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TSC Modelling of Current Ramp Scenarios with ITB-Generated Bootstrap Currents in JT-60U Reversed Shear Discharges

JT-60U

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Outline

- A Modelling of Internal & Edge Transport Barriers (ITB & ETB) relevant to bootstrap currents has been implemented on TSC.

- The TSC nicely reproduced a specified ramp-up of JT-60U RS discharge assisted with the ITB & ETB-generated bootstrap currents.

  - A self-adjustment of the ITB-foot radius (ρ_{foot}) to the magnetic shear reversal (q_{min}) results in a remarkable recover of the ramp-up detail (E36486).
  - A mis-alignement of ρ_{foot} with $\rho(q_{min})$ leads to outward or inward drift of ITBs, which show quite different profile property.

- A fast and strong ITB build-up near plasma core may cause an over-drive bootstrap current which accompanies a negative electric field just inside of the ITB region.

  ➡ The TSC has demonstrated a detailed process of Current Hole formation.

ITB & ETB Modelling on TSC

TSC is a free boundary, axisymmetric, single fluid, time-evolution code with PF coil power supplies,
➤ realistic ramp-up simulation available.

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

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

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

$$\frac{\partial \boldsymbol{B}}{\partial t} = - \quad \times \boldsymbol{E} \quad ; \quad \boldsymbol{B} = \quad \varphi \times \quad \Psi + g \quad \varphi$$

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

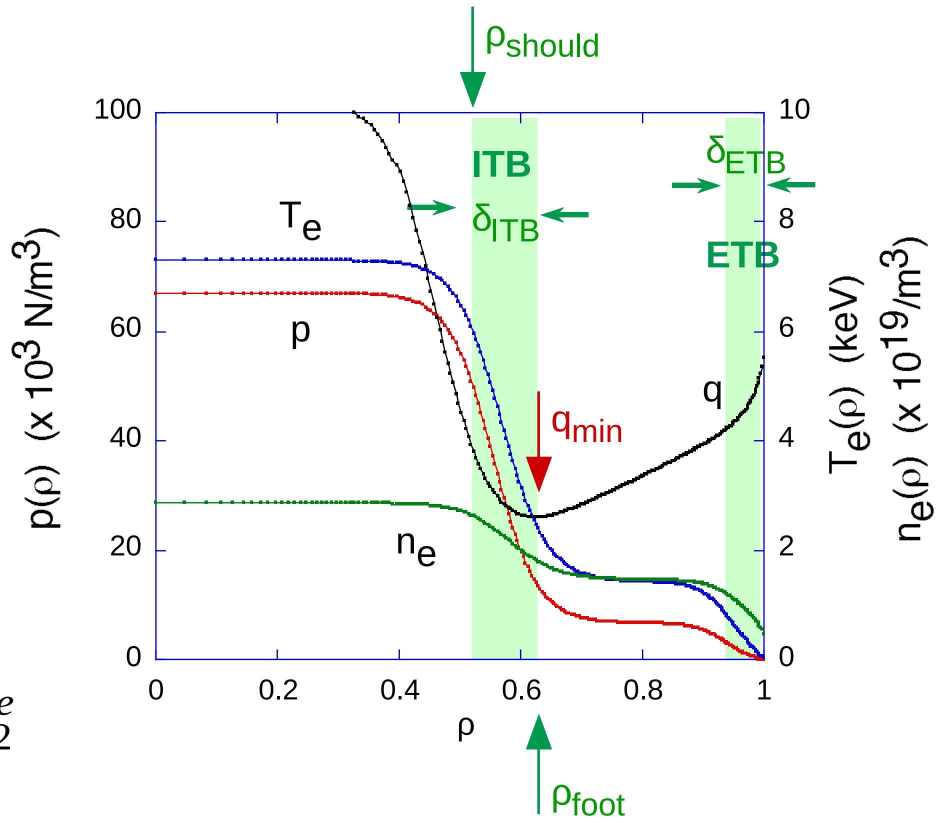
$$\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B} = \eta \boldsymbol{j}_{\mathrm{oh}}$$

- ITB & ETB-generated BS Current

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

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

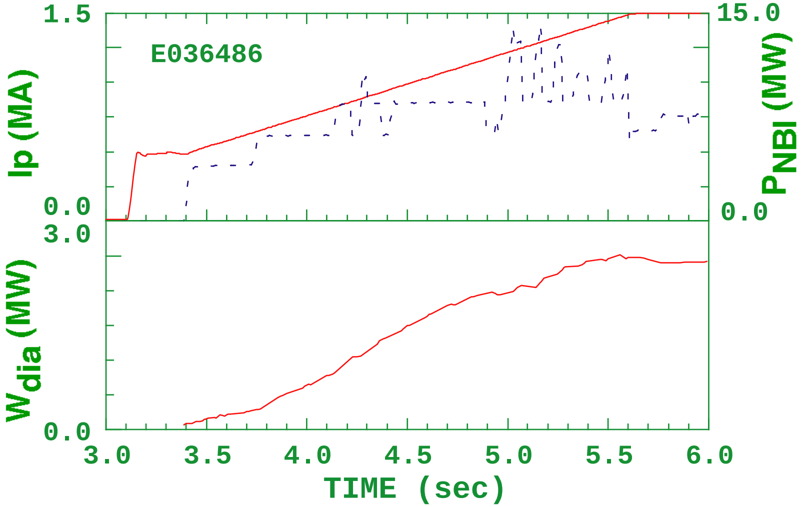
- ITB & ETB Model
  - Prescribed pressure profiles given by functions of hyperbolic tangent of radius (ρ).
  - Radii of ITB-foot & q_{min} monitored were adjusted during TSC simulations.



Standard Ramp-up with ITB-Generated BS Current in JT-60U

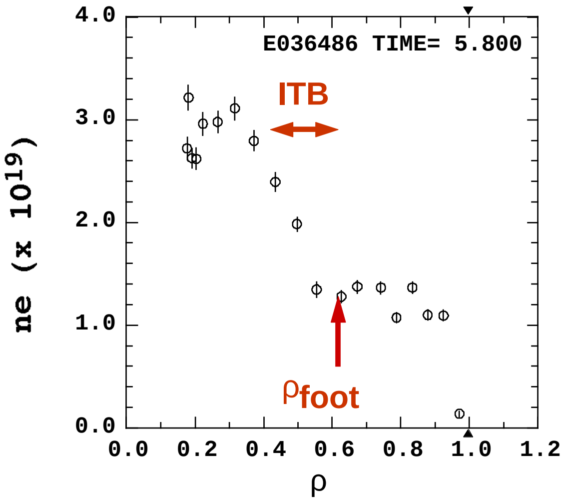
JT-60U

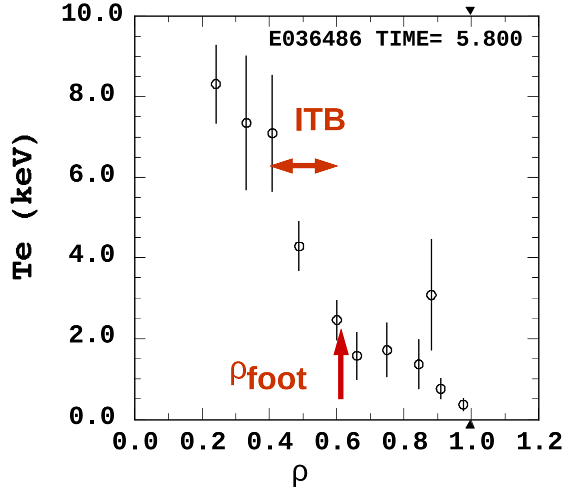
- A well shaped RS discharge of 1.5 MA at 5.8 sec (E36486)

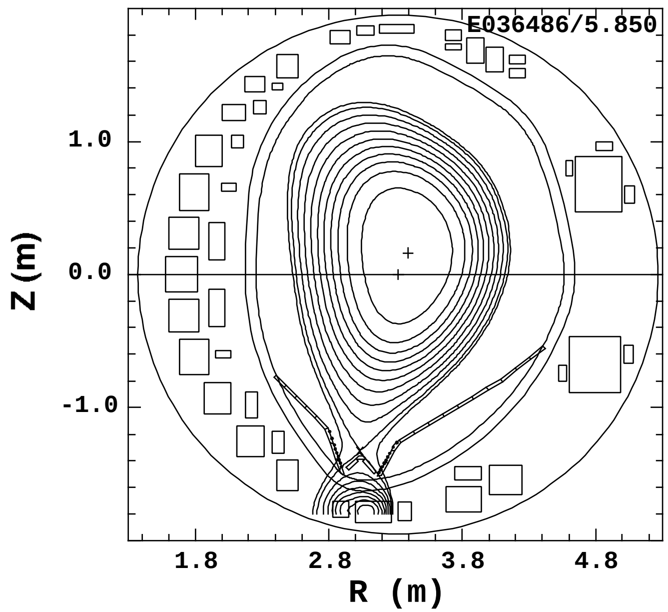


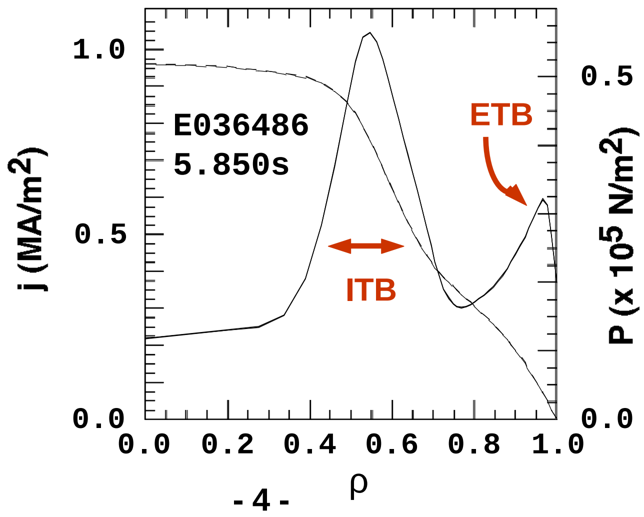
- ρ_{foot} ~ 0.6 from Te(ρ), ne(ρ)
- $\rho(q_{min})$ ~ 0.6 from j(ρ) & q(ρ)

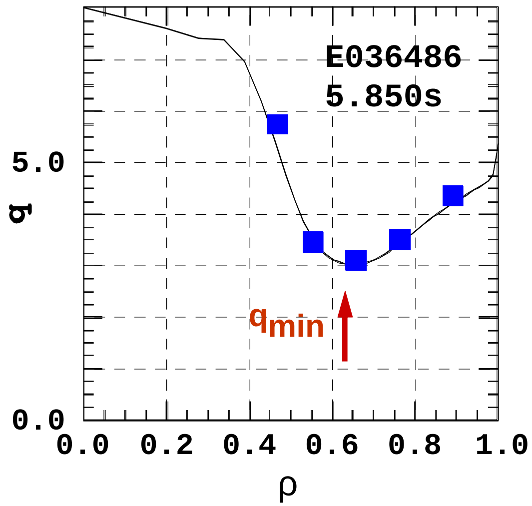
→ ρ_{foot} ~ $\rho(q_{min})$











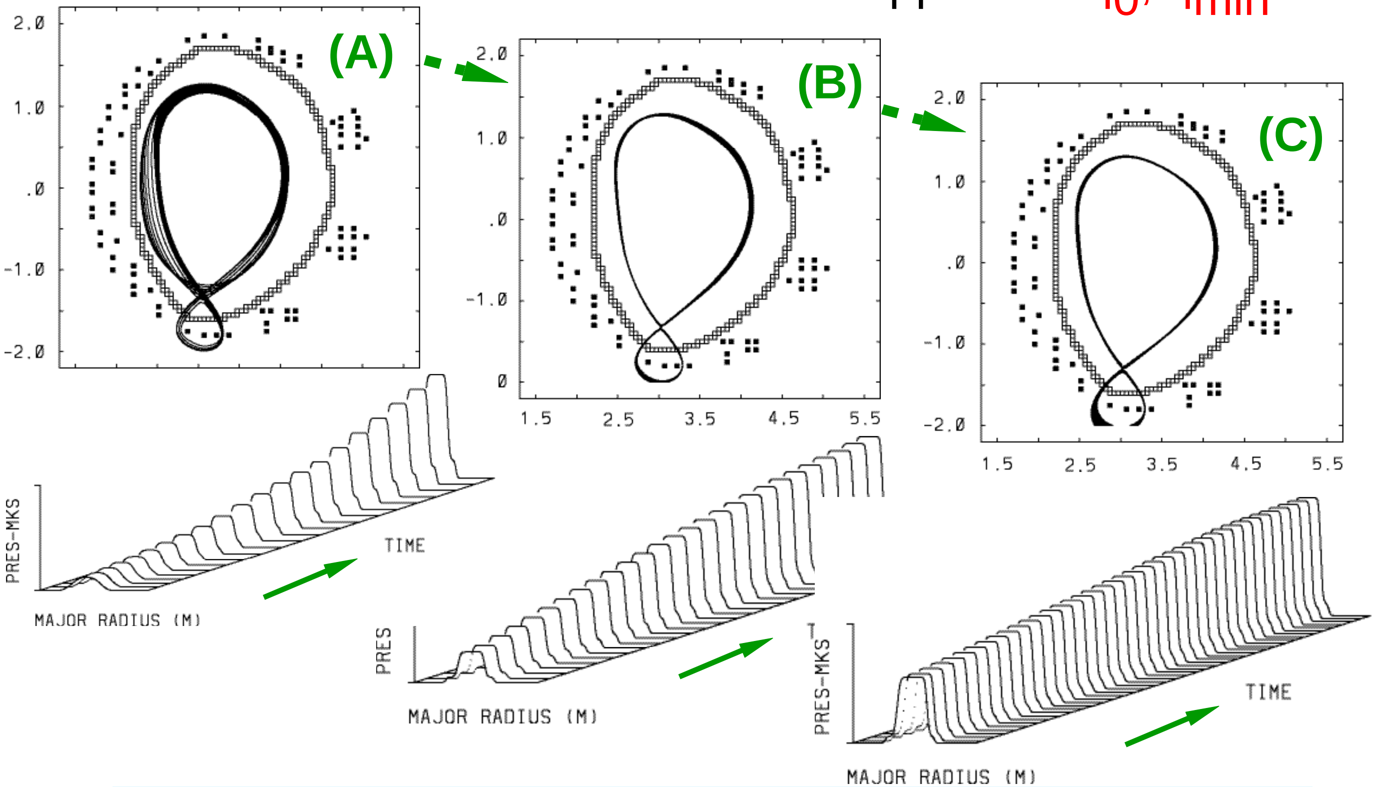
TSC Reproduction of Ip Ramp-up with ITB Model : $\rho_{foot} = \rho(q_{min})$

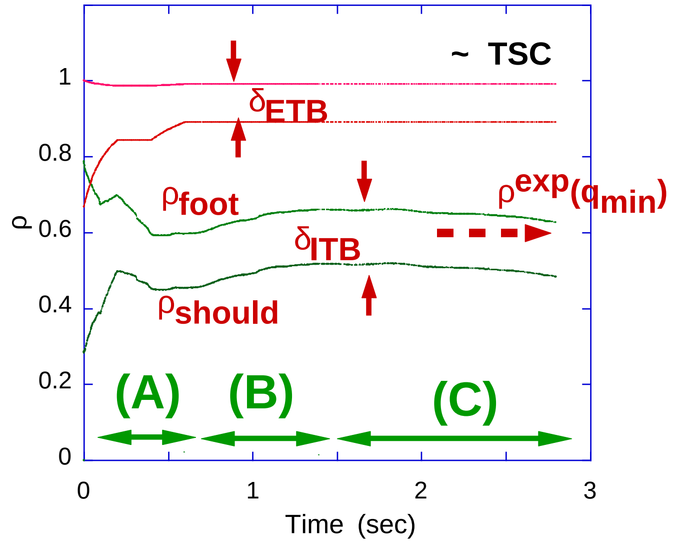
Simulation Inputs :

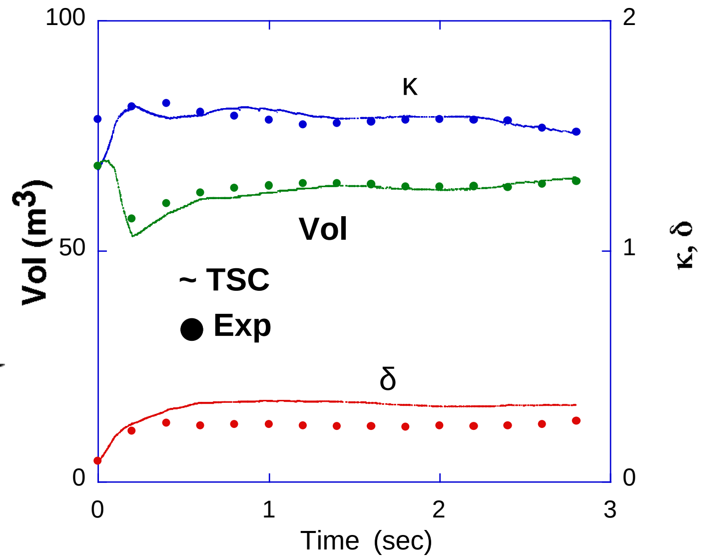
- Initial plasma equilibrium
- PF coil currents in time
- p(ρ), ne(ρ), δ_{ITB} as bellow

Simulation Outputs :

- Position : (Rp, Zp)
- Shape : κ, δ, Vol.
- Ip, I_{bs}, ρ_{foot}, $\rho(q_{min})$
- q-profile : q_0, q_{min}

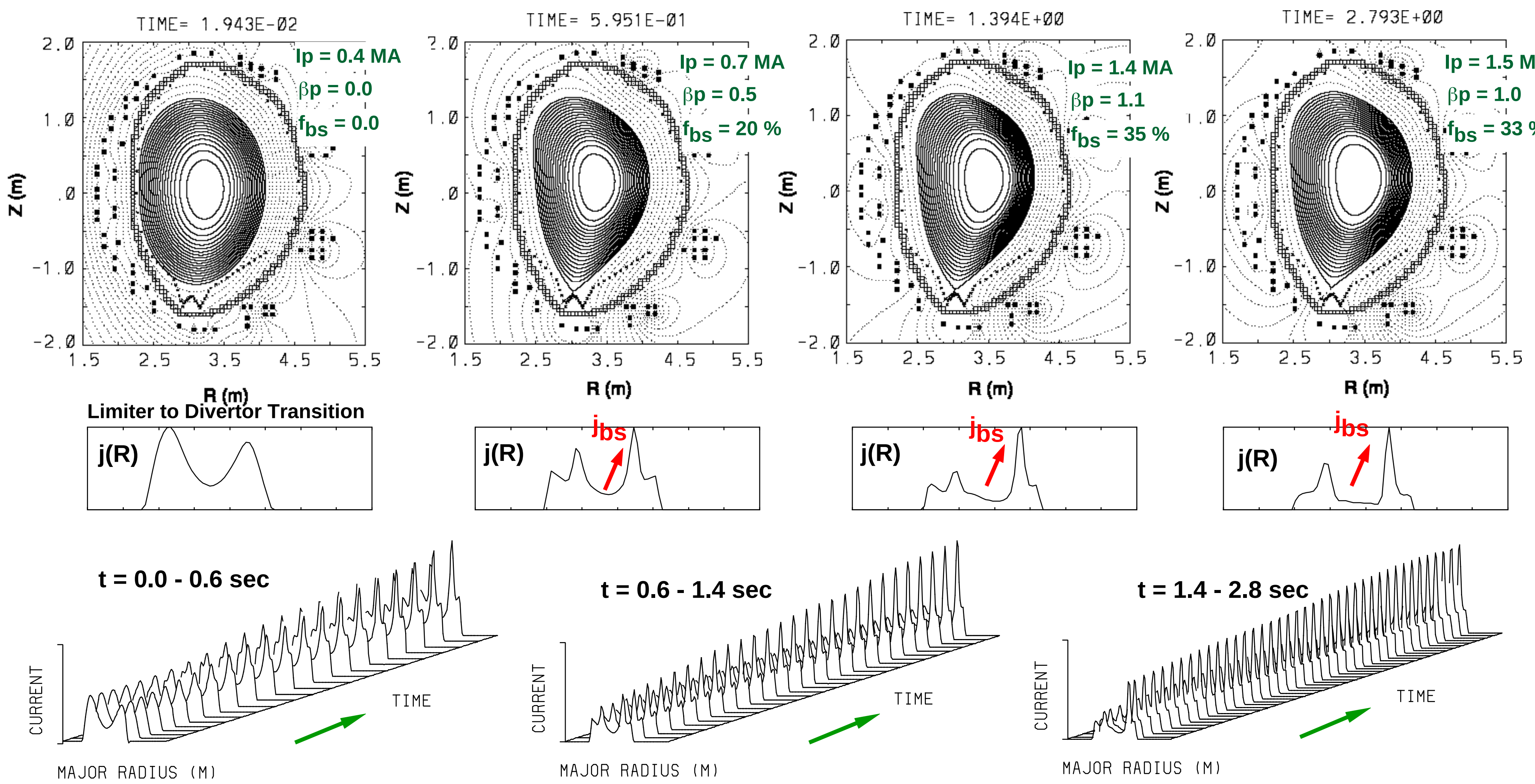






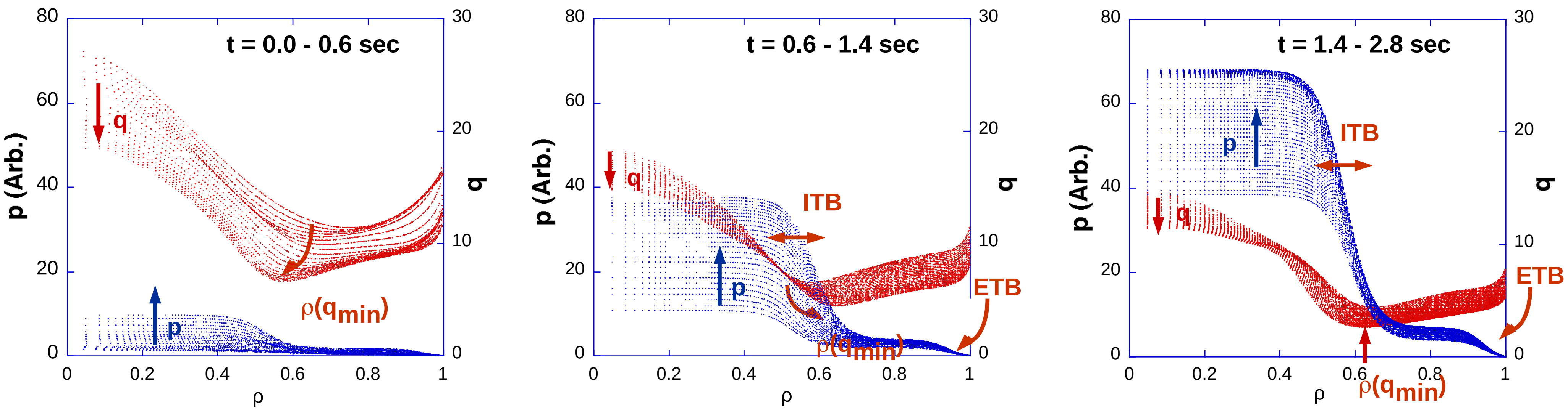
The ITB modeling by self-adjusting ρ_{foot} to $\rho(q_{min})$ results in a remarkable recover of E36486 ramping-up.

Time-Evolution of Equilibria & Current Profile (TSC)

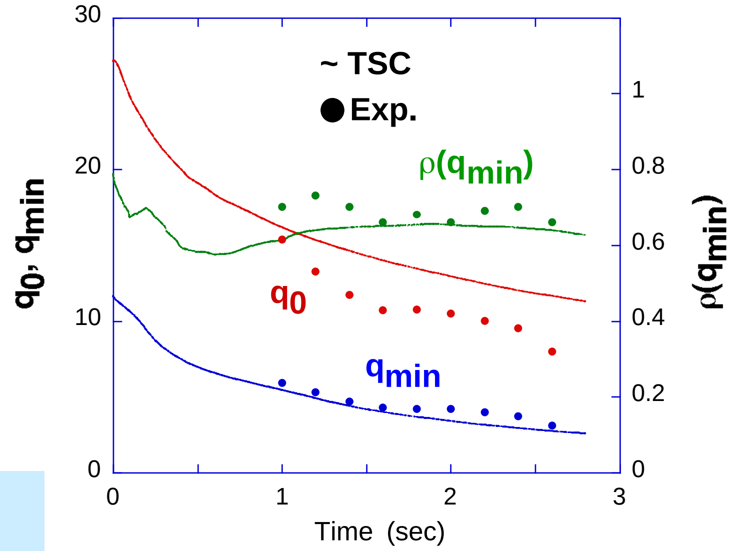


Almost exact plasma shape and very similar j-profile to E36486 was recovered by the ITB model of $\rho_{foot} = \rho(q_{min})$.

Time-Evolution of q-Profile (TSC)

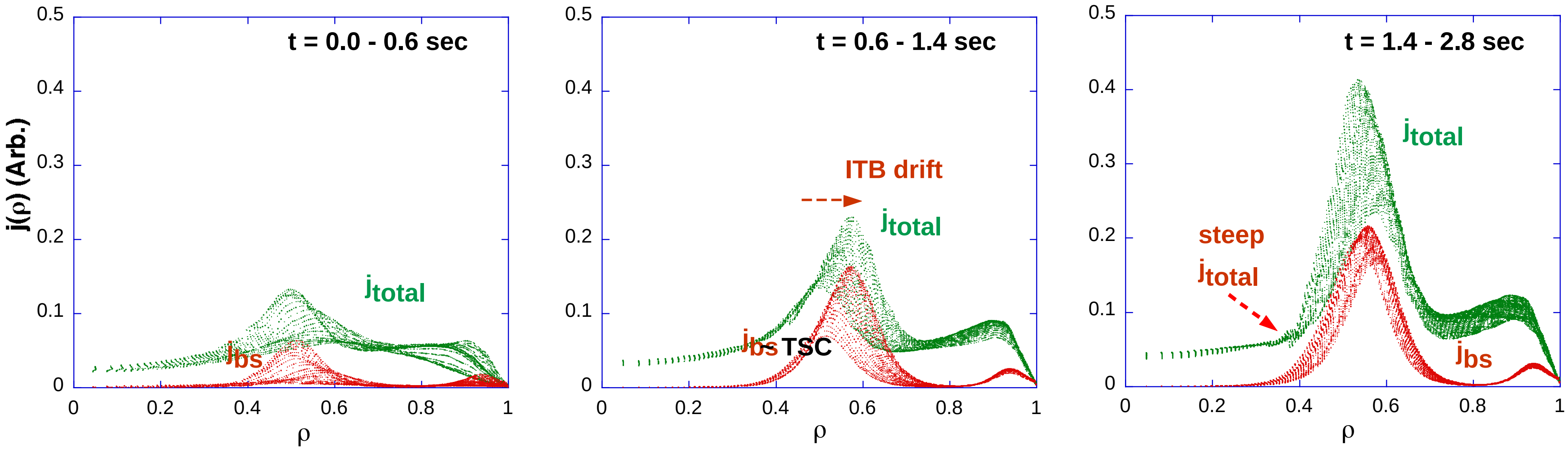


- The ITB location (ρ_{foot}) drifts to ~ 0.6 as well as the experiment of $\rho(q_{min})$.
- q_{min} of TSC agrees with the experiment (~ 3.0).
- q_0 of TSC (~ 11.0) seems larger than the experiment (~ 8.0).

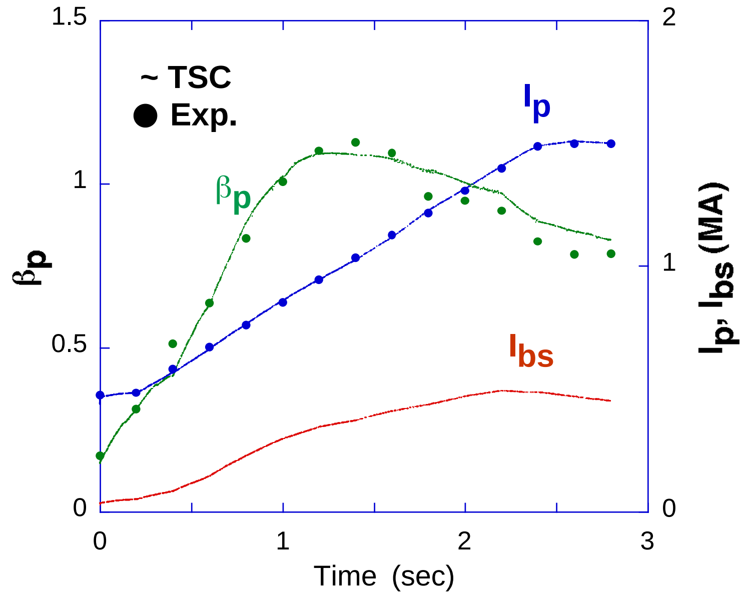


The ITB modeling of $\rho_{foot} = \rho(q_{min})$ can provide similar evolution of $q(\rho)$ to the experiment of E36486.

Time-Evolution of Current Profile (TSC)



- $j_{total}(\rho)$ is localized at ρ ~ 0.6 as experiment, because of the localization of under-drive BS current.
- BS current fraction (f_{bs}) was 40 % at most.
- After a substantial BS current drived, a steep profile of $j_{total}(\rho)$ just inside of ITB region is appearing.



TSC building-up of plasma current was in good agreement with experiment (E36486).

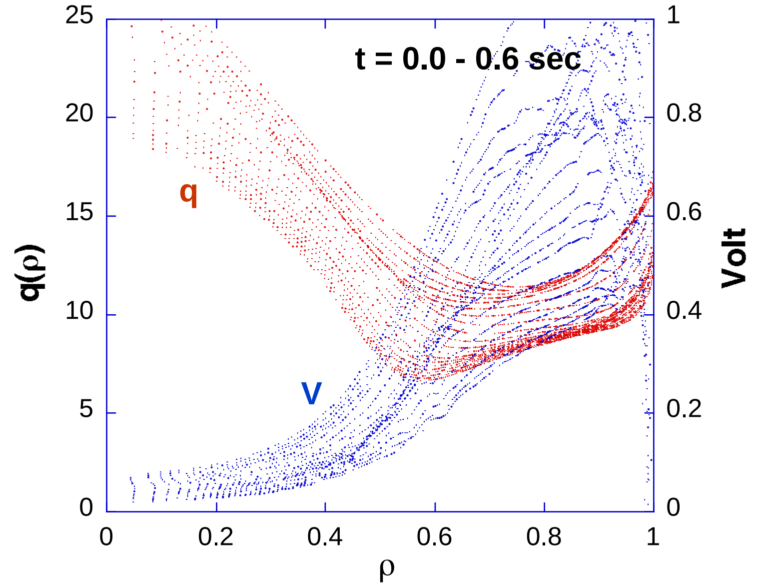
Time-Evolution of E-Profile (TSC)

JT-60U

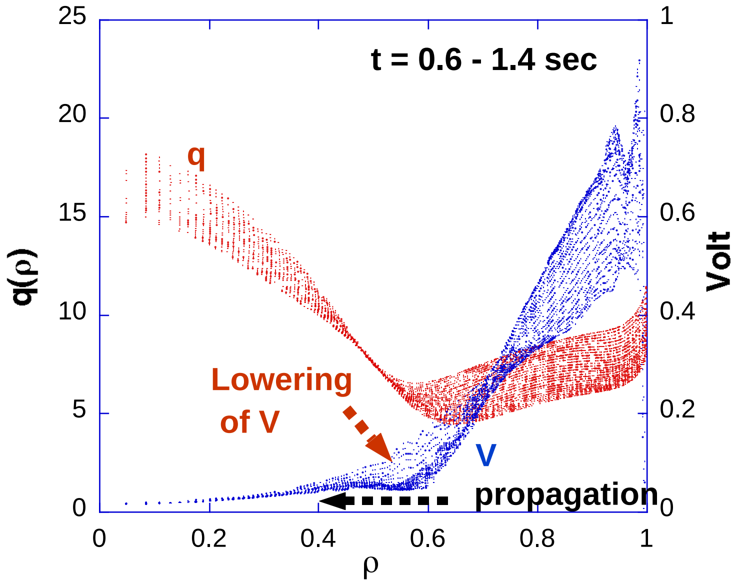
- At initial phase of t = 0.0 -0.6 sec, electric field is decreasing as the plasma temperature arises.
- As BS current increases in accordance with ITB (t = 0.6 - 1.4 sec), total current becomes to locally distribute around the ITB.

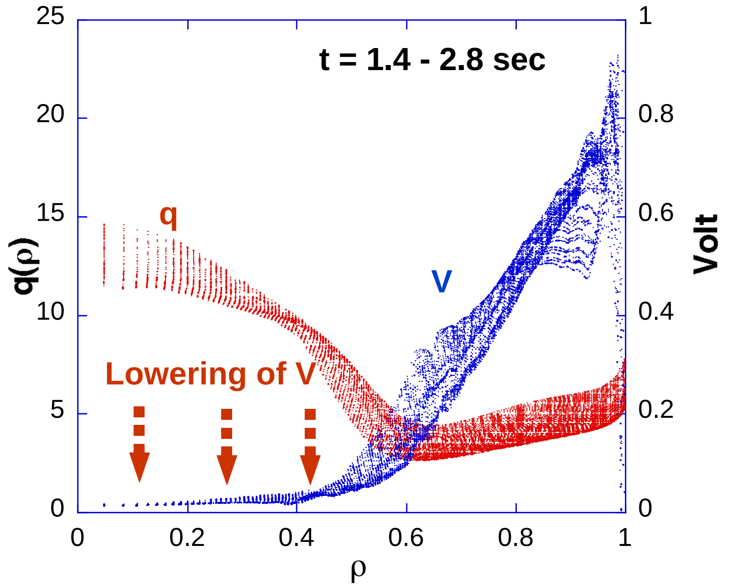
  → lowering of electric field around the ITB

- The low electric field is propagating to plasma core region, and makes a lowering of electric field there, but BS current is still an under-drive.



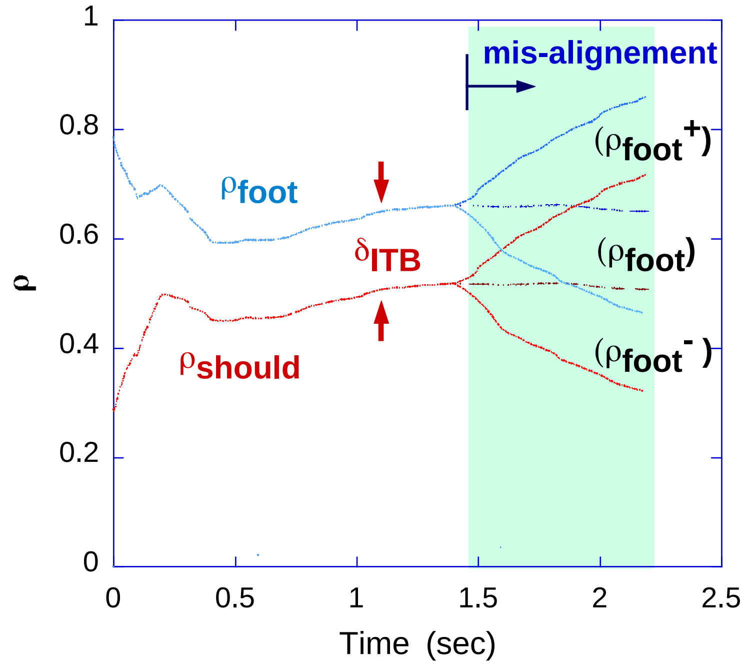
E-profile with a strong deformation evolves in accordance with the locality of BS current distribution.

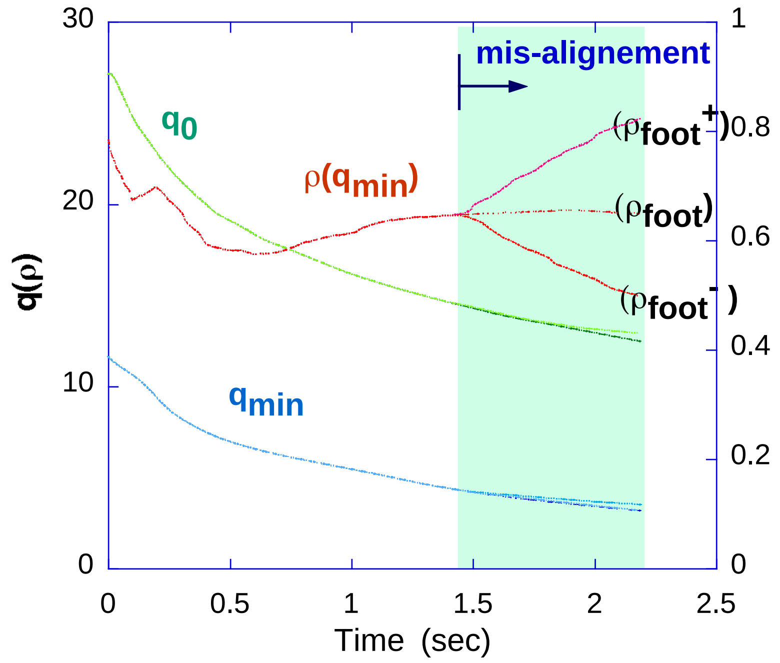




When ρ_{foot} disagrees with $\rho(q_{min})$, how the ITB is moving?

- Motivation induced by the interest of operational reactor scenarios & power estimation of non-inductive, external control of current profile, e.g. NNBI, LHCD, ECCD, FW etc.





mis-alignements starts at 1.4 sec.

Outside Offset : ρ_{foot}^{+}

$= \rho(q_{min}) + \delta_{ITB}/4$

Inside Offset : ρ_{foot}^{-}

$= \rho(q_{min}) - \delta_{ITB}/4$

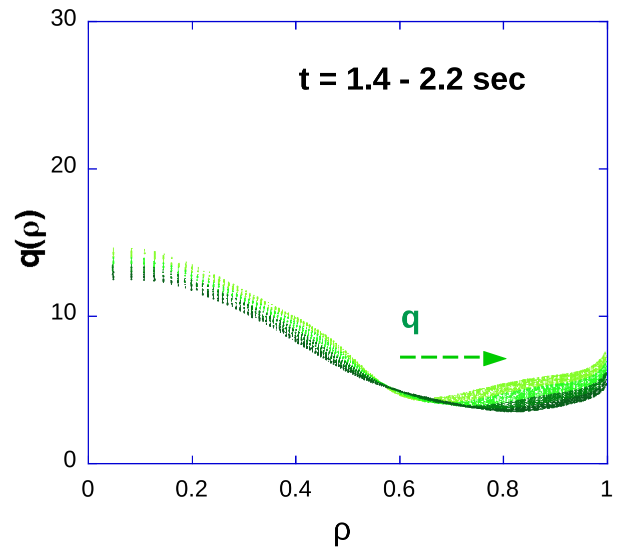
- Small mis-alignement of ρ_{foot} with $\rho(q_{min})$ leads to outward or inward drift of ITBs.
- During the ITB drift, both q_0 and q_{min} is almost unchanged.

Although outward-going and inward-going property looks like symmetric, time-evolutions of current, electric field and q-profiles are quite different as Next.

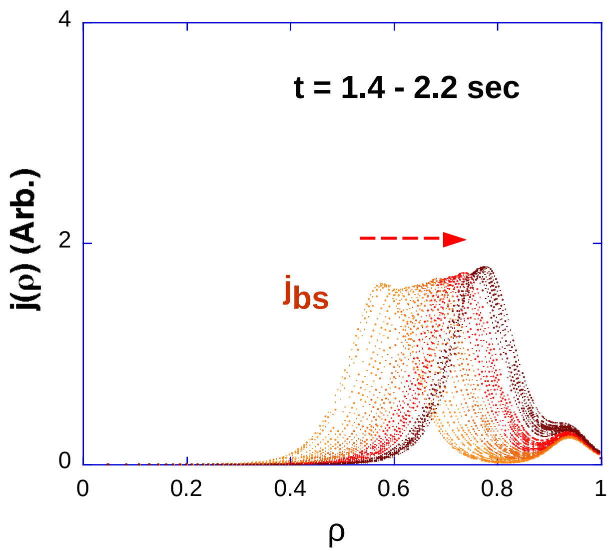
ITB-Expansion for an Outside Offset : $\rho_{foot} > \rho(q_{min})$

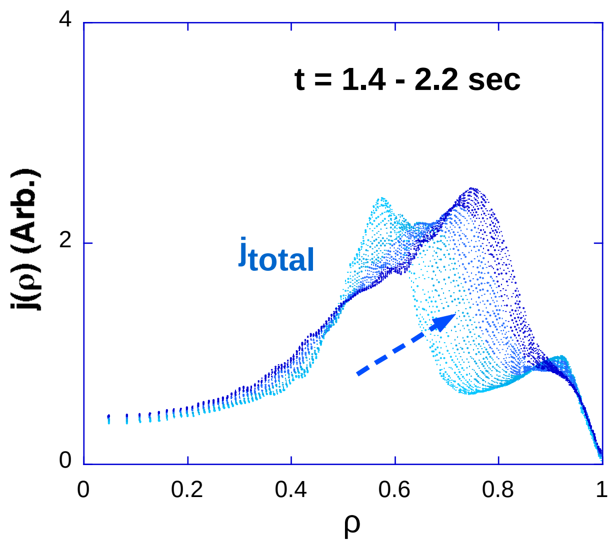
JT-60U

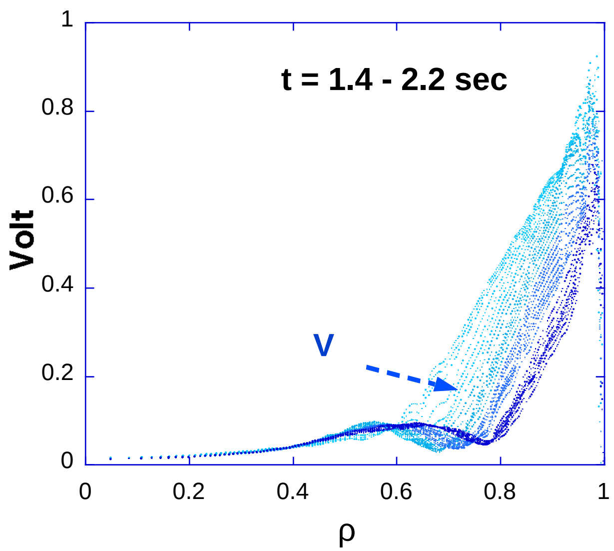
- Time-evolution of q-profile and j_{bs} is almost uniform, parallel, outward-going.
- j_{total} looks outward-going as well, leaving its tracing field behind.
- The electric field profile (V) has a weak deformation.
- Finally, expanding ITB becomes to marge with ETB.



ITB-expansion arising from mis-alignement of $\rho_{foot} > \rho(q_{min})$ is nearly uniform, parallel, outward-going.







ITB-Shrinkage for an Inside Offset : $\rho_{foot} < \rho(q_{min})$

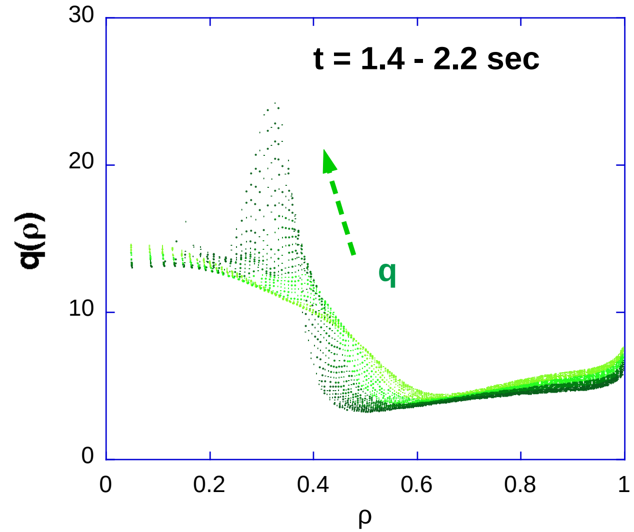
- A remarkable localization of q-profile and electric field appears in the inside front of shrinking ITB.
- BS current j_{bs} is not parallel moving, but substantially increases.

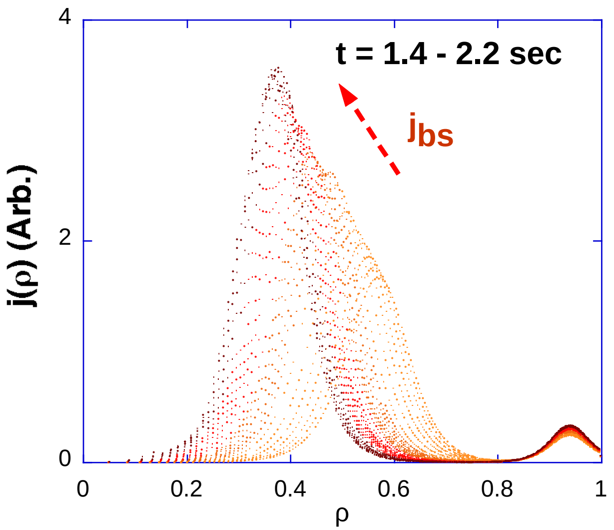
$$j_{bs} \approx -\frac{\sqrt{\varepsilon}}{B_p}\frac{dp}{dr}$$

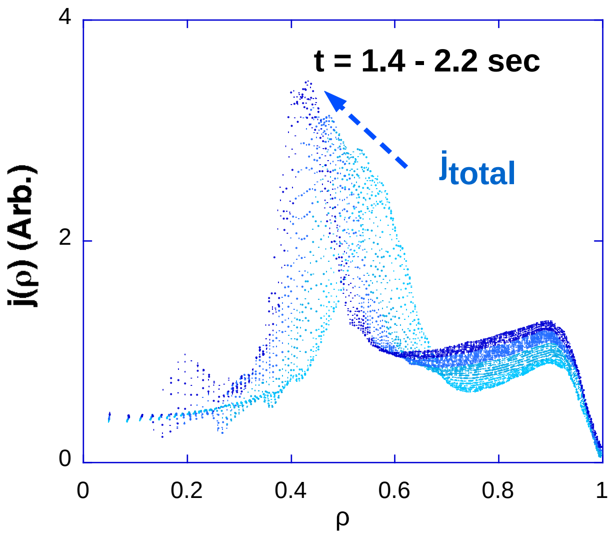
- In the inside front of shrinking ITB, increasing BS current j_{bs} becomes over-drive than j_{total}.

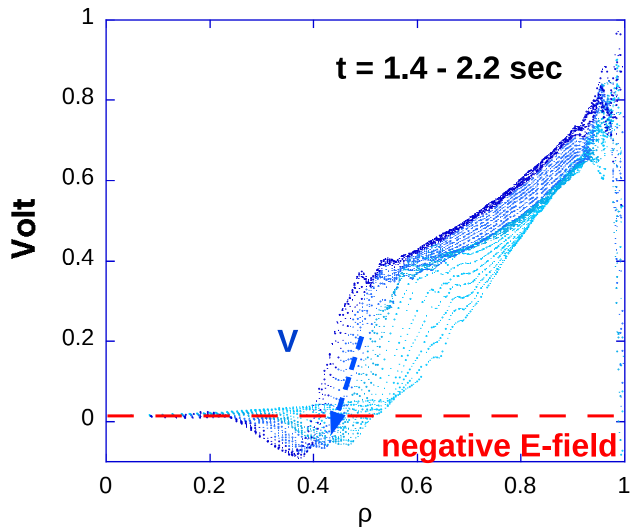
→ Over-drive BS current leads to negative E-field there.

ITB build-up near plasma core region is more easy to dig out the ohmic current from the ITB region.



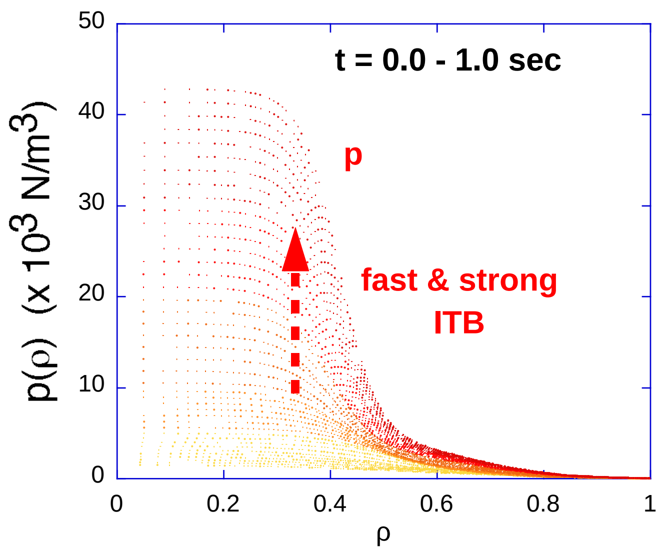


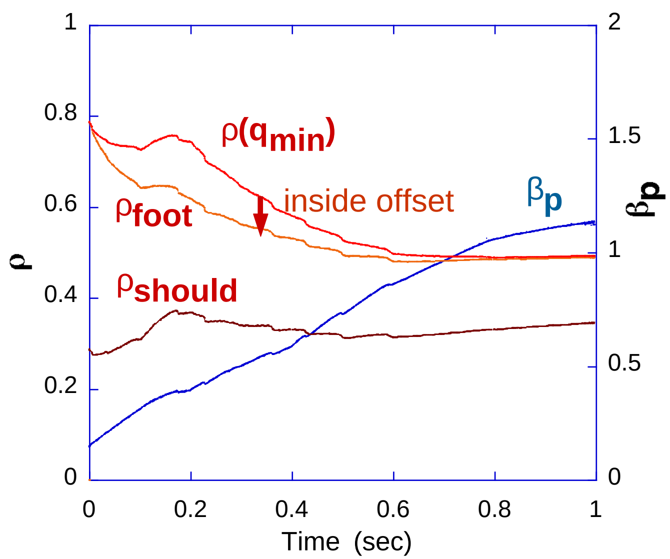


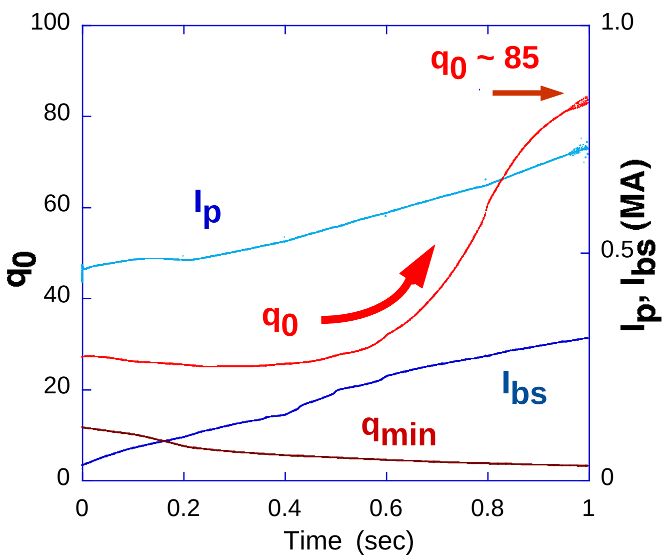


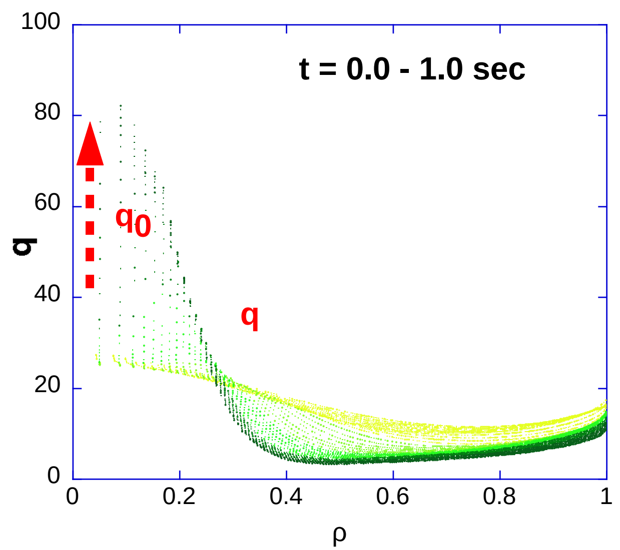
TSC Simulation of Current Hole Formation

- By inputting an inside offset of fast & strong ITB in TSC, ITB moved to ρ_{foot} ~ 0.5 at t = 0.6 sec.
- Ip and I_{bs} continue to ramp-up in simulation as well as E36486
- A remarkable increase of q_0 appeared, then q_0 went more than 80 at t =1.0 sec.







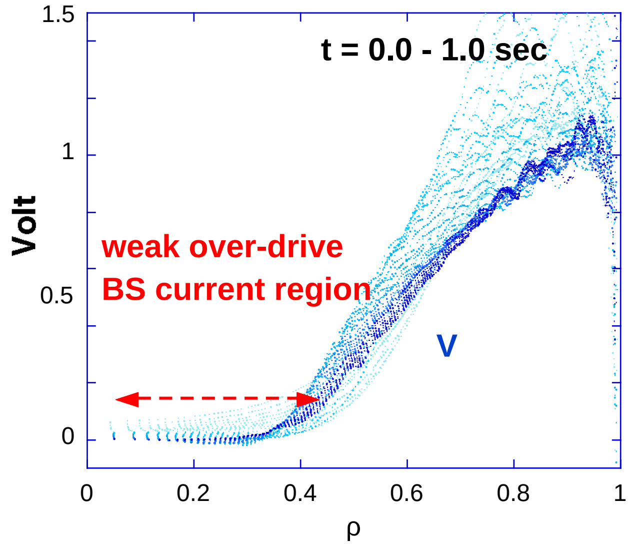


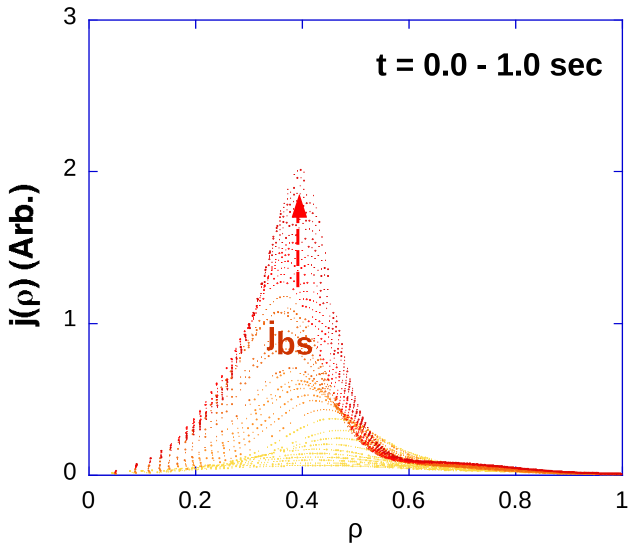
Current Hole Formation due to Over-Drive BS Currents

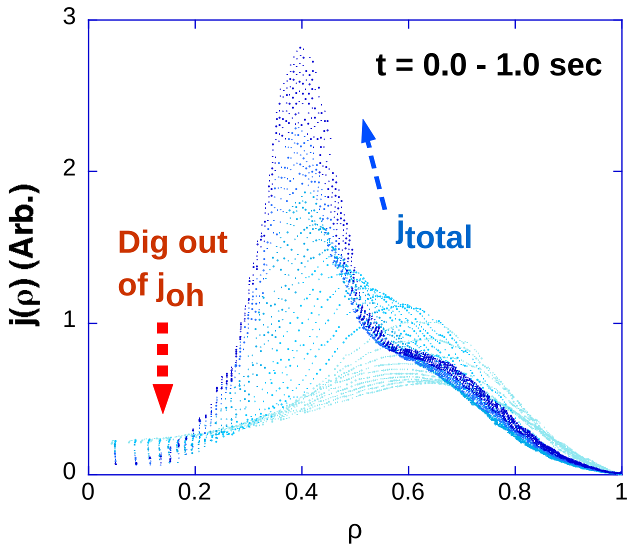
JT-60U

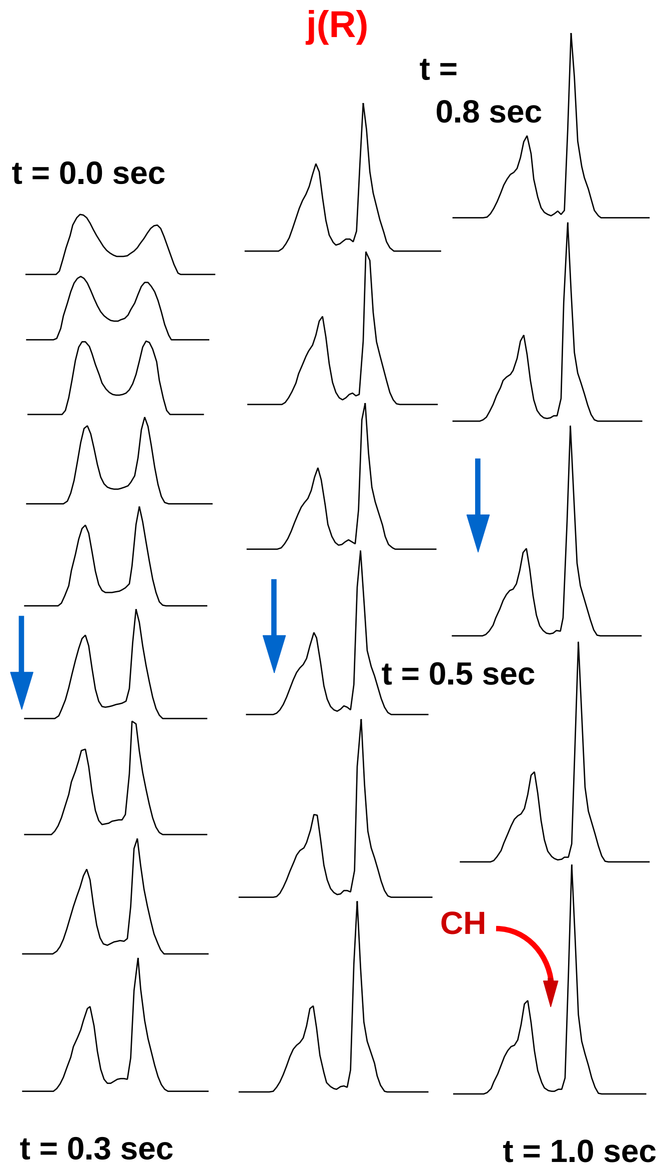
- After t = 0.5 sec, BS current becomes over-driving for wider region inside of ITB.
- In consequence, weak negative electric field digs out the ohmic current from ITB region.

Current Hole





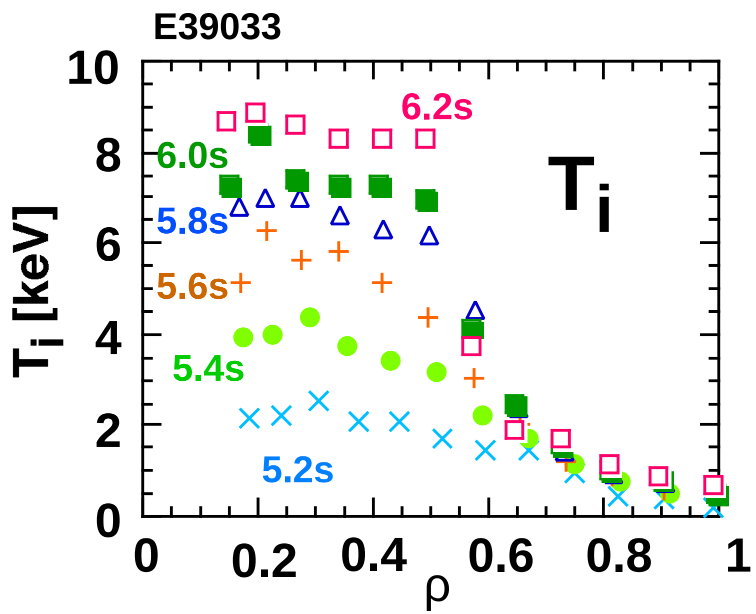


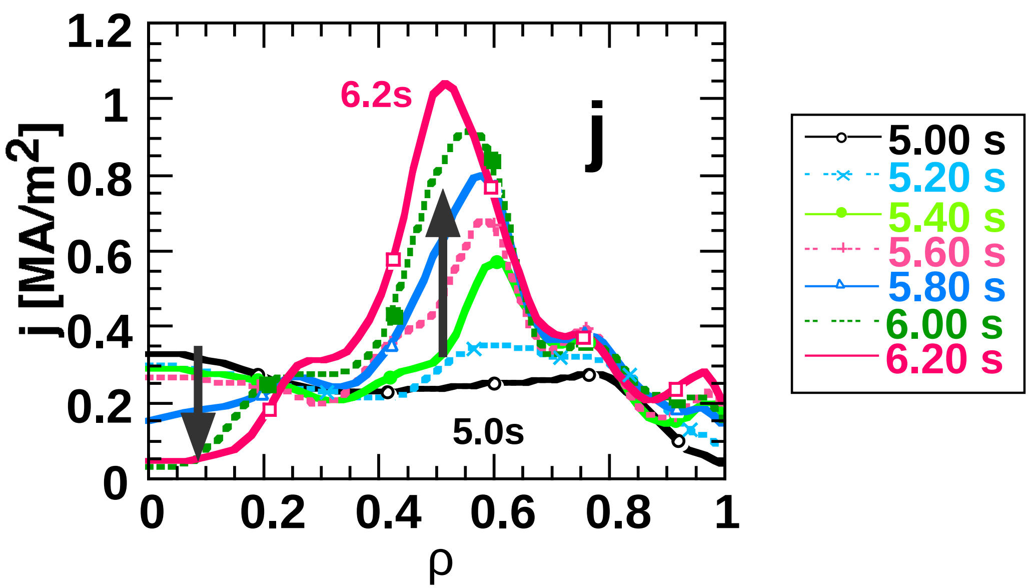


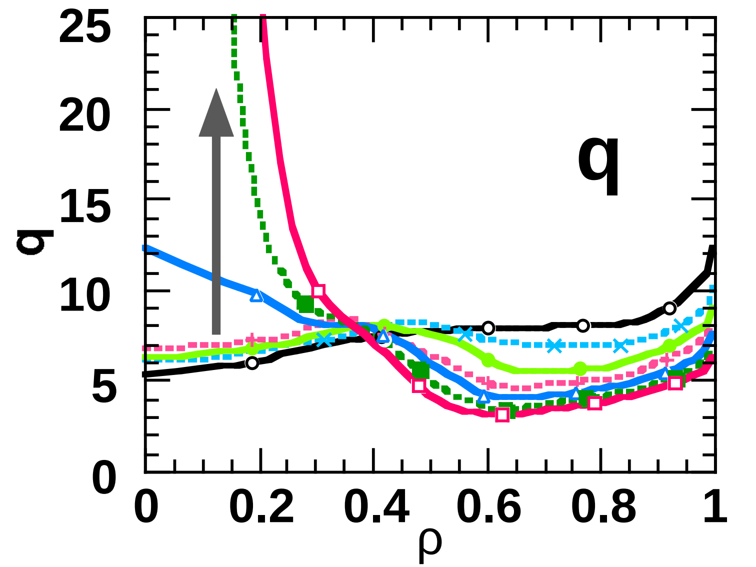
Discovery of Current Hole in JT-60U

- In plasma core region, an area w/o any of Bp was discovered in JT-60U & JET (Current Hole).
  - ITB build-up
    → Off-axis BS current increase
      → j(0) decrease & q(0) rise
  - Formation of Current Hole as single fluid TSC

Stable Current Hole remained alive for several sec.







Summary

- A simple ITB & ETB model was installed in time-evolution MHD code (TSC).
- Current ramp-up with associated BS current was studied for a tokamak operational purpose.
- A specific ramp-up of JT-60U RS discharge was reproduced by the TSC, when the ITB-foot adjusts to the magnetic shear reversal.
- A fast and strong ITB build-up near plasma core was pointed out to cause an over-drive bootstrap current inside the ITB region.

→ The TSC has demonstrated an example process of Current Hole formation.

Following issues are listed for Future Study

- Ramp-up optimization without Center Solenoid for reactor
- ITB model improvement using transport model instead of prescribed pressure
- Possibility of slow ramp-up to reduce AC loss of SC coils in reactor
- External control to expand the ITB region & power estimation of the control