The LAMPF 805 MHz linac has 104 side-coupled cavity chains, called tanks, which are joined together in sets of four or two to form 48 driven modules. Each tank has a different cavity geometry. The average fields in the tanks of a given module should agree to ±1% in order to preserve satisfactory beam dynamics and to make the turn-on problem tractable. These and other requirements make necessary the custom tuning and checkout of each portion of the accelerator. Methods for tuning accelerating and side cavities before and after they are brazed together into tank sections are described. High power tests of transient behavior, long-term stability, and stopband vs duty factor are outlined and related to structure cooling and frequency errors. Particular attention is given to the problem of unflatness. Progress and pitfalls in measuring unflatness at high power are presented. Experiments to determine the cause and to correct unflatness are described.

Introduction

The 805 MHz side-coupled linac now under construction at the Los Alamos Meson Physics Facility (LAMPF) is the final and most lengthy stage in a machine to accelerate protons to 800 MeV. It will be preceded by 750 kV injectors working into a 100 MeV post-coupled drift-tube linac. In its half-mile length, the side-coupled linac will include 9960 cavity resonators: 4960 accelerating cavities (herein called main cells), 4856 side cavities (coupling cells), 120 special coupling cells which connect individual tanks with long bridge cavities (bridge couplings), and 60 bridge couplers spanning the gaps between the tanks of each module. Each of these cavities must be tuned to a precise resonant frequency by careful processes of formation, and in most cases also by deformation, in the course of manufacturing and installation. After the reasons and methods for precise tuning have been explained, a summary of the pre-beam checkout work performed on these accelerator structures will be given.

Tuning Requirements

Steady-state Beam Dynamics

Computer studies of beam dynamics with RF amplitude errors present in the side-coupled structure indicate that tank-to-tank field amplitudes (i.e., average fields across one tank compared to the average field in the adjacent tank) must fall within ±2% of the correct value. Further, these calculations show that satisfactory beam dynamics will result even if there are systematic deviations of up to ±10% from flatness within each tank. The average tank fields are within ±2% of the correct value.1 (Of course, patterns of systematic deviation which would drive a phase oscillation must be guarded against.) Since main cell frequency errors may, when in collision with coupling cell frequency errors, cause steps in the amplitude pattern in a tank,2 the importance of making both main and coupling cell frequency error negligible is evident. The need for a way to adjust the tank-to-tank levels is also apparent, and the adjustment has been provided for in the tuning procedure using a post with variable asymmetry in the bridge coupler.

Transient Beam Dynamics

During the transients when the beam is being turned on or turned off within each RF pulse,3 there is the possibility of excitation of other modes than the normal n/2 operating mode in the accelerator structures.4 5 If other modes are significantly excited, the accelerating fields may be changed enough to cause degradation of or loss of the beam during the transient periods. The careful tuning of the structures for no stopband in their dispersion characteristics is desirable in order to minimize the excitation of nearby modes.

Accelerator Turn-On

When the full side-coupled linac is first brought into operation, the operators will be confronted with the so-called turn-on problem:3 Measurements of the absolute amplitude and phase of the accelerating field in each module will not be available before tests with beam. How then, should 44 amplitude knobs and 44 phase knobs of the RF controllers be adjusted to come somewhere near optimizing the transmission and acceleration of the beam? Computer studies of beam dynamics during a simulated turn-on indicate the operators have an excellent chance of finding near-optimum phase and amplitude settings if the tank-to-tank amplitude errors are ±1%. As this error tolerance is increased, the difficulty in getting a good beam all the way through the linac steadily increases until somewhere about ±6% it is practically impossible for many patterns of errors. Again, a tuning procedure is called for which eliminates frequency error as a cause of unflatness and which provides for the adjustment of tank-to-tank averages.

Tuning Procedure

An accelerating cavity is formed by the space between two segment assemblies. Each segment assembly includes a coupling cavity mounted on one side of the main body. The segment assemblies are brazed together in stacks of about 1.8 m (70 in) long to form tank sections.9 10 The tanks in modules 3 - 12 consist of two of these sections; the tanks in modules 13 - 48, four. Parts of the tuning process occur both before and after the segment assemblies are brazed into sections.11

Because there is coupling between adjacent main cells (herein called direct coupling) when the cells are assembled into a chain of resonators, the frequency of the individual main cell is not the same as the n/2-mode frequency of the chain. The amount of direct coupling present varies from tank to tank along the accelerator.

Pre-brake Tuning

The copper forgings for segment bodies and coupling cell halves are machined to approximate size, but with their re-entrant bosses or nose cones left long. These bosses and nose cones are later cut down
to bring the cells close to the required resonant frequency. The amount to be cut is first estimated by clamping a pair of main cell parts in a two-segment fixture and measuring the resonant frequency. Repeated cuts are made off the noses until the resonance is brought up to about 802 MHz. Then it is straightforward to cut 6 more segment bodies to form cavities with the same resonant frequency. These segment bodies are then stacked with the coupling cell parts clamped on. The coupling cell frequency is then determined from the measured π/2-mode frequency and stopband of this short cavity chain. Repeated cuts are made on the coupling cell bosses until the coupling cell frequency is correct. All the main cell segments for the particular tank and all the coupling cell parts for the particular type of coupling cell may then be sent to the shop for semi-final machining to the dimensions found. The coupling cell halves are also brazed together after machining.

For their final pre-braze tuning, the segments and coupling cells for a complete section are clamped together in a long fixture and the π/2-mode frequency and stopband are measured and compared with their design values. The laboratory where this is done has controlled temperature and humidity. The π/2-mode frequency indicates the tuning of the main cells; when the main cells are tuned correctly, the stopband indicates the required change in frequency of the coupling cells to bring them to correct tuning.

The main cell segments receive their final machining on a lathe in the tuning laboratory equipped with a tracer attachment to follow a standard nose template. The coupling cells need no further machining; they are brought to frequency by making a small deformation of the copper which brings the gap between bosses to the required distance.

Post-braze Tuning

When the completed segment assemblies are brazed into a section, the resonant frequency tends to drop. The average main cell frequency of each section is brought up to the correct value by making a series of dimples in the outside wall of the cells with a hydraulic press as required. The sides of the section then have flats for the cooling tubes milled in then

Fig. 1. Tuning probes. Top to bottom: coupling cell probe, main cell probe, main cell short or E-probe.

Fig. 2. Section through linac showing coupling cell probe in place.

Fig. 3. Main cell tuning tool. Top to bottom: hammer assembly and wrench, extensions, expandable head.
Pre-beam Checkout

Field Distribution Measurement

In order to set the tank-to-tank averages of the accelerating fields, the contribution of each cell to its tank accelerating field must be determined. This is done by pulling a small perturbing object, such as a metal head or needle, along a thread suspended along the beam axis and detecting the resulting change in resonant frequency of the structure. (Thus the measurement is known as a head-null measurement.) Some of the hardware required to do a head-null measurement under vacuum is shown in Figs. 5 and 6. For a small perturbing object, the change in frequency of the structure is proportional to the field intensity squared at the position of the object. The change in frequency may be observed directly, by making the structure part of an oscillating loop, or indirectly, by driving the structure at a fixed frequency and observing the phase shift between structure and source. Both methods have been used at LAMPF.

A small computer

Fig. 5. Vacuum drive box for head-null measurement.

Fig. 6. Evacuated tube for thread running under bridge coupler with rotatable notched post tuner.
interfaced with the resonant frequency detection equipment has proved to be a valuable aid in the adjustment of tank-to-tank averages. The computer makes a baseline correction, finds and stores the cell fields, and displays the result as the measurement is going on. The tank averages with respect to the module average are available seconds after the perturbing needle has transversed the module, allowing post tuner adjustments to be checked quickly.

Field Unflatness Within a Tank

Although the tank-to-tank agreement of averages may be excellent with the above procedure, the fields of individual cells may differ from the tank average by 10% or more. A beam-dynamics calculation was made using measured field distributions for modules 5 - 13. The tank averages were made equal for the calculation. The results indicate that the measured variations in field level about the tank averages will degrade the quality of the beam very little. Nevertheless, it seems desirable to determine the cause and correct tank unflatness if practicable, and a modest effort continues in this direction.

From the chain-of-coupled-resonators point of view, tank unflatness is seen to result from either (1) a combination of accelerating cell frequency errors and coupling cell frequency errors, or (2) a variation in cell-to-cell coupling along the structure. (The effect resulting from the combination of a coupling cell frequency error and direct coupling between accelerating cells described by Lee-Whitmonoz disperse when the accelerating cells are tuned to compensate for direct coupling, which is what is done in practice.) Since the measured field distributions do not change when equal and opposite perturbations are made in the end accelerating cell frequencies for a tank, the coupling cell frequencies contain no significant error. Field variations in cell-to-cell coupling may arise from variations in the geometry of the cells as constructed, which inevitably cover their range of tolerances. Among the factors which may contribute to variations in cell-to-cell coupling are (1) main cell nose cones not concentric with cell outer wall, (2) length of slot joining main and coupling cell not uniform, (3) varying position of coupling cell with respect to main cell segment, (4) varying longitudinal position of septum and nose cone with respect to the outer portion of the main segment body. Factors (1) through (3) are controlled in the manufacturing process, and there is no present evidence that these errors tend to systematically build up a tilt in the field distribution. However, final tuning of main cells is done by moving septums, and this may produce an accumulation of error of type (4) if the average main cell frequency of a whole tank is initially off. For example, if the average frequency is low, all septums may have to be moved away from the center of the tank, the septums being moved farther and farther as the ends of the tank are approached. Care is being taken to ensure that the average frequency of each section is correct, so that only minor septum adjustments back and forth are required.

Field Stability

Long-term Stability Under Constant RF Conditions. Module 5 has been operated several times for periods up to 60 h continuously at 12% duty factor and design field level. The field amplitude stability was better than 1%, as measured by temporary E-nprobes on the axis and H-nprobes in one main cell in each tank. Room temperature varied \( \pm 10^\circ \text{C} \) during these runs. It was necessary to use a high quality coaxial cable between the amplitude sensing probe and the RF controller to achieve this result with the room temperature variation present.

Stability: Low vs High Power. In order for the tuning and field-flattening procedure, which is done at very low power, to be valid at high power, the field distribution of the accelerator structures must be consistent in going from one to the other of these operating regimes. Furthermore, within the high-power regime, the field distribution must be stable with changes in average power level. The structures are temperature controlled to maintain resonance, which helps to satisfy the latter condition. Further discussion of the high power regime is left for a section to follow.

In an initial attempt to detect any change in field distribution between low-power tuning conditions and high-power operating conditions, electric probes were installed in the beam entrance and exit structures in each tank of module 5. The relative signals sensed at these eight points at low power were then compared with the signals for high-power runs with various duty factors. The high-power relative levels were fairly consistent with one another, but not with the low-power relative levels. It appeared that something was causing a change in either the probe calibration factors or in the field distribution in going from low to high power. There was some indication that multipactoring was occuring at some of the probes, which may account for the discrepancy.

A new approach to determining the field distribution at high power is now being attempted. A bead-pull measurement is being made at high peak power (but rather low average power). The result will be compared with a low power measurement. Feasibility studies have indicated that a bead-pull measurement can be made under vacuum and with a polypropylene string and aluminum head subjected to peak fields of up to 130% of the design peak fields in module 5. The progress of this investigation is reported elsewhere where these proceed. 

Stability vs Duty Factor. Within the high-power regime, a variation in field distribution has been observed in the module 5 tests as the duty factor was varied. Depending upon the stephand remaining when the structure was tuned, this variation may be as much as 2% or less than 1%. A theory has now been proposed which accounts for this variation. The variation depends on the amount of initial field unflatness and the stephand. Heating of high-field regions and cooling of low-field regions of the module introduce small main cell frequency errors which interact with the stephand to tilt the field distribution. Calculations were performed for a coupled-resonator model simulating module 5. The model exhibited a tilt which was zero for a positive stephand of about 5 kHz and which increased as the stephand was either increased or decreased from that point. A change in stephand of 50 kHz produced an end-to-end tilt of several percent under full-power conditions, which is in reasonable agreement with the measured field distributions.

Stability Under Transient Conditions. A number of high-power transient tests have been run on module 5. For a large step change in average RF power, the field distribution as indicated by 8 temporary electric probes mounted on the beam axis at the end of each tank was monitored during the thermal transient as the module cooling system and structural parts adjusted to new temperatures appropriate to the new power level. If the initial stephand of the structure was 0.5 kHz low (i.e., the coupling cells were 50 kHz low in frequency), a large step change in power
would sometimes cause the tank to run away -- more and more power going to a mode or modes other than the π/2-mode, a condition from which it would not recover by itself. If the initial stopband were closed or open up to 50 kHz high, the module could usually be brought from zero to full power in a single step without running away.

A scheme has been devised to permit the dynamic measurement of stopband using a swept-frequency diagnostic pulse in addition to the normal RF pulse.16 (Details are reported elsewhere in these proceedings.) The results from this measurement indicate that the instantaneous stopband makes a negative excursion during part of the thermal transient both for a step increase in power and for a step decrease in power. Hence the tendency for the structure to behave better with the stopband initially high is understandable.

Conclusion

Although much remains to be learned, the work of tuning and testing the LAMPF side-coupled accelerator structure is progressing well. Nearly one-quarter of the linac is now in place in the beam tunnel and has had the accelerating cavities tuned. High-power tests indicate satisfactory performance in the areas of long and short term stability and recovery from thermal transients. Individual cells have fields differing from the average accelerating field by as much at 10%, but beam dynamics calculations give no evidence that these deviations will cause any significant degradation in beam quality or in ease of turn-on provided that the tank averages are set uniformly to ±1%. Procedures and equipment permitting continuous and accurate adjustment of tank-to-tank average levels are incorporated in the tuning process.

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