High Power Testing of Superconducting Cavities for LEP

P. Brown, A. Butterworth, E. Ciapala, G. Geschonke, E. Peschardt, J. Uythoven
CERN, CH-1211 Geneva 23, Switzerland

Abstract

The LEP energy upgrade requires the installation of 192 superconducting cavities. Before installation in LEP the four-cavity superconducting modules are tested in a high power RF test stand which exactly models the configuration in LEP. The test procedure and the test results of the last two modules are presented. These modules needed about 30 hours RF conditioning before the specified fields were reached. The conditioning seems to take place primarily in the main power coupler (MC) and during the automated conditioning the MC vacuum signals were used to control the klystron power. High levels of radiation were measured around the modules when running at full field and the MC's showed signs of deconditioning.

1. Introduction

Upgrading the LEP energy to 90 GeV [1] requires the installation of 192 superconducting 352 MHz cavities in addition to the existing conventional 352 MHz copper cavity RF system. Twenty of these superconducting cavities are manufactured from sheet Nb and the remaining 172 from copper which is sputter-coated with a Nb layer [2, 3]. The sheet Nb cavities are the result of a pilot project where bare cavities made in industry were assembled into modules at CERN whilst the Nb-coated cavity modules are completely manufactured by European industry. Four 4-cell cavities with their helium vessels are assembled into a single cryo module, each module having a length of about 12 m [3, 4]. The specified accelerating field is 5 MV/m for the sheet Nb cavities and 6 MV/m for the Nb-coated cavities.

After the contractual acceptance tests and before installation in the LEP all modules are tested in a high power test stand which exactly models the configuration in LEP. Here all functions of the module can be tested, including operation with high RF power. These tests are not performed in LEP because all interruptions to the LEP experimental program must be kept to a minimum.

This paper gives a brief description of the hardware, the test procedures and some results of recent high power RF tests.

2. Description of the Test Stand

The high power RF test stand is an exact copy of the equipment used in LEP and allows the simultaneous testing of two modules (eight cavities) fed from a common klystron as shown in Fig 1. The modules are housed in a shielded block house, about 4.5 m wide and 50 m long.

Below the most important components of the test stand are briefly described.

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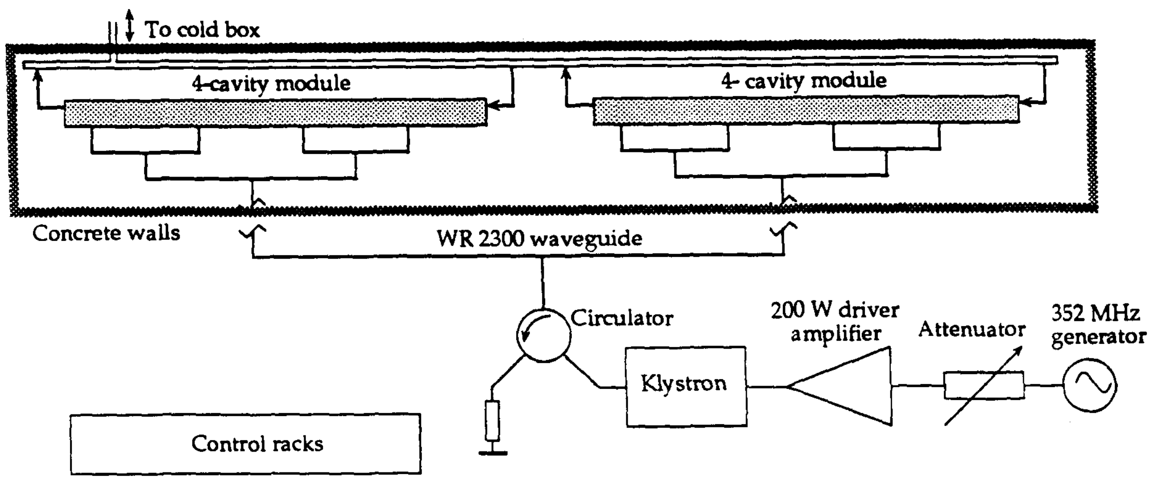

Figure 1 High power Test Stand Layout

2.1 Cryogenics

A dedicated 1.2 kW at 4.5 K cryoplant is used [5]. As in LEP the modules are supplied from a cryo transfer line feeding liquid helium into the first cavity of a module and recovering the gas from the last one. The cryoplant is fully computer controlled and the cool down of a module takes about 40 hours.

2.2. RF Power Installation

The RF power is generated by a synthesiser followed by a 200 W solid state amplifier driving a standard LEP 1.3 MW klystron. The maximum RF power is however limited by the power converter to 300 kW. The klystron is isolated from the cavities by a junction type circulator having 300 kW power rating at full reflection. Output power control is done using both the drive level and the modulation anode of the klystron.

The RF power distribution from the klystron to the cavities, using WR 2300 aluminium waveguides, follows exactly the LEP design [6]. The eight-way power splitting is done with three levels of magic-T's.

The cavity main coupler (MC) [7] is connected to the waveguide system by a doorknob type coax-waveguide transition. The movable MC can be adjusted to set the Q_{ext} value from $3\ 10^9$ to $5\ 10^5$. The cavity vacuum system is separated from the waveguide system by a cylindrical ceramic window.

2.3. Control Electronics

All electronics, including the interlocks, tuning system, temperature monitoring and low power RF are identical to the equipment installed in LEP [8]. Every major piece of hardware is interfaced to an equipment controller (EC). Each cavity, as well as the common cryostat has it's own EC. The klystron, HV and RF distribution systems also have their dedicated EC's. They monitor and control the status of their associated equipment and provide the interface to the "data manager" (DM) which is a VME based controller running under OS9. The DM controls all functions of the test stand and allows local operation via a touch screen or remote operation via ethernet.

2.4 Interlocks

There are two levels of interlocks to protect the cavities and HV system, the first level cuts the RF power and the second switches off the klystron HV. All interlocks are hard wired and their status is read by the local EC. The most important interlocks used during the conditioning all act on the RF and are listed in table 1.

Table 1: The main RF interlocks used in the high power test procedure.

Interlock Description	*Interlock Level*
Main coupler vacuum	$1\cdot10^{-7}$ to $9\cdot10^{-7}$ Torr
Cavity vacuum	$3\cdot10^{-7}$ Torr
Helium pressure	1350 mbar
Helium level	700 mm
HOM coupler fundamental power	20 W
HOM coupler temperature	about 5 K
Window temperatures	60 ^{o}C
Main coupler temperatures	300 K

3. Test Procedures

Before high power testing, the modules have passed the contractual acceptance tests where the individual cavities have all reached the specified accelerating gradient and Q. However, these tests are performed in a low RF power installation with the MC's in the matched position.

The actual high power testing is preceded by low power measurements and adjustments. The main steps of the normal testing procedure are outlined below:

1) Low power adjustments done using a network analyser connected to the cavity via a cross bar transition mounted directly onto the MC's. All measurements are made with the thermal tuners cold and magnetostrictive tuners off:

   - adjustment of the MC to give a MC $Q_{ext}=2.2*10^6$

   - measurement of:
     π - mode and other resonances of the fundamental passband
     a few selected higher order modes

   - measurement of coupling strength to π - mode frequency of :
     monitor antennas
     higher order mode couplers (HOM)

2) The cavities are emptied of liquid He, connected to the waveguide system and then refilled. The testing continues with:

   - measure range of magnetostrictive tuner

   - tune all cavities to LEP frequency

   - condition up to nominal accelerating gradient

The last item, the conditioning process itself, is discussed in more detail in the following section.

3.1 Conditioning

Before installation in the cavities the MC's have been preconditioned at room temperature in a separate test stand with up to 180 kW of RF power throughput in travelling wave mode. Also during the module acceptance tests the cavities have already been individually conditioned to the specified field but at low RF power with the MC's in their matched position. However after transport under vacuum to the high power test stand and adjustment of the MC's to their nominal coupling, reconditioning is again necessary even at very low fields.

Conditioning up to about 1 MV/m is done manually after which an automatic program running on the DM is used. This conditioning program increases the klystron power until the local vacuum in the MC's reaches the lower limit of the "vacuum window" at which point the klystron power is kept constant until the vacuum improves below the lower limit. If the vacuum exceeds the upper limit of the vacuum window the klystron power is reduced. In the ideal case the RF power is continuously adjusted to keep the worst coupler vacuum within the vacuum window.

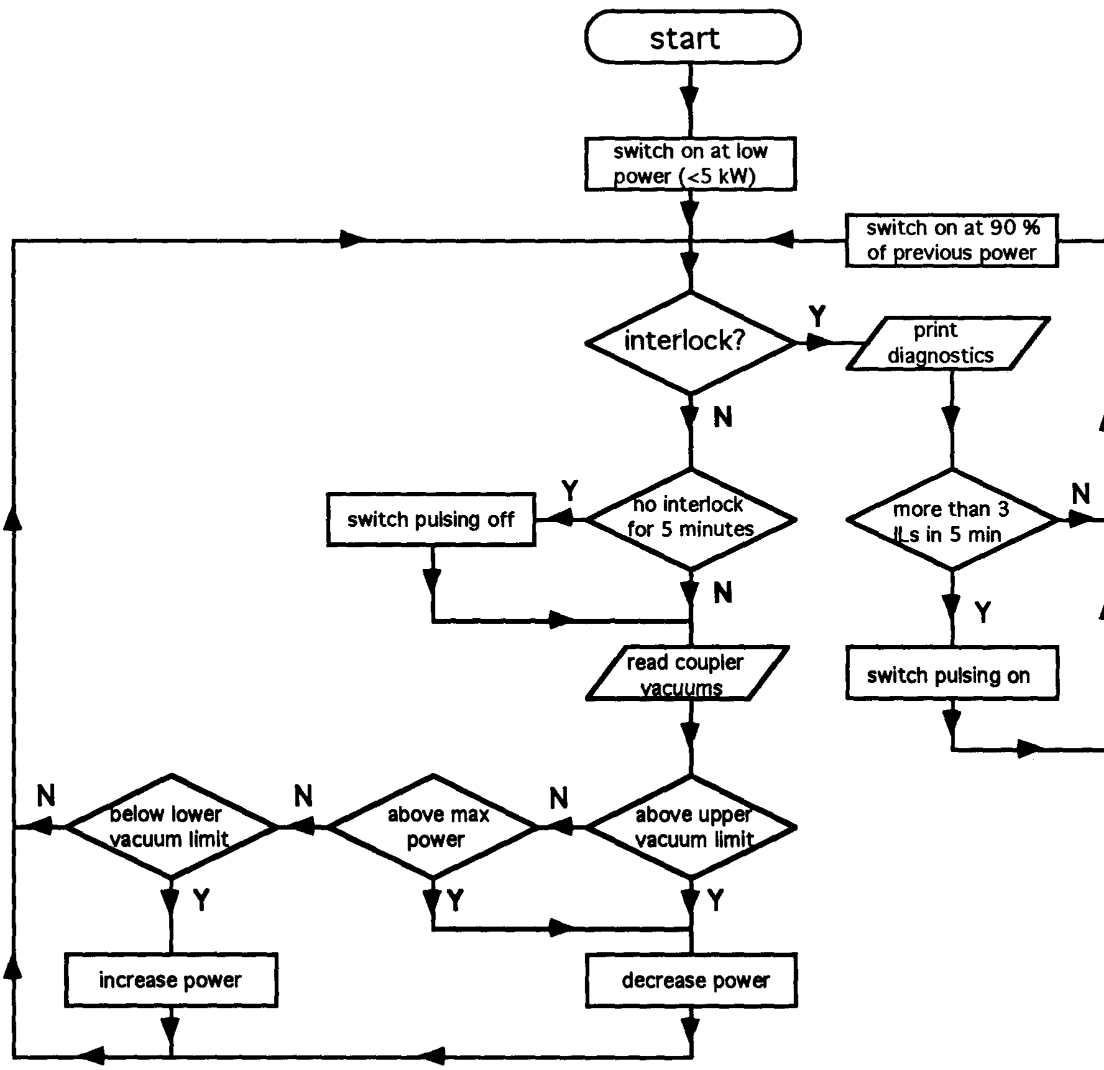

Figure 2 Flow diagram of the conditioning program (cycle option omitted).

The conditioning program cycles at about 8 Hz, however, the vacuum is sampled 1 kHz, which together with a peak hold allows fast vacuum transients to be registered. The worst vacuum reading from any MC during the cycle is used to adjust the RF power for the next cycle. The vacuum window limits, start and maximum RF power levels are all selected from a software menu, the RF power step size is set automatically according to the actual klystron HV and RF power and varies between 0.01 kW and 0.1 kW per cycle.

The program has both cycling mode and pulsed mode options. In the cycling mode, the program begins conditioning from a specified starting value of klystron power until a specified maximum power is reached, the power is then held constant for a specific time before being reduced back to the starting value. For both directions the program uses MC vacuum feedback. This power cycling is repeated until the program is stopped.

If the pulsed option is enabled, whenever the RF has tripped more than three times within five minutes, RF power pulsing is applied. The pulsing is done by increasing the klystron power by several kilowatts for an interval of about 50 ms. The program operates in pulsed mode for five minutes and then returns to normal conditioning operation. A flow diagram of the conditioning program is given in figure 1.

4. Results

Only two modules have been high power tested with the diagnostics as described above, one with sheet Nb cavities and the other with the first industrial series produced Nb-coated Cu cavities. These modules were the first of each type to meet specifications during high power tests, reaching 5 MV/m for the sheet Nb cavities and 6 MV/m for the Nb-coated cavities. Additionally both modules maintained these field levels for many hours.

In both of these modules, the MC's had been equipped with an electron current probe and vacuum gauge mounted near to the ceramic window. The main difference with previous high power tests on other Nb sheet modules was the use of this new vacuum gauge to control the conditioning. Previously the conditioning had been controlled only by interlocks from the cryostat helium pressure gauges and the cavities could not be conditioned to the specified field level of 5 MV/m. Additionally several MC's were damaged during the conditioning.

The individual cavities of the Nb sheet module had already been conditioned to 5 MV/m by using a tetrode amplifier and the MC's set to their nominal positions. The generator was frequency locked to the cavity with the tuning system inactive. After transport of the module to the high power test stand the module still needed complete reconditioning and showed no significant difference compared with the Nb-coated module which had not been preconditioned with the MC's in their nominal positions.

The Nb-coated module tested was the first module fitted with temperature sensors on the HOM couplers to rapidly detect HOM quenches. Some quenches of the HOM couplers did occur during the low power acceptance tests, but none were detected during the high power RF tests.

4.1 Q vs. E

Before the high power conditioning a Q versus E curve for each cavity of the Nb-coated module was measured. One cavity showed a drop in Q at a field level around 4.5 MV/m, but after helium processing for a few hours the Q's were according to specification for all cavities ($3 \cdot 10^9$ at a field of 6 MV/m).

4.2 Main Coupler Electron Current

At accelerating field above 1 MV/m the MC electron current detectors of both modules showed peak currents of more than 100 μA. The pulses were generally shorter than 1 ms. This electron current activity always coincided with vacuum activity in the MC which indicates that the conditioning process is based on electron emission in the MC. On both modules it was necessary to disable the electron current interlock in order to advance the conditioning above 2 MV/m (the maximum hardware interlock value was 100 μA peak).

The detected electron pulses were often synchronous to the mains frequency, which if caused by amplitude ripple of klystron RF output power, indicates that the electron emission has a very sharp threshold.

After the conditioned cavities had been run at high fields for many hours, both MC electron current activity and the MC vacuum activity reduced significantly. This suggests that during normal operation in LEP the electron current interlock could be re-enabled with interlock level set below 100 μA peak.

4.3 Main Coupler Vacuum

During conditioning the most important diagnostics signal was the MC vacuum. In addition to controlling the conditioning as described above it was also the most active RF interlock. The interlock level was set to $2 \cdot 10^{-7}$ Torr at the beginning of the conditioning and increased to $9 \cdot 10^{-7}$ Torr at the end. The upper limit of the narrow software vacuum window was kept just below the interlock level (upper and lower limit of the vacuum window about $2 \cdot 10^{-7}$ Torr apart, the upper limit being about $2 \cdot 10^{-7}$ Torr below the interlock level).

All cavities showed about the same vacuum activity but at different power levels. Usually only two cavities were in the vacuum window at any moment. At certain power levels there were frequent interlock trips caused by vacuum spikes too fast for the conditioning program to control. The conditioning time required to pass these difficult power bands was significantly reduced by using the pulsed mode option as described above. Figure 2 shows a picture of the vacuum activity of the main couplers and the total accelerating field of the module during the conditioning process.

When using the automatic conditioning program both modules took about 30 hours to reach the specified fields. Then after ramping and running the module for several hours at the specified field, reconditioning at specific field levels was again required (see fig 2). This reconditioning was extremely pronounced for the Nb-coated module and initially it took about two hours of reconditioning to again reach 6 MV/m. This reconditioning time was reduced to about 10 minutes after a warm up and cool down cycle of the module. This might indicate that during operation contamination is displaced within the main coupler but is not pumped away, however, with the cavity and coupler warm, the contamination is pumped more effectively. The contamination on the Nb-coated module might have been worse due to the helium processing which had taken place before the high power tests. The Nb sheet module also required reconditioning but only for a maximum time of half an hour.

With a constant klystron power the cavities of Nb-coated module could be detuned up to $\pm 90^{o}$ without observing any significant increase in MC vacuum activity. A similar experiment with the Nb sheet module showed a large increase in vacuum activity causing frequent interlock trips.

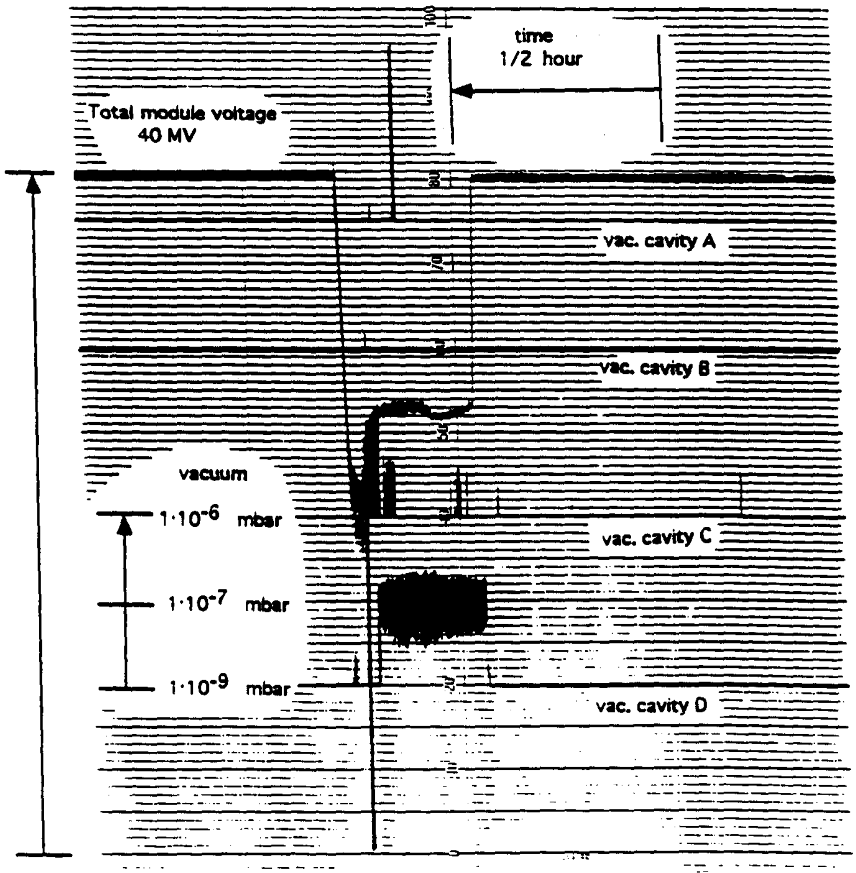

Figure 3 Main coupler vacuum and total accelerating field of the module plotted against time. The logarithmic scale vacuums are plotted for all four cavities with different offsets. The total module voltage is plotted linearly with 50 MV full scale. The plot shows that after the module has been at 40 MV total voltage (5.9 MV/m) for more than 1 hour, reconditioning takes place in cavity D while the cavity power is being reduced. This is followed by some interlocks on vacuum in cavity A, which switches off the RF. After some conditioning of cavities C and D the accelerating voltage can be brought back to 40 MV. (N.B.: There is a small time off-set between pens and the time axis runs from right to left.)

4.4 Radiation

After conditioning the radiation level was measured by using a small ionisation chamber placed on the beam axis close to the beam tube vacuum flange. The radiation level as a function of accelerating field for both modules is given in figure 3.

For both modules the radiation at the specified field level is extremely high: 90 kRad/h for the Nb sheet module at 5 MV/m and 20 kRad/h for the Nb-coated module at 6 MV/m. This high radiation level could possibly give problems to electronic equipment, the super insulation or background for the experiments. About 1 MV/m below the specified field levels the radiation starts to increase sharply. The radiation showed no significant decrease after running many hours at full field.

Once during conditioning of the Nb-coated module, a large vacuum spike was observed and the radiation at 3.2 MV/m increased from the unmeasurable to about 8 kRad/h. This increased radiation level conditioned away within a few hours.

For the Nb sheet module the radiation level measurements with the ionisation chamber were compared with measurements made with two different types of solid state thermoluminescent dosimeters. At the side of the module the more sensitive dosimeters measured radiation levels of between 40 Rad/h and 100 Rad/h. The less sensitive dosimeters measured about 20 kRad/h at the right end of the module and confirmed radiation levels of about 100 kRad/h on the top of the beam tube flange at the left end (the same position as the ionisation chamber). At 1 meter from the flange along the axis this radiation dropped to about 5 kRad/h. The radiation levels at the centre of these flanges were about twice as high as on their tops. During the Q versus E measurements, with only one cavity powered and with the MC matched, the radiation levels of the single cavities were of similar magnitude as with the coupler in the nominal position.

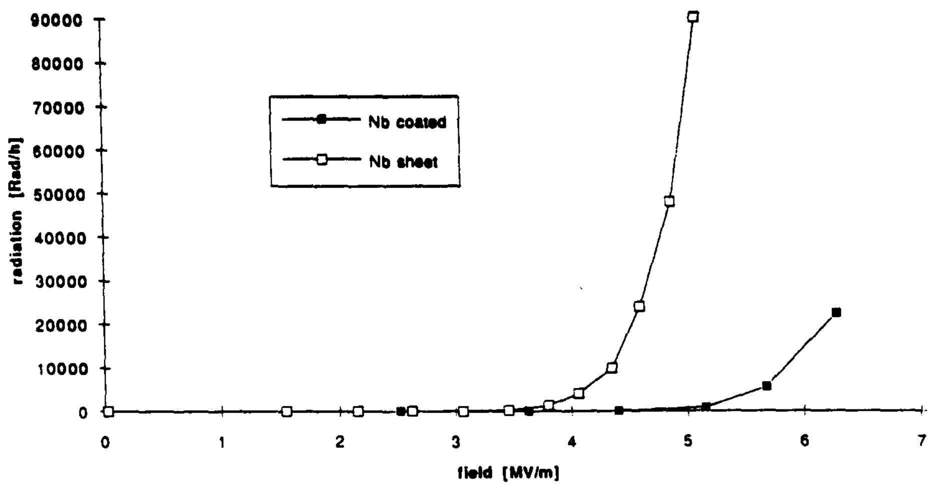

Figure 4 Radiation as a function of accelerating field for both modules after conditioning.

4.5 Heating

The MC's ceramic RF windows are air cooled. In order to avoid condensation during the absence of RF power the window temperatures are regulated to 40 °C by means of electrical heaters. During conditioning the ceramic windows of the main coupler heated to above 60 °C. This was solved by drilling small holes in the doorknob to improve the air flow along the window.

The MC's are cooled by helium gas and are designed to have an equilibrium temperature around 100 K. Running the modules for more than an hour at the design field with a constant helium gas flow increased the temperature above the interlock limit of 300K. To prevent this overheating, the helium flow to the coupler is automatically increased as a linear function of RF power. The need for extra cooling power at high field is not yet fully understood. The flow must be reduced at low RF power to prevent the build up of ice on the MC.

5. Conclusions

During the high power tests of two RF modules, one with Nb sheet cavities and one with Nb-coated cavities, both reached their design field of 5 MV/m and 6 MV/m respectively, after a conditioning period of approximately 30 hours. The efficiency of the conditioning process could be greatly improved by using a fast conditioning program running on the local data manager. The conditioning process was controlled by the local vacuum in the MC's. The MC vacuum was also the only interlock which triggered during the conditioning period once the heating problems of the ceramic windows and the main couplers had been solved. This leads to the conclusion that the high power conditioning process mainly takes place in the main MC's and not in the cavities. The Nb sheet module had been conditioned with the MC's in the nominal position with a tetrode before transport to the high power test stand. There was no significant reduction in the required conditioning time compared to the Nb-coated module which had not been run with the tetrode before transport.

There are high radiation levels when the modules operate at their design field: 90 kRad/h and 20 kRad/h for the Nb sheet and Nb-coated module respectively. The radiation does not seem to diminish significantly with accumulated running hours.

After running at the design field for many hours, the modules needed reconditioning at specific field levels. The reconditioning time for the Nb-coated module was reduced from more than one hour to about ten minutes after a warm-up cycle of the module. This indicates that during RF operation contamination is displaced within the coupler but is not pumped away when the module is at cryogenic temperatures.

Both modules are now installed in LEP and are undergoing commissioning with beam. They have both reached their design accelerating field of 5 MV/m and 6 MV/m respectively with beam currents of several mA.

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