White Paper for *Frontiers of Plasma Science Panel*

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Title:	Self-organization in high beta plasmas: merging of compact toroids
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Self-organization in high beta plasmas: merging of compact toroids

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- ***Research frontier:***

A wide range of magnetofluids is observed to self-organize into preferred relaxed states [1-4]. During the relaxation some of the integral values (invariants) are conserved, or dissipate slower than others. This allows a relatively simple description of highly complex and nonlinear dynamical systems. The relaxation theory based on invariant magnetic helicity [1,2] has been very successful in predicting the gross evolution and structure of reversed-field pinch (RFP) and spheromak plasmas. However, the existing theories do not include large plasma pressure, plasma flows or kinetic effects, and therefore they do not apply to finite-beta tokamaks, beam-heated spherical tokamaks, and especially to the high-beta plasma configurations like the field reversed configuration (FRC), where the plasma current is perpendicular to the magnetic field. Nevertheless, experimentally the kinetic FRCs have been found to be remarkably robust, surviving a very dynamical formation, translation, and bouncing off magnetic mirrors [5]. This robustness has not been understood theoretically, and cannot be described by the zero-beta relaxation theories.

A generalized theory of self-organization and relaxation is therefore needed for finding the self-similarly evolving, dynamically stable, and self-organized states that appear in various dynamic systems. Theoretical predictions of the self-organized states need to be confirmed and aided by numerical simulations and experiments. Theoretical, numerical and experimental studies of merging of compact toroids (spheromaks and FRCs) can lead to improved understanding of self-organization and relaxation processes in non-ideal MHD plasmas. Merging of CTs is often accompanied by a conversion of the plasma kinetic energy and / or the magnetic energy into heat, resulting in the high-beta configurations with finite flows. Highly dynamical nature of merging, which involves reconnection of magnetic field lines, allows the plasma rapid access to a particular minimum-energy state, which can be studied numerically using suitable simulation tools.

- ***Approach to advancing the frontier:***

A comprehensive study of CTs merging, self-organization and relaxation should include three aspects: (1) development and application of the state-of-the-art numerical simulation codes; (2) development of a generalized theory of self-organization and relaxation in high-beta plasma; (3) experimental studies of co- and counter-helicity merging of spheromaks, and the FRCs merging. Theoretical models, and numerical simulations need to be validated against existing experimental results.

Improvements are needed in all three areas to study the plasma dynamics leading to the relaxed states and self-organization. Advanced computational tools, namely 3D nonlinear, high-resolution, and parallel codes, which include kinetic effects (two-fluid or a hybrid description) will be essential to studying CTs merging. Moreover, the Adaptive Mesh Refinement (ARM) methods might be necessary in order to accurately simulate 3D reconnection region; parallel codes and High Performance Computing (HPC) resources will be needed. CTs merging studies will need new analytical theories for kinetic self-organization, based on a two-species (ion and electron) plasma description [6]. Development of new non-invasive diagnostics might be needed for a comparison with theoretical predictions.

Co- and counter-helicity spheromak merging has been used extensively in the experimental studies of magnetic reconnection in laboratory [3,7-9]. In a typical merging experiment, two spheromaks are formed

at the different ends of cylindrical flux conserver with parallel or antiparallel toroidal (azimuthal) currents. The spheromaks are then allowed to move towards the device midplane, where the reconnection of their magnetic fields takes place (Fig. 1). In the counter-helicity merging, the toroidal magnetic fields in two merging spheromaks have opposite directions, so that the reconnection of both the poloidal and toroidal magnetic field components takes place at the device midplane. Aside from the toroidal effects, this problem is similar to the interaction of magnetic flux tubes with opposite helicities, which has been studied in MHD limit in application to astrophysics [10]. In the counter-helicity spheromak merging, the reconnection proceeds until all toroidal flux is annihilated, and a FRC is formed [11,12]. In a co-helicity merging, the tilt instability might develop prior to or after the merging, depending on flux-conserver geometry and spheromaks configuration, which leads to a highly non-axi-symmetric magnetic reconnection process (fig.2) that permits the plasma to relax to a three-dimensional relaxed state [4]. The line-tying and finite plasma pressure can have effect on the relaxation process [13]. Comparison of results of hybrid simulations of counter-helicity spheromak merging with MHD simulations show that even in the MHD-like regime (with relatively small ratio of thermal ion Larmor radius to the flux conserver radius), there are significant differences between hybrid and MHD simulations [14]. This demonstrates the need for the kinetic (hybrid) description of plasma in merging simulations.

- ***Impact on plasma science and related disciplines and potential for societal benefit****:*

Theoretical, numerical and experimental studies of relaxation and self-organization in plasmas would advance the level of fundamental understanding of such basic and universal phenomena, and have the potential to impact other disciplines such as fluid dynamics, space plasma physics and astrophysics.

The proposed research will also strongly impact areas of fusion research and plasma physics. The MHD relaxation theory has been invaluable in understanding and predicting highly dynamical and nonlinear phenomena, for example in studies of reversed field pinches (RFPs) evolution and profiles [1,2]. Similar tools are needed for description of plasma configurations including non-ideal phenomena, such as plasma flows, finite beta, or kinetic effects, for example, in beam-heated spherical tokamaks or compact toroids. In addition, there is an expectation that the relaxed states of high-beta configurations will have improved stability with respect to ideal MHD modes, at least.

The high beta, plasma flows, two-fluid effects and finite Larmor radius effects necessitate the use of sophisticated analytical and numerical tools. Development of these tools greatly advances the level of such kinetic calculations, and is of great practical interest for all related science disciplines, including the fusion energy sciences program. Thus, the tools and approaches developed for field-reversed configuration studies are finding important applications to other small-aspect ratio toroidal devices, e.g., in spheromak merging studies [11-14], and in equilibrium and stability studies of the National Spherical Torus Experiment (NSTX) [15-16]. Development of these tools will also benefit other areas of plasma physics research including space and astrophysical plasmas.

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Figures

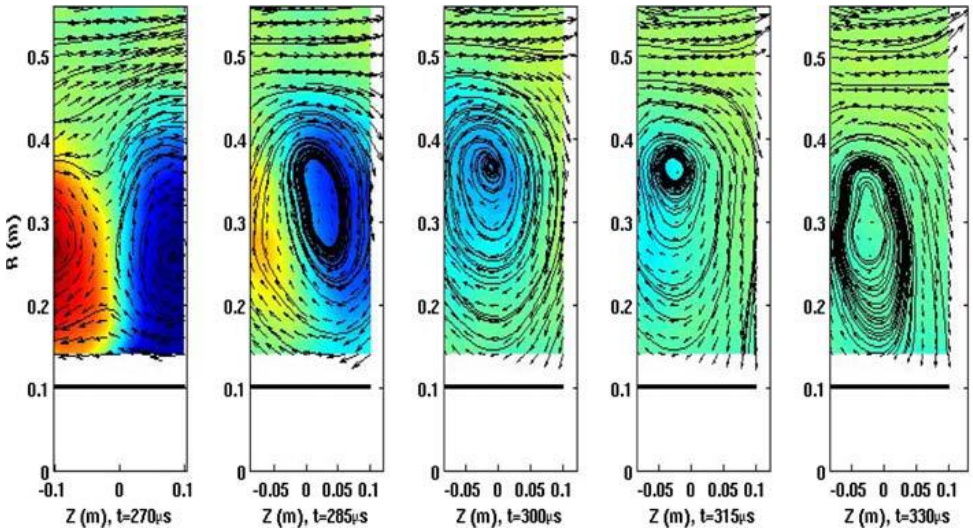

Figure1. Formation of large-flux He FRC by counter-helicity merging of spheromaks in MRX [8].

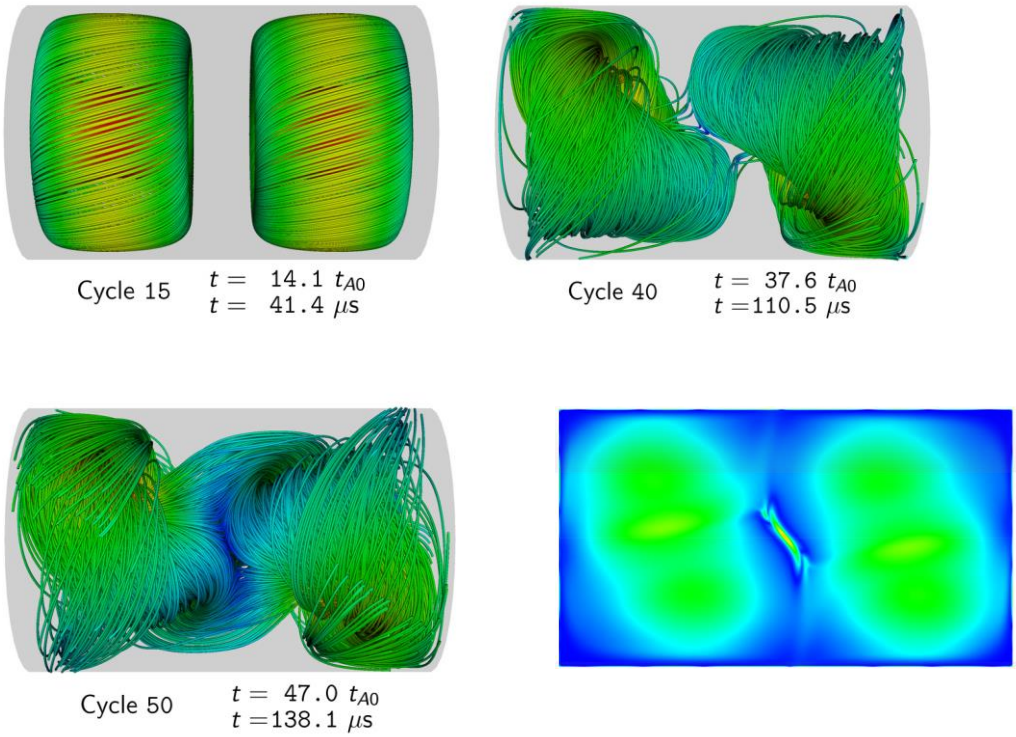

Figure 2. Representative co-helicity spheromak merging simulation results [13]; (a)-(c) magnetic field lines, (d) plasma current.