THE RF SYSTEM AT INJECTION AND RAMP

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Abstract

With the RF voltage and intensities used in 1998 and following interventions during the 1997/98 shutdown no serious problems were encountered due to cavity field spread at injection. However it can be estimated that with an additional 16 cavities and possible higher intensities for 1999 cavities in certain RF units will be prone to tuning problems if the field spreads are not improved. Measurements made and possible remedies will be presented. The RF configuration during the ramp will be discussed, including the limiting conditions for the second Robinson instability.

1 INTRODUCTION

The LEP RF system is made up of half-units, i.e. groups of 8 cavities driven by common klystron. Pairs of half-units share a common klystron HV power supply to make up an RF unit. RF power is fed from the klystron to the individual cavities through a relatively complex waveguide system. Large field spreads during accumulation and at high energy are seen in certain half-units. This becomes critical with high current at injection, where there is high beam loading and the synchronous phase ϕ_s is close to 180 degrees. The main factors contributing to field spread are imperfections in waveguide hybrids and loads, tuning errors, Q external variations and phase errors between cavity and beam which can arise from waveguide length differences or alignment errors.

2 FIELD SPREAD DURING ACCUMULATION

Examples of the evolution of field spread with increasing beam current at injection are shown for four different half-units in figure 2, for the same physics fill where 6 mA was accumulated. The first plot shows the field spread during accumulation in half-unit 472_2. This corresponds roughly the to the 'average' unit during accumulation. Note that the RF voltage (amplitude) control loop adjusts the klystron forward power to maintain a constant total RF voltage. Half-unit 831_2, shown in plot 2, has one cavity in which the field goes to zero. In this situation the cavity can detune, since there is no cavity field reference. However shortly after the start of the ramp, when additional RF power is applied, the cavity recovers and follows the ramp. In half-unit 832_2, shown in plot 3, one cavity has gone to zero field, has completely detuned and does not follow the ramp. A good example with relatively little spread during accumulation is half-unit 471_2, shown in plot 4.

Field distribution with very high beam current (8.3 mA injected with 8 bunches on 8) is shown for the four LEP RF points in figure 3. The field spreads are very large. The most serious effects occur when the cavities become detuned from the ideal reference. This is indicated by either zero field where the cavity has detuned completely from resonance or very high field with high reflected power where the cavity is too close to resonance and is driven by the beam to produce large returned power. For Point 2 (plot 1) this can be seen to be the case for cavities 2 and 4 of half-unit 233_1. Here a total RF voltage greater than the reference value is produced even though the loop has reduced the klystron forward power to zero. In this situation the voltage seen by the beam is negative and the correct synchrotron tune will not be maintained. The situation for Point 4 (plot 2) also shows large field variations and detuned cavities in some units. Point 6 (plot 3) shows significantly better field distribution and no mistuned cavities in the 3 units that were running (Unit 673 was off for RF interventions during this test). Point 8 (plot 4) again shows large differences and mistuned cavities.

3 SOURCES OF FIELD SPREAD, MEASUREMENTS AND REMEDIES

3.1 Imperfections in Waveguide Hybrids and Loads

A simple representation of the waveguide power distribution system is shown in figure 1.

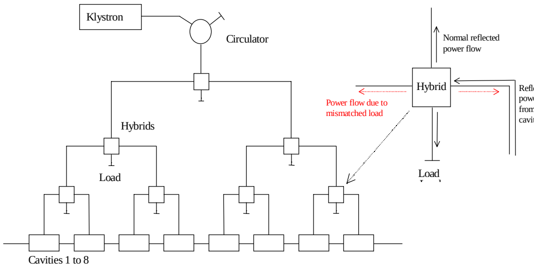
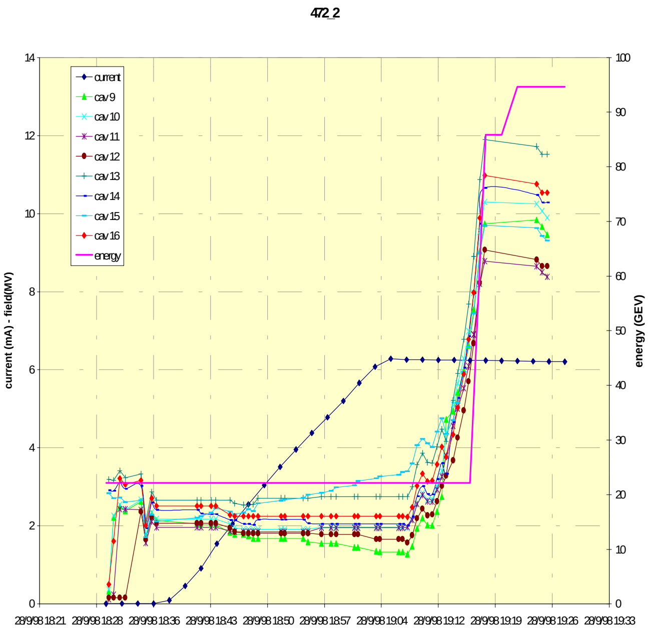
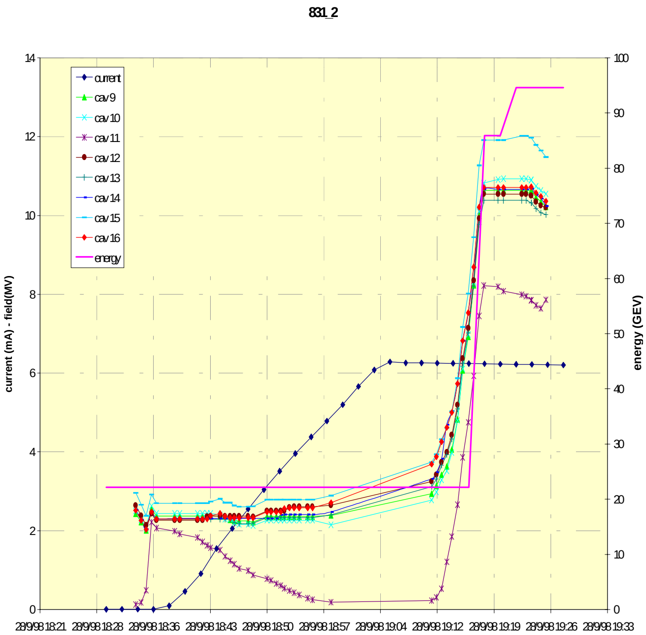


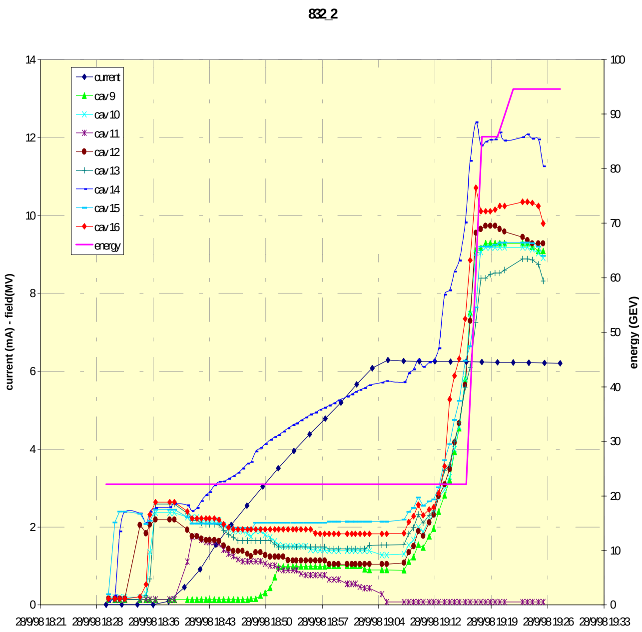
Figure 1: Distribution of Power in the RF Half-Unit



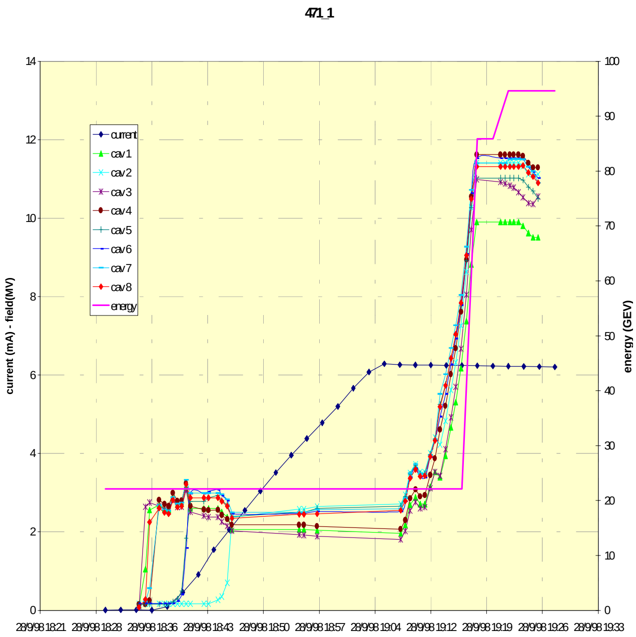
Plot 1)
Unit 472_2 Showing average spread



Plot 2)
Unit 831_2 Showing detuning of a cavity with recovery during ramp

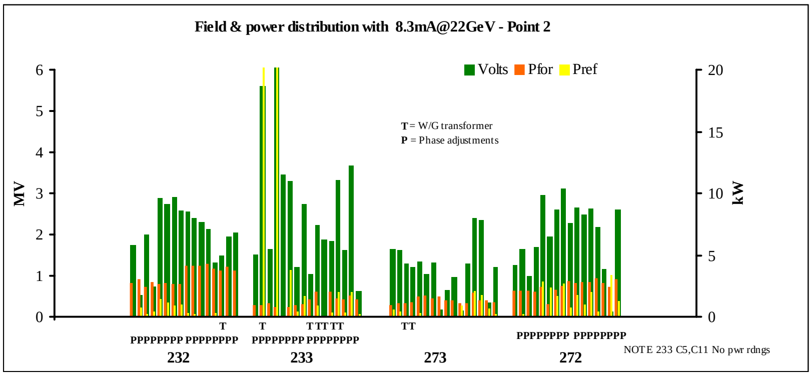


Plot 3)
Unit 832_2 Showing detuning of cavity without recovery during ramp

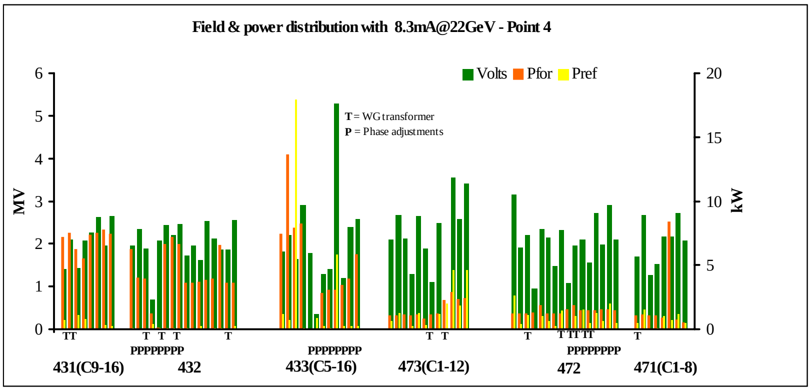


Plot 4)
Unit 471_2 showing low field spread

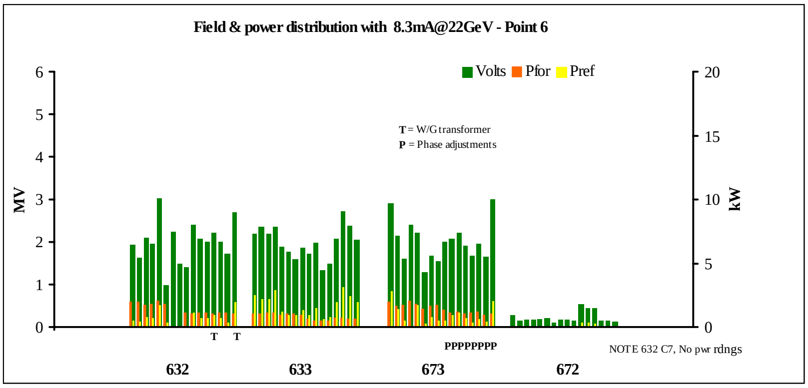
Figure 2: Examples of Field Spread during Accumulation



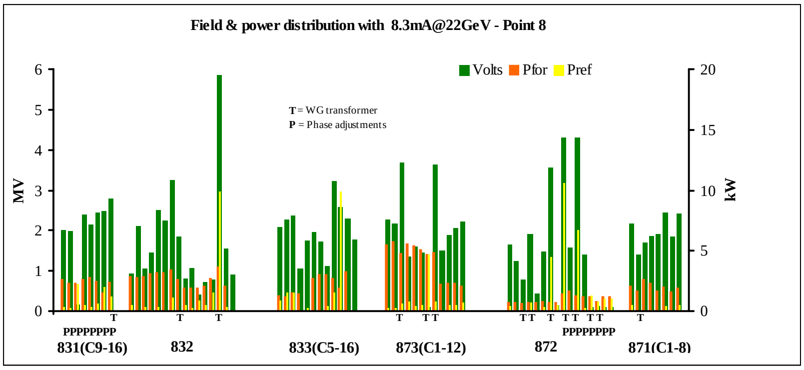
Plot 1) Point 2 Distribution - Large field variations and detuned



Plot 2) Point 4 Distribution - Large field variations and detuned cavities



Plot 3) Point 6 Distribution - Moderate field variations and no detuned



Plot 4) Point 8 Distribution - Large field variations and detuned

Figure 3 : Field Distribution with 8.3 mA at injection. Vrf=510MV

Forward power is normally split evenly by the magic tees out of the side arms. Any returned power from the cavity is split evenly between the load and the input waveguide. If the load is not correctly matched power will be reflected through the two side-arms, back into the cavity and into the neighbouring cavity. This causes power imbalance and cavity field inequalities. The power splitting has been measured for all the magic tees and is relatively good. However the loads have relatively high return losses of about -16dB. An improvement in the return loss characteristics of the load of the order of another –10dB can be obtained with the use of salt water instead of demineralised water. This requires a special cooling plant and has been installed at point 8 for tests.

3.2 *Tuning Errors*

Tuning errors are critical at injection with high beam loading. The vector diagram representing the cavity voltages and currents is shown in figure 4.

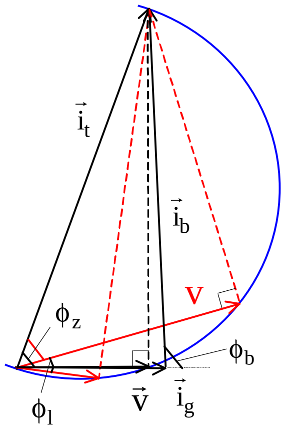


Figure 4 : Cavity Voltage Vector Diagram for High Beam Loading at Injection

The total current $\vec{i}_t$ in the cavity is the generator component $\vec{i}_g$ plus the beam component $\vec{i}_b$ The resultant RF voltage V follows a circle given by $R\vec{i}_t \cos\phi_z$ where ϕ_z, the angle of the complex impedance, is controlled by the tuning system. For optimal tuning the system keeps the RF voltage in phase with the generator current. Any difference from this is considered as a non-zero loading angle ϕ_l. The cavity impedance angle ϕ_z is large with high beam loading at injection (around 75 degrees for 8mA at 22GeV and 510MV RF voltage from 272 cavities) The figure shows that in this situation small errors in ϕ_z can produce big errors in the RF voltage. Tuning errors can result from several causes:

1) *Setpoint errors and tuning faults.*

These can occur due to wrong manipulation of setpoints and hardware problems.

2) *Waveguide reference directional couplers.*

The forward power reference for the tuning system is taken from a directional coupler on the waveguide near the cavity. Bad alignment of the coupler or poor matching of its terminating load will result in partial coupling to reflected power and incorrect measurements of the phase of the forward power. Alignment of the directional coupler loop is checked where problems are suspected. The existing loads have a relatively poor return loss specification, typically –15dB to –20dB. New loads with a return loss of –30dB are presently being installed for all cavities. This should provide a significant improvement.

3) *Unit Phasing*

This is critical with high beam loading at injection. Referring to figure 4 it can be seen that moving the unit phase such that the angle ϕ_b decreases below the point $\phi_b < \pi/2$, part of the RF voltage is produced by the beam. The voltage loop will reduce forward power and for $\phi_b = \phi_z$ no forward power remains for the reference. (This situation would correspond to a unit phase error of 15 degrees in the example of figure 4)

The above effects can be cumulative. The high reflected power from detuned cavities will produce additional field spread and may consequently cause other cavities to become detuned. Because of the risk of provoking cavity field oscillations adjusting cavity setpoints to equalise fields or compensate these effects is impractical. (This may however become an option when the active damping system described by P. Brown in contribution 6.3 of this workshop is implemented). A possible solution to complete detuning of cavities would be to inhibit tuning when reference signals become too low. This would avoid having to wait for long periods for cavities to retune and can be done by software. However these cavities would then produce full reflection and still affect the resulting field distribution in the remaining cavities.

The preferred solution is to try to maintain correct tuning operation, correct unit phase and eliminate other sources of error such as Q external differences between cavities and waveguide length differences.

3.3 *Qexternal variations*

The spread in the effective shunt resistance of the cavities due to differences in the individual power couplers and their assembly tolerances means that different cavities will produce different voltages for the same forward power. The relative spread can be measured from the cavity voltages without beam. For cavities with either very high or very low fields a $\lambda/4$

transformer plate is inserted in the waveguide near the cavity to transform the waveguide impedance seen by the cavity through the coupler. This is described by J. Sladen in presentation 6.4. This operation will be done on approximately 40 cavities during the 1998/99 shutdown.

3.4 Measurement of Cavity Phase Errors Using the Beam

Correct tuning of all cavities must be first verified without beam The procedure is done at injection with 4mA beam current on all cavities of a particular half-unit. With the klystron on open loop, i.e. constant forward power, the unit phase is varied and cavity voltages, forward power and reflected power are measured, averages being taken over a few readings. The individual cavity phase error corresponds to the phase offset for which voltage and powers with beam correspond to those without beam. This is valid since since ϕs ~ 180 degrees.

A typical plot of the results obtained (Half-unit 232_2) is shown in figure 5 and the resulting relative phase differences estimates are shown in figure 6.

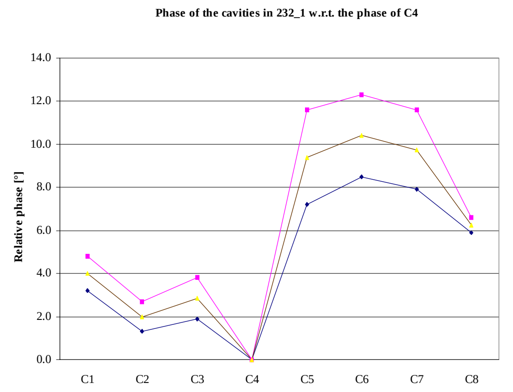


Figure 5: Voltage and Power vs. Unit Phase

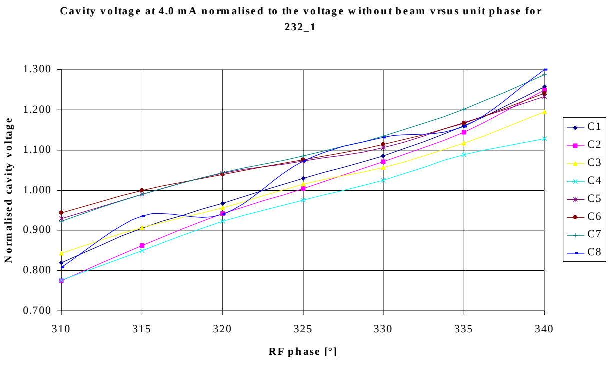


Figure 6: Estimated Relative Cavity Phases

The whole process requires many measurements but is easily automated. During an MD in 1998 10 half units were measured.

3.5 Electrical Measurement of Waveguide Length Differences

Waveguide length measurements and corrections are being made in certain units during the 1998/99 shutdown. All cavities in the half-unit are measured at the same time. The final waveguide bends nearest the cavity are replaced by transitions and loads. A test signal is applied before the first magic tee and phase is measured at the load on the transition for each cavity in turn using a vector voltmeter. Where necessary compensation is done with flexible guides and λ/4 spaced posts. A large amount of work is involved in dismantling and reassembling the waveguide components and it only possible to do a limited number of half-units during the 1998/99 shutdown. Certain half-units with the largest errors have been selected for measurement and correction based on measurements of field spread during injection as well as on the previously described MD measurements. Half-units in which λ/4 waveguide plates are being installed must also be done since these plates will alter the effective waveguide length. In total 16 half-units are being done. Most of these are at Point 2, where there are 7. At the time of this workshop these have just been completed.

The results of the measurements can be compared with estimates obtained from beam measurements. As a further check estimates of phase difference from the field distribution with high current can also be compared. The latter however, is based on the assumption that differences are purely due to RF phase errors and are not introduced by the tuning nor by the factors described previously which can affect the tuning. This comparison is shown in figure 7 for the units of Point 2.

All measurements and estimates indicate large errors (up to 15 degrees) between the two modules of the half-unit, corresponding to length differences between the two longest waveguide stretches. The waveguide measurements indicate relatively small errors between individual cavities. The beam measurements indicate somewhat larger differences between cavities, however these measurements can be influenced by other factors such as tuning errors or reflected power crosstalk. Now that the waveguide length differences have been corrected the beam measurements can be repeated during the next running period and re-compared.

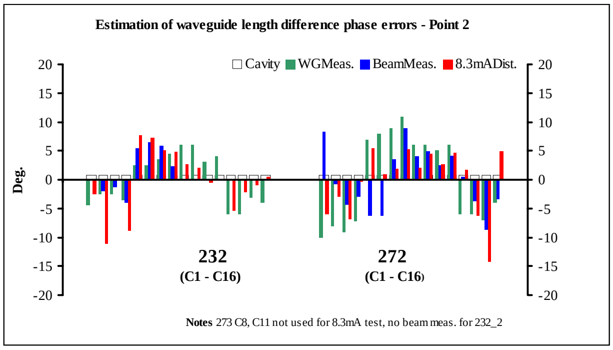


Figure 7: Comparison of Relative Phase Errors from Waveguide Measurements, Beam Measurements and High Intensity Field Spread

4 BEAM LOADING RELATED INSTABILITY AT INJECTION

During 1996 running a beam loading related instability was observed at injection. The effect was a limitation on the current which could be injected accompanied by noise around the synchrotron frequency on the beam longitudinal spectrum. The onset was strongly dependent on the levels of beam loading. This is shown in table 1. The levels are compared to that of the second Robinson limit. The value NR2Limit tabulated is the value of $Y \sin 2\phi_z / 2\cos\phi_s$ which is unity at the second Robinson limit. This can also be expressed in terms of $\alpha = \phi_s - \pi/2 - \phi_z - \phi_1$ which the difference in the beam phase from the generator phase. At the second Robinson limit $\alpha = 0$. For different cavity configurations the 1996 limitations occurred at different currents but all corresponded to very similar values of NR2Limit and α. However this limitation was NOT observed during the high injection intensity carried out in 1998, even with high values of beam loading with NR2Limit approaching unity and α becoming small.

5 RF SYSTEM DURING THE RAMP

5.1 Cavity Setpoint Manipulations

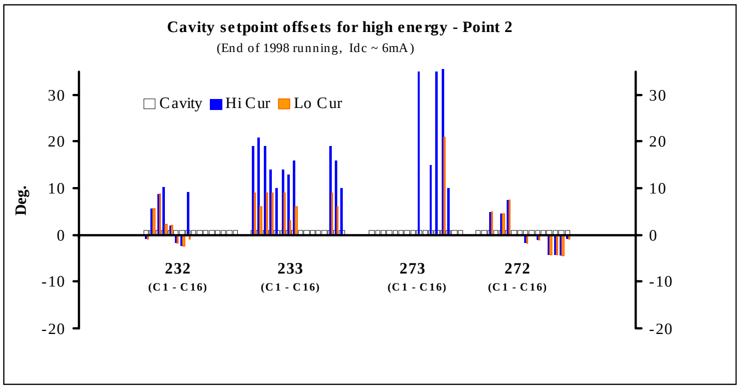
At present the only means of reducing cavity oscillations with high cavity field and high beam currents is by changing cavity setpoints. The values needed depend strongly on field and current. If good damping is obtained for a given field and a given current large oscillations can start to occur as soon as field or current changes. The problem is compounded by the effects of crosstalk through the waveguide system and coupling has also been seen through the beam. Recent encouraging progress which has been made with a new damping system inside the tuning loop is described in presentation 6.3. For the moment, however, setpoints have to be changed in a large number of cavities, both during the ramp and for high beam currents at the end of the fill when the current has decayed. Manual or automatic methods are used to find suitable values and the values are stored as nominal values locally in the equipment. This is described in presentation 6.1. Plots 1 to 4 in figure 8 show the setpoint offsets from the resonance values for the four RF points. It can be seen that there is a large variation in the amounts of offsets required, some cavities needing very large offsets and some none at all. It is interesting to note that for the units at Point 6 many large offsets are required, whereas Point 6 units showed the least irregular field distributions. It is to be expected that the problem of adjusting setpoints will become much more serious as beam currents are pushed upwards. Further sets of nominal values may have to be switched in during the ramp.

5.2 Robinson Second Limit During the Ramp

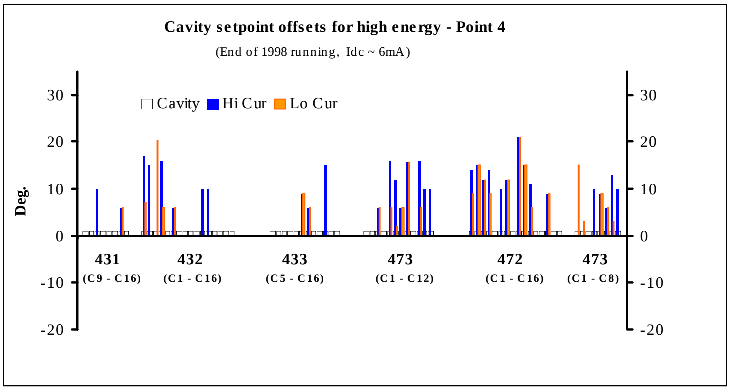
During 1998 running the SC cavity antenna cable power limitation required that RF voltage be kept as low as possible during the early part of the ramp in order keep bunch lengths long. With certain ramp functions used during early running unexplained beam losses occurred part way through the ramp at an energy around 65GeV.

Machine Configuration	Current	RF Config	NR2Limit	α (deg.)
1996 90 deg Optics - 260 MV [1996]	3.2	144 SC	0.78	21.00
	6.2	72 SC	0.76	21.50
1996 108 deg Optics - 450 MV [end 1996]	6.4	176 SC +120Cu	0.90	17.10
	6.9	176 SC +120Cu	0.89	16.60
	7.2	160 SC	0.88	17.70
	7.6	176 SC inc.52 VS+ 120SC	0.86	18.70
1996 102 deg Optics - 510 MV [1998]	8.3	272 SC	0.95	12.20

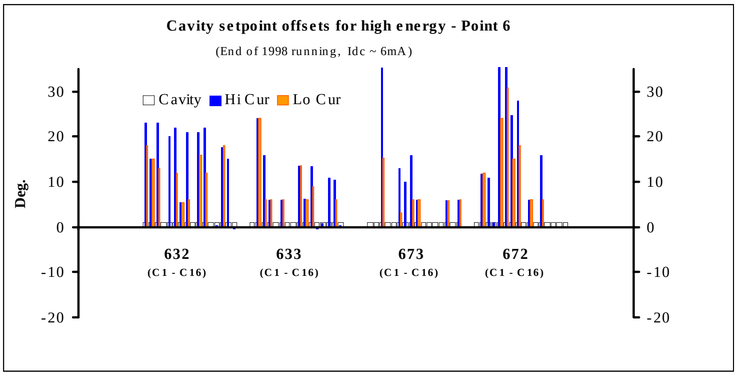
Table 1 – Limiting Beam Currents at Injection



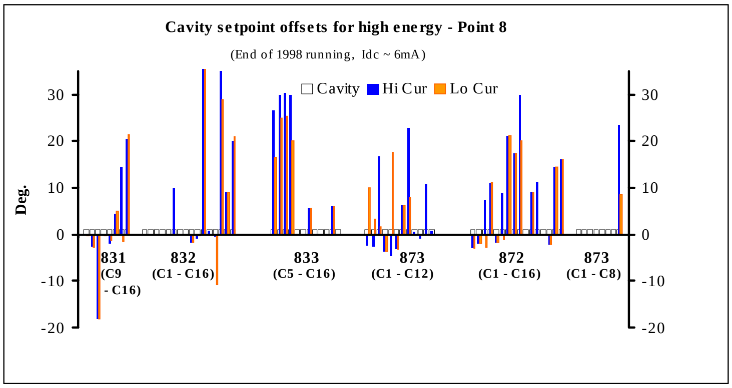
Plot 1) Point 2



Plot 2) Point 4



Plot 3) Point 6



Plot 4) Point 8

Figure 8 : Cavity Setpoint offsets for High Energy – Low and High Current Values

The second Robinson limit was suspected and an MD test verified that this was in fact occurring and that the limit was very close to the predicted value. Figure 9 shows the minimum RF voltage through the ramp for 3 different beam currents. An injection voltage of 510MVand 288 SC cavities without vector sum feedback are assumed. With the replacement of all antenna cables during the shutdown it should not be necessary to run with voltages approaching these limits.

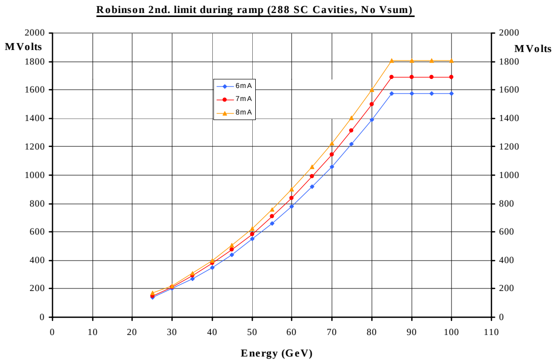


Figure 9: Robinson Second Limit Voltages during the Ramp for Beam Currents of 6mA, 7mA and 8mA.

5.3 *RF Unit Phasing at Top Energy*

A frequent problem from time to time towards the end of the 1998 running period as the RF voltage reserve was diminishing was the further lack of RF voltage due to errors in the phasing of one or two RF units. At high energy and with high current it was relatively easy to identify such errors by comparing klystron forward and reflected power in the different RF units. It would be relatively straightforward to make estimates of unit phase, based on the simple cavity vector diagram model. These would use energy, beam current and RF voltage together with measurements of klystron and cavity forward and reflected powers and cavity fields. Data could be taken directly or retrieved from the logging system. A very high precision is unlikely due to tolerances on power meters and field measurements but a software application to do this could be a useful tool to identify phase errors large enough to cause noticeable Qs drop.

6 CONCLUSIONS

Shut down work presently in progress, such as waveguide length compensation in certain units and replacement of all directional coupler loads can be expected to give a significant improvement in cavity field distribution, both at injection and high energy. Measurements with beam should be done to check the results. For the ramp, the Robinson second limit will not be a problem. However the problem of cavity oscillations will be increasingly difficult to control with increasing beam currents. The recent success of the new damping system is very encouraging. Further software utilities such as cavity tuning and checking of RF unit phase should be provided to help machine operation.

7 ACKNOWLEDGEMENTS

Thanks are due Hans Frischholz for explanations on the waveguide system measurements and modifications, to Olivier Brunner on the l/4 waveguide transformers and to Ernst Peschardt on the cavity phase measurements using the beam.