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Proposal to Produce Large Compact Toroids

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

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J. A. Phillips

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24

PROPOSAL TO PRODUCE LARGE COMPACT TOROIDS

by

J. A. Phillips

ABSTRACT

Relatively large, hot compact toroids might be produced in the annular space between two concentric one-turn coils. With currents in the two coils flowing in the same direction, the magnetic fields on each side of the plasma are in opposite directions. As the fields are raised, the plasma ring is heated and compressed radially towards the center of the annular space. By the addition of two sets of auxiliary coils, the plasma ring can be ejected out one end of the two-coil system into a long axial magnetic field.

Reports on a preliminary experiment done in 1963-65 are included (Appendix A) together with similar work done by A. Eberhagen (Appendix B).

I. INTRODUCTION

It is proposed to produce relatively large, hot compact toroids which on transfer into a longitudinal confinement magnetic field are adiabatically compressed and heated. The configuration allows for ejection of the compact toroids out of the formative region.

The source of the compact toroids consists of two concentric one-turn coils, A and B in Fig. 1a, connected to a pulsed power source such that the currents in the two coils flow in the same direction. When a good conductor (the plasma) is positioned in the annular space between the coils, the magnetic field lines on each side of this conductor are in the opposite directions. As the magnetic fields are raised, the plasma is heated and compressed radially towards the center of the annular space. At the two axial ends of the plasma,

Fig. 1

Two concentric one-turn coils A and B have currents in the same direction. In the annular space within the coils, a ring of plasma is produced by rising currents in the two coils, a. In b, a third coil C is energized. The magnetic field lines between coils CA and CB are cut and retied, c, with the plasma ring accelerated outwards.

magnetic field lines are cut and retied (as in the reversed-field theta pinch), producing a compact toroid. At or near maximum current a third coil, C in Fig. 1b, is energized with current flowing in the same direction as in coils A and B. The fields in the regions AC and CD are to first order cancelled and field lines are tied around the left end of the plasma. The axial pressure on the plasma is now no longer balanced and the plasma ring is moved out of the coils to the right, Fig. 1c.

In the proposed concept the compact toroids would be moved into an axial confinement magnetic field which radially compresses the ring towards the axis with adiabatic heating.

II. EXPERIMENTAL OBSERVATIONS

An experiment, called the "Slingshot," was designed and tested in 1963-1965 by Mather, Phillips, Livermore and Wittman. Slingshot was a plasma accelerator, suggested by Phillips, which made use of the principle of slowly storing magnetic field energy close to or in the plasma accelerator region. A fast trigger places the system in an unstable state with magnetic field energy converted either into plasma thermal or translational energy faster than can be delivered by conventional energy sources.

In the coil systems, shown in Fig. 2 (designed by R. Dike), the two concentric coils, radii 6.25 cm and 10.75 cm and length 7.5 cm, were energized by a capacitor bank of 9 kJ, 45 μ f at 20 kV. The two coils were connected to a common header by the tapered parallel-plate transmission lines A and B. With a rise time of ~ 3 μ s, the peak axial magnetic field was ≤ 2.4 kG. Ring discharges were formed in the annular space between the coils and were compressed to a position approximately midway between the coils where the B_z field passed through zero. Measurements of the radial component of the magnetic field showed that the plasma ring initially compressed axially toward the midplane and then expanded axially outward. A reverse-field theta pinch was thus formed in the form of a hollow ring. The plasma ring appeared centrally located and grossly

Fig. 2

The two-coil system constructed in 1963, which tested the production of plasma rings. The two manifolds, A and B, were connected to a common high-voltage header.

stable. The final step in the slingshot program, to energize a coil C and accelerate the ring out the coil system, was not attempted due to lack of time. The CTR-2 Progress Reports describing the experiment are included in Appendix A.

III. ENGINEERING DESIGN

To ensure the successful tracking of the magnetic fields it would appear that the inductances of the three currents on the two coils (two on the inner coil) should be equal, Fig. 2. This condition can be met if the two coils are driven by the same voltage source, and if

- 1) The three fluxes ϕ_i are equal assuring good separation of field lines in the annular region, and
- 2) The currents are equal on the three coil surfaces with the three magnetic fields equal in strength.

Calculations show (neglecting end effects) that these conditions will be satisfied if

$$r = (2 + \sqrt{2})a, \text{ and } b = 0.768a ,$$

where r , a , and b are defined in Fig. 3. The inductance of each of the three volumes is given by

$$L = 230.1 \frac{a^2}{A} \times 10^{-9} \text{ h} ,$$

with dimensions given in centimeters. The coils in the early experiment apparently has been calculated using these considerations, with an $(a + b) = 4.5$ cm, a calculated $(r - a)$ of 6.25 cm, whereas the experiment has 6.16 cm.

The total magnetic field energy required for a maximum B_z field of B_{z_0} (in kG) is

$$U_T = 0.874 a^2 A B_{z_0}^2 \text{ joules} .$$

If the assumptions are made, $B_{z_0} = 20 \text{ kG}$, $A = 5a$, and current rise time is $4.71 \text{ } \mu\text{s}$, the required magnetic field energies and voltages are shown as a function of length A in Fig. 3.

The values appear to be quite reasonable; for example, for a length of coil A of 20 cm requires 20 kV , an energy of 110 kJ , has an annular space between the coils of 7 cm , and a zero field radius of 14 cm .

IV. INJECTION INTO THE CONFINEMENT FIELD

As described above, energizing coil C in Fig. 1b gives the slingshot magnetic field distribution. The unbalanced force accelerates the plasma to the right. As was stated in the progress reports, the measured force moving the plasma is at first small but increases as the right end of the coil is reached. The CT ring will then move into the confinement region as shown in Fig. 1c.

If cutting and tying of magnetic field lines can be made to work, the slingshot process can be used to translate the CT ring wholly into the confinement field region, shown in Fig. 4. Here, a specially designed coil D and two small auxiliary coils C' are added. The two coils C' are used to

Fig. 3

The stored energy and voltage required to drive a two one-turn coil system as a function of the coil length, radius of inner coil, and spacing between the two coils. The current risetime is $4.71 \text{ } \mu\text{s}$ and maximum magnetic field is 20 kG .

Fig. 4

Figures showing the method by which a plasma ring can be moved axially from its source (a) into a long confining magnetic field (c). Snipper coils C' cut and retie magnetic field lines extending the initial slingshot mechanism into the final field.

reconnect the slingshot magnetic field lines to those of the confining field and the coil D. The slingshot will then be extended to accelerate the plasma deep into the throat of the confining region. The specially shaped coil D not only further extends the slingshot action but also prevents the CT ring from a premature expansion to the axis. A simplification of the system is that the currents in all the coils are in the same direction. The successful operation of the device will depend, of course, on the correct timing of the currents and a matching of field amplitudes.

V. TRAPPED TOROIDAL FIELD

If a trapped toroidal field is desired in the CT, this might be done with one or two Z-pinch discharges, Fig. 5. One or two pairs of rings at each end of the coils would act as electrodes between which axial currents flow. The currents could be driven in opposite directions creating a magnetic field azimuthally around the main axis of the coils, Fig. 5a. When the B_z magnetic

Fig. 5

Two Z-pinchs can be added, a, to produce a toroidal field in the plasma ring, b.

field lines are cut and tied these axial currents will continue to flow, trapping the toroidal field, Fig. 5b. These currents can be driven by two capacitor bank charged with voltages of opposite sign.

Azimuthal uniformity of these axial currents may be difficult to achieve and probably would require a small bias field and heavy preionization. Added features of this particular geometry are: the large effective radii of the outer Z pinch and close proximity to a conducting wall (the outer coil) which would give some stability against an $m = 0,1$ distortions, and the complete stability of the inverse Z pinch on the inside. It may turn out that only one of the Z-pinchs will be needed,--diffusion of the magnetic field of the inverse Z-pinch into the CT ring being sufficient. This pinch has the desirable feature of being completely MHD stable.

VI. DISCUSSION OF PROPOSAL

Grossly stable compact toroids have been formed in the annular space between two concentric coils. If these rings can be transferred into a confinement region, a hot CT could be available for consideration in a fusion reactor.

Possible advantages of the concept include:

- 1) Large compact toroids could be formed with their size limited only by plasma breakdown and coil voltages.
- 2) Formation of the compact toroid can be controlled by independent variation of the two opposing magnetic fields. Also, the B_z magnetic field at the wall need not pass through zero as in the field-reversed theta pinch, which may reduce wall impurities brought into the CT. In addition, it has been pointed out (Rulon Linford) that the proposed geometry allows the magnetic fields to be raised relatively slowly since the Poynting vector at the walls always points radially inward. The compact-toroid formation could then take place over a relatively long time and more conventional low voltage power supplies could be used.
- 3) An efficient mechanism of ring acceleration out of the coils into the component region is available.
- 4) The efficiency of energy transfer could be high with most of the magnetic field energy being transferred into plasma thermal energy, compact toroid energy or ring translational energy.
- 5) Adiabatic heating in compressing the CT ring towards the axis could be large.
- 6) The connection by line tying to the confinement region is facilitated by the magnetic field of auxiliary coils, C' , in the region to the right of the coils, Fig. 1a.

There are questions that need to be resolved:

- 1) The ring formation requires a strong pre-ionization of the plasma to separate the oppositely directed magnetic fields as was found in the experiment. At low deuterium pressures can this be done?
- 2) In the translation of the ring out of the coil system will the plasma ring remain stable?

In the initial concept there is no toroidal magnetic field in the CT. If this field is desired, an axial current through the plasma may be applied between electrodes at each end of the convective coils. One of these Z pinches, an inverse pinch, would be completely MHD stable.

Note

In discussing these ideas with Pulon Linford reference was made to work by A. Eberhagen, Garching, FRG, in which CT rings were formed in the annular region between two coaxial theta-pinch coils. (A reprint describing this work is included as Appendix B). Plasma temperatures and densities were low, ~ 20 eV and $5 \times 10^{15} \text{ cm}^{-3}$, and lifetimes of the plasma configuration were limited to 10-30 μs . These plasma lifetimes were up to ten times larger than the characteristic growth time for MHD-instabilities.

Eberhagen's work supports the early slingshot results in that compact toroids can be made between two concentric theta-pinch coils. Also the lifetimes of the CT rings, even at the very low temperatures of ~ 20 eV, may be sufficiently long to allow transport to a confinement region where the plasma stability should be much greater.

Appendix A

GROUP P-14 MONTHLY REPORT, JANUARY 20, 1964

JAMES A. PHILLIPS, GROUP LEADER

VIII. A plasma accelerator is proposed in which energy is first stored in magnetic energy close to or in the plasma accelerator and then converted into particle energy by a trigger mechanism. It is hoped that the energy conversion will take place faster than can be handled by conventional energy sources.

VIII. PLASMA ACCELERATOR - "SLINGSHOT" (Mather, Livermore, Phillips)

It has seemed to one of us (J. Phillips) that if higher efficiencies of energy transfer are to be achieved in plasma accelerators the inherent slowness of practical energy sources must somehow be circumvented. The suggestion is made that this might be done by first converting energy into magnetic energy close to or in the plasma

accelerator itself at a relatively slow rate. When this is completed, it might then be possible to trigger the system into an unstable regime so that the magnetic energy can be converted either into thermal or translational energy of the plasma considerably faster than can be handled by an entire energy source consisting of switches, capacitors and cables. A number of examples can be cited: 1) in the orthogonal pinch and Scylla, energy is slowly pumped into the reverse magnetic field and then by some field mixing mechanism (an instability?) this energy is transferred quickly into particle energy, and 2) in the hydromagnetic gun, plasma accelerations occur as a result of the magnetic energy stored between the electrodes inducing large voltages when the current sheath collapses off the end of the center electrodes driving the plasma inward and forward at high velocities.

A plasma accelerator which may make use of this idea is shown in Fig. A-1(a). The two concentric coils A and B are driven by two independent power supplies having identical ringing frequencies with the currents in the two coils flowing in the same direction. If a good conductor (the plasma) is located in the annular space between the two coils, the magnetic field lines on each side of the conductor will be in opposite directions. If the plasma magnetic field interfaces are stable, the plasma will be radially compressed by the magnetic fields. At peak currents when the energy is in the magnetic fields between the coils and plasma, a third coil C between the coils and plasma is energized by passing through it a current in the same direction as that flowing in the coils A and B. When this is done, the magnetic fields in the regions AC and CD are to first order cancelled, with the field lines on each side of the plasma joining together around the end of the plasma. At this point the pressures on the plasma are no longer balanced and the plasma is accelerated to the right.

This scheme may have advantages over the conventional conical orthogonal or θ -pinch as shown in Fig. A-2(a). In this geometry axial acceleration is by the $\bar{J}_\theta \times \bar{B}_r$ force, where $\bar{J}_\theta$ is the azimuthal current density in the plasma and $\bar{B}_r$ is the radial component of the magnetic field. In the proposed geometry, Fig. A-2(b), axial acceleration is also given by $\bar{J}_\theta \times \bar{B}_r$ but here $\bar{B}_r$ is the full magnitude of B. A second and important advantage may be that in the proposed geometry the acceleration

may be initiated at maximum current. In the conical pinch the plasma begins to move away from the coil almost immediately and will be at a distance away from the coil where the acceleration is reduced at the current maximum.

A very preliminary test of some of these ideas was made about one year ago. Two coils were energized separately and the impulse given a copper cylinder located between the coils measured. Data taken with the two currents in the same and opposite directions as a function of axial position of the copper cylinder are shown in Figs. A-3(a) and A-3(b). We see, Fig. A-3(a), that with the currents in the same directions the impulse is larger than with each alone and considerably larger than when the currents are in opposite directions, Fig. A-3(b). We also see that the impulse is greatest when the copper cylinder is located just at the entrance of the two coils. This is expected since the change in inductance of the coils with axial position of the cylinder is here a maximum.

A test of the complete geometry is too complicated for a first step. The stability of the plasma is uncertain and the plasma may rip and shred with incomplete acceleration. The modification shown in Fig. A-4 may give some preliminary information on the performance. Here the two coils are in parallel and connected to one energy supply (the geometry may be thought of as a toroidal pinch in which one side of the primary winding has been removed). The acceleration mechanism here cannot be triggered but will be determined by the geometry. An initial force on the plasma will be produced by the current in the "back-strap," the force drops as the plasma moves axially to the right and then increases as the plasma emerges from the coil. Whether or not optimum acceleration can be obtained will be determined by the length of the coil, plasma mass density, and amplitude and period of the primary current. A coil system has been constructed with $\ell = 15$ cm, R outer = 8.6 cm and R inner = 5 cm. The orthogonal pinch condenser supply, 150 μ F at 20 kV, will be used.

V. A-16 BANK INSTALLATION (Holm, Schofield)

A moderately fast capacitor bank system has been designed and is being installed in A-16 for the dense plasma focus and "slingshot" experiments.

The system when complete will consist of forty 14.2- μ F, 20-kV Tobe Deutschman capacitors with a vacuum spark gap and vacuum crowbar gap on each. This bank will be capable of being max charged to 30 kV in about 200 μ sec from a Marx capacitor bank.

The source inductance for this system will be $\sim 4 \times 10^{-8}$ H with an energy storage of about 100 kJ at 20 kV and 225 kJ at 30 kV (in the crowbarred mode).

MARCH 1965

II. "SLINGSHOT" ACCELERATOR (Mather, Wittman)

A small "slingshot" accelerator is now being studied which consists of a 12.5-cm inner and 27.5-cm outer diameter coil system with a length of 7.5 cm. A 45- μ F, 20-kV capacitor bank produces peak currents of ~ 450 kA with a rise time of 3 μ sec. Preliminary measurements show that (1) a magnetic field zero exists approximately centered in the annular region between the drive coils before a plasma is generated and (2) with argon or helium gas filling, a plasma ring discharge is observed to collapse in radius to the equilibrium radius. From end-on integrated light photographs, the plasma ring appears centrally located and grossly stable.

Time dependent visible light photographs of the formation and collapsing stages of the ring discharge have been made in helium at pressures of ~ 100 , 300, and 600 millitorr with RF preexcitation. The initial formation of the ring discharge is strongly affected by RF preexcitation; without RF, a multiplicity of ringed filaments is seen. This suggests the need for very strong preexcitation.

Some general comments follow:

1. At pressures of ~ 600 mtorr the ring discharge collapses to a position approximately midway between the walls of the vacuum vessel ($\Delta r_0 \sim 4.5$ cm) and reaches a minimum cross section Δr of ~ 1.2 cm in 1.4 μ sec. The ringed plasma cross section remains approximately constant during the remainder of the current rise time of 3 μ sec.
2. At a pressure of ~ 300 mtorr similar behavior is observed except that the plasma collapses to a $\Delta r \sim 1.2$ cm in ~ 1 μ sec and then

gradually expands to 1.5 cm during the continued rise of the current.

3. At 100 mtorr a minimum Δr occurs at $\sim 0.8 \mu\text{sec}$. For $t > 0.8 \mu\text{sec}$ the plasma ring dimensions steadily increase. At peak current the plasma ring fills the entire annular region $\Delta r_0 = 4.5 \text{ cm}$.

The effect of the feedpoint, mainly its massiveness, is clearly observed under all operating conditions. This shows up as an out-of-roundness of the plasma ring in the feedpoint region. This effect becomes quite distinct near peak current time. The out-of-roundness effect appears noticeable at the lower pressures at early times -- as the pressure is increased the effect, although still there, is less dramatic during the continued rise of the current.

Preliminary magnetic field measurements show that the current in the plasma ring is approximately one-half the total primary current. The plasma ring at first collapses radially and then begins to spread along the axis of the tube. The axial spread of the plasma ring is expected since no large axial restoring forces are present in this type of accelerator system.

The next step is to determine whether the ring discharge can be ejected from the plasma accelerator by the use of a subsidiary single turn coil $\sim 17.5 \text{ cm}$ diameter located at one end of the drive coil system.

IV. "SLINGSHOT" ACCELERATOR (Mather, Wittman)

Magnetic Probe Measurement

A radial distribution of the B_z magnetic field taken at the midplane of the "slingshot" accelerator system shows that a ring discharge starts near the outer and inner surface of the inner and outer coil, respectively; the plasma fills the annular region, $\Delta r_0 = 4.5 \text{ cm}$ between the coils at $t = 0$, and proceeds to pinch toward the equilibrium radius with time. A schematic of the "slingshot" accelerator is shown in Fig. A-1. The radial extent Δr of the plasma discharge reaches a minimum $\Delta r \sim 1 \text{ cm}$ at peak current ($t_{\text{peak}} \sim 3 \mu\text{sec}$). The plasma ring centers finally about a radius midway between the coils at approximately the same radius where the vacuum B_z field passes through zero. For slightly higher bank voltage, 12.6 kV instead of 9.4 kV, and for the same helium pressures $\sim 100 \text{ mtorr}$, the ring discharge compresses at a faster rate and reaches

approximately the same $\Delta r \sim 1$ cm in 2 μ sec. The jump in the B_z magnetic field across the plasma ring, a measure of the plasma ring current, follows the applied voltage.

Measurements of the voltage on the coil system and the rate of change of current di/dt , neglecting resistance, should yield a value for the inductance of the system with time. The analysis indicates an almost linear increase of the inductance with time.

Measurements of the axial distribution of B_r at approximately the equilibrium radius show generally a linear change in B_r from the midplane of the coil system to the face of the coil. The probe senses the B_r field component of the plasma ring discharge. The interesting point is that the B_r field component increases steadily for ~ 2 μ sec throughout the z distribution and then begins to decrease slowly at first and then more rapidly during the continued rise of the driving current. These results suggest that the plasma ring discharge is compressed radially at first as the current increases and then at ~ 2 μ sec, the ring discharge begins to spread axially. Since no axial restraining forces act on the ring discharges, these experimental results are not too surprising.

Fig. A-1

Fig. A-2

Fig. A-3(a)

Fig. A-3(b)

Fig. A-4

Appendix B

Experiences from Field-Reversal Pinch Experiments in Garching

by A. Eberhagen, Institut für Plasmaphysik, Garching, Germany

The behaviour of annular plasma sheets confined by magnetic fields with antiparallel direction inside and outside has repeatedly attracted our attention at the IPP in Garching. I shall summarize here our experiences gained in the corresponding experiments. They were first carried out in 1962/64 on a theta-pinch with trapped antiparallel magnetic field (1). It was intended then to study the potentialities of this configuration for by-passing the end-loss problem in linear theta-pinch devices.

The production of the annular plasma configuration in the theta-pinch raised no particular problems.

Fig. 1

As is indicated in fig. 1 a) + b) the antiparallel field situation was achieved for a cylindrical plasma sheet by superposition of a magnetic bias field on the initial

preionized plasma and by starting the main theta-pinch discharge with reversed direction. Soon after start of the discharge (i.e. within $1/2 \mu\text{sec}$) joining of the antiparallel field lines occurred in the vicinity of the coil ends with the result that the two exterior parts of the plasma were expelled out of the coil region. Slight magnetic mirrors at the coil ends (mirror ratio: $B_{\text{mirror}} / B_{\text{coil}} \approx 1.2$) improved the reproducibility of the magnetic field line reconnection considerably.

The remaining annular plasma configuration contracted towards the midplane of the coil under the action of the enclosing field lines (fig. 1b). The contraction ratio varied between about 0.3 - 0.8 depending on the discharge parameters chosen. This initial phase of the antiparallel field situation has been studied in detail (2). These investigations confirmed a collection factor of close to unity for the axial contraction wave indicating a well established separation of the axially confined plasma from the regions towards and outside the coil end.

After this straight-forward initial phase of plasma annulus production, however, the hollow cylindric configuration in general was unstable. As Bodin in Culham had already observed about one year before (3), the annular plasma column normally broke up along its axis into several rings, which sometimes moved in the axial direction and in part even recombined, when they met (fig. 1 c) + d).

This behaviour was identified by Bodin as a tearing mode instability which was predicted by Furth, Killeen and Rosenbluth (4), (FKR), to occur as one type of resistive instability in the antiparallel plasma sheet situation. Bodin claimed agreement of his experimental results with FKR-theory with respect to the growth rates (derived from the times for break up of the annular plasma column) and with the corresponding predicted wavelengths (number of observed rings).

Our experiments, however, seemed to indicate growth rates for the tearing modes reduced by at least half an order of magnitude as compared with FKR-theory. As an example we see in fig. 2 a side-on smear picture of such a field-reversal pinch discharge, taken through a line of holes in the coil parallel to its axis and showing

the time dependent axial behaviour of the plasma. The proper time scale can be taken from the dJ/dt -slope on top. No crowbar was applied in this early experiment. In this example only the axial contraction of the plasma column occurred, but the

Fig. 2

tearing instabilities were absent. According to FKR-theory they should have appeared at about $1/2 \mu sec$. I should mention that this non-appearance of the tearing modes only happened in particularly clean discharges. Otherwise - as is shown on fig. 3 - due to the lower plasma temperature the plasma annulus did break up into several rings within the time of observation (fig. 3).

Another interesting result of these early experiments was the observation that the development of tearing instabilities could be triggered by certain artificial perturbations. It is shown in fig. 3 that such perturbations may be probes radially inserted into the plasma (fig. 3a)) or even merely side-pockets in the wall of the discharge tube (fig. 3b) + c)). One notices that the tearing instabilities are shifted axially when the side-pockets are also displaced in z -direction.

Despite of the contradicting results about the tearing mode growth rates it was felt after these early investigations that axial plasma confinement in linear theta-pinch

Fig. 3

with help of field-reversal was unmanageable because of these tearing mode instabilities.

Nevertheless, during the following years this antiparallel field configuration was repeatedly established at different laboratories (5) - (7) in order to clarify the contradicting experimental results mentioned concerning the tearing mode growth rates. In our opinion, though, no clear answer was presented.

Since the question had been raised in this context that our investigations might have suffered from the occurrence of a strong axial contraction and from a relatively short experimental time scale we took up this problem again in 1970/71 (8). These experiments were done on a largely improved theta-pinch with a crowbar installed and with some further modifications in the electrical circuitry in order to eliminate the corresponding crowbar oscillations. As can be seen from fig. 4 a fairly constant slope of the magnetic field in the coil was achieved after the initial peak. For the example presented in fig. 4 we see further:

- ... a side-on smear picture showing the time dependent axial behaviour of the produced plasma hollow cylinder
- ... an end-on smear picture demonstrating the radial development of the plasma annulus
- and finally a diamagnetic signal which measured the diamagnetic flux excluded by the annular plasma cylinder.

Fig. 4

We notice from fig. 4 that after the fast plasma compression and some radial oscillations the well established plasma annulus contracts moderately in the axial direction with some small axial oscillations occurring. During the whole time of observation, i.e. for about 15 μsec in the example presented, no indication of a tearing mode was detectable. According to the FKR-theory growth times of about 1 μsec were expected for the present case.

After this period, when the plasma existed in a quiet state, the annulus was always destroyed by a gross plasma instability. With the help of end-on framing pictures this instability was easily identified as an $m = 2$ -like rotational mode.

Similar results were obtained for all plasma parameters investigated. Stability of the produced plasma annuli were observed for times which were longer than the theoretically predicted growth times for tearing instabilities by at least an order of magnitude. Finally, however, the plasma hollow cylinders were always destroyed by rotational instabilities.

Several effects were considered to give an explanation for the enhanced stability observed. It was shown, for instance, that this was not due to wall effects, inertia effects or to too short a pinching coil.

A very instructive experiment finally offered a possible explanation. It was shown that the initial perturbation for the development of the tearing modes has to exceed a certain level if gross plasma destruction is to result. This is illustrated here by the example shown in fig. 5.

Fig. 5

As an initial perturbation - which in the earlier experiments were, e.g., the side-pockets in the glass tube - here served slits of varying widths in the theta-pinch coil.

The inhomogeneity of the magnetic field produced by these slits should have been experienced by the plasma in its early phases. A slit width of 1.5 cm in the lower example presented, indeed, triggered the beginning of gross destruction during the plasma compression phase. This destruction indicated a behaviour characteristic of that of tearing instabilities and was also in vague agreement with the time scale predicted by FKR-theory.

It is also seen in fig. 5, however, that this gross behaviour vanished after completion of the contraction period, and a stable and axially homogeneous plasma was established once more lasting until the onset of the plasma rotational instabilities.

After this result the enhanced stability observed was thought to be due to a stabilizing effect correlated with the plasma rotation. The potential of this stabilizing effect is demonstrated in the experiment not only by the relatively high level of initial perturbation needed for a visible gross destruction of the plasma annulus, but even more spectacularly by the fact, that after the end of the contraction phase a single plasma annulus was re-established with spatial homogeneity which remained stable until the onset of the rotational instabilities. Apparently this stabilizing mechanism could even override the residual disturbances left over from the contraction phase.

I just mention in this context that calculations have been carried out by Kulev in Jülich, Germany (9) about the stability behaviour of rotating field-reversal pinches. A stabilizing effect on the tearing modes was indeed observed in the calculations for rotating plasma annuli after proper consideration of the appropriate Hall-current terms.

Irrespective of this suggested correlation with the plasma rotation the surprisingly good stability behaviour of the field-reversal pinch against resistive tearing modes at this instant gave rise to reconsider the chances of this configuration for establishing axial confinement in linear devices. One motivation for doing so admittedly were the obvious advantages inherent in this configuration for fusion devices in case of sufficient stability. I just mention here its simplicity, no problem with plasma

equilibrium, high plasma- β and the axial accessibility of the configuration which possibly could be utilized to relieve the thermal and radiation load problem of the first wall. A further point in this respect is the existing possibility to make profit of the axial compression in addition to the radial one for plasma heating as is being done since 1973 by the Kurtmullaev group at the Kurchatov institute in Moscow (10).

Another reason for the reconsideration of the field-reversal pinch was its relationship with the Belt-Pinch experiments underway at Garching at that time. In fact, the field-reversal pinch is topologically equivalent to a Belt-Pinch with purely poloidal magnetic field or with a strict ($q = 0$) - Belt-Pinch with a small aspect ratio. It was of interest to achieve some knowledge about this extreme case. Tearing modes were not considered to be too restricting in a properly designed experiment, even at the absence of additional stabilizing effects. This optimism simply originated from the scaling of the tearing mode growth rates with sheet thickness δ and plasma temperature. In the collision-dominated case FKR-theory predicts for the fastest growing mode:

$$\tau_{\text{colldom, fastest}} \approx \frac{\delta(\text{cm})^{3/2} \cdot T_e(\text{eV})^{1/2}}{3} \quad (\mu\text{sec})$$

which e.g., for a fusion plasma (if collision-dominated, $\delta = 100 \text{ cm}$, $T_e = 10^4 \text{ eV}$) would result in growth times as much as 0.03 sec. (In the collisionless case Laval & Pellet predict (11):

$$\tau_{\text{colless}} \approx 10^{-11} \frac{N^{3/4} (\text{cm}^{-3}) \cdot \delta(\text{cm})^{5/2}}{T_e(\text{eV})^{1/2}} \quad (\mu\text{sec})$$

Tearing modes can, so to speak, be scaled away by choosing appropriate sheet-thicknesses.

If the time scale of the configuration then is expected to be no longer determined by tearing modes one must recall, however, that the field-reversal pinch may also be considered as a toroidal z-pinch with highly elongated cross section. The corresponding wellknown MHD-instabilities are, therefore, likely to occur, but

nothing was known from theory about their behaviour as a function of aspect ratio and elongation. In the limit of high aspect ratio and high elongation the configuration approaches the sheet-pinch and this is even stable in ideal MHD-theory (with no gravitational effects).

From the experimental point of view it was thus very attractive to produce such a Poloidal-Field (PF) Belt-Pinch configuration with proper sheet-thickness δ and try to actually observe its MHD-stability behaviour. In order to prevent plasma rotation from influencing these features the moment of inertia of the produced plasma annulus had to be as large as possible.

The plasma was, therefore, produced between two coaxially arranged theta-pinch coils as shown in fig. 6 (12), (13). These were connected in parallel to a 100 kJoule

Fig. 6

capacitor bank and had a length of 75 cm and radii of $R_i = 8.5$ cm and $R_o = 21$ cm, respectively. In order to achieve large sheet-thicknesses the discharges were generally crowbarred shortly after completion of the implosion phase. Consequently,

the plasma temperatures and densities were relatively low, about 20 eV and $5 \cdot 10^{15} \text{ cm}^{-3}$, respectively. Weak toroidal magnetic fields could be superimposed to the plasma by passing a current through a rod along the z-axis (this rod, however, is not shown in fig. 6).

An example of the computed field pattern for an equilibrium position of the plasma is shown in fig. 7, which also contains the approximate dimensions of

Fig. 7

the coil system. The plasma annuli were produced in the experiment at filling pressures between: $10 \text{ mTorr} \leq p_0 \leq 70 \text{ mTorr}$ and had aspect ratios (R/a) between 15 and 5 and elongations between 60 and 20.

One typical example of the radial structure of the plasma is presented in fig. 8. The plasma parameters shown in this picture were derived from holographic interferometry and inserted probes, whereas the temperature was inferred from pressure balance.

The lifetime of this plasma configuration was limited to 10 to 30 usec by slowly growing disturbances which are illustrated in fig. 9. In this example the end-on smear picture shows the radial performance of the plasma annulus and the side-on smear picture demonstrates the axial behaviour of it. These pictures are composed of three individual registrations from different shots (different brightnesses). The

slowly developing deformation of the plasma eventually assumed the form of (two) irregular rings as may be seen on the next slide (fig. 10).

Fig. 8

Fig. 9

6 μ s

11

16

$p_0 = 50$ mtorr

Fig. 10

Here are shown side-on framing pictures of a produced plasma annulus. Occasionally there was some indication that a plasma helix might have resulted rather than two rings. Superposition of toroidal fields of up to 1 kGauss in the sheet did not change the time history of the plasma deformations. It was particularly noticed that the wavelength of the perturbations was always observed to remain constant at $\lambda = 30$ cm. This could not be changed by taking special care to not excite specific k-modes. For this particular reason great effort was spent to avoid any external perturbation of the configuration and to achieve good homogeneity and low impurity levels (0.1 % - 0.2 % of oxygen in the main discharge) in the preionization plasma.

No rotational MHD-modes were detected in the experiment.

For the identification of these perturbations their growth times τ (deduced from the times τ_0 when the deformation reached the wall, assuming an exponential growth and an initial perturbation of $\delta/10$) were compared with the sheet-thickness δ .

The result is plotted in fig. 11. One recognizes a quadratic dependency of the

Fig. 11

growth times τ on the sheet-thickness δ . The experimental results are in very good agreement with the FKR-theory for resistive tearing modes, if the experimental finding of constant wavelength, $\lambda = 30$ cm, is considered:

$$\tau_{FKR} \approx \frac{1}{2} \cdot \lambda^{-2/5} \cdot \delta^2 \cdot T_e^{7/10} \quad (\mu\text{sec}) \quad \left\{ \begin{array}{l} \delta \text{ in cm} \\ \lambda \text{ in cm} \\ T_e \text{ in eV} \end{array} \right. \left(\begin{array}{l} \lambda = 30 \\ \mu_i = 1 \end{array} \right)$$

$$\tau_{FKR} = \frac{2 \cdot 10^{-6}}{\lambda^{2/5} \cdot \mu_i^{1/5}} \cdot \lambda^{-2/5} \cdot \delta^2 \cdot T_e^{7/10} \quad (\text{sec}) \quad \left(\mu_i = \frac{m_i}{m_e} \right)$$

(The figures in fig. 11 are reduced to a common plasma temperature of $T_e = 20$ eV).

The reason for the constancy of the experimentally observed wavelength is that these modes are enforced by the periodicity condition of the experiment. We note that the fastest growing mode should develop with a wavelength:

$$\lambda_{FKR, \text{ fastest}} = 4 \cdot \delta^{5/4} \cdot T_e^{1/2} \quad (\text{cm}) = 70 \text{ cm} \quad \left\{ \begin{array}{l} \delta = 3 \text{ cm} \\ T_e = 20 \text{ eV} \end{array} \right. \left(\begin{array}{l} \lambda = 30 \\ \mu_i = 1 \end{array} \right)$$

$$= \frac{7 \cdot 16}{\lambda^{1/4} \cdot \mu_i^{1/8}} \cdot \delta^{5/4} \cdot T_e^{1/2} \quad (\text{cm})$$

and would thus not fit into the length of the annulus after contraction. (For the fastest growing mode results, as mentioned before:

$$\tau_{\text{FKR, fastest}} \approx \frac{\sigma^{3/2} \cdot \tau_e^{1/2}}{3} \quad (\mu\text{sec})$$

The excellent agreement between the experimental and the theoretical (FKR) growth times, however, should not be overvalued regarding the inherent simplifications in the application of the theory and in the evaluation (e.g. evaluation of τ in the non-linear regime of a growing perturbation). Nevertheless, it may be taken as a strong indication that the observed gross destruction of the plasma annuli result from resistive tearing mode instabilities.

Further shown in fig. 11 is a comparison of the experimental growth times with the sound transit time multiplied by five. Obviously the plasma lifetime was up to ten times longer than the characteristic growth time for MHD-instabilities. The non-appearance of such MHD-modes during the time of observation do, however, not yet ensure unambiguously the existence of an enhanced stability of elongated cross sections against MHD-modes. It cannot be ruled out for the experiments that at the relatively low temperatures the corresponding initial perturbations are blurred by abundant plasma streaming across the flux surfaces and along the separatrix after diffusion out of the annulus.

Similar experiments at distinctly higher plasma energies are, therefore, necessary to rule out this uncertainty and to arrive at safe statements on the effect of elongated cross sections on the MHD-stability behaviour of toroidal z-pinches. Corresponding plans had to be abandoned in Garching in favour of the other Belt-Pinch activities.

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