

ADVANCED PULSED POWER CONCEPT AND COMPONENT DEVELOPMENT FOR KrF LASER IFE*

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Abstract

The Electra advanced pulsed power development program has the goal of developing and demonstrating pulsed power technology that is applicable for KrF (krypton fluoride) Laser IFE (inertial fusion energy). The application presents efficiency, lifetime and cost challenges that mandate the use of advanced pulse compression topologies. In turn, these advanced topologies require the development of critical components and the establishment of engineering criteria for use in designing them.

The component most critical to realizing any of the advanced topologies under study is the primary energy transfer switch. Therefore, the program has been developing an advanced optically-triggered and pumped solid state switch that is expected to meet the efficiency, lifetime and cost requirements of an IFE driver. Liquid dielectric breakdown studies are also underway, with the intent to develop design criteria relevant to the large electrically stressed areas associated with a viable KrF IFE power plant.

KrF IFE pulse compression and component concepts will be discussed as well as the most recent results from the solid-state switch development and liquid dielectric test efforts.

I. Program Flow

The Electra advanced pulsed power development began in 1999, concurrent with the fabrication and delivery of two spark-gap-based repetitive KrF laser drivers [1,3] to the Naval Research Laboratory. Figure 1 illustrates the program flow. Light background blocks represent program tasks completed as of this writing, whereas the shaded background blocks represent currently active and near-future tasks. The advanced program began with a determination of the KrF IFE driver requirements based on updated system requirements originally outlined by the

Sombrero [2] study, and reported in previous publications [1,4]. An assessment of current state-of-the-art (SOA) component and subsystem technology followed. Using the SOA technology and components, an initial IFE module design and cost analysis was performed. This exercise led to the identification of key components for which a focused research effort would provide improvements in system efficiency and cost. The follow-on phase of the program is referred to as the IRE (integrated research experiment) with a mission to demonstrate all key technology elements for KrF IFE in an integrated environment.

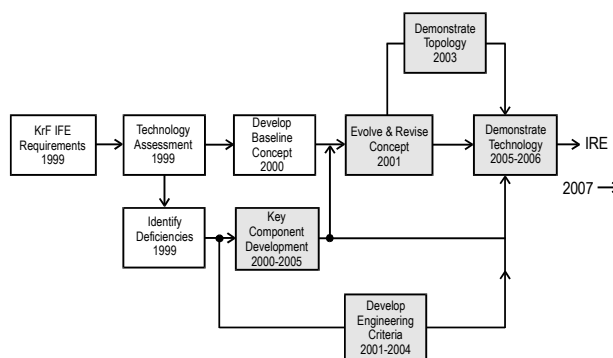


Figure 1. Electra advanced pulsed power development program flow.

Figure 2 illustrates the evolution of the IFE module conceptual design from the original transformer charged three-stage magnetic pulse compressor [5,6] (MPC) through the latest IFE topology that utilizes a solid-state switched Marx charging a one-stage MPC. This evolution was driven by the results achieved in developing a laser gated and pumped thyristor (LGPT) for a primary switch.

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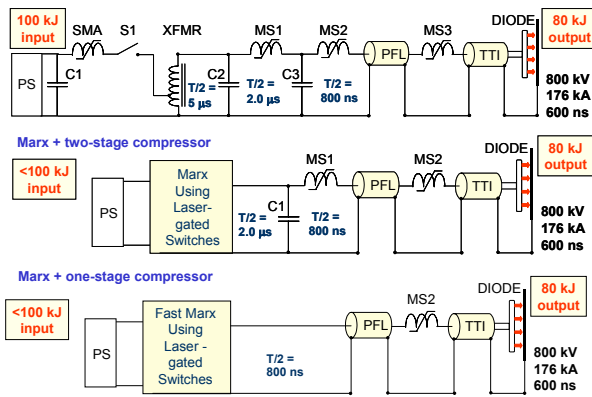


Figure 2. 100 kJ KrF IFE pulsed power module evolution.

Table 1 compares the important figures-of-merit as well as other factors for each compressor topology (and variant) for which a system study was performed.

Table 2 is an energy audit of the Marx-charged one-stage MPC based on our current conceptual model and design. The module's input energy per pulse is 97-98 kJ. From the energy audit we expect 84.5 kJ of usable electron beam energy from this design.

A mechanical layout of the Marx-charged one-stage MPC IFE module is shown in Figure 3. In this design, the 10 meter long water-filled PFL is located above the Marx tank. The Marx is accessed by sliding it clear of the tank through the tank's removable end wall. There is a 10 meter water-filled transit time isolator (TTI) between the output magnetic switch and the load. This specific TTI design is critical for pulseshaping as well as mechanical interface to the vacuum bushings, e-beam diode box and laser chamber.

II. Component Development

Component development efforts have been focused on an improved primary switch that is fundamental to meeting the cost and efficiency requirements for IFE [1,3]. Specifically, a laser gated and pumped thyristor (LGPT) is being developed. A thyristor was chosen because its internal feedback produces current as well as voltage gain, and, because the primary energy transfer is CLC, requiring closing commutation only. Laser gating of such a device has been shown to dramatically reduce closing time and commutation losses [7].

Most of the previous work on laser-gating of thyristors was performed on devices rated for 2-5 kV forward breakdown. Some higher voltage device development [8] was performed but it was hampered by fabrication technique limitations (of the time), edge treatments and passivation.

We have shown via modeling that continuous pumping of the thyristor during conduction reduces forward losses substantially. This technique is made practical by the program's development of laser diode bars at a wavelength and power commensurate with the application.

Table 1. Summary of topologies/systems studied.

System Description	Cost \$/E-beam (J)	Efficiency Wall Plug/E-beam (J)	Risk Factors	Other Factors
Baseline 3-stage w/COTS solid-state primary switch	11.30	81%	Components (none) Materials (moderate)	(1)
3-stage mag pc w/LGPT primary switch	10.03	84%	Components (moderate) Materials (moderate)	(1)
2-stage MPC, Marx-charged LGPT switched	7.65	85%	Components (high) Materials (moderate)	(2)
1-stage MPC, Marx-charged, LGPT switched	8.66 to 8.69	86-87%	Components (high) Materials (moderate)	(2,4)
XFMR charged PFL with MV-class LGT or LGPT/magnetic hybrid	8.35 to 8.75	87.5%	Components (high) Materials (moderate)	(3)
(1) Alternative XFMR design(s) may reduce cost (.60/J), improve efficiency (1%). (2) Reduced charge voltage eliminates XFMR in charging system --cost saving in charging, improve efficiency (1%). (3) Alternative XFMR may reduce cost (.30/J), improve efficiency (.5%). (4) Cost and reliability issues related to reduced liquid dielectric volume, stressed area and floor space yet to be quantified.				

Table 2. 100 kJ IFE module energy audit.

Energy Audit (kJ)				
(- . - -) with saturating core				
		Charging	Main Pulse	Reset
Load	Usable - 600ns, 176kA, 800kV ($\geq 90\%$ P)		84.5	
	Rise/Fall		4.8	
Magnetics	Output Switch Downstream Reset Charging Inductors Laser Charging Inductors	(0.001) (0.002)	0.634 0.065 (0.013) (0.052)	0.013 0.003
Resistances	Water Dielectric (assume 15°C water) Skin Losses (stainless) Downstream Reset Series Connectors (5mΩ) Capacitor ESR Marx Sw Leakage/ESR Charging Inductors Laser Charging Inductors	 0.150 0.063 (0.02) 0.03 (0.012)	0.25 0.13 0.004 0.10 0.10 1.73 0.40 (0.000) 0.80 (0.000)	0.001 0.05
Capacitances	Stray Capacitance (within stage)		0.03	
Laser Drives	20 mJ/cm ²		0.18	
Power Supply	(Assume 5% of Stored Energy)	4.677 (4.620)	---	---
TOTALS:	W/Standard Inductors W/Saturating Inductors	4.920 4.805	93.723 92.588	0.067
EFFICIENCY:	W/Standard Inductors W/Saturating Inductors	86% 87%		

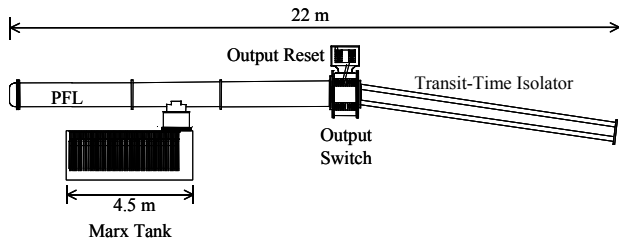


Figure 3. IFE module mechanical layout.

Examples of the simulation results can be seen in Figures 4 through 6. Figure 4 represents the case when a 2 kW optical illumination at the proper wavelength is applied to a $1 \text{ cm}^2 \times 0.25 \text{ cm}$ thick thyristor at a working voltage of 16.7 kV and a current density of $\sim 2500 \text{ A/cm}^2$. The optical pulsewidth is limited to 200 nsec, but the thyristor must conduct current for 800 nsec (T/2) in the IFE application. The peak power dissipated is $\sim 600 \text{ kW}$ and the total energy loss is $\sim 0.25 \text{ J/cm}^2$. When this loss is multiplied by the total silicon area in the IFE Marx, the losses amount to a few percent of the stored energy. With the KrF IFE requirement of $>80\%$ efficiency (wall-plug to flat-top e-beam), single percent energy savings are necessarily significant.

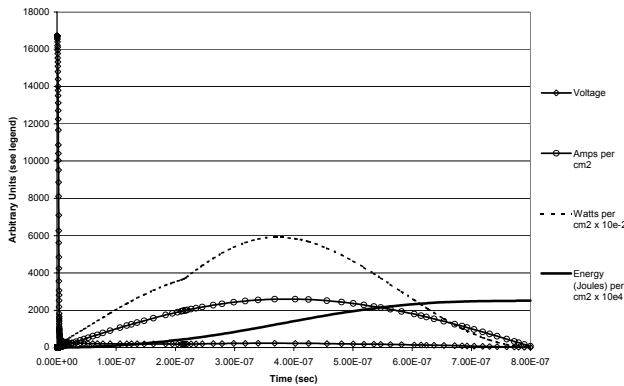


Figure 4. Voltage, current power energy at 2000 watts (optical) per cm^2 for 200 ns.

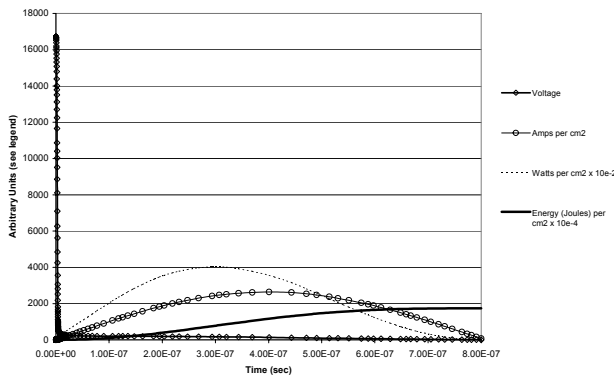


Figure 5. Voltage, current power energy at 2000 watts (optical) per cm^2 for 800 ns.

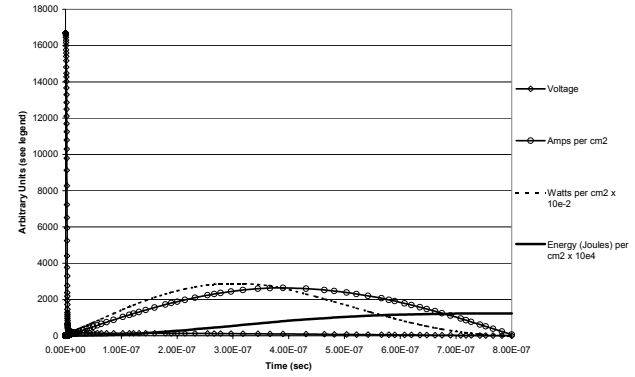


Figure 6. Voltage, current power energy at 3000 watts (optical) cm^2 for 800 ns.

Figure 5 shows the results of a simulation in which all parameters are the same with the exception that the 2 kW optical pulse is held on for 800 nsec. The effect is obvious in that the peak dissipation is reduced to 400 kW and the total energy loss is reduced to $\sim 0.175 \text{ J/cm}^2$. The 2 kW per cm^2 optical fluence is the current design baseline for the IFE-class LGPT. The lasers and drive design are capable of producing as much as 3 kW optical fluence per cm^2 (Si) if necessary and Figure 6 shows the case of a 3 kW optical pulse for 800 nsec. Energy loss per cm^2 (Si) drops to $\sim 0.125 \text{ Joules}$, corresponding to a savings of 1-1.5% of the total energy stored. Moreover, the gain, $\Delta E(\text{Si})/\Delta E(\text{optical})$, for the cases in Figures 4 and 5 is $\sim 60/1$. If interface and drive circuit losses and intrinsic conversion efficiencies are included, the overall gain (energy saved in the primary energy transfer divided by the increase in gating energy) is still $\sim 10/1$.

Our application requires a 16.4-16.7 kV working device, thereby mandating a bulk breakdown design of 23-25 kV. In an asymmetric design, this amounts to a device that is nominally 2-2.5 mm thick. The optimum laser wavelength for gating and pumping such a device is chosen through an iterative trade-off between absorption length, interface characteristics, electrical design (thickness and doping of bases and emitters) and quantum efficiency. For this purpose we have constructed models that predict the optical and electrical characteristics using the Medici [10] series of codes.

In summary, our present IFE module design requires a single device working voltage of 16.4-16.7 kV, $\sim 2500 \text{ Amps/cm}^2(\text{Si})$ peak and a $di/dt \geq 10 \text{ kA}/\mu\text{sec}/\text{cm}^2(\text{Si})$ peak. At a nominal conversion ratio (for these wavelengths in silicon) of 1 J/Cb or 1 W/Amp, the laser diode bars and drive circuitry produce a rate-of-rise of optical fluence (and therefore current) approaching $100 \text{ kW}/\mu\text{sec}/\text{cm}^2$ or $100 \text{ kA}/\mu\text{sec}/\text{cm}^2$ (20 nsec to $2 \text{ kW}/\text{cm}^2$ or $2 \text{ kA}/\text{cm}^2$).

The integrated conceptual design of a building block IFE LGPT is shown in Figure 7. The device has 14 cm^2 active asymmetric thyristor and 2 cm^2 inverse parallel diode arranged as two $1 \text{ cm} \times 8 \text{ cm}$ strips in a common envelope. One such assembly per half-Marx stage will be used in the program's technology demonstrator, whereas,

six to seven such assemblies in parallel will constitute a 100 kJ IFE module Marx design. The “rail” aspect ratio of this package lends itself to extremely low inductance designs (also necessary for fast primary energy transfer). Gating and pumping laser arrays, along with their drive electronics, are an integral part of the package.

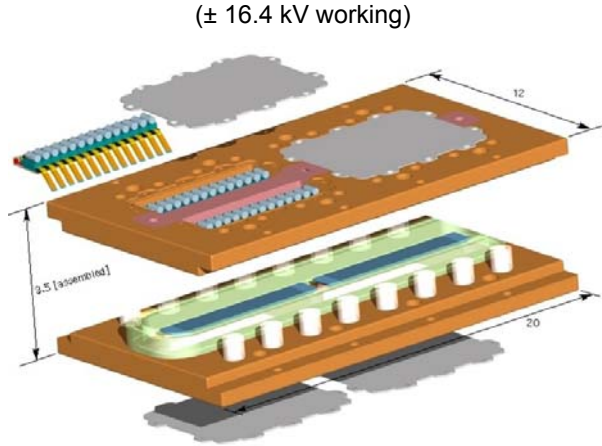


Figure 7. Conceptual design of IFE compatible LGPT.

This effort has to date produced integrated (silicon device and laser arrays) demonstrations at the IFE-required rep-rate (5 pps), current density and charge transfer for bursts of 10^4 shots. An integrated single-shot demonstration of triggered operation at 15.2 kV (single four-layer device) has also been performed. The device in the latter case actually demonstrated a forward blocking of at least 23.8 kV. Triggered operation and forward blocking on the high voltage device were both limited by the power supply. Both were also pulse-charged in 100 μ sec nominally to offset the thermal effects of high leakage currents in these preliminary designs.

The program is developing/adapting advanced fabrication techniques, based on those widely used in IC manufacture, for our high voltage LGPT devices. Edge treatments and passivation of such designs remain a challenge, but modern techniques that utilize junction termination extensions (JTE's), diamond-like-carbon (DLC) or semi-insulating poly-silicon (SiPOS) show promise.

III. Engineering Studies

Present estimates for a 1 GW net output KrF IFE power plant call for 240 each of the 100 kJ IFE pulsed power modules as seen in Figure 3. Even with the reduction in electrically stressed water and oil areas commensurate with the evolution from the original three-stage compressor to the current single-stage unit, these areas are huge ($\sim 10^8$ cm^2 for water and oil). The traditional breakdown formulae were derived from testing that broke down the dielectric sample every shot; not representative of the type of service and conditions that apply here. An alternative approach for predicting the probability of breakdown in large area systems under repetitive

electrical stress is suggested by Ian Smith, et al. [4]. The paper suggests that the probability of breakdown is less sensitive to area than in the currently accepted formula: $p = .5f^{1/m}$, where p is the probability, f is the fraction of breakdown from the single-shot formulae and m is the area exponent. A dependence more like: $p = 0.5 f^{2/m}$ is suggested. In addition, it is postulated that the area effect will essentially disappear at an area that is related to the maximum size impurity or defect allowed; if this can be demonstrated, engineering criteria for defects and electrode smoothness may result.

The Electra program has fabricated a test stand for repetitively stressing 10^4 cm^2 samples of oil or water for use in determining the appropriate criteria in this application. It consists of a thyatron-switched modulator capable of continuous operation at 100-150 pps, a high voltage pulse transformer, and both coaxial and parallel plate test volumes. It is planned to operate the test stand continuously for 2-3 years in order to thoroughly investigate the performance of water and oil dielectrics in IFE service.

IV. Technology Demonstrator

An integrated demonstration of the component, engineering and topology development for the program is currently underway in the design phase of a new front-end amplifier for the present Electra laser, Figure 8. The pulsed power system is a Marx-charged one-stage MPC (same topology as IFE design) with a nominal stored energy of 2 kJ. The pulse parameters are 150-175 kV, 160 kA (80 kA per side), 20/40/20 nsec (rise/flat/fall). The driver must operate continuously at 5 pps for $\sim 10^5$ shots in order to match the maintenance interval of the Electra main amp in the near term.

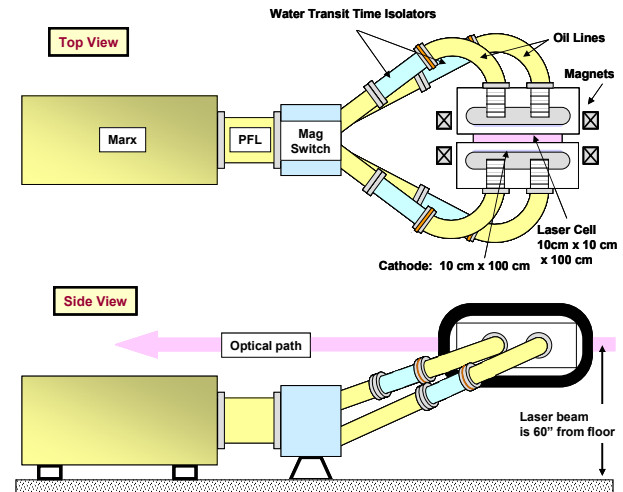


Figure 8. Front end (FE²) laser pulser conceptual view.

The IFE scale Marx-charged MPC is designed to drive a single cathode segment of multiple segment e-beam diode. Modules are arrayed on both sides of the laser volume, thereby allowing the use of straight transit time

isolators (TTI). In contrast to the largely one-axis design of the full IFE module, the FE² design uses a single pulsed power module to drive e-beam diodes on both sides of the laser chamber, through four TTI's. Floor space constraints, optical path, serviceability and absolute timing requirements ($\sigma = 1$ ns) were the controlling factors in this design. In addition to the three dimensional problem of arranging and supporting the TTI's for operation and maintenance, they are necessarily compound in order to produce identical electrical lengths from unequal mechanical lengths.

Overall program requirements mandate that this laser be operational by the end of FY03. Therefore, the pulser will be equipped with a gas-switched Marx primary store initially. A solid state switched unit will be retro-fitted when the IFE LGPT is available (presently planned for FY06).

Discharge time for the Marx in this MPC is ~ 150 nsec ($T/2$). With an erected capacitance of ~ 30 nF the equivalent inductance of the Marx and connections needs to be ~ 150 nH. In order to meet this inductance in the gas switched version, four parallel four-stage Marxes will be used. The solid state retro-fit will most likely require only two Marxes in parallel, owing to the reproducible low inductance current path intrinsic to the rail aspect ratio design of the IFE LGPT.

V. Program Next Phase

The technologies developed in the Electra program will be demonstrated in a follow-on phase known as the IRE (Integrated Research Experiment). Pulsed power, laser, optics, chamber and target technologies will be combined for an integrated demonstration over a planned seven-year period beginning in FY07. We currently plan to build four 100 kJ IFE modules, two 10 kJ Mid-amps and one 2 kJ front-end amp for the IRE.

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