TUNING, CONDITIONING, AND DARK CURRENT MEASUREMENTS: 1300 MHZ NCRF CAVITIES AT THE ARGONNE WAKEFIELD ACCELERATOR (AWA) FACILITY*

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Abstract

In this paper, we present data on: (i) tuning and balancing; (ii) high-power rf conditioning; and (iii) dark current measurements; of normal conducting, standing wave, 7 cell, 1300 MHz accelerating cavities. The six cavities were tuned to 1300 MHz and were balanced to >96% in all cells. They are designed to operate with 10 MW of rf input power but are being rf conditioned beyond this operating point to insure low dark current during operation. During rf conditioning, dark current measurements are being recorded to provide a history of the cavity's surface field enhancement factor, *"β"*, throughout the rf conditioning period. Finally, as the final step we plan to record the breakdown rate at 10 MW to add to the breakdown literature for L-band cavities.

INTRODUCTION

Six normal-conducting, L-band rf cavities are currently undergoing commissioning as part of the linac upgrade to the AWA facility [1] to increase the drive beam energy from 15 MeV to 75 MeV. The cavity design (Fig. 1) is a seven-cell, standing-wave, 1300 MHz cavity made with OFE copper and was reported on earlier [2]. As of September 2013, all six cavities have been tuned and balanced but only one of the six cavities has been conditioned. In the first section of this paper we describe the tuning and balancing of all six cavities and in the second half of the paper we describe the rf conditioning of the first of the six cavities including measurements of dark current and the field enhancement factor, β, during the rf conditioning process. The remaining 5 rf accelerating cavities will be rf conditioned during the Fall of 2013.

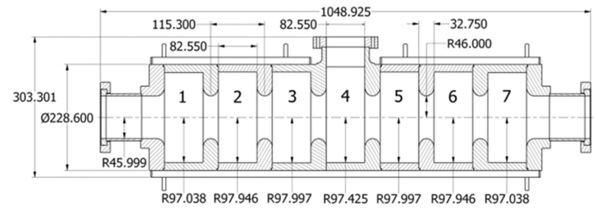

Figure 1: Cross section of the AWA rf cavity.

RF CAVITIES UPON ARRIVAL

Turnkey fabrication of the AWA cavities was enabled by a combination of high fidelity simulations using Omega3p [3], tight machining tolerances, push-pull tuning divots, and the adaptation of a well understood braze joint based on a SLAC design. Using this approach, the cavities were machined to final dimensions (i.e. without iterations), brazed together, and sent immediately to Argonne for tuning and balancing.

Table 1 lists the major figures of merit of the six cavities upon arrival from the vendor. The cavity Q0 was ~98% of ideal and the inter-cell coupling constant, *k*, was 99.5% of design. While neither of these is subject to adjustments during tuning they were within acceptable limits anyway. The cavities came back from the vendor with resonant frequency, f_0, that were between 290-568 kHz low and all cells had voltage field balance better than 87%. These values, for f_0 and balance, were very nearly acceptable without any tuning and balancing. Moreover, all cavities were within the estimated tuning range based on the combination of the push-pull divots and the temperature adjustment of the cooling water.

Table 1: Designed vs. Achieved Cavity Figures of Merit (upon arrival from vendor)

Parameter	Design	Cavity #1	Cavity #2	Cavity #3	Cavity #4	Cavity #5	Cavity #6
f0@38C	1300	-344 kHz	-290 kHz	-406 kHz	-568 kHz	-424 kHz	-360 kHz
T@1300	38^0C	38^0C	20.8^0C	23.6^0C	17.7^0C	9.6^0C	20.0^0C
Q0	25147	24911	24006	24798	24975	24768	24798
Beta	1.28	1.31	1.21	1.27	1.27	1.25	1.27
S11		-19.4dB	-20.2dB	-18.4	-18.5	-19.1	-18.5
Balance	100%	>93%	>90%	>95%	>93%	>87%	>99%
k	2.21%	2.2%	2.2%	2.2%	2.2%	2.2%	2.20%
S21-probe	-60dB				-61.95dB		-61.0dB

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TUNING AND BALANCING

Tuning Divots

Four push-pull tuners (Fig. 2) were used on each of the 7 cells of the rf cavities for a total of 28 divots. The advantage of push-pull tuners over push divots is that they allow for correction of machining errors in either direction. Tuning studs were brazed into holes on the side walls that had I.D. = 1.0" and a floor thickness = 1/8". Based on these dimensions, we estimated that the maximum tuning divot range was equal to half of the floor thickness or 62.5 thousandths. Estimating the volume this would displace, we used SUPERFISH to estimate that the maximum frequency range of the divots would be +/- 80 kHz per cell for a total tuning range of 560 kHz. However, not all of this tuning range can be applied to the frequency shift of the π-mode since the divots must also be used to correct the field imbalance.

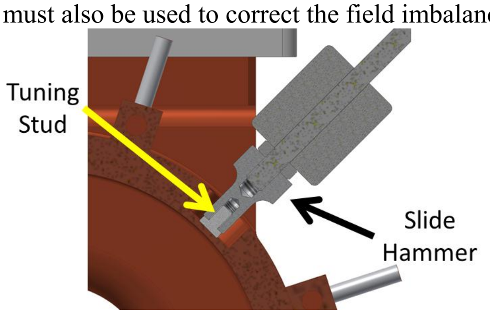

Figure 2: Cross section of a cell with tuning stud brazed in place and slide hammer screwed onto stud.

Beadpull

The beadpull measurement was simulated with SUPERFISH to optimize the size of the bead and the step size to use during the bead pull. The bead used was a metal (Al) needle of length = 0.2", O.D.=0.25", and I.D.=0.008" and was pulled through a horizontal mounted cavity by a 10 pound nylon fishing line with O.D. = 0.007. Beadpull results for all cavities upon arrival from the vendor are shown in Figure 3.

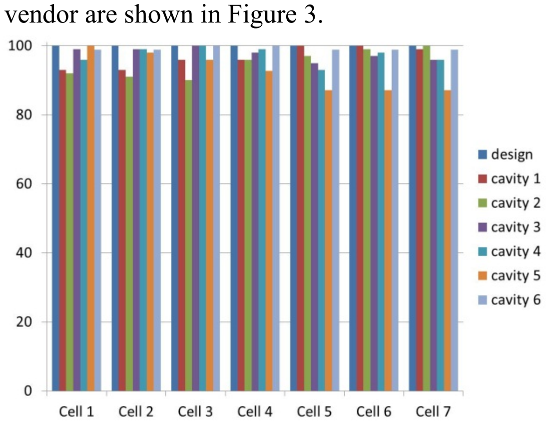

Figure 3: Initial beadpull results before tuning.

Tuning Algorithm

The standard tuning algorithm [4] uses a coupled circuit to model the ideal eigenmodes and eigenvectors while using perturbation theory to model the cavity errors. This algorithm was implemented with an in-house set of matlab codes. The general procedure was to input the frequency shifts due to imbalances from the beadpull measurements into the code to determine the frequency corrections (δf_c) and add that to the overall frequency offset of the π-mode(δf_π). The sum of these ($\delta f_c + \delta f_\pi$) is then applied to the cavity via the tuning divots.

Tuning and Balancing Results

Given that the cavity's frequency tunes were off by 290-568 kHz and that field balance was within 87% of design, then the range of the divots (~560 kHz) is slightly insufficient for a total correction. Several options were considered. We could add 4 more divots per cell but this has the risk of damaging the cavity. We could push divots beyond 62.5 thousandths. In the end, these two ideas were considered too risky and, instead, we decided to lower the operating temperature from 38^{o}C to 20.7^{o}C. Since the tunnel where the linac is installed is air conditioned and the dew point is below 13^{0}C there is no downside to this.

The calculated frequency corrections for the field imbalances were within the range of the tuning divots (80 Hz per cell) in the vast majority of the cases. However, in 3 cases the correction for the largest cell was larger than 80 kHz (Table 2, bold) so the corrections were scaled down. The actual corrections that were applied to each cavity are shown in Table 2.

Table 2: Tuning Applied with the Divots

	Cav 1	Cav 2	Cav 3	Cav 4	Cav 5	Cav 6
Cell 1	0	-28.2	18.9	42.7	-12.4	1.8
Cell 2	0	-15.0	10.991	26.497	4.7	19.6
Cell 3	-10.9	-20.3	-41.6	2	-1.3	-23.2
Cell 4	-37.0	-50.6	-25.0	3.2	-14.5	-29.2
Cell 5	18.6	80.0	**81.2**	**85.656**	**80.9**	40.5
Cell 6	22.1	-22.9	-5.2	38.575	6.8	1.2
Cell 7	12	-11	8.5	25.2	8.8	-10.7

The final frequency of the π-mode was 1300 MHz at an operating temperature of 20.7 ^{o}C. The final field balance, obtained after adjusting the divots, (Fig. 4) had a mean value of 99% and was greater than 96% for all the cells in all the cavities.

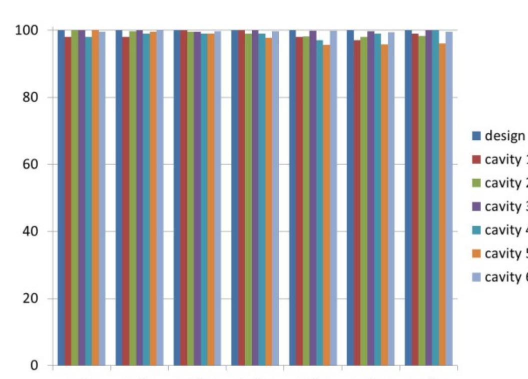

Figure 4: Final beadpull results after tuning.

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RF CONDITIONING

The AWA rf accelerating cavities were conservatively designed to operate a peak surface electric field of Ez=33.5 MV/m at an input power of P=10 MW. The cavities are being rf conditioned beyond this operating point to insure low dark current during operation. As of September 2013, only 1 cavity has been conditioned and we present the results here.

Dark Current

During rf conditioning, dark current measurements were recorded at the end of each phase of conditioning. The dark current was not directly measured but the x-rays generated by the dark current (verified to be linear with dark current) was measured instead (Fig. 5) with the light emitted from a phosphor screen and a PMT.

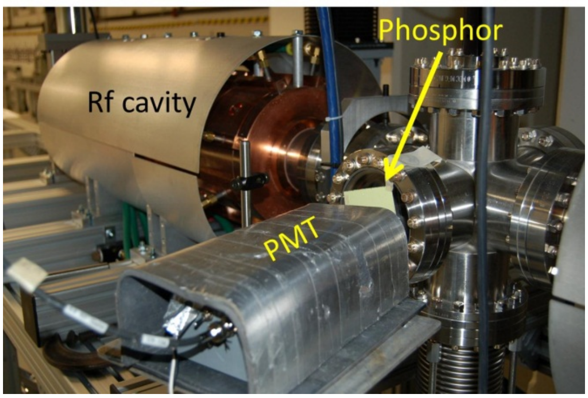

Figure 5: Setup used to measure x-rays from dark current.

Dark current was measured immediately after we had conditioning up to one of the fixed power levels (3, 6, 9, 12, 14 MW) for the first time. This insures that the cavity surface had never seen higher fields than the conditioned level. At that point, the power was lowered back to P=0 MW and the intensity of the phosphor light (proportional to the x-rays which is a proxy for dark current) was recorded as a function of input power (Fig. 6). The data clearly shows that the dark current emitted by the surface is less at the same field after the cavity has been conditioned beyond that point.

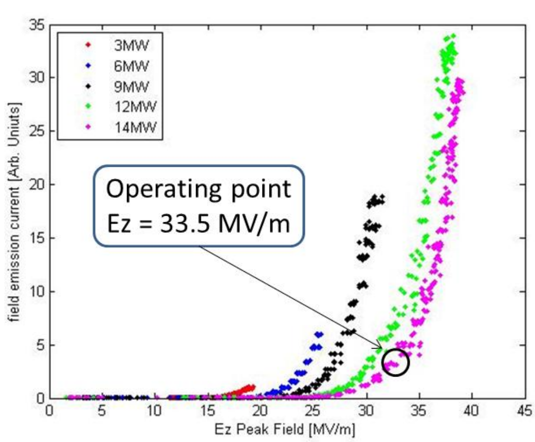

Figure 6: Conditioning History. (dark current vs. field)

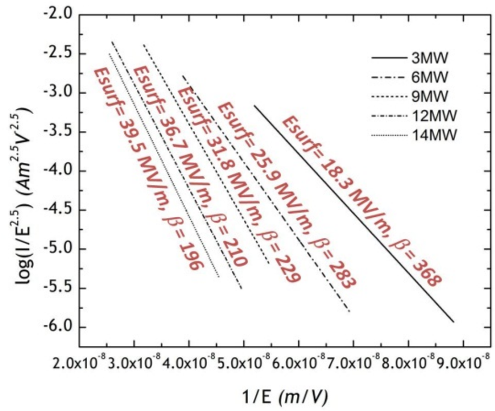

Figure 7: Conditioning History. (β enhancement factor)

The dark current data (Fig. 6) was used to make Fowler-Nordheim (FN) plots (Fig. 7) to get fits of the cavity's surface field enhancement factor, "β", throughout the rf conditioning period. Interestingly, this confirms the not so commonly known rule-of-thumb that the highest field to which the cavity has been conditioned to (E_{SURF}) multiplied by the field enhancement factor (β) is equal to a constant. We can convert the conditioning rf power levels tested to field using the cavity normalization E_{surf}=33.5 MV/m at P=10 MW. Using this, the fields are E_{SURF} = {18.3, 25.9, 31.8, 36.7, 39.5} MV/m. Fitting to the FN data gives β = {368, 283, 229, 210, 196}. Finally, we calculate the product βE_{SURF} = {6.7, 7.3, 7.3, 7.7, 7.7} GV/m and the rule βE_{SURF} = 5-10 GV/m is confirmed.

SUMMARY

Six normal conducting, standing wave, 7 cell, 1300 MHz accelerating cavities for the AWA linac upgrade have all been tuned and balanced. The first of the six cavities has been conditioned to 14 MW and dark current measurements were made. The remaining cavities will undergo rf conditioning soon and we plan to repeat dark current measurements for each cavity. Finally, we will record the breakdown rate at the operating power, P=10 MW, for each cavity.

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