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Development of Large Scale Production of Nd-doped Phosphate Glasses for Megajoule-Scale Laser Systems

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Development of large scale production of Nd-doped phosphate glasses for Megajoule-scale laser systems

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ABSTRACT

Nd-doped phosphate glasses are the preferred gain medium for high-peak-power lasers used for Inertial Confinement Fusion research because they have excellent energy storage and extraction characteristics. In addition, these glasses can be manufactured defect-free in large sizes and at relatively low cost. To meet the requirements of the future mega-joule size lasers, advanced laser glass manufacturing methods are being developed that would enable laser glass to be continuously produced at the rate of several thousand large (790 x 440 x 44 mm^3) plates of glass per year. This represents more than a 10 to 100-fold improvement in the scale of the present manufacturing technology.

1. INTRODUCTION

The US Department of Energy (DOE) and the French Commissariat à l'Energie Atomique (CEA) each plan to build a megajoule scale laser irradiation facility to support fusion energy research.[1,2] These systems, called the National Ignition Facility (NIF) and the Laser Megajoules (LMJ), respectively, each consist of several hundred individual laser beamlines whose output energies are focused onto millimeter sized capsules containing DT fuel.

The NIF and LMJ lasers will use neodymium-doped phosphate glass as a gain medium. The laser glass absorbs energy emitted by the electrical discharge of an array of flashlamps and stores it by the corresponding excitation of a dopant ion (in this case neodymium). During the pumping process the Nd ions form a population inversion between a relatively long-lived metastable excited state and lower lying ground states. When a subsequent laser pulse propagates through the amplifier glass, it extracts the stored energy by stimulating the transition of these excited ions to one of the lower energy states. The photons emitted in this process match the wavelength and phase of the propagating pulse thereby producing a gain in the laser pulse energy.

The laser glass for NIF and LMJ will be formed into large rectangular plates (or "slabs" as they are often called in the laser literature), each about 790 x 440 x 44 mm^3. A total of about 9000 laser glass plates will be needed for the two laser systems: this represents a volume of 130 m^3 (340 tonne) of high optical quality glass. The glass plates are the largest ever produced and the specifications are very stringent especially homogeneity, bubbles, damaging inclusions, and optical absorption (due to impurities). These stringent specifications can dramatically affect the glass production yield and consequently the cost of the laser glass.

In this paper we first briefly describe the design of the LMJ and NIF multi-pass laser systems and the key operating characteristics. Following this we summarize the properties and specifications of the two laser glasses that have been chosen for use on the NIF and LMJ and we briefly discuss how these specifications affect the laser performance. We will also highlight advances that have been made over the years in the scale and quality of laser glass production and compare that with the advanced melting methods that are being developed to produce the glass for the NIF and LMJ. Although details of the production processes are proprietary, we will present highlights showing the change from a one-at-a-time discontinuous production process in the past to a continuous process in the future. Finally, we will briefly discuss the laser glass production schedule and how that integrates into the construction plans for the NIF and LMJ.

2. BRIEF DESCRIPTION OF LMJ AND NIF LASERS

The designs of the NIF and LMJ lasers are described in detail elsewhere. [3,4] Here we only briefly discuss the laser design characteristics and operating parameters that influence the laser glass requirements.

Both the LMJ and NIF are flashlamp-pumped Nd-glass laser systems that utilize a multi-pass laser design which represents a departure from the design of the current ICF laser systems. All current laser systems use the output pulse from a master oscillator to drive a series of successively larger single-pass laser amplifiers; this design is the so-called MOPA [5] (for "master oscillator, power amplifier"). Compared to the multi-pass laser design, the MOPA has a number of disadvantages; in particular it is much larger and therefore more costly. The NIF and LMJ multi-pass design is about twenty-times more compact than the MOPA.

The multi-pass design uses a temporally and spatially shaped output pulse from a preamplifier section to inject into a large aperture laser cavity (about 40x40 cm^2). Two high reflectivity mirrors define the ends of the laser cavity which contains a series of power amplifiers and an optical switching device (Fig. 1). The injected pulse multi-passes back-and-forth through the laser cavity and is amplified on each successive pass through the amplifiers; the small signal gain on a single pass through n slabs is about 1.27^n.[3,6] Both NIF and LMJ use four passes through the main cavity to achieve a total energy in excess of 10^4. The optical switching device consists of a pockels cell and polarizer 7 that is used to switch the pulse in and out of the cavity. The major difference in the two designs is that the NIF uses a single, full-aperture pockels cell and polarizer that directly reflects the beam out of the cavity on the final pass. The LMJ on the other hand does not use an active switch to control the polarization of the beam during the multi-pass operation. Instead a series of small aperture mirrors is used to confine the beam to the cavity for the second and third pass; on the fourth pass the beam propagates through the cavity at a slightly differ angle and thereby avoids the small cavity end mirrors and exits the amplifier cavity.[8] Once the beam is switched out of the main laser amplifier cavity, it propagates to the target chamber where it is frequency converted to the third harmonic (351nm) and finally focused onto the target. In the case of the NIF the beam also passes through a "booster" amplifier as it propagates to the target chamber; the booster increases the output energy by about a factor of two. The LMJ doesn't use a booster amplifier but has more slabs in the main laser amplifier cavity.

Both the NIF and LMJ use a compact laser amplifier design called the "multi-segment amplifier" (MSA).[9,10] These amplifiers consist of a stacked-array of laser glass plates inside a flashlamp pumped cavity (Fig 2). By using square apertures (i.e. square beams) it is possible to tightly pack the individual laser glass amplifiers into a compact matrix and therefore greatly reduce the size and cost of the system. This design requires that the laser glass be manufactured in large rectangular plates. Note that although the laser aperture is square the laser plates are rectangular because they must be mounted at an angle (Brewster's angle) to the propagation direction of the beam. Mounting the glass at Brewster's angle minimizes the Fresnel reflection losses at the surfaces of the glass plates. In addition mounting at an angle increases the coupling efficiency of the flashlamp pumping process by increasing the area exposure to the lamps. Erlandson et al [10,11] have recently described in detail the design and operating characteristics of flashlamp pumped multi-segment amplifiers. The measured small signal gain coefficient is typically about 0.05/cm and the stored energy density about 0.25J/ cm^3 for phosphate laser glass doped at about 3.5 x $10^{20}/cm^3$ and pumped at a lamp explosion fraction of 0.20.

The LMJ and NIF both have a total of 18 power amplifiers for each beamline . The two systems however differ in their distribution of amplifiers between the cavity and booster locations; the LMJ uses an even distribution of 9 and 9 slabs in the cavity separated by a spatial filter whereas the NIF uses 11 slabs in the cavity and 7 slabs in the booster.[12] Because all the laser amplifiers are located in the cavity, the LMJ also uses a full aperture pockels cell and a polarizer to suppress parasitic oscillations.

The operating fluence and irradiance of the NIF and LMJ are higher than any current ICF laser system and approach peak fluences in the laser glass of up to 18 to $20J/cm^2$ and a peak irradiance of about 5.0 GW/cm^2 (3.6 ns effective pulse width). To avoid any optical damage the laser glass must be free of defects, specifically any microscopic inclusions of refractory materials (either metallic or ceramic) left from the melting process. [13]

A prototype laser closely resembling one of the NIF and LMJ beamlines has recently been built and tested [6]. This laser, called "Beamlet", uses 11 amplifiers in the main cavity and 5 in the booster section. A series of twenty large phosphate glass plates (767x428x44 mm^3) having a doping of 3.5 x $10^{20}/cm^3$ were produced for this laser [14] (Fig 3). Although slightly smaller than required for LMJ and NIF, these prototype glass plates were made to nearly identical specifications as required for the NIF and LMJ. Therefore, to a great extent, the quality and size of the laser glass pieces needed for NIF and LMJ have been demonstrated. However, what remains now is to develop the manufacturing capability for producing a large number of these glass plates at a high rate, at the same high quality and at a significantly lower cost. The remainder of this manuscript describes the properties of the laser glasses we will use and our joint efforts at the laser glass manufacturers to develop low cost glass production methods.

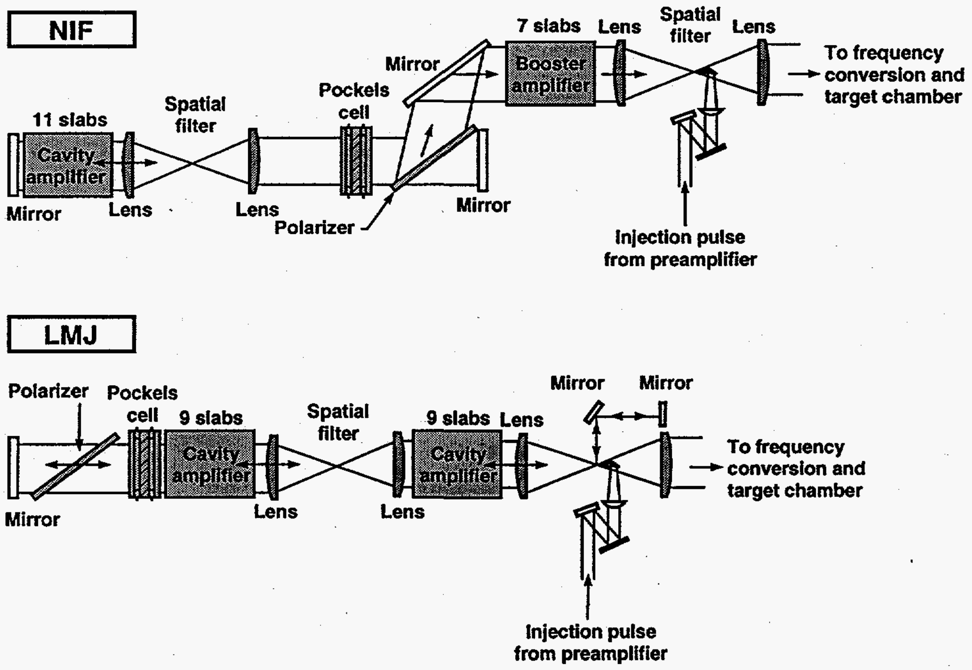

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Figure 1. Highly schematic diagram of the NIF and LMJ multi-pass laser architecture and the basic operating scenario. The laser glass plates, that are discussed in this manuscript, are located in the cavity and booster amplifier sections.

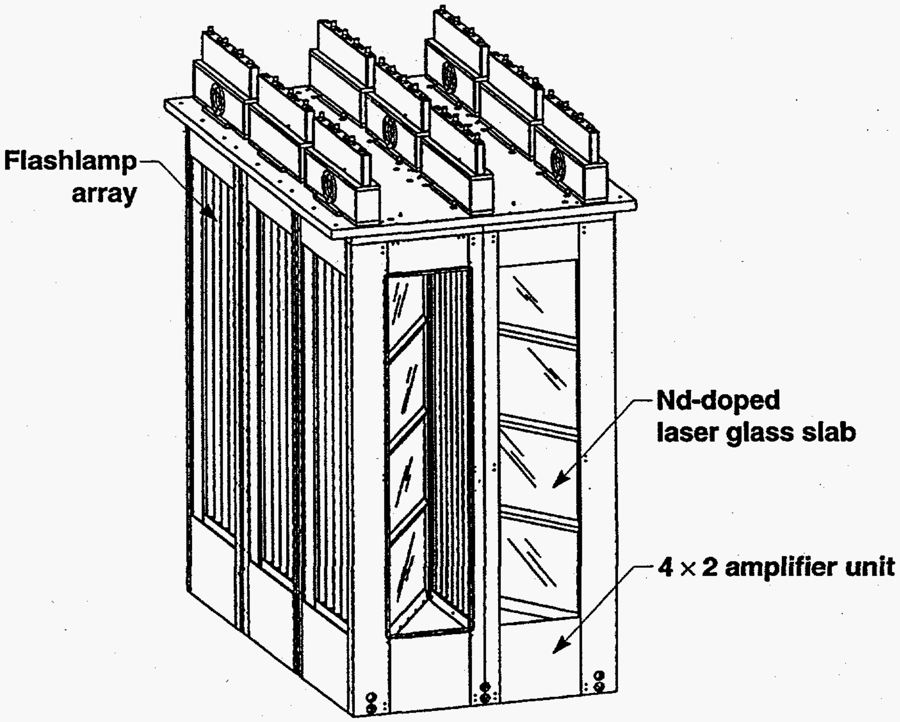

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Figure 2. Drawing of a multi-segment-amplifier (MSA). The MSA consists of a tightly packed array of 4x2 square apertures that contains a corresponding number of rectangular laser slabs mounted at Brewster's angle. The drawing shows three MSA units stacked end-to-end.

3. LASER GLASS REQUIREMENTS, SPECIFICATIONS AND PROPERTIES

3.1. Quantity and size of laser glass required

The NIF and LMJ lasers require a very large number of high quality, high damage threshold optical components. To meet the needs of both lasers, a total of about 9000 laser glass plates need to be produced (Table 1) at the rate of about 1000 to 1500 per year. This is a technological challenge both because of the total volume of high optical quality glass that is needed as well as the large dimensions of the individual glass plates. The dimensions of the slabs are about 440x790x44 mm^3 (i.e. 15.3 liters). (Note: all glass dimensions used in this article refer to the prefinished glass size that is then supplied to the final finishing vendors). Also the technical specifications of the laser glass (as discussed in a later section) are equivalent to or exceed those of any laser glass that has previously been produced. Every effort is being made to keep the dimensions and specifications of the slabs identical for the NIF and the LMJ to minimize the overall production costs. Our cost goal is to manufacture the laser glass for about $1000/liter ($350/kg); this is roughly a factor of three lower than the cost with the current small scale production methods. Given the size of the laser glass order, this level of cost reduction represents a cost savings of about $200 to 300 million over the price that could be achieved with current manufacturing methods.

Table 1: Quantity of laser glass required for the LMJ and NIF projects.

	NIF	LMJ
Number of Beamlets	192	240
Number of slabs / beamlet	18	18
Spares	10%	10%
Total number of slabs	3802	4752
Dimensions (mm^3)	790x440x44	790x440x44
Volume per slab (litre)	15.3	15.3
Total volume (m^3)	58	73
Mass (tonne)	151	190

3.2 Laser glass specifications:

To meet the performance criteria for the NIF and LMJ, the laser glass must meet a number of key requirements . Perhaps the four most important requirements are:

- high net gain,
- efficient energy storage at a high energy density,
- efficient extraction of the stored energy and
- high optical quality to allow the light to propagation with little or no wavefront aberration.

Unfortunately, some of these required characteristics of the laser glass are strongly interrelated. For example, to achieve a high gain and efficient energy extraction it is desirable to have a high Nd emission cross-section. However to achieve high stored-energy densities generally lower cross sections are desired. The interplay of the various laser glass properties is quite complex and beyond the scope of this paper; therefore we refer the reader to other sources for more a more detailed discussion of these issues.[15-19] In this paper we will confine our discussion to the specifications for the NIF and LMJ glass and describe how the different processing steps or glass characteristics affect these specifications. For reference, Table 2 provides a summary of the key specifications.

To achieve a high net gain the laser glass must first have a high gain coefficient. This gain coefficient is a property of the glass and is not generally affected by the processing conditions. However the net gain is a function not only of the gain coefficient but also the losses in the glass which are generally strongly process dependent. The net gain is described by the simple equation:

$$G = \exp{(Z \bullet [g-\alpha])} \qquad (1)$$

where G is the small signal gain, z the laser glass path length (cm), g the gain coefficient (cm^{-1}) and α the transmission loss coefficient (cm^{-1}). The major transmission losses in laser glass come from impurities that absorb at 1054 nm. These impurities may originate from the glass raw materials, the melter refractory or both. We have specified an unpumped absorption loss of less than 0.0019 cm^{-1} at 1054 nm and have found (based on the Beamlet slabs) that the glass is generally less than 0.0010 cm^{-1} .[14] Note that a major fraction of the loss for the unpumped glass is due to ground state absorption by the Nd. During flashlamp pumping this absorption loss becomes negligible because essentially all the Nd is in the excited state. The average gain coefficient across the laser slab is measured to be about 0.05 cm^{-1} when pumped at a flashlamp power equivalent to 20% of the explosion limit of the lamp (this is typically stated as a lamp explosion fraction of 0.20). Therefore, the gain-to-loss is typically at least greater than 25:1 and generally greater than 50:1. To achieve these low loss levels requires the use of very high purity raw materials as well as high purity, low corrosion rate melter wall materials. In addition, extensive quality assurance procedures must be in place to insure the purity of these materials. We have also carried out careful measurements to determine the loss coefficients for the most prevalent and highly absorbing impurities.[20,21]

A second potential loss source is due to birefringence in the glass due to residual stresses. The birefringence induces some small depolarization in the highly polarized beam. This depolarized light is reflected out of the beam by the Brewster angle slabs and the cavity polarizer. In addition small levels of depolarization can degrade the performance of the frequency conversion crystals. The specified birefringence is less than 5 nm/cm with a goal of less than 0.5 nm/cm; to meet this specification requires that the laser glass be slowly and carefully annealed. Considering the large number of slabs to be produced it will be impractical to use the standard annealing methods for the NIF and LMJ glass. Therefore, improve annealing methods are being developed that are designed to reduce the cost and time of final annealing to the specified birefringence level.

Another potential source of transmission loss is due to solarization. Solarization refers to the absorption loss due to the generation of color centers by the UV irradiation from the flashlamp pump light. We use Ce-doped fused silica flashlamp envelopes to reduce the UV component reaching the laser glass. Our specification is that the laser glass must not show increased absorption loss due to solarization when pumped indefinitely by the flashlamps.

The second key characteristic of the laser glass is its energy storage efficiency. Optimum energy storage efficiency is achieved by using the proper Nd doping level plus maximizing the Nd fluorescence lifetime. As a general rule, higher doping levels lead to more efficient capture of the flashlamp irradiation and longer fluorescence lifetimes give higher stored energy densities. When evaluating these two laser glass characteristics it is important to realize that one (the doping level) is largely process independent whereas the other (fluorescence lifetime) is strongly dependent on the melting process. The Nd-doping level is specified based on a combination of computer modeling and laboratory tests of amplifier performance. The doping level is not directly affected by the laser glass melting process with the possible exception of changes caused by evaporative losses during melting. However this latter effect can be easily compensated for by adjusting the batch composition of the laser glass. In contrast, the fluorescence lifetime is strongly affected by the glass processing conditions and thus it is tightly specified. Although the laser glass has an intrinsic lifetime that depends on the glass composition and structure, the lifetime is also strongly affected by impurities that may enter the glass during processing. In particular transition metal ions and -OH groups can cause significant non-radiative relaxation. Contamination by transition metal ions has generally not been a problem because of the high purity raw materials that are required to meet the transmission specification. Water (i.e.-OH) contamination on the other hand can be a large problem because of the hydroscopic nature of meta-phosphate laser glasses. To achieve the maximum fluorescent lifetime we specify that the hydroxyl content be no more than about 60 ppm. This is expressed as an absorption of less than 2.0 cm^{-1} at 3000 cm^{-1} (3000cm^{-1} corresponds to a strong -OH stretching band). To illustrate the effect of small concentrations of -OH on laser performance, we note that hydroxyl concentrations as low as 60 ppm can produce a 15μs decrease in the fluorescence lifetime corresponding to a 1% drop in laser performance. Given the cost of the LMJ and NIF laser facilities, even a few percent drop in performance translates to a significant cost penalty.

One other contaminant that enters the glass during melting and can effect the energy storage efficiency is ionic platinum. Platinum lined vessels are often used for melting the optical glass because of the excellent corrosion resistance of this refractory metal (compared to ceramic refractories).[13] The majority of the Pt that enters the melt is in the form of ionic platinum (presumably Pt^{4+}) although some small amount of metallic Pt also occur (this is discussed in more detail below). Ionic Pt absorbs in the near UV although the tail of the absorption band extends into the visible giving noticeable absorption near 400 nm. This absorption blocks some of the flashlamp irradiation and reduces the pumping efficiently. We specify that the 400 nm absorption due to Pt^{4+} not exceed 0.25 cm^{-1}; this corresponds to a Pt concentration of less than about 150 ppm.[13]

The third critical characteristic of the laser glass is the energy extraction efficiency. Energy extraction from the glass is most efficient at high laser fluences, particularly fluences in excess of twice the saturation fluence (F_S):

$$F_S = h\nu/\sigma, \qquad (2)$$

where h is Planck's constant (J•s), ν the laser frequency (Hz), and σ the emission cross-section (cm^2). The emission cross-section is a function of the glass structure. Having a glass with a high emission cross-section is desirable because efficient extraction can be achieved at lower fluence reducing the chance of laser induced damage to the optic. The important point however is that extraction efficiency depends largely on the intrinsic glass properties and the laser design and not on glass processing conditions. Therefore specifications for the laser glass process do not impact extraction efficiency.

The fourth critical property of the laser glass is its optical quality. This is strongly dependent on the processing conditions and therefore many of the specifications deal with this aspect of the glass product. There are three characteristics of the glass that impact optical quality:

- optical homogeneity
- inclusions
- bubbles

Optical homogeneity refers to the refractive index variation in the optical material and for laser glass this is typically about 1 ppm (i.e. $\Delta n = +/- 1 \times 10^{-6}$). The homogeneity is typically specified in terms of a maximum amount of allowed aberration due to sphere, coma, astigmatism and a smaller amount of higher order terms (see Table 2). For NIF and LMJ we intend to keep this same specification. However the final, finished (that is, polished) laser glass will be specified by using a more sophisticated procedure designed to monitor aberrations at specific spatial frequencies that are known to seed non-linear-growth of intensity noise in the laser beam.

The homogeneity of the laser glass is critical in order to maintain wavefront uniformity of the laser beam. Recall that there are a total of 18 laser slabs in the laser beamline and during the four passes through the amplifier chain the beam passes through the equivalent of 72 laser slabs. Therefore even small optical inhomogeneities can lead to significant wavefront aberration in the output of the beam potentially causing significant degradation in both frequency conversion and focusability of the beam.

Inclusions from ceramic refractory materials, undissolved raw materials, Pt metal, crystallites or impurities can cause optical damage in the glass when exposed to high laser fluences. The most common inclusion source is metallic Pt inclusions from the Pt liners used in the melting system. Improved processing conditions have lead to a dramatic reduction in Pt inclusions in recent years such that the average inclusion density is less than 0.1 per liter of glass or less than an average of 1 - 2 per glass slab.[22,23] Inclusions in the laser glass typically damage at about 2-5 J/cm^2 at the NIF and LMJ pulse lengths.[13] Although very small to begin with, inclusion damage can grow with successive laser shots to several millimeters or even centimeters in size making the laser glass unusable. Also large damage spots (> 150 μm) in the laser glass can seed damage in other optics in the laser chain. In general, if the inclusions are small they can be tolerated as long as the optical damage they produce does not exceed 150 μm in size . This is the basis for the specification given in Table 2. Currently we scan each piece of laser glass with a high fluence laser beam and measure the size of any damage site after 100 shots at fluences between 7 to 14 J/cm^2 (8ns).[24] If the size remains below the size specified in Table 2 then it is acceptable.

The laser glass bubble specification is based on two requirements: first to reduce the amount of light loss due to the obscurations caused by the bubbles and second to keep the size below a certain value that may induce non-linear growth of intensity noise. The obscuration loss is not to exceed 0.01% of the beam aperture per slab and therefore sets the total number of bubbles of a given size allowed in any given slab. The maximum size bubble allowed is currently 100 µm. The diffracted light from bubbles that exceed100 µm can, at high intensities, imprint a holograph diffraction pattern in the next optic that in turn will bring that portion of the beam to focus at another downstream optic and potentially damage it. Because of the regular spacing of many of the optics in the laser chain this non-linear imaging effect could lead to propagation of laser damage throughout the beamline. In general, bubble have not been a significant problem for laser glass. For example, 19 of the 20 Beamlet slabs had no bubbles at all. Similar results were observed for the Nova and Phebus laser glass disks.

Table 2: Technical specification of the laser glass slabs.

NIF/LMJ specifications	
Nd doping	$4.0 \times 10^{20} \pm 0.1$ Nd^{3+}/cm^3
Homogeneity (expressed as wavefront error @ 632nm, Brewsters angle incidence):	
Sphere	$< 0.5\ \lambda$
Astigmatism	$< 0.25\ \lambda$
Coma	$< 0.25\ \lambda$
Higher order aberrations	$< 0.167\ \lambda$
Fluorescence Lifetime (measured on 5x5x0.5 cm^3 sample)	>320 µsec (manufacturing goal : >335 µsec)
Absorption coefficients :	
at 1.053 µm	$\leq 0.0019\ cm^{-1}$
at 400 nm(due to Pt^{n+})	$\leq 0.25\ cm^{-1}$
at 3.3 µm (due to -OH)	$\leq 2\ cm^{-1}$
Bubbles:	
max number (per 100cm^2 area)	total cross section < 0.15 mm^2
maximum diameter	≤ 100 µm
Birefringence	≤ 5 nm/cm (manufacturing goal : ≤ 0.5 nm/cm)
Pt inclusions:	
max number for any one slab	≤ 5 in Clear Aperture
average for all slabs	≤ 2 per slab
max size after laser irradiation	≤ 150 µm.

3.3. Properties of the NIF and LMJ laser glasses

Laser glasses are specially formulated to give the desired laser, optical, thermal-mechanical and physical-chemical properties needed for a specific laser application. Some of these properties are strongly affected by the processing conditions (as discussed in the preceding sections), however, most are controlled by the base glass composition.

We have chosen two glasses for use on the NIF and LMJ that meet the gain, energy storage, extraction efficiency, and damage resistance requirements: LHG-8 (Hoya Corporation) and LG-770 (Schott Glass Technologies Inc.). LHG-8 is the same glass that was used on the Nova and Phebus lasers, however, LG-770 is a new formulation developed to replace LG-750 (LG-750 was used on Nova, Phebus and Beamlet).

The key properties of these laser glasses are summarized in Table 3. The importance of these properties for ICF high-peak power applications has been thoroughly discussed in the literature. [15,16,25,26] In addition a number of recent studies have focused on developing an understanding and quantitative relationships between phosphate glass compositions and desired laser glass properties.[17-19] Consequently, we will not discuss laser glass properties further here.

Table 3 : Properties of LHG-8* and LG-770**, the two laser glasses selected for use on LMJ and NIF.

Glass Properties	LHG-8	LG-770
Optical		
refractive index		
n_d (589.3 nm)	1.52962	1.50675
n_l (1053 nm)	1.52005	1.49908
non-linear refractive index		
n2 (10^{-13} esu)	1.12	1.01
γ (10^{-20} m^2/W)	3.08	2.82
Abbe number	66.5	68.5
Laser		
emission cross-section (10^{-20} cm^2)	3.6	3.9
radiative lifetime at zero-Nd concentration (µs)	365	364
Judd-Ofelt radiative lifetime (µs)	351	349
emission band width (nm)	26.5	25.4
Thermal		
thermal conductivity, 90°C (W/mK)	0.58	0.57
thermal diffusivity (10^{-7} m^2/s)	2.7	3.1
specific heat, Cp (J/gK)	0.75	0.71
Coefficient of thermal expansion, 20-300°C (10^{-7}/K)	127	135
Glass transition temperature,Tg (°C)	485	460
Mechanical		
density (g/cm^3)	2.83	2.59
Poisson's ratio	0.26	0.25
Fracture toughness (Mpa $m^{0.5}$)	-	0.6
Hardness (GPa)	3.43	3.58
Young's modulus (GPa)	50.1	68.1

* Hoya Corporation.
** Schott Glass Technologies, Inc.

4. ADVANCED MANUFACTURING DEVELOPMENT

The glasses made for the present large ICF laser systems (e.g. Nova [LLNL], Phebus [CEA], Beamlet [LLNL] and Omega [Univ. of Rochester]) were manufactured using a one-at-a-time, discontinuous melting process. In this section we briefly compare and contrast this older manufacturing method with the advanced processes now under development for NIF and LMJ. These advanced laser glass melting processes are being developed separately by Schott Glass Technologies (Duryea, PA) and Hoya Corporation (Fremont, CA) under work funded jointly by the Lawrence Livermore National Laboratory and the Centre d' Etudes de Limeil-Valenton. Many of the details of the manufacturing process are highly proprietary to each company. Therefore we give only a generic description of the process. Nevertheless, this description will hopefully give an idea of the level of progress in manufacturing technology that has already occurred or is envisioned to occur as a result of the NIF and LMJ projects.

4.1 Current Technology: Discontinuous Melting Process

In the first step of the discontinuous process, a cullet glass is made by melting the raw starting materials. The cullet glass is usually melted in a relatively inert ceramic refractory crucible, and a bubbling gas is often added to remove unwanted volatile products, particularly water. The cullet melt is cast and then broken into smaller pieces. The cullet is generally full of bubbles, striae, and possibly some small particles of undissolved starting material.

The glass produced from the cullet melt is used in the final melting step which is conducted in large platinum crucibles. During this second melt step, the glass is homogenized to provide the striae-free, high optical quality glass necessary for laser applications. This homogenizing process involves two stages.[27] The first is a refining or "fining" process conducted at high temperatures where the viscosity of the glass is low, allowing bubbles to rise to the surface. The second stage is a stirring process which is generally conducted at temperatures lower than either the melting or the refining stages. The continuous mixing thoroughly distributes all components within the glass melt, eliminating striae and thus ensuring uniformity of the refractive index over the entire casting. Finally, the melt is cooled to a temperature such that the viscosity of the glass is proper for casting into a mold of the appropriate size and shape. After casting, the glass undergoes a coarse annealing step, is inspected for inclusions and striae, and then is fine annealed to remove residual thermal stresses due to the forming process.

4.2 Advanced, Technology: Continuous Melting Process

In contrast to the discontinuous process, the advanced glass melting process will continuously produce large rectangular plates of laser glass at the rate that could exceed 20 per day. A continuous melting system for optical glass is generally divided into four main processing zones [28] (Fig 4): (1) melting, (2) conditioning and refining, (3) homogenization and (4) forming. These regions are interconnected allowing for the continuous flow of glass from one zone to the next. The glass is cast as one continuous "strip" during the forming process; this strip is then cut to the desired length once it has been coarse annealed. Unlike the discontinuous process, the raw material will feed directly to the melter eliminating the need to make a cullet melt.

Both manufacturers will use advanced processing conditions designed to minimize the formation of Pt inclusions in the laser glass. Prior to 1986, Pt inclusion damage represented the major source of damage in laser glass used for high peak power applications. However new processing methods effectively reduce the Pt inclusion concentration by more that 1000-fold to fewer than an average of 1 to 2 per laser glass plate (i.e. less than 0.1 per liter) [22,23]; our experience shows that approximately half the laser slabs have no detectable inclusions. [13,14]

Once the laser glass has been melted and formed into plates, there remains a number of other process steps before the glass can be shipped to the final finishing vendor. Specifically the laser glass needs to undergo pre-fabrication into a size suitable for inspection for striae and Pt inclusions. Following this the glass in slowly annealed to remove any residual strain; this process alone can take many weeks. Finally the glass is fabricated to the final dimensions required by the polishing vendors, inspected for homogeneity and prepared for shipping. Research is under way to develop advanced inspection techniques and/or reliable statistical inspection methods that will reduce the time and cost for inspection.

Significant progress has been made in developing the continuous processing method for production of laser glass. Hoya Corporation (Fremont, Ca) has design, built and tested a sub-scale melter that has melted and formed laser glass into a continuous strip ranging in size from initially a cross-section of 130x18 mm^2 to more recent runs at 28 x 240 mm^2 (see Fig 5). During these runs several tons of laser glass were produced.

Schott Technologies Incorporated (Duryea, Pa) is also designing a continuous laser glass melting system and has done a demonstration run of continuous forming of glass at the size required for NIF and LMJ (Fig 6). The glass shown in the figure 6 represents the largest cross-section of glass formed by continuous strip operations. For these tests Schott used a borosilicate glass BK-7 which is a well known optical glass and under continuous production at Schott.

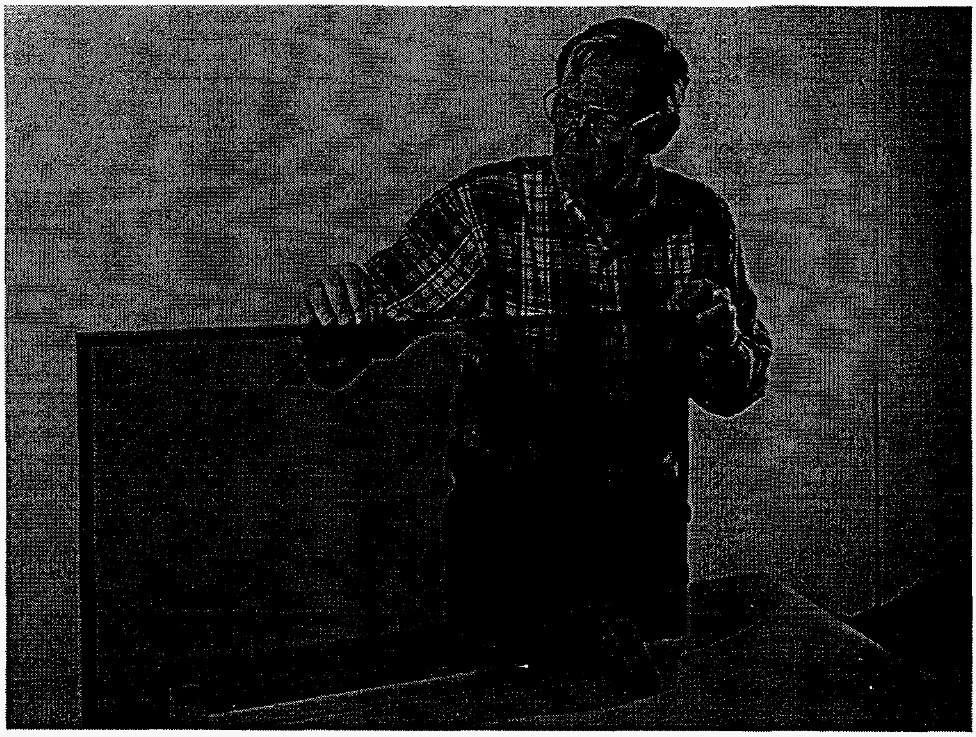

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Figure 3. Photograph of a phosphate laser glass plate manufactured for the Beamlet prototype laser [13]. The size and doping level of this glass is nearly identical to the LMJ and NIF.

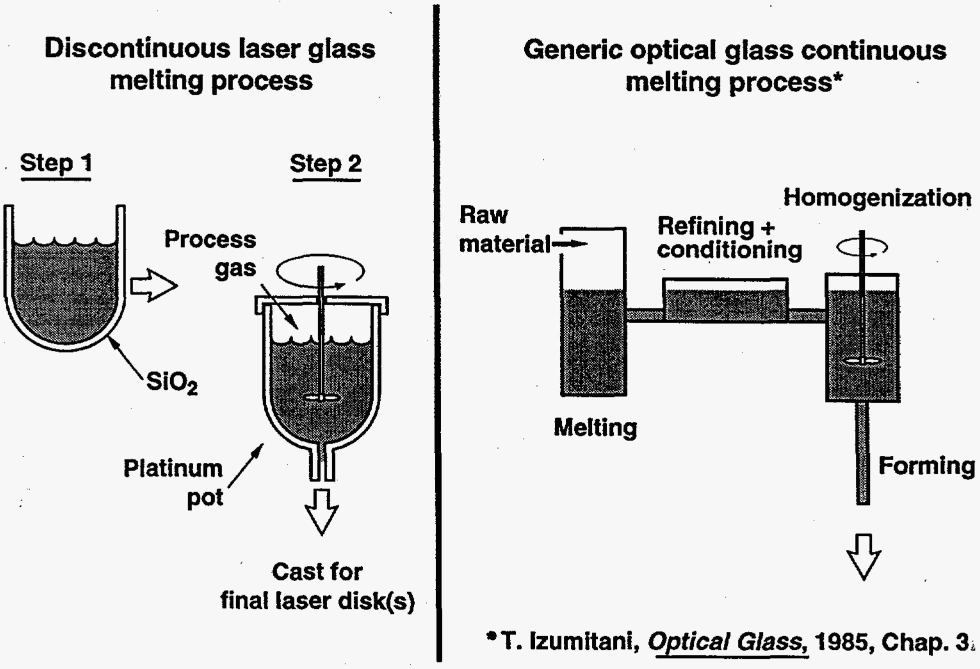

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Figure 4. Schematic diagram of (a) discontinuous and (b) continuous laser glass melting and forming processes.

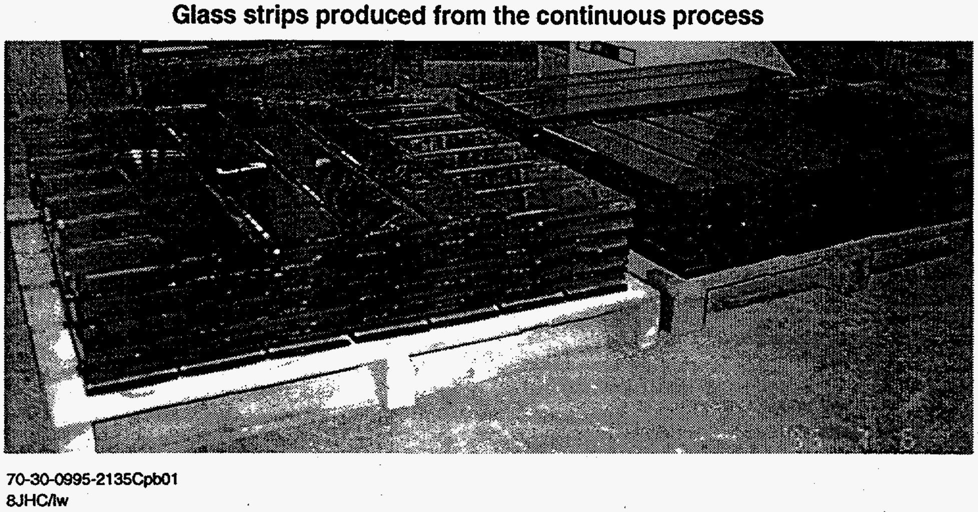
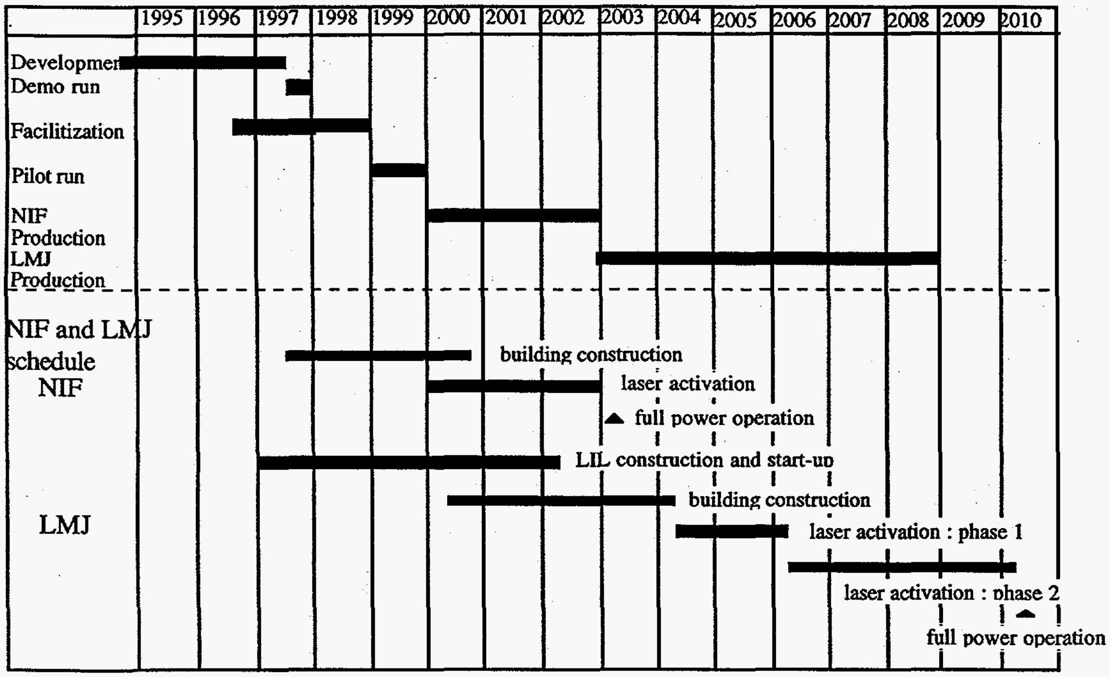


Figure 5. Photograph of pieces of laser glass cut from a continuously formed glass strip having a cross section of about 130x18mm2. This glass was made during an initial test run of Hoya Corporation's sub-scale continuous laser glass melting system.

Figure 6. Photograph of a BK-7 glass slab made by continuous strip forming operations at Schott Glass Technologies. This glass piece is the largest ever produced by continuous strip forming and is the same size as the pieces needed to make NIF and LMJ laser glass slabs.

5. SCHEDULE

Figure 7 : Current schedules for the development and production of laser glass and also the project schedules for the NIF and LMJ.



Our goal is to complete the planned three years of process development work by the end of 1997 (see Figure 7). The development effort will be culminated by a demonstration run at each vendor to validate their continuous melting concept. If the processes are successful, about one year is needed to set-up the full-scale production system and another one year is planned for the "pilot" production of about 10% of the glass needed. The results for the pilot run will be used to establish yield and costs. In addition, the glass from the pilot run will be used by the finishing vendors to demonstrate the advanced laser glass finishing and polishing methods to be used in final production. Since the NIF construction will occur earlier than that of the LMJ, then the first stage of laser glass production will be primarily for that facility. The production of the NIF will take place over three years at a rate of about 1200 slabs per year. This production will be followed by the LMJ production that will last 6 years. On the third year of production the NIF and LMJ may overlap somewhat causing a short term increase in the annual production rate.

Fig 7 also shows abbreviated description of the NIF and LMJ construction schedule. Note that CEA plans to build an intermediate facility called the "Integrated Laser Line" (LIL). The LIL will consist of 8 beams identical to those on the LMJ (which contains 240). The LIL will also contain a target chamber to conduct plasma physics experiments at third harmonic (351nm) energies of up to 60kJ on target. The first goal of this laser is nevertheless to validate the design of the LMJ including the performance of the various laser components and optics.

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