eration in He and Ne to extend the range of coherent wavelengths to 53.2 nm. Conversion is in the range of 10^{-5} to 10^{-6} with further optimization believed to be possible. This work represents the first application of frequency upconversion to the extreme ultraviolet with use of optical nonlinarities of higher order than third, and indicates the feasibility of using such processes to extend the range of available coherent wavelengths ever closer to the soft x-ray range.

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Production of Intense Proton Beams in Pinched-Electron-Beam Diodes*

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A polarity-reversed 10^{12}-W relativistic-electron-beam generator operating in the self-pinched mode is used to produce and propagate intense proton beams. Charge-neutralized beams of 30–50 ns duration consisting of over 4×10^{16} 0.5–0.8-MeV protons distributed over a 120-cm^2 cross-sectional area are routinely produced. The 150–200-kA average ion currents deduced from these measurements are in good agreement with theoretical calculations.

High-power relativistic-electron-beam generators have recently been used to create high-current proton beams in both reflex-triode[1,2] and magnetically-insulated-diode[3] modes of operation. These ion beams may have application to controlled fusion research in the areas of diffuse-plasma heating,[4] magnetic confinement (field reversing p layers),[5] and pellet fusion.[6] Here, we report on the efficient production of intense proton beams using the 10^{12}-W Gamble II pulser[7] driving a field-emission diode in the self-pinching mode.[8] Charge-neutralized beams of 0.5–0.8-MeV protons with average ion currents of up to 200 kA have been propagated 50 cm in the present experiments. The measured ion-beam characteristics are in good agreement with theoretical calculations.[9,10]

Experiments were performed on the Naval Research Laboratory Gamble II generator operated in positive polarity so that ions accelerated by the diode voltage could be extracted from the outer (negative) electrode at ground potential and drifted in an evacuated tube. Approximately 25–30 kJ were delivered to the nominal 1.5-Ω diode during the 50-ns electrical pulse with peak currents (ion + electron) of 500–600 kA flowing across it. *In situ* measurements of intense deuteron currents flowing in the diode with Gamble II operated in negative polarity have been reported elsewhere.[11] Lower-intensity ion beams from pinched-beam diodes have also been reported.[12]

A schematic diagram of the experimental setup

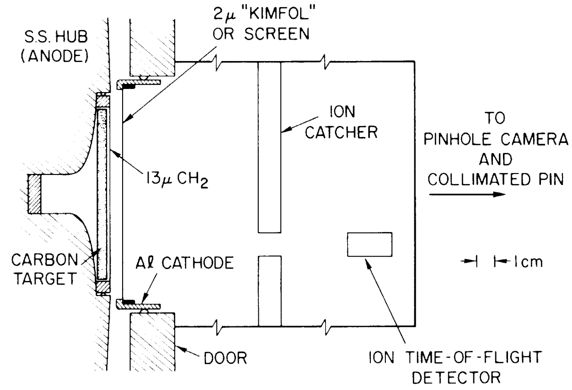

FIG. 1. Experimental setup.

including the anode-cathode region and ion-diagnostic arrangement is shown in Fig. 1. Two anode configurations were employed. The first type of anode (shown in the figure) consisted of a 10-cm-diam carbon target within a brass retaining ring which was, in turn, attached flush with the center-conductor hub. Protons were extracted ei-carbon as shown or from hydrocarbon gases adsorbed on bare carbon anodes. The cathode consisted of a thin aluminum ring 14 cm in diameter, the interior of which was covered either by 2-μm-thick Kimfol polycarbonate foil or by fine-mesh, highly transparent stainless-steel or copper screens. These cathode foils and screens transmitting incident ions were sufficiently conductive to define a ground-potential surface and provided electrons to produce space-charge neutralization of the ion beam. The charge-neutralized ion beam then propagated ballistically in the drift section behind the cathode. Both types of cathode-transmission surfaces were recessed about 4 mm with respect to the aluminum ring in order to prevent premature shorting of the diode due to plasma motion. Greater ion yields were usually obtained by removing the carbon anode so that a vacuum gap between the polyethylene foil and the anode hub was created.

The formation and pinching of the electron beam was monitored by observing target bremsstrahlung from (a) the entire diode using a scintillator-photodiode combination and (b) a region 3 cm in diameter about the anode axis using a well-shielded p-i-n diode viewing radiation collimated by a 3-mm-diam pinhole. The same pinhole was used to form time-integrated x-ray images of the electron pinch which provided information on pinch quality and centering. The time variation of ion current as well as time-of-flight data were obtained with a 125-μm-thick NE-102 scintillator-photodiode pair. Time-integrated measurements of ion yield were made using a nuclear activation technique. A carbon target was exposed to the ion beam and subsequently measured for induced annihilation radiation [0.51-MeV γ rays arising from the reaction $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C$ with two NaI counters in coincidence. From the known thick-target yield of the reaction,[13] the number of incident protons was deduced. The induced reaction exhibits resonances at 0.46 and 1.70 MeV with the yield nearly independent of proton energy between the two values. A difficulty with this technique is either ablation of the activated front surface of carbon or enhanced diffusion of ^{13}N in the heated solid due to the high energy-density of the incident ion beam. In order to minimize such errors, a series of two to four fine mesh screens were routinely placed between the cathode and carbon-activation target. The screens were far enough apart to allow scattering (due to passage through the Kimfol) to "fill in the holes" in the beam, caused by attenuation of one screen, before encountering the next screen. For average proton fluences of about 1×10^{14} cm^{-2}, the inferred yield without any screens was about 1.8 times lower than when a single screen was inserted between the cathode and the carbon target. Nuclear activation measurements using different numbers of screens to attenuate different sections of a single ion beam demonstrated that the final screen reduced the beam flux to a value given by its optical transmission, about 34%. This result suggests that ablation and/or diffusion errors were eliminated when a sufficient number of screens were employed. An additional refinement to the activation measurements was required because activated carbon in the Kimfol deposited on the carbon sample. A typical 15–25% correction to the observed activity of the carbon target was made by subtracting the activity of an aluminum sample occupying $\frac{1}{4}$ of the target area. When metal screens formed the transmission cathode, the correction amounted to only about 2%. A correction of below 5% associated with the reaction[14] $^{12}C(d,n)^{13}N(\beta^+)^{13}C$ produced by naturally occurring deuterium in the anode was usually neglected. However, because of the strong energy dependence of the reaction cross section, analysis of proton beams of greater than about 1-MeV energy do require a deuteron correction.

Figure 2 contains time-synchronized oscilloscope traces depicting diode-current and voltage characteristics, the total and collimated x-ray signals, and the ion-excited scintillator signal.

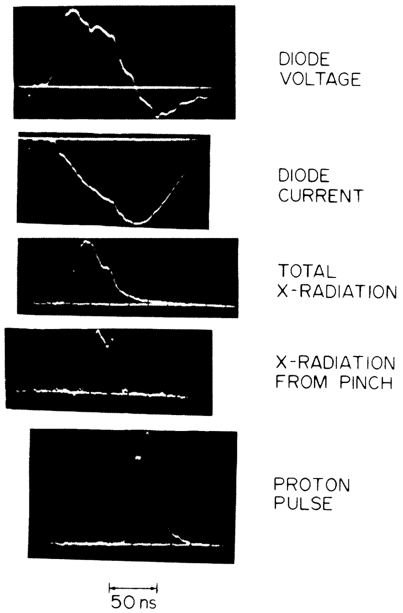

FIG. 2. Typical wave forms for a configuration where impedance collapse occurred 50 ns into the pulse. The peak voltage and current for the top two traces were 1.1 MV and 760 kA on this shot. The diode voltage is uncorrected for diode inductance, which was about 26 nH.

The arrival time of ions at the scintillator is consistent with their having an energy equal to the inductively corrected diode potential less the collisional loss in the Kimfol, and with a start of ion emission coincident with the pinch arrival at the diode axis.[8] These data were obtained with a solid anode and a 0.32-cm^2 area scintillator located 4 cm off axis and 50 cm from the anode.

In excess of 4×10^{16} protons were routinely inferred from activation of a 120-cm^2 area carbon target located 22 cm from the anode when Kimfol cathodes and unbacked-polyethylene anodes formed the diode. At 50 cm from the anode, greater than 70% of this yield was observed. From the diode electrical characteristics and ion-scintillator information about the temporal evolution of the ion pulse, an average ion current of over 160 kA and an ion beam-energy content of over 5 kJ were calculated. Roughly 10% of this energy is deposited in the Kimfol. Because of this energy loss and the threshold for activation of carbon,[11] only ions with initial energies exceeding about 580 keV are recorded by activation. Thus, the above proton yields are conservative in the sense that contributions due to sub-580-keV ions produced late in time are neglected.

When solid carbon anodes replaced the unbacked foils, a reduction in ^{13}N activity of about 35% was observed. However, since the diode voltage during the second half of the electrical pulse for carbon-anode shots was observed to drop to a value close to that required for carbon activation, it is not clear that the ion current was reduced in proportion to the activity. Unbacked, thin-foil anodes exhibit matched-load behavior for the entire electrical pulse. Additionally, thin-foil anodes are observed to pinch about 10 ns earlier than solid carbon, allowing for larger time-integrated ion yields.

A simple analytic model for charged-particle flow in pinched-electron-beam diodes predicts that the ratio of ion to electron current is given by[9]

$$I_i/I_e \gtrsim 0.5(R/D)(2eV/m_i c^2)^{1/2}, \qquad (1)$$

where R is the radius of the cathode, D is the effective anode-cathode gap, V is the accelerating voltage, and c is the velocity of light. More sophisticated numerical techniques[10] result in ratios between 1 and 2 times the value given by Eq. (1) depending on the diode geometry. Because of the nonplanar nature of the cathode used in the experiments and gap closure due to plasma motion, the appropriate value of D is somewhat ambiguous. A lower bound for D is provided by the following empirically modified parapotential-flow expression[15]

$$I = I_i + I_e = 5.5\times 10^{-3}\,(R/D)\gamma \ln[\gamma + (\gamma^2 - 1)^{1/2}], \qquad (2)$$

where γ is the electron relativistic factor. Solving Eq. (2) for D using the time-varying diode current and accelerating voltage yields a changing value of D which characterizes the gap between the anode and aluminum ring including the effects of electrode-plasma motion. A reasonable upper bound is determined by adding the 4-mm transmission-anode recess to this value. Results of these calculations are shown in Fig. 3 for a shot employing an unbacked polyethylene-foil anode. The total diode current and corrected voltage are obtained directly from oscilloscope traces. The diode impedance, obtained from the ratio of voltage to current, demonstrates good matching of thin-foil anodes to the 1.5-Ω generator over the full voltage pulse. The range of R/D shown was obtained from Eq. (2) (upper bound) and the succeeding discussion (lower bound). The initial value of the upper bound to R/D is consistent with that obtained using the 4-mm separation

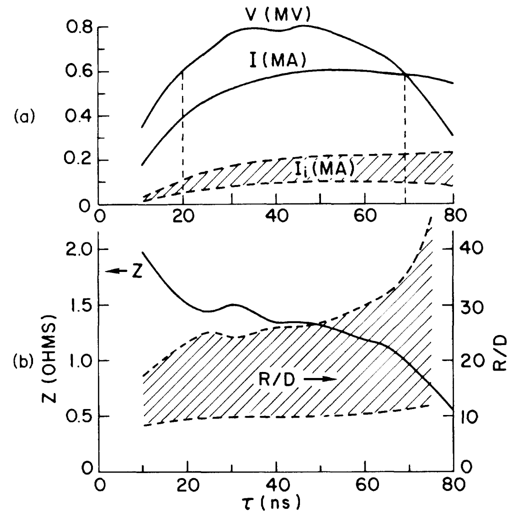

FIG. 3. Theoretical estimate of ion current (I_i) calculated from diode voltage (V) and current (I) wave forms and Eqs. (1) and (2). The electron beam pinches and strong ion emission starts about $t = 25$ ns, typical for unbacked CH_2 anodes.

of the aluminum ring from the anode. The increase above the value with time reflects gap closure due to plasma motion. Using in Eq. (1) the range in R/D shown in Fig. 3(b) results in a predicted ion-current range shown in Fig. 3(a). The two dashed lines at 19 and 69 ns represent the limits inside of which ions striking the target are sufficiently energetic to activate carbon. Within these limits, the mean ion current is calculated to be 93–195 kA corresponding to (3–6) $\times 10^{16}$ protons producing activation. The predicted values from Eq. (1) are therefore consistent with the experimental results discussed above.

It has been demonstrated in this report that intense charge-neutral proton beams can be extracted from self-pinched electron-beam diodes with efficiencies above 30% and drifted in a field-free vacuum region. Of the three techniques employed to date to create such beams, i.e., the reflextriode, the magnetically insulated diode and the self-pinched diode, only the latter utilized no externally applied magnetic field. Ballistic focusing of the ion beams to the high current densities desired for application to fusion research may thus be most easily achieved by using properly shaped pinched-beam-electrode structures.[10,16] Preliminary experiments[12,17] indicate that such focusing is indeed possible.

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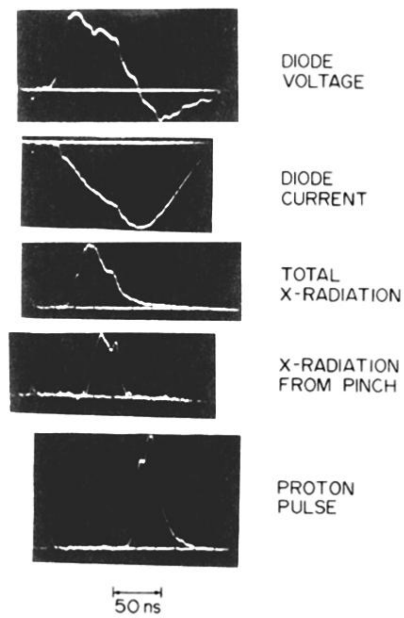

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