AN EXPERIMENTAL TEST OF A MICROWAVE INVERSE CERENKOV ACCELERATOR (MICA)*

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Abstract

We describe first tests of one module of a dielectric-lined vacuum "inverse Cerenkov" accelerator. The module was fabricated by Titan-Beta, based on a design for a smooth-bore, slow wave accelerator powered by S-band microwaves from a SLAC klystron which also produces the injected 6 MeV bunched beam from a thermionic cathode rf gun. The dielectric liner (κ = 9.6) has an outer diameter of 3.14 cm, an inner diameter of 8.9 mm (through which the bunches pass), and a length of 30 cm. Power up to 200 kW was launched into the accelerator in the TM_{01} mode. The dimensions of the alumina dielectric were chosen so that the phase velocity of the wave is slowed to just below c. Observations are reported for acceleration and deceleration of the injected bunch, as a function of the relative phase of the bunch injection. An energy change up to 2% was found. The energy change scales in proportion to the axial electric field. Maximum acceleration was limited by microwave breakdown most likely caused by deficiencies in design of the input coupler and not by the limiting breakdown strength of alumina.

1 INTRODUCTION

The stimulated Cerenkov effect is a well-understood mechanism for absorption or emission of coherent radiation from an energetic electron beam [1, 2, 3]. The electrons move at speeds greater than the velocity of light in the structure (hence the name "Cerenkov"). Although there are several ways to slow light waves, as a general rule the term is used when the slowing is caused by a dielectric element. In the discussion which follows, we consider the application of stimulated absorption in the nonlinear regime of particle trapping, which applies in any electron accelerator device. Thus the label: Microwave Inverse Cerenkov Accelerator ("MICA").

Acceleration of the electrons results from appropriate phasing of an electron bunch which is emitted from a thermionic cathode rf gun, so that a continuous accelerating force can be applied to all electrons, which move synchronously with the slow rf wave. Thus the device resembles an rf linac, but without the periodic loading structures in the waveguide. As the MICA is smooth-bore and the motion of the particles is essentially one-dimensional, we expect that the emittance of the electron bunch produced can be preserved. The MICA experiments described here used a SLAC klystron source of microwave power at 2.85GHz, and with a bunch length of about 5psec, compared with the rf period of 350psec. As a consequence, there should be good trapping and acceleration of a monoenergetic bunch of electrons injected in the appropriate phase. In the MICA, the electrons move down the 9mm diameter hole in the annular alumina dielectric liner as a train of $\sim$ 2mm discrete bunches of electrons spaced by 10.5cm. The outer surface of the alumina is coated with electro-deposited copper. The main limitation is the maximum axial field gradient that can be sustained along the dielectric surface; a test on another structure showed that a field of at least 8.4MV/m could be sustained [4] by the alumina.

As the focus in this paper will be on experimental test results, we briefly summarize the principles of the device, which have been presented elsewhere [5, 6]. We take a cylindrical waveguide of radius R, lined with a dielectric sleeve which has a vacuum hole of radius a. The dispersion relation for waves in this structure [7] allows one to obtain the phase velocity for the TM_{0n} eigenmode: this depends on the dielectric coefficient, κ, of the material, which for our sample of alumina was measured as κ = 9.6. Taking a/R = 0.3, we found that the ratio $R/\lambda_0 >$ 0.15 will cause the phase velocity of the waves to be $< c$, where λ_0 is the free-space wavelength of the microwaves. For these slow waves, the axial accelerating field for $0 < r < a$ is of the form $E_{z1}(r,z,t) = E_0 I_0(k_{1I} r)\cos(\omega t - k_z z)$, where I_0 is the modified Bessel function, $k_{1I} = -ik_1$ is the transverse eigenvalue inside the vacuum hole: $k_1^2 = k_0^2 - k_z^2$; it is found that the field inside the hole is nearly constant in radius, a desirable feature. The field on axis, E_0, can be determined in terms of the total microwave power by integrating the Poynting vector in the cross-section of the waveguide. A set of typical parameters and computed results is given in [5].

The acceleration of electrons in the MICA configuration is straightforward because of the intense axial field E_z and the weak radial field at the beam. The electron energy increases almost linearly as the particles move down the waveguide. When γ_0 is large (γ_0 = 13, for our example), $\gamma \approx \gamma_0 + e|E_0|L/mc^2$. Taking $|E_0|$ = 210 (CGS), L = 150 cm, gives $\gamma = 31.5$. This is for the case where the relative phase of the electrons with respect to the rf field is π, which corresponds to an initial distribution of particles at the position $\lambda_g/2 = \pi/k_z$. Particles in this position will experience maximum axial field. Due to the small difference between the electron velocity and the wave phase velocity, one may expect that the electron will gradually slip from the maximum acceleration position. We find a

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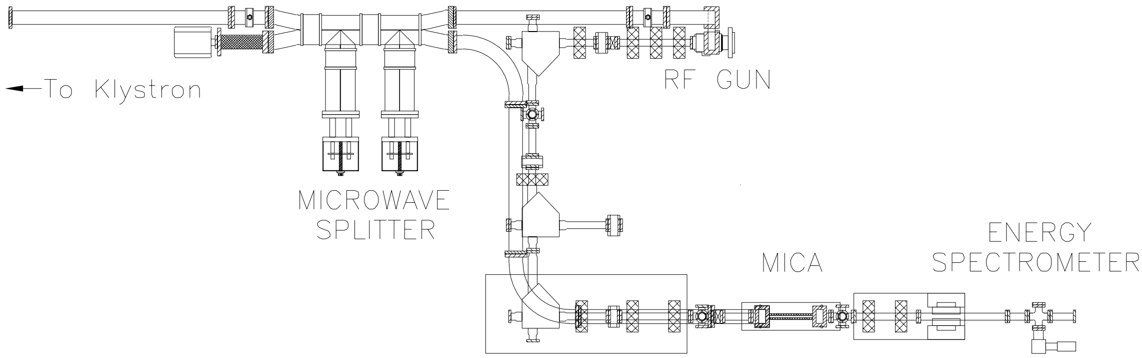

Figure 1: The overall MICA system at the Beam Physics Laboratory at Yale University.

phase slippage of $\Delta\phi \sim 24°$ in a distance of 1.5m with the electrons moving ahead of the rf field, corresponding to a slippage interval of $\sim$ 23ps. For our rf gun with a beam bunch length of only 5 ps, we can expect excellent trapping and acceleration of electrons during the entire propagation along the waveguide, without a taper of the dielectric element. According to this calculation, the electron energy grows to 16 MeV in 150 cm.

2 EXPERIMENTAL HARDWARE

The MICA structure was engineered and built by Titan-Beta, and was installed and tested at the Beam Physics Laboratory at Yale University. In the results we report here, a short section (one module, 30 cm in length) of the entire accelerator was used. Owing to limitations of power output of our klystron, and also that the rf power must be divided between the thermionic rf gun and the MICA, less than 1MW was applied to the MICA structure. Thus our results will check primarily the understanding of the accelerating field developed in this device. Since the same rf source is used for the rf gun and the MICA, there exists a fixed phase relationship between the bunch arrival at the MICA and the crest of the slow rf wave inside the MICA, and this phase can be varied, yielding either acceleration or deceleration. A schematic of the overall MICA system is shown in Fig. 1, showing the microwave transport and power splitting system, the rf gun, the beam transport system leading into the MICA, the MICA module, and the energy diagnostics at the end of the beamline.

As shown in Fig. 1, bunches of electrons, emitted from the 2-1/2 cell rf gun, travel through two $90°$ bending magnets before entering the vacuum channel of the MICA. These two $90°$ bending magnets comprise an acromat giving energy selection and also allow control of the energy spread of the electron bunch using a motor-driven slit. After passing through the MICA module, the electron bunches are deflected by a dipole onto a graphite target coated with phosphor. The graphite target is observed with a CCD camera for energy measurement. The microwave splitter divides the 2.85GHz microwaves in a user-adjusted ratio between the rf gun and MICA. The relative phase between the two microwave channels can be varied up to $360°$. For this experiment, the rf power for MICA module is between 0.32% and 4.0% of the total rf power. The 2.85GHz microwaves are conveyed in and out of the MICA via rectangular TE_{01} waveguide using couplers to be described below, and probes are present at both ends to monitor the transmitted and reflected power. A matched load is attached to the output rectangular waveguide to prevent reflection of the transmitted microwave back into the MICA. The power is converted into the TM_{01} cylindrical mode for the MICA by the input transition waveguide, designed and fabricated by Titan-Beta. At the operating frequency, the manufacturer quoted a reflected power from the input transition waveguide of 4 to 5%, and an insertion loss of -4dB overall. It is not known why the insertion loss is so high, but the conducting walls of the cylindrical waveguide are made of electro-deposited copper, and it is possible there is some microwave loss due to imperfections in the coating. In what follows, we shall take the input wave to be uniformly attenuated by 5.2dB (see below) in power as it propagates to the end of the test section. The module was vacuum pumped at the input and output ends. A short period of rf conditioning with the microwaves was needed to obtain a vacuum of $\sim 10^{-7}$ torr. The experimental parameters are given in Table 1.

Table 1: Experimental parameters

MICA module	O.D.	3.14cm
	I.D.	8.9 mm
	Length	30 cm
	κ	9.6
Electron beam micropulses	Energy	6 MeV
	Current	0.5–1.5 A
	Duration	5–10 psec

3 EXPERIMENTAL RESULTS

We first present results of measurements of the energy change of the electron bunches as a function of the phase. The rf power for MICA is -14.5dB (3.55%) of the total rf power for the data given in Fig. 2. The total rf power from the klystron is measured at $\sim$ 5.75MW: thus the rf power for MICA at about 200 kW. The phase is changed every $30°$. The black dots in the figure are the measured electron energy at different relative phases. This energy is measured by locating the centroid of the electron bunches observed by a camera frame at the energy spectrometer. The solid line is a sine curve fitted to the experimental results. The maximum energy change is $\pm$ 2%.

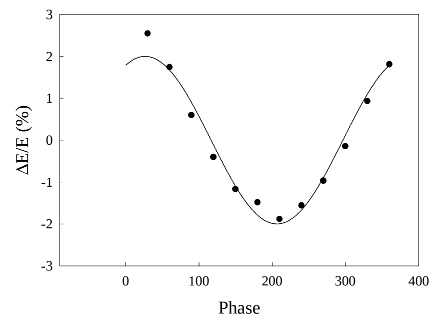

Figure 2: Energy change of electron as a function of phase.

A typical electron bunch snapshot is shown in Fig. 3. The electron bunch is $\simeq$ 2.5 mm in diameter. The solid line represents the energy axis. The total energy range we measured is about 18% of 6 MeV, which represents the length of the tilted solid line. The accuracy of the spectrometer is limited by the magnetic field measurement, which is about $\sim$ 0.25%. The energy increases are toward the upper left direction.

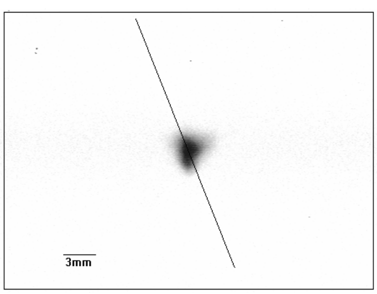

Figure 3: Photograph of the electron bunch profile at the energy spectrometer.

Table 2 is a summary of the experimental results for different splitting ratios of the microwaves. The first column is the ratio between rf power into MICA and total rf power. The second column is the rf power into the MICA. The third column is the measured maximum energy change. It is found that the measured maximum energy change scales in proportion to the axial electric field as expected. Our determination of the MICA module insertion loss by a "cold" bench test gave a value of -5.2 dB. The fourth column of Table 2 is the theoretical prediction [5] of the maximum energy change using this measured insertion loss and the measured microwave power.

When the rf power was increased up to 400 kW, the reflected power from MICA greatly increased and no energy change of the electron bunch was observed. We attribute this to the rf breakdown in the module. When the MICA was disassembled, the transition ceramic end piece in the

Table 2: Summary of experimental results

RF (dB)	RF (kW)	$\Delta E/E(\%)_{expt}$	$\Delta E/E(\%)_{th}$
-14.5	200	2.06	2.48
-19.7	60	1.00	1.33
-25.5	16	0.47	0.69

input transition waveguide was seen to be blackened, most likely caused by rf surface breakdown in the input coupler. The transition ceramic end piece in this design was intended to improve the rf match. Fig. 4 shows the design drawing of the input transition waveguide to the MICA alumina section.

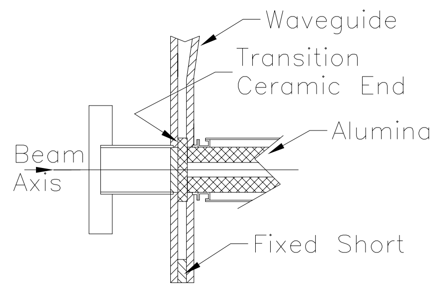

Figure 4: The input transition waveguide

4 CONCLUSIONS

First tests have been described of one module of a microwave inverse Cerenkov accelerator with the provision for adjustment of relative phase for injected electron bunches. Absolute energy change of $\pm$ 2% (acceleration and deceleration), and variation of energy change with relative phase, are in reasonable agreement with predictions. RF breakdown, most likely in the input coupler, prevented measurements with power levels above 200 kW, thereby limiting the absolute magnitude of acceleration that could be observed.

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