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THE IFA-2 COLLECTIVE ACCELERATOR*

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Summary

IFA proof-of-principle experiments (completed on the IFA-1 system) have already demonstrated accurately-controlled motion of the potential well at the head of an IREB, and IFA ion data sets (H^+,D^+,He^{++}) imply that controlled accelerating fields of 50 MV/m have been achieved over 10 cm. A new system, IFA-2, is being developed to demonstrate controlled accelerating fields of 100 MV/m over 1 meter. For IFA-2, a new working gas (N,N dimethyl aniline) has been found that operates at room temperature and requires only one laser (XeCl-307 nm). This new working gas represents a major breakthrough for the IFA in regard to simplicity and ease of operation. Research on this new working gas (IREB-induced ionization cross section experiments, photoionization cross section experiments), and the status of the IFA-2 system, are discussed.

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).[1,2] The potential well is made to move with the desired phase velocity by actively controlling the ionization of a suitable background working gas. Laser photoionization is employed, and a laser sweep is effected by using transit time delays in a programmed light pipe array. The IFA is a direct extension of the collective acceleration process that occurs naturally when an IREB is injected into neutral gas.[1,2] The IFA provides a direct means for controlling the observed large accelerating fields (~100 MV/m) over large distances.

IFA parameters for three development cases are given in Table 1. The first case (IFA-1) represents the IFA proof-of-principle experiments which have already been performed.[3-5] The second case (IFA-2) represents the IFA test bed accelerator which is now being initiated. The third case represents a 1 GeV proton demonstration accelerator. Note that the characteristic IFA ion pulse has a very high power with a short pulse length.

By using larger IREB's, the IFA current and pulse length can be substantially increased over those given in Table 1. Also, theoretical conversion efficiencies of IREB energy into IFA ion energy for moderate ion loading are ~32% for 300 MeV protons, ~16% for 25 GeV uranium ions, and ~10% for 1 GeV protons.[1] These efficiencies may be significantly increased by increasing the ion loading or by recouping some of the lost IREB energy.

In the following, we will briefly summarize the results of the IFA-1 experiments. For IFA-2, a new working gas, N,N dimethyl aniline (DMA), has been discovered[6] that can operate at room temperature and requires only one laser (XeCl). Experiments to measure the IREB-induced ionization cross section of DMA have been completed and are reported here, as are results of initial DMA photoionization experiments. The status of the IFA-2 system is also discussed.

II. Proof-of-Principle Experiments (IFA-1)

For the proof-of-principle experiments (IFA-1), cesium (Cs) was the working gas, and 2-step photoionization was used with a dye laser for Cs excitation and a frequency-doubled ruby laser for photoionization of Cs from the excited state. Over 1000 shots were fired on the IFA-1 IREB machine, which included over 400 complete IFA system shots. The proof-of-principle experiments were performed in three phases. Phase 1 experiments, in which the effective IREB-induced ionization cross section for Cs was measured, were successfully completed in 1977.[3] These results demonstrated that a neutral Cs density of 10^{15} cm^{-3} could be used without interfering with the IFA operation. Since typical IREB densities for use with the IFA are roughly 10^{12} cm^{-3}, this means that the Cs has to be ionized only about 0.1% for the IFA to work as planned. Phase 2 experiments were successfully completed in 1978.[4] Accurately-controlled motion of the front of an IREB was observed with three different programmed sweep rates, using time-dependent beam front diagnostics. These results demonstrated that the IFA-controlled motion of the potential well at the IREB head had been achieved. Phase 3 experiments concerned IFA ion acceleration and involved extensive studies of ion sources and ion diagnostics unique to the IFA-1 system.[5] Three different ion data sets (H^+,D^+,He^{++}) were obtained that imply that controlled accelerating fields of 50 MV/m were achieved (over an acceleration length of 10 cm). Although further ion data is needed to verify this conclusion, the present data is encouraging since it suggests that very high collective accelerating fields have been controlled, and also since this is the first ion data for a scalable collective ion accelerator that uses a linear electron beam.

III. Test Bed Accelerator (IFA-2)

A new system (IFA-2) is being initiated to demonstrate controlled accelerating fields of 100 MV/m over one meter. This system will incorporate many improvements based on our experience with the IFA-1 system. The IFA-2 system will be used to demonstrate the new working gas (DMA), to demonstrate a high data acquisition rate, to obtain extensive ion data, to demonstrate scaling of the acceleration length (to one meter), and to demonstrate power amplification (see Table 1).

TABLE 1. IFA PARAMETERS

	IREB	acceleration region	protons
IFA-1	0.6 MeV 20 kA 0.5 cm radius 10 nsec 0.01 TW 0.1 kJ	50 MV/m 1.2 cm diameter 10 cm length 6.5 nsec of IREB used to accelerate protons	5 MeV 0.8 kA 0.25 cm radius 0.17 nsec 0.004 TW 0.7 J
IFA-2	1.2 MeV 30 kA 1 cm radius 30 nsec 0.04 TW 1 kJ	100 MV/m 2.2 cm diameter 1 m length 16 nsec of IREB used to accelerate protons	100 MeV 5 kA 0.5 cm radius 0.08 nsec 0.5 TW 40 J
1 GeV example	3 MeV 30 kA 1 cm radius 40 nsec 0.09 TW 3.6 kJ	100 MV/m 2.2 cm diameter 10 m length 40 nsec of IREB used to accelerate protons	1 GeV 10 kA 0.5 cm radius 0.04 nsec 10 TW 400 J

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For IFA-2, a search was made to find a working gas that was simpler and easier to work with than the Cs system used in IFA-1. The Cs system requires a chamber heated to above 200°C to produce the vapor at the correct number density. Cs requires special vacuum considerations and must be handled with care. The fact that Cs requires two lasers increases the synchronization problem. Also, the second laser must be aimed down the drift tube from the exit end, which complicates the use of ion diagnostics. In contrast, the "ideal" working gas would operate at room temperature and would require only one laser. Since laser technology has evolved considerably since the Cs system was chosen for IFA-1, a search was undertaken to find a new working gas for IFA-2. The goal was to find a gas that would undergo 2-photon ionization with two photons from a single laser, with the first photon producing a resonant (or near resonant) excitation. Several potential candidates were identified, but the most promising one to date is N,N dimethyl aniline (DMA), used with a XeCl laser. The Cs system is shown in Fig. 1, and the DMA system is shown in Fig. 2. Although these schemes are similar, the practical advantages of DMA over Cs are numerous. DMA will make the system easier to handle, require no heating, need only one synchronized laser, and permit closed-end ion diagnostics. These advantages are clearly worthwhile to pursue for IFA-2, and would be extremely desireable for an ultimate application-oriented IFA.

For IFA-2, the data acquisition rate will be greatly improved over that of IFA-1. The useful data acquisition rate of the IFA-1 system was severely limited due to the jitter in the Blumlein oil self-break switches. These switches produced a jitter of ±6 nsec, which coupled with a 1 nsec window for IREB/laser synchronization, meant that only 1 in about 20 shots had the desired timing. For the IFA-2 system, triggered gas switches will be used to greatly reduce the jitter. In fact, recent results at Sandia indicate that it should be possible to laser trigger such switches with subnanosecond jitter.[7] This means that a single laser could be used to both switch the spark gaps and to sweep the ionization front. This elegant arrangement would virtually eliminate the jitter problem.

A further improvement exists which would actually permit a small, but finite, amount of jitter to be acceptable. For example in IFA-1, the sweep region started precisely at the ion source; i.e., no provision was made to allow a finite amount of jitter. IFA modifications that would include a reliable ion source, allow a specified amount of jitter, and insure ion trapping and acceleration are given in Fig. 3. Basically, the natural acceleration process (for the IREB/gas case) would be used to create the ion bunch and accelerate it to $\epsilon_i \approx 2Z\epsilon_e$ (where ϵ_i is the ion energy, Z is the ion charge, and ϵ_e is the electron energy). The bunch would then normally just transport down the drift tube at constant velocity. However, for the IFA, we would capture this ion bunch in a "pick-up" region where the laser front would be swept at a velocity slightly faster than the "natural process" front velocity. After the pick-up region, the laser sweep would accelerate as indicated. By choosing the length of the pick-up-region and the pick-up velocity, it is possible to design a given amount of jitter into the system. Therefore, if the jitter were reduced to 1-2 nsec, the pick-up region concept could be used to still insure ion trapping and acceleration on every shot.

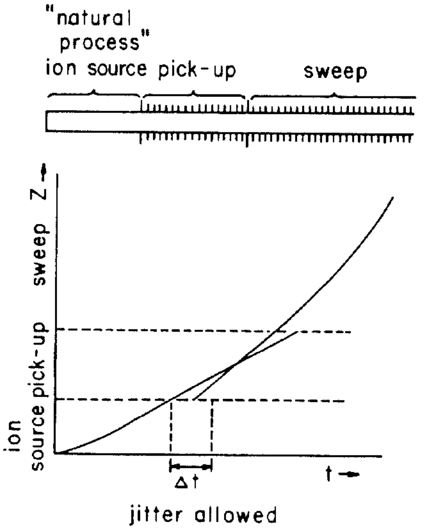

Fig. 3. The IFA Pickup Modification That Permits a Specified Amount of Jitter.

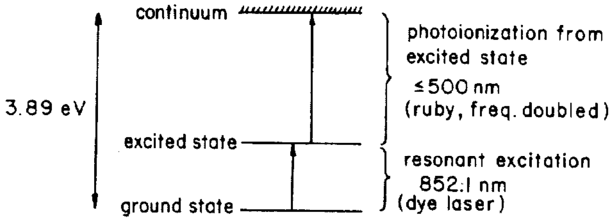

Fig. 1. The Cs System.

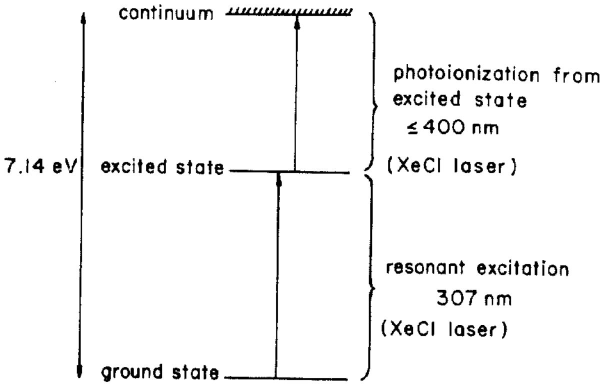

Fig. 2. The DMA (N,N Dimethyl Aniline) System.

The IREB parameters needed for IFA-2 are listed in Table 1. In addition, the current risetime must be small, and the switch jitter must be minimal. An existing Physics International Pulserad 215 WR IREB machine is being modified into a Blumlein configuration to produce the desired IREB parameters. Multiple triggered-switches are to be used to minimize inductance. It is anticipated that the modified IREB machine will be ready for initial experiments in about 6 months.

IV. DMA Experiments

To assess the feasibility of using DMA as the new working gas, IREB drift experiments are required to measure the effective IREB-induced ionization cross section of DMA, and laser experiments are required to measure the photoionization cross section of DMA. The IREB drift experiments have been successfully completed and are reported here. The laser experiments have begun and initial results are reported here also.

The IREB drift experiments in DMA were performed with the IFA-1 IREB machine, and with exactly the same experimental apparatus as was used earlier for similar drift experiments in Cs.[3] The experimental arrangement used is shown in Fig. 4, and has been described in detail earlier.[3] An initial drift section filled with 7

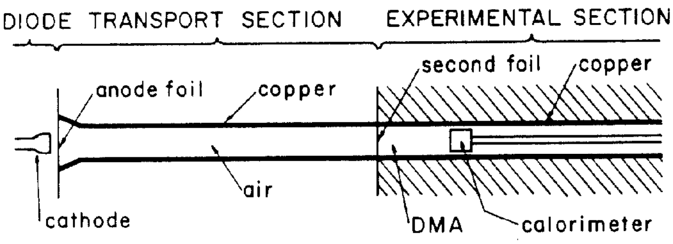

Fig. 4. IREB Drift Experiment in DMA.

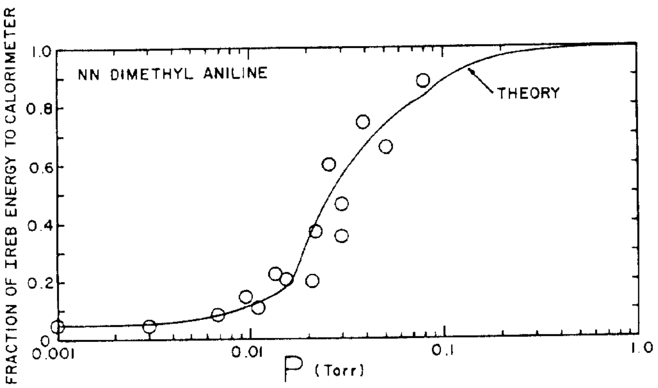

Fig. 5. Pressure Dependence of IREB Propagation in DMA.

Torr air is used to transport the beam up to the main experimental section. A calorimeter is placed 3.3 cm behind the second foil in the main copper drift tube (inside diameter 1.25 cm). By varying the DMA pressure as shown in Fig. 5, the threshold for beam-induced space charge neutralization (and therefore propagation) can be observed. From this sensitive experiment, the effective charge neutralization time τ_n can be deduced. The background ion density n_i is assumed to grow as $dn_i/dt = n_b(t)/\tau_n$ where n_b is the IREB density. Once charge neutralization is reached, the remainder of the IREB is assumed to propagate completely to the calorimeter.

The theory curve[3] shown in Fig. 5 was fitted to the data with only one free parameter $-\tau_n$. As shown, the best fit to the data gives $\tau_n = (0.21 \pm 0.05)/[p(\mathrm{Torr})]$ nsec for DMA. For comparison, $\tau_n = (0.24 \pm 0.12)/[p(\mathrm{Torr})]$ nsec for Cs.[3] These results show that DMA has an effective ionization cross section very close to that of Cs. This means that DMA can be used in the IFA at a pressure where the neutral DMA density is much higher than the IREB density, and yet where IREB-induced ionization effects may be neglected.

Initial laser experiments have been performed to measure the rate at which a XeCl laser can photoionize DMA. A XeCl laser was directed into a section of RF waveguide containing DMA at a pressure of 0.2 Torr at room temperature. The photoionized region of gas had a cross-sectional area of 1 cm^2 and a length of 60 cm. The electron density created was detected by a microwave transmission apparatus, as shown in Fig. 6. Typically, a peak electron density of about 10^{12} cm^{-3} was produced for a XeCl laser intensity of about 10^7 $\mathrm{W/cm}^2$. As shown in the oscilloscope trace in Fig. 7, the ionization growth to a density of 10^{12} cm^{-3} occurred on a time scale of the order of 1 nsec, although the laser risetime was 2 nsec. The 2-photon nature of the photoionization was confirmed in separate measurements which show that the peak electron density scales as I^2 where I is the laser intensity. It was also shown that the peak electron density scales linearly with the gas pressure. Fast ionization growth is needed for the IFA and these initial results for DMA are very encouraging. Further laser experiments will now be performed to accurately measure the photoionization cross section of DMA. The results of these experiments will allow us to finalize the laser power requirements for IFA-2.

V. Conclusions

A new system, IFA-2, is being initiated to demonstrate controlled accelerating fields of 100 MV/m over 1 meter. A new working gas, DMA, has been found that operates at room temperature and requires only one laser (XeCl). IREB drift experiments in DMA have been completed, and the effective cross section for IREB-induced ionization of DMA has been measured experimentally. The results demonstrate that a feasible pressure regime exists for DMA use in the IFA. Initial laser experiments have shown fast photoionization of DMA, and more detailed experiments are in progress. IREB machine modifications which include triggered gas switches have been initiated for the IFA-2 system, and initial IREB experiments should commence in about six months.

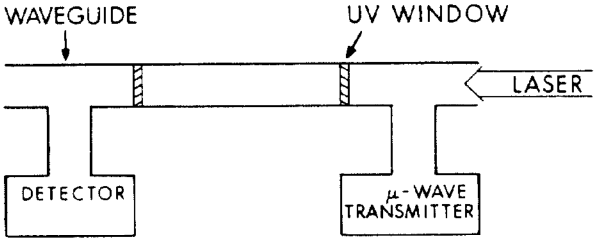

Fig. 6. Microwave Transmission Experiment to Measure Laser Photoionization of DMA.

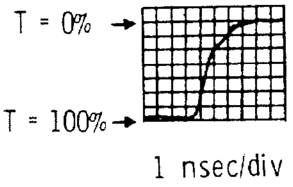

Fig.7. Ionization Growth in DMA With a XeCl Laser. The Change in Microwave Transmission From T=100% to T=0% Occurs for a Plasma Density of $n \approx 10^{12}$ cm^{-3}.

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