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

JT-60U

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Contents

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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.

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- 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 Consept of Low Aspect Ratio Tokamak : VECTOR

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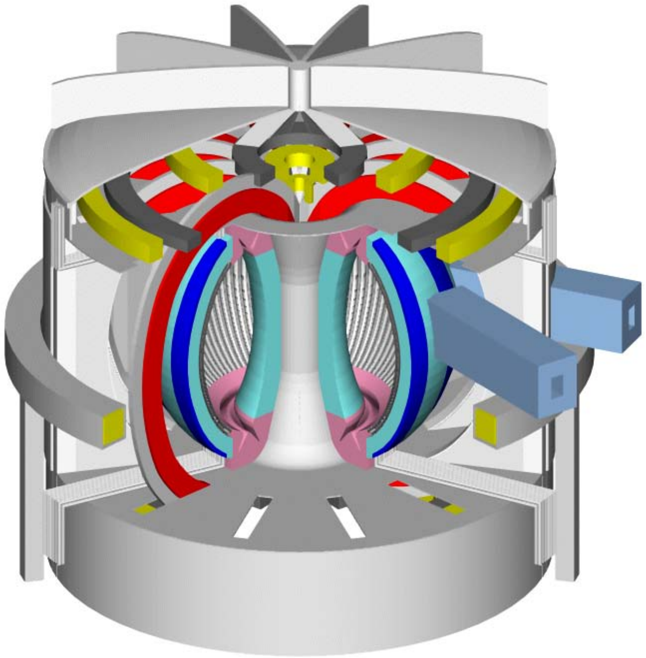

- **CS-less VECTOR offers new challenge of full non-inductive drive scenarios with very slow rampup (~ 0.01 MA/sec !). (cf. ~ 1.0 MA/sec at present)**
- **Feasible scenario for meeting all requirements, ex. plasma positioning and shaping ?**
- **Stable hybrid current build-up with high BS (I_{bs} > 50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

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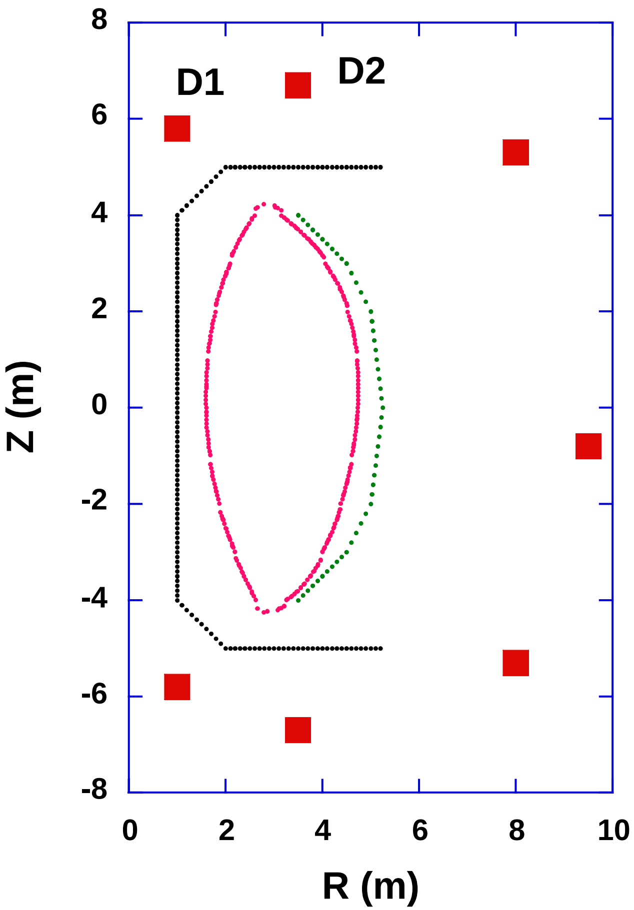
Modeling of ITB-generated, high BS current self-consistent with magnetic shear profile under direct coupling with external control coils

R_p / a_p = 3.2 / 1.4 m
I_p = 14 MA, κ = 2.4
β_N / β_T = 6 / 17 %

Fusion Power : P_F = 2.5 GW
Neutron Wall Load : P_n = 5 MW/m^2
B_{MAX} / B_0 = 19.1 / 5.1 T

Fundamental Requirements for Current Rampup

CS-less tokamak : VECTOR



Essential physics is contained within TSC.

- **from non-inductive techniques**

(1) timescale w/o current profile distortion

S.C. Jardin, NF (2000)

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

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

(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 $HH = \frac{\tau_E}{\tau_{E,y2}} \leq 1.3\ (?)$

(3) power limit $P_{CD} = \frac{n_e R I_p}{\eta_{CD}} \leq 100 \text{ MW}$

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* & *Ψ* time-evolution**

$$\frac{\partial B}{\partial t} = -\nabla \times E \quad ; \quad B = \nabla\phi \times \nabla\Psi + g\,\nabla\phi$$

  - **Ohm's law :** $j_{oh} = j_{total} - j_{bs}$

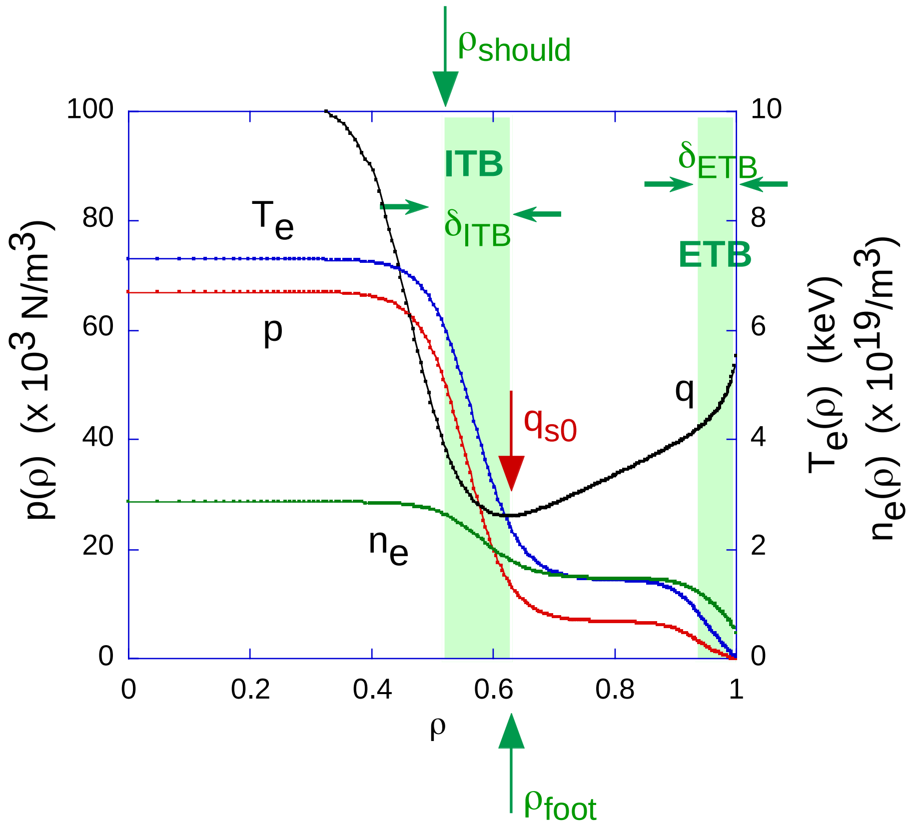
$$E + v \times B = \eta\, j_{oh}$$

- **ITB & ETB**
  - **BS Current**

$$\langle j_{bs} \bullet B \rangle = L_{31}\left[A_1^e + Z_i^{-1} T_i / T_e \left(A_1^i + \alpha_i A_1^e\right)\right] + L_{32} A_2^e$$

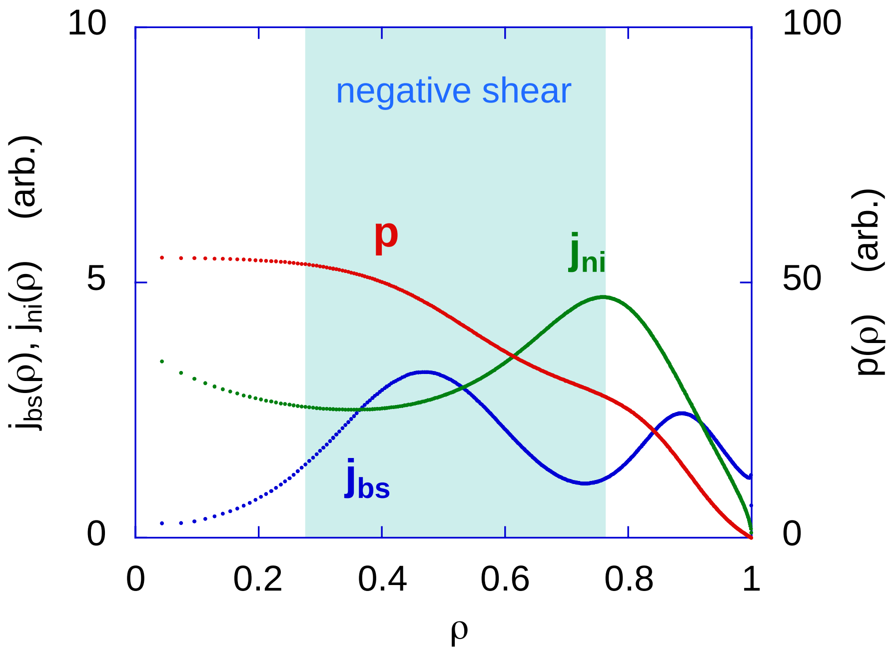
S. P. Hirshman, Phys. Fluids (1988).

- **Pressure profiles prescribed**
- **Radii of ITB-foot & ρ_{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.

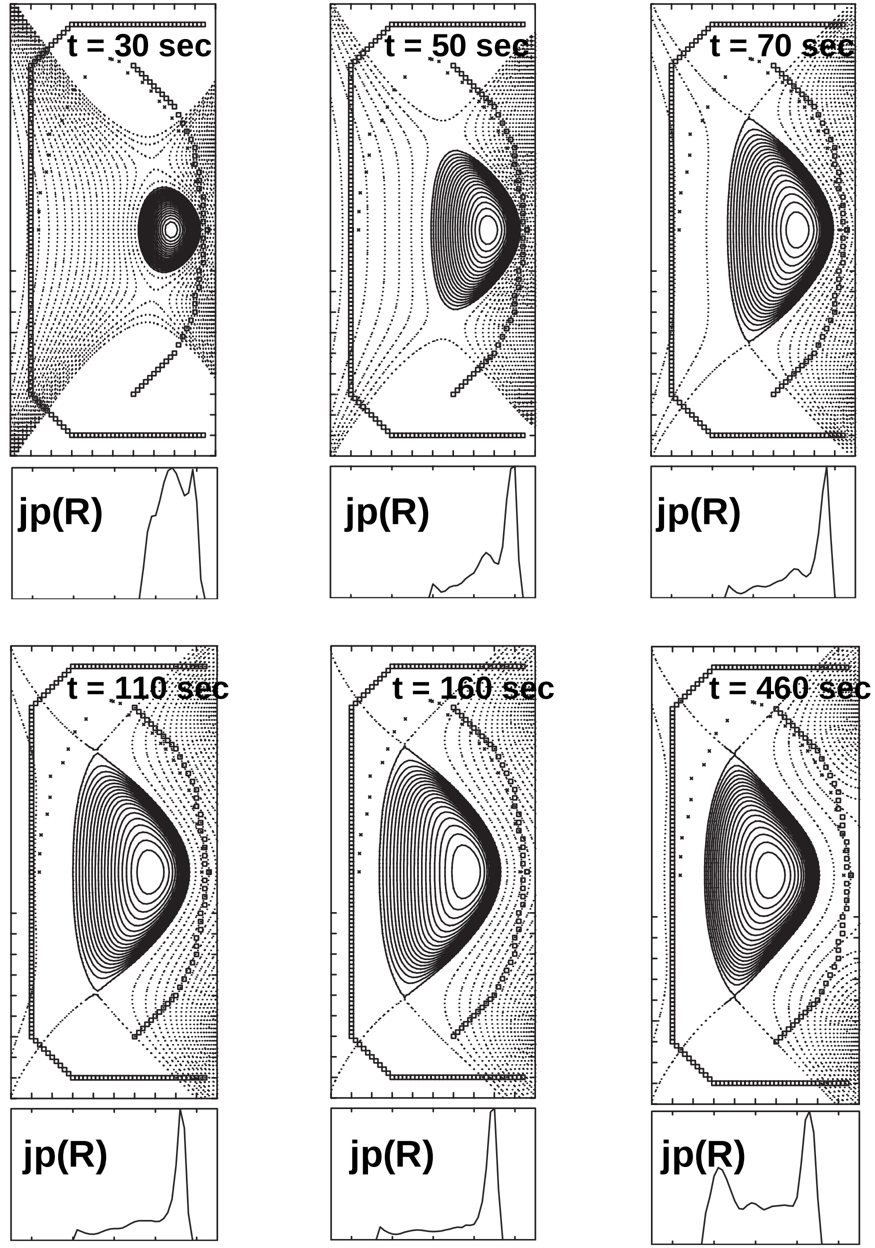


Position & Shape Controls during Hybrid Current Rampup

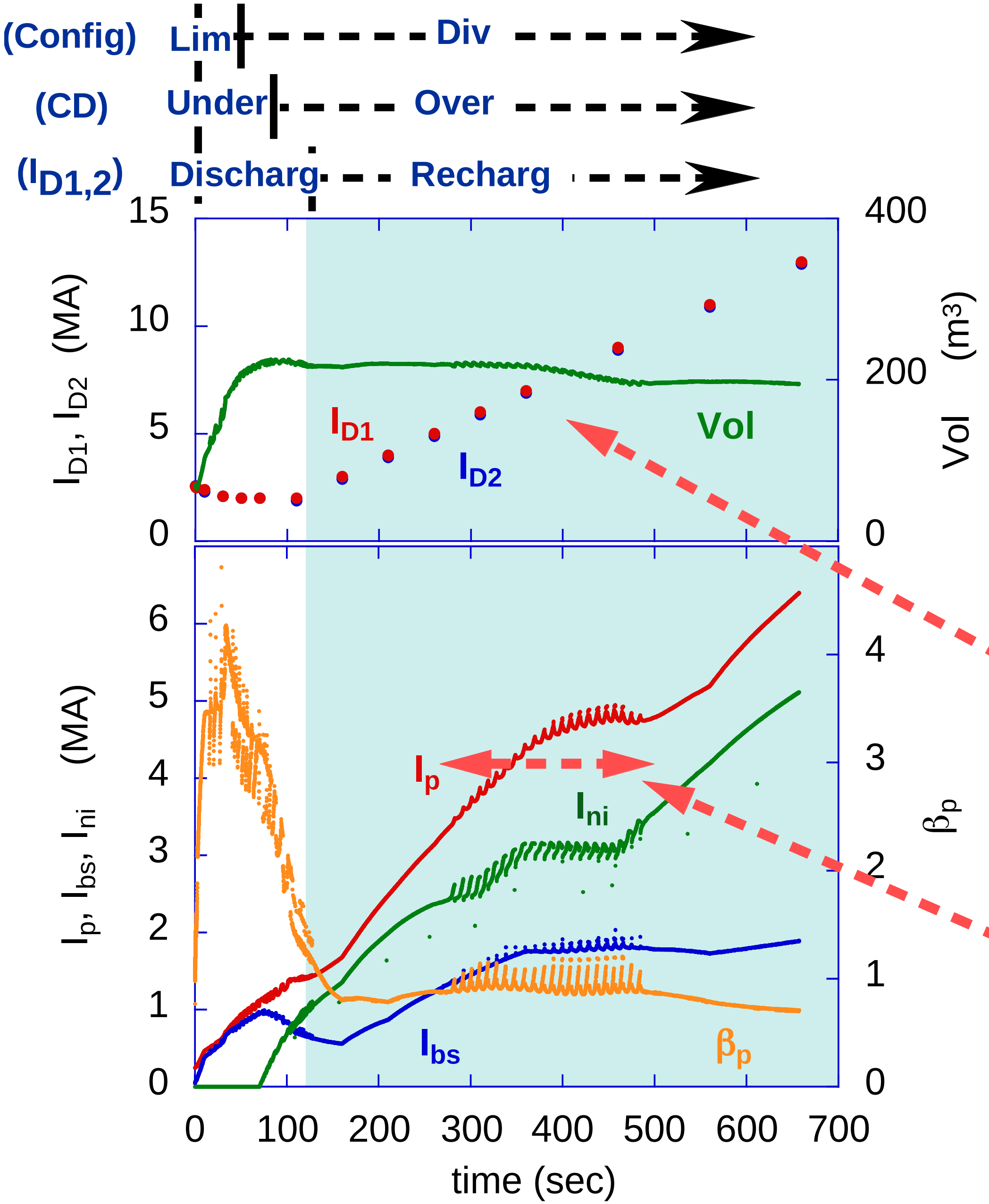
Non-Inductive current ramp of 14MA within 1000 sec with I_{bs} ~ I_{ni} > 50 % of I_p



- **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
  : ~ 0.01 MA/sec, T_e ~ 2 keV
- Limiter to diverter transition, t = 50 sec
- High β_p (< 3.5), lower density than n_{GW} providing high BS fraction (~ 95 %) with ~ 5 % inductive Ip
- Plenty of non-inductive current accomplished an over-driving state at t >130 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_{loop} & "Return Current" due to Over-Current Driving

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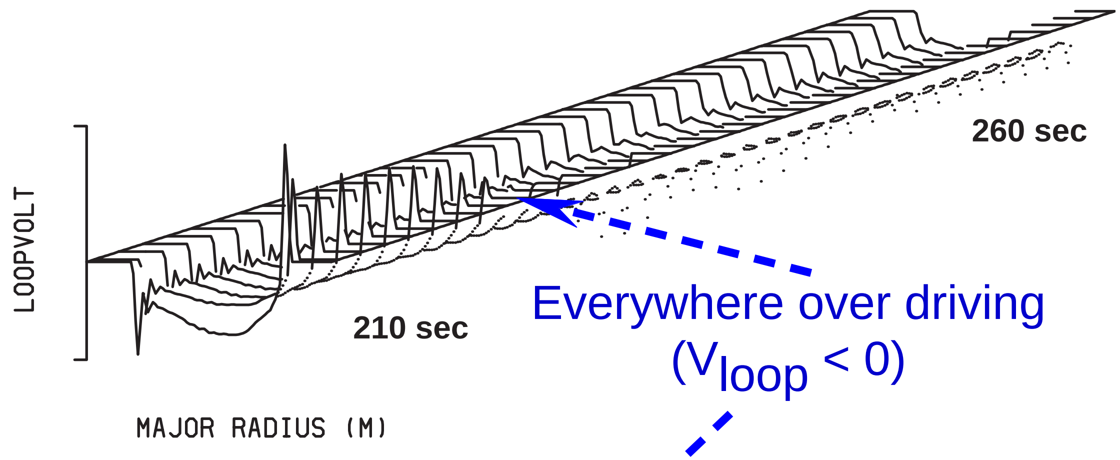
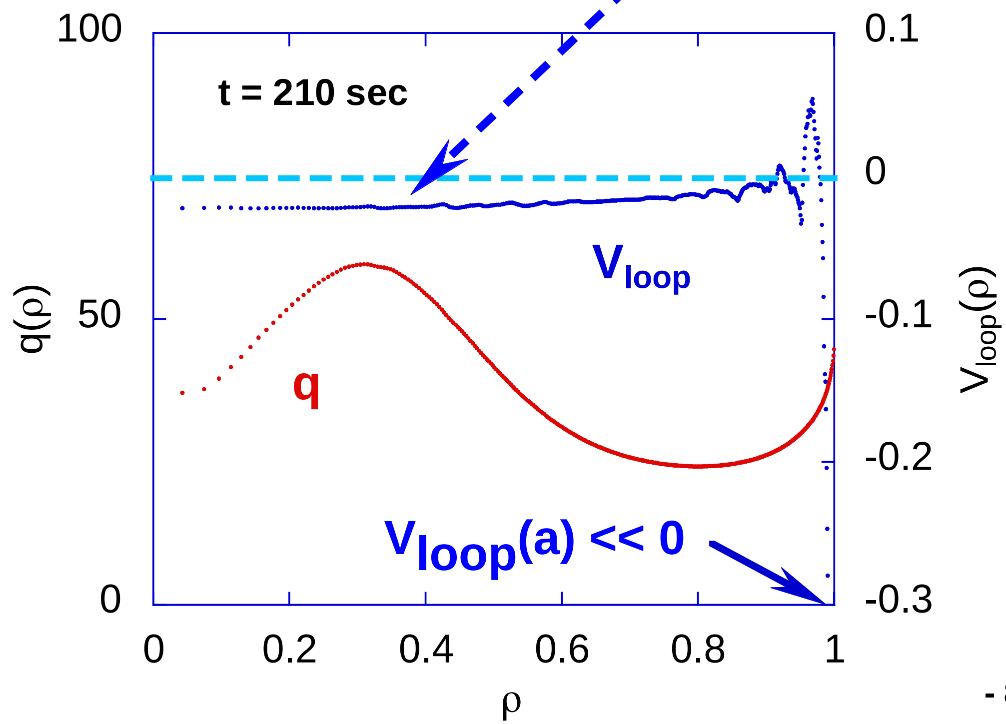
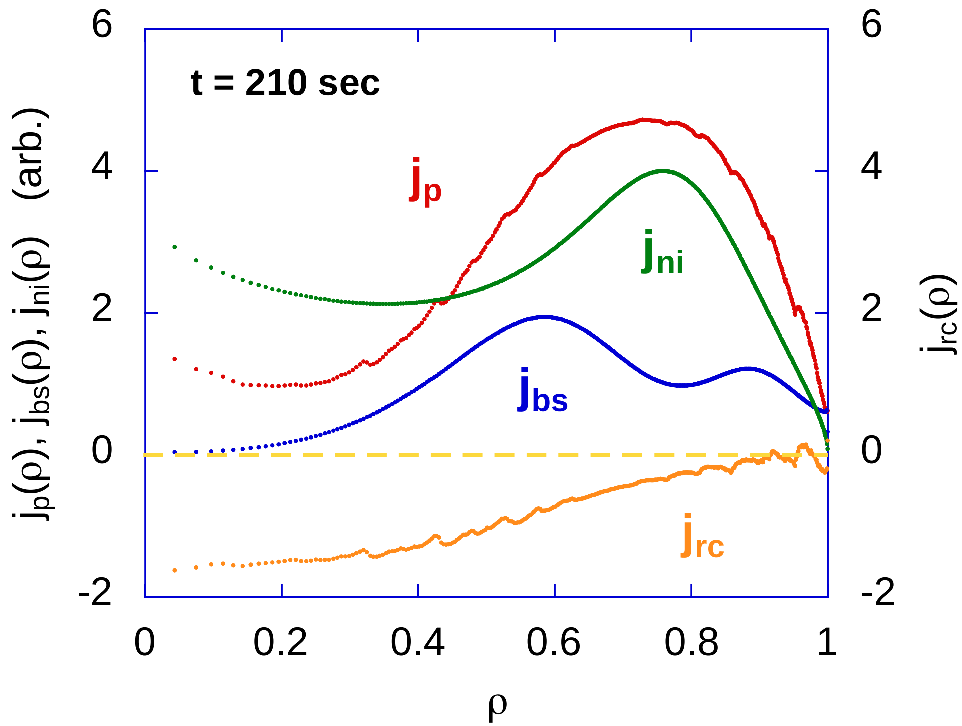


- Strong non-inductive current ramp provides "Return Current" :
  $$j_{rc} = j_p - j_{bs} - j_{ni}.$$
- j_{rc} in core region survives longer, leading to CH formation.
- Strong $V_{loop}(a) < 0$ enables $I_{D1,2}$ to recharge against current rampup.





Cooperative Link between BS Current and Magnetic Shear

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

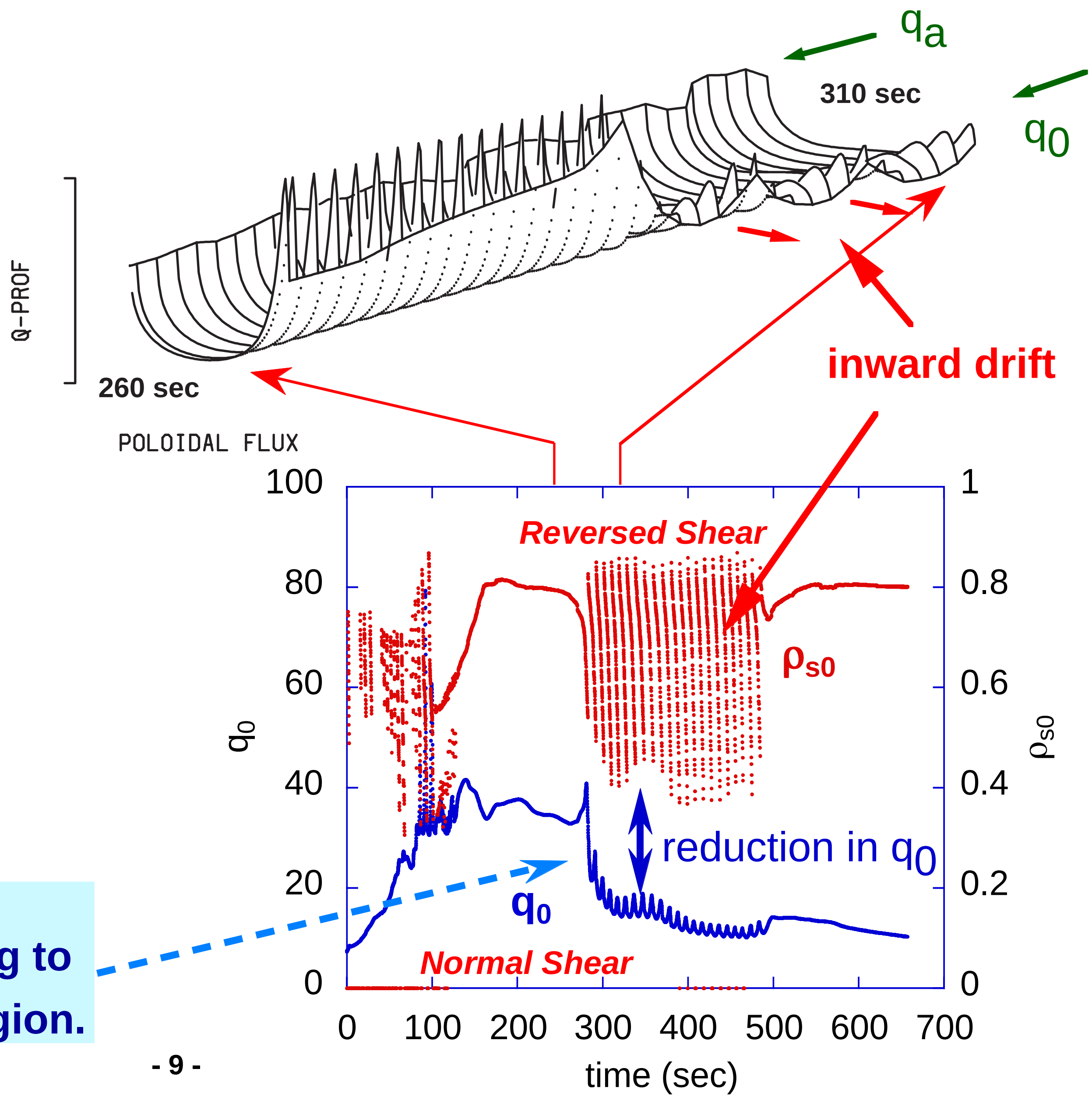
(1) Magnetic shear reversal ρ_{s0} starts to drift inwards, and disappears at magnetic axis.

(2) Then, ρ_{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.

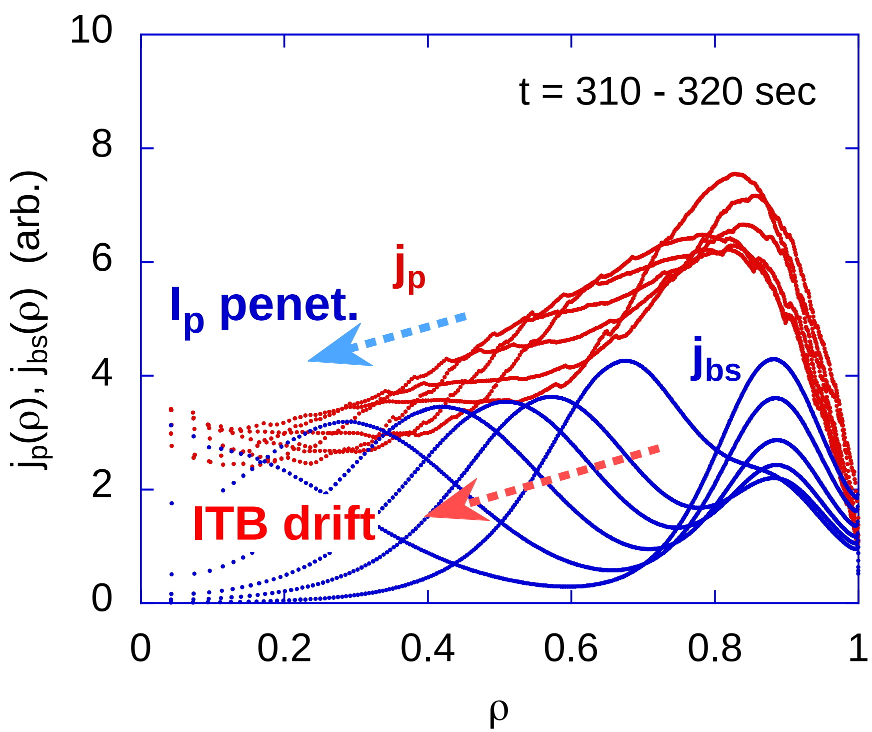


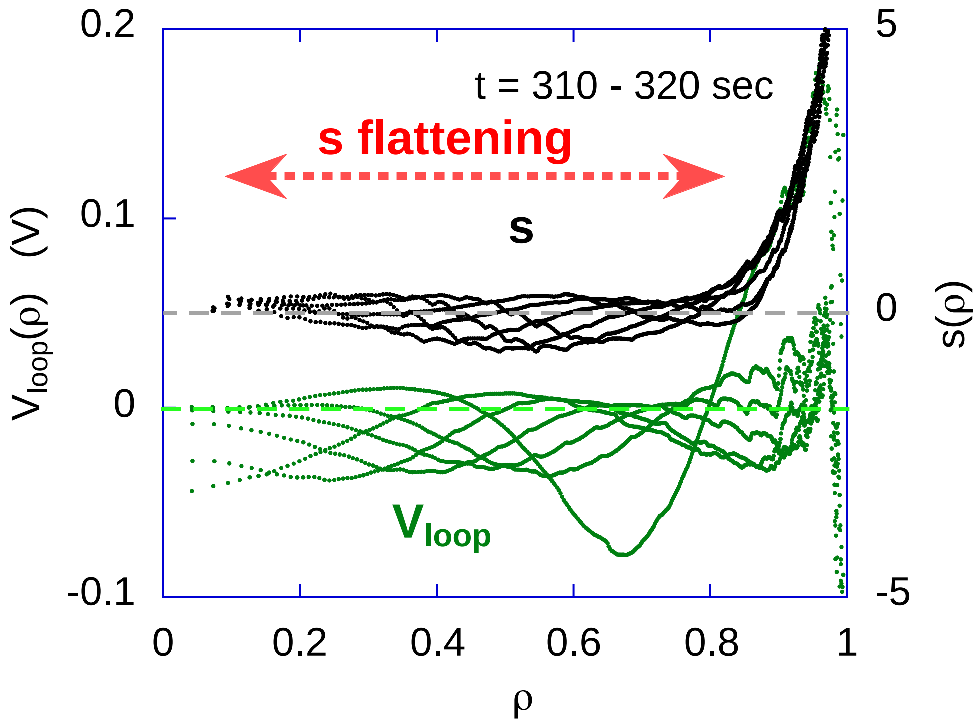
Inward Drift of ITB-generated BS Current

- **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 τ^*:

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





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**