FINAL MODULE TUNING OF THE 805 MHZ SIDE-COUPLED CAVITIES FOR THE FERMILAB LINAC UPGRADE*

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Introduction

As a portion of the Tevatron Collider Upgrade program, the Linac Upgrade will increase the energy of the existing 200Mev linac to 400Mev in order to reduce beam emittance degradation in booster. This project 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 high accelerating gradient (8MV/M). Each module is composed of four accelerating sections connected with three bridge couplers and is driven by a 12MW, 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)

In October 1990 the first 805 MHz side-coupled cavity module started to be tuned, till March 1992 almost one and a half year all seven modules were fabricated, tuned and tested with high full power (about 11 MW) and put into the tunnel for further test. The results indicated that the requirements for satisfactory beam dynamics were met. The $\pi/2$ mode of each section and the TM_{010} mode of the individual bridge coupler agreed within 2KHz of the module accelerating mode, the accelerating cell frequency was tuned within ± 5KHz and the section stopband were 50-100KHz under vacuum. The main cell rms field deviation was <1% within any section except module 2 section 3 (<1.3%) and the section average rms field deviation was <1% except module 1 (<1.5%). The Phase shift from section to section were tuned to <1°. The coupling between waveguide and cavity was tuned match with 30 ma beam loading.

Operating mode and field flatness

The module tuning mainly is to tune the bridge coupler, the bridge coupler has its own modes, it is desirable that TM_{010} mode of the individual bridge coupler agrees within 2KHz of the module accelerating mode. Around the TM_{010} mode there are four modes, TE_{111y} TE_{111x} TM_{011} and TE_{112y}, which may has some effection for operating. It is also desirable all these modes are out of the section passband, if possible, to make the nearest lower mode "symmetrical" with the nearest higher mode about the $\pi/2$ mode by tuning the post at the rear of the bridge coupler. If any of the above modes enters in the section passband, it will perturb the cavity operation.

The bridge coupler for the FNAL Linac are $3\lambda/2$ long, the length of the bridge couplers are from 35cm to 55cm. It is shorter comparing with LAMPF structures, all these modes were out of the section passband, only first module's TE_{111x} was too closed the edge of the passband. The center post interacts strongly with TE_{11n} modes but only weakly with TM_{01n} modes. One may can use it to move TE_{111x} down to make "symmetrical" with TM_{011}, but after module 2 the TE_{111x} was too low to make "symmetry" by adjusting center post penetration. Infact the center post was not necessary for moving the bridge coupler modes because it was considered t if the mode was out of the section passband it's perturbation on the field was negligible, but it can be used for trimming. The phase shift between sections was compensated by tuning bridge coupling cell.

Before the section was put onto the girder, the $\pi/2$ mode was tuned at 850 MHz corrected with vacuum and 25^0c. Since it was done at different time and werther, after all sections were put on it with water cooling, it was found there was < 10KHz defference between sections. (LAMPF the $\pi/2$ mode of the tanks were made to fall in the range 805.000 ± 0.010 MHz). In our case it is impossible to make minimun energy in both attached bridge coupling cells if the section $\pi/2$ modes were defferent. If it was happen, it would be retuned into <2KHz. One can get the defference of the $\pi/2$ mode frequency between sections by tuning minimun energy (field) of operating mode in the bridge coupling cell. Fig.2 shown the minimun energy (field) of the operating mode in the end coupling cell and bridge coupling cell of the module 5 after final tuning.

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The end post was not only for tuning bridge coupler TM_{010} mode equal to the $\pi/2$ mode of the section (like LAMPF), but also for balance the average field of sections. While one tuned bridge coupler TM_{010}, the beadpull was done to check field flatness, several iterations were needed. One can change center post penetration to slightly change TM_{010} but field flatness. When tuning the four-section module, each pair of sections coupled with a bridge coupler was tuned first. If two pair $\pi/2$ modes were defferent more than 2KHz, retuned it. Fig.3 shown the field (E^2) flatness of the module 5.

Mode dispersion and stopband

For coupled resonator module of double periodic accelerator section with nearest neighbor and next nearest neighbor coupling the theoritical analy indicated the dispersion relation is

$$k_1^2 \cos^2 \varphi = (1-\omega_1^2/\omega^2 + k_2 \cos 2\varphi)$$
$$*(1-\omega_2^2/\omega^2 + k_3 \cos 2\varphi)$$

Here k_1, k_2, k_3 are nearest, main cell to main cell, and side cell to side cell coupling constant. ω_1, ω_2 are main cell and side cell resonal frequency, φ is mode phase shift from cell to cell. When $k_2 = k_3 = 0$ the dispersion relation have two similar branches with a stopband between ω_1 and ω_2. If $\omega_1 = \omega_2$, the stopband is zero, be defined confluence , two branches are connected and antisymmetric with $\pi/2$ mode, the modes spacing are equal. It results in an increased mode specing around the operating mode and a non-zero slope of the dispersion curves at this mode, therefore the non-zero group velocity obtained. If $k_2 \neq k_3$ $k_2, k_3 \neq 0$ the accelerating cell and the coupling cell resonal frequencies are $\omega_a = \omega_1/\sqrt{1-k_2}$ and $\omega_b = \omega_2/\sqrt{1-k_3}$,the stopband $\Delta\omega = \omega_a - \omega_b$ and two branches are not antisymmetric, their widthes are defferent. In our case the widthes were about 15.5-16.5MHz and 23.5-24.5 MHz respectively from module 1 to module 7. The mode spacing below operating point was smaller than that of above operating point, therefore the stopband calculated by mode spacing was higher than reality, only when k_2, k_3 are very small or equal, it is true. If possible it is better to get the stopband by measuring ω_a and ω_b. Table 1 shown the section stopband of the module 2, it indicated that the stopband calculated with mode spacing was about 100 KHz higher

Table 1, The section stopband of the module 2

	section#	1	2	3	4
stop-	nearest modes	402	404	421	409
band	modes fit at Air	322	337	336	343
(KHz)	modes fit at Vac	88.7	100	84.5	87.6
	used ω_a ω_b.Air	321	290	354	336

Under vacuum the coupling cell was squeezed, ω_b moved down about 280-110KHz from the section 1 of the module 1 to the section 4 of the module 7, but ω_a only changed a few KHz (<5KHz) so the stopband moved dowm too. In our case it was easy to tune the stopband to near zero, but the plus stopband could compensate field error caused by frequency error of the main cell and it tend to move in negative direction over a period time, so it was tuned 50-100KHz under vacuum.

The module composed with four sections and three bridges attached, three sets additional modes added in between the section modes spacing, these modes distribution mainly depend of the frequency of the bridge coupling cell, especialy the nearest operating modes strongly depend on two center bridge coupling cell frequencies, if one only used these modes to decide the module stopband, it was mistake. But normally it was tuned to close the section stopband if phase shift between sections was met. Fig. 4 shown the effection of the bridge coupling cell frequency to modes distribution.

Phase shift between sections

The change in phase between sections was measured as the drive point was switch from one end of the linac unit to the other. For two side bridge couplers (attached section 1-2 and section 3-4), adjusting the coupling cell frequency can easily make phase shift within 1°, two coupling cells and bridge coupler phase shift compensated each other. How compensation was not cared, two coupling cell frequencies might be big defferent, but it is better to keep each side uniform. For the center bridge coupler the change in phase was measured as the drive point was at waveguide too, the phase shift conpensation were not only from section to section but waveguide to sections. It was found that when upstream coupling cell frequency changed, the change in phase drived at waveguide and down stream had same direction, It drived at upstream had oppsite direction with much more sensitive, vice verse. Before the phase shift tuning one had to mersure phase shift with defferent drive way and recorded the data to decide the tuning strategy. Since any tuning would effect phase so it would be done at last step. Finally all of the phase shift were tuned within 1°. Table 2 shown the phase shift in the module 7.

Table 2, The phase shift of the section to section of the module 7

Bridge coupler#	1-2	2-3	3-4
drive at up Stream	86.3	173.8-.9	179.1
drive at down Str.	86.4	173.8-.9	178.7-179.2
drive at waveguide		173.9	
Phase shift (degree)	0.1	0.1	0.5

As it was said above, after phase shift tuned the bridge coupling cell frequency was remeasured, for the module 6 and 7 the results shown in table 3.

Table 3, Bridge coupling cell frequencies (MHz) after phase shift tuned

module#	section 1-2		section 2-3		section 3-4	
6	826.315	828.577	821.587	822.014	829.120	829.378
7	832.293	832.255	825.925	826.057	833.090	833.051

It indicated that the longer the bridge coupler was the higher the frequency of the bridge coupling cell needed and the center bridge coupling cell frequency was lower than that of sides, becurse of waveguide coupled. It also shown that the frequencies of two side cells attached same bridge coupler were very close. The frequency of the center mode of the system composed of the bridge coupler and two coupling cells with main cell shorted in the module was slowly increase from upstream to down stream in the module and from first module to last one.

Coupling of the waveguide to cavities

The coupling coefficient of a transmission line to a resonant cavity is given by $\beta = Q_0/Q_{ext}$

$$1/Q_l = 1/Q_0 + 1/Q_{ext}\ , \qquad \rho(VSWR) = Z/Z_0 = \beta ,$$

$$reflect\ coefficient\ \Gamma = \frac{\rho - 1}{\rho + 1}$$

A slot was cut in the center bridge coupler to match the power feed via the waveguide for 30ma beam loading. There was a director on the waveguide for measuring forward and revers power to check the coupling coefficient. Compared with Q_0 and Q_l, one can know if there was under or over coupling. The slot interacts fairly strongly with center bridge coupler tuning, especially TM_{010} mode frequency, so the tuning of match had to be done before the post welded, after the post welded only small adjust was possible, the center post could be used as trimming.

References

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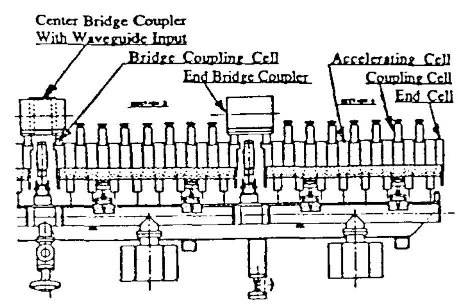

Fig.1. Module 1, Section 3&4

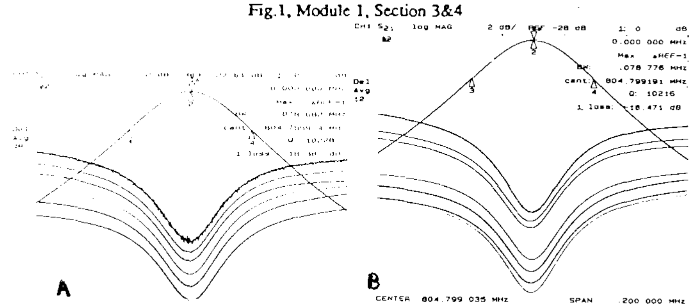

Fig.2 The energy in the end coupling cell (A); The energy in the bridge coupling cell (B) of the operating mode of module 5.

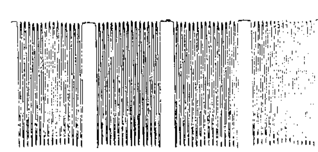

Fig.3 The field flatness of module 5

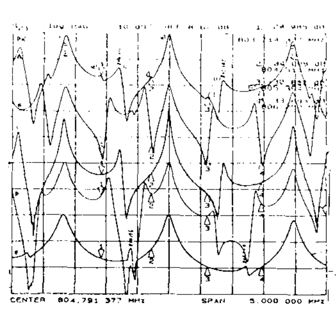

Fig. 4 The effection of the bridge coupling (side) cell to modes distribution.

A, After final tuning modes distribution.

B, Shorted upstream two bridge coupling cells.

C, Shorted center two bridge coupling cells.

D, Shorted downstream two bridge coupling cells.

E, Shorted both up and down stream four bridge coupling cells.