A New Hybrid Inductive Scenario for a Nearly Steady-State Reversed Field Pinch

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ABSTRACT
Steady-state current sustainment is challenging for the Reversed Field Pinch (RFP). The current magnitude is large, while the pressure-driven (bootstrap) current is small, even at the RFP’s high β > 20%. In the TITAN (PPCD) system study [1], the current was designed steady-state using Oscillating Field Current Drive (OCFD), i.e., steady magnetic helicity injection using phased AC induction. Experiments and theory for OCFD are so far promising, but OCFD’s reliance on magnetic relaxation could turn out incompatible with energy confinement requirements. Meanwhile, inductive current profile control has demonstrated tokamak-like current drive in the RFP. Such control is inherently not steady-state. A hybrid scheme is proposed using OCFD to ramp the current, followed by a pseudopulse during which inductive profile control maintains high confinement. The current is not constant but never goes to zero (pseudopulse waveform). The current drive (and profile control) is simple and efficient, and the pseudopulse phases could be separated by only a few seconds. Optimization of the hybrid cycle and other issues will be discussed.

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Poster Synopsis

A nearly steady-state inductive current drive scenario is proposed to address:
- A possible incompatibility of dynamo sustainment with simultaneous high confinement
- Mitigation of engineering challenges for pulsed scenarios

This hybrid scenario combines:
- A dynamo-current free ramp-down period to attain fusion burn
- Oscillating Field Current Drive to efficiently rebuild the current (short non-burn phase)

First analysis of the hybrid scenario finds:
- An optimum cycle period of ~10s of seconds
- 60-70% of steady-state fusion gain Qsteady-state is plausible
- Only a 10% increase in \( I_s \) required to recover steady-state \( P_{th} \)

**TITAN System Study (1990)**
Explored advantages and challenges of a compact, high mass-power-density core.

**Novel features:**
- Single-piece maintenance
- 95% radiating boundary
- Toroidal field divertor
- Lithium blanket also the toroidal field coil
- Steady-state current using OCFD

**Parameters:**
- \( a = 0.6 \text{ m} \)
- \( \beta_s = 23\% \)
- \( R = 3.9 \text{ m} \)
- \( T_e = 0.15 \text{ s} \)
- \( I = 18 \text{ MA} \)
- COE = 4c / kWh (90)

**OFCD Parameters:**
- \( P_{fus} = 2.3 \text{ GW} \)
- \( P_{max} = 29 \text{ MW} \)
- \( Q = 80 \)
- \( P_{th} = 0.97 \text{ GW} \)
- 18 MW/nm² neutron load
- 4.6 MW/m² wall load (mostly radiation)

**Self-Similar Ramp-Down**
Space-time separable magnetic diffusion:
- stationary equilibrium, e.g., fixed \( q(r) \)
- dynamo-free Ohm’s law

**Example:**
- \( V \times B = 0 \)
- \( E = \nabla \times (V \times B) \rightarrow ... \)

**Time dependence:**
- simple exponential for constant \( q(r) \) (e.g., burning plasma)

**Example:**
- \( b_t \) vs. \( t \)

**Ramp-Down End Transient**
- Thermal transient at end of the current ramp-down must be manageable:
- 20X decrease in stored thermal energy
- Fusion power drops to zero
- Increase in Ohmic heating power partially compensates
- Burn and/or confinement control via current profile control could limit the quench rate of the thermal energy

**Resistivity Profile:**
- \( \eta = \rho / \rho_{\text{max}} \) for efficient OCFD

**Avoiding Magnetizing Flux Accumulation**
OCFD uses purely AC inductive loop voltages

**Self-similar ramp-down calls for \( V_s(t) \approx 0 \)**

**Optimal loop voltages likely determined by MHD heating stability and transport controlling the resistivity profile \( \rho(t) \)**

**Evaluating Cycle-Averages**

**Fusion power scaling for the RFP**

\[ P_{\text{fusion}} = \frac{n^2}{a^3} R, \quad \rho \approx \frac{\beta_s^2}{2} R, \quad \rho \approx \frac{\beta_s^2}{2} \]

**for Ohmic heating**

**Standard RFP**

**Parameter dependence:**
- \( P_{\text{th}} \propto \frac{1}{a^2} \)
- \( \frac{T}{T_{\text{IT}}}, \quad T_{\text{IT}} \geq 10 \text{ keV} \)
- \( T_{\text{th}} = \frac{T_{\text{IT}}}{2} \approx 5 \text{ keV} \)
- \( n = 4 \text{ keV} \)
- \( P_{\text{fuel}} = 5 \text{ keV} \)
- \( r = 0.6 \text{ m} \)

**Hybrid Inductive Scenario**
A steady, repetitive cycle that combines:
- a dynamo-free period, based on self-similar current ramp-down (PPCD-like physics)
- current rebuild using OCFD, but without a requirement for fusion-grade confinement.

**Self-Similar Ramp-Down**
Time dependence:
- \( \chi = \nabla \times (V \times B) \rightarrow ... \)

**Hybrid Ramp-Down**

**OFCD**

**Favorable scaling of the AC modulation amplitude expected.**

See adjacent posters on OFCD experiments in MST.