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A Water-Filled Radio Frequency Accelerating Cavity

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Abstract

This is the final report of a one-year, Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). The objective of this project was to study water-filled resonant cavities as a high-energy density source to drive high-current accelerator configurations. Basic considerations lead to the expectation that a dielectric-filled cavity should be able to store up to ϵ/ϵ_0 as much energy as a vacuum one with the same dimensions and thus be capable of accelerating a proportionately larger amount of charge before cavity depletion occurs. During this project, we confirmed that water-filled cavities with $\epsilon/\epsilon_0 = 60-80$ did indeed behave with the expected characteristics, in terms of resonant TM modes and cavity Q. We accomplished this result with numerical cavity eigenvalue codes; fully electromagnetic, two-dimensional, particle-in-cell codes; and, most significantly, with scaled experiments performed in water-filled aluminum cavities. The low-power experiments showed excellent agreement with the numerical results. Simulations of the high-field, high-current mode of operation indicated that charged-particle loss on the dielectric windows, which separate the cavity from the beamline, must be carefully controlled to avoid significant distortion of the axial fields.

Background and Research Objectives

This research addressed a fundamental issue in the technology of radiofrequency linear accelerators (rf linacs), the acceleration of high currents (multi-kiloamperes). Such accelerators have proven their utility over the entire spectrum of accelerator applications except where high currents are required. High currents are generally assumed to be inaccessible with rf linacs, because the intense burst of charge involved in high currents rapidly depletes the stored electromagnetic energy in the accelerator cavities. The flash radiography machine at Los Alamos, PHERMEX, attempted to circumvent this limitation by using very large cavities. While this machine has proved very successful and useful for Los Alamos dynamic experiment diagnostics over the last 30 years, further improvements

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in accelerator performance seem problematical. The objective of this project was to explore a means for enhancing rf linac currents by up to two orders of magnitude, by replacing the vacuum electromagnetic cavities with dielectric-filled ones. The stored energy in a dielectric-filled cavity exceeds that of a vacuum one by the ratio of their dielectric constants, ϵ/ϵ_0 in this case. For pure water, this ratio is roughly 80.

For this project, the objective was to demonstrate that a water-filled cavity would actually function as an electromagnetic resonant cavity for frequencies of interest, that the resonant frequency and Q of the cavity would scale as expected, and to begin to address high-current beam loading effects on the cavity.

Importance to LANL's Science and Technology Base and National R&D Needs

Extending well-understood rf linac technology into the performance regime in which multiple kiloamperes of electron current can be accelerated will have an immediate impact on dynamic radiography capabilities. This clearly impacts Science-Based Stockpile Stewardship (SBSS) needs, as evidenced by the support given the Dual-Axis Radiography Hydrodynamic Test (DARHT) facility and a new Advanced Hydrodynamic Facility (AHF) radiography machine. A simple example can illustrate the significance. If the existing PHERMEX cavities were replaced by water-filled cavities, peak currents of 2-4 kiloamperes with micropulse duration of 20-25 nanoseconds would be possible. More significantly, such an accelerator would facilitate the generation of radiographic "movies," with a sequence of 10-20 bursts, separated by as little as 180 nanoseconds. The capability of following the dynamic evolution of fast processes will enhance our understanding of these processes by a factor that far exceeds 10-20.

In the longer term, use of dielectric-filled cavities may provide a simple and inexpensive source for a variety of industrial and defense applications. The attractiveness of familiar rf linac technology, scaled to high currents and high energy per pulse, can be an enabling technology.

Scientific Approach and Accomplishments

Scientific accomplishments have been documented in full in the two publications listed at the end of this report. Therefore, the discussion of these accomplishments will be limited to the main points here. Briefly, our first objective was to study the resonant

characteristics of cavities filled with dielectric materials. Water was chosen for the initial studies because it is a common material and yet interesting for these applications. Analysis of the resonance characteristics was combined analysis using numerical tools, such as SUPERFISH,¹ to arrive at predictions of the resonant frequencies. By incorporating the known dielectric properties of water,² we derived scalings for the TM_{010} frequency and cavity Q as a function of temperature.³

As useful as the analytic and numerical studies were, they only confirmed the results of earlier work.⁴ The demonstration of concept credibility that we sought could only come from experimental data. To achieve this demonstration, we constructed a simple pillbox cavity, with a diameter of 28 centimeters and a length of 14 centimeters, of aluminum stock. For vacuum cavities, aluminum would be considered much too lossy a material. In our concept, however, cavity Q is dominated by losses in the dielectric material, not by wall losses. This suggests that the overall system will be characterized by relatively low Q and that expensive fabrication techniques to produce high-quality surface finishes are unnecessary. In our experiment, power was supplied by a variable frequency 10 Watt source, driving a simple loop antenna. Cavity fields were measured along the cavity axis as a function of source frequency. The entire structure was able to be heated, and the water temperature was monitored. The transverse magnetic mode, TM_{010} , is the fundamental axisymmetric mode in our cavity. Figure 1 shows the excellent agreement between our measured data, analytic expressions, and numerical results.

We also measured the cavity Q as a function of temperature. Extraction of comparisons between this data and theoretical predictions is complicated by the fact that there are many mechanisms contributing to the measured Q, and we have not quantified all of these. Using reasonable estimates, however, we find good agreement between the temperature dependence measured and that predicted. The theoretical scaling is shown in Figure 2.

The agreement between theoretical prediction and experimental data for water-filled radio-frequency cavities was sufficiently good that there is little question that dielectric-filled cavities will operate as we hoped. The experiments were conducted at low power, however. To be useful for high-current operations, many orders of magnitude higher fields will be required in the cavities. Experiments at such parameter levels require design of powerful electromagnetic power supplies. Design and construction of such power supplies was well beyond the scope of this project. Instead, we conducted a series of fully electromagnetic simulation calculations of our basic cavity. The objective of these calculations was to determine the nature of high current beam transport through the cavity and to assess the effects of beam loading on overall cavity performance.

Details of the numerical calculations can be found in References 3 and 5. Two important effects have been noted in the calculations to date. The first is related to the configuration of a dielectric-filled cavity -- namely, that a vacuum beam transport channel along the axis of the cavity must be present. Since the dielectric is at solid density, transport of charged particles through the material will result in rapid scattering and energy loss. To avoid this, a hollow dielectric cylinder is used to separate liquid dielectric from the beam transport channel. This is not an intrinsic problem, although it may facilitate surface flashover when high fields are used. A significant distortion was observed in the axial accelerating fields in the calculations when the charge impacted the "window." This distortion acted in an accumulative manner to further disrupt beam propagation. The final state seen in the simulations was complete lack of transport through the channels. The consequence of this is that beam transport magnetic fields must be carefully designed to avoid inadvertent scattering of any charge on the window material.

The second understanding to come out of the simulations was that the low Q cavities should dominate over any beam loading effects, at least globally over the entire cavity volume. This is encouraging because it suggests that high currents will not limit the concept; but it is simultaneously discouraging because it implies that very robust power supplies (100-1000 MW) will be needed to reach accelerating gradients of a few megavolts per meter. This also indicates that steady cavity operation is prohibitive. Power dissipation in the cavities can lead to temperature increases on the order of 100°C on time scales of seconds. This is not actually a significant constraint: radiography requirements lead to accelerator utilization times of less than one millisecond. The temperature rise in water over a millisecond is roughly one degree Celsius.

These considerations clearly indicate that powerful electromagnetic sources will be needed to use dielectric-filled cavities, and studies into the design of such systems should be a high priority for future work.

Publications

1. Faehl, R., R. Keinigs, and E. Pogue, "Dielectric-filled Radiofrequency Linacs," Proceedings of the 11th International Conference on High Power Particle Beams, Eds. Karel Jungwirth and Jiri Ullschmied, Academy of Sciences of the Czech Republic, pp. 636-639 (1996).
2. Faehl, R., R. Keinigs, and E. Pogue, "New Initiatives for Producing High Current Electron Accelerators," accepted for publication in the "AIP Proceedings on the Conference on Applications of Accelerators for Research and Industry '96," Ed. Jerome Duggan.

References

1. Halbach, K. and R. F. Holsinger, "SUPERFISH - A Computer Program for Evaluation of RF Cavities with Cylindrical Symmetry," Part. Acc. **7**, 213 (1976).
2. Hasted, J. B., *Aqueous Dielectrics* (1973).
3. Faehl, R., R. Keinigs, and E. Pogue, "Dielectric-filled Radiofrequency Linacs," Proceedings of the 11th International Conference on High Power Particle Beams, Eds. Karel Jungwirth and Jiri Ullschmied, Academy of Sciences of the Czech Republic, pp. 636-639 (1996).
4. Humphries, S. and C. S. Hwang, IEEE Trans. Nuc. Sci. **NS-39**, 2986-2989 (1983).
5. Faehl, R., R. Keinigs, and E. Pogue, "New Initiatives for Producing High Current Electron Accelerators," accepted for publication in the "AIP Proceedings on the Conference on Applications of Accelerators for Research and Industry '96," Ed. Jerome Duggan.

Figure 1. TM_{010} frequency calculated in CFISH (solid) and measured (X) in the experiment as a function of water temperature.

Figure 2. Comparison of cavity Q evaluated with CFISH (solid) and simple theory (bullets).