Performance of the PUSTAREX Device for the Collective Acceleration of Ions in Electron Rings

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Abstract

This paper describes the experiments conducted in Pustarex, a device for collective acceleration of ions in electron rings. The apparatus and its technical performance are shortly described. It has been shown that the formation, compression and acceleration of rings with a small number of electrons ($N_e < 5 \cdot 10^{11}$) agreed with calculations and the parameters of the machine. Difficulties arose from collective effects. The coupling impedance and the effect of negative mass could be reduced by the introduction of capacitive walls. The quality of the electron rings was limited by a collective transverse instability. The origin of it could not be determined uniquely. Ions could be accelerated but only to low energies because of the limited holding power.

A. INTRODUCTION

The Pustarex experiment was the third generation of an experiment for collective ion acceleration in electron rings at Garching. In the first experiment, Kompressor I [1], formation of rings and - taking advantage of the experience with theta pinches - fast compression of the rings were studied. The second experiment, Schuco I [2], was even more similar to theta pinches. It was designed to demonstrate the principle of collective acceleration. This was successfully done [3]. The next experiment should incorporate the essential features of a collective heavy-ion accelerator. It should enable higher repetition rates, long acceleration distances and the possibility of keeping the ring in the compressed state before acceleration for at least a few ms to allow ionization of the trapped ions to high charge states (in the so-called Wartesaal). All these conditions called for the use of stationary fields and for minimization of the pulsed-field energy. Fast rising pulsed fields, however, still seemed necessary to compress the rings rapidly through dangerous resonances. The experiment therefore had to combine pulsed and static fields. The original proposal is laid down in [4].

The concept of the new experiment was presented at a workshop at Garching in 1975. The same year saw the decision to start Pustarex (the name stands for pulsed and static field ring experiment). The more detailed concept, as described in [5], was only modified in minor points that are mentioned in the following section.

The main problem of the experiment was considered to be the immediate environment of the ring, which had to meet numerous partly opposing requirements. As in the foregoing experiments, problems with collective instabilities were expected. Best known among these was the negative mass stability, which could not be suppressed but kept within tolerable limits. More problems were expected with the resistive or ion-electron instability or, more generally, with the precessional mode, which had caused trouble in Schuco and was not yet satisfactorily understood.

When the compression experiments started in January 1978 we expected to have at least three years of operation. It very soon became clear, however, that the experimental time was much more limited, and in fact the experiment was terminated on August 14, 1979 because of the urgent needs for a new plasma fusion experiment. The very limited time available caused the investigation to be less systematic than was desirable. What we wanted to show was that with Pustarex ions could be accelerated in a satisfying way. This success was not achieved. However, we did not discover anything connected with the basic concept that would indeed have prevented Pustarex from becoming a successful heavy-ion accelerator.

B.1. DESCRIPTION OF THE EXPERIMENTAL SETUP

a) Modifications of the proposal

Compared with the proposal [5], the experiment was subject to minor modifications during the construction and operation phases. One of them resulted in the addition of the static coil A (see Fig.1) to facilitate beam injection and ring formation in a pure static field. After improved calculations, pulsed coils 5 and 6

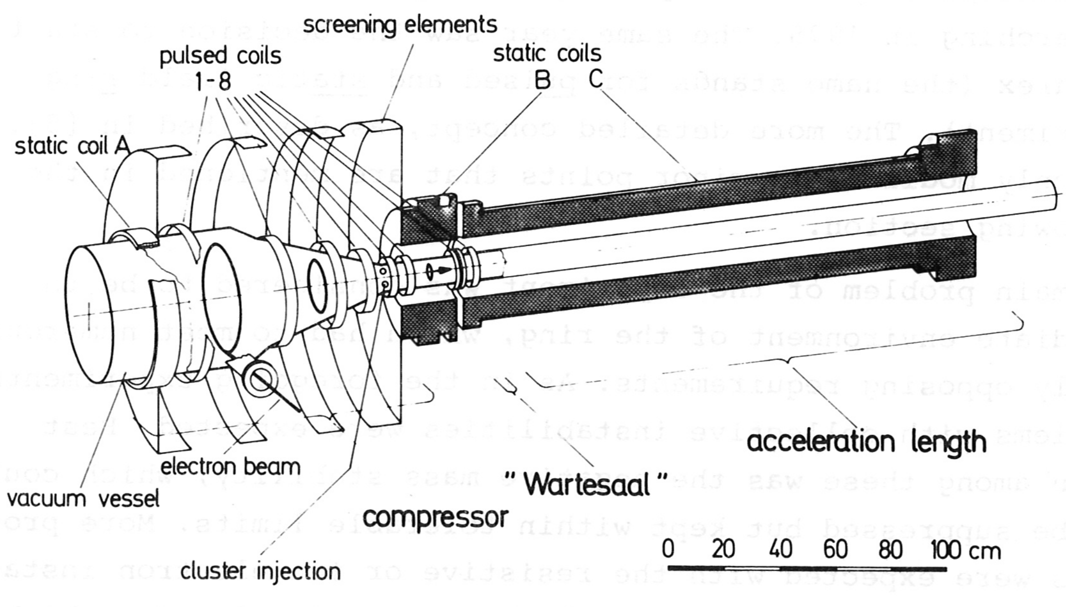


Fig.1: Schematic of the apparatus

were changed to enlarge the Landau damping coefficients and the field index when the ring was close to these coils. For the same purpose the time program of coil 8 was changed. When it was fired together with coil 5 a larger field index resulted during the transport of the ring to the waiting-room. Figure 2 shows the ring radius R and field index n for the system finally used.

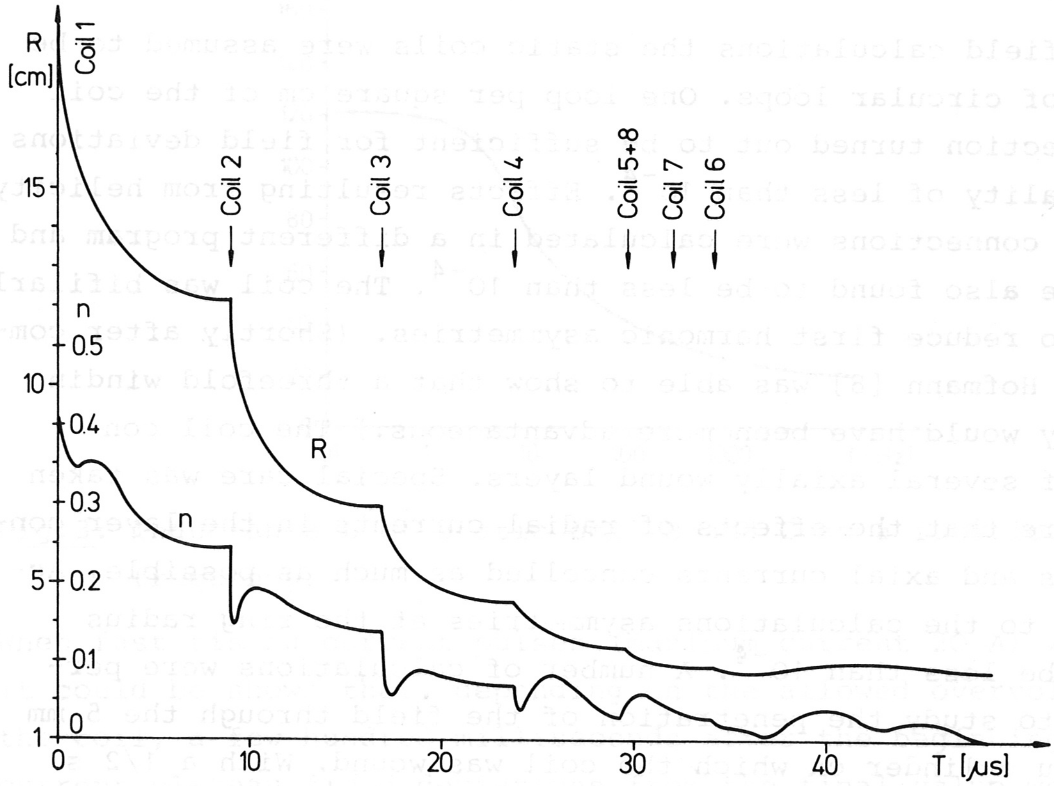


Fig.2: Radius of the ring R and field index n at the ring position as a function of time T

b) Static coils

Three static coils A, B, C (Fig.1) form the magnetic field for beam injection and ring formation, for the waiting-room and for ring acceleration. The ring is formed at R = 19 cm, Z = -65 cm in an axial field of 420 G, which is appropriate for a beam energy of 1.95 MeV with a field index of n = 0.4. In the waiting-room and the accelerator the field strength is about 16.500 G. The coils, originally desigend for 20 kG, were run at this low value because of the low electron beam injection energy which was chosen for a longer lifetime of the Febetron electron gun.

A couple of correcting coils were placed inside the coil C to adjust the accelerating radial component of the field to the holding power of the electron ring.

The static coils were run with a slow rise and decay time (~ 1 s) and a plateau time of 1.5 to 2 s. The correcting coils had a short rise time with a somewhat longer plateau length. Water cooling in coils A, B, C ensured repetition times of ~ 1 min.

In the field calculations the static coils were assumed to be arrays of circular loops. One loop per square cm of the coil cross-section turned out to be sufficient for field deviations from reality of less than 10^{-4}. Effects resulting from helicity and end connections were calculated in a different program and and were also found to be less than 10^{-4}. The coil was bifilarly wound to reduce first harmonic asymmetries. (Shortly after completion Hofmann [8] was able to show that a threefold winding symmetry would have been more advantageous.) The coil consists of several axially wound layers. Special care was taken to ensure that the effects of radial currents in the layer connections and axial currents cancelled as much as possible. According to the calculations asymmetries at the ring radius should be less than 10^{-4}. A number of calculations were performed to study the penetration of the field through the 5 mm thick Cu cylinder on which the coil was wound. With a 1/2 s rise and more than 1 s plateau time field deviations due to penetration problems should be less than 10^{-4}. Not calculated was the effect of Cu winding form itself on the field.

To study the penetration problem, the inductance of the coil was measured as a function of the frequency. In addition, the field rise at different positions for a rectangular current pulse was measured with compensated loops. Figure 3 shows the inductance as a function of the frequency. For high frequencies the fields do not penetrate the Cu cylinder and the inductance is low. With lower frequencies the inductance increases and reaches a probably constant value at a few cycles/s (the coil impedance is mostly ohmic in that area). After a 2 s plateau and 1 s rise time field penetration is probably completed to the desired degree.

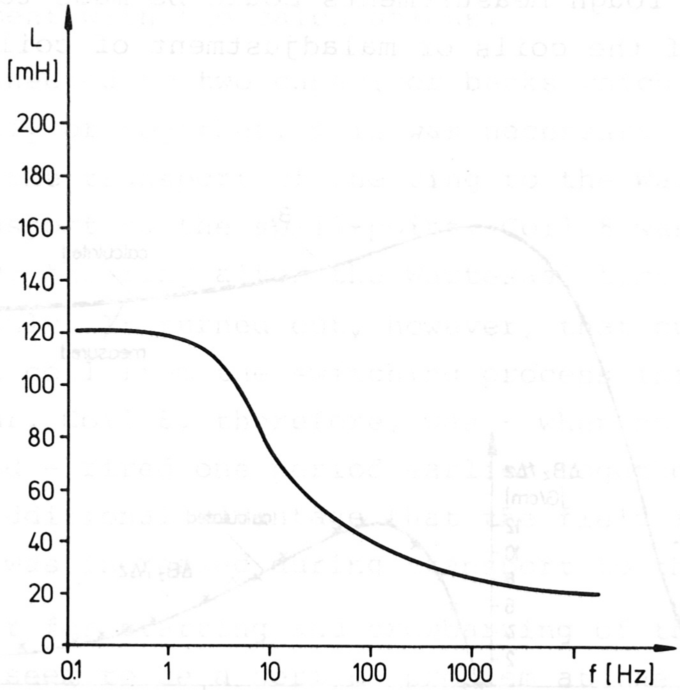
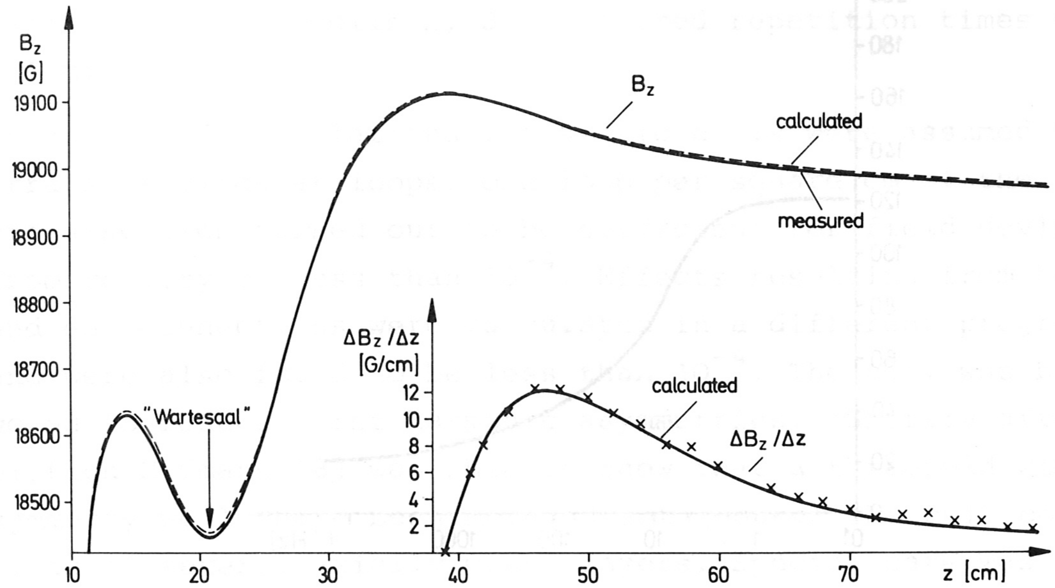


Fig.3: Inductance L of static coil B and C as a function of frequency.

When fast rising current pulses (maximum current 20 A) were used, it could be shown that, depending on the allowed overvoltage at the coil, a few hundred milliseconds after the beginning of the current plateau field deviations from the final value were less than 10^{-4}.

The greatest field accuracy was required in the area of coils B and C. With rotating and compensated Hall probes it was shown that the first and second harmonic disturbances at the ring orbit were smaller than 10^{-4}. As coil A was made with less accuracy, the azimuthal deviations in the injection area, largely determined by coil A, were $\sim 10^{-3}$, which is presumably sufficient for this large field index area.

Figure 4 gives a comparison of the calculated and measured axial field gradients in the first part of the accelerating region. The agreement is very good. With the help of seven correction coils the radial field component in the accelerating region could be varied between almost 1 G and 8 G. As these correction coils were installed only three months before the termination of the experiment, their fields could only be calculated and only very rough measurements could be made to detect mispositioning of the coils or maladjustment of coil currents.



<u>Fig.4:</u> Calculated and measured static field in the region of the Wartesaal, the spill point and the first part of the accelerator. Insert: axial gradient in the accelerating region, measured and calculated

c) <u>Pulsed coils</u>

The eight pulsed coils transported the ring from the formation space to the waiting-room and the accelerator, compressed the ring and increased its energy, and moved the ring fast through dangerous single-particle resonances.

The pulsed coils had one winding with one connection to the collector. As most coils are far away from the ring (axially as well as radially), the question of symmetry was not considered to be serious. When, however, difficulties with the precessional mode were apparent, the coils 6, 7 and 8 were remade with a threefold symmetry azimuthally.

The coils were tested separately and their current time behaviour was found to be very close to the calculated values. The spatial dependence of the axial field of the coils in their shielding environment was also measured and found to be in good agreement with the calculations.

Coil 7 was connected to two capacitor banks which could be fired separately or together. This was necessary because coil 7 is needed for the transport of the ring to the Wartesaal and later for transport to the spill-point. Coil 8 was orginally planned to move the ring after the Wartesaal time beyond coil 7 for roll-out only. It turned out, however, that current oscillations in the coil from the switching process influenced the spill behaviour. Coil 8, therefore, was - when no Wartesaal time was needed - fired one period earlier together with coil 5. This had the additional advantage that the field index at the ring position was increased during transport to the Wartesaal.

The time jitter for starting and crowbarring of the different coils did not seem to be a serious problem at the beginning of the experiment. It turned out, however, that, for example, the number of electrons in the ring and its minor dimension depended on the time delay between ring formation and start of coil 1 due to collective effects. The jitter in starting and crowbarring the different coils made compensation of measuring loops and hence measurement of the particle number in the ring as a function of time rather difficult.

d) Screens

The 5 mm thick Cu screens mainly served three purposes:

1. They mainly shielded the static coils against the pulsed fields.
2. They symmetrized the pulsed fields.
3. They influenced the field and the field index of the pulsed coils.

There was no intention of influencing instabilities by the screen although their presence might have had some unknown effect. The thickness of the screen of 5 mm was calculated to afford a sufficient precaution against penetration of the pulsed fields but to allow penetration of the slowly rising static field with a deviation of less than 10^{-4}.

e) Vacuum vessel

The vacuum vessel used was a fibre-glass laminated epoxy vessel covered on the inside by a Kapton foil. This vessel, which was considered to be more flexible and durable than a glass vessel, was only intended to be used during the initial phase. Later on glass vessels should be used that could be baked and pumped to very low base pressures with only minor modifications in the coil system. As, however, the time for the experiment was limited, we stayed with the epoxy vessel and improved the vacuum by means of a better pumping system. As the base pressure was mostly water vapour and nitrogen, both probably released by the Kapton surface, liquid-nitrogen-cooled cryopanels and a titanium getter pump were added. In addition, a large part of the vessel itself was cooled to 5^{o} C. In this way pressures of about 5×10^{-8} torr could be achieved after a few days pumping. (In side experiments it could be shown that the water vapour is released from the Kapton and does not penetrate through the epoxy wall. It was also shown that a Teflon-covered epoxy vessel would have been more favourable as the release of water is much less.)

f) Electron gun and beam line

An electron gun as described in [6] in a Febetron-Marx generator produced the beam. With a charging voltage of 30 kV the beam energy was 1.95 MeV. The graphite cathode, used during the last year, improved the beam emittance by a factor of at least 2 compared with the needle cathode previously used. The beam was energy-analyzed and focussed with a short magnetic lens. Following the lens was a box, where by application of suitable diaphragms the beam intensity or the maximum angle of divergence could be changed by applying suitable diaphragms. The current pulse through the snout had a length of ~ 10 ns (FWHM) and its peak value could be as large as 400 A. With the help of the steering coils inside the focussing coil the beam could be adjusted to the entrance snout in the vacuum vessel.

g) <u>The entrance snout</u>

Difficulties in compensating the snout for static as well as for pulsed fields were the main reason for changing the original concept to beam injection into a pure static field. The snout is not compensated for the pulsed fields now since it turns out that the electron ring is already far away from the snout when the pulsed field disturbance gets large. The static field disturbances caused by the iron snout are compensated by a current layer, that is shown - as a rolled-up version - in Fig.5. Together with currents surrounding the beam line the field disturbance at the closed orbit was brought below 1%.

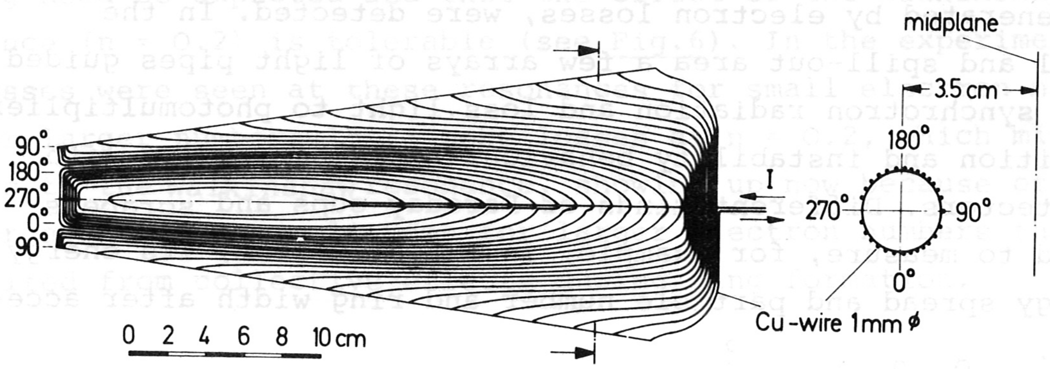


Fig.5: Development of the compensating currents on the iron injection snout

h) <u>Inflector</u>

As the ring motion after formation is more axial than radial, a pulsed radial field with axial inflection seemed more appropriate. For low injected currents almost all electrons were trapped, whereas with increasing current the trapping efficiency decreased as in the Uncompressor experiment [7]. The maximum number of trapped electrons reached 5×10^{12} when radiation shields (inner or outer azimuthally conducting cylinders or side-plates) were present. With no radiation shields and large injected electron numbers strong collective radiation trapped up to 8×10^{12}

electrons. As the radiation losses occur very fast, it is not clear whether in this case the collective axial motion resulting from injection off the closed orbit could be damped by the inflection field.

i) Diagnostics

The main diagnostic elements were single-turn or helically wound multi-turn loops to detect the magnetic field of the ring. As the self-fields were generally very small compared with the compressing pulsed fields, the signals had to be compensated. The particle number, hf and lf activity, ring position, acceleration etc. could be measured with these loops. With photomultipliers γ-rays generated by electron losses, were detected. In the Wartesaal and spill-out area a few arrays of light pipes guided the ring synchrotron radiation and loss light to photomultipliers. Ring position and instability behaviour could be studied with these detectors. Different kinds of Faraday cups and scrapers were used to measure, for example, injected current, its energy and energy spread and particle number and ring width after acceleration.

B.2. SINGLE-PARTICLE BEHAVIOUR

The calculations for ring formation (inflection), ring compression and acceleration were done for single particles. There was no evidence from the experiments for deviations from the calculated behaviour as long as the electron number in the ring was kept small (a few times 10^{11}). This was true of the process of inflection, where a large fraction of the injected particles could be trapped, as well as for ring compression and transport to the Wartesaal and for spill-out and acceleration. There were no losses detected during the compression cycle and - in the case of no additional external focussing - no prespill during transport to the Wartesaal. Acceleration of these rings was possible in the presence of additional external focussing. This single-particle behaviour instilled confidence that the performance of the experiment was according to the calculations and that the calculations were correct. Difficulties that arose were apparently of a collective nature. Especially oscillations of the precessional mode that destroyed the ring with large electron numbers were not seen with small electron numbers. As azimuthal asymmetries in in the regions of small field index could cause the precessional mode [8], this led us to the conclusion that at least the asymmetries of the external field were small enough not to harm the ring.

Other dangerous single-particle resonances were expected at $n = 0.2$ ($\nu_R - 2\nu_z = 0$) and at $n = 0.1$ ($\nu_R - 3\nu_z = 0$). Coils 2 and 3 were designed so that the ring rapidly crossed these resonances. Single-particle calculations show that at $n = 0.1$ no ring widening need be expected and that the effect of the Walkinshaw resonance ($n = 0.2$) is tolerable (see Fig.6). In the experiment no losses were seen at these resonances for small electron numbers. For larger numbers there were losses at $n = 0.2$, which might be due to the Walkinshaw resonance, showing up now because of the larger betatron amplitudes for larger electron numbers that resulted from collective effects during ring formation.

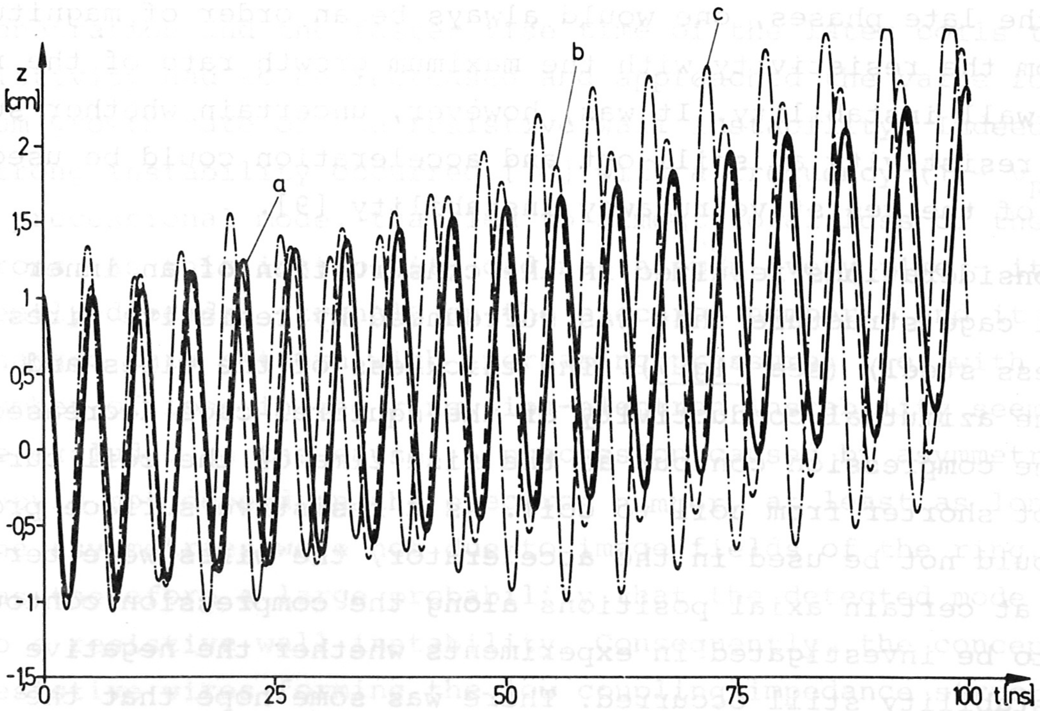


Fig.6: Axial betatron amplitude of a particle crossing the Walkinshaw resonance. a: coupling constant $b = 0$, b: coupling constant $b = -0.07$ (corresponding to the value for Pustarex, c: coupling constant $b = -0.35$ Radial amplitude: 1 cm.

B.3. COLLECTIVE BEHAVIOUR

When the Pustarex experiment was initiated, it was anticipated that most of the difficulties would arise from collective effects. Five types of effects were envisaged: 1. beam-beam interaction during formation of the ring; 2. negative mass instability; 3. resistive wall instability; 4. ring precession, caused by azimuthal asymmetry, which results from displacement of an imaging wall; 5. ion-electron instability. The first four effects can mainly be counteracted by an appropriate choice of the ring surroundings. The success of Pustarex would thus strongly depend on the invention of a ring environment that is helpful against the above-mentioned collective effects and, in addition, compatible with the fast rising compression fields.

In the Uncompressor experiment it has been shown that the beam-beam interaction and the effects of the negative mass instability can be reduced to a tolerable level by using conducting or resistive cylinders. If the resistivity is chosen less than 1 Ω/□ during the early phase of compression and larger than 10 Ω/□ during the late phases, one would always be an order of magnitude away from the resistivity with the maximum growth rate of the resistive wall instability. It was, however, uncertain whether such a large resistivity at spill-out and acceleration could be used because of the resistive runaway instability [9].

These considerations resulted in the construction of an inner squirrel cage structure that was surrounded by resistive wires (stainless steel) (see Fig.7). The thickness of the wires and hence the azimuthal conductivity of the squirrel cage decreased along the compression contour as the rise time of the coil currents got shorter from coil to coil. As a resistive surface probably could not be used in the accelerator, the wires were terminated at certain axial positions along the compression contour. It was to be investigated in experiments whether the negative mass instability still occurred. There was some hope that the negative mass instability that appears at the time of ring formation despite the walls leads to an overshoot in energy spread large enough to make the ring stable even under free space conditions.

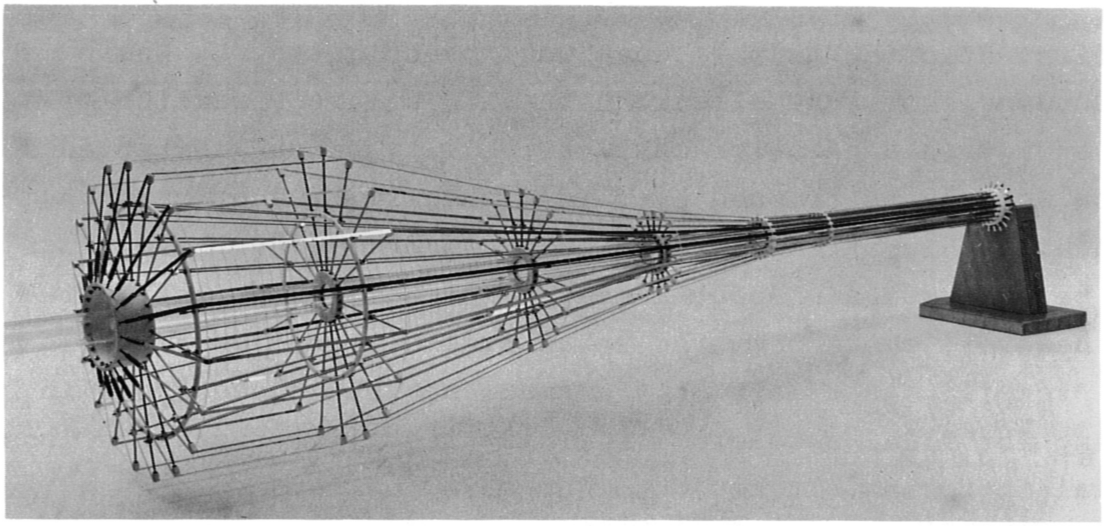


Fig.7: Squirrel cage structure with resistive wires

The experiments showed that with a resistivity of 0.9 $\Omega/\square$ rings with 3 to 4 $\times$ 10^{12} electrons could be formed, i.e. the wires acted like the perfectly conducting sheets in Uncompressor. If during its compression cycle, however, the ring left the area with azimuthal conductivity, a negative mass instability causing heavy particle losses occurred. The conductivity was therefore needed all along the compression contour. Because of the field penetration and the faster rise time of the later coils the resistivity had to be increased and approached the value for maximum growth rate of the resistive wall instability. Indeed a strong instability occurred [10] with a frequency $(1 - \nu_R) \cdot \omega_o$, a precessional mode, that led to almost total loss of the electrons. As this instability did not happen every time - it apparently depended strongly on the electron number - and it barely changed this pattern with increasing pressure, i.e. with the number of ions in the ring, ion-electron instability seemed to be excluded as the cause. A precession caused by asymmetries should not depend on the electron number, at least as long as the asymmetries were not due to image fields of the ring. There was therefore a large probability that the detected mode belonged to a resistive wall instability. Consequently, the concept of resistive wires forming the low coupling impedance structure had to be replaced.

In a first step the no wall case was investigated. As known from Uncompressor, the electrons radiate a large fraction of their energy in a negative mass instability shortly after injection and can be trapped by this mechanism. The electron numbers achieved in a ring were as large as 8×10^{12}. These rings could be compressed without losses. On transport to the Wartesaal, however, there occurred in an area of very low field index a prespill that left only a small number of electrons in the ring for final acceleration. This prespill indicated a loss of axial focussing. It could not be cured by large pressure, i.e. by ion focussing, which works so well in the Dubna experiment [11]. We assumed because of indications from scraper measurements that with large numbers of ions the ring oscillates and probably looses the ions which could have focussed the ring. When an external squirrel cage was installed for additional focussing, large parts of the ring were wiped off because of large-amplitude precessional oscillations and the surviving electrons did not spill correctly.

In our search for new kinds of walls with good azimuthal conductivity to suppress negative mass instability but large resistivity for field penetration and resistive wall instability we concentrated on capacitive walls. After a few tests walls as shown in Fig.8 and described in [12] were used.

A 50 μ Kapton foil covered on both sides with 35 μ Cu was formed to a cylinder. Axial slits at different azimuths for the inner and outer sides formed resonators with certain resonant frequencies. The width of the slits determines the value of the eigenfrequency. This was chosen between the lowest negative mass (≈ 200 MHz) frequency and the eigenfrequencies of the pulsed coils (~ 50 kHz). For reasons of single-particle resonances there were actually 3 slits on the circumference, and for reasons of unperturbed field penetration the cylinder was axially split into rings with a width of 2 mm and a distance of 1 mm.

The main concern with the capacitive walls was ringing of the wall system in the pulsed fields. It turned out that this was no problem at all. Ringing was only oberved when the walls ex-

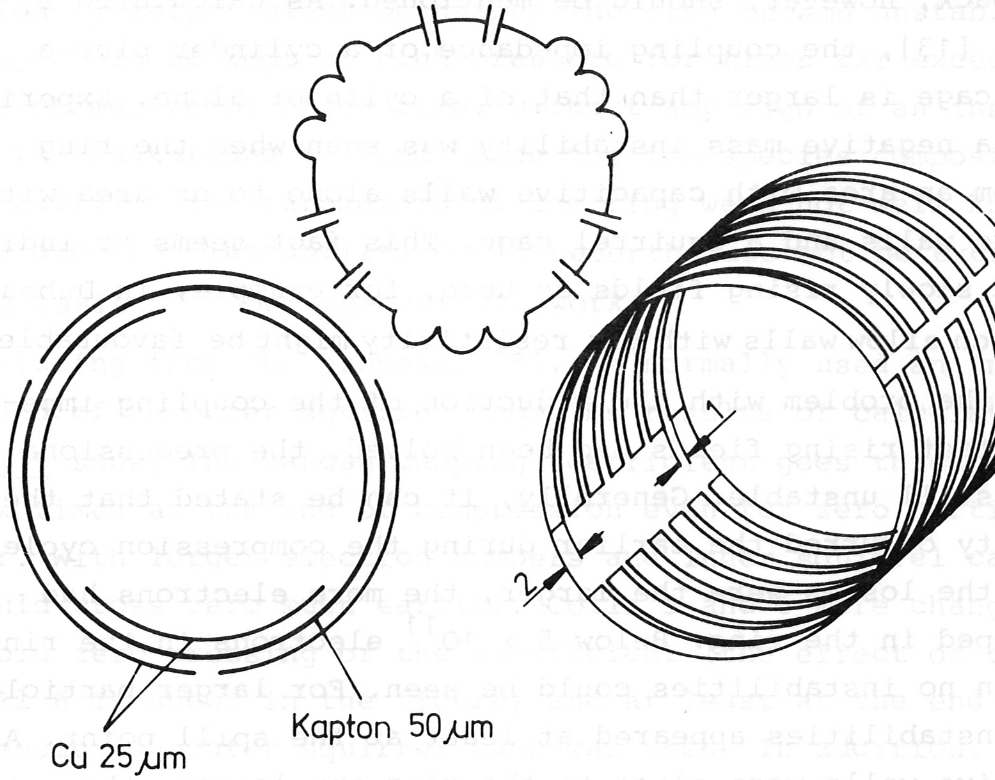


Fig.8: Schematic of capacitive sidewalls

tended over the spill point and a ring was accelerated. This could be cured by an increase of the resonant frequency of the wall in the spill area and the accelerator.

Because of lack of manpower and time these walls could not be installed in the whole vessel before the end of the experiment. For the first compression stages the inner cylinder with wires was therefore used, followed at the smaller radii by the capacitive walls. A remarkable feature of the capacitive walls is that they no longer act as a squirrel cage. They therefore offer the possibility of designing walls for the separate purposes of image focussing and reduction in coupling impedances.

Experimentally it could be shown that no new negative mass instability was excited when the ring moved from the resistive wire area to the capacitive walls. In addition, no effects were observed that could have been attributed to a pulsed field disturbance. It thus seems that capacitive walls are the solution of the wall problem, in the presence of rapidly pulsed fields.

One drawback, however, should be mentioned. As calculated by P. Merkel [13], the coupling impedance of a cylinder plus a squirrel cage is larger than that of a cylinder alone. Experimentally a negative mass instability was seen when the ring moved from an area with capacitive walls alone to an area with capacitive walls and a squirrel cage. This fact seems to indicate that slowly rising fields as used, for example, in Dubna, [11], which allow walls with low resistivity might be favourable.

Although the problem with the reduction of the coupling impedance in fast rising fields had been solved, the precessional mode was still unstable. Generally, it can be stated that the instability occurred the earlier during the compression cycle and that the losses were the larger, the more electrons had been trapped in the ring. Below 5×10^{11} electrons in the ring very often no instabilities could be seen. For larger particle numbers instabilities appeared at least at the spill point. As no resistive walls were close to the ring any longer, the reason for the instability could be ion electron instability or asymmetry. As the occurrence of the instability depended on the electron number, a simple field asymmetry could not be the reason since it should work for single particles, too. This all the more since for such particle numbers for which in certain areas the ring was just barely stable an externally added asymmetry did not drive the ring unstable. If an asymmetry was the reason, it had to be caused by electric images due to misalignment of the squirrel cage. The instability, however, also occurs in areas without squirrel cage, even in the free-space case. On the other hand, it was found in a few cases that the ring did not precess around the assumed field - and squirrel cage - axis. Adjustment of the squirrel cage, however, was not easily possible. A mechanical tool for adjusting the squirrel cage under vacuum conditions was built but could no longer be installed. As the real field axis might change in space and time, proper adjustment could have been very cumbersome.

There were indications that the oscillations were caused by an ion-electron instability. The instability - at least during the late phases - occurred more often and had larger amplitudes for higher pressures. On the other hand, in a region where with a slightly larger electron number the ring became unstable, the ring could be kept at high pressure for times far exceeding the normal compression time, without any sign of an instability. As the background gas and hence the ion species composition and in addition the parameters of the ring were not well known, the ion-electron instability could nevertheless not be excluded on the basis of known theoretical work.

Deviating from the proposal [5], we normally used an inner instead of an outer squirrel cage. As results of calculations on Fig.9 show, the Landau damping coefficient goes through zero a few times at the end of compression even for zero particle number. With larger electron numbers and inner squirrel cage it could cross zero much earlier. Coils 5 and 6 were changed to avoid zero crossing of the coefficient (the effect of changing coil 6 is shown in the figure) and at least at the end of compression an outer squirrel cage was used. In addition, the symmetry of the pulsed coils 6, 7 and 8 was improved (the coils were built with dummy feeds for threefold symmetry). Both measures did not, however, influence the instability behaviour.

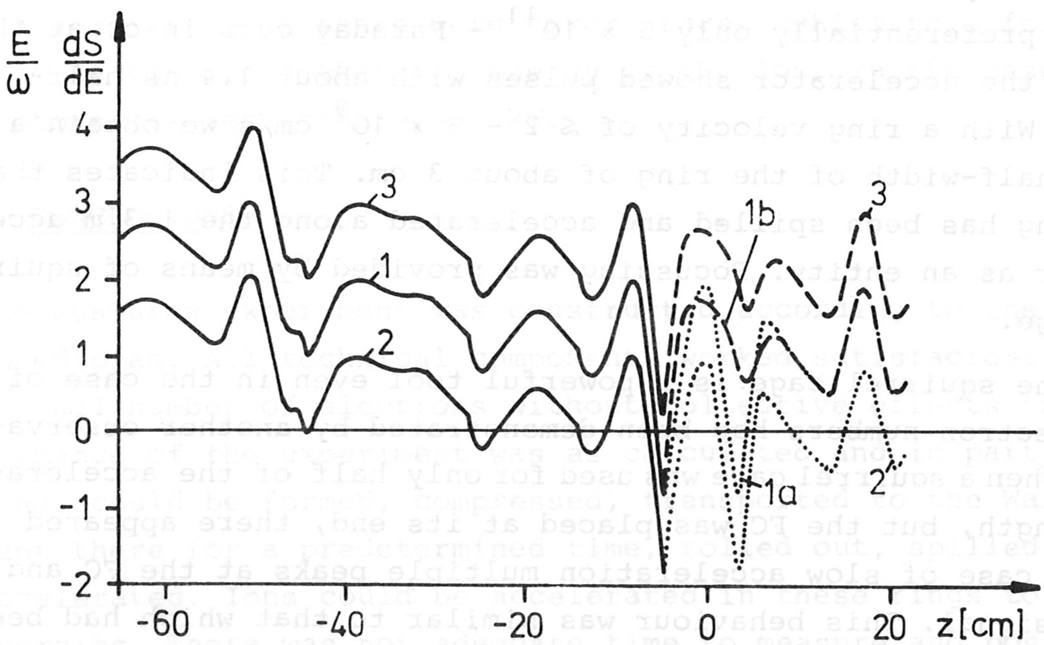


Fig.9: Landau damping coefficient $\frac{E}{\omega}\frac{ds}{dE}$ for the first radial mode. Curve 1/1a: no squirrel cage, old coil 6. Curve 1/1b: no squirrel cage, new coil 6. Curve 2: inner squirrel cage, old coil 6. Curve 3: outer squirrel cage, new coil 6.

In conclusion, we must say that the reason for the precessional mode instability is still unknown. It might very well be true that at different times or areas different reasons are applicable or a combination of reasons - e.g. ions in a ring and in a field with non-constant axis - or something unknown. It can, however, be said that the precessional mode instability was the limiting factor for the acceleration of good rings.

B.4. ACCELERATION EXPERIMENTS

As the experimental time was limited because of the planned termination of the experiment, investigations of the origin of the instabilities were postponed in favour of acceleration experiments. After the installation of seven correcting coils the radial magnetic field in the accelerator was - according to calculations - adjustable to less than 1 G over the whole accelerating distance. No detailed field measurements could be performed for lack of time.

If the number of electrons in the ring, either because of low current injection or because of instabilities, was less than 10^{12} - preferentially only 5×10^{11} - Faraday cups in or at the end of the accelerator showed pulses with about 1.4 ns half-width. With a ring velocity of $\lesssim 2 - 3 \times 10^9$ cm/s we obtain a total half-width of the ring of about 3 cm. This indicates that the ring has been spilled and accelerated along the 1.3 m accelerator as an entity. Focussing was provided by means of squirrel cage.

That the squirrel cage is a powerful tool even in the case of low electron numbers has been demonstrated by another observation. When a squirrel cage was used for only half of the accelerator length, but the FC was placed at its end, there appeared in the case of slow acceleration multiple peaks at the FC and the γ-signal. This behaviour was similar to that which had been reported from Dubna [14]. The assumption that these multiple peaks were related to the precessional oscillations of the ring at the spill point could soon be ruled out. The frequencies did not agree and the muliple peaks were present even if there were no instabilities at the spill point. From probe measurements along the accelerator it turned out that the rings were reflected at the end of the squirrel cage. Consistent with this measurement is the fact that with larger acceleration fields the multiple peaks disappeared as they did when the Faraday cup was placed inside the squirrel cage. At the reflection point the ring apparently looses its wholeness and the large amplitude electrons are peeled off, thus giving multiple peaks at the Faraday cup.

Acceleration of ions could barely be expected with the small holding power of the ring that was achieved. Measurements of the inertia of the rings failed for a few reasons: In most experiments only external loops that gave a poor time resolution could be used. In addition, the reproducibility of the rings and the fields was not good enough for single-shot measurements. Statistical measurements would have been very time-consuming. We therefore concentrated on the detection of traces on cellulose nitrate foils. Indead, under a large variety of conditions traces could be detected when the accelerating field was very soft. Neither the type of ions or their energy could be determined by this method. Part of the foil was covered with a 3.5 μ Hostafan foil. As there were never traces behind this foil, it must be concluded that the energy of the ions in the case of protons was less than ≈ 450 kV.

C. CONCLUSIONS

The Pustarex experiment was constructed according to the proposed plan. All technical components worked satisfactorily. For a small number of electrons without collective effects the performance of the experiment was as calculated and in particular, rings could be formed, compressed, transported to the Wartesaal, kept there for a predetermined time, rolled out, spilled and accelerated. Ions could be accelerated in these rings to low energies. There was not adequate time to measure and possibly correct the static accelerating field to ensure that the ions stay in the ring for the whole accelerating distance.

One of the most critical points for this experiment, the reduction of the coupling impedance, could be solved by the introduction of capacitive walls. Although the coupling impedance of the combined capacitive and squirrel cage walls is larger than that of a cylinder with finite conductivity, this did not seem to give major trouble at the present stage of the experiment.

For larger electron numbers (more than $\sim 5 \times 10^{11}$) transverse collective instabilities occurred that blew the ring up and destroyed it. The origin of this instability is still unknown. There is, however, no reason to believe that anything specific to the Pustarex concept is the reason for this instability, so that there is a definite possibility of obtaining results in Pustarex as good as those from Dubna.

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