BEAM RELATED THERMAL LOSSES ON THE CRYOGENIC AND VACUUM SYSTEMS OF LEP

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Abstract

The LEP Collider was operated in 1997 with 60 superconducting four-cavity accelerating modules (about 2600 MV available) installed at the four interaction points. During operation for physics it was observed that the dissipated heat in the superconducting cavities is not only a function of the acceleration gradient, but it depends also on beam characteristics: number of bunches, bunch length and current per bunch. These beam effects have not been foreseen in the original heat budget of the LEP refrigerators. Three days of LEP Machine Development were dedicated in August 97 to clarify the correlation of the losses with the beam characteristics. The beam dependent heat load of the cryogenic system for the superconducting cavities is described. The dependence on various beam parameters is presented, and scaling laws are given. A possible explanation will be presented and the consequence for LEP operation will be discussed.

1. INTRODUCTION

The CERN Large Electron Positron (LEP) Collider is a 26.6km circumference e+ / e- storage ring. The accelerating system consists of 84 five-cell room temperature Cu cavities and of 240 four-cell superconducting (SC) cavities at 352MHz. The SC cavities are operated at the design field of 6MV/m.

Some evidence of an additional beam induced power loss was seen on the cryogenic system and when investigating the LEP impedance related to the bellows. A systematic measurement of warm bellows temperature along the beam pipe [1] and in between the cryo-modules showed that the power deposited in the bellows placed near the RF modules is higher than expected from their loss factor. This heating is higher near RF modules and decreases with increasing distance from the RF modules. Since the cold inter-cavity bellows are of similar shape, special attention was given to the effects of this additional power loss on the cryogenic system [2]. The measurements done show similar results (see Fig. 1).

Preliminarily assumption, attribute the losses to the Higher Order Modes (HOM) escaping from the SC cavities through the beam pipe. The use of ferrite absorbers mounted between the modules to trap the HOM circulating inside the beam pipe did not reduce the cryogenic losses despite an absorbed power higher than 1 kW (80.5 GeV, 8 bunches, total beam current 5 mA and bunch length 10 mm) [3][4].

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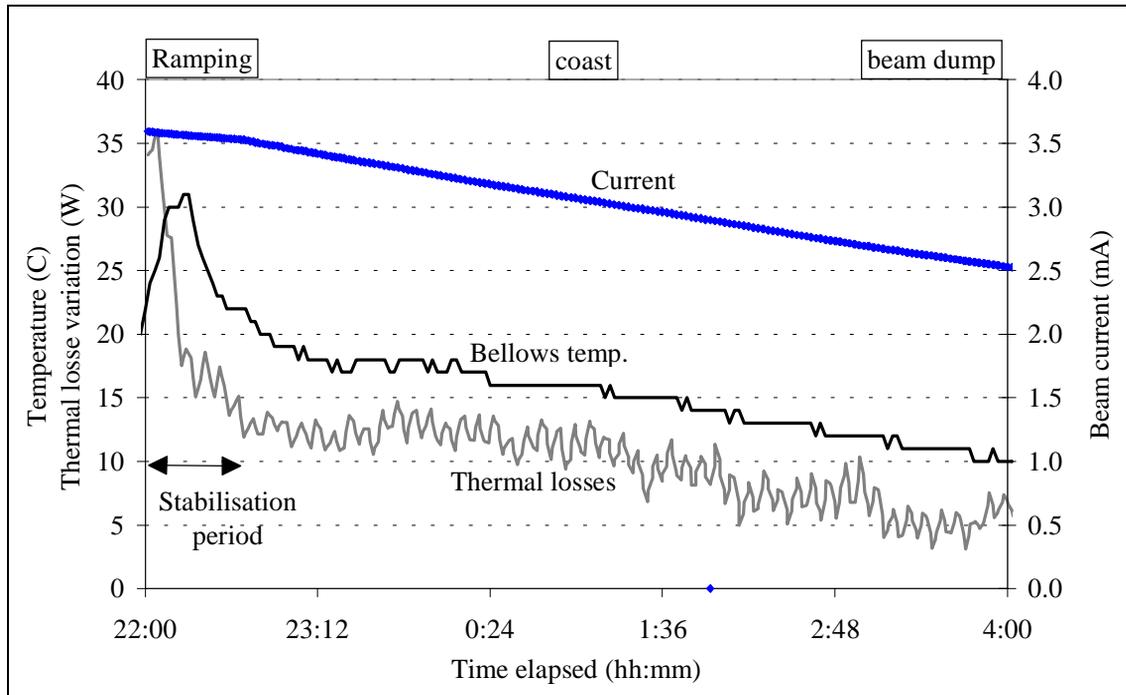
Figure 1: Variation of Cryo Losses and Warm Bellows Temperature as function of Beam Current.

Investigations of the beam related power load for the cryogenic system started at the end of the 1996 LEP running period [5]. Since this unexpected effect can limit the future performance of LEP, extensive measurements were done as soon as stable beam conditions were available in 1997 in order to establish the dependence on the beam parameters and to understand the origin of this effect.
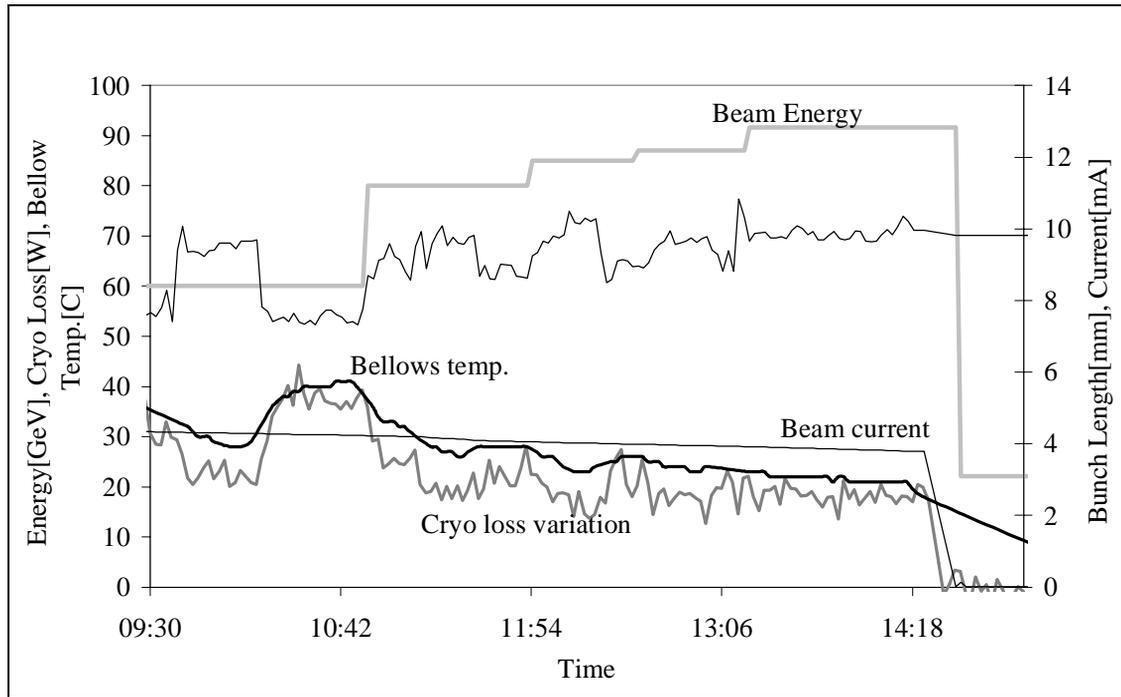
2. MEASURED PARAMETERS

Measurements directly related to the cryogenic loss in the modules will be discussed as well as data collected on warm vacuum bellows mounted between the cavity modules will be presented to confirm the similarity of the mechanisms of power losses (see Fig. 2).

2.1. Cryogenics

Two methods are available for the measurement of the cryogenic power:

a) The opening of the outlet valves of the He return line from the 4-cavity modules depends on the total power dissipated in the modules, as described in [5]. During the 1997 commissioning the calibration of these valve positions were refined on all modules, in order to allow the thermal load variation to be measured. The total cryogenic consumption of a cavity consists of the static losses, the dynamic RF losses, the electric heater power and the beam dependent losses. Reliable measurements of the beam-induced power can best be obtained under conditions where the electric and RF power are kept constant.

b) The cryogenic plants have a reservoir, called "pot", in which the level of liquid He is kept constant by means of electric heating. The power of this heater is a measure of the available spare cryogenic power. A measurement of this electric power can thus be used

to determine changes of the cryogenic power load with varying beam parameters. This gives the integral consumption of all modules of a whole LEP point.

Figure 2: Effect of the beam parameters on the cryo losses and the temperature increase of the warm bellows.

Both measurements depend on the stability of cryogenic conditions; the relaxation time after load changes is of the order of ½ - 1 hour for the first method and 2 hours for the second. Results obtained with these methods can therefore only be compared at least 2 hours after establishing stable conditions. The accuracy of these measurements is estimated to be not better than ± 20 %

2.2. Cold Inter-cavity Bellows temperatures

The temperature of some of the normal conducting cold bellows inside the cryostats was logged during all measurements, as described in [5].

2.3. Bunch length

This year a systematic on-line measurement of the bunch length was available during all our measurements [6].

2.4. Warm Vacuum Bellows

The warm bellows are mounted between the cavity modules to interconnect the vacuum pipes. The shape of these bellows is similar to the one of the inter-cavity bellows. Thermocouple probes where installed on these bellows which where thermally insulated to estimate the power dissipated on these structure. The same bellows but far away from any

modules was also equipped to measure the contribution of the beam itself [5]. In total, more than 40 bellows temperatures were measured in LEP in April 1997.

3. MEASUREMENTS

Systematic measurements were done in order to answer the following questions:

How does the cryo load depend on?
- circulating beam current
- bunch length

Does the cryo load depend on?
- cavity accelerating gradient
- beam energy

Module position
- bunch train bumps
- synchrotron radiation

Measurements were done with one beam of positrons with 8 equally spaced bunches, no bunch train bumps, total current up to 4.5 mA. Some modules were always run at maximum gradient, some were left idling without RF.

In the first session, the beam was ramp up to 91.5 GeV with intermediate stops at 60, 80, and 85 GeV. At each plateau we tried to adjust the bunch length σ to between 9.7 and 10 mm by changing the total RF voltage and the RF frequency, and allowed the cryogenic conditions to stabilise.

In the second session, we tried to measure the effect of bunch length, which was varied by switching off wigglers at 45 GeV, and again by varying RF voltage and frequency. At 45 GeV the bunch length σ was varied between 5.5 and 13.3 mm, at 87 GeV between 9.2 and 13 mm.

In a third session, we measured the current dependence at 80 GeV and at 60 GeV. These measurements were complemented by data taken during normal physics coasts.

4. RESULTS

4.1. Influence of synchrotron radiation from bunch train bumps or from the arcs

At 91.5 GeV the collimators at IP4 (Interaction Point) were fully opened and later bunch train bumps were introduced into the previously flat machine. Fig 3 shows as an example the valve positions measured on one module running at constant field of 40 MV. No effect can be seen anywhere of either of these two experiments. Therefore synchrotron radiation shining into the modules appears not to have an effect on the cryogenic heat load.

### 4.2. Influence of circulating beam current

Many measurements were done with different beam currents. An example is shown in Fig. 4. These data were taken during a physics run with a bunch length of between 11.5 and 12.1 mm. The additional cryogenic heat load due to the beam was measured for most of the modules at IP 4. The two solid lines give the average over all measured modules, and the heat load measured using the previously described "pot" heating. Both measurements are in fairly

good agreement. The discrepancy at high beam currents at the beginning of the fill is due to instabilities in the cryogenic plant after the ramp.

The beam-induced power dissipated by module varies from module to module, between 1.3 W/mA^2 and 3 W/mA^2. The average over the measured modules gives 1.7 W/mA^2, the average "pot" power gives about 2 W/mA^2. In order to compare different bunch configurations, an impedance Z can be defined in analogy to the loss factor, such that the beam induced cryogenic power P_{bcr} can be calculated for any configuration of k_b bunches/beam with a bunch current i_b, and n_b circulating beams. :

$$P_{bcr} = Z * n_b * k_b * i_b^2$$

All measurements in this paper were done with 8 bunches in either one or two beams, therefore for convenience most of the time the power normalized to $i_{tot}^2 = 1$ mA^2 is given, with i_{tot} being the total circulating beam current. A power of 2 W/mA^2 corresponds to Z=16 MΩ per module.
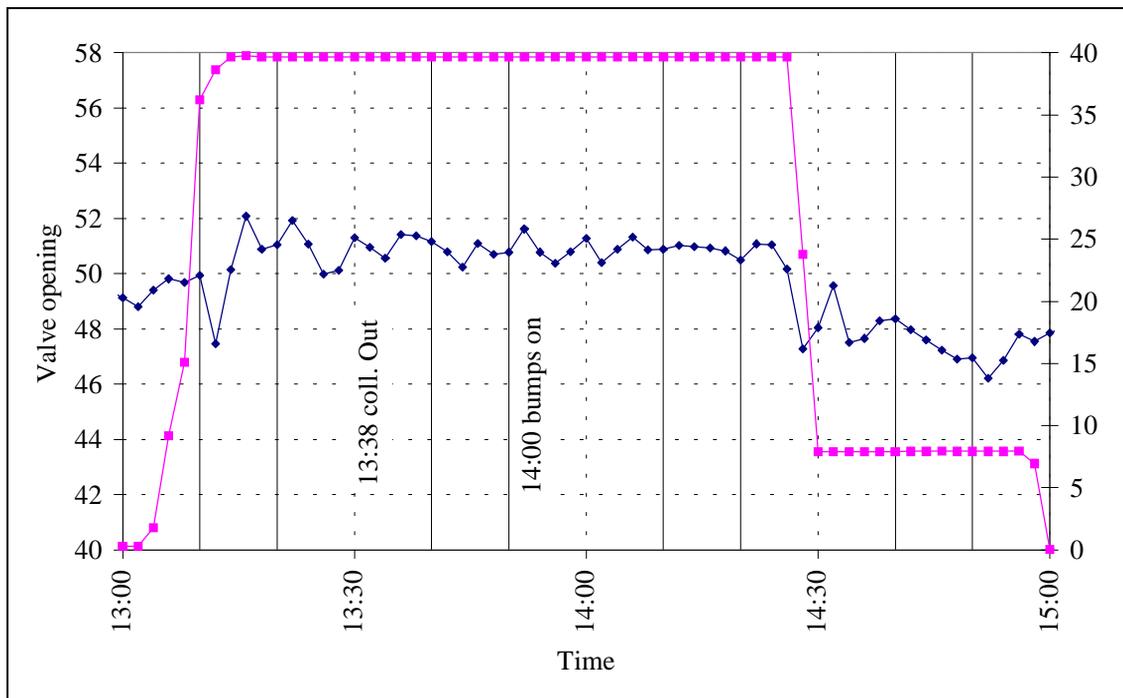
Figure 3: Valve positions during stable running. The valve positions, i.e. the thermal load, did not change when all collimators were moved out, nor when bunch train bumps were introduced.
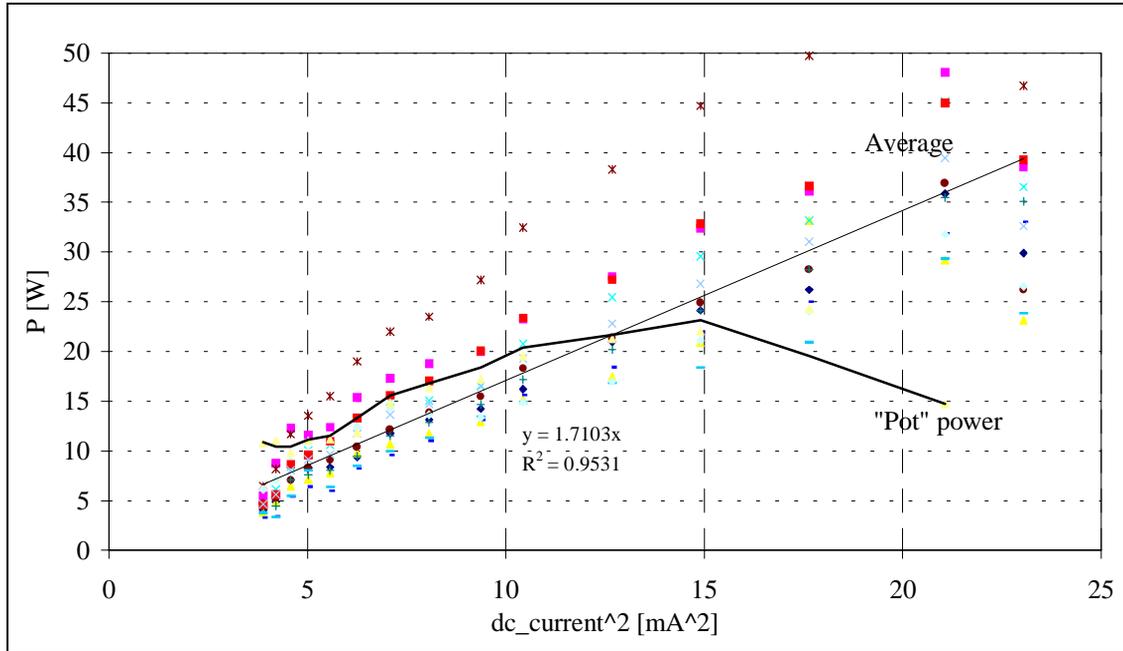
Figure 4: Cryogenic heat load due to the presence of beam. The points were measured using the valve positions of most of the during physics at 91.5 GeV. The solid lines give the average over all measured modules and the power consumption derived from the spare capacity of the cryo plant. The bunch length was measured to be between 11.5 and 12.1 mm. The "Pot" power line above 15 mA^2 and the module measurements above 24 mA^2 are perturbed due to stabilisation of the cryo plant after the ramp.
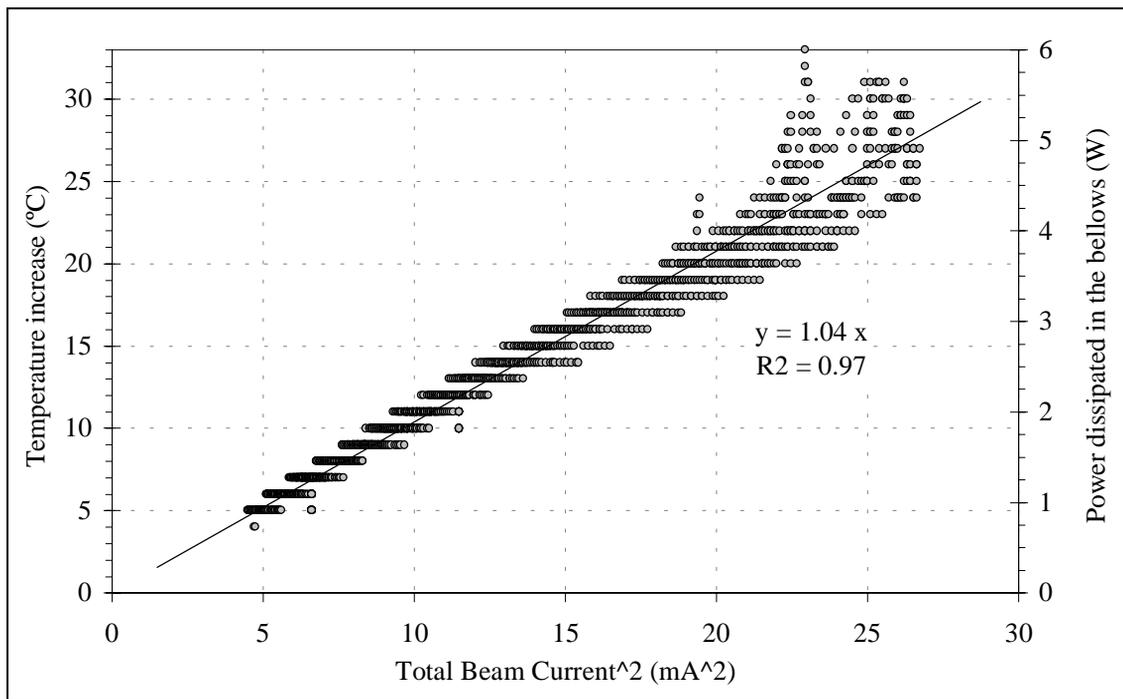

Figure 5: Quadratic dependence of the temperature increase of the warm bellows placed between two cavity modules with the beam current. Estimation of the equivalent power dissipated.

The quadratic dependence of the temperature increase of the warm bellows placed between two cavity modules with the beam current is shown in Fig. 5. An estimation of the power dissipated can be obtained by an in situ thermal calibration of the bellows.

4.3. Influence of bunch length

Many measurements were done with different bunch lengths at different energies. Fig. 6 shows as an example the power (normalized to $i_{tot}^2=1$ mA^2), measured using the valve positions. These measurements include all energies between 22 and 91.5 GeV. The data don't show any energy dependence. Measurements were done at similar bunch lengths at different energies.
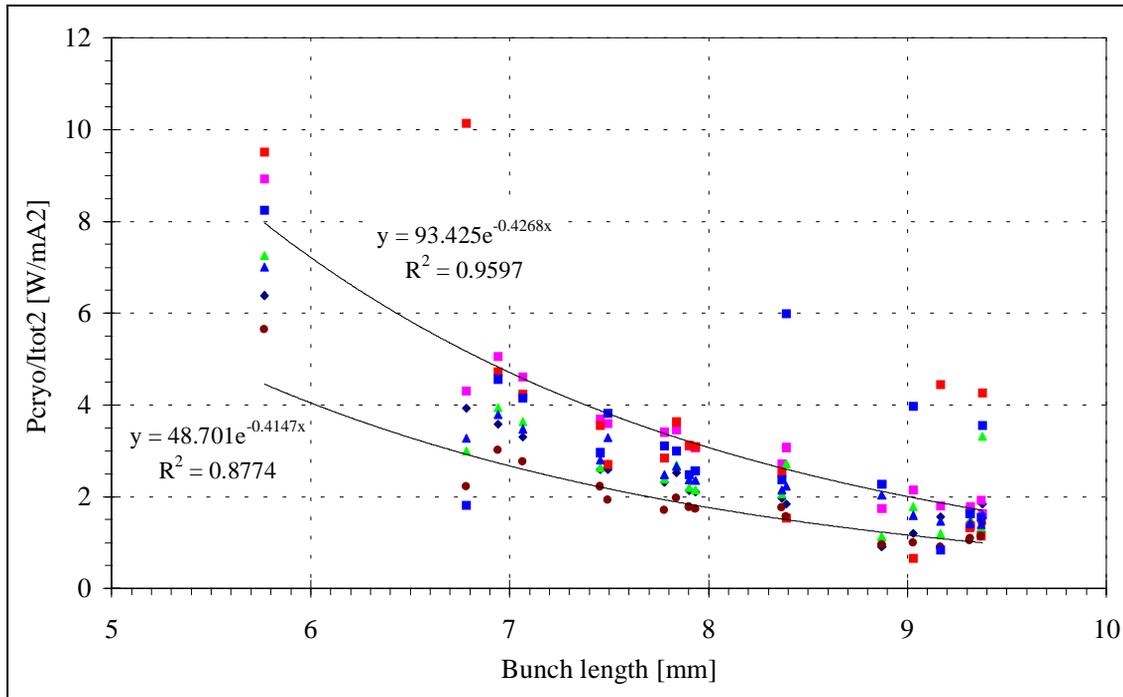

Figure 6: Beam induced cryogenic heat load at IP6 as function of bunch length. Eight equally spaced bunches of positrons were used.

In Fig. 7 the cryo load due to the beam is shown for modules not driven with RF, as a function of bunch length. The data don't show a dependence on beam energy. Measurements of the global consumption using the "pot" of the cryo-plant were taken at the same time. They give at 45 GeV 7W/mA^2 for σ=5.5 mm and 1.9 W/ mA^2 for σ=9.5 mm per module, in agreement with the data shown in Fig. 7.

Fig. 8 shows the dependence of the temperature increase of the warm bellows placed between two modules when decreasing the bunch length. This figure which contains the data collected at different energies, confirm both the exponential bunch length dependence of the losses and the lack of correlation with beam energy.

Further measurements will be carried out since these components which can be equipped easily, reproduce the power deposition mechanisms observed in the inter-cavity cold bellows.
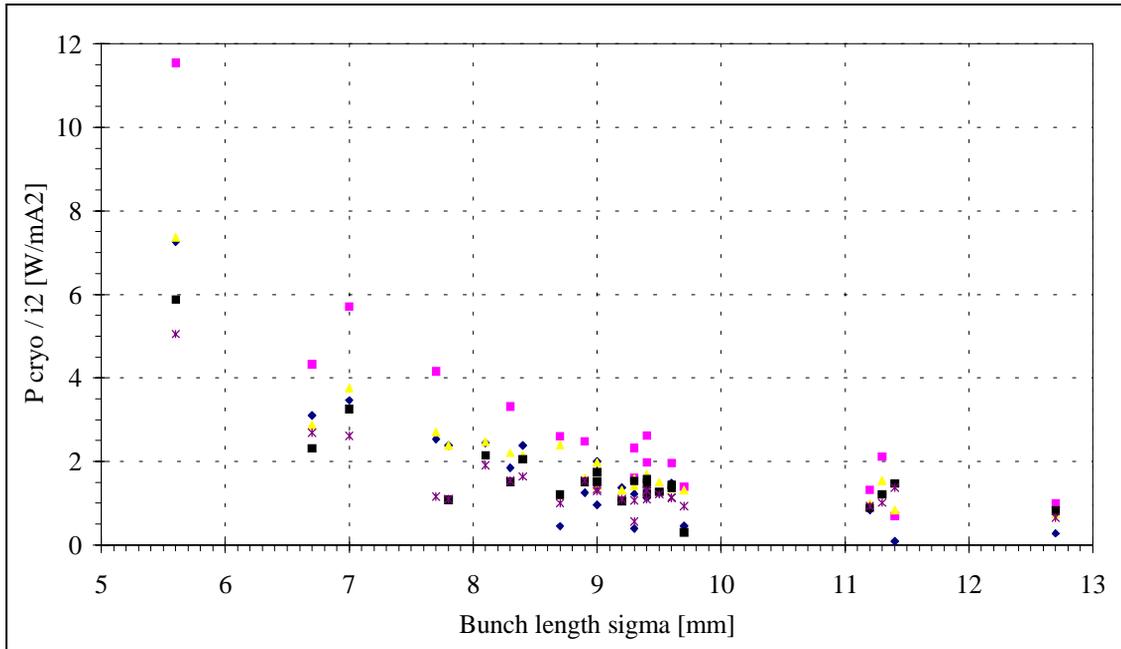
Figure 7 Beam induced cryogenic load measured on modules without RF. Eight equidistant bunches of positrons were used. The data were taken at energies of 45, 60 80, 87, and 91.5 GeV.
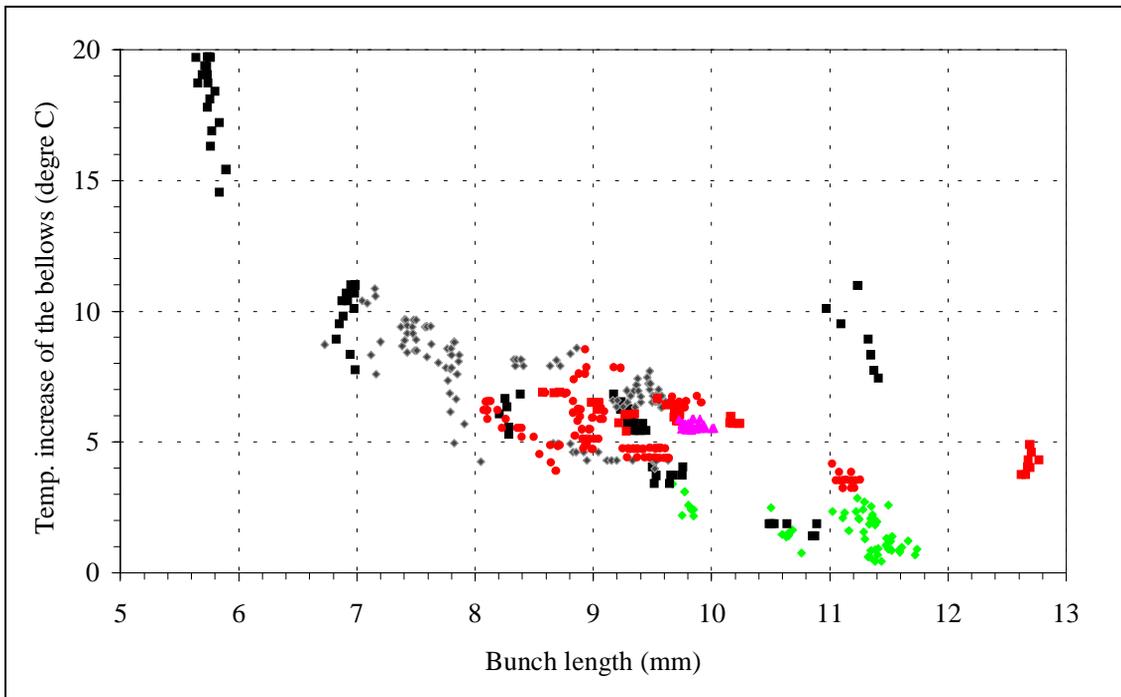
Figure 8: Variation of the temperature increase of warm bellows at different energy when decreasing the bunch length (45, 60 80, 87, and 91.5 GeV).

4.4. Both beams

A series of measurements was done with both beams with four bunches each, at 60 GeV. The modules were driven at constant field of 35 MV. Again the power deposited by the beam at a bunch length of 9 mm was 1.9 W/mA^2, measured using the valve positions. No difference can be seen compared to the experiments with only one beam of positrons.

Also the measurements taken during physics, as shown earlier, show no significant difference to the conditions with only one beam.

5. TEMPERATURES OF COLD (NORMAL CONDUCTING) BELLOWS

In order to allow alignment and thermal movements, the four cavities in a cryostat module are separated by 3 bellows of 193 mm aperture, 62 mm warm length and undulations with 7 mm depth and 3.1 mm width. Two bellows of the same geometry are mounted to the ends of the first and the last cavity before the conical transitions to room temperature. The only normal conducting components of the beam vacuum inside the cryostat are these five bellows and the transition cones. Cryogenic temperature gauges are installed on the cold inter-cavity bellows of some modules, as described in [5]. It is assumed that all the power deposited in the bellows and detected by a temperature rise is finally dissipated in the liquid He bath and thus contributes to the overall cryogenic consumption. The computed loss factors of a complete four-cavity module and of the five bellows of a module [7] are in Fig. 9 and Fig. 10

5.1. Influence of Synchrotron Radiation etc.

During the test described in 4.1 no temperature variation was detected.

Figure 9: Loss factor a complete 4-cavity module [7]

**Figure 10:** Loss factor of the 5 bellows alone [7]

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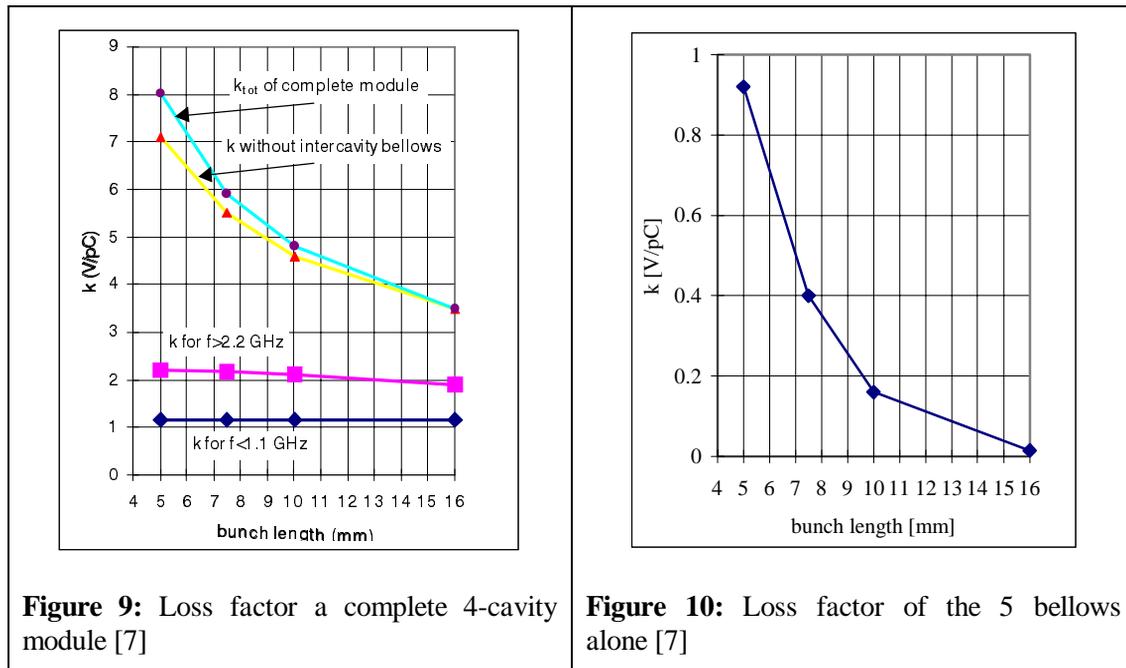
5.2. Temperature dependence on beam current

The temperature dependence on beam current during a normal physics coast is plotted in fig.11. The dependence is linear in i_{tot}^2.

5.3 Dependence on bunch length

Having determined that the temperature is linear in i_{tot}^2, all the temperature data vs. bunch length have been normalized to 1 mA^2. Temperature data at various beam energies and bunch lengths are plotted in Fig. 12. These show a single relationship on bunch length, irrespective of the energy.
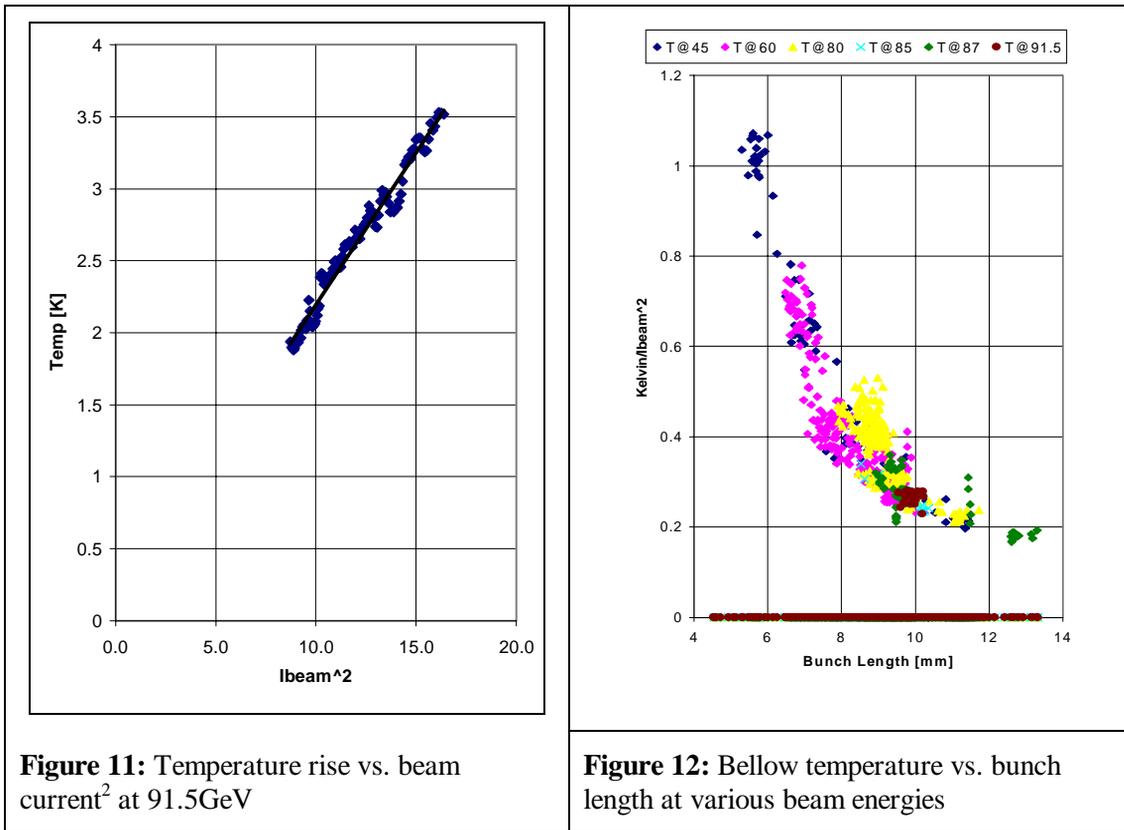
Figure 11: Temperature rise vs. beam current^2 at 91.5GeV

Figure 12: Bellow temperature vs. bunch length at various beam energies

6. CONCLUSIONS

Not all measurements taken could be presented here. The conclusions are:

- The beam deposits additional power P_{bcr} into the cryogenic system, with a large spread between individual modules. The reason for the differences is not understood yet, however, the loss factor of the bellows, strongly depends on the exact bellows geometry. The power measurements done with two independent methods agree within the errors in cases, where both measurements are available.

- P_{bcr} scales with the square of the beam current.

- P_{bcr} is strongly bunch length dependent. Above 9-10 mm bunch length the slope levels off and operation above 9 – 10 mm is recommended, above which the impedance Z is 16 MΩ at the most.

- No dependence of P_{bcr} on beam energy, collimator positions and bunch train bumps was seen.

- No dependence on operation with one beam or both beams was seen.

- The additional cryogenic losses can be explained by power deposited in the normal conducting parts of the cavity system. Temperature increase measured on cavity bellows show exactly the same behavior as P_{bcr} . The loss factor calculated for the bellows could explain the power deposition.

- Upgrading of the cryogenic installation therefore is essential, especially in view of operation at higher gradients (>6 MV/m). In fact, the additional power losses, estimated to be close to 50 W per module at 6 MV/m and 5 mA, are no longer negligible compared to the 280 W of the dynamic RF loss.

Acknowledgement

References

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