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TUNING METHODS FOR THE 805 MHZ SIDE-COUPLED CAVITIES IN THE FERMILAB LINAC UPGRADE

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Abstract

The fabrication and tuning of Side-Coupled Accelerator Structures (SCS) are strongly interrelated. Consideration of mechanical tolerances and fabrication sequences can reduce tuning steps that require repeated machining. With available CNC machines and numerical calculation programs, it is possible to machine cavities to a calculated shape. Accelerating cells are tuned by control of the depth of coupling slots rather than trimming the nose of accelerating cells. Predicting the correct frequency off-sets to use at each manufacturing stage produces a brazed structure of proper coupling with a minimum amount of tuning.

Introduction

Our structure consists of sixteen accelerating cells and fifteen coupling cells brazed into an accelerating section. There are twenty-eight sections in seven rf modules of the Linac upgrade. Construction schedules require that one section be completed every two weeks. Structure tuning and assembly must progress rapidly. Reducing repeated tuning steps was one goal. An automated measurement system is being implemented. [1]

Optimization of the structure was the result of many contributors. Nose cones were carefully shaped to insure minimal sparking. We decided that we would machine the noses once, including ends, and not trim them to adjust the cell frequency. This reduces the chance of scratching the high field region. End frequency adjustments are made in the "inductive" regions (cavity wall) of the cells. Field variation along the structure due to nose cone differences are eliminated.

Our SCS consists of a stack of 15 "interior" segments terminated with a bridge coupler cell at both ends or a bridge coupler cell and terminating cell at each end. For initial tuning, ends are terminated with flat plates. Basic interior segments consist of two accelerating half cells joined through a coupling slot with a coupling cell. This half terminated assembly supports a $\pi/2$ mode. The mode is higher than for a fully terminated interior cell and as cells are stacked the $\pi/2$ frequency is reduced. A plot of the $\pi/2$ frequency vs $1/n$ (the number of half cells) will project the correct $\pi/2$ frequency for an infinite stack. This frequency of the structure is maintained when fully terminated.

A coupling slot is cut into the accelerating cell body after machining the half cells to a SUPERFISH(SF) calculated frequency, f(SF). The depth of the slot is adjusted for the desired $\pi/2$ frequency. Increased depth of the slot lowers the frequency and increases coupling between accelerating and side cells. The length of the coupling slot is estimated for 5% coupling with full slot depth as β varies for each section. LAMPF data were used to estimate early values of f(SF) and coupling slot dimensions. Subsequent construction of R1 through R4 (sections of a prototype module), and aluminum models have allowed us to refine the values for f(SF) and given us reliable Δf values as the slot depth is changed. [2]

A standard five parameter model is used to describe the dispersion of the field modes in the passband. An adequate description is given in ref 1. Final tuning of the structure makes use of the fact that all accelerating cells are tuned to a frequency $\omega 1$ and all side coupling cells are tuned to a frequency $\omega 2$. When actually measuring the cells, the frequencies are not the same as the values calculated by the dispersion equation. Any method of shorting adjacent cells shifts their frequency. Probes inserted consistently provide controlled offsets in each cell. With cells at the same frequency tuning is straight forward. We start with the $\pi/2$ frequency low and just move all the accelerating cells up the amount of

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the error. If the stop band is off we move all the coupling cells the appropriate amount.

Individual cells are all identified and numbered. Frequencies are measured using an HP 8753C network analyzer and recorded on an Excel spread sheet. Temperature, barometric pressure and humidity are recorded for each measurement. Excel is used to correct frequencies to vacuum at 25 C. and for statistical data.

SUPERFISH Measurements

The CNC program is verified both mechanically and electrically on a sample part. Seventeen (two spares) accelerating interior cells without coupling slots are machined to final SF calculated dimensions and delivered to the tuning lab. They are inspected for mechanical defects, and cell length is measured and recorded. The rim is lightly lapped with 15 micron aluminum oxide coated mylar on a granite surface plate to verify flatness and remove copper oxide from the contact surface. Mechanical tolerances are met within 1 mil. Cells are clamped in a special fixture with flat copper terminating plates. We directly measure the SF frequency and Q of the half cells. Our goal is for an average and spread of frequencies within ± 300 KHz of calculated SF values. Table 1 shows our Prototype R machining experience. (frequencies are in MHz.)

Table 1
Prototype R Superfish Machining

Section	R4	R3	R2	R1
Target SF	820.20	820.39	820.59	820.80
Mach. Avg.	820.32	820.21	820.50	820.62
Off-set	+0.12	-0.18	-0.090	-0.18
Spread	0.657	0.535	0.398	0.365
Std. Dev.	0.193	0.108	0.102	0.086

Stacking Order

High and low frequency half cells are paired in a stacking order to best equalize the interior accelerating cells. The goal is to have frequencies within ± 30 KHz. High and low frequency half cells are placed at the ends where their frequency errors are incorporated into the terminating end tuning. Cells midway between highest and lowest are reserved as spares and can replace any cell in the stack. The paired results of selective stacking are shown in Table1.

Slotting

The slot depth is made using a cutter arc identical to the inside radius of the coupling cell. The cutter center is spaced relative to the center of the accelerating cell. A 7.2441 inch center spacing between the coupling and accelerating cells gives full penetration for the slot. We adjust target SF values, which range from 821.59 to 815.71 MHz with ß so that the pre-brazed stack is at 804.900 MHz when the center spacing is 7.264 inches. Typically, the frequency change, $\Delta f/\Delta center$ ranges from 27 to 17 KHz per 0.001". A minimum of ±340 KHz frequency adjustment and associated coupling k1 of 4.7±0.1 % over a ±0.020" center spacing variation is expected. If the SF frequency drifts out of the adjustment range, we have three options. 1) Continuously correct Target SF values as sections are fabricated. 2) If cells are too low the slot can be backed out with small reduction in coupling k1. 3) High cells can be remachined to correct their frequency. We have succesfully used option 1 for most sections. In section R2 where an unintended .002 inch taper of the web thickness from outer to inner radius caused six half cells to be 600 KHz low, we used step 3) to bring them back into range.

We determine the exact slot depth by a sequence of three cuts in the first five accelerating cells of the stack. The paired average SF frequency of the cells is compared to the target SF value and the slot center spacing is adjusted to the expected value for 804.900 MHz. We increase the expected center spacing by .020" and cut the first slot depth. The five cells are stacked in order and the $\pi/2$ frequencies measured and plotted vs the number of half cells to establish the infinite stack $\pi/2$ frequency. A second cut made half way between the measured and final expected value establishes a verification of the $\Delta f/\Delta center$ for the cell. We calculate, cut and verify the third and final slot depth cut. Finally bridge end cells, followed by the accelerating cells, are slotted to the final depth.

End Terminations

End cells are tuned lower than interior cells. Material is removed at the outside radius of terminating ends and below the slot in bridge ends. Cut-out dimensions are determined by clamping the ends on the stack of five completed cells while the machining of the remaining cells proceeds. End cell frequencies are lowered to the projected $\pi/2$ frequency by capacitive loading of the gaps. Balance is established by tuning for minimum energy in the adjacent side cells. Loop pickups inserted through the vacuum ports verify that there is little energy in all side cells. Cells adjacent to the ends are shorted and the end cell frequency is measured. The capacitive loading is removed and the resultant Δf is determined. A SF graph of Δf vs cut-out is made ahead of time for each section. Dimensions are simply taken from the graph and parts taken to the machine shop.

Pre-Braze Measurements.

After final machining the full structure is clamped together on the stacking fixture. Each accelerating cell and the $\pi/2$ frequency are measured and recorded in a spreadsheet. For individual cell measurement shorts are placed in adjacent cells. Shorts in side cells have appropriate spacers so that when the cells are re-measured after brazing on vacuum ports they are re-inserted to exactly the same position. Shorts on adjacent accelerating cells are accomplished by a centerless ground rod .002 inches under the bore size slid across the gap. This capacitively shorts out the desired cells. There are no fingers to scratch or fall off in the bore.

Post-Braze Measurements

After final brazing, welding on flanges and mounting the structure on a permanent cradle the frequency of accelerating cells and the $\pi/2$ mode are checked and compared to the pre-brazed condition. An assessment is made of the amount each accelerating cell must be increased to bring the structure up to the desired $\pi/2$ frequency. Checks here are intended to determine shifts in brazing and handling and to guide us in determining if 804.900 MHz. is low enough to insure all cells will need to be raised.

Section Tuning

Accelerating cells are tuned in a first pass to the same frequency and for a $\pi/2$ frequency of about 804.970 MHz. Indentations machined into the cell walls are pushed in with a punch to raise the cell frequency. Side cells are equalized to 805.030 MHz. Threaded studs brazed on the side cells allow their gap to be pushed in either direction. With our probe designs, cell frequencies can be equalized to ±5 KHz. End cells are adjusted by moving the end wall. A snap ring type groove in the end wall and special tool allow gap adjustment in or out. The frequency shift is about 100 KHz. per .001 inch. Ends are adjusted for minimum energy in the adjacent side cells. A "tuning cell" with adjustable nose pieces is mounted at the flange of the bridge coupling cell. The tuning cell and the end accelerating cell are tuned together until there is minimum energy in both the adjacent side cell and bridge coupling cell. Next the bridge coupling cell is shorted with a band of copper wrapped around the nose. The cell frequency is raised about 160 KHz with this configuration. We load the gap capacitively and measure all thirty-one modes in this configuration. A dispersion program is run and the frequencies, couplings and stopband are determined.

Vacuum Measurements

The section is put under vacuum and the modes are measured. The $\pi/2$ frequency and the stop band are determined and compared to the first pass tuning. From experience we find that the $\pi/2$ mode measured under vacuum is about 18 KHz lower than when it is corrected from atmospheric conditions. The stopband moves down 280 KHz due to deflection of the side cell walls. With measured offsets we retune the structure to 804.966 ± 0.01 MHz with a stopband of +150 KHz under vacuum at 25 C. Each section will have an independently controlled water loop and differential tuning between sections will be adjusted thermally.

Conclusion

We have developed tuning techniques that, in concert with mechanical fabricators, has lead to an efficient fabrication process and allowed the major machine work to be done by industry.

References

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2 T. Jurgens, H.W. Miller, A. Moretti and P. Zhou, 1990 Linear Accelerator Conference, (September 1990)