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IFA PROOF OF PRINCIPLE EXPERIMENTS*

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Abstract

IFA proof of principle experiments are discussed. Controlled beam front motion experiments are reported, which demonstrate that accurate IFA programming of the motion of the potential well at the head of an IREB has been achieved. The status of IFA ion experiments is also discussed.

I. Introduction

The Ionization Front Accelerator (IFA) is a collective effect accelerator which produces controlled motion of a potential well at the head of an intense relativistic electron beam (IREB) for the purpose of accelerating ions to high energies.[1,2] Beam front control is achieved by accurately programming the laser photoionization of a special working gas (Cs). The IFA concept is a controlled extension of the collective acceleration process that occurs naturally when an IREB is injected into neutral gas.[1,3]

Experiments to demonstrate proof of principle of the IFA concept have been performed in three phases, each with a specific goal as follows:

Phase 1. Demonstrate Cs is a feasible working gas.
Phase 2. Demonstrate IFA-controlled beam front motion.
Phase 3. Demonstrate IFA ion acceleration.

Phase 1 experiments were successfully completed and reported at the 1977 Particle Accelerator Conference.[4] Phase 2 experiments have now been successfully completed, and the key results of an extensive data analysis are reported here. Phase 3 experiments are near completion, and present results are reported here also.

II. Description of IFA Experiments

The IFA proof of principle system consists of an IREB machine; an experimental chamber containing a heated, Cs-filled, "transparent/conducting" drift tube;[5] an accurately-programmed photoionization sweep system; and diagnostics. The 2-step photoionization sweep system consists of a dye laser for Cs excitation, a fast electro-optical shutter for the dye laser, a pair of programmed light pipe arrays (for passively sweeping the dye laser pulse), and a frequency-doubled ruby laser for photoionization of the excited Cs. The nominal IREB parameters are electron energy 600 keV, current 22 kA, current risetime 3 nsec, current flat-top pulse length 12 nsec, and beam radius 0.5 cm. The dye laser produces a peak power of about 5 MW at a wavelength of 8521 Å (tuned for Cs excitation), and the dye shutter produces a pulse risetime of about 1 nsec. The frequency-doubled ruby laser produces a peak power of about 100 MW. The IREB is transported from the diode to the experimental section through a copper drift tube (1.25 cm inside diameter, 14.7 cm long) maintained at a pressure of 7 Torr (air) for optimum transport.[4] The IREB then passes through a second foil into the main experimental drift chamber.

The main drift chamber contains the IFA "transparent/conducting" drift tube (1.25 cm inside diameter, 10 cm acceleration length). A pair of opposing windows (top and bottom) allow the swept dye laser light to enter the drift tube, while a narrow slit window along the front permits viewing for beam front diagnostics. The drift tube, together with its continuation (1.25 cm inside diameter, about 40 cm long) and associated Cs oven, are housed in an oil heat bath kept at about 240°C. The nominal operating Cs reduced pressure is 30 microns.[4]

Synchronization of the IREB with the lasers is required with as low jitter as possible. The desired synchronization is indicated in Fig. 1, where the IREB, the dye laser, the fast shutter, and the frequency-doubled ruby laser pulses should be temporally aligned as indicated by the dashed line. The pulses shown are drawn roughly to the correct time scale, and jitter measurements are indicated by the horizontal arrows and by the standard deviation (σ) values. The largest jitter comes from the IREB, and is caused by the self-breakdown oil switches on the Blumlein.

Diagnostics used on full IFA system shots include:

1. IREB diode current monitor
2. IREB diode voltage monitor
3. Marx monitor
4. Blumlein monitor
5. streak monitor
6. dye laser output monitor
7. ruby laser output monitor
8. Cs pressure monitors
9. SUM monitor (IREB + shuttered dye + ruby dble)
10. streak picture
11. open shutter photograph
12. magnetic spectrometer/CLN

The last five diagnostics are the most crucial ones.

Over 1000 shots have been fired on the IREB machine since the inception of these experiments. These include 56 shots for IREB optimization; 185 shots for IREB transport studies in vacuum, air, and Cs, in metallic and dielectric drift tubes; 429 shots in vacuum, air, hydrogen, and helium, all with beam front diagnostics and most with ion diagnostics, to study the naturally-occurring collective ion acceleration process; and 339 complete IFA system shots, all with beam front diagnostics and most with ion diagnostics, to study the IFA acceleration process.

III. Demonstration of IFA-Controlled IREB Beam Front Motion

Complete IFA system shots have been taken with three different light pipe array sets. The sweep rates for these sets correspond respectively to the constant acceleration of a proton from 0 to 2.5 MeV, from 0 to 5 MeV, and from 0 to 10 MeV (each over an acceleration

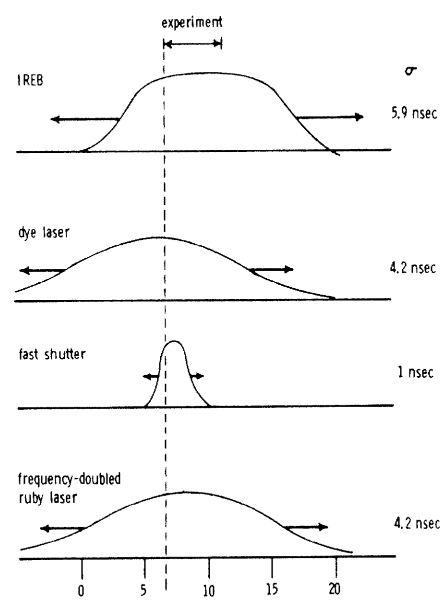

Fig. 1. IFA synchronization.

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length of 10 cm). The sweep times are 9.1 nsec, 6.5 nsec, and 4.6 nsec, respectively. The beginning of the sweep should correspond with the beginning of the IREB current flat top, as noted earlier in Fig. 1. Since the nominal duration of the IREB current flat top is only 12 nsec, accurate timing is critical for obtaining a full, controlled sweep of the IREB beam front.

Since the jitter was significant, a variety of timing situations was created statistically--e.g., lasers early, lasers timed right, or lasers late. For a working IFA, this jitter would be minimized (by using triggered gas switches and other means not available in our experiments), so the timing would be correct with high reliability. However, for proof of principle experiments, the variety of timing situations created is actually useful for understanding all of the possible effects. Basically, three types of IREB beam front motion are created, depending on the timing. Streak picture examples of each of these types are given in Figs. 2, 3, and 4, with brief descriptions as follows:

Lasers early: If both lasers overlap each other and occur before the IREB pulse, then a plasma should be created in the drift tube prior to the arrival of the IREB pulse. When the IREB does arrive, it should propagate quickly through this charge-neutralizing plasma. The streak picture in Fig. 2 clearly shows this effect.

Lasers timed right: If the lasers occur with the desired timing, then IFA-controlled beam front motion should result. The beam front should then synchronously follow the laser sweep motion as programmed by the light pipe arrays. IFA-controlled beam front motion is clearly shown in the streak picture in Fig. 3, for which the "5 MeV" light pipe arrays were used. Controlled beam front motion has also been demonstrated with the "2.5 MeV" and "10 MeV" light pipe arrays.

Lasers late: If the lasers occur near the end of, or after, the IREB pulse, then they should have no effect on the beam front behavior. The beam front motion should be the same as that which is observed for IREB injection into vacuum, with a heated drift chamber. For this case, a natural acceleration process is observed (see Section IV). For a heated drift chamber, protons are apparently predominant, and the resultant beam front velocity corresponds to that of protons with energies up to two times the electron energy (i.e., up to 1.2 MeV protons). This characteristic feature is shown in the streak picture in Fig. 4.

An analysis has been made of all IFA system shots taken to date. Of 339 shots taken, only 184 shots yielded useful beam front information. A summary of the beam front motion observed as a function of laser timing for these 184 shots is given in Table 1. Note that the beam front motion correlates very well with the laser timing. If both lasers are early and overlap, then the beam front propagates very fast. If the timing is excellent (i.e., if the dye pulse begins precisely at the beginning of the IREB current flat top), then the beam front motion fits the IFA programmed sweep very well. If the lasers occur slightly later (good to fair timing), then the IFA sweep process begins to compete with the naturally-occurring acceleration process; many of the streak pictures for this case are ambiguous in that they roughly fit the programmed sweep, but they also roughly fit the beam front motion expected for the natural process. The naturally-occurring process clearly results if the lasers are late, if no lasers are used, or if only one laser occurs early. The latter case is interesting because it verifies that both lasers must fire together to ionize the Cs and creat a plasma before the IREB appears. The data summary in Table 1 also indicates that for our present system, about 60 shots in 339 shots (~ 1 in 6) have roughly the desired timing, whereas 13-21 shots in 339 shots (~ 1 in 20) have precisely the right timing.

Based on these results, we may now say that IFA-controlled IREB beam front motion has been demonstrated, and that the major technological goal of accurately programming the motion of the potential well at the head of the IREB has been achieved.

IV. Collective Ion Acceleration Experiments with the IFA System

Demonstration of collective ion acceleration with the IFA requires that ions be trapped and accelerated in the controlled moving potential well. Our collective ion acceleration investigations with the IFA system have involved (1) experiments with IREB injection into neutral gas, and (2) full IFA ion acceleration experiments.

The neutral gas experiments were performed at room temperature, and without any lasers, but with the identical drift tube and diagnostics as used in the IFA experiments. The naturally-occurring acceleration

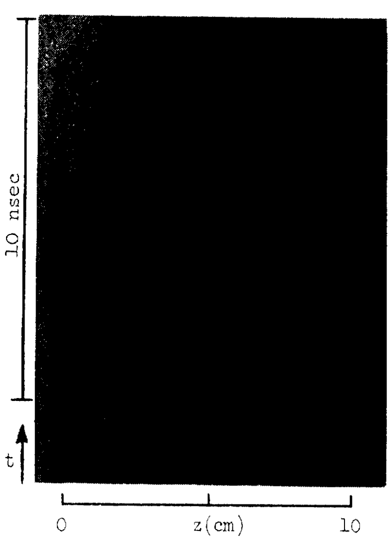

Fig. 2. Lasers early. Streak picture of beam front motion when lasers are early and overlap. Beam enters from the left side.

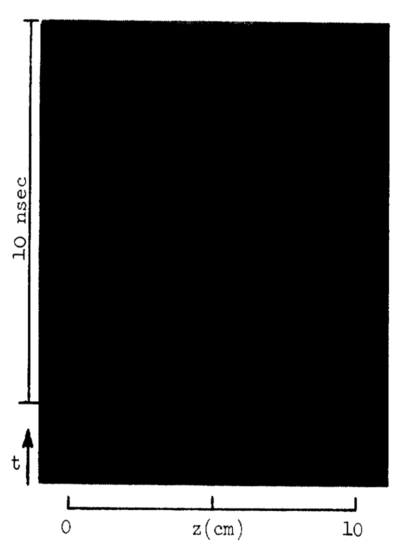

Fig. 3. Lasers timed right. Streak picture of beam front motion when lasers have excellent timing. The programmed sweep is indicated by the solid line. The "5 MeV" light pipe arrays were used in this example.

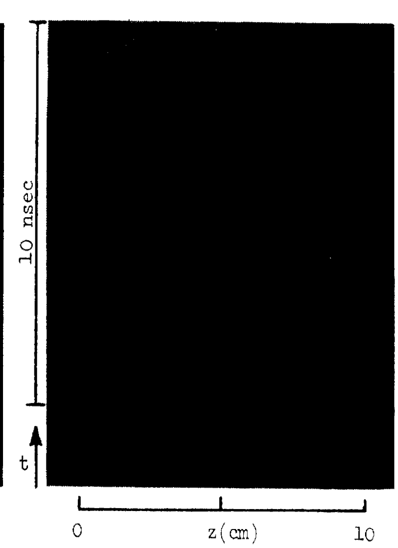

Fig. 4. Lasers late. Streak picture of beam front motion when lasers are late. The natural acceleration process limits the front velocity to less than that of a 1.2 MeV proton ($\mathcal{E}_i \lesssim 2Z\mathcal{E}_e$).

Table 1. Beam front motion versus laser timing for the IFA proof of principle experiments, showing the number of shots observed in each possible category.

			LASER TIMING				
			lasers early (and overlap)	good timing	lasers late	one laser early + one laser late	no lasers
BEAM FRONT MOTION		propagates fast	23	0	0	0	0
BEAM FRONT MOTION		fits sweep well fits sweep, fuzzy fits sweep, ambiguous	0	13 (excellent timing) 8 (good timing) 39 (good to fair timing) (60)	0	0	0
BEAM FRONT MOTION		$\lesssim$ 1.2 MeV H^+	0	0	77	8	16

process was investigated for IREB injection into vacuum, hydrogen, and helium. 429 shots were taken, and the ion acceleration characteristics (correlation of beam front velocity with ion velocity, pressure thresholds and cutoffs, etc.) were found to agree well with an earlier theory.[3] The peak ion energy attained corresponds to $\mathcal{E}_i \approx 2 Z \mathcal{E}_e$ where $\mathcal{E}_i (\mathcal{E}_e)$ is the ion (electron) energy and Z is the ion charge. The actual peak energies obtained were:

1.2 MeV C^+ (for IREB injection into vacuum)
1.2 MeV H^+ (for IREB injection into hydrogen)
2.4 MeV He^{++} (for IREB injection into helium)

Full details of these experiments will be presented elsewhere.

The IFA ion experiments include 287 shots (out of the 339 IFA shots reported above) for which CLN detectors were used. Most of these shots were with the "5 MeV" light pipes and a "vacuum source" (i.e., no fill gas was used, on the assumption that some protons would be created by the IREB interaction with the foil contaminants). Clearly visible ion spectra were obtained on only about 1 out of 10 shots. Many of these occurred when the timing was good (or just slightly later than optimum), and the ion spectrum produced had a peak centered at the position expected for 5 MeV protons. However, the possibility of these tracks being produced by ions other than high energy protons (e.g., low energy carbon ions) cannot be ruled out from the existing data. These data are therefore not conclusive. A small number of shots were also taken with added low pressure fill gases to serve as ion sources. When helium was used, there is evidence that the helium ion spectrum was perturbed toward higher energies when the timing was good, but that the holding power was lower than that required (100 MV/m) to trap and accelerate He^{++} ions with the "5 MeV" sweep rate. Together, these data suggest that controlled accelerating fields of about 50 MV/m may have been achieved--but as noted above, these data are not conclusive.

The lack of conclusive ion data may be due to lack of an adequate ion source, insufficient holding power (due to insufficient laser power), ion losses during transport to the spectrometer, and/or insufficient ion diagnostics. However, since the relative number of shots with excellent timing for the present system is very low (see Section III), it appears to be impractical to investigate various ion sources and other ion diagnostics (e.g., nuclear activation, etc.) with the present system. On the other hand, several system modifications can now be proposed based upon our knowledge of the present system. It is becoming increasingly apparent that these modifications will be required to obtain a definitive ion data base.

V. Conclusions

The second phase of the IFA proof of principle experiments (IFA-controlled beam front motion) has been successfully completed. Accurate programming of the motion of the potential well at the head of the IREB has been achieved. The third phase of the IFA proof of principle experiments (ion acceleration) has produced data which suggest that accelerating fields of 50 MV/m may have been achieved, but the data are not conclusive. It presently appears that several system modifications will be necessary to obtain a definitive ion data base.

Acknowledgments

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