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$_3$Sn 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 S C 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$_3$Sn based ECR ion source on the platform.

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

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

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 124Xe 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].

<table>
<thead>
<tr>
<th></th>
<th>VENUS 28+18 GHz</th>
<th>SECRAL (24 GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Results VENUS 2006-2008</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O 17+</td>
<td>2860 eμA</td>
<td>2300 eμA</td>
</tr>
<tr>
<td>O 18+</td>
<td>850 eμA</td>
<td>810 eμA</td>
</tr>
<tr>
<td>Ar 19+</td>
<td>860 eμA</td>
<td>510 eμA</td>
</tr>
<tr>
<td>Ar 20+</td>
<td>270 eμA</td>
<td>149 eμA</td>
</tr>
<tr>
<td>Ar 21+</td>
<td>36 eμA</td>
<td>14 eμA</td>
</tr>
<tr>
<td>Xe 25+</td>
<td>270 eμA</td>
<td>450 eμA</td>
</tr>
<tr>
<td>Xe 26+</td>
<td>116 eμA</td>
<td>152 eμA</td>
</tr>
<tr>
<td>Re-commissioning (3 weeks)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VENUS 8/2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xe 26+</td>
<td>480 eμA</td>
<td>480 eμA</td>
</tr>
<tr>
<td>Xe 27+</td>
<td>411 eμA</td>
<td>450 eμA</td>
</tr>
<tr>
<td>Xe 29+</td>
<td>211 eμA</td>
<td>152 eμA</td>
</tr>
<tr>
<td>Xe 32+</td>
<td>108 eμA</td>
<td>85 eμA (31+)</td>
</tr>
<tr>
<td>Xe 35+</td>
<td>38 eμA</td>
<td>45 eμA</td>
</tr>
</tbody>
</table>

![Figure 2: Xenon spectrum for medium to high charge states after the re-commissioning.](image)

As an example Fig. 2 shows a high charge state spectrum optimized for Xe 30+, for which the ion beam in-
tensity 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$^{3+}$) 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/Becc 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/Becc ratio of 0.8 percent.

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$_3$Sn 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$_3$Sn. As a first step, LBNL has proposed to build a prototype 56 GHz ECR ion source magnet structure (see Fig. 4) based on Nb$_3$Sn. 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$_3$Sn cold mass.

**REFERENCES**