STATUS REPORT AND RECENT DEVELOPMENTS WITH VENUS

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Abstract

Since the superconducting ECR ion source VENUS started operation with 28 GHz microwave heating in 2004 it has produced ion beam intensities such as 860 eμA of Ar^{12+}, 200 eμA of U^{34+}, or with respect to high charge state ions, 270 eμA of Ar^{16+}, 1 eμA of Ar^{18+} and .4 eμA of Xe^{42+}. In August of 2006, VENUS was connected to the 88-Inch Cyclotron as the third injector ion source extending the energy range and available heavy ion beam intensities from the 88-Inch Cyclotron. This paper will highlight recent developments and results.

In addition, the paper will discuss recent modifications to the VENUS superconducting lead design, which became necessary after an unexpected quench damaged a superconducting lead. Following a quench in January of 2008, the VENUS sextupole coils could not be energized. The lead quenched due to the loss of liquid helium in the upper cryostat. This resulted in localized heating, which vaporized a section of the lead wire. Analysis of the quench scenario, which is discussed in the paper, revealed design flaws in the original lead support and cooling design. The major undertaking of repairing the magnet leads and rebuilding the VENUS cryostat is described.

INTRODUCTION

The VENUS ECR ion source (shown in Fig.1) at the Lawrence Berkeley National Laboratory (LBNL) is a 3rd generation source. The fully superconducting magnet structure has been designed for optimum fields for operation using 28 GHz plasma heating frequency. As a prototype ECR ion source for the Facility for Rare Isotope Beams (FRIB) the emphasis of the R&D is the production

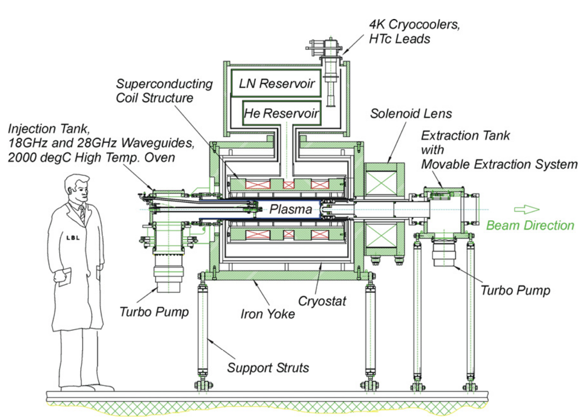

Figure 1: Mechanical layout of the VENUS ion source and cryogenic systems

of medium high charge states such as U^{33+}. As an injector into the 88-Inch Cyclotron the emphasis is on the production of high charge state ions. VENUS has been operated routinely using 28 GHz as its main heating frequency since 2004 and has produced many record beams. Besides 28 GHz, 18 GHz can be injected as a second frequency for double frequency heating or used for single frequency heating ($B_{ECR,18\,GHz}$=0.64T). Table 1 shows a summary of the VENUS ECR ion source performance[1-4].

Two main magnetic confinement and heating configurations are typically used in the VENUS ECR ion source. In the single frequency heated plasma mode a minimum B field of .64 to .75 T is used, which results in a shallow magnetic field gradient at the 28 GHz resonance zone. Up to 6.5 kW of 28 GHz power has been coupled into VENUS using this mode of operation. In the double frequency mode a minimum B field of .45 T is used. This field profile results in a combination of a shallow gradient (for 18 GHz heating) and a steeper gradient (for 28 GHz heating) at the resonance zone. Up to 9kW of combined 18 and 28 GHz power (a power density of about 1kW/liter for the about 9L big plasma chamber) has been coupled into the VENUS plasma chamber so far. The ion source performance continues to improve as we couple more power into the plasma chamber. For typical 28 GHz operation in single or dual frequency mode, the sextupole magnet is energized to produce slightly above 2 Tesla at the plasma chamber wall.

Table 1: Recent VENUS Results

VENUS 28 GHz or 18 GHz +28 GHz							
CS	**^{16}O**	**^{40}Ar**	**CS**	**^{84}Kr**	**^{129}Xe**	**^{209}Bi**	**^{238}U**
6^+	2850		25^+	223		243	
7^+	850		26^+			240	
8^+			27^+	88		245	
12^+		860	28^+	25	222	225	
13^+		720	29^+	5	168	203	
14^+		514	30^+	1	116	165	
16^+		270	31^+		86		
17^+		36	33^+		52		205
18^+		1	34^+		41		202
			35^+		28.5		175
			37^+		12		
			38^+		7		
			41^+			15	
			42^+				.4
			47^+			2.4	5
			50^+			.5	1.9

In September of 2006 the first ion beam from VENUS was injected and accelerated by the 88-Inch Cyclotron.

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So far the Cyclotron has accelerated Ar, Kr, Xe and U beams from VENUS. Substantial gains in both intensity and energy were demonstrated for the heavy masses and very high charge states. For high charge state uranium beams such as U47+ 11 times more beam was extracted from the cyclotron using the VENUS ECR ion source than using the 14 GHz AECRU injector ion source. The ion beam intensities provided by the VENUS ECR ion source for high charge state uranium extends its energy range to the Coulomb barrier range for nuclear physics experiments. Another important application for the VENUS injector is the production of high charge state xenon to extend the mass range of the 16 MeV/nucleon heavy ion cocktail to xenon [4]. Figure 2 shows beam developments conducted with high charge state Xe beams in comparison with the beam intensities achieved using the AECRU injector ion source. 80 to 100 times more beam intensities could be extracted using the VENUS ECR ion source. For the first time neon-like xenon (Xe44+) could be extracted from the cyclotron. Using Glovanisvky's diagram[5] of the (neτi)Te criteria, this result indicates that in the VENUS source the (neτi) product has reached 2·1011sec/cm3.

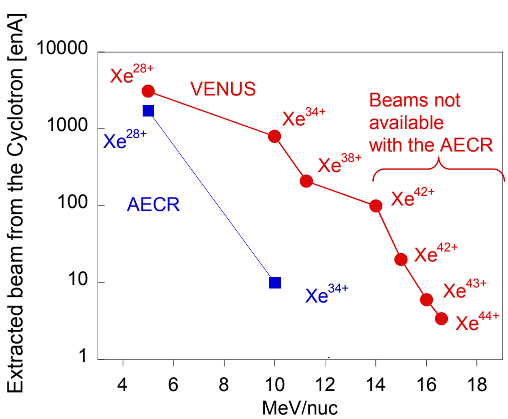

Figure 2: Cyclotron using the AECRU injector in comparison to the VENUS injector at various MeV/nuc and high charge state ions.

VENUS LEAD QUENCH AND STATUS OF THE REPAIR

In January 2008, while the magnet was fully energized to 28 GHz fields, an unexpected quench occurred after which the sextupole coils could not be energized. Analysis of the event suggests that a leak in the pressure relief system lead to a slow loss of liquid helium by evaporation. The liquid level dropped below the service tower level. Consequently, localized heating at the solder joint between the superconducting vacuum feedthrough and the charge lead of the sextupole (see figure 3) initiated a lead quench.

These solder joints are non superconducting and have a resistance of several tens of nOhm. If those joints are insufficiently cooled, they can heat up and initiate a lead quench, which will lead to further heating and consequently burn out. In the case of the NbTi VENUS sextupole wires[3], assuming an adiabatic heating model, it takes about 1.7 sec for the wire to reach 1300 K (melting point of copper) at the sextupole operational current of 465A. However, if the NbTi wire is heated beyond 600K the wire will have irreversible damage and altered superconducting properties.

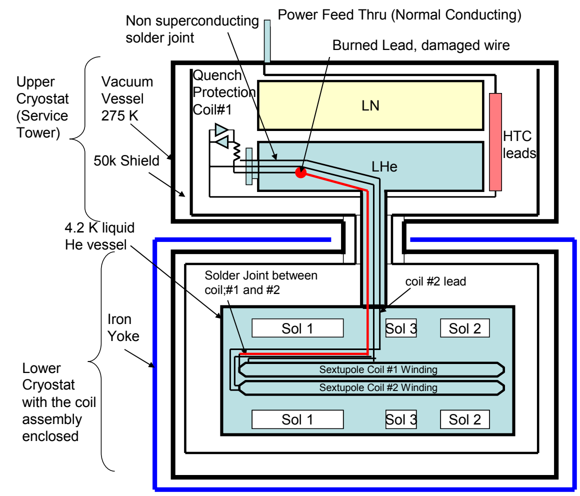

Figure 3: A schematic of the VENUS cryostat and upper service tower. The location of the burned lead is indicated.

The VENUS upper service tower was opened and it was found that about 10 cm of the VENUS sextupole charge lead had been vaporized during the quench. Most likely the 10 cm missing wire was vaporized in the plasma discharge caused by the high voltage build up in the coil during the quench.

As expected from simple thermal calculations, analysis of the remaining wire in the upper service tower showed that the wire was overheated sufficiently to degrade its superconducting properties. The adjacent wire, which was guided in the same insulating sleeve and contacted the quenching lead was also damaged and needed to be replaced as well. Figure 4 shows a cross section of the damaged wire in comparison with an original sample. It can be easily seen how the NbTi wires have melted and fused with the Cu matrix surrounding the conductor.

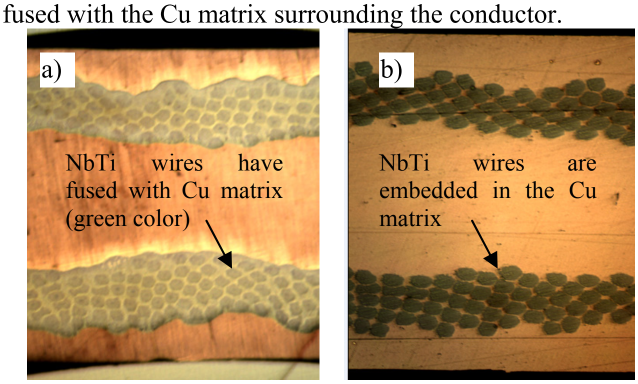

Figure 4: A polished cross section of the VENUS sextupole wire for a) the overheated damaged wire and b) the original sample.

As we analyzed samples further away from the burned section, the wire properties improved. Figure 5 shows the result of the I_s short sample test .5 m from the burned section and .9m from the burned section.

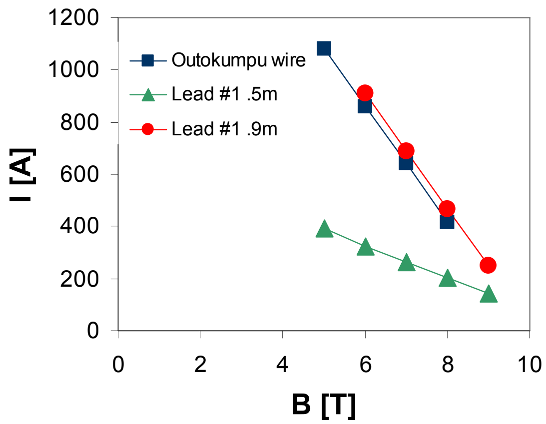

Figure 5: Short sample tests for two sections of the burned lead wire .5m and .9m away from the burned section.

While the first section (closer to the burned lead) clearly showed degradation of the superconducting properties, the second section is well within the specification of the original sextupole wire [3]. Therefore, the remaining lead wire was used for splicing. The magnet system was reassembled and prepared for cool down in a test cryostat. Figure 6 shows a picture of the VENUS cold test assembly and Figure 7 a detailed view

Figure 6 The VENUS magnet assembled for the cold test at the LBNL superconducting magnet test facility.

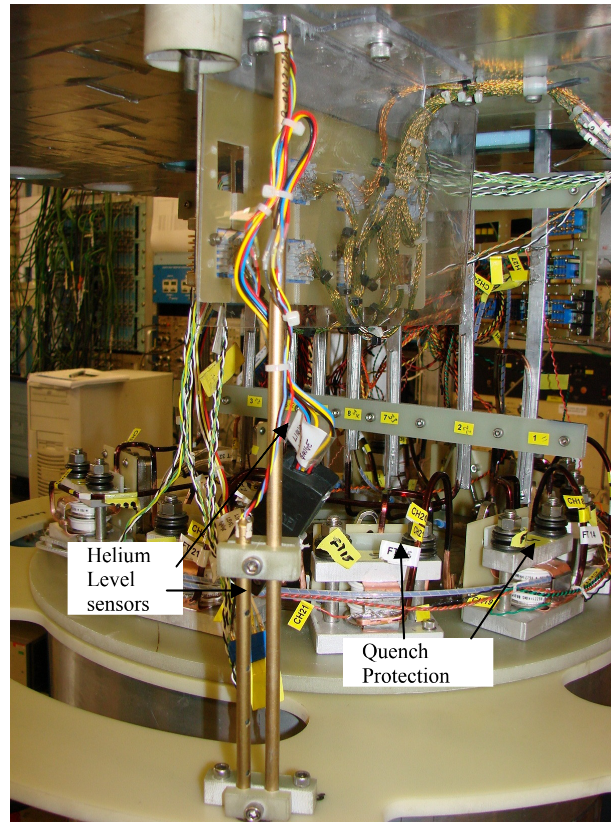

Figure 7: A detail view of the quench protection system, the vapor cooled leads and the diagnostic wiring.

of the quench protection system and the diagnostic's wiring.

VENUS Cold Test

The VENUS magnet was cooled down using the cryostat of the Superconducting Magnet Test Facility at LBNL and energized to full excitation (4.1T, 3.2 T and 2.1 T) without quenches in three ramps. First the solenoids were energized and ramped down, then the sextupole was energized and ramped down, and finally all magnets were ramped up together to full fields. Figure 8 shows the last ramp for the full system. The sextupole magnet was ramped to 493A (110% of its design value), typical operational current values for 28 GHz are 465A to 475A.

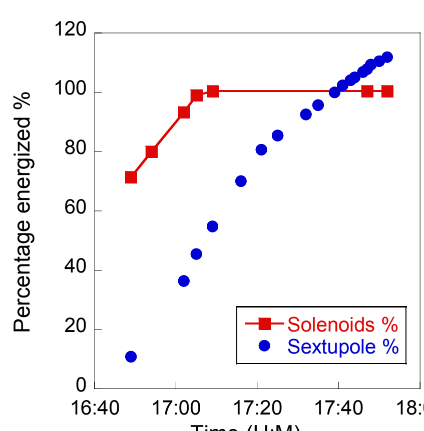

Figure 8: Ramp up of all VENUS magnets during the cold test.

During the ramping of the sextupole, small conductor movements were observed in the sextupole coils. The slippage occurred with and without solenoid field. Figure 9 shows an example of such a slippage event. The terminal voltages across each individual sextupole (A to F) and the whole sextupole coil were recorded by a chart recorder with a sampling frequency of 125 kHz. The *V*(*t*) traces shown in Figure 9 were processed by the following two steps: 1) normalized by subtracting the average of the first ten data points so each trace starts at 0V and 2) shifted by an interval of 2 V from coil A to the whole sextupole voltage for better readability.

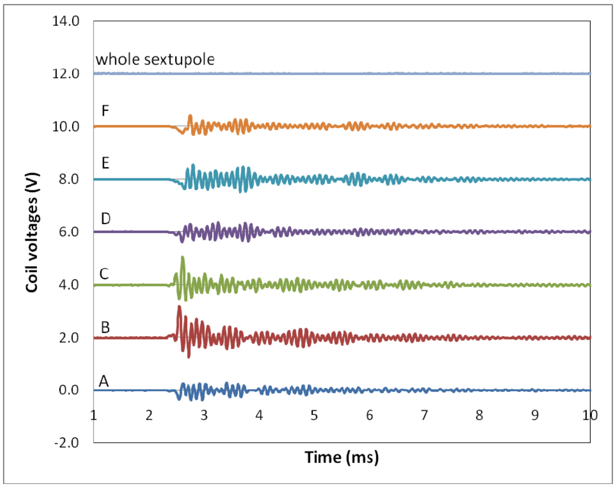

Figure 9: An example sextupole coil slippage during the ramp. Terminal voltages across each individual sextupole coil (A to F) and the whole sextupole are shown.

The voltage spikes had a typical frequency of around 9 kHz but with damping amplitudes. The whole ringing lasts around 5.7 ms. In the example shown, the slippage was initiated by a movement in coil B at 2.33 ms, accompanied by a movement in coil C at 2.39 ms. The peak voltage change was around 1.2 V in coil B, which was the highest of all the slippage events recorded. An examination of the recorded slippage events shows that the slippage did not concentrate in one particular coil indicating that neither a particular coil or part of the structure in the assembly are defective. Since the total flux in the whole sextupole must be conserved, no voltage spike was observed across the whole sextupole. No voltage spikes were observed in the solenoids during the test.

Even though many slippage events were observed when the sextupole current was higher than 400 A (90% of design current) with full solenoid field, none of these slippages with energy release led to any quench, as mentioned above. The high Cu/SC ratio of the VENUS NbTi conductor could be one of the reasons that the small movements of the coils during the ramping do not lead to quenches, but are damped in the system.

Consequences of a lead quench versus a coil Quench

During the training phase and testing phase in 2000 the VENUS magnet quenched about 15 times. However, none of those quenches caused any damage to the magnet. So what is the difference between a lead quench and quenches initiated in the middle of the coil?

Quench inside the coil

The VENUS sextupole magnet coil assembly has an inductance of 1.2H and therefore a stored energy of 150kJ at full excitation current of 500A. The relationship is described by

$$\boldsymbol{E} = \frac{\boldsymbol{L} \cdot \boldsymbol{I}^2}{\mathbf{2}}, \qquad [1]$$

where L is the coil inductance and I the drive current.

During the quench process, this stored electromagnetic energy is converted into heat and the rising coil resistance causes the current to decay. The critical value is the maximum temperature inside the coil during the quench. The quench propagates through the coil from the point of origin, driven by resistive heating and heat conduction. It propagates in a three dimensional process along and transverse to the windings. In the VENUS sextupole coil this propagation is sufficiently fast to dissipate the energy over the whole coil. This prevents overheating of the wire at the origin of the quench.

Using the program QUENCH[6,7] for the VENUS sextupole magnet, it can be estimated that the maximum temperature inside the coil in this case reaches less than 120K, a conservative and reasonable value. Two scenarios were simulated. In the first case only one coil was considered, assuming that each coil is quenched independently. Therefore, the stored energy is dissipated over all coils evenly. In the second scenario it was assumed that the stored energy of all six coils would be dissipated in one coil. The reality lies in between these two extreme scenarios since the adjacent sextupole coils will quench also as the quench progresses and dissipate some of the stored energy.

Figures 10, 11 and 12 show the dynamics of a coil quench. The internal voltage build-up across the coil triggers the quench protection causing the power supply to be shut off within 50ms and the current to be shunted through the quench protection diodes. However, very little energy can be dissipated through the quench protection circuit. Most of the power needs to be dissipated in the coil itself, which contains sufficient specific heat in the copper to safely absorb the stored energy of the magnetic field. The collapsing field and rising temperature causes the adjacent coils to quench. The current decays within 1 sec to less than 200 A preventing any damage to the coil or the lead wire.

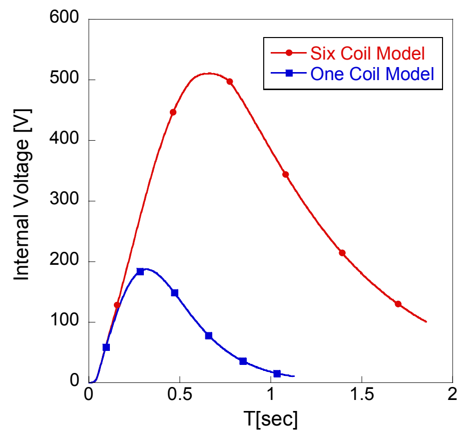

Figure 10: QUENCH Model Calculations for the sextupole magnet, the internal coil voltage is plotted for the two extreme scenarios.

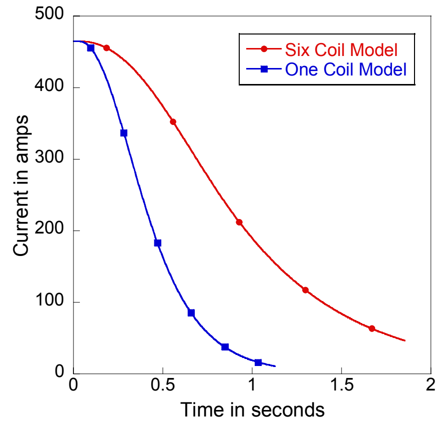

Figure 11: QUENCH Model Calculations for the current decay following a quench.

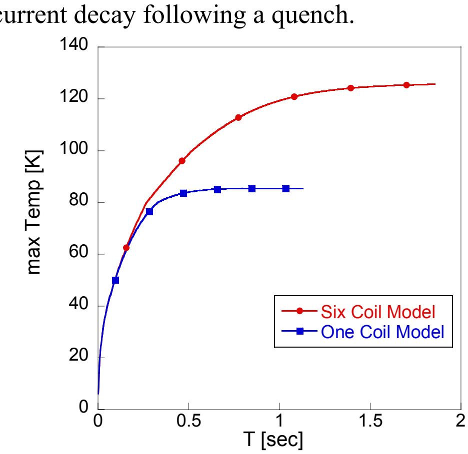

Figure 12: QUENCH Model Calculations of the maximum temperature inside the sextupole coil.

Lead Quench

During a lead quench the quench propagation dynamics is dramatically altered. The VENUS lead-quench started about 1 m above the sextupole coil at the normal conducting solder joint between two superconducting wires due to insufficient cooling. In this particular case, the quench propagation is only linear along the wire and is further slowed down once the quench reaches the liquid helium level. Assuming a longitudinal quench propagation of 5-20 m/sec[8]. It takes 50 to 200 ms for the quench to reach the coil. Although the wire heats up very quickly, the voltage built up is rather low until the quench reaches the coil. The quench protection detection does not engage, resulting in continued full current flow while the quench is propagating through the lead wire (Figure 13). Once the lead wire opens, the inductively-driven internal voltage in the coil sustains a helium plasma arc between the burned out wire-section, which further damages the wire.

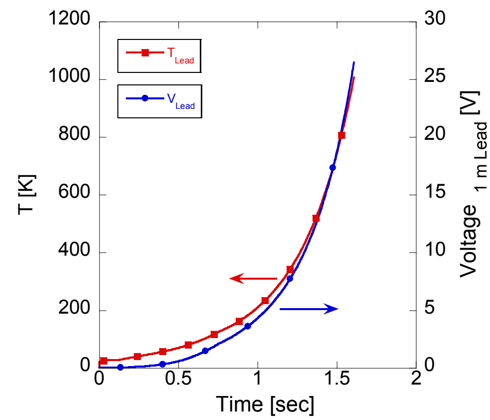

Figure 13 Worst case temperature rise for a 1m long single wire sextupole lead (465 A, .9mm x 1.8mm, 3:1 Cu/sc ratio) and voltage built up in the lead.

An adiabatic model of the temperature rise inside a 1m long wire (not cooled) predicts that in about 1.4 seconds the NbTi wire reaches temperatures above 600K at which point the superconducting properties deteriorate irreversibly, and in about 1.7 seconds the wire reaches 1300K at which point the copper melts. Although this model is simple, it describes a fairly realistic scenario since the VENUS magnet leads were wrapped in shrink tubing which prevented any possibility of vapor cooling of the leads.

Design options available to avoid lead burn-out

A failure as experienced with VENUS causes a severe interruption of the ion source operation, since the repair takes many months. Therefore it is very important to consider lead quench scenarios during the design phase of a superconducting ECR ion source. There are several strategies that can be pursued to avoid this kind of damage.

One possibility is to design the leads to be cryogenically stable. In this case the wire must be heavily reinforced with copper to avoid the risk of reaching elevated temperatures. However, this solution is somewhat cumbersome and carries the risk that in the case of a quench the quench propagation would be very slow and could lead to a coil edge quench, which could damage the first turns of the superconducting coil.

Another design possibility would be to pursue an active quench protection system, which would be a preferred solution for a new magnet system. An active quench protection system could include a) external dump resistors that divert the energy away from the magnet as soon as the quench is detected, and b) heaters in contact with the superconducting coils that spread the quench as quickly as possible once a quench is detected. In addition, the leads must be further protected by adding voltage taps across the normal conducting splicing section, which would enable to detect a lead quench quickly, and would activate the active quench protection before the wire would be damaged.

However, one of the most important diagnostics for the cryogenic system must be reliable and redundant liquid helium sensors, which are interlocked with the magnet power supplies.

VENUS repair

Several improvements are currently being incorporated in the VENUS magnet system to protect it from lead quenches in the future. Most importantly, the liquid helium level will be monitored with two independent liquid helium sensors, which are included in the magnet interlock chain. The current carrying leads have been doubled to increase the superconducting margin of the charge leads. This will reduce the likelihood of initiating a quench in the lead. In addition, doubling the cross section will reduce the current density by a factor of four, without reducing the quench propagation speed too much. In addition, the original shrink-tubing insulation around all lead wires has been replaced with a Teflon spiral insulation, which allows active vapor cooling and liquid helium penetration. Finally, an additional thermal link between the normal conducting solder joint and the liquid helium level will be installed to improve the cooling of this solder joint. Together, these design changes will substantially reduce the probability of a similar failure in the future.

REPAIR SCHEDULE

After the successful cold test the VENUS cold mass will be reinstalled into the helium vessel. The lower cryostat has to be rewelded and the sealed. The service tower will be reconstructed, welded to the lower cryostat and the insulation and the wiring restored. Once the cryostat is reconstructed and inserted into the iron yoke, the VENUS ECR ion source can be reinstalled on the vault roof of the 88-Inch Cyclotron. The present time schedule estimates that these final steps will need four to six months, meaning that this repair will have required more than 12 months until VENUS is fully operational again.

ACKNOWLEDGEMENTS

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