STATUS OF THE VENUS ECR ION SOURCE

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Abstract

The status and future developments of the 28-GHz VENUS (Versatile ECR for NUclear Science) Electron Cyclotron Resonance (ECR) ion source after the two years repair are presented. The fully superconducting ECR ion source VENUS serves as prototype injector for the Facility for Rare Isotope Beams (FRIB) project at Michigan State University (MSU) [1] as well as injector ion source for the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory (LBNL). As such the source has produced many record beams of high charge state ions as well as high-intensity, medium charge state ions. As the FRIB project has now entered the preliminary design phase, LBNL is involved in the design of two new VENUS-like ECR injector ion sources for the FRIB facility. This paper will review the design changes for the FRIB injector, which will allow the installation of the FRIB injector source on a 100 kV platform. In support of the FRIB ion sources design systematic measurements of the heat load due to bremsstrahlung from the plasma for different magnetic fields have been performed and are presented. Finally, a possible future upgrade path for the FRIB injector using an advanced Nb_3Sn magnet structure is described.

A VENUS LIKE ECR ION SOURCE FOR THE FRIB INJECTOR

Fig. 1 shows the current installation of VENUS at the LBNL 88-Inch Cyclotron. The VENUS cryostat operates in a closed loop mode without additional helium transfers after the initial cool down as required for an installation on a high voltage platform as needed for the FRIB front end, but uses liquid nitrogen to cool the normal conducting leads. To adapt this design for the FRIB injector, the liquid nitrogen needs to be eliminated. In addition, the 4K cooling power will have to be increased. Finally, the extraction voltage needs to be enhanced.

HV insulation

The VENUS source high voltage insulation will need to be enhanced to allow reliable extraction at 40kV extraction voltage.

Pre-cooling of the normal conducting leads

The VENUS ECR ion source uses liquid nitrogen to dissipate the up to 70 watts of heat load from the normal conducting copper leads under full excitation. For FRIB the liquid nitrogen pre-cooling will be replaced by a single stage cryocooler.

4K cooling power

The VENUS cryostat is currently using four two stage Gifford-McMahon (GM) cryocoolers providing a total of 6W cooling power at 4K. But measurements of the x-ray heat load into the cryostat at the VENUS source, the SECRAL source, and the SC RIKEN indicate that more cooling power will be needed for the FRIB injector (see section3). For this purpose, three design options are currently being evaluated. In the first option a combination of two 2-stage and two 3-stage cryocoolers would provide a total cooling power of 13 W at 4K. Only minimal design changes are necessary for this option. Alternatively, we are evaluating the possibility of installing a compact external helium liquefier onto the HV platform, or the possibility of developing an insulated 100kV liquid helium fill line. While technically challenging, the last two options would have the advantage that ample cooling power would be available for potential future upgrades such as double frequency heating with 24 GHz or installing a higher frequency (>40GHz) Nb_3Sn based ECR ion source on the platform.

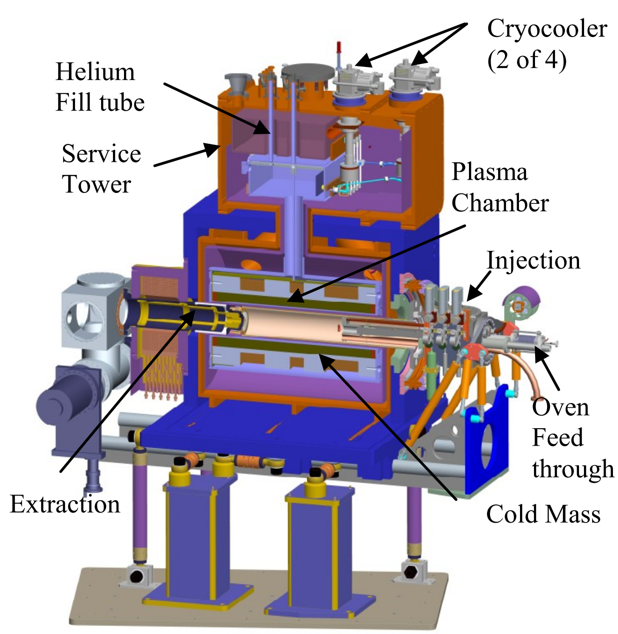

Figure 1: Mechanical layout of the VENUS ion source and cryogenic systems as installed on the vault roof of the 88-Inch Cyclotron

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STATUS OF THE VENUS SOURCE

In January 2008, the VENUS ECR ion source experienced a major setback when one of the sextupole leads evaporated following a lead quench caused by an insufficient liquid helium level in the cryostat. At the 2008 ECR workshop in Chicago [2], we analyzed the failure mode and reported on the repair efforts, which were completed this year. Table 1 summarizes the chronology of the complex and long VENUS repair. In June of 2010 VENUS was finally re-installed at the 88-Inch Cyclotron and the magnet was tested to full excitation without quenches. The first 18 GHz plasma was achieved on July 9th 2010 and the first 28 GHz plasma was ignited on July 21st 2010, which marked the end of this long and difficult repair.

Table 1: Chronology of the VENUS source SC lead failure and its repair

Event	Date	Comments
Quench	1/24/2008	Sextupole magnet does not reenergize
Cryostat opened	1/28/2008	Sextupole coil #1 lead identified as cause
Service tower machined opened	2/29/2008	10 cm of lead # 1 had vaporized
Cable samples tested	3/2008	Lead damage extents into the cold mass
Cold mass extracted	4/15/2008	Wire samples taken
Wire tests completed	6/2008	Wire performance tested and leads are spliced and doubled up
Cold mass prepared for magnet testing	6-8/2010	
Magnet tested in external dewar at LBNL	9/12/2008	Reaches full field without quenches
Cryostat reconstruction complete	11/2009	Transfer to the 88-Inch
First cool down attempt	12/7/2009	He transfer tube weld fails during cool down
Open upper cryostat	2/2010	Replace internal helium fill line tubes
Cryostat repair complete	4/05/2010	Transfer to the 88-Inch
Installation on the roof	4/15/2010	Ion Source re-assembled
Cool down and magnet test	6/16/2010	Reaches full field without quenches
18 GHz	7/9/2010	First plasma and beam
28 GHz	7/21/2010	First 28 GHz operation, repair completed

During the repair, many improvements have been incorporated to prevent a similar accident. In particular, the lead cooling was enhanced by adding copper fins to the sextupole current leads for better heat transfer and the liquid helium level indicator was interlocked.

VENUS re-commissioning results

The VENUS ECR ion source commissioning was started with 18 GHz and two weeks later the 28 GHz waveguide was reconnected to the source as well. After about 2 weeks of conditioning with oxygen, ion beam tests using ^{124}Xe were conducted to assess the performance of the source after the repair. Table 2 shows some performance results before the repair and a few results from the re-commissioning experiments.

Table 2: A few VENUS ion source performance values before and after the repair. Ion beam intensity of the SECRAL ECR ion source are reported as reference[3].

	VENUS 28+18 GHz	SECRAL (24 GHz)
Results VENUS 2006-2008		
O^{6+}	2860 eμA	2300 eμA
O^{7+}	850 eμA	810 eμA
Ar^{12+}	860 eμA	510 eμA
Ar^{16+}	270 eμA	149 eμA
Ar^{17+}	36 eμA	14 eμA
Xe^{27+}	270 eμA	450 eμA
Xe^{30+}	116 eμA	152 eμA
Re -commissioning (3 weeks) VENUS 8/2010		
Xe^{26+}	480 eμA	480 eμA
Xe^{27+}	411 eμA	450 eμA
Xe^{30+}	211 eμA	152 eμA
Xe^{32+}	108 eμA	85 eμA (31+)
Xe^{35+}	38 eμA	45 eμA

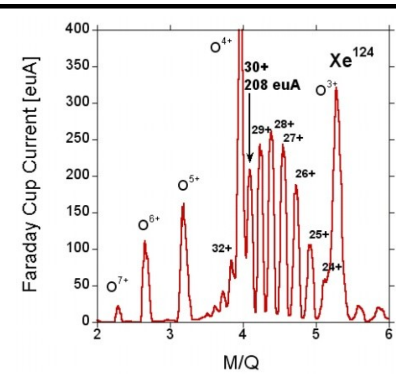

Figure 2: Xenon spectrum for medium to high charge states after the re-commissioning.

As an example Fig. 2 shows a high charge state spectrum optimized for Xe^{30+}, for which the ion beam intensity was almost doubled compared to previous results from 2008 (see table 2). The re-commissioning results demonstrate that the VENUS source performance is far from being saturated and that it would benefit from further optimization. It also shows that for the highest charge states (e.g. Xe^{35+}) further conditioning is necessary.

X-RAY LOADING INTO THE CRYOSTAT

One of the surprising experimental observations during the development and early commissioning of the VENUS ECR ion source were the large amounts of x-ray radiation produced. These x-rays are a hazard for personal and also present a problem for the cryostat if they are absorbed into the coldmass [4]. In order to specify the cooling power for the FRIB injector source, systematic studies of the x-ray intensity and hot energy tail in dependence of various source parameters were conducted using all three LBNL ECR ion sources.

These studies showed that:

- X-rays can add several Watts of heat load to the cryostat and are a major challenge for present and future ECR ion sources (see Fig. 3)
- The maximum observed electron energy and heat load to the cryostat are both strongly dependent on the magnetic field gradient at the resonance zone (see Fig. 3 and [4])
- The maximum observed electron energy is strongly dependent on the microwave frequency[4]
- The energy spectrum shows a strong angular anisotropy[5]

During commissioning tests in 2010, the heat load into the cryostat for 28 GHZ operation was measured for a wide range of Bmin/Becr ratios. Fig. 3 shows the dependence of the heat load in W per kW of rf power injected into the plasma. Up to 1 W per kW was measured for a Bmin/Becr ratio of 0.8 percent.

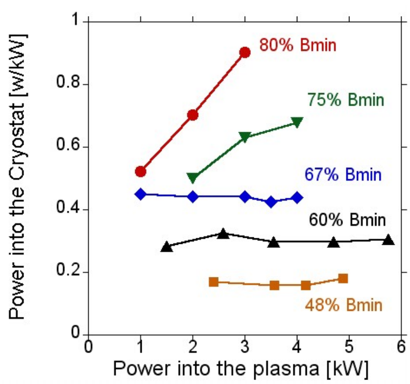

Figure 3: Added heat load into the cryostat due to bremsstrahlung absorbed by the coldmass per kW of microwave power injected into the cryostat for 28 GHz operation.

The VENUS cryostat has currently a total of 6 W of 4K cooling power available with no He consumption. The cryostat has a static 4K heat load of 2.5 W. Another 700 mW are added when the magnets are fully excited to 28 GHz fields. That leaves about 2.8 W of additional cooling power for the heat load due to absorbed x-rays. The results presented in figure 3 clearly demonstrate that for the FRIB injector source the 4K cooling capacity will need to be substantially enhanced compared to the VENUS source to enable tuning of the source over its full magnetic range.

FOURTH GENERATION ECR ION SOURCES

The continuing demand for higher intensities and the complexity of SC magnet structures make their development timely. Modern superconducting ECR ion sources are presently all utilizing Niobium-Titanium alloy (NbTi), since it is ductile and allows simple fabrication methods for wires and cables. However, NbTi performance is ultimately limited by its upper critical field of about 10 T at 4.2 K. The magnetic field strengths necessary for 56 GHz operation require a peak field in the magnet coils of 12-14 T, which cannot be achieved using conventional NbTi conductor. Nb_3Sn has an upper critical field limit of about 20 T at 4.2 K, but is much more difficult to use. A complex structure such as an ECR magnet has never been built in Nb_3Sn. As a first step, LBNL has proposed to build a prototype 56 GHz ECR ion source magnet structure (see Fig. 4) based on Nb_3Sn. It is designed for magnetic peak fields of 8T at injection 5 T at extraction and 4.2 T at the plasma chamber wall and peak fields of up to 15 T on the coils [6, 7].

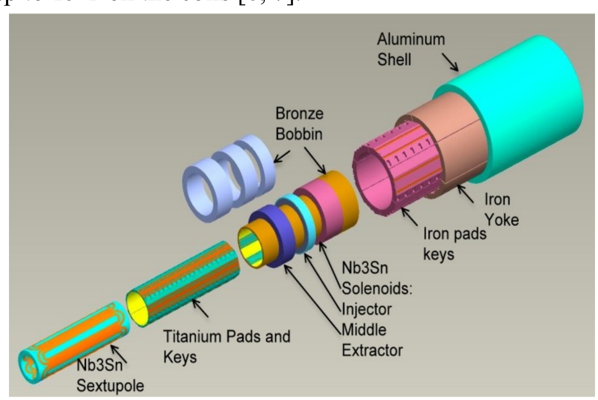

Figure 4: Assembly layout of the Nb_3Sn cold mass.

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