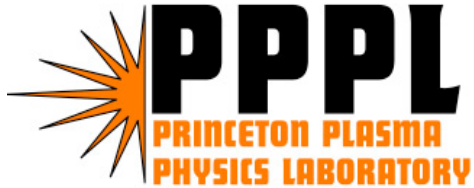



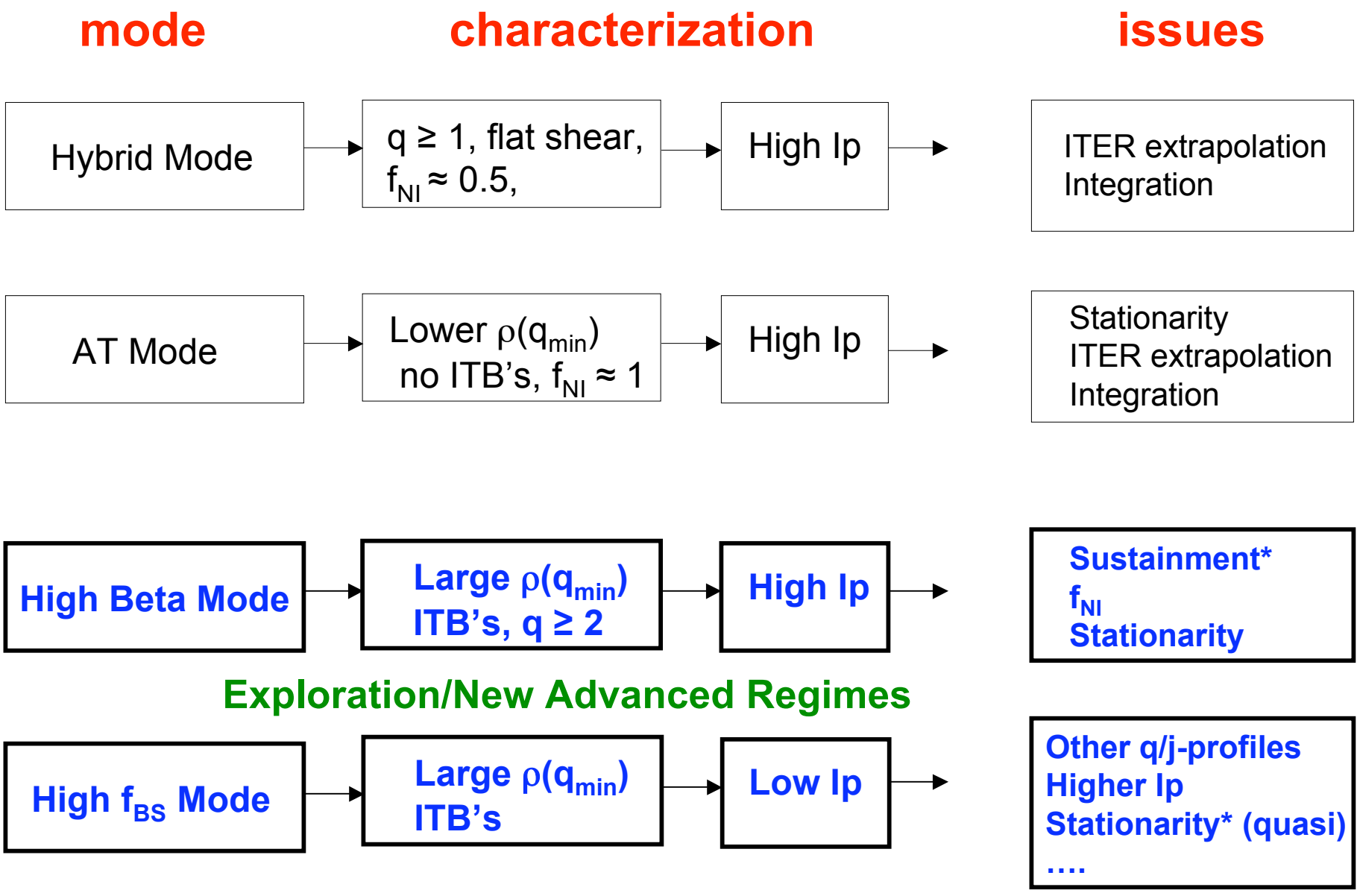

# Suggestions for Advanced Operating Mode Development in DIII-D

C. E. Kessel

*Princeton Plasma Physics Laboratory*

**DIII-D Advanced Tokamak Workshop,**
**February 27-28, 2007**

# Major Advanced Operating Modes

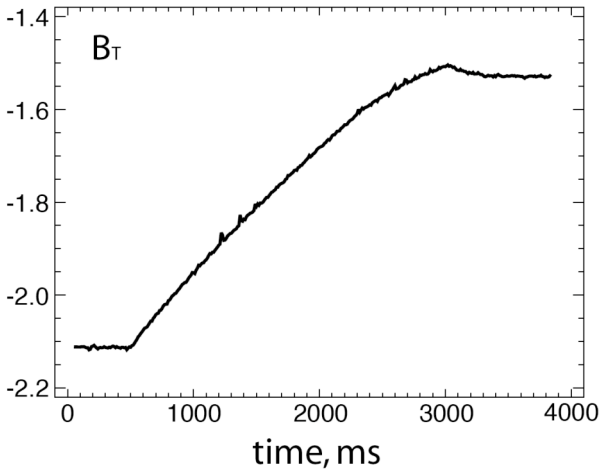


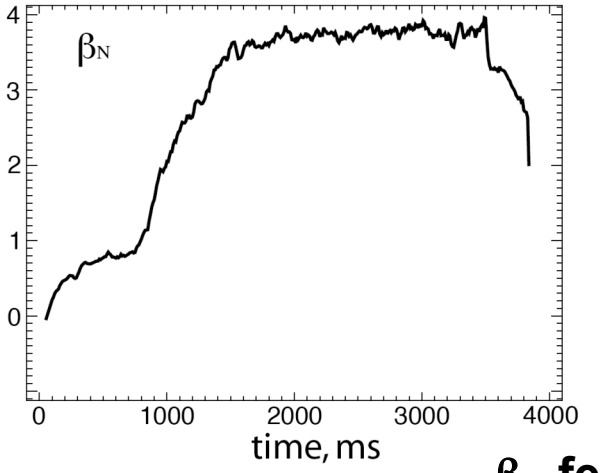
# DIII-D High-β Discharge 122976

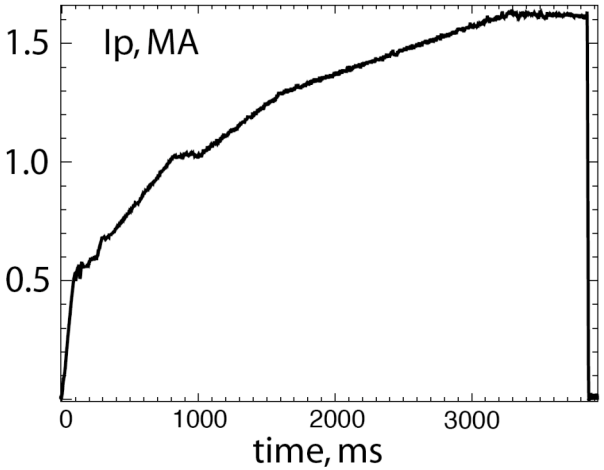
## Ip and $B_T$ Ramps to Produce High $q_{min}$ and large $\rho(q_{min})$

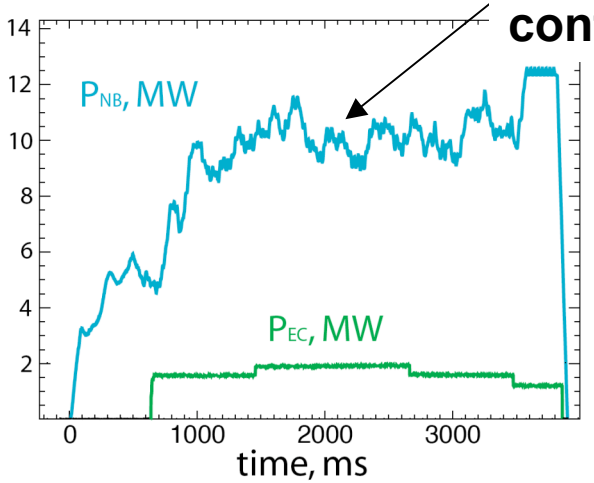
**Plasma reaches $\beta_N \approx 4$ for 2 s**

**Good target discharge to examine q control thru source & discharge optimization**



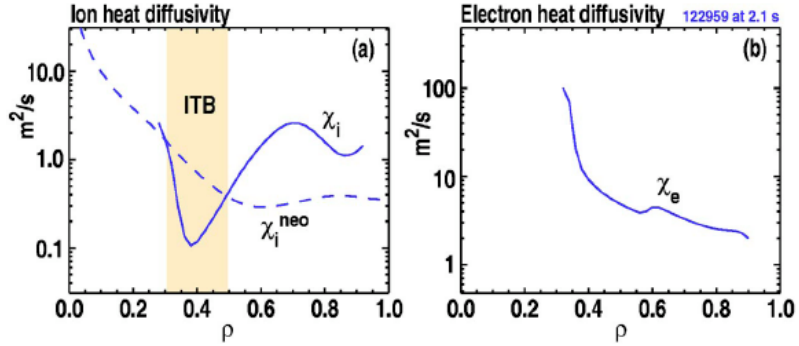



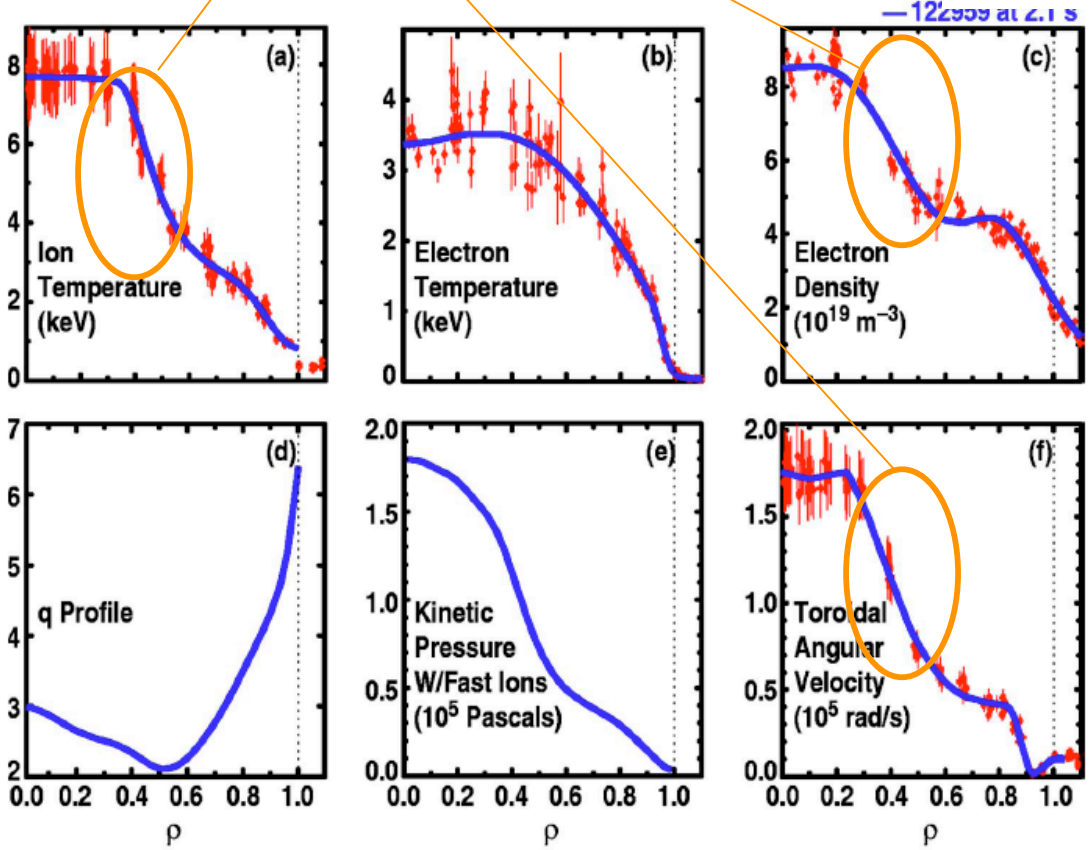



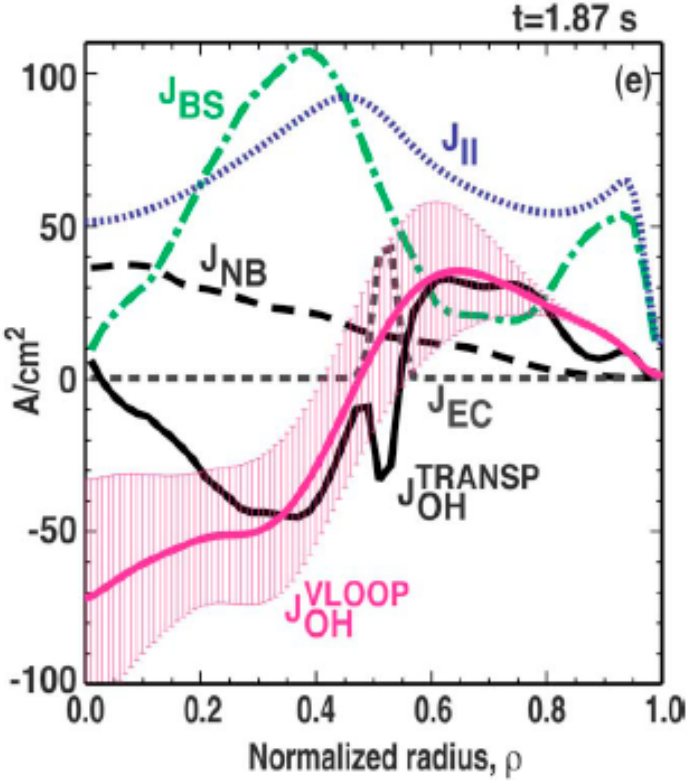

**$\beta_N$ feedback control with NB**

# DIII-D High-β Discharge 122976

**ITB's in ion energy, density, and momentum channels**



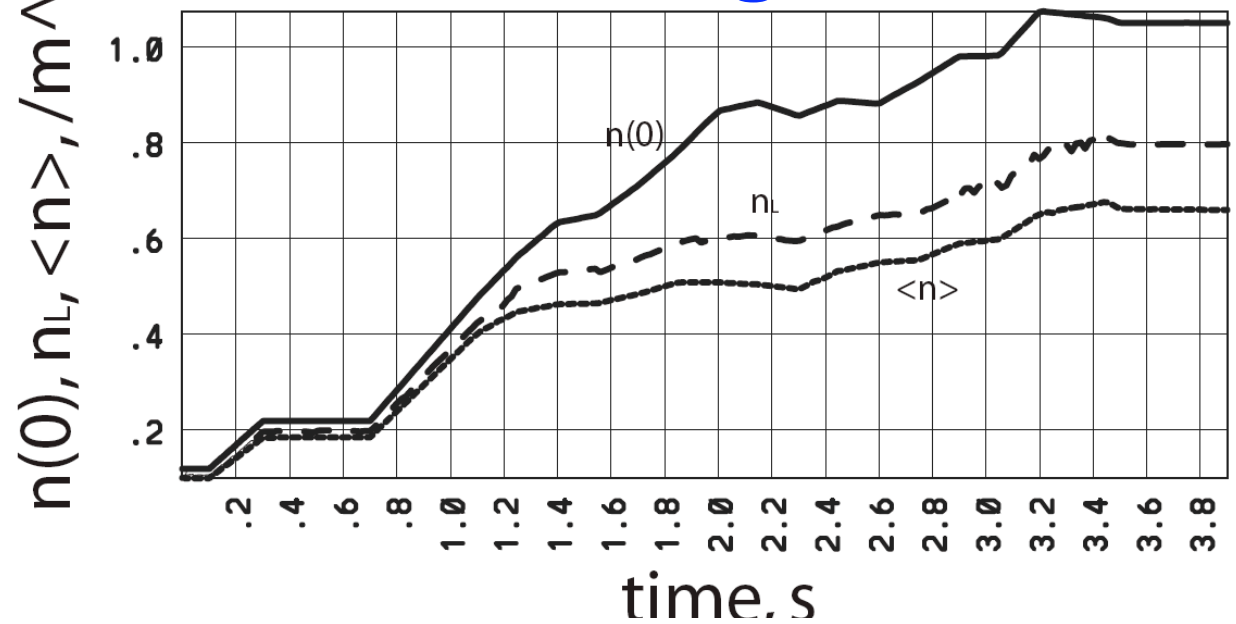



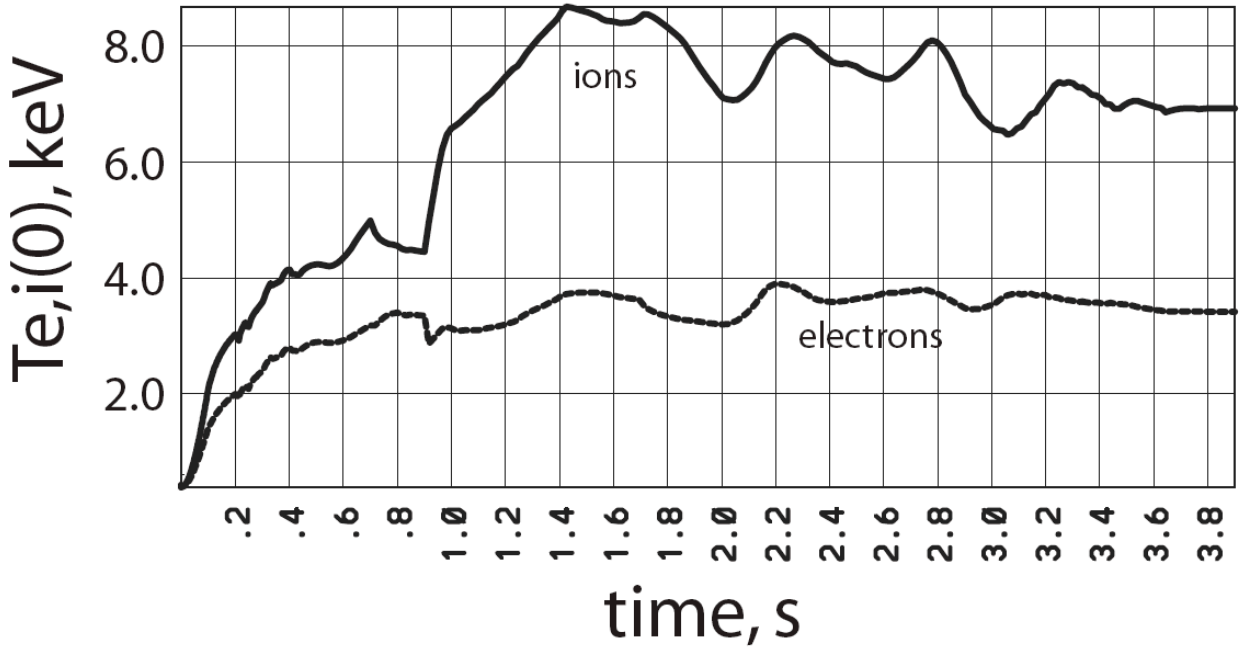



# Simulation of an Experiment to Project to Different Operating Conditions

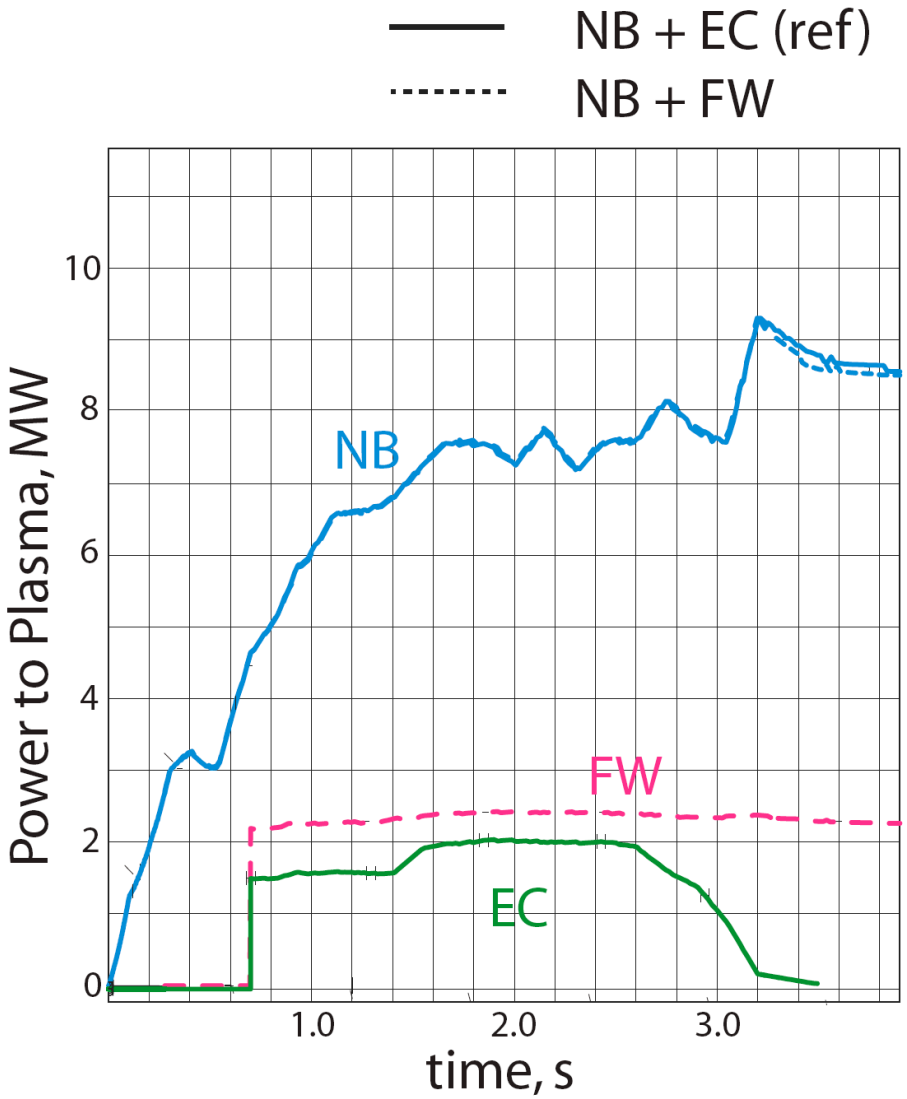
- TRANSP was run on DIII-D discharge 122976, a High Beta plasma
- TRANSP data used in TSC
  - Te, Ti, n passed thru
  - Thermal diffusivities, source heating and current depositions
- CURRAY was used offline to calculate the ICRF-FWCD
  - $n_{fast}$ and $<E_{fast}>$ taken from TRANSP to produce effective maxwellian
  - Injected powers based on L-mode and H-mode operating experience
  - Spectra from ORNL
  - Impurities specified as 2% H, 2% C for L-mode, 5% C in H-mode
  - Have 2 frequencies, 60 and 83 MHz launchers on DIII-D
  - $B_T$ varying throughout shot, so ICRF deposition is changing
- TSC was run with TRANSP data, time-slicing out to CURRAY every 250 ms
  - FW was used to replace EC
  - Density evolution was modified and FW added to EC

# TSC Modeling of 122976



# TSC Simulation: Compare NB + EC (112976) & NB + FW




Using TSC simulation of 122976 as the basis, which had NB and EC H/CD

Replace EC H/CD with **2.2 MW of FW heating only**

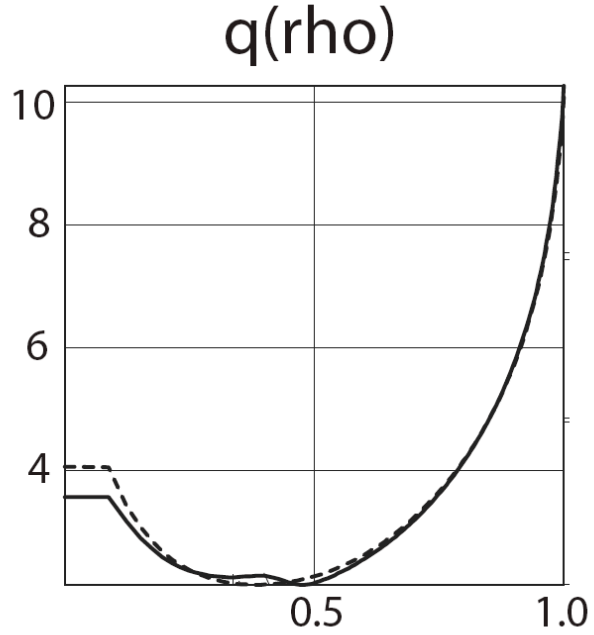
**Add 2.2 MW of FW heating** to EC H/CD (not shown)

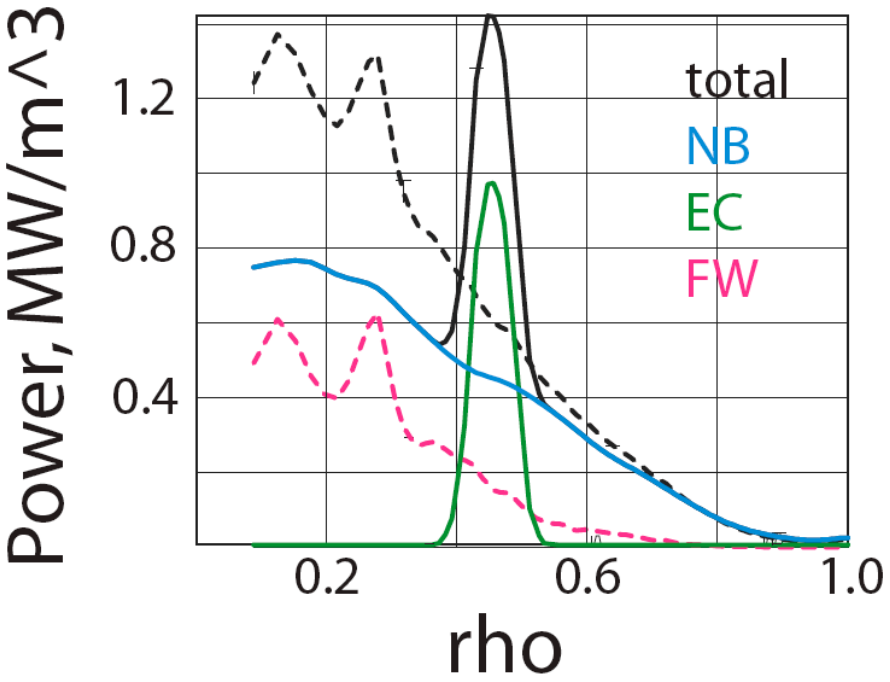
NB +EC (ref) & NB + FW

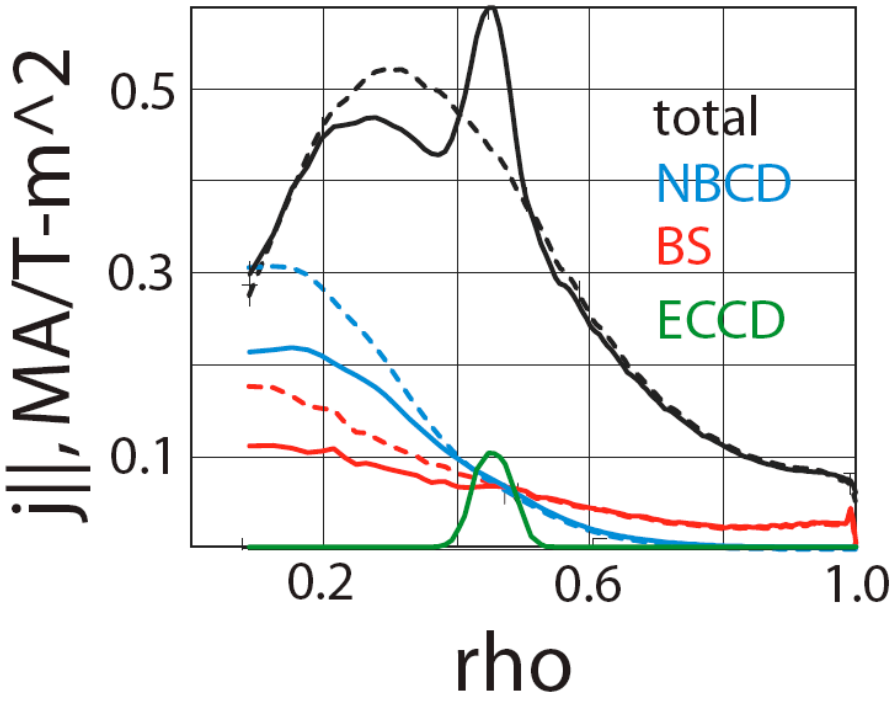
# Profiles at t= 0.9 s

ECCD creates localized $q_{min}$ at slightly larger ρ than FW

FW heating enhances NBCD and BS in core



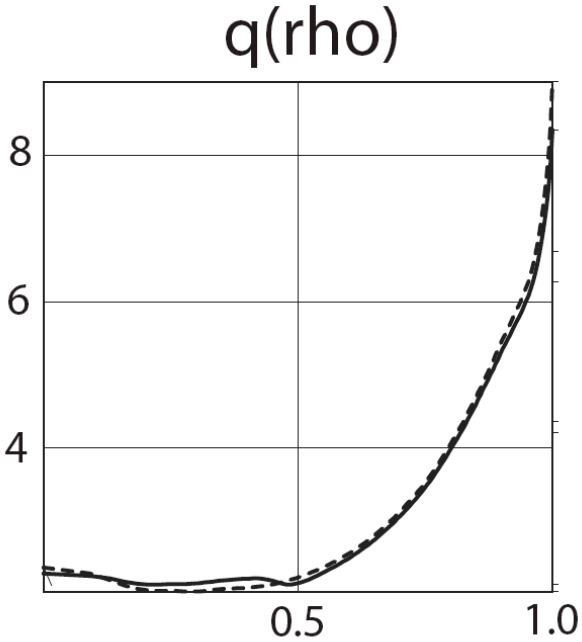



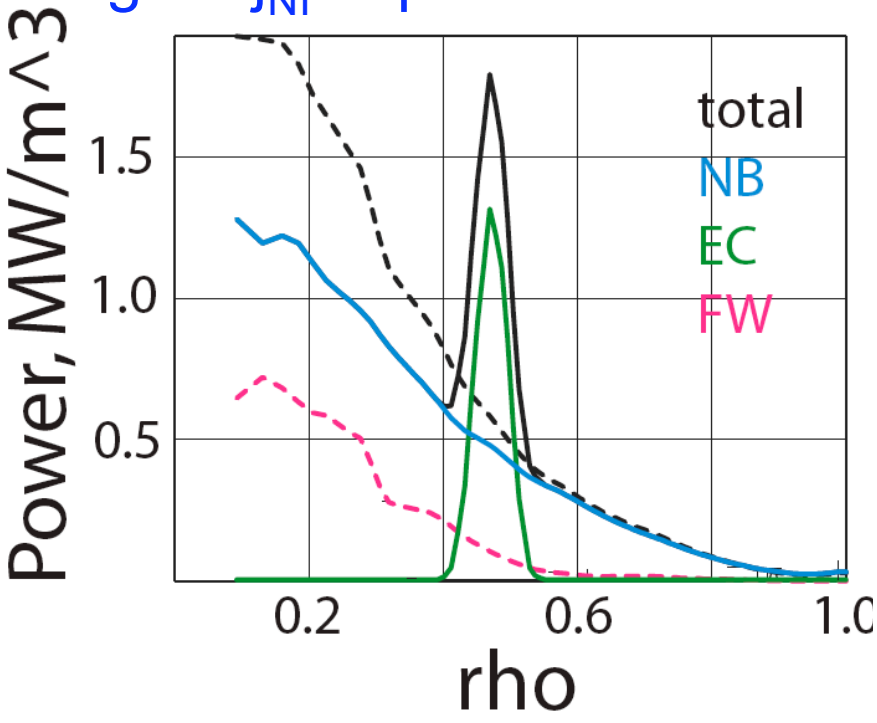
NB + EC (ref) & NB + FW

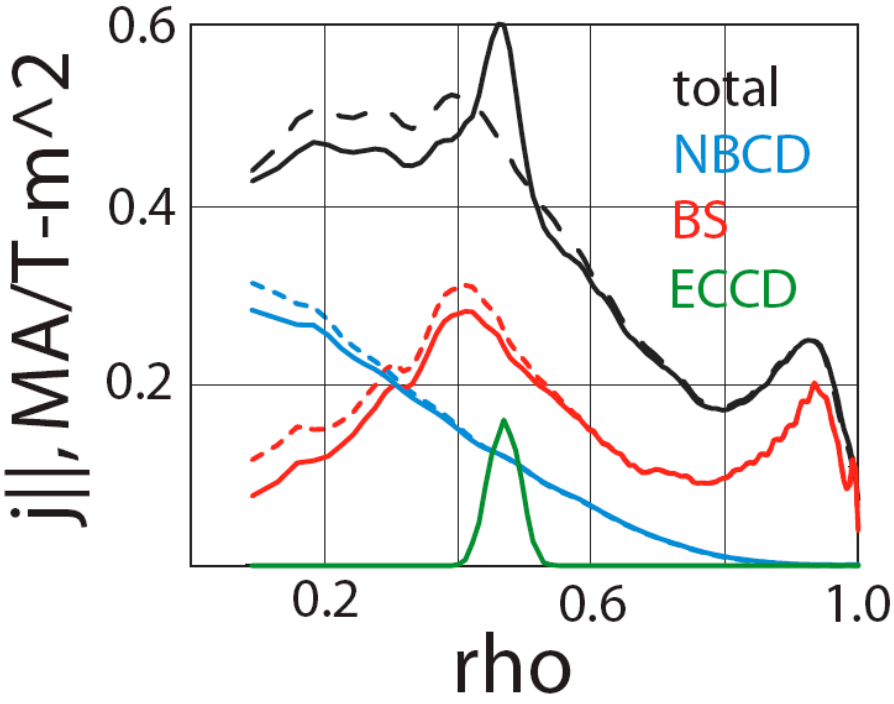
# Profiles at t = 1.5s

ECCD producing slightly higher $q_{min}$ and larger $\rho(q_{min})$

FW heating still providing slightly higher $j_{NI}$ in plasma core



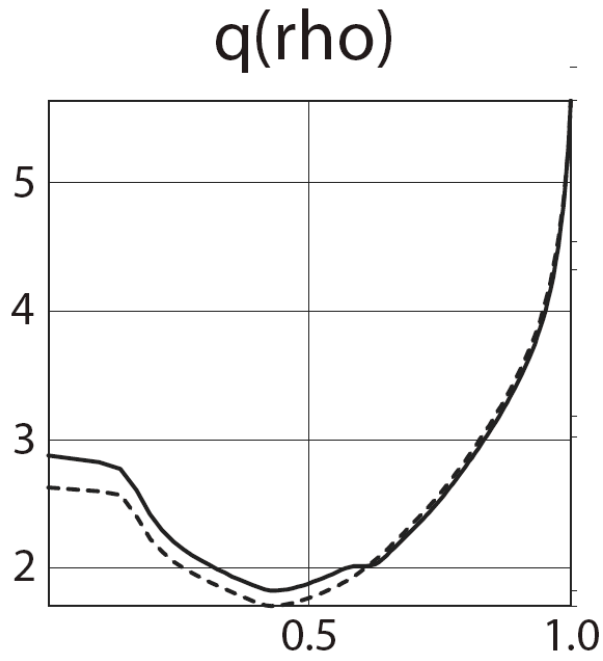



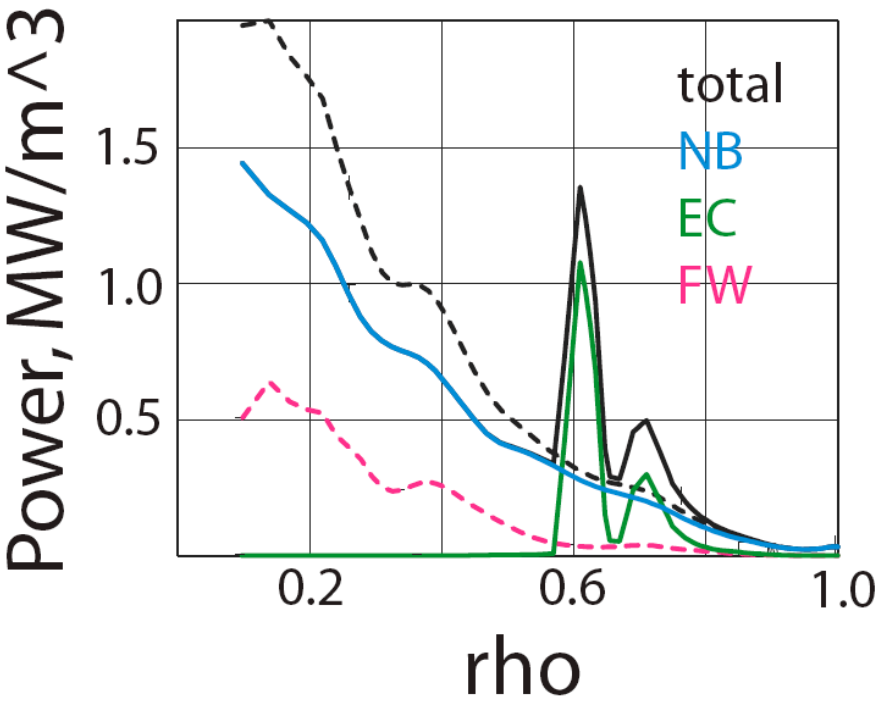
NB + EC (ref) & NB + FW

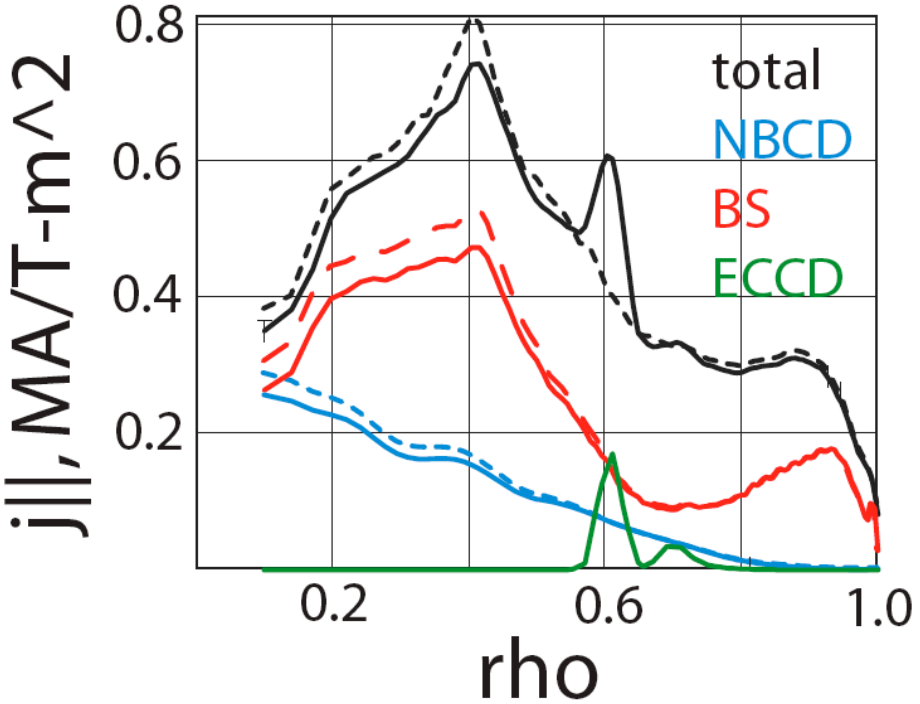
# Profiles at t = 2.5 s

ECCD case has higher $q_{min}$, although CD is diminishing as deposition moves to larger $\rho$

FW & EC cases have same $\rho(q_{min})$



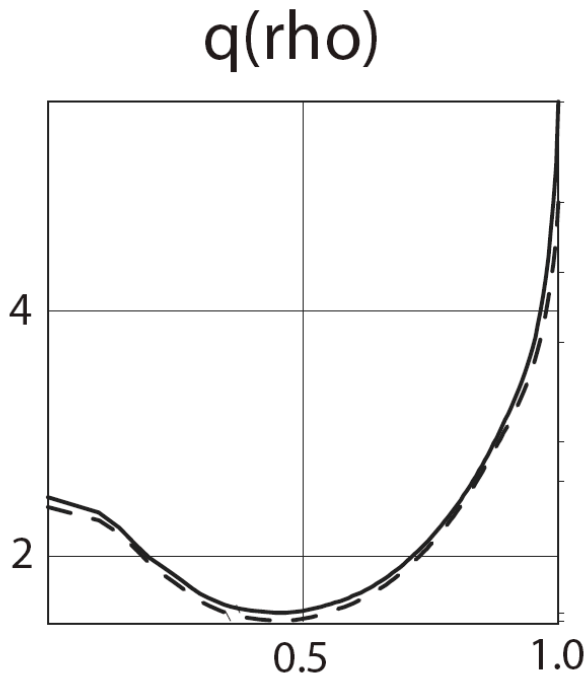



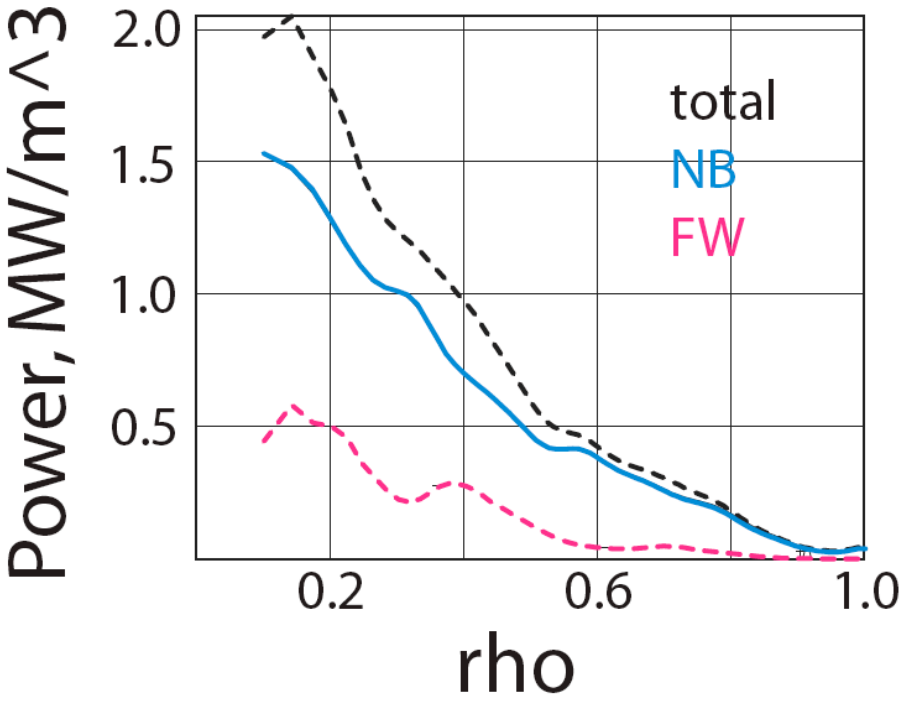
NB + EC (ref) & NB + FW

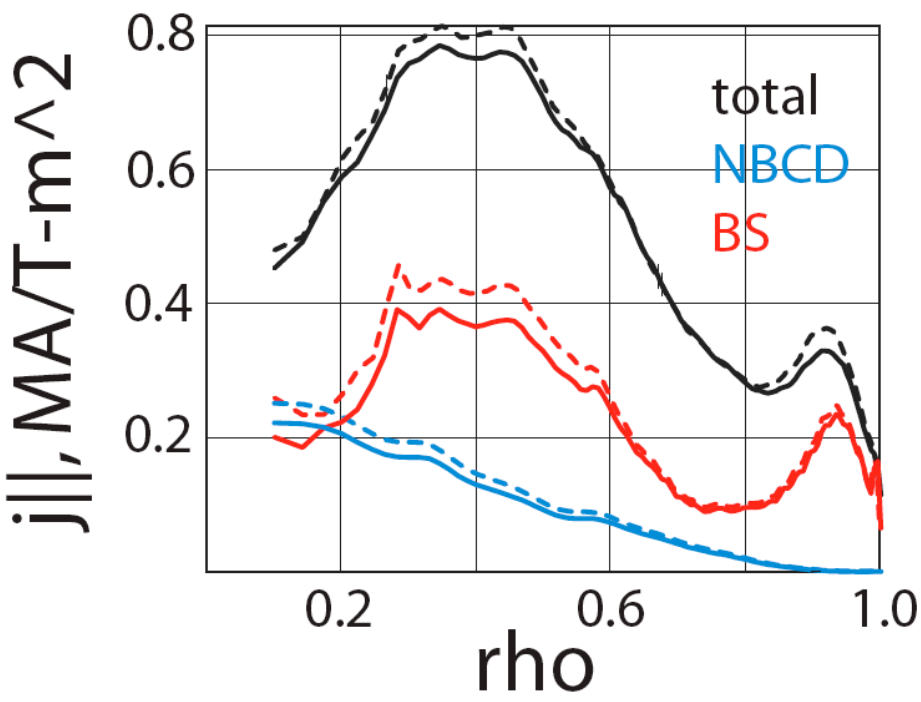
# Profiles at t = 3.4 s

EC has been cutoff due to high density

FW heating continues, but makes little difference to q profile



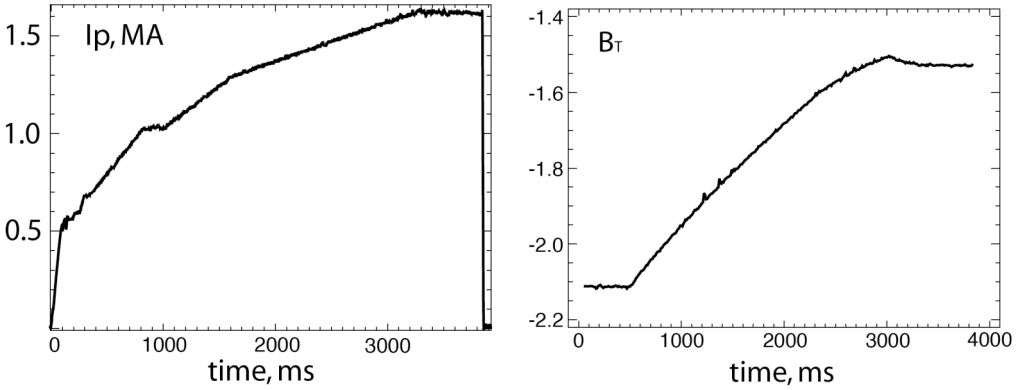



# Simulate High Beta Discharge 122976
# Adding n control and ICRF/FW

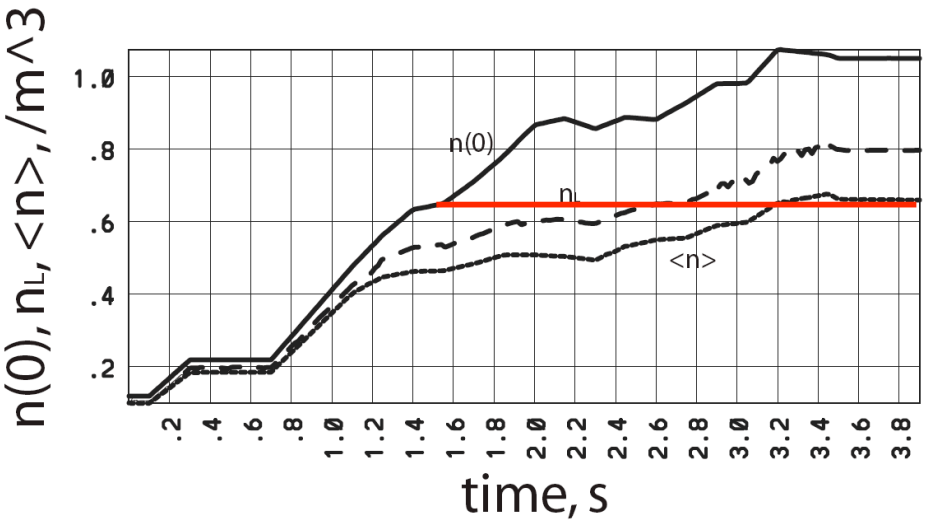
**HOWEVER, n is uncontrolled & EC is eventually cutoff**

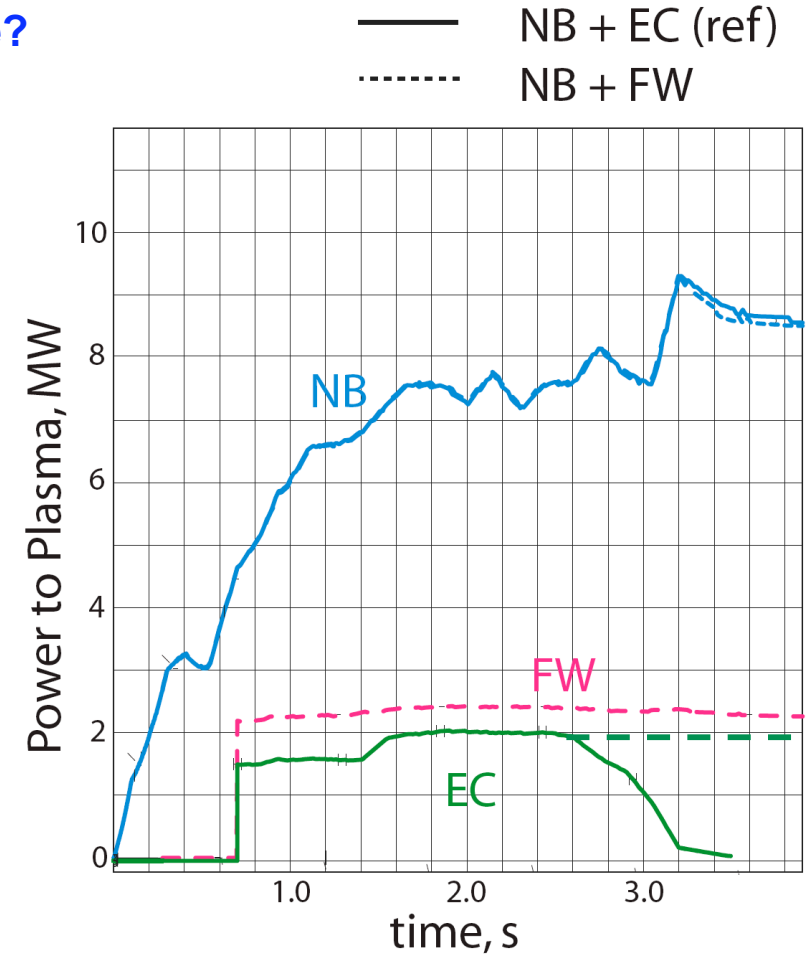
**How can FWCD alter the discharge & how can stopping the density rise improve the discharge?**









# Simulations with TSC and TRANSP Examine Effects of ICRF in D3D High Beta Plasmas

**Take existing discharge and modify it with FWCD and density control**

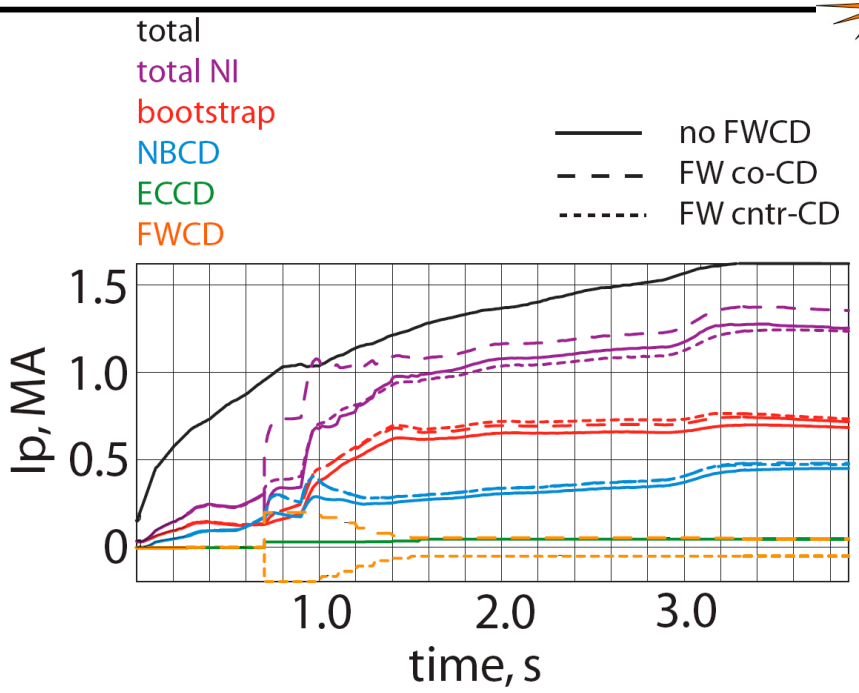
**Stop density rise at $6.5 \times 10^{20}$ /$m^3$**

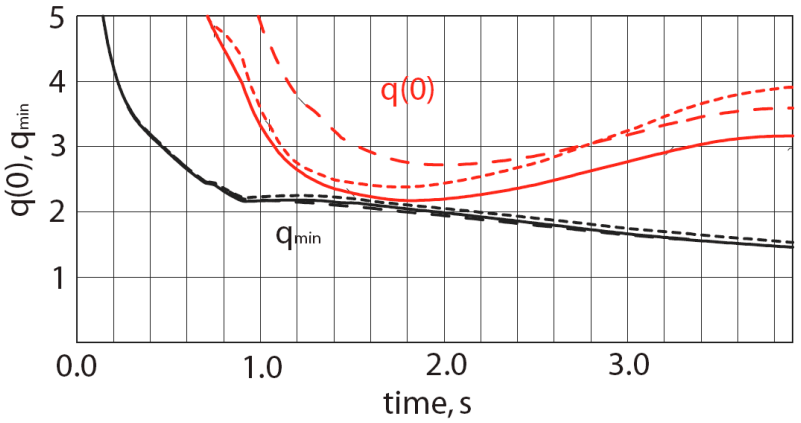
**Inject FWCD at same time as EC**

**Examine co-CD and cntr-CD**

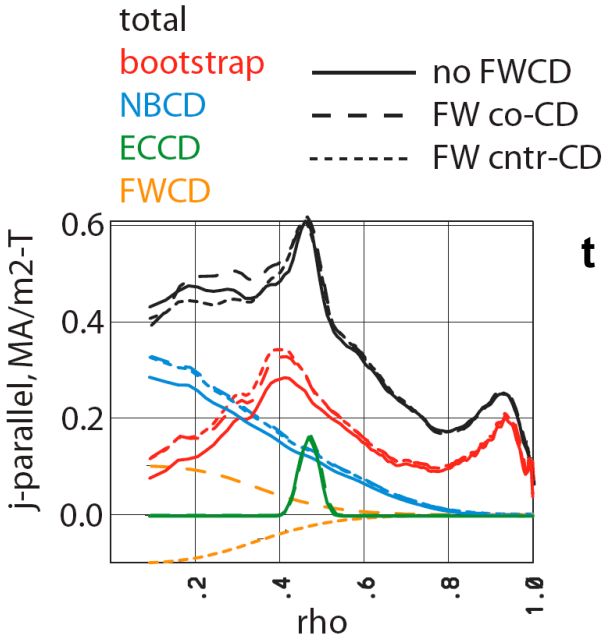
**Some improvement in NICD**

**Changes in q(0) evolution**

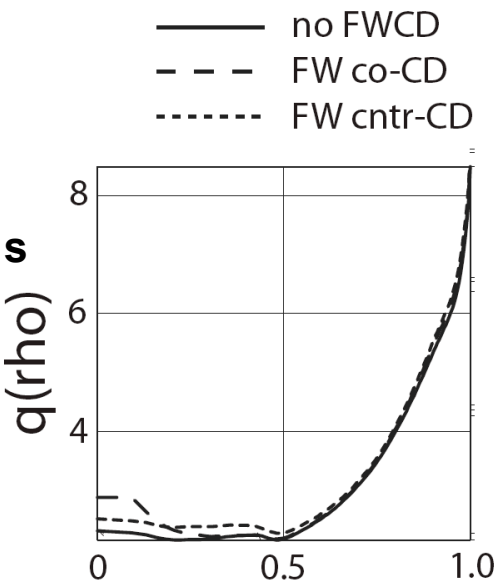


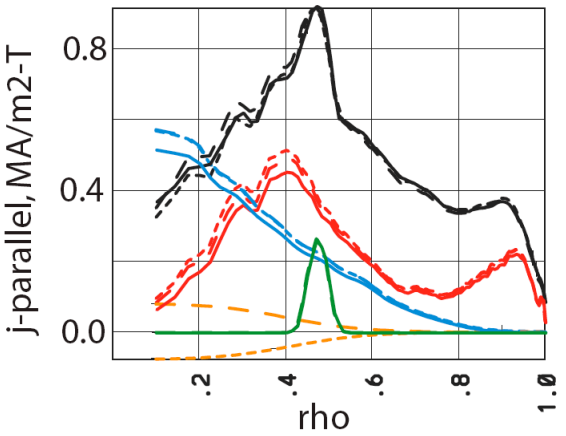



# D3D 122976 is a Complex Discharge with Ip & $B_T$ Ramps, But it Can Be Modeled

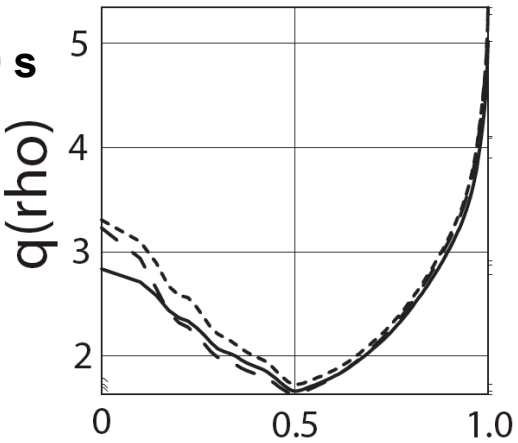



t = 1.5 s




t = 3.0 s




**Complex and transient discharges are difficult to understand experimentally**

**Modeling can provide insights into internal plasma behavior that is difficult to measure**

**Subtle effects can be important in advanced tokamak scenarios**

**Learning how to control plasma profiles will require significant time-dependent modeling**

# How to Reach $\beta_N \approx 5$

- Primary plasma characteristics that affect ideal MHD stability
  - p(0)/<p>
  - $\rho(q_{min})$
  - $q_{min}$ (dictated by $\rho(q_{min})$ and $I_P$)
  - Shaping (limited by structures and PF coil/shape control)
  - Wall location (moving plasma closer to wall)

- Examine with equilibrium and stability calculations
  - p(0)/<p> ≈ 2.15 and 2.8 (n(0)/<n> = 1.15 and 1.35)
  - $\rho(q_{min})$ = 0.45 and 0.65
  - $I_P$ = 1.2, 1.5, 1.7 MA
  - $B_T$ = 1.85
  - Standard shape ($\kappa$=1.85, $\delta$=0.65, $\zeta_o$=0.1, wall varied b/a = 1.4-1.5)

Transiently = the j($\rho$) and p($\rho$) correlation is broken

# How to Reach $\beta_N \approx 5$

- Prescribe parallel current density analytically to give $I_P$ and $\rho$(qmin), model inductive current evolution
- Pressure profile is analytic function with pedestal term
- **Examine $\beta_N = 5$ first**

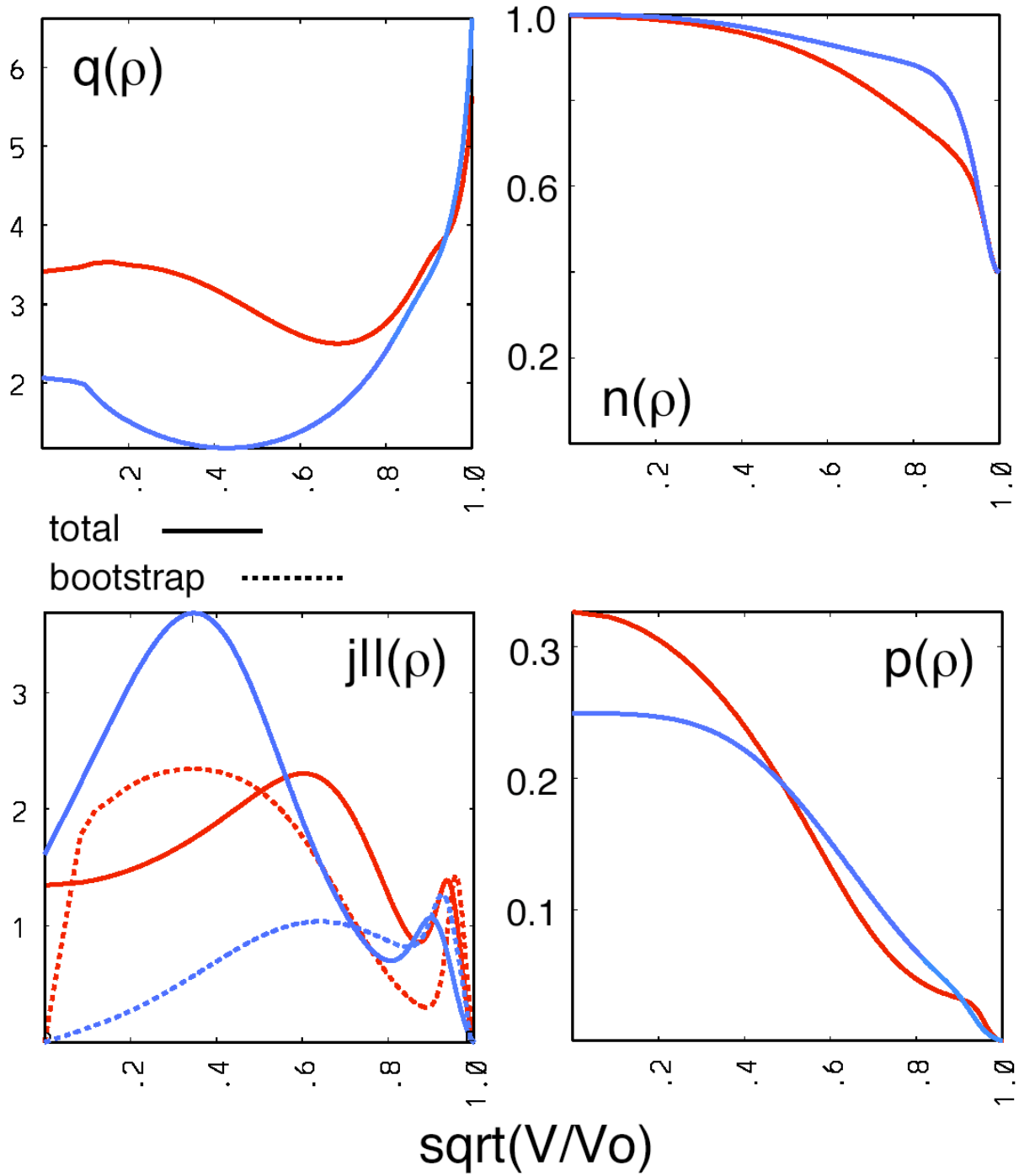
- Best case has $\rho(q_{min}) = 0.65$ and peaked pressure (p(0)/<p>=2.85), wall at b/a=0.5 stable to n=1,2,3
  - $I_P$ = 1.5 and 1.7 MA are good
  - $I_P$ = 1.25 not as good
  - Lowering $B_T$ appears necessary to get to higher $\beta_N$, so re-examine at 1.65 and 1.5 T ---> same good stability behavior, a little better at 1.2 MA

| $\beta_N$ | $\rho_{qmin}$ | $I_P$ | p(0)/<p> | q(0) | $q_{min}$ | n=1 | n=2 | n=3 | $B_T$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| 4.9 | 0.65 | 1.26 | 2.80 | 3.26 | 2.91 | S(0.45) | U | U | 1.85 |
| 4.96 | 0.65 | 1.17 | 2.15 | 4.00 | 3.00 | S(0.45) | U | U | 1.85 |
| 5.08 | 0.65 | 1.50 | 2.13 | 3.44 | 2.29 | S(0.5) | U | U | 1.85 |
| **4.92** | **0.65** | **1.50** | **2.80** | **3.42** | **2.52** | **S(0.48)** | **S(0.5)** | **S(0.5)** | **1.85** |
| **5.0** | **0.65** | **1.7** | **2.84** | **2.93** | **2.10** | **S(0.45)** | **S(0.5)** | **S(0.5)** | **1.85** |
| 5.10 | 0.65 | 1.7 | 2.04 | 2.42 | 1.81 | S(0.5) | U | U | 1.85 |
| **4.93** | **0.65** | **1.5** | **2.88** | **2.87** | **2.14** | **S(0.48)** | **S(0.5)** | **S(0.5)** | **1.65** |
| **5.04** | **0.65** | **1.5** | **2.77** | **2.72** | **1.94** | **S(0.45)** | **S(0.45)** | **S(0.5)** | **1.50** |
| **4.98** | **0.65** | **1.70** | **2.86** | **2.20** | **1.60** | **S(0.48)** | **S(0.48)** | **S(0.4)** | **1.50** |
| 4.94 | 0.65 | 1.20 | 2.79 | 3.18 | 2.58 | S(0.48) | S(0.45) | U | 1.50 |
| 4.90 | 0.65 | 1.20 | 2.82 | 3.19 | 2.69 | S(0.48) | S(0.43) | U | 1.65 |
| 5.09 | 0.65 | 1.5 | 2.51 | 2.67 | 2.17 | S(0.5) | S(0.43) | U | 1.65 |
| | | | | | | | | | |
| 5.08 | 0.45 | 1.20 | 2.80 | 2.76 | 1.75 | U | U | U | 1.85 |
| **4.93** | **0.45** | **1.20** | **2.17** | **2.75** | **1.68** | **S(0.4)** | **U** | **U** | **1.85** |
| 4.95 | 0.45 | 1.50 | 2.90 | 1.99 | 1.20 | U | U | U | 1.85 |
| **4.93** | **0.45** | **1.50** | **2.11** | **2.06** | **1.17** | **S(0.5)** | **S(0.5)** | **U** | **1.85** |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |

**RED:**
**Peaked pressure with large rho(qmin)**

**BEST stability at high $\beta_N$**

**BLUE:**
**Broad pressure with small rho(qmin)**



# High Bootstrap Fraction is an Important Area Integrating Transport, Stability, and Control

***Politzer's experiments are tremendously important*** ---> they push in the "other" direction for AT (other than high $\beta_N$)

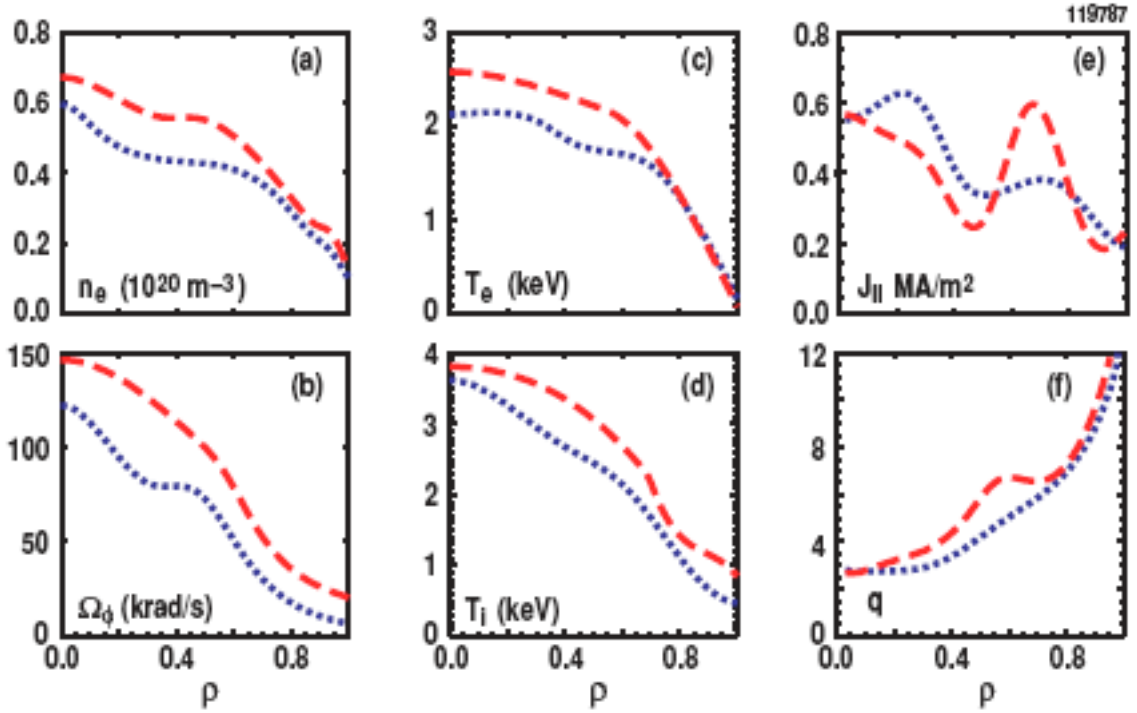
They demonstrate that the transport regime and bootstrap current are strongly coupled at high $f_{BS}$

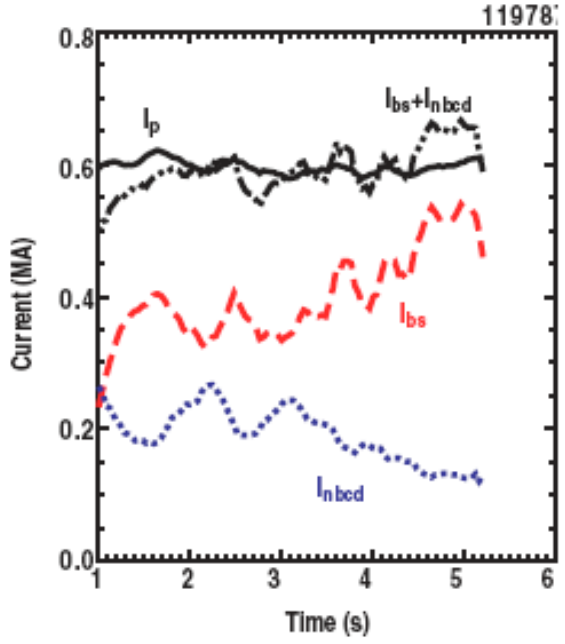
- Confinement was good
- MHD did not appear to degrade confinement
- ITB is present at large radius, producing large $j_{BS}$

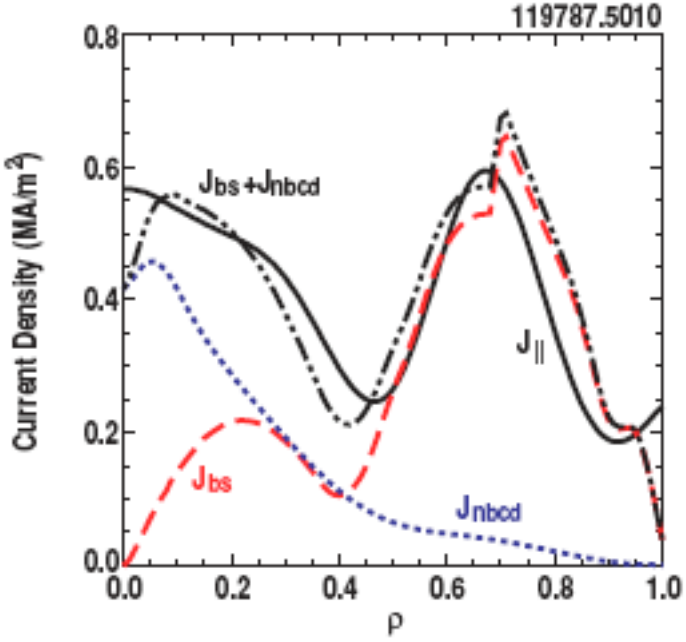
The oscillations present in these plasmas may be sensitive to q/j-profile established, use of Ip control/presence of inductive current, $f_{BS}$, etc. ---> are oscillations bad or good?

---> I have been interested in oscillating the transport regime between 2 states (ITB and H-mode) to control $j_{BS}$

The report of this work clearly shows this area has not been examined in great detail ----> ***it should be!***


119787
(a)
$n_e$ ($10^{20}$ m$^{-3}$)
(b)
$\Omega_\phi$ (krad/s)
(c)
$T_e$ (keV)
(d)
$T_i$ (keV)
(e)
$J_{||}$ MA/m$^2$
(f)
q
ρ


119787
$I_p$
$I_{bs}+I_{nbcd}$
$I_{bs}$
$I_{nbcd}$
Current (MA)
Time (s)


119787.5010
$J_{bs}+J_{nbcd}$
$J_{||}$
$J_{bs}$
$J_{nbcd}$
Current Density (MA/m$^2$)
ρ

# Very High Bootstrap Current Plasmas

- Impact of different densities
- Produce different q/j profiles with available sources, in particular, change shear inside ITB
- Can ICRF/FW be used?
- How is EC being used?
- Ideal MHD analysis, where are the limits
- Plasma configuration as $I_{NI}$/Ip goes from 0.75 to 1.0
  - How is transport, MHD, q/j changing
- ….