Performance of SRF Systems in Large Scale Applications

J. Curt Hovater
Continuous Electron Beam Accelerator Facility
12000 Jefferson Avenue, Newport News, Va. 23606-1909 USA

I. Introduction

In the last ten years superconducting RF (sc) cavities have become a viable acceleration technique used at many facilities. Applications include electron accelerators like CEBAF, heavy ion accelerators like Atlas, and e^+e^- storage rings such as Tristan. The advantage of sc cavities is twofold: one, they can supply high gradients with a nominal RF source, and two, the state of the art in the design and production techniques has risen to a level that is acceptable. Systems such as Atlas and Tristan have proven that a reliable machine can be produced and have increased the confidence of the operability of SRF technology. As new and larger systems come on line, system performance becomes an issue. Because of the nature of SRF systems, rigid machine protection interlocks, vacuum requirements etc., different limitations that may have not occurred in normal conducting accelerators are being observed. Problems concerning gas discharges, tuning, gradient degradation and other phenomena have to be dealt with. This paper discusses operational performance of large scale SRF systems worldwide. Facilities discussed include high beta machines such as Tristan (KEK), LEP (CERN), HERA (DESY) and CEBAF and heavy ion linacs such as Atlas (Argonne). Key operational issues concerning interlocks, controls and system reliability are included. Particular emphasis is placed on CEBAF's operational experience because the author is closest to it and CEBAF will have 80% of installed SRF cavities by January 1994.[1]

II. Performance of SRF Systems

A. TRISTAN

The SRF cavities at TRISTAN have been in use since 1988 in a storage ring application. This facility has had the most experience with high beta cavities, accumulating over 800,000 cavity hours with beam operation.[2] The system consists of thirty-two 508 MHz cavities in 16 cryomodules. The RF system is arranged such that four cavities are powered by one 1 MW klystron. The average operating gradient is approximately 4 MV/m at a beam current of 13 mA. The cryogenic plant is capable of producing 6 kW at 4.2 K. A stepper motor is used for initial/coarse cavity tuning and a piezo-electric tuner for fine tuning (< 7 kHz). Cavity protection interlocks consist of an arc detector for the cavity window, a cavity vacuum interlock, He pressure that detects boil off due to a quench, a fast electronic quench detector, fundamental mode power monitor in the higher order mode (HOM) coupler and window temperature interlock.

Overall the system has been very reliable in the support of physics activities at KEK. An area that has seen problems, though, is the fast quenches which have been observed when running beam. In studies 70% have been attributed to synchrotron radiation from the beam. This was verified by placing radiation intercepts in front of the cryomodules closest to dipoles and observing that the number of trips decreased by 70%.

B. LEP

LEP at CERN is unique in that its cavities are made from sputtered niobium onto copper, thereby reducing material cost. Presently there are 12 cavities installed in three cryomodules operating at 4.2 K.[3] It is planned to install 192 cavities in 48 cryomodules by 1996. Cavity frequency is 352 MHz. This will allow the LEP accelerator to double its presently available particle power. Total operational time with beam has only been a few thousand hours. The cavity gradients during operation have averaged between 3.5 and 5.5 MV/m with a beam current of 6 mA.[1,3] The RF system consists of one 1.2 MW klystron powering 16 sc cavities. When installed, the cryogenic plant will be capable of producing 48 kW at 4.2 K. Cavity tuning is accomplished by a thermal tuner for coarse tuning and a magnetostrictive tuner for fast tuning. Cavity protection interlocks are similar to those at TRISTAN. The cavities are presently limited from achieving higher gradients by field emission. An additional limitation is multipacting around the main power coupler, which has been observed with and without beam.

C. HERA

HERA at DESY presently has sixteen 500 MHz cavities in eight cryomodules operating at an average gradient of 4 MV/m.[1] Next to TRISTAN, HERA has the longest experience in sc-cavity operation for a high beta system at 160,000 hours. The cavities have an operating temperature of 4.4 K. A problem that plagued HERA was "Q" disease; this has been over come with quicker cool down rates and cavity heat treatment.[1] Tuning is accomplished with a mechanical tuner. The low $Q_{ext}, 2\times10^5$, keeps the frequency of tuning relatively low so the need of fine tuning is not necessary. In addition, the input waveguide can be tuned to match the input coupler for different beam conditions. The RF system is comprised of two 1.6 MW klystrons combined to feed 16 cavities. The multipacting threshold on the input couplers can be increased by RF conditioning. Unfortunately this reappears in 5 to 6 weeks after conditioning.[15]

D. CEBAF

As of November 1993, CEBAF presently has 306 cavities in 38 and 1/4 cryomodules operating at 2 K. Operational cavity gradients, during 1992/1993, ranged between 5 and 7.5 MV/m totaling 140,000 hours of cavity operations. Because the stringent energy spread requirement resulting in tight control of microphonics makes the idea of a single klystron driving multiple cavities not practicable in recirculating linacs, each cavity is powered by a single 5 kW klystron operating at 1497 MHz. Tuning is accomplished using a mechanical ball gear tuner driven by a stepper motor. Interlocks are similar to ones mentioned previously with two exceptions. A HOM coupler power monitor is not necessary because CEBAF's current (< 1 mA) does not produce much heating in the load and therefore an interlock is not necessary. A He level interlock is necessary to keep the HOM load in the bath; CEBAF's loads are waveguide loads and need to be kept cold. The cryogenic systems cold compressors limited the energy during the 1992/93 operation. It is expected to have the 2 K cold compressors operational in 1994. Pressure fluctuations during cold compressor commissioning hindered the operability of the system; the present tuning algorithm has only a lock range of approximately 300 Hz. During long down times (more than a couple of hours) the cavities have shown drifts greater than 300 Hz, which has caused problems in tuning.[13]

E. ATLAS

The heavy ion linac at Argonne, operational since October of 1985, consists of 63 superconducting cavities in 10 cryomodules.[4] Average operational gradient is 3 MV/m at an operating frequency between 48 and 145 MHz. The system has over 1.1 million cavity hours of beam operation. The cryogenic plant is small, supplying 800 W at 4.7 K. The RF system consists of one 200 W solid state amplifier per cavity. Tuning is accomplished by a slow pneumatic tuner; for faster control a pin diode is used. Machine protection is mostly concerned with cavity vacuum, which is monitored through ion gauges. The gradient is presently limited by cryogenic capacity and electron loading. Overall, Atlas has been very reliable for heavy ion research with only 5 to 10% of unscheduled down time.[14]

III. SRF Performance Limitations

A concern of SRF technology at large accelerating facilities is performance limitations, i.e., what will cause the system to fail, degrade etc. In general the operability and performance of a modern accelerator depends on the following items:

- Machine protection interlocks; too few and the system could have a catastrophic failure, i.e., vacuum accident, too many and the system can become unbearable to operate
- Complexity; control systems can be quite involved given the level of control needed for recirculating linacs
- Reliability; subsystems must be reliable - i.e., refrigerator, RF controls - and easy to maintain

The first two items clearly are driven by the needs of the accelerator. You would not want a control system and interlock system from a storage ring to run a linac or vice-versa. In both cases a happy medium must be found to meet the particular needs. In the case of machine protection it must be balanced with what is an acceptable failure vs. the risk of a larger failure. Second, the complexity of the control system has to be weighed against the quality of beam that is needed. Increasing both of these will also increase the amount of downtime that you can expect from the system and this affects the third bullet, reliability.

Other problems that could undermine performance such as "Q" degradation over time, have not been observed.[2] Systems such as KEK , HERA, Atlas and to a lesser extent CEBAF have compiled many cavity hours of beam operation and from this we have a large statistical database to draw from.

A. Interlocks

Machine protection interlocks are a necessary evil for all SRF machines. Since the cavities have to operate under extremely high vacuums to insulate them from the atmospheric environment, any vacuum failure could degrade the performance of the cavities. Interlocks in SRF cavities are there to protect the cavities from a catastrophic accident. Compared to normal conducting cavities, sc cavity interlocks are increased in number and sensitivity. A typical SRF cavity protection system will have the following interlocks: arc detector, usually on the input window; window temperature monitor; waveguide/warm vacuum; HOM power monitor (high current machines > 1 mA); helium pressure monitor; helium liquid level monitor; and quench detector. While there is some redundancy it may only be during catastrophic failures that the a particular interlock trips; i.e., if you lose waveguide vacuum an arc may indeed be induced.

Most facilities are limited by their interlocks to some degree, and ultimately interlocks will reduce system availability as gradients are increased. As mentioned above, KEK has experienced fast quenches that are presently under study. CEBAF is limited by waveguide vacuum faults at gradients in excess of 7 MV/m and HERA has to condition the input couplers to get around multipacting.

Figure 1 shows the number of commissioned CEBAF cavities and their limitations. Field emission is by far the largest cavity limitation and is determined during cavity commissioning to ensure that the cavities do not go beyond the allowable cryogenic heat load. Almost all of the limitations shown in Figure 1 occur at gradients above 5 MV/m with an average usable gradient of 7.2 MV/m.[1]

B. Controls

Controlling an SRF cavity is somewhat different than for a normal conducting structure. Due to the high external Q's ($10^5 - 10^7$), sc cavities can be perturbed by microphonics, ground disturbances, mechanical vacuum pumps etc. If left uncontrolled, microphonics will deform the cavity, creating gradient and phase fluctuations that can affect the beam quality. Therefore high gains in the feedback loops are necessary to control the gradient and phase needed for efficient acceleration. Tuning is a complicated endeavor for the same reasons; the high Q allows the cavity to detune from small fluctuations in helium pressure. The control system must also keep track of all the different interlocks, including some that originate in other subsystems such as cryogenics and vacuum.

The level of system complexity is different depending on how the sc cavities are being used. In a storage ring application, such as at Tristan, the system may not be as complicated where multiple cavities are run routinely off a single klystron. The control system can control on the sum of the cavity errors and still meet its requirement for beam quality. In the case of a recirculating linac such as CEBAF, where a single klystron drives a single cavity, the control system is more complex. The specification for beam quality could not be met if a multicavity control system was imposed.

There is quite a bit of literature on sc cavity control systems, including the paper on amplitude, phase and frequency control at this conference, so I will not go further on the subject.[5]

To mitigate some of the complexity, a unique feature of the CEBAF RF control system is the on board microprocessor.[10] The microprocessor allows background processes to run while monitoring faults such as cavity and klystron interlocks. In addition the microprocessor has allowed for new routines and programs to be added to the system easily and efficiently. An example is the temperature drifts associated with the RF electronics. The temperature drifts are monitored with sensors on both the IF and the RF sections of the control module. The information is then processed through the microprocessor and corrections are made based on it. Before installation into the accelerator, each RF control module goes through a rigorous calibration sequence. All phase and amplitude measuring devices are calibrated to a known standard and over the temperature range of 10 to 50 C. Calibration algorithms for gradient, forward power and frequency are installed into on board memory at this time.

An important aspect of a large scale accelerator is the use of a sophisticated computer control system to integrate the different subsystems. In particular the system must rely on graphics based user-friendly control screens and real time data acquisition. Starting with the lowest level and going to the highest level, graphic based screens allow operators to control and maintain single and multiple cavities. At CEBAF the lowest level RF control screen is considered an "expert" screen and is meant to be used by RF engineers and technicians as shown in Figure 2. This particular screen controls a single cavity and as you can see is highly complex. It has over 200 signals being displayed and updated. It was designed for RF on line troubleshooting and is not meant as an operation screen. Attempts to add user-friendly graphics such as symbols for gain blocks failed because the RF experts' needed to have as many signals represented as possible. The graphics limited the number of signals that could be placed on one screen.

Figure 3 shows a screen designed for one linac. The screen allows the operator to individually turn on one cryomodule (8 cavities) or all 20 cryomodules at once. The operator can also monitor phases relative to the crest and overall energy gains for each cryomodule. These actually have become quite useful during beam operations. Once the beam energy has been crested in a linac with proper cavity phasing, the cavities are normalized to zero phase. Operators can then quickly look at a linac/cryomodule/cavity to see if any has drifted or come out of lock. The middle column of Figure 3 displays the cryomodule phase information.

Depending on the facility, cavity tuning is accomplished in a variety of ways. For relatively slow tuning, or where the cavities are relatively stable, a mechanical tuner using a stepper motor is fine. Faster tuning can be accomplished with magnetostrictive or piezo-electric tuners that can run at a few hundred Hz bandwidth. At CEBAF a stepper motor tuner is used to keep the cavities centered at the cavity frequency of 1497 MHz. The external *Q* of the cavity gives a video bandwidth of approximately 125 Hz. The present tuning algorithm has a lock range of about 300 Hz. This narrow lock range has hindered operations in that the cavities must be tuned by hand using a vector network analyzer if they move out of the lock range. For a couple of cavities this does not pose a problem, but for 338 cavities it will become awkward. A tuning algorithm is being developed that will have a lock range of +/-5 kHz.[5] The method is similar to swept network measurement, but instead uses the RF control modules' complex phase modulators to sweep a sideband out +/- 5 kHz. The cavity signal is detected through a 360° continuous phase detector and processed through the microprocessor. The time domain signal is then Fourier transformed to give the frequency domain information necessary for the tuning.

An automated fault recovery is needed for operation of a large number of cavities. Without the ability to recover from single cavity faults the system may not be practical for the user. Presently CEBAF is looking at a system that will reset itself up to three times in ten minutes for the same fault. The idea is to get around random faults but protect for real faults that could damage the machine.

IV. Operational Experience at CEBAF

Recently CEBAF had the opportunity to run continuously 145 cavities with beam during what has come to be known as the north linac test. The test was comprised of various operational tests of components and subsystems, most notably the SRF cavities and the RF controls. Two concerns that were addressed included high gradient operations and cavity beam loading effects. In the case of high gradient operation one cryomodule (eight cavities) was operated at an average gradient of 8 MV/m. The beam loading tests demonstrated the ability of the RF control system to adjust to different beam currents while maintaining the same residual error. A problem that was discovered and is presently being addressed was a linac energy drift of approximately +/- 0.1% over a period of 20 minutes. Additionally a database on system faults was obtained for over 120,000 cavity hours of operation.

A. High Gradient Operations

CEBAF's design gradient is 5 MV/m. Almost all of the cavities have far outpaced this number, with the average installed gradient being 7.1 MV/m (@ 45 W per cryomodule).[6] This leads users and accelerator physicists to speculate on the likelihood of exceeding CEBAF's design energy, 4 GeV, and of reaching higher levels with 6 GeV being a conceivable goal. In order to eventually meet this, each cryomodule will have to have an energy gain of 30 MeV, 10 MeV higher than the design specification.

A test was conceived to operate a cryomodule with beam at its maximum allowable gradient, which is determined during linac commissioning.[11] The particular cryomodule, NL13, was picked for its number of cavities exhibiting low field emission and large useable energy gain of 33.7 MeV. Figure 4 shows the cavity limitations for cryomodule NL13. A large concern during the test was the cavity interlocks, i.e., what would happen when gradients and forward powers were increased beyond 5MV/m and 500 W respectively.

The cavity interlocks behaved somewhat as expected, with the infrared sensor and the waveguide vacuum interlocks limiting the maximum operational gradient. The infrared sensor was designed to measure the temperature of the cold and warm window and protect against possible thermal damage .[7] The IR sensor is a thermopile device that sends a voltage to the RF microprocessor. When the voltage is such that it corresponds to approximately 50° C on the warm window, it turns the RF off.[1] Early on in the test sequence it was noticed that IR sensors were tripping with the increased forward power. In parallel, off-line studies determined that the window in fact could withstand a larger RF forward power, up to 5 kW.[7] The IR sensor trip point was then lowered to a more reasonable trip level to handle the increased forward power. It was also noticed that at larger forward power levels the waveguide vacuum interlock would trip the system. The vacuum in question is between the warm and cold windows. A way around this was to condition the waveguide/window vacuum with RF and increase the gradient slowly up to the maximum. Figure 5 shows a graph of the waveguide vacuum after an increase in forward power. As you can see, the vacuum is getting better after the initial increase. It would be quite easy to condition all of the cavity waveguides by simply detuning them and running the klystrons. No arc faults were observed during the tests.

Overall results of the test were very encouraging. CEBAF was able to achieve the highest energy gain so far of any cryomodule at 32.5 MeV. Additionally we at CEBAF are confident that we can run our cavities up to the operational limits with very little modification to our present RF system.

B. Beam Loading

A number of experiments on beam loading were also done during the north linac test. Earlier tests with beam had not been conclusive as to whether the RF control system would control the cavity gradient as well as without beam. Additionally the tuning algorithm had not taken into account the effects due to beam loading, and during the tests an algorithm was successfully tested.

The reason that compensation with beam is necessary is that for a detuned cavity the phase of the beam induced voltage adds to the total phase of the cavity. This will upset the tuning algorithm if not compensated. The reason is that the phase detector in the RF control system does not measure the detuning angle directly; it compares the incident and transmitted (probe) signals. An algorithm that takes into account the beam induced voltage is shown in Figure 6 along with the cavity voltage vector representation.[8] During the test, two cavities were tested with the algorithm. In one of the cavities a tuning stub was placed inside the waveguide that increased the cavity *Q*ext by a factor of three in order to simulate heavy beam loading . The algorithm was tested between 0 and 200 mA, which for the resonated cavity meant 0 to 600 mA. Since the CEBAF design goal is to run five 200 mA recirculated beams for a total of 1 mA in the linacs at any one time, the test was representative of actual beam operations. The algorithm was successful in returning the correct detuning angle with an error of ≈ 0.5 degrees for the non-resonated waveguide and error of ≈ 2.0 degrees for the resonated waveguide. The larger error in the resonated case was probably due to fact that the tuning angle is also three times more sensitive to frequency changes of the cavity.

The performance of the RF control system was also tested under heavy beam loading, the basis being to measure the effect of beam loading on the quality of cavity gradient and phase regulation and measure the overall stability of the system.[8] In a similar manner mentioned above two cavities' waveguides were resonated to increase the Qext to match the cavity to the lower beam currents available during the test. By doing this the test simulated the actual beam current the cavities will see when in five pass operation. A CW beam at an energy of 30 MeV was run, and phase and gradient fluctuations were then measured as a function of beam current. An external Schottky detector with DC block was used to measure gradient fluctuations independently of noise generated by the electronics of the RF control module. Figure 7 shows the spectra of the residual amplitude noise at different beam currents (0, 40, 80, 160 mA). The similarity in the spectra shows that the residual amplitude noise does not depend on beam current. Furthermore quantitative analyses using an integrated rms gradient spectrum between 0 and 100 Hz showed the relative rms gradient error to be:

$$\frac{\Delta V}{V} \approx \frac{2\times 10^{-5} V}{600 mV} \approx 3.3\times 10^{-5}$$

The specification for uncorrelated amplitude fluctuations is 2×10^{-4}up to 1 MHz.

C. Linac Energy Drift

During operations a 0.1 % energy drift was noticed in one of the dispersive sections at the end of the linac. The energy drift was attributed to RF phase shifts in the linac. Figure 8 shows a BPM output in a dispersive region and the summed phases of two cryomodules. The time period of the drift is approximately 20 minutes. A correlation obviously existed, and upon further investigation the period was shown to be the ambient air temperature cycle of CEBAF's service buildings where the RF controls are housed. It was eventually determined that a particular resistor in the phase section of the RF control module had been ordered in three lots with little regard for temperature coefficient. Two of the manufacturers had temperature coefficients of equal and opposite magnitude. The resistor was connected differentially to an operational amplifier, and when two resistors of different coefficients were installed, an error voltage resulted that ultimately manifested itself as phase shift to the beam. The resistors have since been replaced and we believe the problem to be fixed.

It is also conceivable that part of the drift could have come from the injector cavities drifting in phase with respect to the linac cavities. This is possible but highly unlikely, since the phase drift was highly correlated to the linac service buildings' ambient temperature. Although it is likely that the injector service building has a similar temperature drift, it does not seem conceivable that it would have the same period and phase as in the linac. If this had been the case, beats would have been seen in the energy drift, but none were noticed.

Besides the replacing of the resistors other provisions have been planned to compensate for different linac drifts. First, RF control modules are now being calibrated over temperature as mentioned previously. Second, the RF drive line was built with the idea of having a highly stable fiber optic reference throughout the accelerator complex to monitor and correct for phase drifts.[12] This is presently being installed. Lastly an energy vernier system is being designed that will control the small energy drifts expected in the two linacs and the injector due to phase or amplitude fluctuations.

D. Machine Failures

During the north linac test a large database was compiled of all system failures over 100,000 cavity hours.[9] Figure 9 shows the number of system failures by subsystem. A failure was considered anything that stopped beam operations for more than 20 minutes. The number of failures attributed to SRF was quite small when compared to other accelerator systems. The one repetitive failure that was noticed, ion pump power supplies (10), has been fixed. The rest of the failures can be attributed to infant mortality where no more than two of any one component failed. Overall the SRF system had fewer than 9% of the total failures recorded during the north linac test. Considering that this involved 145 superconducting cavities and their peripheral hardware, and that this was the first time that they had been operated, the number of system failures is quite respectable.

Similarly infant mortality plagued the RF system, which includes the controls, interlocks and high power amplifiers. A large portion of the failures (27) has been attributed to a couple of components within the high power amplifier. The number of failures of the RF system turned out to be slightly less than 23% of the total.

In both systems, SRF and RF, we believe that the number of failures during the next beam operations will be considerably lower than during the north linac test.

V. Summary

Superconducting RF technology has become a reliable and cost effective method of particle acceleration. Large scale operations of superconducting RF have demonstrated and bolstered the confidence in this technology. Problems seen in its infancy have been solved and more laboratories are considering it as a viable alternative to normal conducting acceleration. Operational experience worldwide is now approaching over 2 million cavity hours of beam time and this will double as CEBAF comes on line next year. In addition, cavity performance is continuing to improve with gradients increasing as new manufacturing techniques are learned.

Acknowledgments

The author would like thank the CEBAF Operations, SRF and Linac Departments, especially H. F. Dylla, M. Drury, W. Schneider, J. Preble, K. Brown, Q. Saulter, S. Simrock, R. Nelson, S. Suhring, G. Neil, J. Fugitt, L. Merminga, A. Hutton and M. Byers. S. Noguchi of KEK, G. Geschonke and G. Cavallari of CERN, D. Proch of DESY and K. Shepard and R. Pardo of Argonne provided information used in the laboratory summaries.

---

*Supported by U.S. DOE contract DE-AC05-84ER40150

References

1. H.F. Dylla, et al., "Operating Experience with High Beta Superconducting RF Cavities", Proceedings of the 1993 Particle Accelerator Conference, to be published

2. S. Noguchi, these proceedings and private communication

3. G. Cavallari, these proceedings and private communication

4. K. Shepard, R. Pardo, these proceedings and private communication

5. S. Simrock, these proceedings and private communication

6. J. Mammosser, these proceedings

7. W. Schneider, private communication

8. L. Merminga, et al., "Operation of the CEBAF Linac with High Beam Loading", Proceedings of the 1993 Particle Accelerator Conference, to be published

9. S. Suhring, et al., CEBAF Hardware Team report

10. I. Ashlenazi and G. Lahti, "Microprocessor Control for the CEBAF RF Control Module", Proceedings of the 1989 IEEE Particle Accelerator Conference, pp 1861-1863

11. C. Hovater, et al., "Cryomodule High Gradient Operations", CEBAF Tech Notes 93-041

12 A. Krycuk, et al., "The CEBAF Frequency Distribution System", Conference Record of the 1991 IEEE Particle Accelerator Conference, pp 1470 - 1472

13. C. Hovater, "Front End Test Cavity Tuning Data", CEBAF Tech-Note TN-92-013

14. L. M. Bollinger, "Present and Future Superconducting Linacs", Proceedings of the 1987 IEEE Particle Accelerator Conference, pp 233-238

15. D. Proch., these proceedings

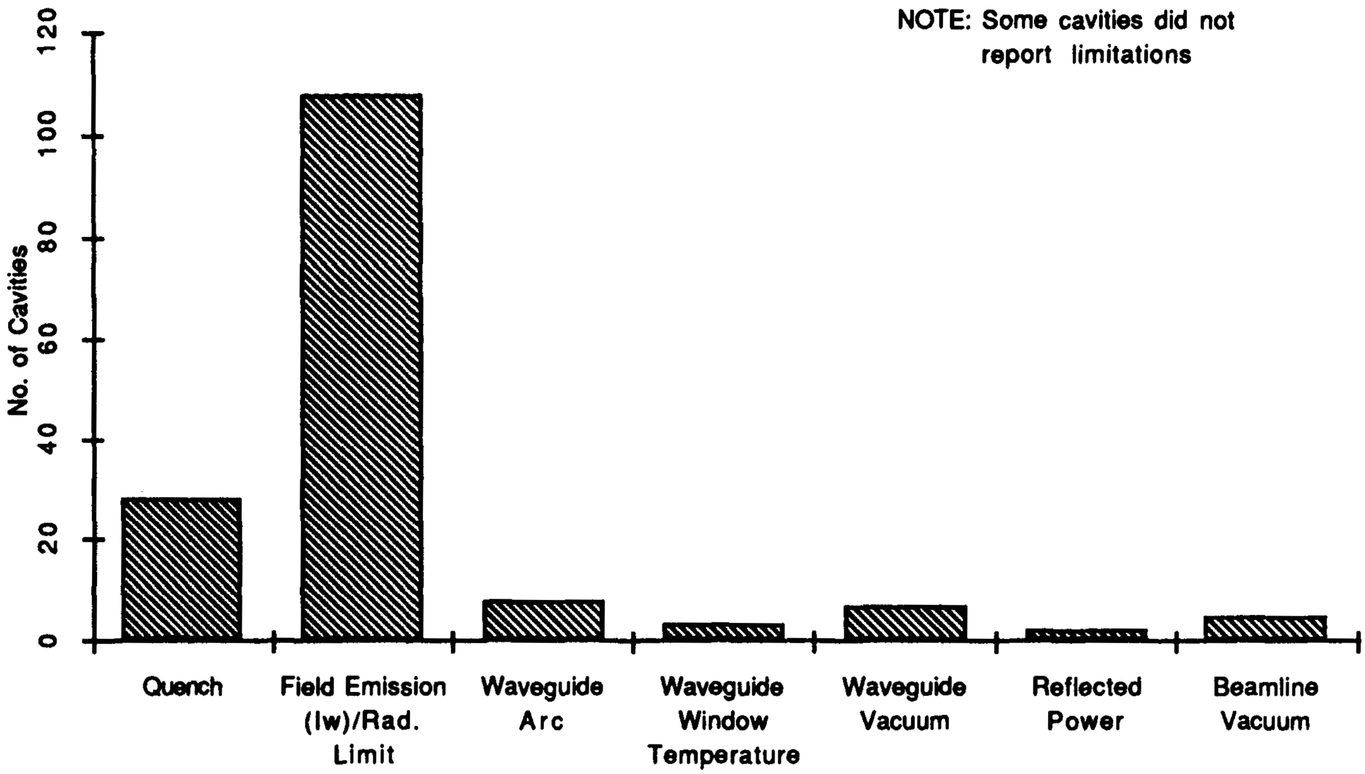
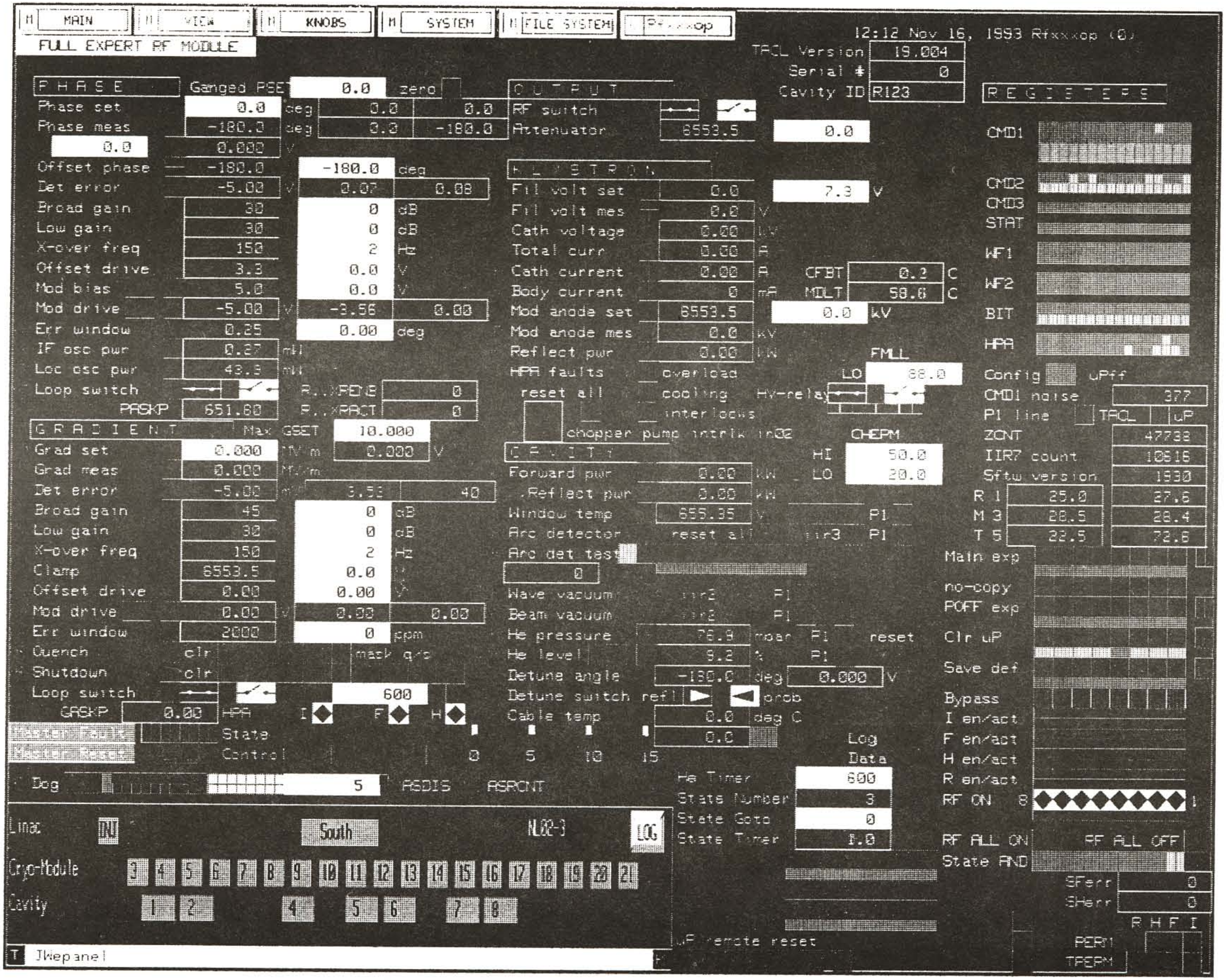


Figure 1. Commissioned cavity gradient limitations



FULL EXPERT RF MODULE

12:12 Nov 16, 1993 Rfxxxop (0)

TACL Version 19.004
Serial # 0
Cavity ID R123

PHASE
Ganged PSET 0.0 zero
Phase set 0.0 deg 0.0 0.0
Phase meas -180.0 deg 0.0 -180.0
0.0 0.000 V
Offset phase -180.0 -180.0 deg
Det error -5.00 V 0.07 0.08
Broad gain 30 0 dB
Low gain 30 0 dB
X-over freq 150 2 Hz
Offset drive 3.3 0.0 V
Mod bias 5.0 0.0 V
Mod drive -5.00 V -3.56 0.00
Err window 0.25 0.00 deg
IF osc pwr 0.27 mW
Loc osc pwr 43.3 mW
Loop switch R..XPENB 0
PASKP 651.60 R..XPACT 0

GRADIENT Max GSET 18.000
Grad set 0.000 MV/m 0.000 V
Grad meas 0.000 MV/m
Det error -5.00 mV 3.53 40
Broad gain 45 0 dB
Low gain 30 0 dB
X-over freq 150 2 Hz
Clamp 6553.5 0.0
Offset drive 0.00 0.00 V
Mod drive 0.00 V 0.00 0.00
Err window 2000 0 ppm
Quench clr mask q/s
Shutdown clr
Loop switch 600
GASKP 0.00 HPA I F H
Master Fault
Master Reset
State
Control 0 5 10 15
Dog 5 ASDIS ASRCNT

Linac INJ South NL02-3
Cryo-Module 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Cavity 1 2 4 5 6 7 8
T Jwepanel

OUTPUT
RF switch
Attenuator 6553.5 0.0

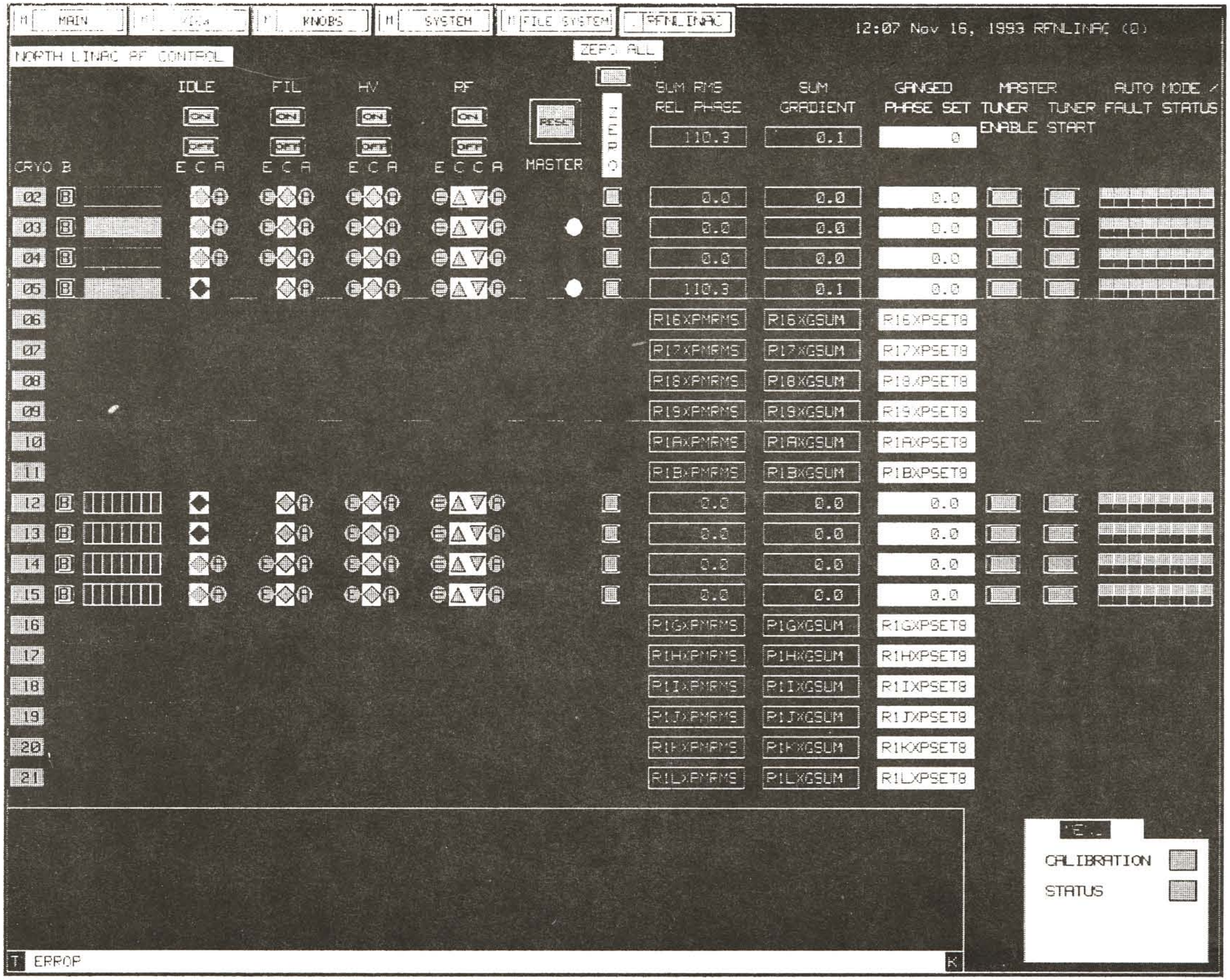
KLYSTRON
Fil volt set 0.0 7.3 V
Fil volt mes 0.0 V
Cath voltage 0.00 kV
Total curr 0.00 A
Cath current 0.00 A CFBT 0.2 C
Body current 0 mA MDLT 58.6 C
Mod anode set 6553.5 0.0 kV
Mod anode mes 0.0 kV
Reflect pwr 0.00 kW FMLL
HPA faults overload LO 88.0
reset all cooling HV-relay
interlocks
chopper pump intrlk in02 CHEPM

CAVITY HI 50.0
LO 20.0
Forward pwr 0.00 kW
Reflect pwr 0.00 kW
Window temp 655.35 V P1
Arc detector reset all ir3 P1
Arc det test 0
Wave vacuum ir2 P1
Beam vacuum ir2 P1
He pressure 76.8 mbar P1 reset
He level 9.2 % P1
Detune angle -180.0 deg 0.000 V
Detune switch refl prob
Cable temp 0.0 deg C
0.0

Log Data
He Timer 600
State Number 3
State Goto 0
State Timer 1.0
uP remote reset

REGISTERS
CMD1
CMD2
CMD3
STAT
WF1
WF2
BIT
HPA
Config uPff
CMD1 noise 377
P1 line TACL uP
ZCNT 47738
IIR7 count 10616
Sftw version 1930
R 1 25.0 27.6
M 3 28.5 28.4
T 5 22.5 72.6
Main exp
no-copy
POFF exp
Clr uP
Save def
Bypass
I en/act
F en/act
H en/act
R en/act
RF ON 8 1
State AND
SFerr 0
SHerr 0
R H F I
PERM
TPERM

Figure 2. RF Expert operations screen. This screen has the ability to monitor and control every function of an sc cavity.



CRYO	SUM RMS REL PHASE	SUM GRADIENT	GANGED PHASE SET
	110.3	0.1	0
02	0.0	0.0	0.0
03	0.0	0.0	0.0
04	0.0	0.0	0.0
05	110.3	0.1	0.0
06	R16XPMRMS	R16XGSUM	R16XPSET8
07	R17XPMRMS	R17XGSUM	R17XPSET8
08	R18XPMRMS	R18XGSUM	R18XPSET8
09	R19XPMRMS	R19XGSUM	R19XPSET8
10	R1AXPMRMS	R1AXGSUM	R1AXPSET8
11	R1BXPMRMS	R1BXGSUM	R1BXPSET8
12	0.0	0.0	0.0
13	0.0	0.0	0.0
14	0.0	0.0	0.0
15	0.0	0.0	0.0
16	R1GXPMRMS	R1GXGSUM	R1GXPSET8
17	R1HXPMRMS	R1HXGSUM	R1HXPSET8
18	R1IXPMRMS	R1IXGSUM	R1IXPSET8
19	R1JXPMRMS	R1JXGSUM	R1JXPSET8
20	R1KXPMRMS	R1KXGSUM	R1KXPSET8
21	R1LXPMRMS	R1LXGSUM	R1LXPSET8

Figure 3. Highest level RF control screen. This screen can turn on and operate up to 160 sc cavities.

Cavity	Maximum Gradient	Reason
1	6.8 MV/m	Field Emission
2	8.2	Field Emission
3	9.2	Quench
4	8.7	Waveguide Vacuum
5	9.6	Waveguide Vacuum
6	10.9	Waveguide Arc
7	7.7	Quench
8	6.3	Qunch

Total allowable energy contribution 33.7 MeV

Figure 4. Maximum allowable gradient limitations of cryomodule 1L13, which was selected for the high gradient test.

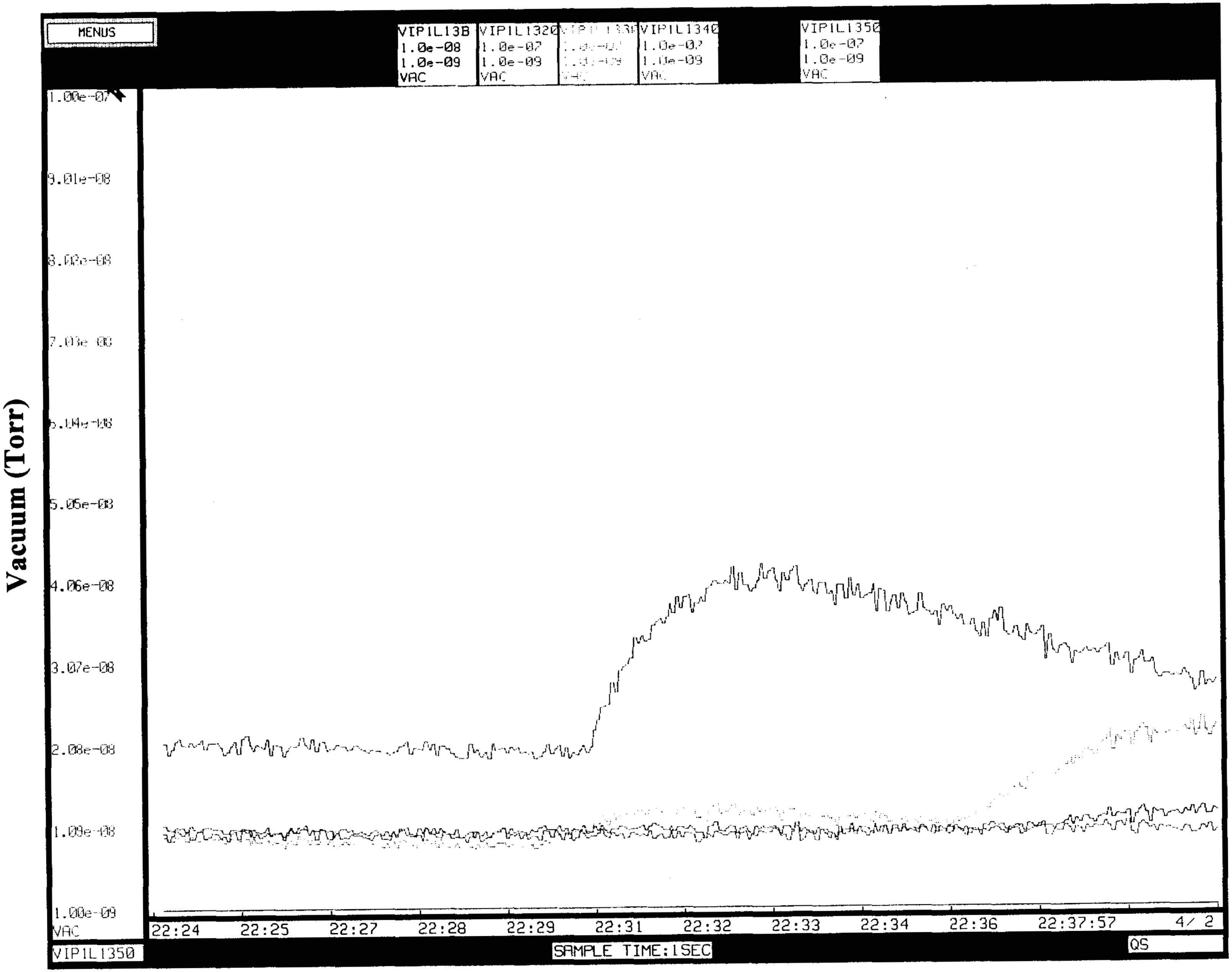
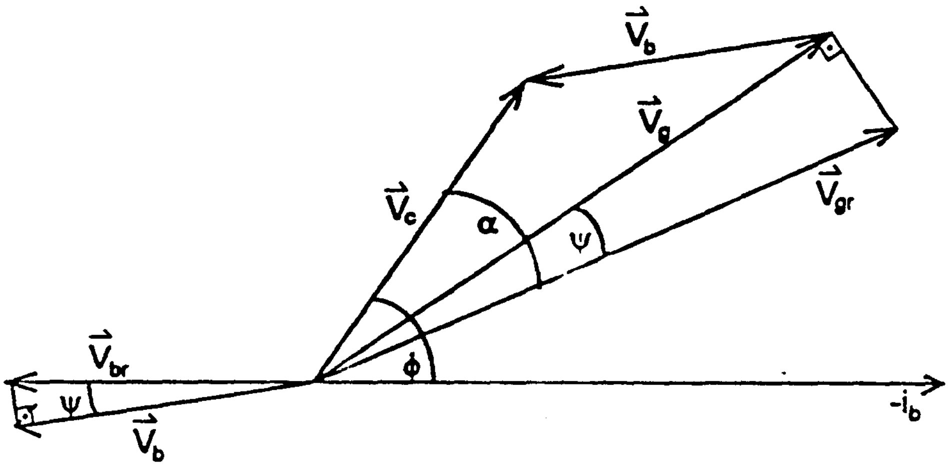


Figure 5. Time plot of the waveguide vacuum. The bump down in vacuum was caused by an increase in forward power from 2 kW to 3 kW.

BEAM LOADING ALGORITHM TEST

A tuning algorithm which compensates for bea
loading effects.



Vector representation of the generator, beam induced and total cavity voltages in an RF cavity.

V_g: Generator voltage
V_b: Beam induced voltage
V_c: Total cavity voltage
V_{xr}: On-resonance
ϕ: Off-crest angle
ψ: Detuning angle
α: Angle between cavity voltage and generator voltage on resonance

The algorithm:

$$\tan\psi = \frac{\tan\alpha[V_c + V_{br}\cos\phi] - V_{br}\sin\phi}{V_c}$$

Algorithm returns correct detuning angle within 0.5^0.

Figure 6. Vector representation of beam loading algorithm

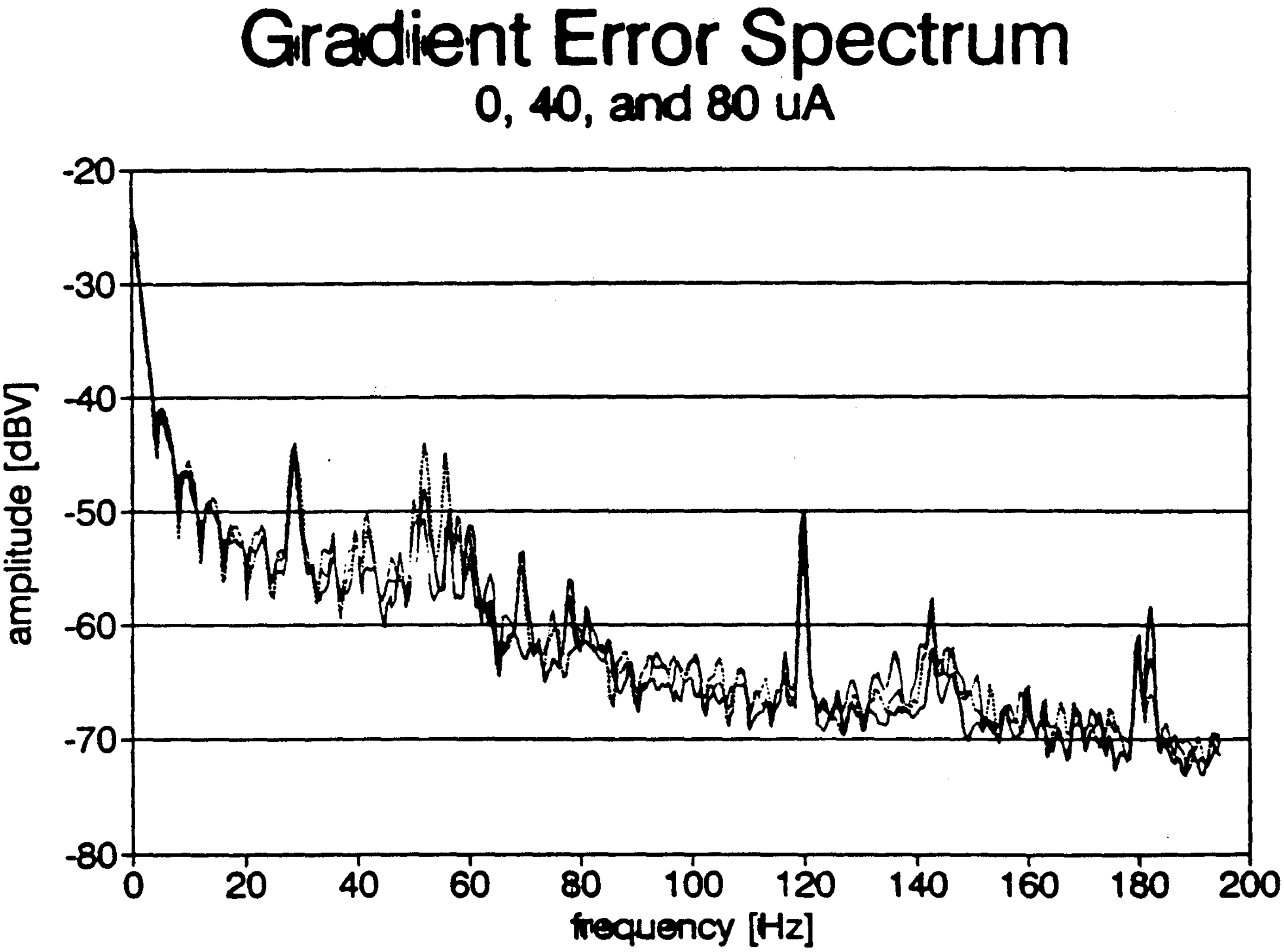


Figure 7. Residual gradient error spectrum of a sc cavity for different beam currents

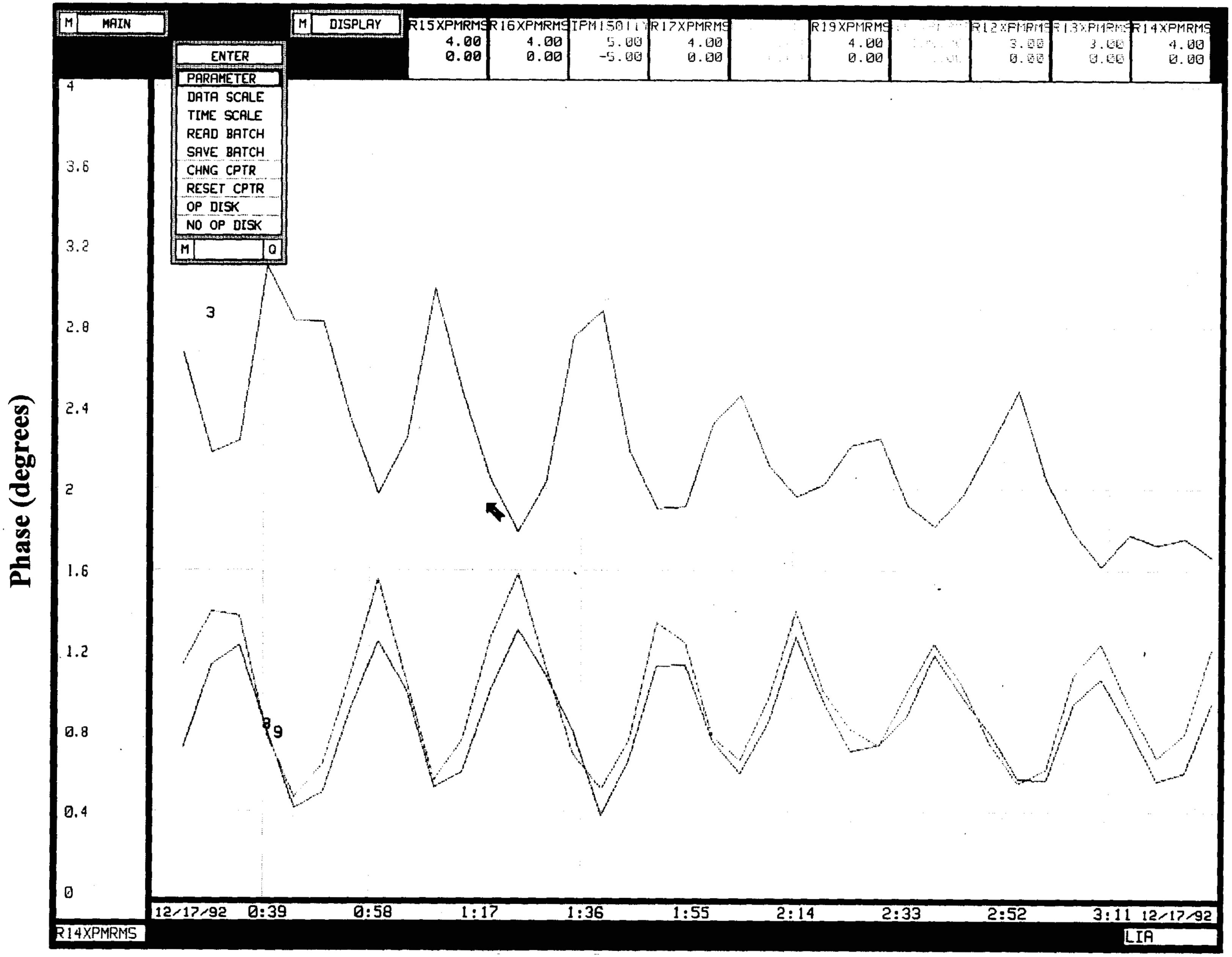
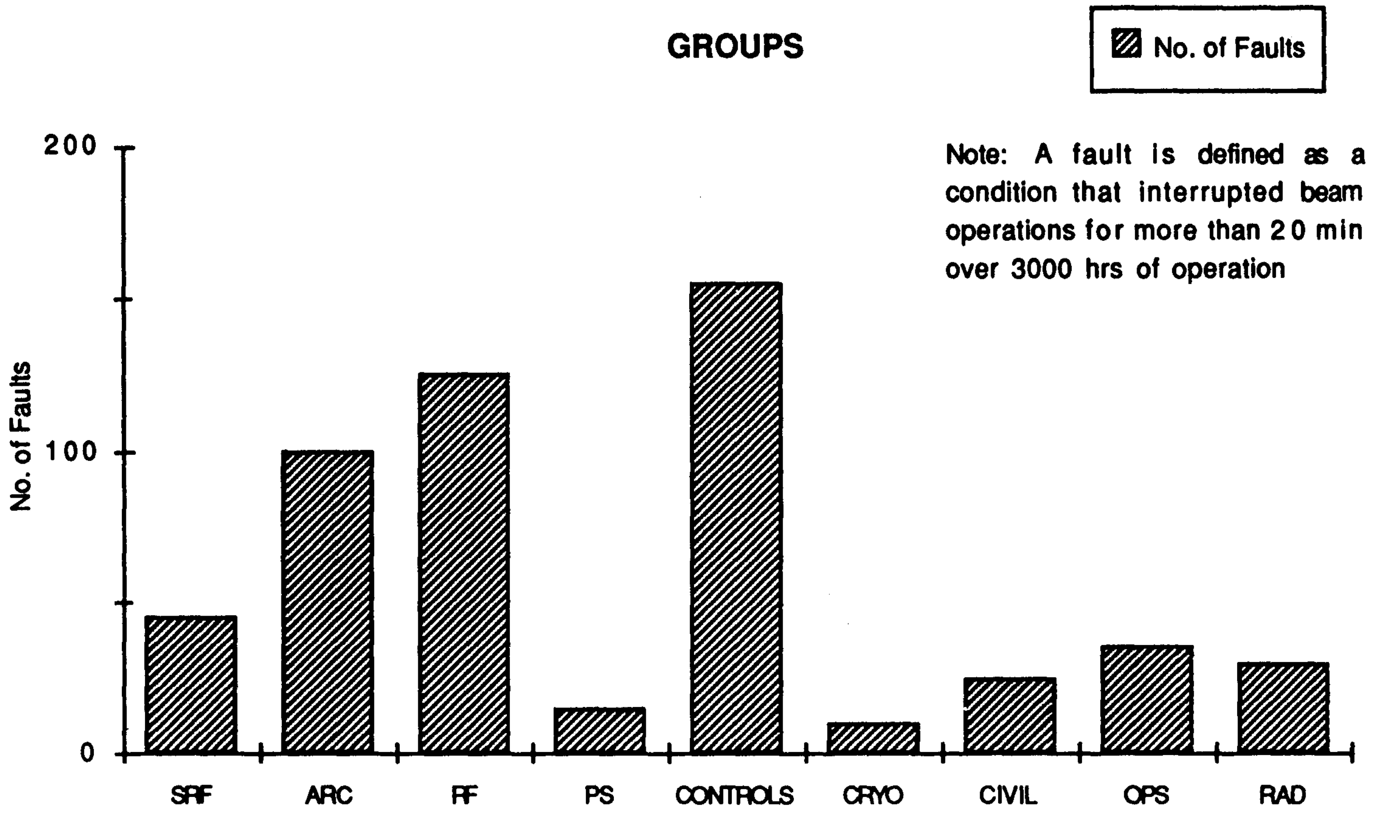


Figure 8. Time plot of the beam position (top trace) and the summed phases of two cryomodules (bottom two traces).



Note: A fault is defined as a condition that interrupted beam operations for more than 20 min over 3000 hrs of operation

Figure 9. Failures by subsystem during north linac test