# TOKAMAK FORMATION VIA LOCALIZED HELICITY INJECTION USING TANGENTIAL BOUNDARY FLOWS

[1,2]P.L. GARCÍA MARTÍNEZ, [2,3]R. FARENGO, [1,2,3]H.E. FERRARI

[1]CONICET CCT Patagonia Norte, Bariloche, Argentina
[2]Instituto Balseiro, Bariloche, Argentina
[3]CNEA Centro Atómico Bariloche, Bariloche, Argentina

Email: pablogm@cab.cnea.gov.ar

Non-solenoidal plasma initiation is a crucial component of many present experiments, as well as envisaged burning plasma devices. This can be achieved by helicity injection, radiofrequency (RF) waves, or induction from the poloidal field (PF) coils [1]. Among the first category, localized helicity injection (LHI) is achieved by using high-power electron current injectors near the edge to produce helical plasma filaments. At low injector current, the filament follows the almost unperturbed vacuum magnetic field structure. As the injected current is increased, the configuration becomes unstable and relaxes to a tokamak-like state [2]. In the past, a closely related experiment demonstrated the feasibility of using the same mechanism to form and sustain tokamak plasmas of conventional aspect ratio [3].

In this work, we present time-dependent 3D magnetohydrodynamic (MHD) simulations of the formation and sustainment of tokamak-like plasmas of conventional aspect ratio using LHI. Existing numerical works in this area have focused on spherical tokamaks [4]. Another key difference is the use of an alternative approach to model helicity injection. Here, we use tangential flows imposed in a region of the boundary that is intercepted by magnetic flux. We have already demonstrated the efficacy of this strategy to form and sustain spheromak configurations [5]. Our results not only contribute to the general understanding of the dynamics of magnetic relaxation but are also relevant to the design of a solenoid-free startup for the TCABR upgrade tokamak [6], which is based on localized current injectors and is currently under development

To model TCABR we set up a toroidal flux conserver with the following geometric parameters: $R_0 = 0.628$, $a = 0.172$ and $\kappa = 1.45$. All distances are referred to $L = 1$ m, the magnetic fields to $B_0 = 1$ T and time to the Alfvén time $t_A \sim 1$ $\mu$s. The vertical magnetization is produced by axisymmetric annular electrodes at the bottom and top ends. The resulting initial contours for the poloidal field are shown in green in Fig. 1 (a). The vertical field strength controls the geometric winding ($w$) of the vacuum field lines.

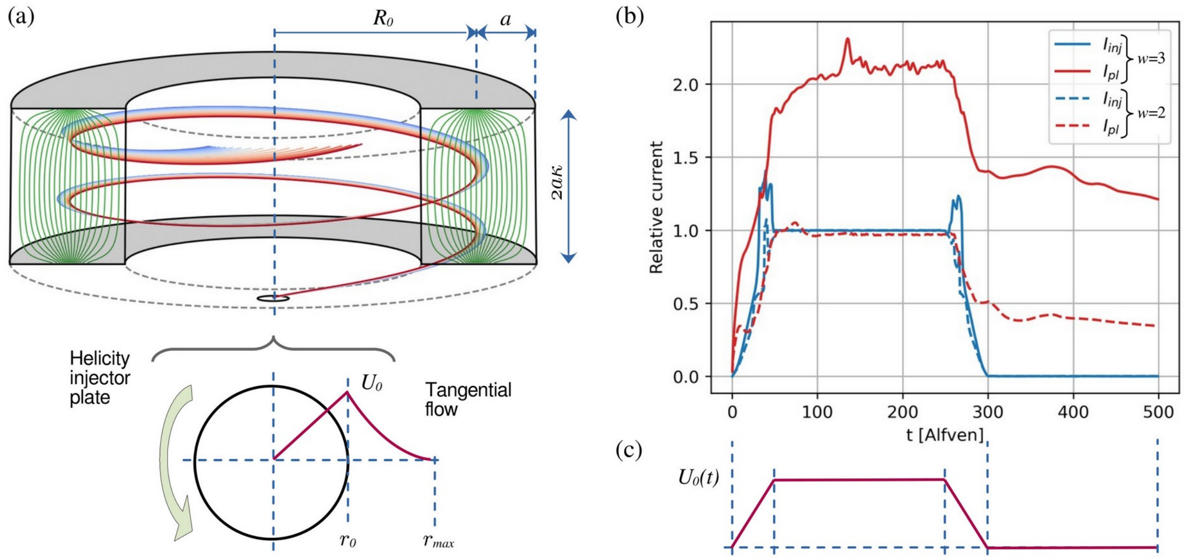


Fig. 1. (a) Geometry of the flux conserver (black/gray), initial path of field lines from the injector for a filament with initial winding $w$ = 2 (red/blue) and initial vertical magnetization (green). The detail of the localized boundary flow imposed at the bottom is shown below. (b) Plasma and injector currents for two cases, $w$ = 2 and $w$ = 3. (c) Time dependence of the amplitude of the imposed driving flow at the boundary.

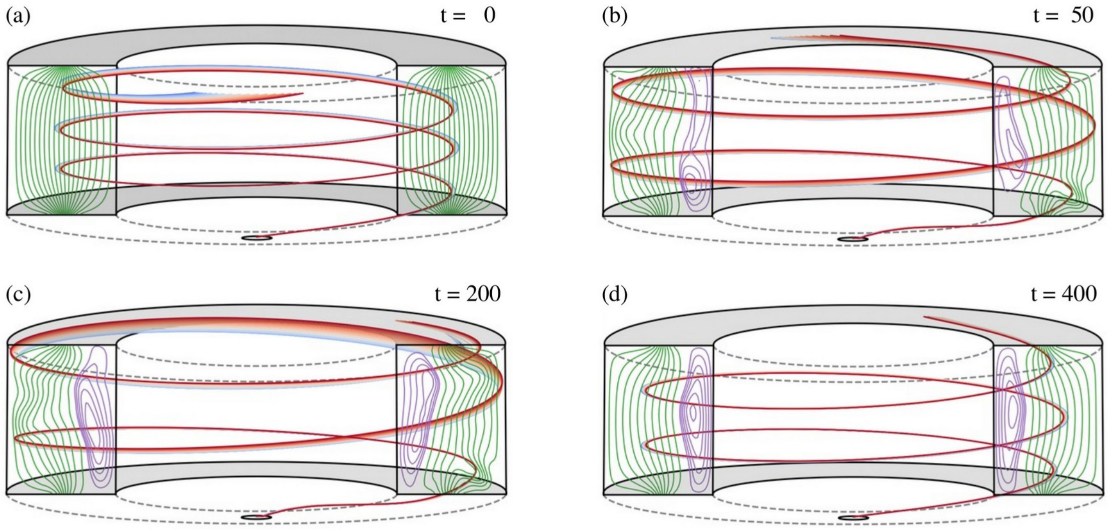


Fig. 2. Evolution of the current filament produced at the injector and the local (at a specific toroidal angle) poloidal flux contours for the $w$ = 3 case. (a) Initial condition, (b) configuration just after plasmoid formation, (c) sustainment phase and (d) quiescent state during decay phase.

The injection of magnetic helicity is provided by the rotation of the footpoints of the field lines intercepting the injector. The flow imposed at the plate is purely tangential and has the profile shown in Fig. 1(a), with $r_0$=0.04 and $r_{max}$=0.08. The maximum value of $U_0$ has the time dependence shown in Fig. 1(c). The results presented here were obtained for $U_{0,max}$ = 5$c_A$ , where $c_A$ ~ 5x$10^6$ m/s is the Alfvén velocity. For further details on the model equations and the numerical method, please see Ref. [5] and references therein.

As $U_0$ is increased, the current through the plate ($I_{inj}$) as well as the toroidal current ($I_{pl}$) start to grow rapidly, as can be observed in Fig. 1(b). At the beginning, $t$ < 10, $I_{pl}$ increases faster than $I_{inj}$ due to the geometric winding, but this tendency changes as soon as the filament becomes unstable. In the $w$ = 2 case, the instability causes a transient drop of toroidal current followed by an increase until the $I_{inj}$ level. In this case, there is neither current amplification nor evidence of closed flux surface formation. In contrast, the toroidal current in the $w$ = 3 case grows until a saturation level slightly greater than 2 is reached (significantly lower than the experimental current multiplication factor reported in Ref. [3]).

The behavior of the current filament originating at the injector plate and the poloidal flux contours at two toroidal locations is shown in Fig. 2 for the $w$ = 3 case. At $t$ = 0, the filament has the imposed winding; however, at later times, the PF induced by the generated currents distorts the filament reducing its winding to $w \lesssim 2.5$. The green contours show the magnetic flux that intercepts the electrodes, while the magenta contours indicate closed flux. These closed contours indicate the presence of closed flux surfaces only during the decay phase, where the fluctuations induced by the driving have faded, and an almost axisymmetric configuration is recovered. To the best of our knowledge, this is the first MHD simulation of a conventional aspect ratio tokamak formation by LHI. Current efforts are mainly directed toward including the capability of prescribing a flexible, time-varying vertical magnetization and exploring different injector geometries and parameters to optimize the plasma current startup in conditions relevant to TCABR upgrade.

## REFERENCES

[1] RAMAN, R. *et al*, Solenoid-free plasma startup in spherical tokamaks, *Plasma Phys. Control. Fusion* **56** 103001 (2014).

[2] BONGARD, M. W. *et al.*, Advancing local helicity injection for non-solenoidal tokamak startup, *Nucl. Fusion* **59** 076003 (2019).

[3] ONO, M. *et al.*, Steady-state tokamak discharge via dc helicity injection, *Phys. Rev. Lett.* **59** 2165 (1987).

[4] O'BRYAN, J. et al., Simulated flux-rope evolution during non-inductive startup in Pegasus, *Plasma Phys. Control. Fusion* **56** 064005 (2014).

[5] GARCIA-MARTINEZ, P. L. et. al., Spheromak formation and sustainment by tangential boundary flows, *Phys. Plasmas* **17** 050701 (2010).

[6] BOUZAN, A. S. *et al.*, Structural analysis of the in-Vessel RMP IM-Coils of the TCABR tokamak, *IEEE Transactions on Plasma Science* **52** n. 9 p. 3847 (2024).