Physics of Steady-State Advanced Tokamaks

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American Physical Society, Division of Plasma Physics
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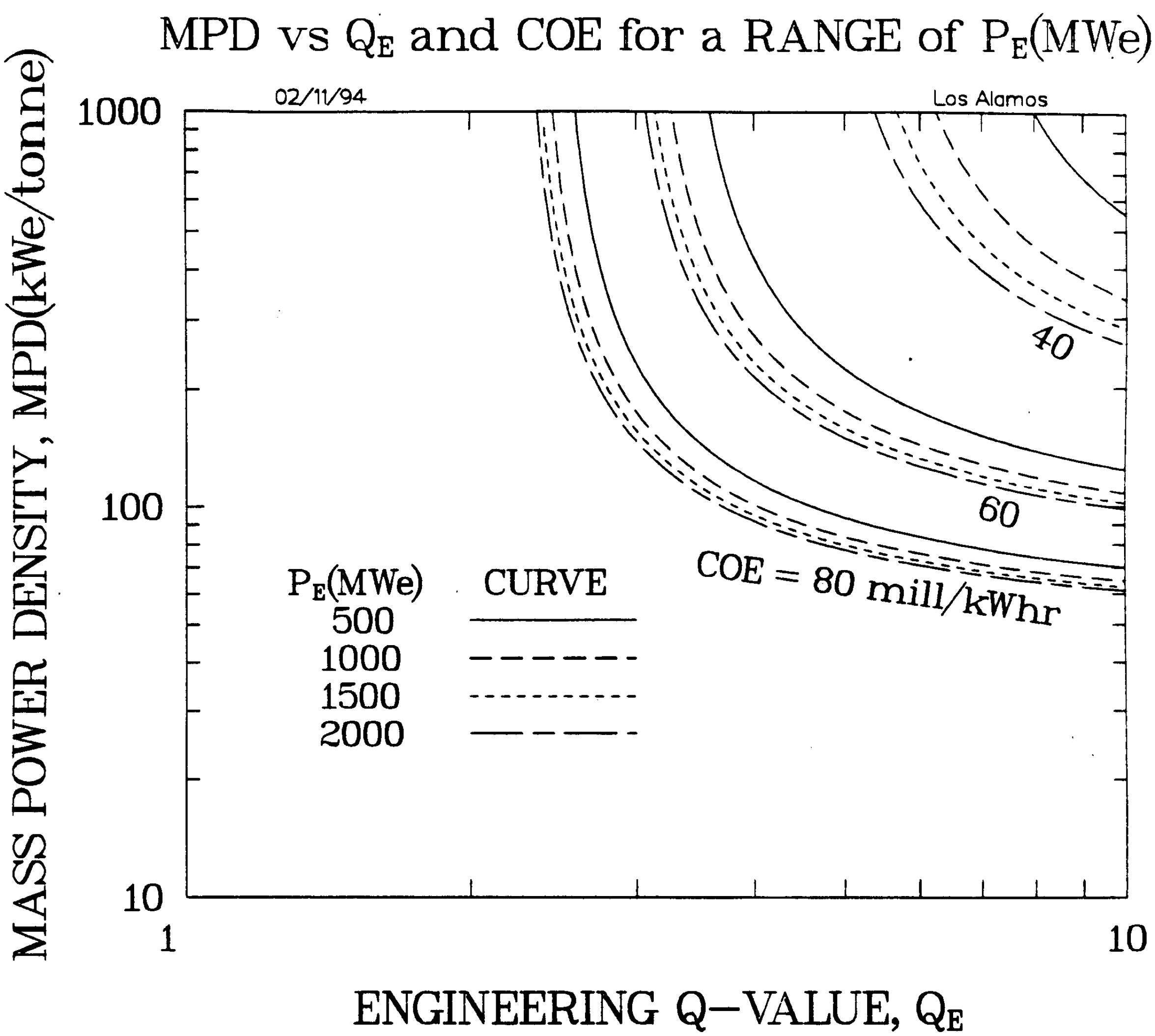
Outline of Talk

- $\Longrightarrow$ ***Reactor advantages of a Steady-State Advanced Tokamak (SS/AT).***
- **Theoretical basis.**
- **Experimental basis.**
- **Future directions in SS/AT research.**

Color key: Good news, Bad news

Economic Fusion Power Requires High Mass Power Density and Engineering Q

Krakowski, LANL, 94



- **High mass power density** means **high electrical output power,** relative to the amount of **high-tech hardware.**
- **High engineering Q** means **low recirculating power, increasing blanket lifetime** per unit energy output, and reducing **capital cost.**

A Steady-State Advanced Tokamak must have Certain Key Features

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- **High confinement,** to permit high Q at reduced size and/or field. The “usual” confinement scalings give:
  $M_{ig} \equiv P_\alpha/P_{loss} \sim \langle n^2T^2\rangle/(\langle nT\rangle/\tau_E) = \langle nT\rangle\tau_E \, \langle n^2T^2\rangle/\langle nT\rangle^2$
  $H^2 I_p^2 A^2 (\beta^*/\beta)^2$
  $\Rightarrow$ high $H^* \equiv H\beta^*/\beta$

- **High β,** for high power at given size and field at the coil.
  $B_o \quad B_{coil} / \varepsilon^{1/2} \quad \beta^* B_o^2 \quad \beta^*/\varepsilon \quad \beta^*_N \equiv \beta^*/(I_p/aB)$
  $\Rightarrow$ high β^*_N

- **High usable bootstrap fraction,** for high Q_{CD}.
  $\Rightarrow$ high $\varepsilon^{1/2}\beta_p$, with good alignment of j_{bs} and j_{tot}

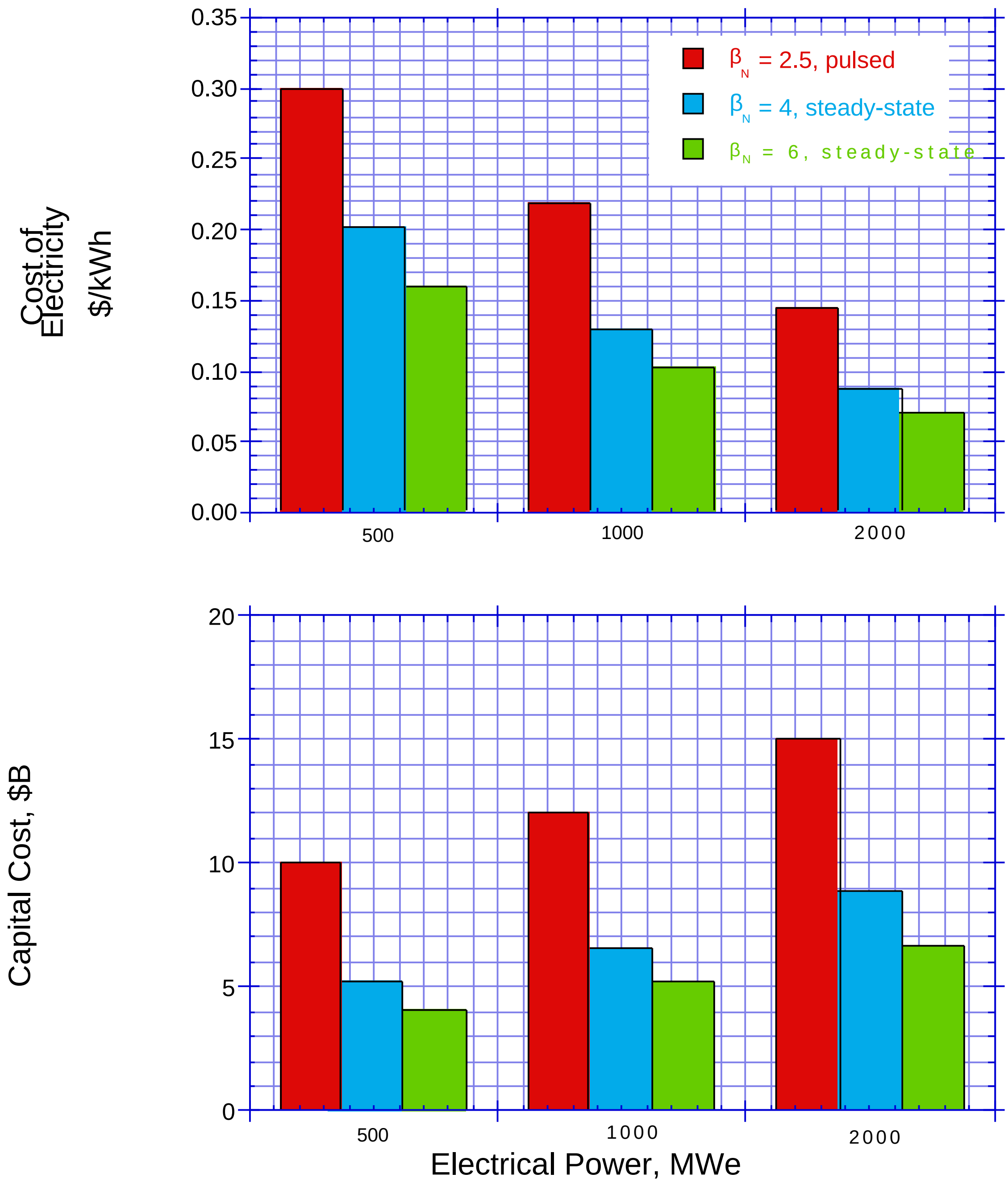
These must be achieved consistently with:

- **Highly dispersive divertor operation.**

- **Low disruptivity.**

Steady-State Advanced Tokamak Physics Improves the Economics of Fusion

Galambos et al., 1995



• The Cost of Electricity can be reduced by a factor of 2.

• The cost of a minimum size fusion reactor can be reduced by a factor of almost 4.

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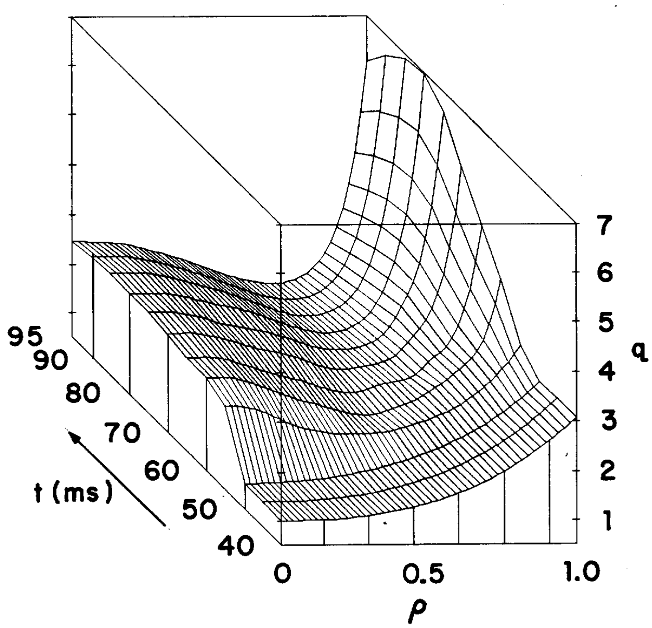
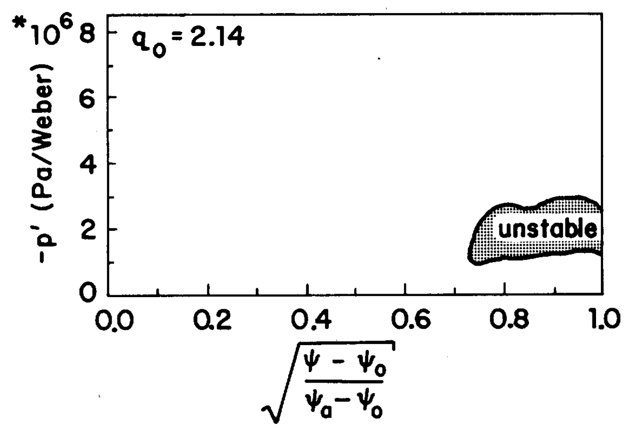
High-n Ballooning Modes are Robustly Stable with Reversed Shear

Chance and Greene, PPPL, 1981

Sabbagh et al., Columbia U., 1989

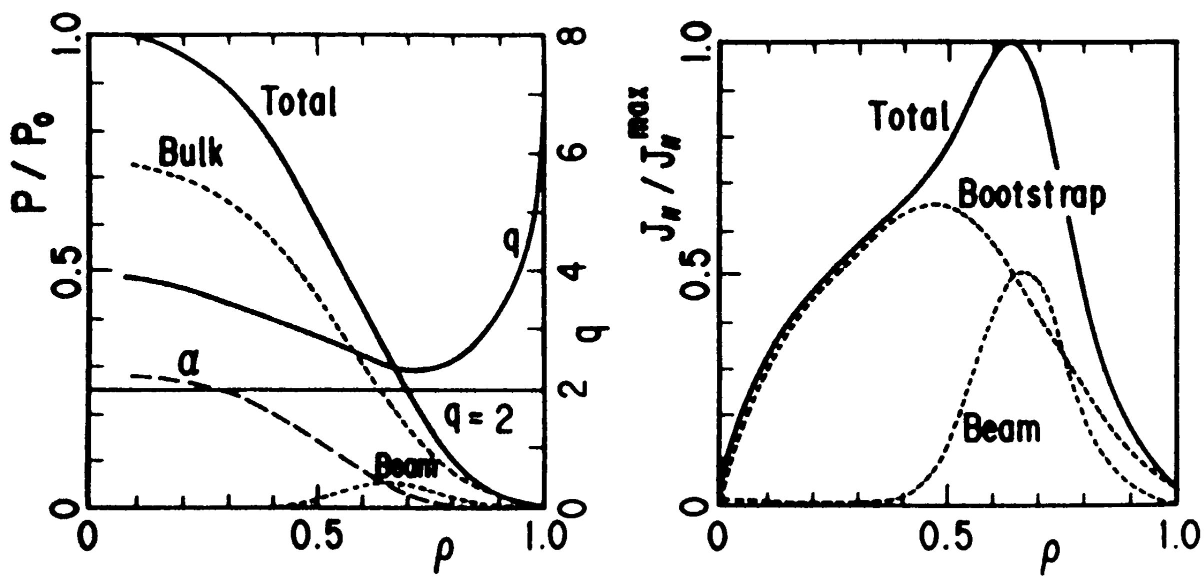




- ∫ dl / B **increases** with R because B falls – but with reversed shear (dq/dr < 0), ∫ dl **decreases** as R increases.
- Net effect: **robust stability against high-n interchange drive for all values of β!**
- Banana toroidal precession becomes negative (dW/dr > 0), making trapped-particle mode resonances **stabilizing.**

Reversed Shear is Synergistic with High Bootstrap Fraction

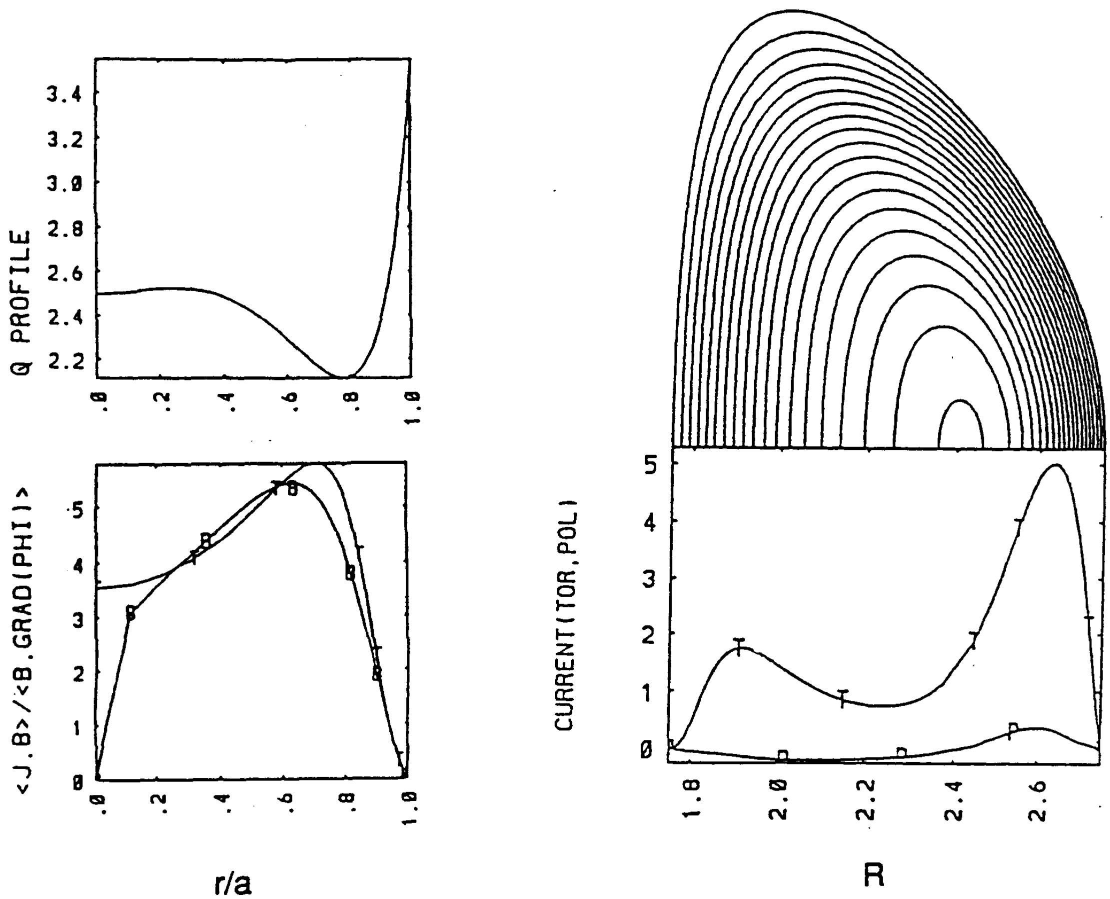
Ozeki et al., JAERI, 1992



- j_{bs} β_p low B_p (high q in core) increases $f_{bs} \equiv I_{bs}/I_p$.
  j_{bs} peaks off axis → reversed shear
- Important role for non-inductive current drive to “pin” the reversal point at large minor radius large R/S region.
- **β_N = 3 β_t = 2.12% β_t/ε = 8.7% f_{bs} = 65%**
- **Stable to n = 1 – 4, ∞, with no conducting wall.**
- Conducting wall would permit higher β_t, but bootstrap current density in core region is already equal to the total required.

The Reversed Shear Regime can Attain Extremely High β_N and f_{bs}

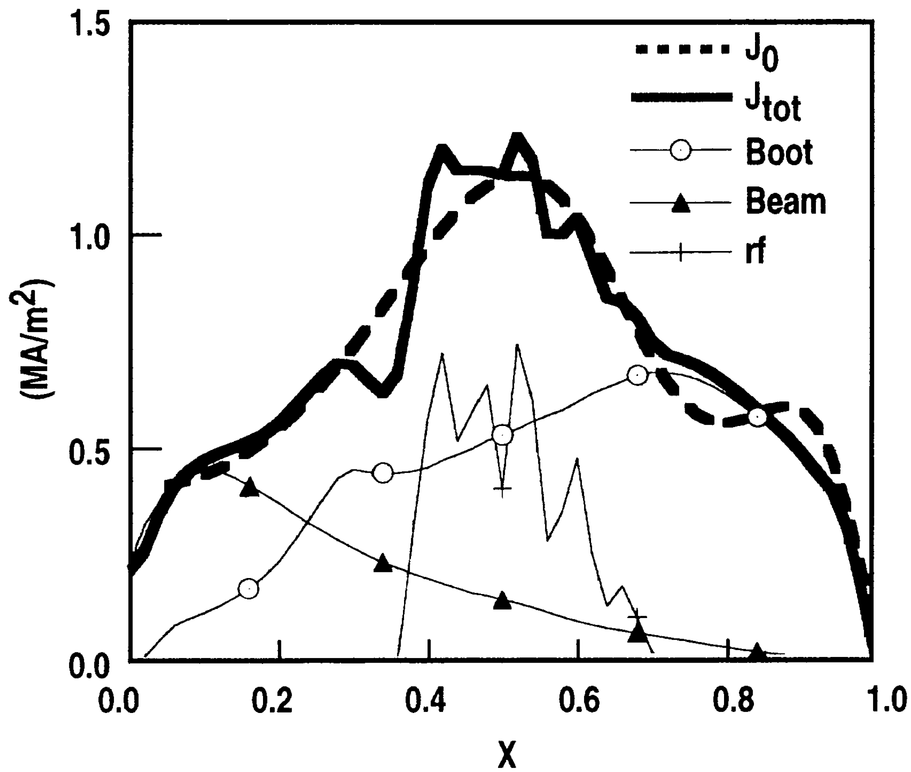
Kessel et al., PPPL, 1994



- β_N **= 5.2** β_t **= 5.2%** β_t/ε **= 23.4%** f_{bs} **= 93%**
- **Stable to n = 1 – 6, ∞,** conducting wall at 1.3a.
- **Shear reversal stabilizes Trapped Electron Modes.**
- The shear reversal also **raises** $\eta_{i,crit}$ (dln T_i/dln n_i)$_{crit}$ **from ~2 to ~4, stabilizing Ion Temperature Gradient Modes.**
- Implies the possibility of a self-consistent transport barrier with high pressure gradient in the reversed shear region.

Simulations including Transport, Current-drive, and MHD Stability access High-performance Reversed Shear Regimes

Turnbull et al., GA, 1995



- β_N = 5.7 β_t = 7.5% β_t/ε = 19.8% f_{bs} = 67%
- **Stable to n = 1,2, ∞, unstable to n = 3,** with stabilizing wall.
- Transport coefficients ~ VH-modes in DIII-D.
- Demonstrates a degree of **consistency** between transport, current drive modeling, and MHD stability.
- Illustrates the need for experimental verification of self-consistency in pulses much longer than $\tau_{L/R}$.

The Highest Performance SS/AT Modes Require Wall-Stabilization of External Kinks

- 70% bootstrap, reversed shear modes can be stable to external kinks with no conducting wall, for $\beta_N \leq 3$.
  Similar parameters can be achieved with only elevated q(o).

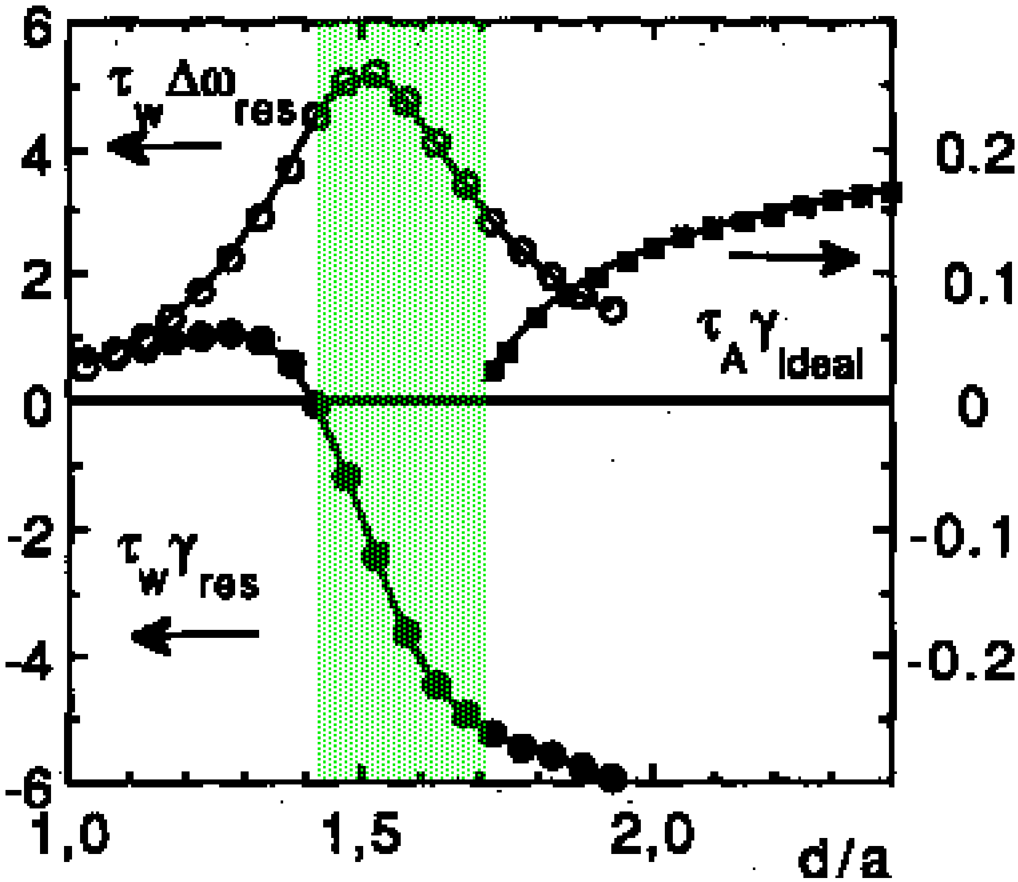
- **If an "ideal" wall can be provided at b/a ~ 1.3, very high values of $\beta_N \geq 5$ can be achieved.**
  - In a non-circular plasma, particularly with high triangularity, there is strong "geometrical" edge shear.
  - This permits the radius of q_{min} to approach the edge of the plasma, while retaining stabilizing shear.
  - Now the bulk of the current is close to edge of the plasma, and a conducting wall can be very helpful.
  - **large stable core reversed shear region.**

- With a real, resistive wall at this location, a **"wall mode"** can grow – in an ideal plasma – with $\gamma\tau_{wall} \sim 1$ and $\omega\tau_{wall} \sim 1$.

- The growth rate of this "ideal" mode, however, is so slow that **non-ideal effects can be strongly stabilizing.**

Plasma Rotation Creates a Region of Stability for the Wall Position

Bondeson and Ward, CRPP, 1994



- Ion sound friction pulls the “wall mode” rotation towards the plasma rotation speed, and **if the plasma is rotating fast enough (~0.2C_S)** and the **wall is far enough away** that it cannot “hold onto” the mode, this **stabilizes the wall mode.**
- If the **wall is too far away,** however, of course the **ideal mode is unstable.**
- Work on improving the theoretical models for ion sound damping used in MARS and NOVA-W is underway.

Resistive Island Formation can Provide Stabilization with Lower Rotation

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Boozer, Columbia U., 1995; Finn, LANL, 1995

- Slowly growing ideal “wall modes” have singular current sheets at all rational surfaces in the plasma.

- Due to the **slow growth time, ~τ_{wall},** these current sheets are energetically required to form **islands.**

- The islands are strongly coupled to plasma rotation via perpendicular viscosity, so the requirement on the rotation speed is only that $\omega_{rot}\tau_{wall}$ and $\omega_{rot}\tau_{res}$ **>> 1.**

- Suggests a close relation to low-β “locked modes.”

- Pomphrey et al., and Fitzpatrick find **edge viscous/inertial stabilization** with rotation speeds ~ Bondeson & Ward’s.

- Betti and Sorotokin find **energetic banana particles** provide **kinetic stabilization in the absence of rotation.**

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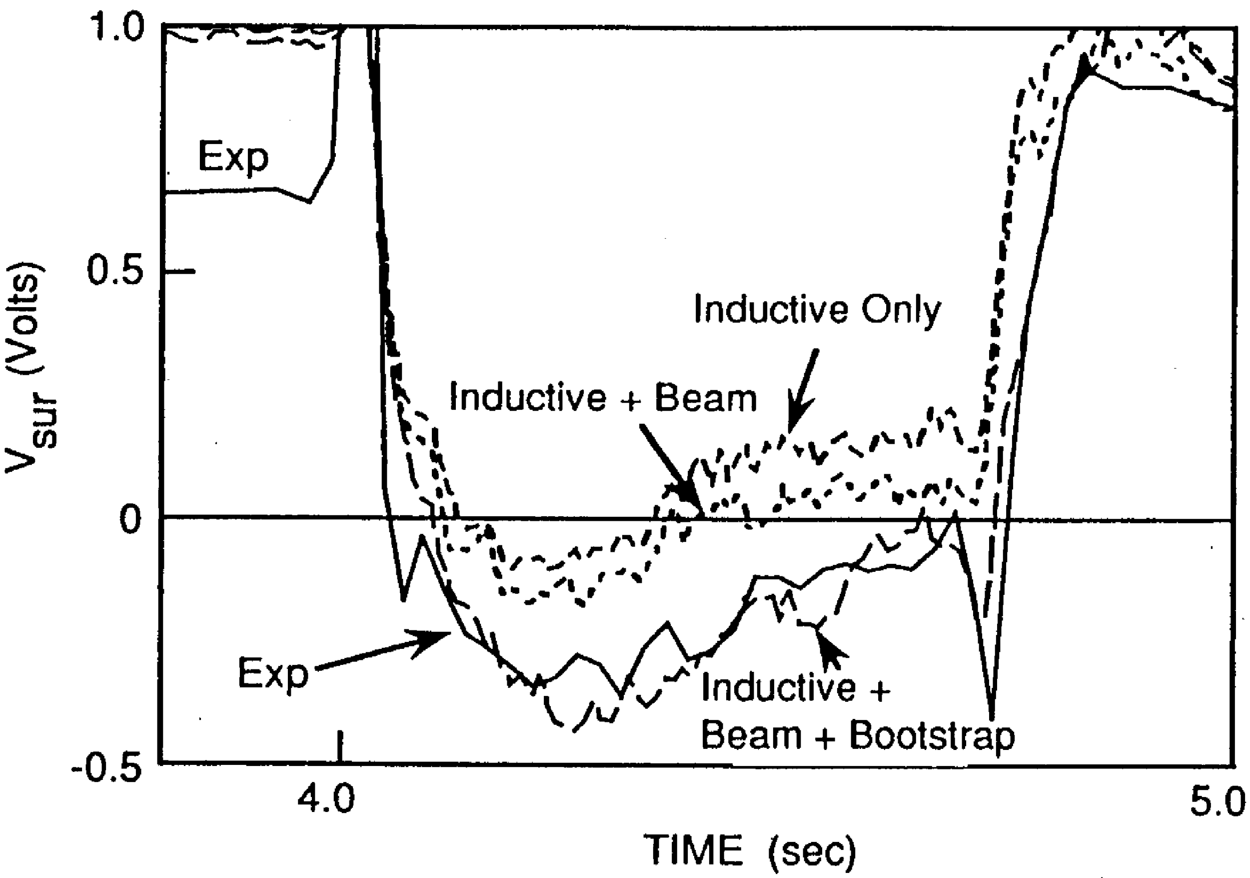
- **Future directions in SS/AT research.**

The Existence of the Bootstrap Current has Been Verified Experimentally

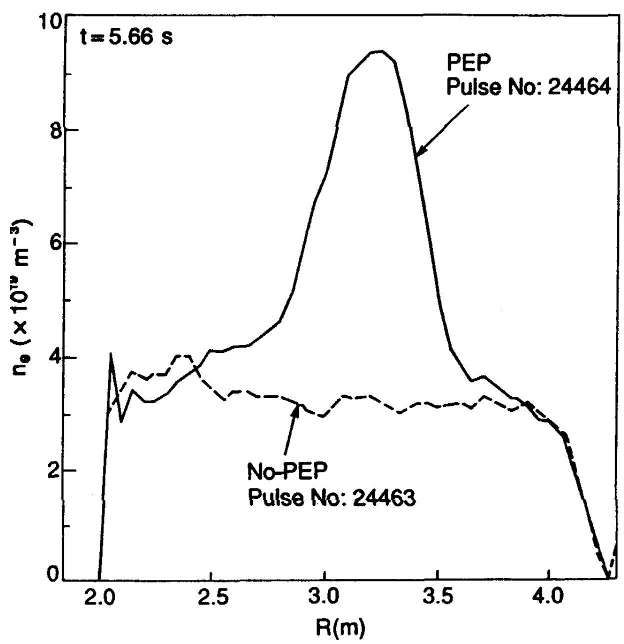
Zarnstorff et al., TFTR, 1986

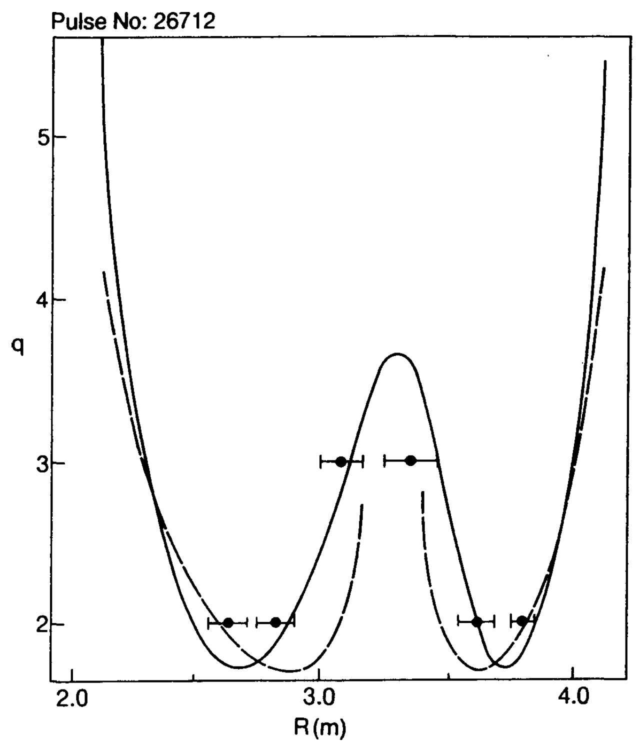


- The **bootstrap current** has now been observed experimentally on many tokamaks.
- It is *fundamental* to the Steady-State Advanced Tokamak concept.

Deep Pellet Injection on JET, before Saw-teeth, Gives Enhanced Performance

Smeulders et al., JET, 1995

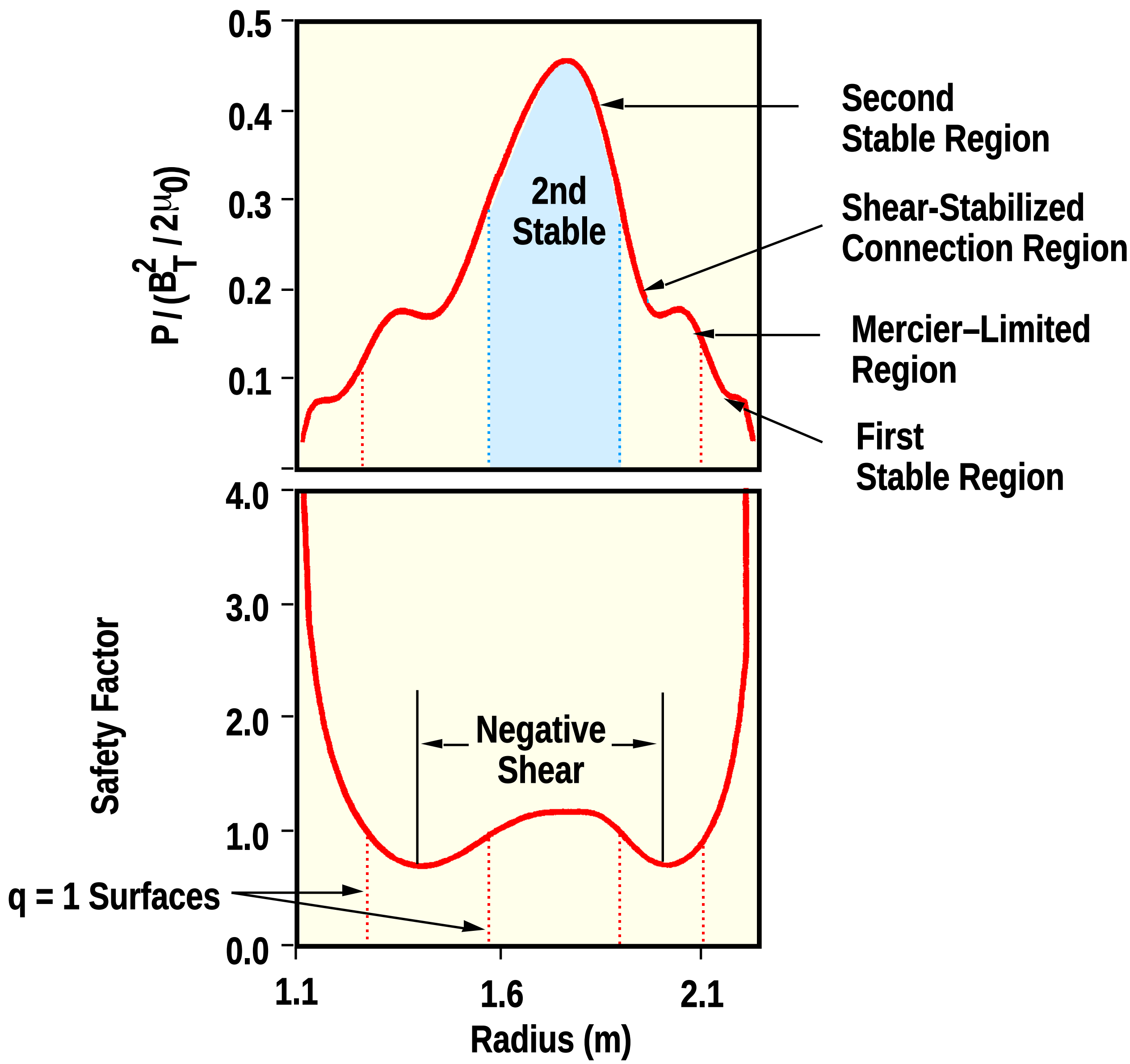




- **Very high pressure gradients** are observed in the plasma core, greater than usual first-stability limits for q(o) ~ 1.
- **Core thermal confinement improves by a factor of ~ 2.**
- Limited experimental data (equilibrium fits and X-ray identification of mode-rational surfaces) indicate ***reversed shear*** in the plasma core.
- **Transient,** because the q(r) profile is not sustained.

DIII-D Finds Enhanced Central Beta Limits with Reversed Shear

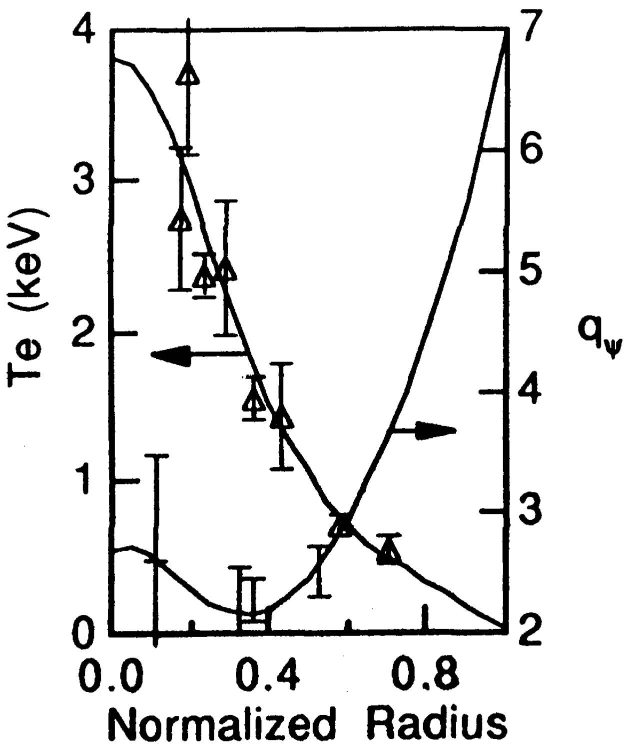
Lazarus et al., ORNL, DIII-D 1992

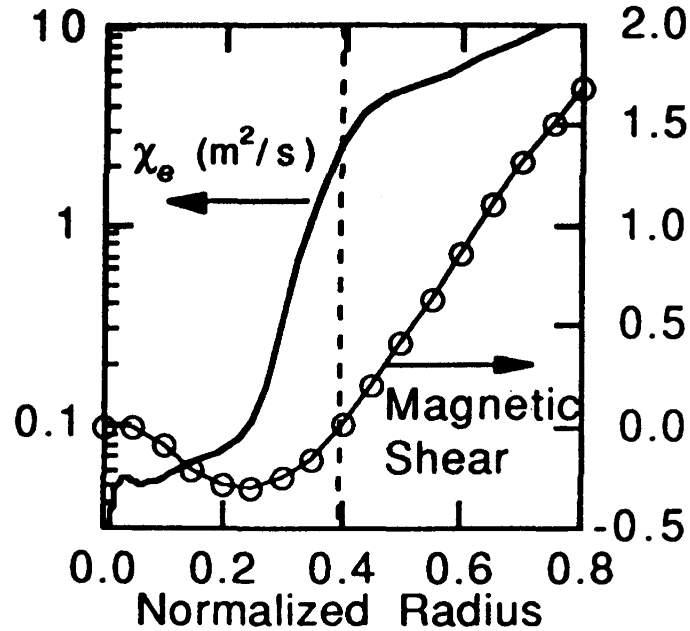


- **Very high pressure gradients** are observed in the plasma core, greater than usual first-stability limits for q(o) ~ 1.
- **Central β = 44% is achieved.**
- **MHD active, and transient.**

Tore Supra has found Enhanced Core Confinement with Off-axis LHCD

Kazarian-Vibert et al., Tore Supra, 1995

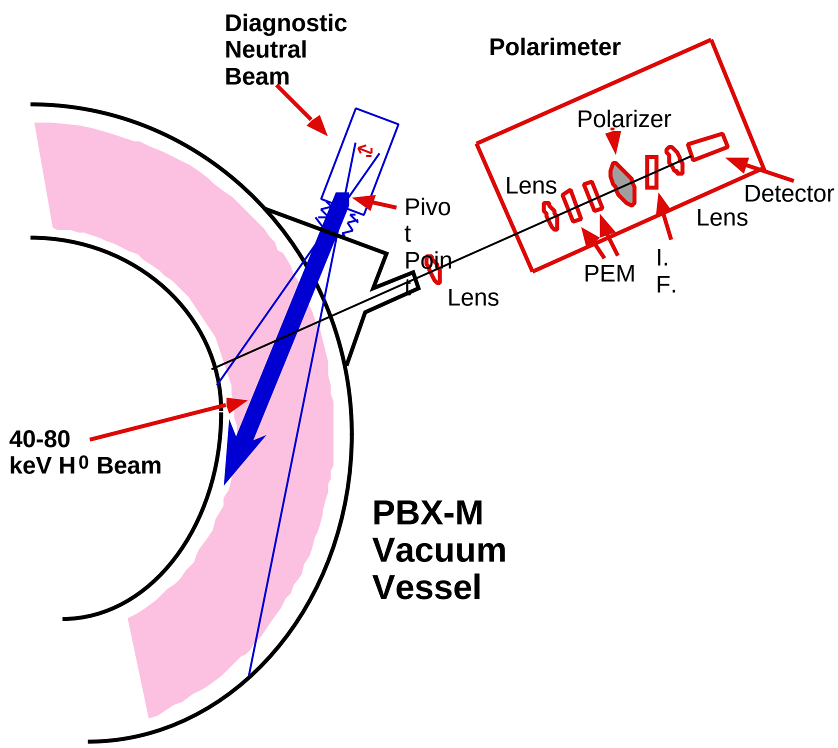




- Low-field operation makes the plasma core inaccessible to Lower Hybrid waves.
- Fast electrons are measured to be localized well off axis.
- **Strongly reduced electron thermal transport** is found in the plasma core with shear reversal or near reversal.
- **This regime is stationary** for the full LH pulse, but it has only been explored so far at **low β_N.**

The Motional Stark Effect Diagnostic has Dramatically Improved Experimental Capabilities for Advanced Tokamak Studies.

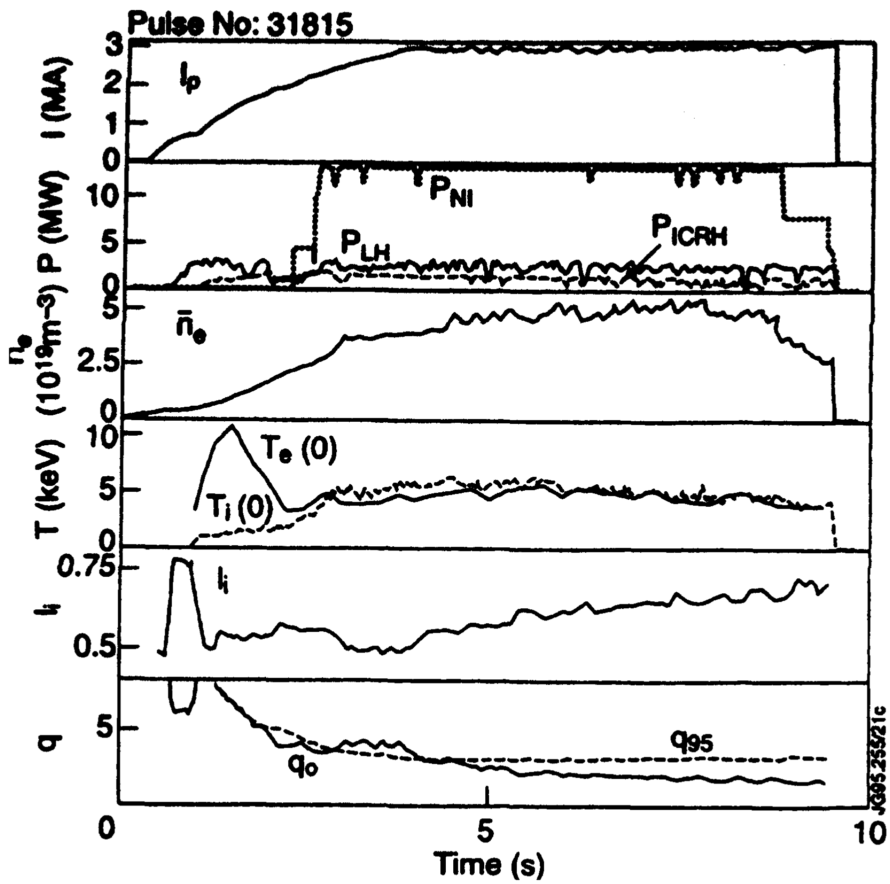
Levinton et al., FP&T, PBX-M, 1989



- **v** x **B** electric field in frame of fast-moving neutral beam atom causes strong Stark splitting in H_α (Balmer) line.
- Polarization of the Stark-split line gives orientation of **B**.
- Orientation of **B** gives magnitude of B_p.
- **B_p(R) strongly determines q(r)** in equilibrium code fits using other known data such as external **B** fields and p(r).

JET Demonstrated the Technique of Early Heating to Freeze in a Hollow q(r)

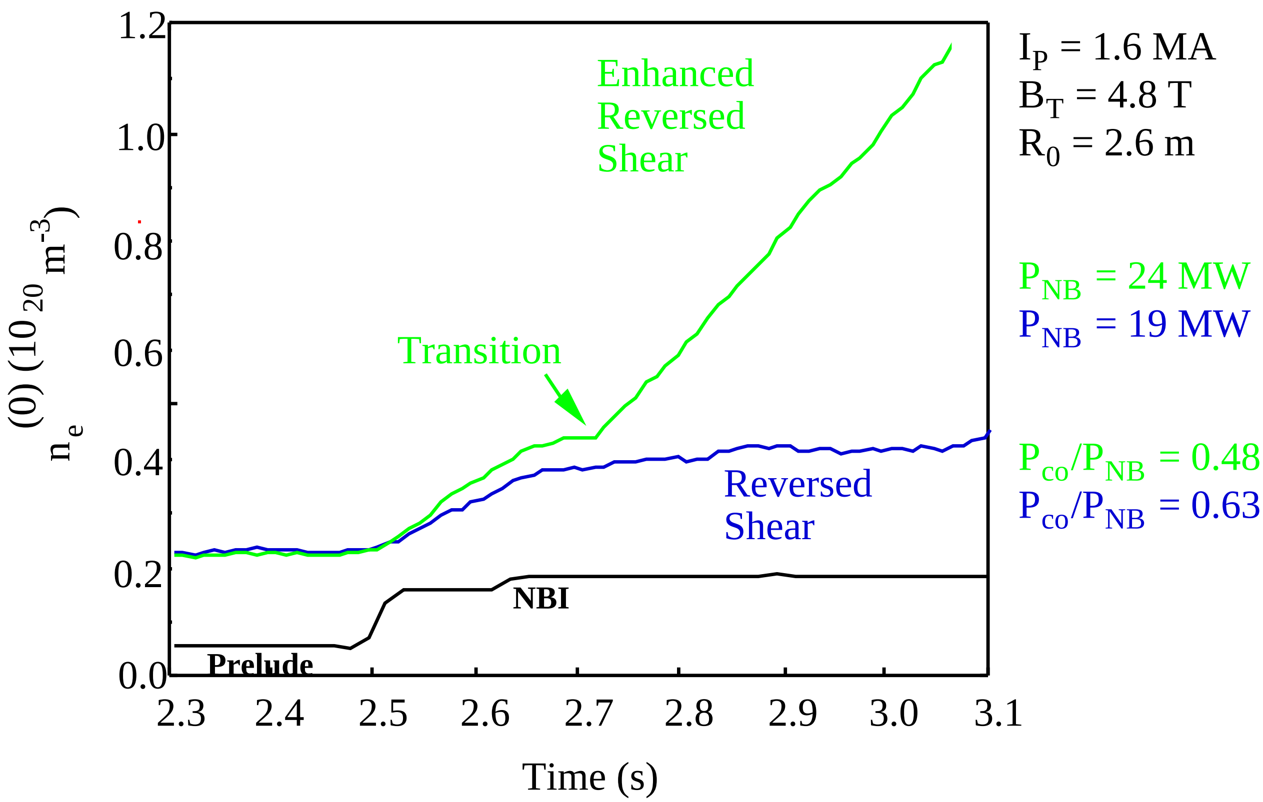
Söldner et al., JET, 1994



- By heating during the current ramp, it is possible to maintain **$q(o) \sim q(a) > q_{min}$ in JET for a few seconds.**
- This technique was used with LHCD alone, **giving enhanced core confinement as on Tore Supra.**
- In combination with strong NBI, **plasma properties were not enhanced,** but they also **were not degraded by the low l_i** associated with reversed shear.

Two Confinement Regimes are Observed in TFTR Reversed-Shear Plasmas

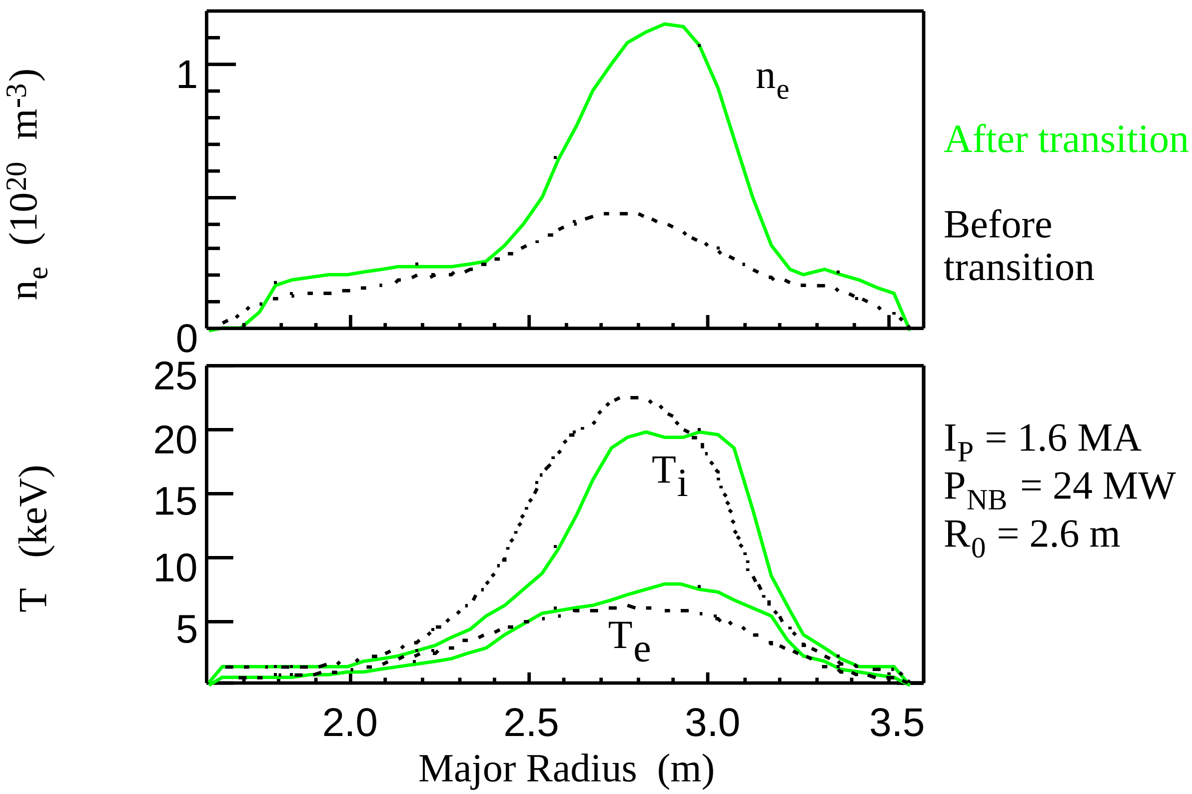
Zarnstorff, TFTR, Wednesday AM, 5IA.02



- Many TFTR R/S discharges are similar to "supershots."
- A reproducible transition to an ***Enhanced Reversed Shear*** **regime** occurs, however, at high beam power.
- **Core particle inventory integrates the beam source.**
- **Ion thermal energy loss is almost uniquely via Q_{ie}.**
- **Electron thermal transport is also clearly reduced in some experimental conditions.**
- **Transient,** destabilized to n=1 mode when q_{min} ~ 2.

Plasma Parameters in TFTR
ERS Modes are Impressive

Zarnstorff, TFTR, Wednesday AM, 5IA.02

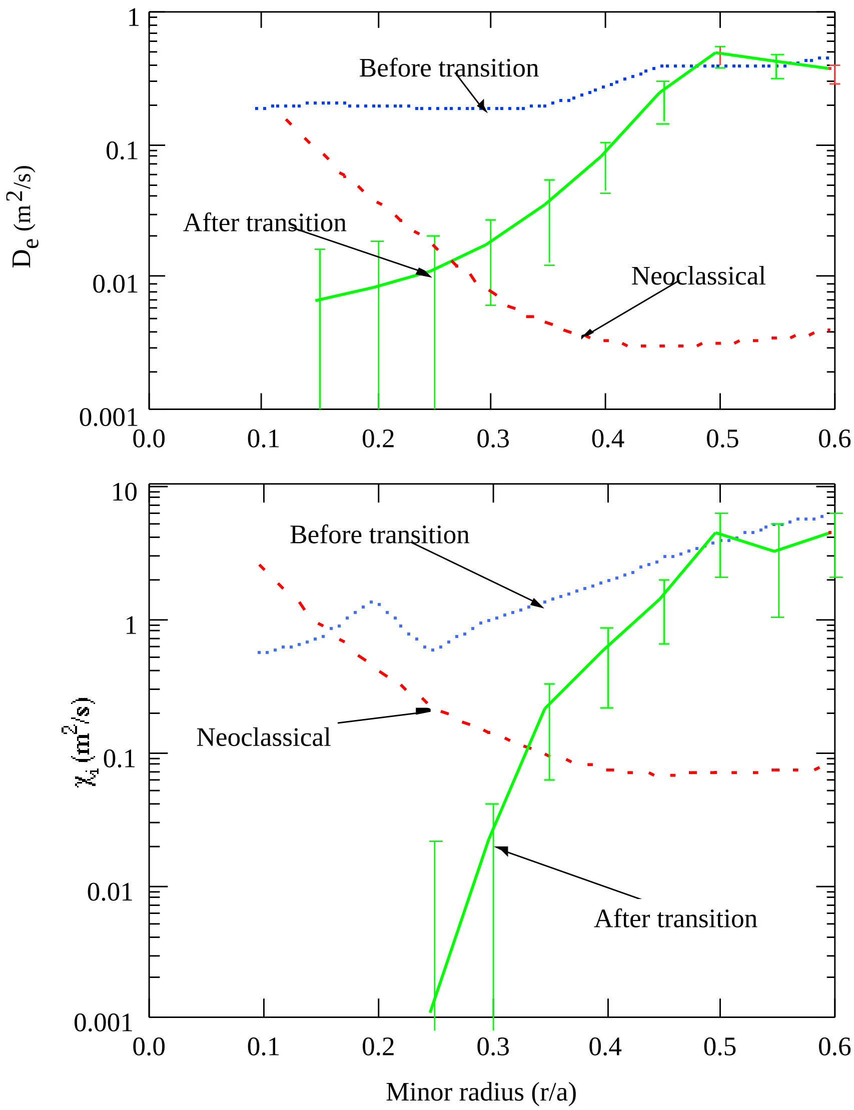


- **P(o)/<P> ~ 8, P(o) = 4.6 · 10^5 Pa**
- n_e(o) = 1.2 10^{20}, T_i(o) = 20 keV, T_e(o) = 8 keV
- **H = 2.2, H^* = 4.2; β_N = 2.0, β_N^* = 3.8, f_{bs} = 0.75**
- **3.5 · 10^{16} DD neutrons/sec at modest B and P_{NB}**
- Small v_φ < 150 km/sec due to balanced injection

  transport reduction *not* due to sheared toroidal flow

χ_i & D_e are Sub-neoclassical in ERS Regime

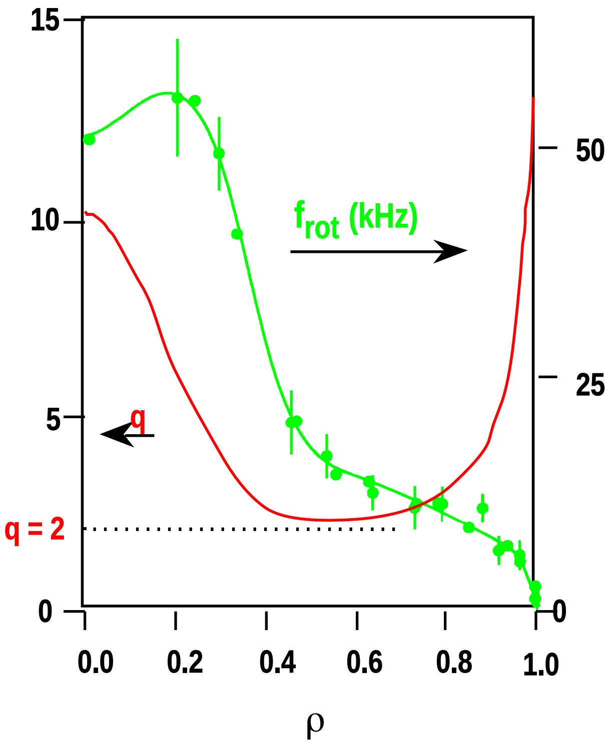
Zarnstorff, TFTR, Wednesday AM, 5IA.02

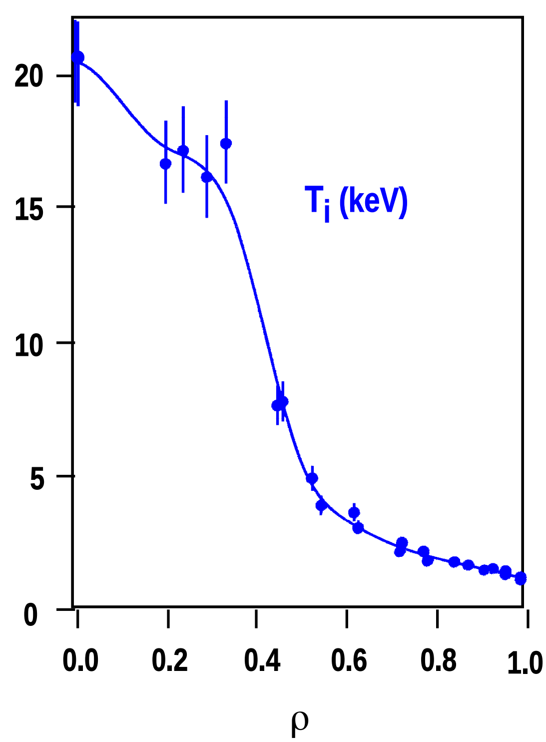


- Careful error analysis indicates that **ion thermal transport is clearly much less than predicted by neoclassical theory.**
- **Particle transport is near true neoclassical (electron-ion).**
- **Neoclassical MHD activity – which causes roll-over in performance – is completely absent, as predicted.**
- **Core density fluctuations are dramatically reduced.**

DIII-D Finds Enhanced Core T_i and V_ϕ in Reversed-Shear H-mode Plasmas

Rice, LLNL, DIII-D, Wednesday AM, 5IA.04





- **β_N up to 4** has been achieved in R/S ELM-free H-modes.
- **Global confinement is ~VH Mode ~ 3x L-mode.**
- The ELM-free edge / Core RS regime is **transient,** ended by **edge-driven MHD** termination activity, as in VH-modes. Probably associated with **high bootstrap current density just at the plasma edge.**

Reversed-Shear Discharges in DIII-D with L-Mode Edges are Also Attractive

Rice, LLNL, DIII-D, Wednesday AM, 5IA.04

- **H ~ 2, with high β^*/β**
- **P(o)/<P> = 5,** $n_e(o) = 6\ \ 10^{19}$, $T_i(o) = 20$ keV, $T_e(o) = 5.5$ keV
- **High DIII-D neutron rates ~ $8 \cdot 10^{15}$/sec – at moderate β.**
- **Strongly peaked density profiles,** good for reactivity.
- **Transient,** terminated by infernal modes.

Reversed-Shear Core Transport Reduction Adds to H-mode Edge Barrier in DIII-D

Lao, GA, DIII-D, Thursday PM, 8I2

- **Core confinement of both ions and electrons improves with reversed shear, with L-mode edge.** (RS → ERS transition?)
- **Edge confinement improves with L → H transition, ion core improves further.**
- Core particle confinement improved in L-mode / ERS. No significant density peaking in well-developed H-mode.

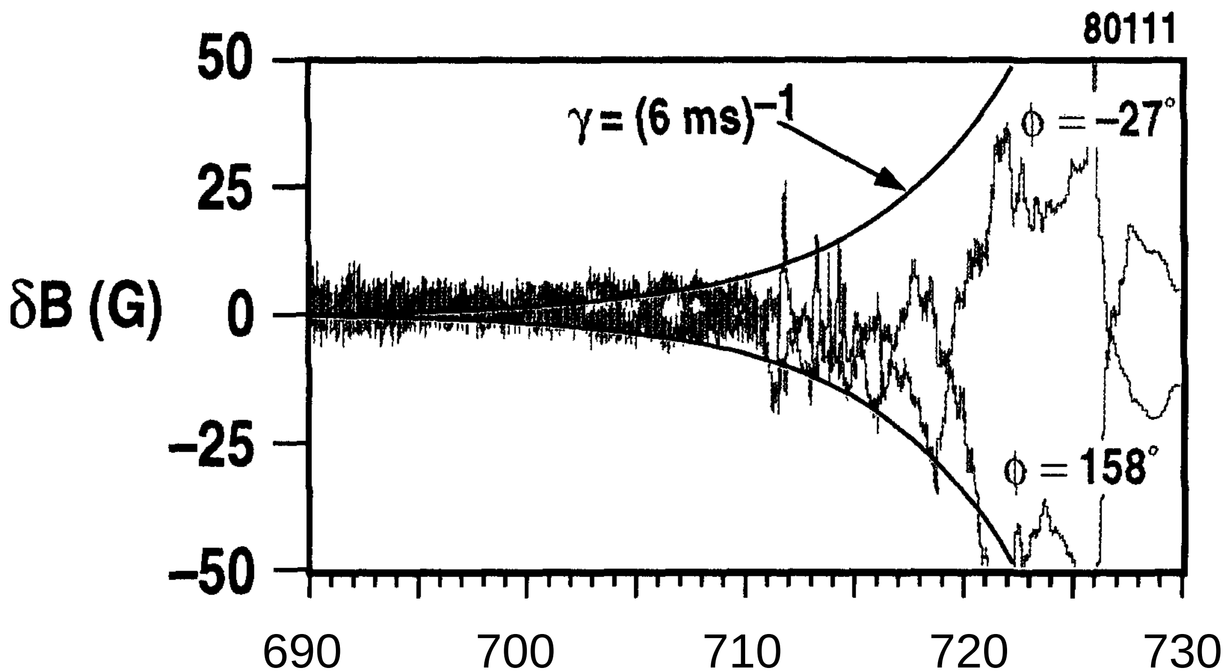
JT-60U is Studying R/S Plasmas

Kimura, JT-60U, Wednesday AM, 5IA.03

- R/S regime is accessed using early-heating technique.
- Initial results suggest **transport barrier for ion heat, electron heat, and particles.**
- *Clearly more research is needed to understand confinement in reversed-shear plasmas.*
- **Attend Invited Papers Session 5IA tomorrow A.M. to hear the latest news.**

DIII-D Sees Wall Modes at High β and low l_i

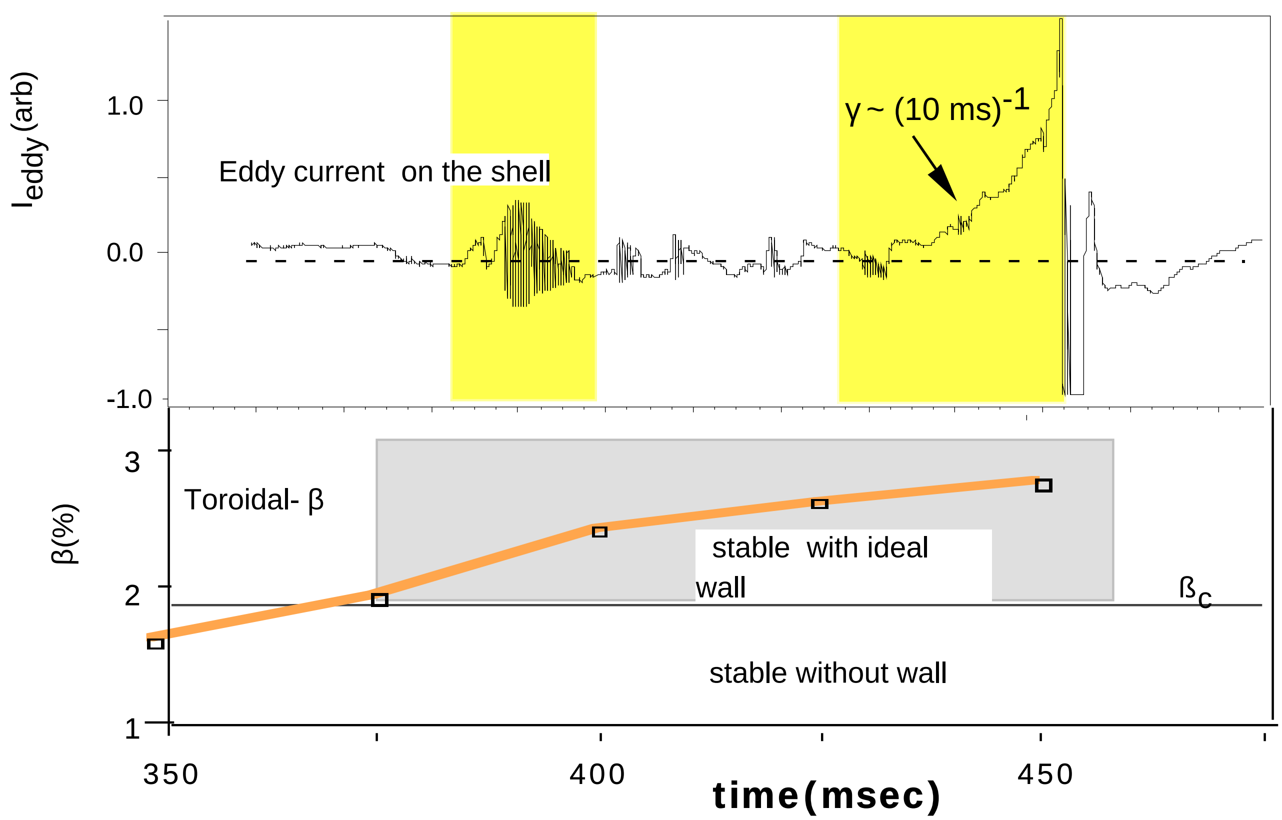
Navratil, Columbia U., Chu, GA, DIII-D, 1995



- **Observed β limit is inconsistent with wall at infinity, ~ matches calculations for ideal wall at real wall location.**
- **Mode growth rates are ~ consistent with "wall modes."**
- q = 3 surface is still rotating (~2 kHz) as wall mode grows.
- MARS calculations are in qualitative agreement, but suggest that ~2-3x higher rotation speed may be required for stability.

PBX-M Sees Very Slowly Growing Modes when the Plasma is Well-coupled to the Thick Aluminum Shell

Okabayashi, Pomphrey, PBX-M, 1995



- **Observed β limit is inconsistent with wall at infinity, ~ matches calculations for ideal wall at real wall location.**
- **Mode growth rates are ~ consistent with "wall modes."**
- q = 3 surface is still rotating (~2 kHz) as wall mode grows.
- NOVA-W calculations are in qualitative agreement, but suggest that ~2-3x higher rotation speed may be required for stability.

HBT-EP Has Greatly Enhanced Stability with Conducting Shells Close to Plasma

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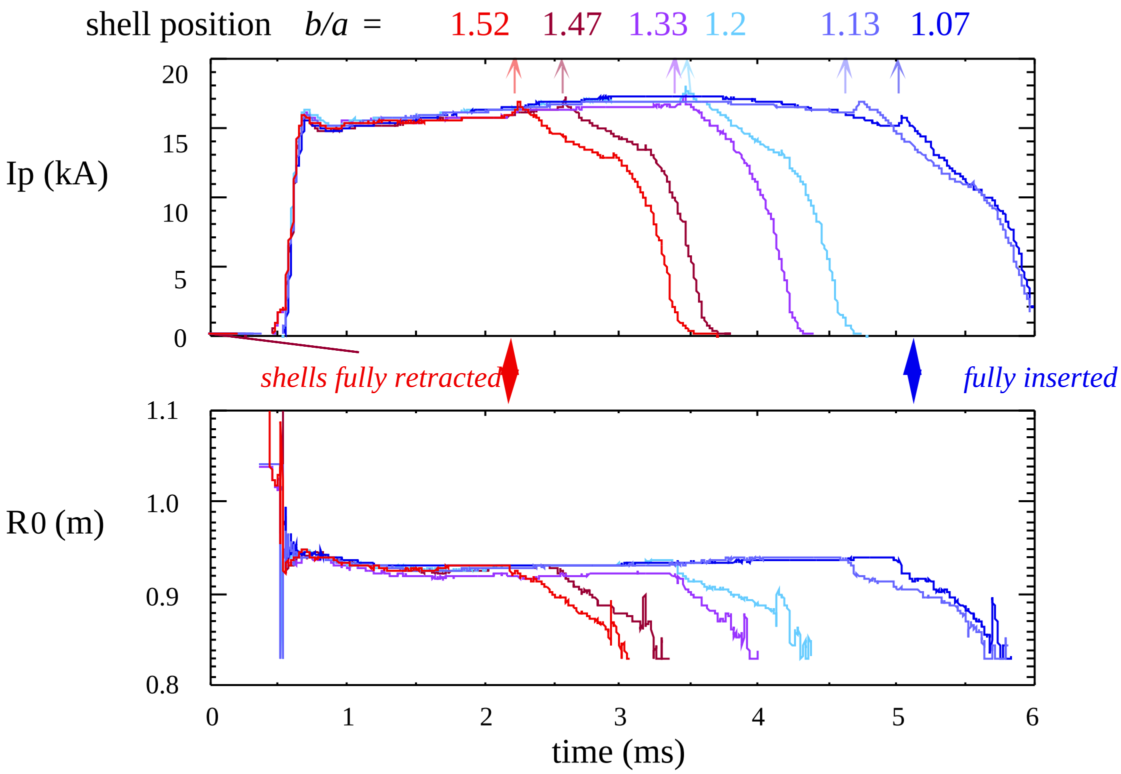
Ivers, Columbia U., HBT-EP, Wednesday AM, 5IA.01



- High values of β_N are achieved by rapid initial formation.
- Successful position control does not depend on shell location.
- **Disruptions are most often prevented if $dI_p/dt > 0$, and $b/a < 1.2$.**

Wall Stabilization is Now Well Established, but Work is Needed to Determine the Plasma - Mode Coupling Mechanism

- **Theoretical model for ion-sound damping is "heuristic."**

- **Resistive island formation / wall-mode stabilization *needs to be calculated numerically and compared with experiment.***
  - PBX-M observation that "wall modes" tend to favor a specific phase orientation suggests a connection to low-β field-error induced "locked modes."
  - DIII-D observation that β-limit falls with increasing field error suggests a similar conclusion (or could be due to rotation braking).
  - Wall mode growth times are similar in DIII-D and PBX-M (~ edge resistive growth times of 5 – 10 ms) despite *very* different wall times (2ms *vs.* 40ms).

- **Experimental studies are needed to distinguish effects**
  - Resistive *vs*. ion-sound damping
    Need studies with higher $S \equiv \tau_R/\tau_A$ and variable rotation.
  - Rotation *vs*. kinetic stabilization
    Need high β / low l_i studies with variable rotation.

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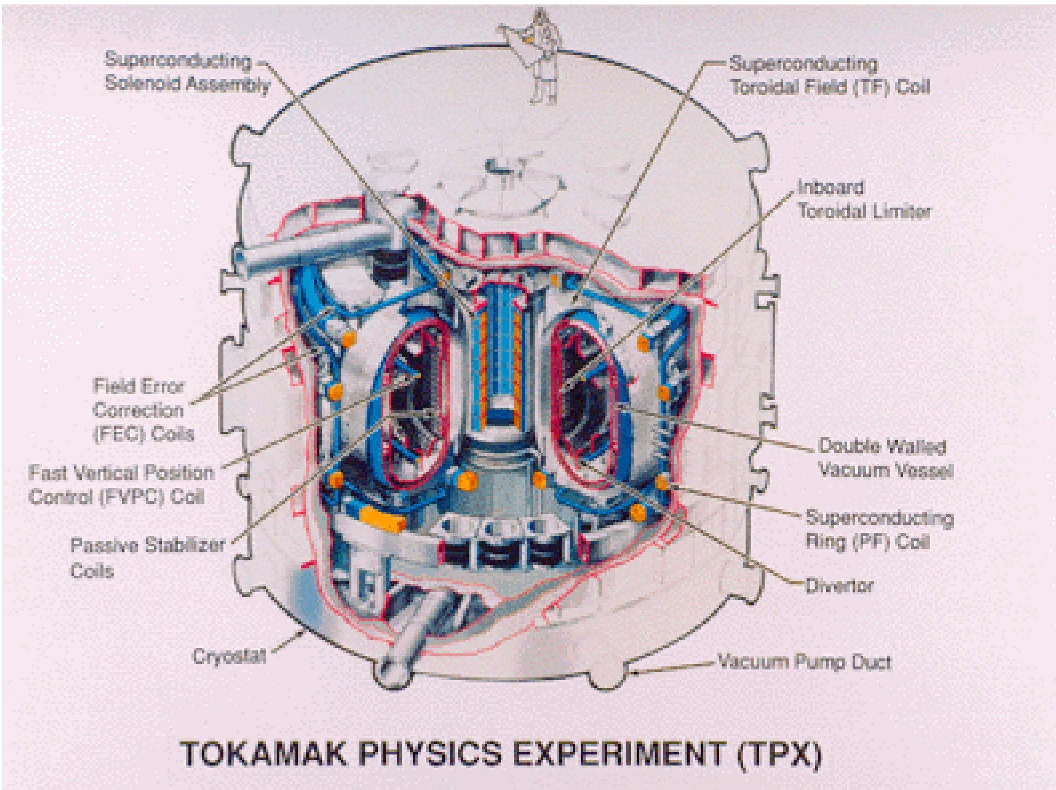
SS/AT Research Priorities

- **Underlying science**
  - Threshold physics of ERS.
  - Physics of flucutation reduction.
  - Under what circumstances are χ_i, χ_e, and D_e reduced?
  - What does this tell us about transport in tokamaks?
- **Current profile control**
  - NBCD, FWCD, MCCD, LHCD, ECCD
- **Pressure profile control**
  - IBW, other internal barriers, pellet injection, α channeling
- **Shaping effects on performance**
  - κ, δ, R/a
- **Integration with dispersive divertor operation**
  - SND, DND, Edge L vs. ELM’ing H, vs. ELM-free H
- α **physics**
  - Stability, heating, burn control
- **Wall stabilization**
  - Rotation speed requirement, underlying mechanism
- **Performance limits**
  - β_N^*, H^*, $f_{bs} \rightarrow P_{fus}$

TPX would have been the Right Next Step in SS/AT Research

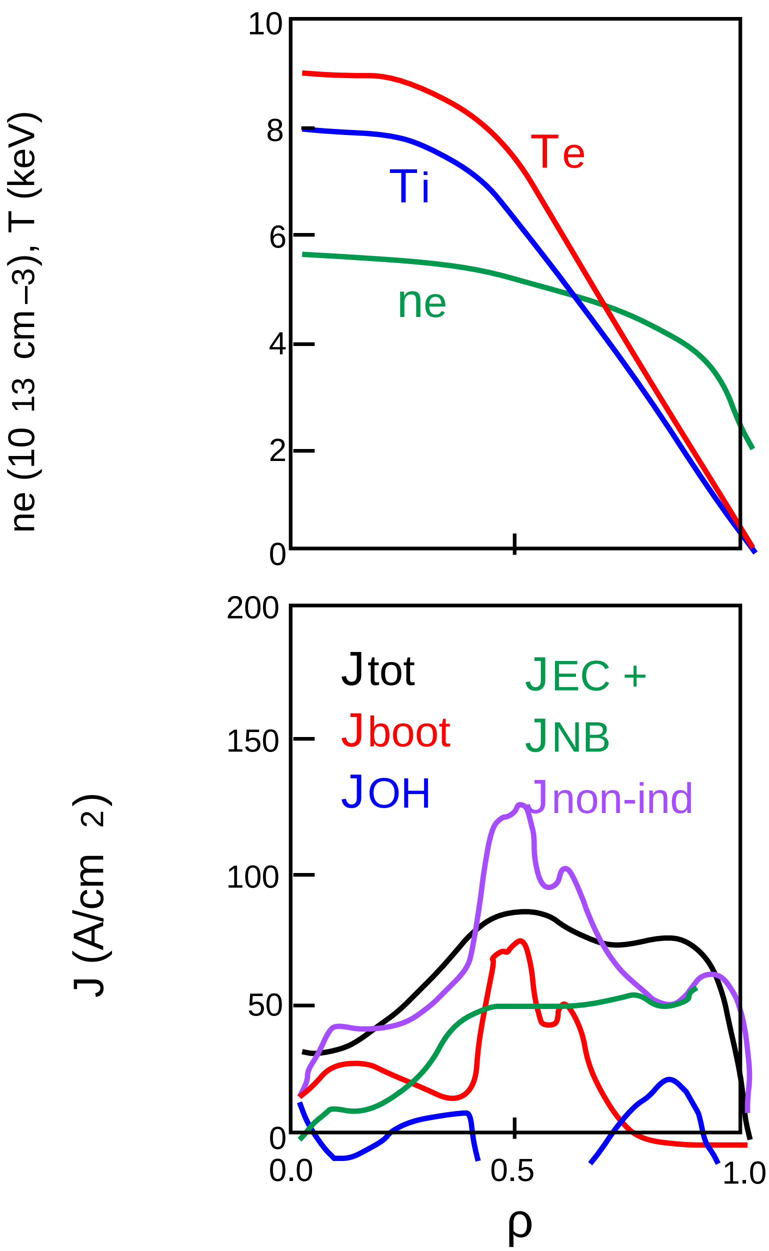


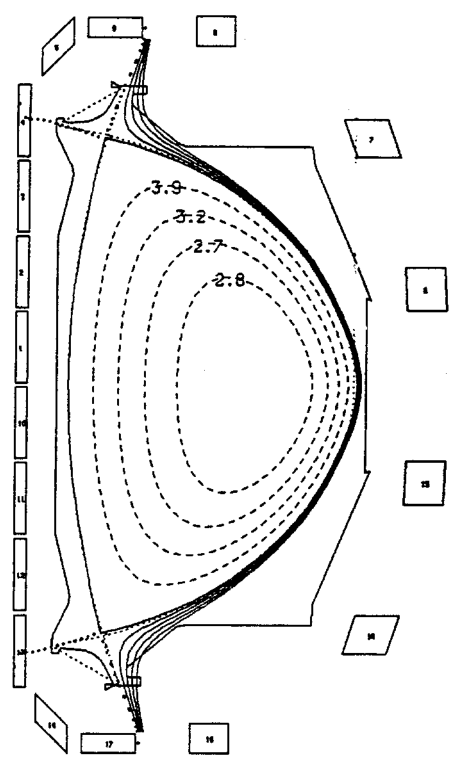
- **Strong shaping and active current profile control.**
- **Divertor optimized for low recyling, strong pumping.**
- **Long pulse (1000 sec) >> $\tau_{L/R}$, >> wall-equilibration time.**
- **Substantial plasma performance (I_pR/a = 9MA ~ TFTR's)**
- **DT capability to study α stability of SS/AT operating modes.**

Operating U.S. Facilities Have Strong Capabilities for Advanced Tokamak Studies

- **DIII-D**
  - **Strong shaping.**
  - **Radiative divertor.**
  - **Nearby conducting wall.**
  - **FWCD, MCCD, ECCD for current profile control.**
  - **10 sec pulse-length extension.**
- **TFTR-AP**
  - **Large size, high field, high temperature for reactor-like parameters, *e.g.* $S \propto \tau_R / \tau_A \propto RBT^{3/2}/n^{1/2}$**
  - **Nearby conducting wall.**
  - **Capability for co / ctr / bal NBI, RF heating.**
  - **FWCD, MCCD, LHCD for j(r) control;**
    IBW for p(r) control.
  - **NB pulse-length extension for ~5 sec. heating.**
  - **DT for α-stability tests, α-heating experiments.**
  - **High fusion power in AT regimes.**
- **C-Mod**
  - **Slot vs. open divertor.**
  - **FWCD, MCCD, LHCD for current profile control.**
  - **7 second pulse-length at 5T.**

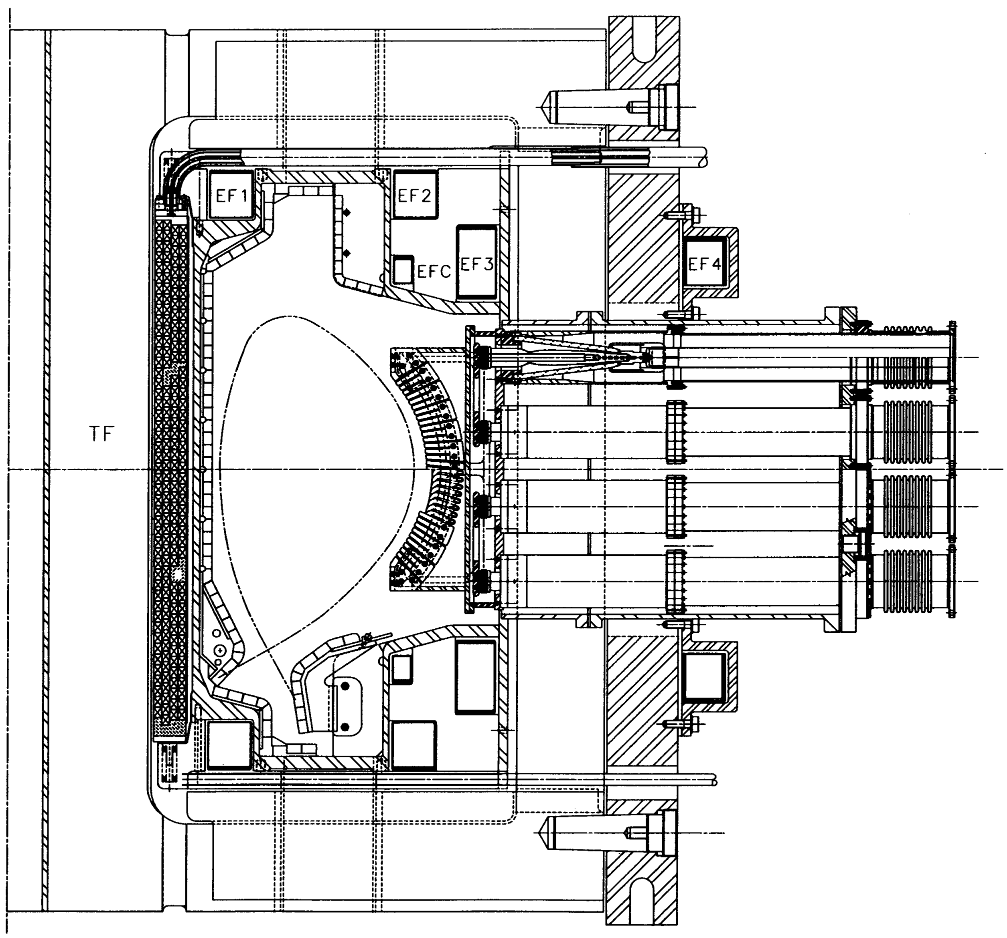
DIII-D will Make Major Contributions to SS/AT Research





I_p = 1.3 MA, B_t = 1.75T, β_N = 5.3, f_{bs} = 0.69

C-Mod will Study Current Profile Control and Steady-State Scenarios



- With ICRF (shown above) and Lower Hybrid power, C-Mod will have tools for heating and current profile control.
- Operation at 5T / 7 sec pulse length will permit current profile control studies at moderate values of β_N.

Shaping Effects are Important for the Steady-State Advanced Tokamak

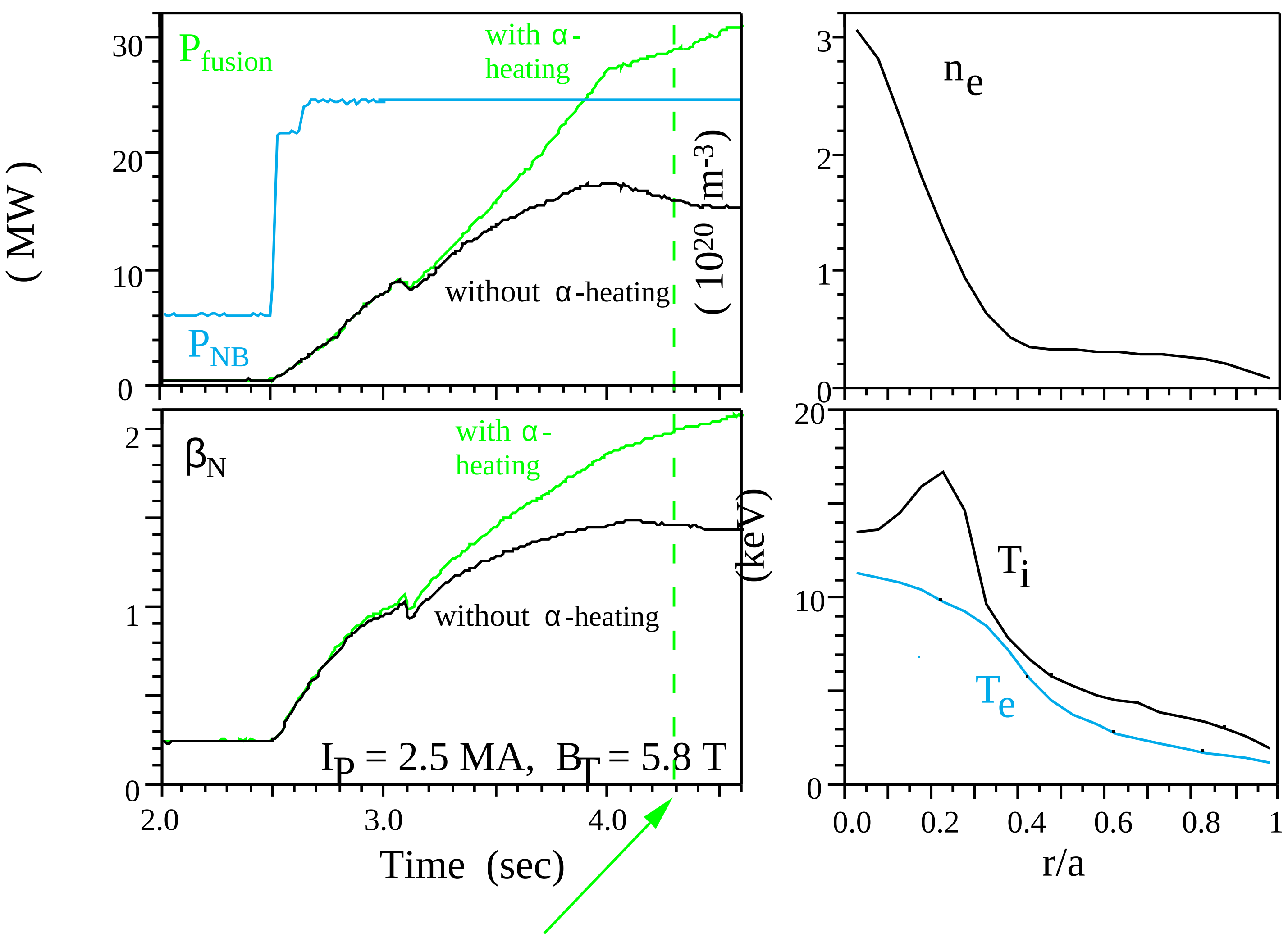
- Experimental results to date point to **higher β_N's** and **higher H's** with **strong shaping** (especially triangularity).

- The **higher current** accessible with greater elongation and triangularity is favorable for β_t and τ_E even at fixed β_N and H.
  - The current accessible with **κ_{95} = 1.8, δ_{95} = 0.5** (TPX) is **40% higher** than can be attained at **κ_{95} = 1.6, δ_{95} = 0.24** (ITER EDA), for fixed R, a, B.

- Theoretically, the **highest performance** wall-stabilized SS/AT modes need **high δ** to allow qmin to move outwards, giving the **largest possible volume of reversed shear.**

- An **engineering price** is paid for these advantages, however.
  - High elongation requires **closer feedback coils** for vertical stability.
  - High triangularity leads to a segmented transformer, with significantly unbalanced currents, making **strong out-of-plane loads on inner TF legs**.
  - Also implies a DN divertor to minimize heat load on short inner divertor leg.

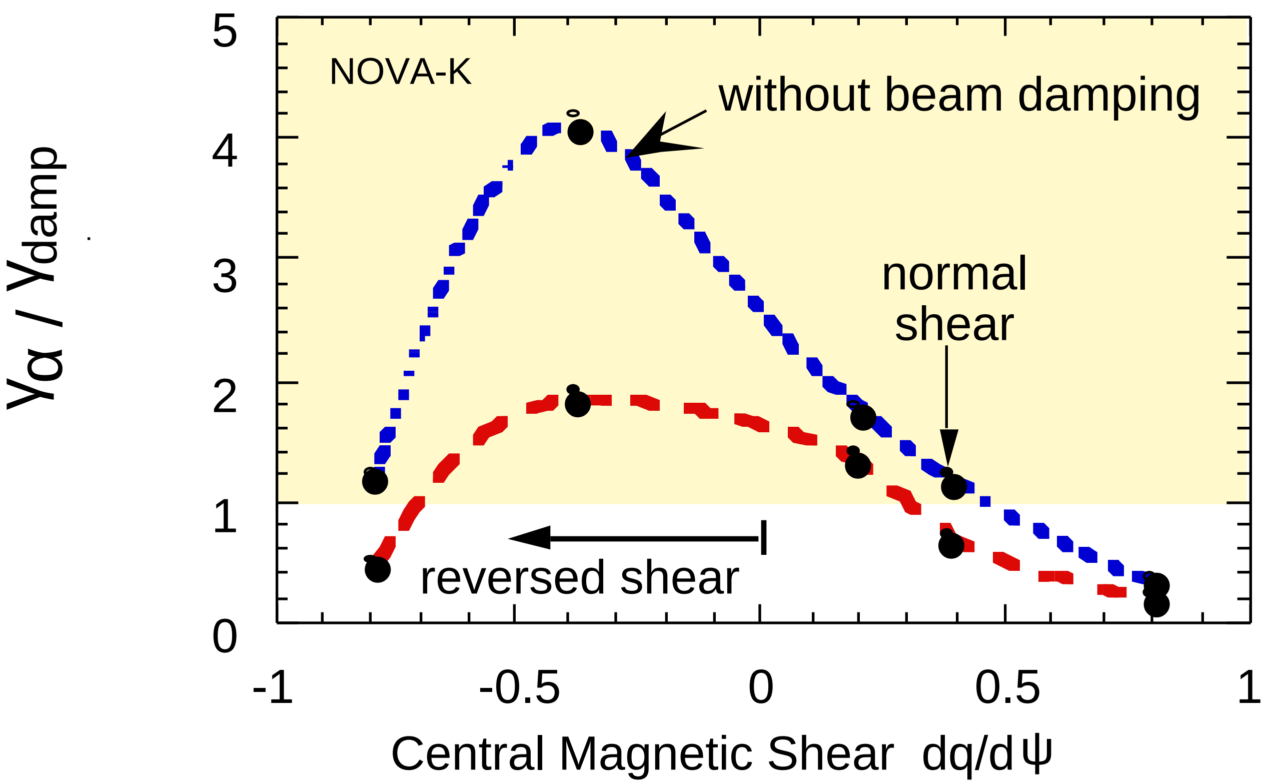
TFTR will Contribute to SS/AT Research While Making P_{fus} ~ 20MW



- β_N = 2 (β_N* = 4) calculated stable for all *n* (PEST) in this regime, and already achieved experimentally.
- Final n_e profile from equilibrium solution using measured D_e (with floor). T_e, T_i, and equilibrium solved using observed χ_e, χ_i (with floor). Z_{eff} = 1.5. No j(r) nor p(r) control included.
- With α heating temperatures do not come into steady state. Q(o) > 5 when Q(a) ~ 1. Beam pulse ~5 seconds planned.

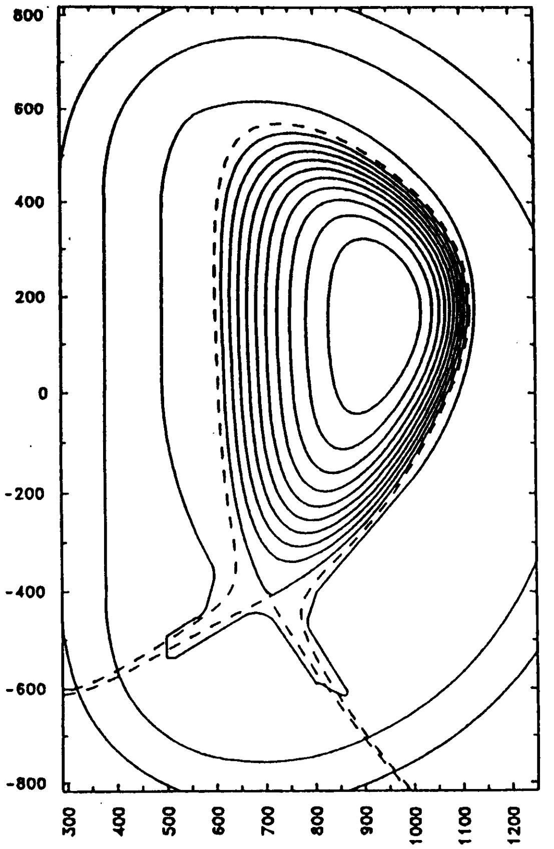
Alfvén Eigenmodes are Sensitive to q(r)

Fu, PPPL, 1995



- **Instability drive increases as q(o) increases.**
- **Reversed shear begins to stabilize TAE.**
- This is an area that needs theoretical and experimental work to validate reversed shear scenarios for DT operation.

SS/AT Studies may be Possible in ITER



I_p = 12.2 MA $\quad B_o$ = 3.9 T

R_o = 8.63 m $\quad a$ = 2.5 m

κ_x = 1.92 $\quad \delta_x$ = 0.53

q_{95} = 3.7 $\quad P_{fus}$ = 1.5 GW

- **For this to become a reality, it will be necessary to support all aspects of SS/AT operation, including:**
  - **Active current profile control** both on and off axis.
  - **Strong particle control** to reduce main-chamber recycling while sustaining a **detached divertor**.
  - **Tight plasma shape control** at high β_p, very low l_i.
- **In constrained budgets, PCAST recommended rescoping ITER to a moderate-pulse ignition experiment.**
- **Advanced tokamak physics capabilities should be built into such a device from the beginning.**

Conclusions

- The Steady-state Advanced Tokamak offers as much as a **factor of 2 reduction in the Cost of Electricity** compared with a pulsed, standard performance tokamak.

- MHD / transport / current drive studies indicate that **high-performance Reversed Shear SS/AT regimes exist.** The best regimes rely on wall stabilization of the external kink.

- Experimental results support many key aspects of high-performance SS/AT regimes.
  - The **bootstrap current** is observed experimentally.
  - **High confinement** and **high pressure gradients** are observed with reversed shear.
  - **Wall stabilization** of the external kink exists, but **is not fully understood.**

- Existing, operating devices in the U.S. program can make major contributions to SS/AT research.

- A next-generation device for SS/AT research needs to carefully incorporate the necessary technical features.