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One of the goals of the present Flash X-Ray (FXR) accelerator upgrade effort [1][2] at Lawrence Livermore National Laboratory (LLNL) is to reduce the cavity transverse impedance, since it has been shown that beam stability is significantly affected by this parameter [3]. Recently, we have evaluated various techniques and cell modifications to accomplish that, both through lab measurements and computer models. A spare cell, identical in every way to cells in the accelerator, was specially modified for the experiments. The impedance measurements were done without the beam, by applying twin-wire techniques. This report describes the results of these experiments and suggests possible cell modifications to improve their performance. The techniques and modifications which are suggested might also be applicable to AHF and DARHT-2 long-pulse accelerator development.

Experimental Setup

A number of modifications were tested on a FXR cell to evaluate the effect on transverse impedance. Figure 1 shows a cross-section of the cell with the modifications. A large ferrite toroid was embedded in the end plate that forms a part of the accelerating gap. This modification was mainly targeted at end cells in each accelerator section, as these could be most readily modified in this manner. A different approach would be required for inner cells which would not be as accessible. For these cells, we tested flexible RF absorbers which covered the walls of the vacuum housing. These absorber sheets could be inserted into the cavity through a vacuum port without major disassembly.

The instrumentation and experimental hardware used for the RF measurements are shown in Figure 2. A section of the accelerator was removed from FXR as part of maintenance and upgrade activities and the opportunity was taken to perform these measurements.

Figure 1. Cross-section of the cell with the modifications

Figure 3 illustrates the measurement setup. A twin-wire transmission line is inserted into the beam pipe and supported by Styrofoam holders. The transmission line is connected to a Network Analyzer (NA) through a balun which performs two functions: 1) it provides the correct impedance match between the NA and the transmission line, 2) it provides the correct phase relationship between the wires to excite transverse modes. Matching sections were added to the end plates of the cell. These matching

sections were machined to specific tolerances whereby impedances are well defined. By utilizing matching sections of different lengths it is possible to create a standard set of calibration fixtures (Thru-Reflection-Line). After the NA is calibrated, matching sections are

added to the test cell and a complete 2-port, S-parameter measurement is performed over some frequency range. The complex data is then corrected to subtract NA, cable, and matching section effects, and normalized by the transmission line impedance. This measurement technique was originally developed by Walling [4], and later refined at Lawrence Livermore National Laboratory for FXR application.

Figure 2. Instrumentation and experimental hardware

Figure 3. Measurement setup

Corner Reflector Tests

The TM_{1n} modes are beam deflecting modes of cavities, and the transverse coupling impedance is a measure of how efficiently the beam interacts with these modes. For these experiments, the TM_{11} dipole mode was excited in the beam pipe test section by driving a pair of parallel conductors out of phase. The measurements were done over a fairly wide frequency range, from 0.175 MHz to 1.4 GHz, however, results are only shown to 1.1 GHz, since above that frequency we noted the appearance of higher order modes. These frequency boundaries represent the 160 degree phase deviation limits we imposed on our test fixture design for accuracy.

Comparisons of the effectiveness of various cell configurations are made with respect to a standard (unmodified) cell in Figure 4. In a standard cell, the strongest transverse resonance occurs at about 820 MHz. After the cell was modified with a metal corner reflector and feedline ferrites, there was a significant drop in the resistance. In a subsequent experiment, a slight improvement over this was achieved by covering the metal corner reflector with a thin layer of RF absorber. Table 1 lists the maximum resistance and its frequency for each of these cases.

Figure 4. Standard vs. modified cell

Table 1. Resistance vs. Peak Frequency

Case	Max. Resistance (Ω/m)	Peak Frequency (MHz)
Standard	2570	821
Modified	1600	813
Modified + Absorber	1140	737

Embedded Ferrite Tests

We also tested a large ferrite toroid embedded in the end plate of the accelerating gap. The type of ferrite that was tested is of high efficiency and low loss, which dispersed most of the energy towards the lower frequencies (Figure 5). A lossier ferrite would have been preferable but was not available in time for these tests. Consequently, the peak transverse resistance remained quite high, although shifted to a lower frequency. Also, the 'Q' of the resonance is lower than in the standard cell. Although a lossier ferrite might be expected to provide higher attenuation over the entire frequency band, these results represent an improvement in performance since beam break-up is also proportional to resonant frequency and the 'Q'.

Figure 5. Standard cell vs. embedded ferrite

Comparing Measured and Computed Results

The measured and computed response [5] of the embedded ferrite compare favorably, as shown in Figure 6. A slight difference in peak frequency is most likely due to small differences in geometry. The difference in amplitude is due to differences in material electrical parameters and thickness. Computationally, the impedance of the cavities varied appreciably with Ferrite thickness and location of embedded Ferrite due to embedded inset to gap.

Figure 6. Comparison of experimental and computed values

RF Absorber Tests

We also tested carbon-loaded RF absorbers of various grades and thicknesses. These are low-density, high-loss, flexible foams that conform to the inner wall of the vacuum housing. All of these absorbers reduce the impedance as shown in the Figure 7 family of plots. Their performance is somewhat dependent on attenuation and thickness, and although these are linear lossy materials some energy redistribution is still evident, possibly due to the combined effects of the absorber and the magnet ferrites. All of these measurements were done at atmospheric pressure, and possible use in the cavity would depend on how well these materials perform in a vacuum. Some types of low-outgassing silicon rubber absorbers may be suitable.

Measurements shown in Figure 7 were done with 6 x 24 inch sheets of absorber joined at the ends and wrapped around the inner cell wall. Since the vacuum port opening through which the absorber might be inserted into the cell is slightly over four inches in diameter, we compared the performance for six- and four-inch wide strips of the same grade and thickness. Results shown in Figure 8 are close enough that no significant advantage would be gained by using the wider strip.

Figure 7. Standard cell vs. cell with absorbers

Conclusions & Recommendations

- The embedded ferrite provided the highest attenuation above 500 MHz, however, the type of ferrite we tested was a “high-efficiency” ferrite with little loss, and most of the energy appears to have been redistributed to a lower frequency by dispersion. Even though the peak resistance remained quite high, these results represent an overall improvement in performance (e.g., 800 MHz BBU mode) since beam break-up is also

Figure 8. Comparison of performance vs. absorber width

proportional to resonant frequency and 'Q', both of which were significantly reduced. Lossier types of ferrites would be expected to provide higher attenuation over the entire frequency band. Although this solution may be the best in terms of performance, this option will be difficult to implement due to the extensive cell modifications that would be required.

- Carbon loaded absorbers in the vacuum housing have also been shown to be effective. The peak resistance at 820 MHz was reduced by as much as 58%, down to $< 1.1 \text{ K}\Omega/\text{m}$ when combined with a corner reflector and feedline ferrites (compared to $2.6 \text{ K}\Omega/\text{m}$ for the standard cell), and down to $1.3 \text{ K}\Omega/\text{m}$ without the reflector and ferrites. A flexible, low-outgassing absorber could be inserted into the housing through the vacuum port with a minimum of down time and disassembly. There are several commercial absorbers of this type that may be suitable, or a custom design for the application may be required. More tests would be needed to demonstrate vacuum compatibility of these materials.
- Model and experiments are in close agreement. Better agreement would be achieved by closer matching of geometry and material parameters.

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