MAGNETIC PROPERTIES OF THE SPHERICAL TORUS

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The Heidelberg Spheromak Experiment (HSE) uses the theta-z-pinch formation method to create compact field reversed plasmas (Spheromaks) with both poloidal and toroidal plasma currents. These plasmas are about spherical and have a full diameter of 24 - 30 cm. For two axially aligned toroids (doubly toroidal configurations) a length of up to 80 cm is possible. Spheromaks with plasma currents up to 300 kA have been created. With internal multiprobe arrays the magnetic structure of the toroids has been investigated during formation and decay.

While previously the standard operation of the experiment aimed at the production of spheromaks and doubly toroidal configurations of the spheromak-type /1,2/, we have modified the device and thus have been able to achieve for the first time the generation of spherical tori with aspect ratio 1.1 /3/. These configurations have been named and studied theoretically by Peng and Strickler /4/. The spherical torus differs from the spheromak (where there is no linkage of material along the center axis of the toroid) by the existence of a current carrying central conductor which adds a vacuum toroidal field to the magnetic configuration. Hence a spherical torus is a tokamak with a very low aspect ratio. While the q-value of a spheromak is everywhere below unity (ideally it is around 0.82 near the magnetic axis and decreases to 0.72 towards the separatrix), a spherical torus has a tokamak-like q(axis) >1 and q increases towards the separatrix. We have also investigated two axially aligned spherical tori.

For the purpose to generate a sperical torus the experimental device was equipped with an axial conductor. Two methods of operation are possible /3/: (1) if the conductor is unshielded against the plasma, part of the poloidal plasma current can commute onto it, (2) with the axial conductor being insulated against the plasma discharge we can drive an externally generated current through the conductor. Thus, (1) the current along the axial conductor will be appropriate to the self-relaxation of the plasma while (2) we can apply any desired external current (and hence any vacuum toroidal field) onto the toroid up to the technical limit of about 30% of the usual maximum plasma poloidal current.

Spheromaks are unstable to n=1 tilt and shift modes. In presence of an axial (currentless) conductor stabilization is achieved only if the diameter of the conductor becomes appreciable compared to the minor radius of the plasma /5/. This is not the case in HSE, where the axial conductor has a diameter of 15 mm. However, if a current of sufficient amplitude (in HSE more than 15% of the poloidal plasma current) is driven along the central conductor, the tilt- and shift modes are suppressed and the plasma decays stably on a resistive time scale.

We have investigated the magnetic topology by internal magnetic probe arrays which allow the simultaneous measurement of all three components of the magnetic field at ten radial positions in the range of r= +- 12 cm. In order to obtain a two-dimensional picture of the plasma, a shot-to-shot scan was performed for different axial probe positions.

Fig. 1 shows the measured poloidal flux pattern in the r-z half plane of a spherical torus for two different times, the intervals being $\Delta\Psi = 1$ mWb. At t = 25 μs the separatrix length is 28 cm, the diameter 26 cm. We have already presented magnetic field profiles both in radial and axial direction for the spherical torus which demonstrate the close accordance between experimental and theoretical equilibrium /3/. For the analytical solution of the equilibrium differential equation we used a streamfunction which varies linearly with the poloidal flux. Such a dependence is to be expected if a complete relaxation into a Taylor-state takes place /6/. Experimentally we find a nonlinear relation between the stream function (i.e. the poloidal current) and the poloidal flux only during the early formation, when the z-pinch dominates and flux amplification takes place. During the whole equilibrium decay phase a linear dependence is present. This is demonstrated in fig. 2 which presents the poloidal current versus poloidal flux at t= 25 μs where the flux at the magnetic axis is 4 mWb. Note that the individual measurements shown scan the whole r,z plane of the confined plasma. The figure shows that a current of about 35 kA flows in the axial conductor at the investigated time point.

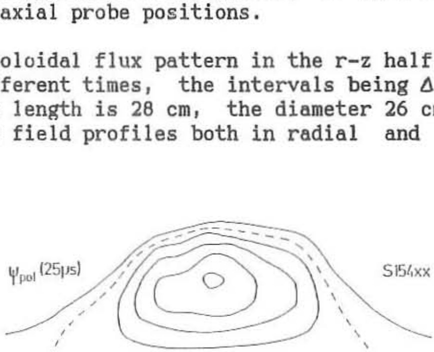

Fig. 1

For the plasma pressure, we find that during the early formation phase an inverted pressure profile is most consistent with the magnetic measurements. Lateron the maximum pressure clearly is seen on the magnetic axis. The relation of plasma pressure to poloidal flux can be assumed best to be linear, however, from the measurements any exponent between 1/2 and 2 might fit into the scatter of the data. This is because the determination of the radial and axial plasma pressure profiles from magnetic measurements is inaccurate since it results from the difference of large quantities.

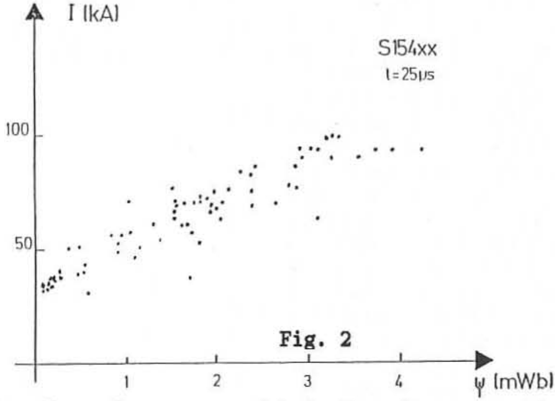

Fig. 2

We can, however, infer the volume averaged beta from the magnetics. Such a study was performed for two axially aligned spherical tori. The details will be reported elswhere /7/. Here we refer to the measurement in one of the two toroids where we find β-values between 11 and 13 %, lower than estimated in our preliminary investigations /3/. The present value results consistently both from (1) a consideration of the measured magnetic energy i.e. the relative contributions from the poloidal, the plasma toroidal, and the vacuum toroidal field energy as compared to the corresponding contributions which are anticipated theoretically as well as (2) from profile fits. Fig. 3 shows a fit of the experimental radial magnetic profiles in the symmetry plane of one of the aligned tori with (a) a force free numerical calculation (Fig. 3a) and (b) another one assuming an average beta of 12% (Fig. 3b), both at t = 32 µs. From our present investigations we anticipate that these results are valid also in the case of a single (standard) spherical torus. We note that the approximative analytical solution of the equilibrium differential equation in the symmetry plane /3/ cannot be used for a determination of the pressure.

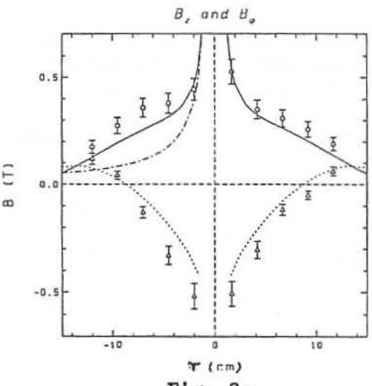

Fig. 3a

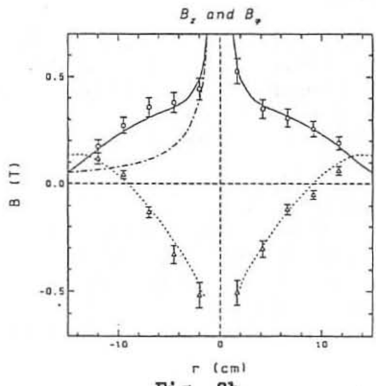

Fig. 3b

Considerable effort has been spent on the determination of the q-profile for various experimental conditions. Fig. 4 shows the q-profile for various time slices for the same scan which was used for the evaluations of figs. 1 and 2. Since the current through the conductor can be considered as a free parameter at least in the case when the current is driven externally, intuitively one might expect that the q-profile would vary with the applied current. Experimentally, with a unshielded conductor, we almost always find a linear stream function and a q-profile as shown. It seems that there is no stable smooth transition to the spheromak case where q is below unity and decreases towards the separatrix. Decreasing the applied axial current, the plasma becomes unstable.

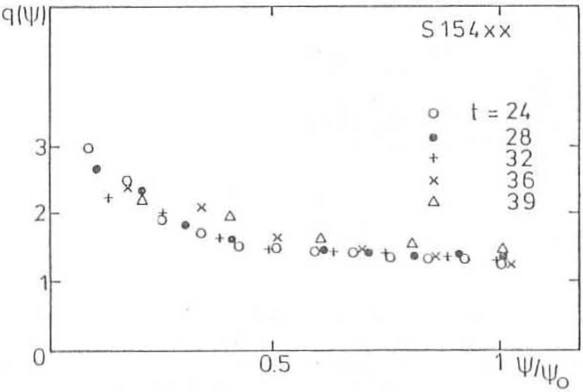

Fig. 4

In conclusion we find that in the modified HSE device spherical tori (both single ones and two axially aligned one) are very well described by a Taylor-like relaxed equilibrium with a stream function $I(\Psi) = I_0 + I_1\Psi$ where I_0 ist the conductor current and I_1/Ψ the eigenvalue of the configuration which is independent over the crossection. The q-profile, as is the whole equilibrium, corresponds well to the one anticipated for the spherical torus /4/.

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References

/1/ Bruhns, H., Allgeier, C., Böckle, G., Raupp, G., Steiger, J., Weichelt, A., Wintermeyer, G., in Controlled Fusion and Plasma Physics (Proc. 12th Europ. Conf. Budapest, 1985) Vol. 9F, Part I, European Physical Society (1985) 659.

/2/ Bruhns, H., Allgeier, C., Raupp, G., Steiger, J., Weichelt, A., ibid., p. 655

/3/ Bruhns, H., Brendel, R., Raupp, G., Steiger, J., Nucl. Fusion **27** (1987), 2178

/4/ Peng, Y.-K.M., Strickler, D.J. Nucl. Fusion 26 (1986) 769

/5/ Taguchi, K., Miyazaki, T. Kaneko, S. J. Phys. Soc. Jap. 54 (1985), 2162

/6/ Taylor, J. B., Plasma Phys. and cont. Fusion Research. Proc. 5th IAEA Conf. Tokyo, Vol. 1, p. 161 (1974); Rev. Mod. Phys. 58 (1986) 741

/7/ Bruhns, H., Steiger, J., Raupp, G. to be published