

# MEASUREMENT OF FREQUENCY RESPONSE OF LBL STOCHASTIC COOLING ARRAYS FOR TeV-I STORAGE RINGS\*

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## Introduction

Lawrence Berkeley Laboratory (LBL) has developed electrodes for the stochastic cooling system which is used in the anti-proton source in TeV-I at Fermilab. The electrodes are in the form of a pair of stripline couplers or loops, the elements of which are mounted on opposite sides of the beam. We have made two different couplers of similar design, the one to operate in the frequency range 1-2 GHz, the other, 2-4 GHz. We have made two different types of measurements; the one involving the response of a single loop pair to a wire signal simulating the beam signal; the other, the response of a 16 loop-pair array to an actual beam. Both sets of measurements were made in the frequency domain, and both involved taking both the so-called sum and difference responses, in which the signals from the two elements of the loop pair are added and subtracted, respectively. The former response shows little variation as the beam or wire is displaced from the midplane of the loop-pair; the latter exhibits a roughly linear variation with displacement, and is used to detect the position variation of the particles in cooling systems. In general, the beam and wire measurements were found to be in excellent agreement.

## Experimental Apparatus and Procedure

### Beam measurements on array

Figure 1 shows a rear-view photograph of the machined metal prototype of the 1-2 GHz array<sup>1</sup> used in TeV-I. The rear-most lower coupling loop is clearly visible, and one can see how the loops are enclosed in pocket assemblies, which enables them to be mounted flush with the walls of the array. The individual loops have a characteristic line impedance of 100 ohms. The signals from successive groups of eight (single) loops are combined pairwise using a stripline combiner. The upper right ground plane has been removed in the photograph to permit viewing of the combiner board; both eight-fold outputs from the 16-loop array are also visible. The initial combiner stages, visible at the lower edge of the combiner board, also serve as impedance transformers to match the loop impedance to the 50 ohm output line.

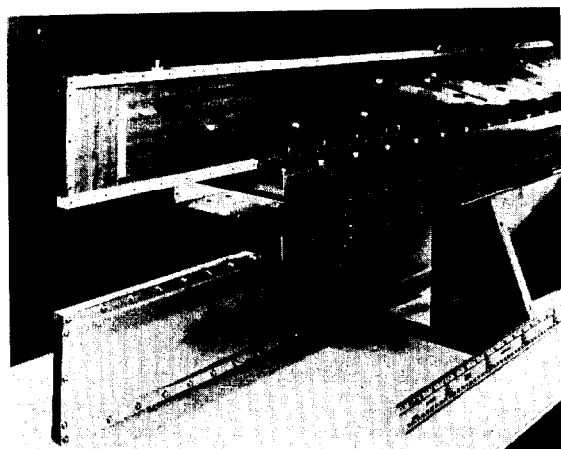


Fig. 1. 1-2 GHz 16 loop-pair array (rear view)

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The couplers for the 2-4 GHz array are quite similar in appearance, being basically scaled-down versions, although it proved necessary to modify the design of the loop "feet" to compensate for the inability to achieve exact scaling. The beam gap between loops of the 2-4 GHz array was the same as that of the 1-2 GHz, but owing to the smaller coupler size, it was made only about 2/3 as wide.

The pickup loops were excited by signals from a 10  $\mu$ A 1.6 MeV electron beam from a small Van de Graaff accelerator. Frequency domain measurements were made possible by modulating the intensity of the electron beam with a variable frequency buncher<sup>2</sup> located in the Van de Graaff terminal. To take into account variations in the d.c. beam current as well as variations in the modulation amplitude with frequency, the pickup signals were normalized to those of a fast Faraday cup.<sup>3</sup>

Measurement of the displacement sensitivity of the difference signals is done by translating the array perpendicular to the beam in 3 mm steps over a  $\pm 9$  mm range and recording the frequency response of the difference signals in each of the positions. While sum signals are also recorded in all positions, they vary only slightly with position, and only those sum signals taken at zero displacement will be reported on here.

The full circuit employed for the 1-2 GHz measurement is shown in Fig. 2. The use of the 180° hybrid permits one to make either sum or difference measurements by choosing the appropriate output of the hybrid. The normalization of the pickup signals to the Faraday cup is accomplished by using the latter signal as the "reference" input to a network analyzer, and the former as the "test" input. Most of the imbalances between the two legs can be corrected for by injecting a common signal into both legs by means of a power splitter and a pair of directional couplers (see figure), and "subtracting" the resulting measurement from the beam data. Corrections due to all elements (other than the 180° hybrid) preceding the directional couplers are determined by measuring their vector insertion losses separately. Finally, to correct the sum and difference measurements for the effects of the hybrid's frequency response, the elements of the truncated scattering matrix for the hybrid (i.e.  $M_{\Sigma 1}$ ,  $M_{\Sigma 2}$ ,  $M_{\Delta 1}$ , and  $M_{\Delta 2}$ ) are measured, and the resulting matrix is inverted and applied to the (corrected) sum and

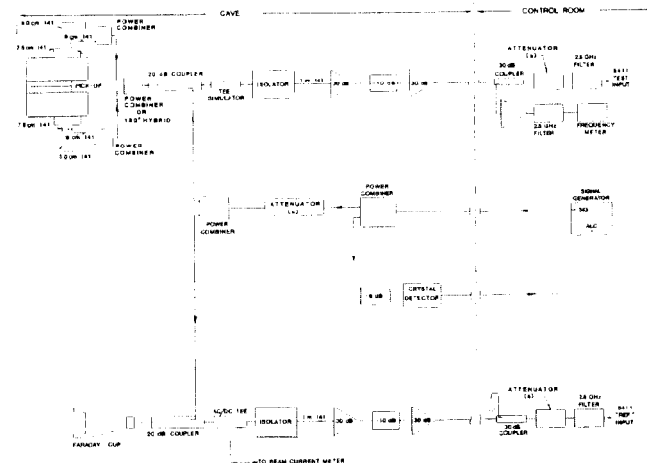


Fig. 2. Electronics for beam measurements

difference measurements to obtain the responses from the upper and lower halves of the array. These are then added and subtracted to obtain the sum and difference signals, respectively, as referenced to the output of the array itself. Additional details of the calibration and correction procedures are given in Ref. 4.

#### Wire measurements on Single Loop Pair

The single loop pair consists of two loop assemblies which are identical with those in the corresponding array, mounted on an enclosure having a cross section identical with that of the array, but having a total length of approximately 15 cm. Each loop is coupled via a stripline impedance transformer to its own 50 ohm output; as with the arrays, the two outputs can be added or subtracted by the use of a 180° hybrid.

The signal used to simulate the beam is injected on a wire which passes between the loops and whose diameter is chosen so that, together with the walls of the enclosure, it constitutes a 200 ohm transmission line. Two sets of network analyzer measurements are made: The first of these refers the sum/difference signal from the loops to the wire input signal; the second, the wire output signal to its input signal. The ratio of these two measurements, corrected for the diminution of the wire signal between the front and rear ends of the loop, is then used to obtain the loop transfer impedance.

Displacement sensitivity measurements were made possible by a mechanical arrangement which made it possible to translate the signal wire in the direction perpendicular to the plates. For the 2-4 GHz loop pair, the displacements varied over the same  $\pm 9$  mm range used for the array measurements; for the 1-2 GHz loop pair, a somewhat more limited range was employed. As with the array data, sum measurements are reported only for zero displacement.

#### Experimental Results

The transfer impedance in the sum mode for the 1-2 GHz array, as measured using the beam, is shown in Fig. 3. The long-dashed curve is the sinusoidal response expected from an ideal coupling loop, with the central frequency and amplitude adjusted to give an "eyeball" best fit to the data; the peak amplitude of 174 ohms occurs at 1.53 GHz, giving an average pickup impedance (from 1-2 GHz) of 168 ohms. The phase (more accurately the deviation from linear phase, sometimes referred to as the extrapolated or zero-frequency phase), is quite close to the expected value of 90°.

Figure 4 shows a comparison between the above sum mode data and those obtained from wire measurements on a single loop pair. Since the transfer impedance is

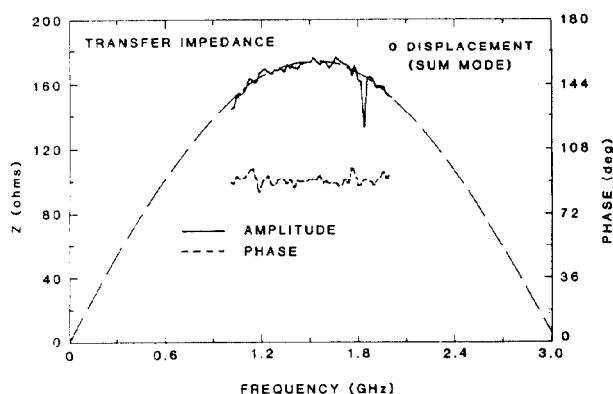


Fig. 3. Beam data (sum-mode) for 1-2 GHz array

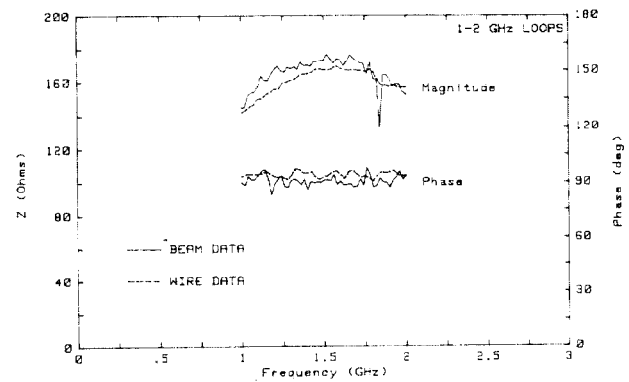


Fig. 4. Comparison of beam and wire sum data (1-2 GHz)

proportional to the square-root of the signal power, and the array delivers (nominally) sixteen times the power of a single loop pair, we elected to facilitate comparison of the two data sets by plotting four times the wire impedance. As can be seen, the frequency variation, the absolute magnitude, and the phase of the coupling loop transfer impedance, as measured using a wire, are in excellent agreement with the values measured using the beam. In fact, the observed discrepancies are of the order of what might be expected from the difference in insertion loss between the array combiner board and the impedance transformer for the single loop.

Results of the beam difference measurements on the 1-2 GHz array are shown in Fig. 5. The spectra, although exhibiting some peaking within the band, do not exhibit the obvious sinusoidal frequency variation that the sum spectra do. Moreover, the peaks in the difference spectra are skewed toward the lower end of the frequency band. The main reason for the discrepancy is that the above spectra result from taking the difference of two large "numbers", i.e. the signals from the upper and lower halves of the array; small discrepancies between these two spectra are magnified in the difference spectra.

For small displacement of the beam, the difference transfer impedance is expected to vary linearly with displacement, the sign change occurring in the signal as the displacement changes sign being reflected in a 180° phase change in the measured impedance. Because of the non-sinusoidal character of the difference spectra, as well as the fact that the ultimate quantity of interest is the displacement sensitivity of the loops over the entire 1-2 GHz band, we have determined these sensitivities by using the band-averaged impedance.

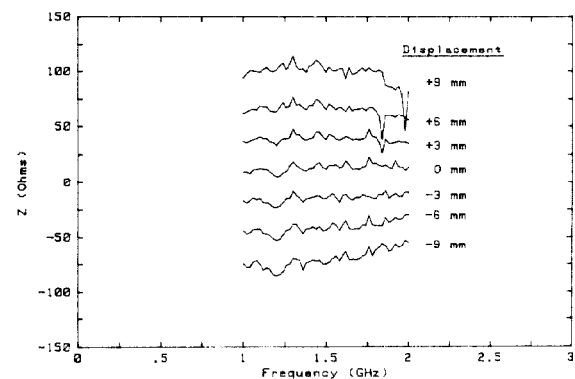


Fig. 5. Beam data (difference mode) for 1-2 GHz array

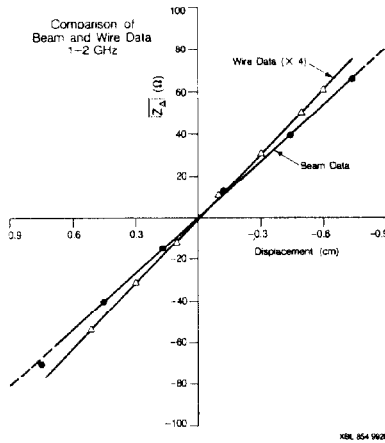


Fig. 6. Comparison of displacement sensitivity (1-2 GHz)

Figure 6 shows the sign-corrected magnitude of the band-averaged difference impedance. For small displacements, the variation with displacement is quite linear (with the possible exception of the point closest to zero displacement, where the difference-of-large-numbers problem is most exacerbated). The beam data points have been displaced horizontally by about 1 mm to compensate for the beam being slightly above the array midplane at the nominal zero displacement (see Ref. 4 for details). At large displacements, the impedance begins to rise more rapidly, as expected. For the linear portion, the displacement sensitivity is 89  $\Omega$ /cm.

Figure 6 also shows the displacement sensitivity obtained from the wire measurements. As were done with the sum data, the single-loop-pair wire data are multiplied by four for purposes of comparison with the array beam data. The wire data are also extremely linear, but exhibit a somewhat higher slope. The quantitative summary of the 1-2 GHz results is contained in the first two rows of Table I. The one notable discrepancy appears to be that the beam data give a higher sum impedance but a lower difference impedance. The source of this systematic discrepancy is not fully understood at present.

Table I: Comparison of beam data results from 16 loop-pair array with those from wire data from a single loop pair.

		Beam	Wire (x4)
1 - 2 GHz	$Z_{\text{sum}}$	168 $\Omega$	159 $\Omega$
	$Z_{\text{diff}}$	89 $\Omega$ /cm	103 $\Omega$ /cm
2 - 4 GHz	$Z_{\text{sum}}$	127 $\Omega$	122 $\Omega$
	$Z_{\text{diff}}$	100 $\Omega$ /cm	104 $\Omega$ /cm

Estimated accuracy  $\pm 5\%$

Similar results were obtained for the 2-4 GHz loops. Figure 7 shows a comparison of the sum data obtained from beam and wire data; as before the single-loop-pair wire data are multiplied by four for purposes of comparison. Once again, one sees excellent agreement between the two sets of data. The 2-4 GHz loops are perforce scaled-down versions of the 1-2 GHz loops, and the TeV-I requirement that the gap between the loops be the same results in a lower geometric factor in the coupling. This effect was somewhat offset by the modification of the loop "feet" mentioned earlier, which also had the effect of peaking the

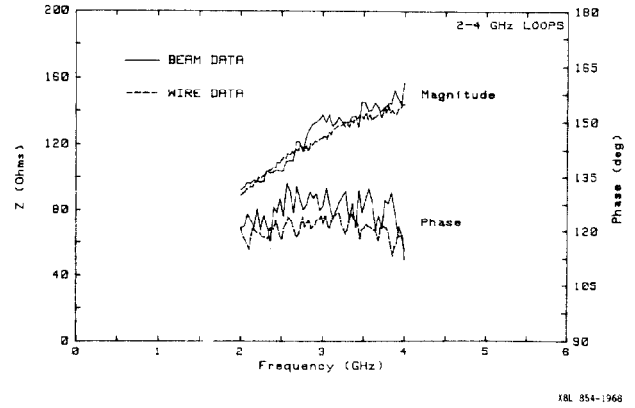


Fig. 7. Comparison of beam and wire sum data (2-4 GHz)

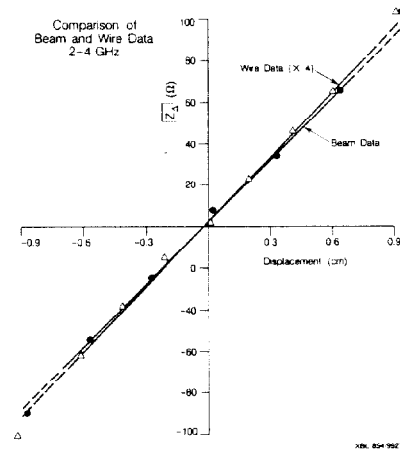


Fig. 8. Comparison of displacement sensitivity (2-4 GHz)

response near the high-frequency end of the band. Because of the decidedly non-sinusoidal shape of the response, the only meaningful performance figure is the band-averaged impedance which, as expected, is lower than that for the 1-2 GHz array. The results of the difference data are summarized in Fig. 8, which compares the deflection sensitivities of the 2-4 GHz loops obtained from the beam and wire measurements. The same features observed in the 1-2 GHz results are again seen here: Both data sets exhibit a linear variation of transfer impedance at small displacement; the measured sensitivities are quite similar, with the wire again showing a slightly greater sensitivity. A full comparison of results is contained in Table I.

#### References

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