IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

THE IFA-2 COLLECTIVE ION ACCELERATOR SYSTEM*

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Summary

A second generation ionization front accelerator system (IFA-2) is being brought into operation. Results of IFA-2 IREB optimization experiments, laser characterization experiments, beam switch experiments, and laser deflector experiments are presented. The status of the IFA-2 system is summarized.

I. Introduction

The ionization front accelerator (IFA) is a high-gradient, high-power, collective ion accelerator in which ions are trapped and accelerated in a strong potential well at the head of an intense relativistic electron beam (IREB).[1] Laser photoionization of a special working gas is used to create a charge neutralizing plasma background through which the IREB will propagate. As the laser is swept, a moving ionization front is created which is synchronously followed by the potential well. With an initial system (IFA-1), accurately-controlled motion of the potential well at the IREB head was demonstrated, and ion data indicated that controlled accelerating fields of 50 MV/m over 10 cm were achieved.[2] A new system[3] (IFA-2) designed to produce controlled accelerating fields of 100 MV/m over a distance up to 100 cm is being brought into operation.

For IFA-1, the working gas was Cs and two-step photoionization was used which required two lasers—a dye laser (852.1 nm) and a frequency-doubled ruby laser (347 nm). The dye laser beam sweep was accomplished using transit time delays in a light pipe array. Synchronization of the lasers with the IREB was difficult because the self-breakdown oil switches used on the Blumlein had a jitter of $\sigma \approx 6$ nsec. For IFA-2, several new features have been introduced. A room temperature working gas, diethyl aniline (DEA), was selected to be used with a single XeCl laser (308 nm). An IFA beam switch section was designed to substantially steepen the IREB rise time. A new laser beam deflector that uses the electro-optic Pockels effect was designed to provide a continuous laser sweep. Laser-triggered gas switches were installed on the IFA-2 IREB machine to insure very low jitter synchronization of the laser with the IREB.

II. The IFA-2 System

The IFA-2 system is shown in Fig. 1, and its design parameters are given in Table 1. The IREB machine[4] has an ethylene-glycol-filled Blumlein that is switched with four UV laser-triggered gas switches.[5] Over 500 shots have been fired on this machine and a switching jitter of $\sigma \approx 1$ nsec has been achieved. The desired peak IREB parameters (1 MeV, 30 kA, 30 nsec flat top) have been obtained. The IREB current pulse has a rise time of about 20 nsec, whereas a much shorter current rise time ($\lesssim 5$ nsec) is required for IFA-2—the IFA beam switch (discussed in Sec. III) was conceived to reduce the rise time to $\lesssim 1$ nsec. An on-line data acquisition system is used to record diode voltage, diode current, Marx voltage, Blumlein voltage, four B-dot switch monitors, laser photodiode, and trigger monitors.

The excimer laser is an XeCl injection-locked amplifier system that produces a very uniform, low divergence beam at 308 nm. Nominal operating parameters are

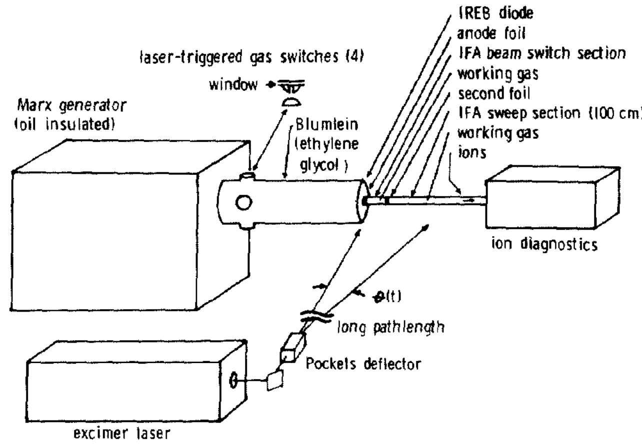

Fig. 1. The IFA-2 system.

Table 1. IFA-2 design parameters.

IREB	laser/gas	acceleration region	protons
1.0 MeV	XeCl laser	100 MV/m	100 MeV
30 kA	308 nm	2.2 cm diameter	5 kA
1 cm radius	DEA gas	100 cm length	0.5 cm radius
30 nsec flat-top	≥ 10 MW/cm^2	16 nsec of IREB	0.08 nsec
≤ 5 nsec risetime	over ~1.5 cm^2	used to accelerate	0.5 TW
0.04 TW	swept	protons	40 J
1 kJ			

1 joule, 30-40 nsec pulsewidth, and 25-35 MW peak power. The laser divergence has been measured and 75% of the energy is within a four-times diffraction limited spot (i.e., a half-angle of 50 microradians). For IFA-2, using DEA, and assuming linear temporal scaling of the photoionization, a swept XeCl laser intensity of about 10 MW/cm^2 is needed over an area of about 1.5 cm^2.

Because the laser intensity required is rather high, it is most practical to sweep the beam in time if possible. To accomplish this, an electro-optic Pockels deflector[6] has been constructed[7] and tested—the results are presented in Sec. IV.

The main IFA-2 drift tube assembly has been constructed, and it is shown in Fig. 2. This includes a beam switch section and a 30 cm IFA sweep section. (The sweep section length will later be extended to 100 cm). All components for the room temperature 30 cm IFA-2 system are now in hand (IREB machine, XeCl laser system, Pockels deflector, IFA beam switch, and IFA sweep section). Initial experiments have been performed with a similar IFA beam switch, as discussed in the following section.

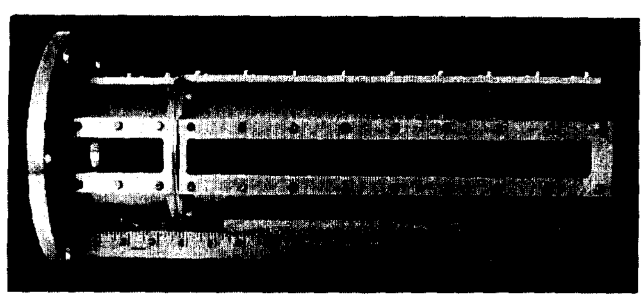

Fig. 2. IFA-2 drift chamber, showing the beam switch section and the 30 cm sweep section.

*Supported by Division of Advanced Energy Projects, DOE, and Defense Programs, DOE.

0018-9499/83/0800-3189$01.00©1983 IEEE

III. IFA Beam Switch Experiments

The IFA beam switch is designed to steepen the rise time of the IREB current pulse to $\lesssim 1$ nsec. The concept is to inject the IREB into a short drift section which is separated by a thin foil from the main sweep section. Initially, the beam will stop and diverge to the walls due to its own space charge (since $I_e \gtrsim I_l$, where I_e is the injected current and I_l is the space charge limiting current). When the beam current reaches its flat-top value, a portion of the IFA laser pulse is applied to the working gas in the entire beam switch region. The IREB then quickly propagates through the photoionized gas and enters the main IFA sweep section with a short rise time. Beam switch advantages are (1) with a shorter rise time, a higher working gas pressure is permitted in the IFA sweep section so less laser power is needed there, and (2) there will be essentially no jitter between the time the beam is switched and the time the sweep begins because both are controlled by the same laser.

Beam switch experiments have been performed with a metallic drift tube with an inside diameter of 2.2 cm and a length of 11.4 cm. Various types of slotted tubes were investigated, but here we report only on a solid tube for which the laser pulse was injected from the exit end through a transparent foil. Typically, the laser beam radius r_l was in the range $0.25 \lesssim (r_l/R) \lesssim 0.6$ where R is the drift tube inside radius.

The key IFA beam switch results to date are summarized in Figs. 3-4. A large number of diagnostics were tried to diagnose the exit particle current from the beam switch section, including a carbon calorimeter, Cerenkov converter, x-ray detector, Rogowski coils, and Faraday cups. The results presented here were all obtained with a Rogowski coil with a central carbon dump, which had a hole to permit the laser beam to be injected into the beam switch section. The Rogowski coil and carbon dump section was evacuated and separated from the beam switch section by a transparent foil. Although the Rogowski coil is our preferred diagnostic, "plasma tails" are frequently seen on the output indicating that the device probably measures less than the true particle current during the pulse rise time. In Fig. 3, we show the diode current (I_{diode}); and the current observed at the end of the beam switch ($I_{Rogowski}$) for the switch filled with 1.5 microns air ($\sim$ no transport), 2 Torr air (excellent transport), and 9 microns DEA with the laser pulse fired early (excellent transport). These results show that the laser photoionization case matches the air transport case very well. In Fig. 4, IFA beam switch results are shown. For 9 microns DEA with no laser pulse, the end of the current pulse propagates. For 9 microns DEA with the laser pulse carefully timed, the beam current switches on with a fast rate of current rise.

Thus, qualitatively the beam switch works. However quantitatively, from this and other data, it appears that it does not switch with a rise time as short as expected, and this has led to a theoretical study of the photoionization process as discussed in Sec. V.

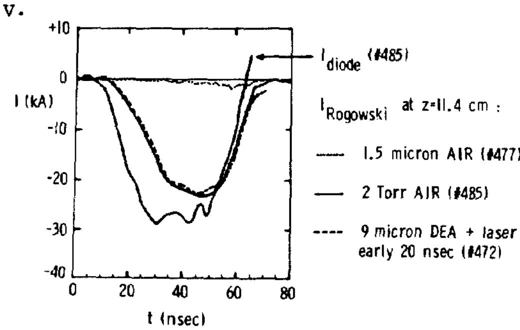

Fig. 3. IFA beam switch transport results.

IV. Pockels Laser Deflector

The ideal laser sweep method for the IFA is a method whereby a laser beam is continually "on" and swept along the IFA drift tube in a programmed manner. Such a scheme would (1) effectively produce a zero-rise time laser beam since it would be on at full power during the sweep, (2) require a relatively long-pulse low-power laser instead of a short-pulse high-power laser as is required for a light pipe array, and (3) be controlled electrically so sweep rates could be varied easily. An electro-optic Pockels deflector system offers all of these advantages, and one has been constructed and tested.

The Pockels deflector concept[6] is shown in Fig. 5 for the simplest device. Two crystals are arranged as shown, the top one exhibiting a Pockels electro-optic effect. For no applied electric field ($E = 0$), the laser beam passes straight through the device. For $E \neq 0$, refraction occurs and the beam is bent through an angle θ where $\theta = (L/d)|\partial n/\partial E|E$. (Here, L and d are the length and width of the crystals, and $\partial n/\partial E$ is the change in index of refraction with respect to a change in the electric field.) The angle θ is typically very small so the laser beam must be as near diffraction limited as possible, and a long path length after the device is needed (see Fig. 1). Although Pockels deflectors have been built for low power lasers with relatively long deflection times, we believe that this is the first such device designed to deflect a high-power laser beam ($\sim$ 30 MW) on a fast time scale ($\sim$ 10 nsec) in the UV (308 nm).

The actual deflector built and tested consists of a series of 10 KD*P crystals.[7] The crystals' optic axes alternate so every crystal contributes to the deflection. The optical path in the deflector has a 1.1 square centimeter input aperture, and a length of 20 cm. Many tests have been performed to study beam quality, to improve beam quality, to measure transmission losses, and to measure deflection for static electric fields. Results of a deflection test using a HeNe laser and a 3X cylindrical telescope are shown in Fig. 6, which demonstrates that the device deflects a laser beam linearly with applied voltage. For our XeCl laser, present transmission tests indicate that 30% of the beam passes through the deflector. Remaining tests are to examine full power damage thresholds and try an actual programmed E to effect a quadratic laser sweep.

V. Temporal Scaling of Photoionization

In the original photoionization experiments,[8] and following other examples in the literature,[9] the ionization was assumed to grow as

$$n_e = A_2 n_o \int_o^{t_o} [I(t)]^2 dt \quad , \tag{1}$$

where n_e is the plasma electron density (cm^{-3}), n_o is

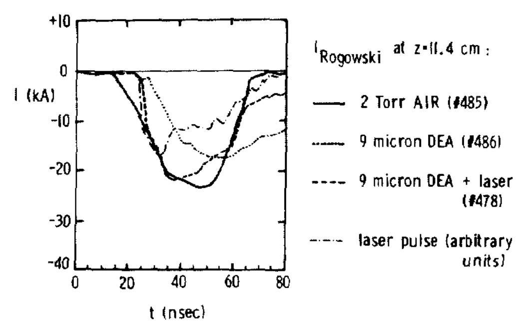

Fig. 4. IFA beam switch results for 9 micron DEA.

the neutral gas density (cm^{-3}), I is the laser intensity (W/cm^2), t_o is the laser pulse length (sec), and A_2 is the measured proportionality constant (cm^4 $sec/joule^2$). In the experiments, it was found the $n_e \propto n_o$ and $n_e \propto I^2$, but t_o was not varied so the temporal growth of n_e was not observed. For a two-photon process with no intermediate state, the characteristic temporal scaling is that given by (1). For constant I, this scaling is $n_e \propto t$.

In reality, the process is most likely a two-step process in which one photon raises the molecule to an excited state (or manifold) and a second photon photoionizes the excited molecule. (In the experiments, the cross section for absorption to the excited state was measured, so indeed an intermediate state does exist.) The process is described in lowest order by

$$\frac{dn^*}{dt} = n_o \sigma_1 \frac{I}{h\nu} - \frac{n^*}{\tau} \quad , \qquad\qquad (2)$$

$$\frac{dn_e}{dt} = n^* \sigma_2 \frac{I}{h\nu} \quad ,$$

where n^* is the excited state density (cm^{-3}), σ_1 is the cross section for excitation (cm^2), σ_2 is the cross section for photoionization from the excited state (cm^2), τ is a de-excitation time (sec), and $h\nu$ is the photon energy (joule). For negligible de-excitation ($\tau >> t$), Eqs. (2) yield

$$n_e = n_o \frac{\sigma_1 \sigma_2}{(h\nu)^2 2} \left[\int_o^{t_o} I(t)dt \right]^2 \quad . \qquad (3)$$

For dominant de-excitation ($\tau << t$), Eqs. (2) yield

$$n_e = n_o \frac{\sigma_1 \sigma_2 \tau}{(h\nu)^2} \int_o^{t_o} [I(t)]^2 dt \quad . \qquad (4)$$

Therefore, for $\tau << t$, (4) applies, and comparing to (1), we must have $A_2 = \sigma_1 \sigma_2 \tau/(h\nu)^2$. For DEA and using an 18 nsec XeCl laser pulse,[8] $A_2 = 3.8 \times 10^{-8}$ cm^4 $sec/joule^2$, $\sigma_1 = 1 \times 10^{-18}$ cm^2, and σ_2 may be calculated from $\sigma_2 = A_2(h\nu)^2/(\sigma_1 \tau)$. For the IFA, we would need $\tau << t$ to hold for $10^{-11} \lesssim t(sec) << 10^{-9}$. Thus, to use DEA in the IFA, we would need

$$\tau < 10^{-11} \text{ sec} \quad , \qquad\qquad (5)$$

$$\sigma_2 > 10^{-15} \text{ cm}^2 \quad .$$

For most substances, $\tau \approx 10\text{-}80$ nsec, and $\sigma_2 \approx 10^{-20} - 10^{-17}$ cm^2. Thus, it is very unlikely that (5) holds. If (5) does not hold, we are typically back in the regime of (3), which for constant I shows the characteristic two-step temporal scaling of $n_e \propto t^2$.

If the correct temporal scaling is $n_e \propto t^2$, then for I constant, and for $t < t_o$, the correct $n_e(t)$ will be smaller than that predicted by (1) by a factor t/t_o. For IFA-2, $t \approx 0.2$ nsec, whereas $t_o \approx 18$ nsec was used to obtain the value of A_2 in (1). Thus, for IFA-2, $t/t_o \approx 0.01$, so the laser power would have to be increased substantially to reach the required n_e. Whereas our original assessment using (1) required $I \approx 10$ MW/cm^2, it now appears using (3) that $I \approx 100$ MW/cm^2 would be required, which exceeds our experimental capabilities. For this reason, we will return to Cs as the working gas. For single-step photoionization of Cs with an XeCl laser, the required swept laser intensity for IFA-2 is $I < 10$ MW/cm^2.

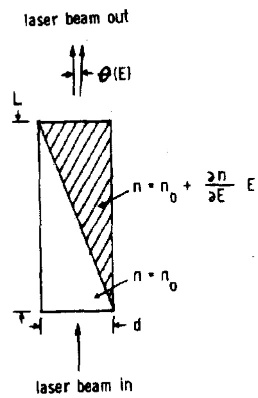

Fig. 5. Pockels deflector concept.

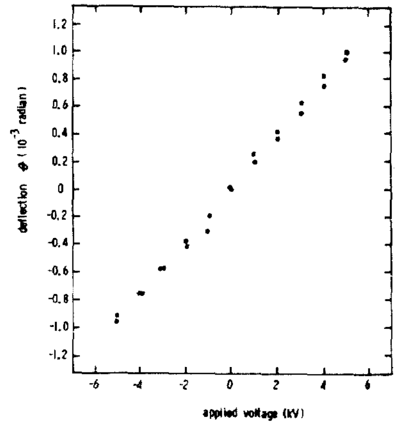

Fig. 6. Deflection angle vs applied voltage for the Pockels deflector.

VI. Conclusions

The IFA-2 system is being brought into operation. Over 500 shots have been fired on the IFA-2 IREB machine. The laser-triggered gas switches work well and a jitter of $\sigma \approx 1$ nsec has been achieved. A low divergence XeCl laser beam has been characterized, and a new Pockels deflector has been tested. IFA beam switch experiments have been performed using DEA as the working gas.

While the beam switch works, it does not switch with a rise time as short as expected, which suggests that the DEA is not ionizing as fast as planned. Recent theoretical analysis indicates DEA can not be used with IFA-2 with our existing laser power. Consequently, we will return to using Cs as the working gas, and we are now implementing the modifications necessary to use Cs in IFA-2. When ready, IFA-2 experiments will commence with a sweep section of length 30 cm, which will later be extended to 100 cm.

Acknowledgments

The assistance of Gary Samlin and Willie Jaramillo with the experiments is gratefully acknowledged.

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