Advances in the high bootstrap fraction regime on DIII-D towards the Q=5 mission of ITER steady state

By

J.P. Qian[1], A.M. Garofalo[2], X. Z. Gong[1], Q.L.Ren[1], S. Y. Ding[1], W.M. Solomon[3], J. Huang[1], B.A. Grierson[3], W. F. Guo[1], C.T. Holcomb[4], J. McClenaghan[5], G.R. McKee[6], C. K. Pan[1], J.R. Ferron[2], A.W. Hyatt[2],G.M. Staebler[2], B. N. Wan[1]

[1] Institute of Plasma Physics, Chinese Academy of Science, Hefei, China
[2] General Atomics, San Diego, USA
[3] Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA
[4] Lawrence Livermore National Laboratory, Livermore, California, USA
[5] Oak Ridge Associated Universities, Oak Ridge, TN, USA
[6] University of Wisconsin-Madison, Madison, Wisconsin, USA

Presented at the 26th IAEA Fusion Energy Conference
Kyoto, Japan
17–22, October, 2016

This work was supported in part by the National Magnetic Confinement Fusion Program of China 2015GB102000 and the U.S. Department of Energy under DE-FC02-04ER54698, DE-AC52-07NA27344, DE-FG02-08ER54999, DE-AC02-09CH11466, DE-FG02-07ER54917 and DE-FG02-06ER54871.

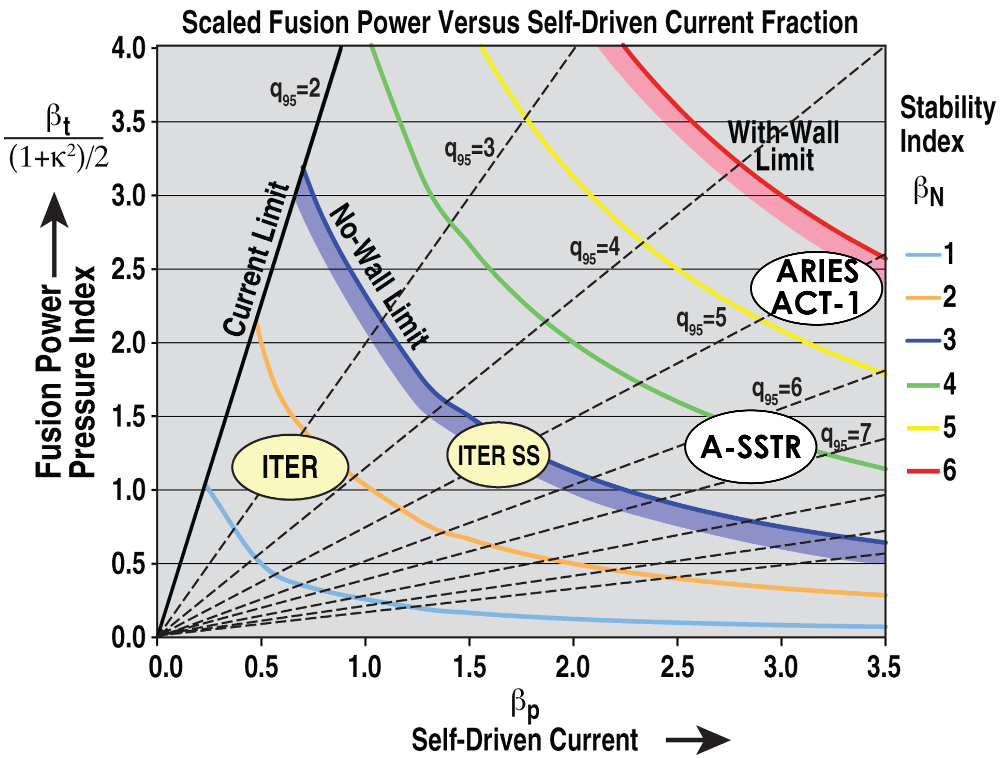
DIII-D NATIONAL FUSION FACILITY

ASIPP

Q=5 of ITER steady state is addressed based on the extended DIII-D high bootstrap fraction scenario

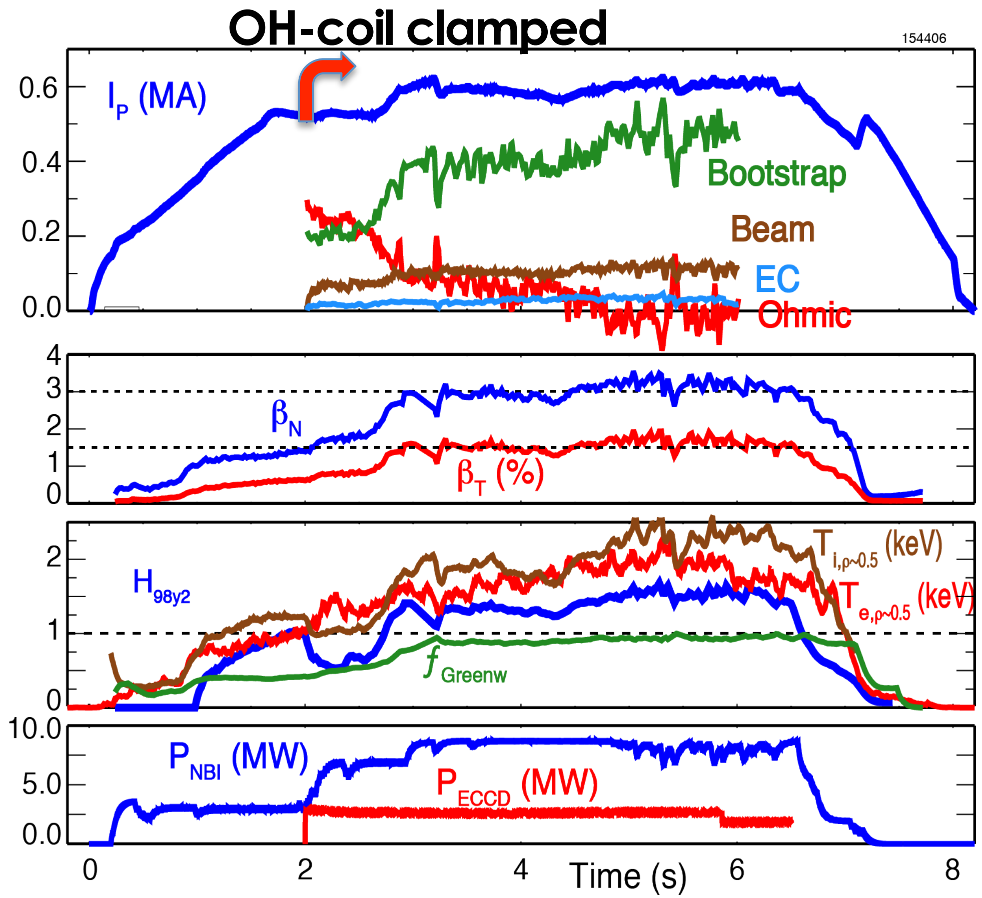
$$f_{bootstrap} \sim \beta_P \sqrt{\varepsilon}$$

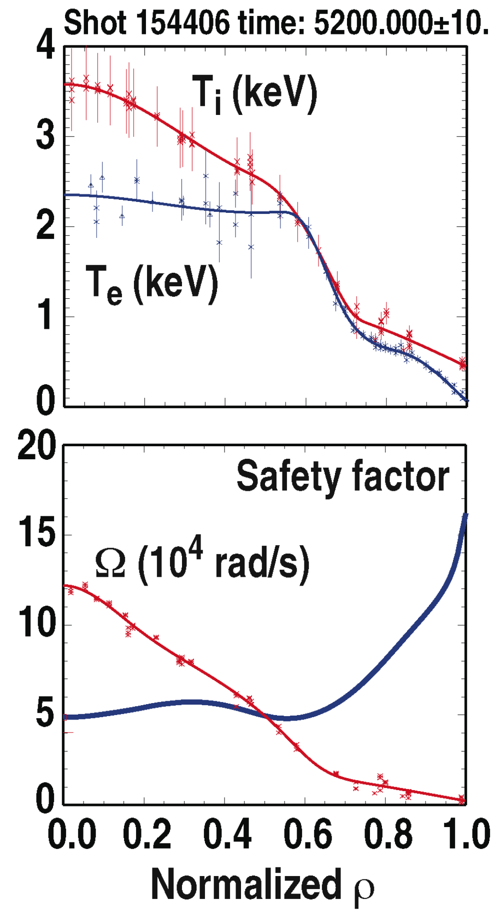
- **High bootstrap current fraction addresses key challenge for steady-state operation:** **minimizes need for external current drive**



DIII-D NATIONAL FUSION FACILITY

Previous EAST/DIII-D joint experiment has demonstrated high bootstrap fraction regime with good confinement





- **Excellent confinement quality associated with formation of ITB at large minor radius**

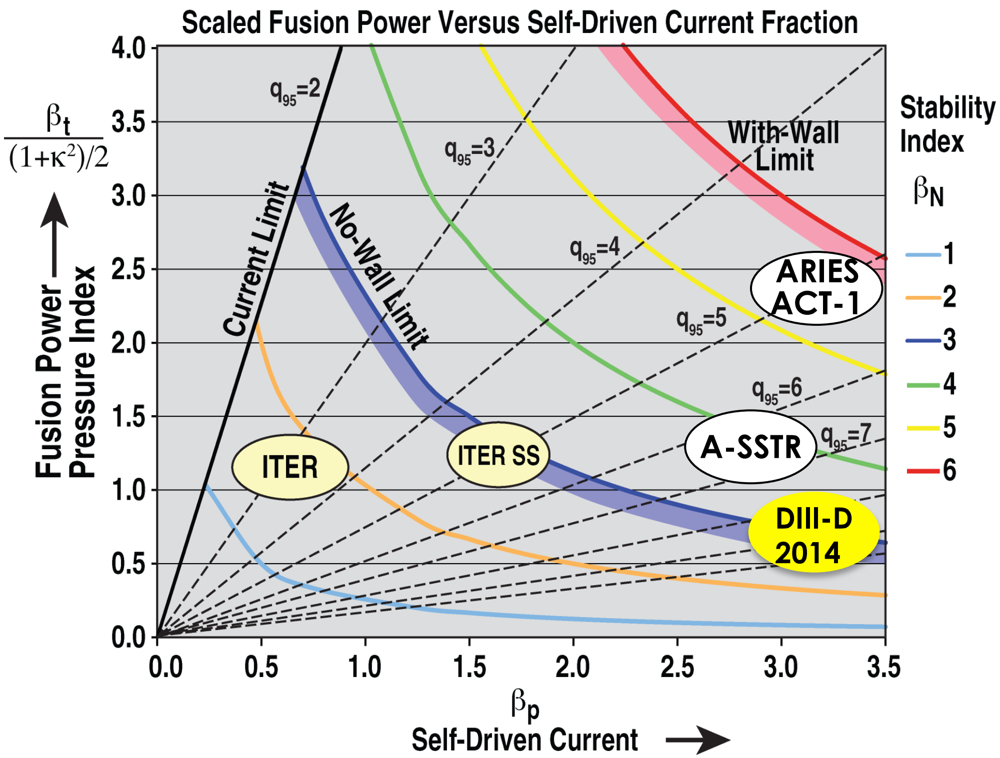
Garofalo et al., IAEA FEC 2014
Gong et al., IAEA FEC 2014
Ren et al., APS 2015
Pan et al., TTF 2016

DIII-D NATIONAL FUSION FACILITY

Q=5 of ITER steady state is addressed based on the extended DIII-D high bootstrap fraction scenario

$$f_{bootstrap} \sim \beta_P \sqrt{\varepsilon}$$

- **High bootstrap current fraction addresses key challenge for steady-state operation: minimizes need for external current drive**



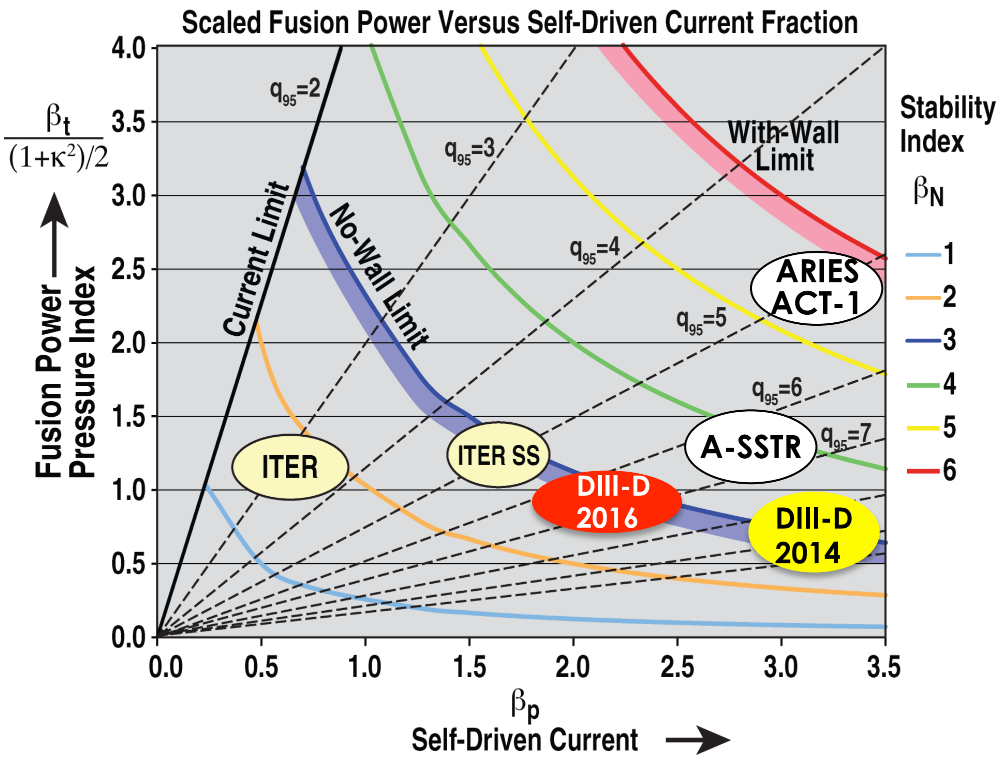
- **DIII-D high β_P scenario**
  - High bootstrap current (~80%)
  - High confinement with large radius ITB
- **ITER steady state requires:**
  - Good confinement at low torque

DIII-D NATIONAL FUSION FACILITY

Q=5 of ITER steady state is addressed based on the extended DIII-D high bootstrap fraction scenario

$f_{bootstrap} \sim \beta_P \sqrt{\varepsilon}$

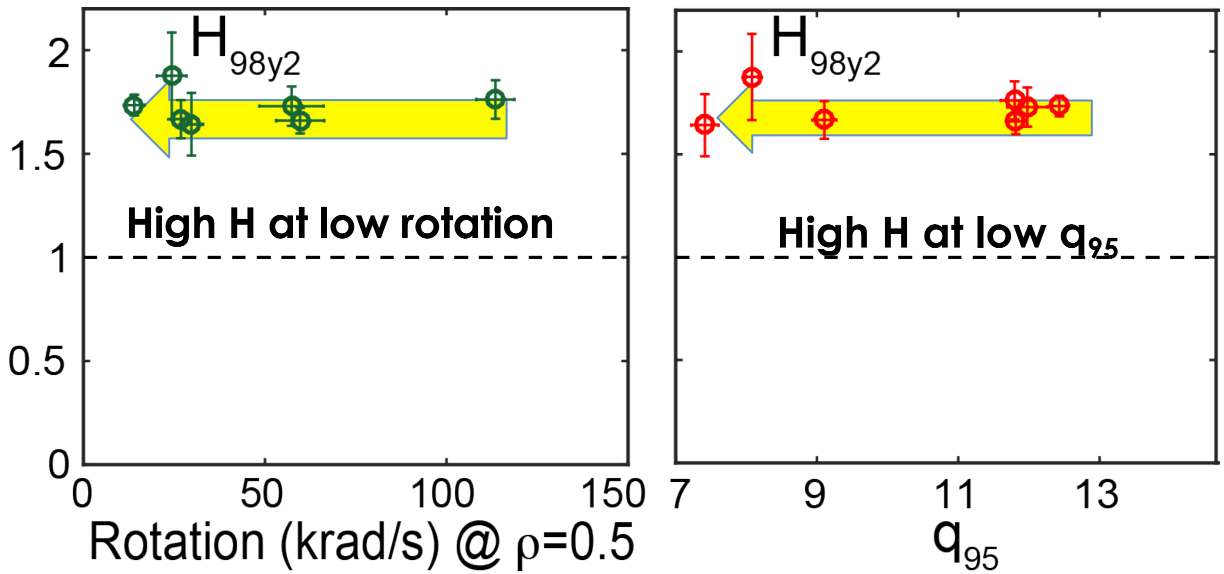
- **High bootstrap current fraction addresses key challenge for steady-state operation:** **minimizes need for external current drive**



- **DIII-D high β_P scenario**
  - High bootstrap current (~80%)
  - High confinement with large radius ITB
- **ITER steady state requires:**
  - Good confinement at low torque

DIII-D NATIONAL FUSION FACILITY

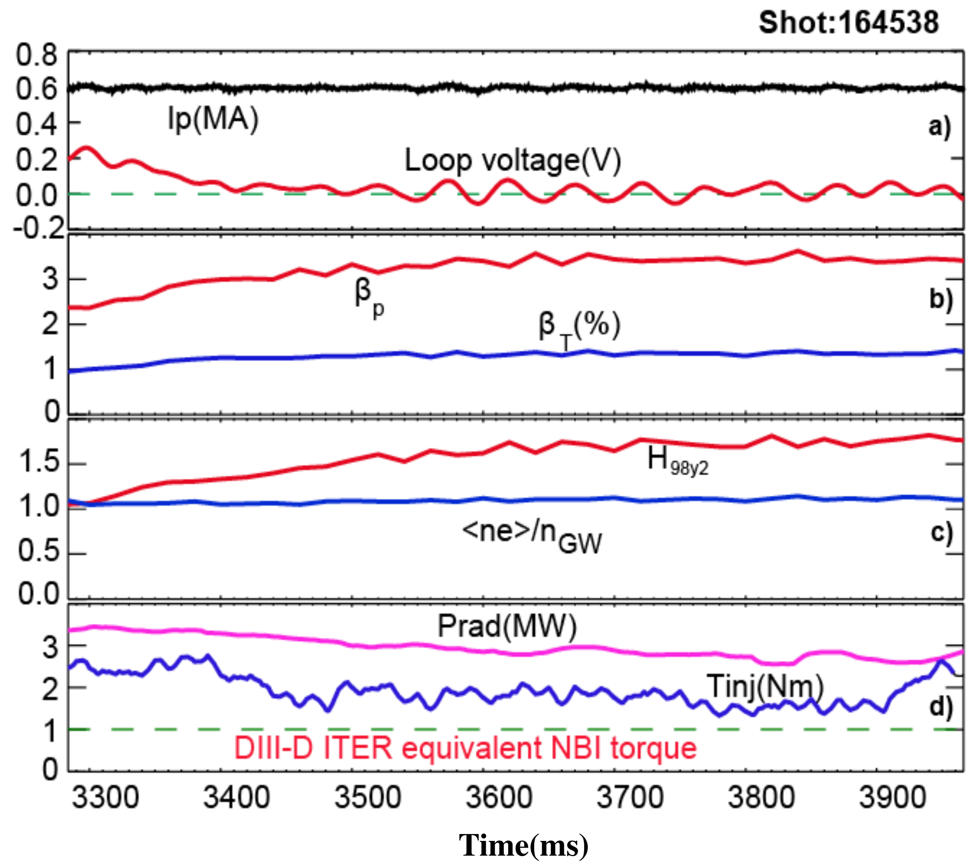
Recent experiment shows large radius ITB, good confinement can be maintained at extended operational regime



- **Extension of DIII-D high β_P scenario to low rotation near ITER NBI equivalent torque**
- **Shafranov shift has key stabilizing effect on turbulence transport**
- **Investigation on lower q_{95} confirmed shafranov shift effect**
- **Extrapolation of DIII-D high β_P scenario to ITER steady state**

Recent experiment confirmed high confinement can be achieved near ITER NBI equivalent torque

- **High β_P scenario**
  - q_{95}~12
  - High f_{bs}~80%
  - Nearly fully non-inductive
- **High confinement**
  - H_{98y2}~1.8
- **Low toroidal rotation**
  - Reduced torque T_{inj}~1.5Nm
  - Close to DIII-D ITER equivalent NBI torque

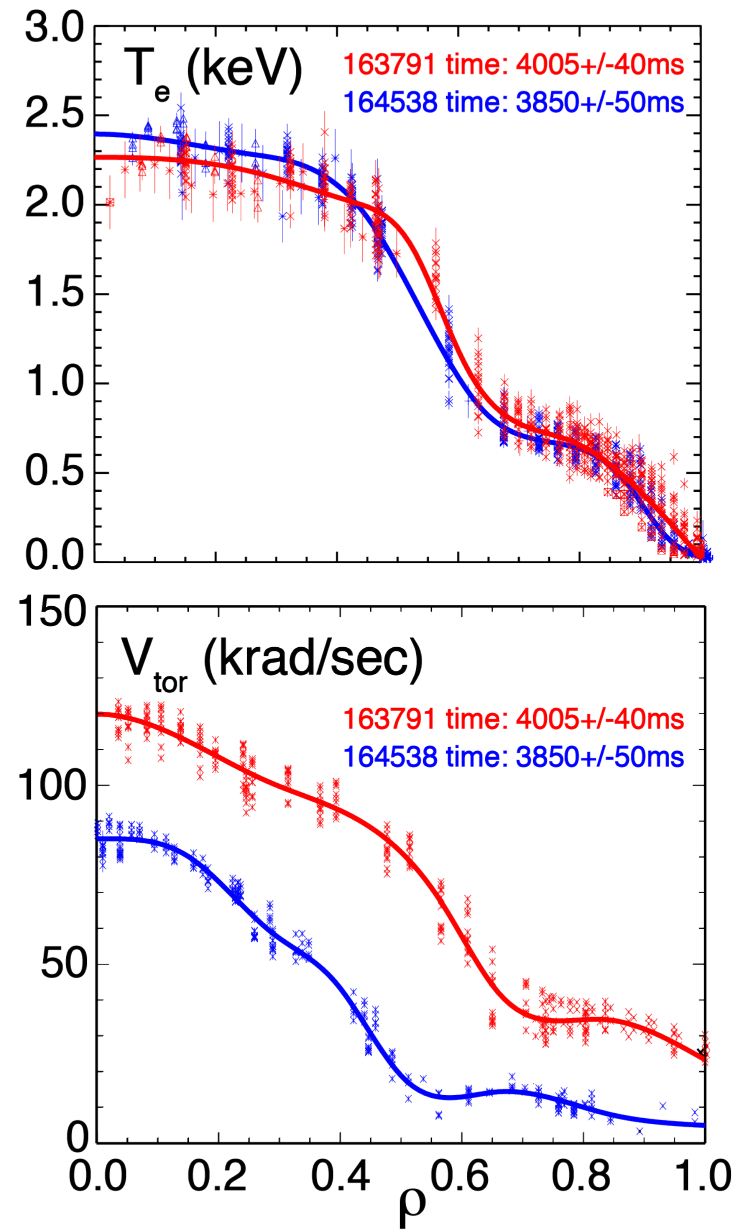


- **No strong impurity accumulation**

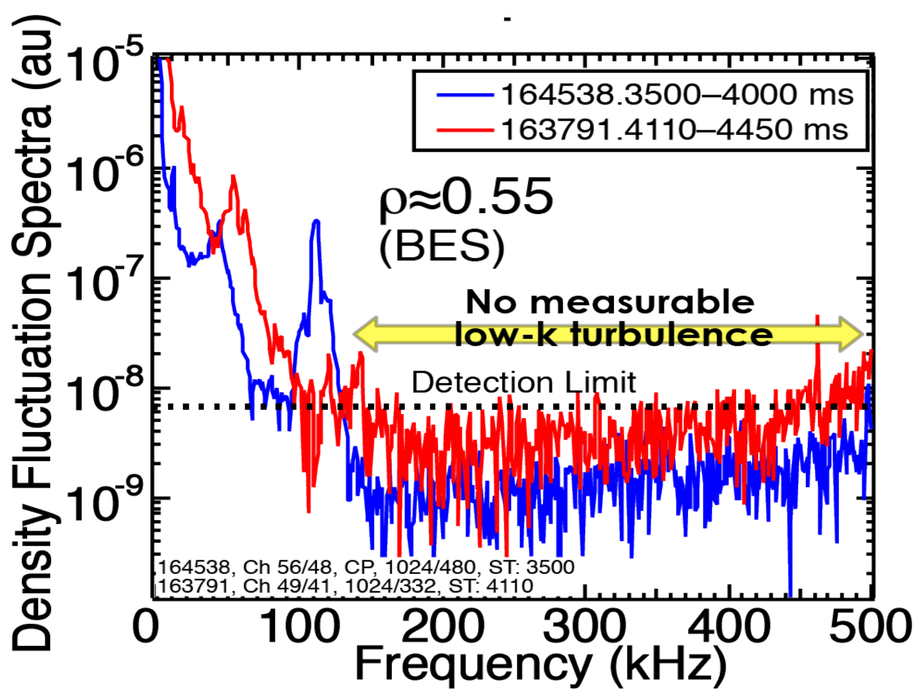
DIII-D NATIONAL FUSION FACILITY

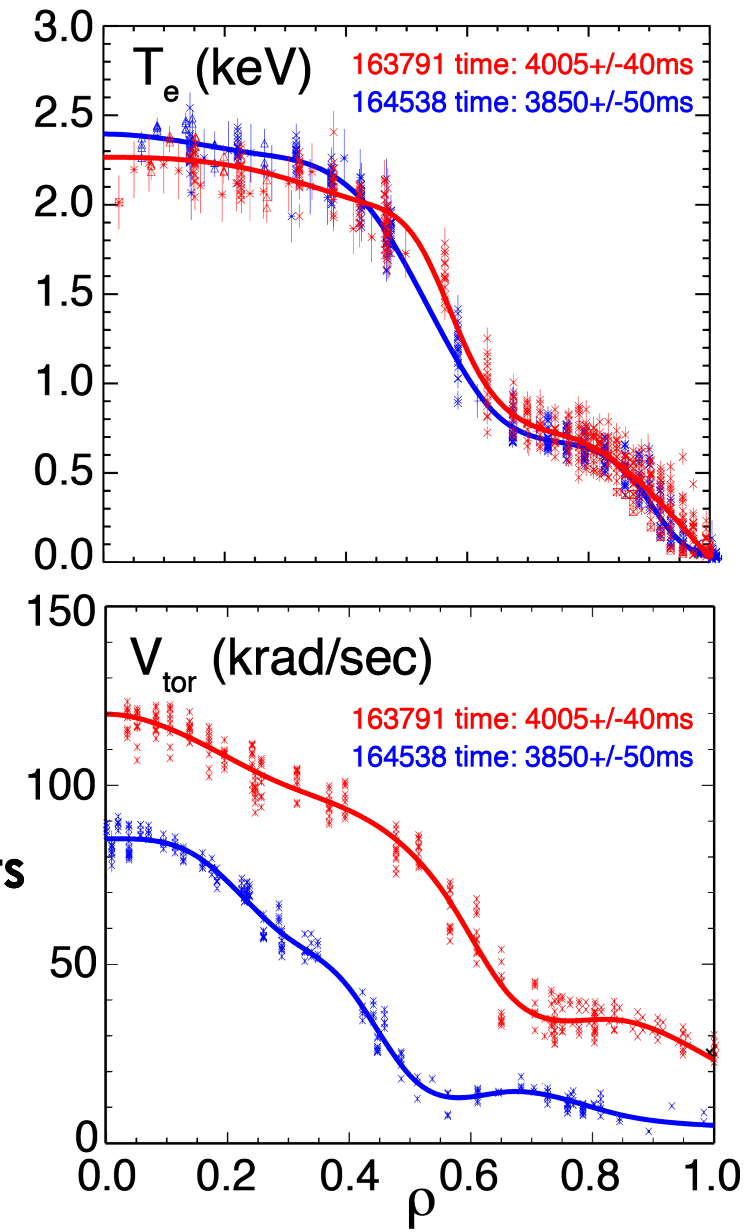
Large radius ITB is maintained at low toroidal rotation

- **Similar Te profiles with large radius ITB in high and low toroidal rotation**
- **High rotation shear does not align with T_e ITB**
- **Toroidal rotation is not the dominant effect on the formation of the ITB**



Large radius ITB is maintained at low toroidal rotation
No ion turbulence near ITB at high and low toroidal rotation





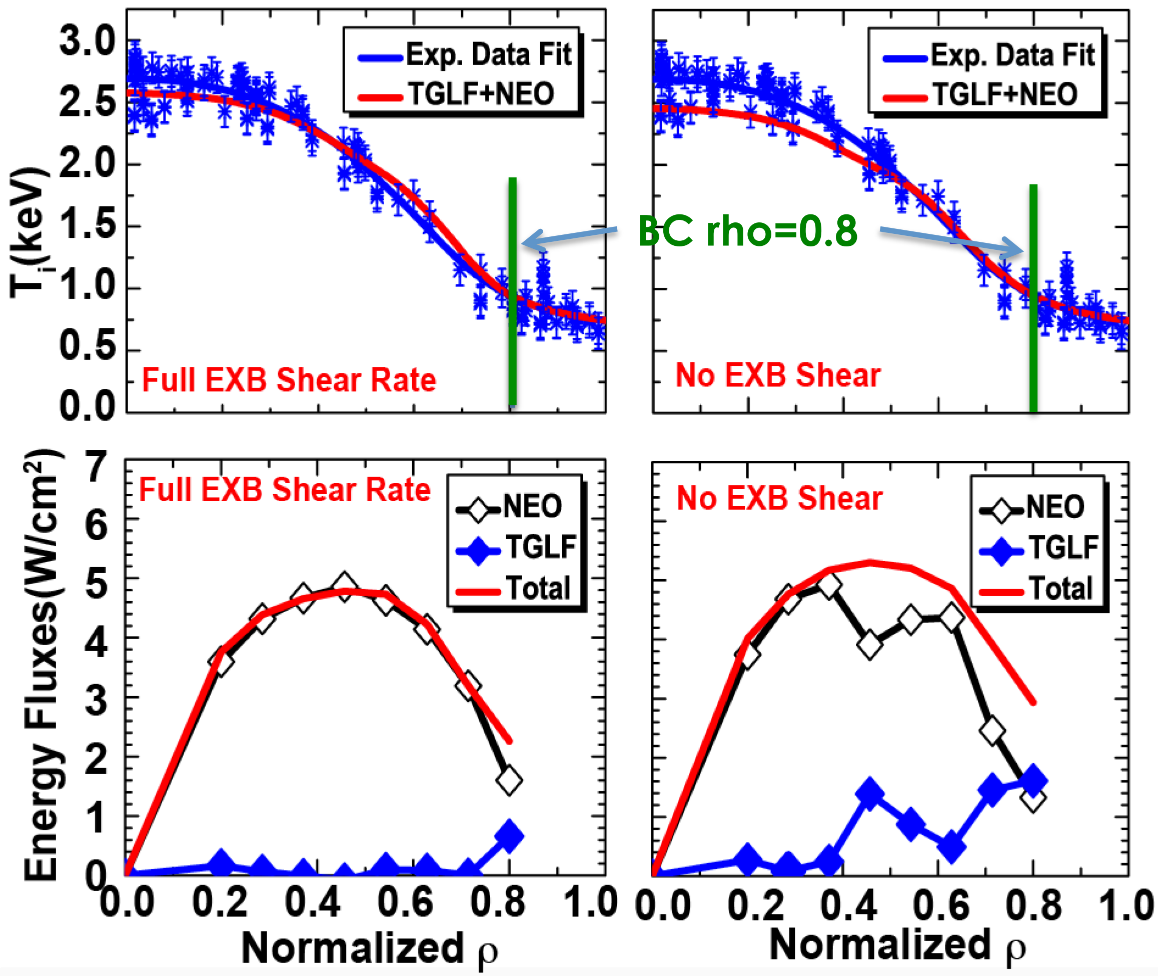
- **Ion scale turbulence measurements from Beam Emission Spectroscopy**

DIII-D NATIONAL FUSION FACILITY

Ion energy transport is dominantly neoclassical

- Evolving just the ion temperature predicted from TGLF +NEO
- Neoclassical transport is the dominant ion energy flux
- Small change in predicted Ti with/ without EXB

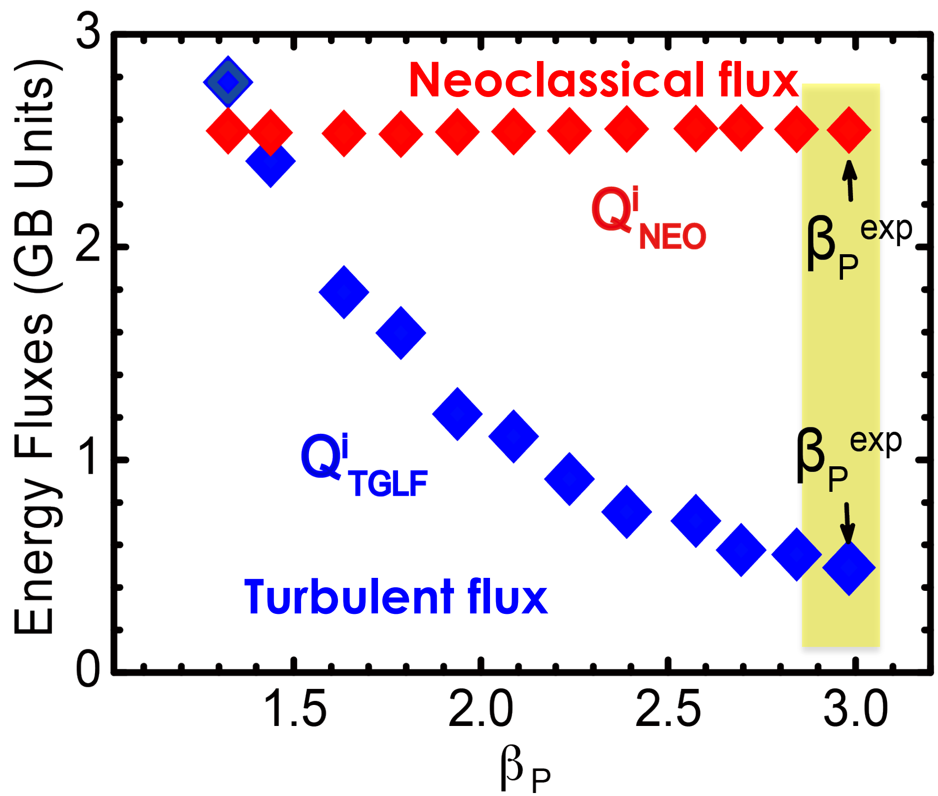
Energy flux is not sensitive to EXB shear



DIII-D NATIONAL FUSION FACILITY

Modeling shows shafranov shift stabilize ion turbulence

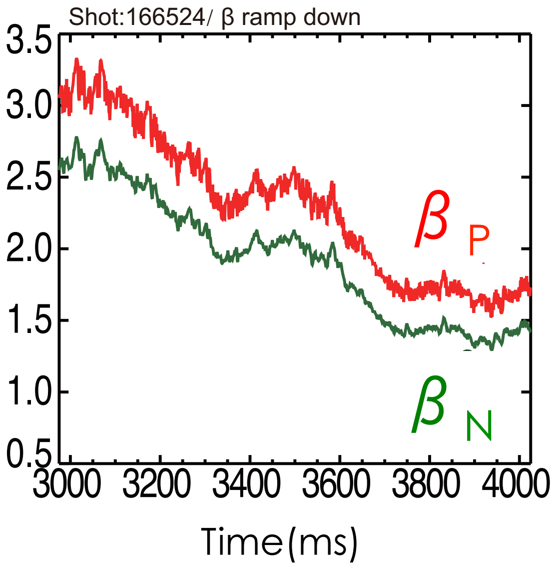
- **EFIT creates a series of equilibria with scaled pressure profiles**
- **Calculations focus on ITB region, rho~0.63 with TGLF and NEO**
- **Turbulent ion energy fluxes by TGLF decrease with the increasing β_P**



Shafranov shift$\propto$ $\beta_P + l_i/2$

DIII-D NATIONAL FUSION FACILITY

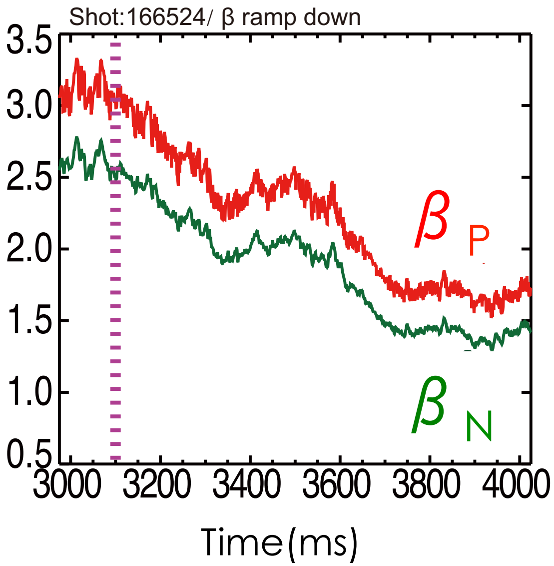
Recent β_P Ramp-down experiment confirmed the TGLF prediction of shafranov shift stabilization

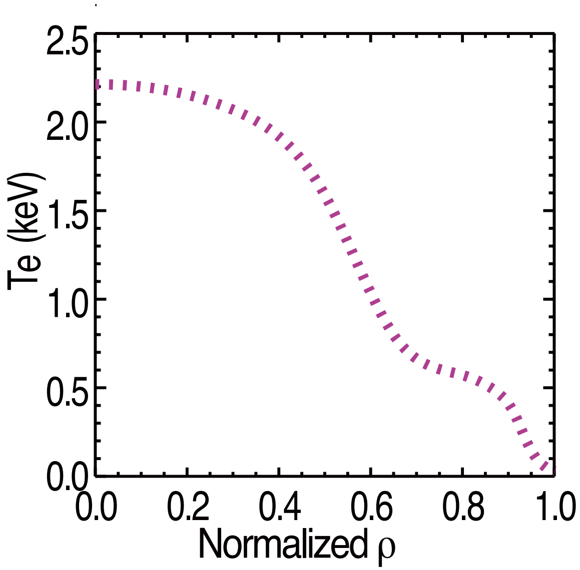


- **Ramp down of β_P obtained with feedback control of the NBI heating power**

DIII-D NATIONAL FUSION FACILITY

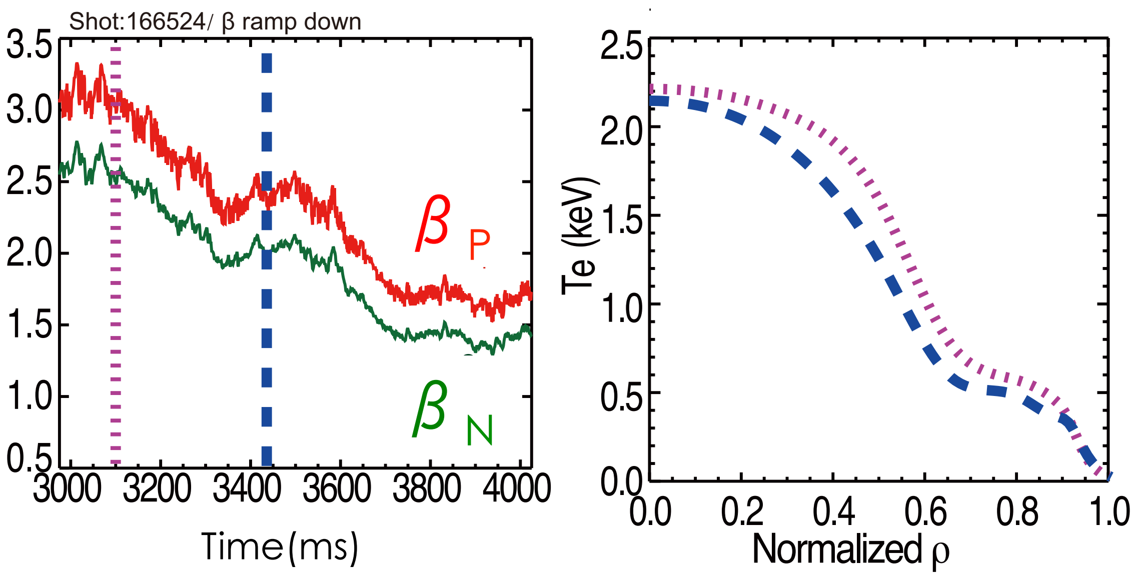
Recent β_P Ramp-down experiment confirmed the TGLF prediction of shafranov shift stabilization





- **Ramp down of β_P obtained with feedback control of the NBI heating power**
- **ITB becomes weaker and disappears when lowering β_P**

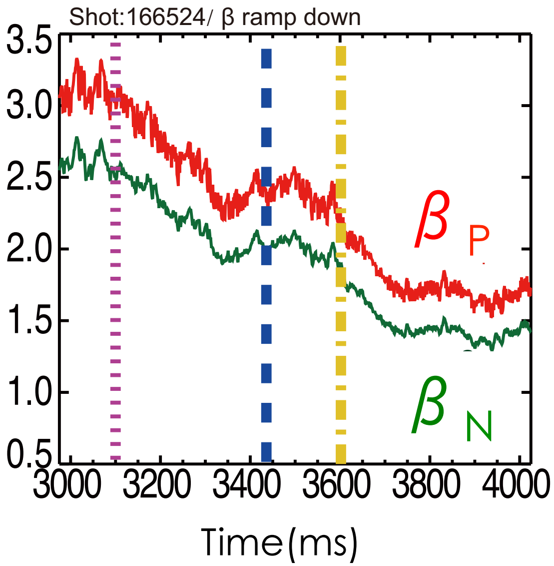
Recent β_P Ramp-down experiment confirmed the TGLF prediction of shafranov shift stabilization

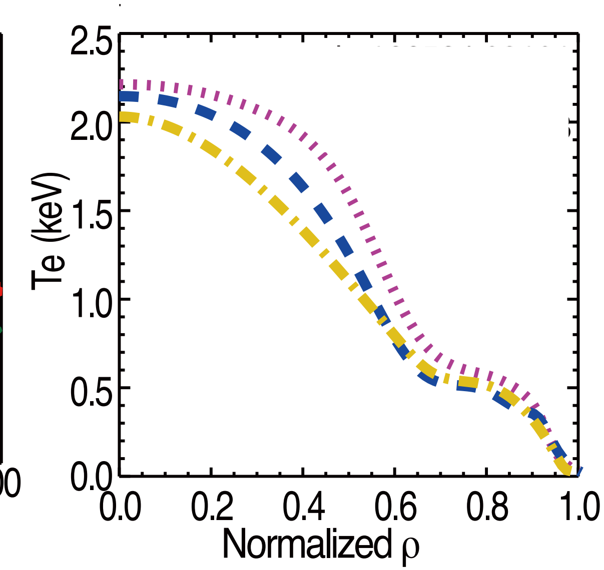


- **Ramp down of β_P obtained with feedback control of the NBI heating power**
- **ITB becomes weaker and disappears when lowering β_P**

DIII-D NATIONAL FUSION FACILITY

Recent β_P Ramp-down experiment confirmed the TGLF prediction of shafranov shift stabilization

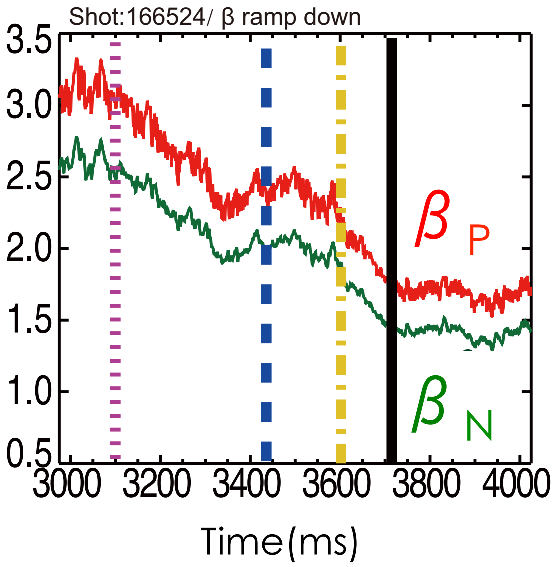


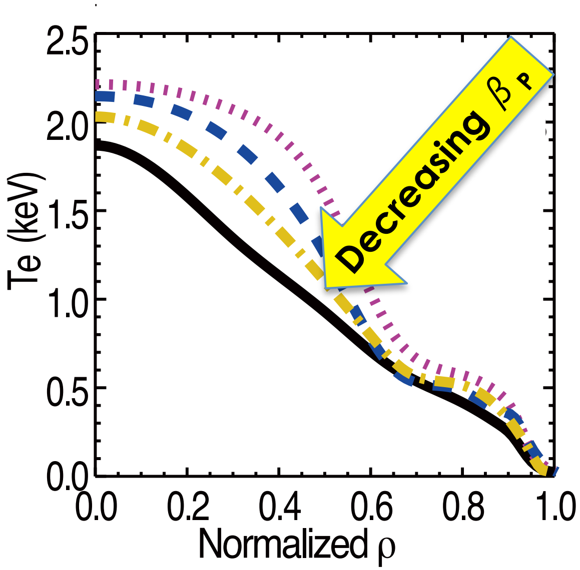


- **Ramp down of β_P obtained with feedback control of the NBI heating power**
- **ITB becomes weaker and disappears when lowering β_P**

DIII-D NATIONAL FUSION FACILITY

Recent β_P Ramp-down experiment confirmed the TGLF prediction of shafranov shift stabilization

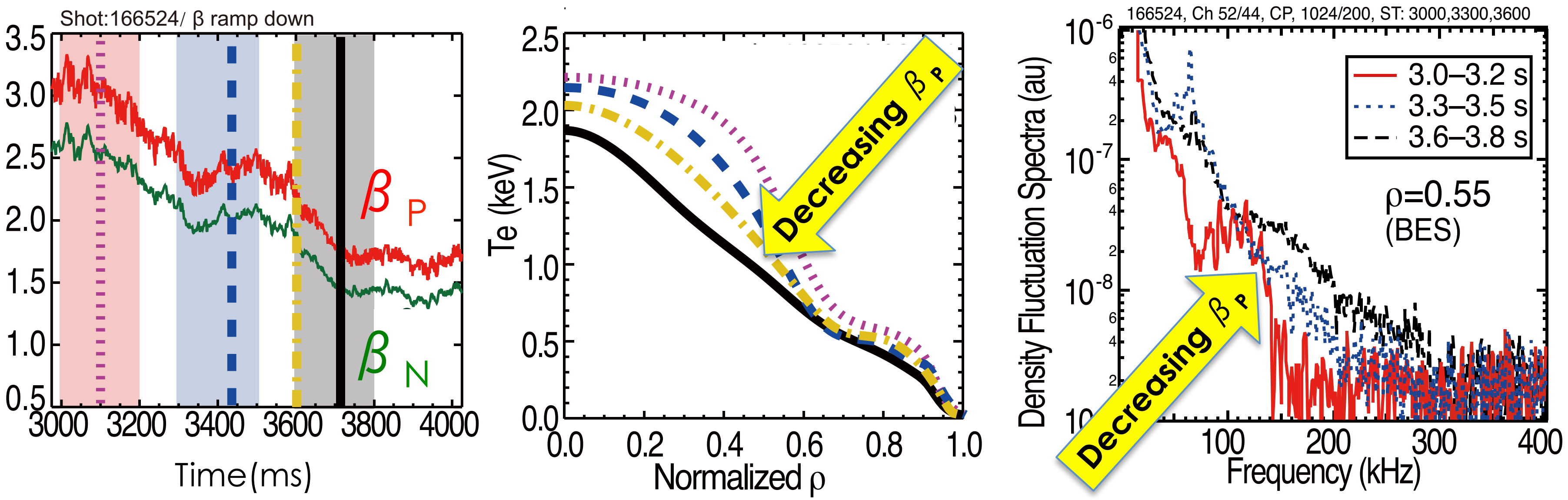




- **Ramp down of β_P obtained with feedback control of the NBI heating power**
- **ITB becomes weaker and disappears when lowering β_P**

DIII-D NATIONAL FUSION FACILITY

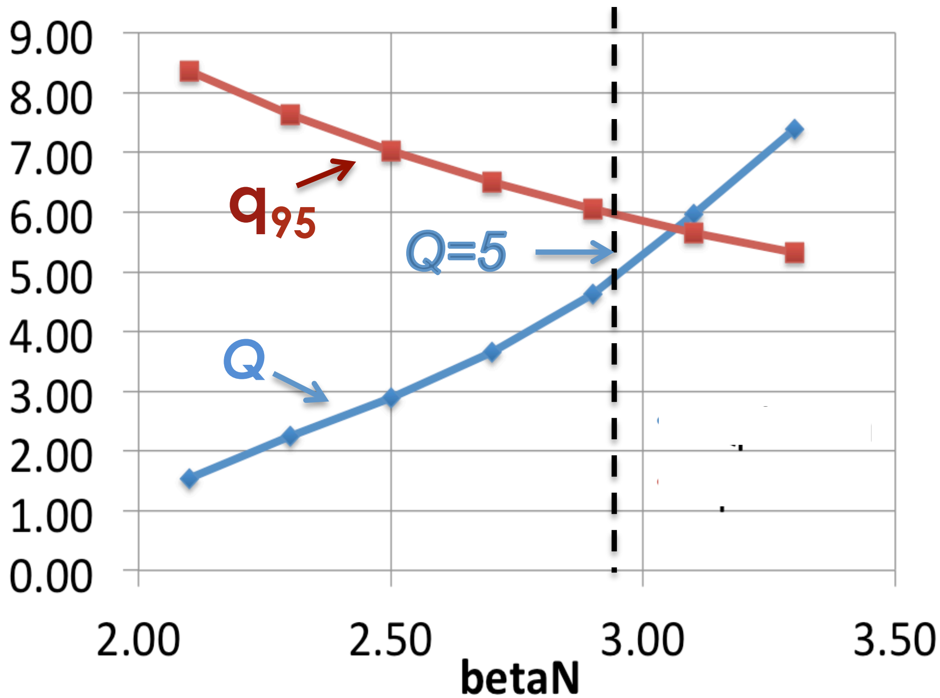
Recent β_P Ramp-down experiment confirmed the TGLF prediction of shafranov shift stabilization



- Ramp down of β_P obtained with feedback control of the NBI heating power
- ITB becomes weaker and disappears when lowering β_P
- Ion-scale fluctuations increase as β_P reduced

DIII-D NATIONAL FUSION FACILITY

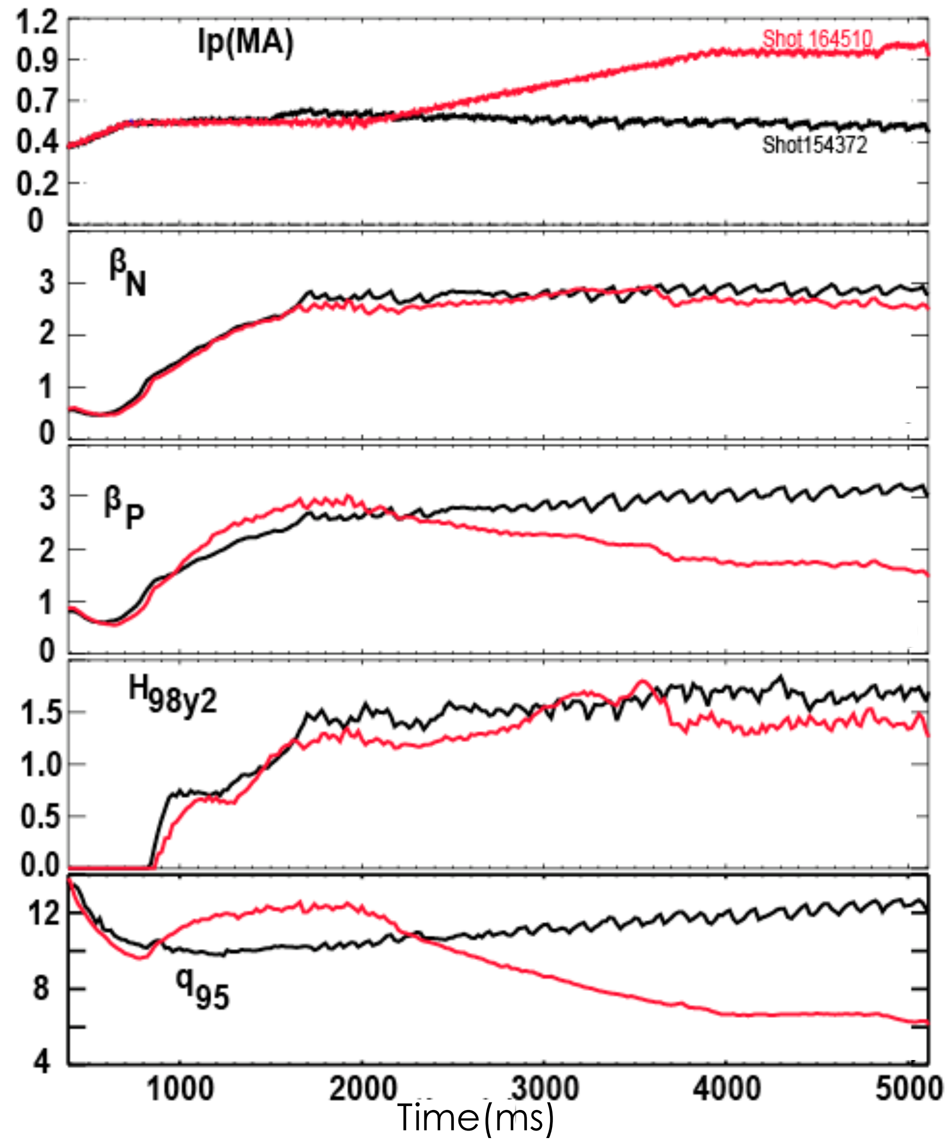
To achieve Q=5 Mission of ITER-SS requires lower q95



- **Using GA 0-D model**
  - H_{98y2}=1.6, f_{BS}=80%
  - Paux = 73 MW, B_T = 5.3 T
- **Reducing q_{95} increases the fusion power**
- **Question:** lower q_{95}→ lower betaP→lower shafranov shift
  - **Can H_{98y2} >>1.0 be maintained?**

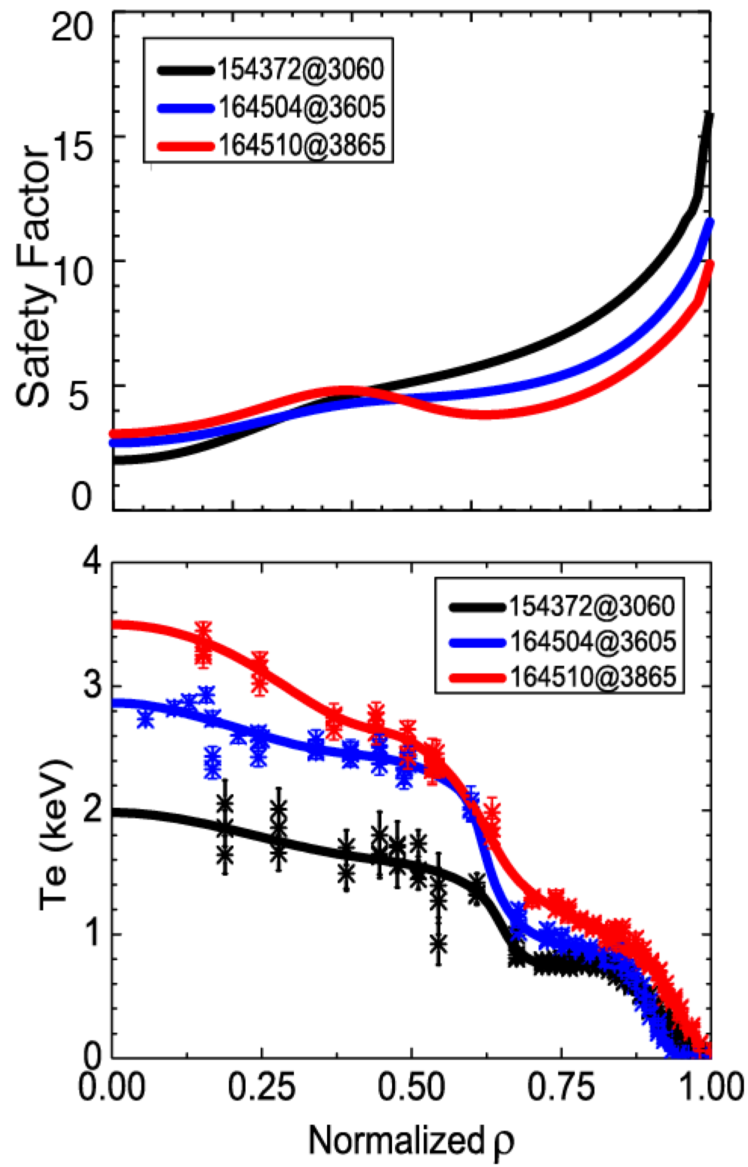
Good confinement plasmas are also achieved when lowering q_{95}

- **Second Ip ramp-up**
  - Ip 0.6MA →1MA
  - q_{95} 11→6.5
- **Good confinement**
  - H_{98y2}>1.5 at q_{95}>7.0
  - Confinement decreases due to weaker ITB

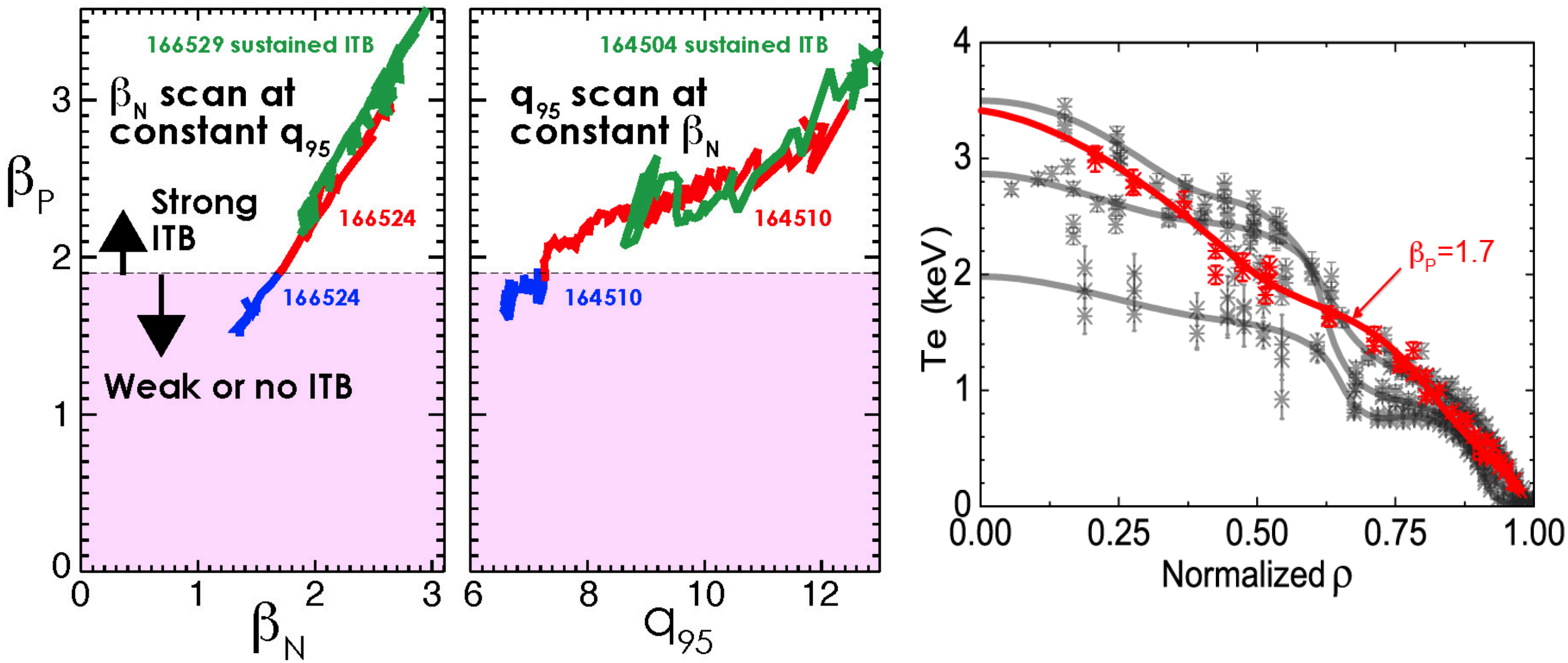


Large radius ITBs can be maintained at reduced q_{95}

- **A broad current profile was achieved at reduced q_{95}**
- **T_e profiles with large radius ITB are produced at high and low q_{95}**
- **Higher plasma current has a higher core T_e**

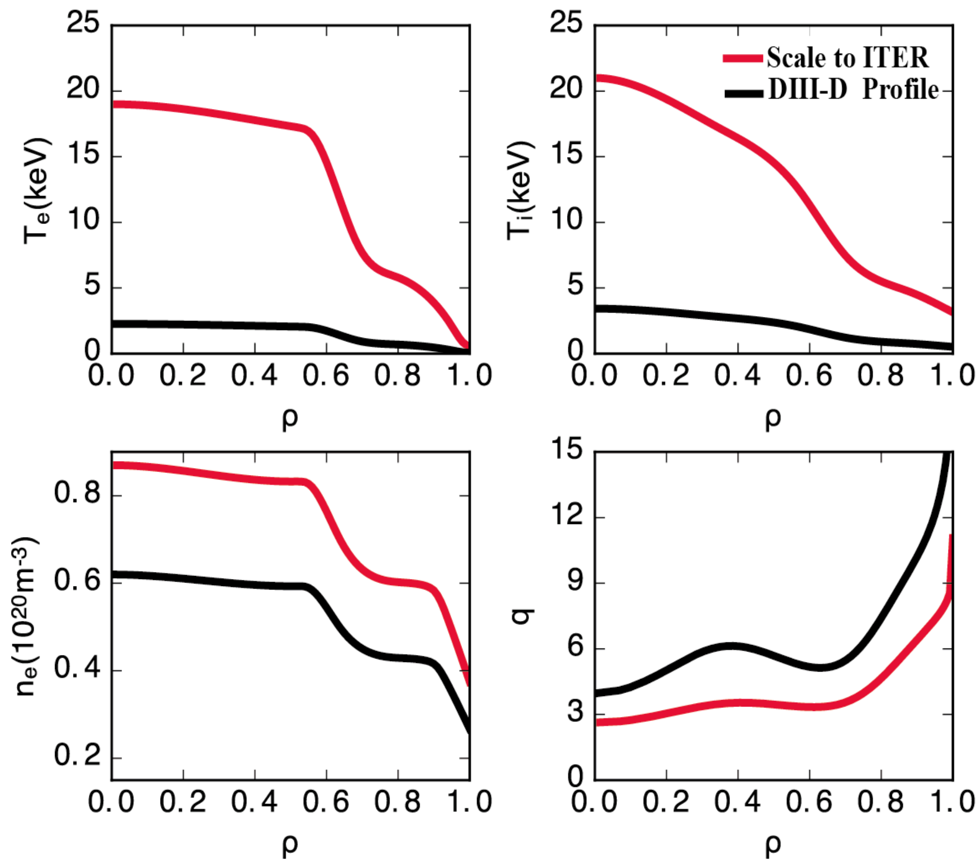


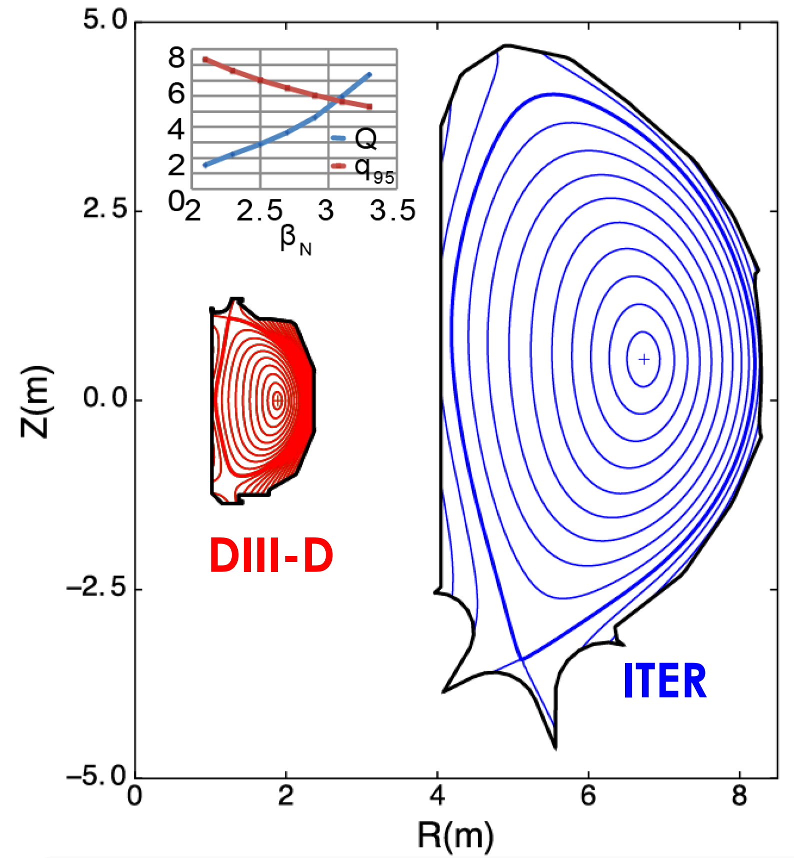
Large radius ITBs can be maintained with sufficient shafranov shift stabilization effect



- Higher β or higher q_{95} → stronger shafranov shift → better for ITB formation

DIII-D high β_P scenario profiles are scaled to ITER according to 0D modeling results





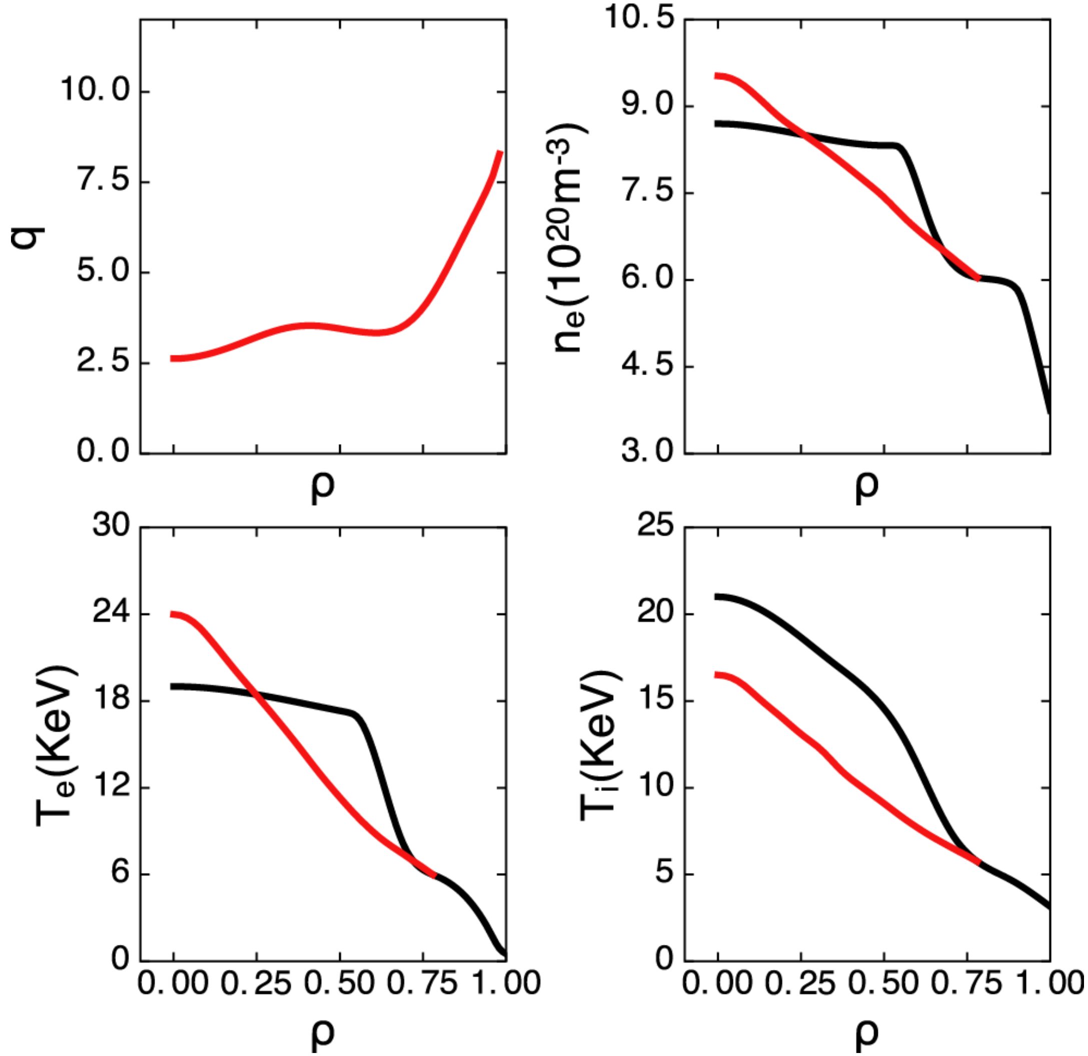
0D modeling (assuming H_{98y2}=1.6):

→ I_P, $T_e(0)$, $T_i(0)$, $n_e(0)$

DIII-D NATIONAL FUSION FACILITY

TGLF indicates Shafranov shift is not sufficient for ITB in ITER

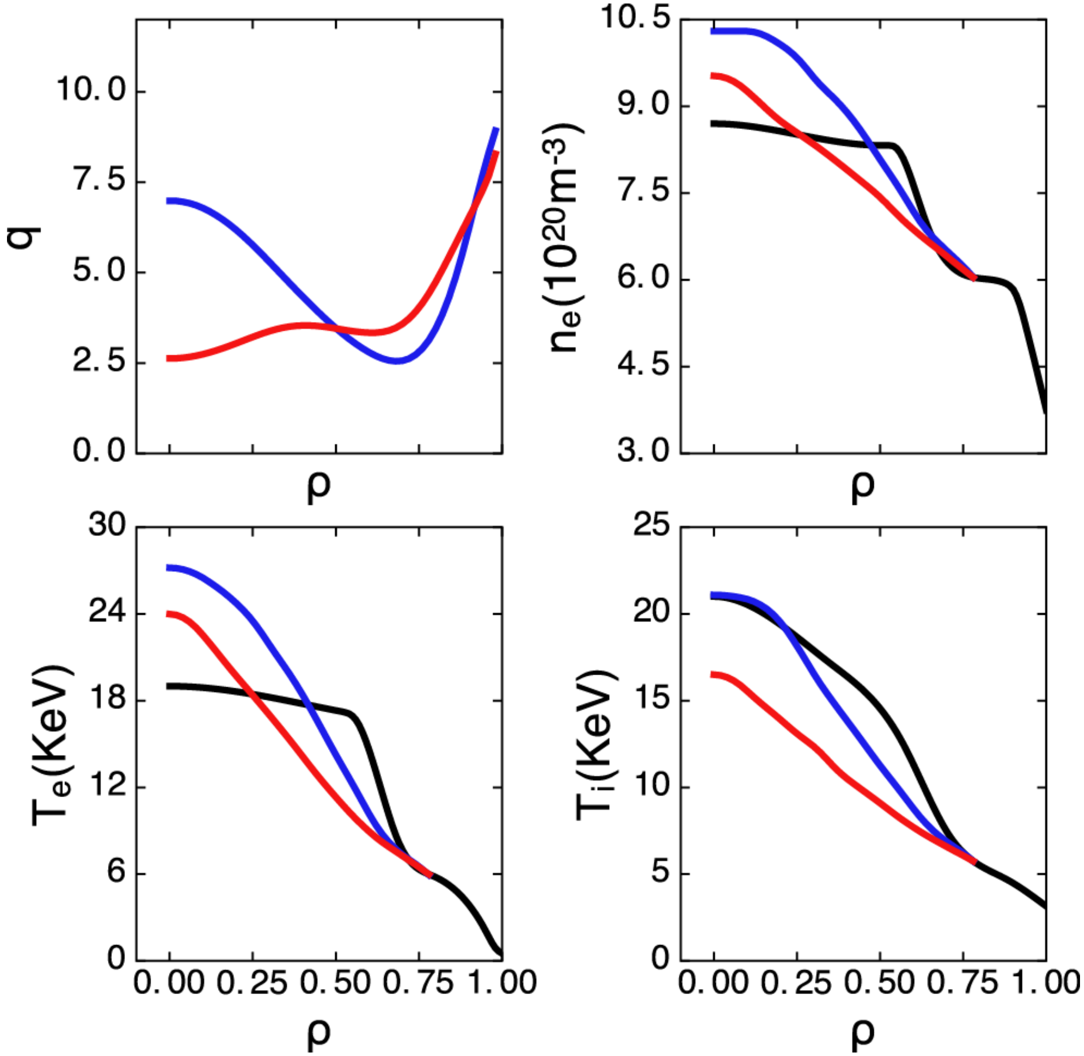
- Evolved T_i is much lower than the scaled temperature
- ITB disappears



DIII-D NATIONAL FUSION FACILITY

TGLF indicates Shafranov shift is not sufficient for ITB in ITER
Larger negative magnetic shear recovers ITB, enables Q=5

- **Increase q(0) to 7 at constant pressure**
- **Improved confinement with turbulence suppressed**
- **Q=5 achieved with high T_e and T_i**



DIII-D NATIONAL FUSION FACILITY

Summary: DIII-D high β_P scenario shows promising path for long pulse fully non-inductive scenario on ITER

- **Large radius ITB and excellent confinement maintained at reduced rotation or q_{95}**

- **Transport analyses suggest that EXB shear has little contribution to turbulence suppression, while Shafranov shift has the stabilizing effect on the turbulence.**

- **0-D and 1.5-D modeling analyses indicate high bootstrap scenario can be a candidate for Q=5 of ITER steady state.**