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EXPERIMENTAL INVESTIGATION OF HEATING PHENOMENA IN LINAC MECHANICAL INTERFACES FROM RF FIELD PENETRATION*

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Summary

In a high duty-factor, high-current, drift-tube linear accelerator, a critical interface exists between the drift-tube stem and the tank wall. This interface must provide vacuum integrity and RF continuity, while simultaneously allowing alignment flexibility. Because of past difficulties with RF heating of vacuum bellows and RF joints encountered by others,[1,2] a paucity of available information, and the high reliability requirement for the Fusion Materials Irradiation Test (FMIT) accelerator, a program was initiated to study the problem. Because RF heating is the common failure mode, an attempt was made to find a correlation between the drift-tube-stem/linac-tank interface geometry and RF field penetration from the tank into the interface region. Experiments were performed at 80 MHz on an RF structure designed to simulate the conditions to which a drift-tube stem and vacuum bellows are exposed in a drift-tube linac. Additional testing was performed on a 367-MHz model of the FMIT prototype drift-tube linac. Experimental results, and a method to predict excessive RF heating, is presented. An experimentally tested solution to the problem is discussed.

Background

A drift-tube linac operating in the TM_{010} mode has a circumferential magnetic field. This magnetic field causes RF current to flow in the walls of the tank and the drift-tube stems according to the equation $\vec{J} = \vec{n} \times \vec{H}$. The wall currents flow parallel to the longitudinal tank axis, and the stem currents flow predominantly on the upstream and downstream edges of the drift-tube stems. The current density involved is about 1500 A/m for the FMIT accelerator.

In the FMIT accelerator design, the drift-tube stem is not rigidly attached to the tank structure.[3] The drift tubes and stems are supported by an external girder system so that the drift tubes are mechanically uncoupled from the tank, except for the vacuum bellows. This design is required for mechanical stability and alignment flexibility. Because of the resulting gap between the accelerator tank wall and the drift-tube stem, an inherent problem of magnetic-field penetration into the bellows region exists. This is undesirable for several reasons.

First, a magnetic field in the bellows region will induce RF currents on the bellow's inner surface, leading to a possibly catastrophic heating problem. Second, current flow along the bellows could lead to multipactoring or arcing between the convolutions.

Experimental Program

An experiment was designed to find a correlation between the drift-tube stem/linac-tank interface geometry and RF-field penetration from the tank into the interface region. Because a full-scale, 80-MHz, TM_{010} resonator was not available, a capacitively end-loaded, half-wave, TEM coaxial resonator was designed, as shown in Fig. 1. A metal stem with a stainless steel bellows was inserted at the point of the current maximum that occurs at the center of the cavity. The adjustable end walls on the cavity permitted the resonant frequency to be set, and the position of the current maximum to be shifted. This allowed the stem to be subjected to either a symmetrical or an asymmetrical $\vec{H}$ field distribution.

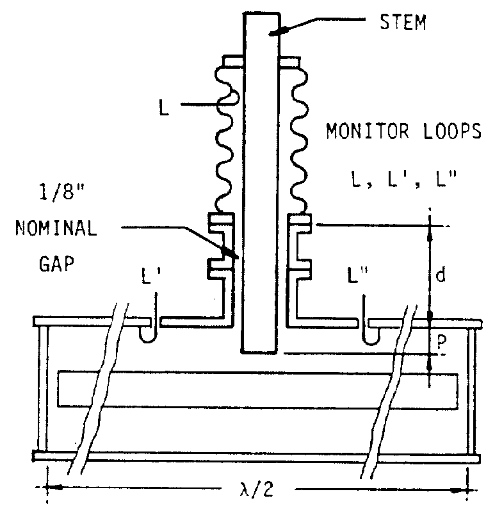

Fig. 1. The 80-MHz TEM coaxial resonator with full-scale bellows/stem assembly.

The bellows/stem assembly is a full-scale mockup of the corresponding FMIT assembly. The magnetic-field distribution to which the stem is exposed in this cavity is similar to that existing in the drift-tube linac. The design made it possible to insert spacers of different lengths between the bellows and the cavity-top flange to vary the length of the coaxial-line stub created by the bellows and drift-tube stem.

The cavity was excited with 20 W of RF power at 80 MHz and the cavity end tuners were adjusted to provide a symmetrical magnetic-field distribution on both sides of the stem, as measured by loops L' and L". The magnetic-field penetration into the bellows region was measured by a monitor loop placed in the bellows. For each "d" (2, 6, 8, and 16 inches were used), the stem penetration (dimension "P") into the tank was varied, and the monitor-loop voltage was measured; when dimension "P" was 4.3 in., the stem was shorted to the cavity-center conductor. The data is plotted in Fig. 2.

In most of the measurements, the stem position, with respect to the tank aperture, could be adjusted in the horizontal plane to maximize the observed bellows field. Moving the stem in this manner produced a resonant condition between the bellows, stem, and tank aperture.

The resonant frequency of this configuration was calculated in the following way: the bellows and stem were considered as a piece of shorted coaxial transmission line less than one-quarter-wavelength long, and therefore inductive. The stem and tank aperture formed a coaxial capacitor. The combination of inductance and capacitance resulted in a calculated

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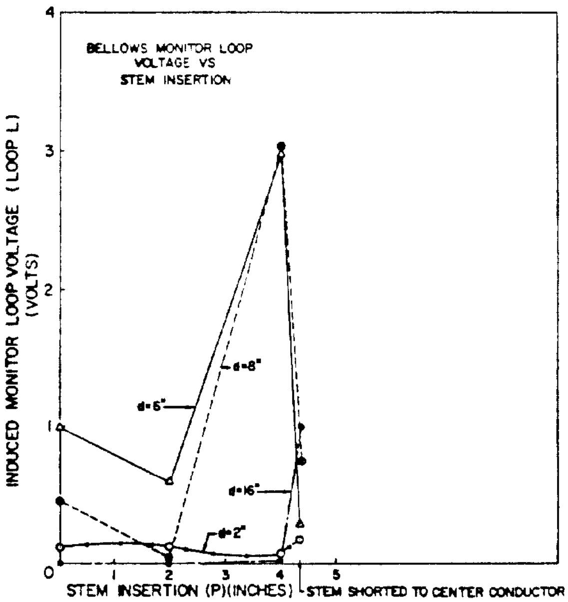

Fig. 2. Bellows monitor loop voltage variation with stem penetration for symmetrical cavity fields.

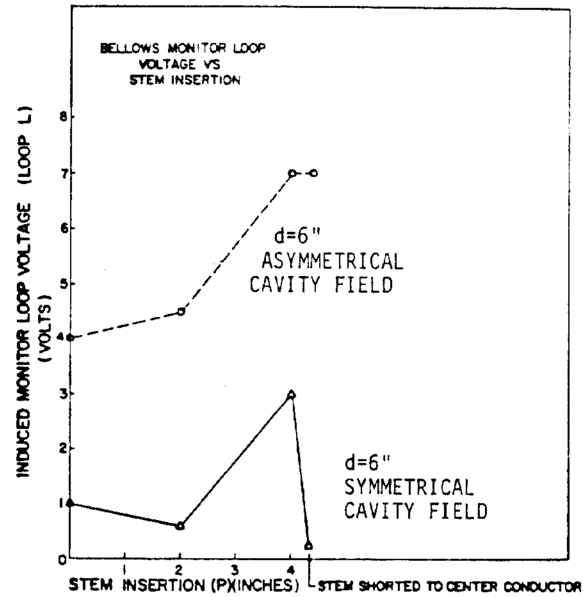

Fig. 3. Bellows monitor loop voltage variation with stem penetration for asymmetrical cavity fields.

resonant frequency of about 95 MHz. This is a rough calculation because of the cylindrical approximation used for the bellows, and capacitive fringing fields in the stem/tank aperture. It was observed that moving the stem from side to side in the tank aperture was equivalent to tuning the capacitance of the resonant circuit. At some stem positions, this resonance would occur at 80 MHz.

The capacitive effect of various spacer lengths, "d", apparently has a much greater effect on the field intensity in the bellows than the resulting length of the transmission line. This is true until "d" gets so large (16 in.) that the capacitance produced is great enough to assure that the structure resonates below 80 MHz, no matter how the stem is adjusted. Also, the depth of the stem penetration into the main cavity does not have much effect until it gets close to the center conductor of the cavity, at which point capacitive coupling between the stem and the center conductor comes into play.

It was postulated that the field in the bellows might be excited by asymmetries in the field around the stem near the tank wall. The asymmetry could be caused by factors such as the stem being off center in the aperture, or in an actual linac by postcoupler adjustment, tuning errors, or drift-tube alignment. This asymmetry condition was investigated for "d" = 6 in. The end tuners were adjusted to asymmetrize by 20% the cavity magnetic fields adjacent to the stem. The bellows field was measured as the stem penetration was changed. This data is plotted in Fig. 3, along with the data for "d" = 6 in. for symmetrical cavity fields for comparison. In the asymmetrical case, the bellows fields are significantly larger. These data indicate that the bellows is coupled more tightly to the tank in the asymmetrical case. The asymmetrical magnetic fields generate asymmetrical RF currents around the stem that drive the bellows assembly in an unbalanced manner.

One-Quarter-Scale Drift-Tube Linac Experiments

During this investigation, a one-quarter scale model of the FMIT prototype drift-tube linac became available. This model contained 15 drift tubes, postcouplers, RF drive loops, and vacuum ports. A brass top hat was installed on the top of one drift-tube stem. This geometry is shown in Fig. 4. The top hat is roughly scaled to simulate the vacuum bellows to be used in the linac girder assembly. Because of the complexity of the bellows convolution geometry, the top-hat dimensions represent only an approximation of the actual bellows dimensions on the 80-MHz linac.

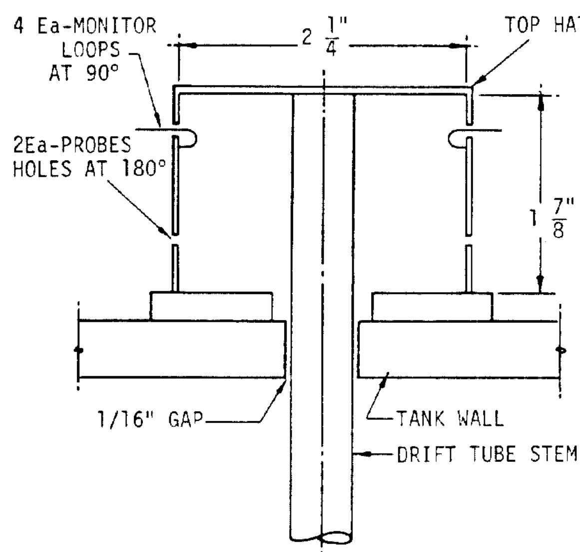

Fig. 4. Quarter-scale model drift-tube stem/top-hat geometry.

The resonant frequency of the top-hat assembly was calculated to be about 650 MHz, using the method previously described. The calculation is not exact, because fringing fields, as well as the loading effect of the drift tube and stem, have been neglected. Bandpass measurements were made to obtain the resonant frequency of the top-hat assembly. The strongest mode occurred at 734 MHz, was about 10 MHz wide and TEM in nature. No mode existed in the one-quarter-scale model linac near this frequency.

To observe the coupling between the scaled linac in the TM_{010} mode and the top-hat assembly, the RF source was tuned to the TM_{010} mode at 367 MHz. The same monitor loop was inserted into both the linac and the top hat to determine the magnetic field levels in both locations. The voltage induced in the loop was 2 VP-P in the linac and 0.4VP-P in the top hat. Because the voltage induced in a loop is proportional to the magnetic flux enclosed by the loop, these data indicate that the magnetic-field intensity in the top hat is 20% of the intensity of the wall field in the linac. The fields in the top-hat were observed to be TEM in nature. From these observations, it is apparent that the TM_{010} acclerating mode is launching a TEM mode into the stem/top-hat assembly. Because of the magnitude of the electromagnetic-field coupling, serious heating and arcing problems can occur in an operational linac.

To determine the loading effect that the drift tube and stem have on the frequency of the top hat's resonant mode, the drift-tube stem was disconnected from the drift tube and the drift tube was supported by a lucite rod inserted axially through the bores of the adjacent drift tubes. The stem was also shortened to penetrate only 4 in. into the tank (tank diameter was 21 in.), reducing capacitive coupling to a very low value. Bandpass measurements indicated that the frequency of the top-hat mode shifted from 743 MHz to 463 MHz. This observation implied that the top hat, drift tube, and stem are the components of a resonant circuit. Each one affects the resonant frequency of the system. With this geometry, the magnetic field intensity in the bellows was 14% of the tank wall field.

From the testing on the quarter-scale model, it must be concluded that the drift tube, stem, top hat, and the linac itself have a very complex interaction that has not been accurately modeled; however, it is apparent that the TM_{010} linac field couples quite easily into the bellows assembly. If the resonance bandpass of the bellows assembly overlaps the drive frequency of the linac, the situation becomes even more serious, probably catastrophic.

80-MHz Full-Power Testing

The seriousness of this field-penetration problem became very apparent when full-power testing was started. A capacitively loaded, quarter-wave resonator was assembled, as shown in Fig. 5. The bellows and stem assembly is identical to the FMIT design. The main cavity resonates in a TEM mode at 80 MHz. With the shorting collar removed, this structure will produce TEM fields in the bellows region. The stem was flood-cooled and the base-flange was conduction-cooled by brazed-on copper tubing, both with room temperature tap water.

The structure was evacuated to 10^{-6} torr, and enough RF power was applied to achieve a stem-current density of 433 A/m. This is 25% of the FMIT wall-current density. Based on the results with the quarter-scale model, the RF currents in the bellows of this test structure are approximately the same magnitude as in the bellows of an operational linac. Thermocouple instrumentation indicated a bellows temperature of 191°C under steady-state conditions. This is clearly unacceptable.

Because the FMIT design requires high reliability, a program has been initiated to develop an RF joint between the stem and the spanner-hatch cover that can carry the required RF currents conservatively, while at the same time leaving the drift-tube stem almost completely mechanically isolated from the linac. With the structure in Fig. 5, various RF joint designs can be tested at the full FMIT wall-current density of 1500 A/m.. Testing has just been completed on the RF shorting collar depicted in Fig. 5. The RF joint was achieved with silver-plated beryllium copper springs that encircled the stem. Testing continued for 200 hours, with a current density of 1500 A/m through the springs. Upon disassembly, no evidence of overheating was observed in the springs.

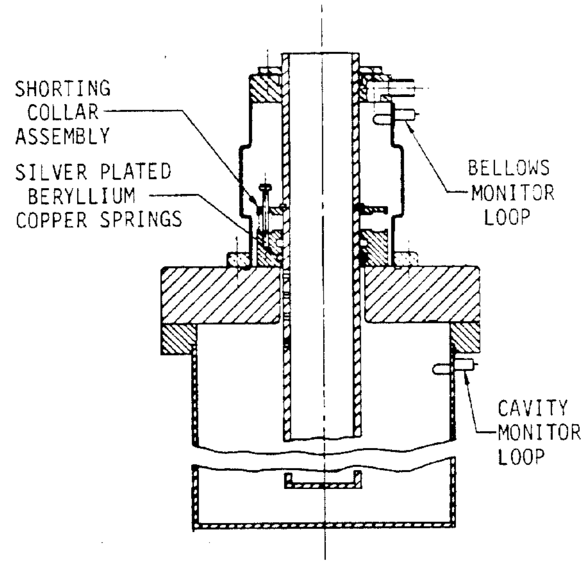

Fig. 5. The 80-MHz structure for testing drift-tube stem/tank wall RF joints.

Conclusions

Experimentation indicates that a drift-tube linac in the TM_{010} mode will couple electromagnetic fields into a vacuum bellows external to the linac, if the drift-tube stem is not connected to the linac at the inner wall. For a simplified geometry, this result is predictable; but the model is inadequate for explaining the complexities of an actual linac geometry. Excessive temperatures will be reached, and arcing can occur in the bellows region of a high-duty-factor linac; this is a very serious problem. A conservative design philosophy requires an RF current shunt between the drift-tube stem and the main tank. A successful RF shorting collar has been tested utilizing silver-plated beryllium-copper spring rings.

References

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