EX1-4

Evolution of Bootstrap-Sustained Discharge in JT-60U

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21st IAEA Fusion Energy Conference
Chengdu, China
16 - 21 October 2006

Outline

- Introduction
  - Motivation and Objective
- Experimental Results
  - Bootstrap-driven discharge (f_{BS} ~ 1)
    - Evolution of self-sustained phase
    - Comparison with high f_{BS} discharge (f_{BS} ~ 0.9)
  - Bootstrap overdrive ($f_{BS} > 1$)
- Conclusions

Motivations and Research Objectives

- External power required to drive the necessary I_p has a large impact on the recirculating power fraction, and therefore on the cost of electricity.
  - Study characteristics and controllability of plasmas with $f_{BS} \sim 1$
- If BS overdrive ($f_{BS} > 1$) could be achieved, this may be used for I_p ramp-up. In this case requirements for external current drive can be reduced substantially.
  - Demonstration of BS overdrive

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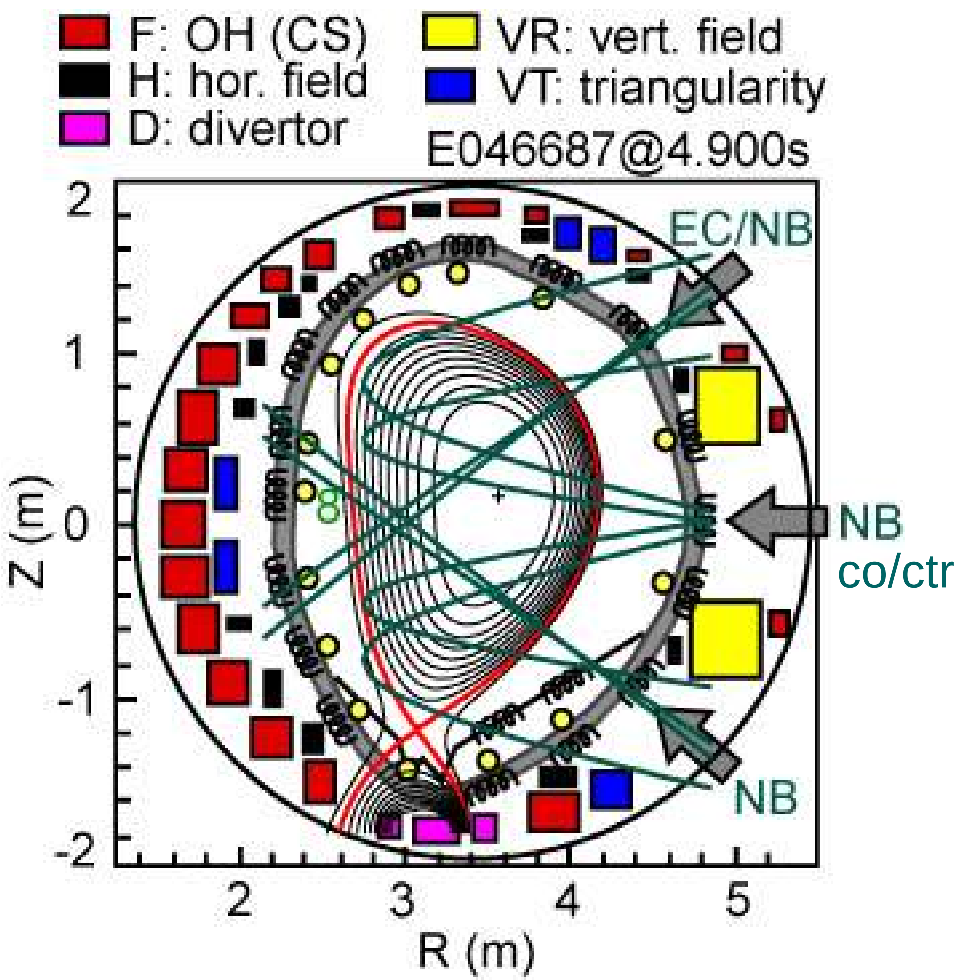
Fundamental impact on designs of ST reactors and “slim-CS” tokamak reactors with limited central solenoid (CS) capability.

JT-60U Coil System and Operational Scenarios

JT-60U Coil Configuration



Surface loop voltage is given by

$V_l = -M_{l,OH}\dot{I}_{OH} - \Sigma M_{l,PF}\dot{I}_{PF} - L_{ext}\dot{I}_p$

3 types of control scenarios:

- constant I_p
  $L_{ext}\, dI_p/dt = 0$
- constant OH coil current
  $M_{l,OH}\, dI_{OH}/dt = 0$
- constant surface flux
  $V_l = 0$

$B_t = 3.7 - 4.0$ T
$I_p = 0.5 - 0.6$ MA
($q > 10$)

Power Balance for Ramp-up Experiment

Poynting flux across the plasma surface is kept at zero.

$$V_l I_p = P_{ext} - dW_m^{ext}/dt$$
$$= dW_m^{int}/dt \boxed{- P_{el}} + \boxed{V^2/R_{Sp}}$$

$\uparrow$ $\int \mathbf{E}\cdot\mathbf{j}_{NI} dV$ $\quad$ $\uparrow$ $\int \mathbf{E}\cdot\mathbf{j}_{OH} dV$

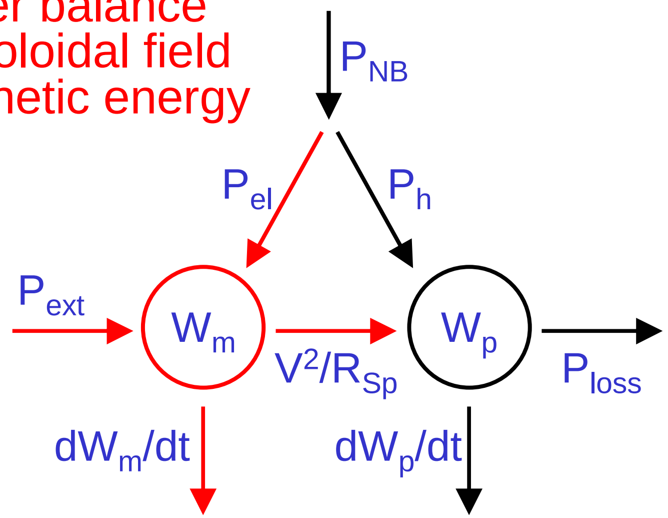
$I_p = I_{NI} + V/R_{Sp}$; $I_{NI} = I_{CD} + I_{BS}$;

$P_{ext} = V_l^{ext} I_p$; $P_{el} = - V I_{NI}$;

$W_m^{ext} = L_{ext} I_p^2/2$; $W_m^{int} = L_{int} I_p^2/2$;

$W_m = W_m^{ext} + W_m^{int}$

power balance
for poloidal field
magnetic energy



Overdrive power $(I_{NI} > I_p)$

$P_{el} = dW_m/dt - P_{ext} + V^2/R_{Sp} > 0$
for ramp-up

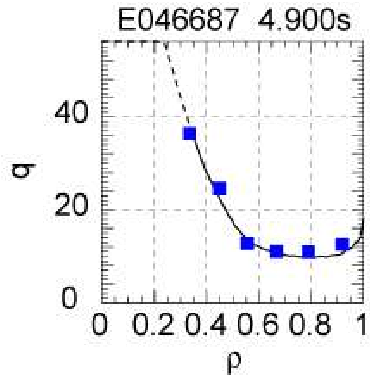
For constant flux control $(V_l I_p = 0)$

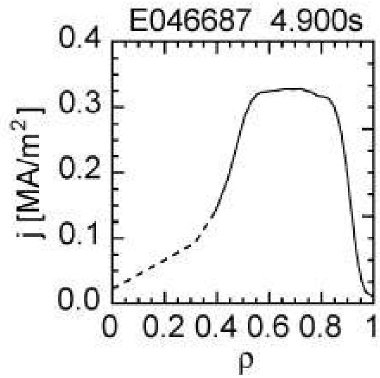
$dW_m^{int}/dt = P_{el} - V^2/R_{Sp} \cong P_{el} > 0$
for ramp-up

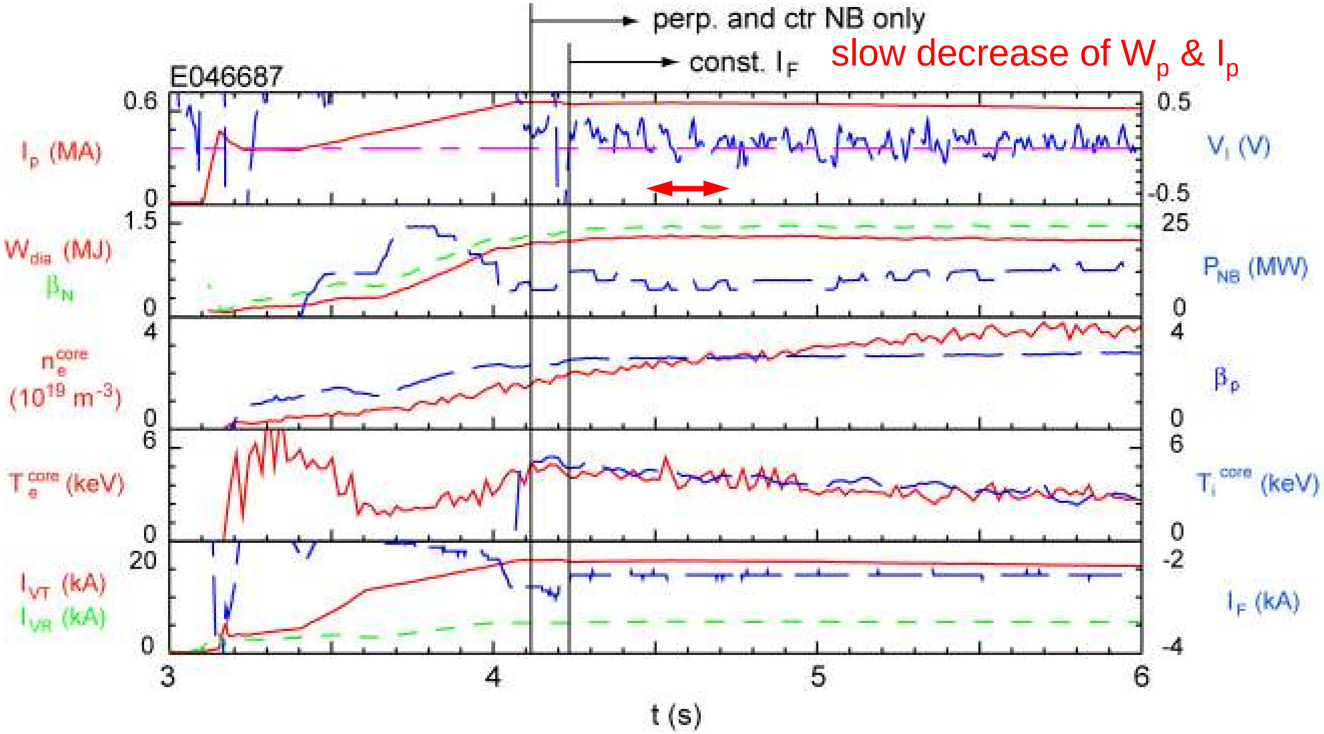
$P_{ext} = dW_m^{ext}/dt > 0$ is supplied by the external circuit.

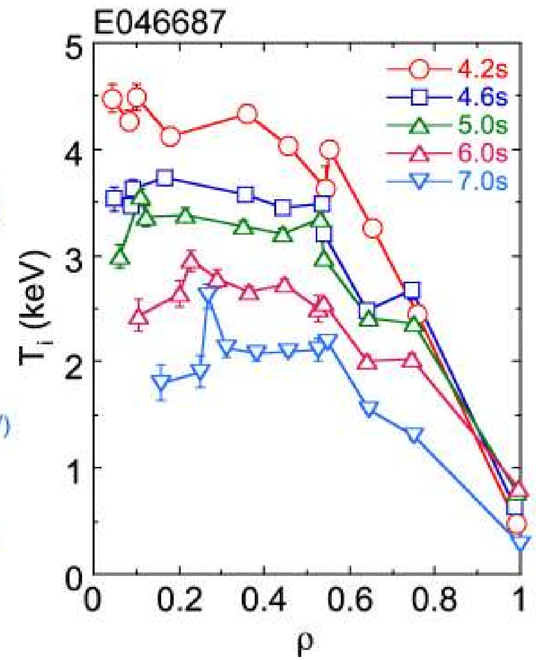
Fully Bootstrap-Driven Discharge

- Fully BS-driven plasma is realized
- Duration of self-sustained phase is limited by slow confinement degradation (this case), or by β collapses



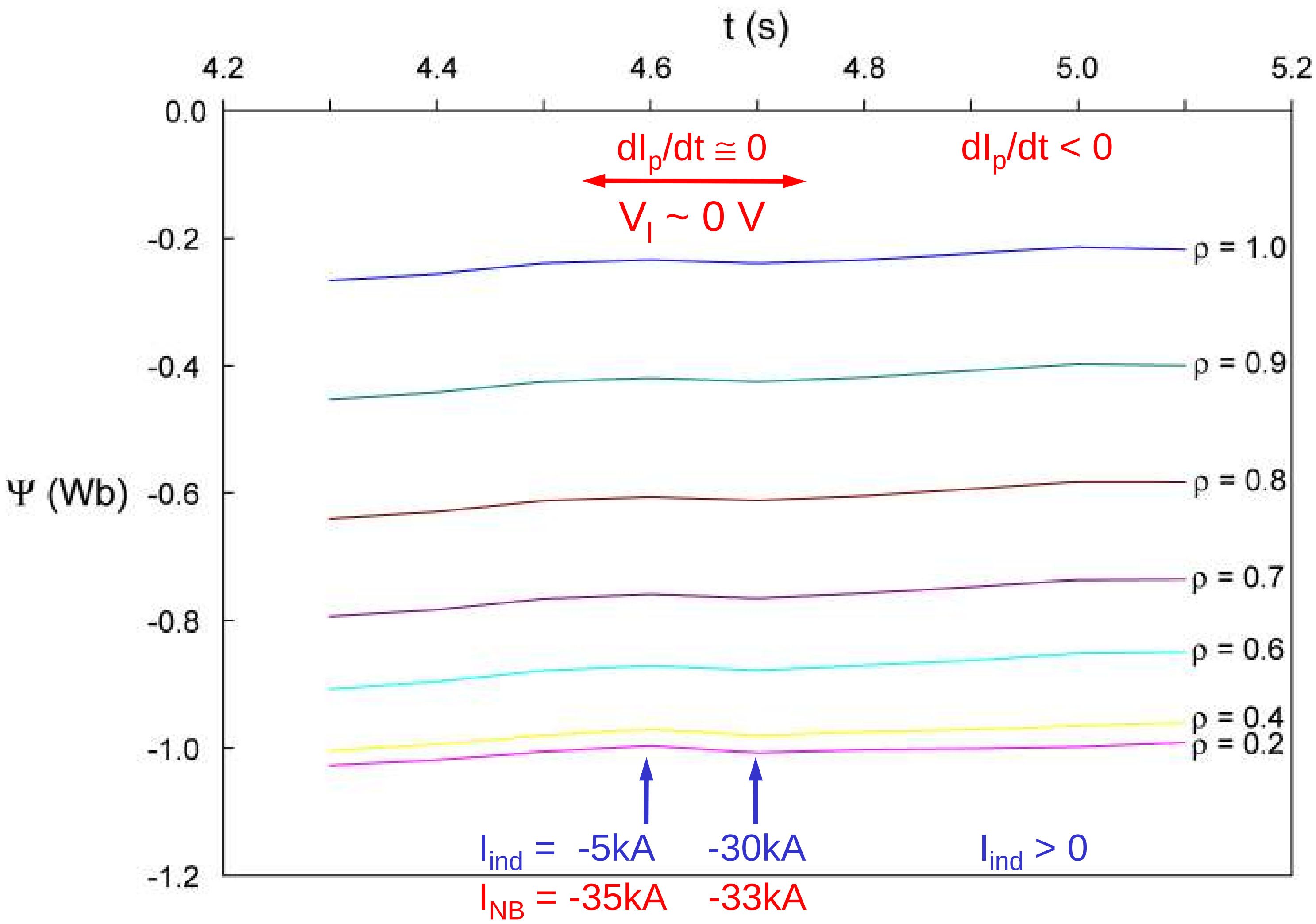






Loop Voltage is Kept Nearly Zero for 0.2 s

MSE-based reconstruction: Poloidal flux is nearly constant for ~ 0.2 s.



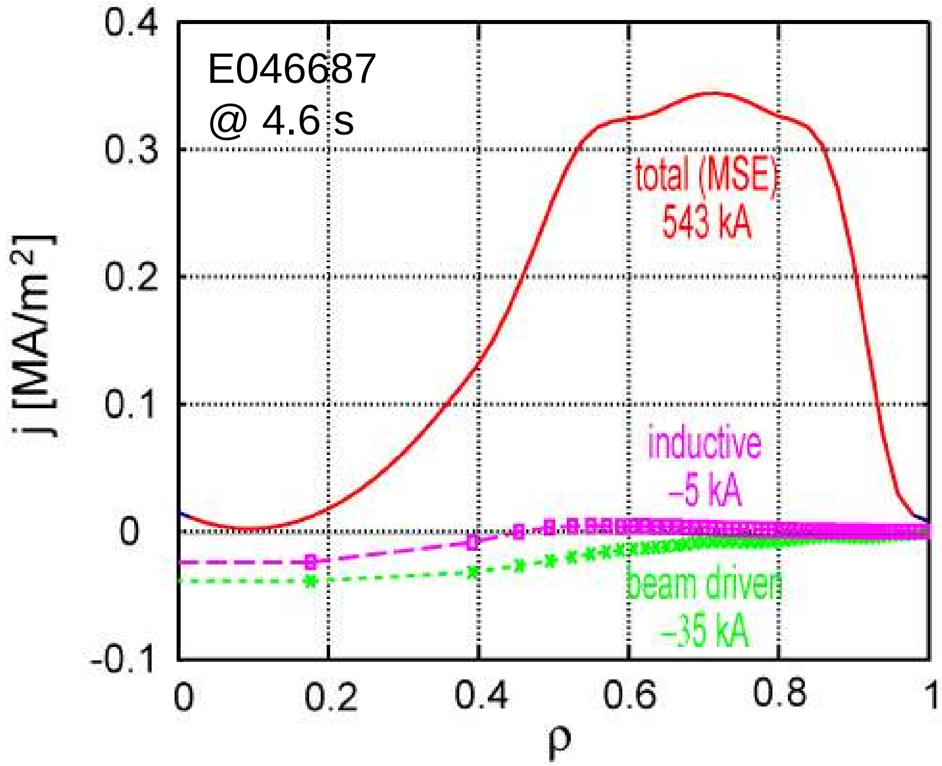
Bootstrap-Sustained Discharge

Total current = 543 kA (MSE)

Inductive current = -5 kA (calculated from V_l profile)

Beam driven current = -35 kA (calculated by OFMC/ACCOME)

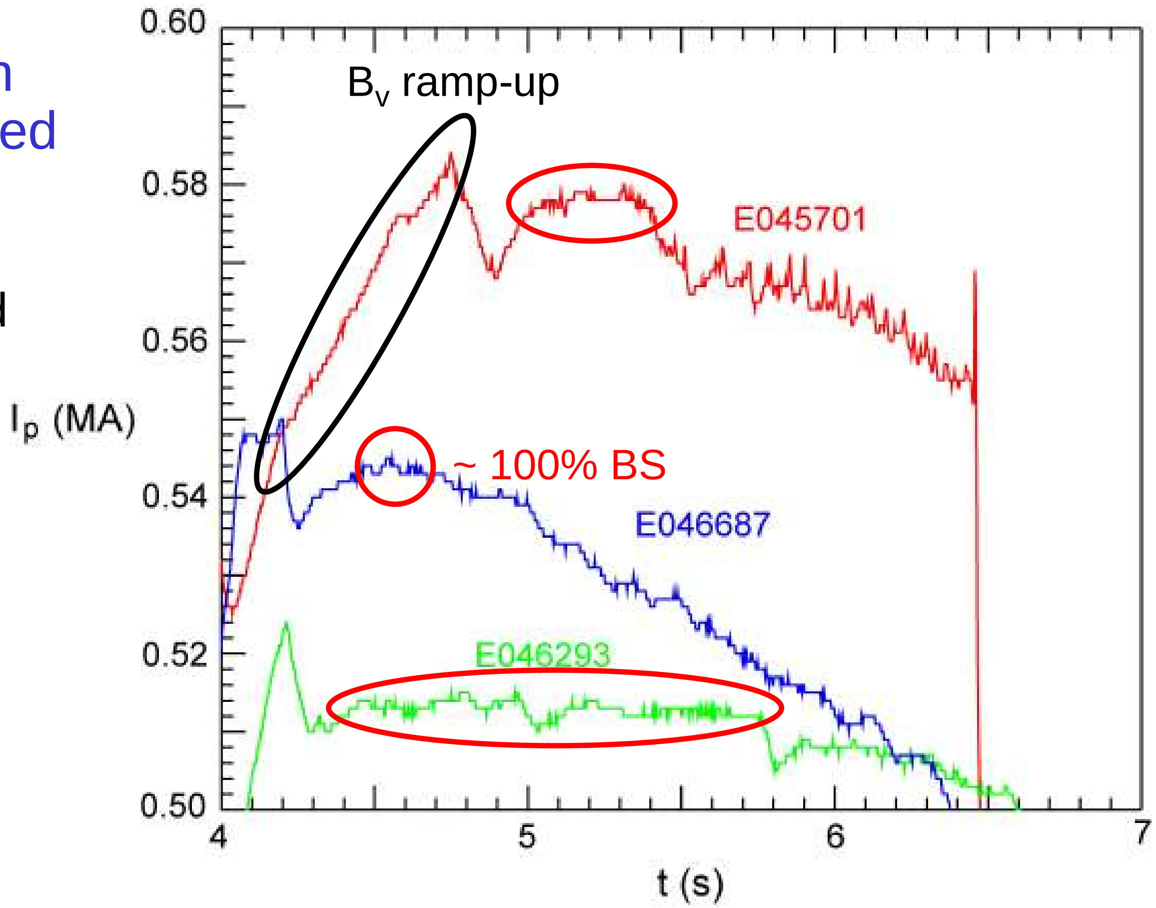
$\rightarrow$ Bootstrap current = 583 kA (possibly slight overdrive)



Examples of BS-Sustained Plasma

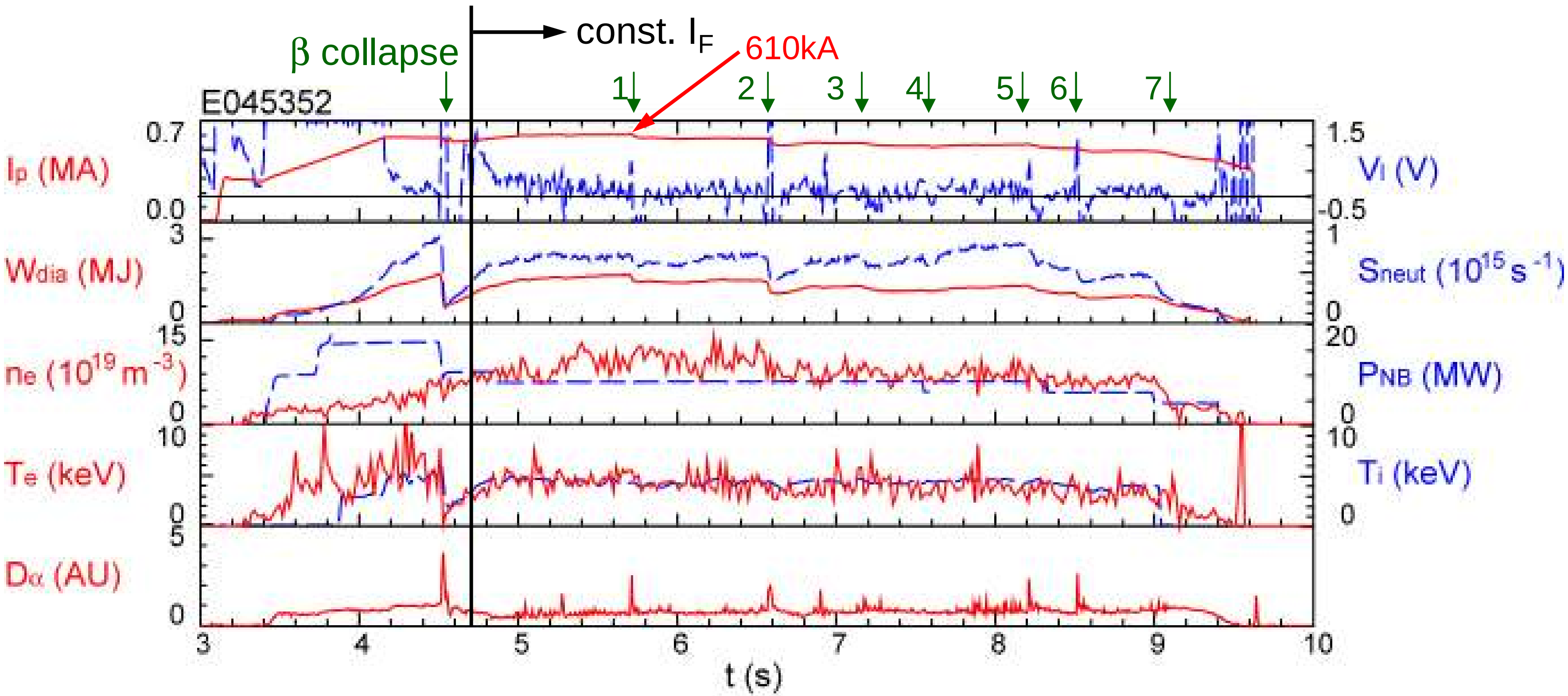
- Several discharges with f_{BS} ~ 100% were obtained
  - E046293
    constant I_p maintained at 0.51MA for 1.3 s noninductively
    (BS + negative NB)

all with const. OH coil current



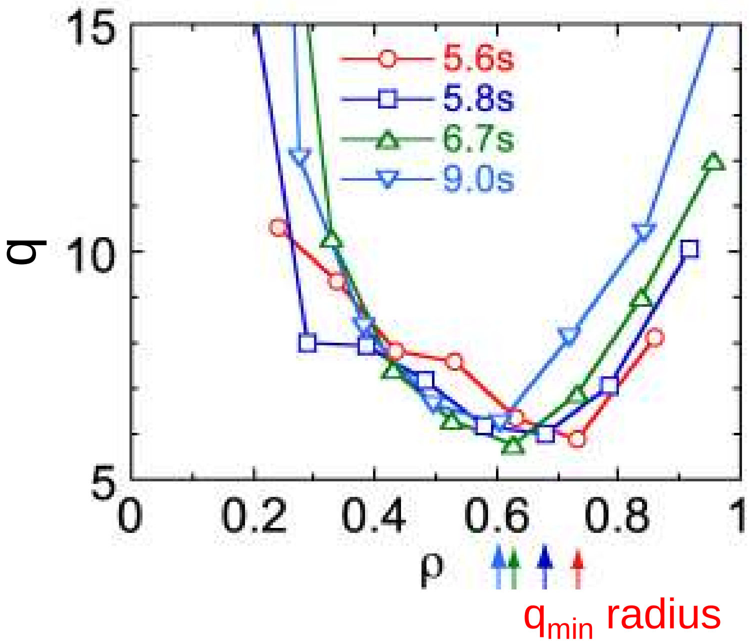
Dynamics of BS-Driven Plasma

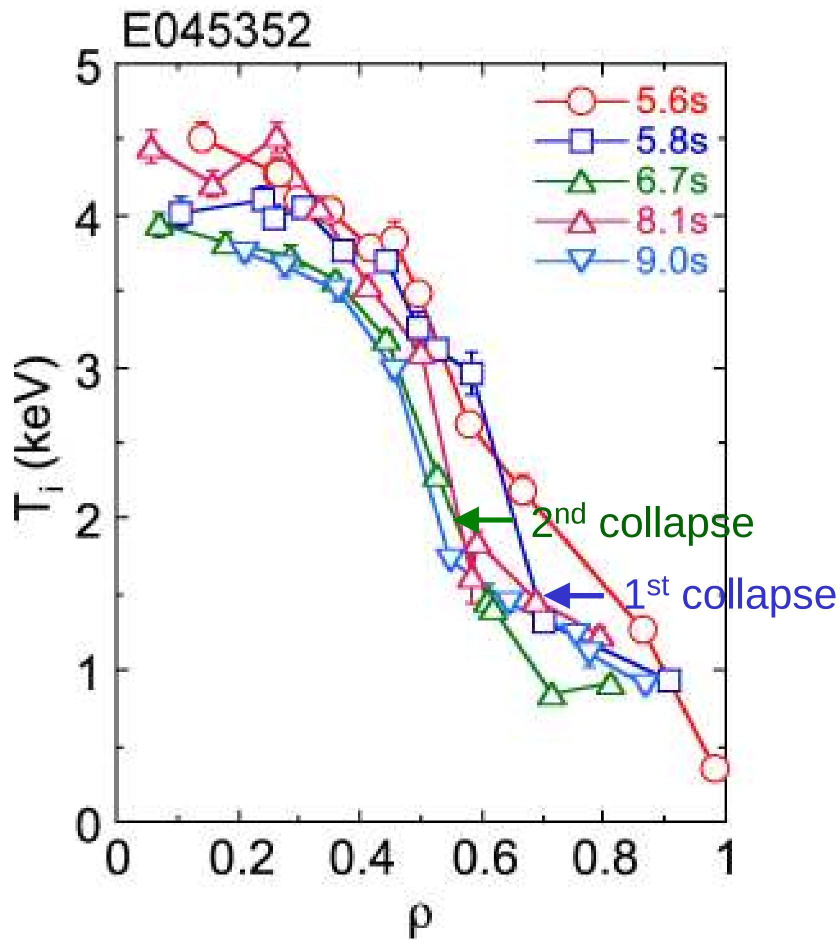
- Stored energy W_p increases and I_p increases to 610kA
- ITB shrinks at β collapses, then recovers partially
- I_p is self-sustained (not driven by NBCD or OH coil)



Evolutions of T_i and q Profiles

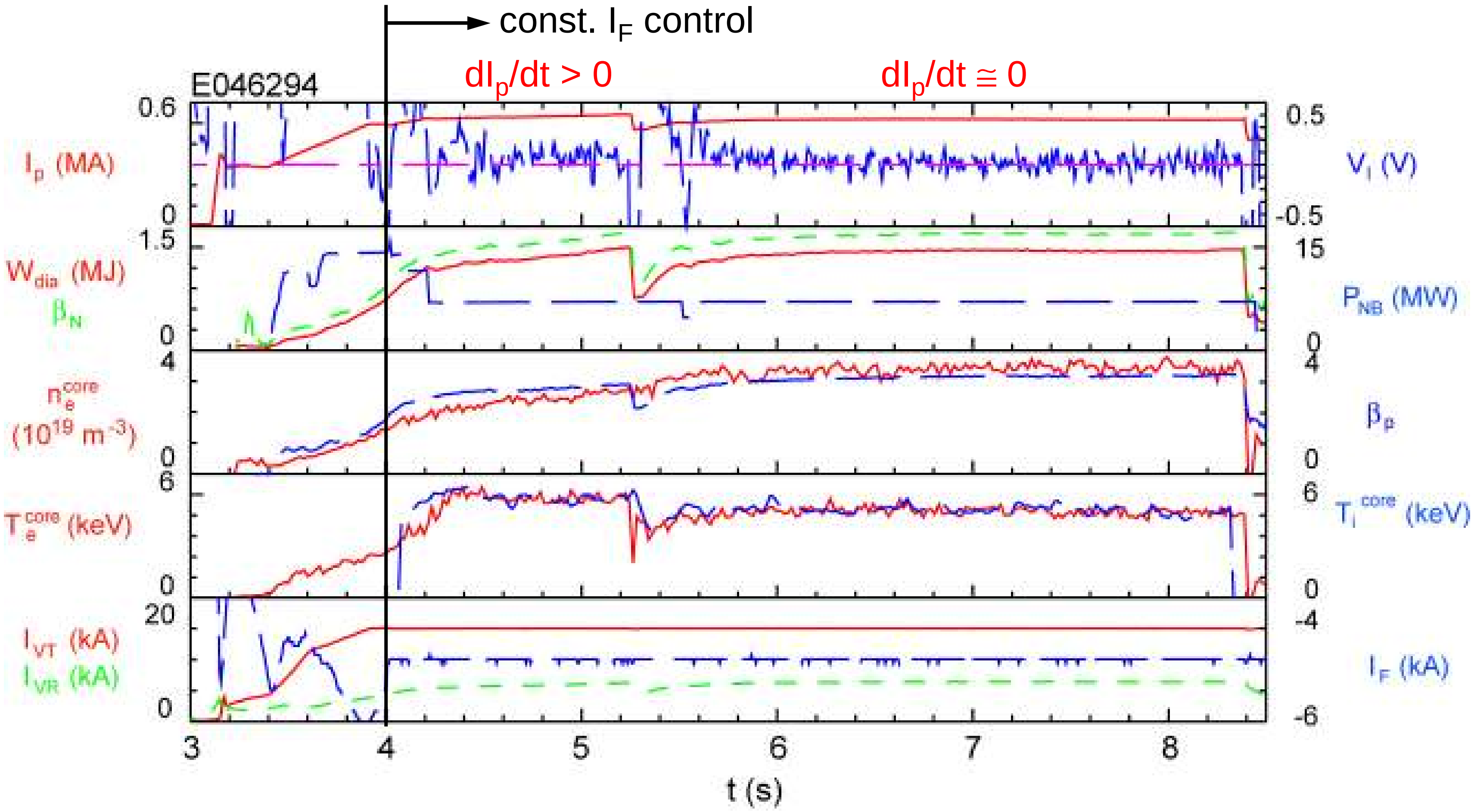
- ITB is eroded (becomes narrower) at β collapses, and both W_p and I_p decrease.
- Spontaneous recovery of ITB, W_p, and I_p occurs.
  - However, complete recovery to the original level is not achieved.





Stable Sustainment Aided by Co-NBI

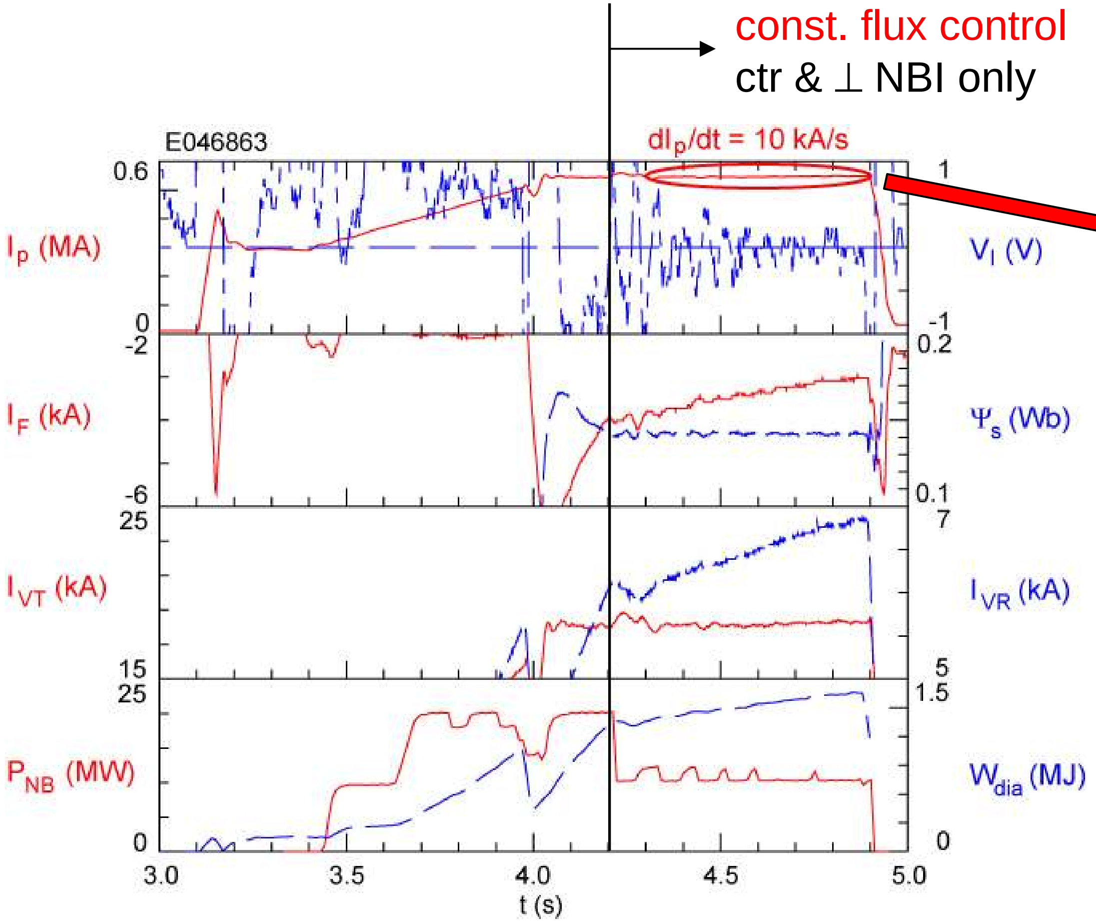
- Steady sustainment achieved for over 2s with I_{NB} ~ 40 kA (f_{BS} ~ 0.9)
  - Confinement is better with co-NBI (1.2 MJ / 5.9 MW vs. 1.0 MJ / 8.1 MW)

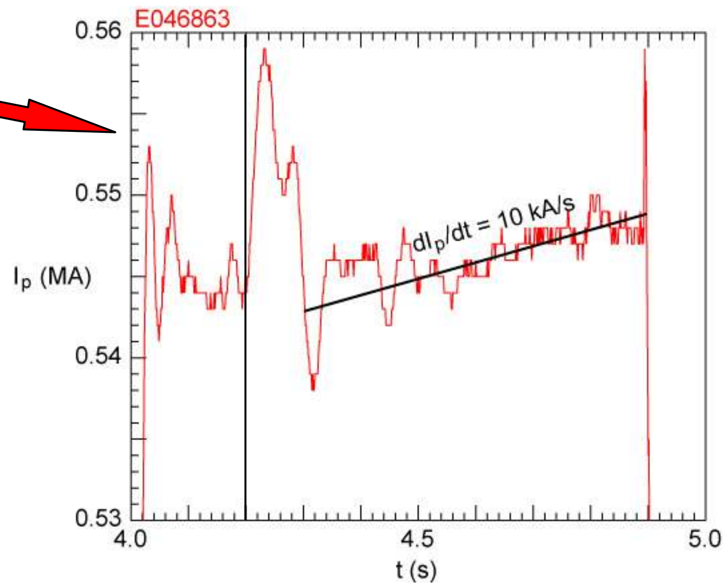


Evidence of Bootstrap Overdrive

IAEA 2004: CS recharging with $V_l < 0$ achieved (const. I_p control)

- Slow ramp-up at 10 kA/s for 0.5 s with zero inductive flux input





Conclusions

- A fully bootstrap-driven discharge with f_{BS} ~ 1 was realized
  - I_p = 510 kA was maintained for 1.3 s (with net I_{NB} = –35 kA).
- Dynamics of BS-sustained plasma
  - In discharges without a β collapse, slow degradation of confinement resulted in slowly declining W_p and I_p.
  - ITB shrinks radially at β collapses, resulting in W_p and I_p decrease. Subsequently, partial recovery of ITB and I_p occurs spontaneously.
  - Addition of positive I_{NB} (< 10% of I_p) helps steady sustainment of I_p greatly.
- Evidence of bootstrap overdrive was observed
  - Slow I_p rampup (10 kA/s for 0.5 s) was observed with no inductive flux input.

Extension to higher I_p and a more complete characterization of controllability of such a plasma remain topics of further research.