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Scott Fochs, Mark Rhodes, Charles Boley

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B-Field interactions and electrode optimization in the plasma electrode Pockels cell

Scott N. Fochs, Mark Rhodes, Charles Boley
University of California
Lawrence Livermore National Laboratory, PO Box 808 L-490
Livermore, CA 94550

Abstract

We use a 32 cm plasma electrode Pockels cell (PEPC) prototype at Lawrence Livermore National Laboratory (LLNL) to determine switching performance in the presence of external magnetic fields. The interaction with external magnetic fields is important because of the B-fields generated by the high current flow through amplifier flashlamp arrays, and their proximity to the PEPC. We have experimentally determined what is the maximum allowable magnetic induction for good PEPC operation, and then we calculate the magnetic induction generated by a flashlamp array to determine the minimum PEPC to amplifier spacing. We have also experimentally determined the effect of a tandem PEPC placement. We consider several cathode designs. We revisit the hollow cathode design and we investigate the tradeoffs between the hollow cathode and planar magnetron. The recent development of a metallic body for the future 1x2 PEPC has led us to do experiments with a biased boundary in the PEPC. Experimental results of various biasing potentials and dielectric coating materials for the PEPC body are discussed.

1. Calculation of B-fields generated by amplifier flashlamp arrays

If a magnetic field is imposed perpendicular to a current flow in a plasma, $\mathbf{J} \otimes \mathbf{B}$ forces will push the plasma in direction's perpendicular to the current flow. In the case of the Pockels cell this would mean either a pinching of the plasma column or a push toward or away from the KDP crystal at the center of the two plasma columns. This is the case for the NIF CDR design and is illustrated in Figure 1.1.

Figure 1.1 PEPC orientation for the NIF baseline design.

Initially, we did numerical calculations for the magnetic fields generated from a flashlamp array using the 2D Finite Element Analysis (FEA) code Maxwell. With this code, the fields from a booster amplifier could not be calculated since the booster amplifier does not lie in the same plane as the amplifier close to the Pockels cells. Here, we use exact solutions for the magnetic vector potential $\mathbf{A}$ and magnetic induction $\mathbf{B}$ for finite length current elements. The solution for an array of these elements is simply the addition of the vector fields generated by each individual element. Using this technique we can calculate the fields in 3 D for any flashlamp array at any location in 3 space. The magnetic potential due to a current density $\mathbf{J}$ can be written as.

$$A = \frac{\mu_o}{4\pi} \iiint_{dv} \frac{J}{R} dv \quad (1.1)$$

Equation 1.1 can be simplified if we assume a thin wire current element. Using Ampere's circuital law, we can convince ourselves that this is a valid assumption if the area of interest is outside the actual diameter of the wire. With this being the case for the flashlamp array of a NIF amplifier (i.e. no flashlamps overlap either each other or the Pockels cell), Equation 1.1 becomes,

$$A = \frac{\mu_o I}{4\pi} \oint_C \frac{dl'}{R} \quad (1.2)$$

where I is the total current through the wire, and R is the distance from element dl' . With the current flowing in the z direction and using Figure 1.2, Equation 1.2 becomes in Cartesian coordinates,

Figure 1.2 Schematic of current loop.

$$A_z = \hat{a}_z \frac{\mu_o I L}{4\pi} \int_0^L \frac{dz'}{\sqrt{(z' - z)^2 + x^2 + y^2}} \quad (1.3)$$

where L is the length of the current element. Equation 1.3 has a solution in closed form and is given by

$$A_z = \hat{a}_z \frac{\mu_o I}{4\pi} \ln \left[\frac{L - z + \sqrt{x^2 + y^2 + z^2 - 2zL + L^2}}{-z + \sqrt{x^2 + y^2 + z^2}} \right] \quad (1.4)$$

The magnetic induction B is given simply by

$$\mathbf{B} = \nabla \times \mathbf{A}, \quad (1.5)$$

which for the case of a current in the z direction, gives the vector components B_x and B_y . At this point the equations for $\mathbf{B}$ become lengthy and will not be written. Figure 1.2 is configured as a rectangle current loop because that is approximately the way the flashlamps are configured for NIF. For the case of the amplifier assembly the flashlamps are configured such that the flashlamps are pulsed in pairs and electrically connected in series. Like that of Figure 1.1, the current in each flashlamp flows in opposite directions. This gives some degree of canceling effects of the magnetic forces and fields. To make the model more accurate, we also included the wires connecting the pair of flashlamps in the model. This gives a rectangular current loop for each pair of flashlamps. We now have the magnetic potential components A_x and A_y and the magnetic induction components B_x , B_y , and B_z . It is assumed that a coax cable is used to bring the current to the pair of flashlamps and thus no field is induced by the incoming current. The total magnetic potential and induction are now the sum of all the flashlamp pairs in the amplifier assembly. In other words, the total is the sum of Equation 1.4 and the results of Equation 1.5 offset for the location of each pair of flashlamps in the amplifier assembly. For example, the total magnetic potential in the z direction could be written as

$$A_{\text{Total}} = \sum_{x_0} \sum_{y_0} \sum_{z_0} A_z(x - x_0, y - y_0, z - z_0). \quad (1.6)$$

Using this approach, we calculated the magnetic vector potential $\mathbf{A}$ and induction $\mathbf{B}$ due to the NIF amplifier flashlamps. As a check on the mathematics, we made a comparison between the FEA 2D code Maxwell and the analytical results. For the comparison we calculated the magnitude of the induction for a single amplifier array using both Maxwell and our analytical approach. Since Maxwell is a 2D code, we set the length of the flashlamps in Equations 1.4 and 1.5 to large number such as 1000 meters. The numerical and analytical results agree to within 1 %. We did Calculations for a 12x4x5 amplifier flashlamp array and, not surprisingly, the maximum field was determined to be at the plane that cuts the flashlamps in two. Using Figure 1.1 as a reference, the plane would be the y, z, plane centered at the mid-plane of the flashlamps. For the NIF baseline and a flashlamp current of 28 kA, the calculated magnitude of the magnetic field and the flux lines are given in Figure 1.3.

Figure 1.3 Magnetic field magnitude generated by a 12x4x5 NIF baseline amplifier flashlamp array.

The two lines of Figure 1.3 represent the space allotted for the PEPC in the original NIF baseline design. With this being the case, the magnitude of the field generated by flashlamps is in the 30-50 Gauss range. This is well in excess of the 10 Gauss field that we experimentally predict to have a significant effect on the plasma. For the NIF baseline case, the flashlamps in Figure 1.3 have inherently alternating current directions along the horizontal axis due to the fact that the flashlamps are

connected in pairs as current loops. However, along the vertical direction of Figure 1.3 the current is not alternating from lamp to lamp. We found that alternating the current from lamp to lamp in both the horizontal and vertical direction optimized the cancellation effect and can significantly reduce the field levels. One can reduce the magnetic field levels even more by increasing the distance from the amplifier array. A schematic of the two cases is given in Figure 1.4.

Figure 1.4 Flashlamp current direction and field magnitudes for the NIF baseline case and the case where field cancellation is optimized.

We show The actual calculation for the right hand sided case of Figure 1.4 with Figure 1.5.

Figure 1.5 Magnitude of the magnetic field with alternating flashlamp current in all directions.

The vertical line in Figure 1.5 is the gives a field magnitude of < 3 Gauss, which from experiments, should not significantly impact the PEPC operation. For the case of NIF, the amplifier next to the PEPC was eliminated and interference from flashlamp arrays is no longer an issue, however we have demonstrated that one must take into consideration the effects of flashlamps when placing the PEPC next to a large laser amplifier.

2. PEPC experiments with external B-fields

To determine the effect of an external field on the PEPC operation, we have constructed an experiment on a 32 cm aperture prototype Pockels cell. We are concerned here with magnetic fields perpendicular to the current flow in the PEPC, where the forces will cause the plasma to either pinch or be forced from the face of the crystal. The external magnetic field is generated by a two coils on either side of the PEPC. We mounted the coils around the cell in two configurations giving a magnetic field in the two directions perpendicular to current flow in the PEPC. A photograph of the two configurations is shown in Figure 2.1.

Figure 2.1 Experimental setup to simulate external magnetic fields on the 32 cm aperture prototype PEPC. In both photographs the anode is on the right and cathode is on the left.

Each field coil consists of 17 windings of 10 gauge copper wire. The coils can be used at either DC or pulsed mode. In DC operation the coils can generate a field of 12 Gauss and in pulsed mode the coils can generate a field of up to 100 Gauss. We show the measured extinction ratio for the case of 40 Gauss in both perpendicular directions in Figure 2.2.

Figure 2.2 Measured extinction ratio (E.R.) for a 40 Gauss external magnetic field (NIF baseline case).

In each extinction ratio plot the cathode is on the left and the anode is on the right. The direction of the magnetic field is parallel to the page for the case on the left and perpendicular to the page for the Figure on the right. Both field components are perpendicular to current flow as in the NIF design. The PEPC operation is severely disrupted in the presence of a 40 Gauss field in either direction. Figure 2.3 shows results for an external field of 11 Gauss.

Figure 2.3 Measured extinction ratio (E.R.) for a 11 Gauss external magnetic field.

The cross pattern that is seen on the extinction ratio plots is due to the stress induced birefringence in the window of the PEPC. The corners of the windows have greater stress and more birefringence and, therefore, more depolarization. With an external field of 11 Gauss, the PEPC operation still does not reach the NIF specification of an E.R. of greater than 50 all across the aperture. As shown by Figure 2.3, the upper and lower right hand corner of the right plot, and the lower left hand corner of the left plot show switching deficiencies. We found that fields in the B_y direction disrupt the PEPC performance more than those in the B_z direction. We lowered the external field to 3 Gauss and the resulting E.R. plots are given in Figure 2.4.

Figure 2.4 Measured extinction ratio (E.R.) for a 3 Gauss external magnetic field.

The E.R.'s 2.4 easily meet the NIF specification of a greater than 50 E.R. across the whole aperture. We have determined that a maximum of a 5 Gauss magnetic field can be tolerated by the 32 cm PEPC prototype.

Another concern is how the magnetic fields generated by the current flowing through a PEPC effect the performance of an adjacent PEPC. To address this concern we constructed a PEPC simulator and placed it on top of the 32 cm prototype PEPC. This experiment is shown in Figure 2.5.

Figure 2.5 32 cm PEPC prototype with PEPC simulator placed on top.

The simulator is identical to the 32 cm prototype with the exception that the plasma is simulated by an aluminum plate. We pulsed the simulator with a separate PFN at the same current levels as the PEPC underneath. Figures 2.6 and 2.7 show the switching performance of the PEPC when the simulator is on and off.

Figure 2.6 Extinction Ratio plot with the simulator off.

Figure 2.7 Extinction Ratio plot with the simulator on.

We found that there was no discernible effect on switching with tandem PEPC operation. We even went so far as to over current the simulator by as much as 50%, and we still did not see an adverse effect. We have concluded that the interaction between adjacent PEPC cells does not effect the PEPC optical performance.

3. Experiments with planar magnetron and hollow cathodes

In order to lower the costs and increase pumping efficiency for NIF, the individual beams are packed tightly. As the beam spacing is minimized, the cathode and anodes must be made smaller and/or placed closer to the optical aperture. The physical space necessary for a cathode design becomes an important criterion. Plasma non-uniformity's in and near the cathode sheath region significantly degrade PEPC performance. This precludes the placement of cathodes to close to the optical aperture. Our definition of cathode to KDP standoff is illustrated in Figure 3.1. We have done experiments to determine the overall performance of several magnetron cathodes, and hollow cathode designs, and have determined the stand-off requirements for each design. To determine the standoff requirements, we placed the cathodes over the edge of the optical aperture, and we recorded the effects on switching performance. Figure 3.2 is an extinction ratio plot of our standard planar magnetron design. Here, we show both the on state of the PEPC, or switch in to the amplifier, and the off state of the PEPC, which is the case were the pulse is switched out of the regenerative amplifier. The plots of Figure 3.2 show that the planar magnetron cathode requires a minimum of 4.8 cm standoff to meet the NIF specification of minimum extinction ratio of 50:1. This large space requirement is offset by the fact that the planar magnetron can be made thin. We have tried several other magnetron designs such as, a thinner planer magnetron and a magnetron consisting of only one row of magnets, and have seen similar or slightly worse results. The extinction ratio plots for a large 3.68 cm depth hollow cathode are given in Figure 3.3. The hollow cathode requires significantly less standoff than that of the magnetron cathode. This small standoff requirement is offset by the fact that the hollow cathode is a large device and requires

Figure 3.1 Cathode to KDP standoff.

Figure 3.2 Extinction ratio plots for the planar magnetron cathode.

Figure 3.3 Extinction ratio plots for the 3.68 cm depth hollow cathode.

more physical space than that of a magnetron cathode. We have tested a 2.54 cm depth hollow cathode in an effort to reduce the physical size of the cathode. The extinction ratio plots of this experiment are shown in Figure 3.4. A decrease in hollow cathode depth yields the worst performance of all of the cathode designs. In all of the experiments we have found that the overall performance of the large depth hollow cathode is better than that of the magnetrons. The hollow cathode exhibits better plasma uniformity and switching uniformity, but operates at a pressure of 100 mTorr instead of the 35 mTorr of a magnetron cathode. The higher pressure tends to make it easier for the plasma to leak to ground through the vacuum system. This can be circumvented by an increase in the baffling of the vacuum system, but this may be at a cost to the PEPC base pressure. We are currently designing a NIF 4x1 prototype that will be able to accommodate all of the cathode designs. With this configuration we will be able to determine the tradeoffs in space, performance, and pressure.

Figure 3.4 Extinction ratio plot for a 2.54 cm depth hollow cathode.

4. Boundary potential bias experiments

The next generation 2x1 PEPC body is made from aluminum instead of the previous designs that were made from a dielectric substance. The current cost for a glass cell is prohibitive and plastics do not have the required mechanical rigidity. This poses two problems. A suitable dielectric coating must be found to prevent arcing to the cell walls at the boundaries of the plasma, and the potential of the body can be at any of the three potentials of the cathode, anode, or floating. We have performed experiments with the 32 cm prototype, placing metal plates on the top and bottom wall with two different coatings and at the different boundary potentials. The two coatings are hard anodization, which is the current coating on the 1x2 PEPC body, and a coating called parylene. We have determined with experiments that a 50 μm parylene coating is capable of holding off ~ 18 kV and a 100 μm hard anodization coating is capable of holding off ~ 1000 V. Parylene is a vapor deposited coating that will peel if scratched while hard anodization is much more durable. We have found that a parylene coating is much less susceptible to peeling if the surface underneath is anodized. We attribute this to the fact that the anodized coating is porous, giving the parylene more surface area to cling to.

The boundary potential options are illustrated in Figure 4.1. Since we use ballast resistors on the segmented anodes there are two possible anode potentials. With the operating parameters of the 32 cm prototype, the voltage drop across the ballast resistors is ~ 600 V at the peak of the current pulse. A picture of one configuration where plates are placed into the PEPC is shown in Figure 4.2. We found that placing the plates at cathode potential increased the amount of plasma pinching and created an area of deficient switching in the corner near the anode.

Figure 4.1 Schematic of the possible potential the PEPC body could be set to.

Figure 4.2 Metal plates in the 32 cm PEPC prototype to simulate a metallic PEPC body.

We show this in the plasma image plots and extinction ratio plots of Figure 4.3. For the case of the data of Figure 4.3, and for the rest of the data presented, there is only one plate at the top of the cell. With the potential of the plate floating, there is slightly less pinching and only a slight degradation of switching performance in the upper corner near the anode. We show this data in Figure 4.4. The results for the plate at anode potential are shown in Figure 4.5. There is a noticeable decrease in plasma pinching and no degradation in the switching in the upper corner. We achieved the same results with the plate set to the anode bus potential, however the anodized coating broke down in several places. This breakdown damage consisted of ~ 1 mm spots where the coating was ablated away.

Figure 4.3 Plasma image and measured extinction ratio for a plate place at the top of the cell at the cathode potential.

Figure 4.4 Plasma image and measured extinction ratio for a plate place at the top of the cell at the floating potential.

Figure 4.4 Plasma image and measured extinction ratio for a plate placed at the top of the cell at the anode potential.

The most unforeseen result of these experiments was when the damaged plate was placed back to the anode potential. The plate did not arc even in areas where the coating was ablated. We even went so far as to physically scratch the anodized coating to simulate mechanical damage, and the plate still did not arc. We did all of the above experiments with parylene coated plates and achieved the same results with the exception that the coating did not breakdown when the plate was connected to the anode bus potential. Since the anodized coating did not breakdown when the plate was placed at anode potential regardless of whether or not it was damaged, we will first run the 2x1 PEPC in this configuration.

5. Conclusion

Experiments have shown that the PEPC is sensitive to external magnetic fields greater than 5 Gauss. This is an important fact to consider when placing a PEPC near a source of magnetic fields like that of a flashlamp array. For a NIF 12x4x5 amplifier flashlamp array, with the currents alternating in all directions, the amplifier to PEPC spacing must be greater than 1.6 meters. We have also completed experiments that show that the magnetic fields generated by individual PEPC's do not effect the performance of adjacent cells. We have revisited the hollow cathode and have done experiments showing better performance at the pressure of 100 mTorr instead of 35 mTorr. The hollow cathode needs less cathode to optical aperture standoff and exhibits better plasma and switching uniformity. The tradeoffs are an increase in cathode size in a location that requires small size, and the higher operating pressure of 100 mTorr requires more baffling to prevent plasma leakage to ground through the vacuum system. We have done experiments showing that biasing a boundary at the anode potential actually improves PEPC performance. An anodized coating does not breakdown with a boundary at anode potential, even in the case of a damaged coating. Based on these results we are first configuring the next generation 2x1 PEPC with an anodized aluminum body.

Technical Information Department • Lawrence Livermore National Laboratory
University of California • Livermore, California 94551