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"Nova Performance at Ultra High Fluence Levels"

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NOVA PERFORMANCE AT ULTRA HIGH FLUENCE LEVELS*

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Abstract

Nova is a ten beam high power Nd: glass laser used for inertial confinement fusion research. It was operated in the high power high energy regime following the completion of construction in December 1984. During this period several interesting nonlinear optical phenomena were observed. These phenomena are discussed in the text.

Introduction

The Nova experimental facility consists of a ten arm laser system and five experimental stations and was completed in December 1984. Two of these stations are used for inertial confinement fusion (ICF) experiments and the other three are dedicated to doing large aperture (30 to 74 cm) laser experiments. The laser system is deployed in a master oscillator-power amplifier architecture (see Fig. 1) and uses Nd: phosphate glass for the active medium. The fundamental wavelength of the system is 1.05 microns. Frequency converters constructed from potassium dihydrogen phosphate (KDP) crystals are located at the end of each of the ten arms and are used to produce high power frequency doubled (0.53 microns) and tripled (0.35 microns) beams for either ICF or laser experiments. Thus, the Nova laser system can produce high power beams with wavelengths ranging from the infrared to the ultraviolet. The operating characteristics of the Nova target irradiation facility are summarized as:

Number of beams: 10
Energy: 50-100 kJ in 2.5 ns
Power: 100 TW in 100 ps
Wavelength: One micron, one-half micron, one-third micron
Pulse width: 100 ps to 100 ns
Number of experimental stations: five - two target chambers
three laser stations
Focusing: 100 micron spot with an f/4 optic (ten beam)
0 to 5 cm line foci (two beam)
Pulse shaping: Flexible
Cost: $186 million

Performance Summary

A Nova chain consists of five disk amplifier stages with apertures of 5, 10, 15, 20.8, 31.5 and 46 cm. Upon exiting the 46 cm amplifier stage the beam is expanded to 74 cm to reduce its fluence. This lower fluence reduces the damage threat to the optics used to transport the beam over the long air path (i.e., between 65 and 100 meters) from the end of the laser to the ICF target chamber. With the exception of the 46 cm amplifier stage, all stages consist of three basic components: a flashlamp pumped amplifier with Brewster angle disks, a Faraday rotator-polarizer combination, and a vacuum spatial filter. The 46 cm stage has no rotator-polarizer combination. The function of the rotator-polarizer combination is to isolate each stage from damage causing back reflections. The spatial filter is used to control beam breakup and to expand the beam to the proper size for amplification in the next stage.

In ten arm operation using a 2.5 ns pulse duration more than 100 kJ of one micron light were used to drive the frequency converters which produced 44 kJ of one-half micron light for target experiments. Inertial confinement fusion targets have also been irradiated with one-third micron energies in excess of 20 kJ by using a converter drive of 50 kJ and a 1 ns pulse. In tests using one arm, Nova has produced 15 kJ of one micron light and more than 7 kJ of one-half and one-third micron light using a flat 2.5 ns pulse to drive the frequency converter. In other single arm tests, one micron beam powers approaching 10 TW were reached with a 1 ns pulse. One infers from these single arm tests that the Nova laser system will produce 100 TW of one micron light in a 1 ns pulse. At longer pulse lengths ($\tau > 2.5$ ns) 50-100 kJ of one-third and one-half micron light can be produced. However, operating the laser system at these large optical powers and energies will require exposing many of the optical elements to both high power and high energy densities. For instance, during these single arm tests several of the optical components were exposed to average fluences exceeding 10 J/cm^2 and power densities in excess of 6 GW/cm^2. During these same high power tests, several nonlinear optical processes were encountered which if left unchecked will ultimately limit the performance of the system.

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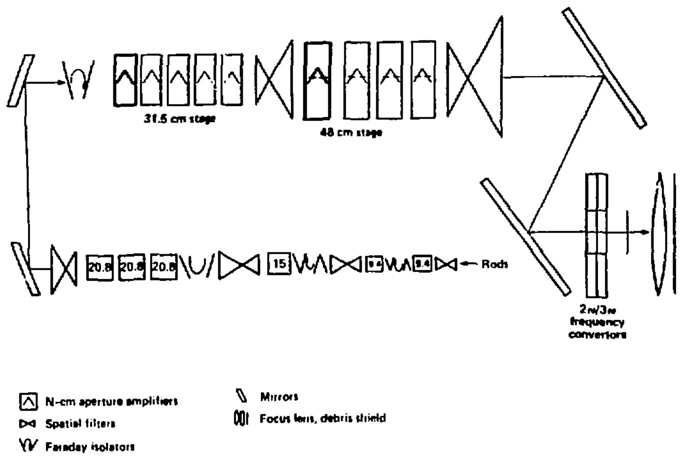

Figure 1. Optical staging of a NOVA beamline.

Nonlinear Optical Processes

At ultra high power densities (and fluences) several nonlinear optical processes are capable of limiting system performance. The processes encountered during Nova testing were

1. An intensity dependent rotation of the beam's electric field,[1,2]
2. Low spatial frequency "beam breakup",[2]
3. Temporal pulse distortion via gain saturation,[3]
4. Stimulated (rotational) Raman scattering,[4] and
5. Beam-induced damage to the optical components of the system.[5]

Although these nonlinear optical phenomena have been known for a long time, "engineering around" all of them simultaneously was and continues to be a challenge on a system the size of Nova.

The study of the interplay between these interesting but undesirable nonlinear effects and the desired nonlinear frequency conversion process[6] has been fascinating. Frequency conversion experiments conducted with a Nova beamline showed that the first three phenomena on this list conspired to produce anomalous frequency conversion results (see Fig. 2). These three phenomena will be the object of our attention in the remainder of this paper. Early testing showed that

- The peak efficiency was less than expected,
- The peak efficiency occurred at much lower intensities than expected, and
- The efficiency "rolls over" at low intensity, i.e., after reaching a maximum, the efficiency decreases with increasing drive.

The Type II frequency tripling conversion scheme employed on Nova was originated by Craxton et al.[7] at Rochester, and although it is relatively insensitive to the intensity and phase fluctuations of the drive beam, it is extremely sensitive to the beam's polarization field.[8] Thus, one would guess that the nonlinear optical process that contributes most to the anomalous frequency conversion behavior is Item #1 (above) with the second and third items contributing in a less direct way. The last two items on the list are treated elsewhere and will not be discussed further here.

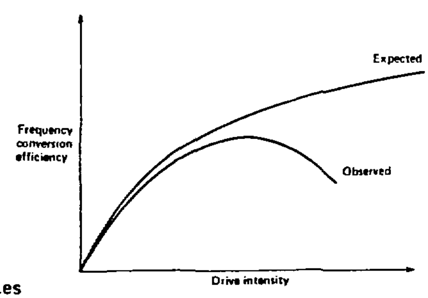

Figure 2. Comparison of expected and observed frequency conversion of a NOVA beamline.

Our experiments showed conclusively that the major source of the anomalous frequency conversion behavior is the nonuniform and the intensity-dependent rotation of the polarization of the drive beam. In particular, high conversion efficiencies can be attained only if the amplitudes of the projection of the drive beams electric field vector onto the axis of the converter crystal is in exactly the correct ratio. To understand why this is so, assume perfect phase matching. Then the equations that govern the frequency doubling process are:

$$\frac{dE^e_\omega}{dz} \sim - E^o_\omega E^e_{2\omega} \tag{1}$$

$$\frac{dE^o_\omega}{dz} \sim - E^o_\omega E^e_{2\omega} \tag{2}$$

$$\frac{dE^e_{2\omega}}{dz} \sim + E^o_\omega E^e_\omega \tag{3}$$

where E^e_ω and E^o_ω are respectively the projections of the drive beam's electric field onto the extraordinary and ordinary axis of the crystals. For optimum doubling, $E^o_\omega = E^e_\omega$, i.e., a mix ratio of 1. Therefore, proper orientation of the electric field is 45° to the "o" axis. Similarly, optimum tripling is achieved with a mix ratio of 2. Therefore, the 1ω incident field should be linearly polarized at an angle

$$\theta_o = \tan^{-1} \sqrt{1/2} = 35.2° \tag{4}$$

The doubling polarization condition means physically that it takes a $1\omega^e$ photon and a $1\omega^o$ photon to create a $2\omega^e$ photon. Similarly, for tripling, the condition states that it takes two $1\omega^o$ photons and a $1\omega^e$ photon to ultimately generate a $3\omega^e$ photon.

Returning to the three basic equations, we observe that if both components of the drive field go to zero simultaneously, the derivative of all three fields is zero. Thus, at this point, all of the energy is in the second harmonic wave and remains there; i.e., this is a stable solution to the equations. However, if the value of either the "o" or "e" component of the fundamental beam goes to zero (prematurely) and the other does not, then for 2ω

$$\frac{dE_{2\omega}}{dz} = 0 \tag{5}$$

$$\frac{d^2E_{2\omega}}{dz^2} \neq 0 \tag{6}$$

Thus, at this z position in the crystal, the electric field of the second harmonic wave has reached its maximum prematurely. Past this point, the amplitude of the second harmonic wave decreases, i.e., a back conversion process starts.

Careful examination of the equations leads one to the conclusion that if one of the drive fields goes to zero prematurely, then the initial values of the fields were not optimum. Thus, the source of the back conversion process (for perfect phase matching) is an incorrect initial value of the $1\omega^o$ and $1\omega^e$ fields.

Hence, the preceding discussion shows that the anomalous frequency conversion behavior can be explained solely on the basis of polarization mismatch. Furthermore, it is easily shown that a small fraction of energy in the wrong polarization can poison the Type II frequency conversion process. For instance, if the polarization field is oriented 10° from the optimum orientation for doubling, i.e., approximately 4% of the drive beam's energy is in the S (wrong) polarization field, the mix ratio will be 2:1 instead of the optimum 1:1. Hence, only two out of three photons in the incident beam are available for the conversion process. This means that the maximum achievable doubling efficiency is 67% and will be achieved at some finite intensity I_0. For beam intensities larger than I_0, the back conversion process starts and the conversion efficiency decreases with increasing drive.

The situation on Nova is more complicated than one would surmise from the discussion so far. Since the beam was linearly polarized in our example, the proper mix ratio could be achieved by merely rotating the crystal. This "fix" will not work on Nova because Nova's beam is not uniformly polarized, nor is the polarization linear. At most points in the aperture the beam is elliptically polarized. Experiments have shown that the source of the elliptical stress polarization field is stress induced birefringence in the amplifier disks and the lenses of the vacuum spatial filters. Furthermore, the orientation and eccentricity of the ellipse are position dependent. Thus, rotating the crystal would improve the conversion efficiency of part of the beam, while making other portions of the beam convert with a lower efficiency. Furthermore, Item #1 on the nonlinear optical processes list implies the orientation of the ellipse is power dependent. The power dependence is a result of the intensity dependent index of refraction. To see how the rotation comes about we write the electric field as the sum of left and right handed circularly polarized beam.

$$\underset{\sim}{E} = \underset{\sim}{E}_{+} + \underset{\sim}{E}_{-} \tag{7}$$

where

$$E_{\pm} = A_{\pm} \exp(ik_{\pm}z) \tag{8}$$

and $A_{\pm}$ denotes the amplitude of the right/left component of circular polarization. If we denote

$$\theta_{\pm} = 1/2(k_{+} \pm k_{-})z \tag{9}$$

then the electric field can be written as

$$\underset{\sim}{E} = e^{i\theta_{+}} \left[\left\{ A_{+}e^{i\theta_{-}} + A_{-}e^{-i\theta_{-}} \right\}_{x} + i \left\{ A_{+} e^{i\theta_{-}} - A_{-} e^{-i\theta_{-}} \right\}_{y} \right] \tag{10}$$

Rearranging terms, we obtain

$$e^{i\theta_{+}} \underset{\sim}{E} = \left[(A_{+} + A_{-})\cos\theta_{-} + i(A_{+} - A_{-})\sin\theta_{-} \right]_{x}$$

$$+ \left[- (A_{+} + A_{-})\sin\theta_{-} + i(A_{+} - A_{-})\cos\theta \right]_{y} \tag{11}$$

or

$$E = \begin{bmatrix} \cos\theta_{-} & \sin\theta_{-} \\ -\sin\theta_{-} & \cos\theta_{-} \end{bmatrix} \begin{bmatrix} E_{x} \\ E_{y} \end{bmatrix} \tag{12}$$

Thus, the polarization vector has rotated through the angle θ_{-}.

Denoting the intensity dependent portion of the index of refraction by n_2

$$k_{+}Z = \frac{2\pi}{\lambda} \frac{n_2}{n_0} \int A_{+}^{2}\, dz \tag{13}$$

$$k_{-}Z = \frac{2\pi}{\lambda} \frac{n_2}{n_0} \int A_{-}^{2}\, dz \tag{14}$$

Thus

$$\theta_{-} \sim B_{+} - B_{-} \tag{15}$$

where

$$B_{\pm} = k_{\pm}\, z \tag{16}$$

After some manipulation one can show that[9]

$$\theta = 1/3\ Bc \tag{17}$$

where

$$\epsilon = (A_+ - A_-)/(A_+ + A_-) \quad \text{(eccentricity of the ellipse)} \tag{18}$$

and B is the nonlinear phase retardation in radians accumulated by the beam in traversing the optical components of the system.

$$B = \int \frac{n_2}{n_0} \, I dz \tag{19}$$

Experiments conducted with Nova showed that the eccentricity of the polarization ellipse (for a small portion of the beam) was ~0.2 and that the ellipse rotates roughly 10° for a drive of 2 GW/cm^2. Earlier it was pointed out that this amount of field rotation can significantly alter the shape of the frequency conversion efficiency curves.

Further experimentation confirmed that the beam's depolarization is the source of the anomalously low frequency efficiency. Figure 3 compares the tripling efficiency obtained using a portion of one of Nova's beams with and without a polarizer. Note the marked improvement in efficiency obtained by repolarizing the beam.

The anomalous frequency conversion behavior of the Nova beams can be corrected in several ways. For instance, the beams can be repolarized by placing a 74 cm aperture polarizer between the system's final spatial filters and the frequency converters. Preliminary tests have shown that this scheme will produce tripling efficiencies approaching 70% (see Fig. 3). Since only a few per cent of the drive beam's energy is in the wrong polarization, the addition of the polarizer reduces the one micron drive to the frequency converters by only an insignificant amount. A second method for increasing the conversion efficiency is to use a Type I - Type II tripling arrangement.[10] This tripling scheme is less sensitive to polarization and although the energy in the wrong polarization is lost to the conversion process, it does not poison it. The decision as to which scheme will be deployed on Nova will be made in the next few months.

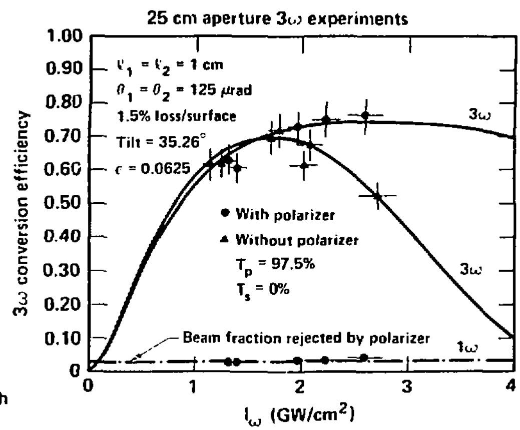

Figure 3. Frequency tripling efficiency using a 25 cm portion of a NOVA beam.

Item #2 on the nonlinear optical processes list is low frequency beam breakup. Beam breakup is the growth of beam modulation in the form of small amplitude ripples on a high intensity background beam. The source of this growth is again the intensity dependent index of refraction, n_2, of the optical components. However, ripples of different spatial frequencies grow at different rates. The fastest growing spatial frequency and its gain are governed by the parameter B.[11] Analysis shows that the first peak in the gain spectrum has a value

$$G_{MAX} = e^{2B} \tag{20}$$

and occurs at

$$\theta_{MAX} = \frac{B}{N} \tag{21}$$

where

N is the number of disks

B is the B integral accumulated by the beam while traversing the N disks of the amplification stage

and

θ is the familiar Fresnel diffraction parameter

$$\theta = \frac{K^2 L_V}{2k} \tag{22}$$

where

K is the wave number of the perturbation

and

L_V is the interdisk spacing

with

$$L_V = n_0 D \tag{23}$$

and

n_0 is the index of refraction of the laser disk

and

D is the dimension of the disk aperture.

Thus, the beam's modulation can increase significantly if the beam breakup is not carefully controlled. Large amplitude modulation not only increases the rotation of the polarization field discussed earlier but also imposes a severe damage threat to the optical components of the system.

An example of large gain over a narrow band of θ's is shown in Fig. 4. In this example a ten disk amplifier stage with a gain of one and a B of two was used. Substituting Eqns. (22) and (23) into (21) and solving for Fig. 4 the wavenumber K_{MAX} one finds that

$$K_{MAX} = \left(\frac{2kB}{N\, n_0\, D}\right)^{1/2} \tag{24}$$

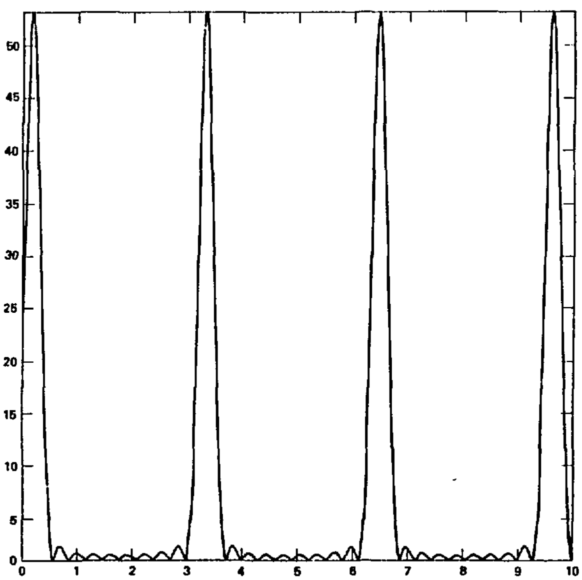

Figure 4. Beam breakup power gain, G_0 as a function of the (Fresnel) parameter $\theta = \frac{K^2 L_v}{2k}$.

The important point to note in Eqn. (24) is the inverse scaling of the wave number with the number of disks and the aperture dimension. Because of this scaling, this mode could ultimately limit the performance of a large aperture system when it is operated in the high energy high power regime. A low pass filter will not be effective in controlling its growth because its frequency is so low. Although this type of beam breakup was not seen on Nova when a beam was operated at 8 TW in a nanosecond, the beginning of beam breakup was observed on 10 TW shots.

Item #3 on the Nonlinear Optical Processes list is temporal pulse distortion. Significant extraction of energy from a high gain amplifier always produces changes in pulse shape. A square output pulse requires a monotonically increasing pulse in all amplifier stages. It is convenient to define the square pulse distortion (SPD) of the system as the ratio of the maximum to the minimum intensity of the pulse in the system when the input is set to give a flat or square shaped output pulse.

The SPD for a Nova chain has been calculated as a function of output energy and is shown in Fig. 5. This curve is also the pulse shape that must be injected into a chain to produce a square output pulse. The contrast ratio between the leading and trailing edge of the pulse means that late parts of the pulse accumulate a larger B integral than earlier ones. It also means that for a fixed output power, beam breakup and intensity dependent polarization rotation will get worse for longer pulse lengths. Finally, because the slope of the SPD is getting very large for beam energies exceeding 18 kJ it will be impractical to operate the Nova system much above this level while at the same time producing a well controlled temporal pulse.

Summary

Several nonlinear optical processes can be observed when the Nova system is operated in the high energy high power regime. However, we are confident that energies in the 50 to 100 kJ range will be available for target experiments in the near future. In the meantime, the system will be operated at one-half power. This power level is sufficient to conduct most planned ICF experiments.

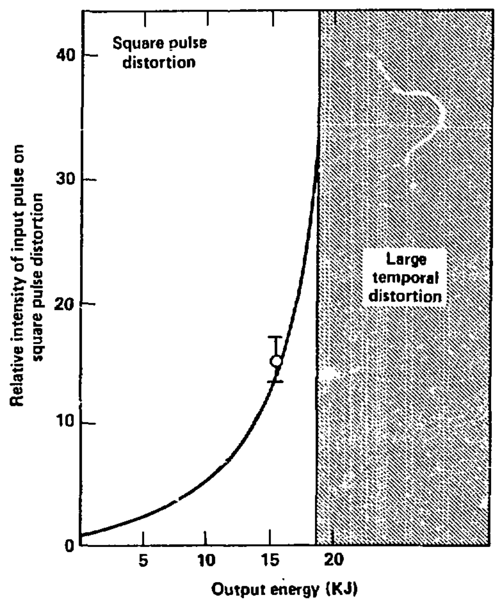

Figure 5. Square pulse distortion of a NOVA beam as a function of output energy.

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References

1. P.D. Maker, R.W. Terhune, and C.M. Savage, Scientific Laboratory, Ford Motor Company, Dearborn, Michigan, Phys. Rev. Lett., Vol. 12, No. 18, 507 (May 4, 1964); and A. Owyoung, R.W. Hellwarth, and N. George, California Institute of Technology, Pasadena, California, Phys. Rev. B, Vol. 5, No. 2, 628 (January 15, 1972).

2. V.I. Bespalov and V.I. Talanov, JETP Lett., Vol. 3, 307-310 (June 1966); and J.B. Trenholme, Lawrence Livermore National Laboratory, 1975 Laser Annual Report, p. 237-241.

3. L.M. Frantz and J.S. Nodvik, J. Appl. Phys. 34, 2346 (1963); and J.B. Trenholme and K.R. Manes, Lawrence Livermore National Laboratory, UCRL-51413 (November 1972).

4. V.S. Auerbach, A.I. Makarov, and V.I. Talanov, Sov. J. Quantum Electronics, 8, 472 (1978); and M.A. Henesian, C.D. Swift, and J.R. Murray, Lawrence Livermore National Laboratory, Optics Letters, 10, 565 (November 1985).

5. R.W. Hopper and D.R. Uhlmann, J. Appl. Phys., Vol. 41, No. 10, 4023-4037 (September 1970); M. Sparks and C.J. Duther, J. Appl. Phys., Vol. 44, 930-934 (1974); and W.L. Smith, Opt. Eng., Vol. 7, 489-503 (1978).

6. P.A. Franken et al., Phys. Rev. Lett., 7, 118 (1961); J.A. Giordmaine, Phys. Rev. Lett. 8, 19 (1962); and P.D. Maker, R.W. Terhune, M. Nisenoff, and C.M. Savage, Phys. Rev. Lett., 8, 21 (1962).

7. R.S. Craxton, Optics Communications, Vol. 34, No. 3 (September 1980).

8. S.B. Arifzhanov, A.A. Gulamov, V.I. Redkorechev, and T.U. Smanov, Sov. J. Quantum Electronics, 7, 15 (July 1985); and M.A. Henesian et al., to be published.

9. J.B. Trenholme (private communication).

10. M.A. Henesian (private communication); and G.J. Linford, W. Seka et al., Applied Optics, Vol. 22, 13 (July 1983).

11. See Reference 2.