Naval Research Laboratory

Washington, DC 20375-5000

(2)

NRL Memorandum Report 6615

Critique of Nondiffracting Beams

P. SPRANGLE AND B. HAFIZI*

Beam Physics Branch
Plasma Physics Division

**Science Applications International Corp.*
McLean, VA

April 3, 1990

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	1990 April 3	Interim

4. TITLE AND SUBTITLE

Critique of Nondiffracting Beams

5. FUNDING NUMBERS

JO #47-0899-0-0

6. AUTHOR(S)

P. Sprangle and B. Hafizi*

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Washington, DC

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL Memorandum
Report 6615

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

ONR
Arlington, VA

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

*SAIC, McLean, VA

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release;
distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

None

14. SUBJECT TERMS

Nondiffracting beams
Bessel beam
Electromagnetic directed energy pulse train

15. NUMBER OF PAGES

21

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

CRITIQUE OF NONDIFFRACTING BEAMS

A number of researchers have discussed the possibility of generating electromagnetic beams or pulses which can propagate without the usual degree of transverse spreading. Nondiffracting directed radiation beams have been the subject of a number of special sessions at various conferences.[1,2] Our intention in this note is to discuss i) the Bessel beam[3,4] which has been called[4] "remarkably resistant to the diffractive spreading commonly associated with all wave propagation"; and ii) the electromagnetic directed energy pulse train[5-7] which is claimed[7] to be "significantly improved over conventional, diffraction-limited beams", and to[5] "defeat diffraction". In this note we show that diffraction is not eliminated or reduced in any of the proposed schemes and that conventional Gaussian beams will propagate at least as far for a given transmitting antenna dimension.

Durnin et al.[4] have studied, analytically and experimentally, a solution of the scalar wave equation whose transverse profile is that of a Bessel function of order zero, J_0. The field $\psi(r,z,t) = J_0(k_\perp r)\exp[i(k_z z-\omega t)]$ is a solution of the scalar wave equation where $k_\perp$, the

Manuscript approved February 27, 1990.

transverse wave number, is given by $k_\perp^2 = \omega^2/c^2 - k_z^2$, ω is the frequency and k_z is the axial wave number. Some of the properties of the solution are: i) the transverse profile of ψ is independent of z, ii) the intensity function, $J_o^2(k_\perp r)$, falls off like $1/r$ for $r >> 1/k_\perp$, iii) the power contained in each transverse lobe, between the adjacent zeros of $J_o^2(k_\perp r)$, is of the same order, and iv) $J_o(k_\perp r)$ is an axisymmetric superposition of plane waves propagating at an angle $\sim k_\perp/k_z$ to the z axis. In most of what follows, we will be interested in the qualitative comparison and scaling of various quantities and, hence, will not be concerned with factors of order unity.

Using arguments based on geometric optics, Durnin et al.[4] found the propagation distance of the central lobe of the Bessel beam to be given by $\sim 2Rr_o/\lambda$, where R is the radius of the aperture (radius of clipped Bessel beam), r_o is the typical spacing between adjacent zeros of J_o, i.e., $r_o \approx \pi/k_\perp$, and λ is the wavelength. They compare the propagation distance (diffraction length) of the apertured Bessel beam with a Gaussian beam which has a spot size of approximately r_o. That is, the center lobe of the Bessel beam nearly matches the Gaussian beam as shown in Fig. 1. The diffraction distance (Rayleigh length) of the Gaussian beam is given by the well-known formula, $Z_G \approx \pi r_o^2/\lambda$. Since $R >> r_o$, they observed that the Bessel beam propagated further than the Gaussian beam, by a factor $\sim (2/\pi)R/r_o$.

Our interpretation of the results of Durnin and co-workers differs in a number of fundamental ways. We first note that the cartesian counterpart of $J_o(k_\perp r)$ is $\cos(k_\perp x)$, which is simply a plane wave propagating at an angle to the z axis. Plane waves do not diffract since there is no spatial variation transverse to the propagation direction; however, when clipped or

apertured, plane waves diffract. Bessel beams, when apertured, will diffract in a similar way.

To be specific, let us consider a Bessel beam limited by a finite aperture of radius R. If $N >> 1$ is the number of lobes within the aperture radius, then $R \simeq Nr_o$. For the Bessel beam, the diffraction length is given by $Z_B \simeq R/\theta_B$, where $\theta_B \simeq k_\perp/k_z \simeq \lambda/2r_o$ is the diffraction angle and $\lambda = 2\pi(k_z^2 + k_\perp^2)^{-1/2}$ is the wavelength. The diffraction length associated with the central lobe of the apertured Bessel beam is, therefore, $Z_B \simeq 2Nr_o^2/\lambda = 2Rr_o/\lambda = (2/\pi)NZ_G$. Since the lobes carry about equal power, there is sufficient power in the off-axis lobes to replenish the central lobe. Each of the N lobes diffract away sequentially starting with the outermost one. Roughly speaking, the outermost lobe diffracts after a distance $\sim \pi r_o^2/\lambda$, the next one diffracts after a distance $2\pi r_o^2/\lambda$ and so on until the central lobe diffracts away after a distance $\sim N\pi r_o^2/\lambda$, which is approximately equal to Z_B. The central lobe persists as long as there are off-axis lobes to replenish its diffraction losses.

A far more meaningful measure for comparing the diffractive properties of beams would be to ask the following question. For a given aperture (source) size and a target size, which is some distance away, what beam configuration or shape will maximize the power transmitted to the target? If this procedure is used to compare a Bessel beam with a Gaussian beam, we would use a Gaussian beam having a spot size equal to the aperture, $R = Nr_o$. The power through the aperture is the same if the peak amplitude of the Bessel beam is $\sim N^{1/2}$ larger than that of the Gaussian beam. In this case the Gaussian beam will propagate N times <u>further</u> than the Bessel beam. In addition, by appropriately focusing the Gaussian beam, nearly all the power can be focused on a target of dimension r_o in a distance Z_B. For

the same total power through the aperture, a focused Gaussian beam delivers ~ N times more power on the target than the Bessel beam.

Another solution to the wave equation which has been studied for its diffractive properties is the electromagnetic directed energy pulse train.[5-7] This pulse form is a superposition of fundamental Gaussian pulses, ψ_k, which are exact solutions to the homogeneous wave equation $(\nabla^2 - c^{-2}\partial^2/\partial t^2)\psi_k = 0$, where $\psi_k(r,z,t) = (4\pi iV)^{-1}\exp(ik\eta - kr^2/V)$, $1/V = 1/A - i/R$, $A = z_o + \xi^2/z_o$, $R = \xi + z_o^2/\xi$, $\eta = z+ct$, $\xi = z-ct$, $k = \omega/c$ and z_o is a constant. The solution, ψ_k, which has been studied by Ziolkowski and co-workers,[6] represents a pulse train traveling to the left which is modulated by an envelope traveling to the right (z direction). The functions ψ_k, for all k, form a complete set and each basis function has infinite energy, i.e., $\int_{-\infty}^{\infty} d^3\underset{\sim}{r}|\psi_k|^2 \to \infty$. A finite energy pulse can be formed by a superposition of the basis functions with the weight function F(k), i.e., $f = \mathrm{Re}\int_0^{\infty} dk\,\psi_k(r,z,t)F(k)$. Ziolkowski and co-workers[6] have examined a particular pulse form both numerically and experimentally. This pulse form is called a modified power spectrum (MPS) pulse which is given by

$$f(r,\xi,\eta) = \mathrm{Re}\left[(z_o+i\xi)^{-1}(a+r^2/\beta(z_o+i\xi)-i\eta/\beta)^{-\alpha}\exp\left(ib\eta/\beta - br^2/\beta(z_o+i\xi)\right)\right],$$

where the function f is an exact solution to the scalar wave equation for the pulse amplitude and a, b, α, β, and z_o are arbitrary constants. The initial shape of the MPS pulse is shown in Fig. 2 for particular values of a, b, α, β and z_o. The MPS pulse has finite energy and its shape evolves as it propagates. To determine the propagation distance of this pulse, Ziolkowski and co-workers note that the radial profile is dominated by the factor $\exp(-bz_o r^2/(\beta(z_o^2+\xi^2)))$. They use the minimum spot size, $w_o = (\beta z_o/b)^{1/2}$, (which occurs at the pulse's center, ξ=0) to calculate the

diffraction length, $Z \simeq \pi w_o^2/\lambda = \pi\beta z_o/(b\lambda)$. The numerical and experimental results indicate that the MPS pulse propagates significantly further than this diffraction length ($Z \simeq \pi w_o^2/\lambda$) before the amplitude begins to fall off like 1/z.

In our interpretation of their results, the diffraction length for the MPS pulse is not $\sim \pi w_o^2/\lambda$, but is properly given by $Z_{MPS} \simeq \pi w_o R/\lambda$, where R is the transmitting antenna dimension (radius of aperture) and $R > w_o$. This can be understood by first noting that the diffraction angle associated with a pulse having a typical transverse spatial variation of $\sim w_o$ is $\theta_{MPS} \simeq \lambda/(\pi w_o)$. As in the case of the Bessel beam, we note that the energy in the MPS pulse is radially spread out, typically over the full width, R, of the aperture. Consequently, the diffraction distance is given by $Z_{MPS} \simeq R/\theta_{MPS}$. The numerical and experimental studies of the MPS pulse span a wide range of values for λ, w_o and $R > w_o$. In all cases we find that the observed propagation distance is fully consistent with the length $Z_{MPS} \simeq \pi w_o R/\lambda$ for wavelengths within the main part of the spectrum. Utilizing the same transmitting antenna radius R, an unfocused Gaussian beam with spot size R, would propagate a distance $\sim \pi R^2/\lambda$; this is greater than the MPS pulse propagation distance since $R > w_o$. An appropriately focused Gaussian beam can be focused to a dimension $\sim w_o$ in the distance $\sim Z_{MPS}$. Such a Gaussian beam focuses more power on the target than a corresponding MPS pulse.

Other researchers have considered alternative approaches for propagating electromagnetic beams or pulses. One such study indicates the possibility of generating wave packets with a broad frequency spectrum.[8] The high-frequency end of the spectrum determines the furthest distance the pulse can propagate, in complete accord with our understanding of diffraction.

In conclusion, we find that when a proper comparison is made, Bessel Beams and Electromagnetic Directed Energy Pulse Trains have no particular range advantage over conventional Gaussian beams.

Acknowledgment

This work is supported by the Office of Naval Research.

References

1. Proceedings of the SPIE Conference 873 on Microwave and Particle Beam Sources and Propagation, Los Angeles, 1988, edited by N. Rostoker (Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1988).
2. Proceedings of the SPIE Conference 1061 on Microwave and Particle Beam Sources and Directed Energy Concepts, Los Angeles, 1989, edited by H. E. Brandt (Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1989).
3. J. Durnin, J. Opt. Soc. Am. A4, 651 (1987).
4. J. Durnin, J. J. Miceli and J. H. Eberly, Phys. Rev. Lett. 58, 1499 (1987).
5. R. W. Ziolkowski, in Ref. 1, p. 312.
6. R. W. Ziolkowski, D. K. Lewis and B. D. Cook, Phys. Rev. Lett. 62, 147 (1989).
7. R. W. Ziolkowski, Phys. Rev. A 39, 2005 (1989).
8. T. T. Wu, J. Appl. Phys. 57, 2370 (1985).

Figure Captions

Fig. 1 Transverse intensity profiles of a Bessel beam and a Gaussian beam. The full width at half maximum (FWHM) of the Gaussian beam is the same as that of the central lobe of the Bessel beam. The parameters are the same as those in the experiment of Ref. 4: $\lambda = 6328\text{Å}$ and FWHM = 70 μm.

Fig. 2 Plot of modified-power spectrum pulse $f(r,\xi,\eta)$ at $t = 0$, i.e., $\xi = \eta = z$. The parameters for this pulse are the same as those in Ref. 7: $a = 1$ cm, $\alpha = 1$, $b = 1 \times 10^{10}$ cm^{-1}, $\beta = 6 \times 10^{15}$, and $z_o = 1.667 \times 10^{-3}$ cm.

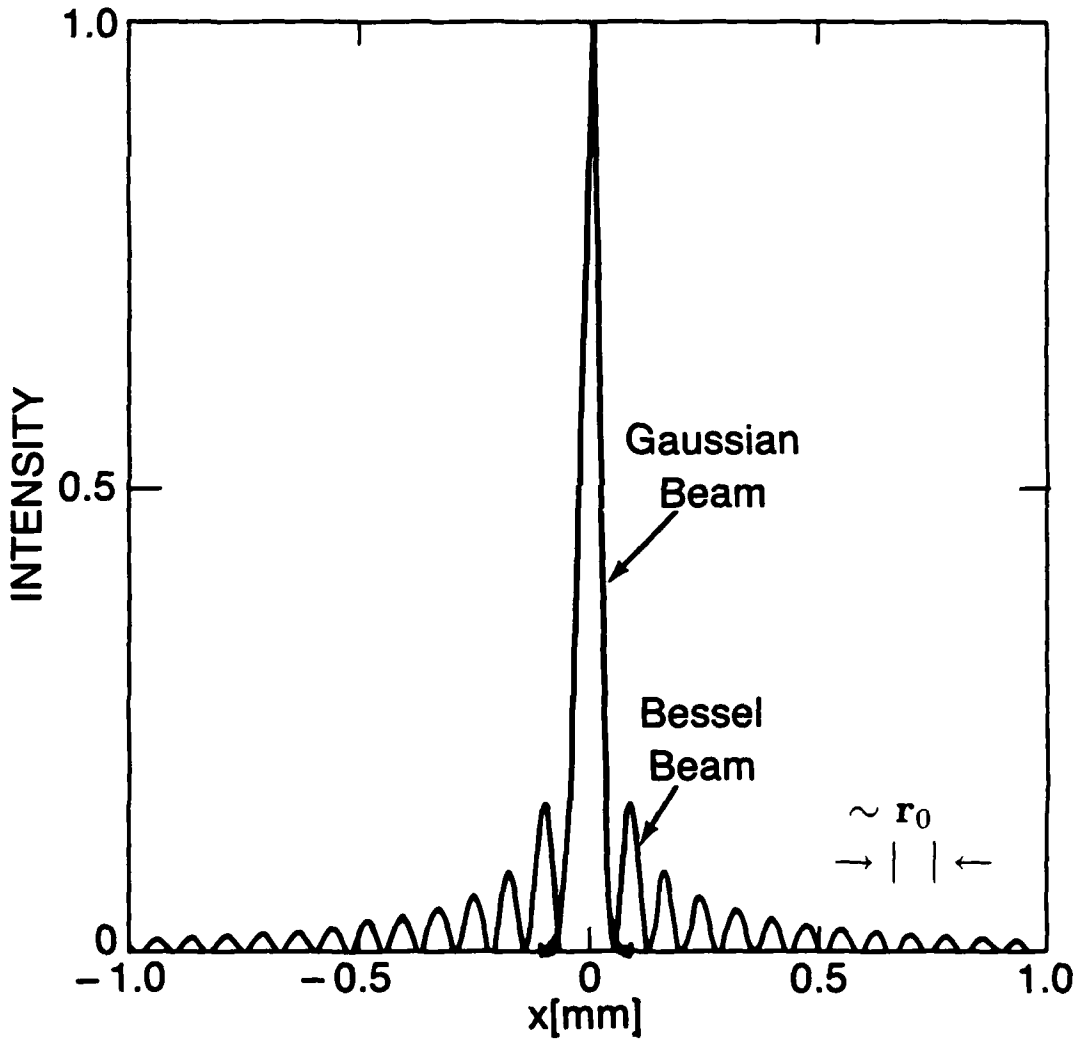
1.0
0.5
0
INTENSITY
Gaussian
Beam
Bessel
Beam
~ r0
−1.0
−0.5
0
0.5
1.0
x[mm]

Figure 1

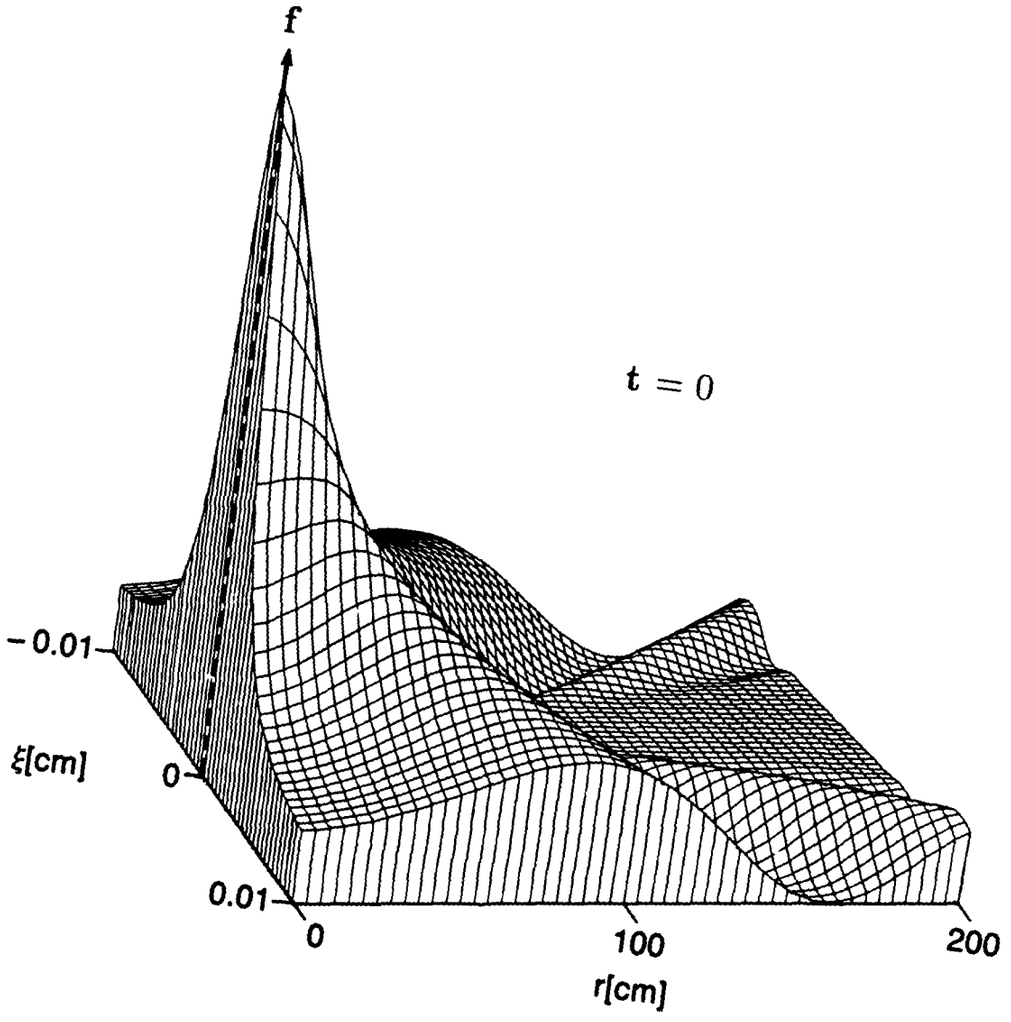

Figure 2

DISTRIBUTION LIST

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

Attn: Code 1000 - Commanding Officer, CAPT John J. Donegan, Jr.
1001 - Dr. T. Coffey
1005 - Head, Office of Management & Admin.
1005.1-Deputy Head, Office of Management & Admin.
1005.6-Head, Directives Staff
1200 - CAPT R. W. Michaux
1201 - Deputy Head, Command Support Division
1220 - Mr. M. Ferguson
2000 - Director of Technical Services
2604 - NRL Historian
3000 - Director of Business Operations
4000 - Dr. W. R. Ellis
0124 - ONR
4600 - Dr. D. Nagel
4603 - Dr. W. W. Zachary
4700 - Dr. S. Ossakow (26 copies)
4707 - Dr. W. M. Manheimer
4730 - Dr. R. Elton
4770 - Dr. G. Cooperstein
4780 - Dr A. W. Ali
4790 - Dr. C. M. Tang
4790 - Dr. G. Joyce
4790 - Dr. M. Lampe
4790 - Dr. Y. Y. Lau
4790 - Dr. A. Ting
4790 - Dr. E. Esarey
4790 - Dr. J. Krall
4790A- B. Pitcher (20 copies)
4790 - Dr. P. Sprangle
4793 - Dr. W. Black
4793 - Dr. S. Gold
4793 - Dr. D. L. Hardesty
4793 - Dr. A. K. Kinkead
4794 - Dr. A. W. Fliflet
4794 - Dr. M. Rhinewine
4795 - Dr. C. A. Kapetanakos
4795 - Dr. J. Mathew
5700 - Dr. L. A. Cosby
5745 - Dr. J. Condon
6840 - Dr. S. Y. Ahn
6840 - Dr. A. Ganguly
6840 - Dr. R. K. Parker
6843 - Dr. R. H. Jackson
6843 - Dr. N. R. Vanderplaats
6843 - Dr. C. M. Armstrong
6875 - Dr. R. Wagner
2628 - Documents (22 copies)
2634 - D. Wilbanks

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

Dr. R. E. Aamodt
Lodestar Research Corp.
2400 Central Ave., P-5
Boulder, CO 80306-4545

Dr. J. Adamski
Boeing Aerospace Company
P.O. Box 3999
Seattle, WA 98124

Dr. T. M. 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. W. Becker
Univ. of New Mexico
Institute for Mod. Opt.
Albuquerque, NM 87131

Dr. Robert Behringer
9342 Balcon Ave.
Northridge, CA 91325

Dr. G. Bekefi
Mass. Institute of Tech.
Room 36-213
Cambridge, MA 02139

Dr. Steven V. Benson
Physics Building
Duke University
Durham, NC 27706

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

Dr. Amitava Bhattacharjee
Columbia University
S. W. Mudd 210
Dept. of Applied Phys.
New York, NY 10027

Dr. Anup Bhowmik
Rockwell International/Rocketdyne Div.
6633 Canoga Avenue, FA-40
Canoga Park, CA 91304

Dr. G. Bourianoff
1901 Rutland Drive
Austin, TX 78758

Dr. Charles Brau
Vanderbilt University
Nashville, TN 37235

Dr. R. Briggs
SSC Laboratory
Stoneridge Office Park
2550 Beckleymeade Ave.
Suite 260
Dallas, TX 75237

Prof. William Case
Dept. of Physics
Grinnell College
Grinnell, IA 50112

Dr. R. Center
Spectra Tech., Inc.
2755 Northup Way
Bellevue, WA 98004

Dr. K. C. Chan
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

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

Dr. S. Chen
MIT Plasma Fusion Center
NW16-176
Cambridge, MA 01890

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

Dr. William Colson
Naval Postgraduate School
Physics Dept.
Monterey, CA 93940

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

Dr. R. A. Cover
Rockwell International/Rocketdyne Div.
6633 Canoga Avenue, FA-38
Canoga Park, CA 91304

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
2440 Embarcadero Road
Palo Alto, CA 94303

Dr. Philip Debenham
Center for Radiation Research
National Bureau of Standards
Gaithersburg, MD 20899

Director
National Security Agency
Fort Meade, MD 20755
ATTN: Dr. Richard Foss, A42
Dr. Thomas Handel, A243
Dr. Robert Madden, R/SA

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

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

Dr. Dwight Duston
SDIO/IST
The Pentagon
Washington, DC 20301-7100

Dr. Luis R. Elias
Creol-FEL Research Pavillion
Suite 400
12424 Research Parkway
Orlando, FL 32826

Dr. C. James Elliott
X1-Division, M.S. 531
Los Alamos Natl. Scientific Lab.
P. O. Box 1663
Los Alamos, NM 87545

Dr. Anne-Marie Fauchet
Brookhaven National Laboratories
Associated Universities, Inc.
Upton, L.I., NY 11973

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

Dr. J. Gallardo
Brookhaven National Laboratory
Associated Universities, Inc.
Upton, L.I., NY 11973

Dr. B. B. Godfrey,
Chief Scientist
WL/CA
Kirtland AFB, NM 87117-6008

Dr. John C. Goldstein, X-1
Los Alamos Natl. Scientific Lab.
P.O. Box 1663
Los Alamos, NM 87545

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

Dr. K. Halbach
Lawrence Berkeley Laboratory
University of California, Berkeley
Berkeley, CA 94720

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. B. Hui
Defense Advanced Research Projects Agency
1400 Wilson Blvd.
Arlington, VA 22209

Prof. V. Jaccarino
Univ. of Calif. at Santa Barbara
Santa Barbara, CA 93106

Dr. B. Carol Johnson
Ctr. for Radiation Research
National Inst. of Standards and Tech.
Gaithersburg, MD 20899

Dr. Ron Johnson
Ctr. for Radiatiuon Research
Natl. Inst. of Standards and Tech.
Gaithersburg, MD 20899

Dr. Shayne Johnston
Physics Department
Jackson State University
Jackson, MS 39217

Dr. R. A. Jong
Lawrence Livermore National Laboratory
P. O. Box 808/L626
Livermore, CA 94550

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

Dr. C. Joshi
University of California
Los Angeles, CA 90024

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

Dr. Brian Kincaid
Lawrence Berkeley Laboratory
University of California, Berkeley
Berkeley, CA 94720

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. J. LaSala
Physics Dept.
U. S. M. A.
West Point, NY 10996

Dr. Michael Lavan
U.S. Army Strategic Def. Command
ATTN: Code CSSD-H-D
P. O. Box 1500
Huntsville, AL 35807-3801

Dr. B. Levush
Dept. of Physics & Astronomy
University of Maryland
College Park, MD 20742

Dr. Anthony T. Lin
Dept. of Physics
University of California
Los Angeles, CA 90024

Dr. Chuan S. Liu
Dept. of Physics & Astronomy
University of Maryland
College Park, MD 20742

Dr. N. C. Luhmann, Jr.
UCLA
7702 Boelter Hall
Los Angeles, CA 90024

Dr. A. Luccio
Brookhaven National Laboratory
Accelerator Dept.
Upton, NY 11973

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

Dr. R. Mako
205 South Whiting Street
Alexandria, VA 22304

Dr. Joseph Mangano
Science Research Laboratory
1600 Wilson Blvd.
Suite 1200
Arlington, VA 22209

Dr. Siva A. Mani
Science Applications Intl. Corp.
1040 Waltham Street
Lexington, MA 02173-8027

Dr. T. C. Marshall
Applied Physics Department
Columbia University
New York, NY 10027

Dr. Xavier K. Maruyama
Dept. of Physics
Naval Postgraduate School
Monterey, CA 93943

Dr. B. McVey
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. David Merritt
Space & Naval Warfare Command
Attn: PMW 145A
Washington, DC 20363-5100

Dr. A. Mondelli
Science Applications Intl. Corp.
1710 Goodridge Drive
P.O. Box 1303
McLean, VA 22101

Dr. Mel Month
Brookhaven National Laboratories
Associated Universities, Inc.
Upton, L.I., NY 11973

Dr. Gerald T. Moore
University of New Mexico
Albuquerque, NM 87131

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

Prof. J. Nation
224 Phillips Hall
School of Elec. Eng.
Cornell University
Ithaca, NY 14850

Dr. George Neil
TRW
One Space Park
Redondo Beach, CA 90278

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

Dr. Brian Newnam
MSJ 564
Los Alamos National Scientific Lab.
P.O. Box 1663
Los Alamos, NM 87545

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

OUSDRE (R&AT)
Room 3D1067, The Pentagon
Washington, D.C. 20301

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

Dr. J. Palmer
Hughes Research Laboratory
Malibu, CA 90265

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

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

Dr. John A. Pasour
Mission Research Laboratory
8560 Cinderbed Road
Suite 700
Newington, VA 22122

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

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

Dr. S. Penner
Center for Radiation Research
Natl. Inst. of Standards and Tech.
Gaithersburg, MD 20899

Dr. M. Piestrup
Adelphi Technology
13800 Skyline Blvd. No. 2
Woodside, CA 94062

Dr. D. J. Pistoresi
Boeing Aerospace Company
P. O. Box 3999
Seattle, WA 98124-2499

Major E. W. Pogue
SDIO
The Pentagon, T-DE Rm. 1E180
Washington, DC 20301-7100

Major Donald Ponikvar
U. S. Army SDC
P. O. Box 15280
Arlington, VA 22245-0280

Dr. Donald Prosnitz
Lawrence Livermore National Lab.
Box 5511 L-626
Livermore, CA 94550

Dr. D. C. Quimby
Spectra Technology
2755 Northup Way
Bellevue, WA 98004

Dr. G. Ramian
Quantum Institute
University of California
Santa Barbara, CA 93106

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

Dr. S. Ride
Arms Control
Stanford University
Stanford, CA 94305

Dr. C. W. Roberson
Office of Naval Research
Code 112S
800 N. Quincy Street
Arlington, VA 22217

Dr. K. Robinson
Spectra Technology
2755 Northup Way
Bellevue, WA 98004

Dr. Marshall N. Rosenbluth
Dept. of Physics
B-019
Univ. of Calif., San Diego
LaJolla, CA 92093

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

Dr. A. Saxman
Los Alamos National Scientific Lab.
P. O. Box 1663, MSE523
Los Alamos, NM 87545

Dr. E. T. Scharlemann
L626
Lawrence Livermore National Lab
P. O. Box 808
Livermore, CA 94550

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. M. J. Schmitt
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

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. S. B. Segall
KMS Fusion
3941 Research Park Dr.
P.O. Box 1567
Ann Arbor, MI 48106

Prof. P. Serafim
Northeastern University
Boston, MA 02115

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. Earl D. Shaw
Bell Laboratories
600 Mountain Avenue
Murray Hill, NJ 07974

Dr. R. L. Sheffield
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

Dr. D. Shoffstall
Boeing Aerospace Company
P.O. Box 3999
Seattle, WA 98124

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

Dr. Todd Smith
Hansen Labs
Stanford University
Stanford, CA 94305

Dr. R. Sudan
Lab. of Plasma Studies
Cornell University
Ithaca, NY 14850

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

Dr. T. Tajima
Institute for Fusion Studies
University of Texas at Austin
Austin, TX 78712

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

Dr. L. Thode
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Norman H. Tolk
Physics Department
Vanderbilt University
Nashville, TN 37240

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

Dr. H. S. Uhm
Naval Surface Warfare Center
White Oak Lab.
Silver Spring, MD 20903-5000

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

Dr. John E. Walsh
Wilder Laboratory
Department of Physics (HB 6127)
Dartmouth College
Hanover NH 03755

Dr. Jiunn-Ming Wang
Brookhaven National Laboratories
Associated Universities, Inc.
Upton, L.I., NY 11973

Dr. Roger W. Warren
Los Alamos National Scientific Lab.
P.O. Box 1663
Los Alamos, NM 87545

Dr. J. Watson
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Mark Wilson
Natl. Inst. of Standards and Tech.
Bldg. 245, Rm. B-119
Gaithersburg, MD 20899

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

Dr. Ming Xie
Dept. of Physics
Stanford University
Stanford, CA 94305

Dr. Simon S. Yu
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Naval Research Laboratory
Washington, DC 20375-5000
Code 4830
Tim Calderwood

Do NOT make labels for
Records-----(01 cy)