PS/LR/Note 79-3
22.1.79

RF Adjustment Techniques Using Relative Measurements

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Introduction

Every linac facility has a method by which suitable settings can be found for the rf field amplitudes and phases in each tank. For example, at Rutherford, a procedure for measuring the time-of-flight of a bunched particle beam was used for adjusting the rf.[1] This was an absolute measurement from which one could determine the absolute energy of the beam. In contrast, at LAMPF, the adjustment procedure for the entire 805-MHz linac (consisting of 44 separate rf units) is based on relative measurements only.[2,3] The quantity measured is the change in the time-of-arrival of a bunched beam at each of two separated detectors.

The purpose of this note is to suggest how these relative measurements could be used at the new linac at CERN. A computer program for implementing the techniques has been written for the control computer, the users' instructions for which is included in this note.

The measurement technique

A particle beam, after being accelerated through a portion of a linac, consists of a sequence of beam bunches separated in time by the period of the rf. As these bunches pass through a non-destructive pickup loop, a signal, having the same frequency as the rf, is induced in the circuit of the pickup loop. By comparing this induced signal to a reference signal of the same frequency, one can measure a phase shift between the two signals. This phase shift is completely arbitrary, and is used only as a reference point. If anything is done that causes a change in the time-of-arrival of the beam bunch at the pickup loop, then this change in the arrival time will be measured by a change in the phase shift between the induced and reference signals.

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Energy versus phase curves

Having one pickup loop allows one to measure phase changes of the beam at the loop as a function of any parameter. But if a second loop is situated downstream from the first loop by a distance, D, then one can measure the changes in the arrival times of the beam at each of the two loops, from which one can calculate the change in the energy of the beam by

$$\Delta W = - E_r c \eta^3 \ (\Delta t_2 - \Delta t_1)/D,$$

where E_r is the rest energy of the particle, c is the speed of light, $\eta = \beta\gamma$, evaluated at the approximate energy of the beam, and Δt_1 and Δt_2 are the changes in the beam arrival times at the two loops. The ability to measure energy change as a function of any parameter can be extremely useful.

A particularly informative parameter is the rf phase of the tank. Single-particle calculations have shown that the energy versus phase curves for the new linac at CERN have distinctive shapes that depend quite strongly on the rf amplitude. If the ability exists to quickly and accurately measure these curves, then, by comparing the measured curves with pre-calculated curves, one is able to quickly adjust the rf amplitude and phase of a tank.

As examples of what one might expect these energy versus phase curves to look like for the new linac, some preliminary calculations were made using PARMILA. Calculated curves corresponding to rf amplitudes of 100, 102, and 104 percent of design value for Tank 1 are shown in Fig. 1. Along the abscissa is plotted the phase displacement of the beam from the synchronous phase. These curves are seen to depend strongly on the rf amplitude. In particular, at an amplitude near 102%, there will be a curve having a significantly long flat portion, indicating that the energy does not change with phase. This condition is an easy one to detect, being insensitive to calibration errors. After finding this condition, the amplitude could be lowered by 2%, which should be near the design value. By generating another curve at this amplitude, one would find the synchronous phase to lie at the intersection point of the two curves.

The above statement is strictly true only if the beam energy is correct at the input of Tank 1. Otherwise these curves will be somewhat displaced. Portions of these curves corresponding to amplitudes of 100% and 102%, and corresponding to initial energy displacements of -10, 0, and +10 keV, are shown in Fig. 2. The intersection of the two curves corresponding to the same input energy still occurs within 1 or 2 degrees from the synchronous phase.

Computed energy versus phase curves corresponding to rf amplitudes of 94, 100, and 106 percent of design value for Tank 2 are shown in Fig. 3. In this case, the curves corresponding to the 94% and to the 106% amplitude both have nearly flat portions that should be easy to detect, and intersect near the synchronous phase. However, if the input energy is displaced by ± 50 keV, then the intersection point moves drastically, as shown in Fig. 4. Fortunately, it appears to be easy to tell that the input energy is wrong: If the input energy is low, then the intersection will occur on the steep portion of the curve corresponding to the 94% amplitude; if the input energy is high, then the intersection will occur on the level portion of the curve; at the correct input energy, the intersection should occur at the knee of the curve. This feature gives one the ability to check the input energy and to take corrective measures.

Similar computed energy versus phase curves for Tank 3 are shown in Figs. 5 and 6. The three curves at each amplitude in Fig. 6 correspond to input energy displacements of - 100, 0, and +100 keV.

The Δt procedure

Additional information can be obtained using the same measurements if, instead of varying the rf phase between two measurements, one turns the rf amplitude from "off" to "on" between two measurements. By doing this, one can measure the difference in the time-of-arrival of the beam at each loop produced by turning the tank from off to on. The theoretical values for the time differences between the "off" and "on" conditions are assumed to be known or calculable. If the tank is adjusted perfectly, and the input energy is correct, then the measured differences should agree with the theoretical differences. The disagreement between the measured and theoretical values are denoted by Δt_1 and Δt_2 for the first and second loops, respectively.

If one varies the phase of a tank, and measures and plots Δt_2 versus Δt_1, then one generates a "variable phase curve" referred to in Reference 3. The slope of this curve will depend on the rf amplitude in the tank. If one generates a second variable phase curve for a different rf amplitude, these two curves will intersect at a point. The distance from this intersection point to the origin gives an indication of the energy displacements at the input and output of the tank. This point of intersection corresponds (very nearly) to the condition in which the input and output phase displacements are equal, and the output energy displacement is the negative of the input energy displacement. The slope of the variable phase curve also gives information about the rf amplitude in the tank.

Determination of absolute energy- and phase-displacements

Near the design conditions, a linear relationship exists between Δt at each loop and the input and output phase- and energy-displacements, $\Delta\phi_{in}$, ΔW_{in}, $\Delta\phi_{out}$, and ΔW_{out}. But $\Delta\phi_{out}$ and ΔW_{out} are also linear functions of $\Delta\phi_{in}$ and ΔW_{in}. Consequently, one can express Δt_1 and Δt_2 as linear functions of $\Delta\phi_{in}$ and ΔW_{in}, find the universe relationship, and write

$$\Delta\phi_{in} = a\ \Delta t_1 + b\ \Delta t_2\ ;$$
$$\Delta W_{in} = c\ \Delta t_1 + d\ \Delta t_2\ .$$

The coefficients, a, b, c, and d, depend on the rf amplitude, but one should be able to set the amplitude properly based on either the energy versus phase curves or the "variable phase curves" described earlier. Knowing these coefficients and having measured Δt_1 and Δt_2, one can calculate $\Delta\phi_{in}$ and ΔW_{in}, from which one can calculate also $\Delta\phi_{out}$ and ΔW_{out}.

This is an extremely powerful method under certain conditions. A basic limitation, of course, is that the beam must remain sufficiently bunched as it passes the loops so that a phase shift can be measured. For this reason, this scheme would certainly not work for Tank 1, where a

750 keV beam would have to travel to the end of Tank 2 without debunching. The scheme might work for Tank 2, and should work for Tank 3.

Another limitation is the accuracy with which the measurements can be made. If one expects an rms error of δt in the measurement at each loop, then one would expect rms errors in the estimates of the phase- and energy-displacements to be

$$\delta\phi_{in} = \sqrt{a^2 + b^2}\ \delta t \ ;$$

$$\delta W_{in} = \sqrt{c^2 + d^2}\ \delta t \ .$$

The Δt computer program, ENPHI

A computer program has been written for implementing the techniques mentioned above. The program is accessed from the systems touch panel at either MAXI console. Starting with the "Home Page," one touches "Beam Quality," "Tank Appl Prog," and "Call DT Prog," in that order. This brings the Δt program into memory and starts it running. ENPHI (for "energy and phase") writes a page, shown in Fig. 7, on the users touch screen, which is used for issuing commands to the program. A data file, DK2:[210, 210] ENPHI.DAT, is read by the program. This file, an example of which is shown in Fig. 8, contains information concerning the linac and the graphical displays, etc.

The user is then asked, via the keyboard scope, to specify which tank of the linac he wants to start working with: 1, 2, or 3. A 1, 2, or 3 must be entered, or the program will continue to ask. If the program was called by mistake, and one wishes to "drop" the program, enter a 1, 2, or 3 and then touch the button marked "DROP."

The program has the ability to calculate and display on the storage scope three types of information:

1. Energy versus phase curves;
2. Δt_2 versus Δt_1;
3. The input and output phase- and energy-displacements, as calculated from Δt_1 and Δt_2.

Each of these displays has its own graph background.

Touch-panel options

A description of each command, issued by pushing a touch-panel button, is given below.

Button 1. SPECIFY TANK

This button allows the user to specify the tank number: 1, 2, or 3.

Button 4. DROP

This button causes the storage scope to be erased and the program to be dropped.

Button 5. SPECIFY GRAPH LIMITS

Using this button, the user can change the graph limits (the real values associated with each graph boundary) for any or all of the three types of graphs. The user is first shown the limits for the energy versus phase curves. (The order is left, right, bottom, and top.) If the user wishes to change any of these values, he must specify all four values, in free format, separated by commas. If the user does not wish to change these values, he simply presses the "return" key. The user is then shown the limits for the remaining two types of graphs, which he may or may not change in the same way. The units are as follows: phase in degrees; energy in MeV; and Δt in nanoseconds.

Button 6. DRAW DW VS PHI GRAPH

Pressing this button causes the storage scope to be erased and the background for the energy versus phase curves to be drawn.

Button 7. SPECIFY PLOT SYMBOL

Using this button, the user can specify the plot symbol to be used for the energy versus phase curve or for the Δt_2 vs Δt_1 plot. This allows separate curves to be plotted using different symbols.

Button 8. MARK AMPLITUDE CURVE

When generating an energy vs phase curve, the program remembers the position of the latest point plotted. After the plotting has been stopped (by pressing "STOP"), a curve may be marked with the rf amplitude. A horizontal line is drawn from the last point plotted to the right boundary of the graph, where the amplitude is written.

Button 9. START DW VS PHI CURVE

This button causes the program to read the data from the pickup loops and to store these initial values. The program then continues taking data from the loops and subtracts the initial values to find and plot the energy changes. This continues until the STOP button is pressed.

Button 10. STOP

This button causes the measuring and plotting process to be stopped. This applies to all three types of graphs.

Button 11. CONTINUE

This button causes the measuring and plotting process to be continued until the STOP button is pressed.(All buttons other than STOP are ignored.) The initial values, as set by button 9, are <u>not</u> redefined. The process to be continued is determined by the type of graph background that has been selected.

Button 13. DRAW DPHI-DW GRAPH

This button causes the storage scope to be erased and the background to be drawn for the energy displacement versus phase displacement.

Button 14. CALCULATE DPHI-DW

Pressing this button causes a tank off-tank on measurement to be made, from which the input and output phase- and energy-displacements are calculated and plotted. The input displacements are plotted with an A; the output displacements are plotted with a B. The A and B are joined by a straight line to indicate that they are related. In addition to the plotted points, the numerical values are written on the scope, along with the tank amplitude and phase values.

Button 15. DRAW DT1-DT2 GRAPH

This button causes the graph background to be drawn for the Δt_2 vs Δt_1.

Button 16. CALCULATE DT1 - DT2

This button causes a tank off-tank on measurement to be made. The theoretical values are subtracted from the measurements and the results plotted and written on the storage scope, along with the tank amplitude and phase values.

Summary and conclusions

The ability to measure the change in the phase of the beam at two separated detectors would supply valuable information for adjusting the phases and amplitudes of the new linac at CERN. The measurements are strictly relative ones, and could be made quickly and under computer control. If pickup loops were installed immediately following each tank, with a fourth loop further downstream of Tank 3, then one could easily generate energy change versus phase curves for each tank. Although four loops would be installed, only two sets of electronics would be needed since only two loops are used at a time. The same electronics could be switched from loops 1 to 3, and from loops 2 to 4.

Being able to quickly measure how the beam energy changes as a function of rf phase allows one, by comparing the measured curves with pre-calculated curves, to adjust the rf in the tank.

The more complicated procedure, which involves turning a tank off and on between measurements, should work for Tank 3 and might work for Tank 2. This procedure gives additional information, and theoretically would allow one to estimate quite accurately the energy- and phase-displacements of the beam.

A computer program has been written in FORTRAN for applying the techniques described in this note. Since, at this writing, the necessary hardware for making the measurements does not exist, the portion of the program involved with the loop measurements must be added later.

References

1. Batty, C. J. and D. Warner, 1960, An accurate determination of the PLA beam energy by a time of flight method, Rutherford Lab. Rept. NIRL/R 76.
2. Crandall, K. R., 1976, The Δt tuneup procedure for the LAMPF 805-MHz linac, Los Alamos Report LA-6374-MS.
3. Crandall, K. R. and D. Swenson, 1970, Side coupled linac turn-on problem, LASL Internal Rept. MP-3-98.

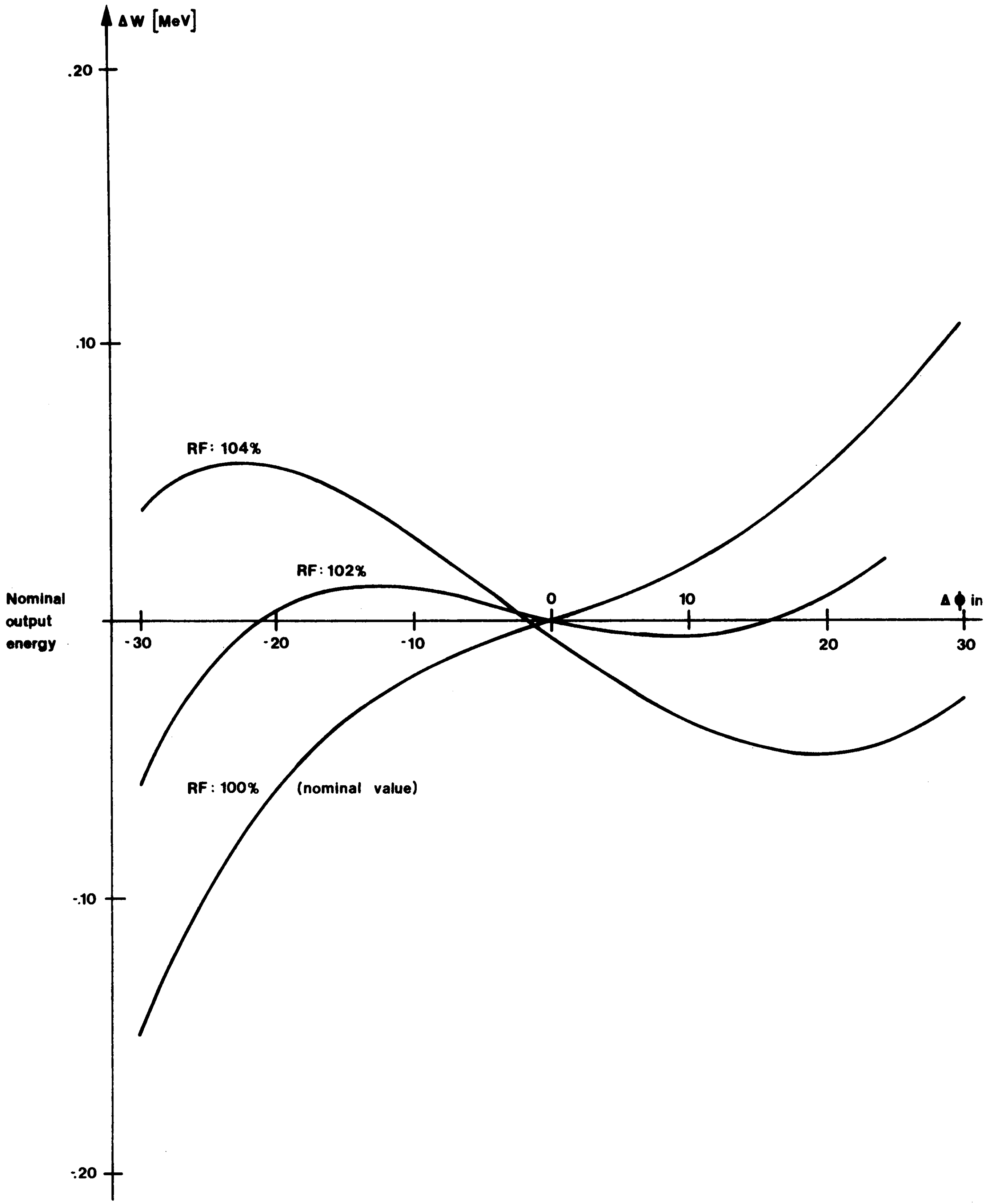

Fig. 1: Output energy of tank 1 vs input phase
(computed curves, program PARMILA)

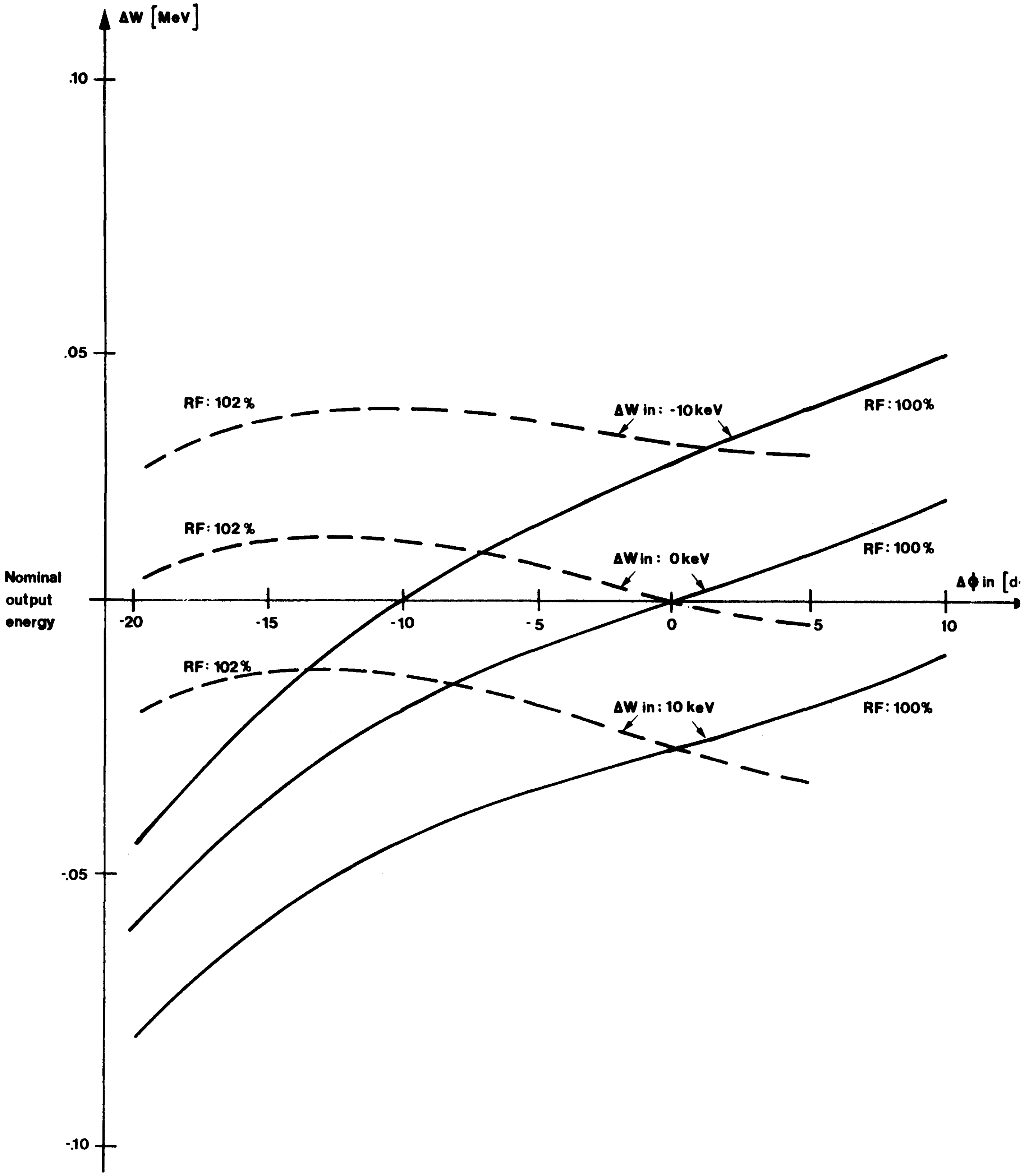

Fig. 2: Output energy of tank 1 vs input phase; input energy is a variable parameter

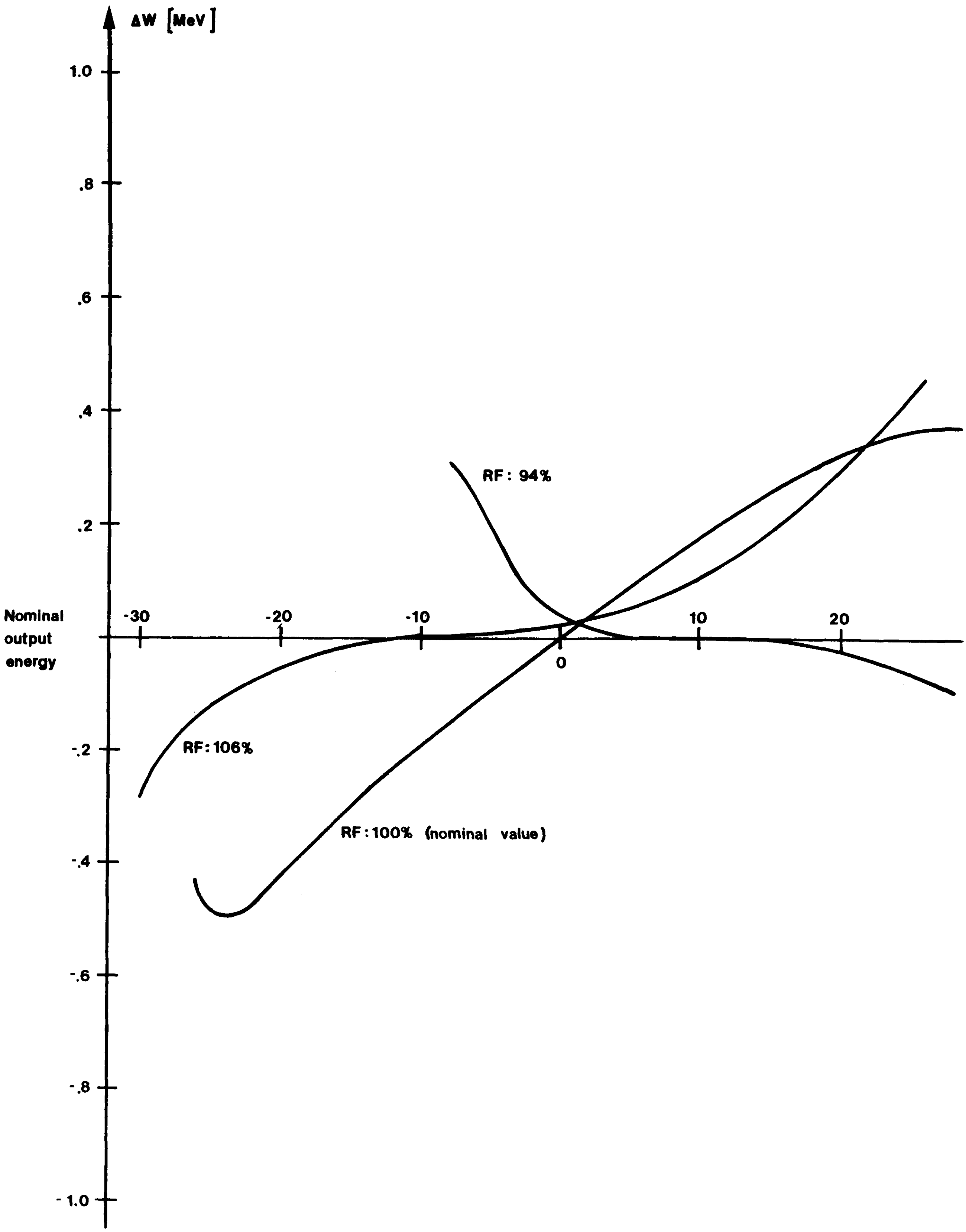

Fig. 3: Output energy of tank 2 vs input phase

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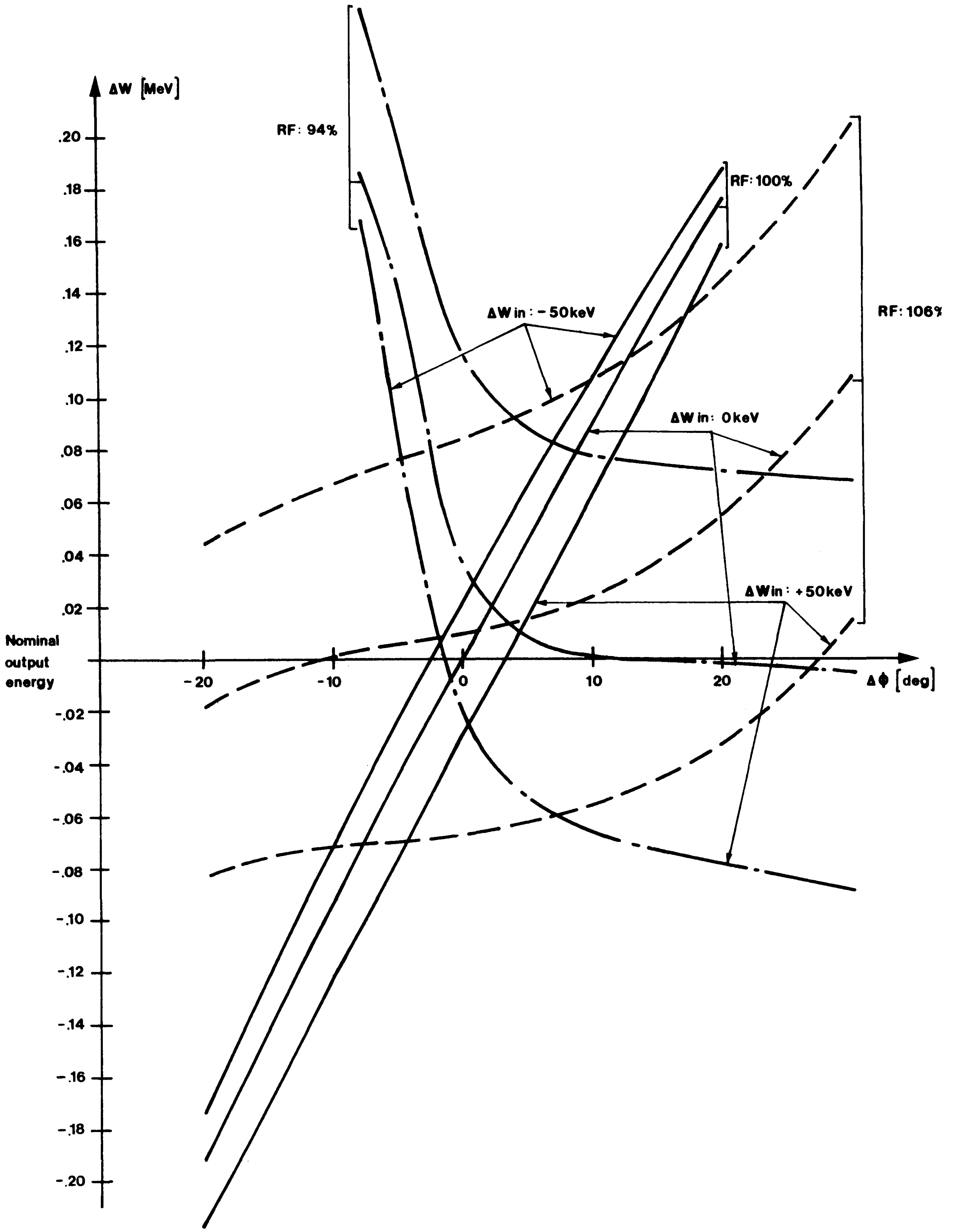

Fig. 4: Output energy of tank 2 vs input phase; input energy is a variable parameter

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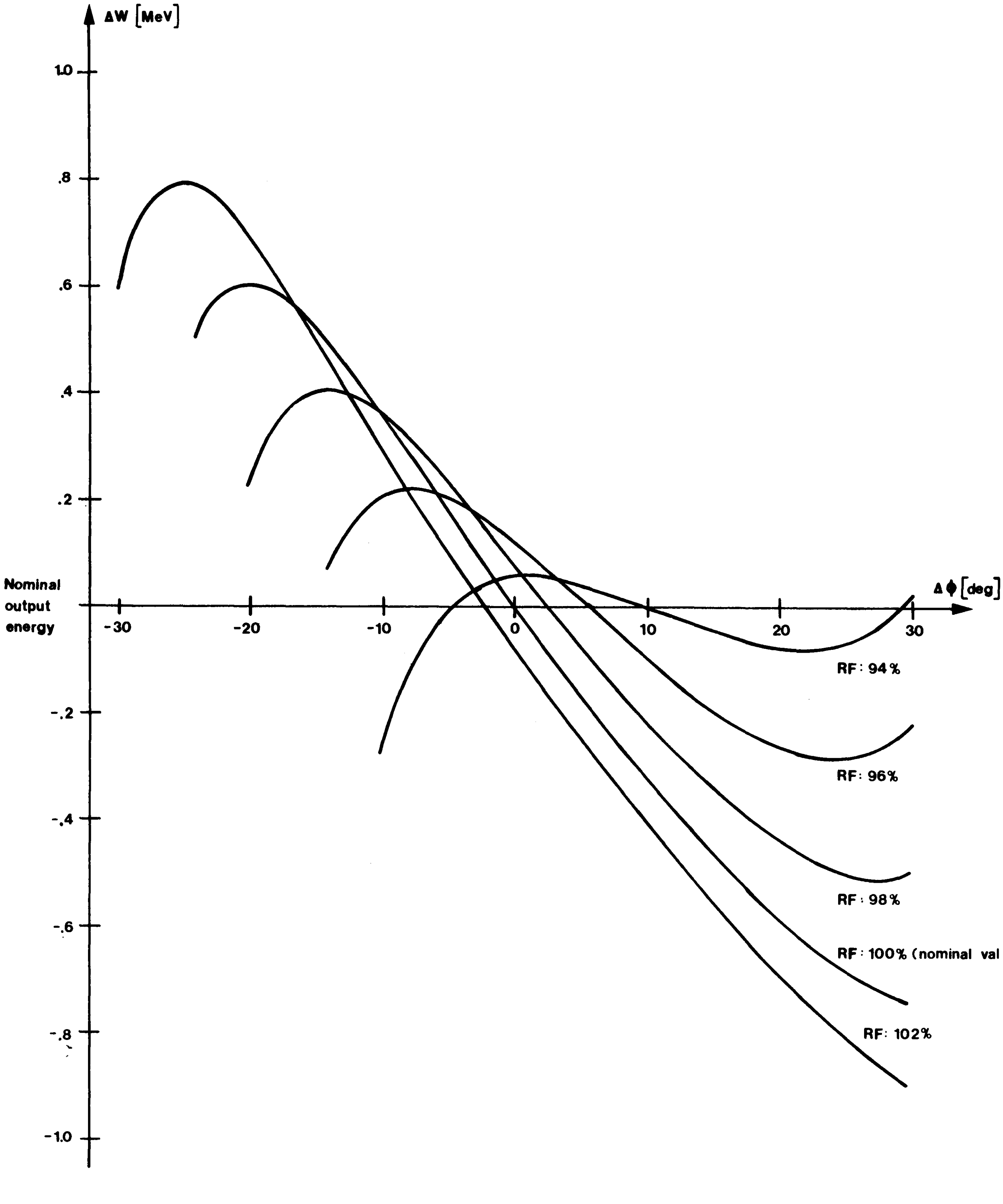

Fig. 5: Output energy of tank 3 vs input phase

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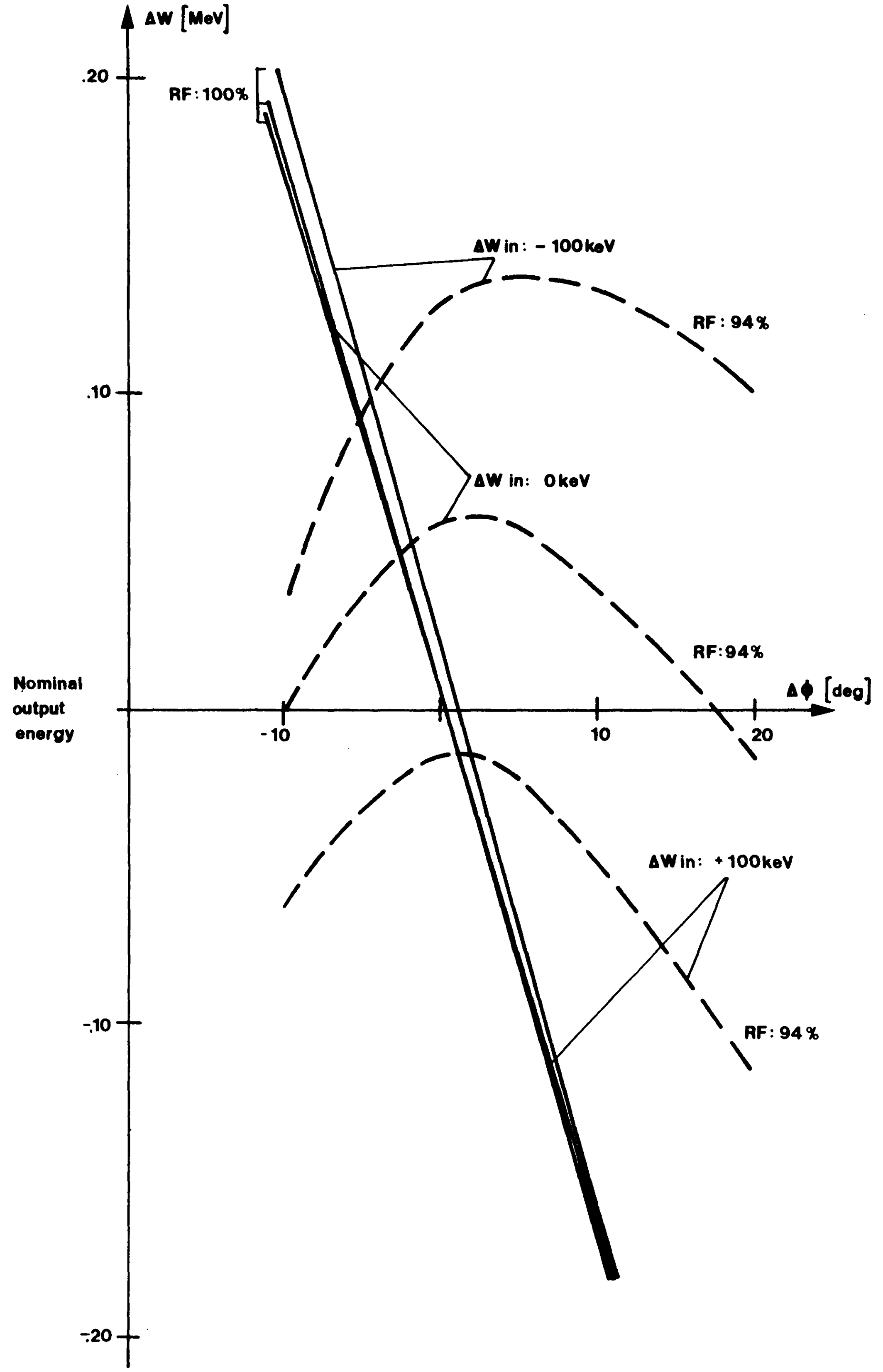

Fig. 6: Output energy of tank 3 vs input phase; input energy is a variable parameter

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PAGE NUMBER   194    DELTA-T PROGRAM                    DATE:79- 1-10  TIME:12:28:18

LEVEL     2

PREVIOUS PAGE       0

SIDEWAYS LINK       0

        SPECIFY                                          ---------
         TANK                                              DROP
                                                         ---------


        SPECIFY         DRAW          SPECIFY            MARK
         GRAPH       DW VS PHI         PLOT            AMPLITUDE
         LIMITS        GRAPH          SYMBOL             CURVE


         START         -------       ---------
       DW VS PHI        STOP         CONTINUE
         CURVE         -------       ---------


         DRAW                          DRAW
        DPHI-DW      CALCULATE       DT1-DT2           CALCULATE
         GRAPH        DPHI-DW         GRAPH             DTB-DTC


LINK OF BUTTON  1=
LINK OF BUTTON  2=
LINK OF BUTTON  3=
LINK OF BUTTON  4=
LINK OF BUTTON  5=
LINK OF BUTTON  6=
LINK OF BUTTON  7=
LINK OF BUTTON  8=
LINK OF BUTTON  9=
LINK OF BUTTON 10=
LINK OF BUTTON 11=
LINK OF BUTTON 12=
LINK OF BUTTON 13=
LINK OF BUTTON 14=
LINK OF BUTTON 15=
LINK OF BUTTON 16=
```

```
N1RMOPH-1$          DEVICE NAME FOR TANK 1 PHASE
N2RMOPH-1$          DEVICE NAME FOR TANK 2 PHASE
N3RMOPH-1$          DEVICE NAME FOR TANK 3 PHASE
N1RATANK-1$         DEVICE NAME FOR TANK 1 AMPLITUDE
N2RATANK-1$         DEVICE NAME FOR TANK 2 AMPLITUDE
N3RATANK-1$         DEVICE NAME FOR TANK 3 AMPLITUDE
N9CAMSM-1$          DEVICE NAME FOR LOOP AFTER T1 (DUMMY)
N9CAMSM-2$          DEVICE NAME FOR LOOP AFTER T2 (DUMMY)
N9CAMSM-3$          DEVICE NAME FOR LOOP AFTER T3 (DUMMY)
N9CAMSM-4$          DEVICE NAME FOR 2ND LOOP AFTER T3 (DUMMY)
13.100,13.500,1.500,  DISTANCES BETWEEN LOOPS (METERS)
10.,30.4836,49.967,   DESIGN ENERGIES OF THE TANKS (MEV)
100,800,100,800,20.,70.,-.5,.5,    GRAPH LIMITS FOR DW VS PHI
100,600,400,900,-20.,20.,-.5,.5,   GRAPH LIMITS FOR DW VS DP
100,900,100,900,-.5,.5,-.5,.5,     GRAPH LIMITS FOR DTC VS DTB
10,2,0,10,2,3,        N, M, K FOR DW VS PHI (GRAPH PARAMETERS)
CHANGE IN ENERGY VS. TANK PHASE
938.256,            REST ENERGY (MEV)
202.56,             FREQUENCY (MHZ)
0.299725,           VELOCITY OF LIGHT (M/NS)
0.080,0.100,0.100,  DISTANCES FROM END OF TANKS TO FIRST LOOP (M)
6.939,12.958,13.359,   TANK LENGTHS (M)
1.500,0.050,0.200,     DESIGN VALUES FOR TB (DUMMY)
-.338,-79.,.001725,-2.59,  TRANSFER MATRIX ELEMENTS FOR TANK 1
-.191,-50.,.0182,-.489,    TRANSFER MATRIX ELEMENTS FOR TANK 2
-.066,29.6,-.0387,-.046,   TRANSFER MATRIX ELEMENTS FOR TANK 3
0,                         PRINT FLAG
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Figure 8 : Data file