A Fully Non-Inductive Current Ramp-Up and Relevant Issues in CS-Less Tokamak Reactor

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A fully non-inductive current rampup of low aspect ratio JAERI tokamak "VECTOR" was computationally studied via axisymmetric MHD simulation:

- Internal Transport Barrier (ITB)-generated BootStrap (BS) current is always self-consistent with magnetic shear profile.
- Essential physics of direct interaction between plasma and coils is contained within the model, such as discharge / recharge of coil currents during the non-inductive rampup.

- Plenty of non-inductive currents can afford both to rampup plasma current and to recharge diverter-coil currents for plasma shaping, simultaneously.
- Despite the intention of monotonic rampup, cooperative link between ITB-generated, high BS currents and BS current-modulated magnetic shear exhibited an oscillatory current-rampup, shortening ramp time.
Reactor Concept of Low Aspect Ratio Tokamak: VECTOR

- CS-less VECTOR offers new challenge of full non-inductive drive scenarios with very slow rampup (~ 0.01 MA/sec!). (cf. ~ 1.0 MA/sec at present)
- Feasible scenario for meeting all requirements, ex. plasma positioning and shaping?
- Stable hybrid current build-up with high BS \( I_{BS} > 50\% \) and non-inductive current \( I_{ni} > 50\% I_p \)?

\[
\begin{align*}
R_p / a_p &= 3.2 / 1.4 \text{ m} \\
I_p &= 14 \text{ MA}, \quad \kappa = 2.4 \\
\beta_N / \beta_T &= 6 / 17 \% \\
\text{Fusion Power} : P_F &= 2.5 \text{ GW} \\
\text{Neutron Wall Load} : \\
P_n &= 5 \text{ MW/m}^2 \\
B_{MAX} / B_0 &= 19.1 / 5.1 \text{ T}
\end{align*}
\]

Modeling of ITB-generated, high BS current self-consistent with magnetic shear profile under direct coupling with external control coils.
Fundamental Requirements for Current Rampup

CS-less tokamak: VECTOR

- from non-inductive techniques

1. timescale w/o current profile distortion

\[
\tau > \tau_0 = \frac{a^2 \mu_0}{\eta(0)} \sim 100 \text{ sec for } T_e = 3-5 \text{ keV}
\]

\[
(\tau_0 >> ) \tau > \tau_a = \frac{a^2 \mu_0}{\eta(a)} \text{ for inductive}
\]

2. recharging of coil currents during rampup

ex. shaping coils (D1, D2)

- from confinement, MHD Physics

1. density limit

\[
n < n_{GW} = \frac{I_p (\text{MA})}{\pi a^2}
\]

2. energy confinement

\[
HH = \frac{\tau_E}{\tau_{E,y^2}} \leq 1.3 \ (?)
\]

3. power limit

\[
P_{CD} = \frac{n_e R I_p}{\eta_{CD}} \leq 100 \text{ MW}
\]

Essential physics is contained within TSC.
**ITB & ETB Modelling on TSC**

- **Numerical Model of TSC**
  - Momentum eq. of single fluid $m$:
    \[
    \frac{\partial m}{\partial t} + F(v)(m) = j \times B - \nabla p
    \]
  - Faraday's law for $g$ & $\Psi$ time-evolution
    \[
    \frac{\partial B}{\partial t} = -\nabla \times E \quad ; \quad B = \nabla \phi \times \nabla \Psi + g \nabla \phi
    \]
  - Ohm's law: $\dot{j}_{oh} = \dot{j}_{total} - \dot{j}_{bs}$
    \[
    E + v \times B = \eta \dot{j}_{oh}
    \]
- **ITB & ETB**
  - BS Current
    \[
    \langle \dot{j}_{bs} \cdot B \rangle = L_{31} \left[ A_i^e + Z_i^{-1} T_i / T_e \left( A_i^i + \alpha_i A_i^e \right) \right]
    \]
    \[+ L_{32} A_2^e\]
  - Pressure profiles prescribed
  - Radii of ITB-foot & $\rho_{S0}$ monitored, adjusted during TSC simulations.
  - If $q_{S0}$ on $q_0$ (PS), then all ETB. If $q_{S0}$ on $q_a$ (NS), then all ITB.
Position & Shape Controls during Hybrid Current Rampup

Non-Inductive current ramp of 14MA within 1000 sec with $I_{bs} \sim I_{ni} > 50 \%$ of $I_p$

- Stable transition to diverter configuration, taking-off from outer limiter position
- Low $T_e$ plasma to shorten rampup-time & reduce heat load on limiter
- Recharge of coil current to suppress plasma volume against current rampup
Fully Non-Inductive Current Rampup w/o CS

- Slow ramp rate to avoid CH formation: \( \approx 0.01 \text{ MA/sec}, T_e \approx 2 \text{ keV} \)
- Limiter to diverter transition, \( t = 50 \text{ sec} \)
- High \( \beta_p (< 3.5) \), lower density than \( n_{\text{GW}} \) providing high BS fraction (\( \approx 95 \%) \) with \( \approx 5 \% \) inductive \( I_p \)
- Plenty of non-inductive current accomplished an over-driving state at \( t > 130 \text{ sec} \).

D1, 2 coil currents recharged against rampup with non-inductive current assistance, avoiding plasma volume expansion

Oscillation due to cooperative link between BS current and magnetic shear profile
Negative $V_{\text{loop}}$ & "Return Current" due to Over-Current Driving

- Strong non-inductive current ramp provides "Return Current" :\[ j_{\text{rc}} = j_p - j_{\text{bs}} - j_{\text{ni}}. \]
- $j_{\text{rc}}$ in core region survives longer, leading to CH formation.
- Strong $V_{\text{loop}}(a) < 0$ enables $I_{D1,2}$ to recharge against current rampup.
Cooperative Link between BS Current and Magnetic Shear

When $\frac{I_{bs}}{I_{ni}} > 0.6$

(1) Magnetic shear reversal $\rho_{s0}$ starts to drift inwards, and disappears at magnetic axis.

(2) Then, $\rho_{s0}$ jumps outwards, at $\rho \sim 0.8$.

(3) These inwards drifting and outwards jumping repeats, until $\frac{I_{bs}}{I_{ni}} < 0.6$

During the oscillatory rampup, $q_{0}$ becomes much lower, leading to a current penetration to core region.
Inward Drift of ITB-generated BS Current

- Strong locality of BS current profile modulates magnetic shear profile, causing inward drift of ITB.
- As far as BS current is enough, inward drift is repeatable, leading to flatten magnetic shear profile.

ITB drift effects a penetration of plasma current into core region, avoiding Current Hole formation even faster ramp time $\tau^*$:

$$\tau_a << \tau^* << \tau_0$$
Summary

A fully non-inductive drive scenarios on JAERI CS-less tokamak "VECTOR" was computationally studied via axisymmetric MHD simulation using TSC.

- Plenty of non-inductive currents can afford both to rampup plasma current and to recharge diverter-coil currents for plasma shaping, meeting requirements from non-inductive techniques and confinement, MHD physics.

- Cooperative link between high BS currents and BS current-modulated magnetic shear exhibited an oscillatory current-rampup, shortening ramp time.

Future Studies:

- ITB-relevant transport model instead of our prescribed profile
- Validation through JT-60U CS-less rampup experiment
- Day-long control of α-heated, burning plasmas
- BS current modeling, driving and recharging efficiencies