

DTIC FILE COPY

Naval Research Laboratory

Washington, DC 20375-5000



NRL Memorandum Report 6237

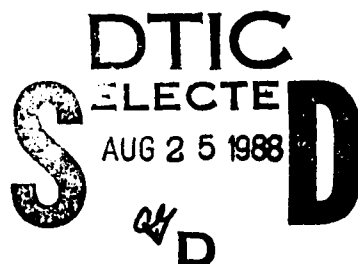
AD-A198 072

Asymptotic Growth of Cumulative and Regenerative Beam Break-Up Instabilities in Accelerators

Y. Y. LAU

*Plasma Theory Branch
Plasma Physics Division*

June 28, 1988



Approved for public release; distribution unlimited.

88 8 24 015

ADA 198072

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 6237			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			10. SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO. DOE	PROJECT NO. AT05-86 ER-3585	TASK NO.
			WORK UNIT ACCESSION NO.		
11. TITLE (Include Security Classification) Asymptotic Growth of Cumulative and Regenerative Beam Break-Up Instabilities in Accelerator					
12. PERSONAL AUTHOR(S) Lau, Y.Y.					
13a. TYPE OF REPORT Interim		13b. TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Year, Month, Day) 1988 June 28	
15. PAGE COUNT 22					
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 (2)		
19. ABSTRACT (Continue on reverse if necessary and identify by block number) It is found that the asymptotic growth of the cumulative beam break-up instability is independent of the focusing magnetic field, according to the model of Panofsky and Bander. The analysis is extended to include the transition from the cumulative to the regenerative type, both in the presence and absence of a focusing magnetic field.					
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

ASYMPTOTIC GROWTH OF CUMULATIVE AND REGENERATIVE BEAM BREAK-UP INSTABILITIES IN ACCELERATORS

The beam break-up instability (BBU) continues to be a critical factor which places a limit on the current and on the pulse length in both rf and induction accelerators.¹⁻⁸ A transverse displacement of the particle beam excites a non-axisymmetric mode in the accelerating structure (cavity). This non-axisymmetric mode further deflects the beam sideways, reinforcing the mode itself. Depending on whether a wave with negative group velocity is present to provide feedback, BBU may either be regenerative or cumulative.^{2,4,6}

Much theoretical effort on BBU in the past twenty years has been devoted to the cumulative type,^{2,3,5,7,8} where the accelerating units are assumed to be decoupled from each other electromagnetically. Information is carried only by the beam. Under this assumption, Panofsky and Bander² found that the transverse displacement of the beam grows asymptotically like $\exp(at)^{1/3}$, at a given distance downstream, when the focusing magnetic field is absent. The model including a general focusing magnetic field was laid down in Ref. 2, but it was stated there that, except for the case of weak focusing, it is not possible to obtain the asymptotic growth analytically. In a pioneering paper published somewhat later, Neil, Hall and Cooper⁵ used an entirely different approach and found that the asymptotic growth of the cumulative BBU behaves instead like $\exp(bt)^{1/2}$ in the presence of a strong solenoidal magnetic field. Here, a , b are parameters proportional to the beam current. These peculiar time dependences, at first sight, are not expected from the usual experiences with beam-circuit interaction. However, the asymptotic growth is firmly established, at least in the case of zero focusing magnetic field, both in the "continuum" limit, (where coupled partial differential equations are solved^{2,3}), and in the discrete model (where the individual beam-cavity



A-1

interaction is passed onto the subsequent ones through multiplication of matrices^{5,8}). From the above asymptotic growths, scaling laws on the beam current were established.

In this paper, we use the continuum model and adopt a mode coupling analysis. The asymptotic growth is calculated analytically, for both cumulative and regenerative BBU, in the presence of a general focusing magnetic field. This work was motivated by an attempt to understand the origin of the asymptotic dependences mentioned above, and by the need to assess the importance of the BBU in the two beam accelerator concept⁹ currently explored at the Naval Research Laboratory. The present analytic theory yields three specific results which hitherto were not given in the literature. First, the asymptotic growth $\exp(bt)^{1/2}$ exhibited in the cumulative BBU in the presence of a strong solenoidal magnetic field⁵ is a result of the coupling between the slow beam-cyclotron mode and the cavity mode. Second, this growth is reduced to $\exp(at)^{1/3}$ as $t \rightarrow \infty$. That is, the asymptotic growth of the cumulative BBU is independent of the focusing magnetic field - as if the focusing magnetic field were absent. Third, the treatment of the cumulative BBU is extended to the regenerative type with the inclusion of a negative group velocity v_g . The exponentiation factor is modified by a quantity which depends only on the group velocity, but is independent of the other properties of the structure. Here, we shall present the model and the results. The implication will be discussed but the details will be given elsewhere.

For simplicity, consider a continuous beam with coasting velocity v , relativistic mass factor γ , and current I streaming in a focusing magnetic field B inside a series of identical accelerating units. Let $\xi(z,t)$ be the transverse displacement of the beam from the axis, $q(z,t)$ be a measure of the deflecting force produced by the non-axisymmetric mode (with $e^{i\omega_0 t}$

dependence) in the individual accelerating units.¹⁰ In the continuum treatment of the cumulative BBU, the governing equations for ξ and q may be written as^{2,3,10}

$$\left(\frac{\partial}{\partial t} + v \frac{\partial}{\partial z}\right) \left[\gamma \left(\frac{\partial \xi}{\partial t} + v \frac{\partial \xi}{\partial z}\right)\right] + \gamma \omega_c^2 \xi = q(z, t), \quad (1)$$

$$\frac{\partial q(z, t)}{\partial t} - i \omega_0 q(z, t) = -i \gamma \omega_0^3 \varepsilon \xi(z, t), \quad (2)$$

where $\omega_c = |e|B/\gamma m_0 c$ and ε is the dimensionless coupling constant proportional to the beam current.¹¹ As usual, Eq. (1) expresses the deflection of the beam by the mode, whereas Eq. (2) describes the excitation of the mode by the beam's transverse displacement ξ .

Assuming a dependence $\exp(i\omega t - ikz)$ for the solutions, Eqs. (1) and (2) yield the dispersion relation

$$D(\omega, k) \equiv \left[(\omega - kv)^2 - \omega_c^2 \right] (\omega - \omega_0) - \omega_0^3 \varepsilon = 0. \quad (3)$$

In the terminology of mode coupling,^{12,13} this dispersion relation describes the interaction between the cavity mode ($\omega = \omega_0$) and the fast and slow beam-cyclotron mode ($\omega - kv = \pm \omega_c$).

From the general stability theory, the dominant asymptotic growth of disturbances may be determined from the Green's function¹²

$$G(z, t) = \int_{\Gamma} d\omega \int_{-\infty}^{\infty} dk e^{i\omega t - ikz} / D(k, \omega) \sim \int_{\Gamma} d\omega e^{i\omega t - ik(\omega)z}, \quad (4)$$

where the Bromwich contour Γ lies sufficiently far in the lower half complex ω plane, and $k(\omega)$ is the meaningful solution obtained from the dispersion relation $D(\omega, k) = 0$.

Let us first recover the previously established results from Eq. (4).

When the focusing magnetic field is absent, $\omega_c = 0$ and

$k(\omega) = \omega/v \pm (\omega_0/v) [\omega_0 \epsilon / (\omega - \omega_0)]^{1/2}$. Substitution of this $k(\omega)$ in (4) yields the following asymptotic formula (from a saddle point calculation²):

$$|G_n(z, t)| \sim \exp(1.64W^{1/3}), \quad (5)$$

where

$$W = \epsilon \left(\omega_0^3 z^2 / v^2 \right) (t - z/v), \quad (t > z/v > 0). \quad (6)$$

The asymptotic solution (5) was first obtained by Panofsky and Bander [cf. Eq. (33) of Ref. (2)] and was confirmed by Neil and Cooper³ and by Gluckstern et al.⁷ in two rather different analyses. In the other limit, where a strong focusing magnetic field is present, the dominant interaction is expected to be between the (positive energy) cavity mode ($\omega = \omega_0$) and the negative energy beam-cyclotron mode,^{13,14} for which $\omega - kv = -\omega_c$. In this case, the dispersion relation (3) may be approximated by $(\omega - kv + \omega_c)(\omega - \omega_0) = -\omega_0^3 \epsilon / 2\omega_c$, yielding $k(\omega) = (\omega + \omega_c)/v + \epsilon \omega_0^3 / (2v\omega_c(\omega - \omega_0))$. Substituting this $k(\omega)$ in Eq. (4) and performing a saddle point calculation similar to that given in Ref. 2, one obtains the asymptotic solution

$$|G(z, t)| = |G_s(z, t)| \sim \exp[(2\rho W/z)^{1/2}], \quad (7)$$

where $\rho = v/\omega_c$ and W is given by Eq. (6). With the use of the appropriate coupling constant¹¹ in W , the asymptotic formula (7) is easily shown to be identical to the growth factor given in Eq. (5.13) of Neil et al.⁵ The simple interpretation, in terms of mode coupling, of the asymptotic dependence $\exp(bt)^{1/2}$ evident in (7) is given here for the first time. It is not readily extracted from the original analyses in Ref. 5.

For general values of ω_c , Eq. (3) gives

$$k(\omega) = \frac{\omega}{v} \pm \frac{1}{v} \left[\omega_c^2 + \frac{\varepsilon \omega_o^3}{(\omega - \omega_o)} \right]^{1/2}, \quad (8)$$

and the saddle point contribution may also be calculated analytically (contrary to the assertion of Ref. 2, at least for a coasting beam). The dominant contribution to (4) gives

$$|G(z, t)| \sim \exp \left\{ \operatorname{Re} \left[\frac{iz\omega_c}{v} \omega_s \tau \left(1 + \frac{1}{2\omega_s^3 \tau^2} \right) \right] \right\}, \quad (9)$$

where the dimensionless time τ is

$$\tau = W(\rho/z)^3, \quad (10)$$

and ω_s is the root of the fourth degree polynomial:

$$\omega_s^3 (1 + \omega_s) = (1/2\tau)^2. \quad (11)$$

It is easy to show that there is one and only one root of ω_s in Eq. (11) with $\operatorname{Im} \omega_s < 0$ for all values of $\tau \neq 0$, and we should use that root of ω_s in (9).

The solution (9) implies that, given a focusing magnetic field, the asymptotic growth is independent of the strength of the magnetic field. To see this, consider a time long enough so that $2\tau \gg 1$. Then Eq. (11) gives $\omega_s = (1/2\tau)^{2/3} e^{-i2\pi/3}$ and the solution (9) reduces to (5), the formula corresponding to zero focusing magnetic field. This is a rather surprising result, obtained directly from the model of Panofsky and Bander,² but is, at first sight, contradictory to the findings of Neil et al.⁵

The above paradox may be resolved by noting that in the "strong focusing" regime, defined as $2\tau \ll 1$, Eq. (11) gives $\omega_s = -i(1/2\tau)^{1/2} [1 - i(1/4)(2\tau)^{1/2}]$. Substitution of this ω_s into (9)

yields (7) in the limit $2\tau \ll 1$. In fact, the condition $2\tau \ll 1$ may easily be shown to be similar to the one imposed by Neil et al⁵ when they derived Eq. (7) using an entirely different approach. Thus, the dimensionless time $\tau \sim 1/2$ marks the transition from the strong focusing to the weak focusing regime [cf Eq. (11)]. From Eqs. (10) and (6), the time (t_T) about which this transition occurs is $t_T = (z/v)(\omega_c/\omega_0)^3/2\varepsilon$.

As an example, consider a 1 kA, 30 MeV electron beam coasting in a solenoidal magnetic field of 3 kG inside a disk-loaded waveguide whose individual cavities support a deflecting TM_{110} mode with $\omega_0/2\pi = 1$ GHz. Suppose that a misalignment, say, produces an "excitation" at some axial location and we examine the BBU in response to this excitation 3m downstream. For these parameters, $\varepsilon = 4.13 \times 10^{-4}$ [cf. Ref. 11] and $t_T = 33$ ns. Thus, if the pulse length substantially exceeds t_T , the cumulative BBU would evolve at the later stage as if the focusing magnetic field is absent.¹⁵

The present model may readily be generalized to treat the regenerative BBU with the inclusion of a negative group velocity v_g . The asymptotic formulas given below explicitly show the change of the character in the BBU growth with the sign of v_g . The simplest way to include the effects of a non-zero group velocity is to replace the factor $(\omega - \omega_0)$ in Eq. (3) by $(\omega - \omega_0) - v_g(k - k_0)$, where (ω_0, k_0) may now be taken as the point of intersection of the dispersion curves in the (ω, k) plane between the "beam line" and that of the slow wave structure formed by the accelerating units. With this replacement, the Green's function (4) may again be re-evaluated. In the case of no focusing magnetic field, it gives

$$|G_n(z, t)| \sim \exp \left\{ 1.54W^{1/3} \left(\frac{1}{1-\beta_g} \right) \left(1 - v_g t/z \right)^{2/3} \right\}. \quad (12)$$

whereas in the case of strong focusing, it reads

$$|G_s(z, t)| \sim \exp \left\{ (2\rho W/z)^{1/2} \left(\frac{1}{1-\beta_g} \right) (1-v_g t/z)^{1/2} \right\}, \quad (13)$$

where $\beta_g \equiv v_g/v$. It is obvious that (12) and (13) reduce to (5) and (7), respectively, as $v_g \rightarrow 0$. Since $v_g < 0$ for regenerative BBU, it is easily seen from Eqs. (12) and (13) that both G_n and G_s grow like a simple exponential function of time [i.e., $\exp(Ct)$] as $t \rightarrow \infty$ when $v_g < 0$. This, of course, is consistent with what is expected from the outset when a backward wave interacts with an electron beam^{12,13}. It also reaffirms the potential danger of the regenerative BBU, as $\exp(Ct)$ grows considerably faster than either $\exp(at)^{1/3}$ or $\exp(bt)^{1/2}$ for large t .

The following point may also be of interest. A comparison of (12) with (5) and (13) with (7) suggests that the modification in the exponentiation due to a non-zero group velocity depends only on v_g and is otherwise independent of the accelerating structure. It is expected, then, that the same modification would emerge in a matrix formulation similar to the ones given in Refs. 5 and 8. The asymptotic formulas (12) and (13) would provide an immediate determination of the potential prevalence of the accumulative or regenerative BBU from a knowledge of the structure (e.g., Brillouin diagram^{10,15}).

Finally, we remark that Eqs. (12) and (13) are also valid when $\beta_g > 0$. In that case, the BBU becomes convective¹² and there would be an additional restriction on the solutions (12) and (13); namely, disturbance growth is possible only for $z/v < t < z/v_g$ at a given position z . In fact, all of the various asymptotic time dependences examined in this paper may easily be understood in terms of the analyticity of the Laplace transform or the Green's function. From Briggs' stability theory,¹² it may be shown that the $\beta_g > 0$ and the $\beta_g < 0$ cases correspond to, respectively, analyticity in

the lower half ω plane including the real ω axis, and a branch point somewhere in the lower half ω plane. The special case $\beta_g = 0$ (cumulative BBU) corresponds to analyticity in the lower ω plane, but with a branch point on the real ω axis, leading to an exponential growth whose exponent is a fractional power of time, as exhibited in Eqs. (5) and (7).

In addition to the general theory reported above, a similar formulation has been carried out to calculate the excitation of the BBU in the accelerated beam, by the misalignments in the primary beam, in the two beam accelerator configuration recently proposed by Friedman and Serlin.⁹ The preliminary conclusion is that, in the parameter regime currently studied, the BBU does not appear to be serious.

I would like to thank M. Friedman and D. Chernin for helpful discussion. This work is supported by the U. S. Department of Energy, Contract No. DE-AI05-86-ER13585.

References

1. The Stanford Two Mile Accelerator, ed. R. Neal; W. A. Benjamin, Inc., New York (1968), p. 205.
2. W. K. H. Panofsky and M. Bander, Rev. Sci. Inst. 39, 206 (1968).
3. V. K. Neil and R. K. Cooper, Part. Acc. 1, 111 (1970).
4. R. Helm and G. Loew, Linear Accelerators, Eds. P. M. Lapostolle and A.L. Septier, (North Holland, Amsterdam, 1970), Ch. B.1.4.
5. V. K. Neil, L. S. Hall and R. K. Cooper, Part. Acc. 9, 213 (1979).
6. P. B. Wilson, in AIP Conf. Proc. No. 87, p. 504, (American Institute of Physics, New York, 1982).
7. G. J. Caporaso, A. G. Cole and K. W. Struve, IEEE Trans. NS-30, 2507 (1983); G. J. Caporaso, F. Rainer, W. E. Martin, D. S. Prono, and A. G. Cole, Phys. Rev. Lett. 57, 1591 (1986).
8. R. L. Gluckstern, R. K. Cooper and P. J. Channell, Part. Acc. 16, 125 (1985).
9. M. Friedman and V. Serlin, Appl. Phys. Lett. 49, 596 (1986).
10. The quality factor Q associated with the accelerating structure is an extremely important parameter in assessing the potential danger of BBU, once the beam current and the pulse length are given. In this paper, we focus mainly on the growth of BBU and its transition in different regimes, as the stabilizing influence due to a finite Q may be accounted for phenomenologically by simply multiplying the Green's function by $\exp(-\omega_0 t/2Q)$.
11. The coupling constant ε depends on the accelerating structure and on the deflecting mode under consideration. The configuration treated in Ref. 3 consists of a circular waveguide loaded with identical apertured disks along the guide axis. In that case, $\varepsilon = 0.0248 (I/1kA)\beta/\gamma$ if the deflecting mode within the individual cavities is the TM_{110} mode. Here, $\beta = v/c$, c is the speed of light.

In the more general configuration treated in Refs. 2 and 5, the accelerating units are separated by a distance L and the n -th unit is located at $z = nL$. In that case, $\varepsilon = (v^2 \kappa / \omega_0^2 L) I / (17 \beta \gamma k A)$ where κ is proportional to the "transverse impedance" of the structure. [κ has a unit of inverse length; it is identical to the k defined in Eq. (3.11) of Ref. 5]. Note that ε is independent of the focusing magnetic field but is inversely proportional to γ .

12. R. J. Briggs, Electron Stream Interaction in Plasmas, MIT Press, Cambridge, MA, (1964), Ch. 2.
13. See e.g., M. V. Chodorow and C. Susskind, Fundamentals of Microwave Electronics, (McGraw-Hill, New York, 1964) for a general discussion of mode coupling and beam-circuit interaction.
14. A. Bers and S. Gruber, Appl. Phys. Lett. 6, 27 (1965); L. S. Hall and W. Heckrotte, Phys. Fluids 9, 1496 (1965).
15. It should be emphasized that the damping mechanisms associated with phase mixing and a finite Q might have a decisive influence on the 3BU growth. Nevertheless, from an analytical point of view, it is interesting that the asymptotic growth in an unstable system described by the dispersion relation (3) is independent of ω_c . In the case of an accelerating beam, a careful examination of the Green's function would show that the asymptotic growth of the cumulative BBU is also independent of the focusing magnetic field, in the sense described here. In fact, the analyses and the conclusions given in this paper need not be restricted to a solenoidal focusing magnetic field. For general linear transverse focusing, we simply replace ω_c by $k_\beta c$, where k_β is the betatron wave number, and the asymptotic formulas remain valid.

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. Ossakov (26 copies)
4700.1 - Dr. M. Friedman (5 copies)
4700.1 - V. Serlin
4710 - Dr. J. A. Pasour
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. G. Joyce
4790 - Dr. I. Haber
4790 - Dr. R. Fernsler
4790 - Dr. S. Slinker
4790 - Dr. T. Godlove
4790A- W. Brizzi
6840 - Dr. S. Y. Ahn
6840 - Dr. A. Ganguly
6840 - Dr. R. K. Parker
6843 - Dr. N. R. Vanderplaats
6875 - Dr. R. Wagner

* 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. Bruce Anderson
Lawrence Livermore National Laboratory
L-436
P. O. Box 808
Livermore, CA 94550

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. Robert Behringer
Office of Naval Research
1030 E. Green
Pasadena, CA 91106

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. T. Berlincourt
Office of Naval Research
Attn: Code 420
Arlington, VA 22217

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

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

Dr. J. A. Byers
Lawrence Livermore National Lab.
Attn: (L-630)
P. O. Box 808
Livermore, CA 94550

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

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

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

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. F. S. Felber
11011 Torrynana Road
San Diego, CA 92121

Dr. H. Fleischmann
Cornell University
Ithaca, NY 14850

Dr. Lazar Friedland
Dept. of Eng. & Appl. Science
Yale University
New Haven, CT 06520

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 Surface 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. A. Kolb
Maxwell Laboratories, Inc.
8835 Balboa Avenue
San Diego, CA 92123

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. S. P. Kuo
Polytechnic Institute of NY
Route 110
Farmingdale, NY 11735

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 85721

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

Dr. John Madey
S.P.R.C.
Physics Department
Stanford University
Stanford, CA 94305

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

Dr. S. Ride
Johnson Space Center
Houston, TX 77058

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

Dr. Marshall N. Rosenbluth
Institute for Fusion Studies
The Univ. of Texas at Austin
Austin, TX 78712

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

Dr. J. Scharer
ECE Dept.
Univ. of Wisconsin
Madison, WI 53706

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
Boboken, 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 Laboratory
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