TWO CAVITY AUTOACCELERATION OF AN INTENSE RELATIVISTIC ELECTRON BEAM

P. D. Coleman, T. R. Lockner, and J. W. Poukey
Sandia National Laboratories
Albuquerque, NM 87185

Abstract

Three series of experiments have been performed using two 40 Ω coaxial autoacceleration cavities to accelerate an intense relativistic electron beam. First, conventional magnetic transport was used to propagate a 1.8 MeV, 11 kA beam through two 1 m long cavities. An increase of 700 ± 130 keV in kinetic energy was achieved which represents 80% of the maximum theoretical acceleration for an 11 kA beam passing through two 40 Ω cavities. Multiple accelerated pulses were generated and no adverse interaction between the cavities was observed. In the second experiment, Ion Focused Transport (IFT) was used to successfully propagate a 9 kA beam through the accelerator again achieving multi-pulse operation with both cavities. An energy increase of 560 ± 30 keV was attained which is 78% of the theoretical maximum. Finally, IFT was used to propagate a ≈ 25 kA beam through a 1 m long cavity, then a 0.5 m long cavity, demonstrating two stages of temporal energy compression. Gap leakage and current transport losses limited the acceleration to 1.25 ± .16 MeV which corresponded to an 84% increase in kinetic energy.

Introduction

The autoaccelerator concept is an attractive candidate for a compact, lightweight, high-energy, intense relativistic electron beam (IREB) accelerator. In an autoaccelerator, an IREB interacts with a passive cavity resulting in energy transfer from one portion of the beam to another. In the U. S. two configurations, the long pulse mode[1,2] and the short pulse mode[3,4,5], have been pursued. This paper describes results of successful two cavity operation in the short pulse mode.

The performance of the autoaccelerator can be closely simulated by a transmission line model. Consider the ideal case of a beam of constant current I that propagates down a drift tube which is connected to a coaxial cavity at a gap in the drift tube. Let the cavity have impedance Z and length $L = c/\tau$, where τ is the one-way transit time for an electromagnetic pulse in the line. As the beam passes the cavity, it launches a wave down the coaxial line and for a time 2τ the beam is decelerated by an induced voltage across the gap of IZ. After 2τ, the reflected wave has returned to the gap, and in order to meet the boundary condition of constant current at the gap, an accelerating voltage of IZ appears on the gap. This ringing process continues over the pulse width of the beam.

This paper describes theoretical simulations and experimental results from three sets of experiments performed using a two cavity autoaccelerator. First, experiments were performed using conventional magnetic transport of an 11 kA beam in the accelerator. These experiments were designed to investigate operation of a multiple cavity accelerator in the short pulse mode. In particular, attention was paid to operation of the accelerator over several cavity ringing periods and to the possibility of communication between the cavities leading to beam instabilities.

A similar run was conducted using Ion Focused Transport (IFT)[6,7,8] as the means of propagating the beam through the accelerator. With this method of transport, a preionized channel is formed in a very low pressure gas. The radial electric field of the relativistic electron beam ejects the plasma electrons from the channel leaving a positive core which electrostatically guides and focuses the beam. IFT can help with virtual cathode problems that arise with high current, low energy beams and also damp transverse motion resulting from beam instabilities.

Finally, we investigated the operation of a system with the potential for achieving a kinetic energy gain greater than 100% in the short pulse mode. The experiment was performed using IFT to propagate an ≈ 25 kA beam past a 1 m and a 0.5 m cavity. An autoaccelerator using cavities with a fixed one way transit time, τ, can only achieve a maximum theoretical energy gain of 100%. That is, the cavities would extract all the energy from the leading portion of the beam and deposit it in the trailing portion. To obtain more than two times the injected kinetic energy (a gain of greater than 100%), this energy compression process must be repeated on the accelerated portion of the beam. This implies a second stage of temporal energy compression using cavities of length 0.5 τ, for example.

Experimental Configuration

A schematic of the experiment is shown in Figure 1. A foilless diode was used to inject the IREB into a 5 cm diameter drift tube. Each coaxial cavity had an impedance of 40 Ω and was 1 m in length (a one way transit time, τ, of 3.5 ns which includes the radial transit time from the beam line to the entrance of the coaxial section). A 10 kG field was used for beam propagation in the magnetic experiments. For the IFT shots, the drift tube was filled with 10^{-4} torr of Argon and a low energy electron gun was used for creating the ionized channel. (The details of channel generation using a low energy electron beam have been described elsewhere.[8])

Single turn, low inductance, B-dot monitors were located at the entrance and shorted end of the cavities for measuring cavity and beam currents. A PIN diode was used to record the Bremsstrahlung radiation generated when the beam struck the carbon beam dump. E-dot probes were placed in the cavities to record the induced voltage waveforms. Data were recorded on oscilloscopes with an overall system bandwidth of 300 MHz.

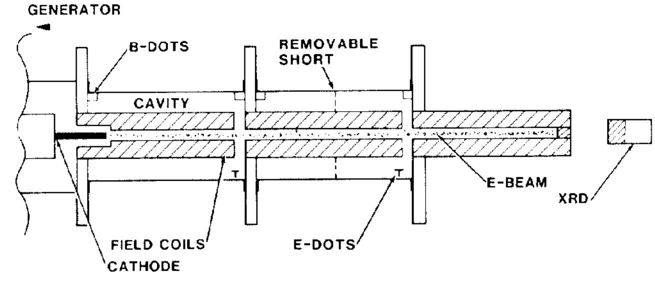

Figure 1. Schematic of autoaccelerator experiment.

CH2387-9/87/0000-0969 $1.00 © IEEE

PAC 1987

Magnetic Transport Results

The magnetic transport experiments were performed using a 1.8 MeV, 11 kA, 60 ns beam propagated through two 1 m long cavities. Current monitors indicate both cavities were excited by the beam and showed the expected 4τ = 14 ns ringing period. In addition, the cavities rang for four cycles without adverse cavity interactions.

The gap voltages and beam energy gain were determined through two independent measurements, the transformation of the cavity current to gap voltage (via transmission line (T-line) equations) and relative X-ray measurements on 0,1,and 2 cavity systems. T-line calculations show that both cavities contributed approximately equally to the beam's acceleration and that a total acceleration of 790 keV was indicated.

X-ray measurements also confirmed the beam's acceleration. The X-ray intensity due to the beam striking the carbon dump is proportional to $IV^{2.8}$ where I is the beam current and V the beam energy. By comparing the XRD response for no cavities present to both cavities present and using the diode voltage, one can calculate the voltage gain. Figure 2 shows a comparison of the output energies calculated from current measurements and XRD measurements with both cavities operating. The XRD analysis yielded an acceleration of 610 keV so that the average of the two estimates indicate an acceleration of 700 ± 130 keV was achieved. Leakage currents across the gaps limited the acceleration to 80% of the theoretical maximum of 880 keV for an 11 kA beam passing through two 40 Ω cavities.

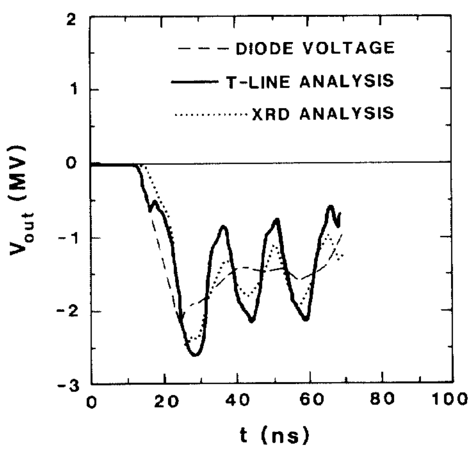

Figure 2. Comparison of the output energies derived from XRD signals and transmission line analysis of measured currents (magnetic transport).

IFT Results Using Two 1 m Cavities

This section describes an experiment which used IFT to transport an IREB through two 1 m long cavities. The IFT successfully transported 70% of an injected 9 kA beam through the accelerator. This resulted in approximately 8 kA and 7 kA of current at the gap 1 and gap 2 locations respectively.

Again, two independent measurements of beam energy were obtained using measured cavity currents and relative X-ray measurements. T-line analysis of the cavity currents indicated 260 kV of acceleration from Gap 1 or 81% of the theoretical value for an 8 kA beam and a 40 Ω cavity. A voltage of 270 kV was indicated for gap 2 (96% of theoretical for a 7 kA beam). By comparing the XRD signals for no cavities and two cavities, as was done previously, an output energy of 2.2 MeV was obtained (580 keV of acceleration). Figure 3 shows a comparison of the output energies derived from the measured cavity currents and that of the XRD signals. The two estimates are seen to agree well throughout the waveforms, and averaged together indicate an acceleration of 560 ± 30 keV on the first accelerated pulse. This is 78% of the expected acceleration for a 9 kA beam passing through two 40 Ω cavities.

MAGIC was used to simulate operation of one of the autoacceleration gaps using IFT. A simulation was run with a 2 MeV, 10 kA injected beam propagating down an IFT channel with the ratio (f_e) of channel to beam linear charge density equal to one (see Fig. 4). Classical operation of the gap was confirmed. The plasma electrons are expelled leaving an ion core that guides the beam. The simulation shows that the beam propagates stably through the gap, first being decelerated then accelerated by the expected ± 400 keV. It also indicates electrons being eroded from the head of the beam are sprayed onto the gap surfaces. This may enhance gap emission resulting in less efficient acceleration.

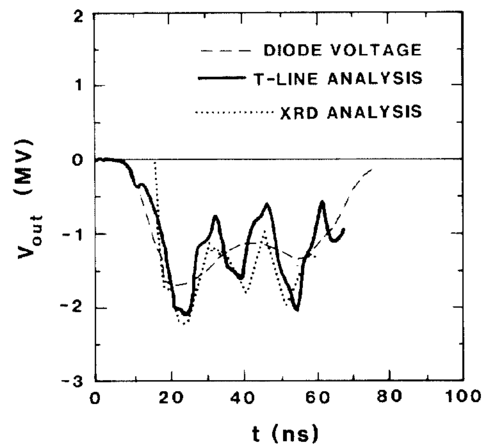

Figure 3. Comparison of the output energies derived from XRD signals and transmission line analysis of measured currents (IFT results).

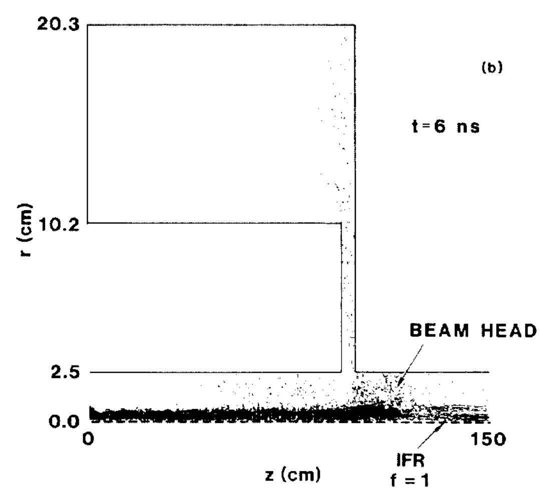

Figure 4. MAGIC simulation of IFT autoaccelerator gap. Beam input: 10 kA, 2 MeV, β_{perp} = 0.1, r_{beam} = 0.8 cm. Channel: r_{ch} = 0.8 cm, f_e = 1.

Energy Doubling Investigations

In these experiments, IFT was used to propagate the beam through two accelerating cavities. Both cavities were 40 Ω impedance with the first being 1 m in length (τ = 3.5 ns) and the second being 0.5 m long (τ = 1.75 ns) (see Fig. 1). In order to obtain maximum acceleration with the two 40 Ω cavities, the beam current was increased over that of the previous sets of experiments. A peak current of 32 kA was transported to the first gap. However, at these higher currents the IFT was less efficient than at the 9 kA level and only 20 kA reached the second gap.

In these experiments, it was necessary for the low energy portion of the beam exiting the first gap to be removed before reaching the second gap in order to avoid virtual cathode formation there. Two processes contributed to the removal of the low energy beam. With the IFT, the channel electrons are expelled at the expense of the beam electrons' energy at the head of the beam. This results in current loss or "erosion" at the head of the beam as it propagates down the plasma channel. In order to further enhance removal of the low energy portion of the beam, a 2.8 cm diameter aperture was placed 7 cm downstream of the first gap. MAGIC simulations show that the radius of the low energy portion of the beam is larger than that of the high energy portion. The aperture then results in scraping off a portion of the low energy beam. These two effects together resulted in the entire low energy portion of the beam being removed before reaching the second gap.

Studying the integrated E-dot waveforms, two things were noted. First, the interval between acceleration and deceleration was 7 ns for the first gap and and only 3.5 ns for the second, corresponding to the 1 m and 0.5 m cavity lengths respectively. Also, the initial decelerating voltage was greater than the following acceleration pulse indicating the occurrence of emission across the gap.

T-line analysis indicated a total of 1.42 MV of acceleration or a voltage gain of 94%. Without gap emission, so that equal acceleration and deceleration would have occurred, the data suggest that an energy increase of 1.72 MeV (energy gain of 115%) would have been attained. Figure 5 shows the resultant estimate of the output beam energy (derived from XRD measurements) compared to that obtained from the measured currents. The two estimates averaged together indicate an acceleration of 1.25 ± .16 MeV occurred resulting in a kinetic energy gain of 84%.

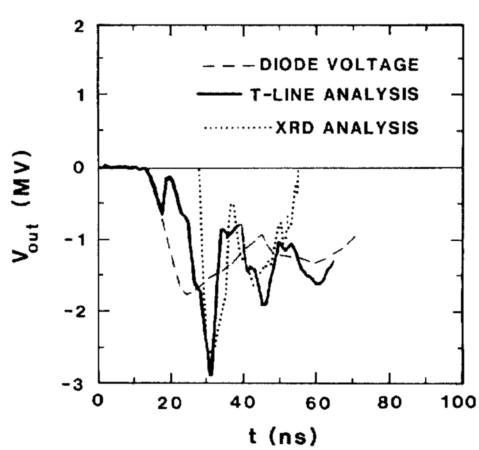

Figure 5. Comparison of the output energies derived from XRD signals and transmission line analysis of measured currents (energy doubling investigations).

Conclusions

A two cavity autoaccelerator has been used in the short pulse mode to study the acceleration of an IREB under three conditions. Magnetic transport was first used to propagate an 11 kA beam past two 1 m, 40 Ω cavities. The beam kinetic energy was increased from 1.8 MeV to a peak of 2.5 MeV with both cavities contributing approximately equally to the acceleration. This represents 80% of the maximum theoretical acceleration. Significantly, no interaction between the two cavities was observed over three cavity transit times and three accelerated pulses were obtained.

The next set of experiments used ion focused transport (IFT) to successfully replace the magnetic guiding field. A 9 kA injected beam was transported through the accelerator and acquired 560 keV of additional energy from the two cavities (78% of the maximum theoretical acceleration). Again the cavities operated over several cavity transit times. Simulations and experiments indicated that emission across the gap, arising from the initial injected beam electrons being sprayed against the gap surfaces, could be a potential problem with the use of IFT.

Finally, experiments were performed to investigate achieving a particle kinetic energy gain greater than 100%. An ≈ 25 kA beam was propagated through a 1 m and then a 0.5 m cavity using IFT. The initial decelerated portion of the beam leaving the first gap was successfully removed before reaching the second gap, thereby avoiding creation of a virtual cathode in the gap. The second cavity was excited and further modulated the accelerated beam at twice the initial frequency, thereby achieving the second stage of energy compression. The beam achieved a peak kinetic energy gain of 84%. Current transport losses and gap emission prevented the achievement of a gain greater than 100%. However, the necessary physical prerequisites of removal of decelerated electrons and multiple stages of energy compression were attained. This achievement implies that autoaccelerators operating in the short pulse mode can be used to obtain energies well over twice the injected energy via several stages of energy compression.

Acknowledgments

The authors wish to thank I. Molina, S. Hogeland, and J. Leija for their help in construction and operation of the experimental facility. This work was supported by the Naval Surface Weapons Center.

References

1. T. R. Lockner and M. Friedman, J. Appl. Phys. 51, 6068 (1980)
2. T. R. Lockner, M. Friedman, P. Palmadesso, and B. R. Kusse, J. Appl. Phys. 54, 6160 (1983).
3. M. Friedman, Phys. Rev. Lett. 31, 1107 (1973).
4. M. Friedman, Appl. Phys. Lett. 41, 419 (1982).
5. G. W. Still, J. D. Ivers, J. A. Nation, and S. Zhang, J. Appl. Phys. 60, 585 (1986).
6. D. S. Prono, IEEE Trans. on Nuclear Science, NS-32, 3144 (1985).
7. W. E. Martin, G. J. Caporaso, W. M. Fawley, D. Prosnitz, and A. G. Cole, Phys. Rev. Lett. 54, 685 (1985).
8. C. A. Frost, S. L. Shope, C. A. Ekdahl, J. W. Poukey, J. R. Freeman, G. T. Leifeste, M. G. Mazarakis, R. B. Miller, and W. K. Tucker, Proceedings of the 1986 Linear Accelerator Conference, Stanford Linear Accelerator Center Report No. 303, 537, 1986.