Pulsed Power Requirements for a High Power KrF Laser Inertial Confinement Fusion Test Facility

J.D. Sethian, S.P. Obenschain,
Plasma Physics Division, Naval Research Laboratory, Washington, D.C. 20375

M.W. McGeoch
PLEX Corporation, 21 Addington Rd, Brookline, MA 02146

I.D. Smith, P.A. Corcoran and R.A. Altes
Pulse Sciences, Inc. 600 McCormick St., San Leandro, CA 94577

Abstract

A conceptual design for the pulsed power of a 68 kJ Krypton Fluoride (KrF) laser amplifier is discussed. The amplifier features double sided electron beam pumping with eight diodes on either side of the laser cell. This amplifier is based on the technology developed for the recently completed Nike laser system. We envision a system in which thirty-two of these amplifiers are combined to produce a 2 MJ KrF laser direct drive inertial confinement test facility.

Introduction

A Krypton-Fluoride (KrF) laser pumped with large area electron beams is a promising candidate for an ICF driver because of its outstanding beam quality, its short wavelength, and straightforward scaling to a large system. The Nike laser at NRL¹ is the first step in the development of a KrF ICF driver, and is being used to explore the advantages and limitations of this approach by studying ablatively accelerated planar targets. If experiments with Nike show that the highly uniform laser beam that is unique to KrF is both necessary and sufficient for high gain, we would recommend the construction of a multi-megajoule KrF facility. (We define high gain as a target that produces greater than 100 times more fusion output energy than the laser input energy). Although this facility would be too large to build at the Naval Research Laboratory, we have produced a conceptual design and cost estimate for it.

The facility consists of 32 amplifiers, each producing 68 kJ of KrF laser light. For compactness and optical efficiency the 68 kJ amplifiers are grouped in pairs to produce sixteen 136 kJ multiplexed laser lines. With this system we predict a spherical target will be irradiated with 2.0 MJ of laser light in 7 ns with a non-uniformity of less than 0.5%.²

The 68 kJ Amplifier

The heart of the 68 kJ Amplifier is the laser cell that is 3.6 m long, 1 m wide and 2.7 m high. The cell is filled with a mixture of krypton, fluorine and an argon buffer. The laser beam enters and exits the cell through a pair of 100 cm square windows at the 1 m x 2.7 m ends. Stacking the windows one on top of the other gives an effective aperture of 1 m x 2 m. The laser gas is pumped by injecting electron beams across the laser axis from the opposing 2.7 m x 3.6 m walls. The electron beams disassociate the krypton and fluorine to create an excited KrF dimer, which then decays back to Kr and F₂, producing radiation at 248 nm. The electron beams are produced by sixteen field emission diodes, with each driven by its own parallel plate pulsed power system. Although this amplifier is capable of generating a total of 68 kJ of laser light, each of the individual diodes in it are actually slightly smaller than the diodes in the final "60cm Amplifier" of the Nike laser. The 60cm Amplifier, which produces a laser output of 5 kJ, has been described in detail elsewhere³, however it is instructive to

compare the parameters of the two systems. This is done in the table below:

	60cm Amplifier Nike (existing)	68 kJ amplifier HIGH GAIN FACILITY (concept)
E-Beam	700 kV, 500 kA	800 kV, 330 kA
Pulse duration (flat top)	240 nsec	250 nsec
PFL stored energy/diode	90 kJ	83 kJ
Cathode area	200 cm x 60 cm	100 cm x 48 cm
Cathode current density	42 A/cm ²	68 A/cm ²
Diodes per amplifier	2	16
Total specific pump power	350 kW/cm ³	800 kW/cm ³

In most cases the parameters of the 68 kJ amplifier are within 10-20% of that of the Nike 60cm Amplifier. The major difference is the higher specific pump power which is due to both the higher diode power per unit area and an assumed higher energy transmission from cathode into the gas. We achieve the latter by incorporating a new laser cell pressure foil structure based on the "suspension bridge" design conceived and partially tested at Los Alamos⁴. Even though the pump power is higher it is within the parameters that have been achieved in other systems, some of which have operated at over 1 MW/cm³. (In fact, the smaller 20cm Amplifier of the Nike laser has operated as high as 550 kW/cm³.)

Figure 1 shows the view of the 68 kJ Amplifier from inside the cell, looking into the e-beam diodes on one side. For comparison,

the same view for the Nike 60cm Amplifier is shown in the upper portion of the drawing:

Figure 1: View inside the laser cell, looking into the electron beam diodes for both the proposed 68 kJ amplifier and the existing Nike 60cm amplifier. The diodes along one wall of the cell are shown. An equal number of diodes line the opposite wall.

Figure 2 shows the top view of the cell, as looking down upon the e-beam diodes. It is in this view that the most unique aspect of this 68 kJ amplifier can be seen: the amplifier is of a "segmented" design, meaning that there are portions of the laser cell that are unpumped (i.e. "missed" by the electron beam). At first glance it was thought that such a design would be severely compromised since the unpumped fluorine, which is a UV absorber, would attenuate so much of the light produced in the pumped regions that the amplifier efficiency would be seriously reduced. However, after carrying out calculations with an experimentally tested KrF amplifier model⁶, it was determined that this is not the case as the reduction in Amplified Stimulated Emission from the segmentation compensates for the absorption. In addition to laser considerations, such a design allows significant simplification in the pulsed power: 1) the electron beams can be guided in the standard fashion with a simple parallel magnetic field; 2) because the diodes can now be surrounded with return current planes on all four sides, the self field is reduced, the guide field can be relatively low, and the diode closure is reduced; and finally 3), the

return current planes reduce the system inductance and hence relax the requirements on the pulsed power.

Figure 2: Top view of the 68 kJ amplifier showing the diodes, insulator/switch assemblies and the guide magnet. Note the "unpumped" regions.

The end view of the laser cell, looking along the path of the laser beam, is shown in Figure 3. This view clearly shows the two 100 cm x 100 cm optical windows that make up the effective optical aperture of 100 cm x 200 cm. Note that comparing Figures 2 and 3 shows the cell is pumped by sixteen separate electron beam diodes.

Figure 3: End view of the laser cell.

One of the features of this design is that each diode is connected to its own pulse line through two monolithic vacuum insulator sections that contain both the SF_6 -insulated switch and the insulating gas around the cathode stalk. The details of this are shown below in Figure 4. The plastic insulator body

is fabricated by casting and/or machining a single piece onto which split metal grading rings are pressed. This arrangement is considerably less expensive than the conventional one in which the switch is located in a separate housing and the insulators and grading rings are individual components that are stacked and held together by external tie rods. This design also substantially decreases the inductance.

Figure 4: Top view of the integrated switch/insulator stack section. There are two of these per cathode.

Although mechanically unconventional, potential plots both before and after switching show that the insulator is graded quite uniformly and the average field is well below the threshold for breakdown.

Each pair of switches (and hence each diode) is fed by a water dielectric rectangular cross section pulse forming line (PFL) of depth 1 m (to correspond the cathode dimension), width 55 cm, and length 5 m (corresponding to a pulse duration of 300 nsec and a flat top duration of 250 nsec). The PFLs are charged to 1.64 MV in 1.8 μs by a Marx bank. One Marx charges four PFLs. Each Marx has eleven stages, with two 3.0 μF capacitors per stage and each stage charged to ± 90 kV.

We have simulated the pulsed power behavior of this amplifier, assuming the anode cathode gap has an initial value of 5.5

cm and a closure velocity of 2.3 cm/ μ sec. Best results are obtained if we assume the diode is driven by a 130 nsec, 1.28 Ω pulseline followed with a 20 ns long 1 Ω peaker section at the output end of Figure 3. This is very similar to the successful arrangement of the Nike 60 cm Amplifier.³ We found that if the output switches are fired at near peak charge on the waterline, the diode voltage ramps down and the current ramps up by about 6%, averaging 790 kV and 690 kA, respectively, throughout the top part of the pulse. The power to the diode remains almost constant at 54.5 TW $\pm$ 2 %. This is more than adequate to meet the laser uniformity requirements.

As said at the outset, we have designed and estimated the cost of an entire 2 MJ laser facility. As part of that effort, we determined that the cost to develop the pulsed power for the 68 kJ amplifier comes out to \$20 M for the first unit, where we have allowed a 25% contingency. The cost reduces to about \$ 7.1 M in a quantity of 32 for the 2 MJ laser facility. Part of the savings is in the "learning" applied when building a large number of units, and part is due to the fact that a lot of the amplifier subsystems (i.e. gas handling, gas recovery, control systems) would be shared with other components of the facility. The entire cost of the 2 MJ laser facility, including target chamber, all support services, and a 25% contingency, has been estimated to be \$950 M. These numbers were obtained with the same algorithms used in costing previous LMF designs⁷, the NIF⁸, and other large pulsed power systems,⁹ as well as experience in building the Nike laser.

The first step in building the 2 MJ facility would be to construct a 68 kJ module. We believe that this represents the major risk in the development of the 2 MJ facility. Taken individually, none of the parameters of the 68 kJ amplifier represent a significant extension of the Nike 60cm Amplifier, but as a whole the amplifier represents a factor of ten increase in laser output energy. After

developing the pulsed power for the 68 kJ system, the next step would be to develop it into a laser amplifier. This would involve adding a front end, driver amplifier, and multiplexing/ demultiplexing optics. If these tests were successful, we would be confident that we could design the entire facility.

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