Toroidal Confinement in Screw Pinches with Non-circular Plasma Cross-Section

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Abstract: Toroidal Screw Pinches with elliptical or bar shaped plasma cross-section can be operated below the Kurskal-Shafranov limit also at high-β values. In this case piston heating can be used. Experimental results are given. They show a belt-pinch plasma which is grossly stable for about 100 μsec. The life-time is obviously limited by diffusion.

The most simple toroidal confinement systems are of the axisymmetric type with a toroidal plasma current. Besides simplicity a further advantage is here that usually the toroidal equilibrium is automatically obtained by compression of the poloidal flux towards the conducting wall. Typical representatives of this class are of the Tokamak and of the Screw Pinch type.

A Tokamak by definition operates below the Kruskal-Shafranov limit and is therefore m = 1 stable. This implies, however, very small β-values and a compression ratio near one. Consequently the temperatures can be obtained up to now only by Ohmic heating with all its problems or, perhaps, by some other methods which, however, are just now being tested really in experiments.

The toroidal Screw Pinch on the other hand operates at high β-values and at higher compression ratios. It can be heated therefore rather effectively by piston or fast magnetic compression heating. However, at high β-values, necessary for these heating mechanism, the screw pinch is basically m = 1 unstable.

With respect to high-β-confinement therefore the question arises how to change the high-β Screw Pinch into a stable equilibrium. One possible way is here to stay above the Kruskal-Shafranov limit and to get stability by an additional dynamic stabilization. This principle seems to work experimentally but technically it is rather complicated.

A second way is to go below the Kruskal-Shafranov limit even at high-β-values in the Screw Pinch by changing the plasma cross-section from a circular to a strongly elongated one. Then one might obtain something like a high-β Tokamak which operates without any limiter and which could be heated by piston or fast magnetic compression heating.

The basic principle for this transition to other cross-sections is very simple. In a simplified sharp boundary model one needs for the toroidal equilibrium a certain ratio of the toroidal field B_z to the poloidal field B_φ at the plasma surface which is roughly given by

$$\left.\frac{B_z}{B_\varphi}\right|_{r_p} \approx \left(\frac{2A\delta}{\beta}\right)^{1/2} \tag{1}$$

A is the coil aspect ratio and δ the relative shift of the equilibrium position.

For stability with respect to the Kruskal-Shafranov modes the pitch length of the helical field at the plasma surface has to exceed the major circumference of the torus. This requires a second condition for the field ratio which can be written as

$$\left.\frac{B_z}{B_\varphi}\right|_{r_p} = q \cdot \frac{2\pi R}{u_p} \quad ; \; q \geq \frac{2}{2-\beta}. \tag{2}$$

Here R is the major radius of the torus and u_p is the minor circumference of the plasma cross-section. For a circular cross-section with plasma radius r_p the stability condition is then in the usual form

$$\left.\frac{B_z}{B_\varphi}\right|_{r_p} = q \cdot \frac{R}{r_p} \;. \tag{3}$$

For an elongated cross-section of height h, we have practically $u_p \approx 2$ h and the Kruskal-Shafranov condition becomes

$$\left.\frac{B_z}{B_\varphi}\right|_{r_p} = q \cdot \frac{\pi R}{h} \;. \tag{4}$$

Compared to the circular cross-section one can fulfill here, at fixed B_z, the stability condition (4) for much higher poloidal fields B_φ because h can be chosen independently of R. Consequently stability and equilibrium can be obtained simultaneously also for high-β-values in contrast to the circular case. In this way the critical β for an m = 1 stable equilibrium can be increased considerably.

The equilibrium considered in equ.(1) is necessarily connected to a radial plasma shift which by flux compression produces the restoring force compensating for the drift force.

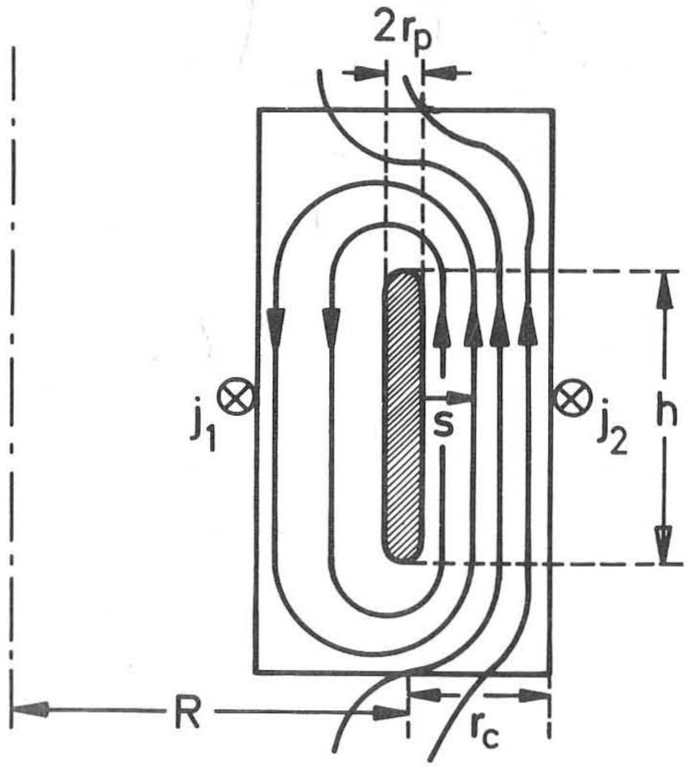


Fig.1: Scetch of currents and poloidal field in the compression coil.

One can obtain, however, also an equilibrium with the help of an additional transverse magnetic field the j x B force of which just compensates for the drift force without any radial shift of the plasma. Experimentally this transverse field can be produced easily by an additional toroidal current j_2 which flows in the outer wall of the compression coil which now has a rectangular cross-section as it is shown in fig.1. The current j_1 at the inner wall is the primary for the induction of the toroidal current in the plasma.

The current j_2 results now in a separatrix for the poloidal field. One has a last closed flux surface while the more outer ones do not close within the compression coil.

Let us denote the distance of the separatrix from the plasma by s and the other dimensions of the coil and the plasma as indicated in fig.1. Then we define the following quantities:

$$\sigma = \frac{s}{r_c} \; ; \; \epsilon = \frac{r_c}{r_p} \; ; \; A = \frac{R}{r_c} \quad .$$

Simple model calculations in a sharp boundary model indicate then, that also for the system of fig.1 a high-β equilibrium below the Kruskal-Shafranov limit should be possible if

$$\frac{h}{2R} \gtrsim 4\pi \sqrt{\frac{\beta}{A.\epsilon}} \; . \; F(\sigma) \qquad (5)$$

where $F(\sigma)$ is a certain function of σ.

For example with $A = 3$; $\epsilon = 6$; $\sigma = 0{,}5$ and $\beta \approx 1$ it follows from (5) $h/_{2R} \gtrsim 1{,}1$.

In a Screw Pinch with a rectangular cross-section of the compression coil the plasma after the first implosion is usually not in axial equilibrium. It starts with height h, and is subject to an axial contraction to the final height h. The degree of this axial contraction $h_o/_h$ can be estimated only very roughly in the simple model under certain assumptions. It turns out that h_o/h should be in the order of 2 for the parameters mentioned above. Initially one should fulfill then $h_o \gtrsim 4\ R$ for these parameters.

This is only a very rough model which indicates some essential features of a configuration with very elongated plasma cross-section. More detailed theories have been done by a number of authors [1,2,3,4,5]. Here are considered, however, mainly special cross-sectionsof elliptical and triangular shape. With respect to fast compression heating in a Screw Pinch one would like, however, plasma cross sections with nearly flat sides as in the belt pinch. For ohmically heated Tokamaks also special elliptic cross sections may be advantageous because they allow higher plasma currents and therefore higher ohmic heating rates as it has been pointed out by Artsimovich and Shafranov /6/. Besides stability with respect to Kruskal-Shafranov modes it is necessary to consider also localized and balloning modes. For special ellipsis like cross-sections some authors give positive results also for these modes [1,4]. For non elliptical shapes Herrnegger [7] has investigated a special analytical solution of the toroidal equilibrium with a nearly bar-shaped cross-section. Similar calculations are reported also by Luc et al.[8]. It turned out that also for this special belt pinch like configuration the generalized Mercier criterion [9] is satisfied. Of course this is only a necessary condition but these calculations give some indication that also bar shaped cross-sections could be stable for localized modes. But nevertheless in this situation the stability behaviour of Screw Pinches with non-circular cross-sections has to be investigated experimentally.

At Jülich one is essentially concerned with elliptical and triangular cross-sections of moderate excentricity and with the influence of the shape on stability. Experiments are carried out so far on the TESI installation. This is a special hard core θ-pinch which produces the closed configuration [10]. As an example fig.2 shows the magnetic surfaces 2 μsec after ignition as they follow from very precise probe measurements. They agree relatively good with calculations. The plasma behaves grossly stable and disappears after about 25 - 30 μsec mainly because of the decay of the currents.

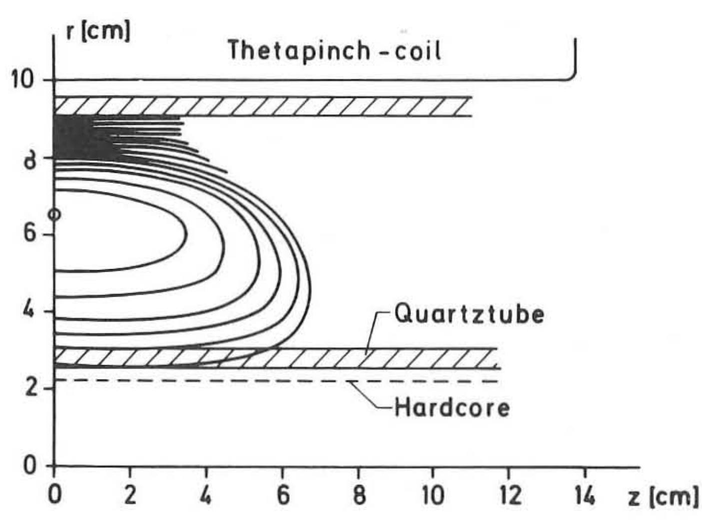


Fig.2: Magnetic surfaces, measured 2 μsec after ignition in the Jülich RESI experiment.

At Garching we are interested in very elongated cross-sections with nearly flat sides. These belt pinch experiments are carried out so far on the 110kJ device ISAR IV [11,12]. The toroidal screw pinch coil has a rectangular cross-section, a height of 110 cm which is somewhat more than 4 times the major radius of 23 cm, according to the simple model mentioned above. The toroidal and the θ-pinch currents are produced simultaneously by one bank in a screwed arrangement of copper layers which form the compression coil as it is shown in fig.3. Horizontally there are 30 copper loops in parallel which can be short-circuited by spark gaps. This allows an adjustment of the outer toroidal current j_2 for a proper equilibrium position and for momentum compensation. The bank is crowbared with a time constant of 600 μsec. The total field is about 7 kG. Filling pressure is from 20 to 50 mTorr deuterium.

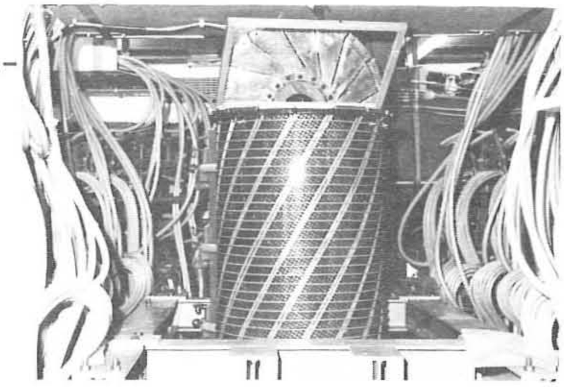


Fig.3: Coil-system of ISAR IV belt pinch.

The influence of the j_2 variation by crowbaring the copper loops on the equilibrium is shown in fig.4. These are streak pictures taken end-on from the top of the torus through a radial slit. The top picture is with open loops. j_2 is too large, the plasma is pushed inwards and then reflected. The second picture is with short-circuited loops. j_2 is smaller but the initial outward momentum is not fully compensated. A change of the crowbar time of the loops gives the third case where the plasma remains more or less in the midplane. The discharges are very reproducible and fig.5 gives a streak picture at 50mTorr which is obtained from five subsequent shots. The clear fast implosion, a slow oscillation and then a grossly stable behaviour during the observation time of 50 μsec is to be seen. The sharp boundaries in the pictures indicate a very straight plasma belt but these pictures give only local information. With respect to the gross stability behaviour there are three further problems: the degree of axial contraction, the behaviour of the edges with their unfavourable curvature and the deformations in toroidal direction.

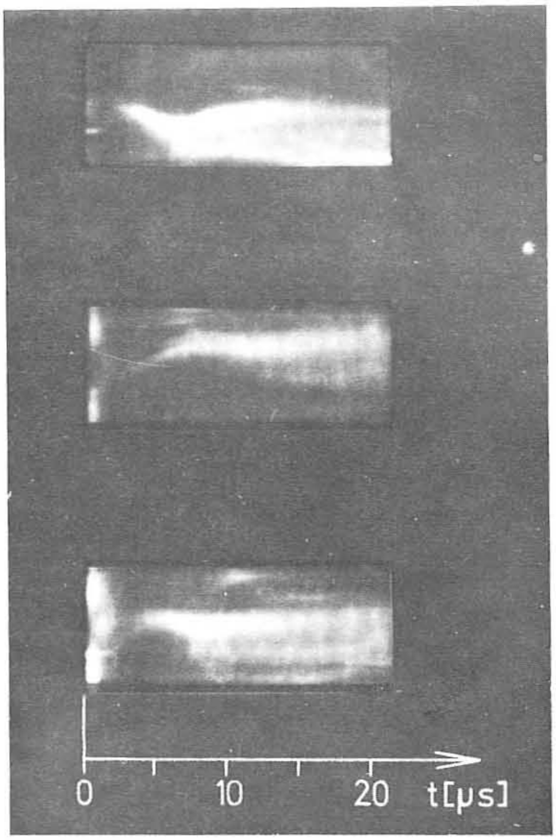


Fig.4: End-on streak picture. p_o = 50 mTorr D_2

For this reason there were taken framing pictures side-on of the whole plasma belt through the perforated coil and end-on of one half of the toroidal circumference.

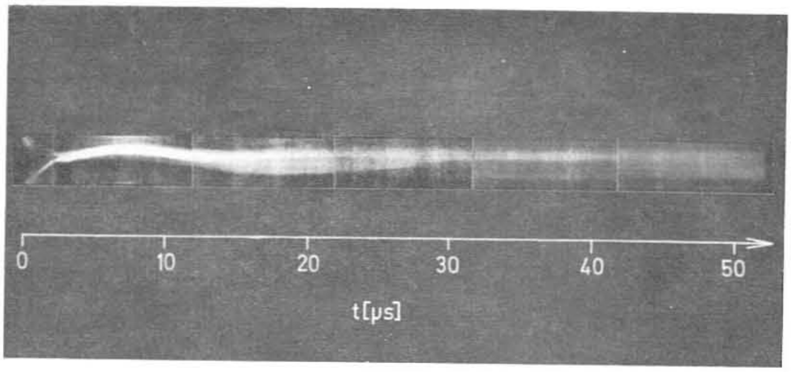


Fig.5: End-on streak picture. p_o= 50mTorrD_2

A typical result is shown in fig.6 giving three framings of one shot again at 50 mTorr.
5 µsec after ignition the formation of a well defined sharp belt.
15 µsec later the axial contraction without any deformation at the ends.
After 25 µsec the final state. The ends behave more or less stable and no serious deformation is to be seen.

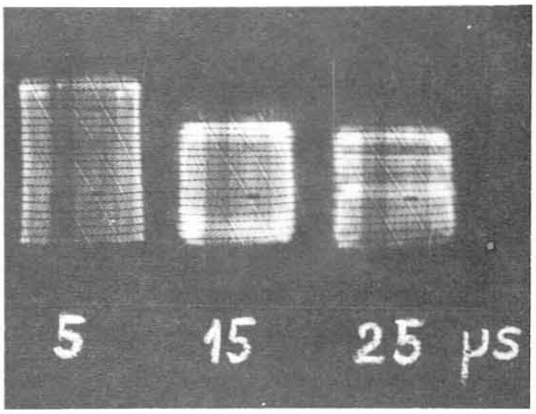


Fig.6: Side-on framing pictures. p_o = 50 mTorr D_2

The bright region in the midplain could be two colliding waves as a result of the axial contraction. Note, that here we have a ratio of h/2R of about 1 and an axial contraction factor around 2, which is not inconsistent with the simple model mentioned earlier.

The toroidal behaviour can be seen in

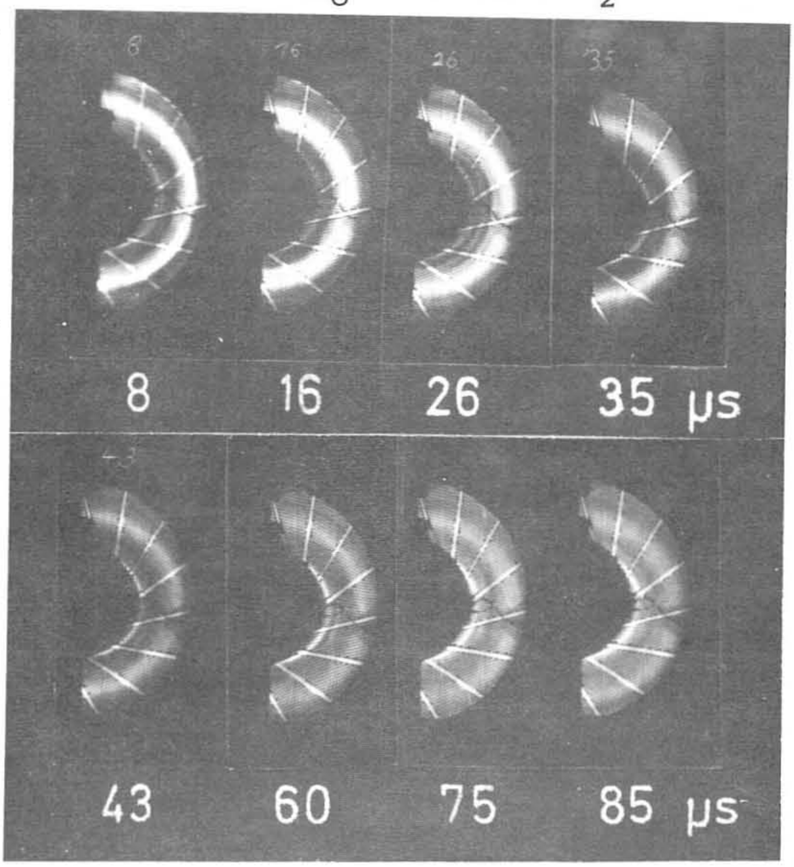


Fig.7: End-on framing pictures. p_o= 50mTorr D_2

fig.7. It gives a series of end-on framings at various stages of the discharge. For technical reasons we cover only 1/2 of the circumference. First implosion, axial contraction and then a stable stage with no essential deformations except a small deviation from a circle. But also this slight asymmetry does not destroy the plasma belt. Its width is increased somewhat but it can be clearly seen still after 85 µsec.

In order to obtain information on the long time behaviour of the ends and on possible motion in axial direction one can take side-on streak pictures with the streak slit all over the height of the tube at the equilibrium position. A typical example of these observations is shown in fig.8. One recognizes the axial contraction and then the plasma stays essentially symmetrical for at least 100 µsec. Note, that also in this time scale at the upper and lower edges there appear no serious instabilities. There are some structures with respect to the height for which so far we have no explanation.

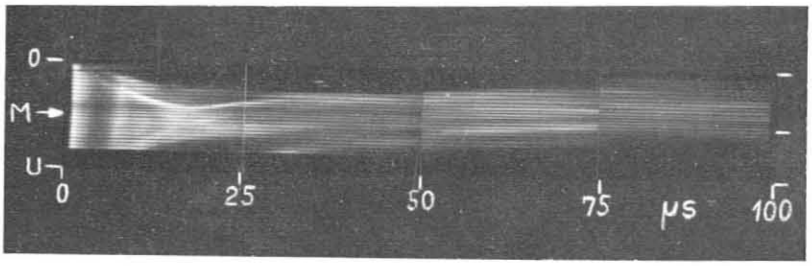


Fig.8: Side-on steak picture. p_o=50 mTorrD_2

Besides these optical observations there were performed probe measurements of the magnetic field. A typical radial distribution of the fields after the first implosion is shown in fig.9. For technical reasons it is only around the plasma centre in the toroidal midplane. Note, that the point of symmetry of $B_\varphi(r)$ is shifted by about 0.5 cm outwards with respect to the plasma centre. The B_z-measurements give at this stage a β of about 85 % at the axis.

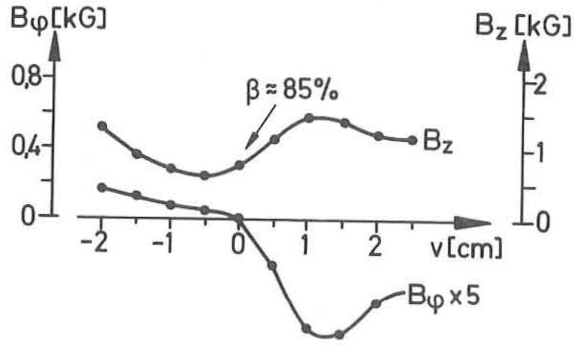
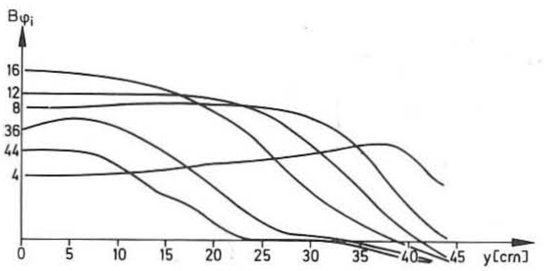


Fig.9: Measured radial field distributions after the first implosion. Torus midplane. p_o = 20 mTorr D_2.

A second set of measurements concerned the axial component B_y, of the poloidal field at the inner and outer wall of the tube as a function of the distance from the midplane: B_y (y,t).

Fig.10 gives the measured distribution along the inner surface for various times. After initial stages the axial component decreases towards the end because of the field curvature. Then the distribution contracts towards the midplane because of the axial contraction. In certain regions, B_y changes its sign. This indicates field lines which leave the coil so that there could be situated the separatrix.



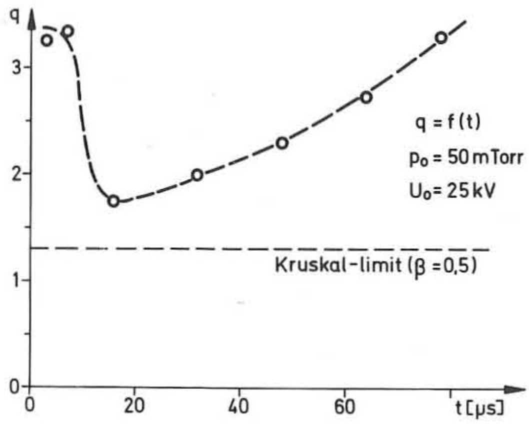


Fig.10: Axial field component $B_y(y)$ at various times after ignition.

Fig.11: q(t) as evaluated from optical and magnetic field measurements. p_o = 50 mTorr.

The optical and the probe measurements allow also a first evaluation of the development of the q-value in the configuration. The rough result is shown in fig.11. The first drop of q down to about 1.8 is due to the axial contraction while the further increase is the result of the different decay times for the poloidal and the toroidal field. But all over the time q is well above the value for the Kruskal-Shafranov condition at reasonable β-values.

A further point of interest is the time behaviour of the toroidal plasma current I_z. Field measurements indicate an exponential decay with a time constant τ_z of about 60 - 80 μsec. Assuming classical resistivity in a simple model this would correspond to electron temperatures of about 25 eV which on the other hand is in agreement with pressure balance for a mean electron density of about $n_e \approx 5.10^{15} cm^{-3}$ as it follows from the compression ratio.

For the belt pinch geometry it turns out that there are two different time scales for the decay of the toroidal and the poloidal plasma currents in the sense that the poloidal θ-pinch current decays faster than the current I_z because of the different L/R ratios. In other words, the containment changes at our low electron temperatures from a θ- pinch after about 30 μsec to a stabilized z-pinch and the decay time τ_z then limits the plasma life-time to about 80 - 100 μsec as is observed experimentally. For higher temperatures both time constants and therefore also the containment should be increased drastically provided that classical diffusion can be assumed and that energy losses at higher temperatures do not become dominant. Radiation losses can be overcome by fast compression heating. At long time scales, however, charge exchange and heat conduction have to be taken into account. These losses should be compensated by corresponding ohmic heating rates, and, it might be, due to estimates by Bateman [13], that this limits the energy confinement time. But this depends strongly on the situation out of the plasma belt and about this at present we know very little, so that precise predictions cannot be made at this time.

A second question of interest is the long time MHD stability behaviour of the configuration. Here we are still at the beginning. W.Grossmann has performed an ideal MHD analysis of a simplified belt pinch model [14]. He has shown that higher m-modes with respect to the torus axis should grow faster than the observed stable behaviour of about 100 μsec at ISAR IV. Finite Larmor radius effects yield, however, plausibility arguments that these modes should grow serveral orders of magnitude slower than predicted by ideal MHD theory. Also wall stabilization has been shown to be a strong effect in the belt pinch geometry. But even here precise theoretical predictions cannot be made and lots of work has to be done especially in the Vlasov regime when one approaches the collision free situation.

Therefore experimentally the further steps are in 3 directions. In the present experiment we are going to measure temperature and density distributions by laser-scattering and holography. I intended to give you the first results here but the technique of high voltage insulation was against us and we had some trouble which delayed the measurements. Secondly we use a new coil system which will allow to go also to smaller q-values in order to find the stability limit of the belt-pinch.

The decisive question is, however, whether or not the plasma life time can be drastically increased at higher temperatures. In other words the question for stability and diffusion processes in the keV temperature regime.

For this reason as a third branch we are building a new device of 1 MJ with a discharge tube of 1.5 m diameter and 2.5 m hight. The experiment will operate at 40 kV charging voltage. However, during the initial piston heating stage it is planned to add a 120 kV pulse with the help of a small high voltage bank which then is decoupled by a saturated transformer [15]. The main bank is crowbared with a measured time constant of 2.6 msec at a field of about 8 kG.

In this arrangement ion temperatures up to 1.8 keV should be obtained at densities around $10^{15}cm^{-3}$. Part of the installation has just been tested successfully. Of course, we are aware of the possible difficulties we may meet. But I think, it is worth to do such an experiment now in order to find out whether or not the belt pinch can be a useful configuration for a long time confinement of high-β-plasmas.

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