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LINAC DESIGN ELEMENTS FOR SPACEBORNE ACCELERATORS*

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Abstract

Los Alamos National Laboratory, in collaboration with SLAC and Goddard Space Flight Center, have begun developing a high-duty-factor, MeV-range linear accelerator intended for use on satellites, specifically to probe the magnetosphere-ionosphere linkage. The design makes use of C-band cavities operating at moderate gradients, individually powered by 500 W RF amplifier chips. We present the results of technology maturation efforts including RF amplifier performance studies, cavity tuner design and an initial acceleration test using a DC beam source and single RF cavity.

INTRODUCTION

The advent of compact, high-power RF amplifier chips, such as the Wolfspeed CGHV59350 high-electron-mobility transistor (HEMT) [1], has enabled the development of new electron linear accelerators, wherein every cavity has its own independent RF power source and no high voltage is required. A separate paper at this conference [2] describes the general approach taken in this development effort.

Broadly speaking, a 1 MeV, 10-mA beam operating at a 10% duty cycle (1 kW average power) is required to effectively probe the coupling between the earth's magnetosphere and ionosphere. More details about the satellite-specific requirements leading to these operational parameters may be found in [2] and [3].

For the past several years, LANL, SLAC and Goddard have been collaborating on the technology maturation required to successfully construct such an electron linac suitable for operation on a satellite. These include optimized linac structure and cavity design; RF amplifier performance characterization, including radiation hardness testing; experimental demonstration of key features such as cavity operation with frequency tracking; and initial acceleration tests.

SYSTEM DESIGN AND OPERATION

The Accelerators-in-Space (AiS) electron linac concept differs in several respects from conventional electron accelerator design, reflecting the very different environment in which it must operate.

With a final beam kinetic energy of 1 MeV (β=0.94), the beam remains non-relativisitc throughout most of the accelerator. The AiS linac does not make use of a graded-β structure; instead, every cell has a nominal accelerating gap corresponding to β~0.2 (~10 kV electrons) with an instantaneous design gap voltage of 20 kV. When $\beta_{beam} >> \beta_{cell}$ the transit-time factor approaches unity and every cell delivers the same energy increment to the beam, has the same power dissipation (and therefore the same rate of temperature rise), and requires the same RF power input (allowing identical RF systems for every cell). The use of identical cells and a low β_{cell} also minimizes the detrimental effects from the failure of any given cell: as every cell has its own RF source, the cell-to-cell phase advance can be dynamically adjusted to provide the optimum energy gain.

Rather than maintaining the AiS structure at a fixed temperature to stabilize its resonant frequency, the linac is allowed to heat up during operation. The C-band HEMTs have approximately 1 GHz bandwidth, so tracking the frequency change of any given cell is quite feasible. Rather, the issue is maintaining every cell at the same frequency.

TECHNOLOGY MATURATION

Our technology maturation efforts can be broken into four main areas: HEMT performance, operation of the HEMT with a cavity, cavity tuner system, and an acceleration test. We do not have sufficient space to present the entirety of the maturation efforts; therefore, we present what we consider the most interesting results relative to a background in conventional high-power accelerator design. We will also, in this paper, not consider topics such as redundant power feeds for each cell.

The CGHV59350 HEMTs typically have small-signal gains of around 10 dB. Our RF power system concept makes use of two such chips: the "cavity driver" providing 440 W of RF power, and an "amp" providing up to 50 W as input to the cavity driver; a schematic is shown in Figure 1.

HEMT Performance

Several aspects of HEMT performance are of particular concern for spaceborne applications. These include basic performance (power output, small signal gain, etc.), operating in low-power-consumption modes, and power droop over the pulse.

The nominal design for a single cell is the acceleration of a 10-mA beam through a 20 kV gap; generating that gap field requires approximately 200 W of RF power, so each cell nominally requires 400 W of RF power. We would also like to maintain a 10% overhead in RF power for control

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margin and loss compensation, so our desired available RF power is 440 W. (Cells in the front portion of the linac deliver somewhat lower energy gain due to transit-time effects.) The nominal minimum output of the HEMT is 350 W; in practice, we find HEMTs can usually produce significantly more power even when operated at 50 VDC, the lower end of their operating range.

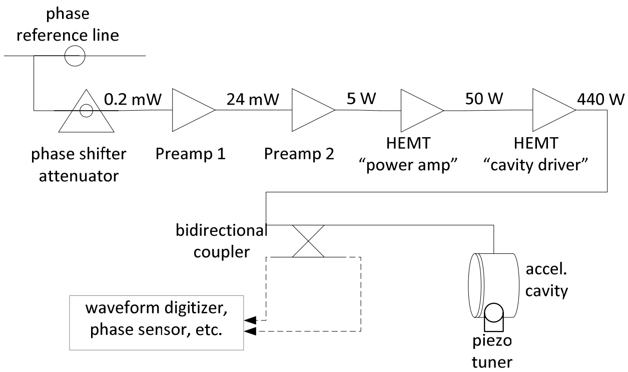

Figure 1: Conceptual RF drive circuit for a single accelerator cavity, based around HEMTs. Note the lack of circulator between "cavity driver" HEMT and cavity.

We measured the maximum power output of 20 HEMTs when operated under nominal conditions, e.g. 50 VDC drain-source voltage, 1 A quiescent drain current. The results are summarized by the histogram shown in Figure 2; half of the HEMTs provide 440 W or greater, and would thus be suitable as a "cavity driver." All tested HEMTs provided more than 350 W; the "low-output" HEMTs can be used as power amps in Fig 1.

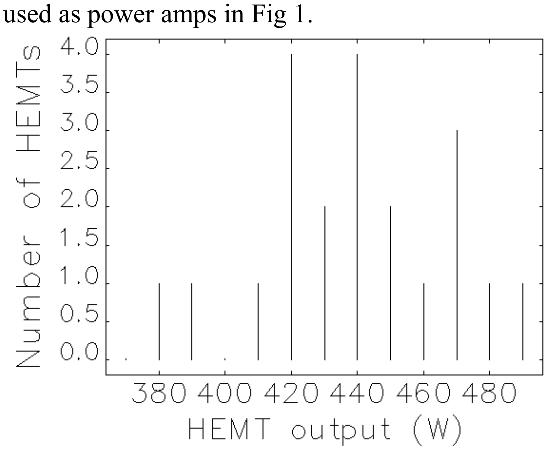

Figure 2: Histogram of power output for 20 HEMTs.

Cavity Drive Operation

Our intent is to power a standing-wave cavity with the HEMT, without an interposed circulator or isolator. The CGHV59350 specifications allow for a VSWR of 5:1, or 50% reflected power, when the cavity is operating at its nominal maximum output.

To test this, we drove a temperature-unstabilized resonant cavity with an HEMT, with unity coupling.

In operation, the reflected power was approximately 100% for ≤ 1 µs as the cavity filled, but for the remainder of the 100 µs RF pulse the cavity reflected little power. We observed no ill effects on the HEMT, either within a single RF pulse or over extended run times. We observed droop in the HEMT output starting at about 10% reflected power during the macropulse if the HEMT and cavity frequencies were mismatched, for instance due to cavity temperature rise; adjusting the HEMT frequency to match the cavity restored unity coupling and full-power operation with no apparent degradation.

Tuner System

As described above, the AiS linac will not have temperature stabilization, so all cells must be maintained at the same frequency. We have designed a simple tuner and demonstrated its tuning range to achieve this goal. Figure 3 shows models of the cavity with the tuner. Figure 4 shows the results of the measurement compared with CST [4] simulations.

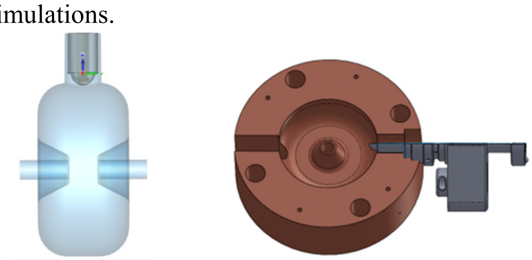

Figure 3: CST (left) and solid model (right) models showing the tuner concept.

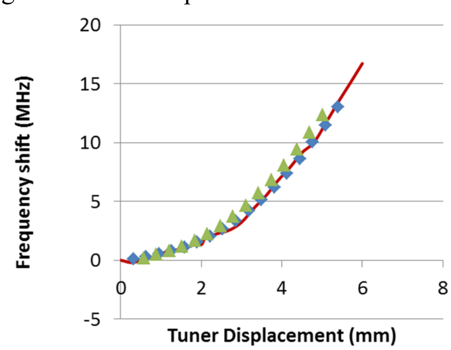

Figure 4: Cavity frequency shift vs. tuner position for two separate sweeps of the tuner (blue and green points) versus CST simulation results (red line).

The demonstrated tuning range corresponds to a temperature increase of approximately 180°C. Our expected rate of frequency change during normal operations is -44 kHz/sec (for an 0.1 kg cell), corresponding to a temperature change rate of ~ 0.9°C/sec, and could be compensated with a tuner insertion rate of ~0.7 mm/min.

As noted above, however, the ultimate objective is not to lock the linac to a single frequency, but to ensure that all cells are resonant at the same frequency both at the start of operations, and as the linac temperature increases during operation. This should require much smaller tuner motion ranges and slew rates.

Acceleration Test

This test represents the culmination of the first stage of our experiments. A single prototype cavity, powered by a single HEMT, was used to modulate (at low power) and

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accelerate (at higher power) an incoming 20-kV electron beam.

The experimental setup is illustrated in Figure 5. A low-current 20 kV DC beam was passed through a prototype cavity powered at various levels. The deflection of the beam by a fixed-field dipole spectrometer is proportional to the beam momentum, allowing measurement of the energy gain delivered to the beam. (As the beam from the e-gun was DC, the cavity actually modulated the beam energy spread; however, only the fraction of the beam at the highest beam energy was properly focused on the screen.)

With the dipole turned off and degaussed, and cavity off, we established the "zero" position on the screen. Then, with the cavity still off, we adjusted the dipole such that the 20 kV beam impacted at the edge of the screen; this calibrates the combination of dipole field and drift distance to displacement on the screen for a known energy. Finally, as cavity power was increased, the beam's position on the screen could be used to determine the energy gain provided by the cavity, and therefore the shunt impedance.

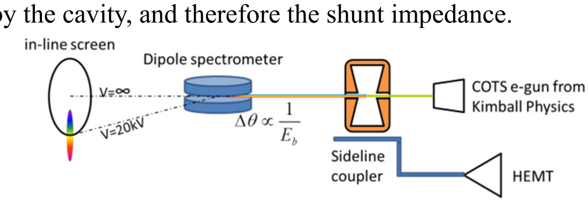

Figure 5: Schematic of acceleration test.

Example images are shown in Figure 6 for the dipole off "zero", dipole on with (b) 20 kV and (c) 30 kV DC beams, and (d) cavity on at 264 W. In (b)-(d) the dipole field is constant.

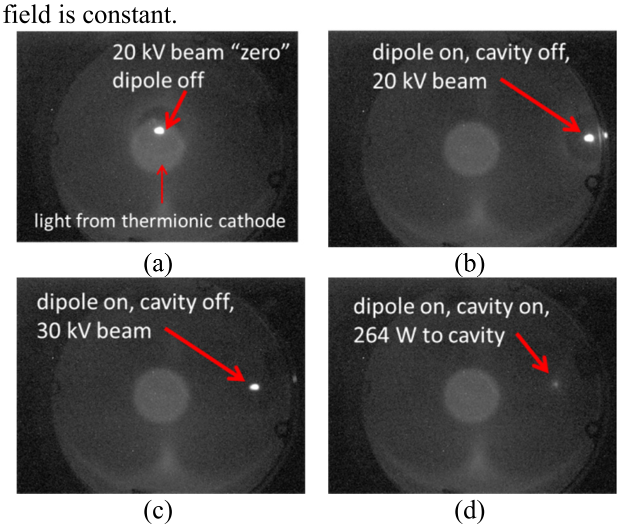

Figure 6: Beam images from in-line screen under various conditions.

We also measured the position of a 30-kV DC beam on the screen with the cavity off. Measuring the RF power to move a 20 kV beam from its starting position to the 30-kV DC spot provides a second calibration for the spectrometer, as well as an alternate method of determining the shunt impedance.

The final energy measurements for our beam, which was initially at 20 kV, are plotted in Figure 7. While the HEMT was operating at approximately 530 W, the cable connecting it to the cavity (inside a shielded enclosure) imposed ~3 dB attenuation, limiting our maximum power to the cavity to 264 W. The shunt impedance of our prototype cavity, based on these measurements, is 2.4±0.1 MΩ including transit-time effects.

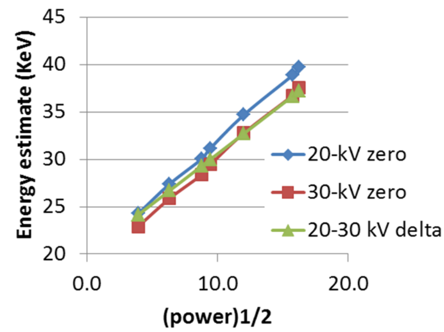

Figure 7: Beam kinetic energy vs RF input power using a 20-kV calibration (blue line), a 30-kV zero calibration (red line) and a third calibration using the power required to move the beam between the 20-kV and 30-kV calibration positions, for a fixed dipole field (green line).

FUTURE PLANS

At the moment, our team is concentrating effort on the construction and test of a 10-cell prototype, intended to accelerate an electron beam to 200 kV. The prototype will make use of an improved cavity design and an RF system that mimics a flight-appropriate system as closely as possible. The 10 cells are physically independent, so we may explore the use of the first cell as a buncher cavity to improve beam capture, as well as the placement of focusing solenoids along the linac. Finally, the prototype will allow exploration of various control algorithms for maintaining cell-to-cell frequency and phase stabilization.

CONCLUSIONS

We have demonstrated key aspects of technology required for the development of satellite-based linacs. These include RF power source characterizations, tuner design, and beam acceleration with energy gain measurements.

ACKNOWLEDGEMENTS

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