Plasma Current Startup without the Ohmic Solenoid in JT-60U and Implications for ST Reactors

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Joint Spherical Torus Workshop and US-Japan Exchange Meetings (SYW 2002)

8th Spherical Torus Workshop

US-Japan Exchange Meeting on Stability and Confinement in Spherical Tori

US-Japan Exchange Meeting on Theory and Simulation Study for Spherical Tokamaks

PPPL

18-21 November 2002

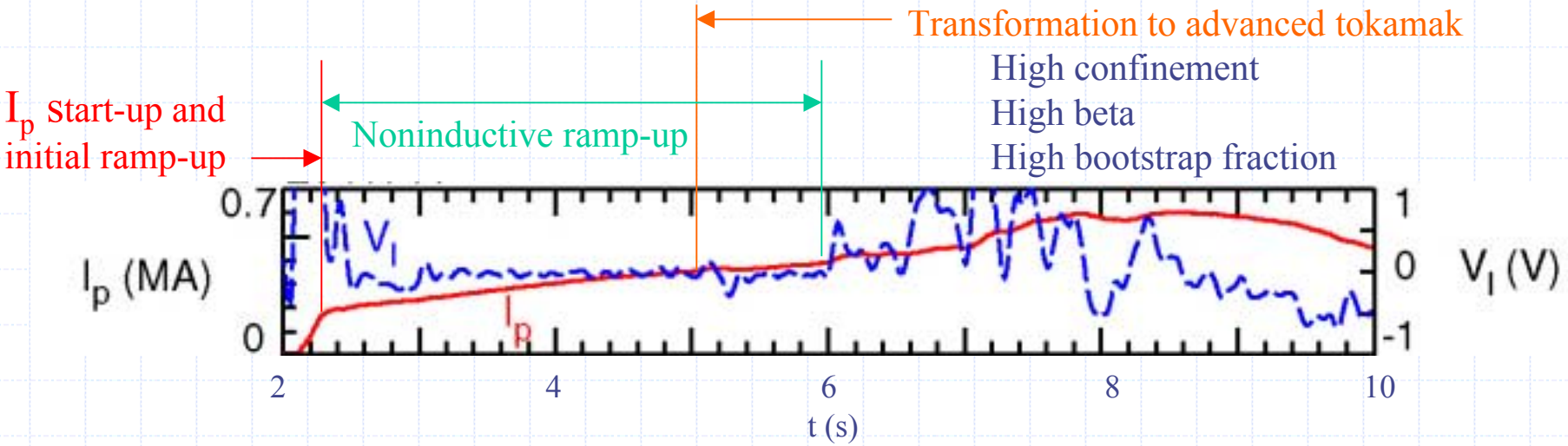
Outline

- Motivation
  - Why do we want CS-less operation?

CS: center solenoid (OH coil)

- JT-60U CS-less Ramp-up Experiment

  Integrated scenario consisting of:
  - I_p startup (inductive)
  - I_p rampup by noninductive overdrive (mostly noninductive)
  - Controlled transformation to advanced tokamak plasma (mostly inductive)
- Remaining Issues

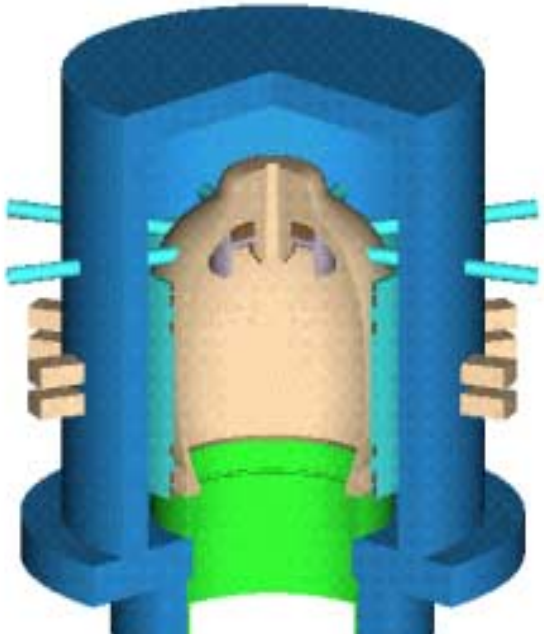


ST Reactors Require CS-less Operation

- CS-less operation is a requirement for ST reactors

ARIES-ST
(1 GWe)

R = 3.2 m
R/a = 1.6
I_p = 31 MA
B_T = 2.1 T
β_T = 54%
f_{BS} = 99%
P_{fusion} = 2.9 GW
Neutron wall load
= 4.1 MW/m^2
Recirculating power
fraction = 0.32

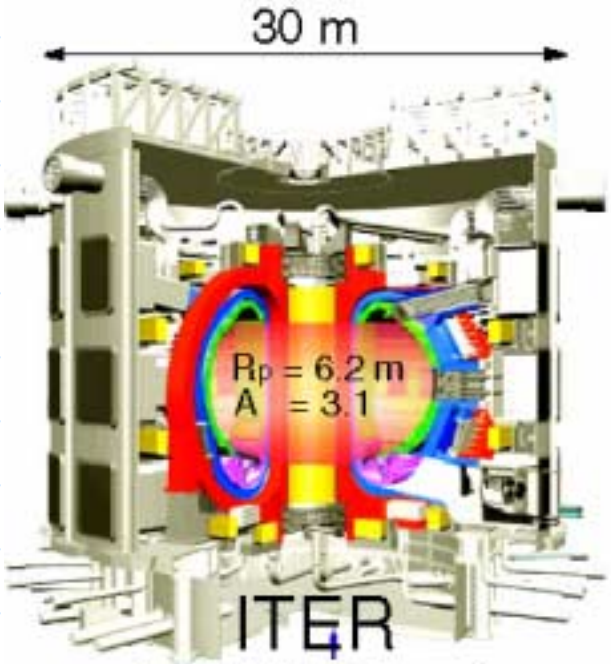


Fixed
Components

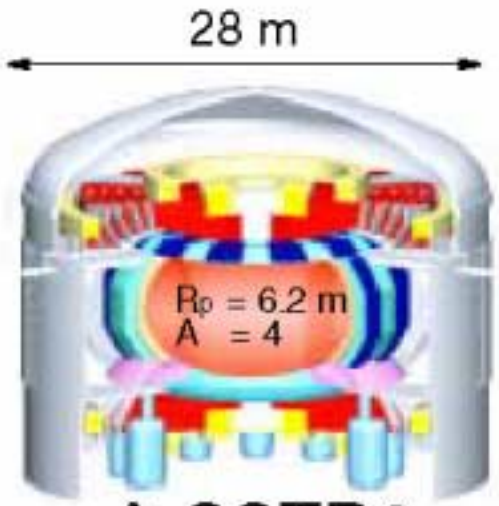
Replaceable
Components

Examples of CS-less Tokamak Reactors

- Improved economic competitiveness may be realized by a CS-less design.



ITER
(18000 ton)
P_F=0.5 GW



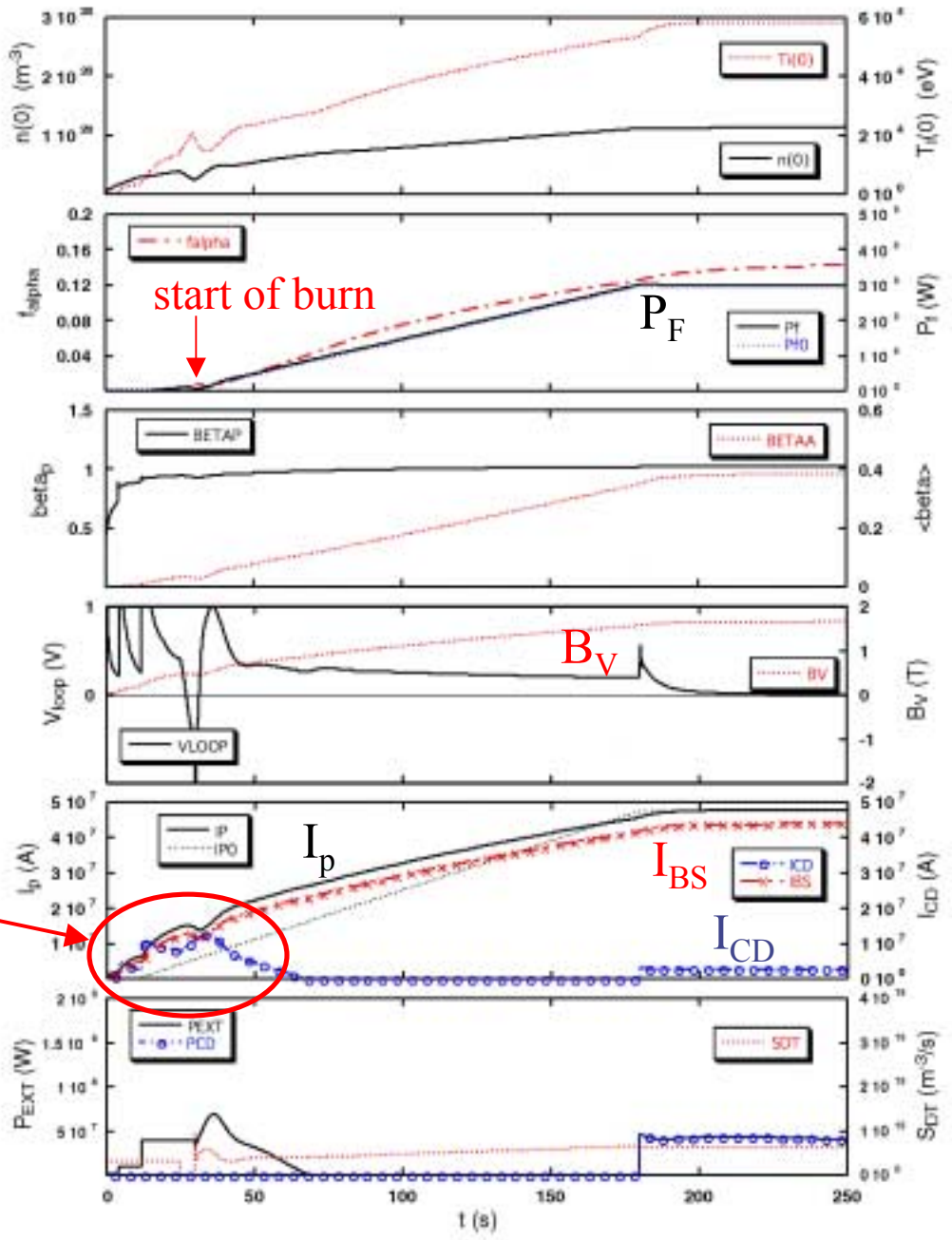
A-SSTR2
(28000 ton)
P_F=4 GW

VECTOR
(~9000 ton)
P_F = 3.7 GW

S. Nishio, et al., paper FT/P1-21, 19th Fusion Energy Conference, Lyon 2002.

Simulation for an ST Reactor

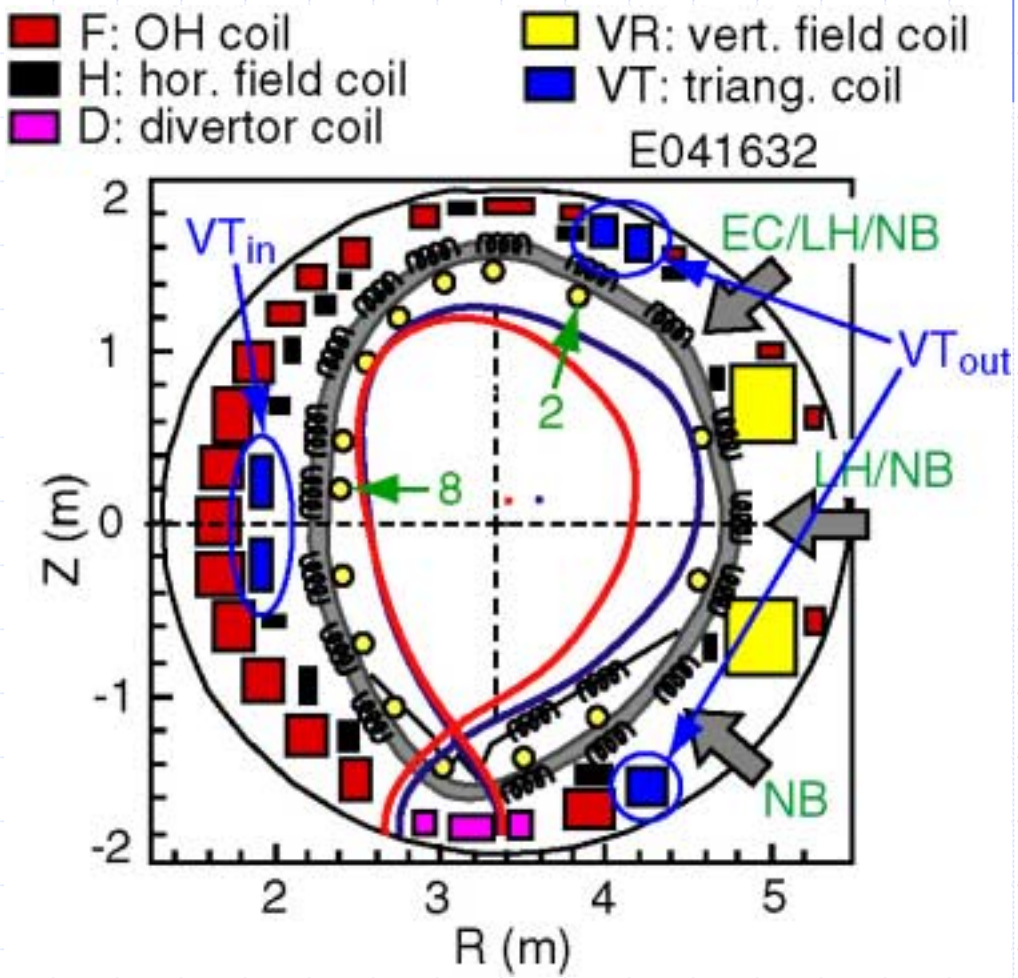
- CS does not exist in an ST reactor
  → Combine noninductive CD and inductive drive by outer PF coils
- I_p ramp-up by B_v ramp-up is highly effective once burning starts
- But initial I_p ramp-up until start of burn must be provided by other means



O. Mitarai, Y. Takase,
Fusion Science and Technology
(January 2003 issue)

JT-60U Coils and Heating/CD Systems

- OH solenoid ÅFÅ current is kept at zero (no flux input)
- **EC/LH** preionization as well as the vertical field coil (**VR**)and the triangularity coil (**VT**) are used for I_p ramp-up
- **Full cross section divertor configuration** is used for I_p ramp-up by **LHCD**
- **Inward shifted divertor configuration** is used for the high-power **NB** heated advanced tokamak phase



Flux and B_v Contributions from VR and VT Coils

- Flux @ R = 3.4 m

$$\Delta\Phi\ (\text{Wb}) = (30.1 + 88.1)\ \Delta I_{VT}\ (\text{MA}) + 257.6\ \Delta I_{VR}\ (\text{MA})$$

VT in VT out VR

In the present experiment

$I_{VT} = -7.3 \rightarrow +6.5$ kA

$I_{VR} = 0.1 \rightarrow +1.1$ kA

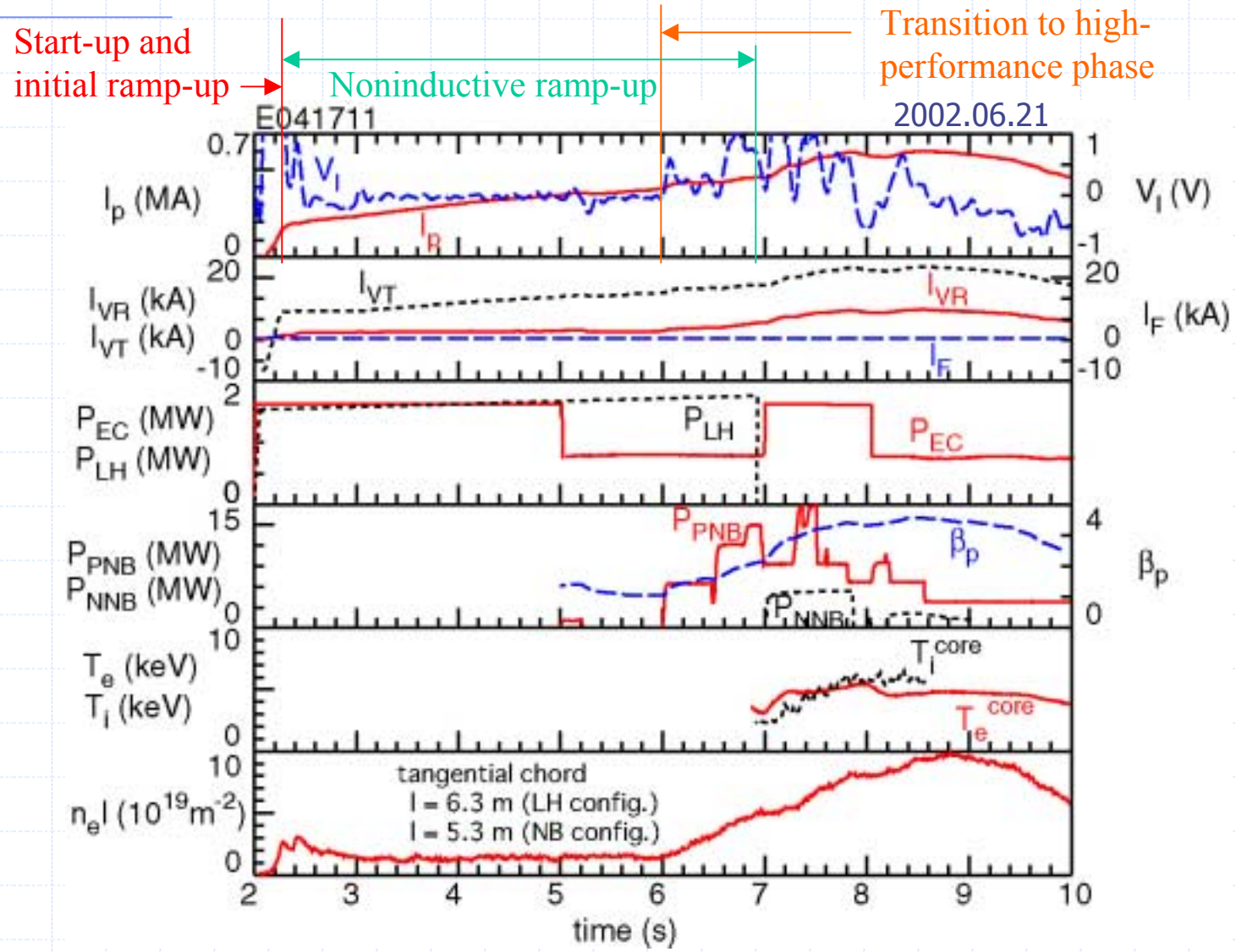
Flux contribution from the inner VT coil is ~20% in these experiments

- Vertical Field @ R= 3.4 m

$$B_v(\text{T}) = (-0.537 + 1.948)\ I_{VT}\ (\text{MA}) + 8.720\ I_{VR}\ (\text{MA})$$

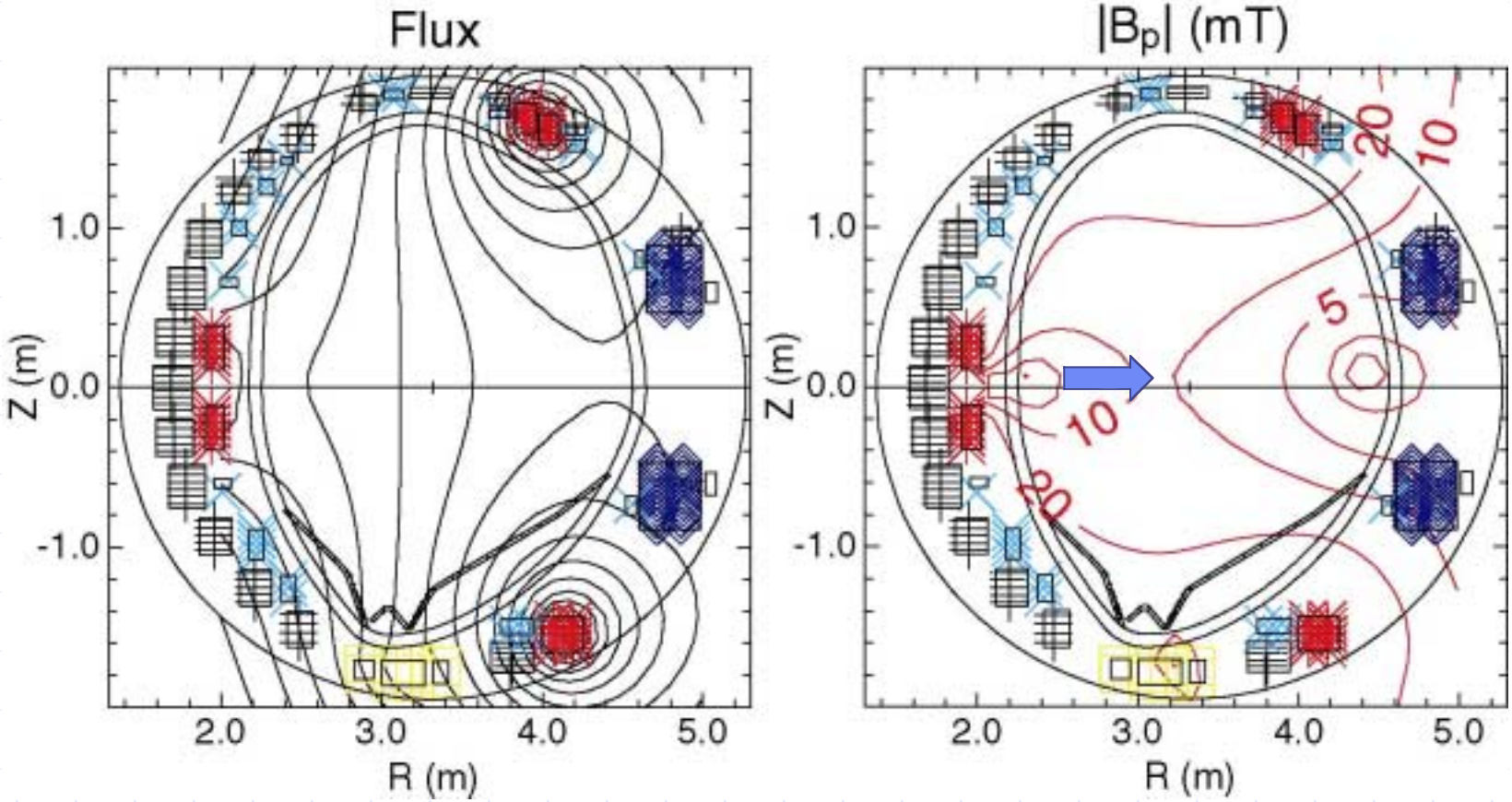
VT in VT out VR

CS-less Formation of High-Performance Plasma Demonstrated



Magnetic Configuration Just Before I_p Start-up

- "Field null" (minimum $|B_p|$ region) is formed by VT coil (2 locations)
- "Field null" moves radially outward by VT and VR coil ramps

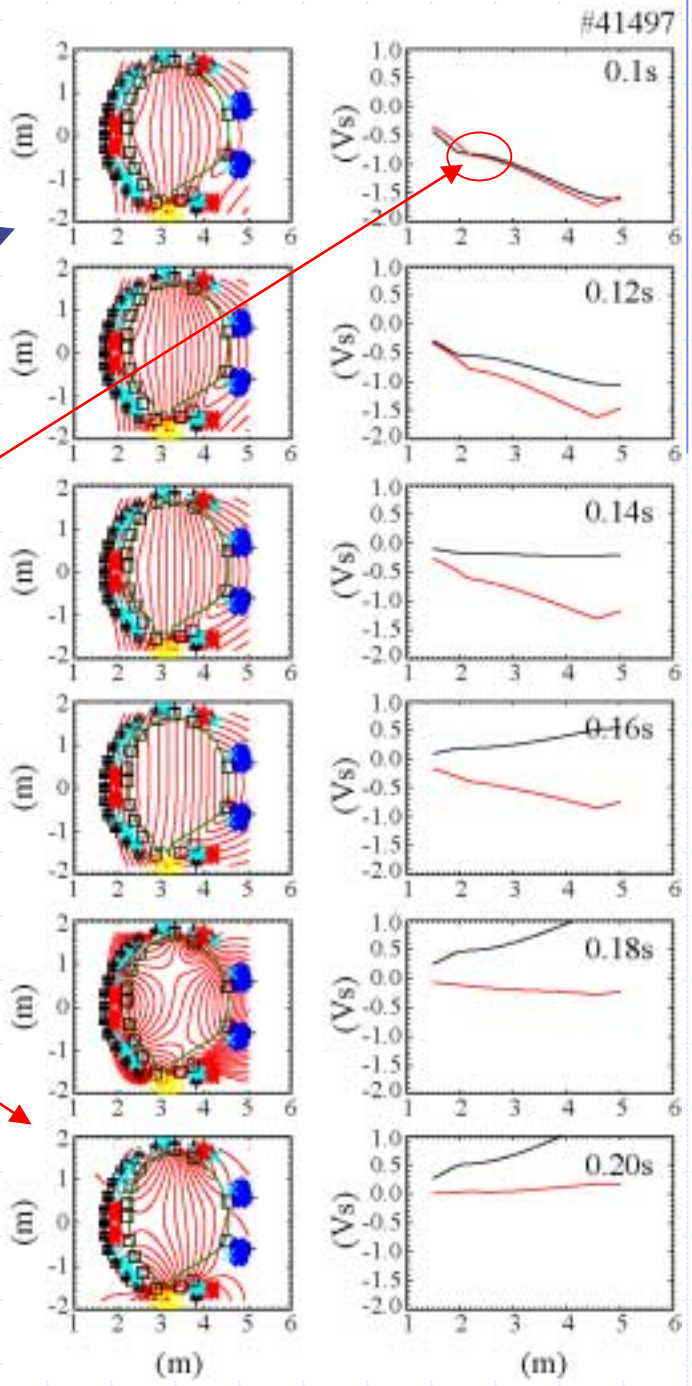


Vacuum Field Evolution

41497: no I_p start-up (no gas)
41495: I_p start-up at 0.105 s

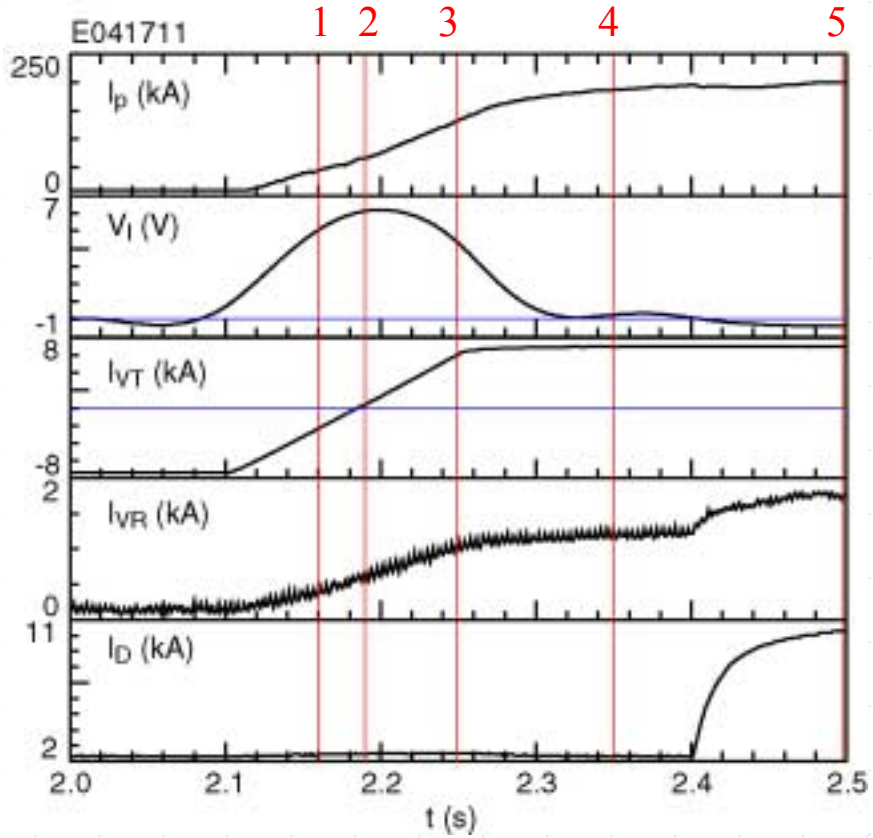
- A small "field null" exists on the inboard midplane before VT and VR coil ramp
- Initially B_v is in the wrong direction
- B_v does not reverse sign until 0.19 s (0.09s after start of VT and VR ramp)
- Poloidal equilibrium, but no toroidal equilibrium?

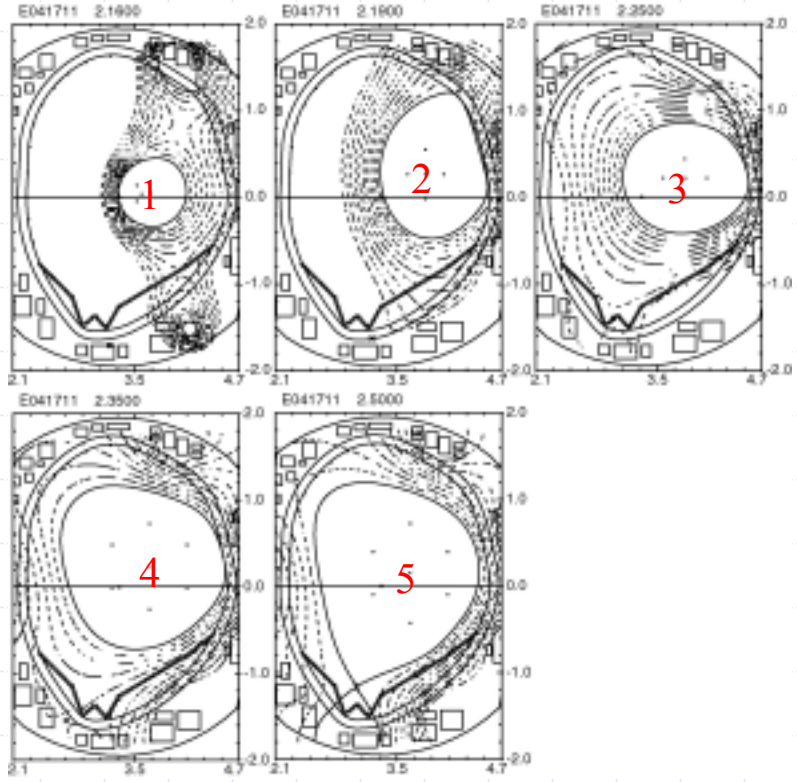
Right: Flux profile on the midplane
Black: coil currents only
Red: coil currents and eddy currents
Left: flux contours (with eddy currents)



Configuration Evolution During CS-less I_p Start-up

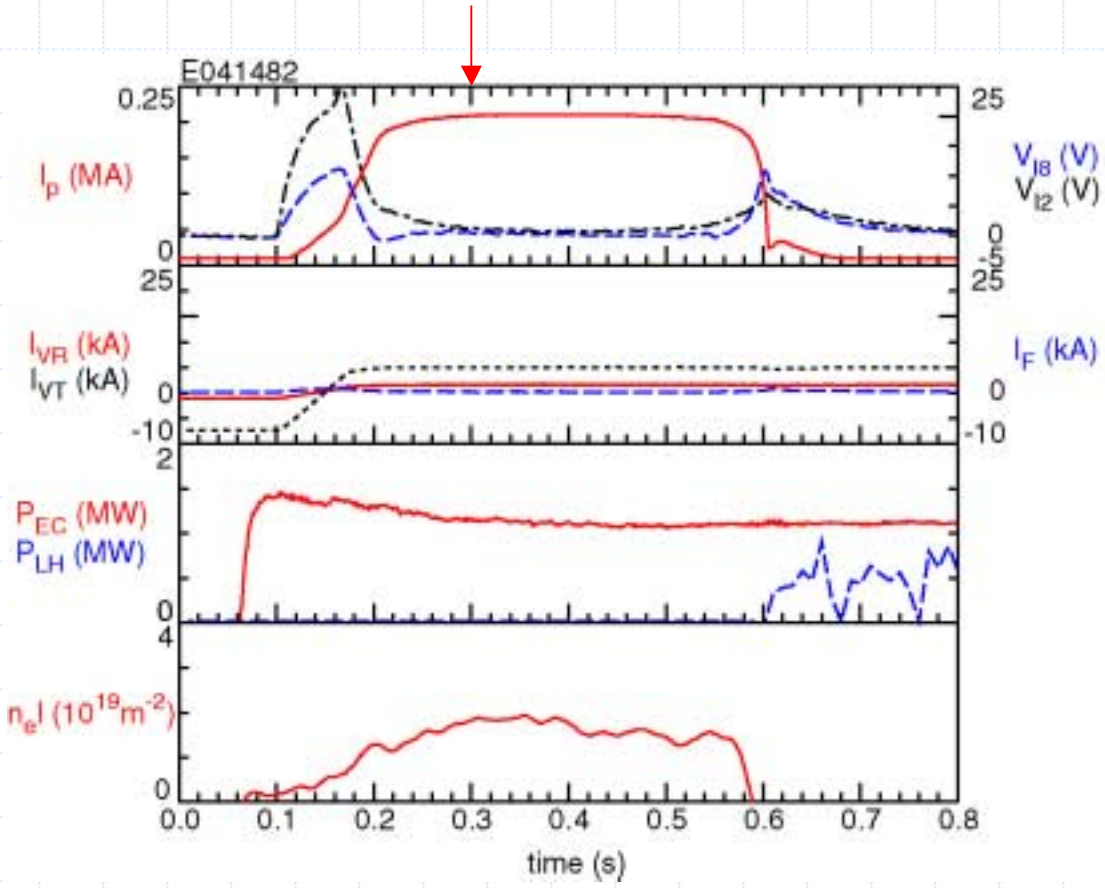
- I_p ramp-up accomplished by EC/LH preionization and VT/VR coil ramps
- Transition to divertor configuration (5) and further I_p ramp-up by LHCD

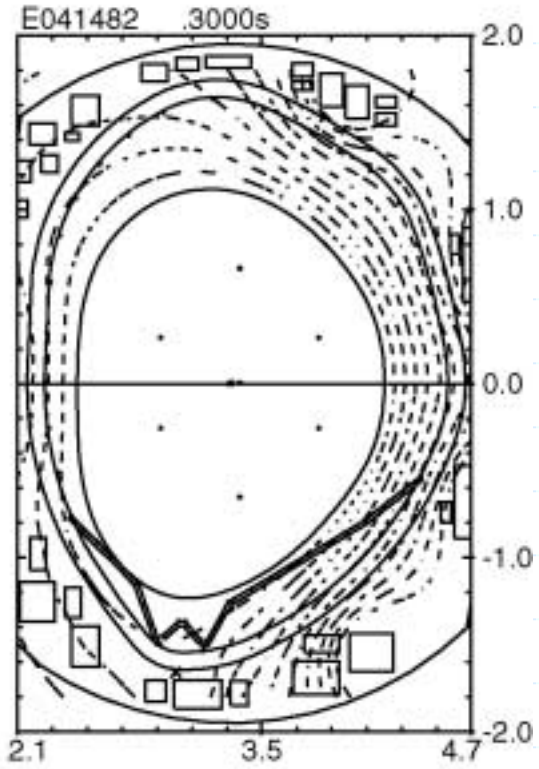




I_p Start-up and Maintenance without LHCD

- I_p ramp-up accomplished by EC preionization and VT/VR coil ramps
- I_p maintained at 200 kA by EC alone (no plasma position feedback)

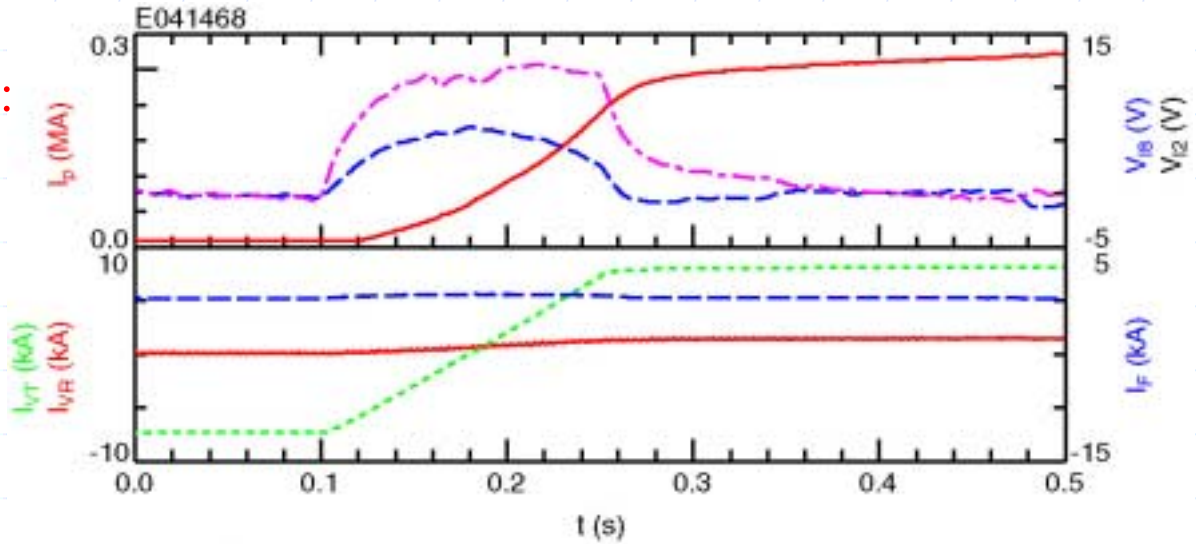




Comparison with OH Start-up

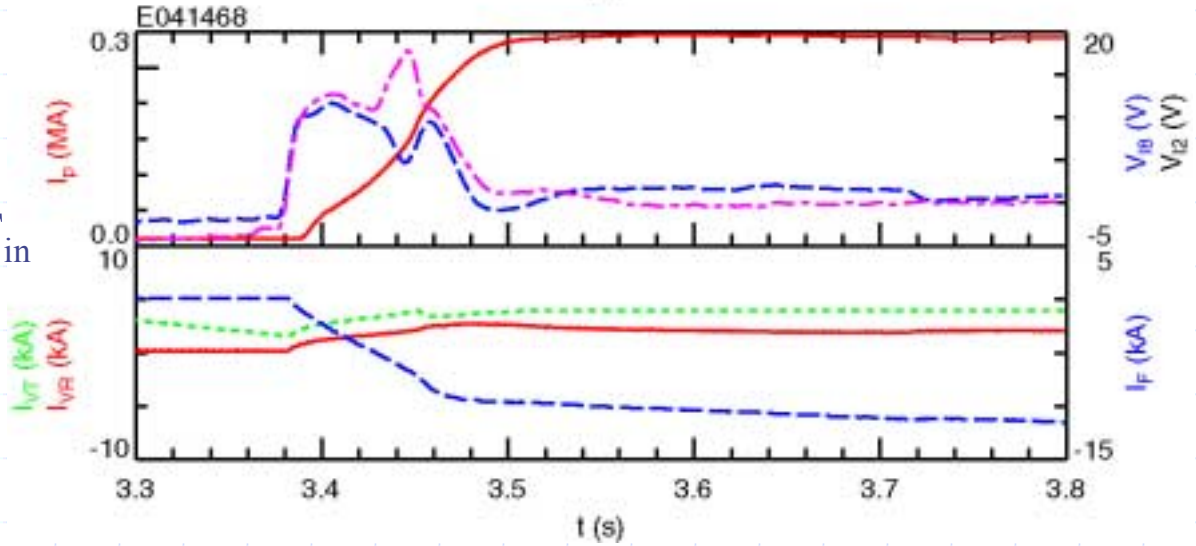
- VT/VR coil start-up:

20% flux from VT_{in}



- OH coil start-up:

70% flux from $OH+VT_{in}$



Noninductive Ramp-up Efficiency

- $(dW_m/dt) / P_{NI} = 3.6\%$
- $(dW_m/dt - P_{ext}) / P_{NI} = 2.2\%$ (40% contribution from PF coils)

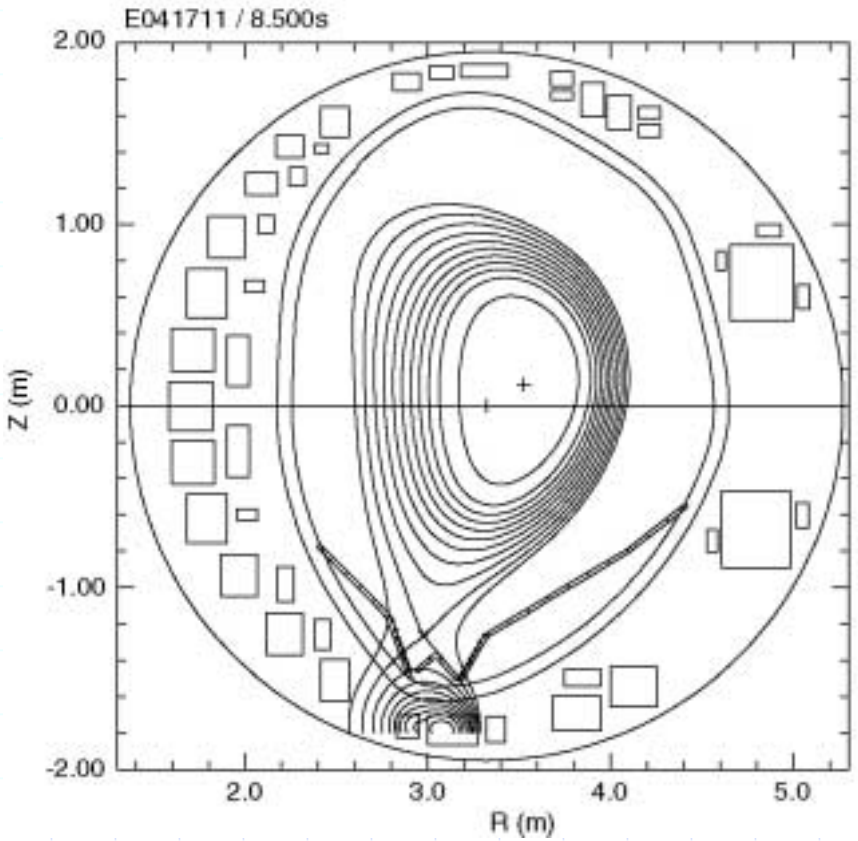
where $W_m = (L_{ext} + L_{int}) I_p^2 / 2$: total poloidal magnetic field energy

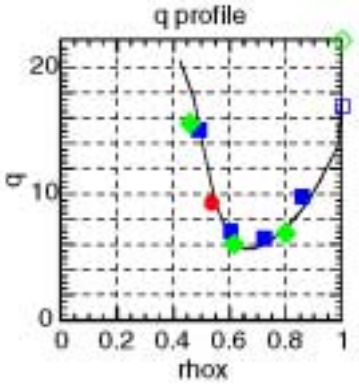
$P_{NI} = P_{LH} + P_{EC}$: total noninductive input power

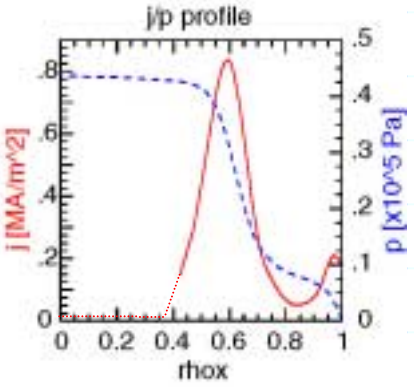
P_{ext} : Poynting flux provided by PF coils

Advanced Tokamak Equilibrium and Pressure and Current Density Profiles

- Start NB heating when I_p becomes high enough for beam ion confinement
- Deeply reversed shear configuration with "current hole" is formed
  - Current hole and ITB already formed during LHCD ramp-up





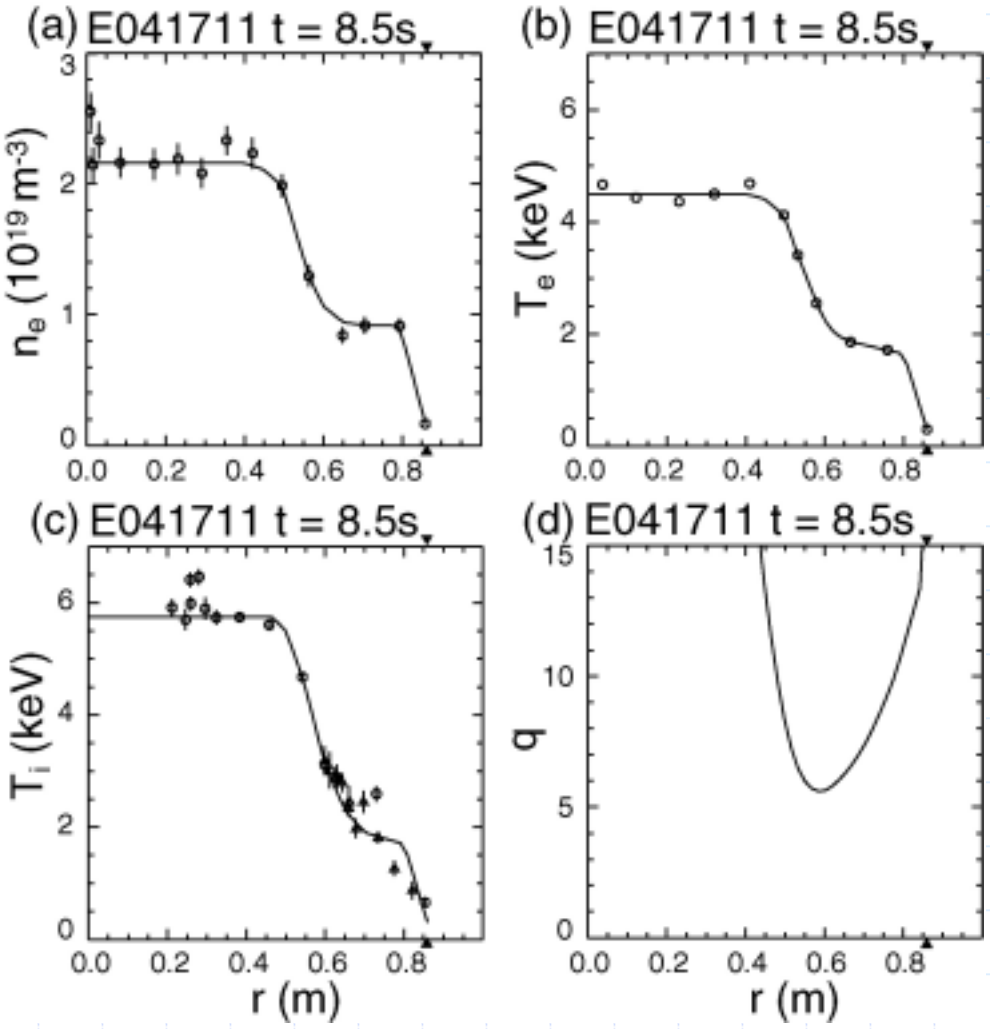


$L_{ext} = 5.6\ \mu H$
$L_{int} = 1.4\ \mu H$
$(l_i = 0.67)$

Density and Temperature Profiles of High-Performance Plasma

- Reversed shear for r/a < 0.7
- ITB + H-mode

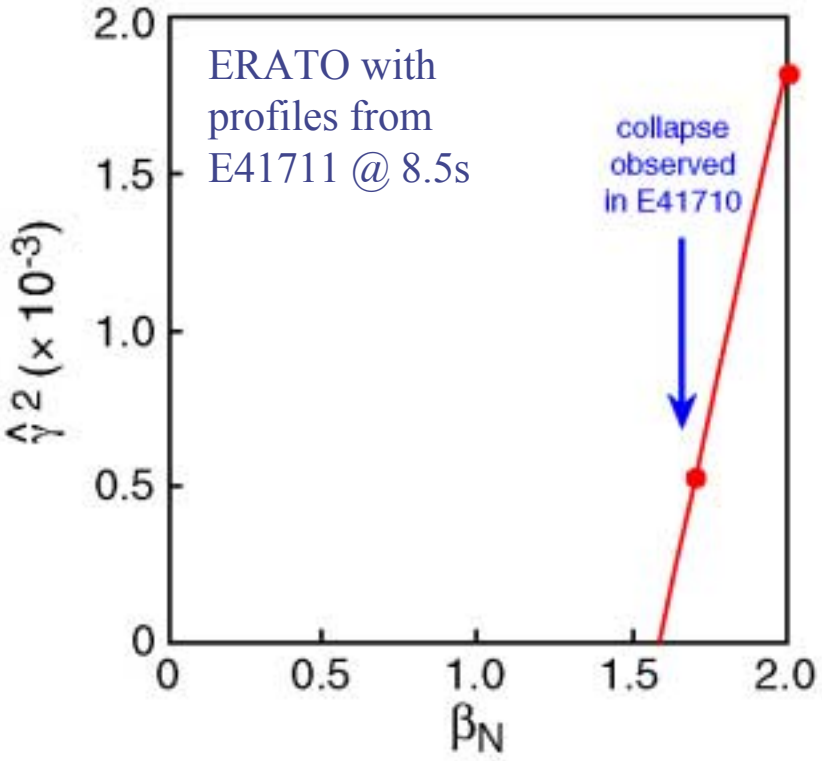
$I_p = 0.6MA$
$\beta_p = 3.6$
$\beta_N = 1.6$
$H_H = 1.6$
$f_{BS} > 90\%$
$l_i = 0.67$
$q_{95} = 13$
$q_{min} = 5.6$ @ r/a = 0.7



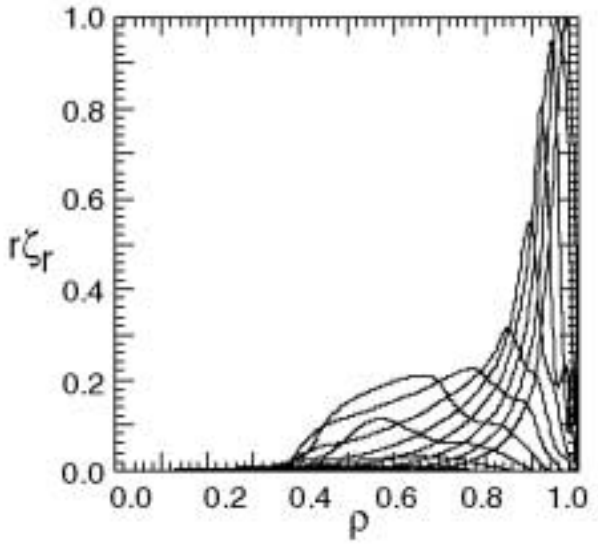
Y. Takase, et al.,
J. Plasma Fusion Res.
(Rapid Communications)
78, 719 (2002)

Stability Limited by n = 1 Kink-Ballooning Mode

- No β collapse observed at $\beta_N = 1.6$ in E41711
- β collapse observed at $\beta_N = 1.7$ in E41710

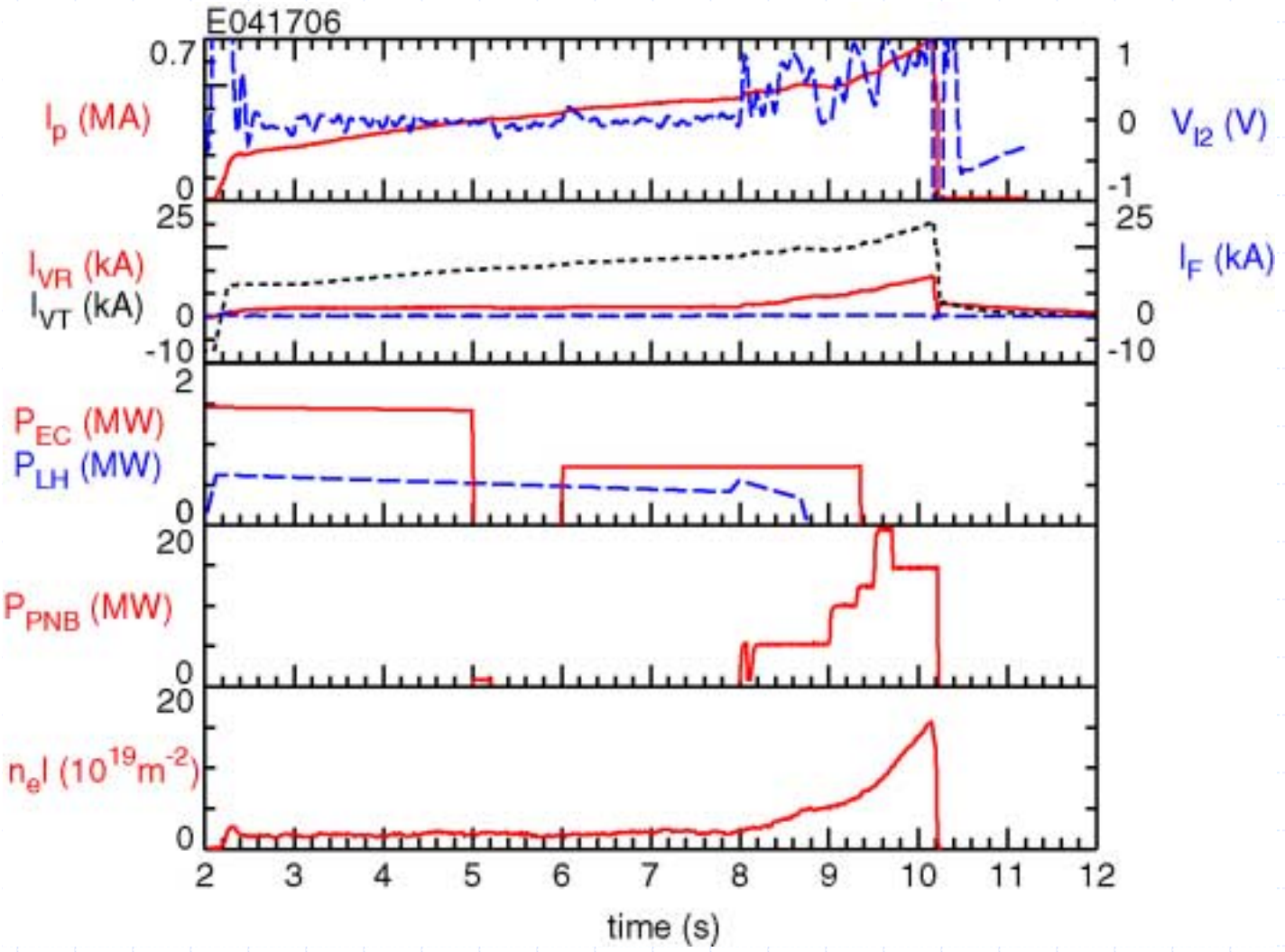


Growth rate of the n=1 kink-ballooning mode for the equilibrium at maximum stored energy of E41711.



Eigenfunctions of the n=1 kink-ballooning mode.

Disruption at $\beta_N = 1.7$ ($I_p = 0.7$ MA)



Summary of CS-less Ramp-up

- Inductive ramp-up by VT and VR coils is effective
  - Strong preionization by EC (fundamental) and/or LH is required for effective I_p start-up (use of PF swing from negative B_v)
  - Inner VT coil provides 20% flux (VR and outer VT coils provide 80%)
  - I_p start-up by VR ramp alone is possible but less effective (~ 50 kA)
  - Static field by VT followed by VT and VR ramp-up is more effective
    - Formation of "field null" is effective
  - Further improvement of start-up scenario is possible
- Noninductive I_p ramp-up by LHCD (+ ECCD)
  - Decouples $\Delta\Phi$ and B_v from PF coils
    - but ramp-up efficiency is not very high (a few %)
  - Maintenance of 250 kA (but not further ramp-up) was possible by EC alone
    - I_p ramp-up by EC alone should be possible but requires higher power
- An integrated scenario with controlled I_p ramp-up, transformation to advanced tokamak plasma, and controlled ramp-down is demonstrated:
  - ITB + H-mode plasma with $\beta_p = 3.6$, $\beta_N = 1.6$, $H_H = 1.6$, $f_{BS} > 90\%$

Remaining Issues

- Demonstrate a scenario that uses no turns on the inboard midplane
  →ÅUse inboard top/bottom coils
- Extension to higher I_p, higher β_N
- Application of CS-less operation to ST
- Develop control algorithm that can react to β collapse, etc.

Start-up Scenario for TST-2

- PF1 creates field null too far out in R
  (may not be efficient)

- Merging with external coils
  (PF1 + PF6)
  appear promising

  ↑

  (collaboration with TS-3/TS-4 group)

Experiment in Kashiwa (2004 ?)