High Field Conditioning of Cryogenic RF Cavities*

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Abstract

Space-based and other related accelerators have conditioning and operation requirements that are not found in most machines. The use of cryogenic copper, relatively poor vacuum, and limited power storage and operating time put unusual demands on the high-field conditioning process and present some concerns. Two CW cryogenic engineering model "sparker" cavities have been fabricated and tested at Grumman to address some of these concerns. Results of these tests have been very positive. The cavities have been tested to fairly high field levels. Tests included initial and repeated conditioning as well as sustained RF operations. The two cavities were an engineering model DTL and an engineering model RFQ. Both cavities operated at 425 MHz. The DTL was conditioned to 46 MV/m at 100% duty factor (CW) at cryogenic temperature. This corresponds to a gap voltage of 433 kV and a real estate accelerating gradient (energy gain/total cavity length) of 6.97 MV/m. We believe this to be record performance for cryo CW operation. During cryo pulsed operation, the same cavity reached 48 MV/m with 200 μsec pulses at 0.5% DF. The RFQ was conditioned to 30 MV/m CW at cryo, 85 kV gap voltage. During a brief period of cryo pulsed operation, the RFQ operated at 46 MV/m, or 125 kV gap voltage. Reconditioning experiments were performed on both cavities and no problems were encountered. It should be noted that the vacuum levels were not very stringent during these tests and no special cleanliness or handling procedures were followed. The results of these tests indicate that cavities can run CW without difficulty at cryogenic temperatures at normal conservative field levels. Higher field operation may well be possible, and if better vacuums are used and more attention is paid to cleanliness, much higher fields may be attainable.

I. INTRODUCTION

The use of accelerators in space presents special problems that are not encountered with most machines. The use of cryogenic copper for machines that require CW operation is favored since the resistive wall loses can be reduced by cooling with on board liquid hydrogen fuel. Vacuum levels are generally in the range of 10^{-6} to 10^{-7} Torr as opposed to the 10^{-8} Torr or better that one typically encounters in normal machines. The most significant problem may be that the amount of operating time available in space is dictated by the amount of energy stored on the platform. Conditioning requirements must be fairly well known in advance, and cannot be excessive.

A series of experiments was conducted to address these concerns. Two engineering model RF cavities, a drift tube LINAC (EMDTL) and a radio frequency quadrapole (EMRFQ), were fabricated. The designs were representative of cavity designs for real machines. Tests were performed to explore the difficulties of operating cryogenic copper cavities in vacuums of 10^{-5} to 10^{-7} Torr. High field operation of these cavities was explored. Tests were also performed to determine the requirements for reconditioning cavities after periods of inactivity, and to quantify the time required for any such reconditioning.

II. CAVITIES

Figure 1 shows the EMDTL cavity. Table 1 outlines some relevant parameters. The cavity consists of two complete DTL cells. It was manufactured from OFHC copper with an as machined finish. The RF surfaces of the cavity were treated to obtain high Q Enhancement Factor (QEF) [defined as Q(room temp)/Q(operating temp)]. The treatment, developed at Grumman, includes a deoxidation dip followed by a brightening and passivating treatment. No additional cleaning or bake out of the surface was performed. After assembly the cavity was stored in a machine shop environment.

The cryostat is a stainless steel vacuum vessel with twenty-five layers of super insulation separating the cavity from the vessel walls. Supercritical neon cryogen (27 K @ 425 psi) cools the cavity. Design operating temperature for both cavities is between 31K and 34K, although during the longest operating periods the cavities reached 41K.

The forward and reflected powers were measured using a

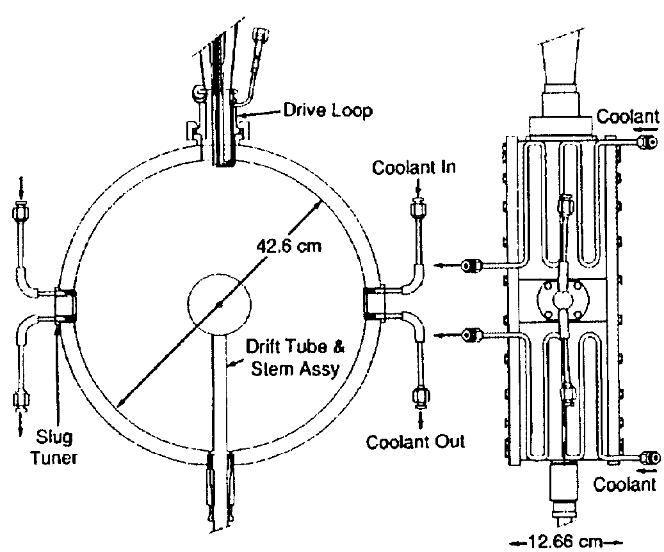

Figure 1. Engineering Model DTL Cavity Showing front cross section and exterior side view

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	EMDTL	EMRFQ
Cavity Parameters at Cryo (31 K)		
Frequency (MHz)	424.430	422.201
Q(unloaded)	100518	23581
Design Operating Point (QEF=4)		
Peak Field (MV/m)	28.42	36.54
Power (kW)	17.9	16.7
Peak Voltage (kV)	265.25	77.63
Actual Operating Point		
QEF	5.14	3.46
Peak Field (MV/m)	28.42	36.54
Power (kW)	13.9	19.32
Peak Voltage (kV)	265.25	77.63

Table 1. Summary of important parameters for engineering model cavities

directional coupler at the output of the amplifier. Two pickup loops sampled the cavity field at the outer wall. One of the loops was connected to an RF detector for cavity field measurement. The other was used to provide a signal to a phase-locked-loop frequency tracking system.

The EMRFQ is illustrated in figure 2. Some relevant parameters are outlined in table 1. The cavity is 48 cm in length and was made from tellurium copper. The RF surfaces were machined to a standard finish then treated for high QEF. The EMRFQ then went through several stages of electroforming ending in a finished cavity. After the cavity electroforming was completed no further cleaning was performed and the cavity was stored in a machine shop environment.

III. CONDITIONING EXPERIMENTS

A. First Time Conditioning

Experiments were performed to explore three areas, first time conditioning, operation at high fields, and reconditioning. First time conditioning experiments evaluated different techniques for processing the cavity to operational levels for the first time. The use of room temperature pulsed and CW conditioning and cryo pulsed conditioning before cryo CW operation was investigated, as well as the feasibility of going directly to cryo CW operation. High field experiments were performed for both pulsed and CW operation. Reconditioning experiments were performed after inactive periods of 1 and 12 hours at operating temperature. Table 2 is a summary of peak operating conditions. Cavity fields were calculated using the measured net power into the cavity along with the measured Q and the stored energy as calculated by the program Superfish.

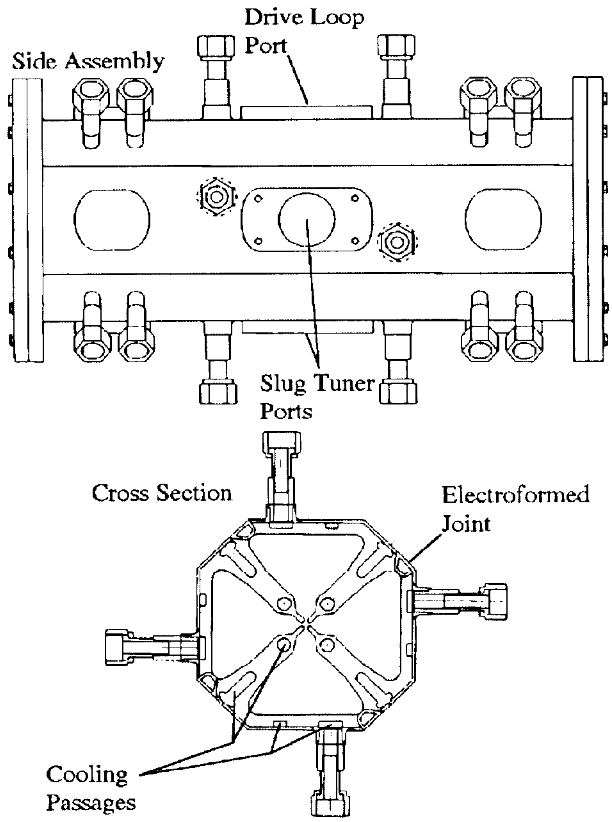

Figure 2. Engineering Model RFQ showing front cross section and exterior profile.

The first cavity tested was the EMDTL. The EMDTL

CAVITY	DF	Pulse Width	Peak Field	Real-Estate Accel Gradient	Stand By Time	Recondx Time
EMDTL	CW	6 sec	46 MV/m	6.97 MV/m	NA	NA
EMDTL	CW	51 sec	28 MV/m	4.24 MV/m	NA	NA
EMDTL	0.5 %	200 μsec	48 MV/m	7.27 MV/m	NA	NA
EMRFQ	CW	5 sec	31 MV/m	NA	NA	NA
EMRFQ	CW	31 sec	28 MV/m	NA	NA	NA
EMRFQ	0.5 %	200 μsec	45 MV/m	NA	NA	NA
EMDTL	CW	10 sec	28 MV/m	4.24 MV/m	1 hour	instant
EMDTL	CW	7 sec	33 MV/m	5.00 MV/m	12 hour	instant
EMRFQ	CW	5 sec	13 MV/m	NA	First Time	45 sec

Table 2 Summary of peak operating conditions for engineering model experiments

was conditioned both pulsed and CW at room temperature before any operations at cryo. During cryo operations the cavity was conditioned well in excess of design field in pulsed mode, then conditioned CW. This conditioning sequence worked quite well; no difficulties were encountered. The cryogenic portion of conditioning progressed faster than the room temperature portion. This result encouraged us to be more aggressive when the EMDTL was tested for a second time after extended exposure to air. During the second test the EMDTL was conditioned CW at cryo with no room temperature conditioning or cryo pulsed conditioning. No problems were encountered; the cavity conditioned quite readily.

On the basis of our success with the EMDTL, we decided to condition the EMRFQ for the first time at cryogenic temperature CW with no intermediate steps. This approach worked very well. Figure 3 shows 6 of the first 9 CW bursts. All of these were of six second duration with a forward power of 3 kW. During the first six periods the AFC was off. By the third operation period the cavity field was stable although not at the correct frequency. When the AFC was activated during the sixth operating period the cavity field shot way up and significant breakdown was visible. During the eighth operating period the field appears to drop down to a multipacting level, but this is gone in the ninth operating period and the cavity was operating smoothly at 18 MV/m. Due to leaks in the cooling system that developed during the experiment, the vacuum steadily degraded during the EMRFQ test. Near the end of the test the vacuum would climb to the high 10^{-5} Torr range while the RF was on and the cryogen was removing heat. This made conditioning progressively more difficult and limited our ability to reach design operating levels. The bulk of the difficulty in conditioning is generally encountered in the beginning at the lower field levels and at the end at very high field levels. We believe that with better vacuum, we could have conditioned from 18 MV/m up to the conservative design levels of 36 MV/m fairly easily.

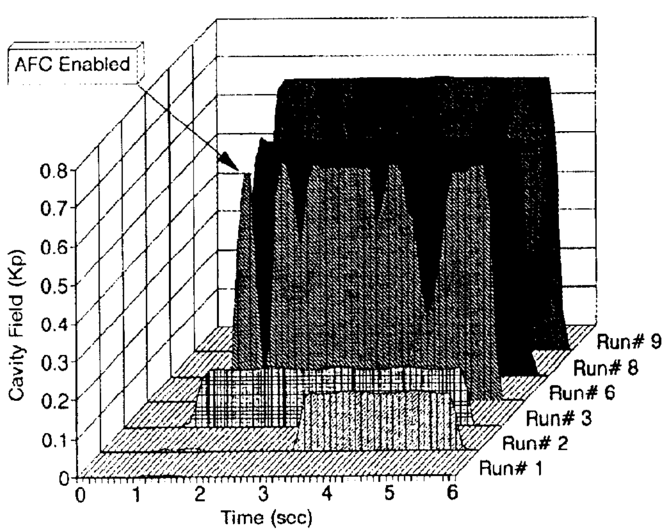

Figure 3. Profiles of six of the first nine RF runs showing rapid progression of conditioning

B. High Field Conditioning

The bulk of our high field conditioning was conducted with the EMDTL. Vacuum problems during the EMRFQ test prevented high field CW operations although high field pulsed operations took place. The EMDTL was conditioned to fields well in excess of design levels without great difficulty. No special processing techniques were used to reach these levels. Peak CW levels were limited by the ability of the cavity to hold the fields. Sparking and microdischarge would cause the amplifier to trip out due to high reflected power. The use of a circulator between the amplifier and the cavity may have allowed us to condition the cavity to higher levels without the inconvenience of amplifier trip-outs. Peak pulsed levels were limited by the available power from our amplifier at the time. The ease with which pulsed conditioning was performed leads us to believe that much higher fields could have been reached. As with the EMDTL pulsed conditioning of the EMRFQ was limited by the available power. There is no other reason that higher fields could not be reached.

C. Reconditioning

Numerous reconditioning experiments were conducted with the EMDTL. The cavity was put in standby mode for various lengths of time and then turned on. The goal was to assess the time and energy requirements for operation of cavities in space. We found that no reconditioning was required after periods of up to 12 hours. It should be noted that we were restarting with a burst length of about six seconds at design field of 36 MV/m.

IV. CONCLUSION

These experiments demonstrated the operation of CW RF cavities at cryogenic temperatures in vacuums of 10^{-5} to 10^{-7} Torr. This is consistent with the operation of advanced accelerators in the environment of space. The EMDTL was conditioned to 46 MV/m for a six second CW burst and 36 MV/m for a 51 second CW burst. The EMDTL was conditioned to 48 MV/m pulsed, limited only by available power. It was found that no reconditioning was required to restart the EMDTL after 12 hours at standby. The EMRFQ was conditioned CW for the first time at cryo with no preconditioning at room temperature or pulsed. The EMRFQ was conditioned to 46 MV/m during pulsed operation.

We believe that these experiments have demonstrated the feasibility of this type of operation. While the experiments were not completely rigorous (i.e., we were limited to CW bursts of 30 seconds) they were as complete as time and resources permitted. The experiments showed no major problems or obstacles, and indicated that cryo CW operation may be easier than expected rather than harder