3D Numerical Simulations of the Dynamics of a Flux Core Spheromak

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Motivation

- The PROTO-SPHERA proposes the formation and sustainment of an ST-like plasma by dc helicity injection.
- Helicity injection curent drive requires relaxation.
- A certain amount of “open” flux through the electrodes is needed for helicity injection, Flux Core Spheromak (FCS).
- STs have higher elongation than spheromaks (κ>2), the tilt mode could appear.
- The relaxation of a FCS with open flux and high elongation has not been studied.

This work

- Study the relaxation of a FCS with open flux and high elongation.
- Solve the 3D resistive MHD equations with the VAC code.
- Constant density (zero β), uniform cartesian grid.
- Code tested by recovering known results.

$\hat{n}$

Geometry, boundary and initial conditions

Cylindrical flux conserver with electrodes (Fig.1)

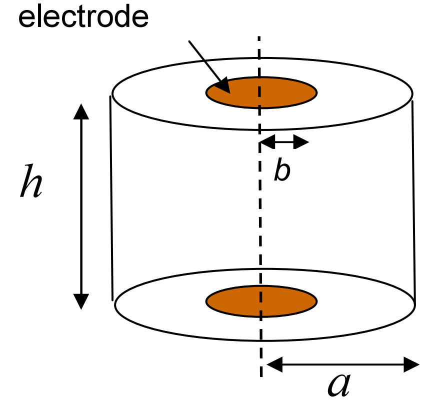


Fig. 1

Boundary conditions

flux conserver: $\mathbf{B}\cdot\hat{n} = \mathbf{J}\times\hat{n} = 0$

electrodes: B_z constant $\rightarrow \psi_e$: "open" flux

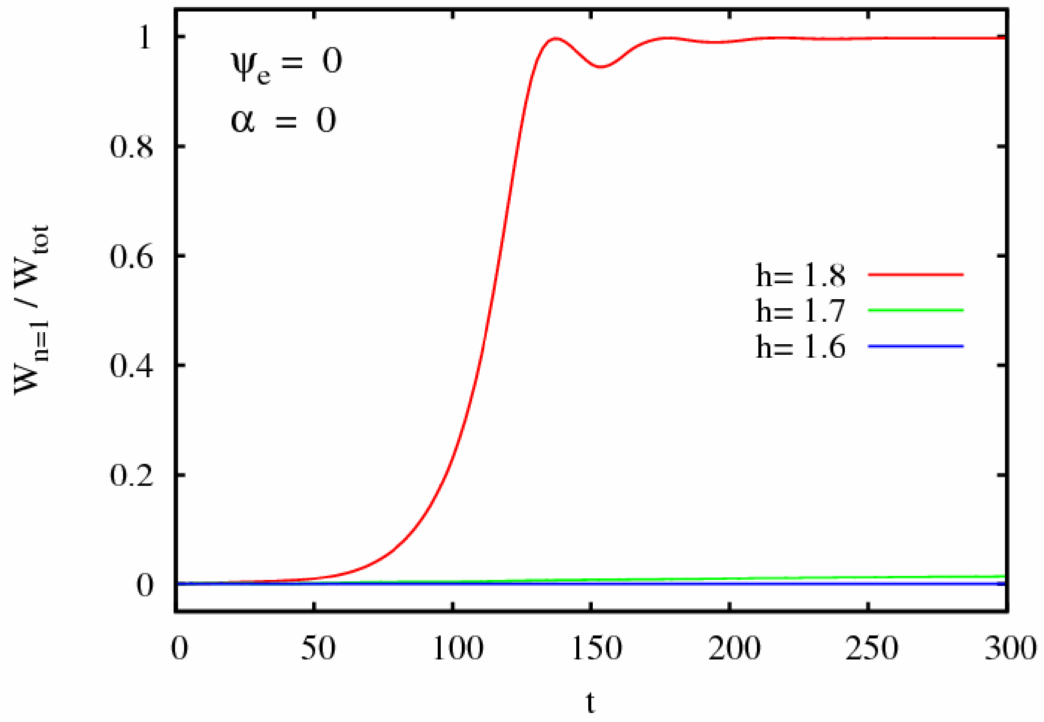
Initial condition: force-free FCS obtained from:

$$\nabla\times\mathbf{B} = \lambda(\psi)\mathbf{B} \qquad \lambda(\psi) = \bar{\lambda}\left[1 + \alpha(2\psi - 1)\right]$$

where: λ =J.B/B^2

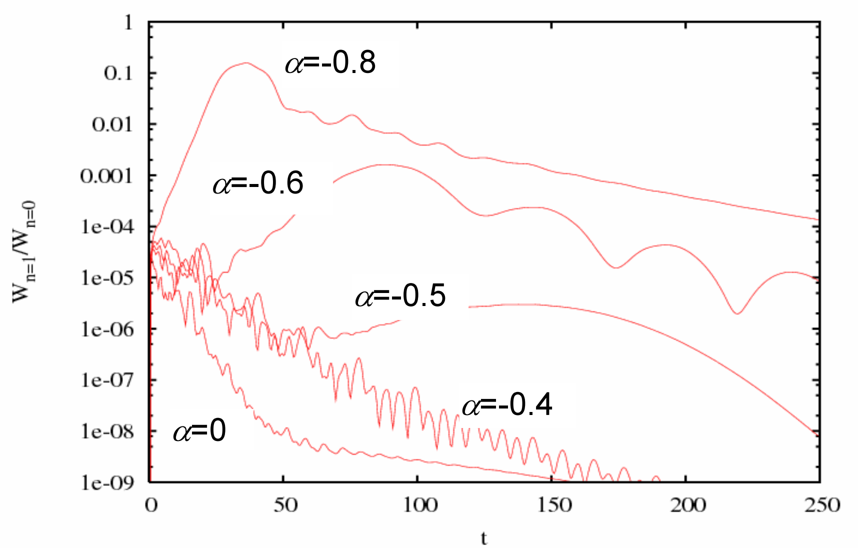
VAC Code

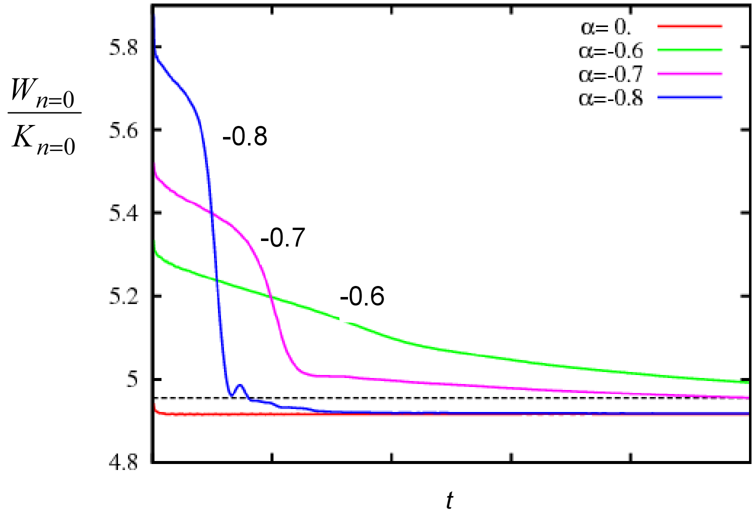
- **Solves 3D resistive MHD equations in cartesian grid: 100×100 × 75.**
- **Uniform resistivity, $\tau_A = a/v_A$, $\tau_r = \mu_0/(\eta\lambda^2)$, $S = \tau_r/\tau_A \sim 400$.**
- **Tested by recovering known results, i.e. tilting threshold.**



No open flux, low elongation

- The only relevant parameter is the slope of the λ profile (α).
- Initial condition: regular spheromak (κ=1, ψ_e=0).

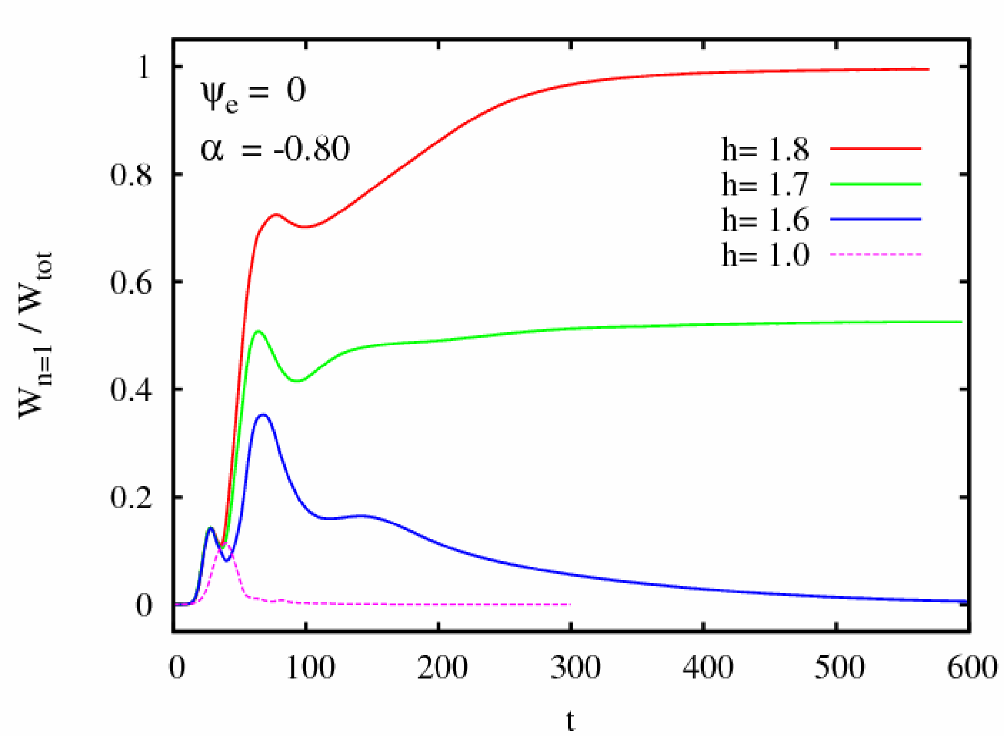




- The energy in the *n*=1 mode increases with α.
- The relaxation rate increases with α.
- Incomplete relaxation unless | α | is large enough.

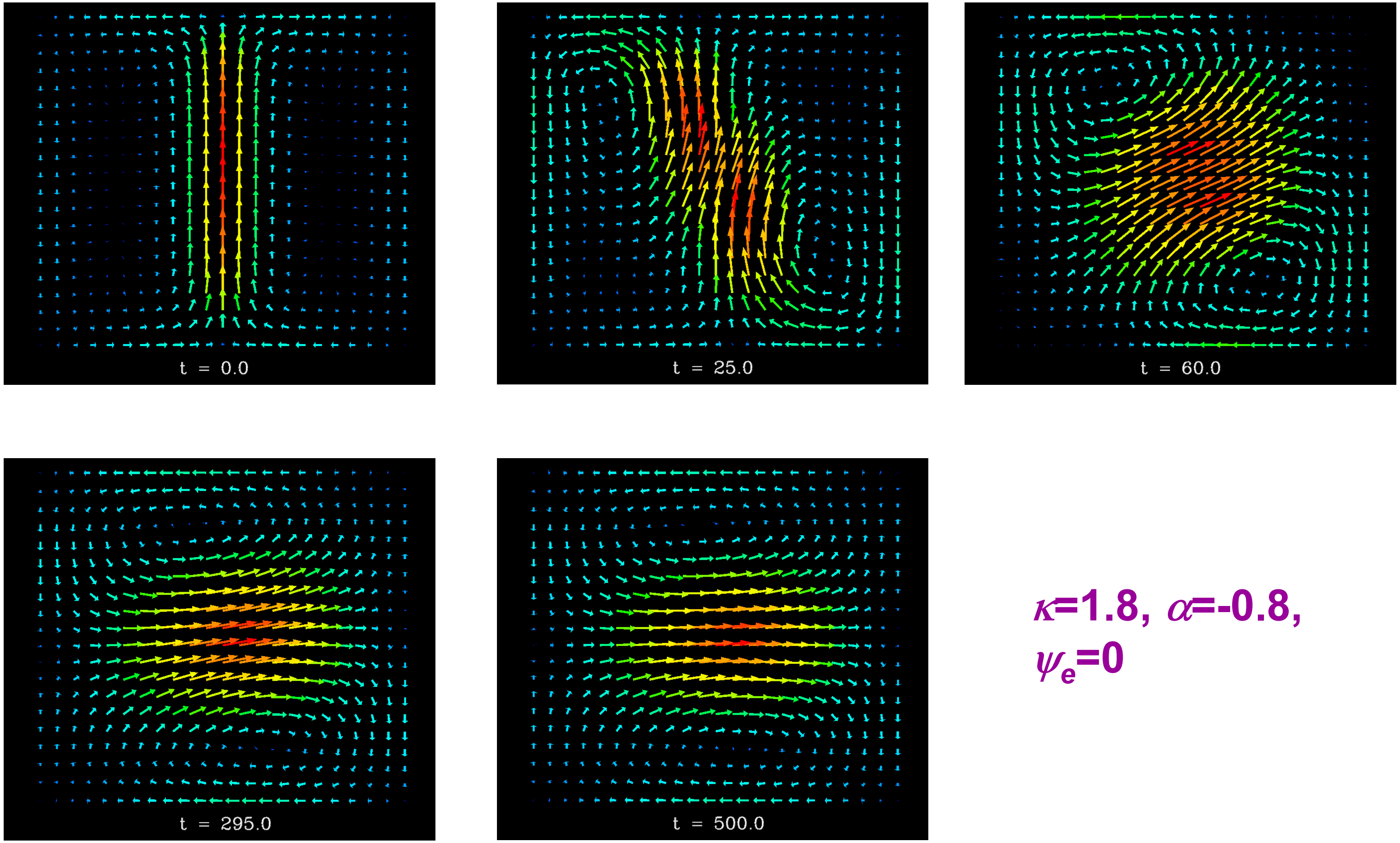
No open flux, high elongation

- Kink and tilt modes appear.



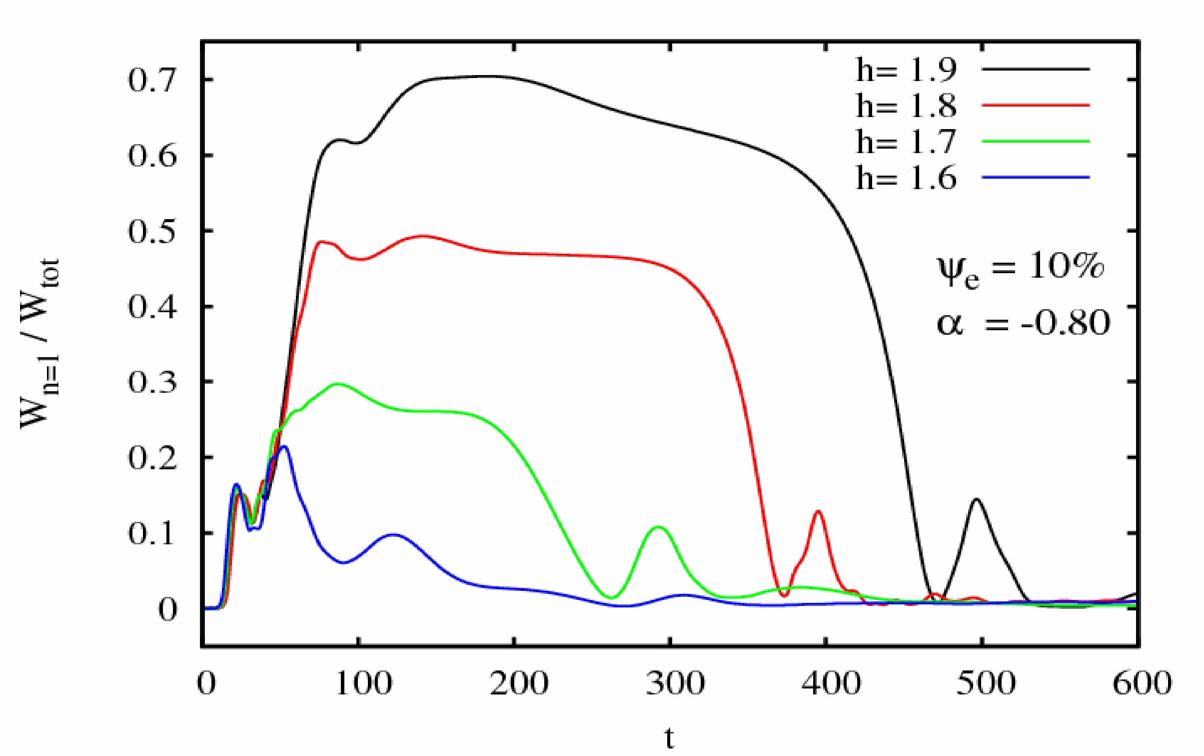
- First peak due to kink, second peak due to tilt.
- When κ>1.6 the tilt survives.

Kink and Tilt



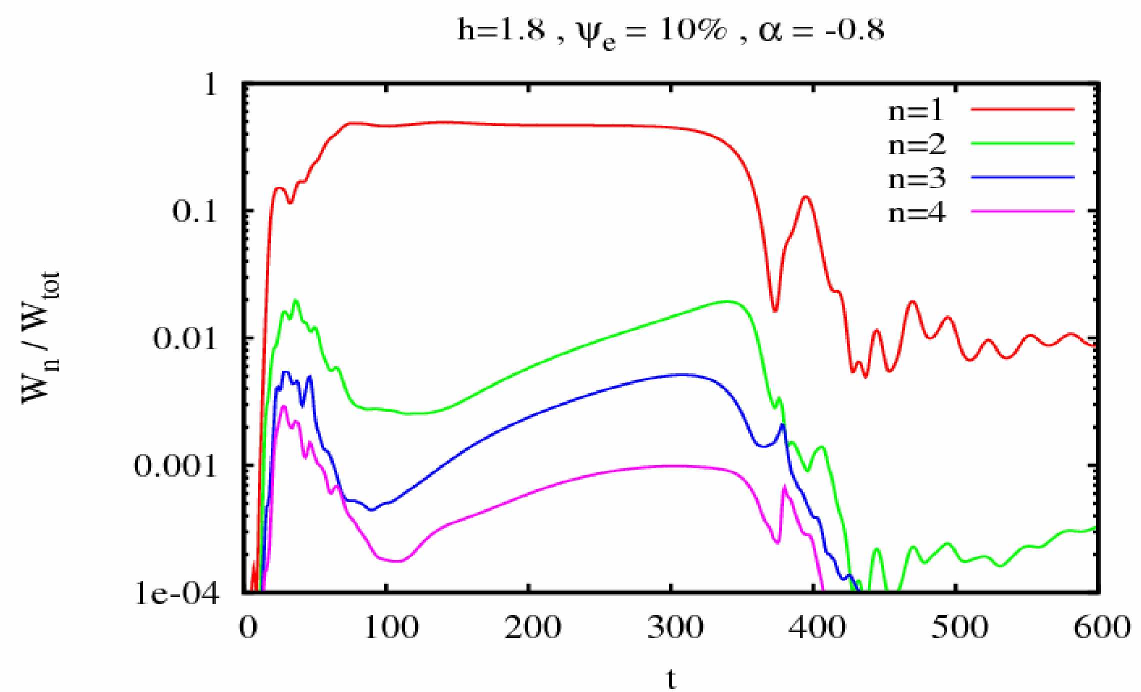
κ=1.8, α=-0.8, ψ_e=0

Open flux, high elongation



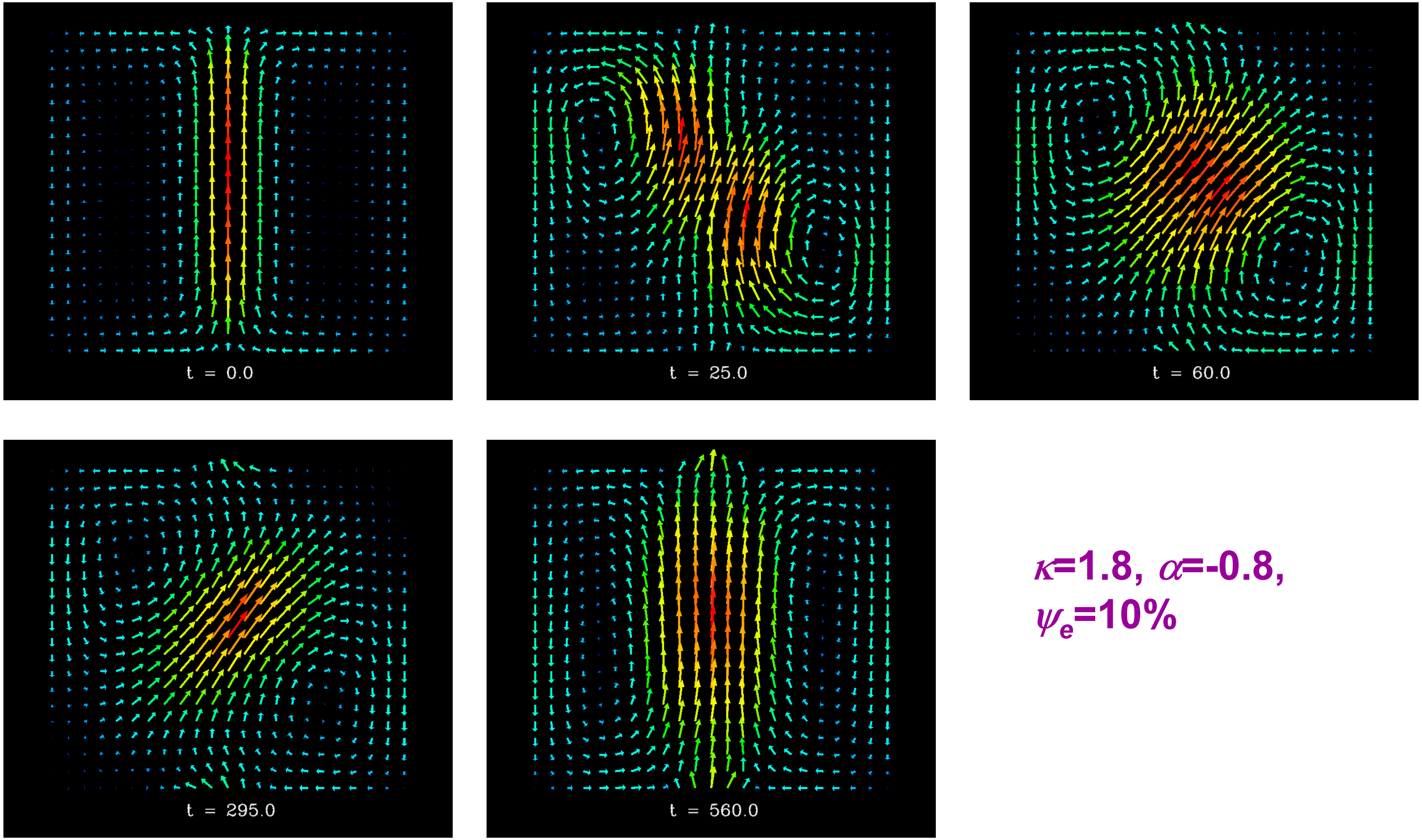
- **Kink and tilt modes appear.**
- **Tilt saturates at lower amplitude.**
- **Tilt disappears!.**

Mode activity



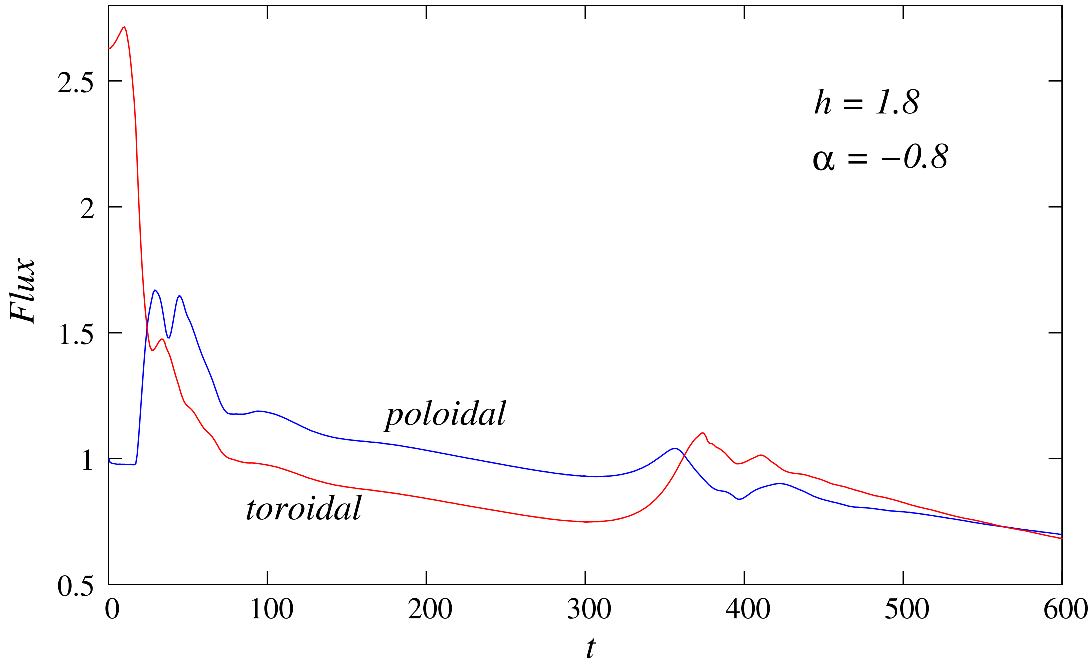
- Initially all the modes grow fast.
- During the final increase in the *n*=1 mode amplitude the others decrease.
- When the energy of the *n*=1 mode remains constant the others grow.
- When the *n*=1 energy decreases all the others also decrease.

Kink and Tilt



κ=1.8, α=-0.8,
ψ_e=10%

Poloidal flux amplification



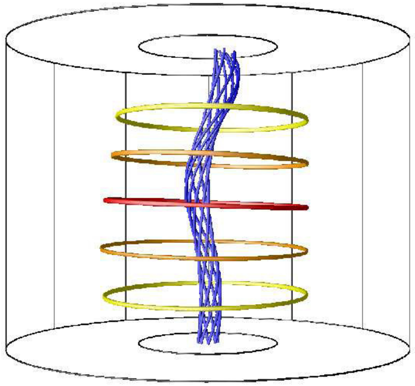
- During the kink the poloidal flux increases fast and the toroidal flux decreases.
- During the tilt, when the *n*=1 mode remains stable, both fluxes decrease.
- When the tilt disappears there are small increases in both fluxes.

Spheromak formation from an unstable screw pinch

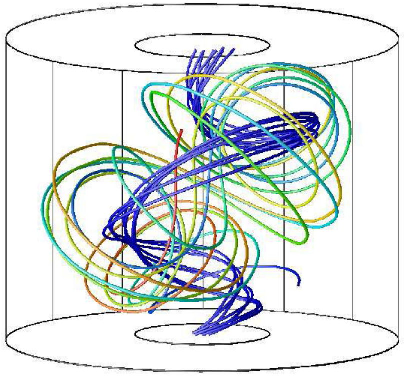
- Same geometry but periodic boundary conditions at electrodes.
- Initial condition: force-free screw pinch with non uniform λ profile

$$\nabla \times \mathbf{B}(r) = \lambda(r)\mathbf{B}$$

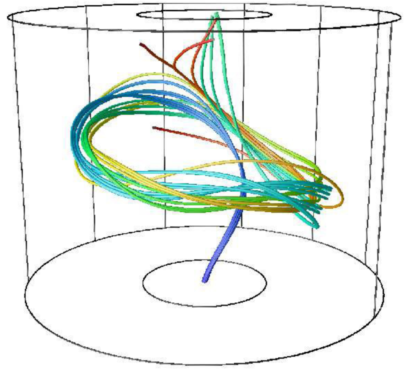
Formation sequence



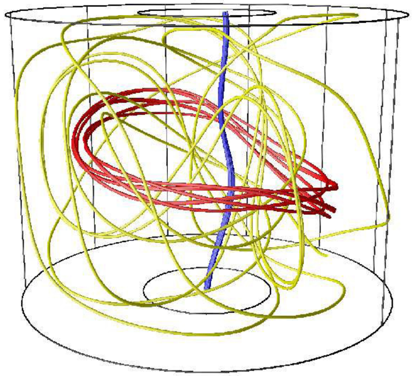
t=30. Kink



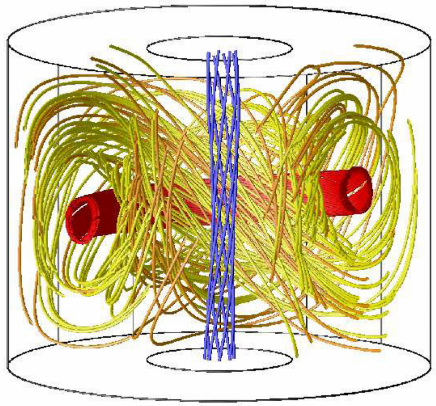
t=45. Saturation



t=69. Reconnection

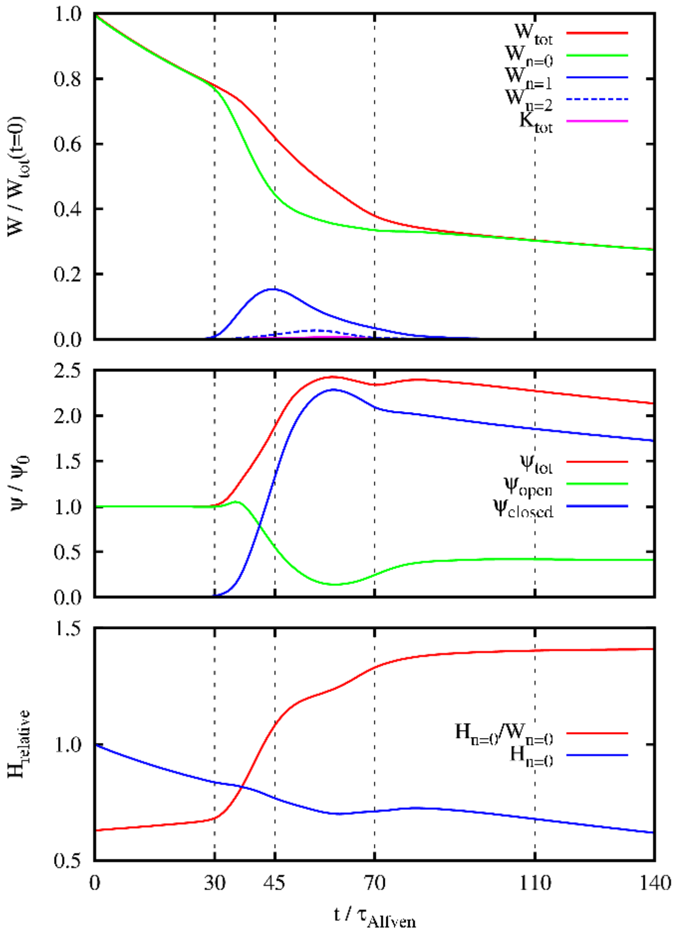


t=71. Reconnection

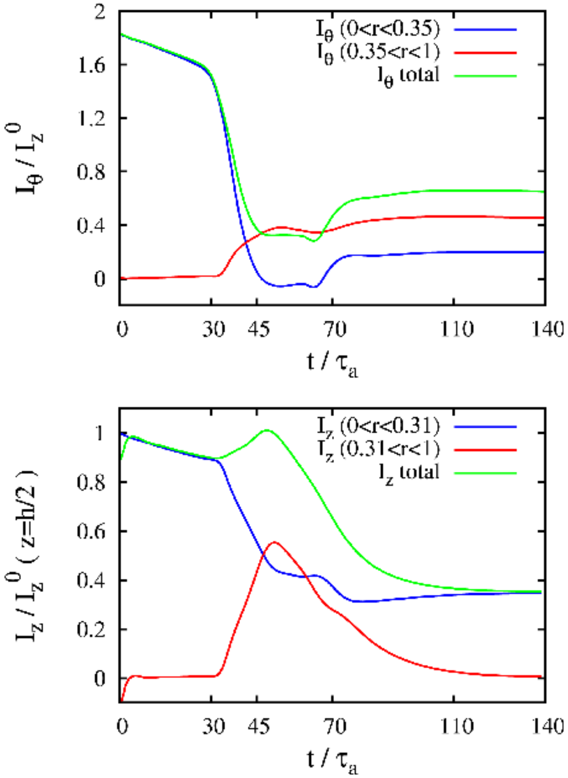


t=110. Closed flux surfaces

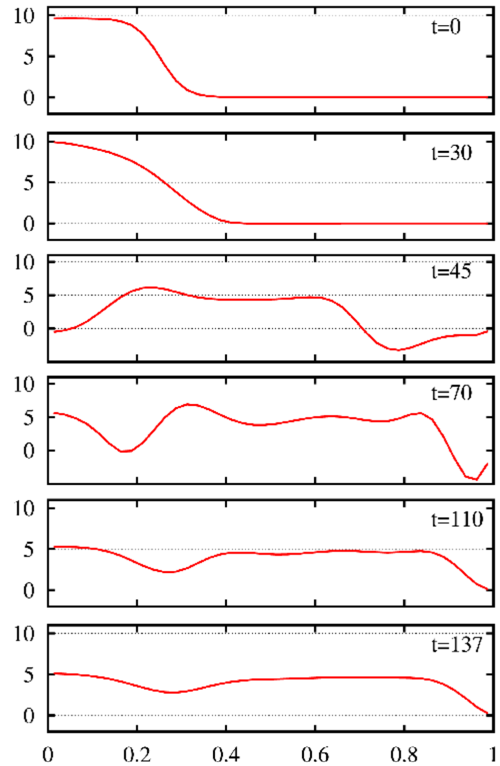
Evolution of different quantities during formation



Magnetic energy, poloidal flux and relative helicity



Toroidal and poloidal currents



λ profile