On the physics of improved confinement during pulsed poloidal current drive in MST reversed-field pinch

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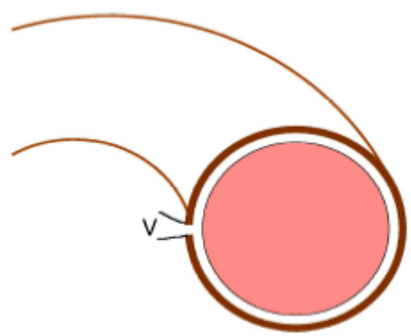
Abstract

Reduction of core-resonant magnetic fluctuations and improved confinement in the Madison Symmetric Torus reversed-field pinch have been routinely achieved by applying the surface poloidal electric field. The created inductive poloidal electric field drives current in plasma which leads to the improved confinement. 3-D resistive MHD modeling has been used by several groups to study the effect. Due to limitations in computing power the 3-D models are studied with smaller Lundquist numbers and usually the plasma density is not evolved. With these limitations and the ambiguity of the results the exact mechanism of fluctuation reduction is not evident from such modeling. We develop a relatively simple 1-D model in cylindrical geometry which assumes poloidal and axial symmetry during the drive. We use resistive MHD model with realistic plasma parameters and assume that there is a vacuum gap between plasma boundary and conducting wall of the vessel. Evolution of plasma density is taken into account and plasma boundary moves self-consistently with momentum equation. During the drive there is a repulsive force between the image currents in plasma and currents driven in the conducting shell by the applied voltage. The force pushes plasma inwards and drags with it the equilibrium magnetic field embedded in the plasma. This leads to compression (pinching) of magnetic field, plasma current and density toward the core region. We start from an initial unstable equilibrium and examine stability at intermidiate moments of time during the drive. For this we calculate the growth rates of unstable eigenmodes in the plasma. Our results show that the modifications to the plasma current profile during the drive are stabilizing. The initial stabilization is due to the direct modification of the current profile near the edge and it is enhances later in time due to the flattening of lambda profile in the core region which is due to the pinching effect.

Outline

- Reduction of core-resonant m=1 magnetic fluctuations and improved confinement in the MST RFP have been routinely achieved by applying inductive poloidal electric field at the plasma surface



- 3-D modeling is limited to low S. Plasma density is not evolved.
- We study self-consistent 1-D model with realistic S. Evolve plasma density.
- Time evolution of growth rates of initially unstable core-resonant tearing modes is examined.
- Stabilizing changes to the current profile are discussed.

Model

- Cylindrical vessel with radius a. Plasma radius $r_p<a$. Vacuum gap $r_p <r<a$.
- Axially and azimuthally symmetric electric field E_θ is specified at r=a.
- At t=0 plasma is in a force free equilibrium. At t>0 plasma motion is described by the resistive MHD equations in the limit p=0.

$$\frac{\partial \rho}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho v_r\right) ,$$

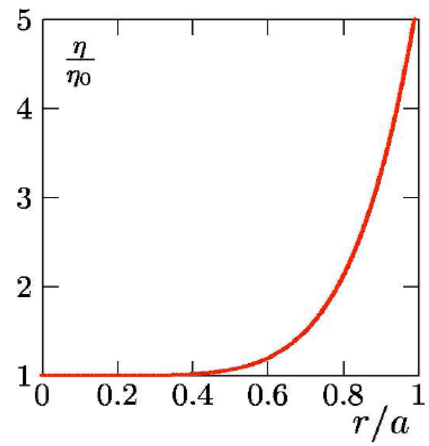
$$\frac{\partial v_r}{\partial t} = -v_r\frac{\partial v_r}{\partial r} - \frac{1}{\rho}\left[B_z\frac{\partial B_z}{\partial r} + \frac{1}{r}\frac{\partial}{\partial r}\left(rB_\theta\right)B_\theta\right] ,$$

$$\frac{\partial B_\theta}{\partial t} = -\frac{\partial}{\partial r}\left(v_r B_\theta\right) + \frac{1}{S}\left[\left(\frac{\eta}{r} + \frac{\partial \eta}{\partial r}\right)\frac{\partial B_\theta}{\partial r} + \eta\frac{\partial^2 B_\theta}{\partial r^2} + \frac{1}{r}\left(\frac{\partial \eta}{\partial r} - \frac{\eta}{r}\right)B_\theta\right] ,$$

$$\frac{\partial B_z}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}\left(rv_r B_z\right) + \frac{1}{S}\left[\left(\frac{\eta}{r} + \frac{\partial \eta}{\partial r}\right)\frac{\partial B_z}{\partial r} + \eta\frac{\partial^2 B_z}{\partial r^2}\right]$$

- Plasma boundary r_p moves self-consistently with momentum equation.
- Electromagnetic fields in the vacuum gap are evolved according to Maxwell's equations.

- Total time of the electric field drive t_0=7 msec
- Plasma resistivity profile



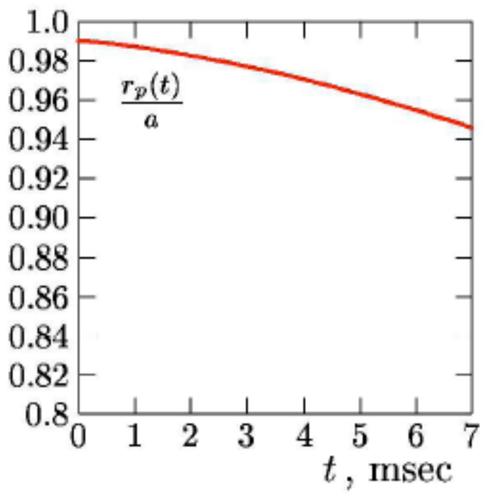
- Resistive scaling: the result does not change with transformation $B = \tilde{B},\ E = \tilde{E}/\alpha,\ v = \tilde{v}/\alpha,\ t = \tilde{t}\alpha,\ S = \tilde{S}\alpha,\ J = \tilde{J},\ \rho = \tilde{\rho}$ this scaling is confirmed numerically
- Parameters: B_0=1.5kG, n_0=10^{13}cm^{-3}, S=10^6
- Start with r_p/a=0.99 at t=0
- Initial unstable equilibrium

$$\lambda(r) = 2\Theta_0(1 - (r/r_p)^{\alpha_0}) \text{ with } \alpha_0 = 2.75 \text{ and } \Theta_0 = 1.75$$

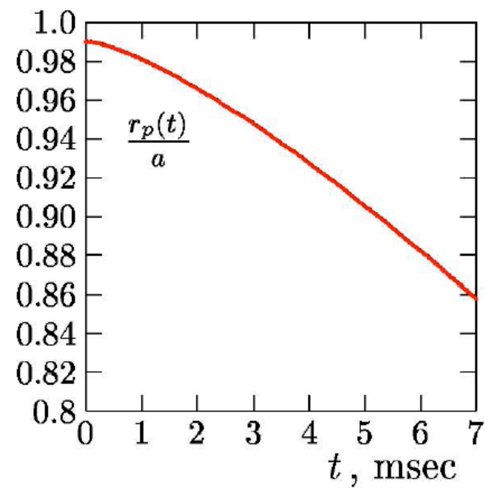
- There is a repulsive force between the image currents in plasma and currents driven in the conducting shell
- The image current is opposite to the one in the shell and it is trying to shield the magnetic field created by currents in the shell
- The resultant force pushes plasma inwards and drags with it the equilibrium magnetic field embedded in the plasma
- This leads to compression (pinching) of magnetic field, plasma current and density toward the core region

- Radial location of plasma boundary vs. time

E=0.3V/m



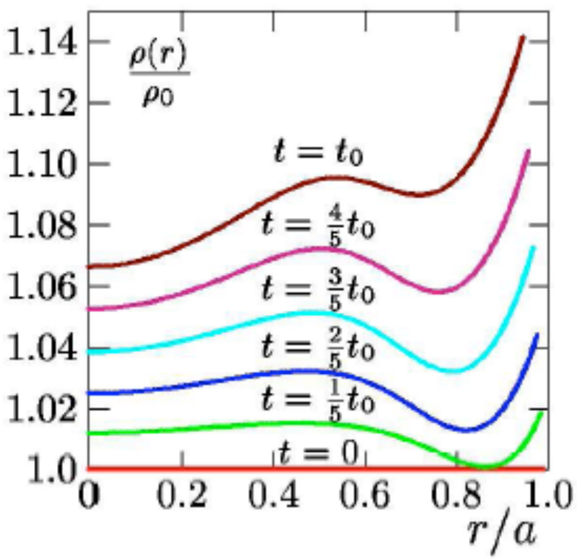
E=0.6V/m



- Plasma boundary moves inward

- Plasma density profiles at different moments of time

E=0.3V/m



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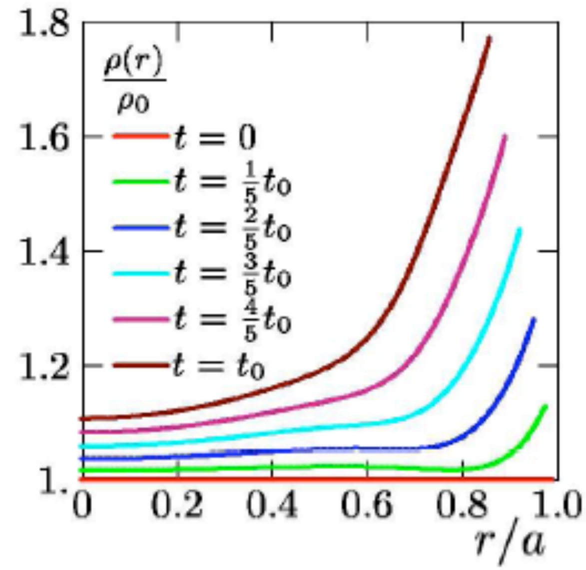
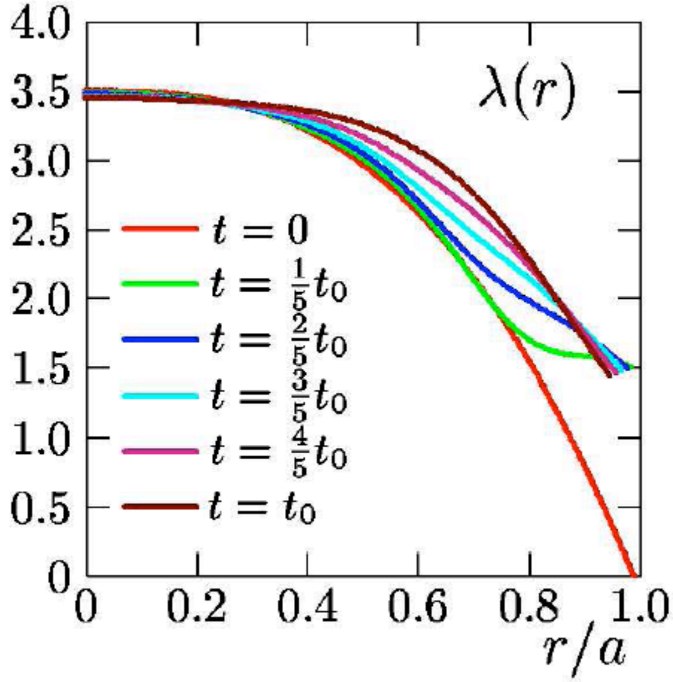


- Density increases noticeably
- Density increase and plasma displacement are observed in experiment

$\lambda = (J \cdot B)/B^2$ profiles

E=0.3V/m



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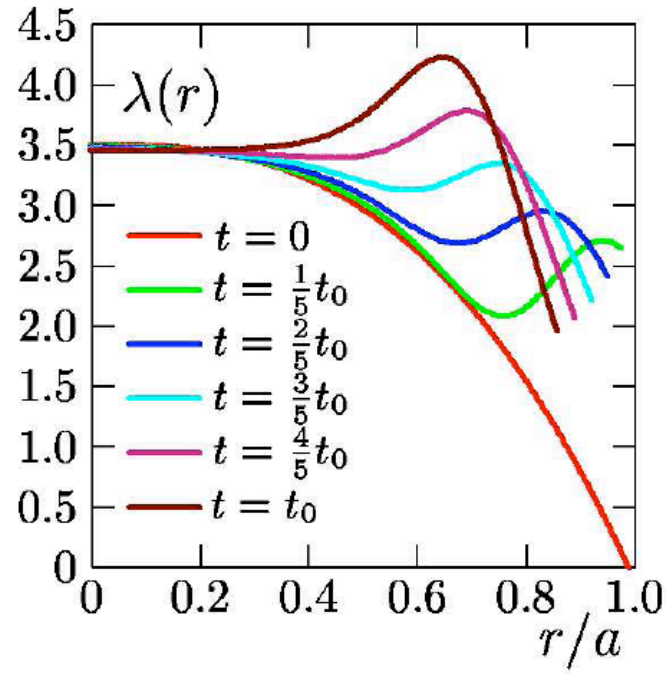
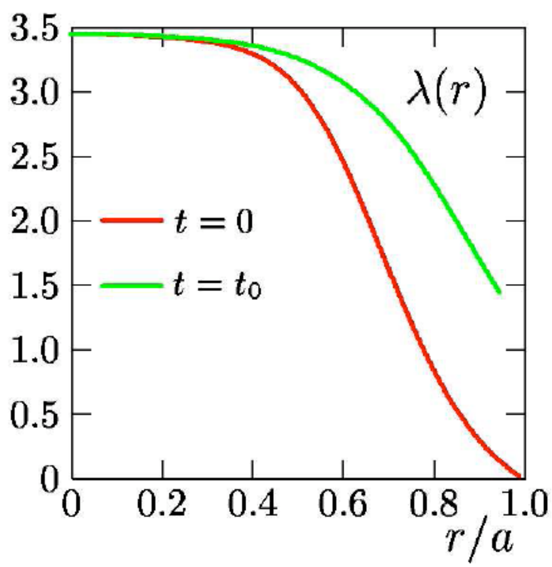


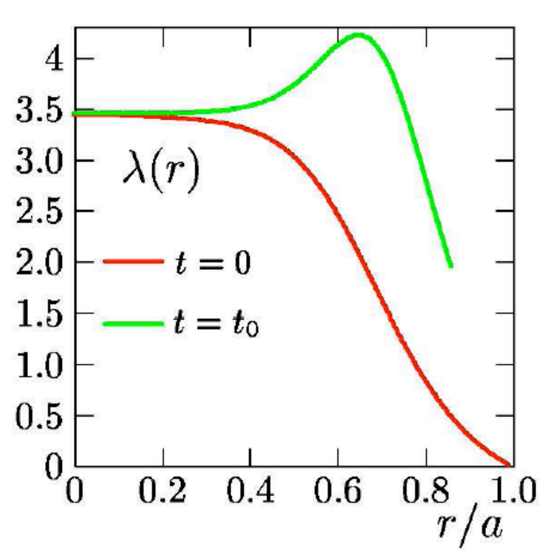
- Strong and fast modification of the edge current
- In central part current profile changes continuously and the changes become noticeable later in time.
- λ profile flattens in the core
- All profiles slowly decay on resistive time scale
- In the limit of high S, λ profiles stay approximately constant at r=0, such that there is simultaneous increase of current and magnetic field there

- Comparison of λ profiles at t=0 and t=7msec with the resistive decay accounted for in the first

E=0.3V/m



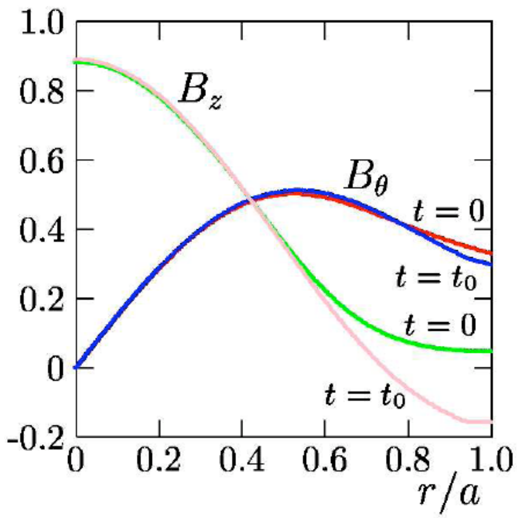
E=0.6V/m



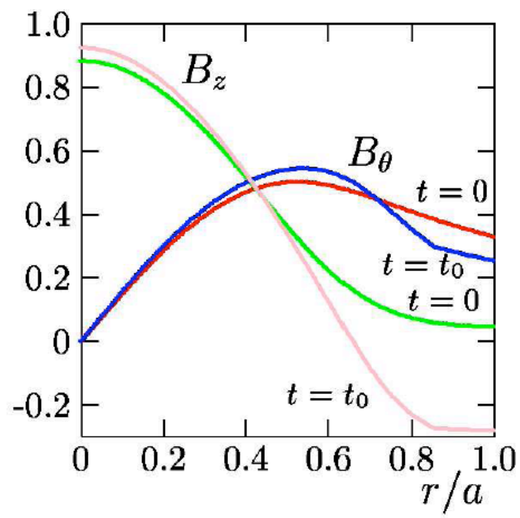
- Profiles flatten in the core

- Profiles of magnetic field components at t=0 and t=7msec

E=0.3V/m



E=0.6V/m

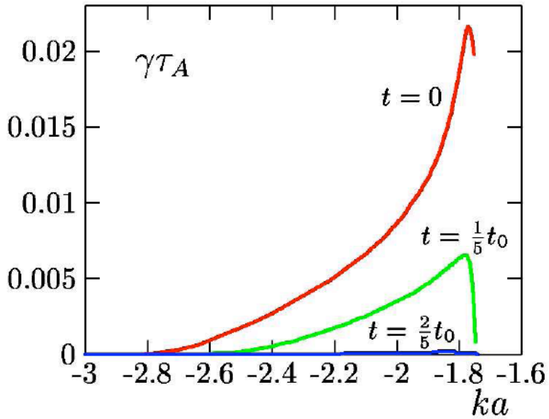


- Magnetic field (and current) increased in the core region
- Field reversal magnified at the edge

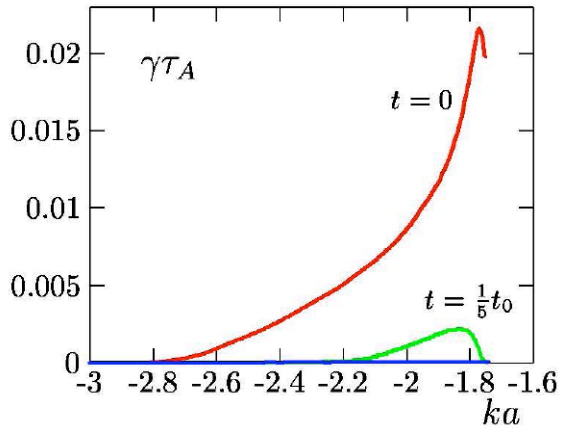
- Stability of the found λ profiles is examined
- Eigenvalue problem for resistive plasma with vacuum gap is solved
- Analytic solution in vacuum layer, combinations of modified Bessel functions, is matched with the numerical solution in the plasma
- We consider m=1 modes and scan k continuously

- Growth rates are calculated for $S=10^4$

E=0.3V/m



E=0.6V/m



- Modes are stabilized due to the modification of current profile due to the applied electric field
- The closer initial equilibrium to marginal stability the faster stabilization

- During the drive the initial stabilization is due to the modification of the current profile near the edge

- This stabilization enhances later in time due to the flattening of λ profile in the core region