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A SURVEY OF THEORETICAL RESEARCH ON THE EXTRAP CONCEPT

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1. Introduction

During the initial period of fusion research, the Z-pinch was given considerable interest, due to its potential of producing hot plasma confinement in a rather straightforward way. Unfortunately,all experiments performed at that time on conventional, circular Z-pinches resulted in an unstable plasma. Further investigations on Z-pinches have been conducted at a limited number of laboratories. Among these, recent experiments with the Extrap configuration, being based on the Z-pinch but with an applied transverse field, have revealed substantially improved stability. In the Extrap experiments, which were performed on a relatively small scale, the pinch was found to be macroscopically stable when a sufficiently strong, transverse octupole magnetic field was superimposed.

One of the earliest versions of toroidal Extrap geometry is outlined in Fig.1 and may serve as an illustration of the basic properties of this scheme. A Z-pinch is immersed in an octupole field produced by currents in a set of ring-shaped external conductors[1]. The currents in the rings of Fig.1 are all antiparallel to the pinch current. For control of the plasma loop force, a vertical magnetic field component can be added to this system. Four magnetic x-type zero points and a resulting magnetic separatrix are formed by the superposition of the Z-pinch and octupole magnetic fields.

The figure shows an example of the class of Extrap configurations which also includes geometries with other numbers, positions and current directions of the external conductors, as well as the possible superposition of a relatively weak toroidal field[1].

The theoretical analysis of Extrap includes an extensive area of diversified problems. These are related to the high beta value, the non-circular plasma cross section with its separatrix, the magnetic o- and x-points, and to the strongly inhomogeneous conditions of the plasma which extends itself from a hot weakly magnetized core to a cool and moderately magnetized, partially ionized boundary region (see Fig.1).

Previously performed theoretical work on Extrap has partly been described in earlier reviews[1,2]. The problem areas to be studied are of a general physical interest which reaches beyond the application to Extrap and other high-beta confinement schemes. MHD theory thus forms a useful starting-point in the analysis, but cannot give a complete description of the plasma behaviour at the high beta values prevailing in Extrap. A corresponding self-consistent kinetic theory has so far not been elaborated, and considerable efforts are required for such a purpose. Consequently, further theoretical analysis on Extrap is needed, thereby leading into unexplored and important areas of basic plasma physics.

2. Breakdown and Start-Up

In the field geometry of Extrap a theoretical approach to plasma breakdown and build-up does not become a straight-forward task. Earlier proposals[1] to start breakdown and build-up near the field null of the imposed octupole field, and to combine this with a superimposed toroidal field, have been supported by experiments[3,4,5].

The breakdown conditions have been discussed in terms of orbit analysis in presence of an electric field, including the "meander-type" (snake-like) particle motion in the weak-field region close to the pinch axis[6,7,8-10]. Studies have also been devoted to the interaction between electrons and neutral gas in a strongly inhomogeneous magnetic field[11].

With the special aim of understanding the start-up process in fully toroidal Extrap geometry, an MHD analysis has further been elaborated on breakdown and its dependence on the external magnetic field conditions[12-14]. Different options for the start-up process are described in this connection. An approach which includes the energy balance of the electron gas in toroidal geometry[13] yields breakdown voltages which agree with experiments in the device EXTRAP-T1.

All these investigations predict that breakdown in Extrap requires higher electric fields than in systems with a strong toroidal field such as in tokamaks. This is confirmed by experiments[5,6,15]. Electron cyclotron resonance can further be used to facilitate breakdown near the intended pinch axis, especially in presence of a weak superimposed toroidal (axial) magnetic field which is matched to the corresponding resonance[5].

A zero-dimensional time dependent model[16] has finally been developed for start-up, including the interaction between the plasma and the external circuits in toroidal geometry.

3. Equilibrium

3.1 Dissipation-Free Models

In a first approximation the radial momentum balance of the Extrap pinch is represented in its integral form by the Bennett relation

$$n_o T_o \bar{a}^2 = \mu_o J_p^2 f / 8\pi^2 K \qquad (1)$$

where n_o and T_o are the density and temperature at the pinch axis, f is a profile factor of order unity, J_p the pinch current, and K Boltzmann's constant.

Studies on dissipation-free plasma equilibria in linear geometry were undertaken at an early stage by means of a numerical model[17]. This was followed by a discussion of the exact solutions of the Grad-Shafranov equation and a proposed method for obtaining approximate solutions[18]. An integral method of obtaining analylytical self-consistent equilibria by expansion in the plasma non-circularity has been developed[19]. Investigations on linear geometry can also be performed in terms of conformal mapping[20]. From the constants of motion of kinetic theory, it has further been shown that MHD-like momentum balance equations can be deduced for a steady state[21], also including the magnetic weak-field regions where there are large local Larmor radii. For the strongly inhomogeneous Extrap field it is impossible to find sufficiently many constants of the motion for a unique description of an equilibrium state. A new method to determine approximate constants of the motion has been developed by the use of separable potentials[22]. Moreover, one study has been devoted to the generation of flux coordinate systems in straight Extrap geometry[23]. Another study of fully analytical MHD equilibria, exhibiting a more well-defined boundary than that of the Bennett equilibrium, was performed for circular Z-pinches with smooth current and pressure profiles[24]. Finally, parameter conditions for the existence of generalized ν-conductor Extrap equilibria have been obtained[25] in the approximation $\nu \gg 1$.

Toroidal dissipation-free equilibria were first discussed in terms of the Grad-Shafranov equation[1,18,26].The free-boundary equilibria and a corresponding control of the plasma loop force and position have been treated by means of a computer code[27-29]. The results of these calculations were found[7,30] to be consistent with experiments in toroidal sector geometry. Analytical solutions for small deviations from circularity of the plasma cross section are further available[31]. These solutions summarize in a compact form the main features and parameter dependencies of the numerically computed equilibria. Finally, a two-dimensional analogy of toroidal geometry was developed at an early stage, by means of conformal mapping[32].

3.2 Dissipative Models Including Plasma Transport and Ohmic Heating

The steady-state plasma balance and related transport phenomena in presence of various dissipative mechanisms were considered at an early stage[33-36], thereby touching upon the boundary conditions,plasma profiles, scaling laws, the possibilities of steady operation, plasma-neutral gas interaction, and the plasma heat balance.

Further investigations on the plasma profiles, scaling laws and the boundary conditions include a low-density model with net radial flow, circulation of matter, and dominating transverse losses, for which the magnetic field strength was found to become peaked towards the boundary region[37]. The pinch radius was further found to become a function of the energy balance[37-39], in agreement with earlier results[1,35,36]. The maximum possible pinch radius is limited by the magnetic separatrix. An increase of the plasma losses caused by the separatrix and its x-points, which act as sinks, influences the plasma boundary conditions. This reduces the pressure gradient and the current density in the immediate neighbourhood of the separatrix[40]. A cold-mantle and the associated cool partially ionized boundary layer will affect the plasma boundary conditions in a similar way by reducing the temperature gradient[1,41,42].

In addition, resistive effects have been considered, with emphasis on their influence on the plasma relaxation times[43], and the resulting particle and heat fluxes in the case of specified plasma profiles for a non-circular Z-pinch[44]. As compared to the circular pinch, the deviations in confinement time were found to be of second order in the non-circularity.

Recent analysis of an earlier proposed state[1,33] of diffusion-driven steady "bootstrap-like" plasma balance indicates that such a state can exist for certain plasma profiles, when particle volume sources are introduced and the heat losses are balanced by auxiliary heating or energy producing reactions[45]. The radial diffusion velocity v_r of the plasma and the poloidal magnetic field induce an electric field which drives the pinch current. The diffusion-driven current increases with the square root of the beta value, thus becoming much larger in a Z-pinch with a strong poloidal magnetic field than in a tokamak. This is expected to generate relevant pinch currents and magnetic field profiles for Extrap, also under reactor-like conditions where there is alpha particle containment and heating. The relevance of this result may be questioned with respect to the singularity problem at the pinch axis, and to the applicability of the underlying MHD theory. Concerning the singularity problem there are, however, two points in favour of the obtained result. First an investigation of a resistive steady state of the Z-pinch has been performed at an early stage[46], thereby showing that MHD solutions exist which have no singularities at the pinch axis. Second, the present analysis[45] indicates that, for physically relevant parameters, the radial velocity v_r approaches the limit of the ion thermal speed first at an extremely small radial distance from the pinch axis, even in cases of an enhanced diffusion rate due to anomalous effects. Also the applicability to the present problem of MHD-like theory, including collisional effects, requires a more detailed examination. Consequently, there are several arguments in favour of the existence of a diffusion-driven bootstrap-like balance in Extrap, but further investigations are necessary on such a state.

The presence of a large neutral gas reservoir outside of the magnetic separatrix introduces a cold-mantle and a partially ionized boundary layer through which the plasma density of the pinch core becomes coupled to the external neutral gas density[1,41]. In other words, the plasma core acts as an ionization "pump" of neutral gas. This effect complicates the effort to reach high pinch temperatures, in the case of a moderately large available power input. It thus implies that an increase in pinch current J_p does not always lead to a substantial increase in plasma temperature, but can result in an increased accumulation of matter and particle density in the pinch core.The ways to avoid this effect in the experiments are to decrease the filling density and the volume of the neutral gas reservoir, and to increase the power input. Recent experiments appear to confirm such a picture[4,47].

To treat in a self-consistent way the complicated problem of a fully ionized pinch surrounded by and interacting with a neutral gas blanket, an approach has been made in terms of a full set of particle, momentum and heat balance equations, to be solved by means of a computer. This investigation started at the stage of a zero-dimensional code which showed that the maximum plasma density and temperature become sensitive to the profile shapes and the impurity content[48]. The development of a more advanced model is being prepared[49]. Further considerations have been devoted to the influence of the partially ionized low-beta plasma in the region outside of the magnetic separatrix [50,51]. Here it should be noticed that the steady balance of a linear pinch with a circular cross section and a neutral gas blanket can be described by 6 equations for 6 unknown variables[49]. Then the pinch "radius" $\bar{a}$, defined as the characteristic radius (the "bulk") of the current density profile, becomes uniquely determined by the three first moment equations. The introduction of a magnetic separatrix imposes an additional constraint which, in a way, overdetermines the system. It results in a non-circular pinch cross section, but does not change the general features of the plasma balance, as long as the distance a_x of the x-points from the magnetic axis (compare Fig.1) exceeds the average pinch radius $\bar{a}$ by a sufficiently large margin. However, there are values of plasma density, temperature and pinch current for which the Bennett relation (1) would correspond to a pinch radius $\bar{a}$ exceeding the x-point distance a_x. As a consequence, a lack of equilibrium would then occur for which the plasma boundary layer becomes scraped off by the separatrix, in this way making a steady balance consistent with the resulting values of the pinch and separatrix radii [52].

The balance between the applied heat sources and the heat losses represents an important and non-trivial problem in a high-beta plasma. When the ohmic power is the only heat source, the first condition for generation of a hot, fully ionized plasma is to pass the radiation barriers. This imposes a lower limit on J_p/N where N is the line density[53,54]. A second condition is represented by the ratio F_λ between the heat loss due to thermal conduction across the magnetic field and the ohmic heating power. This ratio has been found to scale in a way mainly depending on the plasma profiles, and not in a direct way on the absolute value of such parameters as the pinch current[34]. An estimation of F_λ for the fully ionized plasma core is obtained by assuming a current density profile of the form

$$j = j_o[1 + (j_a/j_o) - (r/\bar{a})^\alpha] \qquad (2)$$

where subscripts ($_o$) and ($_a$) refer to the pinch axis and to the pinch boundary region. Combining this assumed form with the Bennett relation (1) and Ohm's law, the heat loss ratio becomes

$$F_\lambda = k_\lambda[\alpha^3(\alpha+3)^2/(\alpha+1)^3(\alpha+2)](n_a/n_o)^2(T_o/T_a)[1+B_{to}^2/B_p^2(\bar{a})] \qquad (3)$$

where $B_p(\bar{a})$ is the poloidal field strength generated by the pinch current at the radius $\bar{a}$, B_{to} is the toroidal field strength at the pinch axis, $k_\lambda \simeq 1.4Z\sqrt{A}$ from the expressions of the resistivity, transverse heat conductivity and the electron-ion and ion-ion collision frequencies in a strong magnetic field[55], and where (Z,A) represent the charge and mass numbers. In presence of a cold-mantle, the temperature T_a becomes fixed at a relatively low value, i.e. $T_a \lesssim 10^5$K. For reaching temperatures T_o above 10^6K at high beta values for which $B_{to} \lesssim B_p(\bar{a})$, it is therefore seen that the density ratio n_a/n_o must be kept as low as possible. Physically this implies that the total heat conduction loss is minimized by keeping the plasma density low in the boundary region. Small density ratios n_a/n_o should also become established in a case where the plasma-neutral gas balance corresponds to a fully developed cold-mantle[41]. Another way of decreasing the ratio (3) is to increase the toroidal field and to decrease the beta value, thereby approaching a state similar to that of an RFP with respect to the heat balance[53,54,56]. Possibly the temperature gradient at the plasma boundary, which is included in the profile factor f of expression (1), can also be minimized for certain profiles, thereby leading to the smallest possible values of f. Finally, anomalous resistivity would enhance ohmic heating. This does not necessarily lead to an increase in the heat losses by the same factor, because ohmic heating and heat conduction across a magnetic field depend on electron-ion and ion-ion collisions in the classical case, and these effects could scale in different ways, as functions of increasing anomalous effects. The detailed heat balance and the corresponding plasma profiles thus need to be further investigated in the case of a high-beta Z-pinch at high axial temperatures.

When there is an aim of reaching thermonuclear temperatures at magnetic fields and pinch currents which lead to alpha particle containment in a high-beta Z-pinch such as Extrap, the problems of the Pease-Braginskii limit[57,58] have to be faced. The pinch current required for alpha particle containment is far above this limit, and Ohmic heating then becomes insufficient. A steady-state heat balance still becomes possible, by means of alpha particle heating which then balances the total heat losses[45]. The problem which remains in this connection is to find how the start-up process of a thermonuclear plasma has to proceed, in order to overlap the pinch current regime situated between the Pease-Braginskii limit and the high-current range within which alpha particle heating becomes sufficient to replace ohmic heating, and to balance the heat losses. This transition requires further analysis, partly in terms of auxiliary heating methods. Another possible option is to ramp-up Extrap in a tokamak-like mode, and then to reduce the toroidal magnetic field component, as a state of ignition has been reached. Such scenarios, in which a comparatively large pinch radius is aimed at in a final equilibrium state, differ from that of the radiative collapse to a very small radius which can take place in a dense Z-pinch[59].

3.3 Auxiliary Heating

Ohmic heating in the Z-pinch becomes comparatively efficient, due to the high current density. Nevertheless auxiliary heating mechanisms are of interest to a further development of the Extrap concept, also in connection with profile shaping. Due to the relatively high power density of the rather compact and dense Extrap plasma, the performance of auxiliary heating does not become a simple task when aiming at the goal of replacing ohmic or alpha particle heating. Here only two methods will be shortly mentioned.

The meander-type particle orbits, which pass through the magnetic axis, perform oscillations to which an externally imposed electric field can be tuned[7,9]. The corresponding frequency is associated only with a small group of particles near the pinch axis, and this becomes an advantage for auxiliary heating based on meander resonance.

The wave propagation and absorption in Extrap is found to be quite different from that in systems with a strong toroidal magnetic field[7,9]. Thus, ion-cyclotron damping becomes important already at moderately high temperatures.

4. Stability

Stability theory on Extrap has so far been worked out in terms of a rather extensive MHD-like analysis, and of some special examples and general considerations in terms of a fully kinetic approach. The MHD-like analysis is here defined as a common name for all areas within which the ion and electron excursions are small enough to preserve a macroscopic fluid-like behaviour of the plasma. Thus MHD-like theory both includes conventional MHD analysis and finite Larmor radius (FLR) analysis. The FLR effects represent comparatively small kinetic corrections in a refined approximation of MHD fluid theory. A fully kinetic approach includes on the other hand large particle excursions and corresponding phase-mixing effects which must be treated in terms of the Vlasov and Boltzmann equations.

Among the macroscopic instability modes which appear to be the most dangerous ones, the free boundary electromagnetic kink, sausage and ballooning modes, and the electrostatic flute type mode can be mentioned. At this stage a detailed examination of all instability modes would become premature, because there does so far not exist a theoretical basis on which all relevant features of Extrap physics can be described, including kinetic large particle effects. A summary of the instability modes discussed so far in connection with Extrap is given in Table 1.

4.1 Non-Dissipative MHD Analysis

The earliest considerations on Extrap stability were due to the idea of stabilizing the Z-pinch by means of an imposed inhomogeneous transverse magnetic field, instead of using an imposed longitudinal (axial) homogeneous magnetic field[1,2,26,33]. This idea was based on the fact that rigid displacements of a superconductor in an inhomogeneous magnetic field are counteracted by the forces which arise from image currents induced within the plasma volume. In this way the imposed magnetic field inhomogeneity has an effect anlogous to that of magnetic shear, but in a more efficient way, because the imposed octupole field of Fig.1 has strong inhomogeneities within the plasma volume, both with respect to its direction and its modulus. Consequently the inhomogeneous transverse magnetic field is expected to become more efficient in stabilizing long-wave nearly rigid m=1 kink perturbations than a homogeneous longitudinal magnetic field. Analysis of rigid-body perturbations by means of the energy principle indicate that such a stabilizing effect exists[2,60], and this has also been confirmed by later investigations[20]. As a consequence of the imposed inhomogeneous magnetic field, the plasma pinch cross section becomes non-circular.

A superposition of a toroidal magnetic field has been proposed at an early stage[1,33]. This is not expected to weaken the inhomogeneity effect of the transverse magnetic field noticeably, as long as the toroidal field strength does not exceed the poloidal field strength at the pinch surface.

In a general MHD analysis the plasma cross section cannot be treated as a rigid body. It becomes deformed and the corresponding perturbations therefore have a fine-structure which includes an extensive spectrum of wavelengths in space. The first attempts of an analysis in this direction were made with an equivalent two-dimensional model having surface currents, and in which the stability of axisymmetric modes was examined[32]. A surface-current model was later developed to study MHD stability at weak non-circularity. It showed that part of the sausage modes become stabilized[61].

The MHD stability of Extrap has further been investigated by calculating various equilibria by means of the GATO code[40,62]. It was found that the MHD spectrum always becomes unstable. Non-circular cross sections are always more MHD unstable than circular ones. In the best cases the growth rates of the most unstable modes were found to be the same as for a circular cross section. It was further found that the modes could be splitted into two subgroups which were labelled as free boundary modes and internal modes. For a square-shaped plasma cross section, and when the current density vanishes smoothly at the boundary, the free boundary mode growth rates are reduced. Due to these results, a mechanism for stabilization was proposed, being based on the fact that reduced pressure gradients arise at a boundary which is localized close to the magnetic separatrix. The importance of a square-shaped plasma was later explained as being due to the m=1 mode splitting which always occurs in an elongated plasma[63]. In the square-shaped plasma the m=1 mode remains degenerated to all orders in the non-circularity ε. However, the m=2 mode splits already to order ε and the risk for destabilization of one of its branches at too large values of ε was pointed out.

Part of the so far performed experiments seem to be consistent with the proposed stabilizing mechanism due to the magnetic separatrix, but there are also observations according to which the plasma remains stable for pinch radii which appear to be smaller than the radial extensions of the separatrix[47,64]

An analysis of the stability of toroidal equilibria to axisymmetric modes has earlier been performed[65] in terms of the energy principle. This analysis shows that configurations with a toroidal current that decreases monotically towards the boundary, and which are maintained in equilibrium by an external magnetic field such that the decay index is negative throughout the plasma region, become unstable in the absence of active or possive feedback.

Stability analysis by means of the MHD energy principle has been applied to two-dimensional displacements which were found to become unstable for all parameter values[20]. An expression for the growth rate of long-wavelength m=1 kink modes has been derived for arbitrary current profiles in a circular Z-pinch, without an externally imposed magnetic field[66]. These results show that stabilization cannot be achieved by a smooth current profile alone, but must in the case of Extrap also be due to the imposed external magnetic field and its influence on the cross-sectional shape. The analysis has been further extended to arbitrary current profiles, treated by normal mode analysis[67]. It was then found that peaking of the current profile towards the axis decreases the instability growth rate. By an expansion in the non-circularity parameter, an analytic expression has been obtained for the growth rate of m=1 displacements for an arbitrary current profile[25]. In this analysis it was also found that the growth rate reduces to a low level when the total current contained in the outermost boundary layer becomes sufficiently small, in agreement with the earlier proposed smooth current profile for a plasma which extends out to the magnetic separatrix[40,62]. This condition is, however, not sufficient to explain the absence of unstable long-wave kink modes in Extrap[25].

In an MHD model the m=1 modes have further been studied under the influence of weak toroidicity, a non-circular plasma cross section, and in presence of currents induced in the external conductors[68]. According to this analysis the non-circularity becomes destabilizing, but the m=1 mode could be stabilized by the induced currents, at small non-circularity.

A stabilizing contribution from the Hall effect has been demonstrated for small wavelength kink instabilities near an elliptic magnetic stagnation line[69]. In terms of a Hall model, long wavelength m=1 modes have been found to be unstable for all pressure profiles which go to zero at the plasma surface, unless feedback stabilization can be regarded as being important[70]. Losses near the x-points, in combination with non-linear MHD effects, were suggested to be the mechanisms behind the gross stability of the long wave length m=1 displacements in the older type of Extrap discharges.

For certain current distributions the magnetic field lines can have a "good" curvature along certain fractions of the plasma perimeter, thereby leading locally to flute-stable parts of the pinch cross section[33,36,43]. However, it is not clear at this stage whether current profiles can be established in Extrap which yield average-minimum-B properties without getting into conflict with other stability criteria. Moreover, a ballooning-type instability is predicted to arise[36,52] in the weak-field regions near the x-points of the separatrix in Fig.1,when the pinch radius given by eq. (1) tends to exceed the radial distance of the separatrix from the pinch axis. At a fixed pinch current J_p, this would put an upper bound to the conductor current J_v.

In an investigation on the interchange instability of Extrap in fully 2D geometry[71] it was found that, due to the necessary peaking of the pressure profile near the pinch axis, there is practically no difference between the marginally stable 1D geometry and Extrap profiles.

The weak-field regions of the x-points have further been suggested to act like conducting rods which stabilize the plasma perturbations, through the corresponding induced image currents[72,73].

Finally, attention should be drawn to a strong line-tying effect which could contribute to stability by clamping the electric potential at the magnetic separatrix as well as in the region of the partially ionized low-beta plasma of Fig.1. This occurs when the separatrix and the field lines outside of it end upon a surrounding metal wall[74], such as that of a vacuum vessel.

4.2 Dissipative MHD Analysis

Resistive equilibrium and stability has been reconsidered[43] in connection with Extrap. Provided that conventional results obtained for tokamaks can be applied to Extrap, the time scale of tearing mode filamentation becomes comparable to the duration of so far performed Extrap experiments. This applies in particular to cases where a rather strong toroidal magnetic field is superimposed on the Extrap configuration.

Dissipative effects are too weak in the hot plasma core[1] to contribute to the experimentally observed stability . In particular, it has been shown that viscous damping of the m=1 mode in the core becomes too small to affect stability[75]. On the other hand, the relatively cool partially ionized boundary layer will influence the over-all plasma stability, both by smoothing the pressure and current profiles, and by introducing rather strong joint viscosity-resistivity effects on localized perturbations[1,42]. It should be observed that neither viscosity nor resistivity could have stabilizing effects alone, but that their combination leads to a stabilizing mechanism[76]. This has been further confirmed in an analysis of short wavelength kinks at a magnetic stagnation line where visco-resistive stabilization becomes important[77]. Also the partially ionized low-beta plasma in the region outside of the magnetic separatrix can contribute in a similar way to stability[78].

4.3 Non-Dissipative MHD Analysis with Kinetic Modifications

The effect of anisotropy on stability has been examined in terms of double adiabatic theory for toroidal plasmas, yielding two second order differential equations for which specific stability criteria were derived[79,80]. This effect has been examined in the special case of m=1 small wavelength modes in the

Z-pinch[81,82]. Pressure anisotropy cannot stabilize kinks with short axial wavelengths that, according to ideal MHD theory are unstable at an elliptic magnetic stagnation line[83].

The finite Larmor radius (FLR) effects are kinetic corrections of MHD theory which hold when the Larmor radius remains small as compared to the characteristic dimensions of the system and of the perturbations to be studied. At an early stage FLR effects were proposed to add a stabilizing mechanism to the MHD properties of the Extrap system[1,42]. This mechanism was further investigated in connection with linear[84] and toroidal[40,62] equilibria. In the linear case the internal modes were found to be stabilized provided that the pinch line density does not exceed a critical value of the order of 3-5 x 10^{18} ions per meter[85,86]. Moreover, it was found that the internal kink modes of a pure Z-pinch are stabilized by both anisotropy and by the gyroviscous FLR terms of the ion pressure tensor, for small axial perturbation wave lengths[87].

From the Vlasov-fluid model a set of stability equations have been defined for the Z-pinch configuration that include first order ion kinetic effects such as those from FLR and resonant ions[88,89]. Results for the m=1 internal kink mode show that FLR effects are always stabilizing, and for sufficiently short wave lengths absolute stabilization is found[90]. From the Vlasov-fluid model a set of approximate stability equations of the cylindrically symmetric Z-pinch have been derived in the limit of small gyro radii[91] . As compared to MHD theory, a substantial reduction in the growth rate was then found for the modes m=0 and m=1.

In a finite Larmor radius model it has further been shown that the effects due to ion magnetic viscosity, Hall current and electron diamagnetism all become important to the stability of Z-pinch systems[92]. Attention has finally been drawn to an additional stabilizing FLR effect due to violation of the second adiabatic invariant[93].

Stability of the thermodynamic equilibrium can be put forward as a simple test of the validity of the dynamic equations. When applying this to the model of perpendicular gyroviscous magnetohydrodynamics, this model turns out to be invalid, because it predicts exponentially growing Alfvén waves in a spatially homogeneous static equilibrium with scalar pressure[94]. In this model the component of the momentum balance equation along the magnetic field is replaced by incompressibility.

4.4 Dynamic MHD Analysis

Recently an alternative explanation of the experimentally observed stability of Extrap has been put forward being based on a dynamic state of oscillations around an equilibrium. One approach is based on the idea that start-up can lead to compressional non-linear damped oscillations. These are proposed to have a dynamic self-stabilizing effect on the Extrap pinch[39,72], due to the image currents induced in the oscillating plasma body by the imposed octupole field.

Another scheme of dynamic feedback stabilization has further been proposed which is based on non-linear nearly rigid displacements of the plasma column from its equilibrium position, at velocities of the order of Alfvén velocity[95,96]. As a result m=1 modes with long axial wave lengths are found to be stabilized, as long as the currents in the external conductors become sufficiently large.

4.5 Basic Questions of Kinetic Theory

In Extrap configurations with a purely poloidal magnetic field, such as that of Fig.1, the weak-field region near the o-point at the pinch axis acts as a scattering center which tends to establish uniform plasma density and temperature distributions[2,37,73,97]. In some sense the plasma core therefore acts like an inserted metal conductor. A similar situation prevails near the x-points, in cases where the plasma extends out to the magnetic separatrix.

In fact, even in the case of a superimposed moderately strong toroidal field B_{to}, the ion Larmor radius a_i cannot be considered to be small as compared to the characteristic macroscopic dimensions within any part of an experimentally studied Extrap pinch[98]. The number of ion Larmor radii contained within the average pinch radius $\bar{a}$ becomes[34,98]

$$\theta_i = \int_0^{\bar{a}} (1/a_i)dr = [\mu_o e/(8\pi^2 m_i K)^{1/2}] \cdot [1+B_{to}^2/B_p^2(\bar{a})]^{1/2} f_i J_p/\sqrt{T_o} =$$

$$= [e(\mu_o/\pi m_i)^{1/2}] \cdot [1+B_{to}^2/B_p^2(\bar{a})]^{1/2} g_i \sqrt{\bar{N}} = [e(\mu_o/\pi m_i)^{1/2}] h_i \sqrt{N/\bar{\beta}} \qquad (4)$$

where $\bar{\beta}$ is the average plasma beta value and (f_i, g_i, h_i) are profile factors of order unity. The definition of θ_i given here differs somewhat from the definitions of the corresponding parameter $\bar{s}$ used in research on FRC configurations[99]. Some typical data of so far performed Extrap experiments[4,5,7,47,64] are given in Table 2 as well as data of the Extrap reactor case and those recently being reported[100] for NET.

In order to estimate the importance of kinetic effects, and the corresponding limit of validity of pure MHD analysis, it is not sufficient to compare the average ion Larmor radius $\bar{a}_i$ to the average minor radius $\bar{a}$ of the plasma. The dynamics of any plasma perturbation eigenmode depends namely on the integrated behaviour of its entire spectrum of wave lengths λ. Thus the ion excursions to LLR effects become substantial for the part $\lambda \lesssim \lambda_{ci}$ of the spectrum given by the critical wave length

$$\lambda_{ci} \equiv k_i \bar{a}_i = k_i \bar{a}/\theta_i \tag{5}$$

Here the dimensionless constant k_i is expected to be at least of the order of 8, which corresponds to an ion Larmor diamater being equal to a quarter wave length. For $\lambda \lesssim \lambda_{ci}$ it is obvious that MHD theory becomes a poor approximation, because the ion then "sweeps" in one gyro period over a distance where the component of the perturbation having the wavelength λ varies from zero to its full amplitude. An analogous case of large particle excursions in an unmagnetized plasma has recently been studied by means of a computer code[101]. In this case kinetic effects due to a large Debye distance λ_D were found to create substantial changes away from an MHD behaviour when $\lambda_D \gtrsim \lambda/4$.

For any plasma perturbation the fundamental question thus arises whether there can exist any noticeable spatial inhomogeneities in its macroscopic structure within the distance of an ion Larmor diameter. If this is so, the corresponding influence on the fine structure of an eigenmode could become essential to stability, thereby tending to convert the mode into a rigid-body-like perturbation.

In a hot high-beta plasma the individual ions make large excursions not only in the transverse but also in the longitudinal direction of the magnetic field. The longitudinal excursions[98,102,103] lead to important kinetic effects for wave lengths being smaller than the distance $2\pi u_i/\omega_i$ which an ion travels along a field line at the thermal speed u_i during the gyro time $2\pi/\omega_i$. This condition leads to a critical wave length λ_{ci} for the longitudinal excursions, being almost identical to that obtained from eq. (5). Thus $\lambda \lesssim \lambda_{ci}$ applies as a condition for kinetic effects to be important, both in respect to transverse and longitudinal excursions.

The physical mechanisms of the transverse and longitudinal large Larmor radius (LLR) effects just described are different from those of the MHD-like FLR effects[104]. The latter are based on a small differential $\underline{E} \times \underline{B}$ drift of the ions with respect to the electrons which gives rise to charge separation, whereas the transverse and longitudinal LLR effects are based on phase mixing through large particle excursions. In several cases the LLR effects on the plasma become much stronger than those of the FLR mechanism.

In many equilibrium cases electric quasi-neutrality can be preserved also when there are large ion Larmor radii. For certain time dependent perturbations this becomes less clear, such as for a plane magnetoacoustic compression wave propagating perpendicularly to a homogeneous unperturbed magnetic field. When the electrons are tied to the field lines of such a wave, charge separation may inhibit large ion excursions across the magnetic field[98]. Possibly quasi-neutrality can be restored by "cuts" in the Maxwellian tail, but this question requires further analysis.

In addition to the large particle excursions, attention should be paid to the kinetic effect which arises from phase mixing by the guiding centre drifts in an inhomogeneous magnetic field[52,104]. This makes the high-energy parts of the particle spectrum drift faster across the magnetic field than the low-energy parts, thereby tending to smear out a plasma perturbation in space. Such a phase mixing becomes pronounced in a high-beta plasma with strong spatial magnetic field inhomogeneities. A first estimate of this effect has been made[105] in terms of the expected kinetic damping of a density perturbation in a Z-pinch, by comparing the corresponding damping time to the time for an Alfvén wave to travel around the circumference of the pinch cross section. In combination with eq. (5) this indicates that the part $\lambda \lesssim \lambda_{ci}$ of the wave length spectrum also becomes subject to a strong phase mixing effect from the guiding centre drifts.

Finally there may exist limitations of the conventional normal mode analysis in the case of large particle excursions^{106}. Thus, it is not clear that an ansatz based on a time dependence of the form $\exp(i\omega t)$ leads to a complete description of the time development for any perturbation, also in the limits of free streaming and of LLR effects. This question has to be further examined, preferably in terms of a fully kinetic approach, such as by a Fourier-Laplace analysis including the corresponding inverse transforms.

The basic kinetic questions outlined here for Extrap and similar systems can be summarized as follows (compare also eqs. (4)-(5) and Table 2):

- In so far performed Extrap experiments on a comparatively small scale the number θ_i of contained ion Larmor radii has been in the range of 3 to 9, leading to $\lambda_{ci} \gtrsim \bar{a}$. In the Extrap reactor case given as a numerical example in Table 2 the corresponding parameters are of the order of $\theta_i \simeq 40$ and $\lambda_{ci} \simeq 0.2\bar{a}$. This implies that almost the entire wave-length spectrum of a perturbation becomes subject to strong LLR effects in the experiments, and that LLR effects should be substantial even for the Extrap reactor, by influencing the fine structure of any plasma perturbation. The LLR effects should also become important to other high-beta systems, including the second stability regime of tokamaks^{103}.

- For conventional tokamaks, where θ_i is about one order of magnitude larger than in the Extrap reactor case, MHD theory becomes on the other hand a good approximation.

- The dynamics of Extrap is thus in an intermediate situation, between the MHD behaviour of a fluid with small particle excursions and that of a freely streaming gas with large such excursions. Therefore MHD theory does not alone give a relevant description of Extrap dynamics, and large particle excursion (LLR) effects unavoidably have to be taken into account here, regardless of these effects having or not having a stabilizing influence on the plasma. An approach in terms of a complete kinetic theory is then desirable, but becomes a difficult task. As a first approximation, a hybrid model[107] can be applied in which perturbation wave lengths λ above the kinetic limit λ_{ci} are treated in terms of MHD analysis, and special kinetic treatment is given to wave lengths $\lambda \lesssim \lambda_{ci}$.

- The limitations of normal mode analysis have to be further examined, in respect to LLR effects, with the special aspect that such effects have features in common with free-streaming, at least during the first phase of an initial value problem, and that the free-streaming case can lead to solutions[98,102,103,106] which do not have a simple time dependence of the form $\exp(i\omega t)$. In addition, it has to be stressed that ω^2 does not always turn out to be real, such as in the case of overstability. The case of marginal stability can then not be determined from $\omega^2 = 0$, and the principle of exchange of stabilities becomes invalid[108]. An example of overstability is given by the oscillations of growing amplitude in the case of the gravitation instability in presence of FLR effects[104].

4.6 Kinetic Analysis

So far the present problems of kinetic stability have only been tackled in some special cases. A variational principle and a theorem for comparison have been elaborated for the kinetic stability of two-dimensional Vlasov equilibria, being valid for internal modes in straight[109] as well as toroidal[110] geometry. For displacements with no longitudinal variation, the system is under these conditions found to be kinetically stable, if it is MHD-stable. Passive feedback from a wall located near the plasma surface is shown to be sufficient for stabilizing long wavelength modes in Extrap.

The stability of the m=1, free boundary mode has recently been investigated by means of the complete set of Vlasov-Maxwell equations [111,112]. With the methods of this analysis large Larmor radius effects are accounted for in the limit of long axial wave lengths and weak non-circularity. An axial magnetic field did not have an influence on the dispersion relation for this type of mode which was always found to be unstable in presence of a weak octupole field, regardless of the particular form of the equilibrium pressure profile. It was further proposed that nonlinear gross stability might result from the combined action of the dynamic effects[95,96] described in Section 4.4 and of losses near the x-points of Extrap[66].

Recently the kinetic theory of the m=1 kink instability of the Z-pinch has been treated in terms of an integral formulation including large excursion betatron orbits[113].

Kinetic damping has then been found to stabilize modes of short wave length. Also in the analysis of a number of recent Z-pinch experiments at the Imperial College in London[114] the observed improved stability has been interpreted as the result of LLR effects.

A few simple but explicit examples on LLR effects have further been given. The first demonstrates the phase mixing due to transverse ion excursions in a dilute ionized gas.It results in a strong "kinetic damping" of the perturbations and of the forces driving such instabilities as the electrostatic gravitation mode[98,103]. The physical behaviour of the gas then becomes radically different from that described by MHD-theory, and the time dependence of the perturbations cannot even be expressed in terms of normal modes of the form exp(iωt), but includes a factor $\exp[-(ka_i)^2\sin^2(\omega_i t/2)]$. The kinetic effects are considerable in this example, at least when the ion Larmor radius a_i becomes larger than $\lambda/2\pi$ where λ is the wavelength of the perturbation. The second example illustrates how the electrostatic fluid motion in a dilute ionized gas becomes distorted by LLR effects, and how this leads to a rather complex time dependence of the macroscopic fluid quantities[115]. The third example demonstrates the phase mixing due to longitudinal ion excursions which result in a strong kinetic damping of the short wave-length part of the Alfvén wave spectrum, also in a plasma of high electron density[102] i.e. at small Debye lengths.

A first attempt has recently been made to combine kinetic and fluid theory in a hybrid LLR-MHD model of kink perturbations[52,107] The main kinetic mechanisms due to LLR and guiding centre drift dispersion are included as constraints in this approach, thereby restricting the plasma perturbations to a class which can be treated in terms of MHD theory. This leads to a lower and an upper limit of the ratio $\bar{a}/a_x$ between the pinch radius $\bar{a}$ and the x-point distance a_x from the magnetic axis of Fig.1. At the lower limit the ratio $\bar{a}/a_x$ becomes too small and the imposed octupole field too weak to be able to stabilize the plasma. The upper limit is due to the fact that $\bar{a}/a_x$ cannot exceed unity without leading to a lack of equilibrium or ballooning instability at the x-points. The resulting necessary criteria for instability include the ratio $M = B_{pa}/B_{va}$ between the magnetic field strengths from the pinch and conductor currents at the pinch surface, as well as the number θ_i of contained ion Larmor radii. They appear to be largely in agreement with so far performed experiments, but further investigations are necessary for tests of this simple hybrid LLR-MHD approach.

5. Summary of Present State of Extrap Theory

The present state of Extrap theory can be summarized as follows:

- Some progress has been made in the understanding of plasma breakdown and build-up, leading to first estimates of the required break-down voltages.
- Dissipation-free equilibria in Extrap geometry are now fairly well understood, and within this area progress has been made in terms of kinetic theory.
- Much work is still needed on dissipative equilibria, especially on self-consistent models of transport and associated problems of heating and heat balance, plasma-neutral gas and plasma-wall interaction, and of radiation losses including impurity effects.
- Considerable efforts have been devoted to ideal MHD and MHD-like analysis of Extrap stability.The corresponding effects on linear stability can at this stage be surveyed, and it is clear that this analysis alone cannot account for the experimentally observed plasma behaviour. The possibility of non-linear dynamic stabilization is open, and investigations concerning this issue have started recently.
- Kinetic effects have to be included in a theory on Extrap. Kinetic analysis is still at an early stage, but it is

probable that effects due to large ion excursions across and along magnetic field contribute in an important way to Extrap physics, and probably also the phase mixing effects due to the guiding centre drift motion.

- A number of effects listed in Table 3 have been proposed to contribute to the observed stability, some of these possibly in a joint way. However, theory and experiments are still at too early a stage for definite conclusions to be drawn about the mechanisms which mainly contribute to macroscopic stability.

- The earliest experiments on Extrap were collision dominated, whereas present and planned experiments have marginal or low collisionality. This fact could also have an important influence on stability.

- Microinstabilities and effects due to anomalous transport have only been briefly considered and require further analysis. A distinction between classical and anomalous losses is difficult at the relatively low temperatures in present experiments. Such a distinction should become possible only for the temperatures aimed at in a larger experiment.

To sum up, Extrap theory is still at a rather early stage of development, even if there are now some indications how to combine the most important mechanisms for an explanation of the observed macroscopic stability. Nevertheless, further advanced methods of plasma analysis have to be employed in the search for a complete understanding of the experiments. Thus, a complete picture of Extrap stability requires all relevant destabilizing and stabilizing effects to be "integrated" over the cross section of the strongly inhomogeneous plasma, thereby taking the proper boundary conditions into account.

Table 1. Investigated instability modes in Extrap.

Instability modes	References
Free boundary modes in general	40,62
Internal modes in general	40,62,85,86
Axisymmetric modes in general	32,65
Kink modes	1,2,20,25,26,33,52, 60,63,66-70,75,77,81,82, 83,87,90,91-96,111-114,107
Sausage mode	1,61
Ballooning mode	33,36,52
Electrostatic interchange (flute) mode	1,33,36,42,43,71,98,103

Table 2. The number θ_i of contained ion Larmor radii and the relative magnitude $\lambda_{ci}/\bar{a}$ of the limiting wave length λ_{ci} of pure MHD behaviour for experiments with the linear device Extrap-LO ($B_{to} = 0$), the fully toroidal device Extrap-T1 ($B_{to} \simeq B_p(\bar{a})$), the Extrap reactor case ($B_{to} = 0$), and a system study of NET[100].The data on $\bar{a}$, θ_i and λ_{ci} for LO and T1 have been estimated from measured quantities and assumed profile shapes.

	Extrap LO	Extrap T1	Extrap Reactor	NET
J_p (A)	0.9×10^4	2.9×10^4	10^7	1.5×10^7
T_o (K)	10^5	3×10^5	3×10^8	2×10^8
$\bar{a}$ (m)	8.1×10^{-3}	52×10^{-3}	1.5	1.68
θ_i	3.4	8.5	43	300
$\lambda_{ci}/\bar{a}$	2.4	0.95	0.19	0.027

Table 3. Proposed stabilizing effects in Extrap.

Stabilizing Effects	Basic Physical Mechanisms
MHD-Like Effects	
External inhomogeneous magnetic field	Induced plasma currents and forces due to motion across inhomogeneous external field; similar to shear,
Magnetic field line curvature and length	Regions with good curvature may in certain cases form fluid stable parts, linked by short connection lengths.
Magnetic separatrix	Shaping of plasma cross section and of smooth pressure and current density profiles. Magnetic limiter can short-circuit plasma boundary by line-tying to a conducting wall.
Passive external conductors (or walls) and x-points	Induced image currents.
Cold-mantle and surrounding low-beta plasma	Smooth shaping of pressure and current density profiles, and introduction of joint viscosity-resistivity effects.
Fast pinch oscillations	Dynamic stabilization. Non-linear effects.
Kinetic corrections due to finite Larmor radius (FLR) effects	Charge separation and current due to differential $\underline{E}\times\underline{B}$ drift of ions and electrons, and Hall effect.
Kinetic Effects	
Non-adiabatic scattering at o- and x-points	Local flattening of temperature and density profiles.
Transverse large Larmor radius (LLR) effects	Phase mixing and kinetic damping of perturbations due to large ion excursions across the magnetic field.
Longitudinal large Larmor radius (LLR) effects	Phase mixing and kinetic damping of perturbations due to large ion excursions along the magnetic field.
Energy dispersion of guiding centre drifts	Phase mixing due to corresponding velocity dispersion.

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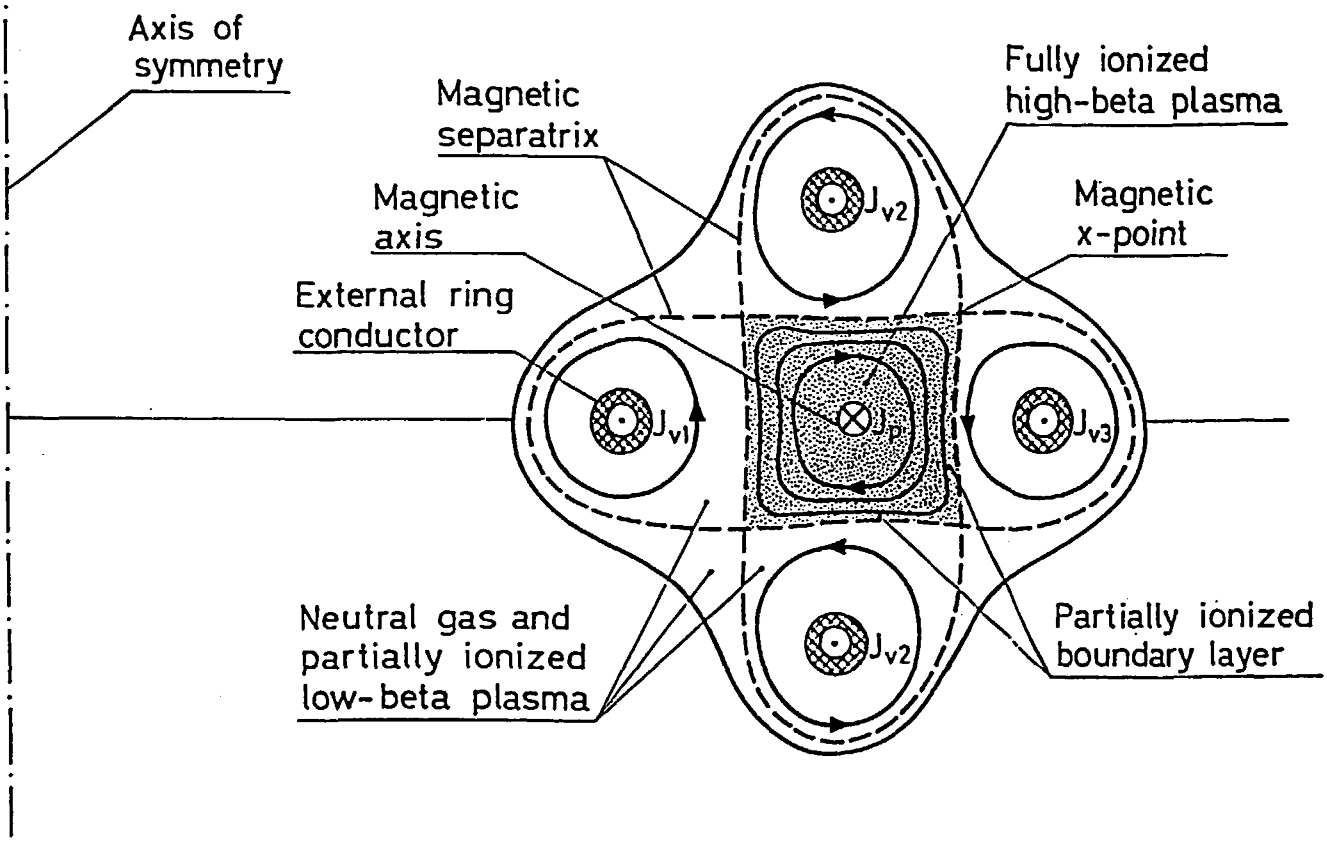

Fig.1. Outline of a toroidal Extrap (External Ring Trap) configuration showing an earlier proposed special case of four external ring conductors. The latter carry currents which are antiparallel to the pinch current which flows in the fully ionized high-beta plasma. There are four magnetic x-points at a common separatrix. The shape of the non-circular plasma cross section depends on the current profile. The figure shows a fully ionized plasma bounded by a thin partially ionized boundary layer which extends from the magnetic separatrix towards the plasma interior. In the volume outside of this layer there is neutral gas and a partially ionized low-beta plasma. The geometry represented by the figure gives one example of a class of possible Extrap configrations. Geometries with other numbers, positions and current directions in the ring conductors also belong to this class. A weak toroidal magnetic field can be superimposed along the pinch axis.

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A SURVEY OF THEORETICAL RESEARCH ON THE EXTRAP CONCEPT

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A review is given of the theoretical analysis on the Extrap concept which consists of a Z-pinch being immersed in an octupole field generated by currents in a set of external conductors. This analysis includes research on plasma breakdown and start-up, equilibrium and stability, in terms of MHD and kinetic theory.

Extrap theory includes an extensive area of diversified problems, being related to a high beta value, a non-circular plasma cross section with a magnetic separatrix, and strongly inhomogeneous plasma conditions in space. This also leads to unexplored and important areas of plasma physics, reaching far beyond the special applications to the Extrap configuration.

At present progress has been made in the analysis of breakdown, of dissipation-free equilibria, and in identifying the instability modes and possible stabilizing mechanisms in Extrap. Nevertheless much work still remains within the area of dissipative equilibria and transport, as well as in the efforts to reach a complete theoretical understanding of the experimentally observed stability.

Key words: Magnetic plasa confinement, high beta,
Z-pinch, Extrap