THE NEW GARCHING FAST ERA EXPERIMENT

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Summary

A single-turn coil for fast electron ring compression and magnetic expansion acceleration was built. It combines a fast magnetic field rise ($\frac{dB_z}{dt}/_{injection} = 3\times10^9$ G/s) for very fast resonance crossing (within less than 100 ns) with a smooth and weak expansion field (B_r = 5 G, $\frac{dB_r}{dr}/_{spill\ out} < 0.5$ G/cm). The first experiments showed strong collective behaviour of the electron ring at particle numbers of $N_e = 5\times10^{12}$, mainly radial collective oscillations with the frequency $(1-\nu_r)\,\omega_o$, which could be suppressed by increasing the corresponding Landau damping coefficient.

I. Introduction

The first Garching electron ring experiment [1-3] was made to have fast electron ring compression (compared with other ERA-experiments) in order to profit from fast crossing of single particle resonances and lower requirements on the base pressure in the apparatus. In the three-stage compression arrangement, rings with 5×10^{12} electrons were compressed [3] to minor dimensions smaller than 0.5 cm. This should allow acceleration of these rings (after being loaded) in a weak expansion acceleration structure of a radial magnetic field component of about B_r = 5 G. The observed axial broadening of the ring was attributed to the Walkinshaw resonance [2].

In order to reduce this broadening by still faster compression and to obtain a smooth expansion acceleration structure, a single-turn coil compressor [4] was built (32 cm in diameter, 75 cm in length). This coil with its relatively small inductance (of only 105 nH) allows a magnetic field rise of $\frac{dB_z}{dt} = 3\times10^9$ G/s, which is a factor of 15 higher than in the previous three-stage compressor, and which initially gives a very fast electron ring compression such that all dangerous resonances are crossed in less than 100 ns ($\nu_r = 1$ is not crossed). The G-factor [5] for the dominant Walkinshaw resonance ($n = 0.2$) is about 0.1^7 (for a relative betatron amplitude of $A_r/R = 0.05$), which should not lead to strong axial broadening.

Owing to the fast magnetic field rise the current distribution on the coil only consists of surface currents during the interesting times (a few tens of μs). With a smooth current distribution on a certain shape of the inner coil surface the desired smooth distribution of the radial magnetic field component B_r can be achieved even at relatively large mechanical tolerances of the coil. The derivatives of B_r at the electron ring spill-out point can also be made very small ($\frac{dB_r}{dr} < 0.5$ G/cm).

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The larger coil volume affords more space for applying diagnostics and arrangements for changing the electron ring environment or the magnetic field pattern. Though it is unfavorable with regard to energy consumption, it might probably serve as a model to study the initial stages of collective ion acceleration at small rates.

II. Apparatus

a) Electron beam

The electron source consists of a Marx generator (Febetron 705) with special cathode and electrode structures [6], delivering an electron current of up to 450 amps into an emittance of about $40\pi \times 55\pi$ (mrad cm) [2]. The pulse length is roughly 8 ns (HWHM). The instantaneous energy spread is smaller than 0.5 %; but during the pulse the energy varies by up to 3 %. The beam current can be attenuated. Arrangements for increasing the instantaneous energy spread are prepared.

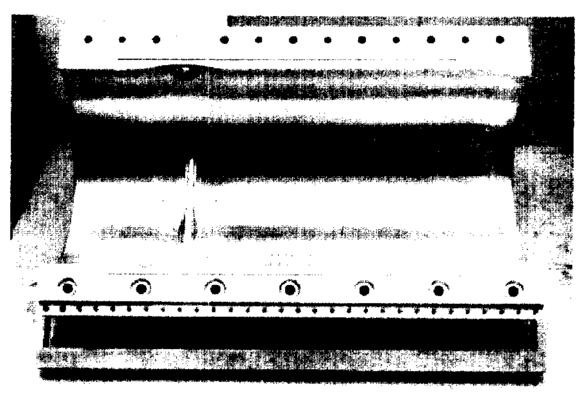

Fig. 1 One half of the compression and magnetic expansion coil (main coil)

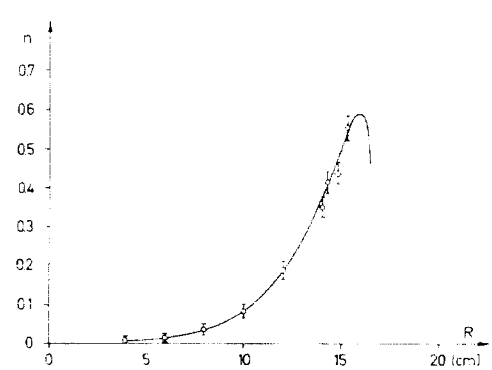

Fig. 2 Radial dependence of n

b) Compressor

The beam is injected into the main coil at a radius of 16 cm in the left part of the coil in Fig. 1, where only one half of the aluminum coil is shown. In the injection (and compression) plane the coil has a bump, which provides a magnetic field index of n = 0.55 around the injection radius. The electron ring is compressed in this plane (initially about 2 mm per electron revolution) to a radius of R = 2.3 cm at a field index of a few 10^{-2} in T = 9.4 μs.

The radial dependence of the field index n is given in Fig. 2; the circles being measurements with magnetic probes.

With the coil crowbarred at current maximum (T = 9.4 μs), a small additional coil, situated at R = 6 cm and z = -6 cm, provides the roll-out and spill-out of the electron ring into the acceleration section at any instant during a relatively long time interval.[4]

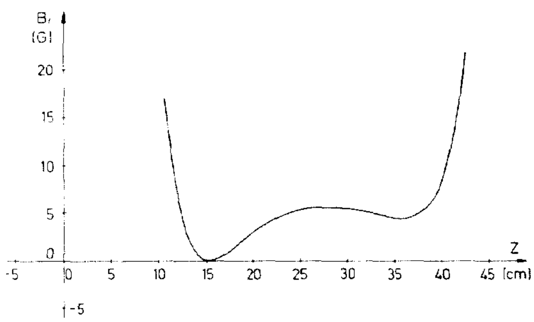

Fig. 3 B_r-dependence on z

In Fig. 3 an example of the radial magnetic field component B_r at the spill-out time is given. It is chosen to be only about 5 G in the acceleration section, since the holding power values that have been reached are relatively small (with an electron number of N_e = 5 x 10^{12} and a minor radius of about 0.35 cm at R = 2.3 cm).

c) Field parameter variations

The magnetic field parameters (n, $\frac{\partial n}{\partial r}$) can easily be changed by an active (Helmholtz coil) or passive n-corrector or by putting a conducting tube of a certain rotational symmetric shape on the axis. In this way it was possible to increase n and $\frac{\partial n}{\partial r}$ by more than one order of magnitude. If relatively poor, but mechanically strong conductors (e.g. stainless steel) are used for these tubes, then n decreases as a function of time during the ion loading phase.

The application of an additional azimutal field seems to be important for shifting betatron tunes [7] to avoid resonances, especially the most dangerous ν_r = 1 - resonance, and to increase Landau damping coefficients for transverse collective instabilities [8]. This additional B_ϕ will be produced by a current through an axial rod in a single-stage LC-circuit which is in preparation. The time behaviour of the tunes is given in Fig. 4.

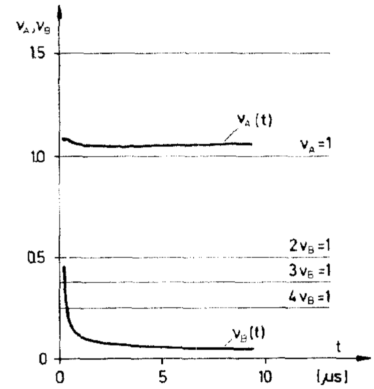

Fig. 4 Time behaviour of the tunes

III. Measurements and results

The first experiments with the fast compressor began at the end of last year. The results are not completely understood and more detailed measurements have to be done.

a) Self inflection

Single particle calculations without inflector field have shown, that a small number of electrons can be captured due to the very fast magnetic field rise. This number should be proportional to the injected current (constant emittance). Experiments without an active inflector showed however a strongly different dependence on injected current: At maximum current (450 A) the number is roughly 1/5 of that with half current. The absolute numbers are in the range of some 10^{11} electrons. The behaviour is qualitatively explained by collective beam-beam [3] and beam-wall interaction during the first few revolutions.

b) Experiments with active inflection

The use of an active inflector increases the captured particle number by roughly one order of magnitude. Parameter variations of the injection magnetic field and the inflector timing relative to the beam injection (450 A) resulted in a particle number of not more than 6 x 10^{12} in compressed phase (R = 2.3 cm). From single particle calculations [9] (which didn't take collective effects into account) one would expect roughly three times more particles (for an electron pulse length of 10 ns and inflector field ramp of 15 ns length). Certainly the inflection process is influenced by collective effects, as has been demonstrated by numerical calculations of the phase space behaviour of the first revolutions taking the self fields into account [3]. As experimental evidence for the action of collective effects nearly the same particle number was found at half beam injected. Experiments with variation of the inflector position and RF measurements will hopefully decide if these effects or longitudinal collective instabilities play the important rôle.

c) Transverse collective oscillations

For particle numbers roughly above 10^{12} the first mode of collective radial motion has been observed. Its frequency $S = (1 - \nu_r)\omega_0$ gets down into the MHz-region for the low effective field index values at the end of compression. This instability has been identified by X-ray emission from a thin wire (being hit by the ring at small radii), by probe measurements of the ring magnetic field and by synchrotron radiation observation. These axially resolved light measurements (and also the X-ray emission) indicate that the collective motion occurs in radial direction up to amplitudes comparable with the electron ring diameter. Fig. 5 gives an example of the time derivative of the radial magnetic field component of the ring (above) and of the synchrotron radiation (at (9000±250) Å).

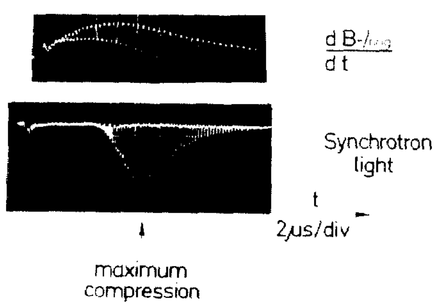

Fig. 5 Collective radial instability

The oscillation starts when the ring is at a radius of about 4 to 6 cm, before the synchrotron emission can be detected, which then (due to the ring motion relative to the optical aperture) is recorded as spikes (2 for each revolution).

Changing the magnetic field index the frequency $(1 - \nu_r)\omega_0$ was shifted as expected. Loading with ions (a few %) has slightly decreased the frequency, but strongly enhanced the transverse instability. The ion loading fraction has been estimated with ionization cross section data from the literature. The base pressure normally is in the range of 2×10^{-7} Torr.

In order to find out the driving source of the instability different ring environments and structures have been investigated: free space up to R = 16 cm and z = ± 11 cm, dielectric walls at z = ± 3 cm, resistive walls at different z with 4 $\Omega/\square$, 160 $\Omega/\square$ or 2.5 k$\Omega/\square$ and structures to change the electric field inside the compressor. None of them changed the onset and growth rate of the instability very much; the driving source still has to be found.

This radial collective instability has been suppressed by increasing $\frac{\partial n}{\partial r}$ (and n), so that at small radii the Landau damping coefficient went up. Fig. 6 shows the time dependence of the original values for $\left|\frac{E}{S}\frac{\partial S}{\partial E}\right|$ (dotted line), while the other curve represents the stable case.

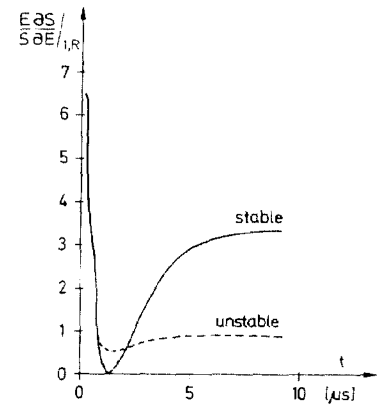

Fig. 6 Landau damping coefficients

The instability should also be suppressed by the application of the additional azimuthal magnetic field B_φ .

d) Ring properties

The electron rings don't show strong particle losses during compression (except at inflection), when the transverse collective oscillations are suppressed. The particle number is typically 4×10^{12}, while the minor dimensions for the unloaded ring at R_{Ring} = 2.3 cm are approximately a = .3 cm and b = .35 cm, as evaluated from the synchrotron radiation distributions. Thus, the radial dimension is by a factor of 3 larger than expected, while the axial dimension is nearly equal to the calculated value. Owing to the fast electron ring compression there seems to be very small axial blow up. The ring survives without dilution for at least 50 µs, that is 5 times the compression time.

e) First roll out experiments

By switching the roll out coil the ring is pushed towards the acceleration section, as can be seen from the synchrotron radiation in the lower part of Fig. 7. (For comparison the upper part gives the radiation without roll out coil switched.) During the roll out the ring gets from a region with $\left|\frac{E}{S}\frac{\partial S}{\partial E}\right| = 3$ into regions with $\left|\frac{E}{S}\frac{\partial S}{\partial E}\right| = 1$, and collective radial oscillations start again. As the particles

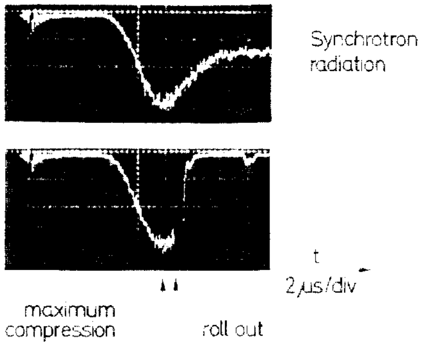

Fig. 7 Synchrotron radiation with and without roll out coil switched

are lost at an inner scraping wire, only a very small number of particles returns to the compression area at the end of the half wave of the roll out current (see 6 μs later in Fig. 7). In this case the voltage of the roll out capacitor bank was chosen to be so small, that the ring did not get to the spill-out point, in order to study the ring behaviour during the roll out phase.

For additional image focussing and increase of the Landau damping coefficient [10] a squirrel cage of 20 copper stripes at a radius of 1.8 cm (see Fig. 8) is used. The results are not yet clear.

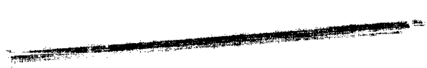

Fig. 8 Squirrel cage

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