CONSTRUCTION AND TESTING OF THE DUAL SLOT RESONANCE LINAC*

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Abstract

The dual slot resonance (DSR) linac is a novel method of providing enhanced coupling to a coupled cavity linac system, resulting in very strong coupling. For the 11-cell, 2856 MHz structure described here, the acceleration mode bandwidth is about 650 MHz, which is an order of magnitude greater than many traditional side-coupled and axis-coupled linacs. The strong coupling promotes phase and amplitude stabilization, and offers decreased sensitivity to fabrication errors. We describe the construction, tuning, and RF conditioning of the prototype structure.

INTRODUCTION

The basic concept of the DSR linac was reported in [1], and that article contains a more in-depth explanation of this linac type. FAR-TECH was granted a patent for this technology [2]. The geometry of a pair of linac cells is shown in Figure 1, which shows a half-geometry of the vacuum region inside the linac structure. A group of two resonant slots connect two adjacent linac cells through an intervening swept triangular volume which we refer to as a “void”. The void region serves to provide RF coupling between the two slots. Each group of two slots has two collective resonant modes: a mode at around 1 GHz, and the working mode at the target operating frequency of 2.856 GHz. The mode split between these collective modes is so large that the pair of slots can effectively be considered a single oscillator at 2.856 GHz. The two slots serve the same purpose as a coupling cell in a side coupled linac. The advantages of the DSR linac include: a very large coupling with about 22% bandwidth, a compact geometry, no additional radial space required for the coupling cells, and shunt impedance competitive with a side-coupled linac. Simulations with HFSS [3] and with Omega3P [4] predict a shunt impedance ZT^2 of 85 $\mathrm{M}\Omega/\mathrm{m}$. This is competitive with other linac designs featuring large coupling such as the PWT design [5], and is slightly less efficient than an equivalent side-coupled linac, which might have about 8-10% higher ZT^2 with the same basic cavity and nose cone shape. The linac is designed for the UCLA Pegasus laboratory to aid in ultrashort electron bunch experiments [6] by boosting the beam energy by a design 10 MeV. The linac can also be operated in bunching phase, which will further shorten the bunch length and enable better resolution for experiments such as electron diffraction studies. It is hoped that the DSR linac design will also find uses in industrial and medical applications.

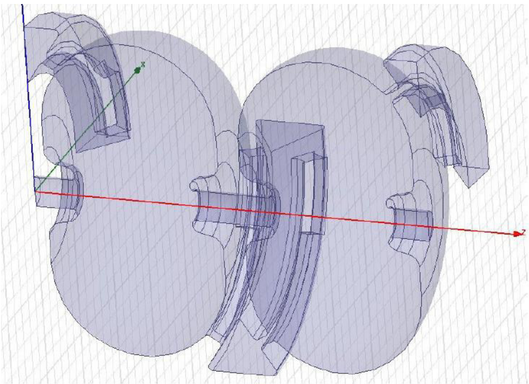

Figure 1: HFSS geometry used to model two cells of the DSR linac.

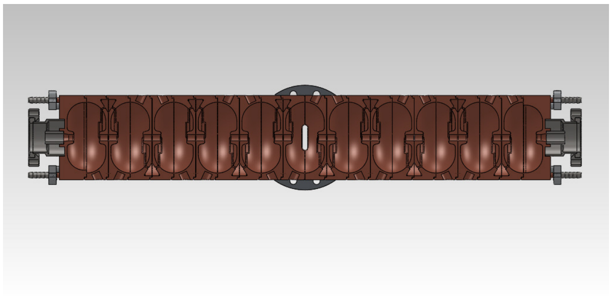

Figure 2: A cross section view of the 11-cell DSR linac.

DESIGN AND CONSTRUCTION

Design

An 11-cell DSR linac was designed with HFSS and Omega3P, as shown in Figure 2. End cells were transversely displaced in order to limit dipole kicks, and the central coupling cell shape was designed to minimize the mode pull due to the RF coupler. The linac is cooled with four cooling tubes running the length of the structure. The RF connection is via a WR284 waveguide and Skarpaas flange, and vacuum connections to the beamline are made with 2.75 inch ConFlat flanges. The beam clear aperture diameter is 8 mm. The band surrounding the accelerating mode extends from 2.513 to 3.153 GHz, making the frequency spacing from the accelerating mode to the closest nearby modes 45 MHz in our 11-cell structure. In a linac with $\pi/2$ phase advance per cell, the dispersion curve should be closed by tuning the even and odd oscillators to the proper frequency. The tolerance for the amount of closure depends on the overall bandwidth, and we have estimated that a residual stop band of as much as 3 MHz will not harm the electrical properties of the structure. Time

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* Work supported by DOE Office of High Energy Physics, DOE-SBIR #DE-FG02-08ER85034

ISBN 978-3-95450-138-0

Figure 3: A finished half-cavity copper part.

dependent studies simulating the RF fill transient, as well as steady-state field balance sensitivity studies, reveal that a larger stop band, beyond 10 MHz, does indeed start to affect performance.

Construction

The copper components for a half cell were made with a combination of lathe and 5-axis milling processes, which is more complicated than what is required for other linac types. We estimate that components for this linac type are 50-100% more expensive to machine than for conventional linac types, but this added cost is only a small fraction of the overall cost of producing the structure, and is offset by the simplified tuning method discussed below. Figure 3 shows a finished half-cavity part. The full linac was brazed with Au/Cu alloy in a dry hydrogen atmosphere using three braze steps.

TUNING AND BEAD PULL

The purpose of bead pull and structure tuning is to close the dispersion curve, achieve the correct operating frequency, and properly balance the field gradient in each cell. Tuning steps were interspersed with bead pull measurements and data fitting to a matrix model. A matrix description used one oscillator for each linac cell and one oscillator representing the collective mode of a pair of slots. The full eigenvalue equation has the form:

$$\mathbf{MV} = \frac{1}{f^2}\mathbf{V} \tag{1}$$

with $\mathbf{V}$ describing the voltage in each oscillator, and $\mathbf{M}$ for an example five-oscillator system is given by:

$$\mathbf{M} = \begin{bmatrix} \frac{1}{f_1^2} & \frac{k_{ac}}{2f_1^2} & \frac{k_{aa}}{2f_1^2} & & \\ \frac{k_{ac}}{2f_2^2} & \frac{1}{f_2^2} & \frac{k_{aa}}{2f_2^2} & \frac{k_{cc}}{2f_2^2} & \\ \frac{k_{aa}}{2f_3^2} & \frac{k_{ac}}{2f_3^2} & \frac{1}{f_3^2} & \frac{k_{ac}}{2f_3^2} & \frac{k_{aa}}{2f_3^2} \\ & \frac{k_{cc}}{2f_4^2} & \frac{k_{ac}}{2f_4^2} & \frac{1}{f_4^2} & \frac{k_{ac}}{2f_4^2} \\ & & \frac{k_{aa}}{2f_5^2} & \frac{k_{ac}}{2f_5^2} & \frac{1}{f_5^2} \end{bmatrix}, \tag{2}$$

where the matrix for the full 21-oscillator system follows the same pattern, f_i is the natural frequency of the i^{th} oscillator, k_{ac} is the coupling coefficient from the cell to the coupling slots, and the remaining coupling terms are the next nearest neighbor coupling terms from one accelerating cell to another (k_{aa}) and from one set of coupling slots to another (k_{cc}).

The tuning procedure is significantly different for the DSR structure than for a conventional side-coupled structure. Adjustments made to a single slot in a two slot system are capable of adjusting the field balance of the structure, and these adjustments can be performed after the final braze. The effect of such tuning is shown in Figure 4, which shows the slope of the before and after plots to be mostly consistent, except between cells 7 and 8 where the adjustment was made. Adjustments to both slots also have an effect on the resonant frequency of the surrounding cells, and can be used to tune the structure frequency as a whole, as long as the dispersion curve tolerance is adhered to. Although the structure was built with dimple tuners in each cell and deformable wall push-pull tuners at the end cells, these did not have to be used to arrive at the final tune, and all tuning was performed entirely by slot adjustments. The tuning method consisted of tightening a two-piece aluminum collar around the linac while monitoring the mode frequencies. In the final field balance measurement, all cells were within $\pm 1.9\%$ of the average. The dispersion curve was closed to within 400 kHz, much better than the initial goal.

We believe this tuning method, together with relaxed tolerances afforded by the large bandwidth, can simplify the production of a DSR linac structure. RF measurements of the as-machined half cell components were consistent enough that we believe it may be possible to machine the components to their net final shape in one machining pass with no additional tuning cuts. It may also be possible to eliminate any stack-up and bead pull tests performed ahead of the brazing operation. In this scenario, the only difficult stage would be the final tuning, which can be guided by a computer model.

POWER DISTRIBUTION

For the installation at the Pegasus laboratory, we have acquired or built the major waveguide components to distribute the power to the linac, including a high-power phase shifter, directional coupler, power divider, and several adapters between different flange types. The power divider, shown in Figure 5, was designed and built by FAR-TECH following the idea of the variable tap-off (VTO) device developed for ILC [7]. The device has four waveguide ports including an input port, an isolated port, and two output ports. In order to change the power split, the fastening bolts must be loosened and the central cartridge rotated to the new position. The device was designed for infrequent changes to the power ration, as the adjustment also de-pressurizes the SF_6-filled waveguide. A challenge for the power divider RF design was to optimize the RF

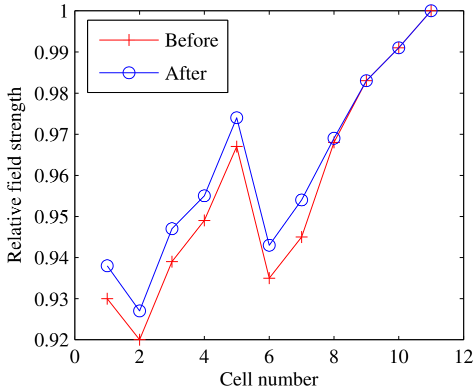

Figure 4: Effect of tuning slots balance between cells seven and eight.

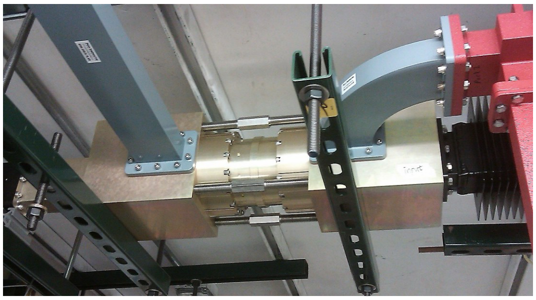

Figure 5: The waveguide variable power divider.

parameters (return loss, isolation, range of power split adjustment) while keeping the device as compact as possible, at just over 22 inches in length. The device was optimized with a computer-based minimization procedure, which resulted in a measured isolation and return loss of better than 24 dB for any power split setting, and adjustment of the power split between 0% and >98% from the input to the #2 port. The power divider was able to transmit the full klystron output of 12 MW under 1 atm of SF_6 pressure.

RF CONDITIONING AND TESTING

The linac was brought to the UCLA Pegasus laboratory for conditioning. After two days of conditioning, the input power was consistent with a 9.3 MeV energy gain through the structure using the calculated shunt impedance. The cavity field estimate should be considered imprecise because the lack of a flat top on the input RF pulse had the effect of the system never reaching steady-state, and the number was obtained by averaging the net input power over the last half of the pulse. Figure 6 shows the linac installed in the Pegasus beamline, just ahead of the spectrometer magnet. The testing of the linac with beam is reported by R. Li [8]. In actual operation, the linac reached 7.5-8.0 MeV energy gain with 1.8 MW power input. The energy gain was limited by the power divider setting, and with more power as well as slightly better vacuum ($< 3 \times 10^{-8}$ Torr), the full design energy gain of 10 MeV would likely be realized. The linac is used to boost the energy of the Pegasus laboratory gun, as well as to perform bunch compression through velocity bunching. This has allowed the facility to achieve $<$ 100 fs electron pulses which are needed for ultrafast electron diffraction experiments.

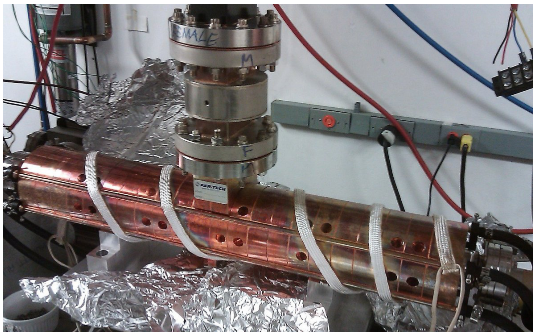

Figure 6: The DSR linac as installed in the Pegasus beamline at UCLA.

CONCLUSIONS

We have conceptually developed, built, and tested a linac structure based on dual slot resonance coupling. The linac was installed at the Pegasus laboratory at UCLA, where it is used to boost the beam energy and perform velocity bunching to achieve $<$ 100 fs bunch length for ultrafast electron diffraction microscopy applications. The new linac design is more compact than a side-coupled structure and the large bandwidth, combined with the unique properties of the structure, results in simplified manufacturing.

ACKNOWLEDGMENT

We thank R. Li, H. To, and P. Musumeci of UCLA for their collaboration.

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