Tuning of the First 805 MHz Side-Coupled Cavity Module for the Fermilab Upgrade*

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I. Introduction

The FNAL Linac Upgrade provides for the replacement of the last four linac drift-tube tanks with seven side-coupled cavity modules which are more efficient and will operate at higher accelerating gradient (8 MV/m). Each module is composed of four accelerating sections connected with three bridge couplers and is driven by a 12 MW, 805 MHz klystron RF power supply. Sixteen accelerating cells (main cell) and fifteen coupling cells (side cell) are brazed into an accelerating section (fig. 1).

The cavity tuning must meet several requirements for satisfactory beam dynamics. The requirements include 1) The correct frequency of the accelerating mode (805 MHz), 2) proper field flatness throughout a module, 3) Adequate shunt impedance to reach design gradient within the klystron power limits and 4) amplitude and phase stability. Beam dynamics studies indicated that the field distribution could have a ± 2% rms variation from section to section before serious degradation of the longitudinal beam emittance occurred. It was decided to make the average field agree within ± 1% of the theoretical value from section to section and to limit the rms main cell field deviation to ± 1% within any section. This is more accurate than LAMPF(1)(2)(3) (±2%, ±6%).

The tuning of the accelerating mode directly affects field distribution, input cavity power and stability. At the correct accelerating mode of the module, it is desirable for the TM_{010} $\pi/2$ mode of each section and the TM_{010} mode of the individual bridge couplers to agree within 2 KHz of the module accelerating mode. This minimizes reactive fields in the bridge coupling cells and provides a null signal to monitor cavity tuning changes at high power. The stability of the field distribution in the $\pi/2$ mode depends on main cell frequency errors, the relative average tuning of the accelerating and coupling cells (stopband) and the amount of power being transmitted along the structure. Stability is assured by tuning accelerating cells equally, adjusting the average coupling cell frequency higher than accelerating cell frequency (positive stopband) and proper cooling. We tune the accelerating cells to ±10 KHz and the stopband positive 50 to 100 KHz. Water cooling tubes on the edge of the accelerating cells and a programmed water temperature assure proper cooling.

The bridge coupler frequency, $3\beta\lambda/2$ section spacing and bridge coupling cell tuning are adjusted to preserve the correct section to section phase at the $\pi/2$ operating frequency of the module. To present a satisfactory standing wave ratio to the input waveguide and to insure proper field flatness throughout the module, the mode spectrum must be clear of bridge coupler resonances except for the desired TM_{010} $\pi/2$ resonance. Unwanted modes in the bridge coupler are adjusted outside of the section pass-band with tuning posts. To reduce bridge coupler losses coupling to a section is larger than between accelerating cells (7% vs. 5%). Two modes generated by the bridge coupler and coupling cells are adjusted to be symmetrical outside the section pass-band.

II. Post-Braze Section Tuning

Before brazing, the structure is tuned in a clamped configuration to 804.900 MHz. After final brazing, welding flanges and mounting the structure on a cradle, the frequency of accelerating cells and the $\pi/2$ mode are compared to the prebrazed condition. Bridge coupling cells are shorted for these measurements. For specific tuning steps see the tuning notes of Miller.(4)(5) For 16 sections completed, the brazing operation, on average, shifts accelerating cells higher by about 10 KHz. The side cells, which are normally low by 2 to 5 MHz, are easy to tune equal and higher to provide a near zero stop band. From experience we preset the stopband high by about 300 KHz in air. Due to flexing of the side cells, this results in the desired positive 50 to 100KHz stopband under vacuum.

With near zero stopband, the effect of individual cell errors on the field tilt is theoretically zero. Any field deviations in a section are then caused by coupling constant errors. Before further tuning, a bead pull was done to measure the field distribution. If an individual cell field was high or low by more than 1% of the average field in the section, then an attempt was made to understand the cause and make corrections. If the correction was difficult we relied on only keeping the rms field throughout the section to <±1%. There is some indication from the first accelerator module (Prototype R) that errors in coupling of as much as 1% resulted from an offset in the side cell gap centers. This happened when we tuned some inaccessible cells from one side. This exceeds the expected coupling errors due to slot machining tolerances. To control this effect, both sides of the coupling cell are now moved equally when adjusting side cells and coupling accuracy of ±0.5% can be achieved over the length of the section.

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Bending of the web between acceleration cells can affect the nearest-neighbor coupling and hence can cause or correct the local tilt in the field distribution. This can also change the frequency of the two accelerating cells involved as well as the $\pi/2$ mode. Web bending has been used when one cell is higher and an adjacent cell lower than a required final tuning average. After each adjustment of the main cells the $\pi/2$ frequency is rechecked to make an assessment of the amount each accelerating cell must be increased as the structure is brought up to the desired $\pi/2$ frequency. It is important to keep the same conditions such as probe type and shorting configuration when tuning individual cells. Probe re insertion errors can easily cause frequency errors of 30KHz.

The tuning of Prototype R indicated that too large a tuning on any one cell can affect several adjacent cells by as much as 20%. Accelerating cells are therefore tuned in three or four passes. Each pass consists of raising the frequency of main cells by hammer and punch "dinging" of detentes provided on the outside surface of the cell to decrease the inductive volume. End cells are tuned by moving the accelerating nose in or out using a snap-ring groove at the section ends. End cells are properly adjusted when there is minimum energy in their adjacent side cells. Bridge coupling cells are shorted for the section tuning. As tuning progresses, the accelerating cell frequencies converge to a measured spread < 5KHz. At each step the $\pi/2$ mode, each cell frequency and Q are measured.

At the final step the mode spectrum is measured.The modes are used in a dispersion calculation with a five parameter fit to determine cell frequencies, coupling constants and stopband. The side cell $\pi/2$ mode is measured in air with the end accelerating cells shorted. Dispersion calculated and measured $\pi/2$ frequencies agree to within 20 KHz. Measurements, except for the side cell $\pi/2$ frequency are repeated with the section under vacuum to determine the five parameter fit and stopband compared to air. The accelerating $\pi/2$ mode shifts down 4KHz and the stopband shifts down by 270 KHz under vacuum. The disagreement and reduction in the $\pi/2$ mode at vacuum is in part due to a < 0.0004 inch deflection of the cavity ends which lower each end cell frequency about 32KHz. The shift in the stop band is due to deflection of the side cell walls. A stop band between 50 and 100 kHz is accepted. With experience, we have been able to preset the stopband in air so it is about +90 KHz on the first vacuum measurement. After tuning the main cells and side cells to the correct $\pi/2$ frequencies, the shorts on bridge coupling cells are removed and the end cells are tuned. An adjustable tuning cell is put on the bridge coupler ends. The tuning cell is an extended accelerating cell. The section ends are tuned by adjusting this cell and the end accelerating cell until there is zero energy in the bridge coupling cell and the adjacent side cell at the $\pi/2$ frequency. For an ideally tuned section there is no coupling cell energy at the $\pi/2$ mode.

A final bead pull is made before mounting the section on a girder. The field distribution is checked to be within specification and documented. The sections are tuned on different dates and data for atmospheric corrections are taken at different times. When all four sections are on the girder, we re measure the $\pi/2$ frequency and check for stored energy in bridge coupling and adjacent side cells. We also check for shifts due to handling. If necessary, small adjustments are made.

On Prototype R, while we were learning, we intentionally kept the section tuned low because the accelerating cell frequency is not easy to lower. It was originally planned to have individual water temperatures on each section (this may be changed in production) and each section was tuned to slightly different frequencies when corrected for vacuum at 25°C. Table 1 records the frequencies for the sections under vacuum at independent temperatures when nearly equalized. The last column shows the section $\pi/2$ frequency at 25 °C (equal water temperature on each section).

Section	Temperature T (°C)	$\pi/2$, Vac, @ T°C	$\pi/2$, Vac, @ 25°C
R-1	25.0	805.0015	805.0015
R-2	23.0	805.0013	804.9739
R-3	22.7	805.0010	804.9695
R-4	22.0	805.0020	804.9609

Table 1, Section Frequency (MHz)

III Bridge Coupler Tuning

As mentioned above, the purpose of bridge coupler tuning is to get the correct $\pi/2$ mode, phase shift and field flatness between sections with stability. The bridge couplers for the FNAL Linac are $3\beta\lambda/2$. Comparing required lengths (35 to 55 cm) with LAMPF structures and from experience with a 200 MeV prototype we expect three posts to be required for tuning. There are three modes, TE_{111Y}, TE_{111X}, and TM_{011} near the TM_{010} mode. TE_{111X} is the nearest lower mode and TM_{011} is the nearest higher mode. Both modes are out of the cavity chain passband. The two modes were adjusted to be about "symmetrical" with the $\pi/2$ mode by a post at the rear of the bridge coupler (opposite the waveguide feed iris). A fine adjustment was later made to equalize the phase shift across the bridge coupler. This was measured by switching the drive from one end to the other. An example is shown in Table 2 of the modes before and after tuning for the Module 1 section 3-4 bridge coupler.

Mode	TE_{111Y}	TE_{111X}	min,max cavity	TM_{010}	TM_{011}
No Post	744.038	782.008	785.983 835.469	804.765	864.307
Post	750.247	772.661	783.669 832.246	804.763	858.65

Table 2, Module 1 Section 3-4 Modes

The center post was not notched to allow balancing of the section to section fields. Instead, we make a differential adjustment of the end posts when they are used to adjust the TM_{010} mode. After tuning, the posts are clamped in place, marked and then taken to a shop and welded in position. Upon remounting the bridge couplers, the posts require adjusting in or out by < 1/16 inch. Snap ring like grooves in the post are fitted with a tool for this adjustment. A small probe hole is provided at the center top of the bridge coupler to drive or pickup signals during tuning.

When tuning the four sections of a module, each pair of sections coupled with a bridge coupler were tuned first. An adjustable tuning cell, mounted on the bridge coupling cell at the end of each two section pair, was used to keep the sections π/2 frequencies equal during tuning. After tuning end bridge couplers, the adjustable cells were removed and the center bridge coupler was installed and ready to tune. The end tuning posts on the bridge coupler were roughly adjusted first so that the resulting π/2 mode frequency was close to the average of the two sections. Next the center post was adjusted in to make the TE_{111X}, and TM_{011} modes symmetrical with the TM_{010} mode and fixed. The TM_{010} mode increases slightly so the end posts are again adjusted to bring back the π/2 mode to 805 MHz ± 1KHz. A bead pull was made to check field flatness section to section. If it is not flat, differential positioning of the end posts are made. Moving one in and one out keeps the π/2 mode unchanged. Seven iterations were made to complete tuning. The posts were then marked, machined to length and welded in place.

A slot is cut in the center bridge coupler to match the power feed via the waveguide. The slot interacts fairly strongly with the above tuning and all posts have to be retuned after matching to the waveguide. For testing purposes, we slotted to match for minimum reflected power and then retuned the posts. Later it will be necessary to over couple to allow for beam loading. The phase shift was checked across the bridge coupler by driving the structure from one end and then the other while measuring at the accelerating cells nearest the bridge coupler. The bridge coupling cells were tuned to compensate this phase shift to <1 deg. Finally, under vacuum, all measurements were repeated and recorded.

IV Results and conclusions.

The Module 1 Side coupled cavity with bridge couplers was final tuned during April 1990 in the low level RF tuning lab. The π/2 frequency with power iris cut is 805.001 MHz. The stop band is +246 KHz. Driven at the waveguide port, the reflected power is -45db (VSWR = 1.01) The loaded Q is 9544. The individual cell field rms deviation from average in each section is less than 1%. The average field in each section agrees with the theoretical value calulated. The peak field decreases 0.5% over the module length due to gap spacing as ß increases. (See Fig. 2)

The four sections were checked at a single temperature (keeping the π/2 frequency constant). The field tilt from R1 end to R4 end was 5%. Changing R1,R2 down $4^{o}C$ and R3,R4 up $4^{o}C$ the π/2 frequency remained unchanged and the field tilt was 16% from the R1 end to the R4 end. Tuning experience has progressed so that by Module 3 we have been able to tune sections to agree to ± 1KHz. That plus the tilt sensitivities measured above suggest a single temperature water system will be adequate. We will decide on retuning all modules for a single water system temperature after the full power test of the prototype module.

Adequate tuning procedures have been developed for the Fermilab Linac Upgrade tuning. They continue to be improved to facilitate production and provide a simpler cooling system.

References

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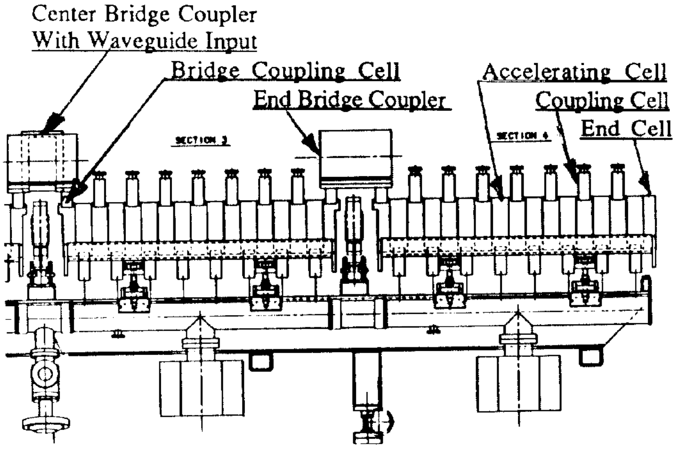

Fig.1, Module 1, Section 3&4

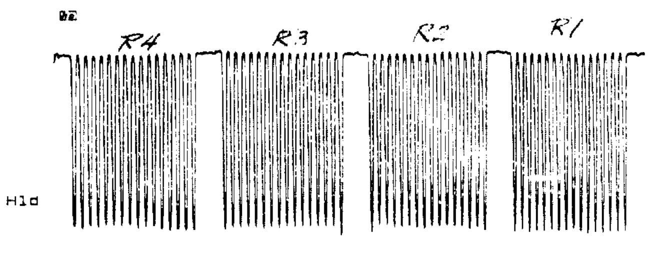

Fig.2, Module 1 Beadpull after Final Tuning