones of the project.

TABLE 1. Major Milestones of the VENUS Project

Date	Milestone
09/1997	Prototype Magnet completed
09/2001	Final Magnet Tests: 4T Injection, 3T Extraction, 2.4 T Sextupole achieved
06/2002	First Plasma at 18 GHz
09/2003	160 eμA of Bi^{24+}, 160 eμA Xe^{20+}
09/03-11/03	Cryostat Modification for 28 GHz operation
01/04-04/04	Gyrotron system assembly at CPI
05/26/04	First 28 GHz Plasma
06/04	320 eμA Xe^{20+}
08/04	245 eμA Bi^{29+}, 15 eμA Bi^{41+}

II. THE VENUS ECR ION SOURCE

The following sections describe briefly the design of the VENUS ECR ion source, the superconducting magnets, the cryostat, the microwave system, and the beam analyzing system. A detail description of the various components can be found in the paper referenced in each section.

The mechanical design

Fig. 1 shows the mechanical layout of the VENUS ECR ion source. The vacuum system design uses only UHV compatible components and metal seals. It is optimized for good plasma chamber pumping. Therefore the turn around time after the source has been vented to air is only about two to three hours before the source reaches high performance again. Two off-axis wave guides (18 GHz and 28 GHz), two high temperature ovens, 2 gas feeds, and a water cooled biased disk are inserted from the injection tank. All surfaces exposed to the plasma are made from aluminum. The mechanical design is described in more detail in [1, 2].

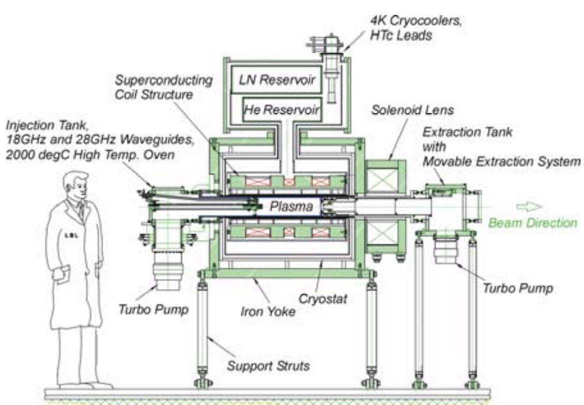


FIGURE 1. Mechanical layout of the VENUS ion source and cryogenic systems

The Superconducting Magnets

The design and development of the superconducting magnets are described in [2, 3]. The sextupole coils are wound around a pole with iron in the center, which enhances the peak field about 10%. The main challenge for the superconducting magnet design comes from the strong forces that the sextupole coils experience strong in the axial field of the solenoids. These forces, if not sufficiently counteracted, cause azimuthal movements of the sextupole coils and lead to quenches. VENUS is the first superconducting ECR ion source that uses a new clamping scheme utilizing liquid metal filled bladders to prevent any movement of the energized coils [3]. During commissioning of the superconducting magnets, the sextupole reached 110% of its design field after a few training quenches (2.4T) with the solenoids operating at design field (4T at injection and 3T at extraction). Another important step for the magnet commissioning was the development of a PLC (Programmable Logic Controller) based external regulation loop for the superconducting magnet power supplies. It allows ramping of the magnets in a reasonable time and stabilizes the magnets at the requested currents without fast oscillations, which can cause quenches.

The Cryogenic System

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 [4, 5]. In addition, the cryostat has provisions for a fourth cryocooler. The main modification during the 18 GHz commissioning phase was the development of a novel heat exchanger for the cryocoolers, which efficiently couples the cryocoolers to the LHe reservoir [4] and minimizes the temperature gradient between the cryocooler heads and the helium reservoir. The present system provides up to 2 W of cooling power to remove heat generated by bremstrahlung, 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 the full capacity of the 10 kW 28 GHz gyrotron power supply. The heat leak related to bremstrahlung is discussed in more detail in section V.

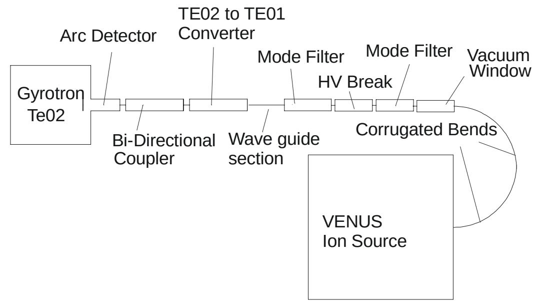
The Low Energy Beam Transport System

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 [5, 6]. 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 IV.

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 a 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 watts to 10 kW continuous wave (CW) RF output at 28 GHz [7]. The gyrotron may be operated locally via its front panel or remotely via either RS-232 and/or Ethernet connections. 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 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.

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



III. COMMISSIONING RESULTS AT 18 AND 28 GHZ

The VENUS source was initially tested 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, which means that the extraction and ion beam transport characteristics are very similar. However Bi is easier to use, since it 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.

The 18 GHz commissioning was carried out in 2002 and 2003 while preparations for the 28 GHz operation were progressing. During the 18 GHz commissioning period, a number of improvements were made to the cryostat system, the 18 GHz microwave system, and the magnet power supply control system [8, 9]. 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 liters, the maximum microwave power density available for VENUS is only .22 kW/liter 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/liter in double frequency mode and about 1 kW/liter in single frequency mode [10].

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/liter. 4.5 kW is the maximum power injected so far in the early test. Fig. 3 shows the analyzed current dependency to the microwave power coupled into the plasma for a few sample ion beams. The approximately linear increase in current for all the ions with rf power shows that 4.5 kW is well below the saturation point.

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

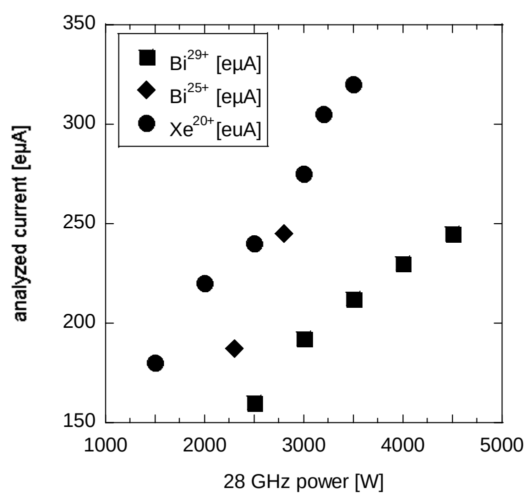


Table 1 states the initial performance of VENUS at 18 GHz and preliminary results at 28 GHz for oxygen, xenon, and bismuth. For comparison, the published data from other high performance ion sources are included.

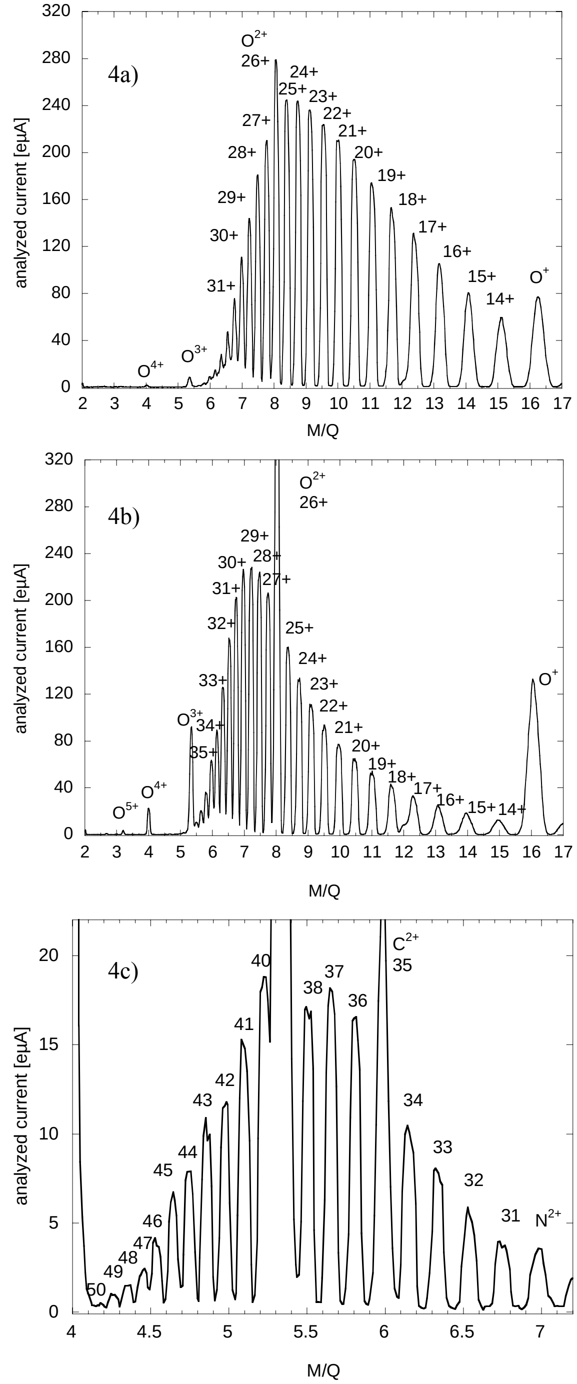
TABLE 1. Preliminary commissioning results of VENUS at 18 GHz and 28 GHz in comparison with three other high performance ECR ion source, the double frequency heated AECR-U [10] **and the 18 GHz ECR ion source GTS** [11] **and SERSE 28 GHz** [12]

		VENUS	*VENUS*	*AECR-U*	*GTS*	*SERSE*
f(GHz)		*18*	*28*	*10+14*	*18*	*28*
^{16}O	6^+	1100	1200	840*	1950	
	7^+	324	>360	360*		
Xe	20^+	164	320		310	380
	27^+	84	120	30	168	
Bi	24^+		243			
	25^+	160	243	70		
	27^+	150		75		
	28^+	128	240	60		
	29^+	115	245	55		
	30^+	102	225	57		
	31^+	86	203	48		
	32^+	60	165	41		
	33^+	43		32		
	34^+	34		25		
	36^+	26		16		
	37^+	23		11.9		
	38^+	20		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		

* 3 frequency heating (8.6, 10, 14 GHz)

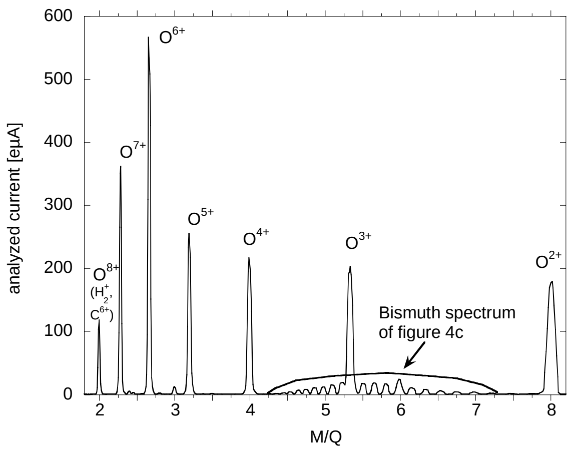
Figure 4 displays three charge state distribution (CSD) spectra as the source tune is shifted from low (4a), to medium (4b) and high charge state production (4c). The low to medium charge states are relevant for RIA, the high charge states with an M/Q lower than 5 are of interest to the 88-Inch Cyclotron. The CSD- peak was shifted from 24+ to 37+ between spectrum 5a and 5c. In the latter spectrum, the lower bismuth charge states disappear. These wide shifts in the CSD distribution are possible since VENUS has a strong plasma confinement, which allows reaching several different charge state distribution equilibria.

FIGURE 4. Analyzed Bi current for an ion source tune at 28 GHz optimized for low (4a), medium (4b), and high (4c) charge states. Note the different current scales in the spectrum 4c.



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 4c is plotted again in Fig. 5. By comparing the spectra Fig. 4a), Fig. 4b) and Fig. 5), 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. 4a and Fig. 4b). 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.5). The same rf power and very similar confinement fields were used to obtain 5b) 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 100V to 36 V. This 'gas mixing' effect is well known and used in ECR ion sources as well as EBIS/EBIT sources [13].

FIGURE 5. Oxygen charge state distribution from the Bi spectrum of Fig. 4c



IV. EMITTANCE MEASUREMENTS

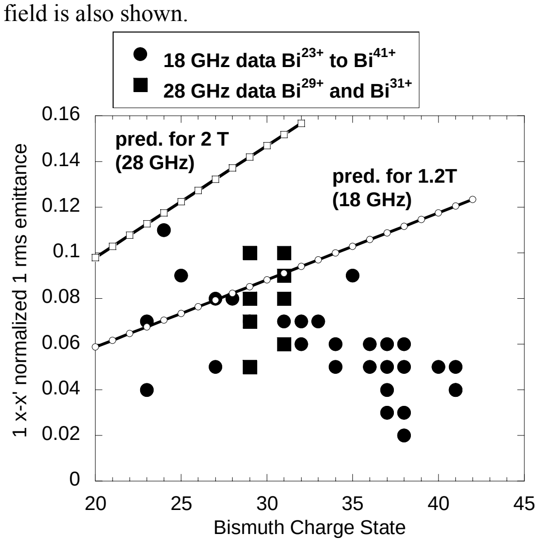
Two main contributions to the ion beam emittance have to be considered for an ECR ion source extraction system: (1) the ion beam transverse temperature, and (2) the induced beam rotation (angular momentum) due to the decreasing axial magnetic field in the extraction region. Considering that the ions in an ECR plasma are relatively cold with temperatures in the order of 1eV or less, the emittance contribution due to the magnetic field becomes the dominant factor for most modern ECR ion sources [6]. Assuming an uniform plasma density distribution across the plasma 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 $\varepsilon^{100\%} = 5 \cdot \varepsilon^{rms}$, a waterbag distribution)

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

where ε is the normalized x-x' rms emittance in $\pi \cdot$mm$\cdot$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 [6]. Following this dependence, the emittance should decrease with ion mass and increase with charge state for a charge state distribution. However, the experimental results don't show this behavior.

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. 6. 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 4mm are also plotted in Fig. 6. It can be clearly seen that the measured emittance does not follow the predicted 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 [14, 15]. 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 [14, 15].

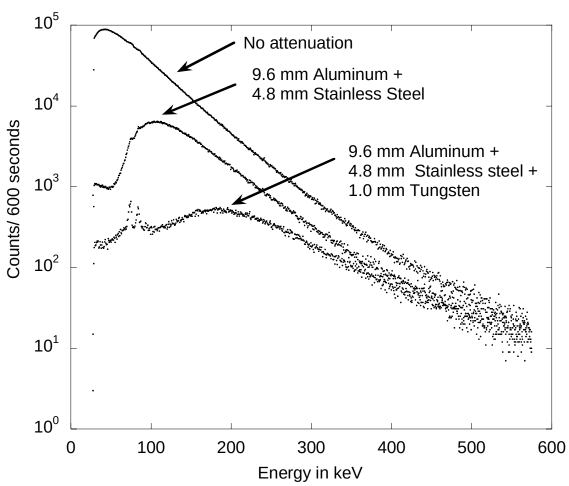
FIGURE 6. Dependence of the emittance value from the ion charge state for bismuth for the 18 GHz heated plasma and the 28 GHz heated plasma. In addition, the predicted emittance dependence from the magnetic field is also shown.



V. PRELIMINARY BREMSTRAHLUNG MEASUREMENTS ON VENUS

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 [16] 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 [17].

FIGURE 7. Axial bremstrahlung measured for 2 kW of 28 GHz microwave power.



The VENUS cryostat has several calibrated carbon glass resistors, which are located in the cryostat and on the cold heads of the cryocoolers. The temperatures can be measured to an accuracy of 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 [9]. 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 tungsten alloy 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 7 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.

VI. RADIAL ELECTRON LOSSES

There are two indications that the radial electron losses occur predominately in localized areas on the plasma wall. First, when the polyester high voltage insulation for the plasma chamber was recently removed, it was found to be discolored due to x-ray damage at the location along the plasma flutes where there is a local minimum in the magnetic field. Second, a hole was melted in the water-cooled aluminum chamber during an uncontrolled power excursion by the 28 GHz gyrotron. During the power excursion the superconducting magnets quenched, which was probably caused by the intense bremstrahlung heating.

The location of the hole was measured prior to the successful repair of the chamber and it coincided with the location of one of the two discolored areas of the insulation. The hole in the plasma chamber occurred along one of the plasma flute although it was rotated 3 degrees from the flute centerline. The axial position was 6 cm displaced toward injection from the midpoint between the injection and extraction coils whose centers are 50 cm apart. An analysis of the magnetic field strength as a function of axial position shows that the hole occurred where the field has a local minimum. At this location, the large gradient in the solenoid field produces a radial component that partially cancels the radial field produced by the sextupole. The VENUS plasma chamber has a hexagonal symmetry with V-shaped grooves that increase the radius by about 4 mm at the plasma flutes [5]. As a result the wall field is greatest at the flute centerline and decreases as one rotates azimuthally. At the hole location, magnet flux lines guide the hot trapped electrons along a trajectory that brings them tangent to the ECR heating surface. This may provide enhanced heating since the electrons will stay in resonance longer than when the flux line is normal to the ECR surface and the trapped electrons pass through the resonance rapidly. At a 6-degree rotation at the edge of the V, the flux lines no longer intersect the ECR surface and are not heated. It appears that the hot electrons are preferentially lost along a narrow line in the axial direction. The x-ray discolorations on the insulation were roughly 1.5 cm wide azimuthally and 5 cm long axially, which is consistent with a line loss. They occurred at the location of the hole and at a 120-degree rotation. The field has threefold symmetry, but there were only two discolored spots. This probably indicates that the plasma wall and the sextupole have a slight misalignment.

FUTURE PLANS

During the next year we are planning to continue the commissioning at 28 GHz power levels of up to 10 kW. First test for the production of uranium ion beams are also planned to verify the performance measured for Bi also for U.

A major focus will be the design and construction of an improved plasma chamber that is able to absorb the high power x-ray radiation emitted from the ECR plasma and reduce the bremstrahlung loading in the cryostat and in the superconducting coils. This should also protect against bremstrahlung-induced quenches. 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 10 or more, which would reduce the 28 GHz the heating rate to about 0.1 W per kW of microwave power or 1.0 W at 10 kW. Since without shielding VENUS has operated at 4.5 kW and about 5 W of bremstrahlung heating, the new shielding should also provide sufficient protection against induced quenches.

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