Radio Frequency Measurement and Analysis Codes*

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Abstract

This paper describes a comprehensive set of computer codes for measuring, analyzing, and displaying field distributions in rf cavities. Development work began in 1984 for 8086-based computers. The codes now run on 486 and 386 PCs and include extensive on-line documentation. BEADPULL and QUADPULL collect frequency shifts as a metal or dielectric bead traverses a resonant cavity at constant speed. QUADPULL measures fields in all four quadrants of radio-frequency quadrupole (RFQ) cavities. Analysis codes apply the Slater perturbation theory[1] to convert frequency shifts to fields. BEADPLOT plots the field distributions and calculates field integrals. DTLPLOT analyzes and plots BEADPULL measurements in drift-tube or coupled-cavity linacs. QUADPLOT does the same for QUADPULL data in RFQs. Supporting programs prepare design data for comparison with the measurements and compute averages of multiple measurements. COUPLING extends the accuracy of an impedance analyzer for Q and VSWR measurements. The code plots reflection coefficients on a Smith chart and analyzes the resonance circle to get β.

Introduction

The measurement and analysis code package includes more than 25 programs for characterizing the fields in rf accelerator cavities. Analysis codes compare measured data to design data from SUPERFISH[2] or from RFQ design codes. Measurement codes use Hewlett Packard (HP) instruments to record the field distribution in a resonant cavity. The codes communicate with instruments on the General Purpose Interface Bus (GPIB), which is the common name for the communications protocol defined in ANSI/IEEE Standard 488-1978. Our GPIB hardware is from National Instruments Corporation.[3] We compile GPIB codes with the Lahey FORTRAN compiler[4] F77L and link the codes with a National Instruments object module that addresses the GPIB hardware. Analysis codes use Lahey's F77L-EM/32 compiler. Debugging tools from both Lahey and National Instruments proved invaluable for the development work.

Accelerator Cavities

Many accelerators use cavities that operate in a TM_{010}-like mode. The TM_{010} mode in a "pillbox" (a right circular cylinder) has two nonzero components of the electromagnetic field: E_z and H_ϕ. Higher-order pillbox TM_{01x} modes and TM_{010} cavities like the drift-tube linac (DTL) and the coupled-cavity linac (CCL) have nonzero components of E_z, E_r, and H_ϕ. The designer most often is interested in E_0, the average axial electric field. For a cell of length L:

$$E_0 = \frac{1}{L}\int_{-\frac{L}{2}}^{\frac{L}{2}} E_z\, dz\,.$$

The RFQ accelerator operates in a TE_{210}-like mode. The TE_{210} mode cannot exist in a pillbox because metallic end walls short out the transverse electric field. The lowest-frequency TE_{21} pillbox mode is the TE_{211} mode. However, a mode resembling TE_{210} exists over most of the RFQ length because the RFQ vanes do not touch the end walls and vane undercuts permit magnetic field lines to wrap around the vane ends into adjacent quadrants. For the RFQ we also seek information about fields near the beam axis. With no vane-tip longitudinal modulations, the only component of the electric field is E_r. This radial field focuses the beam. Vane-tip modulations make a nonzero E_z component that bunches and accelerates the beam.

Perturbation Measurements

Figure 1 is a bead-perturbation measurement showing the relative distribution of axial electric field in a DTL cavity. All figures in this paper are pictures of a computer-code display. A small metallic or dielectric object (the "bead") displaces electromagnetic stored energy, causing an observable frequency shift. This frequency shift is proportional to the original amount of stored energy within the bead volume:

$$\frac{\delta f}{f} = \frac{\delta U}{U},$$

where f is the resonant frequency and U is the cavity's total

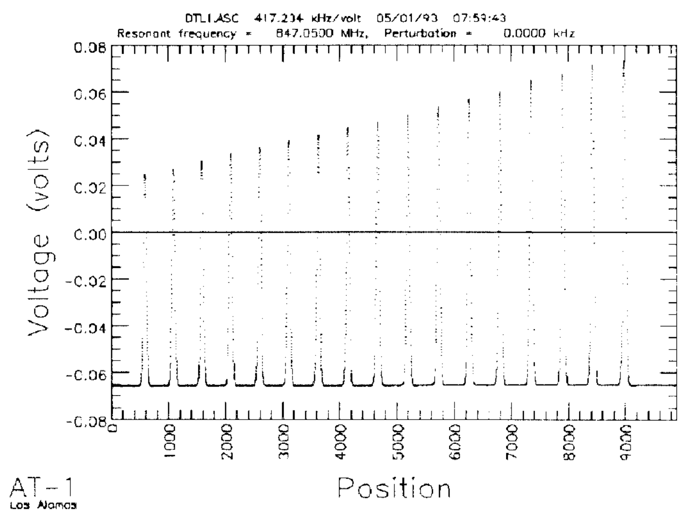

Figure 1. Program BEADPLOT display of a BEADPULL measurement on a 17-cell DTL.

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stored energy. Since U is proportional to the square of the electric or magnetic field, this effect offers a way to measure the fields in the cavity. This Slater perturbation method dates back to the 1940s. For spherical bead shapes:

$$\delta f = f_0 - f = \frac{3f_0}{4U}\int_V \left(\varepsilon E^2 - \tfrac{1}{2}\mu H^2\right)dV$$

where the integral is over the volume of the sphere, U is the total cavity stored energy, H is the magnetic field, E is the electric field, and f_0 is the unperturbed frequency. Electric and magnetic terms shift the frequency in opposite directions. A bead in predominantly electric field lowers the cavity frequency and a bead in the magnetic field raises the frequency.

Axial Bead-Perturbation Measurements

For DTLs and CCLs the path of the bead is the axis of the accelerator. The bead is a small metal sphere attached to a thin nylon monofilament line. A system of pulleys keeps the line taut and guides the bead through the cavity at constant speed. Program BEADPULL records at regular intervals the small changes in the cavity's resonant frequency. The data are voltages from a double-balanced mixer measuring the phase shift between the rf drive and a pick-up probe in the cavity. This phase versus frequency has a negative slope. Lower cavity frequency produces a positive phase signal as shown in Fig. 1 for a 17-cell DTL. The baseline signal for no perturbation occurs at −0.065 volts. BEADPULL supports many combinations of instruments and instrument settings. The program controls the rf output level and modulation level of the HP 8660C/D synthesized signal generator. The operator can run the motor manually, or the program can run it through a HP multiprogrammer. The code starts and stops the bead at locations of mechanical or optical switches. BEADPULL has measured DTL cavities whose hardware is inaccessible, for example under vacuum and at cryogenic temperature. The program's main menu is a scrollable table containing setup values and options. The edit keys move a selection bar through the menu.

Bead-Perturbation Measurements in RFQ Cavities

Measurements on or near the RFQ axis are impractical for several reasons. Axial measurements provide no information about the quadrupole and dipole admixture of the field distribution. Also, small spacing between vane tips makes the alignment of the bead path critical. Slight alignment errors produce larger effects than those we are attempting to measure. Finally, fluctuations caused by the vane-tip modulations dominate the measurement. Tolerances on the vane-tip machining guarantee the correct field pattern if the voltage distribution along the vanes is correct. Therefore, we infer the electric-field distribution from a measurement of the magnetic field near the cavity outer wall. One RFQ-tuning goal is a pure quadrupolar field pattern. Differences among quadrants mix dipole-field components with the predominantly quadrupole field, effectively shifting the

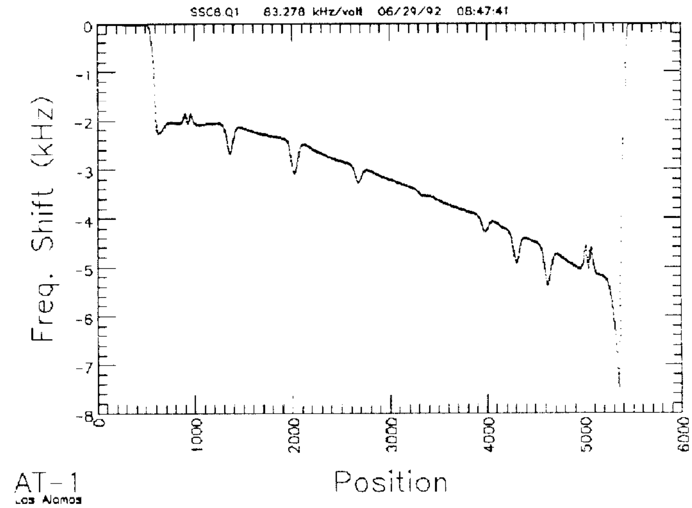

Figure 2. Program BEADPLOT display of a QUADPULL measurement in one quadrant of an RFQ.

quadrupole pattern off axis. Four measurements, one in each RFQ quadrant, quantify the dipole and quadrupole field admixture. Program QUADPULL has all the features of BEADPULL plus the ability to measure all four RFQ quadrants in a continuous loop. It inverts the data for the two quadrants in which the bead travels in reverse. Figure 2 shows frequency-shift data for one quadrant of the SSC RFQ.[5] Dips in the curve are magnetic field enhancements near slug tuners. The bead passing close to ribbed vacuum ports made the double peaks. These features do not appear in the electric field near the vane tips.

Analysis Codes

The two main analysis codes are DTLPLOT for DTL and CCL data and QUADPLOT for RFQ data. Both codes allow user control of the ordinate scale, and can compare measurements to one another or to design fields. Programs DTLAVG and QUADAVG calculate averages of multiple measurements on the same cavity.

Analysis of DTL and CCL Measurements

DTLPLOT analyzes axial bead-perturbation measurements on DTL or CCL cavities. For each cell the code finds the maximum field E_{peak}, the average field E_0, and an integral of the frequency shifts proportional to stored energy. Figure 3 illustrates an accurate way to compare a measured field distribution to a desired distribution. It uses data from DTLNORM, which predicts E_{peak} and E_0, from peak shapes calculated by SUPERFISH. DTLNORM integrates the design fields over the bead volume so the predicted fields include a correction for the nonzero size of the perturbing bead. DTLPLOT divides measured peak heights by predictions of E_{peak} for the desired E_0 in each cell. DTLPLOT also can correct for changes in the peak heights caused by the differences in gap length that occur when adjusting the end half drift tubes for tilt-sensitivity measurements.

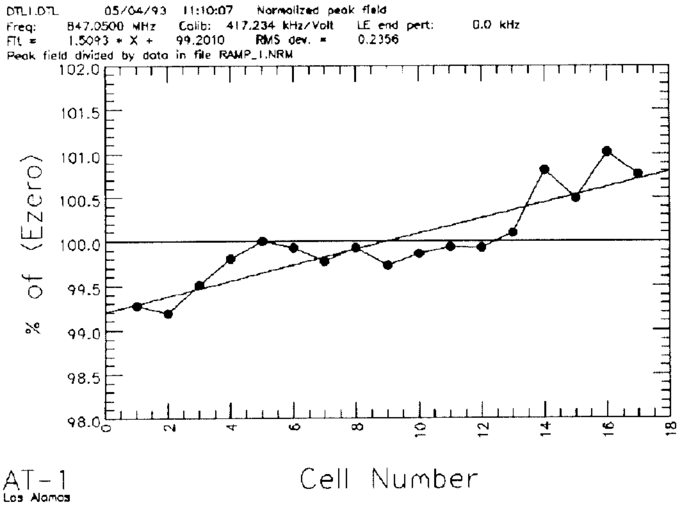

Figure 3. Program DTLPLOT display of E_0 relative to the design distribution.

Analysis of RFQ Measurements

DTLPLOT analysis requires no user input other than configuration data from a file used with all measurements on the same structure. QUADPLOT uses an interactive graphics session to fit a baseline to data outside the cavity and to locate the ends of the rf structure. The code displays the data with several markers that the operator manipulates with the edit keys. After the first setup, the program usually places the markers correctly for subsequent measurements. The code then only needs confirmation to continue. This procedure lines up the four separate measurements for combining the fields to obtain quadrupole and dipole components.

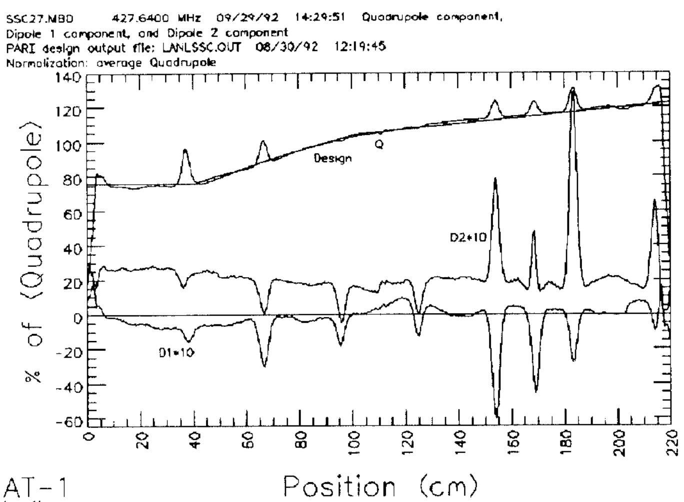

Figure 4. Program QUADPLOT display of the quadrupole and dipole field components.

After the analysis QUADPLOT displays selected data versus longitudinal position in a variety of formats. Figure 4 is a common choice. It shows the measured quadrupole component superimposed on the design field and two orthogonal dipole components (multiplied by 10 to show details). The code also can plot individual quadrant fields, other linear combinations of dipole field components, a "zero" component used as an error indicator, or the difference between the quadrupole component and a quadrant field. Quadrant fields $F_1(z)$ through $F_4(z)$ are numbered counterclockwise as viewed from the low-energy end of the RFQ. The quadrupole, dipole, and "zero" components are:

$$F_Q = \tfrac{1}{4}(F_1 + F_2 + F_3 + F_4)$$
$$F_{D1} = \tfrac{1}{2}(F_1 - F_3)$$
$$F_{D2} = \tfrac{1}{2}(F_2 - F_4)$$
$$F_Z = \tfrac{1}{4}(F_1 - F_2 + F_3 - F_4)$$

Fields $F_i(z)$ are positive functions of longitudinal position z. Adjacent quadrants have opposite phase. Lloyd Young's RFQ tuning code[6] reads QUADPLOT data to compare with a theoretical description of the fields.

Other Programs

Program COUPLING controls the HP 4191A impedance analyzer to measure reflection coefficients versus frequency. From an analysis of the resonance circle in the complex plane, the program extracts the resonant frequency, the voltage standing wave ratio, coupling β, and the unloaded Q. It displays Smith charts of the measured data. PCFIELDS analyzes the magnetic field distribution near post couplers in DTL cavities. LANLHELP displays documentation on the screen. Its companion program DOCUMENT formats and indexes the documentation for hard copy.

Acknowledgments

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