Title
SYSTEMATICS IN THE CONTROL SETTINGS OF THE BERKELEY 88-INCH CYCLOTRON

Author
Clark, D.J.

Publication Date
1977-09-01

Submitted to Nuclear Instruments and Methods

UC-28
LBL-6502
Preprint c.1

SYSTEMATICS IN THE CONTROL SETTINGS OF THE BERKELEY 88-INCH CYCLOTRON

D. J. Clark, R. A. Gough, W. R. Holley, and A. Jain

September 1977

Prepared for the U. S. Department of Energy under Contract W-7405-ENG-48

SYSTEMATICS IN THE CONTROL SETTINGS OF THE BERKELEY 88-INCH CYCLOTRON*

D. J. Clark, R. A. Gough and W. R. Holley

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

and

A. Jain†

Bhabha Atomic Research Centre
Variable Energy Cyclotron
Calcutta - 700 064, India

September 1977

Abstract:

A modern isochronous cyclotron requires a large number of control settings to produce a wide variety of beams and energies. During fifteen years of operating experience with the Berkeley 88-Inch Cyclotron we have developed a system for prediction of parameters for new beams. This system substantially reduces the accelerator time required for their implementation. These predictions are based on a combination of computer calculations (from extensive field maps) and simple scaling laws which are derived. The use of model beam solutions is discussed; their range of applicability is specified by equations derived by placing limits on "acceptable" phase errors. A comprehensive set of operating parameters has evolved which spans the entire operating range of the cyclotron. The concepts discussed in this paper have proven valuable in maintaining the high operational efficiency and versatility of the Berkeley 88-Inch Cyclotron and should be useful to many other laboratories operating similar facilities.

*Work performed under the auspices of the U. S. Energy Research and Development Administration.

†Supported by the International Atomic Energy Agency and the National Research Council.

1. Introduction

The determination of optimum operating values for about 50 parameters needed to obtain an optimized external beam in a modern sector-focused cyclotron is a common problem in the various laboratories operating these accelerators. Many settings can be calculated in advance, using measurements of magnetic and electric fields, and orbit calculations. Those remaining are adjusted during operation to optimize beam intensity and quality. Eventually almost all of the parameters are "tuned" by operators and cyclotron development groups. The result is a set of best operating parameters for each beam. The questions we wish to discuss in this article are how the sets of parameters are obtained and how they can be treated systematically and extended from existing optimized beams to new beams.

In formulating control settings there are several systems in use in various laboratories. Scaling of central region parameters for several systems is discussed in ref. 1. In the constant orbit pattern system, developed extensively at Michigan State University, the number of turns is kept constant over a wide range of energy and particles by letting the dee voltage be proportional to particle energy/charge. The constant orbit pattern means the ion source and the puller electrode (attached to the dee) can be fixed in position. This system eliminates the usual backlash and reproducibility problems in the center region, and simplifies tuning. However, for ions heavier than α particles, which are usually accelerated only partially stripped of electrons, the charge exchange loss during acceleration requires maximum dee voltage for maximum intensity beams. Thus at the 88-Inch Cyclotron we operate at full dee voltage for heavy ions and find that the optimum settings include a number of center region settings and turn patterns. About 65-70% of the beam time is currently devoted to heavy ion beams.

2. Experience at the LBL 88-Inch Cyclotron

About 50 parameters need adjustment in the Berkeley 88-Inch Cyclotron, for the acceleration of a beam of specified energy/nucleon and charge-to-mass (q/m) ratios. A typical set is shown in Table I for 104 MeV oxygen (4+) ions. Parameters 1-3 are the main coil current, rf, and dee voltage; 4 to 20 are the trim coil currents required to produce an isochronous field. These are calculated with the program CYDE. Only the minimum number of trim coils are switched on to produce the required field. The field is generally isochronous between 7 and 37 inches. It is required to decrease between 0 and 7 inches to meet vertical focusing requirements. Between 37 inches and extraction radius of about 39 inches the field falls below isochronous values. Different rates of fall have been found suitable for different sets of beams. Parameters 21 and 22 are the radial and azimuthal location of the ion source center and 23 is the ion source rotation. Due to the initial ion energy, the ion source has to be "off center" with respect to the magnet for proper centering of the first orbit. Parameters 24 and 25 represent the X and Y coordinates of the puller electrode.

The deflector consists of three segments, called the entrance, middle and exit segments, respectively. Parameters 26 to 38 represent the coordinates of these segments; 39 and 40 are the voltages of the first two segments. The third segment is not presently in use except for beams with very high energy-to-charge ratios, E/q (e.g. 130 MeV α).

Parameters 41 to 50 represent the angles and currents in the five sets of harmonic (valley) coils. The first set is needed to produce a first harmonic in the magnetic field for proper centering of the orbits, and the fifth set for precessional extraction of the beam.

The original control settings were based on magnetic field measurements (ref. 2), electrostatic field maps (ref. 3), equilibrium orbit calculations (ref. 4), calculated sets of trim coil currents to produce approximate isochronous magnetic fields (ref. 5), and ray tracing deflector calculations (ref. 6).

In the process of designing a new center region for axial injection in 1969 (ref. 7) the code PINWHEEL (ref. 8) was modified to a version called PINMOD, which added an optional source-puller gap width at an optional angle, and independent dee-dummy dee gap widths on each side of the source-puller. In each of these three gaps the electric field was assumed to be uniform for simplicity. The results were compared with electrolytic tank measurements made at the University of Maryland (with M. Reiser's group) and the orbit patterns were very similar. The design was completed with the PINMOD program, rather than by making further detailed electrolytic tank measurements. The center region settings used now are based on this program.

To calculate the trim and main coil settings to produce operating magnetic field radial profiles the computer code LP-90 (ref. 5) proved to be difficult to use. A period of graphical fitting followed, and then a least-squares fitting code TRIMCO, kindly supplied by H. Kim of the University of Maryland, was made operational. TRIMCO was written by R. Berg at Michigan State University (ref. 9). TRIMCO was incorporated into the chain of cyclotron codes called CYDE, which now includes the measured magnetic field maps of a number of main field levels, trim coil contributions at these levels at each radius, calculation of equilibrium orbit parameters in an isochronized field for the desired energy, calculated trim coil currents, and equilibrium orbit properties in the final fitted field. The effect of each trim coil in gauss/amp decreases at high average fields due to magnet saturation, and so the trim coil effect is a function of field level. Since the trim coils make a significant contribution to the average field, especially at high fields, the question arises of what field level to assume for calculating trim coil effects. The original assumption was that the trim coils' effects were those existing in the final approximately isochronous field. However, using trim coil currents calculated from this assumption it was difficult to accelerate high magnetic field beams to full radius, and large discrepancies were found between calculated and measured beam phase history during acceleration. Then a parameter was added to the CYDE code to select any desired level between that of the main coil only, and that of the final field with all trim coils on. The optimum value of this parameter, as determined by agreement between calculated and measured phase histories, is .5-.6 of the way between the final field and the main coil field alone. A comparison of phase histories calculated with the original and the present methods along with the measured values is shown in fig. 1. The measured phase history shown is adequate for acceleration, but not optimized for minimum phase slip. With the original program, severe phase slip is incorrectly predicted.

3. Scaling Laws

There are a number of useful scaling laws which help in systematizing the control settings and extending them to new beams.

For a particle of mass m and charge q moving in a circle of radius r with velocity v in a plane perpendicular to a magnetic field B, we can set the inward magnetic force equal to the mass times the acceleration (MKS units):

$$qvB = mv^2/r \quad \text{or} \quad mv = Bqr. \tag{1}$$

From eq. (1) we can obtain the particle revolution frequency:

$$\omega_p = v/r = Bq/m, \; f_p = \omega_p/2\pi = \frac{v}{2\pi r} = \frac{Bq}{2\pi m} \tag{2}$$

Non-relativistic energy E is, using eq. (2):

$$\begin{aligned} E(r) &= \frac{1}{2} mv^2 = \frac{1}{2} m(2\pi)^2 f_p^2 r^2 \propto q^2 B^2 r^2/m \\ E &\propto mf_p^2 R_f^2 \propto mf_p^2 \propto B^2 q^2/m. \quad E = K\frac{q^2}{m} \end{aligned} \tag{3}$$

where R_f is extraction radius, E(r) is energy as a function of radius and E is energy at radius R_f. The energy constant K is usually defined with B at maximum value and describes the energy capability of the cyclotron. It is the energy of the α particles or protons at maximum B.

In a cyclotron, harmonic modes of acceleration can be used in which the radiofrequency system operates at a frequency which is a multiple h, the harmonic, times the particle frequency:

$$f_{rf} = hf_p. \tag{4}$$

Combining eqs. (2) and (4) we get:

$$f_{rf} = hB\,q/(2\pi m) \propto hB\,q/m. \tag{5}$$

From eq. (5) we see that for a given operating f_{rf} and B all particles with the right hq/m will accelerate. Thus C^{3+} and O^{4+}, having nearly the same q/m, will accelerate at the same f_{rf} and B on the same harmonic, except for a very small frequency difference ($<$ .1%). Since f_p is the same (eq. 2), the energies of two such beams are seen from eq. (3) to be proportional to m; e.g. 96 MeV C^{3+} and 128 MeV O^{4+}, or E/m = 8 MeV/nucleon for both particles. This property of two beams accelerating with the same settings can be a problem, but it can also be extremely useful in producing a new difficult ion such as Ar^{8+} from settings for an existing beam such as Ne^{4+}. The two beams can be separated either by the small difference in f_p if large enough, or can be distinguished by the different $E \propto m$ measured in an energy detector.

Another problem in tuning which sometimes arises is also illustrated by eq. (5). Beams with different q/m but the same hq/m can accelerate together at the same f_{rf} and B. At low energies, where their isochronous fields are similar, they can accelerate to full radius, and if the deflector is mistuned, the wrong beam can be extracted. An example observed by us was a beam of Ne^{3+} on h = 5 brought to an experimental target accidentally, instead of the desired beam Ne^{5+} on h = 3. They were identified by a total energy measurement, since $E \propto q^2$ in this case from eq. 3, and the energies have the ratio $(3/5)^2$.

The center region settings depend upon the number of turns. Neglecting transit time and gap-crossing resonance effects, and assuming in-phase acceleration, the radius of the source and puller, for centered beam, is proportional to the radius of the first turn:

$$r_s \propto r_o \qquad (6)$$

(It can be shown, for example, that $r_s = 0.75\ r_o$ for a single dee cyclotron.)

The number of turns is:

$$N = \frac{E}{2qV_D} \propto \frac{E}{qV_D} \qquad (7)$$

for a single dee cyclotron with dee voltage V_D, and acceleration on the peak of V_D. Combining eqs. (3), (6), (7) and using qV_D as the energy gain on the first gap crossing, we have:

$$r_s \propto \frac{1}{\sqrt{N}} \ . \qquad (8)$$

So for a constant turn number mode of operation the source and puller are left in fixed position as mentioned earlier. It is then seen from eq. (7) $V_D \propto E/q$.

In the 88-Inch Cyclotron V_D is run near maximum for heavy ions to reduce charge exchange losses, so we have a constant dee voltage mode of operation. N and r_s vary with particle and energy. It is useful to find the condition for beams with the same number of turns at constant V_D. This is found from eq. (7) as :

$$E/q = \text{const.} \qquad (9)$$

These beams have the same center region from eq. (8) and have harmonic coil settings with the same azimuths, but amplitudes which are approximately proportional to main coil current. Another form of eq. (7) is obtained by using it with eqs. (2) and (3):

$$N \propto Bf_p/V_D \ . \qquad (10)$$

The condition for constant N and V_D obtained from eq. (10) is another form of eq. (9):

$$Bf_p = \text{const.} \qquad (11)$$

The relation of protons (p) to heavier ions (HI) along a line defined by eqs. (9) or (11) is:

$$E(p)/q(p) = E\ (HI)/q\ (HI) \text{ or}$$
$$E\ (HI) = E(p) \times \frac{q(HI)}{q(p)} \tag{12}$$

This indicates that heavy ion energies are integral multiples of proton energies with the same center regions and number of turns along lines given by eqs. (9) or (11).

The scaling of deflector settings is as follows. For all ions of all energies to follow the same trajectories through the electrostatic deflector channel, the instantaneous radius of curvature, r_i (Θ), must be the same function of angular position Θ. Since $qvB(\Theta) - q\ V_{Def}/g = mv^2/r_i$, $r_i = mv^2/\ [qvB(\Theta) - qV_{Def}/g]$ where V_{Def} and g are electrostatic deflector voltage and gap, and $B(\Theta)$ is the magnetic field along the trajectory. Dividing numerator and denominator by $qvB(\Theta)$ and using eqs. (1) and (3) with $r = R_f$, we have:

$$r_i = \frac{R_f\ [B_f/B(\Theta)]}{1 - \frac{V_{Def}}{g}\,\frac{B_f}{B(\Theta)}\,\frac{R_f/2}{E/q}}$$

where B_f is the azimuthally averaged magnetic field at extraction radius. For $r_i(\Theta)$ to be the same for different beams, the ratio $B_f/B(\Theta)$ should also be the same independent of magnetic field level (i.e. constant fringing field contour), and

$$\frac{V_{Def}}{g} \propto \frac{E}{q} \tag{13}$$

In fact, $B_f/B(\Theta)$ does not change except at the highest field levels, where the fringing field begins to change shape. So the approximate scaling law for the deflector is relation (13). Thus the deflector has the same settings for all beams along lines specified by eqs. (9) or (11). These are the same lines we just determined for N = const. Relation (13) is very useful for scaling deflector voltage with E/q for new beams.

It is useful to plot the operating beams on a log-log graph of B vs f_p forming a resonance chart as shown in fig. 2. Ions with a given q/m appear on lines of slope = + 1.0, since from eq. (2) we have $\log B = \log f_p + \text{const.}$ Ions with a given number of turns and center region (assuming fixed dee voltage) lie on lines with a slope = - 1.0 because of eq. (11) giving $\log B = - \log f_p + \text{const.}$ Since this condition is equivalent to constant E/q (from equation 9), slope = - 1.0 lines are lines of approximately constant deflector strength (relation 13). Heavy ions lying on these lines have energies which are integral multiples of proton energies (from equation 12). So for beams on the same harmonic along one of these slope = - 1.0 lines, we can use the same center region, approximately the same deflector settings and scale the valley coil currents proportional to the main coil current.

Figure 2 also shows the entire operating regime of Berkeley 88-Inch Cyclotron. While all of the commonly used beams are run on first and third harmonics, selected beams which have been run on harmonics 5, 7, 9, 11, 13 and 15 are also indicated. For beams on harmonics $h > 7$ special modifications to the center region were found useful to reduce the source-puller transit time to meet orbit centering requirements (ref. 10).

4. Solution "Stretching"

In order to minimize the amount of data storage needed to set up any desired particle and energy, we have selected a number of trim coil solutions for "model beams" which can be used to run any nearby beam by "stretching" the solution. The stretching requires small changes in some of the following parameters: f_{rf}, magnetic field level using the main coil or trim coil 17, harmonic (valley) coil currents, V_D and V_{Def}. Trim coil and center region parameters can be left unchanged. The model beams which lie on a line given by eqs. (9) or (11) have the same number of turns in our system of V_D = const., so they can use the same center region (relation 8), deflector positions and voltages (relation 13), and harmonic coil azimuths with amplitudes proportional to main coil current. Nearby model beams can also use the same settings, by adjusting V_D, the inner harmonic coil and the deflector voltage. These common center region and deflector modes greatly simplify the parameter systematics of the cyclotron.

The number of model beams needed to cover the operating range of the cyclotron depends on how far a trim coil solution can be stretched either in q/m (fixed magnetic field) or in magnetic field B (fixed q/m). When a model beam trim coil solution appropriate for $\varepsilon_a \equiv \frac{q_a}{m_a}$ is used to accelerate a beam with a different $\varepsilon_b \equiv q_b/m_b$, the difference in the isochronous field shapes leads to phase errors between the beam "b" and the rf accelerating voltage. The phase error can be specified by a value at extraction radius (R_f), $d_f = \sin\phi_b$ $(r = R_f)$ and by an extremum value at smaller radius (R_e), $d_e = \sin\phi_b$ $(r = R_e)$. The convention for phase used here is that the energy gained by a particle in crossing the accelerating gap is given by $\Delta E = qV_D \cos\phi$. We have assumed here that the model solution has $\sin\phi \approx 0$ for all radii. For q/m stretching at fixed magnetic field it can be shown (ref. 11) that the phase errors are given by the following formula:

$$\pi h \frac{K^2}{931V_D} \varepsilon_b \left(\varepsilon_b^2 - \varepsilon_a^2\right) = 2d_f - 4d_e \mp 4\sqrt{d_e^2 - d_f d_e} \qquad (14)$$

where h is the harmonic number of acceleration, V_D is the peak rf voltage in MV, $K = E_b \times m_b/q_b^2 \approx E_a \times m_a/q_a^2$ is the cyclotron energy constant in MeV, and q is in electron charges and m is in A.M.U. The extreme limits on stretching in q/m are obtained by setting $d_e \pm 1$ and $d_f = \mp 1$. Simplified phase histories for these conditions are shown in fig. 3a. Of course with these phase histories very little if any beam would be accelerated to extraction radius. We have found that external beams generally can be easily obtained with little loss in beam quality or intensity if we stay within more conservative stretching limits set by $d_e = \pm .5$, $d_f = 0$. Simplified phase histories for these conditions are shown in fig. 3b. In this case eq. (14) reduces to:

$$\pi h \frac{K^2}{931V_D} \varepsilon_b \left(\varepsilon_b^2 - \varepsilon_a^2\right) = \mp 4. \qquad (15)$$

We have chosen a minimum number of model beams such that any new beam we wish to run will be within the limit set by eq. (15) for at least one model solution.

The above discussion applies to stretching at fixed magnetic field B where the lack of isochronism is caused by relativistic effects and can be treated analytically. Stretching a solution from one magnetic field level to another (e.g. keeping same q/m but changing energy of beam) brings into play relativistic effects and also possibly large variations in field radial profile due to saturation. For some regions of the resonance chart the relativistic effects dominate (typically when the energy is above 10 MeV/nucleon) and results analoguous to those for q/m stretching can be derived (ref. 11). For the conditions $d_e = \pm .5$, $d_f = 0$ the limits on energy stretching for a given ion can be obtained from the following formula assuming changes in magnetic field are independent of radius (i.e. ignoring saturation effects):

$$\frac{\pi h E_1}{931 m V_D q} \left(E_1 - E_0 \sqrt{\frac{E_0}{E_1}} \right) = \pm 4 \qquad (16)$$

where E_0 is the model energy, E_1 is the limiting energy to which the solution will stretch, and V_D is the dee voltage for the stretched beam.

In the regions of the resonance chart where saturation effects lead to appreciable field profile variations with changing field level, eq. (16) is not applicable. For these cases sets of CYDE runs were made at several energies near model energies (E_0) to determine limits (E_1) for which phase errors corresponding to $d_e = \pm .5$, $d_f = 0$ were reached. In addition the program CYDE has been used to confirm the stretching limits obtained from eqs. (15) and (16) and results have been verified on the cyclotron.

A grid of model beams has been chosen to satisfy limits of stretching at constant magnetic field level specified by eq. (15) and limits of energy stretching at constant q/m consistent with (16) and the CYDE results described in the preceeding paragraph. The first and third harmonic regions of this grid are shown in fig. 2. About 200 points, distributed over 20 lines of constant q/m, are required to run <u>any</u> first or third harmonic beam. In the lower portion of the figure ($K < 40$) only 7 lines of constant q/m are required, a consequence of the K^2 dependence in eq. (15). Model beams which have been run and those for which trim coil solutions have been calculated with CYDE are distinguished in fig. 2 in a way which is easily updated. In the first and third harmonic regions of the figure, only model beams are indicated; many other beams which have been run are deleted for clarity. Occasional erratic energy spacing of some ions is the result of utilizing previously existing solutions which had been extensively developed. The quantitative stretching predictions described above have permitted reliable tune out of new beams without advance scheduling of accelerator time for testing, with a net improvement in operational efficiency.

5. Concluding Remarks

We have found that about 200 model beams are necessary to span the useful operating range of the cyclotron, as shown in fig. 2. A considerable amount of beam development time has been spent during the past 15 years to optimize the many parameters on a large number of the grid points shown. These data are used to generate settings for the missing model beams, using the scaling laws described previously. In this way a complete tabulation for the control settings has been produced. Much future beam development and CYDE calculation time will thus be saved. When a new beam is required it is located on fig. 2 by its q/m and E/m and the appropriate nearby model beam is determined. The model beam parameters are set, with the appropriate small changes in a few parameters. This procedure has been found successful in practice. In most cases, for small stretching, only f_{rf} and B need changing to produce external beam. The other parameters are then tuned for optimum beam.

A future project will be to store the data in a computer and have parameters for any beam available on demand. Another useful development will be a computerized smooth interpolation of all the parameters to give the optimum settings for each particle and energy. In this case the trim coil setting can either be interpolated or recalculated for each case.

References

1. M. Reiser, Nucl. Instr. Meth. 18-19, 370 (1962).
2. J. H. Dorst, Nucl. Instr. Meth. 18-19, 135 (1962).
3. H. A. Willax and A. A. Garren, Nucl. Inst. Meth. 18-19, 347 (1962).
4. J. D. Young, et al., Nucl. Instr. Meth, 18-19, 347 (1962).
5. A. A. Garren, Nucl. Instr. Meth, 18-19, 309 (1962).
6. A. A. Garren et al., Nucl. Inst. Meth. 18-19 525 (1962).
7. D. J. Clark et al., 5th Int'l Cyclotron Conf., p. 610, Ed. R. W. McIlroy, Butterworths, London (1971).
8. M. Reiser, private communication.
9. H. Kim, private communication.
10. D. J. Clark and A. Jain, private communication.
11. W. R. Holley, to be published.

Table I. Control settings for typical 88-Inch Cyclotron beam.

	Element, mass, charge		0 16	+4
	Energy (MeV)		104.0	
1.	Main Coil (Amps)		1661.04	
2.	Frequency (MHz)		5.7164	
3.	Dee Volts (kV)		65.6	
	Trim Coils		**(Amps)**	
4.		1	703.0	
5.		2	-591.0	
6.		3	-253.0	
7.		4	-30.3	
8.		5	0.0	
9.		6	76.0	
10.		7	0.0	
11.		8	111.0	
12.		9	0.0	
13.		10	62.0	
14.		11	0.0	
15.		12	-239.0	
16.		13	0.0	
17.		14A	62.0	
		14B		
18.		15	-1079.0	
19.		16	-1701.0	
20.		17	0.0	
	Center Region			
21.	Radius		45.2	
22.	Azimuth (Deg)		23.8	
23.	Rotation (Deg)		21.3	
24.	Puller E/W		31.0	
25.	Puller N/S		51.7	
	Deflector Positions		**(Inches)**	
26.		1	39.4	
27.		2	0.392	
28.		3	40.382	
29.		4	0.402	
30.		5	40.423	
31.		6	0.451	
32.		7	42.887	
33.		8	0.636	
34.		9	43.571	
35.		10	1.25	
36.		11	48.492	
37.		12	1.745	
38.		JACK	0.08	
	Deflector Voltages		**(KV)**	
39.	Ent Volts		72.4	
40.	Mid Volts		72.0	
	Valley Coils		**(Deg)**	**(Amps)**
41,42		1	110	200
43,44		2	0	49
45,46		3	0	0
47,48		4	0	0
49,50		5	138	18.6
	Reference Date		5.22.75	
	Time		2200	

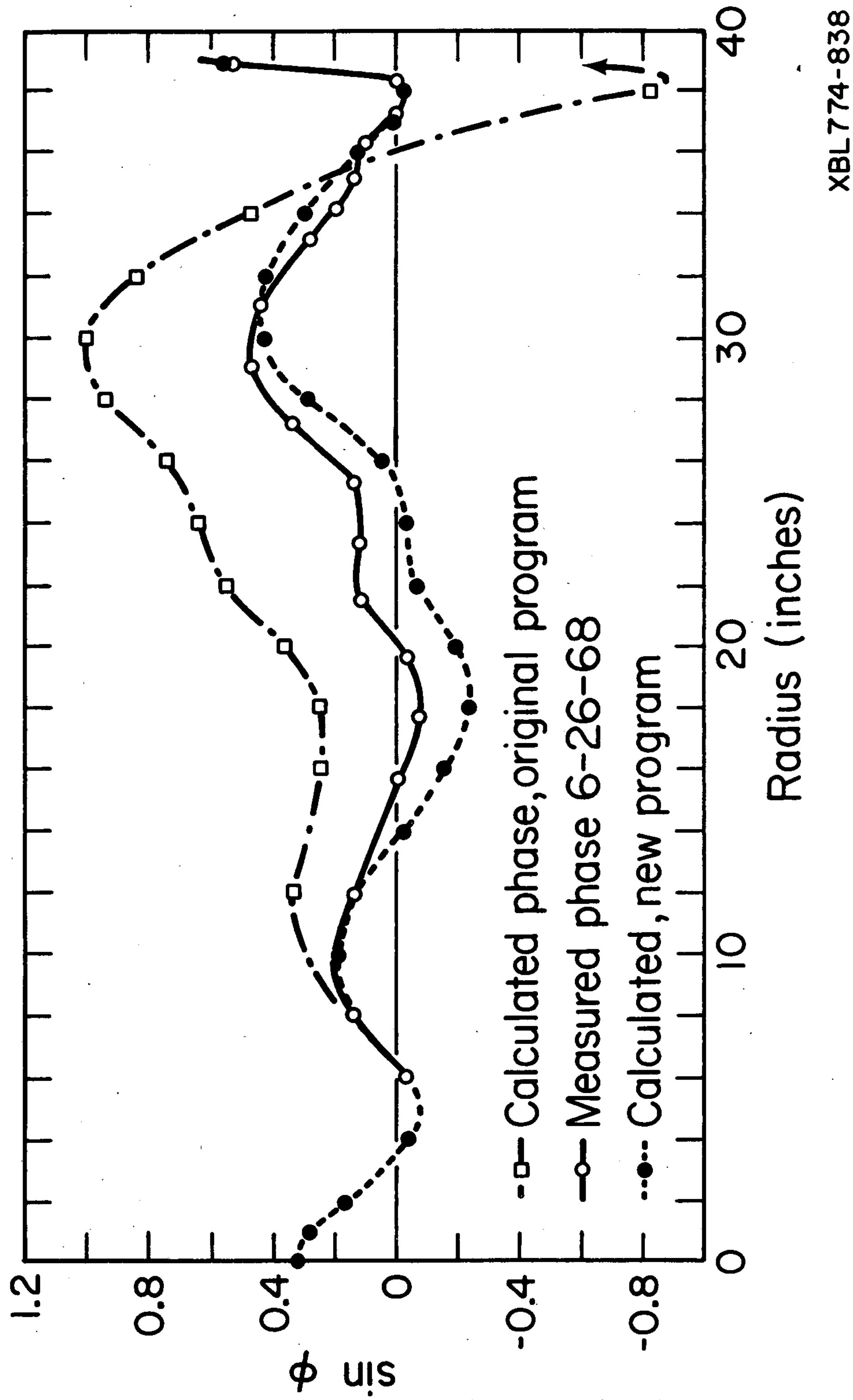

Fig. 1. Measured and calculated phase histories, showing improved agreement of new program with measurements, for 120 MeV α particles. Calculation has two adjustable parameters: starting phase and rf frequency, which are adjusted for good fit to measurements. Trim coil solution is not fully optimized.

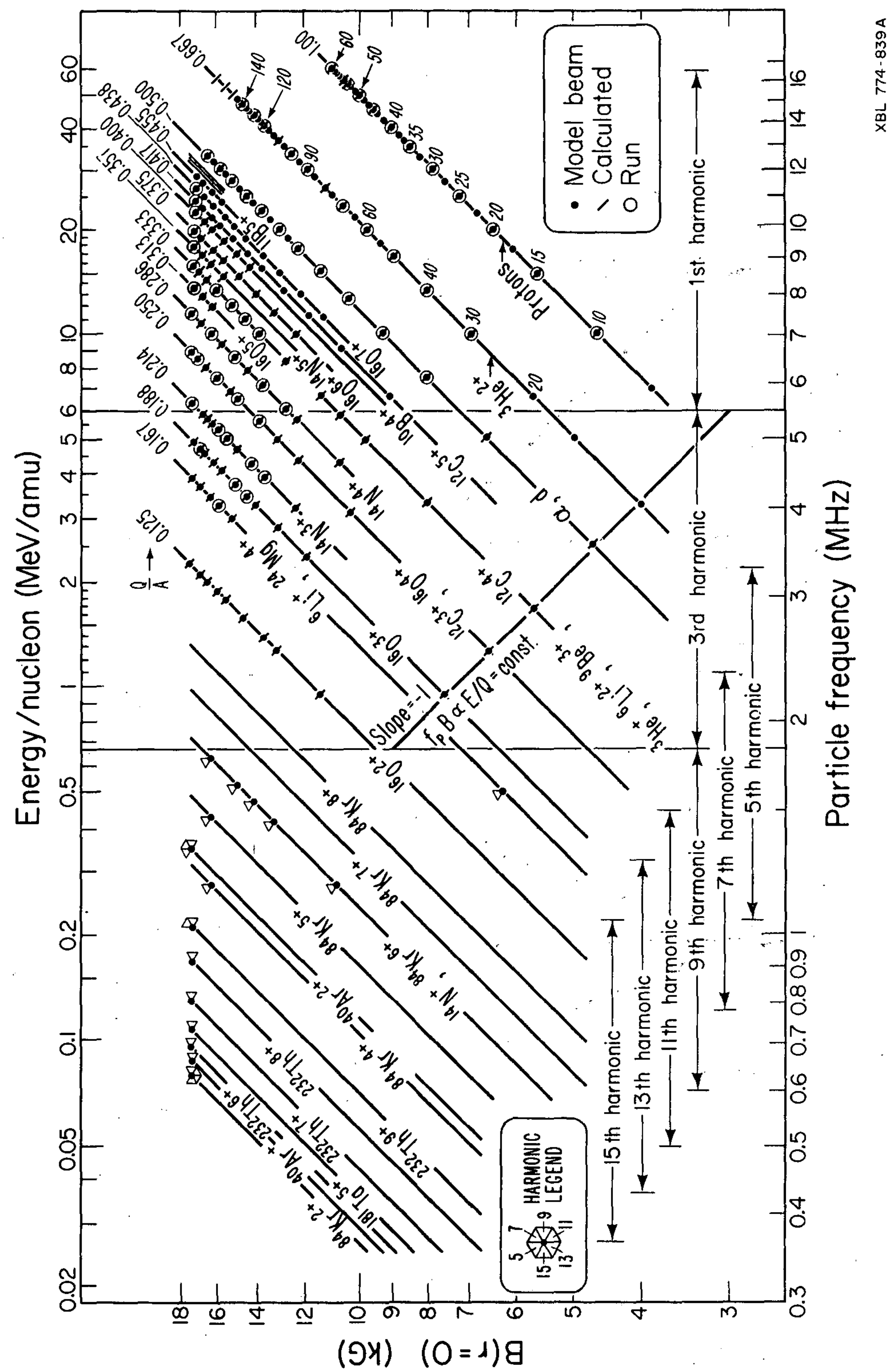

Fig. 2. Resonance chart for the Berkeley 88-Inch Cyclotron. Points in the first and third harmonic regions represent the grid discussed in sec. 4 of the text. In the region $\lesssim$ 0.7 MeV per nucleon selected beams are shown which have been run on higher harmonics.

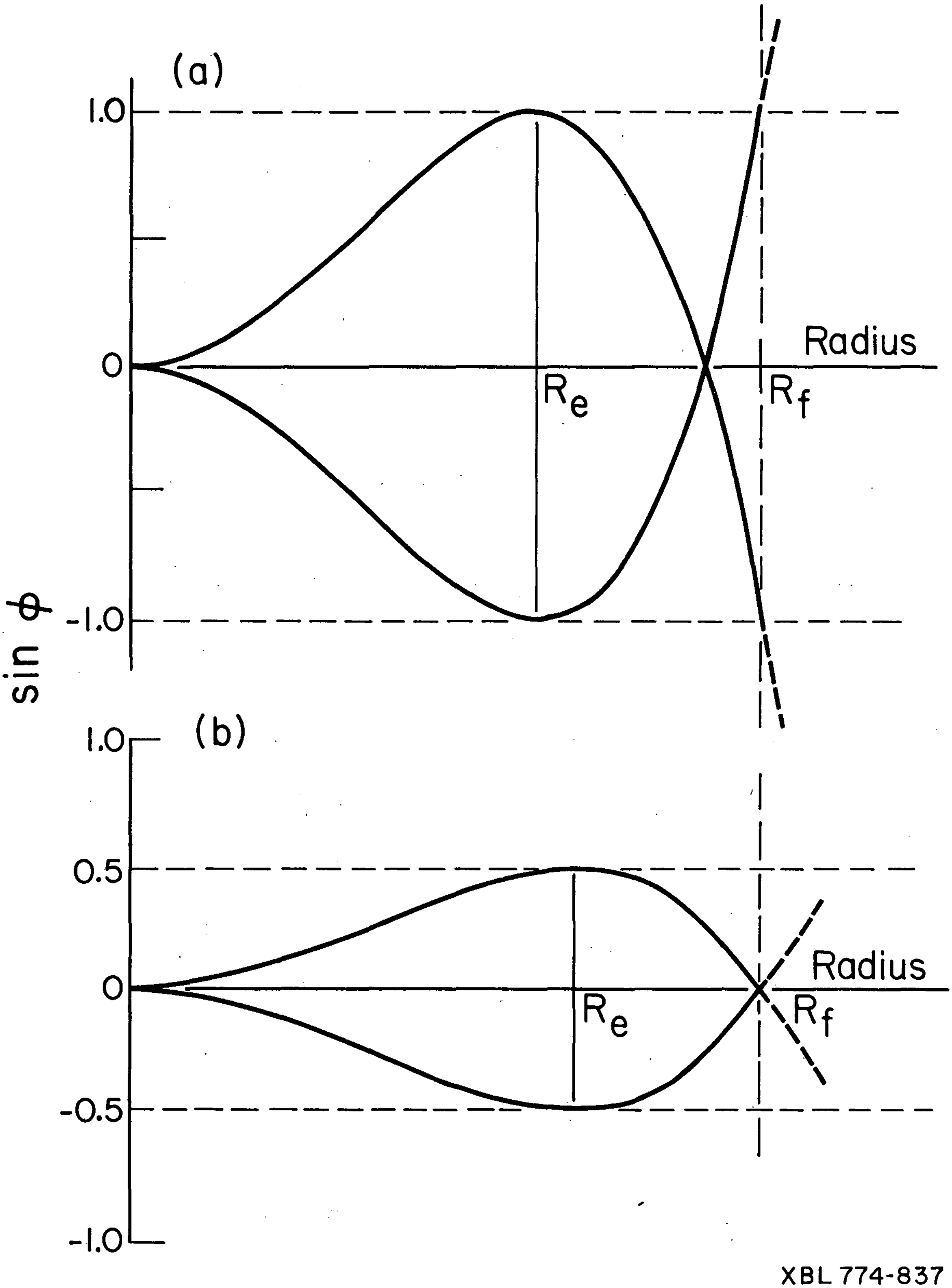

Fig. 3. Simplified phase histories illustrating (a) extreme and (b) more conservative phase error limits as discussed in the text.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720