Title

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COMMISSIONING OF THE SUPERCONDUCTING ECR ION SOURCE VENUS *

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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. The magnetic field strength has been designed for optimum operation at 28 GHz. The four-year VENUS project has recently achieved two major milestones: The first plasma was ignited in June, the first mass-analyzed high charge state ion beam was extracted in September of 2002. The paper describes the ongoing commissioning. Initial results including first emittance measurements are presented.

VENUS ECR ION SOURCE

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. This frequency choice has several design consequences. To achieve the required magnetic confinement, superconducting magnets have to be used. The size of the superconducting magnet structure implies a relatively large plasma volume. Consequently, high power 28 GHz microwave coupling becomes necessary to achieve sufficient plasma heating power densities. Finally, the extraction of the high current, multi-species ion beam out of the ion source plasma in the presence of a high magnetic field is a challenging task, and VENUS will provide an essential database for the design of future ECR high current injector systems.

Fig. 1 shows the mechanical layout of the ECR ion source. The mechanical design is described in detail elsewhere [1]. The water-cooling of the ion source is sufficient to allow continuous operation at 15 kW microwave input power.

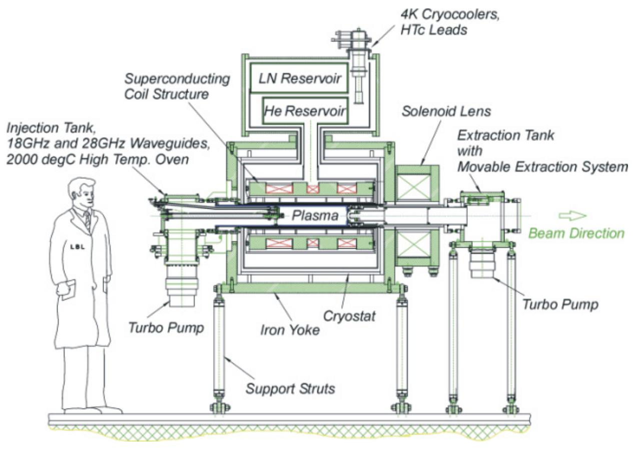

Figure 1: Mechanical layout of the VENUS ion source and cryogenic system.

The design and development of the superconducting magnets are described in [1,2]. The sextupole coils are wound around a pole with iron in the center, which enhances the peak field 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 [2]. 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 their design fields, 4T at injection and 3T at extraction respectively.

The cryogenic system for VENUS has been designed to operate at 4.2º K with two cryocoolers each providing up to 45 W of cooling power at 50º K and 1.5 W at 4º K in a closed loop mode without further helium transfers. During the acceptance test in September 2001, the cryostat failed to meet design specifications. The heat leak exceeded the design goal of 1.5 W and was measured to be about 3 W, which is at the limit of the two croycoolers' capacity. Furthermore the heat exchanger, which couples the LHe Reservoir to the two 1.5 W cryocoolers did not function properly, making it necessary to frequently transfer liquid helium. Thorough analysis of the original heat exchanger showed, that the thermal resistance of the flexible copper link was too high to efficiently transfer heat from the helium reservoir to the cryocoolers. Therefore, a new design approach was developed. Sets of fins machined from blocks of high conductivity copper are mounted directly on each cryocooler head and act as helium vapor

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condensers. A tube was installed to transfer helium vapor from the reservoir to the condensers. There the vapor condenses, and the liquid helium returns to the reservoir through a second tube [3].

The two cryocoolers now provide sufficient cooling power for 18 GHz operation [3]. For 28 GHz operation, the expected x-ray flux will add to the heat load of the cryostat. Therefore, we are currently constructing a cryostat extension with an additional (third) cryocooler.

Beam Transport System

The low energy ion beam transport system shown in Fig. 2 consists of a moveable accel-decel extraction system (operating at voltages up to 30 kV), a solenoid lens, and a large gap, 90 degree double focusing analyzing magnet [4, 5]. 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. In this kind of arrangement, a single solenoid lens is used to adjust the divergence of the beam going into the magnet. The beam diameter cannot be adjusted independently at the same time with only a single solenoid lens. Consequently, a large gap (18 cm) magnet was chosen to accommodate the ion beam size at high intensities [1].

After the mass analyzing section, a two-axis emittance scanner has been installed. In order to measure the actual ion source emittance instead of the magnet acceptance, 100% ion beam transmission with minimal aberrations through the analyzing section is essential.

In the early commissioning phase, during which total currents between 1 and 5 emA have been extracted, ion beam transmissions of 80 to 100% have been measured. Systematic emittance measurements are being carefully compared to the beam transport simulations. These studies will improve the theoretical understanding of the multi-ion species beam transport and will provide guidance for the design of future high current ECR injector systems.

FIRST COMMISSIONING RESULTS

The first plasma was ignited in June, the first mass-analyzed high charge state ion beam was extracted in September of 2002. Several technical challenges were solved during the first commissioning months. A PLC (programmable logic controller) based external regulation loop for the superconducting magnet power supplies was developed. 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. In addition, a new quartz HV break was developed for reliable 18 GHz microwave operation up to 2 kW. Holes were drilled into the waveguide inside the ion source vacuum chamber for better pumping in this long waveguide section to suppress a parasitic ECR discharge found in initial tests.

	AECR-U 10+14 GHz	SERSE 14 GHz	SERSE 14+18 GHz	VENUS 18 GHz
O^{6+}	570	430	540	810
O^{7+}	300	225	225	220
Ar^{11+}	270	260	260	290
Ar^{12+}	192	200	200	180

Table 1 First VENUS commissioning results compared to best performance data from the AECR-U and the SERSE [7] ion sources at the given frequencies. The VENUS ion source has not been tested for very high charge state production.

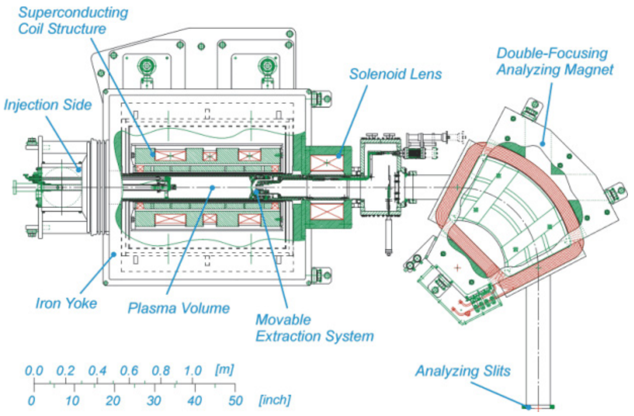

Figure 2: Mechanical layout of the beam transport system for VENUS.

The vacuum system design, which uses only UHV compatible components and metal seals, is optimized for good plasma chamber pumping. Therefore, after initial operation with plasma, the base pressure is excellent (injection chamber low 10^{-8} mbar, extraction chamber low 10^{-9} mbar). So far, oxygen and argon gases have been used in the tests. Heavy ion beam production for very high charge states and metal ion beam production will be started this summer. Some preliminary results are presented in Table 1.

Venus has a plasma volume of about 9 liters, which is large compared to the AECR-U [6]. The microwave power density used in the AECR-U at peak performance is 1700 W/liter in double frequency mode and about 1000 W/liter in single frequency mode. A total power of 10 kW will be required to achieve an equivalent power density in VENUS. Once the 28 GHz gyrotron has been installed at the end of this year, this power density will be available.

Fig. 3 shows the analyzed O^{6+} current in eμA as a function of 18 GHz microwave power. The current increases almost linearly with power, demonstrating that more rf power is needed to reach optimum performance.

In Fig. 4 the analyzed O^{6+} and O^{7+} current is plotted as a function of the radial field. For reference, the ratio of the radial field to the electron cyclotron resonance field (radial mirror ratio, B_{rad}/B_{ecr}) for 18 GHz is also shown. The current values peak at a radial mirror ratio of about 2, similar to the radial mirror ratio for maximum performance observed in SERSE at 14.5 GHz [8]. For 28 GHz operation, this maximum would be at 2 to 2.2T sextupole field. Therefore, the confinement of VENUS

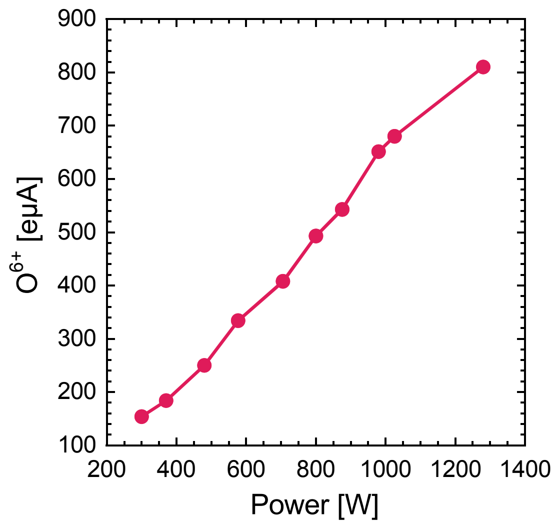

Figure 3: Analyzed O^{6+} current in dependence of the coupled RF power.

should be sufficient to achieve maximum performance at 28 GHz.

Systematic emittance studies with argon have begun recently, and first results are presented in Fig. 5. The 1-rms normalized emittance values for different argon charge states are plotted. Several charge states have been measured for various ion source and tuning conditions (rf power, plasma stability, extraction matching and ion optics). The different values are graphed to show the spread in measured emittance values.

The theoretical minimum emittance caused by the ion source axial magnetic field at the extraction is also plotted in this graph. The strong axial ion source magnetic field at the extraction induces a beam rotation that leads to emittance growth as described in [5]. There is a good agreement between the measured data and the predicted values. This suggests that the extraction system is well matched to the extracted ion beam current. On the other hand, these measurements differ from previously measured emittance values at the AECR-U ion source [9], in which the emittance values decline for the higher charge states. It may be that the VENUS source tuning is not yet optimized for very high charge state production, in which higher charge states are extracted closer to the beam axis [5].

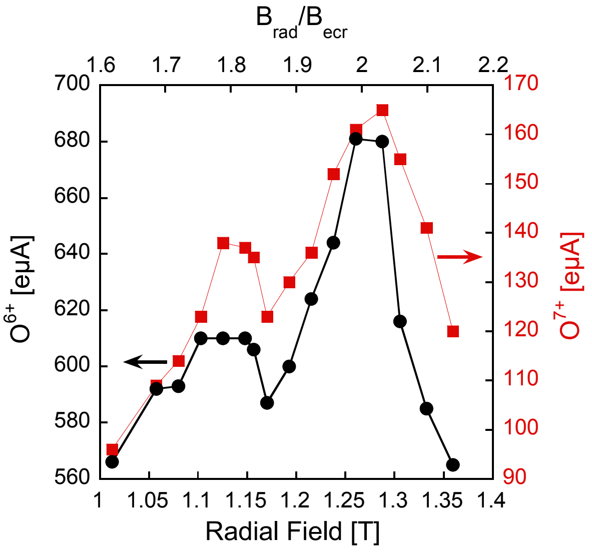

Figure 4: O^{6+} and O^{7+} ion beam intensity versus the radial magnetic plasma confinement field.

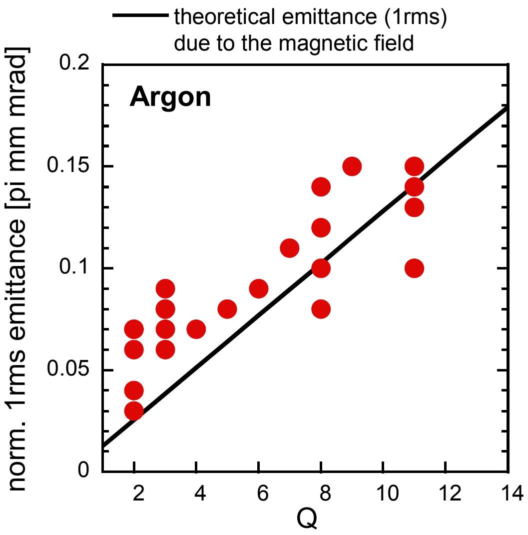

Figure 5: Measured emittance values for different charge states of argon in comparison with the predicted [5] theoretical minimum values due to the magnetic field.

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