SUCCESSFUL BETATRON ACCELERATION OF KILOAMPERE ELECTRON RINGS IN RECE-CHRISTA

D. Taggart, M. R. Parker, H. Hopman and H. H. Fleischmann
School of Applied and Engineering Physics
Cornell University, Ithaca, NY 14853

Summary

This paper describes first experiments in which the strong electron rings normally trapped in the RECE-Christa device are accelerated in a plasma-betatron-like arrangement. Using a cold, collisional background plasma (T_e = 1-2 eV, $n_p = 10^{11}$-10^{12} cm^{-3}) generated by the ring in a gas fill of 50 - 200mTorr H_2, electron rings with currents of up to 2 kA were accelerated from about 1 MeV to 2.5-3 MeV. It appears that this method may be useful in significantly extending the parameter range of betatrons, in particular its ring current into the 10 kA range.

Introduction

In early betatron experiments[1], the ring currents, j_θ, normally were space-charge limited to a few amperes. Various methods have been considered to raise this limit and had some success: (i) higher energy injection[2] led to j_θ < 50 A; (ii) the addition of strong toroidal fields in a "modified betatron" arrangement[3] is projected to permit the acceleration of 5-10 kA beams to 50 MeV in experiments presently under construction[4]; and/or (iii) the addition of a charge-neutralizing plasma in a "plasma betatron"[5] which is of main interest here, would avoid the space-charge problem altogether.

In the earlier plasma-betatron experiments[5], the beam electrons either were generated through a runaway process from the plasma itself or were injected into a rather tenuous plasma at rather low energies (typically 50 keV). Results were somewhat ambiguous with J_θ = 10-100 A and final beam energies E_f = a few 100 keV. Ring lifetimes and acceleration appeared limited by various instabilities, with the negative-mass and the two-stream beam-plasma modes most often considered the culprits. This situation is matched by that in physically related runaway Tokamak discharges: in cases where large runaway currents were obtained[6], the beam energies appeared limited to the 100 keV range; in other cases[7] where MeV electrons were observed their current was only a few hundred amperes.

Here, we describe first positive results on the acceleration of kA-electron rings in the MeV range. Extending our earlier experiments with Astron-type field-reversing kA-rings, charge-neutralized rings first are generated by injecting and trapping MeV electrons and then accelerated betatron-style. In contrast to earlier plasma-betatron experiments, beam stability apparently is obtained through the collisionality of the cold-dense gas-plasma background and the angular spread of the fast electrons.

Apparatus

The RECE-Christa device[8] is shown in Fig. 1. In brief, intense electron beam pulses (2.5 MeV peak energy, 50 kA, 80 nsec) are injected tangentially at a radius of 15 cm into a vacuum tank (5 m long, 60 cm dia.). The base magnetic field consists of a nearly homogenous, steady-state axial field of 400-500G, a toroidal field generated by an axial current I_z = 30-100 kA, and some fast-pulsed axial fields ($t_{1/4}$ = 25 μsec, B_p < 30 G) used in the trapping and axial translation of the rings.

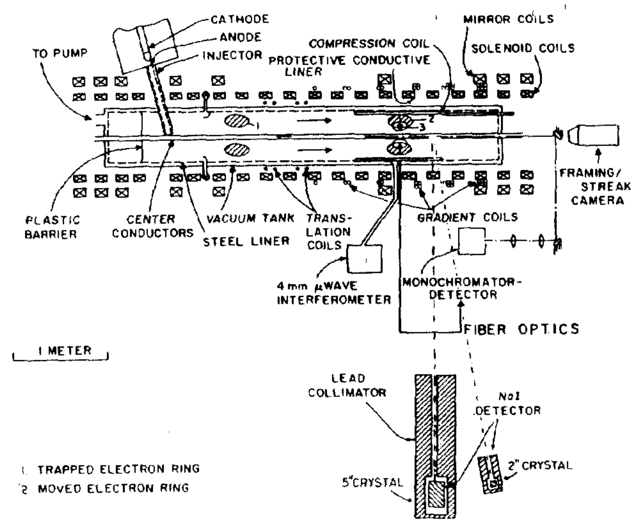

Fig. 1: RECE-Christa Device

In our field-reversal experiments[9], strong electron rings routinely are trapped upstream in a puffed-in gas cloud, translated axially into a low-gas-density region downstream and then investigated. Rings normally are found to behave stably over a wide range of parameters with lifetimes ranging up to a few msec, depending on the gas pressure downstream.

For the present experiments, the acceleration arrangement shown in Fig. 2 was placed in the downstream region. An accelerating flux coil (10 cm dia., 1.5 m long, 180 turns, 10-20 V/turn, ϕ < 10 mVsec) is positioned around the axial conductor; our normal compression coil[10] is used to provide the required net increase of the axial field at the ring position. The coils are energized from two separate capacitor banks having a nearly identical quarter-cycle time of 260 μsec. In contrast to our field reversal experiments, the gas fill in the tank now consists of a steady-state fill of 50-200 mTorr H_2 plus the normal gas puff upstream.

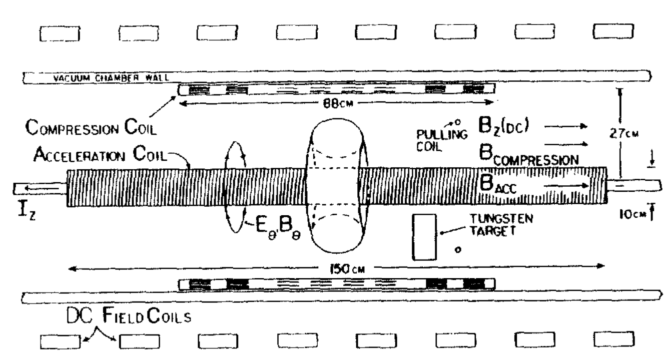

Fig. 2: Details of Accelerator

0018-9499/83/0800-3165$01.00© 1983 IEEE

The ring geometry and strength is diagnosed[11] through an arrangement of magnetic probes (passively integrated with RC = 2 → 4.5 msec) positioned both axially along the acceleration coil and at the tank wall. A rough energy analysis is performed by pulling the rings axially into a tungsten target (see Fig. 2) and measuring the resulting X-rays using two NaI detectors (see Fig. 1). Of these detectors, the larger (5x5 inch, well shielded) is used with varying absorbers placed in front, while the smaller (2x2 inch, less strongly shielded) is used as monitor. The detector signals again are integrated (RC = 50 μsec). All probe and detector signals are recorded and subsequently analyzed using LeCroy 8210 digitizers and a LeCroy 3500 system. Plasma densities in the ring region can be measured using a 4-mm μwave interferometer (see Fig. 1). Typically $n_p = 10^{11}$-10^{12} cm^{-3} is observed. Due to the high gas density, this plasma is very cold(T_e = 1-2 eV, T_i = 1 eV) and thus highly collisional and resistive.

Experiments and Results

Using this arrangement, initial acceleration experiments were performed recently. Sample recordings of the magnetic probe and X-ray detector signals are given in Fig. 3. Fig. 3a shows the net change of the applied axial field in the ring region generated by the acceleration and compression coils, indicating an approximate doubling of the total applied field during the acceleration (B_{zo} = 450 G). Fig. 3b shows the ring generated field (i.e.-RC corrected probe recordings with the pulsed fields subtracted) from various probes spread along the axis (# 19 in the ring center, # 18 upstream, #s 20 and 23 downstream). After ring generation upstream, the ring is seen to move into the acceleration region (t≈100 μs); then, after initiation of the acceleration at 280 μsec, the probe recordings increase slightly in this case, indicating the induction of a small plasma current in the ring; but the signals then remain quite constant during the rest of the acceleration phase. After completion of the acceleration, the ring is pulled downstream and destroyed on the W-target. Consistent with the probe readings, the X-ray detectors show strong initial spikes during beam injection, only little intensity during acceleration, and again sizable spikes at the end.

The total ring current in this case is found to be 1.7 kA. In other cases where initial ring currents were larger (up to about 4 kA) a more pronounced continuous loss of current is observed with ring currents remaining after acceleration ranging up to 2 kA.

Fig. 4 shows a typical time development of the average ring radius during acceleration as derived from probe recordings. In case A, the acceleration and compression fields approximately satisfied the betatron condition, and the radius - as expected - remains constant; in case B, the compression field was reduced by about 40% (relative to case A), and the radius increases.

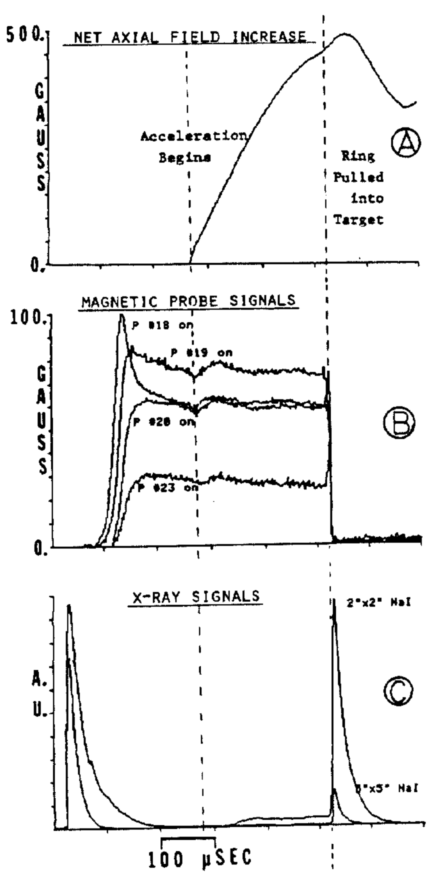

Fig. 3: Sample Recordings; (a) Net B_z -field Increase, (b) Ring Generated Fields at Various Axial Positions, (c) NaI X-ray Detector Signals.

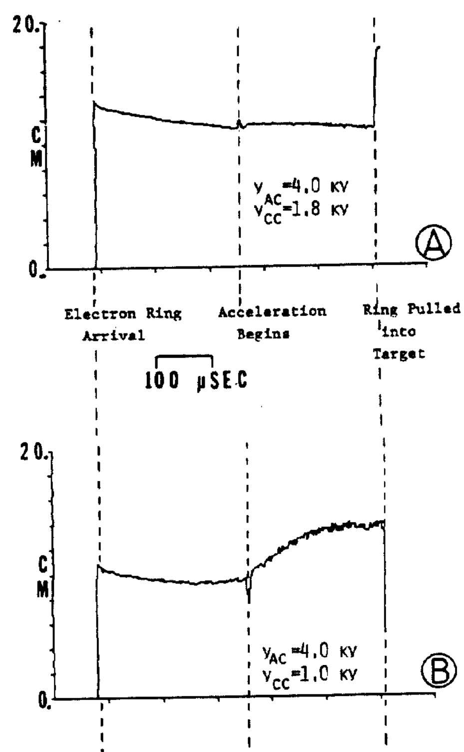

Fig. 4: Time Dependence of Average Ring Radius for Different Compression Coil Voltages.

Results of the energy measurements are shown in Fig. 5. In part A, the intensity ratio I_{5x5}/I_{2x2} of the two detectors is plotted for various accelerator voltages and absorber combinations. In all cases, 5 cm Pb is placed in front of each detector, while the indicated additional Al and Fe absorbers only cover the 5x5 inch detector. While intensity fluctuations are present (mainly due to fluctuations in the average energy of the electrons as well as statistics in beam behavior during extraction) these fluctuations clearly are quite small compared with the differences for various absorbers. Part B gives theoretically expected absorption intensity ratios [with Pb+(Al, Fe) absorbers to Pb absorber only] together with the averaged experimental data from Part A. The theoretical curves were calculated by folding the forward directed X-ray energy spectrum (as given in Ref. 12, assuming a monoenergetic, monodirectional electron beam) with the energy dependent attenuation coefficients of the various absorbers. So far no corrections for multiple scattering of the X-rays were included; while quite small (≈10%) such corrections would tend to increase the derived energy values. Clearly, the energy of the electrons after acceleration is in the range of 2.5-3 MeV which is quite well consistent with the observed ring radii and fields after compression. Unfortunately, the initial beam energy could not yet be determined with comparable accuracy; however, the observed ring radii and fields indicate average initial energies around 1 MeV. The inferred acceleration from about 1 to 3 MeV again is consistent with that expected from the applied pulsed fields.

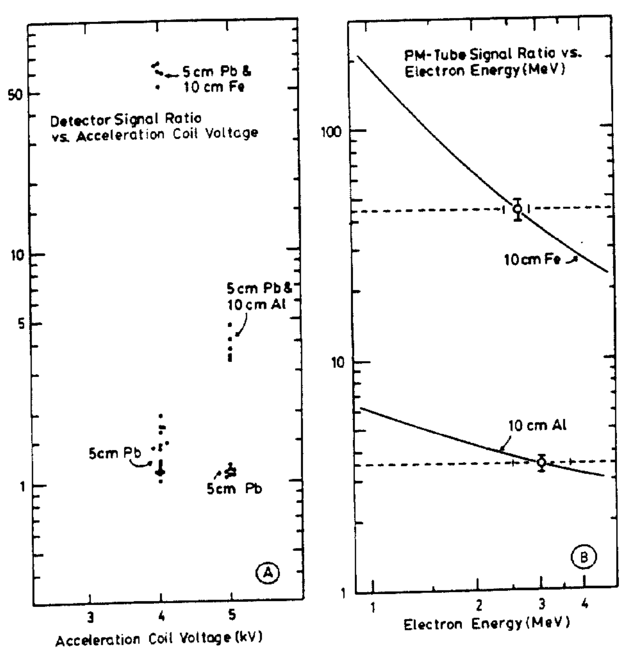

Fig. 5: (a) Observed Intensity Ratios (I_5x_5/I_2x_2) for Various Absorbers and (b) Calculated Absorption Ratios for Various Beam Energies.

Discussion

While the observed energy gain from about 1 to 3 MeV is not yet large compared with other betatrons, the performance, in particular the accelerated currents, clearly constitutes a very significant improvement over earlier betatron experiments. We feel that this performance improvement vis-a-vis earlier plasma betatron experiments is mainly due to the very different parameters of the background plasma. Due to the high energy of the injected electrons, the neutralizing background plasma is variable over a wider range and can be made much colder and more collisional than in the earlier experiments. In addition, the injection mechanism probably also provides a sizable - although unknown - angular spread of the fast electrons which again will aid in suppressing various beam and beam-plasma instabilities. Using these ingredients, it appears that this method also should be extendable to higher beam currents and energies. With some changes, the present arrangement may be extended to final beam energies around 5 MeV, and such experiments are intended.

An interesting question exists concerning the beam losses observed in the acceleration of strong rings. Their origin is not clear at this point although a variety of potential mechanisms offer themselves including remaining beam plasma turbulence, orbital resonances, possibly also an untrapping of the fast particles during acceleration (e.g. due to conservation of the toroidal flux in the beam). Clearly, further experiments will have to be performed on this question.

References

Work supported by Department of Energy

1. e.g. D. W. Kerst, Phys. Rev. 58, 841 (1940).
2. A. I. Pavlovskii, G. D. Kuleshov, A. I. Gerasimov, A. P. Klement'ev, V. O. Kuznetsov, V. A. Tananakin, and A. D. Tarasov, Sov. Phys. Tech. Phys. 22, 218 (1977).
3. e.g. P. Sprangle, C. A. Kapetanakos, and S. J. Marsh, Proc. 4th Int. Conf. High Power El. & Ion Bem Res. & Tech., 803 (1981).
4. C. Kapetanakos, P. A. Sprangle, and S. J. Marsh, NRL Memorandum Report # 4666 (1981).
5. e.g. G. J. Budker, CERN Symposium 1, 68 (1956) and J. G. Linhart, Proc. 4th Int. Conf. Ion Phen. Gases, 981 (1960).
6. G. Fussmann, et. al., Phys. Rev. Lett. 47, 1004 (1981).
7. H. Knoepfel and S. J. Zweben, Phys. Rev. Lett. 35, 1340 (1975).
8. H. A. Davis, R. A. Meger, and H. H. Fleischmann, Phys. Rev. Lett. 37, 542 (1976).
9. D. J. Rej, M. Tuszewski, H. A. Davis, and H. H. Fleischmann, App. Phys. Lett. 33, 910 (1978).
10. M. Tuszewski, D. J. Rej, and H. H. Fleischmann, Phys. Rev. Lett. 43, 449 (1979).
11. D. J. Rej, M. R. Parker, and H. H. Fleischmann, Phys. Fluids 26, 323 (1983).
12. W. Dickinson and E. Lent, Univ. California Report UCRL-50442 (1968).