Presentation 66

World-Wide Superconducting Cavity Performance Survey

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66.1 Introduction

The success of superconducting accelerating systems in several laboratories all over the world seems to support the idea that the guaranteed voltage can be calculated by the design gradient multiplied by the installed (nominal) acceleration section length, or, even worse, gradients obtained sometimes in tests are taken as guaranteed achievement for accelerator application. There is no doubt that considerable progress has been made from the first laboratory experiments with superconductors exposed to RF fields to building cavities equipped with all necessary auxiliaries and integrating them in an accelerator. However, one should not forget that accelerator equipment based on much older experience is not perfect, nor will equipment based on new technologies be perfect. Therefore we will try to draw a realistic picture of the application of superconducting acceleration systems.

In the first paragraph a few interesting installations with superconducting acceleration systems are picked out, this list is certainly not exhaustive. In the second paragraph dedicated hardware components and their performance will be reviewed and finally running experiences will be discussed.

66.2 Some SC RF Installations

The 'grandfather' of the SC accelerators is the HEPL (University of Stanford, USA) linac using 1500 MHz cavities. This machine came into operation in 1977, i.e. only 14 years ago, and is used today for free electron laser studies. The team constructing this machine did a very good job, finding solutions for many problems which are copied by other teams even today. However, being the first in a new field, design can only be based on the (small) existing knowledge and laboratory experiments, the full truth can only be found in the full scale experiment. In fact this machine behaved well in operation and still works today but performance of the SC cavities was lower than expected, having:

- Multipacting due to the cavity shape limits the field level
- Serious irreversible Q-degradation occured due to operation under bad vacuum
- The absence of a safe higher order mode (HOM) damping system limited the beam current (trapped modes)

Evidently later teams used the experience gained with this machine, taking up the working solutions and trying to avoid (now) known traps.
Another milestone is the heavy ion accelerator ATLAS at the Argonne National Laboratory close to Chicago, USA. It uses a completely different cavity design due to the 'slow' particles but this accelerator has accumulated more than 40000 hours of beam time without any serious problems.

A more recent machine is the S-DALINAC tunable 10-130 MeV electron recyclotron built at Darmstadt, Germany, in collaboration with the University of Wuppertal. It uses 5 and 20-cell cavities at 3 GHz and is continuously upgraded, e.g. by cavities of newer high RRR material. These modifications and the running in is often done by post docs, i.e. the machine itself is still an experiment, and MD is mostly done during the day, customer physics runs during the night. Since the beam current is very low, no HOM coupling system is necessary and problems with synchrotron radiation do not exist. The average field obtained (except in one defective cavity) is 4.2 MV/m, but there is a large spread. In total 2500 h beam operation have been achieved. The most serious problems encountered with this machine came from the cryogenic pumps (1.8 K working temperature).

At CERN a LEP type SC cavity with pulsed (feedback) RF system was installed in the SPS to improve injection of leptons into LEP. During the proton part of the SPS super-cycle the cavity is forced to zero field by the feedback system (otherwise the proton beam would be lost). Some unscheduled tests have been done during running in. During lepton acceleration the cavity is pulsed for a fraction of a second per lepton cycle. Without beam 7.1 MV/m were obtained on the peak of the pulses. With beam additional fluctuations of the cavity voltage were induced (beam induced voltage) and due to the high gain of the feedback system all fluctuations were violently corrected. This could lead to excessive RF power at the highest field levels causing a trip. To avoid such an event, the maximum field was reduced to 5.5 MV/m (9.4 MV) during operation. 11000 hours of running time with beam have been accumulated without any real problem nor degradation. It should also be mentioned that - after the running in period - the cavity did not need any special attention at all.

Evidently the best reference point is the SC accelerating system in the 32 GeV $e^+e^-$ collider TRISTAN at KEK (Tsukuba, Japan), since it is the largest system in operation today and there are many similarities with the system planned for CERN (see Figure 66.1). There are however, some important differences in detail. The KEK working frequency is 508 MHz and 5-cell cavities have been chosen. Today there exist two batches of 16 cavities each, developed and built in collaboration with Mitsubishi. The first batch has accumulated 7000 h beam time, the second batch 4000 h. For the first batch (second similar) 9.25 MV/m average field were obtained in the bare cavity tests, 7 MV/m once installed in TRISTAN. After one year of operation, an average of 6.7 MV/m was found. Thus there has been no significant field performance degradation (see later).

All these fields have been obtained without beam. Regular physics runs were done with not more than 4.7 MV/m average. There was no hard limit but increasing the field level increased also the probability for a cavity break-down. To keep operation stable, not more than one trip per physics run (not necessary followed by a beam loss) was tolerated (TRISTAN at 32 GeV). The most striking fact in this context was that the break-downs happened with very high probability in cavities close to the arcs (RF location around IP as in LEP) where the cavities receive the highest doses of synchrotron radiation.

Today there are several approved projects under construction or test:

At DESY for the HERA electron ring 16 cavities of 4 cells at 500 MHz are foreseen (LEP-like cavities, manufacturer Dornier), installation is on its way. This team was the 'unhappy discoverer' of the '100 K effect': An irreversible Q-degradation observed after a first good test under certain conditions (high RRR material, a 'hydrogen rich' chemical treatment and special cooling conditions) which has delayed cavity installation. This problem has been encountered also at other laboratories (e.g. Saclay, Wuppertal, Cornell), but the problem is well understood now and remedies exist. It should be stressed that at CERN this phenomenon has not been encountered, even after cool down conditions to provoke the effect, and that Nb/Cu cavities - the bulk of the ordered LEP SC cavities - are insensitive to it.
At CEBAF (Constant Electron Beam Accelerator Facility, the 'heart' of the SC cavity team came from Cornell University) in Virginia, USA, a one-bunch-per-bucket recirculating linac is under construction. The total beam current will be 200 μA with 4 passes, the HOM couplers are of waveguide type and the RF loads - due to the very small power coupled out - are directly in the liquid helium. The main couplers are also of wave guide type. 338 1500 MHz 5-cell cavities (manufacturer Interatom) have been ordered. The average field of 7 prototypes made by different manufactures (USA and Europe) was 7.4 MV/m (between 3.5 and 10)

Finally at CERN for LEP 192 4-cell cavities at 352 MHz (24 solid Nb, 168 sputtered Nb/Cu) are foreseen. The first unit has been installed in LEP since the end of 1989 (2 cavities made at CERN, 2 at Intermat). All individual cavities made 5 MV/m in the surface acceptance test, however, the average module field was only 4.6 MV/m (see later). With beam, safe operation was possible at 3.6 MV/m (25 MV for the module). A second module with 4 sputtered Nb/Cu cavities made at CERN was just installed, 5 MV/m average were obtained in the surface acceptance test of the module. Field processing was only stopped due to the tight schedule, and there was no indication of a limitation. A third module similar to the second one is on its way.

66.3 Some Dedicated Hardware Components

66.3.1 CAVITIES

Today 5-6 MV/m is a usual design value and we have mentioned already in the list above some real cavity field performance data. In this context it is important to remember that a copper cavity can (generally) be pushed above the nominal performance value for a short time (e.g. during transients), but a SC cavity can (generally) not surpass its quench limit without break-down. If SC cavities are ordered at 5 MV/m design field guaranteed, a cavity which quenches at, say, 5.05 MV/m has to be accepted but can evidently not be run at a nominal field of 5 MV/m, the slightest transient will lead to a trip. Things can get even worse if a batch of cavities is driven by a common power source (see later). Thus a certain 'overvoltage factor' has to be included. Based on the generally higher fields found for the Nb/Cu cavities, LEP Nb/Cu cavities were ordered with 6 MV/m design field.

Of course the field is not the only important parameter, but a small degradation of the cavity Q is of lower importance since it is not seen by the beam and thus the experiments, provided that the installed refrigeration system is capable of delivering enough helium and the electricity bill can be paid (fortunately the bill increases more slowly than for the 'cold' power)

For all cavity parameters it is of utmost importance to know if the cavity will keep its performance - accidents will not be considered here - during a life of several years in the machine and with beam.

66.3.1.1 Performance Degradation  As already mentioned above, at e.g. Argonne, CERN SPS no real performance degradation was observed but again KEK is the main reference point. According to S. Noguchi, KEK, (data January 1991) the performances concerning field, Q-value and electron activity (expressed by the field enhancement factor) are as shown on Figure 66.2 i.e. no systematic degradation of those parameters can be observed during 7000 hours of beam time (the time scale is in days in the beam line).

66.3.2 POWER COUPLER

The task of the power coupler is to transport RF energy into the cavity but for SC cavities this has to be done with a minimum of cryogenic losses. For cavities transmitting several tens of kW to the beam (i.e. KEK, DESY (500 MHz) and CERN (352 MHz)) coaxial antenna couplers with ceramic window (KEK planar, DESY and CERN coaxial) are used.
Problems with ceramic RF windows at high power are well known, but if air, especially loaded with dust from the tunnel, enters a (cold) SC cavity, the effect may be catastrophic for this cavity and even the adjacent ones.

On three occasions at KEK (up to 125 kW power transmission possible) window leaks developed, one contaminated 2 cavities which had to be removed from the beam line (a few weeks repair). For the CERN SC cavities (identical windows as the LEP copper cavities) no such problems have been encountered so far, but the windows broke twice on Cu cavities at high power. In this context it may be worthwhile to recall that the original LEP design asked for 2 x 3 mA beam current, corresponding to a maximum power of 60 kW per SC cavity. Thus the ceramic windows of the copper cavities foreseen for 120 kW and tested up to 180 kW, guaranteed a sufficient safety margin. However, new requirements (multi bunch schemes) ask for up to 125 kW per cavity and as seen from the experience with the copper cavities this is not fail safe any more! Therefore new diagnostics and interlocks have to be designed, built and tested for the long term.

Another problem encountered at CERN has been the heating of the RF joint on the power coupler. This was observed on two cavities of the first module in the detuned state but not in the normal operational state. After this, the vacuum joint was modified (conical design) giving a better RF contact and the problem has not been encountered again so far.

66.3.3 Higher Order Mode Damping System

The higher order mode damping system has the task of removing the electro-magnetic energy deposited by the beam, otherwise the beam current would be limited due to this loading. Generally people talk only about HOM couplers but in fact there are three basic components:

- HOM coupler(s) with incorporated stop filter for the fundamental mode
- A large-band RF energy transport system: Cables and connectors or rigid lines
- RF Loads

The low current machines do not need such a system but e.g. KEK, DESY and CERN use several models of HOM couplers with incorporated (superconducting) stop-filters and flexible cables for RF transport.

Problems have been encountered during the design, test and running of this equipment at all laboratories. First, it is difficult to cool all coupler parts directly by liquid helium (cryogenic and RF requirements have to be fulfilled!), so some parts are only cooled by conduction which can lead to (local) quench of the couplers sometimes lasting for quite some time.

A related problem is the run-away by heating of the stop filters by HOM or fundamental mode power. Such heating can lead to small mechanical deformations sufficient to detune the filter (capacitance with mm gap!) which increases the fundamental power flux, increasing again the heating and so forth. This positive feedback was observed e.g. at CERN for the coupler 2 - having otherwise very promising properties - and lead to the development of coupler 5a,b pushing the sensitivity to this effect above the design limit.

This effect had even worse consequences at KEK where 2 connectors of the power transport system burnt and the corresponding cavities had to be removed from the TRISTAN ring for a few weeks. We hope at CERN that such an accident - should it happen despite other precautions - could be repaired in the tunnel thanks to the cryostat which can be opened rather easily, provided the HOM coupler and its ceramic window are not damaged.

Another difficulty arises from the fact that the power transport system has to pass the insulation vacuum where cooling does not correspond to normal atmospheric conditions for which the specifications of cables and connectors are defined in the manufacturer's catalog. These data are largely overestimated under these conditions and the performance of a cable depends strongly on its length. This power limit is a serious one: At KEK on two occasions, connectors (already modified after 'high' power tests under vacuum) were burnt and the cavities had to be removed from the ring for repair. To avoid such destruction, the beam current in TRISTAN is limited!
1990/91 shut-down all 64 connectors (2 couplers per cavity) were replaced by a more performant design representing 2.5 months work in all. It is hoped that during the next run the beam current can be increased considerably.

To avoid significant construction complications for the cryostat, assembly difficulties and large cryogenic losses due to wave guides or rigid lines, one has to use cables with connectors – as long as the power flux is small enough. However, as soon as the beam current is increased above a certain limit, cables cannot be used any more. According to estimates done in context with the multi-bunch options for LEP, 2×8 bunches (of nominal charge) should still be manageable with cables and connectors. The Nb/Cu bunches will be already equipped for this option, the (older) bulk Nb cavities will be marginal. However, for more bunches new couplers with rigid lines have to be installed, probably in a clean room outside the tunnel, i.e. modules have to be dismounted and remounted in the tunnel. To make this transition feasible without replacing the whole cryostat, the lately modified design already has ports to the outside above the HOM locations to house possible rigid lines.

66.3.4 Frequency Tuners

The task of the tuning system is to keep the resonance frequency on its nominal value, fighting the perturbing mechanisms

- Temperature drift of supports, pressure drift of He bath
- Externally induced oscillations (e.g. vacuum pumps, thermo acoustic oscillations plaguing also the LEP cavities)
- Ponderomotive oscillations (self excited mechanical oscillations): An increasing RF field changes the cavity shape (and frequency) by radiation pressure; the corresponding detuning (tuner too slow) lets the field go down again so that the cavity moves elastically back to its original shape, thus retuning and restarting the cycle. This effect was definitely observed at CEBAF, it has to be checked that oscillations of the LEP cavities at high field are not driven by this mechanism.

Today the high-β cavities similar to the SC LEP cavities are all tuned by elastic change of the cavity length. The advantages of this method are the absence of multipacting due to ‘strange’ objects in the cavity (e.g. plungers) and no moving parts inside the cavity (risk of contamination, leaks due to broken bellows), but the tuning system is limited in velocity by the mechanical cavity resonances which would lead to auto-oscillations of the control system if the gain is increased above a certain limit. RF tuners have none of these problems but the tuning range is very limited for a reasonable coupling device.

A variety of ‘drives’ to change the cavity length are in operation. Evidently the drive has to withstand the vacuum and elastic forces of the cavity (and He tank) and has to have enough stroke and velocity, whilst avoiding the slightest random movement (μm fraction precision required). Most laboratories use a double drive, one fast but with small stroke, one slow but larger stroke.

66.3.4.1 Piezo crystals

They are fast but the range is only a few kHz (KEK, Darmstadt, CEBAF). Some problems have been encountered:

For the Darmstadt accelerator the piezo crystals were in the He bath in an early design. However, after a few weeks the crystals were penetrated by liquid He disabling the crystal by break through of the high voltage from the controller, so the design had to be changed.

A more severe problem was encountered at KEK. In two cases piezo crystals exposed to strong doses of (synchrotron-) radiation ceased operation and had to be replaced (directly accessible).

66.3.4.2 Magnetostrictive Bars

They are comparable to piezo crystals in tuning performance (CERN, Darmstadt tests) but have the advantage of not being brittle and supporting shear forces in all directions. The initially shocking fact that they are made from magnetic material (Q-degradation by trapped magnetic flux !) has shown to have no visible effect. Furthermore the material nickel
as chosen at CERN - is a well known cryogenic construction material. Up till now no problems have been encountered with such a device.

66.3.4.3 Stepping motor drives They are slow but the range is (nearly) unlimited (KEK, DESY: due to large bandwidth no fast tuner necessary). Today screw, gear and motor are located outside the vacuum tank (KEK, DESY, CEBAF), however, a strong connection with large cross section has to connect the drive at room temperature to the cavity at He-temperature, causing some cryogenic losses.

For the early CERN experiment with a 500 MHz 5-cell cavity at PETRA in 1983, all 3 tuner drives had their screw located inside the vacuum tank to reduce the cryogenic losses. Specially coated (ball-bearing) screws for vacuum and low temperature were used, but two out of three got stuck after a few weeks (survival with one was fortunately possible), therefore we prefer a tuner without moving parts!

66.3.4.4 Thermal tuner The thermal tuner uses the expansion of the (magnetostrictive) tube, controlled by a heater element. It is slower than a stepping motor and needs a permanent small He gas flow, but no moving parts are necessary. For the first prototypes there have been some problems with tightness of the helium gas cooling circuit but these problems seem to be understood and are now solved.

66.3.5 External Components

The cavities are one component of a whole system, also the other components - depending themselves on e.g. electricity and cooling - have to work properly.

66.3.5.1 RF Power Supply At LEP one klystron supplies 16 (8) cavities, corresponding at 5 MV/m to 140 (70) MV in total. Assuming a synchrotron phase angle of about 25° off maximum (priv. comm. J. Jowett) in case of any failure, whatever the basic reason, 127 (63.5) MV of voltage are lost. Apart from all considerations of synchrotron frequency changes and dynamic aperture (see elsewhere), this voltage has to be available instantaneously somewhere else, otherwise there is little chance to recover the beam or even part of it.

66.3.5.2 Cryogenics Fortunately at 350 MHz one can easily work at 4.2 K and no cold pumps -which caused many problems at the Darmstadt accelerator – are necessary. Also large cryo plants work reliably, e.g. BEBC, TEVATRON, HERA, for many months, and automatic control is progressing. From experience with the first module in LEP one can say that setting up is sometimes painful (large response times) for impatient RF people used to fraction of seconds responses, but once a working condition is found, the refrigerator works reliably.

Should the refrigerator stop for any reason, there is in principle, enough helium in the LEP cryostat to run for another few minutes at full field before the liquid He level reaches the first interlock position. Theoretically this may allow restarting the refrigerator if the basic problem was only of transient nature (e.g. short power cut). However, the stop of the refrigerator and the associated commutation of valves to the security position as well as the restart will very probably create such perturbations in the cryogenic system, that a stable operation with all cavities at full field cannot be guaranteed any more.

66.4 Beam Operation

Since the beam current is very low, the beam experience at Darmstadt is not very representative for LEP.
66.4.1 Experience at KEK

At KEK experience has been gained during the running of the cavities for a long time under different operational conditions.

As already theoretically predicted, the synchrotron phase angle stability (2nd Robinson criterion) asks for stabilization of the phase of the cavity-voltage for SC cavities for a (nearly) matched beam. Otherwise a beam coming too early changes the cavity voltage (beam induced voltage) such that there is no change in the voltage seen by the beam, and thus there is no longitudinal focussing mechanism any more. Therefore the vector-sum of the cavity fields (incl. beam induced) controls the klystron phase.

Break-downs of cavities with beam are not rare, especially for cavities close to the arc. Therefore a 'recovery scheme' has to work to bring quenched cavities or units up again as soon as possible. Actually at LEP the klystron with 16 cavities is switched off if one of them quenches, an individual detuning for the particular quenched cavity might be tried to 'save' the other 15 cavities.

66.4.2 Experience from CERN/LEP

One problem limiting the global performance at CERN (also the case at KEK to a lesser extent) comes from the common RF supply from one generator due to the spread in the coupling strength of the main couplers. When the cavity excitation is unequal, increasing the generator power will increase this difference (scaling). Furthermore each cavity has its own quench limit and the field increase is stopped as soon as the first cavity hits its limit, see Figure 66.3. (operation can only be done somewhat below this state as already indicated above). All the possible further voltage increase of the other cavities up to their limits is lost for operation. One way out is a variable coupler (CERN) or a RF-transformer (DESY) which allows an even excitation profile. Alternatively, each cavity can be set individually according to its performance. To check for possible cavity Q-degradation the variable coupler at CERN is also designed to allow very low coupling values to determine the Q-values of individual cavities by (more precise) RF measurement in the tunnel.

66.5 Conclusion

- There is no reason to assume that superconducting cavities have a better reliability than other accelerator components, i.e. beams will be lost due to cavity break-down or other failures and there will be periods where LEP will not work due to unscheduled repair work on cavities.
- The technology is still relatively young (first machine came into operation in 1977) but it is already used worldwide with success. It should be mentioned that SC cavities do not need large additional teams of experts (see e.g. the SPS SC cavity)
- Several projects are under construction worldwide, i.e. people are confident that this technology is worth the effort.
- A final request: Enough (parasitic) beam time in LEP is needed as early as possible to observe the whole system under different operational conditions and thus allow adaptation of the controls and interlocks. By taking the risk of sacrificing a 46 GeV-beam and a few Z°, the chances are strongly increased that W± pairs will be paid back later.

66.6 Acknowledgement

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Figure 66.1: Tristan superconducting cavity cryostat
Figure 66.3: LEP cavity performance