DEVELOPMENT OF KrF LASERS FOR INERTIAL FUSION ENERGY†


1. Introduction

The success of the inertial fusion program depends on the development of efficient, high power drivers. Extensive efforts in the USA and abroad have pushed the technology of Krypton Fluoride (KrF) lasers to the point where multi-kJ laser energy can be generated and deposited on targets. However, lasers with energy output 10-40 times higher will be needed in the future. To achieve this goal issues such as reliability, efficiency, and cost have to be taken into consideration. In this talk we will describe how to proceed with this development.

Two large KrF laser facilities, NIKE and ELECTRA, are being used at NRL (Naval Research Laboratory) as part of the inertial fusion program. Part of this program is to improve the overall system efficiency of the lasers and to evaluate their usefulness as drivers for inertial fusion.

2. Excitation of high power KrF lasers

High energy/power KrF lasers are pumped with two counter streaming, large-area electron beams(1). Each electron beam is created in a field-emission diode that is powered by a low impedance pulsed-power driver. The diode consists of a planar cathode and anode. Typically, the electron energy used in a large KrF amplifier is of the order of 600 keV, the current is of the order of few hundred kAs, and the pulse duration is a few hundred nanoseconds. The electron beam, with a rectangular crosssection, is guided by an external magnetic field. The beam passes through metallic ribs (Hibachi) and a pressure foil to the laser gas (Fig. 1 ).

Measurements performed on NIKE (at NRL) indicated that the electron-beam to gas energy transfer efficiency was 40%-50%. It is believed that the rest of the energy was lost as (1) heat to the anode and pressure foils, (2) generation of RF, and (3) by the removal of the high current density portion of the electrons beam produced by edge effects in order to ensure homogenous energy deposition into the KrF gas.

The low energy transfer efficiency reduces the overall system efficiency and introduces demands on pellet design, heat removal, and prime input power that may be difficult to achieve.

3. Mechanisms responsible for the low efficiency

There are three main mechanisms that are responsible for the low efficiency:

1. A large amplitude instability(2) (transit-time instability) that developed in a planar diode (fig2 left). Theory shows that when a space-charge-limited diode is under the influence of a small amplitude electromagnetic wave, the diode conductance/length, G, and capacitance/length, C, are a function of the frequency of the wave, f, and of the cathode anode electron transit time, T. The instability supports growing electromagnetic and beam waves at frequencies, \( f_n \sim (n+1/4)/T \) \( (n=1,2,...) \) where the conductance is negative. Experimentally we found that the NIKE diode with a length \( l=2m \) was unstable while ELECTRA diode with a length \( l=1m \) was stable. Theory suggests that the most unstable mode for both diodes is near \( f=2.5GHz \), for
which the attenuation/gain coefficient $\alpha = -3.9 \text{ Np/m}$. One can find that for NIKE the gain for the unstable mode is $\exp(-\alpha l)=2440$. For ELECTRA the gain will only be $\exp(-\alpha l)=50$. Since losses from the ends of the cathode region are linearly proportional to the diode size, there is a critical diode size below which the losses are larger than the gain and the instability will not grow (e.g., ELECTRA).

The instability converts $>10\%$ of the energy into RF and introduces large spread in electron energies and large amplitude current fluctuations (Fig. 3 left). Moreover, the mutual interaction between the current-modulated beam and the hibachi, which acts like a RF cavity, amplifies the effects of the instability on the electron beam. The wide electron energy spectrum enhances energy losses to the anode and pressure foils (energy loss to the foils and to the RF $\geq 45\%$).

2. Beam halo (fig. 4 left). Experiments and computer simulations show that at the cathode edges the electric field increases its value enhancing the current density by a factor $\sim 2$. The increase in current density results in non-uniform pumping of the laser gas and causes damage to the anode and pressure foils. This problem was alleviated in NIKE by propagating the beam through an aperture cutting out all the electrons at the beam edges (energy loss $\approx 5\%$). However this compromises the system efficiency.

3. Beam rotation (fig. 5). Electrons follow the combined applied and the beam self-magnetic fields and reach the Hibachi at a skewed angle. Some electrons at the beam edge strike the ribs without depositing any energy into the laser gas. The beam as a whole rotates around its axis and is cut by the apertured anode (energy loss $\approx 5\%$).

The total energy loss by these mechanisms is about 60%.

4. Elimination of the energy loss mechanisms

Better understanding of the physics of large area electron diodes can reduce or eliminate the energy loss by these mechanisms and potentially improve the electron to gas energy transfer efficiency from 40% to 90%.

1. Theory and simulation$^{23}$ have shown that the cathode and anode, which resemble a parallel-plate transmission line, guide the electromagnetic waves that are powering the transit time instability. Electromagnetic waves that are guided by parallel-plate transmission lines have phase and group velocities equal to the speed of light. These waves can be slowed down and even stopped (stop band) by loading the transmission line (i.e., the diode) with series stubs (i.e., short-circuited sections of transmission lines) (fig. 2 right). Theory shows that the electron beam that emerges from such a diode is stable with a narrow energy spectrum, which includes almost no slow electron component (fig. 3 right). The elimination of slow electrons reduces energy loss to the anode and pressure foils improving efficiency. Moreover, the electrons in the diode will follow more predictable, well-defined paths when the transit time instability is eliminated. A major loss in KrF lasers is due to the interception of the electron beam by the support structure (Hibachi) for the pressure foil. Well-defined current paths should allow one to design foil support structures that coincide with the slots in the cathode to minimize this interception. Elimination of the instability and a redesigned Hibachi would reduce energy losses to the foils to 25% and eliminate RF. Moreover, the lowered energy deposition in the foils will allow the use foils half as thick, further reducing the energy loss to 12%.

1990
2. Theory, experiment and particle simulation showed that the beam edge is eliminated when diodes are modified such that the cathode edges are “shadowed” by non-emitting metallic wedges (fig. 4 right). The metallic wedges reduce the electric field and suppress electron emission at the cathode edge. By eliminating the beam halo there will be no need to aperture the anode and remove electrons at the edges of the beam.

3. Rotating the cathode around its axis in the opposite direction to the beam rotation can match the beam shape to the aperture in the anode. The skewed trajectories of electrons inside the hibachi could be straightened by introducing low-pressure gas inside the hibachi. The gas inside the hibachi will get ionized eliminating the self-fields of the beam and beam cavity interaction. All beam electrons will now be able to reach the laser gas without intersecting the hibachi ribs.

5. Conclusions
The improved efficiency of KrF lasers relaxes demands on pellet design (i.e., gain) and/or prime power. Moreover, elimination of energy losses will enable us to construct rep-rated pulse power devices with output energy per pulse of future KrF laser energy 10-40 times higher than energy levels obtained at present.

† Supported by DOE.
*CTI Alexandria, VA. **MRC Newington, VA. ***JAYCOR McLean, VA.

References
FIG. 3. Results from particle simulation: (Left) planar diode. (Right) modified diode. (Top) cathode anode voltage. (Bottom) histogram of particle energy.

FIG. 4. (Left) current density at the beam edge for a flat cathode and (Right) current density at the beam edge for a cathode with field shaper.

FIG. 5. Beam profile on the anode.