

# ON THE MAGNETOHYDRODYNAMIC EVOLUTION OF THE $m=0$ INSTABILITY IN THE DENSE Z-PINCH

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It has been clear since the early days of fusion research that  $m=0$  instabilities are responsible for ion acceleration and neutron emission in z-pinch type devices, through beam-target effect [1]. Although they are undesirable for energy production purposes, their physics is most interesting, their proper study might be relevant to some astrophysical problems, such as the origin of some cosmic rays, and can lead to applications in the fields of beam and x-ray generation. It is clear that a full understanding of the evolution of the  $m=0$  instability calls for heavy numerical simulation, where kinetic effects are properly taken into account. However, it may be possible to gain some insight about the global features of the process from a magnetohydrodynamic (MHD) point of view. Namely, if it is assumed that the population of accelerated ions is negligible in comparison with the background ions, it is possible to study the ion beam formation due to the electric field generated by the instability. It has been shown by Haines that in order to account for the directional preference of ion acceleration, a Hall-MHD model needs to be assumed at least, where the Hall term is kept for Ohm's law [2]. It turns out that for such a model, the neck of the instability cannot develop if axial flow is not considered. Thus, if multiple necking occurs, this must lead to convective cells.

On the other hand, experiments in dense plasma devices, such as Z-pinchs [3], dynamical Z-pinchs [4] and plasma foci [5-11], often show localized regions of strong medium and hard X ray radiation, commonly known as hot spots. Depending on the device, their typical size range from 50 to 500  $\mu\text{m}$ , with densities from  $10^{27}$  to  $10^{28} \text{ m}^{-3}$ , and lifetime spans from 1 to 15 ns. Their temperatures have been observed to range from 0.2 to 10 keV, and they are surrounded by a plasma cloud of lower temperature and density. The appearance of these dense plasma objects is enhanced by high Z impurities which may be added to the plasma, may originate from the electrode material, or simply if the plasma itself is not hydrogenic, as in the case of Ref. [3]. High energy (MeV) electron beams, propagating in the axial upstream direction are often correlated with hot spot formation [5,10,12] in plasma foci. The precise nature of hot spots has been subject to wide debate. Although it is widely recognized that they are related to  $m=0$  instabilities, Choi et al. [5] have found that in the case of the plasma focus, they appear, not only during, but before the development of the instabilities. Mosher and Colombant have proposed an effective mechanism that reproduces the experimental electrical and radiation characteristics of hot spots, based on a radiation dominated quasi-two-dimensional model [3]. Their model shows high density localized pinch spots arise on high Z discharges, in contrast to the spindle pinchs predicted for hydrogenic discharges. Maxon et al. [13] have found, from a two-dimensional magnetohydrodynamic

simulation of a tungsten annular pinch, that hot-spots of 1 keV and  $44 \text{ g cm}^{-3}$  may form as a result of the sausage instability. No attempt was made by them to explain the generation of the electron beams.

It must be noted that Rout and Shyam [7] have reported long lived hot spots ( $1\mu\text{s}$ ) in purely deuterium plasmas, in contradiction with most observations, but it may be speculated their results arise from electrode impurities, or of some other kind, inadvertently introduced into the device. Their claim is the smallness of their chamber might help to stabilize the structures observed.

Bifurcating bright-spots arise from fibre Z-pinch plasmas [14,15] which recede from the neck of the instability, and remind shocks, such as the Herbig-Haro objects observed in stellar jets [16]. These might probably be regarded as objects of a different nature, since they occur even in the absence of high Z ions, such as in the pure  $\text{D}_2$  fibre MAGPIE experiments [15].

It may be speculated that when high Z ions are present, hot-spots may actually arise from a radiative mechanism, where high current densities may be trapped in relaxed convective cells. In the conventional sense, radiative collapse is achieved in a hydrogenic Z-pinch, when its current is larger than the Pease-Braginskii current, defined as the equilibrium current, where the Ohmic heating is balanced by Bremsstrahlung radiation losses [17, 18]. If such losses are larger, the pinch collapses, since the electromagnetic pinch force increases faster than the thermal gradient pressure. The energy stored in the magnetic field surrounding the pinch is dissipated in the plasma, sustaining the radiation source. This critical current is of the order of 1.6 MA in a deuterium plasma. In ordinary plasma focus devices,  $m=0$  instabilities set in at currents of a few hundreds of kA, well below the Pease-Braginskii current. Impurity seeding might help by adding recombination and line radiation losses, however thermal instabilities tend to condense them, and line homogeneity is lost.

On the other hand, it has been experimentally observed that  $m=0$  instabilities yield spheromak-like, or force-free field structures in plasma focus discharges [19- 21]. The question is whether such closed magnetic field structures may be able to trap currents, high enough to sustain the magnetic field needed to drive a closed structure radiative collapse. The theoretical basis for such kind of structures, as a result of magnetohydrodynamic relaxation, was established long ago by Ikuta [22] and Jensen and Chu [23], and it was noted by Deutsch et al. [19] their work could be relevant to explain the dense plasma focus observations. However, as Kukushkin et al. [20,21] have properly stated, the Hall-effect should be accounted for. It is reasonable to speculate that there is some kind of dynamo effect that transforms the externally produced azimuthal magnetic field (which in the compact toroid would play the role of the toroidal field) into a poloidal magnetic field, via turbulent relaxation. This picture resembles that of the reversed-field pinch, which has been approximately described by Taylor's relaxation theory [24], on which Refs. [22,23] rest. This idea has been extended to the case of Hall-MHD by Turner [25]. Although this extension has been objected by Taylor, on the basis that the generalized magnetic helicity chosen by Turner

is not as well conserved as the original one [26], it establishes nevertheless an approximation to the closed relaxed structures which may trap the flow and current. Once Hall-MHD is assumed, the electron fluid decouples from the ion, and freezes the magnetic field. Thus, it remains to find out the way to describe the evolution of the resulting structure into the well collimated electron beam observed in the experiments.

It may be concluded that it is possible in principle to explain the appearance of some kind of hot-spots in some Z-pinch type devices, such as the plasma focus, as the collapse of force-free field structures that may form as a consequence of  $m=0$  instabilities. This might help to explain their large lifespan reported by some authors [7].

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