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Bootstrap Current Effects on Stable Non-Inductive Current Buildup in Low Aspect Ratio Tokamaks

JT-60U

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Motivation & Outline

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- A non-inductive current buildup of low aspect ratio JAERI tokamak "VECTOR" was computationally studied via axisymmetric MHD simulation.
  - VECTOR without center solenoid offers new challenge of very slow current build-up (~ 0.01 MA/sec !) of full non-inductive drive scenarios.
  - Simulation modeling of high BootStrap (BS) current generated by Internal Transport Barrier (ITB), which should be always self-consistent with magnetic shear profile, is important for stable operation of low aspect ratio tokamaks.

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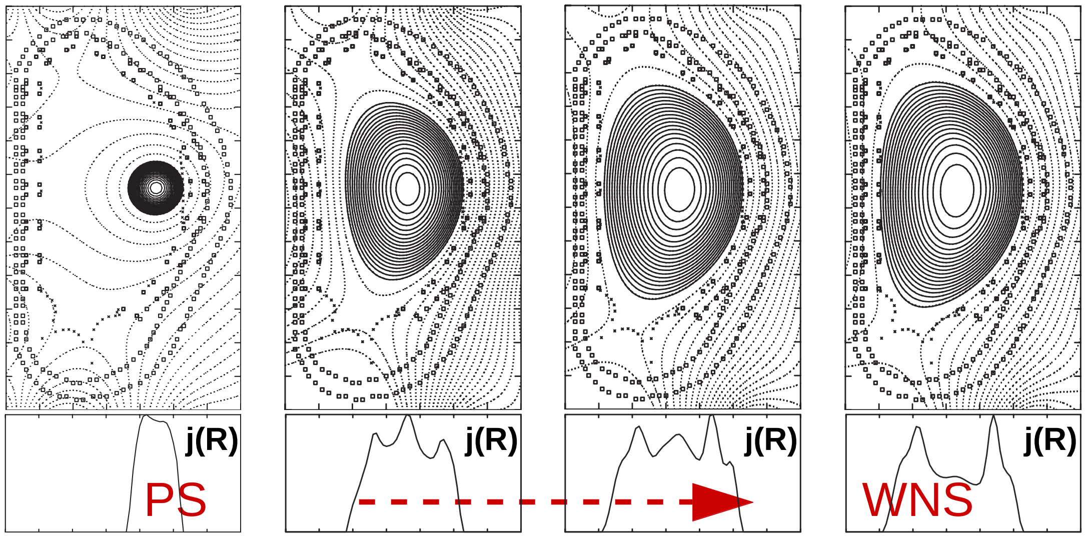
- Despite the intention controlling a monotonic plasma current buildup, cooperative link between ITB-generated BS currents and BS current-modulated magnetic shear exhibited a sef-organized oscillation of builing-up current and its profile.
- The newly found oscillation was discussed in following aspects:
  - underlying physics and operation conditions,
  - hybrid current build-up scenario using external non-inductive drive,
  - advantage/disadvantage of the cooperative link in controlling the ITB structure.

Hybrid Build-up with Non-Inductive Current Drive

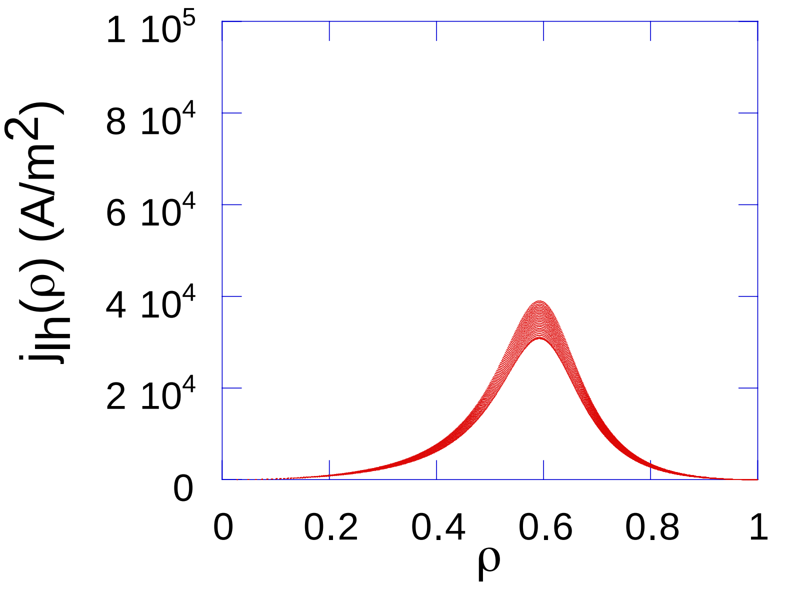
- ITER-FEAT operation scenario #4
(Inductive build of 9 MA steady-state scenario,
fusion power > 300 MW, Q > 5)

**"ITER Engineering Design",
J. Plasma & Fusion Res. (2002)**

- Slow Ip ramp for 24 sec : ~ 0.3 MA/sec
- Low Te target plasma till SOH
(Heat load to outside limiter)



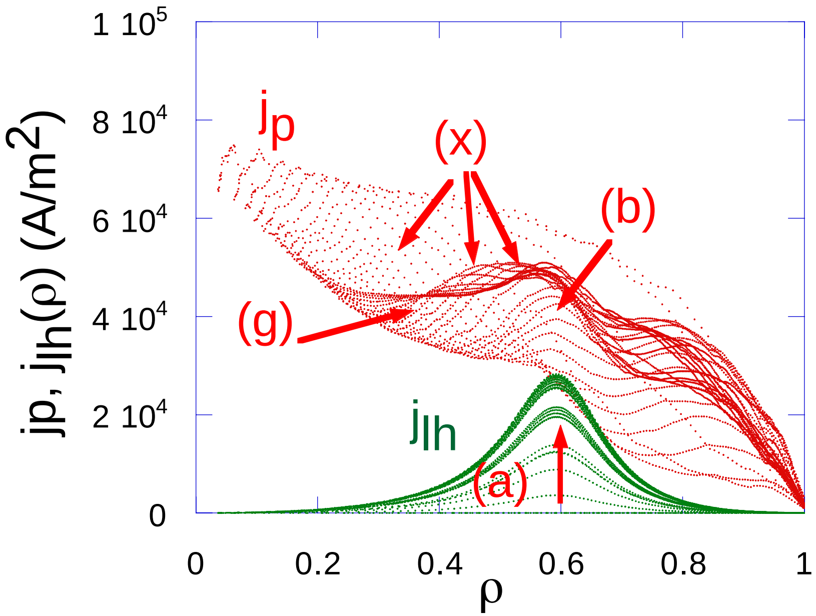
+ Non-Inductive Current Drive

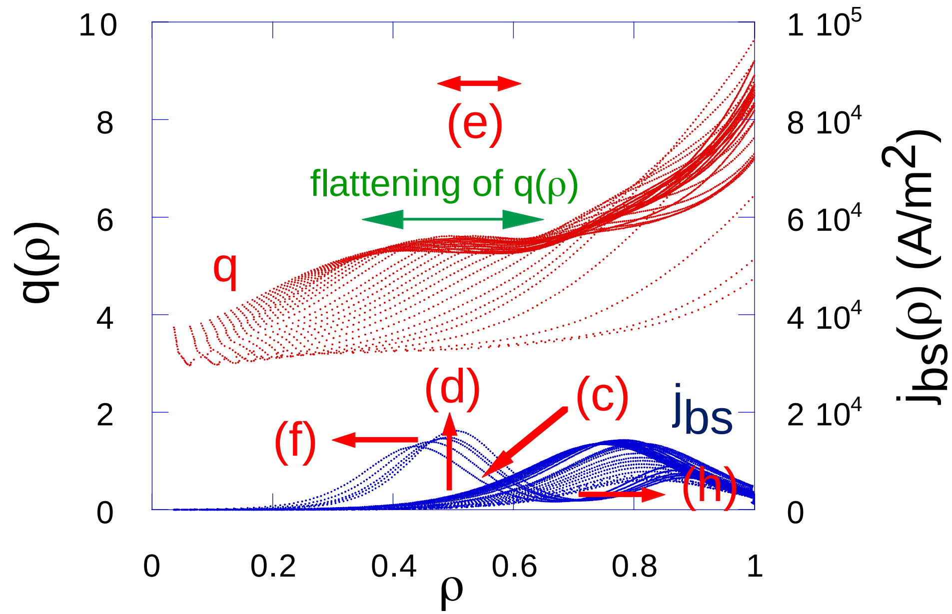


- I_{lh} : ~ 20 % of Ip
- I_{bs} : ~ I_{lh} ~ 20 % of Ip

Monotonic current build-up leads to a recurrent appearance of Negative Shear region.

Forward & Backward Transition and Mechanism (t = 0.0 - 5.5 sec)





Cooperative link between non-inductive & BS currents

(a) External drive of substantial non-inductive current (> 20 % of plasma current)

(b) Formation of NS profile

(c) ITB formation near NS region

(d) Growth of ITB-generated BS current (~ 20 % of plasma current)

(e) Profile mismatch of BS and non-inductive currents

(f) Inward drift of NS region

(g) Disappearance of NS region

(h) Disappearance of BS current

(x) Recurrence to PS profile

Profile Evolution of Magnetic Shear during PS to WNS Transition

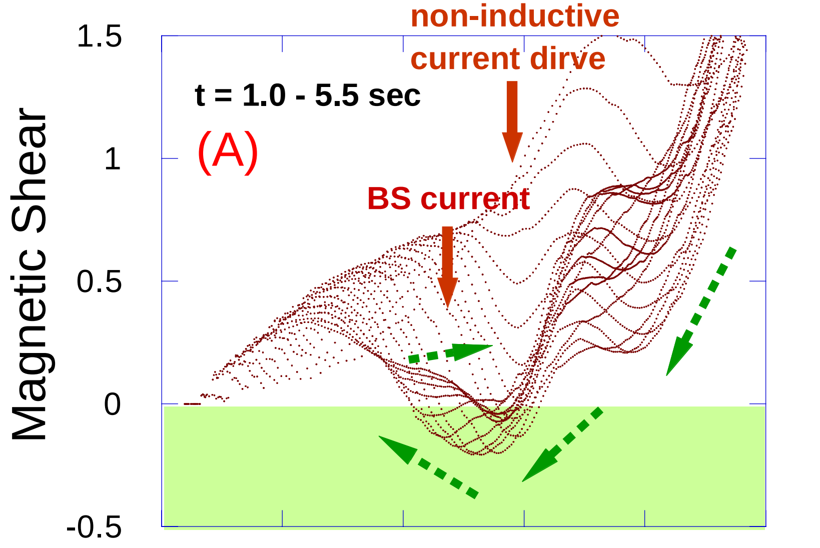
(A-1) Non-inductive current deforms local shear to NS.

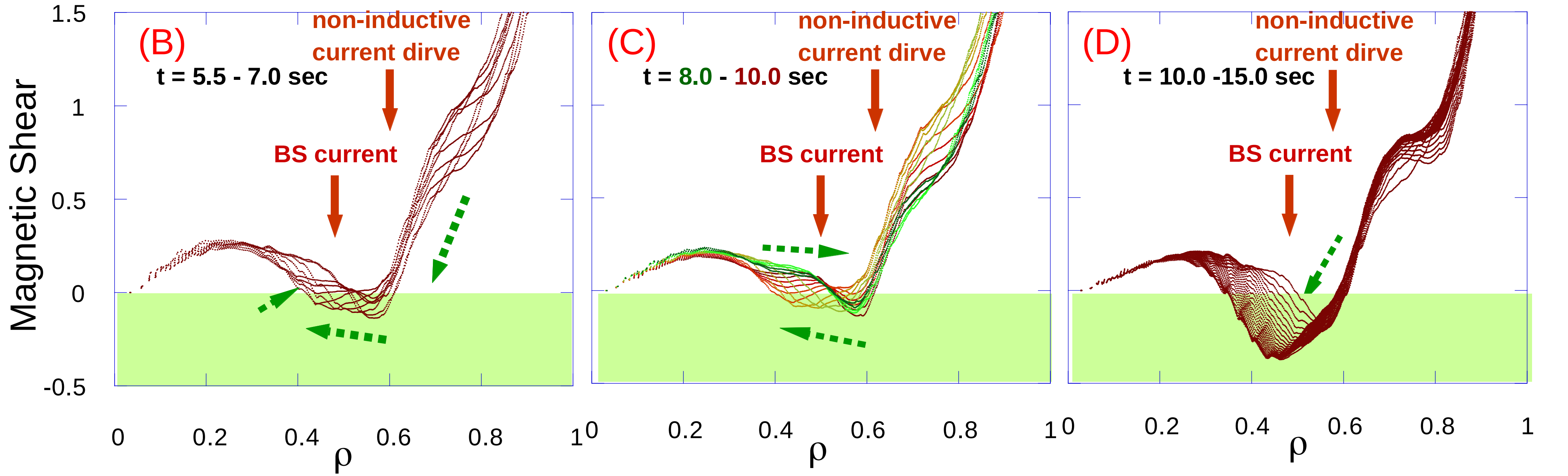
(A-2) ITB-generated BS current drags NS region inwards, and eventually erases it (loss of ITB).

(B) Again NS region appears, and same thing as (A), backward going to PS.

(C) Same as (B), approaching the WNS profile.

(D) PS profile never come back anymore (WNS accomplishment).





Reactor Consept of Low Aspect Ratio Tokamak : VECTOR

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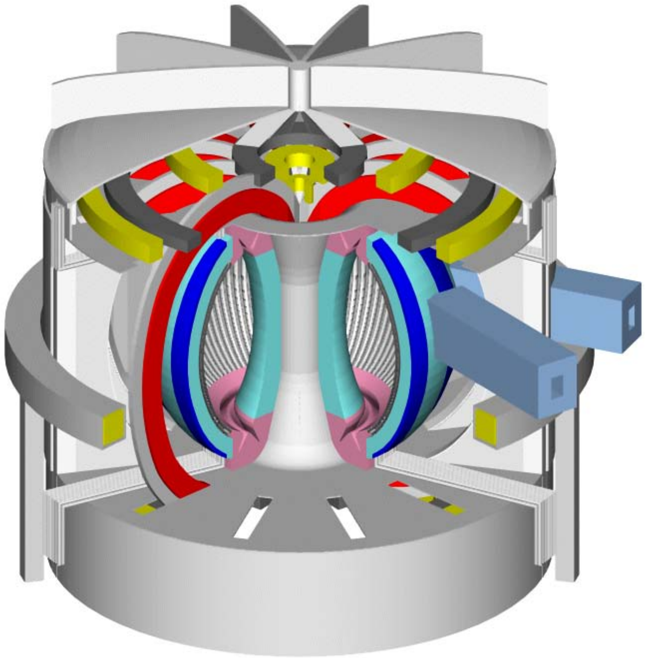


- CS-less tokamak like VECTOR needs very slow current build-up scenarios (~ 0.01 MA/sec !).
  cf. normally ~ 1.0 MA/sec at present.
  - Stable current build-up with high BS current fraction (~ 100 %) ?
  - Hybrid current build-up with high BS and non-inductive currents (~ 50 % I_{bs} and ~ 50 % I_{lh}) ?

→ Self-consistent simulation modeling of ITB-generated, high BS current with magnetic shear profile

Plasma Major Radius	: R_p = 3.2 m	Fusion Power	: P_F = 2.5 GW
Plasma Minor Radius	: a_p = 1.4 m	Neutraon Wall Load	: P_n = 5 MW/m^2
Plasma Ellipticity	: κ = 2.4	Maximum Field	: B_{MAX} = 19.1 T
Plasma Current	: I_p = 14 MA	Field on Axis	: B_0 = 5.1 T
Normalized Beta	: β_N = 6	Toroidal Beta	: β_T = 17 %

ITB & ETB Modelling on TSC

- **Numerical Model of TSC**
  - Momentum eq. of single fluid ***m*** :

$$\frac{\partial \boldsymbol{m}}{\partial t} + \boldsymbol{F}_v(\boldsymbol{m}) = \boldsymbol{j} \times \boldsymbol{B} - \nabla p$$

  - Faraday's law for *g* & *Ψ* time-evolution

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E} \quad ;$$

$$\boldsymbol{B} = \nabla\phi \times \nabla\Psi + g\nabla\phi$$

  - Ohm's law : $\boldsymbol{j}_{\mathrm{oh}} = \boldsymbol{j}_{\mathrm{total}} - \boldsymbol{j}_{\mathrm{bs}}$

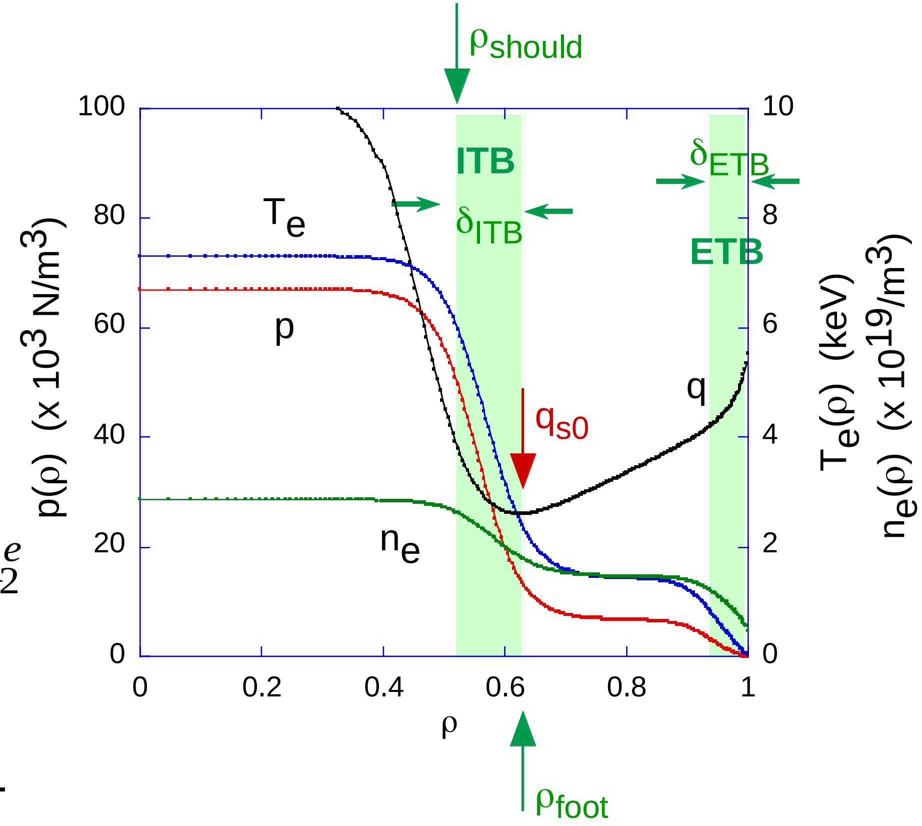
$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \eta \boldsymbol{j}_{\mathrm{oh}}$$

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

S. P. Hirshman, Phys. Fluids 31 (1988) 3150.

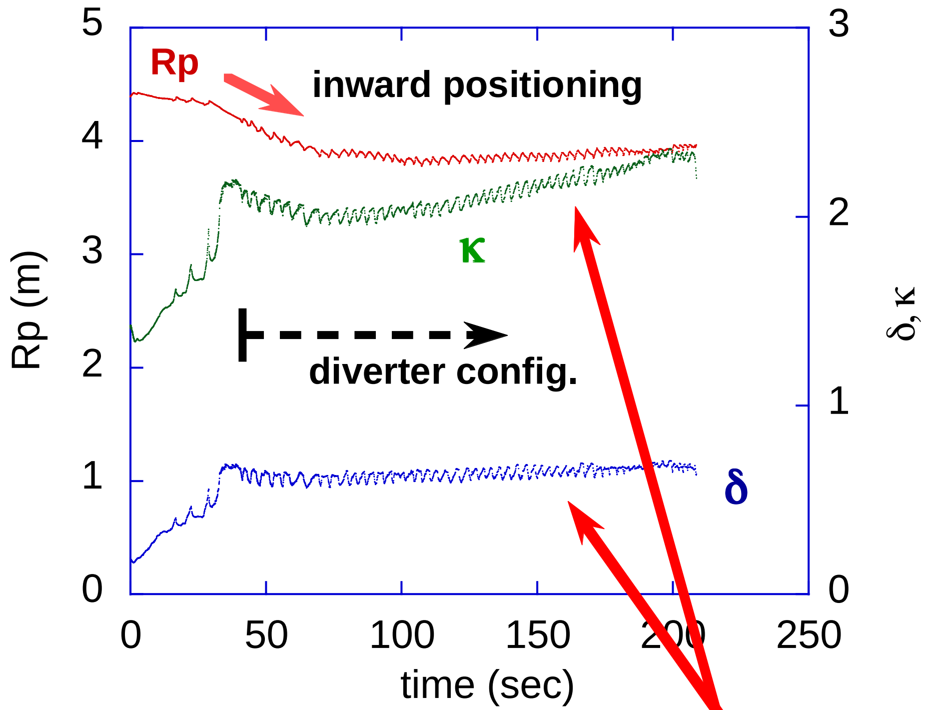
$$\langle \boldsymbol{j}_{\mathrm{bs}} \bullet \boldsymbol{B} \rangle = L_{31}\left[A_1^e + Z_i^{-1} T_i / T_e \left(A_1^i + \alpha_i A_1^e\right)\right] + L_{32} A_2^e$$

- **ITB & ETB Model**
  - 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.

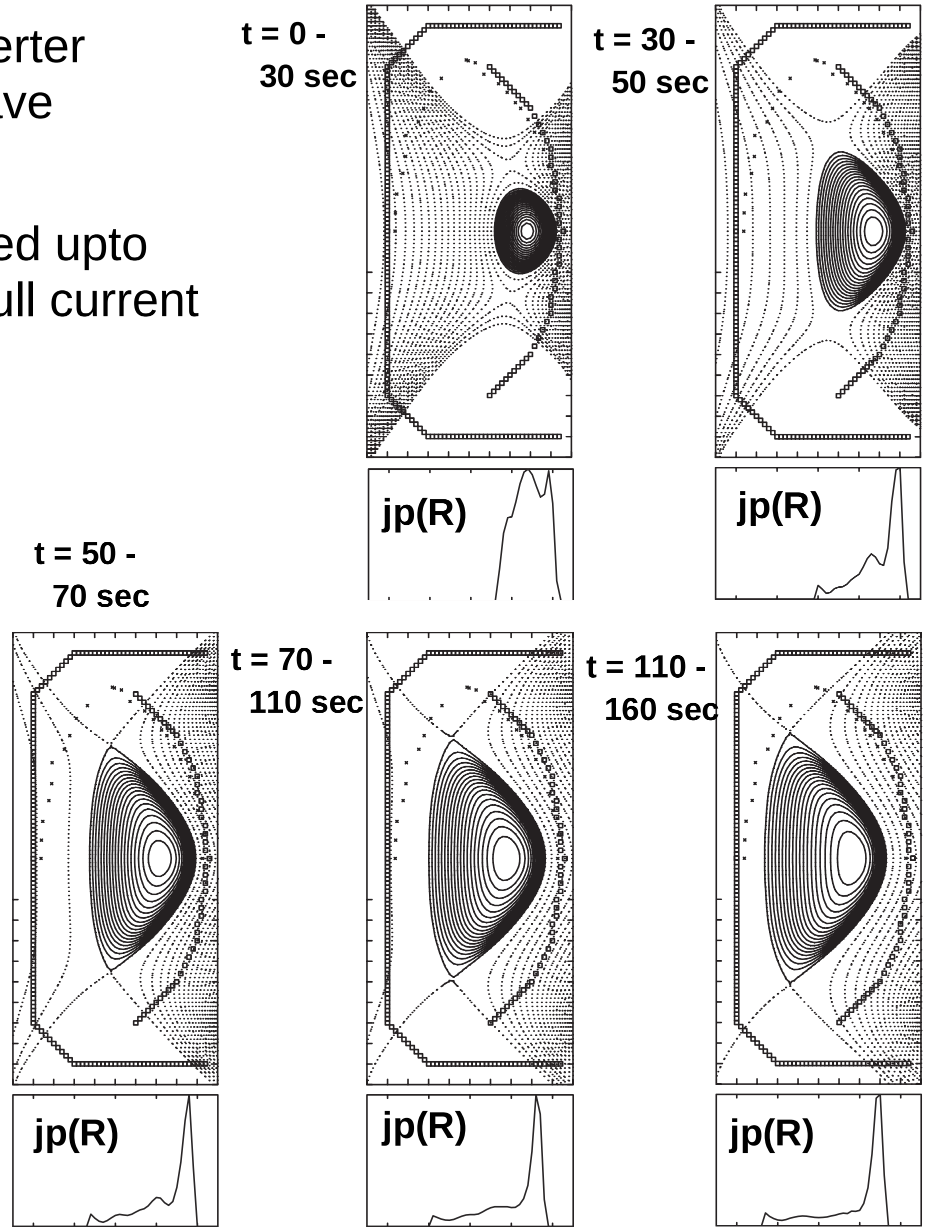


Position and Shape Controls during Current Ramp-up in VECTOR

- Controlled, stable transition from limiter to diverter configuration, taking-off from outer limiter to save inductive flux of coils.
- Almost non-inductive current ramp was followed upto 210 sec by the TSC simulation, while 14 MA full current ramp designed witin 1000 sec.



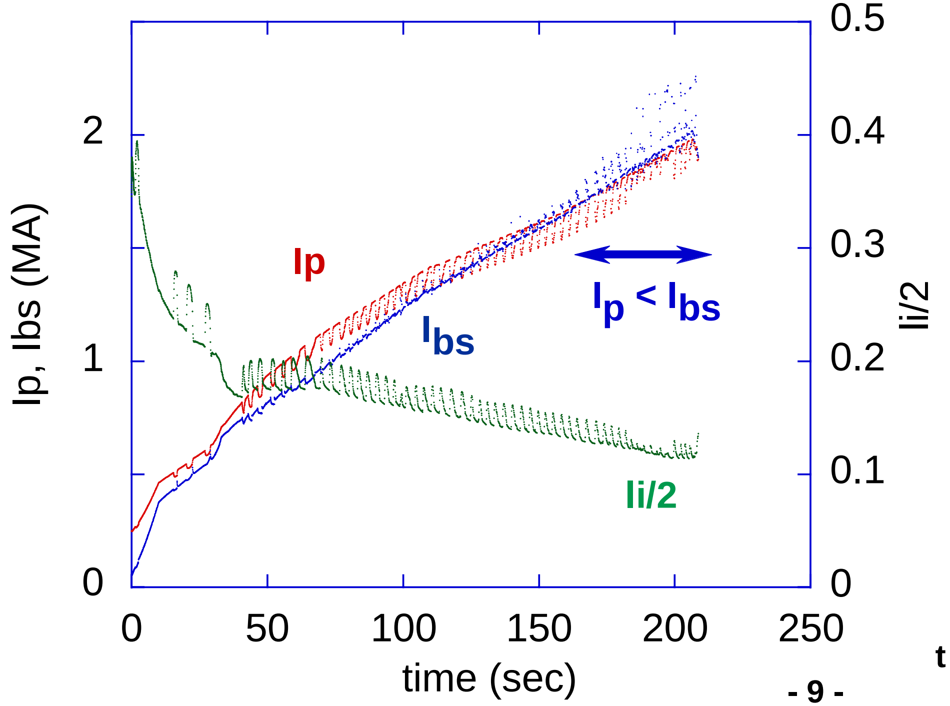
Small oscillations of Rp, δ,κ are the results, not the model assumed!

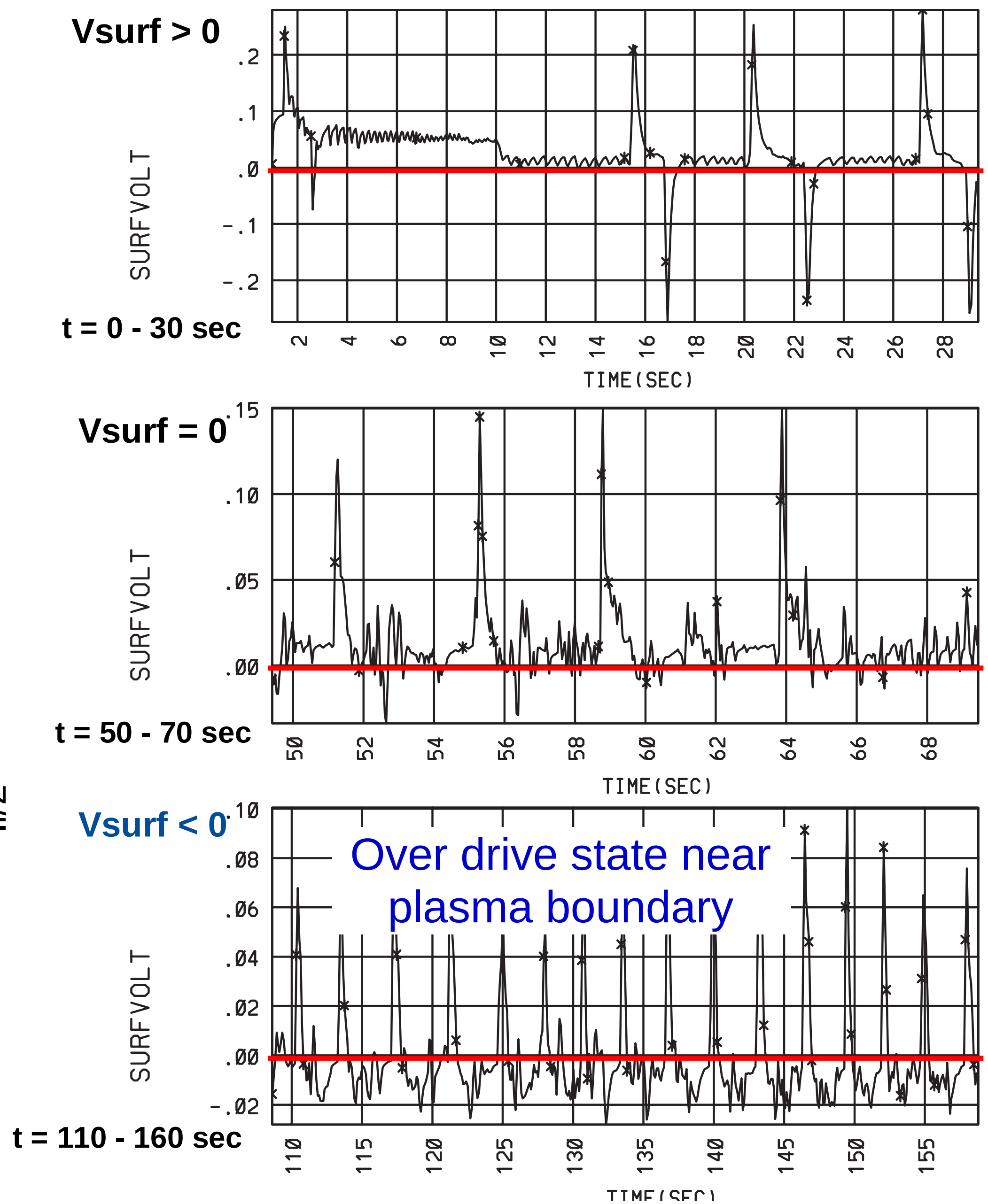


High βp, Slow Current Buildup with High BS Current Fraction

- Slow ramp rate : ~ 0.01 MA/sec (cf. ~ 0.3 MA/sec in ITER scenario #4)
- High β_p (~ 3.5) expecting high BS fraction (> 95 %) with < 5 % inductive Ip
- An over drive state was realized at t >130 sec as shown by the Vsurf < 0.

Oscillating current ramp-up was observed till 2 MA build of full current of 14 MA.

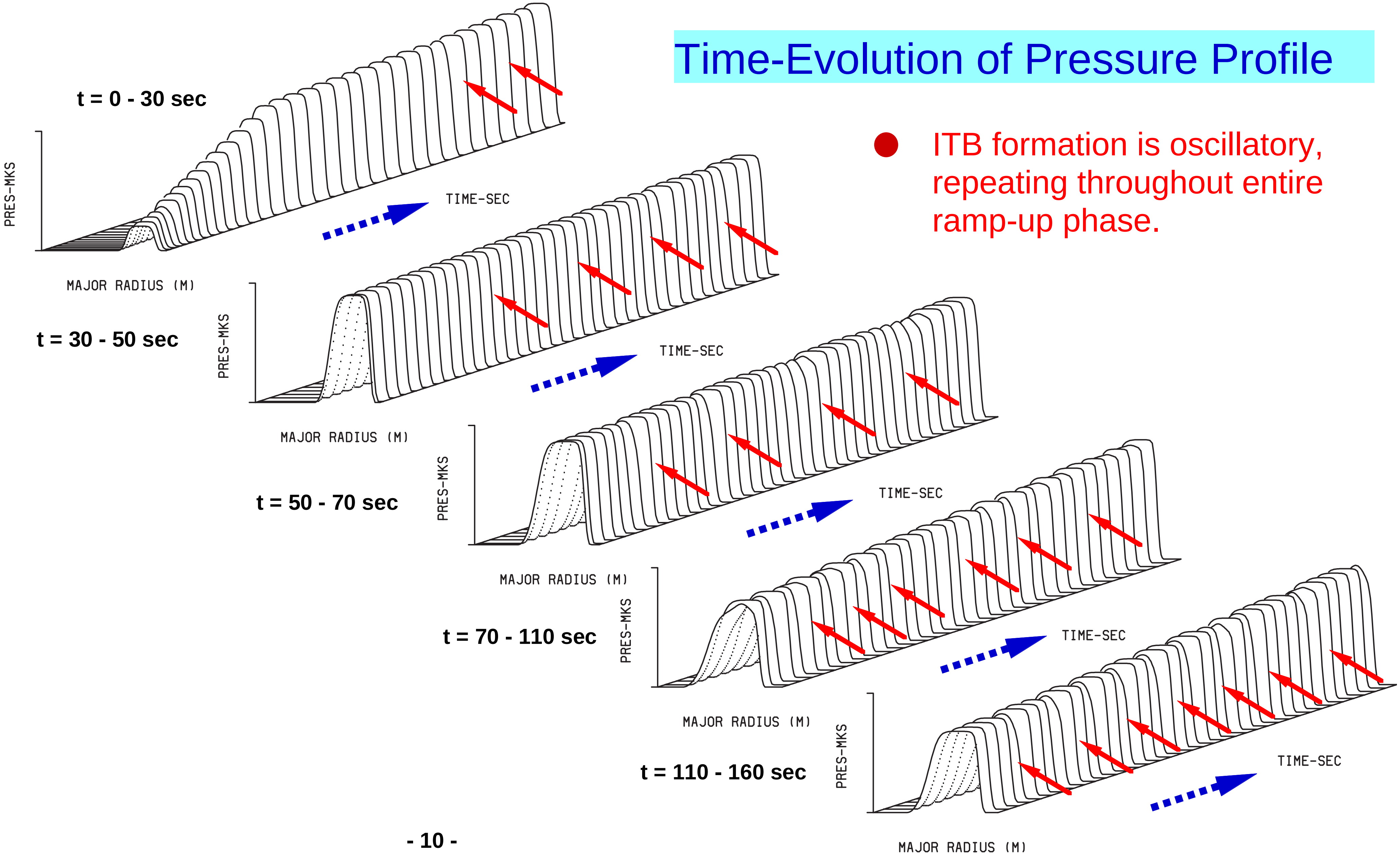




Oscillatory ITB formation

Time-Evolution of Pressure Profile

- ITB formation is oscillatory, repeating throughout entire ramp-up phase.

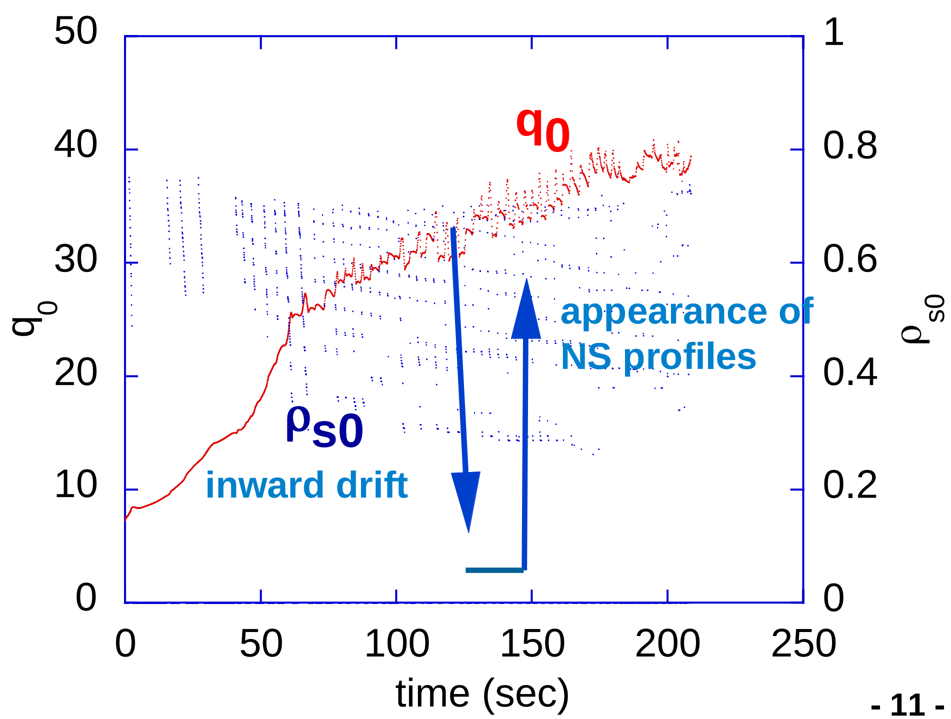


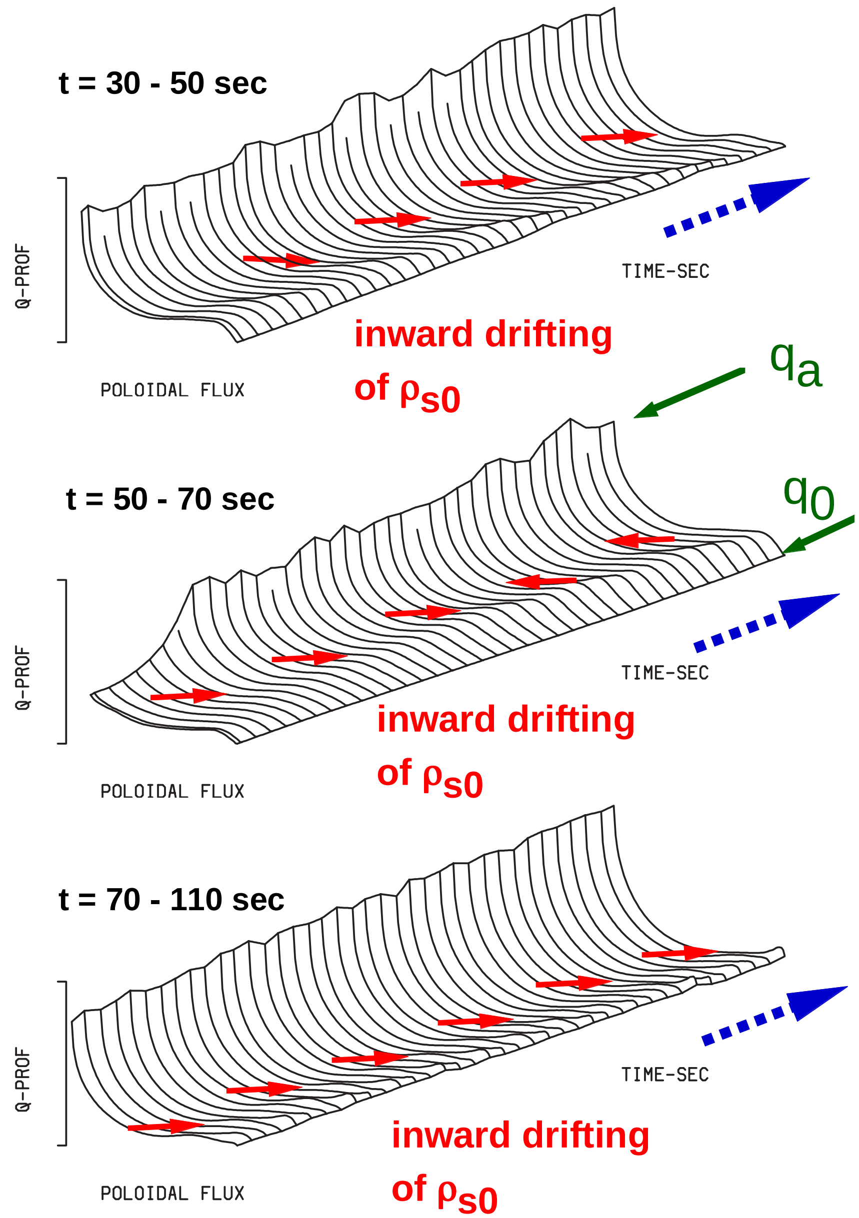
Recurrent Appearance of NS Region during Ramp-up

(1) Increase of q_0 during is oscillatory ramp-up.

(2) Location of shear reversal ρ_{s0} drifts inwards to disappear at magnetic axis.

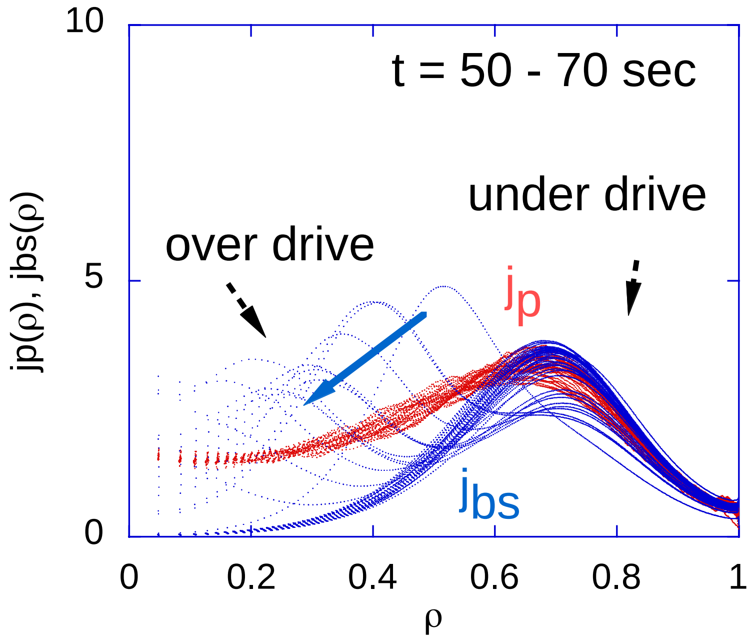
(3) Appearance and disappearance of NS profiles repeats during slow ramp-up of fully BS current-driven plasmas.





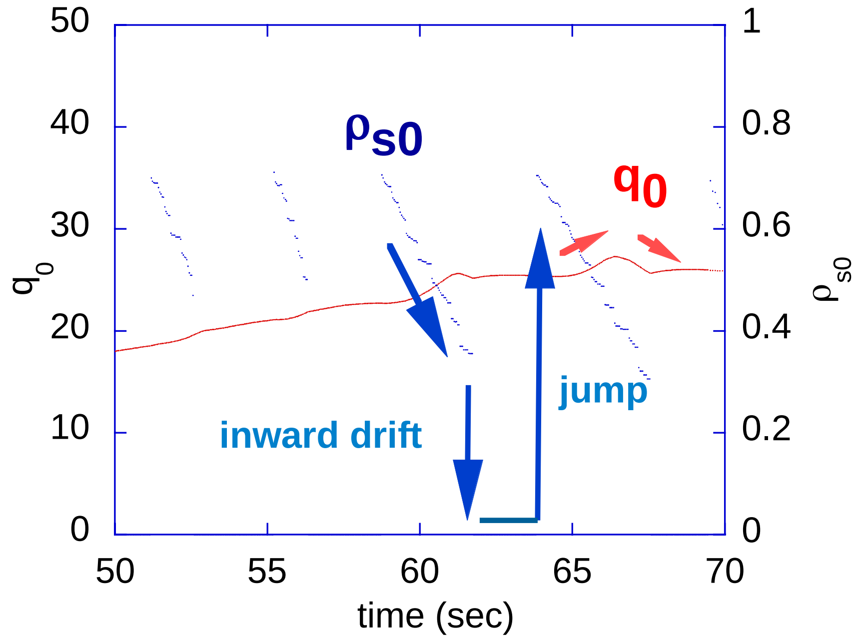
Inward Drift of ITB-generated BS Current

- Strong locality of BS current with high fraction makes jp(r) an over current drive state around the drifting ITB region, while making an under drive state in other region.
- Such profile structure strongly modulates the magnetic shear profile, causing the inward drift of ITB.



- q0(t) increasing in time also shows oscillatory behovior in accordance with inward drifting property of the ITB.
- Recurrence cycle was 4 times / 20 sec, i.e. the period time is ~ 5 sec (<< 1000 sec).

Inward drift of ITB-generated BS current lifts up the current around core region, otherwise being kept much lower (Current Hole?).

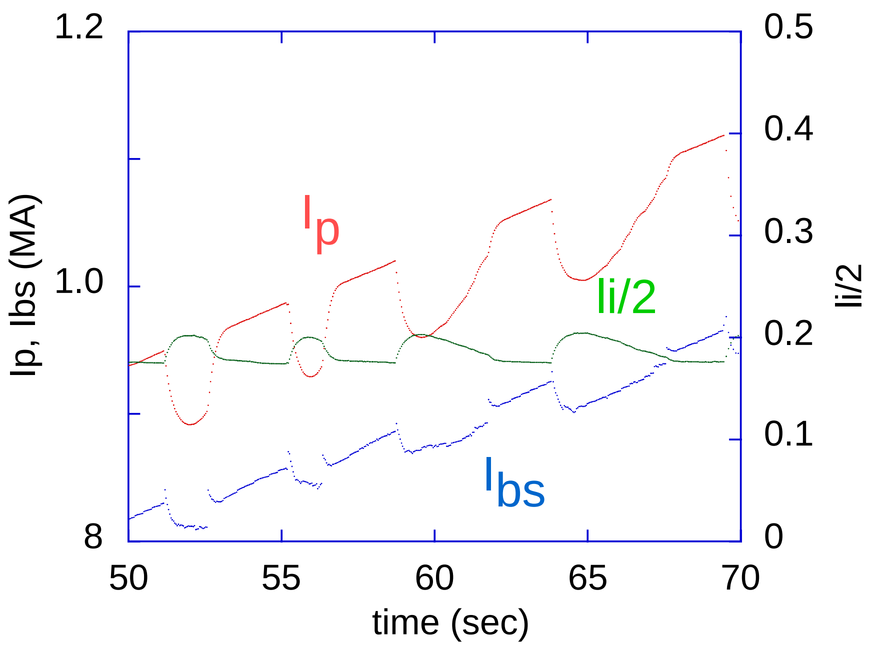


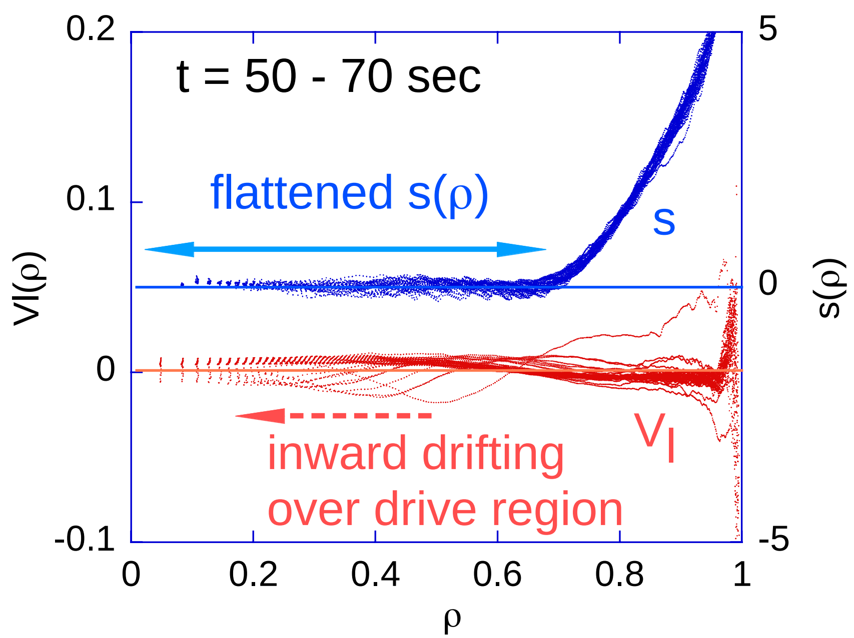
Flattening of Shear Profile due to Oscillatory Inward Drift

- As a whole, BS current I_{bs} remains less than total current Ip (under drive state), however, over and under drive regions can co-exist because strong locality of BS current property.
- Ip oscillates in accordance with li fluctuation arising from the oscillatory inward drift of ITB-generated BS current.

- Negative V_l region appears around the ITB ($\rho \sim 0.6$), and then, drifts inward to magnetic axis.

Magnetic shear was flattened to almost ZERO over wide region $0 < \rho < 0.6$, avoiding Current Hole formation.





Inward Drift of BS Current & Shear Profile (t = 110 -160 sec)

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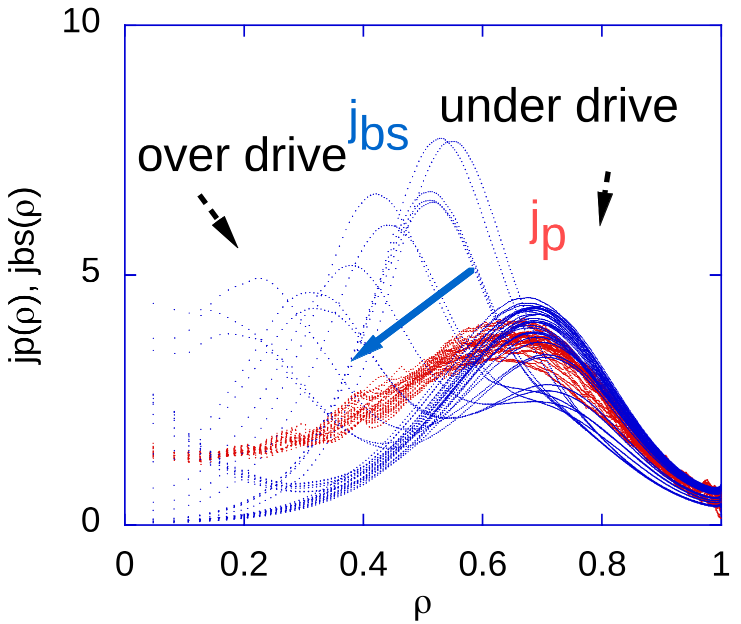
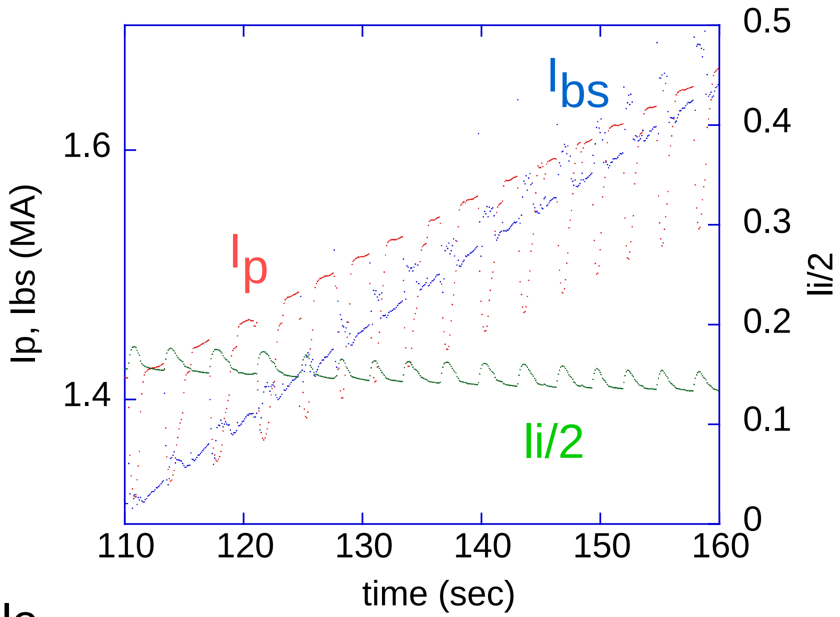
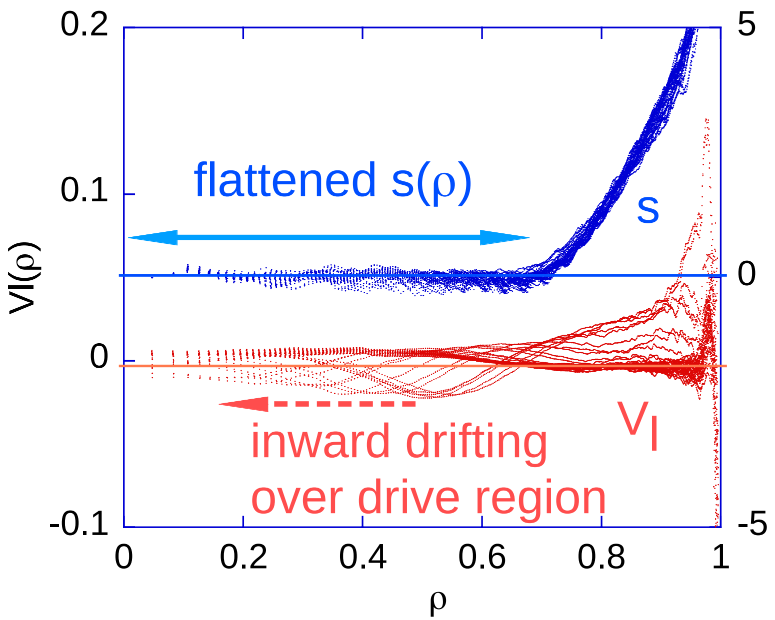
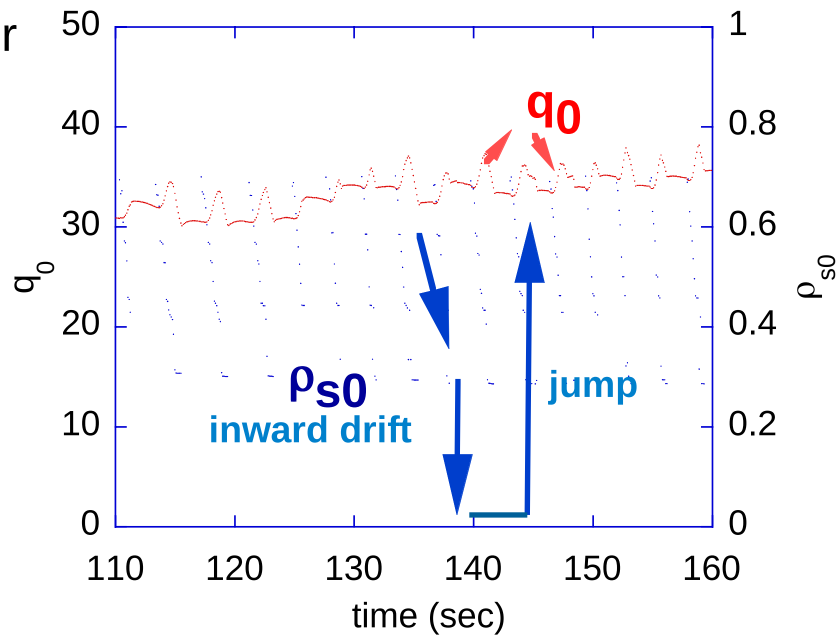




- Similar to t = 50 -70 sec
- Recurrence cycle becomes shorter as ~ 3 sec.





Summary

- A non-inductive current buildup of low aspect ratio JAERI tokamak "VECTOR" was computationally studied via axisymmetric MHD simulation.
    - ITB-generated high BS current, being always self-consistent with magnetic shear profile, was modelled in the simulation.
    - From an economical point of view, a new challenge of full non-inductive drive scenarios without center solenoid was investigated at very slow current build-up rate (~ 0.01 MA/sec !).
- Despite the intention controlling a monotonic plasma current buildup, cooperative link between ITB-generated BS currents and BS current-modulated magnetic shear exhibited a sef-organized oscillation of builing-up current and its profile.
    - As a consequence of the cooperative link, magnetic shear was flattened to almost ZERO over wide region $0 < \rho < 0.6$, avoiding Current Hole formation.

Following issues are listed for Future Study :

- Model improvement of ITB-relevant transport instead prescribed pressure
- Validation of the simulation model through JT-60U CS-less ramp experiment
- Hybrid ramp scenario of lower BS current with external non-inductive driving