VENUS: THE NEXT GENERATION ECR ION SOURCE

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Abstract

The construction of VENUS, an Electron Cyclotron Resonance ion source designed to operate at 28 GHz, is nearing completion. Tests with the superconducting magnet assembly produced axial magnetic field strengths of 4 T at injection and 3 T at extraction and a sextupole field of 2 T at the plasma wall. These fields are sufficient for optimum operation at 28 GHz. We expect a shift to higher charge states and an increase in the beam intensities (about 4 times) compared to those obtained with the AECR-U, which operates at 14 GHz. Initial operation will be at 18 GHz, but best performance is expected when operation with a 10 kW, 28 GHz gyrotron becomes possible. The high beam intensities and the large axial magnetic field at extraction make it challenging to extract, analyze and transport the beam into the 88-Inch Cyclotron. The analyzing system which consists of a solenoid lens and a large gap 18 cm spectrometer-magnet with higher order field corrections has been optimized utilizing 3D magnet and ray-tracing codes including space charge effects. The status of the construction and design aspects of the source and beam transport system are described below.

1 INTRODUCTION

VENUS (Versatile ECR for Nuclear Science) is a next generation Electron Cyclotron Resonance ion source designed to produce intense high charge state ions for injection into the 88-Inch Cyclotron [1,2]. The 88-Inch Cyclotron is currently fed by the LBL ECR which began operation in 1985 and the AECR in 1990 which was upgraded to the AECR-U in 1995 [3]. In addition to becoming the third injector ion source for the cyclotron, VENUS will be tested to see if it meets the performance requirements for the RIA heavy ion driver. Later will require 4 to 6 particle μA of U^{30+} for injection into an RFQ. [4]

In Table 1 the major features of VENUS are compared with the AECR-U. The key differences between the two sources result from the change in operating frequencies with VENUS designed to operate at twice the frequency of the AECR-U. The high magnetic fields for VENUS also set it apart from its predecessor. The solenoid fields can operate up to 4 T at injection and 3 T at extraction and the sextupole coils will produce a field of 2 T at the plasma wall. The overall size of VENUS is significantly larger to keep the current densities in the superconducting wires below the critical current. Since the plasma density is expected to scale as frequency squared and VENUS has a larger plasma chamber, we expect that it should be able to utilize at least 10 kW of 28 GHz microwave power.

VENUS is designed to operate at 30 kV so that the higher intensity beams can be efficiently extracted and transported. A new low energy beam line (LEBT) which has an large acceptance 90 degree analyzing magnet has been designed to transport the high intensity beams and is described in Section 2.4 below.

Table 1: Comparison of AECR-U and VENUS

	AECR-U	**VENUS**
Magnetic Field (AT)	317,000	3,000,000
Peak Axial Field	1.7 T	4 T
$B_{rad\ \ wall}$	0,8T	2.0 T
Plasma wall ID	7.6 cm	13.5 cm
Microwave: Frequency	10, 14 GHz	18, 28 GHz
Microwave: Total Power	2,600 W	14,000 W
Extraction: High Voltage	15 kV	30 kV

2 SYSTEM OVERVIEW

2.1 Plasma Chamber

Figure 1 shows an elevation view of VENUS. The plasma chamber is constructed from an aluminum tube with gun-drilled water cooling channels to provide sufficient cooling for operation with 10 kW of 28 GHz microwave power. The plasma chamber will be pumped by a 1000 l turbo pump mounted on the injection end of the source. The design of the injection end provides for 3 off axis microwave feeds and two off axis ovens as well as a cooled biased disk on axis. The primary design goals were to minimize the microwave leakage out of the plasma chamber, maximize the pumping conductance and provide a biased disk for enhanced charge state production. The plasma chamber length is 50 cm corresponding to the distance between the main solenoid coils and 13.5 cm in diameter.

2.2 Superconducting Magnets

The magnetic fields are generated by a superconducting magnet structure consisting of three solenoid magnets and a race track superconducting sextupole structure. The two outer solenoids produce an axial magnetic mirror field, whose center strength can be lowered by the middle solenoid run with opposite polarity. The six racetrack coils are wound around a pole piece made of iron in the center and aluminum at each end. The primary challenge in the construction of the magnet structure was to develop a new clamping scheme to withstand the strong magnetic forces between the coils and eliminate coil movement leading to quenching. A key feature of the clamping was

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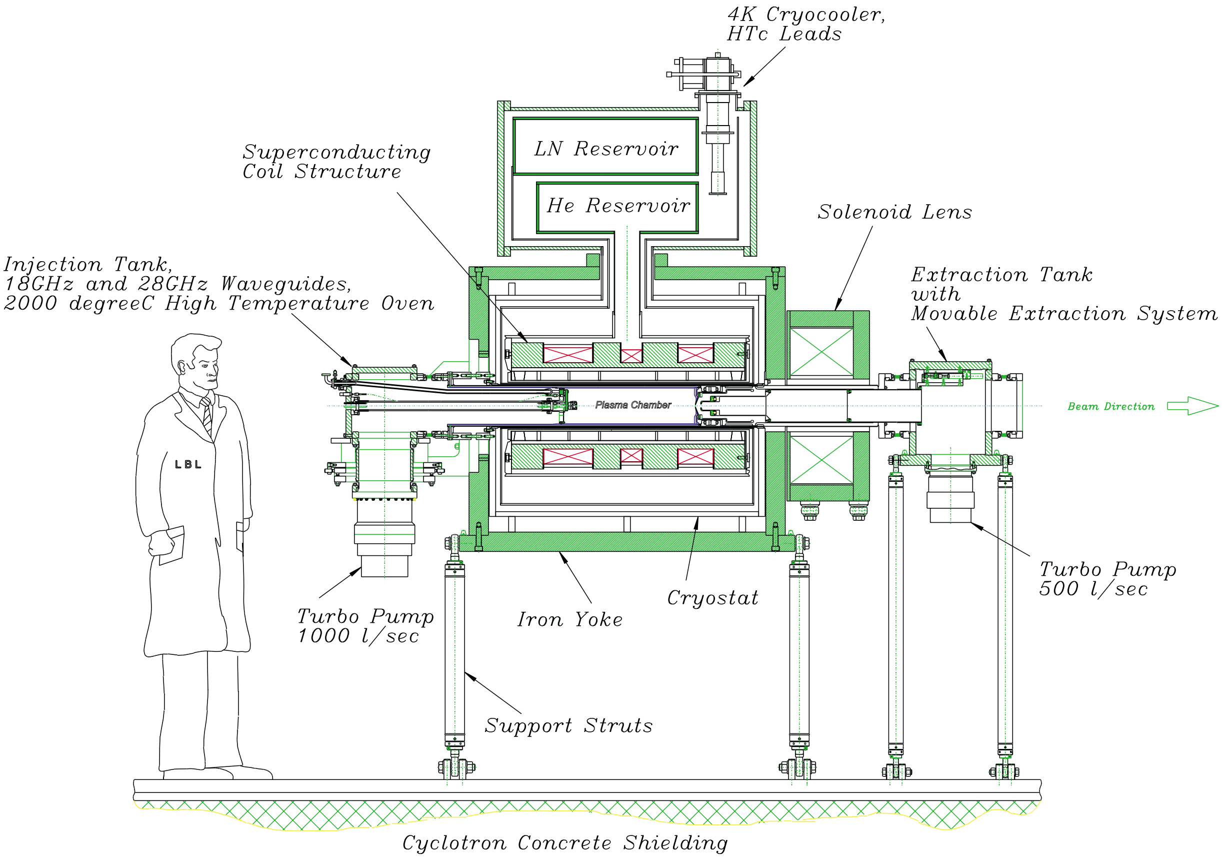


Fig. 1. An elevation view of VENUS showing the iron yoke, cryostat and cryocoolers, the superconducting magnets and the solenoid focusing lens.

the development of expandable bladder system using thin stainless steel sheets which were inserted between the race track sextupole coils and then inflated with liquid metal [5]. The magnet assembly was tested in a 51cm ID cryostat. Initially the solenoids were tested without the sextupole over a variety of fields to simulate the maximum field at the coils and the axial forces that will be experienced in service. The solenoid coils reached full design fields with no quenches. The sextupole experienced training quenches when tested by itself and when tested in progressively stronger solenoid fields. After 13 quenches it reached 505 A with the solenoids operating at design field. The design current for the sextupole with the solenoids at 100% is 438 A and the "short sample" current is 550 A.

2.3 Cryogenics

The cryogenic system for VENUS is designed to operate at 4.2º K with 2 cryo-coolers each providing up to 45 W of cooling at 50º K and 1.5 W at 4º K. Although it is anticipated that liquid helium will be used to speed the initial cool down, during stable operation the cryo-coolers will run in a closed loop mode without further helium transfers. High Tc superconducting links will be used between the 50 ºK and 4 ºK transition to minimize the heat leak through the 8 current leads. The cryostat is surrounded by a warm iron yoke and one of the main design challenges is to provide sufficiently strong links to support the magnet within the cryostat against the strong forces between the superconducting coils and the iron yoke. The worst case (12,500 lbs/link) occurs if the large solenoid coil is operated at maximum current when the other solenoids are off.

2.4 LEBT

The low energy beam transport (LEBT) for VENUS will provide for extraction, mass analysis and transport to the axial injection line for the 88-Inch Cyclotron. Unlike the LEBT for the AECR-U, the new LEBT [6] was designed from the beginning to handle high intensity beams where space charge forces strongly affect the transmission. Several computer codes were used in the simulation and design process including IGUN, GIOS and KOBRA. The two main design goals were to first provide good resolving power and matching into the cyclotron injection line and second to produce a high intensity beam with small emittance which matches the baseline requirements for the RIA driver linac. The test which was modeled by scaling the charge state distribution from the AECR-U up to the higher intensity. The extracted beam

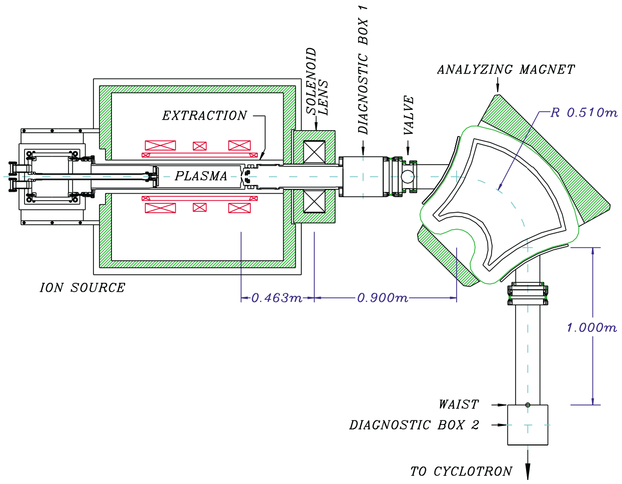


Fig. 2. LEBT for VENUS showing the source, solenoid lens and large aperture 90 degree analyzing magnet.

has a wide range of ion charge states. Its proton equivalent intensity is 25 mA[7].

Figure 2 shows the basic components of the LEBT. After extraction at voltages up to 30 kV, a Glaser lens matches the beam into the 90 degree analyzing magnet. It was decided to match directly into the analyzing magnet rather than to provide a waist in front to reduce minimize the space charge effects. Furthermore, the magnetic field of a solenoid lens sufficient to focus the beam from VENUS at extraction voltages (up to 30 kV) would have required a 1.0 T field. In the current design, the sole purpose of the solenoid lens is to adjust the angle of the beam going into the magnet. Since a single solenoid lens cannot control the actual beam diameter, a large magnet gap must be chosen to accommodate the highest anticipated beam intensities. One possibility for future high field superconducting ECR ion sources would be to incorporate the first magnetic focusing element of the LEBT into the superconducting magnet structure. This would provide greater design flexibility and could lead to cost savings.

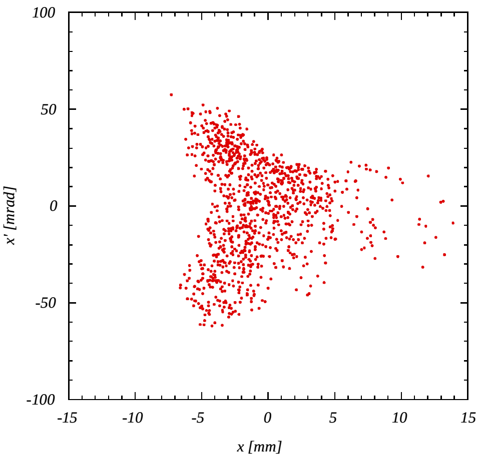
Table 2: 90 degree analyzing magnet parameters

Bending radius	51 cm
Vertical gap in vacuum chamber	16 cm
Horizontal acceptance	30 cm
Maximum Rigidity	0.18 Tm
Maximum Power	10 kW

The 90 degree analyzing magnet [7] is double focusing with specially shaped poles to provide correction for the sextupole term in both the horizontal and vertical plane. The shaping of the poles is an improved design based on an ANL-magnet [8] and will be described in [7]. Simulations based on particle tracking through the calculated fields of the final magnet design show that

(I) Uncorrected Magnet:

Horizontal emittance $\varepsilon_{\text{rms norm}} = 0.10\ \pi$ mm mrad



(II) Corrected Magnet:

Horizontal emittance $\varepsilon_{\text{rms norm}} = 0.04\ \pi$ mm mrad

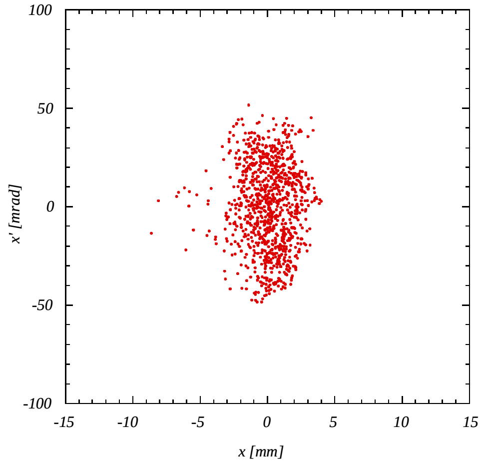


Fig. 3. Results of particle tracking showing the reduction in the transverse size of the beam when the sextupole aberrations are corrected.

sextupole aberrations of the large gap magnet can be corrected. This is illustrated in Fig 3. Simulations show that for beams filling 50% of the vertical gap the normalized rms emittance can be as low as 0.04 π mm mrad which is well within the baseline design for the RIA driver linac [9]. In addition, this higher order correction improves the mass resolution of the system, which will be important for regular operation with the Cyclotron.

3 CONSTRUCTION STATUS

VENUS is scheduled to begin test operation at 18 GHz in the fall of 2001. The construction of the cryostat, shown in Fig. 4, is nearing completion at Wang NMR, Inc. The cold mass has been suspended in the cryostat and work on the upper assembly is underway. The cryostat and magnet assembly are scheduled for delivery in Berkeley in June. Installation of support equipment on the cyclotron vault roof is well along and construction of the source stand and other components is complete. First plasma tests will probably be done during the summer of 2001 with a 14 GHz klystron prior to the arrival of a 2 kW 18 GHz klystron. The first tests with analyzed beam are scheduled for fall of 2001. Whether we purchase a gyrotron or complete the coupling of the LEBT to the axial injection system depends on funding levels in FY02. Ideally, we would like to purchase the gyrotron and begin testing at 28 GHz prior to completing the injection beam line.

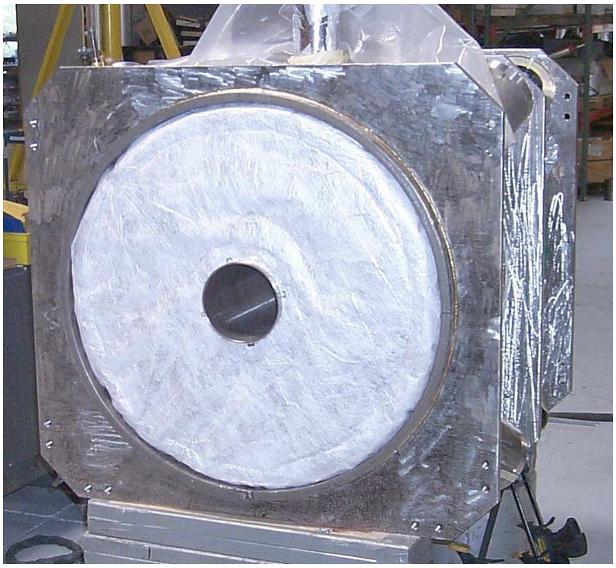


Fig. 4. VENUS cryostat with the cold mass and bore tube installed prior to welding on the end caps.

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