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OPERATING EXPERIENCE WITH THE LEP200 SUPERCONDUCTING RF SYSTEM

P. Brown, O. Brunner, A. Butterworth, E. Ciapala, H. Frischholz, G. Geschonke,
E. Peschardt and J. P. H. Sladen – CERN, Geneva, Switzerland.

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During 1999 and 2000, the RF system was pushed to its absolute maximum limits for physics. By mid-2000 maximum total RF voltages of well over 3600 MV could be sustained, allowing beam energies of up to and even over 104 GeV for new particle searches. This corresponded to average gradients approaching 7.2 MV/m in the SC cavities, well above the design value of 6 MV/m.

This level of performance was achieved due to the very successful high-field conditioning of the niobium-copper sputtered SC cavities, the many RF system improvements made in previous years and by a cryogenics system cooling power upgrade.

Operation at very high energies however brought new difficulties, many related to the high fields and increased RF power levels. Running with the RF system at its limit required new operational procedures and facilities as well as constant follow up of cavity and RF system performance. LEP high energy running proved very successful, the beam energies and integrated luminosities obtained largely exceeded the most optimistic expectations.

Finally, a vast amount of experience has been gained during the construction and operation of the LEP SC RF system. Some critical design issues in SC RF systems can be reviewed in the light of this experience.

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OPERATING EXPERIENCE WITH THE LEP2 SUPERCONDUCTING RF SYSTEM

P. Brown, O. Brunner, A. Butterworth, E. Ciapala, H. Frischholz, G. Geschonke, E. Peschardt and J. P. H. Sladen, CERN, Geneva, Switzerland.

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Operation at very high energies however brought new difficulties, many related to the high fields and increased RF power levels. Running with the RF system at its limit required new operational procedures and facilities as well as constant follow up of cavity and RF system performance. LEP high energy running proved very successful, the beam energies and integrated luminosities obtained largely exceeded the most optimistic expectations.

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1 INTRODUCTION

The LEP2 RF system was a substantial upgrade of the LEP1 normal-conducting copper cavity RF system by the progressive addition of a large number of SC cavities, to push beam energies from 45 GeV to over 100 GeV[1]. The layout of the RF system is shown in figure 1. The cavities were installed around the even-numbered interaction points of LEP. The LEP1 copper cavities were arranged in units of up to 16 cavities driven by two klystrons operating at slightly different frequencies. The two klystrons shared a common HV DC power converter. For the LEP2 SC cavities operating with a single frequency the RF unit was split into two independent 'half-units', cavities 1 to 8 being driven by one klystron and cavities 9 to 16 by the other. Four SC cavities were housed in one cryomodule.

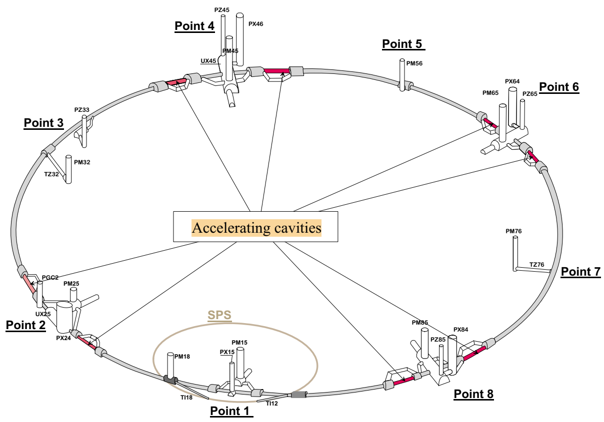


Figure 1: LEP RF system layout

The numbers of SC and room temperature copper cavities in 2000, the last year of LEP operation, is shown in Table 1.

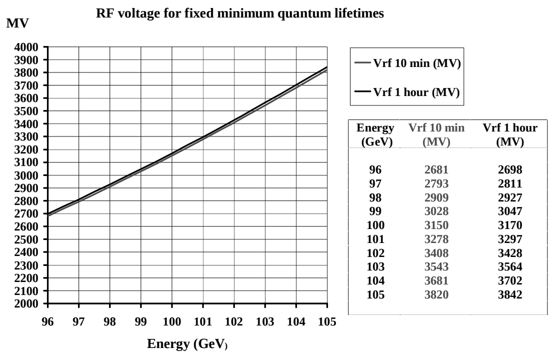
Of the 288 SC cavities 272 were made of niobium sputtered on a copper substrate (NbCu) and 16 were solid niobium.

Point	SC Cavities	Copper Cavities
2	64	28
4	80	
6	80	28
8	64	
Total	**288**	**56**

Table 1: LEP cavity numbers in 2000.

2 THE PUSH TOWARDS HIGH ENERGIES

W physics at LEP from 1996 to 1998 at energies from 84.5 GeV to 94.5 GeV required operating RF voltages of up to 2870 MV, approaching the design gradients of 5 MV/m and 6 MV/m in the niobium and NbCu cavities respectively. Running in 1999 and 2000, the last two years of LEP operation, was devoted to the search for new particles. Energies approaching and exceeding 100 GeV were needed. Figure 2 shows the RF voltages required for running at such energies. With good integrated luminosity a fundamental requirement, the cavities would be required to operate well above the design gradients on a routine basis. This required conditioning of the cavities, both during the yearly LEP start-up period and frequently during operation.



Energy (GeV)	Vrf 10 min (MV)	Vrf 1 hour (MV)
96	2681	2698
97	2793	2811
98	2909	2927
99	3028	3047
100	3150	3170
101	3278	3297
102	3408	3428
103	3543	3564
104	3681	3702
105	3820	3842

Figure 2: RF voltage requirements for high energy.

3 CAVITY CONDITIONING FOR HIGH ENERGY RUNNING

In-situ conditioning of RF cavities played a key role in bringing the RF cavities well beyond their design fields and making LEP high energy running possible in 1999 and 2000. Both pulsed and continuous RF conditioning was used. Set periods were assigned for RF conditioning at the start of each year’s running. Additional conditioning was done whenever possible during the year. Running cavities at or near their maximum gradients during operation also contributed to conditioning, limited in its extent however by the requirement to have minimal trip (fault or protection system induced switch off) rates.

3.1 Conditioning in 1999

During the 1998 conditioning period, the NbCu cavities had already been pushed to an average of 6.8 MV/m, well beyond their 6 MV/m design gradient[2]. The reduced Q-value of the cavities at such high gradients however prevented running all cavities together at these levels, due to limited available cryogenics power. During the 1998/1999 winter shutdown an upgrade of all four RF cryoplants from 6.7 kW to 12.3 kW nominal cooling capacity was carried out[3], this being needed in any case for the future use of these cryoplants in LHC. Conditioning just before the 1999 running period brought substantial increases in voltages for the NbCu cavities and an average gradient of 7.27 MV/m in these cavities. The 16 pure niobium cavities could not be pushed above their design gradient. The sum of the maximum voltages reached at the start of the 1999 running period was 3608 MV. The safe operating level of 3120 MV at the start of the year was considerably less but this was gradually brought up to 3530 MV by the end of the year, almost reaching the conditioning level.

3.2 Conditioning in 2000

During the 2000 shutdown the cavities were conditioned to still higher levels, reaching a total of 3716 MV, with an average gradient of 7.47 MV/m in the NbCu cavities[4]. The individual RF half-unit voltages obtained, together with their 1999 and 1998 conditioning levels, are shown in figure 3.

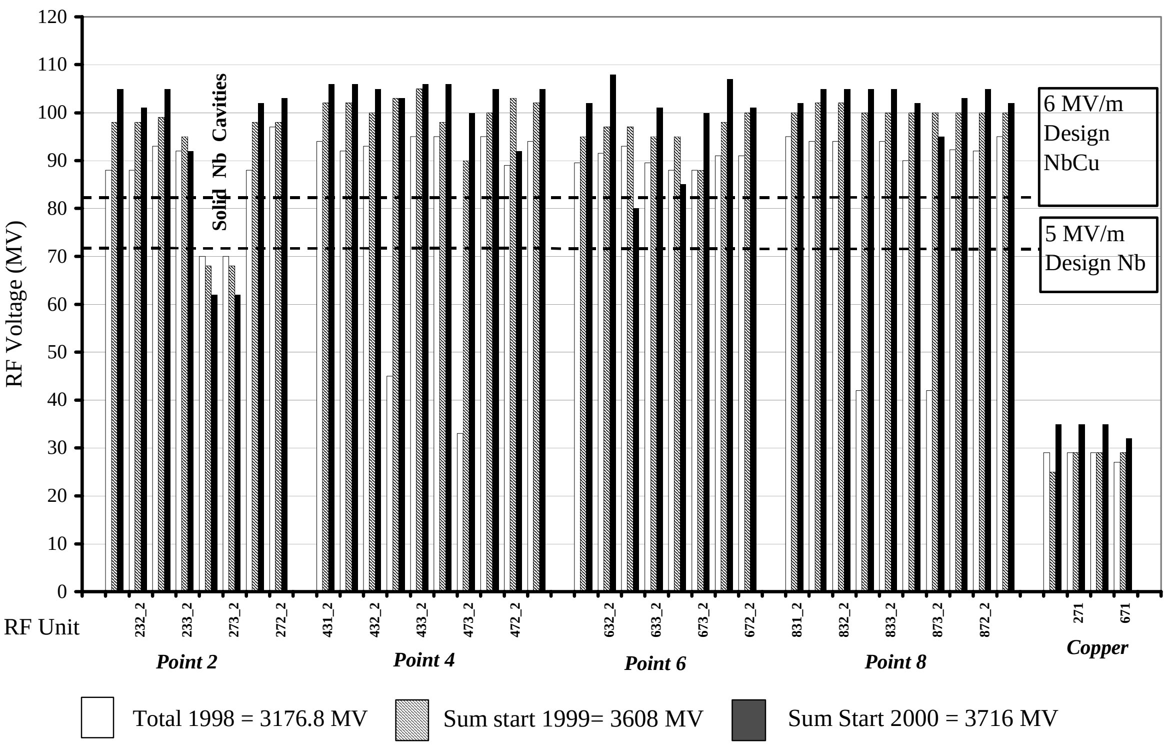


Figure 3: RF unit voltages after conditioning in 1998, 1999 and 2000

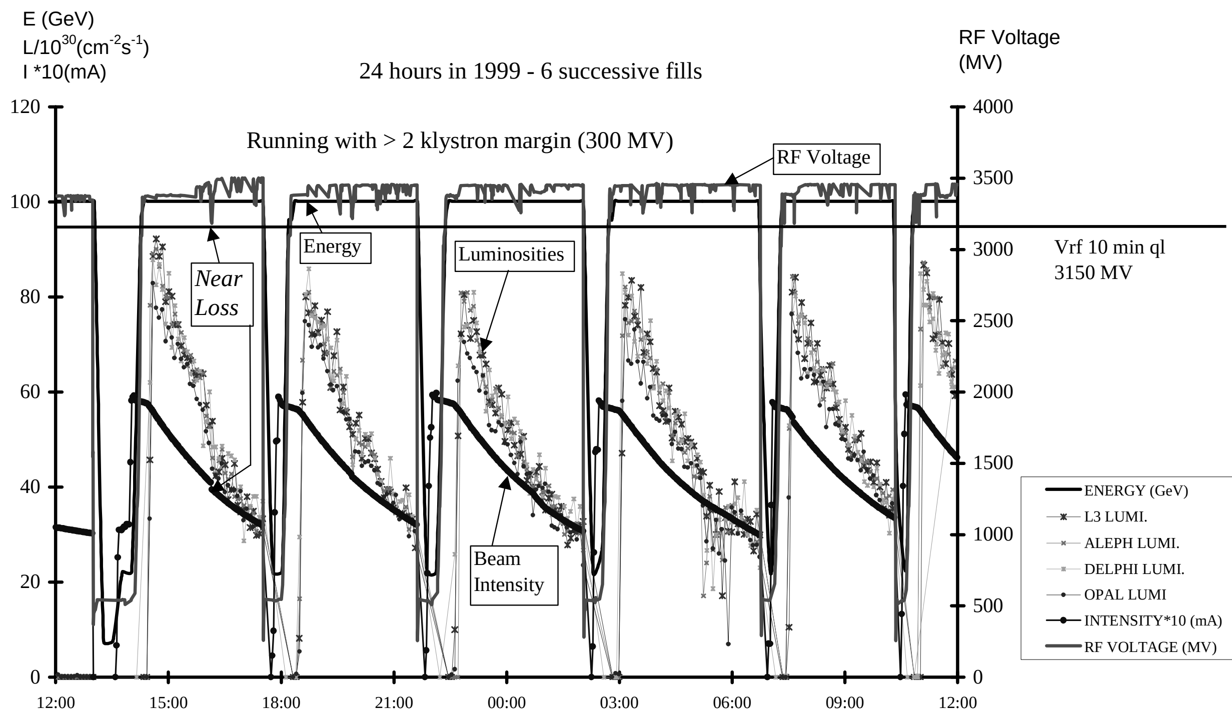


Figure 4: LEP operating cycles in 1999 – 6 fills in 24 hours

The improvements with respect to 1999 also include the gains made during 1999 running. In-situ helium processing was also carried out on severely degraded cavities. Success was limited and the procedure was abandoned because of the high risks involved.

4 LEP OPERATION AT HIGH ENERGY

4.1 LEP operation in 1999

The operating strategy was based on running with an RF voltage margin of two RF half-units. Two half-units could be off at the same time due to trips and the quantum lifetime still be sufficient for no appreciable beam loss in the time needed to switch back on. Initial operation was at 96 GeV with 3120 MV. Over the year the operating RF voltage was increased progressively allowing the energy to rise to 98, 100 and finally 101 GeV. For each energy step the RF system was pushed gradually to that needed for the next step. Running at the new energy then started but with reduced beam intensity. When stable operation was reached at full intensity the voltage was pushed again towards the next energy step. Improvement of the RF voltage was achieved by running at maximum voltage as long and as often as possible and also by cavity conditioning during periods without beam.

The operating cycle for physics is shown in figure 4. This shows several cycles of operation over a good 24-hour period. Around 6 mA total beam intensity was accumulated and accelerated to an “RF stop” a few GeV below top energy. Here any RF system adjustments needed were carried out, e.g. the damping of cavity oscillations. Acceleration then continued to top energy, 100 GeV in this case. After stabilisation of the RF and cryogenics systems the RF voltage was put to its maximum value. If all half-units were available this corresponded to that for minimum quantum lifetime plus the two half-unit equivalent reserve. The beams were put into collision, shown in the figure by the decay of beam intensity due to beam-beam interaction and the production of luminosity in the four experiments. The RF voltage was maintained at its maximum level throughout the coast. When luminosity dropped to a low value the beam was dumped, the magnets recycled and a new cycle begun. A number of RF trips occurred during physics, shown by dips in the total RF voltage. The beam generally suffered no degradation. During the first cycle however, the unsuccessful switch on of one half-unit accompanied by the trip of another caused the voltage to closely approach the quantum lifetime limit. A partial beam loss resulted with a sudden drop in luminosity.

4.2 LEP Operation in 2000

For 2000 running, to obtain physics at the highest possible energies, a new mode of operation was introduced, based on a ‘mini-ramp’ procedure[5] for increasing the energy during the physics coast.

The initial part of the run was as before with a two half-unit RF voltage margin. When the risk of trips following the voltage ramp had diminished, the energy was increased such that the margin was reduced to one half-unit. When good integrated luminosity had been accumulated the energy was increased to the maximum with no RF reserve. Physics continued at this energy till the beam was lost – most often due to an RF trip.

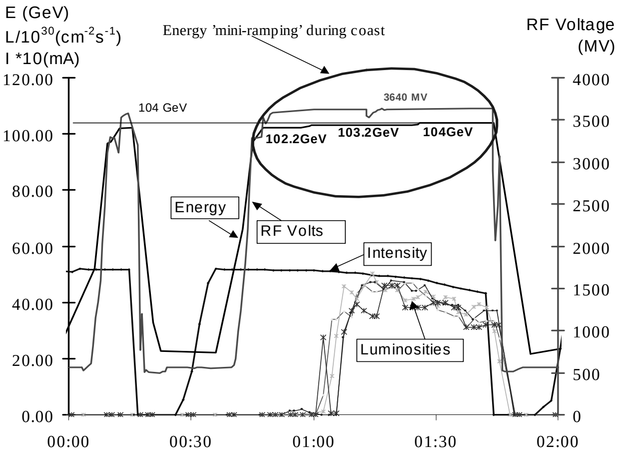


Figure 5: Mini-ramp acceleration in 2000

An example is shown in figure 5. Before going into physics the RF voltage was gradually brought to its maximum level, 3640 MV in this case, where it remained for the duration of the coast. The energy was increased by mini-ramp from an initial safe 102.2 GeV, with two half-units RF voltage reserve, to 103.2 GeV, with just one half-unit reserve. Physics started and luminosity was accumulated over 20 minutes. The trip of one half-unit at this energy (shown by the dip in the total voltage) had no effect on intensity or luminosity. The energy was increased to 104 GeV where it was kept for 16 minutes. At this energy the RF voltage was close to the quantum lifetime limit and the beam intensity decayed more rapidly than previously. The beam was lost two minutes after attempting to go to higher energy still, from the trip of a half-unit.

The mini ramp procedure was tested successfully at the end of 1999. The length of running at each energy was estimated on the basis of maximising the 'Higgs sensitivity' i.e. the mass of a Higgs particle which could be discovered with a 3σ significance based on the overall integrated luminosity, weighted with energy[6].

This mode of operation resulted in physics fills of shorter duration than those in 1999. A typical 24-hour period is shown in figure 6. Practically all of the physics fills in 2000 ended with RF unit trips.

Overall performance at high energy

The integrated luminosities obtained at high energy during each of last two years of LEP running were higher than in any of the previous years, despite the more difficult operating conditions.

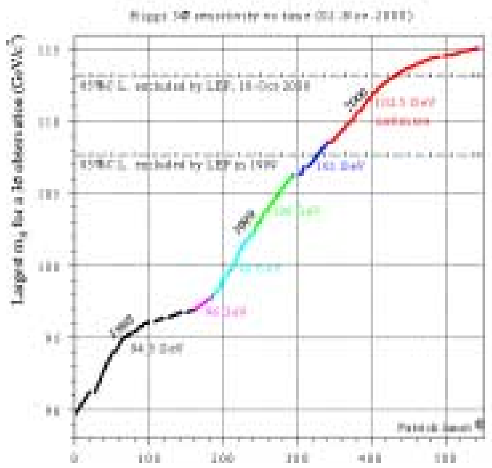


Figure 7: Higgs sensitivity vs. days at high energy

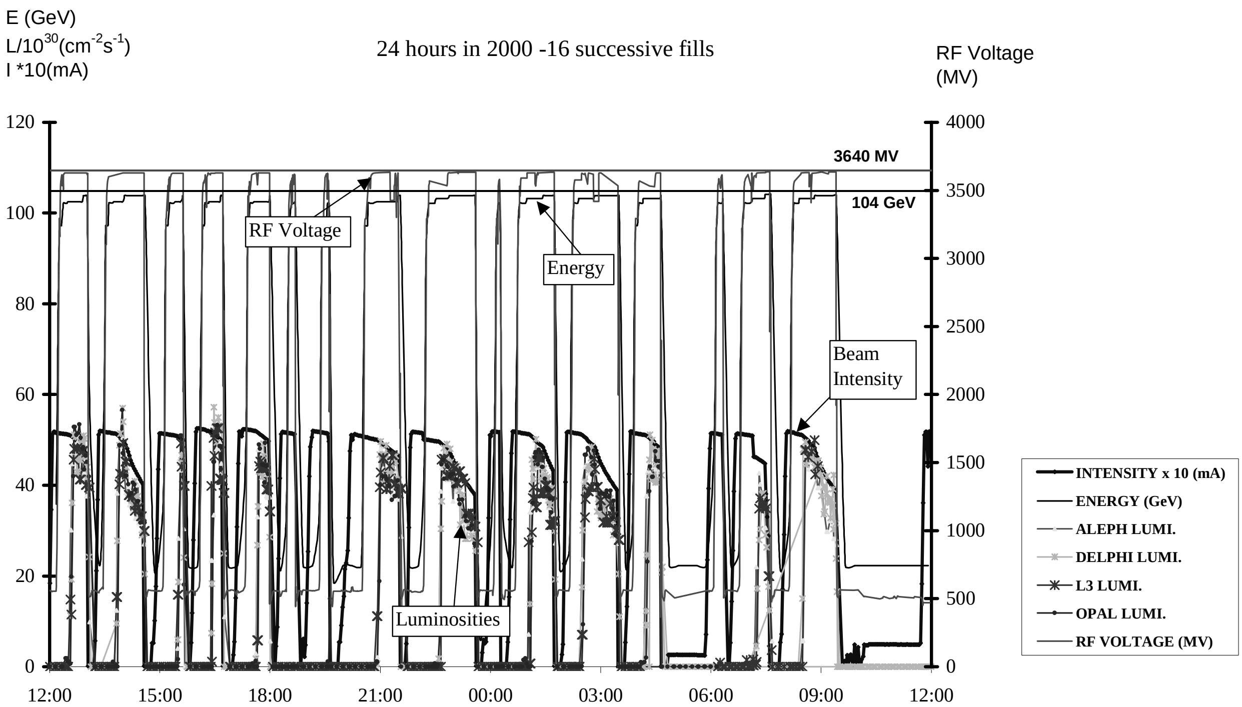


Figure 6: LEP operation over 24 hours in 2000.

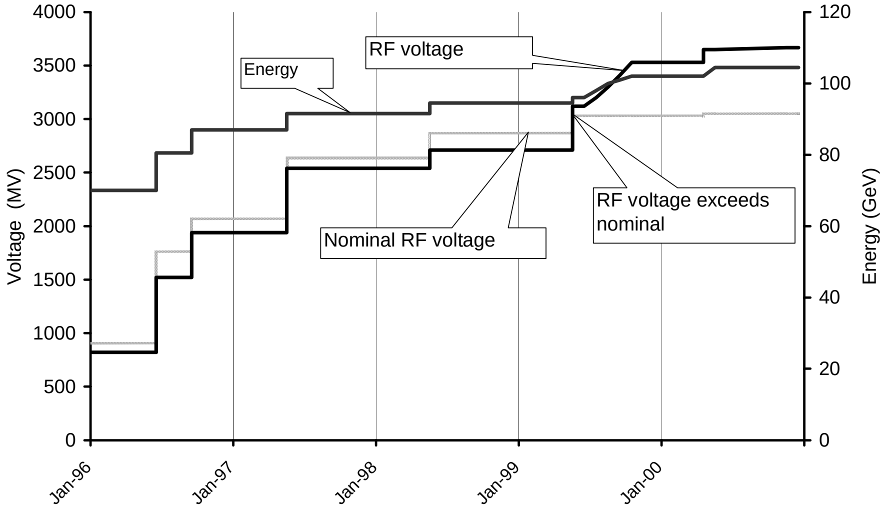


Figure 8: Maximum voltage and energies from 1996 to 2000.

Out of a total 1000pb^{-1} obtained in the 11 years of LEP running 254 pb^{-1} and 233 pb^{-1} were obtained in 1999 and 2000 respectively[7].

Figure 7 shows the evolution of Higgs sensitivity over days of running at high energy. 1999 and 2000 saw large increases. The most optimistic prediction for 2000 running, assuming that 7.5 MV/m could be reached in the NbCu cavities, was 115.5 Gev/c^2. Over 115 Gev/c^2 was reached, just less than 7.5 MV/m having been reached.

The overall efficiency was good thanks not only to the excellent overall performance of the cavities and high power equipment but also to special procedures and facilities introduced to optimise operational efficiency.

The overall evolution of the RF voltage and energy from 1996 to 2000 is shown in figure 8. The maximum energy achieved was 104.2 GeV and the maximum voltage in physics with appreciable luminosity 3675 MV.

5 ACHIEVING AND OPTIMISING HIGH ENERGY OPERATION

While the conditioning of the cavities to the necessary gradients was essential some other limitations had to be overcome for high energy LEP running with beam. Furthermore a number of facilities and special procedures were introduced to optimise operational efficiency.

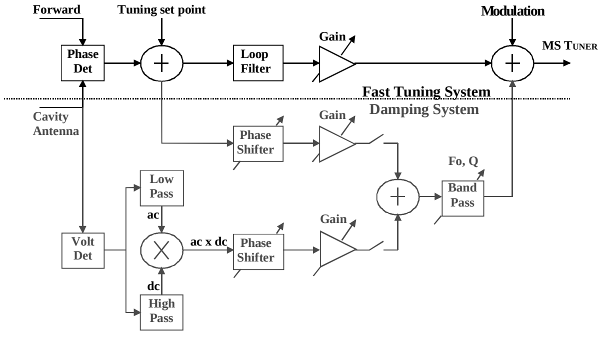


Figure 9: Active damping system to counteract ponderomotive oscillations

5.1 Damping of ponderomotive oscillations

Lorentz detuning resulted in the excitation of a strong longitudinal mechanical resonance of the cavities near 100 Hz resulting in a ponderomotive instability[8]. The growth rate of the instability is proportional to the square of the cavity field and to the tangent of the detuning angle, hence dependent on the beam intensity. During lower energy running this was compensated in a simple manner by introducing fixed offsets into the tuning loop to bring the cavity tune back towards resonance, the values depending on operating conditions. This became more difficult operationally as gradients were pushed higher. To overcome this a narrow-band feed-forward compensating system was introduced into the tuning system[9]. The block diagram is shown in figure 9.

This compensation was introduced on all cavities during 1999. It proved very successful. Even if the compensation on its own was not completely effective for some cavities, stable operation could nevertheless be obtained using tuning offset control procedures that were simpler than before.

5.2 Post-mortem diagnostics

When running at high energy beam loss would produce multiple RF trips, mainly due to helium pressure rise or increase in reflected power. The rapidity of events made the cause of the beam loss difficult to identify. For operation in 2000 a fast post-mortem diagnostics system was installed to allow precise synchronised time-stamping of RF unit trips and beam intensity changes[10]. The system was based on eight local DSP controlled fast acquisition and event recording units, one in each of the eight RF sectors, connected to critical RF control signals and fast beam intensity monitors and synchronised by the Global Positioning System (GPS). The layout of the acquisition system in each RF sector is shown in figure 10. An overall control application armed and synchronised the local acquisition units at the start of each fill. During the run RF unit state changes were logged locally as time-stamped events, together with absolute changes in beam intensity of more than 400μA from the previously logged value. The resolution was 10 μS. At the end of the fill the data was recovered from all the acquisition units, the events ordered and the complete history stored in an ORACLE database for subsequent analysis and display. This system proved invaluable for high energy running.

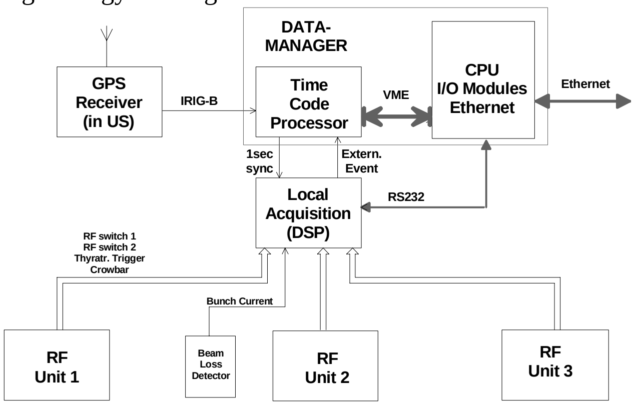


Figure 10: Local data acquisition for post-mortem diagnostics

5.3 Fast cavity detuning after an RF trip

For high energy operation experience indicated that the RF trip margins were slightly less than expected from known voltages and quantum lifetime limits. This could be attributed to the transient residual impedance of cavities that have just tripped but not detuned generating an opposing voltage. The effect of this can be estimated from continuous beam loading theory, the cavity filling time of 1.8 ms being short compared to the tuning response time. Figure 11 shows the reduction in the effective margin as a function of beam intensity. This was not verified systematically but corresponded well to practice.

In order to minimise the effects the cavities were automatically detuned by the maximum amount at the fastest rate allowed by the magneto-strictive cavity tuners.

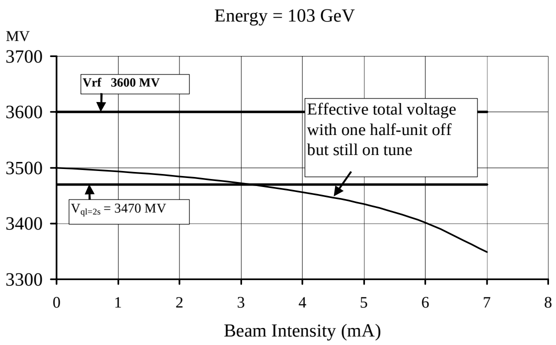


Figure 11: Estimated reduction of effective voltage due to transient residual impedance of tripped cavities

5.4 Automatic back-off of RF unit voltage

The voltage of all the RF units was set by a single RF Global Voltage Control (GVC) system[11]. The GVC controller continuously checked the state of all the units and adjusted their voltages to maintain the desired total voltage. Voltage loss resulting from a unit or half-unit trip was automatically compensated by increasing the voltages of others – if sufficient reserve was available. A very important feature implemented for high energy running was the automatic adjustment of maximum permitted unit or half-unit voltages. Temporary limitations, such as individual cavities out of tune, would be detected by the unit controller and a safe maximum voltage level returned to the GVC controller. When normal conditions were re-established the voltage would be returned to normal. In this way continuous operation with the maximum possible voltage was maintained and trips avoided.

5.5 RF frequency shift

A dedicated application program read the machine energy and the total available voltage from the GVC. If the voltage approached a dangerously low level a negative shift was applied to the RF frequency. For example at 100 GeV a shift of -70 Hz would change the longitudinal damping partition number J_x from 1.0 to 0.6 and produce an effective gain of 23 MV, at the expense of slightly worsened physics background conditions. This small but significant gain, equivalent to a quarter of an SC half-unit voltage, was sufficient to save many beams from being lost when running close to the RF limit.

5.6 Automatic RF unit switch-on

For high energy running the switch on procedure, run locally in the RF unit on request from the control room, was streamlined to provide fastest possible switch on. Additionally the unit controller could be set to switch a unit back on automatically immediately after a trip, if the local diagnostics revealed the cause as not serious. This feature proved extremely useful in operation.

6 MAINTAINING CAVITY PERFORMANCE

Maintaining maximum voltage for physics required sustaining maximum voltages for as long as possible. Stops of longer than a few hours resulted in appreciable time to re-establish the previous voltage levels. With such a large system the daily follow-up of problems was essential, as was the continuous monitoring of performance and reliability. Pushing the cavities to maximum at all times, within very small margins from the trip limit, had a conditioning effect that resulted in gradual improvement in the operable cavity voltages. This together with dedicated conditioning when no beam was available allowed important gains to be made. Improvements in certain cavities were however inevitably accompanied by degradation of others. Slightly degraded cavities could generally be recovered by pushing

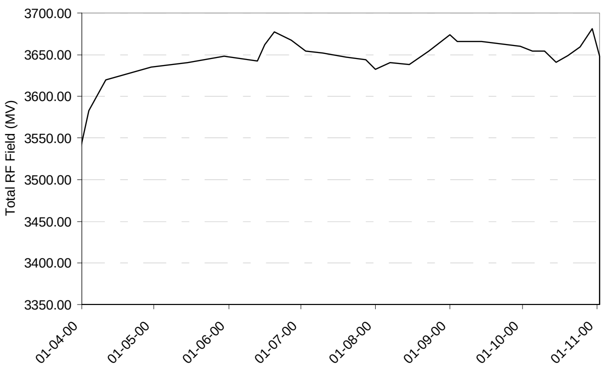


Figure 12: Evolution of RF voltage for physics in 2000.

gradually back to maximum. The day-by-day variation of the maximum voltage for physics in 2000 is shown in Figure 12. The rise was rapid at the beginning of the year then followed an irregular but overall increasing curve. The best period started on 6th September 2000 with a value of 3675 MV. After pushing gradually to this value there was some initial backing off to improve stability but most of the gain was maintained for several weeks.

The distribution of the available voltage in the RF units on the 6th September 2000 is shown in figure 13. The values for conditioning after the 1999 startup are also shown. Most half-units showed substantially increased voltages, however in some cases the available voltages are lower. This is discussed in the following section.

7 CAVITY RELIABILITY FOR HIGH ENERGY RUNNING

7.1 Solid niobium cavities

If the solid niobium cavities were pushed to the point of a quench a high pressure rise and loss of helium would generally interrupt operation of the cryoplant for some time, of the order of 30 minutes to an hour. Subsequent reconditioning of the cavity was a very long process, carrying with it the risk of further quenches. For this reason the niobium cavities were not pushed to out and out limits as were the NbCu cavities and the final operating voltages of the niobium cavities were in fact less than at the start of the high energy running period.

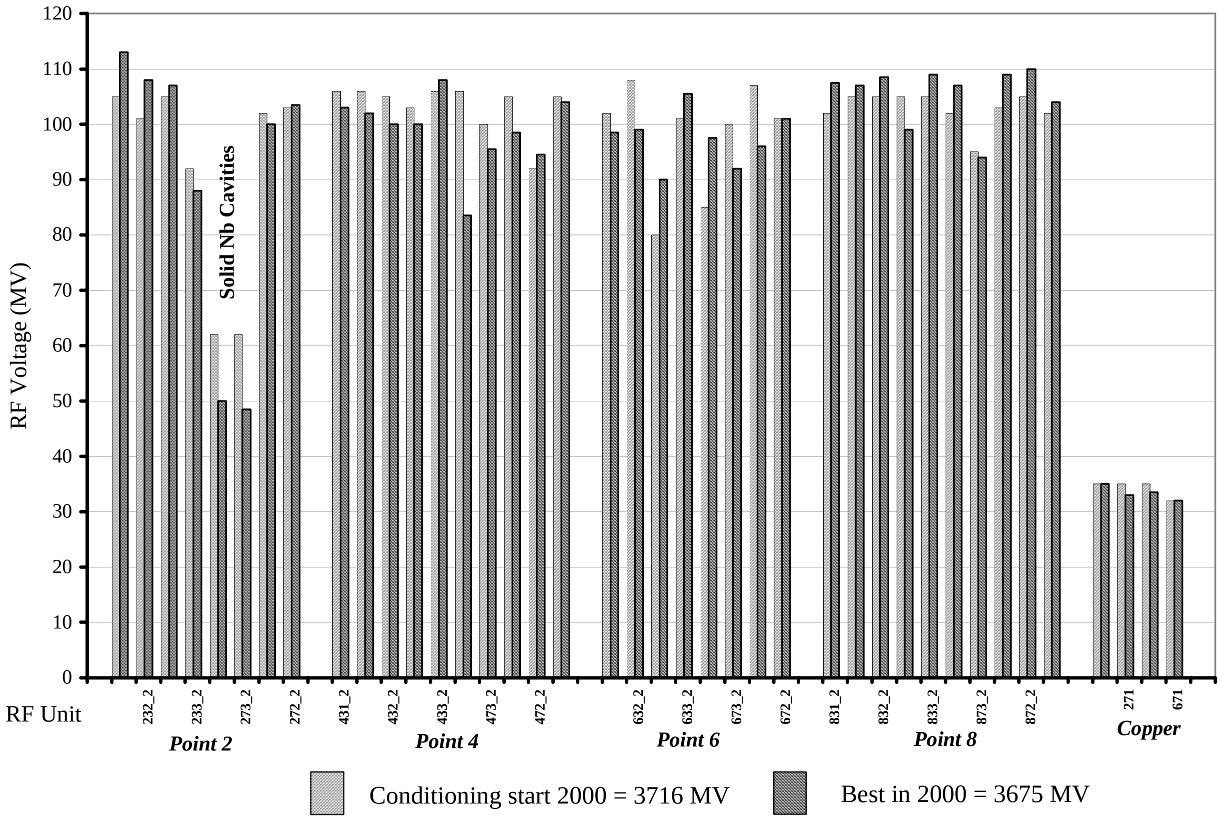


Figure 13: RF voltage distribution on 6th Sept. 2000 compared to maximum levels gained during conditioning.

7.2 Feed-through connections for HOM couplers on solid niobium cavities

A serious problem occurred with these cavities at the beginning of 2000. RF feed-throughs for the HOM coupler cables were found to be corroded to the point where no connection was made to the external loads. The connectors were cleaned with partial success. Unfortunately one coupler remained with no connection to either of its two loads. With beam intensities above 5.5 mA the temperature of cooling gas around the coupler showed runaway. The cavity was therefore left detuned throughout the year. The beam intensity was limited to 5.3 mA and a close watch was kept on HOM coupler temperatures.

7.3 Cavity degradation during operation

Eight cavities degraded during running in 1999. Conditioning and pulse processing recovered three. Four others were partially recovered, but showed higher radiation levels than before, up to around 60 krad/hour at 7.3 MV/m. One cavity – C16 in unit 473, degraded while trying to recover the cavity just next to it (C15) by helium processing. The module was removed for cavity rinsing during the 1999/2000 winter shutdown. The originally degraded cavity had to be recoated. The HOM coupler of cavity 13 in unit 233 was found to be passing fundamental power, possibly due to accidental damage. The cavity was left detuned during the year. An attempt to realign the coupler during the following shutdown was unsuccessful.

During 2000 three cavities suffered degradation. Cavity 4 in unit 473 exhibited frequent changes in sustainable maximum voltage. Conditioning and helium processing were of no avail. The module containing this cavity would have been taken out to rinse the cavity had LEP operation continued. Two other cavities could not be recovered by conditioning and were given small tuning offsets to limit their voltages, allowing the other cavities in the respective half-units to be run normally.

8 RF SYSTEM RELIABILITY

Many improvements had been made to improve the reliability of the system over the years. By 1999 practically all sources of spurious faults had been eliminated by hardware modifications and improvements.

The fault statistics for the RF system in 1999 are shown in figure 14.

Maximum field and RF 'Wattcher' reflection interlocks were the most frequent. Helium interlocks were generally consequences of field emission in the cavities and unavoidable. For 2000 the reflection and maximum field interlock sensitivities were reduced, with no evident increase in equipment damage. In 2000, with cavities running near the conditioned maximum all the time, helium interlocks were dominant.

Figures for klystrons and circulator replacements are given in table 2.

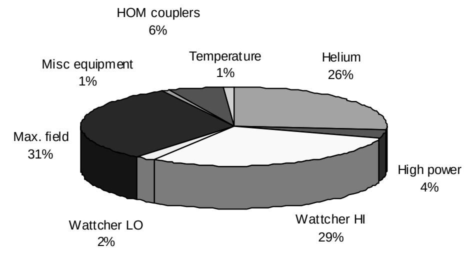


Figure 14: RF faults in 1999– breakdown by type.

Year	Klystrons	Circulators
1997	5	1
1998	6	0
1999	8	1
2000	4	3

Table 2: Klystron and circulator replacements

Although the RF system was run at much higher power than in previous years, 700 kW per klystron compared to 500 kW, the number of klystrons and circulators replaced annually was roughly the same. However running at high power with beam did produce unexpected localised over-heating of waveguides. The reasons are not understood, but from the heating patterns trapped waveguide modes were suspected.

9 REVIEW OF LEP2 SC RF SYSTEM PERFORMANCE

The successful operation of the LEP2 RF system was due in large part to the excellent performance and reliability of the niobium copper cavities. The successful elimination of multipacting by the introduction of a DC bias voltage on the couplers was crucial[12].

While the high power RF system was based on that of the copper cavity system it saw some important changes for SC cavity operation. The use of one klystron for eight cavities, rather than 16 as originally planned, was primarily for power reasons but it made an enormous improvement to operational flexibility. A variable power coupler would have allowed field equality in the eight cavities of one klystron by the adjustment of individual cavity voltages. The choice of coupling factor, B=1000, for the fixed couplers, with matching for a beam current of 12 mA, was somewhat high for the intensities actually used (8 mA maximum). This meant higher than needed forward power but on the other hand the lower impedance limited adverse intensity dependent effects. Many improvements were made on the waveguide system and its components. Accurate waveguide length adjustment played an important role in equalising cavity fields. Both klystrons and circulators proved very reliable.

The cavity tuning system, using thermal and magnetostrictive expansion of the longitudinal nickel bars of the structure supporting the cavity, proved very reliable. The drawbacks arising from long heating or cooling times could be minimised by maintaining close reference values in the absence of beam.

The introduction of active damping to counteract ponderomotive oscillations and the reduction of cryogenics induced oscillations, by small modifications to the cryogenic supply-line transitions, were crucial for performance. Reaching of gradients well above the design values would not have been possible without the cryogenics upgrade. Furthermore without the successful in-situ replacement of all antenna cables in the 1998/99 shutdown[9] the continuation to high energy running would have been compromised.

Hardware and software improvements had to be introduced continuously to improve the system's reliability and facilitate its operation, especially for high energy running. Full remote control, monitoring and diagnostics facilities were vital for efficient operation. The excellent stability and reliability of the RF low power and synchronisation systems were indispensable. Finally, the performance of the LEP RF system surpassed all expectations. The overall reliability of this very large system was surprisingly good. However intervention, maintenance and improvements were continually required.

10 ACKNOWLEGEMENTS

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