150
10/29

Dr-1604

UCRL-20049
UC-28 Particle
Accelerators and High
Voltage Machines
(TID-4500 56th Ed.)

MASTER

EFFECT OF VERTICAL LENS AT RADIAL REGENERATION NODE IN BERKELEY 184-INCH SYNCHROCYCLOTRON

A. C. Paul and H. Grunder

August 1970

AEC Contract No. W-7405-eng-48

UCRL-20049

LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

Printed in the United States of America
Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy $3.00; Microfiche $0.65

EFFECT OF VERTICAL LENS AT RADIAL REGENERATION NODE IN BERKELEY 184-INCH SYNCHROCYCLOTRON

A. C. Paul and H. Grunder

Lawrence Radiation Laboratory
University of California
Berkeley, California 94720

August 1970

ABSTRACT

An attempt is made to understand and correct the vertical growth in the peeler of the 184-inch cyclotron. We show that a vertically focusing quadrupole field with its origin at the radial regeneration node improves the extraction efficiency somewhat, but cannot make all vertical orbits stable.

INTRODUCTION

The effect of a vertical focusing quadrupole field placed at the radial node of the regenerator in the Berkeley 184-inch cyclotron has been investigated both by the matrix method[1] and by numerical integration of the equations of motion.[2] The regenerative extraction system consists of an azimuthally extended peeler (fringe field of magnet) and a discrete regenerator 14 deg wide (Fig. 1). The radial node occurs at 161 deg for all turns up to N - 1, when the node ceases to exist, N being the last turn prior to extraction (Fig. 2). For turns N - 1 and N a vertical node occurs at the center of the regenerator, 116 deg azimuth (Fig. 3).

Stability diagrams have been calculated, for a quadrupole field placed at the radial node, from the single-turn transfer matrix obtained from the matrix product

$$T(\ ) = A(\ )\,P(\ )$$

$$\begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} 1 & 0 \\ Q & 1 \end{pmatrix}.$$

Here Q is the equivalent quadrupole lens strength given by $\frac{dB}{dR}\,\frac{R}{B}\,\Delta\theta$, where $\Delta\theta$ is the width of the perturbation and the A matrix has been numerically calculated for a typical particle for each of the last five revolutions. The trace of the T matrix, $T_{11} + T_{22}$, is plotted as a function of lens strength Q in Fig. 4 and 5. These diagrams are representative of the diagrams obtained for various matrices calculated for particles of different horizontal betatron starting phases. It can be seen that the absolute value of the vertical trace for the final two or three revolutions is greater than 2, which leads to the observed vertical beam growth and subsequent particle loss. A reduction of the trace of the last two turns

(N, N-1) is possible. However, these turns cannot be made stable for any quadrupole field strength without inducing instability for previous turns. This means that a quadrupole field at the radial node cannot eliminate the vertical growth. The effect on vertical beam growth was calculated numerically by tracking ten particles representing five horizontal phases at two vertically conjugate phases. The magnetic field used in this calculation was the existing 184-inch cyclotron field plus the field shown in Fig. 6. These particles all had an original vertical betatron oscillation amplitude of 0.25 in. The center radius of the quadrupole field R_0 was placed at the radial regeneration node, R = 82.12 in., θ = 161.5 deg.

The maximum vertical amplitude obtained by either particle and the average maximum vertical amplitude of the conjugate pair obtained anywhere are plotted in Fig. 7 as a function of quadrupole strength. It can be seen that there is a minimum in the maximum vertical amplitude at a gradient of about -0.2 to -0.3.

This reduction in amplitude is brought about by improved matching of the phase space, as shown in Fig. 8. Here a vertical eigenellipse of 0.25 in. amplitude is transformed through one turn by the transfer matrix T. The maximum amplitude is also plotted against quadrupole strength, and agrees with the results of the numerical orbit integration, Fig. 7. A calculation of the extraction efficiency, ϵ, as a function of vertical amplitude distribution, $\rho(Z)$, can be made by integrating the differential extraction efficiency $\eta(E, Z)$ over the energy vertical amplitude spectrum, as shown in Ref. 2:

$$\epsilon = \frac{\iint \eta(E, Z)\, \rho(E)\, \rho(Z)\, dE\, dZ}{\iint \rho(E)\, \rho(Z)\, dE\, dZ}.$$

In actuality, the lens operates on the particle distribution at each turn and should therefore be considered as a factor in the differential extraction efficiency. However, this calculation is simplified considerably by assuming that the dominant action of the quadrupole field is to reduce the vertical amplitude incident on the existing extraction system. Then a scaling of the vertical distribution commensurate with the observed reduction of maximum vertical growth represents the dominant effect of the quadrupole field. The calculation then is carried out by considering this modified distribution incident on the differential extraction efficiency, given in Table I.

This calculation has been carried out for the several vertical distributions shown in Fig. 9. These distributions represent direct scalings of the measured vertical distribution[2] by reducing the amplitude scale as indicated. The radial (energy) distribution is that given in Ref. 2. Figure 10 shows the extraction efficiency as a function of quadrupole strength under the assumption of validity of vertical distribution scaling for the amplitude variation of Fig. 7.

It is concluded that an optimum gradient, -0.2, will increase the extraction efficiency from 10% to 18%.

REFERENCES

1. A. C. Paul, Study of a Multi-Element Regenerative Extraction System for the Berkeley 184-Inch Cyclotron, UCRL-19804, September 1969).
2. A. C. Paul, Study of the Regenerative Extractor of the Berkeley 184-Inch Synchrocyclotron, UCRL-18211, April 1968.

Table I. Differential extraction efficiency as function of energy and vertical amplitude. Taken inpart from Ref. 2.

	Vertical amplitude (inches)							
Energy (MeV)	0	1/16	1/8	3/16	1/4	5/16	3/8	7/16
	1/2	9/16	5/8	11/16	3/4			
660	0.	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.			
665	0.	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.			
670	0.	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.			
675	0.	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.			
680	.20	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.			
685	.25	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.			
690	.30	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.			
695	.35	0.	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.			
700	.39	.01	0.	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.			
705	.43	.10	.02	0.	0.	0.	0.	0.
	0.	0.	0.	0.	0.			
710	.47	.21	.10	.03	0.	0.	0.	0.
	0.	0.	0.	0.	0.			
715	.52	.29	.16	.12	.07	.05	.04	.02
	.01	0.	0.	0.	0.			
720	.59	.39	.21	.17	.24	.15	.13	.10
	.08	.04	.02	.01	.01			
725	.66	.47	.27	.16	.07	.12	.09	.08
	.10	.06	.05	.04	.03			
730	.58	.44	.30	.22	.17	.13	.11	.08
	.05	.05	.04	.03	.02			
735	.46	.38	.27	.22	.17	.14	.12	.09
	.07	.06	.04	.03	.02			

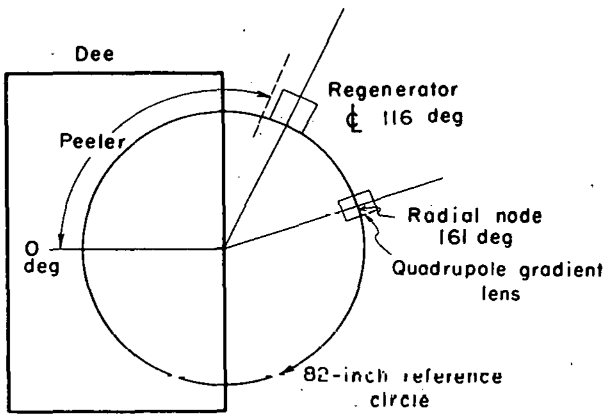

Fig. 1. Plan layout of regenerative extraction system of the 184-inch cyclotron, showing location of quadrupole gradient.
XBL708-3584

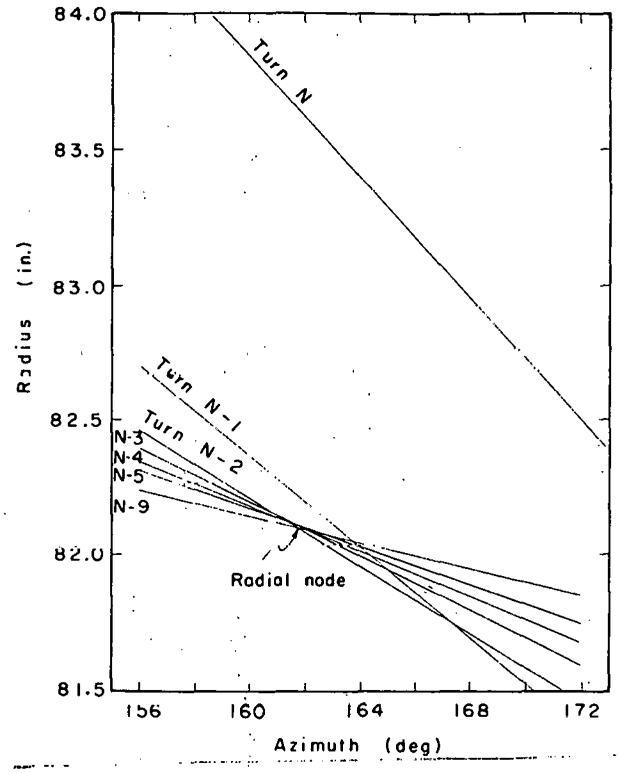

Fig. 2. Radial node for typical particle of 730 MeV. XBL708-3585

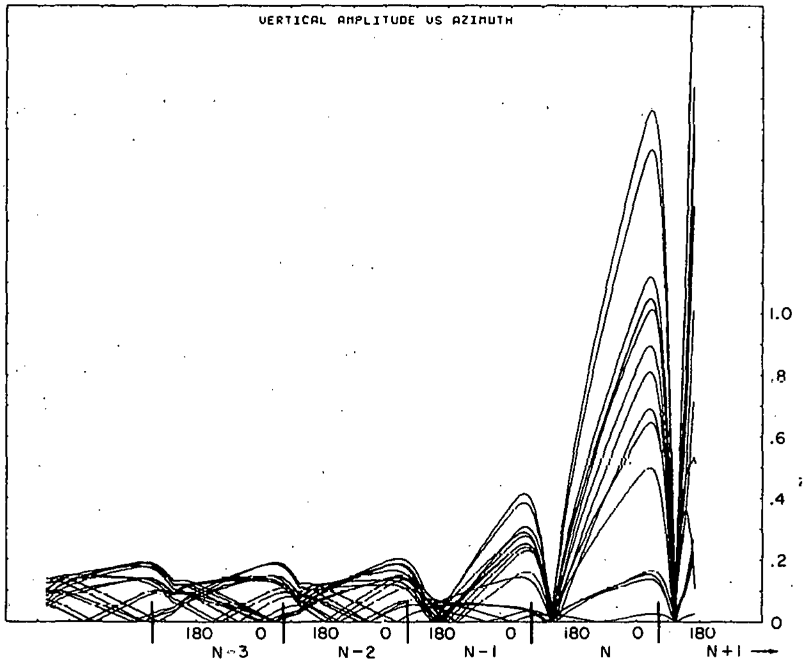

Fig. 3. Vertical amplitude of conjugate pairs of several radial phases on last five revolutions of regeneration. Regenerator is centered at 116 deg. These particles have been tracked for 100 to 200 revolutions before beginning regeneration; no quadrupole gradient is present.
XBL706-3161

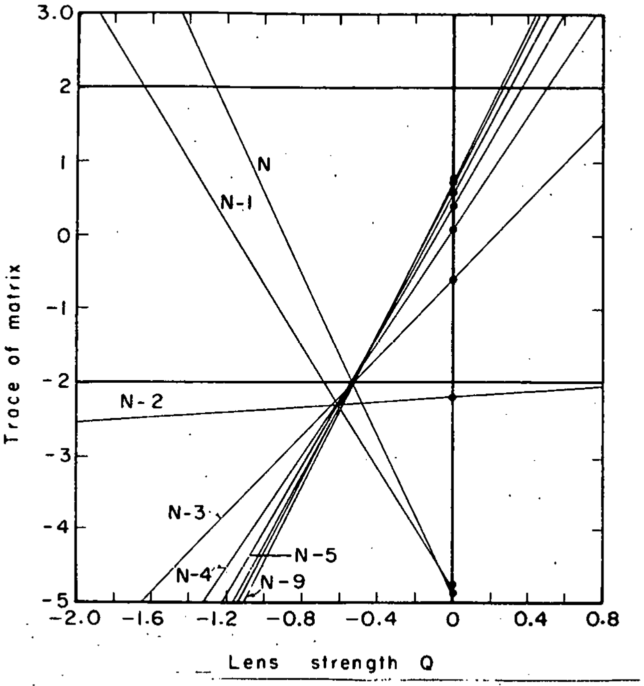

Fig. 4. Trace of vertical transfer matrix as function of quadrupole lens strength at radial regeneration node for last five resolutions in 184-inch cyclotron. Particle K6.

XBL 708-3587

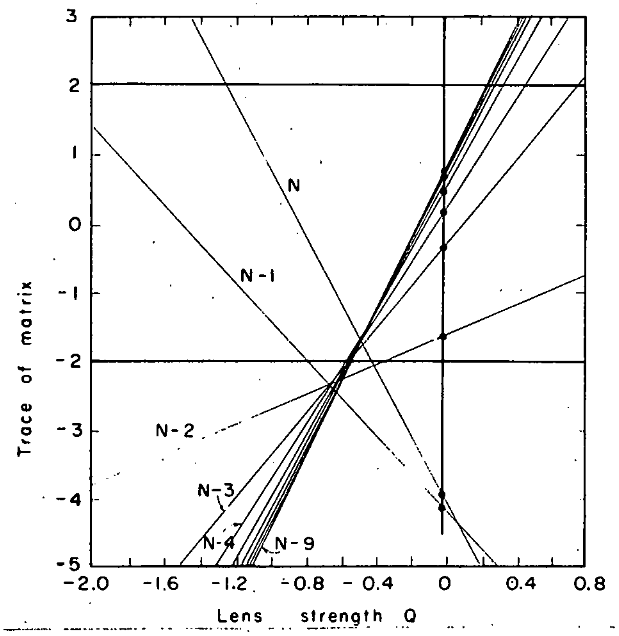

Fig. 5. Trace of vertical transfer matrix as function of quadrupole lens strength at radial regeneration node for last five resolutions in 184-inch cyclotron. Particle K3.

XBL708-3588

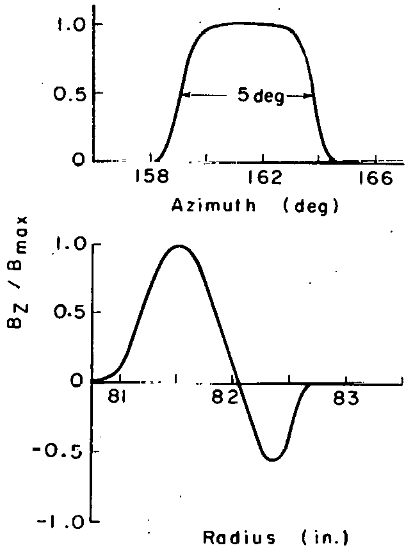

Fig. 6. Len field at radial node, showing radial and azimuthal profiles. XBL708-3589

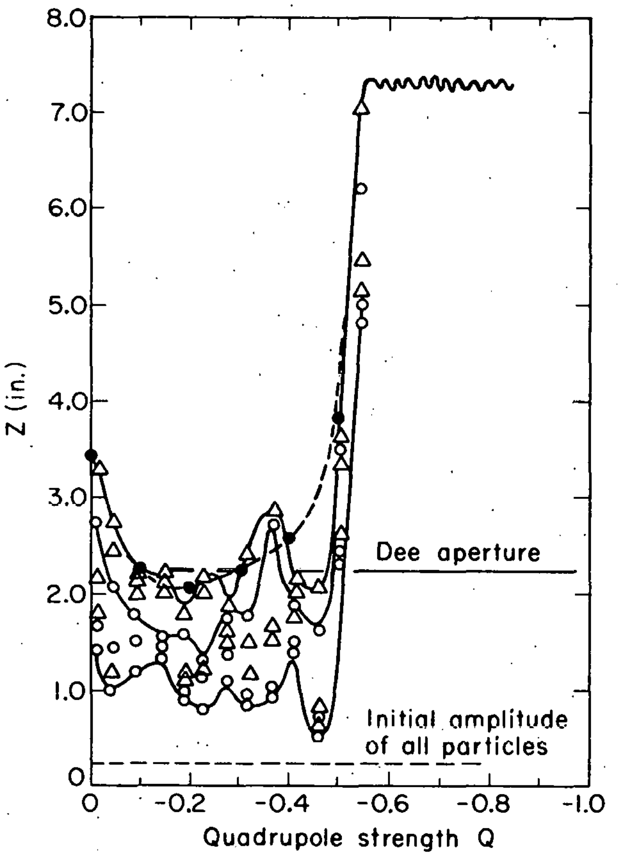

Fig. 7. The result of numerical orbit integration in the magnetic field of the 184-inch cyclotron plus the quadrupole gradient shown in Fig. 6. The maximum vertical amplitude of each pair of eigen points is indicated Δ for each of the five horizontal starting phases. The average vertical amplitude obtained by each vertically conjugate particle pair is indicated ⊙. Only particles that were sucessfully extracted are shown. This requires $166 \leq \theta \leq 172$ deg. for R = 106 in.
XBL708-3590

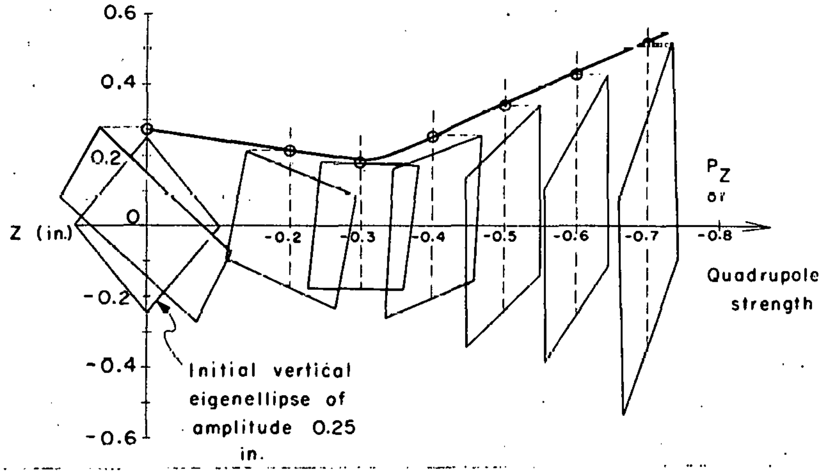

Fig. 8. Transformation of a 0.25-in. vertical eigen ellipse through one revolution as a function of quadrupole gradient.
XBL708-3591

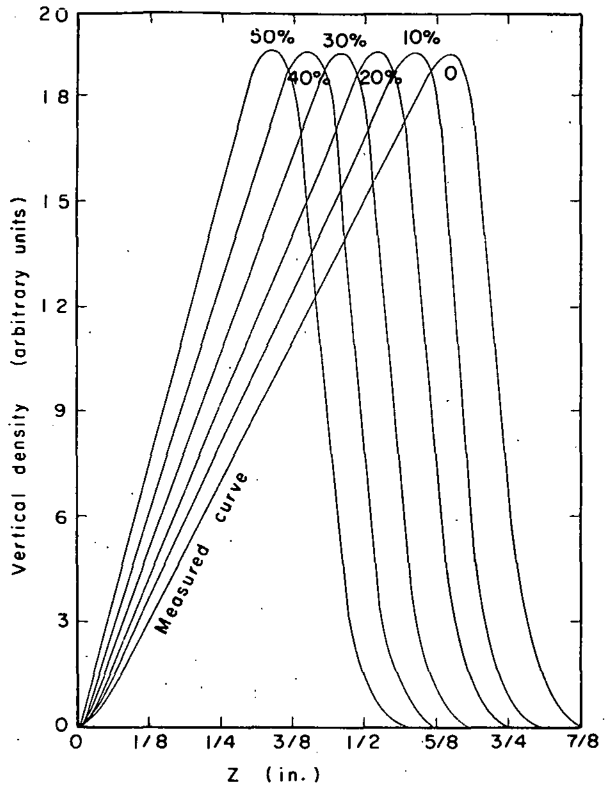

Fig. 9. Vertical phase-space distributions used to calculate the extraction efficiency. Each curve was obtained by reducing the vertical amplitude scale by the percentage indicated. XBL708-3592

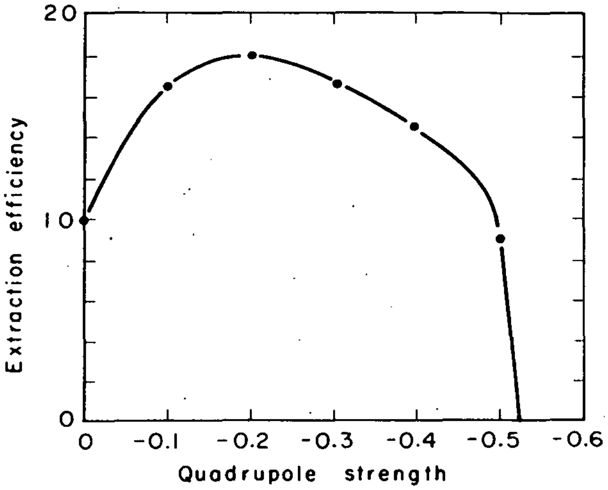

Fig. 10. Extraction efficiency as function of quadrupole strength calculated under the assumption of scaling the vertical particle distribution. XBL708-3593

TECHNICAL INFORMATION DIVISION
LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720