3438 IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

PERFORMANCE TESTS OF THE 600-kW cw, 80-MHz, RADIO-FREQUENCY SYSTEMS FOR THE FMIT ACCELERATOR*

R. F. Nylander, M. V. Fazio, F. F. Bacci,† and J. D. Rogers,†† AT-5, MS H827
Los Alamos National Laboratory, Los Alamos, NM 87545

Summary

The high-power rf system for the Fusion Materials Irradiation Test (FMIT) accelerator consists of 14 sets of equipment,** each of which can deliver up to 600 kW (cw) at 80 MHz into a load having a VSWR of 1.4 or less (any phase). The equipment was designed and constructed to FMIT specifications by Continental Electronics Mfg. Co. (CEMC) of Dallas, Texas.

Four sets have been shipped to Los Alamos for use with the accelerator [two with the radio-frequency quadrupole (RFQ) and two with the drift-tube linac (DTL)]. The first set was fully tested at CEMC; results are summarized in Table I. Further tests conducted at Los Alamos, both into a resistive (electrolytic) load and into a resonant cavity ($Q \sim 21\,000$), have confirmed that this system meets, and in most cases far exceeds, the specified performance limits.

The first of the 13 production sets (No. 5) also was tested at CEMC before shipping any of the rf equipment to the Hanford Engineering and Development Laboratory at Richland, Washington. Because of the differences in behavior observed when No. 1 was operated at Los Alamos with a different tube installed in the final power amplifier (FPA) cavity, CEMC agreed to test No. 5 with two tubes having widely differing characteristics (notably primary screen emission). As expected, behavior differed markedly, and some design modification was necessary to meet all specifications with either tube. Results of final performance tests on No. 5 are summarized in Table I also.

As noted in the table, detailed test results are presented in the CEMC Acceptance Test Reports (ATRs) dated April 7, 1982 and January 3, 1983. Discussion of the most significant aspects of CEMC's tests and of those performed at Los Alamos follows a brief description of the equipment.

Equipment Description

Functionally, each set of equipment is simply a three-stage amplifier. The first stage uses a triode (3CW5000A7), the second (Driver) and third FPA, tetrodes (4CW50000E and 8973/X2170). All three stages operate in the grounded-grid configuration. Both the input and output cavities of each stage are tunable during operation. Provision is made for adjusting both resonant frequency (tuning) and impedance (loading) in all cavities except the input of the IPA, making a total of 11 motor-driven mechanisms.

The first two stages are well within the power and frequency range of conventional cavity-amplifier design with which CEMC has had extensive experience. Even so, during the test program's early stages, rf arcing developed in the Driver and FPA, destroying two tubes in each stage. It is now believed that the arcing in the Driver resulted from problems originating in the FPA; however, before those problems were fully understood, air circulation in the Driver was improved in an attempt to reduce this arcing tendency. More extensive and difficult changes were made to the FPA.

The FPA design is not novel, although it incorporates several features that are proprietary to CEMC. This application involves operation at a higher frequency than previous designs for this power level, and therein lie the problems. CEMC believes the rf arcing mentioned above was due to L-band parasitics originating in the tube under certain load conditions, when the instantaneous anode voltage is relatively low. Because the arcing primarily was in the region between the grids, CEMC felt that ferrite loading in that region would suppress the parasitics, but direct bypassing of the screen and grid to ground did not allow sufficient volume to add the ferrite. Ferrite loading in other areas was ineffective. Furthermore, it added

TABLE I	SPECIFIED PERFORMANCE (AT4-201, 80 MAR 5)			TEST RESULTS NO. 1 (DALLAS, 82 MAR 2-12)					TEST RESULTS NO. 5 (DALLAS, 82 DEC 15-20)					UNITS
LOAD VSWR	≤ 1.4	3.0	∞	< 1.1	~ 1.4	~ 1.4	~ 3	∞	< 1.1	~ 1.4	~ 1.4	~ 3	∞	
PHASE	ANY	FIXED	ANY	—	V_{MAX}	V_{MIN}	SEE TEXT	ALL	—	V_{MAX}	V_{MIN}	SEE TEXT	ALL	
POWER OUTPUT (80 MHZ)	600	200	250	600	600	600	200	250	600	600	600	200	250	KW
DUTY	CW/P	CW	P	CW/P	CW/P	CW/P	CW	P	CW/P	CW/P	CW/P	CW	P	
PULSE WIDTH	1.0	—	0.3	1.0	1.0	1.0	—	0.3	1.0	1.0	1.0	—	0.3	MS
REP RATE	120	—	120	120	120	120	—	120	120	120	120	—	120	HZ
GAIN (MIN, 30-90 % OUTPUT)				SEE PLOTS										
(CW)	38	38	—	39.8	40.4	39.4	42.9	—	40.7	42.9	39.5	45.7	—	DB
(PULSED)	38	38	—	41.1	42.6	39.6	—	—	41.1	41.8	41.2	—	—	DB
LINEARITY (30-90 % OUTPUT)				(WORST DEPARTURE FROM LEAST SQUARE FIT)										
(CW)	±10	±10	—	1.8	2.3	1.0	7.1	—	2.9	−9.5	3.5	6.0	—	%
(PULSED)	±10	10	—	1.9	5.4	3.6	—	—	2.9	−2.9	−1.4	—	—	%
STABILITY (0-100 % OUTPUT)	(NO DISCONTINUITIES)			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
(ANY DRIVE LEVEL, WAVESHAPE)														
SPURIOUS	−40	−40	SEE TEXT	−62	−56	60	−68	SEE TEXT	−66	−56	−52	−56	SEE TEXT	DB
40-200 MHZ (1 KHZ BANDWIDTH)				(CORRECTED 2ND HARMONIC LEVEL − 30 KHZ BANDWIDTH)										
AM S/N RATIO	60	60	—	−72	−61.5	−65	−78	—	(TEST WAIVED)				—	DB
80 ± 0.003 MHZ (EXCL LINE FREQ)				(ABOVE 360 HZ)										
3 DB BANDWIDTH	200	200	—	> 200	> 200	> 200	> 200	—	> 200	> 200	> 200	> 200	—	KHZ
SYMMETRY	< 0.5	—	—	.03	.2	.15	.15	—	.59	.3	.25	.03	—	DB
100 KHZ LEVEL (WORST CASE)				−.2	−.35	−.45	−.6	—	−.92	−.6	−.58	−.58	—	DB
AMPLITUDE DRIFT (MAX, 1 MIN)	±3	±3	—	<0.5	<0.5	<0.6	<0.5	—	1.7	2.0	< 1.0	< 1.0	—	%
PHASE DRIFT (MAX, 1 MIN)	±3	±3	—	1.0	1.1	<0.5	1.0	—	< 0.5	(WAIVED)		< 0.5	—	DEG
FREQ (AM)				SEE ATR FOR PHOTOS AND DATA										
RESP (PM)														
LEVEL STEP														
PHASE STEP														
PHASE SHIFT VS LEVEL														
X-RADIATION (MAX, 1 FT)	2.5	—	—	—	< .2	< .2	—	—	—	—	—	—	—	MR/HR
RF LEAKAGE (MAX, 1 FT)	1	—	—	—	< .2	< .2	—	—	—	—	—	—	—	MW/CM²
HEAT RUN	200	—	—	—	100	100	—	—	—	4	2	—	—	HRS
	(NO. 1 ONLY)			SEE ATR FOR DETAILS & CHART RECORD										

*Work supported by the US Department of Energy.
†Westinghouse Hanford employee working at Los Alamos.
††Continental Electronics Mfg. Co., Dallas, Texas.
**Three additional sets have been manufactured; these are to be used on other DOE projects.

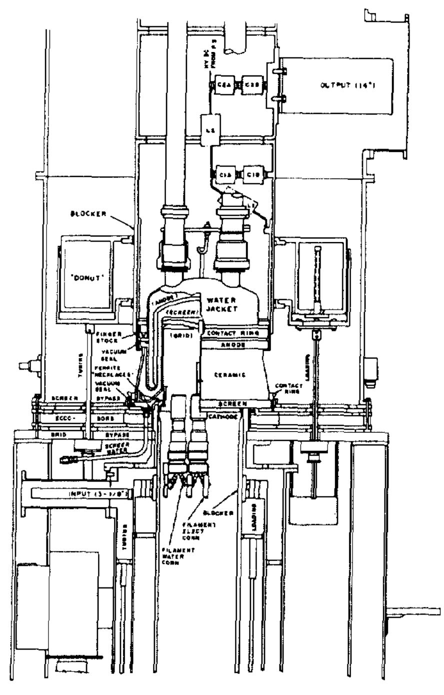
0018-9499/83/0800-3438$01.00©1983 IEEE

to the dissipation within the cavities, compounding the cooling problems that already had appeared.

Also, because of space limitations, the corona (contact) rings supplied with the tube could not be used. This left the vacuum seals exposed to high-voltage fields and resulted in poor contact between the anode and the output cavity's center conductor. This condition caused a third FPA tube failure.

Modifications

The modified design is shown in Fig. 1. A $\lambda/2$ cavity, filled with dissipative material (Eccosorb[R]*), was added in the grid/screen region to produce a low impedance between the screen and the control grid in the active region. Parasitics were suppressed by adding ferrite "necklaces" around the grid contact ring. Air circulation was improved by adding a large blower at the top of the output cavity and allowing some of this air to escape between the Eccosorb[R] blocks in the screen region. Also, holes were added in the input cavity to allow air to impinge on the metal portion of the tube envelope at screen potential, which still reaches temperatures somewhat above the maximum recommended in the tube data sheet (200°C).† To protect the tube from rf arcing, should it occur in spite of these precautions, special contact rings were added at both ends of the main ceramic. Also, optical arc detectors were added.



This drawing contains proprietary data, to which CEMC reserves all rights. It is reproduced by permission of CEMC for illustration purposes only, not for manufacturing.

Fig. 1. Final FPA cavity design.

*Registered trademark of Emerson and Cuming.
†The tube manufacturer (Eimac Div. of Varian Associates, San Carlos, California) was contacted, and formal acceptance of the higher operating temperature was obtained under full warranty. The tube design is being modified for better heat transfer in the screen region, but modified tubes are not yet available.

Some of these changes (the ferrite "necklaces" and improved air circulation in the screen cavity) were not incorporated in the prototype unit. It met all performance specifications when tested at CEMC, as shown in Table I. However, when these tests were repeated at Los Alamos with a different tube, the problems experienced earlier reappeared. Another tube was installed, but before tests with the electrolytic load could be completed, the load and some of the 14-in. transmission-line components were damaged. The FPA appeared to be operating satisfactorily; therefore, we decided to begin tests with the resonant load rather than wait for repair of the test stand.

Meanwhile, tests on No. 5 began at CEMC. Initially, it appeared that no further modifications would be necessary. However, because of the difficulty experienced with the prototype, Los Alamos proposed, and CEMC agreed, that a second tube be installed in the FPA. This tube had significantly higher primary screen emission, when tested by Eimac before shipment. In other respects, its behavior was similar to the others. When operation was attempted, parasitic oscillations appeared from 800 to 1000 MHz with the high VSWR load at some phase settings.

In the course of investigating this problem, the Eccosorb[R] material in the screen cavity overheated. CEMC decided to rearrange this material to improve air circulation by channeling inward the air entering from the output cavity before allowing it to exit the screen cavity. Ultimately, adding the ferrite necklaces suppressed the parasitics, which were probably responsible for the overheating; thus, reconfiguring the material may have been unnecessary. However, all production units are being modified in this manner, and the four units at Los Alamos will be modified at assembly or, in the case of the prototype, if a problem develops or the tube must be changed.

Tuning

The specification requires that the amplifiers pass all tests without retuning the cavities. Because it was not possible to change load conditions over the range required without interrupting operation, it was most expedient to conduct all tests at one VSWR before changing to another. Initially, the amplifiers were tuned with a matched load, following the usual procedure of maximizing output power and minimizing the reflected (80-MHz) power at each stage's input. Although this procedure worked quite well, we found that some retuning was necessary for several reasons:

(1) The simple procedure described above does not necessarily result in optimum performance with a mismatched load.

(2) Some of the cavities required at least half an hour to reach thermal equilibrium. Therefore, once the optimum settings were established, only tests conducted after the first hour of operation under each load condition were considered valid.

(3) When the FPA tube was changed, retuning was necessary to suppress parasitic oscillations under certain load conditions. With the ferrites in place, the amplifier is stable with either tube under all specified load conditions unless the FPA is grossly mistuned.

(4) Changes in dc bias voltages can affect behavior to the degree that retuning is required to restore optimum performance. Only the FPA screen voltage is regulated; thus, line voltage variations produce many different effects.

Despite these difficulties, only a few tests had to be repeated, and then it was found that performance was affected very little by the retuning that had been done.

Performance Tests with Resistive Load

Performance tests were conducted using procedures adopted during development (see ATRs), using an electrolytic load (also designed and built by CEMC) to establish the VSWR and a motor-driven 14-in. coaxial phase-shifter (designed and built by Dielectric Communications) As seen in Table I, performance was specified at full power for a VSWR of 1.4 under two extremes of phase designated V_{MAX} (maximum rf anode voltage) and V_{MIN} (maximum rf anode current). Performance also was specified at 200 kW with a VSWR of 3 and at 250 kW (pulsed) into an infinite VSWR of any phase. Additional tests were made at unity VSWR to explore further the amplifiers' frequency response, but no requirements were imposed beyond the basic 3-dB bandwidth specification. Finally, a 200-h heat run was conducted on No. 1 to establish reliability and long-term stability. At the end of the run, the amplifiers were examined for signs of damage and overheating.

Results of the tests at CEMC are summarized in Table I; details are available in the ATRs. A few additional comments are given below.

The amplifier gain was at least 40% (1.5 dB) greater than specified for all load conditions tested. Linearity was within the ±10% limit from 30 to 90% of full-power output. There was an ~3-dB difference in gain between V_{MAX} and V_{MIN} on No. 5, although the variation with power level at fixed phase was about the same in all cases. The variation with phase is plotted for No. 5 at the 50% power level (Fig. 2). This variation is responsible for some of the difficulty in controlling amplitude and phase with a resonant load under transient conditions.

Amplitude and phase drift over a 1-min period were well within limits. During the 200-h heat run, amplitude remained constant for several hours without adjusting either the amplifiers or the load.

The heat run was performed at a load VSWR of 1.4, 100 h at V_{MAX} and 100 h at V_{MIN}. During the first few hours the output power began to drop, and the HVPS had to be changed to a higher voltage tap to restore it to its initial level. The remainder of the test went smoothly. No equipment reached excessive temperatures; the hottest measured on the HVPS oil tank's surface was 113°F, and that represented an ~20°C rise over the outside ambient. However, when the amplifiers were disassembled for inspection, some damage to finger stock was noted, and temperature-sensitive paint in the screen region of the FPA tube

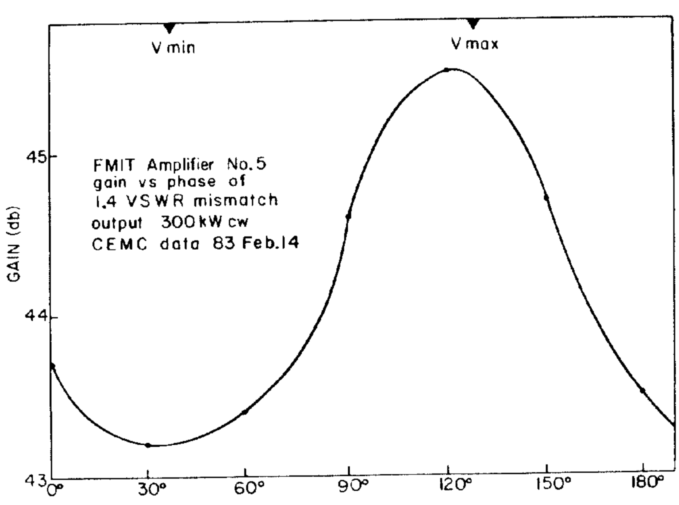


Fig. 2. Gain versus relative phase.

envelope indicated a temperature between 200 and 250°C had been reached. The equipment was repaired and modified after inspection, then operated again long enough to reach thermal equilibrium. Some tests were repeated to ensure performance was unaffected by the modifications or by the change to higher anode voltage during the heat run. The equipment then was disassembled and re-inspected before shipment to Los Alamos.

At Los Alamos, the equipment (Set No. 1) was installed in a duplicate test stand, and many of the tests were repeated. However, before this program could be completed, the failures in the load and in the 14-in. coaxial transmission line forced us to abandon these tests and to move the equipment into position for tests with the resonant load.

Resonant Load Testing

The high-power rf system has been successfully operated, open loop, into a resonant cavity at 600-kW peak, 24-kW average power.

This resonant cavity consists, in part, of the 8-ft-diam FMIT DTL tank. Because the actual drift tubes are not yet available, a single, stainless steel, dummy drift tube (DDT) has been installed in the tank to make it resonant at 80 MHz in a TEM mode. Stainless steel was chosen as the DDT material to lower the resonator's Q, thereby reducing the voltage gradients across the drift-tube to end-wall gaps. This was necessary to permit running two rf systems, each at 600-kW peak power, without causing sparking in the cavity. The cavity Q with the DDT is 21 000. Because the DDT cooling can dissipate only 25 kW of average power, we are limited to about a 2% duty factor when testing two amplifier systems at full power.

Conditioning the cavity to 24 kW of average power took ~10 h, operating one amplifier at a 4% duty factor. The amplifier behaved in a very stable manner at all power levels in open-loop operation.

Recently we have closed the cavity-amplitude and phase-control loops around a single rf system. The main problem encountered involved turning on the rf system with the cavity-amplifier control in the closed-loop configuration and the cavity empty. During the cavity fill time, the load impedance presented to the tube changes from an infinite VSWR to unity. This causes a >10-dB change in amplifier gain. This fact, coupled with the overshoot in the control system, causes output power to rise to ~800 kW at the pulse's leading edge. To prevent this, we decided to turn on in an open-loop condition, to a preset power level, and to close the cavity-amplitude loop approximately one-cavity fill-time constant (~120 μs) later.

With the amplifier operating at the 400-kW level, a step disturbance simulating beam loading was introduced into the cavity amplitude controller. During the transient at the leading edge of the step disturbance, the cavity field amplitude was held constant to within 3%. The transient damped out in ~40 μs, resulting in a steady-state error of well under 1%.

A phase-control loop was employed to maintain zero phase shift between the rf chain input and output. A ±45° step phase error was introduced into the control loop. The transient error resulted in a phase shift that reached a steady-state value in 40 μs of well under 1°.

We are currently in the process of adding a second rf system to the cavity to test the concept of multiple rf drive sources powering a single structure.

Acknowledgments

We thank the following people for their contributions to this program: C. Friedrichs, R. Bratton, J. Sainz, D. Draper, E. Bentley, and H. MacDonald.