THE GARCHING ELECTRON RING ACCELERATOR EXPERIMENTS

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Abstract

The Garching ERA experiment consists of a field emission electron source, an electrostatic accelerator (up to 2 MeV) and a fast three-stage magnetic compressor. Compression of rings of up to $2 \cdot 10^{12}$ electrons to energies of 12.6 MeV has been achieved. A compressor II for performing roll-out experiments is under construction.

Introduction

In October 1968, a group of physicists and engineers of Max-Planck-Institut für Plasmaphysik*) started work on the electron ring accelerator. Since it was intended to keep the size of this effort relatively small, the attempt was made to make the best use of commercially available hardware, technological "know-how" available in the Institute, and the knowledge of other laboratories as far as it was accessible. It was therefore decided to use as electron injector a Febetron field emission gun, and three pairs of single-turn coils as compressor. Fig. 1 gives a schematic of the machine (one coil of each of the three pairs is removed). The quarter-periods of each of the three compression circuits was chosen to be about 9 μs – in the range in which many fast plasma compression experiments are also conducted. Three major advantages result from this increase in speed, compared with other ERA experiments:

1) While the motion of the electrons is still adiabatic, all instabilities are crossed faster during compression. As far as the growth of the instabilities depends on deviations from field symmetry, the requirements on the symmetry are correspondingly less stringent.

2) All conductors behave during the compression period almost ideally, since the electric currents have no time to "diffuse" much into the interior of the conductors. Therefore, all inductances may be considered to be time independent, and the magnetic field is determined by the instantaneous total currents in each of the coil pairs.

3) The requirements made on the base pressure in the apparatus are relaxed. It was possible to operate at a pressure of 10^{-5} Torr, and, indeed, to use a vacuum vessel made of

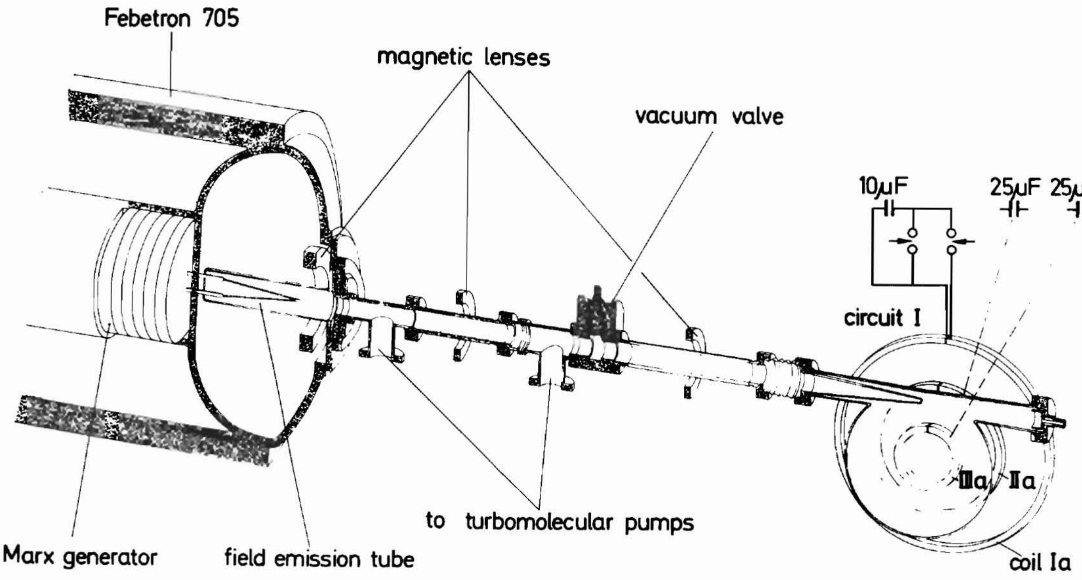

Fig. 1 Schematic of field emission tube, the beam guiding system, and the compressor. The charging voltage of the capacitors shown is 40 kV.

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*) members: C. Andelfinger, E. Buchelt, W. Dommaschk, R. Griek, W. Herrmann, D. Jacobi, A. U. Luccio, P. Merkel, W. Ott, H. B. Schilling, A. Schlüter, U. Schumacher, G. Siller, P. Ulbricht, M. Ulrich

plastic (lucite). The main disadvantage seems to be that the leads to the coils are relatively bulky; their (apparent) diamagnetism distorts the field symmetry. However, this effect seems hardly to be larger than that caused by the twist of the winding of a many-turn coil. The measured deviation of the field from azimuthal symmetry is everywhere less than 0.5 %, except near the injection snout. The snout effect is compensated by conducting and ferromagnetic layers to such an extent that the remaining disturbance is about 1 % on the inflection orbit.

The Febetron 705 gun delivers about 5 000 A of electrons with a peak energy of about 1.9 MeV; out of these a varying fraction of 60 ... 100 A lies in an emittance cone of 130 mrad·cm. Apart from this useful current being somewhat small, further drawbacks consisted in the large instantaneous ($\pm$ 3 %) and the large time dependent (- 6 %) variation of energy, and in the low life expectancy of the tubes (about 500 shots). Its main - and up to now decisive - advantages are the relatively low price and the possibility of making improvements.

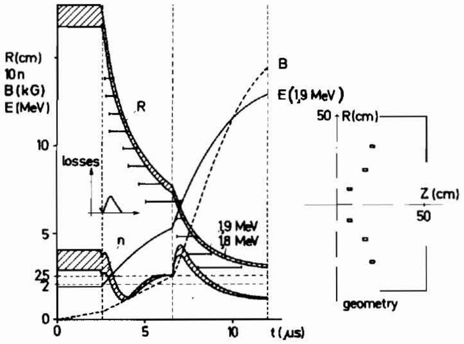


Fig. 2 A meridian half cross section through the compressor coils and the "Dosen" copper shield. On the left-hand side various quantities are shown versus time as seen from the ring. Injection time is 2.5 μs.

Compression experiments

In October 1969, the first electron rings were produced and compressed by all three stages. They contained a few times 10^{10} electrons. Improvement of the beam guiding system and of the inflection, as well as optimization of the time sequence of the compression stages, has allowed an increase of this number by a factor of about 100. Further improvement, in particular of the electron source, should make rings of almost 10^{13} electrons feasible.

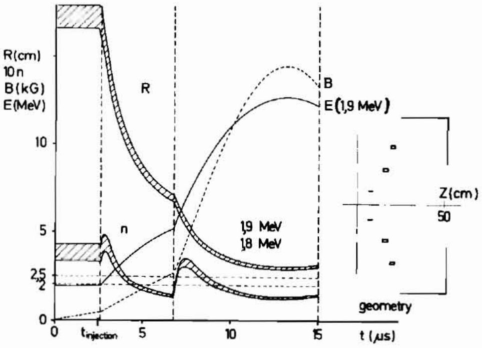


Fig. 3 Modified version, otherwise as in fig. 2.

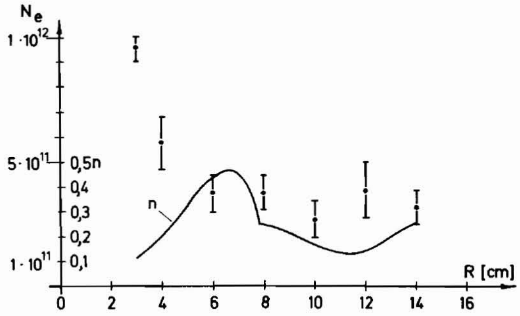


Fig. 4 Number of particles in the ring as a function of the radial position of the Faraday cup. Also given is the theoretical n at that position.

Injection and Compression

The beam of electrons is inflected into the compressor by a pair of coils inside the vacuum vessel. The azimuthal extent of the inflector is 180°. In order to reduce the asymmetry due to the presence of the conductors, the other half of the circumference is covered by a passive conductor. During inflection the magnetic field rises at the rate $\dot{B} \approx 3 \cdot 10^9$ G/s. The radius of the orbit of inflection is 18.5 cm for 1.9 MeV electrons. The subsequent history of the major ring radius R, of the field index on the orbit, of the magnetic field on the orbit, and of the energy of the electrons is shown in fig. 2. The total time taken by the radius of the orbit to reach its minimum value of about 3 cm is 10 μs after inflection. The γ of the electrons should then be 25 and the field index near 0.1. Also indicated in the figure are the Faraday cup signals at different positions indicating the position and extent of the ring. The fact that the measured signals occur earlier than would correspond to the calculated orbits of the electrons of original energy between 1.8 and 1.9 MeV is not surprising since any betatron oscillations present as well as the occurrence of electrons of of energies below 1.8 MeV would have precisely this effect. During our last experiments this field geometry and the timetable of the magnetic compression were somewhat changed, as indicated in Fig. 3. This was, in the first instance, prompted by the observation of some unexpected differences between the calculated and measured magnetic fields during the later stages of the compression. This was attributed to a deviation from the ideal behaviour of the innermost coil pair, which was therefore replaced by a thinner conductor. We also postponed the passage of the ring through the instabilities between n = 0.2 and 0.36, so that they should occur at smaller radii of the electron ring where we would expect possible existing field asymmetries to be smaller, as also the derivative dn / dR. We pay for this improvement with a slower crossing of these instabilities. Indicated in both fig. 2 and 3 are also the conductors called "Dosen", by which we have tried to minimize the effect of externally present conductors on the field produced by the compression coils. The currents induced in these conductors have, of course, been taken into account in the calculations.

Diagnostics

The particle numbers in the ring and its positions were measured by using a Faraday cup made of lead with a cross section of 5 mm x 5 mm and a length of 50 mm shielded by 0.2 mm Cu. This cup shows a time resolution of 1 ns. Particularly as long as the particle number was relatively small, we found the Faraday cup the most convenient diagnostic tool. Though the reliability of its signals was impaired by possible and unknown scattering of electrons, by the production of secondary particles, and by the possible influence it might have on both the magnetic and electric field present. This is clearly demonstrated in fig. 4, where the particle number in the ring as taken from the Faraday cup signal is plotted versus the position of the cup. It appears that at smaller radii there are more electrons in the ring then at larger radii. This must be due to the fact that the Faraday cup itself acts as a source of instabilities by which the amplitudes of the oscillations of the electrons are increased. The ensuing loss to the walls would depend in a complicated way on the value of n and its derivatives and on the proximity of the walls, which for radii below 4 cm are further away than for larger radii.

The X-ray signal produced by the Faraday cup was also monitored. Most use of this signal was, however, made when the Faraday cup was removed and replaced by a thin copper or gold wire which influenced the ring much less than the cup did.

After earlier attempts had not given sufficiently reliable data, it became possible during the last few weeks to measure the magnetic field produced by the ring. A little pickup coil placed in the center of the compressor and compensated by two coils for the effects of the first and second stages of the compressing field, gives a signal which is proportional to the (time derivative of) $N_e \cdot R^{-2}$. Since the radius of the ring may be considered to be known, the number of electrons in the ring can easily be evaluated. Fig. 5 shows such measurements from which it follows that the number of particles in the ring can exceed that measured by the Faraday cup. The optimum value achieved so far is $2 \cdot 10^{12}$. It has not yet been possible to measure this number during the third stage of compression as well. We do not, however, expect any change during this stage since no additional particle loss is indicated by the Faraday cup measurements.

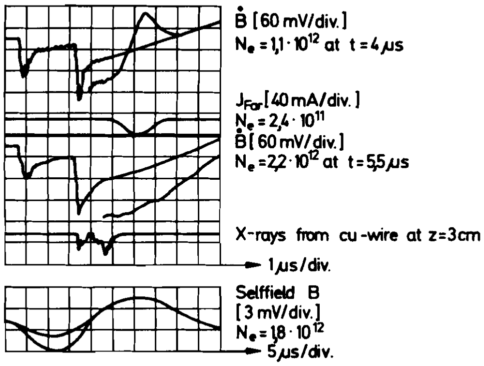


Fig. 5 The upper two oscillograms show $\dot{B}$ traces with and without injection of electrons. The signal without injection is due to incomplete compensation. The consecutive firing of two stages of the compression field is clearly visible. The difference in the traces is the effect of the self-field of the ring. The lower traces show the integrated signal on a different time scale.

During the last stage of the compression the synchrotron light emitted by the ring could be measured in the red and infrared. This method allowed us in a simple way to determine the minor extent of the ring in the axial direction. The results in both regions are compatible with b = 3 mm (fig. 6).

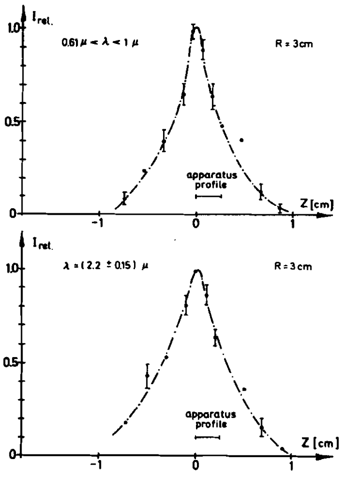


Fig. 6 Light distribution as a function of the z-coordinate for the red and infrared spectral regions.

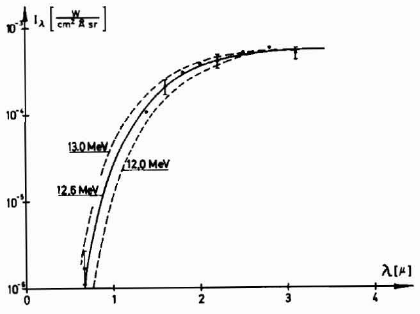


Fig. 7 Calculated spectrum of synchrotron light on a logarithmic scale for three assumed particle energies.

The wave length dependence of the signal fitted the calculated values surprisingly well, assuming the predicted value of 12.6 MeV as the energy of the electrons (fig. 7).

Instabilities

Beginning at the injection time and extending for about 20 revolutions, a Faraday cup placed 3 cm off the midplane picks up a signal which corresponds to the arrival of altogether 10^{10} ... 10^{11} electrons. This effect is accompanied by a microwave signal and a fast variation of $\dot{B}$; it indicates a bunching of the electrons in the ring. The particle losses in this process are not drastic, as evidenced by the fact that the signals also occur when the rings formed are quite good, as judged by Faraday cup measurements or magnetic measurements.

The observed magnitude of the axial extent of the ring after compression is larger than can be accounted for by adiabatic compression starting from the emittance at inflection. This suggested that the width was increased by resonances or instabilities during the passage through particular n-values. No particular particle loss could be attributed to n = 0.36. In the first set-up (fig. 2) a particle loss was measured by an off-midplane Faraday cup which could be ascribed to both the passage through 0.25 and through 0.2. In the modified set-up (fig. 3) these two values are clearly separated and a loss at n = 0.25 is only observed when there is a disturbance in the field, i.e. by a nearby radial Faraday cup or a slit in the field-shaper to be described below. At n = 0.2 the off-midplane Faraday cup always shows a signal if it is closer than 3 cm to the midplane. To demonstrate that it, was in fact, the crossing of 0.2, we used the arrangement in fig. 8, where a barrel-like field shaping conductor was placed in the centre of the machine. The equatorial curvature of this conductor was chosen to correspond to a field index of n = 0.21. In this arrangement the off-midplane Faraday cup showed no signal, as was expected.

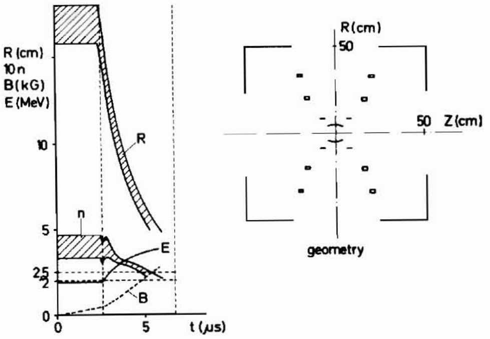


Fig. 8 Compressor of fig. 3, modified by the insertion of the field shaper called "Fassl" in the centre.

Preparation of roll-out experiment

A compressor II is under construction which should allow roll-out and spill-out experiments using the principles of the existing compressor. Since the new machine will be much less flexible than the present one, extensive numerical calculations were performed. Fig. 9 shows the arrangement of the coils and fig. 10 a perspective drawing of them. Also indicated are the leads and collectors connected to the coils. Fig. 11 shows the calculated time behaviour of various quantities at the radial and axial position of the ring. Coil pairs 1 and 2 are for compressing the ring in the midplane to a radius of about 6 cm within 12 μs after injection. The coils 3 and 5 are then to be fired to compress the ring further while accelerating it at the same time in the axial direction. Final spill-out shall be accomplished by coil 4. Coil 6 is passive all the time, but is necessary in order to have the ring compressed near the midplane.

There are plans to produce the positive B_r - component, necessary for "expansion" acceleration by a metallic rod on the axis whose diameter increases in the z-direction. The ring is then accelerated into higher fields. Such a rod could, in addition, be used for B_φ - stabilization of the ring during the spill-out and acceleration phases.

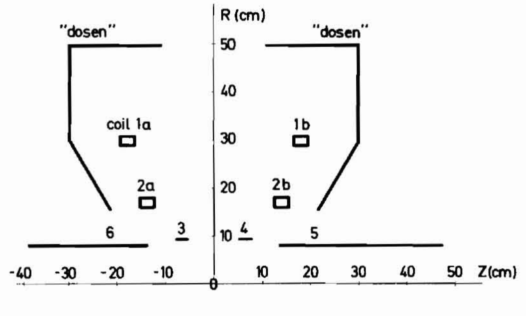


Fig. 9 Schematic of compressor II.

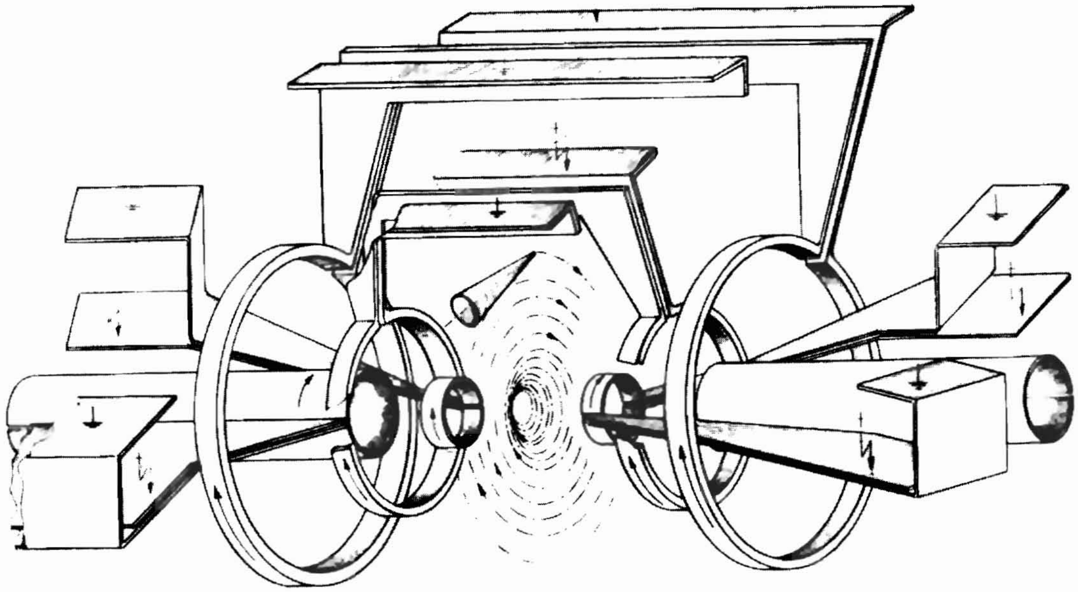
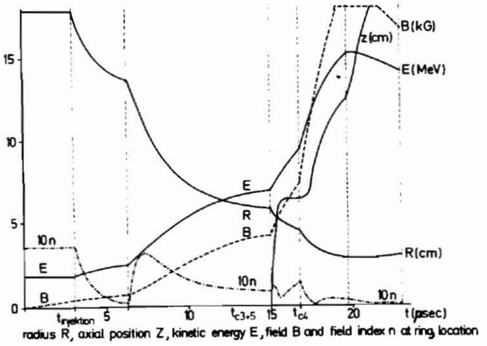


Fig. 10 Perspective drawing of compression coils of compressor II



radius R, axial position Z, kinetic energy E, field B and field index n at ring location

Fig. 11 Compressor II: Calculated time behaviour of the same quantities as shown in figs. 2, 3 and 8. In addition, the axial position of the ring is given, starting at t = 15 μs.

DISCUSSION

H. HERMINGHAUS : Have you any explanation for that long time delay of several μs between laser pulse and maximum photo emission?

A. SCHLÜTER : This effect was unexpected. It seems to be connected to a macroscopically noticeable movement of the ions evaporated by the laser light.