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PULSED POWER ASPECTS OF THE NIF PLASMA ELECTRODE POCKELS CELL*

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Abstract

The *Plasma Electrode Pockels Cell* (PEPC) embodies technology essential to the National Ignition Facility (NIF). Together with a thin-film polarizer, PEPC functions as an optical switch for the main amplifier cavity, allowing optical pulses to be trapped, and then released, and enabling NIF to take advantage of the attendant gain and cost-savings.

Details of the genesis, development, and prototyping of the PEPC are well documented. [1]–[5]. After moving from its laboratory setting to the NIF facility, PEPC—via its performance during the two-year NIF Early Light (NEL) campaign and its ongoing operation during facility build-out—has proven to be a fully functional system. [6, 7] When complete, NIF will accommodate 192 beams, capable of delivering 1.8 MJ to a fusion target. Forty-eight Plasma Electrode Pockels—driven by nearly 300 high-power, high-voltage pulse generators—will support this complement of beams.

As deployed, PEPC is a complex association of state-of-the-art optics; low-voltage and high-voltage electronics; and mechanical, gas, and vacuum subsystems—all under computer control. In this paper, we briefly describe each of these elements, but focus on the pulse power aspects of the PEPC system.

I. BACKGROUND

A. Plasma Electrode Pockels Cell: Optical Performance and Electrical Operation

PEPC's location in a NIF beamline is represented schematically in Figure 1. The depicted beamline represents one of the nearly 200 beamlines that will be operational in NIF. The path of light through the optical system is as follows: A low-preamplified optical pulse enters the cavity in the transport spatial filter, passes through the power amplifier, and then enters the periscope section of the beamline. From there, the light reflects off of a mirror (LM3) and a thin-film polarizer, passes through the Pockels cell, and enters the slabs of the main amplifier. Exploiting the two, 90°-polarization rotations introduced by the Pockels cell via the second and third passes, the beam completes four gain passes through the main amplifier before being switched out of the cavity, where it re-enters the power amplifier before propagating to the target chamber.

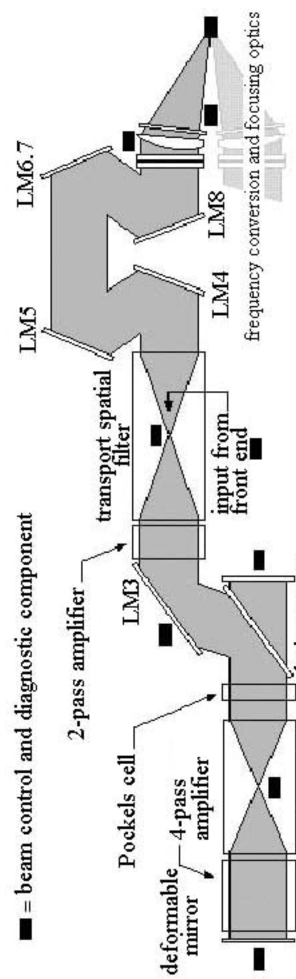

Figure 1. Location of the Pockels cell in NIF

The required lateral dimensions of the KDP, square cross section of the NIF beam coupled with its fluence and power density eliminate the possibility of using more conventional techniques (such as metallic ring electrodes or transparent, conductive thin films) for impressing a uniform electric field on the KDP across the entire face of the crystal. Thus, plasma "electrodes" are formed in the low-pressure (~70 millitorr) process gas that resides on both sides of the crystals in cell. An electron density of ~10^{12} cm^{-3} provides sufficient conductivity to produce an equipotential surface at the face of the crystal, thus allowing a uniform electric field to be applied to the entire

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KDP crystal, resulting in uniform, efficient switching. [Four, 5] Application of a 16.4kV/cm field in the crystal (or equivalently 16.4 kV (V_π) to the 1-cm thick crystal) produces a birefringence that results in the required 90 degree rotation of the polarization of the laser beam.

Thus, electrical requirements for the Plasma Electrode Pockels Cell can be summarized as follows: Initiate allow-density plasma within the individual channels of the cell. Raise the electron density in the channels to a level sufficient to provide equipotential surfaces for the application of the required crystal bias. Apply crystal bias during passes during passes 2 and 3, effecting a 90° polarization rotation on each of the passes. Avoid any beam interactions on passes 1 and 4.

II. ELECTRICAL/PULSED POWER CONSIDERATIONS

B. Cell Design

As Figure 2 illustrates, the NIF Pockels cell actually comprises a 4x1 vertical array of optical apertures, and consequently, interacts with four independent beams. Each of the four 40 cm x 40 cm (clear) apertures comprises a non-linear KDP crystal sandwiched between plenums of low-pressure gas that, when sufficiently ionized, serve as optically transparent electrodes for the application of crystal bias. A glass midplane, with its four embedded KDP crystals, divides the cell in half along the vertical axis.

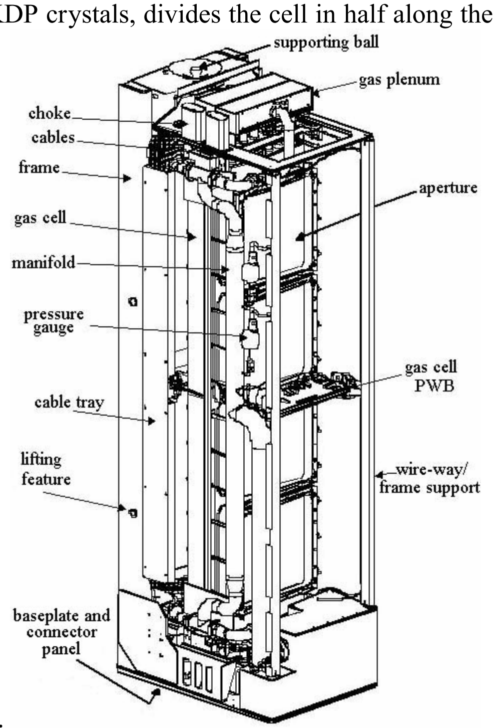

Figure 2. Illustration of Plasma Electrical Electrode Pockels Cell assembly details, including four optical apertures. The Unit is 2.6 meters tall, and weighs 800 kilograms.

From an electrical standpoint, it is impractical to treat each aperture as a separate and independent entity. In particular, four independent plasma channels exist within the Pockels Cell, with each spanning a pair of crystals on a given side of the cell centerline. Bias is applied to pairs of crystals, with bias pulses simultaneous applied to top pairs and bottom pairs of crystals. Thus, ten separate excitations are applied to a single NIF Pockels cell: four low voltage, low current excitations are applied to the four gas channels to establish the low density plasmas (referred to as the simmer), the electron density is increased by superimposing four multi-kiloampere pulses to the low density plasma and, finally, a pair of bias pulses is applied to the crystals using the plasma channels as electrodes.

The dimensions of the individual plasma channels are approximately 85 cm x 45 cm x 5 cm. The anode for each gas cell is segmented into 6, individually-ballasted electrodes to promote current sharing and plasma uniformity. Single-element cathodes utilize a planar magnetron design to promote ionization and achieve required plasma conductivity and uniformity. [8] As a hedge against contamination of the optical surfaces, electrodes are fabricated from high purity graphite. Ideally, material sputtered from the surfaces of the electrodes combusts in the presence of the oxygen in the process gas (99% He, 1% O_2) and is pumped away as CO or CO_2.

The 85-cm span of the plasma channel is sufficiently long to require a secondary anode to initiate the plasma. A so-called starter anode, heavily biased, is located only a few centimeters from the cathode to initiate the breakdown and provide a ready source of electrons for establishing the plasma throughout the channel.

The nominally planar plasma in the cells has a tendency to pinch, producing a wasp-waisted channel. While this is relatively unimportant during the initiation phase is unacceptable during the period when the crystal bias is applied. To mitigate this tendency a pair of techniques is used to increase plasma uniformity. [10] In the first, a so-called magnetic spreading technique, a substantial fraction of the current delivered to the cell is diverted around the plasma in two identical current loops that route their way around the exterior of the gas cell. Approximately 20% of the total discharge current is diverted into each of these circuits, producing **JxB** forces that substantially offset the pinch effect. [9] However, this alone has been found insufficient for producing the required plasma uniformity. Biasing the anodized aluminum cell body to a potential near that of the plasma also enhances plasma performance by imparting a net outward drift to the electron-dominated plasma. [10]

The combination of the plasma, the ballast resistors, the spreader circuit, and the coaxial cable used to deliver the pulse, present to the pulse generator an impedance of ~1 Ω in series with ~10 μH. Peak currents (plasma plus spreader currents) are about 2.2 kA. [11]

As mentioned, NIF employs a four-pass main amplifier architecture that requires a mechanism for switching the beam in and out of the main amplifier cavity. PEPC is required to turn on between the first and second passes of the laser beam, remain on for passes 2 and 3, and then return to a quiescent state between the third and fourth passes. These requirements determine the permissible risetime, flattop, and falltime of the applied bias. In particular, the permissible bias applied during the propagation of passes 1 and 4 is less than 2% of V_π. During passes 3 and 4, the applied bias may deviate by less than 2% from V_π.

As noted, pulses are applied to pairs of crystals by coupling plasma channels that have been established on both sides of the crystals. The dielectric constant of KDP is approximately 25. The large cross-sectional area of the KDP results in a pair of crystal with 6nF of capacitance. Under normal circumstances, a pulse arriving at the cell simultaneous to a companion pulses sees a 6-nF capacitance. To achieve the requisite risetime and falltime the Switch Pulse Generators (SPGs) are designed to have an output impedance of 6.25 Ω. Pulses are delivered to the Pockels cells on 8 parallel 50-Ω coaxial cables (RG-217). A slight amount of "peaking" is achieved by placing 7.5 Ω and 70 nH in parallel with the effective capacitance of each pair of crystals. It should be noted that simultaneous arrival of both bias pulses is essential. The top and bottom regions of the cell are so tightly coupled that a pulse that arrives early sees not only the 6 nF of the nominal load but also the 6 nF of its companion set of crystals. The obvious effect is an increase in risetime and the reduction of applied voltage.

The use of multiple excitations introduces the added issue of counter-propagating pulses and the potential for damage, especially in the lest robust elements of the pulse generators. For this reason, the Pockels cell is equipped with 8 common mode chokes that block these counter-propagating SPG pulses. These chokes are part of the cable system that distributes the simmer and plasma excitations. Diodes are sufficient for isolating the simmer supply from the main PPG discharge.

III. PULSE GENERATOR DESIGNS

Each Pockels cell is supported by a pair of switch pulse generators (SPGs) and four plasma pulse generators (PPGs). Each PPG contains the elements that initiate and then fully develop / maintain the required plasma. The SPGs provide the bias to pairs of KDP crystals in the cell.

Low voltage, low current simmer supplies residing in the PPGs create a plasma in each of four plasma channels by initiating a glow discharge in the process gas. As noted, this initiation process is aided by the existence of auxiliary ("starter") anodes located in close proximity to the planar magnetron cathodes. The short gap between the auxiliary anode and the cathode promotes ready breakdown and supplies ions and electrons necessary to create a uniform glow discharge in the larger gas cell. Drive current to the starter anode is heavily ballasted to limit energy delivered to the gap. The impedance between the segmented anode and the cathode is effectively is limited by the supply itself. Once the supply detects a breakdown event it reduces its output voltage and drops into a current regulated mode. Typically, the simmer event is started 300 ms prior to the arrival of the main plasma discharge and extends for 100 ms after the optical pulse has passed. The simmer discharge, easily observed during final electrical testing, is shown in Figure 3. Note the constriction of the simmer discharge. No plasma spreading or cell body bias is used for the simmer discharge.

Figure 3. Simmer discharge in the NIF Pockels Cell.

Each PPG also contains a capacitive discharge circuit used to increase the electron density in the plasma established by the simmer discharge. Early PPGs were equipped with a thyratron main switch but on-going improvements in semiconductor technology have permitted a transition to a single, optically-triggered thyristor, greatly decreasing the overall complexity of the units as well as decreasing acquisition costs. A simplified schematic of the PPG is shown in Figure 4. Units are deployed as standard 19” rack-mount chassis, requiring only 120 VAC power and an optical trigger for inputs. The simmer excitation is delivered to the cell on RG-58, while the main discharge is transmitted on RG-213. Each unit is also equipped with a current transformer that provides a timing fiducial to the control system. While no embedded controller is included in the unit, all interaction is remotely effected via the PEPC control system.

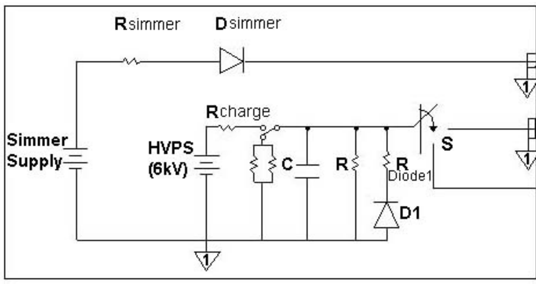

Figure 4. Simplified schematic of PEPC PPG.

Each PPG stores approximately 60 J for delivery to the Pockels cell. As noted, a sizeable fraction of the stored energy is diverted to a plasma spreading circuit and for supplying body bias. These effects are evident in Figure 5, captured during the main plasma discharge. Note as well the obvious segmentation of the anodes.

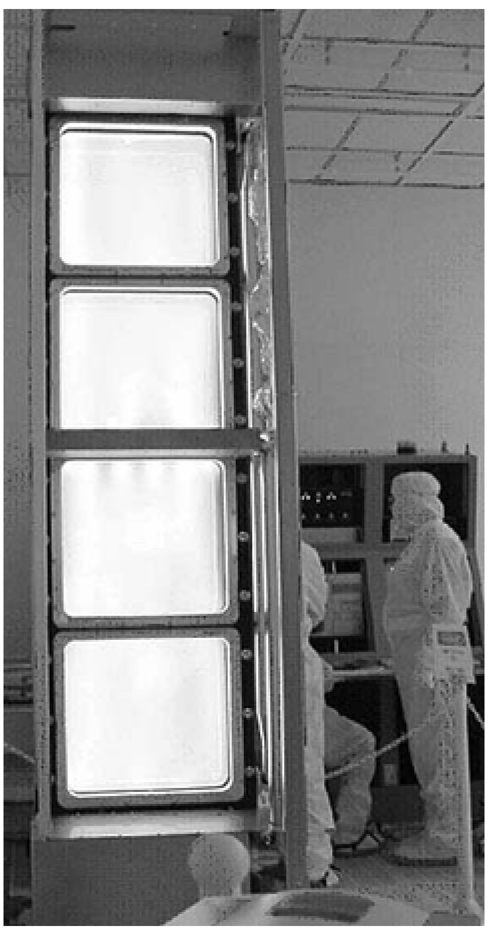

Figure 5. Main plasma discharge in a Pockels cell under test in a cleanroom environment.

The final excitation, produced by the SPG, induces the required birefringence in the KDP and causing the 90° polarization rotation of the light traversing the cell. The SPGs are low impedance drivers whose output pulses results from switching a 6.25-Ω PFL in the pulser. The plasma channels act as the electrodes for the uniform application of the electric field to the KDP crystals.

Each SPG comprises a standalone cabinet containing a thyratron main switch, a 6.25-Ω pulse forming line, 40-kV power supply, and ancillary equipment. A simplified schematic is shown in Figure 6. As in the case of the PPGs, power is supplied by a 120 VAC circuit. An optical trigger is supplied by the NIF timing system. An output current monitor provides a timing signal to the control system. The power supply is remotely adjustable for “fine tuning” the optical performance of the Pockels cell. No embedded controller is included in the unit. All “intelligence” is embedded in the control system, which controls all SPG functions.

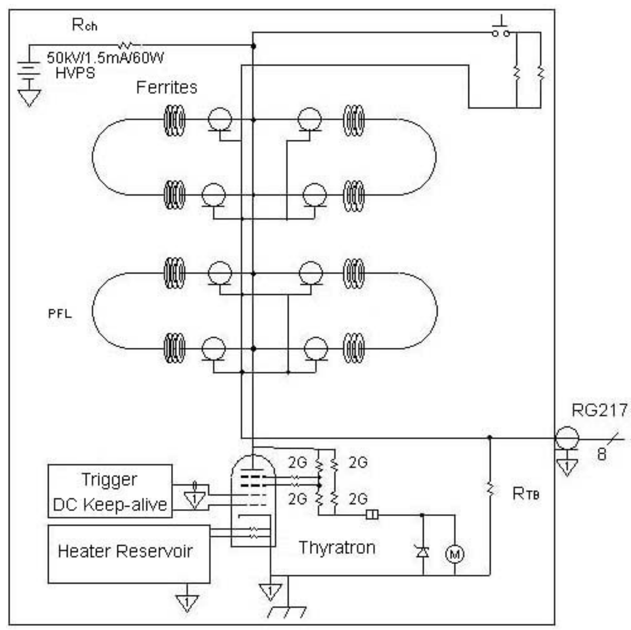

Figure 6. Simplified schematic of PEPC SPG

IV. PEPC SYSTEM CONSIDERATIONS

C. PEPC Control System

PEPC is a complex subsystem and, as such, relies on the contributions of many components. Each of these components is designed as a line replaceable unit, i.e., a defective unit in the facility is replaced by a spare device; all repairs take place in an offline facility.

Though only a small portion of the larger NIF laser system, PEPC is nevertheless a significant subsystem in both importance and sheer magnitude of equipment deployed. When fully deployed, PEPC will comprise more than 5000 inter-rack cables. Nearly 100,000 meters of high voltage coaxial cable will have been installed. The pulsers and control systems will occupy more than 160 racks. Forty-eight Pockels cells will interact with 192 NIF beams.

PEPC is interacts with other NIF subsystems. In particular, PEPC is interfaced with and dependent upon the precision NIF timing system and well as Front End Processors (FEPs), data acquisition equipment and computer software/controls provided by the NIF Integrated Computer Control System (ICCS).

The overall PEPC control system is depicted in block diagram form in Figure 7. The figure also illustrates the relative location and interdependence of the PEPC control system within the global NIF control system. As noted, PEPC is dependent upon the NIF timing system for the precise optical triggers that allow it to effectively interact with the beam as well as capture necessary performance data. It interacts with the system archives to store data from system shots. The PEPC supervisory system is capable of autonomous operation for independent subsystem testing such as that required following installation and during commissioning phases. The supervisory system merges seamlessly with the NIF Shot Supervisory and Shot Director software for integrated, main laser shots.

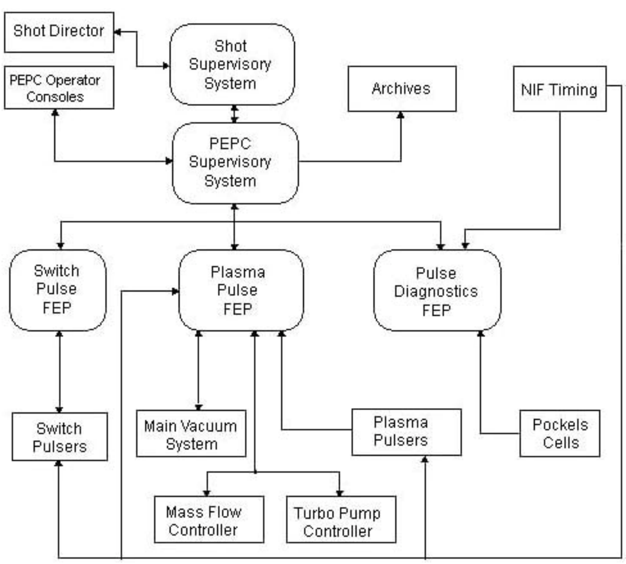

Figure 7. PEPC Subsystem within the larger NIF Control System.

V. SUBSYSTEM SHOT OPERATIONS

PEPC operation is essentially limited to the last five minutes of the shot countdown. In particular, 280 seconds before the main laser is fired, the control system initiates a sequence of events that culminate in PEPC interaction with the main laser beam to achieve four-pass main amplifier performance. At this point almost 5 minutes before the system shot, gas flow is initiated in the cells, which heretofore are held at the base pressure of the onboard turbomolecular drag pumps. The system waits until pressure stabilizes at 70 millitorr (less than 10 seconds) before starting the low voltage simmer supplies in the plasma pulse generator. Five pulses are applied at the standard PEPC heartbeat rate of 0.2 Hz. The voltage and current of the simmer supplies are monitored for nominal performance. If the simmer passes its performance checks, control system moves to the next phase.

At this point, the main plasma pulse generator discharges are initiated. Waveform data for the PPG main current pulses are compared by a software algorithm to known standards. Once the PPG waveforms have passed their limit checks, the SPGs are started. Once again, the SPG waveforms, corresponding to the applied voltage across the KDP crystals, are automatically checked for performance. SPG temporal alignment is particularly critical. Thus, the control system is capable of temporal resolution of 1 ns. Once all SPGs are determined to be operating normally, flags are displayed on the consoles available to the PEPC operator and the shot director. PEPC continues to fire once every 5 seconds as other systems—such as the flashlamp power conditioning system and the pre-amplifier module power conditioning unit—charge. PEPC continues to trigger until 5 seconds after the main shot, allowing post shot data to be acquired and archived. The computer control system then shuts down PEPC in reverse order, actively monitoring and displaying performance for the operator until the cell pressure has stabilized again below 5x 10^{-5} Torr.

VI. PEPC PERFORMANCE TO DATE

Installation of PEPC equipment in the National Ignition Facility began in the summer of 2002. A pair of Pockels cells was installed, along with all necessary ancillary equipment e.g., 4 SPGs, 8 PPGs and more than 30 individual control and diagnostics chassis occupying 12 racks. For 2 years, the Pockels cells supported shot operations with near flawless performance. Recently, the number of Pockels cell and pulse generators has doubled and is being made ready for shot operations that will occur concurrently with the installation phase of NIF. Additional equipment is on-hand and/or in the production pipeline for installation, activation and commissioning in the facility.

VII. FUTURE

PEPC will mirror NIF's upcoming "build out." Over the next 3 years 48 Pockels cells, 192 PPGs and 92 SPGs along with their ancillary equipment will be fabricated, assembled, installed, and commissioned. All other assemblies will arrive fully tested and ready for installation and commissioning.

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