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Development of ECR Ion Source and LEBT Technology for RIA*

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Abstract
The Rare Isotope Accelerator (RIA) Linac driver requires a great variety of high charge state ion beams with up to a magnitude higher intensity than currently achievable for the heaviest masses. The goal of the RIA injector R&D program for VENUS is the reliable production of intense medium charge state ion beams, e.g. 8 puA (particle µA) of U^{29+}. Therefore, the superconducting ECR ion source VENUS has been designed from the beginning for optimum operation at 28 GHz at high power (10 kW). In addition, a high intensity Low Energy Beam Transport, LEBT, that was developed to analyze and transport these multiply-charged, space charge dominated beams. During the last year VENUS was commissioned at 18 GHz and preparations for 28 GHz operation continued. Tests with various gases and recently metals have been performed with up to 2000 W of 18 GHz RF power. Promising performance has been measured in those preliminary beam tests. For example, 180 pµA of O^{6+}, 15 pµA of Ar^{12+}, 7.5 puA of Xe^{20+} and 4puA of Bi^{24+} were produced in the early commissioning phase, ranking VENUS among the currently highest performance 18 GHz ECR ion sources. In FY04 a 10 kW 28 gyrotron system will be added, which will enable VENUS to reach full performance. The emittance of the beams produced at 18 GHz was measured with a two axis emittance scanner developed with earlier RIA R&D funds.

Introduction

The RIA driver linac should produce up to 400 kW of beam power for ions from protons to uranium. A 1.4 GV superconducting linac is being designed to provide protons up to 900 MeV and uranium at 400 MeV/nucleon. The heaviest beams are the most challenging both from the point of view of the linac and from the ion source. Therefore, much of the preliminary design effort, and R&D for the linac focuses on the issues associated with accelerating uranium beams. Similarly, the ion source development is focused on the production of sufficiently intense high charge state uranium beams. The RIA ion sources have to produce 8 pµA or more of U^{29+} for 400 kW beams [2] assuming efficient acceleration of multiple charge states in the linac. The performance record for uranium beams is currently held by the double frequency heated AECR-U ion source in Berkeley, which produced 1.4 pµA of U^{29+} and 0.8 pµA of U^{31+} [3] using a high temperature oven. Recently its sister source at ANL, ECR 2, produced 1.2 pµA of U^{28+}

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using a sputter probe [4]. This means that an improvement in ECR ion source performance by a factor of almost 8 will be needed for 400 kW uranium beams.
The ion source requirements for RIA were recognized at the start of the RIA R&D as critical item. Electron Cyclotron Resonance (ECR) ion source development and the low energy beam transport (LEBT) system were identified as areas where focused R&D and prototyping could enhance the performance, reduce the costs, and impact the engineering and construction schedule for RIA.

At Berkeley, VENUS (Versatile ECR for Nuclear Science), the next generation Electron Cyclotron Resonance ion source designed to produce and transport intense high charge state ions for injection into the 88-Inch Cyclotron, was identified as ideal R&D source [5]. VENUS is the first ECR ion source specifically designed for operation at 28 GHz. At this frequency, the semi-empirical scaling laws [1] predict that the plasma densities will be sufficient to provide the intense high charge state beams needed for RIA. At 28 GHz (twice the frequency of the AECR-U), the optimum confining fields are 2 T at the plasma wall, 4 T at injection and 2 T at extraction. These field strengths can only be produced with superconducting magnets. Similar superconducting ECR ion sources will be needed for international next generation accelerator projects such as the Radioactive Ion Beam Factory Project at RIKEN in Japan, and the Large Hadron Collider (LHC) at CERN. Several design enhancements have been incorporated into VENUS to meet the RIA R&D requirements. For example, its extraction voltage was increased to 30 kV and the Low Energy Beam Transport, LEBT, has been built to transport very intense beams. The novel LEBT is designed to analyze and to efficiently transport intense multicharged beams where space charge forces must be corrected for in order to avoid beam loss. A two axis emittance scanner was incorporated into the beam line from the beginning to measure the beam quality of the various beam. Therefore, VENUS will be able to provide an essential database for the design of the RIA driver linac.

RIA R&D on VENUS

The R&D work in FY03 focused on the commissioning of VENUS at 18 GHz and on design, procurement and fabrication of equipment for operation at 28 GHz. An extensive development program at 18 GHz for VENUS and the LEBT initially with gases and recently with metals was carried out. Initial characterization of the transverse emittance in the horizontal and vertical planes at 18 GHz was done (see commissioning results). Fig. 1 shows a picture of VENUS and its analyzing magnet after installation on the roof of the 88-Inch cyclotron in June 2002.

The 28 GHz gyrotron microwave system was procured and modifications of the cryostat and injector system were designed. 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. During 2000, a 28 GHz gyrotron was used successfully to power the SERSE ECR ion source in Catania [6] and the waveguide system planned for VENUS takes advantage of this development. The components are expected to be delivered in December of 2003 and commissioning of VENUS at 28 GHz will begin in the Spring of 2004. Fig. 2 shows a 3D view of the mechanical layout of the 28 GHz microwave system.

Fig. 1. VENUS ECR ion source installed on the vault roof of the 88-Inch Cyclotron.

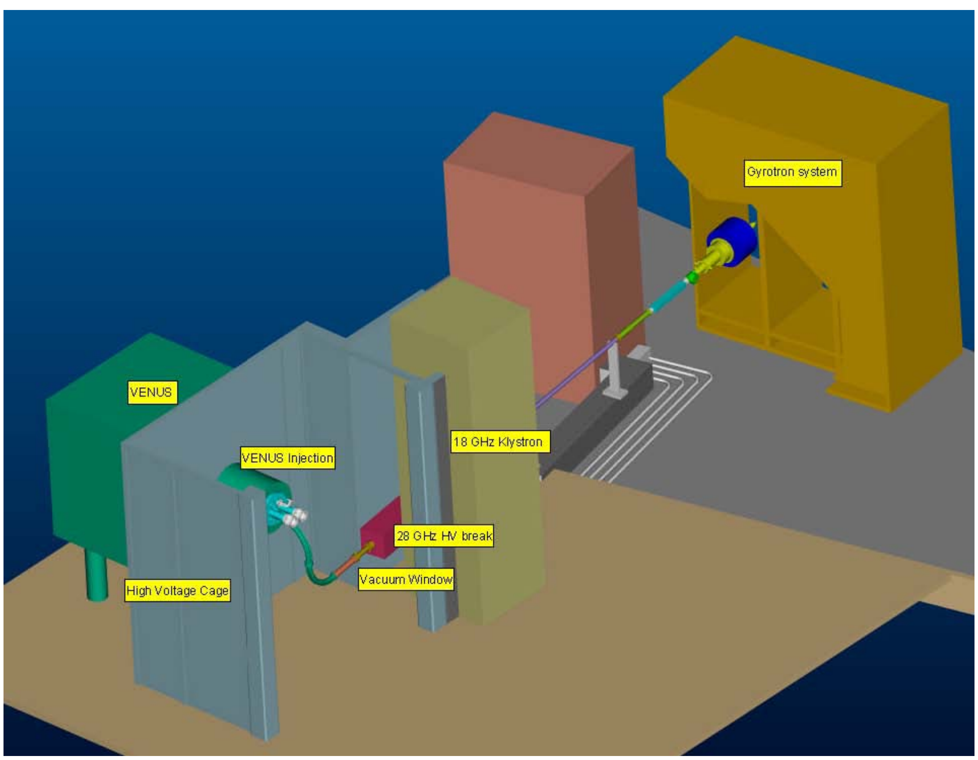

Fig. 2 Schematic view of the 28 GHz system for VENUS. The 10 kW 28 GHz is transported in the TE_{01} mode through 1.248 inch diameter waveguide.

Commissioning Results at 18 GHz

During the commissioning period, a number of improvements were made to the cryostat system, the 18 GHz microwave system, and the magnet power supply control system. Novel heat exchangers for the two cryocooler were designed and they enable VENUS to operate in closed loop operation without the addition of liquid helium. Since this modification, VENUS has operated in closed loop with a magnet temperature below 4.5 ºK (for more than 11 months). A new waveguide high voltage break was designed and installed, which uses a thin quartz plate sandwiched between to water cooled and matched copper waveguide sections. This new design provides reliable operation with minimum reflected power at 2 kW and more than 25 kV isolation. The 18 GHz injection waveguide in VENUS was modified to provide additional pumping, which enables operation at full power. The RF screen at the injection side of the plasma chamber was improved to reduce the microwave leaks and to eliminate long-term temperature shifts that affected operation of the bias probe. A digital control system for the ion source operation and interlock system was developed using process logic controller. The programming of the regulation loop for the superconducting magnet power supplies was a particular important step. This eliminated initial power supply instabilities related to the low resistance and high inductance load presented by the superconducting coils. Following this change the magnets were successfully operated without quenching at currents required for optimum operation at 28 GHz.

VENUS is now operating at the full capacity of the 2 kW, 18 GHz klystron. The operation experience has been excellent. The UHV vacuum system designed for good plasma chamber pumping enables the ion source to recover very rapidly after being exposed to air. Its performance in terms of charge state production, beam intensity, stability, and emittance has been very promising. In Table 1 some ion beam intensities

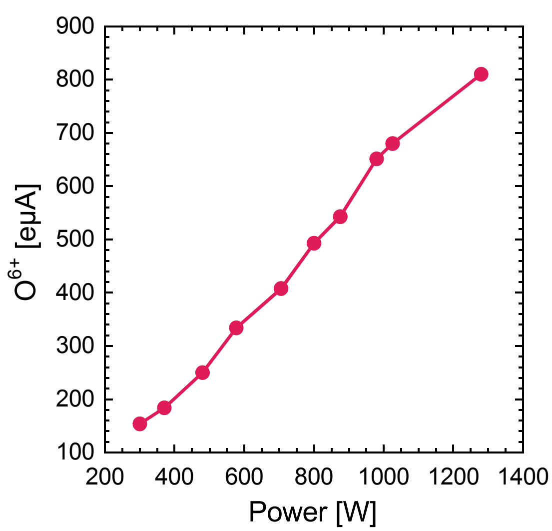

Fig 3: Analyzed O^{6+} current in dependence of the coupled RF power

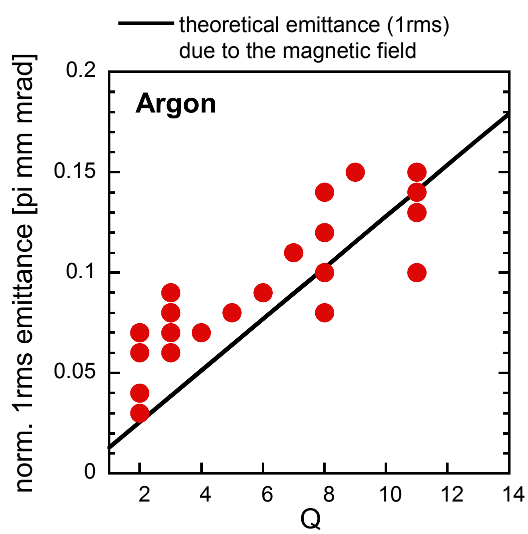

Fig 4: Measured emittance values for different charge states of argon in comparison with the predicted [5] theoretical minimum values due to the magnetic field

from VENUS are presented. However, the performance is still increasing as we gain more tuning experience. As a reference, the data are compared to those previously measured on the Berkeley AECR-U using two frequencies 10 + 14 GHz operation. Although the microwave power density in Venus at 2000 watts is about 10% of that of the AECR-U (since its plasma volume is about a factor of 10 greater than the AECR-U), its performance already exceeds the AECR-U.

Table 1. A comparison between best performance of the AECR-U and initial results with VENUS at 18 GHz. Ion currents are in eμA.

	O^{6+}	O^{7+}	Ar^{11+}	Xe^{20+}	Xe^{27+}	Bi^{25+}
AECR-U 10+14 GHz	570	300	270		30	75
VENUS 18 GHz	1100	324	290	164	84	100

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. Once the 28 GHz gyrotron has been installed at the end of 2003, full performance can be expected.

The first emittance measurements with argon were performed in the spring of 2003 prior to reaching full power operation and results are presented in Fig. 4. 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 [7]. 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 [8], 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 [8]. With the source is now running at full power, systematic emittance measurements for various charge state distributions and source conditions will be done through the Fall of 2003.

Recently a high temperature oven has been installed in VENUS. A prototype of this oven has been developed and successfully tested previously with LBNL ECR ion source for temperatures up to 2000 C [9]. Therefore it should be well suited for the production of uranium beams, which is optimized at about 1700 C. Fig. 5 shows initial results (first day of tuning) for VENUS at 18 GHz with a high temperature oven for ^{209}Bi charge state distribution. The different symbols indicate slightly different tunes of the ECR ion source. The maximum $^{209}Bi^{24+}$ intensity represents a current of 4 pμA.

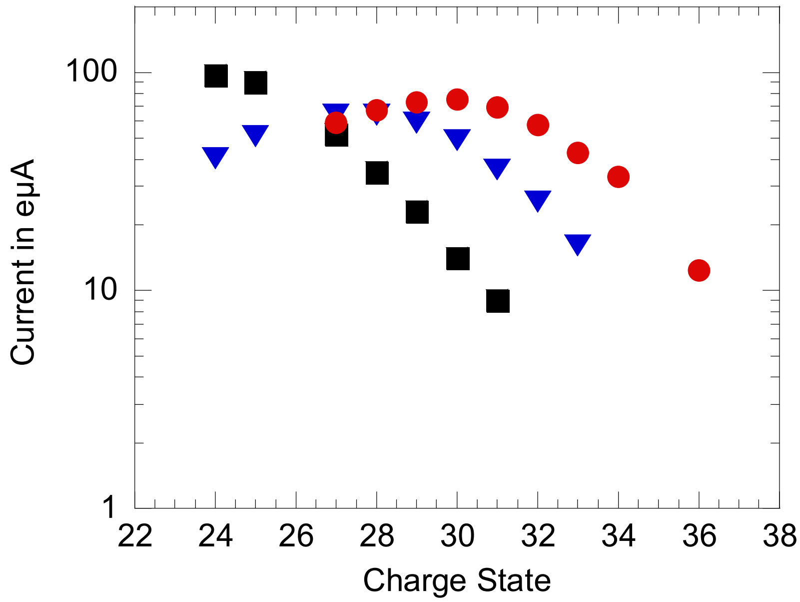

Fig. 5 Initial results for VENUS at 18 GHz with a high temperature oven for ^{209}Bi charge state distribution. The different symbols indicate different tunes of the ECR ion source. The maximum $^{209}Bi^{24+}$ intensity represents a current of 4 pμA.

Project Timeline for FY03

Table 2 Achievements in FY03 and near term goals

Sept 16, 02 to present	VENUS at liquid helium temperature for 11+ months closed loop
September 02	18 GHz commissioning initiated
November 02	Order for long lead items for 28 GHz microwave system
February 03	New 18 GHz RF high voltage break fabricated and installed
February 03	18 GHz waveguide modified full power at 18 GHz
February 03	Plasma chamber rotated
April 03	Begin 18 GHz beam and emittance tests
April 03	Procurement initiated for 28 GHz power supplies and controls
May 03	28 GHz high voltage break designed
August 03	Bias probe shorting fixed –full power long term tests ok
August 03	Mechanical design of 28 GHz waveguide system complete
August 03	High temperature oven testing in VENUS
September 03	Gyrotron tests scheduled at vendor
October 03	Installation of the third cryocooler scheduled
November 03	Installation of waveguide components for 28 GHz scheduled
December 03	28 GHz system installation scheduled

R&D plan for FY04

In FY04, the installation of the 28 GHz gyrotron system and subsequent commissioning of VENUS at 28 GHz will have the highest priority. Systematic emittance measurements for a variety of ions and plasma condition will be done. In addition, we plan to develop uranium and other metal ion beams. Ion optic simulation studies for the extraction and beam transport through the LEBT will be done and compared with experimental results.

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