Naval Research Laboratory

Washington, DC 20375-5000

NRL Memorandum Report 6378

AD-A202 670

Beam Breakup Instabilities in Linear Accelerators: Transition, Phase Mixing and Nonlinear Focusing

D. G. COLOMBANT AND Y. Y. LAU

Plasma Theory Branch
Plasma Physics Division

December 13, 1988

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 6378	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION Naval Research Laboratory 6b OFFICE SYMBOL (If applicable) Code 4790	7a NAME OF MONITORING ORGANIZATION
6c ADDRESS (City, State, and ZIP Code) Washington, DC 20375-5000	7b ADDRESS (City, State and ZIP Code)
8a NAME OF FUNDING/SPONSORING ORGANIZATION U.S. Department of Energy 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c ADDRESS (City, State, and ZIP Code) Washington, DC 20545	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO: DOE PROJECT NO: AI05-86 ER13585 TASK NO: WORK UNIT ACCESSION NO:

11 TITLE (Include Security Classification)
Beam Breakup Instabilities in Linear Accelerators: Transition, Phase Mixing and Nonlinear Focusing

12 PERSONAL AUTHOR(S)
Colombant, D.G. and Lau, Y.Y.

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year Month Day)	15 PAGE COUNT
Interim	FROM ______ TO ______	1988 December 13	20

16 SUPPLEMENTARY NOTATION

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Beam break-up; Linear accelerators; Electron beam instability; Beam-circuit interaction

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

The temporal and spatial evolution of the cumulative beam breakup instability (BBU) is analyzed numerically using a continuum model. It is found that neither phase mixing nor linear transverse focusing is sufficient to render BBU stable in a long pulse machine, when external damping is absent. A sufficiently strong nonlinear octupole focusing field may limit the BBU growth, however. Keywords:

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a NAME OF RESPONSIBLE INDIVIDUAL Y. Y. Lau	22b TELEPHONE (Include Area Code) (202) 767-2765 22c OFFICE SYMBOL Code 4790

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

S/N 0102-LF-014-6603

BEAM BREAKUP INSTABILITIES IN LINEAR ACCELERATORS: TRANSITION, PHASE MIXING AND NONLINEAR FOCUSING

The control of beam breakup instabilities[1] remains a major concern for accelerator builders. Various remedies have been examined[2]: lowering the quality factor Q of the deflecting modes, increasing the focal strength, phase mixing, nonlinear focusing, and detuning of the cavities, etc. All of these may readily be incorporated in the continuum models,[1-7] from which asymptotic formulas have been obtained for certain cases. These formulas have frequently been used to compare with experimental observations and with other more elaborate theoretical works.[6,8] At the moment, they are the only ones available to describe the transition of BBU from the cumulative type to the regenerative type.[7,9]

In spite of the versatility in the continuum model, a direct numerical integration of the governing partial differential equations does not seem to have been published, although the evolution of BBU has been calculated in great detail by other means, in some limiting cases.[1,3,10] Here, we analyze the evolution of the cumulative BBU by a direct numerical integration, intending to look into the effects of phase mixing and nonlinear focusing which defies analytic treatment. This work was also motivated by the recent observation[7] that the asymptotic growth of the cumulative BBU is independent of the <u>linear</u> transverse focal strength. It is then of interest to determine in what way nonlinear focusing affects the temporal and spatial evolution of BBU.

To isolate the mechanism of phase mixing and of nonlinear focusing, we ignore the damping associated with finite Q. Setting Q equal to infinity should not be construed as this damping effect being unimportant. It serves the additional purpose of providing a more stringent test for the numerical scheme. For without a finite Q, the solution grows much more

Manuscript approved October 17, 1988.

rapidly, making the accuracy in the numerical integration more demanding. In any case, the effect of finite Q enters only through the well-known decay factor exp $(-\omega_o t/2Q)$ in the amplitude of the solutions, where ω_o is the breakup mode frequency.

Our numerical results reveal the following. When Q is infinite, the cumulative BBU evolves asymptotically (at a fixed distance from the injector) at a rate which is independent of the linear transverse focal strength.[7] The excellent agreement with the analytic formula adds to our confidence in our numerical calculation. [In a separate test, the numerical solution agrees with the analytical results to within 20% over nine orders of magnitude variations in the beam's transverse displacement.] When the analysis is extended to include a finite spread in the betatron frequency, we find that this finite spread has virtually no effect on the above-mentioned asymptotic behavior. While neither a linear focusing force nor a finite spread in the betatron frequency, by themselves, can provide long-term stabilization of BBU, a sufficiently strong nonlinear focusing force may limit the amplitude of the beam's transverse displacement, even in the limit $Q \to \infty$.

For a continuous coasting beam, the evolution of the cumulative BBU is governed by the following normalized equations[1,3]

$$(\partial/\partial T + \partial/\partial Z)^2 X + \Omega^2 X = A \tag{1}$$

$$\partial^2 A/\partial T^2 + A = 2\varepsilon X. \tag{2}$$

Here $T = \omega_o t(>0)$, $Z = \omega_o z/c(>0)$, $\Omega = k_\beta c/\omega_o$ where k_β is the betatron wavenumber, ε is the dimensionless coupling constant[7] which is proportional to the beam current and shunt impedance but is independent of the focal strength, Q(Z,T) is a measure of the strength of the deflecting mode which drives the BBU and X(Z,T) is the normalized transverse displacement of the beam. In all numerical calculations, we assume initial rest condition and homogeneous boundary conditions; only one non-trivial boundary condition is imposed at $Z = 0$: $X(0,T) = 1$ for $0 < T < 0.2$ and is zero otherwise. Thus, X is normalized to the initial displacement, imparted upon the beam at $Z = 0$ for a short time (similar to a delta function excitation.[1,3-8])

Shown in Fig.1 is the spatial distribution of X(Z,T) at four different times, obtained from a fourth order numerical scheme in space and time. We set $\varepsilon = 0.000413$ and $\Omega = 0.14$. The dotted curves in this figure are obtained from the asymptotic solution[7]:

$$|X(Z,T)| = B\,\frac{Z^{1/4}}{(T-Z)^{3/4}}\,\exp\left\{\sqrt{\frac{2\varepsilon Z(T-Z)}{\Omega}}\;p(\tau)\right\} \qquad (3)$$

where $\tau = \varepsilon(T-Z)/(\Omega^3 Z) > 0$, $B = C/[\mathrm{Max}(1,\tau/2.81)]^{1/12}$,

$$p(\tau) = \begin{cases} \dfrac{1.1573}{\tau^{1/6}}\left(1 - \dfrac{0.21}{\tau^{2/3}}\right) & \text{for } \tau \geq 5 \\ 1 - 0.0556\tau + 0.004\tau^2 & \text{for } \tau \leq 5 \end{cases} \qquad (4a,b)$$

and C is a constant to be determined by a "one-point fit" with the numerical solution. Equation (3) describes the transition from the strong focusing solution[8] [$p(\tau) \to 1$, Eq. (4b)] to the weak focusing solution[1] [Eq. (4a)] as τ increases.[7] This transition occurs when $\tau \approx 0.5$. The excellent agreement, over a wide range of τ, between the numerical solution and the analytic theory shown in Fig. 1 may be regarded as a validation for both the numerical scheme and the analytic result that X evolves at a later time as if the linear focusing force were absent.[7] The numerical data shows that the spatial variation of X is biased toward the "slow beam-cyclotron mode".[7]

The effect of phase mixing due to a spread in the betatron frequency may be examined by pretending that the electron beam consists of N groups of particles, the ith group bearing its individual betatron frequency Ω_i. Thus, we replace Eq. (1) with N equations

$$(\partial/\partial T + \partial/\partial Z)^2 X_i + \Omega_i{}^2 X_i = A, \qquad i = 1, \ldots N \tag{5}$$

and the quantity X in the right-hand side of Eq. (2) is replaced by $\langle X\rangle = G_1X_1 + G_2X_2 + \ldots + G_NX_N$ where G_i represents the fraction occupied by the ith group ($G_1 + G_2 + \ldots + G_N = 1$). In the "spread mass" model,[11,4] $\Omega_i = \Omega(i/N)^{1/2}$ and $G_i = 6i(N - i)/N(N^2 - 1)$. The solution $\langle X\rangle$ is shown in Fig. 2 for $\varepsilon = 0.000413$, $\Omega = 0.14$, $N = 8$. A virtually identical figure was obtained when we increased N to 16. From this figure, we see that a finite spread in the betatron frequency has no effect on the long-time growth of the cumulative BBU. This is due to the fact that the cumulative BBU grows asymptotically at a rate independent of the linear focusing force, and a finite spread in the betatron wavelength cannot alter this long-time behavior.

A nonlinear octupole focusing force may be handled also by solving Eqs. (1) and (2), except that the $\Omega^2 X$ term in Eq. (1) is now replaced by ΛX^3 in a simplified model. The evolution of X is shown in Fig. 3 for the case $\Lambda = 0.0392$. Here, we see that the amplitude of X is limited at large T, in marked contrast to the cases of linear focusing and phase mixing. It is possible that the change in the phase relationship[1] between A and X due to nonlinearity might have contributed to the stabilization shown in Fig. 3, but this issue remains to be examined in the future.

In summary, an accurate numerical scheme was devised to analyze the classic model of cumulative BBU. It is suggested that this line of attack could be fruitfully applied to a great variety of problems in a rather straightforward manner. Interesting areas such as phase mixing and nonlinear focusing were analyzed in this initial study, and some unexpected features reported.

Helpful discussions with S. Zalesak and D. Chernin are gratefully acknowledged. We also thank M. Friedman, C. W. Roberson and P. Sprangle for their support. This work was supported by the Department of Energy, Contract No. DE-AI05-86-ER13585 and by the Office of Naval Research.

References

1. W. K. H. Panofsky and M. Bander, Rev. Sci. Inst. 39, 206 (1968).

2. R. Helm and G. Loew, Linear Accelerators, Eds. P. M. Lapostolle and A. L. Septier, (North Holland, Amsterdam, 1970), Ch. B.1.4, p. 173.

3. V. K. Neil and R. K. Cooper, Part. Accel. 1, 111 (1970).

4. R. J. Briggs, University of California Report. No. UCID-18633 (1980), unpublished.

5. G. J. Caporaso, Proc. of the LINAC '86, Stanford Linear Accelerator Center p. 17 (1986).

6. R. L. Gluckstern, R. K. Cooper and P. J. Channell, Part. Accel. 16, 125 (1985); R. L. Gluckstern and F. Neri, Proc. 1987 Particle Accelerator Conference, p. 1017.

7. Y. Y. Lau, Naval Research Laboratory Memo Report No. 6237 (1988).

8. V. K. Neil, L. S. Hall and R. K. Cooper, Part. Accel. 9, 213 (1979).

9. R. L. Gluckstern, Bull. Am. Phys. Soc. 33, 918 (1988).

10. D. Chernin and A. Mondelli, to be published in Particle Accelerators.

11. E. P. Lee, Phys. Fluids 21, 1327 (1978).

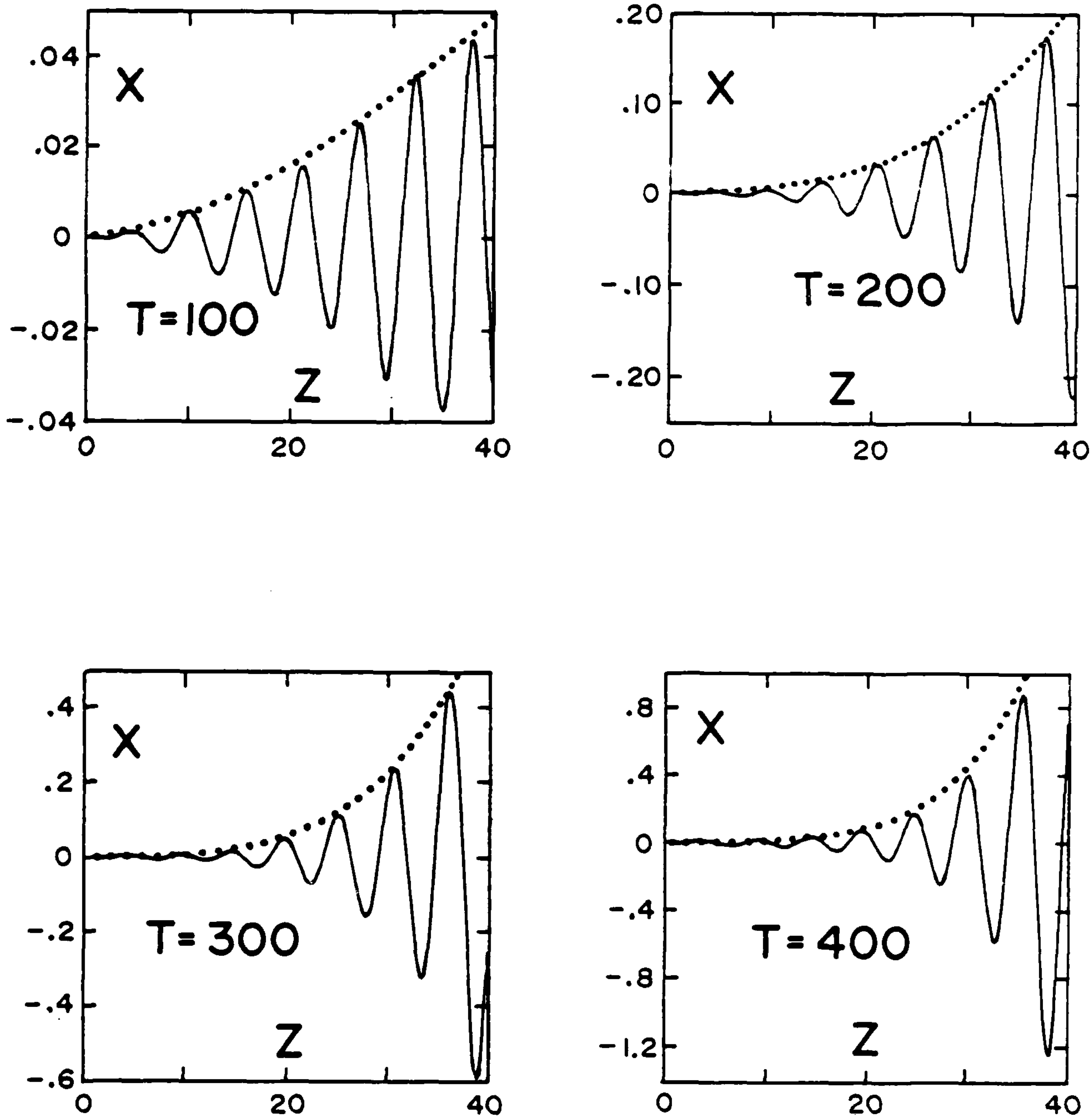

Fig. 1 Evolution of X(Z,T) and comparison with the analytic theory (dotted curves).

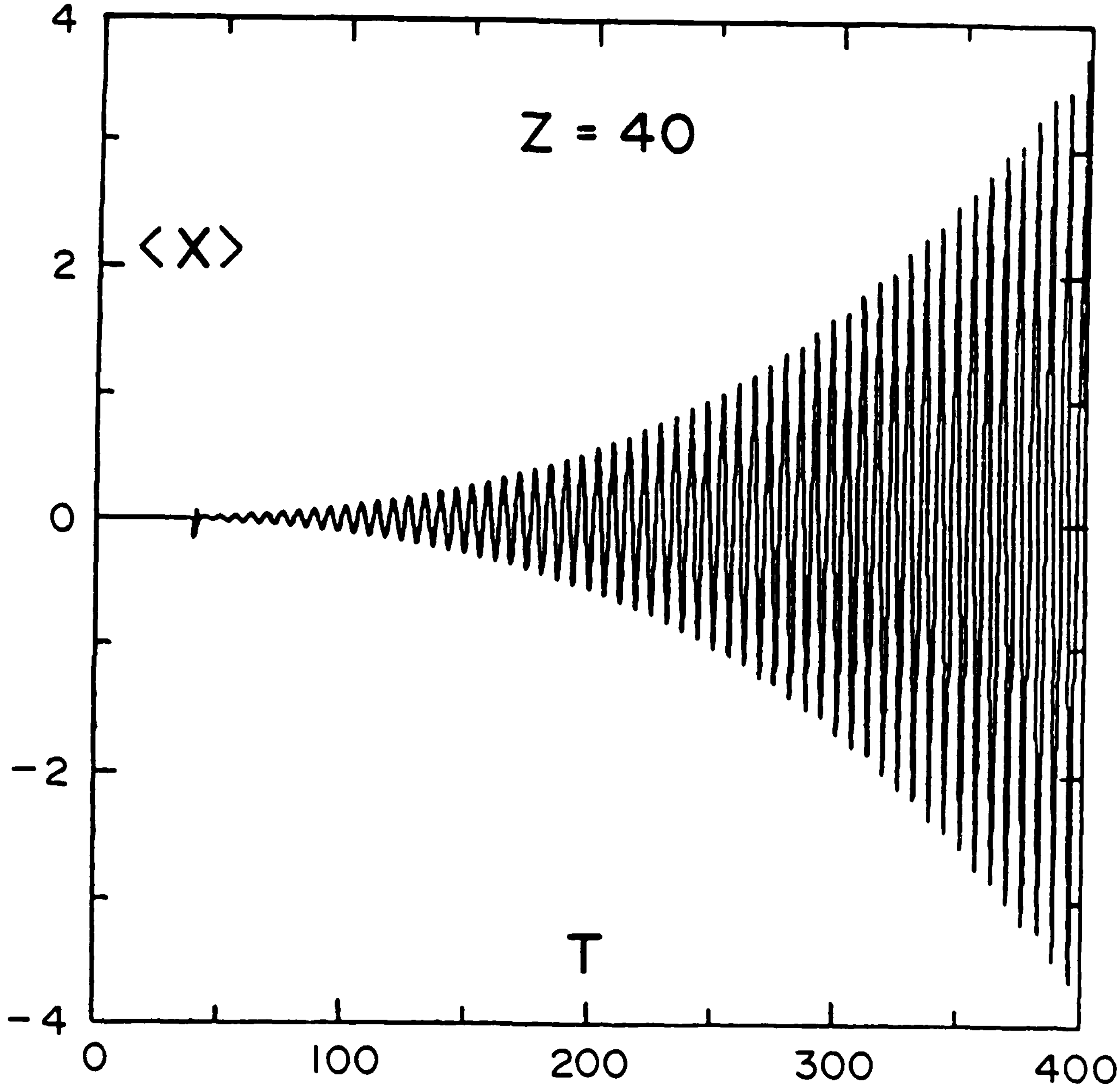

Fig. 2 Temporal evolution of <X> at Z = 40, including the effect of phase mixing.

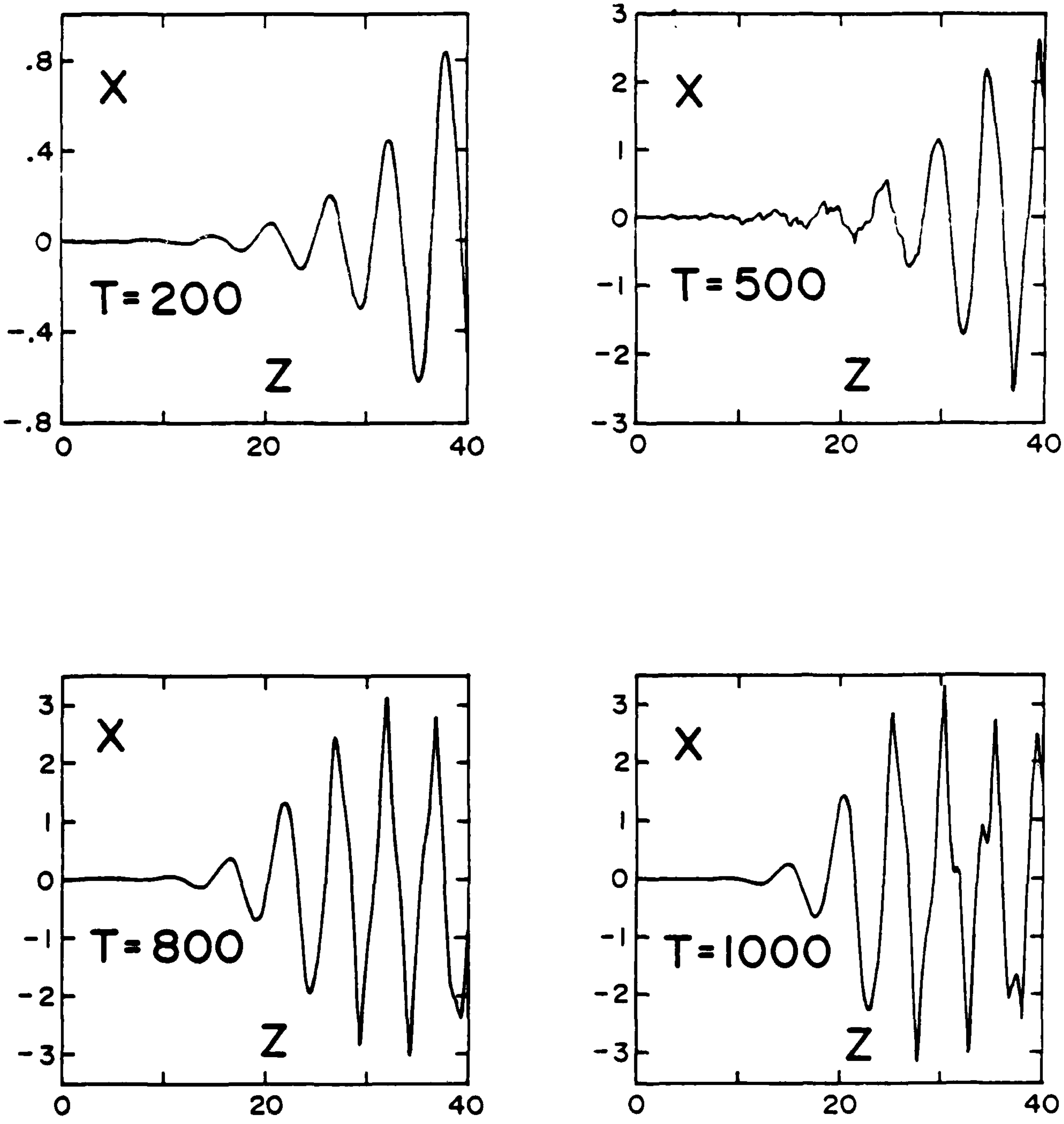

Fig. 3 Evolution and saturation of X(Z,T) in the presence of nonlinear octupole focusing.

DISTRIBUTION LIST*

Naval Research Laboratory
4555 Overlook Avenue, S.W.
Washington, DC 20375-5000

Attn: Code 1000 - Commanding Officer, CAPT W. G. Clautice
1001 - Dr. T. Coffey
1005 - Head, Office of Management & Admin.
1220 - Mr. M. Ferguson
2000 - Director of Technical Services
2604 - NRL Historian
2628 - Documents (22 copies)
2634 - D. Wilbanks
4000 - Dr. W. R. Ellis
4600 - Dr. D. Nagel
4603 - Dr. W. W. Zachary
4700 - Dr. S. Ossakow (26 copies)
4700.1 - Dr. M. Friedman (5 copies)
4700.1 - V. Serlin
4710 - Dr. C. A. Kapetanakos
4730 - Dr. R. Elton
4730 - Dr. B. Ripin
4740 - Dr. W. M. Manheimer
4740 - Dr. S. Gold
4790 - Dr. P. Sprangle
4790 - Dr. C. M. Tang
4790 - Dr. M. Lampe
4790 - Dr. Y. Y. Lau (40 copies)
4790 - Dr. D. G. Colombant
4790 - Dr. G. Joyce
4790 - Dr. I. Haber
4790 - Dr. R. Hubbard
4790 - Dr. R. Fernsler
4790 - Dr. S. Slinker
4790 - Dr. T. Godlove
4790A - W. Brizzi
6840 - Dr. R. K. Parker
Records 1 copy

* Every name listed on distribution gets one copy except for those where extra copies are noted.

Prof. I. Alexeff
Dept. of Electrical Engineering
University of Tennessee
Knoxville, TN 37996-2100

Dr. T. Antonsen
University of Maryland
College Park, MD 20742

Assistant Secretary of the
Air Force (RD&L)
Room 4E856, The Pentagon
Washington, D.C. 20330

Dr. W. A. Barletta
Lawrence Livermore National Lab.
P. O. Box 808
Livermore, CA 94550

Dr. L. R. Barnett
3053 Merrill Eng. Bldg.
University of Utah
Salt Lake City UT 84112

Dr. G. Bekefi
Mass. Institute of Tech.
Bldg. 26
Cambridge, MA 02139

Prof. Herbert Berk
Institute for Fusion Studies
University of Texas
Austin, TX 78712

Dr. I. B. Bernstein
Mason Laboratory
Yale University
400 Temple Street
New Haven, CT 06520

Prof. A. Bers
Dept. of Electrical Engineering
MIT
Cambridge, MA 02139

Prof. Charles K. Birdsall
Dept. of Electrical Engineering
University of California
Berkeley, CA 94720

Dr. H. Brandt
Department of the Army
Harry Diamond Laboratory
2800 Powder Mill Rd.
Adelphi, MD 20783

Dr. Charles Brau
Los Alamos National Scientific
Laboratory
P.O. Box 1663, M.S. - 817
Los Alamos, NM 87545

Dr. R. Briggs
Lawrence Livermore National Lab.
Attn: (L-71)
P.O. Box 808
Livermore, CA 94550

Dr. Lee Buchanan
DARPA/DEO
1400 Wilson Blvd.
Arlington, VA 22209

Prof. O. Buneman
ERL, Stanford University
Stanford, CA 94305

Dr. K. J. Button
Francis Bitter Natl. Magnet Lab.
Mass. Institute of Technology
Cambridge, MA 02139

Prof. J. D. Callen
Nuclear Engineering Dept.
University of Wisconsin
Madison, WI 53706

Dr. Malcolm Caplan
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. Maria Caponi
TRW, Building R-1, Room 1184
One Space Park
Redondo Beach, CA 90278

Dr. George Caporaso
L-626
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Prof. Frank Chan
School of Eng. & Applied Sciences
Univ. of Calif. at Los Angeles
7731 K Boelter Hall
Los Angeles, CA 90024

Dr. V. S. Chan
GA Technologies
P.O. Box 85608
San Diego, CA 92138

Dr. D. P. Chernin (3 copies)
Science Applications Intl. Corp.
1720 Goodridge Drive
McLean, VA 22102

Prof. M. V. Chodorow
Ginzton Laboratory
Stanford, University
Stanford, CA 94305

Dr. William Colson
Berkeley Research Asso.
P. O. Box 241
Berkeley, CA 94701

Dr. William Condell
Office of Naval Research
Attn: Code 421
800 N. Quincy St.
Arlington, VA 22217

Dr. Richard Cooper
Los Alamos National Scientific
Laboratory
P.O. Box 1663
Los Alamos, NM 87545

Prof. B. Coppi
Dept. of Physics, 26-217
MIT
Cambridge, MA 02139

Dr. Bruce Danly
MIT
NW16-174
Cambridge, MA 02139

Dr. R. Davidson
Plasma Fusion Center
Mass. Institute of Tech.
Cambridge, MA 02139

Dr. John Dawson
Physics Department
University of California
Los Angeles, CA 90024

Dr. David A. G. Deacon
Deacon Research
Suite 203
900 Welch Road
Palo Alto, CA 94306

Deputy Under Secretary of
Defense for R&AT
Room 3E114, The Pentagon
Washington, D.C. 20301

Dr. W. W. Destler
Dept. of Electrical Engineering
University of Maryland
College Park, MD 20742

Director of Research (2 copies)
U. S. Naval Academy
Annapolis, MD 21402

Dr. Gunter Dohler
Northrop Corporation
Defense Systems Division
600 Hicks Road
Rolling Meadows, IL 60008

Dr. Franklin Dolezal
Hughes Research Laboratory
3011 Malibu Canyon Rd.
Malibu, CA 90265

Dr. A. Drobot
Science Applications Intl. Corp.
1710 Goodridge Road
McLean, VA 22102

Dr. Dwight Duston
Strategic Defense Initiative Org.
OSD/SDIO/IST
Washington, DC 20301-7100

Dr. Luis R. Elias
Quantum Institute
University of California
Santa Barbara, CA 93106

Dr. W. Fawley
L-626
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. H. Fleischmann
Cornell University
Ithaca, NY 14850

Dr. R. Gajewski (5 copies)
Div. of Advanced Energy Projects
U. S. Dept of Energy
Washington, DC 20545

Dr. Richard L. Garwin
IBM, T. J. Watson Research Ctr.
P.O. Box 218
Yorktown Heights, NY 10598

Prof. Ward Getty
University of Michigan
Ann Arbor, MI 48109

Prof. Ronald Gilgenbach
Dept. Nucl. Engineering
University of Michigan
Ann Arbor, MI 48109

Dr. R. L. Gluckstern
Physics Department
University of Maryland
College Park, MD 20742

Dr. B. B. Godfrey
Mission Research Corporation
1720 Randolph S.E.
Albuquerque, NM 87106

Dr. V. L. Granatstein
Dept. of Electrical Engineering
University of Maryland
College Park, MD 20742

Dr. R. Harvey
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, CA 90265

Prof. Herman A. Haus
Mass. Institute of Technology
Rm. 36-351
Cambridge, MA 02139

Dr. William Herrmannsfeldt
Stanford Linear Accelerator Center
P. O. Box 4349
Stanford, CA 94305

Dr. Fred Hopf
Optical Sciences Building, Room 602
University of Arizona
Tucson, AZ 85721

Dr. Bertram Hui
Naval Surace Warfare Center
White Oak
Silver Spring, MD 20903

Dr. Stanley Humphries, Jr.
Dept. Chemical & Nuclear Engineering
University of New Mexico
Albuquerque, NM 87131

Dr. G. L. Johnston
NW 16-232
Mass. Institute of Tech.
Cambridge, MA 02139

Dr. Howard Jory
Varian Associates, Bldg. 1
611 Hansen Way
Palo Alto, CA 94303

Prof. Terry Kammash
University of Michigan
Ann Arbor, MI 48109

Prof. Donald Kerst
3291 Chamberlin Hall
University of Wisconsin
Madison, WI 53706

Dr. K. J. Kim, MS-101
Lawrence Berkeley Lab.
Rm. 223, B-80
Berkeley, CA 94720

Dr. J. Krall
Science Applications Intl. Corp.
1710 Goodridge Drive
McLean, VA 22102

Prof. N. M. Kroll
Department of Physics
B-019, UCSD
La Jolla, CA 92093

Dr. Thomas Kwan
Los Alamos National Scientific
Laboratory, MS608
P. O. Box 1663
Los Alamos, NM 87545

Dr. Edward P. Lee
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

Dr. Willis Lamb
Optical Sciences Center
University of Arizona
Tucson, AZ 87521

Dr. Rulon K. Linford
CTR-11, Mail Stop: 646
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Prof. J. M. J. Madey
117 Physics Bldg.
Duke University
Durham, NC 27706

Dr. J. A. Mangano
Science Research Laboratory
15 Ward Street
Sommerville, MA 02143

Dr. J. Mark
Lawrence Livermore National Lab.
Attn: L-477
P. O. Box 808
Livermore, CA 94550

Dr. W. E. Martin
L-436
Lawrence Livermore National Lab.
P. O. Box 808
Livermore, CA 94550

Dr. A. Mondelli
Science Applications Intl. Corp.
1710 Goodridge Drive
McLean, VA 22102

Prof. George Morales
Dept. of Physics
U.C.L.A.
Los Angeles, CA 90024

Dr. Philip Morton
BIN26
Stanford Linear Accelerator Center
P.O. Box 4349
Stanford, CA 94305

Dr. J. Nation
Cornell University
Ithaca, NY 14850

Dr. Kelvin Neil
Lawrence Livermore National Lab.
Code L-321, P.O. Box 808
Livermore, CA 94550

Dr. T. Orzechowski
L-436
Lawrence Livermore National Lab.
P. O. Box 808
Livermore, CA 94550

Prof. E. Ott
Department of Physics
University of Maryland
College Park, MD 20742

Dr. Robert B. Palmer
Brookhaven National Laboratories
Associated Universities, Inc.
Upton, L.I., NY 11973

Dr. W. K. H. Panofsky
Stanford Linear Accelerator Center
P. O. Box 4349
Stanford, CA 94305

Dr. Richard H. Pantell
Stanford University
Stanford, CA 94305

Dr. Dennis Papadopoulos
Astronomy Department
University of Maryland
College Park, Md. 20742

Dr. R. R. Parker
NW16-288
Plasma Fusion Center
MIT
Cambridge, MA 02139

Dr. C. K. N. Patel
Bell Laboratories
Murray Hill, NJ 07974

Dr. Richard M. Patrick
AVCO Everett Research Lab., Inc.
2385 Revere Beach Parkway
Everett, MA 02149

Dr. Claudio Pellegrini
Brookhaven National Laboratory
Associated Universities, Inc.
Upton, L.I., NY 11973

Dr. Sam Penner
National Bureau of Standards,
RADP B102
Washington, DC 20234

Dr. Hersch Pilloff
Code 1112
Office of Naval Research
Arlington, VA 22217

Dr. Donald Prosnitz
Lawrence Livermore National Lab.
Attn: L-470
P. O. Box 808
Livermore, CA 94550

Dr. Sidney Putnam
Pulse Sciences, Inc.
600 McCormack Street
San Leandro, CA 94577

Dr. M. Reiser
University of Maryland
Department of Physics
College Park, MD 20742

Dr. C. W. Roberson (5 copies)
Code 1112
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217

Dr. Marshall N. Rosenbluth
Physics Dept.
University of California, San Diego
La Jolla, CA 92093

Dr. N. Rostoker
University of California
Department of Physics
Irvine, CA 92717

Dr. E. T. Scharlesmann
L626
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. Michael Schlesinger
ONR Code 1112
800 N. Quincy Street
Arlington, VA 22217-5000

Prof. S. P. Schlesinger
Dept. of Electrical Engineering
Columbia University
New York, NY 10027

Dr. Howard Schlossberg
AFOSR
Bolling AFB
Washington, D.C. 20332

Dr. George Schmidt
Stevens Institute of Technology
Physics Department
Hoboken, NJ 07030

Dr. H. Schwettmann
Phys. Dept. & High Energy
Physics Laboratory
Stanford University
Stanford, CA 94305

Dr. Marlan O. Scully
Dept. of Physics & Astronomy
Univ. of New Mexico
800 Yale Blvd. NE
Albuquerque, NM 87131

Dr. A. M. Sessler
Lawrence Berkeley Laboratroy
University of California
1 Cyclotron Road
Berkeley, CA 94720

Dr. W. Sharp
L-626
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. R. Shefer
Science Research Laboratory
15 Ward Street
Somerville, MA 02143

Dr. Shen Shey (2 copies)
DARPA/DEO
1400 Wilson Boulevard
Arlington, VA 22209

Dr. D. J. Sigmar
Oak Ridge National Laboratory
P. O. Box Y
Oak Ridge, TN 37830

Dr. Jack Slater
Spectra Technology
2755 Northup Way
Bellevue, WA 98004

Dr. Lloyd Smith
Lawrence Berkeley Laboratory
University of California
1 Cyclotron Road
Berkeley, CA 94720

Dr. R. Sudan
Cornell University
Ithaca, NY 14850

Dr. David F. Sutter
ER 224, GTN
Department of Energy
Washington, D.C. 20545

Dr. T. Tajima
IFS
Univ. of Texas
Austin, TX 78712

Dr. R. Temkin
Mass. Institute of Technology
Plasma Fusion Center
Cambridge, MA 02139

Dr. Keith Thomassen, L-637
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. K. Tsang
Science Applications Intl. Corp.
1710 Goodridge Drive
McLean, VA 22102

Dr. H. S. Uhm
Naval Surface Warfare Center
White Oak Lab.
Silver Spring, MD 20903

Under Secretary of Defense (R&E)
Office of the Secretary of Defense
Room 3E1006, The Pentagon
Washington, D.C. 20301

Dr. J. Walsh
Physics Department
Dartmouth College
Hanover, NH 03755

Ms. Bettie Wilcox
Lawrence Livermore National Lab.
ATTN: Tech. Info. Dept. L-3
P.O. Box 808
Livermore, CA 94550

Dr. Perry Wilson
Stanford Linear Accelerator Center
P. O. Box 4349
Stanford, CA 94305

Dr. J. Wurtele
M.I.T.
NW 16-234
Plasma Fusion Center
Cambridge, MA 02139

Dr. A. Yariv
California Institute of Tech.
Pasadena, CA 91125

Dr. S. S. Yu
L-626
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550