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Note

Computer Processing of Plasma Interferometer Signals*

INTRODUCTION

To determine plasma density as a function of time in the 2XII [1] CTR experiment we measure the phase variation of a 70 GHz wave propagating through the plasma with respect to a signal transmitted over a reference path. The voltage output of this interferometer [2] is a sinusoidal function of the phase shift, whose period varies with the plasma decay rate. In the slab plasma approximation this differential phase shift may be expressed as

$$\Delta\phi = \frac{2\omega}{c}\left[R - \int_0^R \left(1 - \frac{n_0 f(r)}{n_{co}}\right)^{1/2} dr\right],$$

where n_0 is peak density at the center; $f(r)$ is the radial density distribution; n_{co} is the critical cutoff density, i.e., the index of refraction goes to zero for plasma densities greater than or equal to this amount; and R is the maximum plasma radius. While the plasma in this experiment is cylindrical at the midplane, it can be argued [3, 4] that, although refractive effects will certainly affect the amount of power propagating between the two antennas, the phase shift is only slightly in error with this model. Furthermore, for plasmas where $R \gg \lambda_0$, the free-space wavelength, $\Delta\phi$ varies rapidly as n_0 approaches n_{co}. Thus, small errors in the $\Delta\phi$ measurement produce only slight errors in the density calculation. The purpose of this paper is to show a set of programs that calculate $n(t)$ from a datum set, sin $[\Delta\phi(t)]$.

This set of FORTRAN IV routines retrieves digitized signals from the data-system magnetic tape [5, 6] and performs the analysis. This routine was divided into two programs because of storage limitations. The first retrieves the data from magnetic tape, applies voltage-offset corrections, derives information on peak amplitudes and phase quadrants, and writes this and the corrected interferometer data into a digital disk file. The second program reads this file and calculates line density, peak density, inverse line density, and inverse peak density. Output is to a line printer, and the density can also be illustrated on a plotter as a function of time.

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DATA RETRIEVAL AND PREPARATION

Figure 1 is a flow chart for the code DNDAT, which, besides correcting the raw data, must determine the peak amplitudes of the sinusoid and find the phase quadrant ($n\pi/2$) for each data point. This information is required by the second program to correctly calculate $\Delta\phi$.

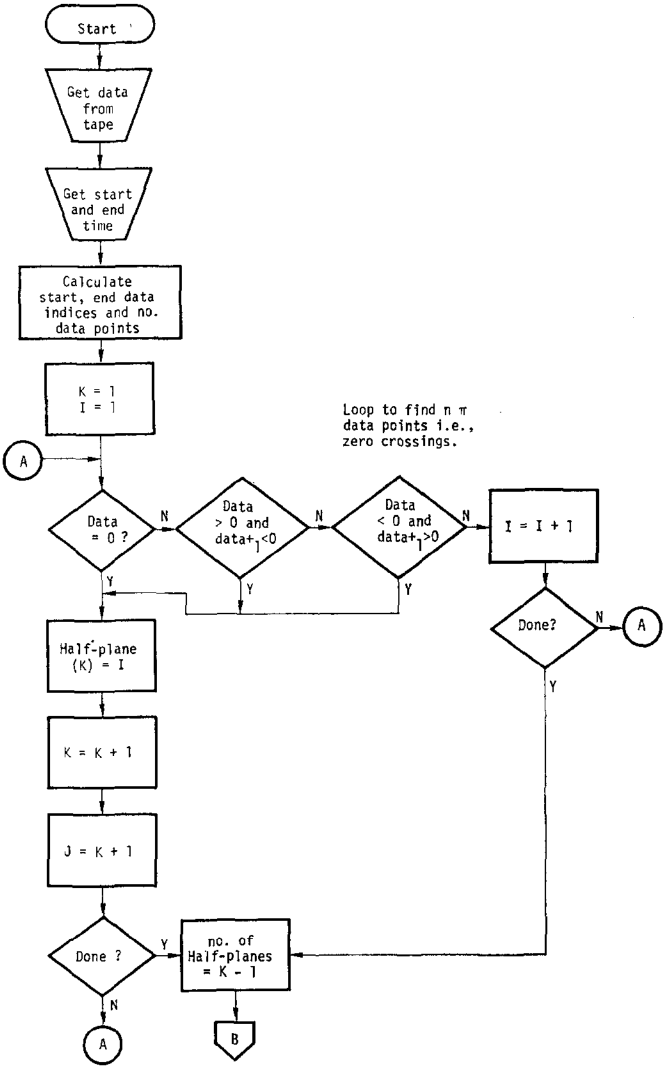

FIGURE 1

On entry, the magnetic-tape retrieval subroutine finds the correct record and reads it into memory. Analog disk-voltage offsets or background noise components are subtracted from each data point.

The operator specifies the initial and final examination times and the code calculates the indices of these points. This is done because the high density and

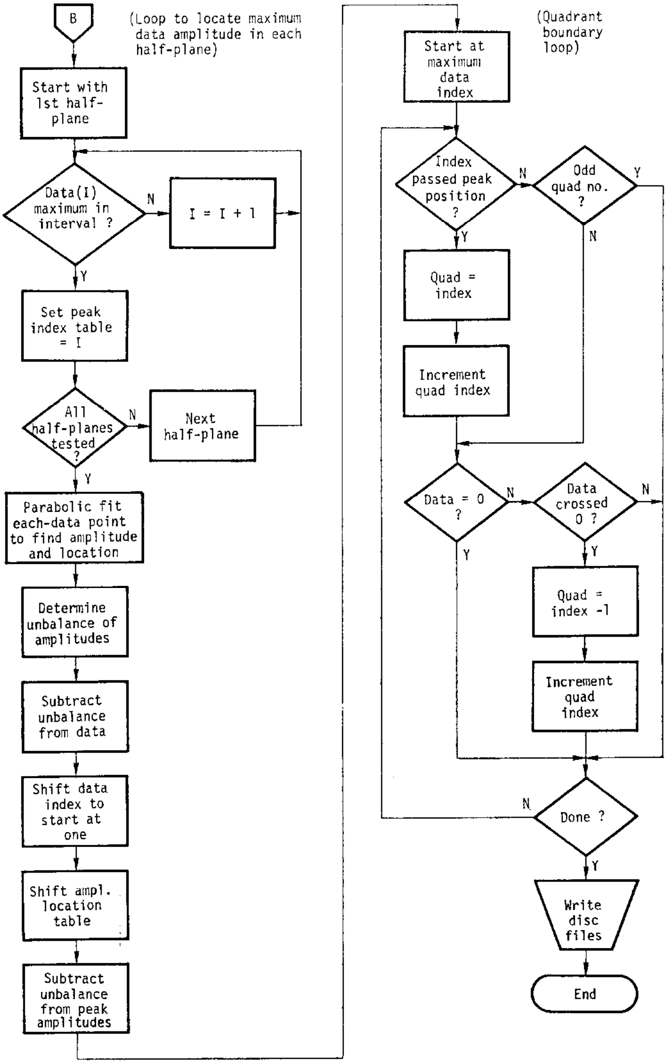

FIG. 1. Data retrieval flow chart.

turbulence levels early in the experiment generally result in unintelligible output, and a slight negative imbalance in the interferometer can cause an error if the final point is too late in time.

Since we know that this final data point is in the first quadrant ($0 \leqslant \Delta\phi \leqslant n\pi/2$) and that in our case $\Delta\phi$ decreases in time, the subsequent determinations of zero crossings, amplitude values and positions, and quadrant boundaries are performed

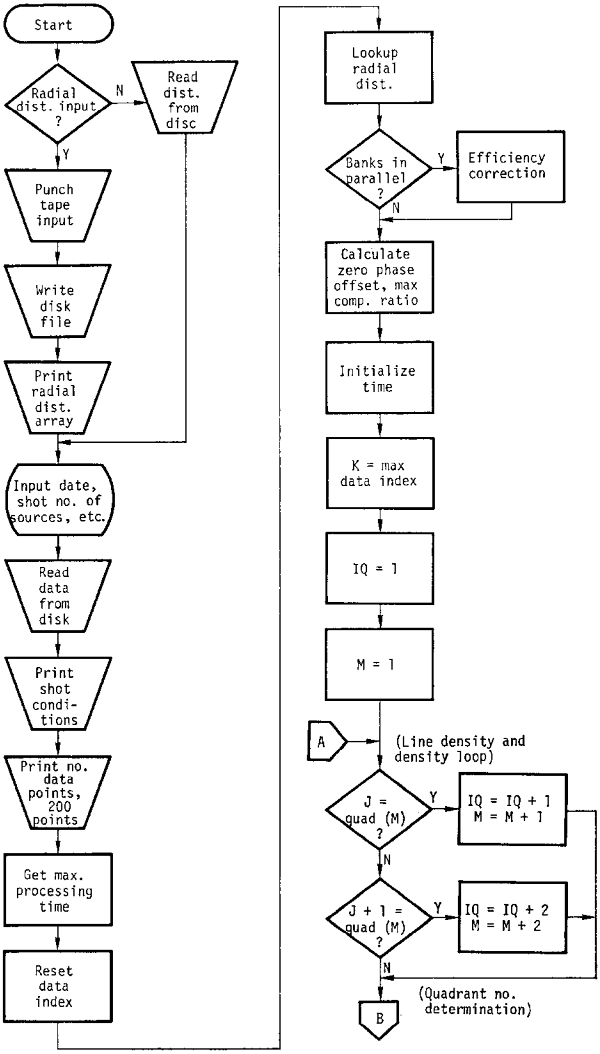

FIGURE 2

scanning backward from the final index to the initial one. Thus, the indices where the data change sign are found ($\Delta\phi = n\pi, \pi = 1, 2, \ldots$) in the next loop and are saved in an array. Also, a count is kept of the number of these points.

Next, using this information, each interval $n\pi \leqslant \Delta\phi \leqslant (n+1)\pi$ is scanned to determine the largest positive or negative value within it, and the index of each of these points is saved. As the interferometer output was digitized at discrete time intervals, these points should lie near but not necessarily at an actual voltage peak. This is particularly true early in time when $d(\Delta\phi)/dt$ is large. Therefore, a parabolic

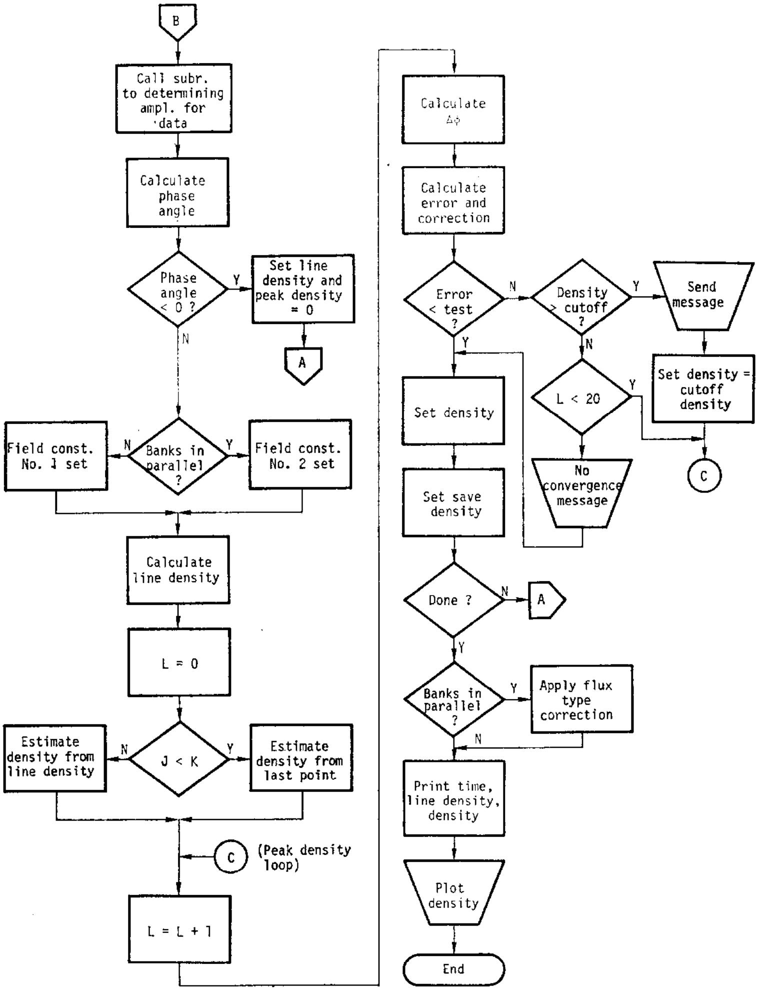

FIG. 2. Density processor flow chart.

fit is performed, using this maximum point and the two points on either side of it, to determine the maximum voltage amplitude and its position for each of these phase intervals.

The interferometer unbalance is calculated from the variation in data amplitude at the $\Delta\phi = \pi/2$ and $3\pi/2$ points, and the correction is applied to the data and amplitude arrays. As a convenience, the initial data index is shifted to unity.

The quadrant boundaries are determined by scanning the data backward and testing whether a point has passed the position of a peak ($\Delta\phi = i\pi/2, i = 1, 3, 5,\ldots$). or whether it has changed sign from the previous point ($\Delta\phi = k\pi/2, k = 2, 4, 6,\ldots$), or whether it is zero. The index of each of these boundaries is stored in the array QUAD.

DENSITY DETERMINATION

The flow chart for this code is shown in Fig. 2. Upon entry, the program reads either from disk or from paper tape the relative radial-density distributions which are needed to determine the peak density for a variety of plasma-injection conditions. Following this, the operator inputs date, shot number, injection conditions, and the capacitor-bank voltage, which determines the magnetic field and, consequently, the compression ratio as a function of time. This ratio determines, in turn, the variation of the radial density distribution under the assumption that the plasma behaves adiabatically, i.e., its radius is an inverse function of the square root of the compression ratio. The rest of the input data are then read from the disk file written by the previous program, and some initial printer output is given. The operator gives the maximum processing time desired, and the maximum data index is reset.

The following program segment, as illustrated on the flow chart, tests the plasma-injection conditions to determine which radial-distribution table to use in the subsequent calculations. Also, there is a correction to be made if the capacitor banks are connected in parallel rather than in series. Phase offset and the maximum compression ratio are also calculated.

To start the line-density and density calculation, the time is initialized to the time of the maximum data point plus 10 μsec. It will be decremented by 10 μsec each time around this loop as the calculation proceeds from the last point to the first. The assumption is made that the last data point lies in the first quadrant. As the data index is decremented during the calculation. its value is checked against the current entry in the quadrant boundary table. If they match, the quadrant number is incremented, as is the boundary index. A similar test follows that covers the situation where two successive data points are spaced more than one quadrant apart. Given the correct quadrant, a subroutine (YZERO) is called that interpolates to correct for slight amplitude changes and finds the correct amplitude for the data range. After the phase angle is calculated, a test is made to see if it is less than zero—a condition which can occur for data near the system's noise level. Following a series/parallel bank test, the compression ratio is calculated, an antenna-position correction applied, and the line density calculated.

The value of the peak density is initially estimated from the line density. Subsequently, the initialization is the previous density value. The integrand of the $\Delta\phi$ integral is calculated, and a Simpson integration is performed over the plasma radius. A differential is also calculated at the same time for use in a Newton–Raphson correction scheme. The phase so calculated is compared with the measured, a correction is computed, and a convergence test is made. A limit of 20 iterations is allowed before an error message is transmitted. Another possible condition is that a density greater than the maximum allowed may occur, in which case an exit is made with an appropriate message.

When all of the data have been processed, a small magnetic-field correction is applied and the program proceeds to output. An option is available to provide line-printer output in addition to a plot. If printed output is desired, the code lists time, line density, and density. It then calculates the inverses of these quantities and prints them. A semilog plot of the plasma density may also be generated.

When all of this is completed, one can either process another shot by again calling the data retrieval program or rewind the tape and finish.

CONCLUSION

Whereas, previously, when reducing photographs of the interferometer signals, the lower density limit was on the order of $1\text{–}2 \times 10^{11}$ cm^{-3}, the use of the present digital data system in conjunction with the routines outlined in this paper has increased the overall sensitivity of the interferometer to the low -10^{10} cm^{-3} range.

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