RECENT PRODUCTION OF INTENSE HIGH CHARGE ION BEAMS WITH VENUS

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Abstract

Several modifications have been made to VENUS to enhance its performance at high microwave power and bring its beam production closer to the levels predicted by scaling laws for 28 GHz operation. Two of these modifications allowed for an increase of injected microwave power: the cooling scheme on the plasma chamber wall was improved to eliminate damage caused by localized electron heating, and the extraction electrode was redesigned to remove the thermal energy from incident hot electrons more effectively. A further modification was the reduction in the diameter of the waveguide which launches 28 GHz power into the plasma chamber. With these remedies, the source now operates stably up to 10 kW of injected power and allows for more favorable magnetic field configurations. The extraction of high charge state ion beams from VENUS has been substantially enhanced as demonstrated by the recent production of a number of intense CW beams: 4.75 emA of O^{6+}, 1.90 emA of O^{7+}, 1.06 emA of Ar^{12+}, 0.523 emA of Ar^{16+}, 0.115 emA of Ar^{17+}, 0.77 emA of Kr^{18+}, 0.355 emA of Kr^{26+} and 0.007 emA of Kr^{31+}. For the first time VENUS has been able to produce more than 1 emA of O^{7+} and Ar^{12+}, and enhance the intensity of the higher charge state ion beams by a factor of 2 and higher.

INTRODUCTION

VENUS is the first 3rd generation superconducting ECR ion source (ECRIS) operating at 28 GHz with magnetic field maxima of 4 T on axis and 2 T radial at the inner surfaces of the plasma chamber [1]. Beginning with its initial operation in 2002, VENUS produced a number of record CW beams from an ECR source and delivered a wide variety of highly-charged, heavy ion beams to enhance the capability of the 88-Inch Cyclotron [2]. However, VENUS was limited in its potential magnetic field configurations at higher input microwave power due to a thin-edged plasma electrode, shown in Fig. 1, which insufficiently transported away the heat load generated by hot electron bombardment. In order to avoid melting this electrode, higher extraction peak fields were required to reduce the flux of hot electrons to the plasma electrode by guiding them to the chamber radial walls. Consequently these higher extraction fields resulted in the lowest total magnetic fields on the chamber surface occurring in localized areas on the chamber radial walls, as shown in Fig. 2, leading to an intense heat transfer to these spots by the hot electrons. This localized heating severely deteriorated the plasma chamber walls over time and resulted in two burned out plasma chambers; even while operating with microwave power limited to 7 kW or lower [3, 4]. This very restrictive constraint on input heating power resulted in VENUS not reaching its full potential even after 15 years of operations.

This article presents and discusses the two recent modifications addressing insufficient chamber cooling, which now allow for more input microwave power. These improvements, coupled with the studies into the effects of reducing the exit diameter of the 28 GHz waveguide from 31.8 mm to 20.0 mm which are also discussed, have allowed for operating VENUS with more preferable magnetic field configurations, with more power, and have led to a stable plasma resulted in significant enhancements on the extracted beam current.

NEW PLASMA ELECTRODE

Figure 1 shows the previous plasma electrode having a slant taper of a minimum thickness of ~ 0.6 mm at the aperture edge of Ø10 mm and ~1.4 mm at Ø16 mm slant-step transition region. This electrode design is poor in transporting away the thermal load on the thin edge and thus not suitable for the hot ECR plasma operating at high microwave power. The high thermal heat load on the electrode thin edge could lead to microscopic and macroscopic surface melting in certain locations, and the presence of molten aluminium decreases plasma stability. Heat transport simulations indicate that for a circular region of radius of ~ 8 mm it takes ~ 950 W power, equivalent of 775 W/cm^2 in an area of $S = \pi(0.8^2\text{-}0.5^2)$ cm^2, for the thin edge temperature rising up to ~ 350 ^{0}C in which the aluminium recrystallization will occur.

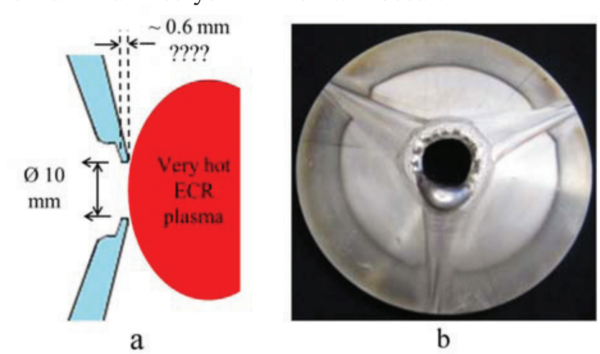

Figure 1: a). The previous plasma electrode with the aperture supported by a very thin slant backing resulted in poor power transportation; b). This thin aperture edge was melted for a few hours of operation at ~ 7.5 kW microwave power with extraction peak field lower than the minimum total field at the chamber walls.

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When VENUS was operated at total microwave power of 7.5 kW with the extraction field lower than the minimum total field at the chamber walls for about a few hours, the thin-edged extraction aperture melted, as shown in Fig. 1b, and resulted in an unstable plasma. A modification was then made to the extraction electrode by eliminating the slant-step transition which has led to a minimum thickness of ~ 3.8 mm at the aperture edge. This thickness increase improves thermal conduction from the primary heat load of electrons near the inner aperture edge to the outer radius of the electrode where it is thermally connected to the water-cooled chamber. Simulations have shown the revised plasma electrode with the 3.8 mm minimum thickness should withstand up 30% more power than the thin-edged electrode to reach recrystallization. Indeed, in operating for months with the modified electrode using low extraction magnetic fields, essentially no corrosion has been observed and the plasma remain stable even at microwave power of ~ 10 kW.

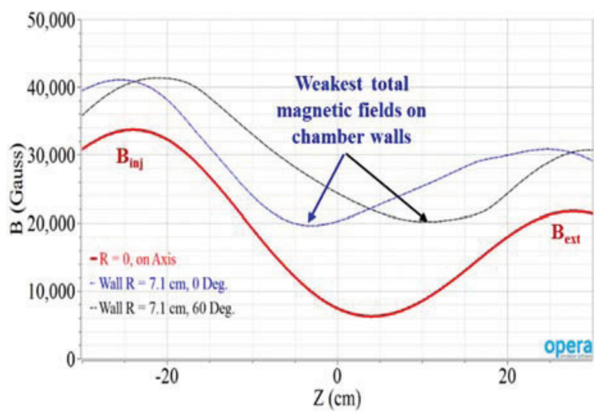

Figure 2: VENUS had been operating for many years with constrained magnetic field configurations like the one is shown. There were always magnetic holes on the plasma chamber walls due to the peak field at extraction is higher than the total fields at some locations of the walls.

NEW COOLING SCHEME FOR THE PLASAMA CHAMBER

The previous cooling scheme of the VENUS plasma chamber had a wide water channel right behind a ~ 2 mm thick aluminium wall that is in touch with each of the six plasma flutes, as shown in Fig. 3a. Though the overall cooling capacity of the chamber is sufficient to remove much more than 10 kW power, the chamber was burned out twice along a flute, shown in Fig. 3b, due to hot electrons reaching the chamber wall at the location of the magnetic weak point. Hot electron bombardment can easily result in power being deposited at these small magnetic holes in excess of the critical heat flux of 1 MW/m^2 [4]. When the temperature at these locations exceeds 150 ^{0}C, the cooling water immediately outside the hot spots is vaporized dramatically reducing cooling and the localized temperature can continue to rise to 350 ^{0}C. Above these temperatures the aluminium can recrystallize and lead to catastrophic failures.

To reduce the localized overheating on the chamber walls, we have rotated the existing plasma chamber 30^0 to align the plasma flute along a section of ~ 7-mm-thick aluminium situated between two adjacent water channels, as shown schematically in Fig. 3c. The two adjacent cooling channels are at ~ 5 mm azimuthally from the center of the plasma flute, therefore cooling the plasma flute contact area is through lateral thermal conduction instead of the direct back-cooling. VENUS has been operating with this new cooling scheme for about one year and although it has run frequently with a total microwave power of 10 kW for extended periods, no visible damage has been found in the chamber surfaces.

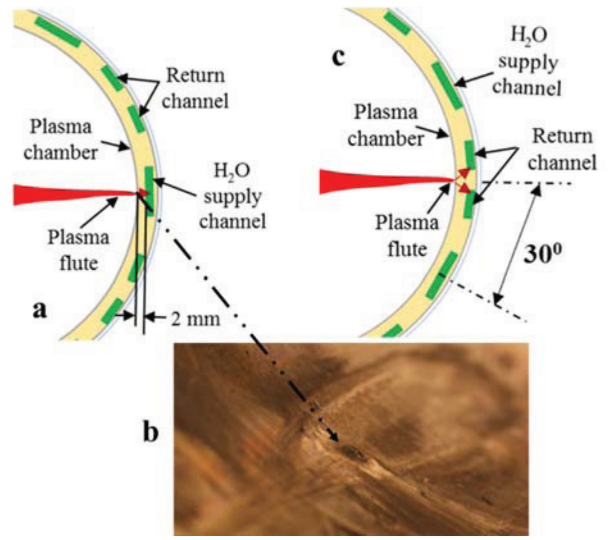

Figure 3: **a**. The previous plasma chamber cooling scheme aligned a water channel with ~ 2 mm thick wall right on a plasma flute (red colour); **b**. The resulted burned out at a location where the total magnetic field is the weakest; **c**. New scheme by rotating 30^0 of the chamber to align a plasma flute onto a section of ~ 7 mm thick solid aluminium that is cooled laterally (indicated by the two green arrows) by two adjacent water channels.

MAGNETIC FIELD CONFIGURATIONS

With sufficient cooling to the plasma chamber, VENUS can operate with a wider range of magnetic field configurations; most importantly it can operate using lower peak extraction fields. In comparison to the previous constrained field configuration shown in Fig. 2, the field strength at extraction is now typically run about 10% lower when $B_{min} \leq 0.5$ T, while the fields at injection and the chamber walls remain about the same. Having a low extraction field is expected to result in an increase of hot electrons lost to the plasma electrode, reducing some of the heat load to the hot spots along plasma flutes where chambers have been burned out previously. Improved cooling at the extraction electrode and along the flutes allows for higher input microwave power. These subtle changes and the ensuing results have demonstrated that with better plasma chamber cooling VENUS can operate with more preferable magnetic field configurations while

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maintaining good plasma stability so that more microwave power can be injected into the ECR plasma resulting in better performance. It is important to note that the performance improvements with these modifications are with little operation time. Exploration into newly available magnetic field configurations, such as with higher B_{min} fields, will continue.

LAUNCHING 28 GHZ MICROWAVES WITH A 20 MM CIRCULAR TRANSITION

Following the first successful coupling of 28 GHz microwaves into SERSE [5], all subsequent 3rd generation ECRISs use oversized circular waveguides (Ø ~ 30-32 mm) to launch the 24-28 GHz TE_{01} circular microwaves into their ECR plasma and have substantially enhanced ECRIS performance. However, the question remains how to achieve the best coupling of higher frequency microwaves ($f \geq 20$ GHz) into an ECRIS. In other words, it is not clear how to maximize the forward power and minimize the reflection through microwave mode or launching scheme. For frequency f > 20 GHz, HE_{11} microwave was proposed for better heating ECR plasma because of its Gaussian energy concentration on axis [6], but so far two explorations have failed to demonstrate the expected enhancements [7, 8].

The merits of launching scheme with optimum size of the coupling waveguide had not been explored until recently by the ECR group of IMP [8]. In an over-simplified analysis, as schematically shown in Fig. 4a, a coupling waveguide of about the same diameter as the plasma chamber will not work very well as much of the input microwave power will easily escape the plasma cavity and stream back to the microwave generator causing substantial variation of the forward power level and possible damages to the microwave generator. On the other hand, limiting reflected power by employing a very small-diameter waveguide such as a quasi-zero one shown in Fig. 4b won't work either as little power is transported into the chamber. Based on this simple analysis, it should be expected that the optimum diameter for a coupling waveguide into an ECRIS should fall somewhere between zero and the chamber diameter, schematically illustrated in Fig. 4c.

Exploration of the different coupling waveguides is underway in VENUS and the first test has been carried out by tapering the straight circular waveguide of Ø31.8 mm down to Ø20 mm at the coupling exit into the plasma chamber. Preliminary tests with TE_{01} microwaves and different operating magnetic field configurations, combined with the better chamber cooling, demonstrated different operation characteristics. The plasma is now more stable at higher input power and shows no saturation for many high charge ion beams even at total power reaching ~ 10 kW. In these tests the source is operated with a low central field, B_{min} of 0.3 ~ 0.5 T (B_{ecr} = 1 T for 28 GHz microwaves) but with high microwave power. Such a low B_{min} was chosen in order to lower the electron spectral temperature, T_s, of bremsstrahlung radiation as this spectral temperature is proportional to B_{min} [9]. Operating with such field configurations with lower B_{min}, was suggested before, and when doing so the generated heat load to the VENUS cryostat is typically ≤ 1 W even at microwave power of 10 kW injected [10].

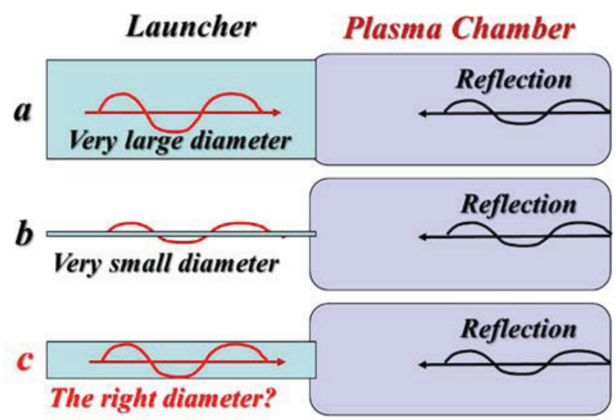

Figure 4: **a**. A launching waveguide of very large diameter enables high portion of microwave power escaping; **b**. Launching waveguide of very small diameter won't work due to that little power can be transported; **c**. There should be an optimum launching waveguide of the right diameter producing the best microwave coupling to an ECRIS.

NEW RESULTS AND COMPARISON

Table 1 lists the recent VENUS performance compared to previous VENUS production and that of some other sources for a few example heavy ion. It is clearly seen that for very highly charged ion beams, VENUS shows a factor of ~ 2 or greater improvement, and for lower charge states the results from VENUS are very comparable [8, 11]. This is the first time that VENUS has produced more than 1 emA of O^{7+} and Ar^{12+}, which had been strived for many years but never achieved until the improved cooling. The production of 0.5 emA of Ar^{16+}, 0.1 emA of Ar^{17+} and 0.007 emA of Kr^{31+} has also set new beam records from VENUS, demonstrating that the source potential has not yet been fully realized.

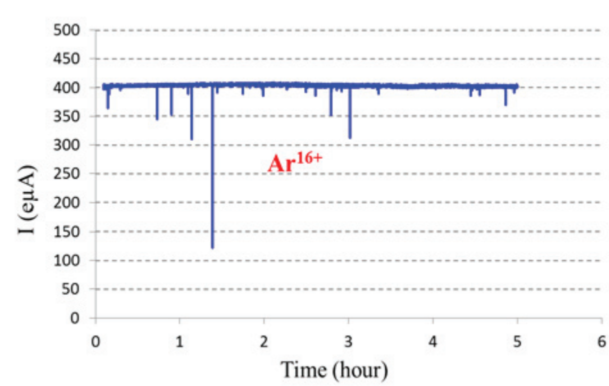

Figure 5: A measurement of 0.4 emA of Ar^{16+} produced with VENUS for 5 hours demonstrates the good beam stability at high microwave power of 8 kW, though with a few trips of unknown causes.

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Figure 5 shows a measurement of the beam stability of 0.4 emA of Ar^{16+} produced with VENUS at microwave power of 8 kW. Excluding a few trips, this measurement has demonstrated with sufficient chamber cooling VENUS can stably produce intense high charge state ion beams even at high microwave power of 8 ~ 10 kW for hours, and it should work the same for days or weeks if all inputs kept stable.

Table 1: Recent Performance of VENUS and Comparison

	VENUS 28+18 GHz (≤ 2015)	VENUS 28+18 GHz (2016)	SECRAL 24+18 GHz	SuSI 24+18 GHz
$^{16}O^{6+}$	2.85	**4.75**	2.3	2.2
O^{7+}	0.85	**1.90**	0.81	1.4
$^{40}Ar^{12+}$	0.86	**1.06**	1.42	0.86
Ar^{14+}	0.514	**0.84**	0.846	0.53
Ar^{16+}	0.27	**0.523**	0.35	0.22
Ar^{17+}	0.037	**0.115**	0.05	
Ar^{18+}	0.001	**0.004**		
$^{78}Kr^{18+}$	^{84}Kr	**0.77**		
Kr^{23+}	0.088	**0.42**		
Kr^{28+}	0.025	**0.089**		
Kr^{31+}		**0.007**		

*: Quoted currents are in unit of emA.

DISCUSSIONS

The performance of VENUS has been substantially enhanced by a combination of the few presented, recent modifications, and exploration into the performance gains from these modifications will continue. The improvement of a factor of 2 or higher for very highly charged ions enables VENUS to further enhance the capability of the 88-Inch Cyclotron. Because this limited exploration was not done systematically in order to determine the contribution of each modification individually, the question arises as to which one of the modifications plays the most important role in VENUS new achievement?

Getting a clear answer to this question would require a long time and great effort. However, a very plausible scenario would be that the two cooling modifications to the plasma chamber have allowed VENUS to operate at higher microwave power with more preferable magnetic field configurations. In addition, the smaller 28 GHz launch waveguide of Ø20 mm reduces the reflected microwave power to minimize the interference with the 28 GHz microwave generator. Thus the combination of these changes enables VENUS to manifest its potential.

It is worth of pointing out the future generation of ECRIS will likely operate with microwave power much greater than 10 kW [12]. Based on Geller's scaling [13]: q_{opt} the optimum charge state is proportional to the angular frequency ω, power dependence on q_{opt} and ω:

$$q_{opt} \sim \log(\omega^{3.5}) \text{ and } P_{\mu} \sim \omega^{1/2} q^3 V$$

Using SECRAL's best bismuth results [8] and assuming the same chamber volume V, one would find that as we move toward 45 GHz sources:

@ 24 GHz Bi $q_{opt\,1} \sim 30+$ and $P_{\mu 1} \sim 8.5$ kW →

@45 GHz, Bi $q_{opt\,2} \sim 36+$ and $P_{\mu 2} \sim 20$ kW

With a power level of 20 – 30 kW launched into an ECR plasma chamber the cooling will definitely become much more challenging, thus the plasma chamber should be very well engineered.

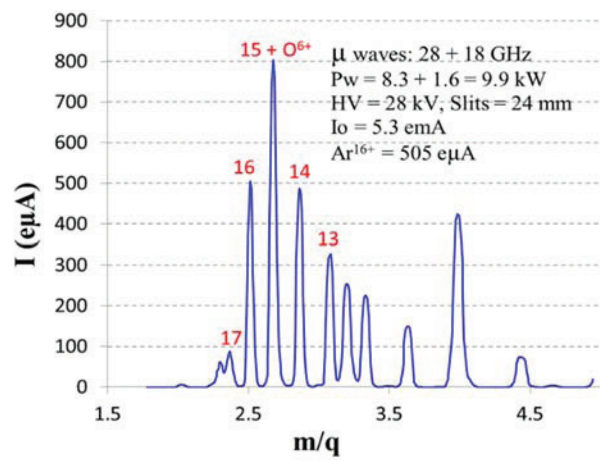

Figure 6: Argon charge state distribution produced recently with the VENUS which was optimized on Ar^{16+} and peaked at either 15+ or 16+ for the first time. Oxygen gas was used as the support gas with microwave power ~ 10 kW.

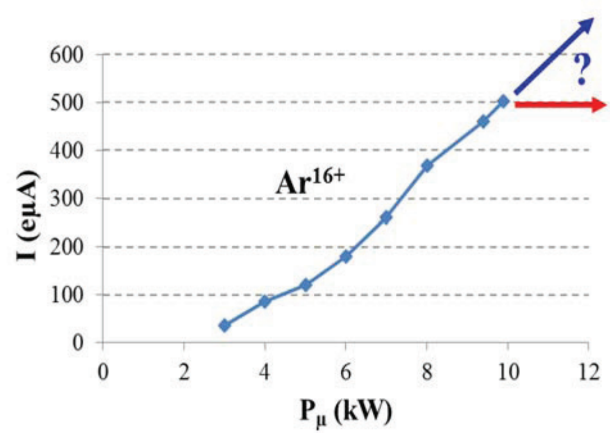

Figure 7: Intensity of Ar^{16+} versus injected microwave power up to 10 kW shows no sign of saturation indicating that higher intensity is possible with more microwave power.

Figure 6 shows a VENUS spectrum optimized for Ar^{16+} with oxygen as the support gas. It is the first ever charge state distribution of argon produced by VENUS peaking at either Ar^{15+} or Ar^{16+} with intensity of 0.5 emA. The curve of the intensity of Ar^{16+} versus the microwave power up to 10 kW in Fig. 7 shows no sign of saturation indicating higher yield of Ar^{16+} would be possible with more microwave power. This should also be the case for other

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high charge state ions, such as O^{7+}, Ar^{17+}, Ar^{14+}, Kr^{28+} and Kr^{31+}, etc.

Tests of two different sizes, Ø15 and Ø25 mm, of the 28 GHz coupling waveguides have been planned to explore a better coupling of the 28 GHz microwaves to VENUS. Even though so far no any conclusive evidence supports the role of the microwave mode played in the ECRIS performance, investigation of the effects of TE_{01} and TE_{11} microwaves are planned for future developments.

Based on the discussed modifications that have led to the recent performance enhancements with VENUS, it is reasonable to arguably conclude that a well cooled ECRIS can stably operate at > 10 kW microwave power. The maximum operating power could likely to be determined by the combination of plasma chamber cooling and the magnetic field configurations.

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