Presentation 67

RF Performance

By G. Geschonke

67.1 Introduction

The RF system of LEP 200 will consist of 128 copper and 192 superconducting RF cavities, grouped in 20 RF units, each of these being fed by an RF power plant consisting of 1 MW klystron amplifiers and the RF power distribution network.

In such a complex system it is unavoidable that faults occur. Possible causes for performance reductions due to the RF power plant and the superconducting RF cavities will be discussed.

67.2 Performance reductions

67.2.1 RF power distribution to SC cavities

Sixteen superconducting cavities forming one RF unit are fed - at least in the first phase - by one 1 MW klystron amplifier. The RF power is split by an array of Magic T power splitters down to the level of 62 kW. Therefore all cavities of a unit receive the same input power.

Two factors may limit the performance:

1. The maximum achievable accelerating field. Not all cavities have the same maximum electric field; some are limited at lower field levels than others.
2. Differences in coupling strength..

The coupling factor b (or equivalently the external Q-value, Q_{ext}) is adjusted so as to minimise the the total RF power required for the nominal beam current. The coupling strength is given by the geometry of the coupler, namely by the penetration depth of the antenna. No fine adjustment is possible. The accelerating field achieved in a cavity v_g is determined by :

$$v_g \sim \sqrt{Q_{ext}} \sim 1/\sqrt{b}$$

The cavity which reaches its maximum electric field at the lowest input power therefore limits the performance of the whole RF unit of 16 cavities.

Experience at CERN is available from two four-cavity modules so far installed in LEP. In the following table the measured Q_{ext} and corresponding E-fields are given, calculated for the case where all cavities reach at least 5 MV/m. The fields achieved with the adjusted coupling factors vary considerably.

Module 1				
	cavity 1	cavity 2	cavity 3	cavity 4
Q_{ext} [10^6]	1.8	2.1	2.4	2.2
E-field [rel units]	1	1.08	1.15	1.1
E-field [MV/m]	5	5.4	5.75	5.5

Module 2				
	cavity 1	cavity 2	cavity 3	cavity 4
Q_{ext} [10^6]	3.2	2.95	3	2.26
E-field [rel units]	1.18	1.14	1.15	1
E-field [MV/m]	5.9	5.7	5.75	5

67.2.2 Coupling strength of power coupler

Apart from the effect discussed above, another consequence of poor adjustment of the coupling factor is shown in Fig 67.1. Here is drawn the total RF power necessary to accelerate a current of 6 mA at a synchronous phase of 116 Deg with the cavities running at 5 MV/m, as a function of coupling factor b. ($b = Q_0/Q_{ext}$).

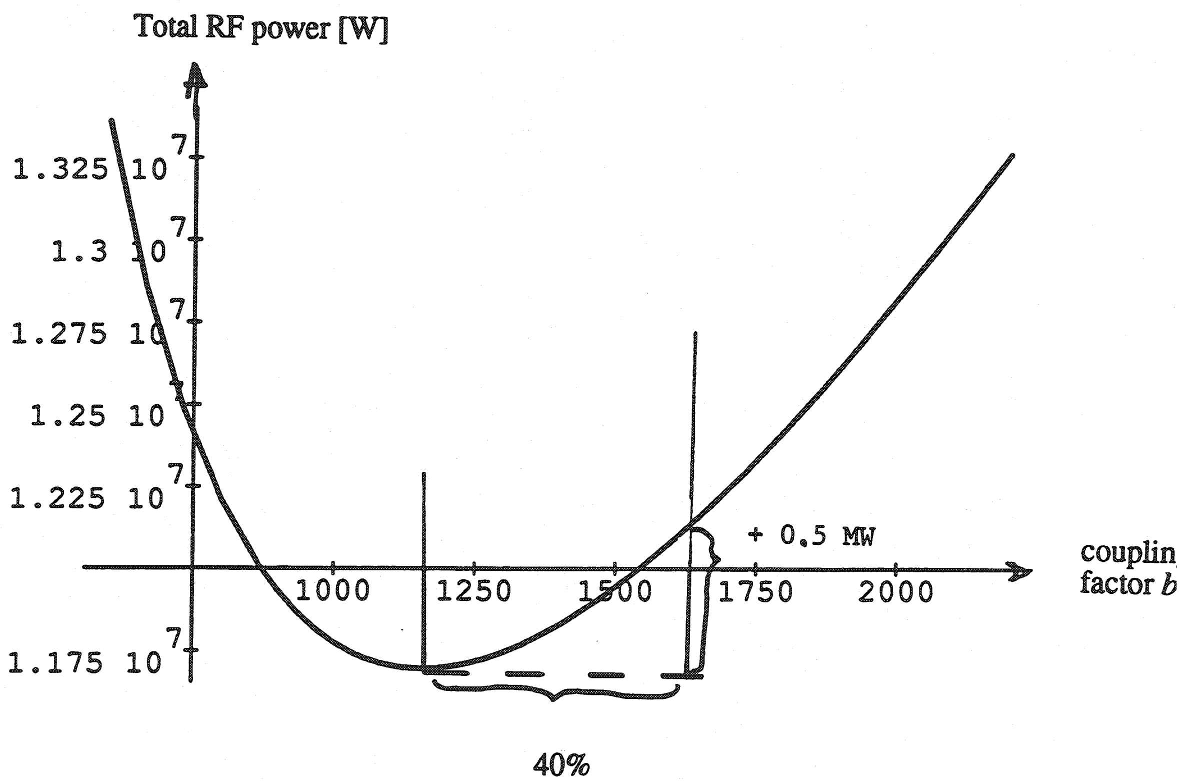

Figure 67.1: Total RF power necessary for 2×3 mA, cavity field 5 MV/m, synchronous phase 116°, as a function of coupling factor

The optimum b is around 1180. If the adjusted value is wrong by 40% , then the total required power goes up by 500 kW. This effect could eventually lead to a current reduction of $\frac{0.5}{10} \times 100\% \approx 5\%$ due to limited installed RF power.

These effects could be reduced or eliminated in two ways:

1. Foreseeing a possibility for adjusting the coupling factor. Two possibilities exist:

   (a) A piston waveguide transformer adjacent to the power coupler's doorknob transformer could be used to adjust the matching. The phase of the cavities has to be kept correct by a suitable position of the pistons.

(b) A moveable antenna of the power coupler would allow the penetration depth to be adjusted in situ. This solution is being pursued by CERN; a prototype is being tested. This solution would completely solve all problems relating to coupling strength.

2. Detuning the cavities individually so that the cavities with the lowest E_{max} are operated outside resonance and therefore are excited to lower fields. This would allow all cavities to be operated at their maximum performance but would not, however, solve the problem of matching to total beam current.
This solution is somewhat undesirable, since it makes control quite complicated, because the cavities will have to be detuned additionally for reasons of Robinson stability.

67.2.3 Trips of the RF power plant

The RF units are very complex installations, consisting of many active components. The failure of almost any of them causes the whole unit to be switched off, and as a consequence the beam will probably be lost.

The main components of one RF unit are :

28 racks of control electronics
4 MW power converter
HV interface with modulator and thyratron crowbar circuit, controlled via optical fibres.
Klystron(s) and driver amplifiers
RF power distribution via circulator and waveguides, handling up to 1 MW cw power flow
16 accelerating cavities including cryostats
RF reference distribution via optical fibres with phase compensation system
Local regeneration of all required frequencies from reference frequencies sent via optical fibres.
Cryogenic plant
⋮

Much of the equipment needs to be protected by a complex interlock system to avoid damage and ensure personnel safety.

The following numbers of interlocks are used for the different systems (per RF unit) :

High voltage interface	13
Klystron	15
RF distribution	18
Cryostats	40
Cavities	64
total number of interlocks	150

In total there will be 12 RF units with superconducting cavities and 8 with copper cavities, with a similar number of interlocks.

Therefore:

- RF trips are unavoidable
- Operation must be possible with one or probably two RF units off
- The working point of LEP in Q-space has to be chosen to be such that enough margin is available for variations in synchrotron tune Q_s due to a trip of one RF unit, without beam loss.

67.2.4 Improvements foreseen

No statistics can be given yet for the number of such trips, because experience gained so far with the copper system has resulted in an improvement programme mainly on high voltage equipment, but also on other systems in order to significantly increase reliability. The new stations being built now will profit fully from this programme.

Work has started on a global RF voltage control system, which in the case of a tripping RF station will automatically increase the power of the others (if possible) in order to avoid Q_s changes.

The loss in circumferential RF voltage in the case of a tripping RF station can be reduced by half, if two klystrons are installed per unit. This might become necessary, depending on the total current in LEP. In this case the RF distribution will be changed so that each klystron feeds only eight cavities instead of 16. The interlock and some other controls hardware have been modified, so as to allow only one klystron to be switched off. However any fault coming from the HV system will still cut the whole unit.

67.3 Fault conditions acting directly on the beam

Contrary to LEP in its initial state, the installation of superconducting cavities made a new type of interlock necessary that dumps the beam.

After a quench detected by the quench detection system via the quench detector proper or the vacuum or pressure interlocks, the RF power going into this cavity is switched off. Under certain conditions it is possible that the beam being kept circulating by the other cavities deposits power into this cavity. This power is dissipated in the liquid He. Therefore the He pressure gauge has an interlock output that activates the beam dump. In the absence of a dedicated beam dump this is done by switching off all RF stations around the ring.

During LEP operation **all superconducting cavities have to be kept cold**, even if they are not driven with RF power. The reasons for this are :

a) The vacuum in uncooled cavities will be very bad, the system being unbaked and pumped only at the extremities of four-cavity modules. One can expect the pressure to be in the 10^{-7} mbar range at best.

b) The cavities are uncooled and thermally very well insulated. The tuning state is uncontrollable, since the thermal tuner depends on the cavities being cold. Therefore the beam induced modes will deposit power in the cavities, which might lead to uncontrolled heating.

67.4 Experience at KEK

KEK so far has the biggest operating superconducting RF system installed in an accelerator. The information I refer to was given to us by S. Noguchi in July 1990. There the energy was lowered to 29 GeV for operation in 1990. The reasons for this were - among others - request from the experiments, but also the desire to leave some margin for safe operation, even in the case of up to three klystrons being switched off. (They had installed then 26 klystrons of 1 MW each for the copper and eight for the superconducting system.)

The average accelerating gradient used for operation was 3.7, sometimes 3.5 MV/m, the maximum 4.7. The maximum fields achieved in the cavities are >6 MV/m for most cavities, going up as high as 8.9 MV/m in the best case. Some cavities however, were limited to much lower fields. The worst one was 4.1 MV/m, five were between 4.9 and 6 MV/m.

A few cavities closest to the arc suffered some field limitation with beam, probably due to effects from synchrotron light, even though no direct synchrotron light can hit the cavities.

67.5 Operating experience with superconducting cavities at CERN

One module of four superconducting cavities has been installed in LEP since beginning of 1990. To make the cavities operational, five machine development sessions of four to five hours were necessary. The first machine development was done on 29.4.1990, where the accelerating field provided by the beam was proven with beam by measuring a change in synchrotron tune Q_s. Acceleration up to 50 GeV was achieved using both copper and superconducting cavities.

All subsequent machine developments were used to improve this performance.

67.5.1 Final maximum performance achieved

- 32 MV during surface tests (4.7 MV/m) before installation in LEP tunnel (The design voltage is 34 MV for 4 cavities corresponding to 5 MV/m).
- 30 MV in LEP (4.4 MV/m) limited by one cavity, which has the smallest E_{max} and also the loosest coupling (reaches highest field first).
- 26 MV/m is considered operationally safe (3.8 MV/m)
- Towards the end of operation the unit was used routinely as integral part of the RF system.

67.5.2 Problems encountered

- Liquid He levels were unstable at first until the right parameters for cooling plant control were found. Among other factors, it turned out that the cavity sum voltage had to be incorporated into the cooling plant control.
- RF trips due to quench indications during accumulation were cured by adjusting the sensitivity of the quench detection system.
- Oscillations of fields in cavities were cured by modifying the parameters of the voltage loop.
- All operating parameters for the klystrons and the associated equipment had to be adjusted, partly, because the gain of several control loops is different from the copper system.
- The correct procedures for switch-on with beam had to be established.

67.5.3 Remaining problems

- The cavities suffer from mechanical oscillations resulting in phase oscillations of up to $\pm 10-15$ degrees.
- Detuning of cavities to prevent Robinson instability is not possible because the phase oscillations trigger the quench detection system if the cavities are excited outside their resonance.
- If the cavities have moved far off resonance, it takes more than 20 to 30minutes for the thermal tuner to bring them back to their correct frequency.

67.5.4 Routine operation during physics runs

From 6.8.1990 until the shutdown at the end of August the first four-cavity module was operational and we tried to use it during routine physics runs as much as possible. No major problems were encountered, there were only some trips due to minor reasons.

67.6 Conclusion

- RF trips will be unavoidable.
- Operation must be possible with one or more RF stations off.
- Two klystrons per RF unit will improve effects of RF trips.
- Variable power couplers are highly desirable.
- All cavities have to be cold all the time
- Experience at CERN is encouraging; the first four-cavity module participated in physics runs, however not to its full specifications.