First Operation of a full-size Superconducting Cavity Unit in LEP

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Abstract

The results of the commissioning and first operation in LEP of a full-size superconducting cavity module are reported. It was operated in the laboratory at a total accelerating voltage of 32 MV. RF power generation, distribution and controls are similar to the LEP copper RF system already in operation. Liquid helium is supplied by a 1 kW refrigerator with the cold box in the klystron tunnel 30 m distant from the cryostat. Initial operating experience on the acceleration of LEP beams, higher order mode excitation, the RF and cryogenic system and controls are described.

Introduction

In 1979 a research and development program was started at CERN to design and produce superconducting (sc.) cavities allowing to upgrade LEP [1] to 100 GeV per beam. The latest step of this development was the production [2], test [3] and installation of the first cryo-module with four 4-cell cavities into the LEP ring being commissioned now. On several occasions tests were done with beams at injection energy (20 GeV), during acceleration and at 50 GeV.

This paper describes the installed system and experience gained during commissioning.

The Global System Layout

Figure 1 shows the global layout of the system. In front is the accelerator tunnel with the cavity cryo-module connected to the waveguide system and the helium transfer line. In the background is the klystron gallery housing klystron, control system and cold box of the refrigeration plant.

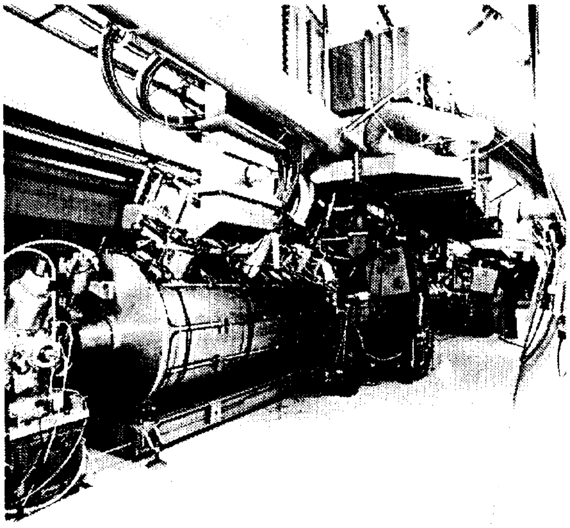

Figure 2: *The cryo-module with wave guides and helium transfer line*

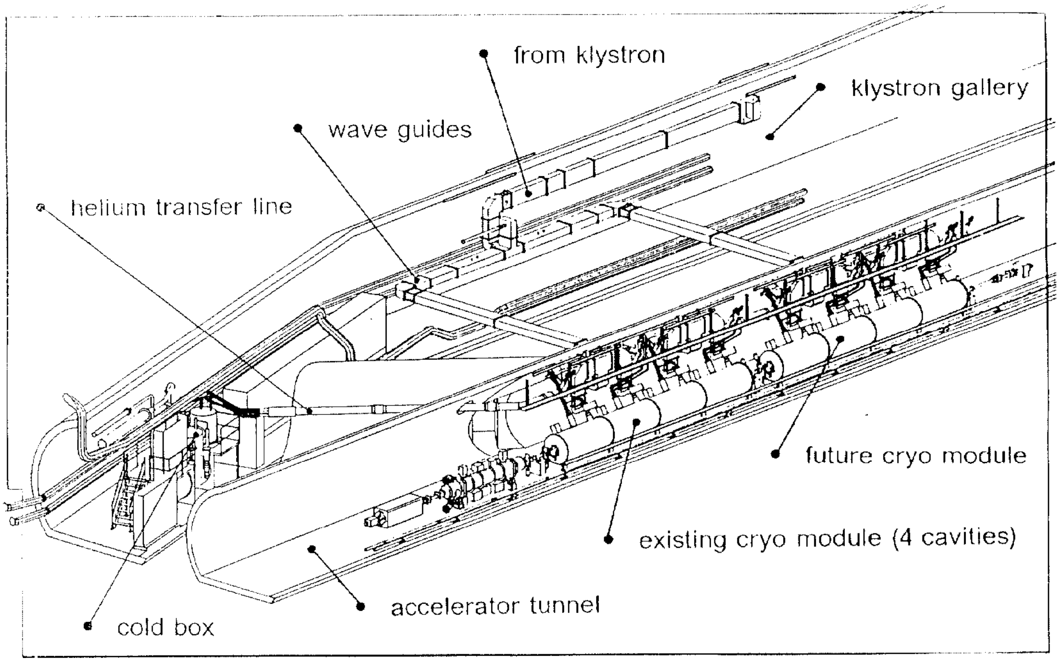

Figure 1: *The global layout of the superconducting cavity station*

The Cryo-Module

Figure 2 shows the cryo-module [3] as it is installed in the accelerator tunnel. Above the module the wave guide bends can be seen, here connected to a N-type transition for low power measurements. This transition is replaced now by a flexible wave guide part, connecting to the magic Tee of the main RF system to be seen on top. The straight circular pipe on top is the main helium transfer line, on top left the flexible lines towards the cryogenic domes of the cavities can be seen.

The module [3] itself consists of four identical elements bolted together to form one common cryostat. Each element consists of a sc. solid niobium 352 MHz 4-cell cavity equipped with helium tank [2], power-coupler [4], two higher order mode (HOM) couplers [4], tuning system [5] and the supporting cryostat frame. The insulation vacuum of each element is closed by a stainless steel skin covering the cryostat all around. Leak tightness is assured by large O-rings. The ends of the module are closed by lids with cryogenic transitions for beam pipe connection. Two of the individual cavities have been built at CERN, two in industry. The assembled module was tested [3] before installation in the tunnel.

The RF System

For cost and compatibility reasons the frequency of the sc. cavities is identical to the existing copper cavity system. Therefore the layout of the RF units for both cavity types is very similar. A *single* 1 MW klystron [6] protected by a circulator will feed 16 sc. cavities in parallel. The RF power is transmitted to the cavities via WR2300 wave guides, the splitting being done with magic Tees. 60 kW of RF power is available per cavity leaving some reserve for gradients or currents higher than the LEP design (2x3 mA, 5 MV/m giving 8.5 MV/cavity). So far only four cavities are connected to the klystron.

The klystron itself has similar control loops as for the copper RF system [7]. It is operated at constant voltage and RF drive, the power being controlled via the modulating anode. After switching on the RF at low power and locking of the tuners the output power is controlled by a 'voltage loop' using the scalar sum of the fields in the four cavities as control signal.

The tuner of the sc. cavities changes the cavity length via magnetostriction and thermal expansion of rods in the support frame [5]. It is driven by a phase detector with an intermediate frequency of 20 kHz as used in the existing RF system.

The Refrigeration System

Liquid helium for cavity cooling is produced in an existing He liquefier modified as refrigerator with 800 W cooling power at 4.5 K [8]. The piston compressor is installed at the surface, the cold box in the klystron gallery, both being connected by two warm He pipes along the 50 m deep pit. A 30 m long rigid transfer line leads from the cold box into the accelerator tunnel and to the sc. cavities.

To keep a maximum of operational flexibility for this pilot installation, each cavity has one inlet for liquid helium, one outlet for cold gas. The connection between transfer line manifolds and cryostat is done by flexible transfer lines. The flow in each of these lines is controlled by a cold valve. All helium tanks are connected on their top to the common gas collector so that - due to the 1.4% inclination of LEP - the module can be operated like 'roman fountains'. To keep the refrigeration load constant, heaters are installed in the helium tanks compensating the varying RF load.

This refrigeration system must be very reliable since the cavities have to remain superconducting even if they are only idling. To achieve this goal and to save manpower, compressor, cold box and cavity helium tanks were equipped with an industrial process control system. The software was developed by CERN where now several helium refrigerators run continuously over months without presence of operators.

The Interlock System

The Interlock System includes all parameters already used in the laboratory test [3]. Particular attention was given to quench detection with circulating beam since transmitting power into a quenched cavity could lead to destruction. Therefore a three level system is applied. The first (fast) level uses the permanent sampling of all individual cavity voltages. If one of the field levels decreases twice by 8% within 20 ms a quench is assumed and the RF drive is switched off, but no beam dump is forced.

Two additional (slow) interlock levels are connected to the helium pressure in the cryostat. If the RF generation continues after a quench - slow quenches not recognized by the fast detector have been observed in the laboratory - the He pressure will rise and at an increase of 200 mbar the second interlock level switches off the high voltage of the klystron.

Also the circulating beam generates RF fields in the cavities. If the cavity does not become sc. again after switching off the RF power this is a dangerous situation. Therefore a third level at 250 mbar He pressure increase forces a beam dump in switching off all RF stations in LEP.

There exists another *indirect* quench interlock. The RF power is switched off in case of a cavity vacuum (e.g. leak) above 10^{-6} mbar. In case of a quench gas is desorbed from the cavity surface also degrading the cavity vacuum and thus triggering this interlock.

Digital Control

The control system of the sc. cavities is an integral part of the existing RF system. To a large extent use was made of existing equipment. As for the copper cavities each major piece of equipment has its own equipment controller [9] (EC), providing the interface between the equipment and the local data manager. These ECs can read and set the status of the associated crates via a number of digital and analog links. ECs are installed for each cavity, the common cryostat and - as for the existing system - the RF power system. Some software and hardware had to be developed to the special requirements of the sc. cavities. The data manager allows (as for the copper cavities) either local control of the RF station via a touch screen or remote operation from the main control room via the LEP control network.

Installation in the Tunnel and Running In

Sc. cavities should never be exposed to 'dusty' normal air. Therefore it is part of the installation scheme that only whole cryo-modules - evacuated and closed with RF compensated valves on both ends - will be transported from the test area at the surface into the tunnel. The available space to move those 4-modules along the tunnel is at certain places only a few centimeters larger than the module.

At a cavity vacuum of $1 \cdot 10^{-7}$ mbar a first cooldown was done. Low power RF measurements of antenna couplings and transmissions at He temperature showed no difference to the laboratory measurements. The module was kept cold since then, the vacuum of the cold cavity being in the 10^{-11} range.

Cavity Performances

The nominal voltage of 34 MV per module at 5 MV/m could not be obtained, since one of the cavities was excited about 20% stronger than the others, thus the performance limit of this cavity at about 5.3 MV/m limited the field increase of the whole module due to the common RF generator. Once installed in the accelerator, the time for processing was very limited due to the LEP schedule, but so far 30 MV were obtained (32 MV in the laboratory). In the moment 25 MV is considered a safe operational level for this module.

A Q-measurement with RF is not possible with main coupler mounted and cryogenic difference measurement of the *averaged* Q-value is considered not precise enough in the actual setup.

To operate the cavity on resonance, the tuning phases have to be adjusted. As already observed in the laboratory test [3] slow mechanical oscillations of the cavity (a few Hz) driven by thermal oscillations in the He gas piping - gas circuits for coming cavities will be improved in this respect - could not be completely compensated by the tuner. It was also observed that the compensation heaters driven with 50 Hz line power induced 100 Hz mechanical cavity oscillations by heat or bubble waves. Heaters are operated now with DC current eliminating these (coherent) oscillations completely. A residual tuning phase jitter of about ± 2° remained for two cavities while two others did not allow the same gain in the tuner servo loop (excitation of self oscillation) and up to ± 10° remained at driving frequencies between 4 and 19 Hz. The phase jitter of ± 2° is considered acceptable for LEP since the cavity oscillations are statistically independent and the relative field error will decrease with the square root of the number of cavities. The jitter of up to ± 10° for the two other cavities does not perturb the operation of cavity and accelerator but has to be improved before the installation of more cavities.

Finally with beam the phase of the sc. module with respect to the other cavities was adjusted by maximizing the synchrotron frequency.

Operational Experiences

Cavity Operation with Beam

During the first days after the winter shutdown (March 1990) the module was idling, no unexpected occurrences being detected. To avoid any influence on LEP operation all cavities were detuned by about -5 kHz using the thermal tuner. It takes about 10-15 minutes to retune.

Several machine development periods were dedicated to sc. cavities with beam. The field probe calibration was checked by switching off the module and observing the change in synchrotron frequency. A comparison to similar tests for the copper cavities confirmed the probe measurements, e.g. at 25 MV ± 4%. So far 3.2 mA have been accumulated with 7 copper stations and the sc. station, each giving ≃ 10 MV. Initially the maximum current seemed to be limited by false quench detector trips. This was due to beam induced signals and was cured by smoothing and desensitizing the detector.

Acceleration under Remote Control

To avoid synchro betatron resonances the ramping of magnets and RF voltage is done in a synchronous way under computer control. So far it was possible to ramp 2.45 mA total current (disabling the fast quench detectors to avoid false tripping of the sc. module leading to beam loss in earlier tests). With the sc. module included a new maximum LEP energy of 50 GeV was obtained, the sc. module contributed 10 MV at the start of the ramp and 25 MV at the end.

Cryogenics

The cryogenic supply system had initial stability problems with coupled control loops acting on pressure and levels in the helium tanks, the loop sensitivity being high as gas buffer volumes had to be kept small for space reasons. Careful tuning and using He-bath heaters controlled by the RF level (feed forward) led to much better stability. One can run now safely at 25 MV. This refrigerator will be upgraded to 1200 W cooling power in autumn to be ready for up to 3 modules.

Higher Order Mode Measurements

Measurements of identified modes can be done in the laboratory but using the beam to find possible dangerous modes and determine the total deposited beam power is very important, especially in view of higher beam currents. Calculations with the actual bunch length of 20 mm have been made [10] yielding a loss factor of $k_1 = 0.22$ V/pC for the electromagnetic fields trapped in the cavities below the cut-off frequency of the beam pipes, the total energy stripped off from the beam being 3 times higher.

For a single bunch - always extrapolated to the nominal current of 0.75 mA (66 nC) - 10.9 W were expected per cavity. A *bolometric* power meter connected directly onto the cavity indicated in fact 12 W. Furthermore for 2x4 bunches it showed that individual bunch powers could be added. Therefore couplers (2 per cavity) and cables (2 per coupler) are well suited for the design current of 2x3 mA, however, an increase to e.g. 2x36 bunches of 100 nC cannot be supported.

A scan for sharp resonances in the spectra revealed one high-Q mode, also visible in the laboratory test [3]. This mode matches well in frequency to a 'beam pipe mode' predicted by calculation [11].

Remaining Problems

A few problems remain to be solved in the near future. The mechanical oscillations of some cavities not compensated by the tuning system have to be examined and the remaining phase jitter to be reduced. This problem may also to be linked to the fast quench detector giving sometimes trips which seem not to be real. Furthermore the cryogenic system has to be fine tuned to allow a larger freedom of operation and to prepare the arrival of new modules. Finally, more experience has to be gained in 'standard operation', accumulating and ramping maximum possible beam currents. For possible higher beam currents the question of HOM losses above the cut-off frequency has to be examined.

Conclusions

The first full cryo-module with four sc. 352 MHz 4-cell cavities was operated in the LEP collider. The module was used together with the copper cavities to accelerate the beam up to 50 GeV in synchronous operation with the other accelerator components.

30 MV total voltage were obtained, 25 MV are a safe operational level, these voltages being confirmed by beam observations. HOM measurements proved the coupling scheme adequate for the LEP design current of 2x3 mA. Despite the very limited time available the module is nearly operational and will be integrated as standard LEP equipment in a near future.

Acknowledgement

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