Physics of Steady-State Advanced Tokamaks

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Outline of Talk

• 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

- 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

• **High confinement**, to permit high Q at reduced size and/or field. The “usual” confinement scalings give:

\[ M_{ig} = P_\alpha / P_{loss} \approx \frac{<n^2T^2>}{(<nT>/\tau_E)} = \frac{<nT>\tau_E <n^2T^2>}{<nT>^2} \]
\[ \propto H^2I_p^2A^2(\beta^*/\beta)^2 \]
\[ \Rightarrow \text{high } H^* \equiv \frac{H_{\beta}^*}{\beta} \]

• **High** \( \beta \), for high power at given size and field at the coil.

\[ B_o \propto B_{coil} / \varepsilon^{1/2} \Rightarrow \beta^* B_o^2 \propto \beta^*/\varepsilon \propto \beta^*_N \equiv \beta^*/(I_p/aB) \]
\[ \Rightarrow \text{high } \beta^*_N \]

• **High usable bootstrap fraction**, for high \( Q_{CD} \).

\[ \Rightarrow \text{high } \varepsilon^{1/2}\beta_p \text{, with good alignment of } j_{bs} \text{ and } j_{tot} \]

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

\[ \int \frac{dl}{B} \text{ increases with } R \text{ because } B \text{ falls} \]

- but with reversed shear (\(dq/dr < 0\)), \(\int dl\) decreases as \(R\) increases.

- Net effect: robust stability against high-n interchange drive for all values of \(\beta\)!

- 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

- \( j_{bs} \propto \nabla \beta_p \) \( \Rightarrow \) low \( B_p \) (high \( q \) in core) increases \( f_{bs} \equiv \frac{l_{bs}}{l_p} \).
  \( \Rightarrow \) \( j_{bs} \) peaks off axis \( \rightarrow \) reversed shear

- Important role for non-inductive current drive to "pin" the reversal point at large minor radius \( \Rightarrow \) large R/S region.

- \( \beta_N = 3 \quad \beta_t = 2.12\% \quad \beta_t/\epsilon = 8.7\% \quad f_{bs} = 65\% \)

- **Stable to** \( n = 1 - 4, \infty \), **with no conducting wall.**

- Conducting wall would permit higher \( \beta_t \), but bootstrap current density in core region is already equal to the total required.
The Reversed Shear Regime can Attain Extremely High $\beta_N$ and $f_{bs}$

Kessel et al., PPPL, 1994

- $\beta_N = 5.2$  $\beta_t = 5.2\%$  $\beta_t/\varepsilon = 23.4\%$  $f_{bs} = 93\%$
- Stable to $n = 1 - 6$, $\infty$, conducting wall at 1.3a.
- Shear reversal stabilizes Trapped Electron Modes.
- The shear reversal also raises $\eta_{i,\text{crit}} (d\ln T_i/d\ln n_i)_{\text{crit}}$ from $\sim 2$ to $\sim 4$, 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

- $\beta_N = 5.7$  $\beta_t = 7.5\%$  $\beta_t/\epsilon = 19.8\%$  $f_{bs} = 67\%$
- Stable to $n = 1,2, \infty$, unstable to $n = 3$, with stabilizing wall.
- Transport coefficients $\sim$ 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 $q(0)$.

• If an “ideal” wall can be provided at $b/a \sim 1.3$, 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 $q_{\text{min}}$ 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.
  • $\Rightarrow$ large stable core reversed shear region.

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

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

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, \( \sim \tau_{\text{wall}} \), 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 \( \omega_{\text{rot}} \tau_{\text{wall}} \) and \( \omega_{\text{rot}} \tau_{\text{res}} \gg 1 \).

• Suggests a close relation to low-\( \beta \) “locked modes.”

• Pompfrey et al., and Fitzpatrick find edge viscous/inertial stabilization with rotation speeds \( \sim \) Bondeson & Ward’s.

• Betti and Sorotokin find energetic banana particles provide kinetic stabilization in the absence of rotation.
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• Theoretical basis.

• ⇒ *Experimental basis.*

• 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

Smeuldiers et al., JET, 1995

- **Very high pressure gradients** are observed in the plasma core, greater than usual first-stability limits for \( q(0) \sim 1 \).
- **Core thermal confinement improves by a factor of \( \sim 2 \).**
- 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.
• **Very high pressure gradients** are observed in the plasma core, greater than usual first-stability limits for $q(0) \sim 1$.

• **Central $\beta = 44\%$** 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 $\beta_N$. 
The Motional Stark Effect Diagnostic has Dramatically Improved Experimental Capabilities for Advanced Tokamak Studies.

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

- $\mathbf{v} \times \mathbf{B}$ electric field in frame of fast-moving neutral beam atom causes strong Stark splitting in $\mathrm{H}_\alpha$ (Balmer) line.
- Polarization of the Stark-split line gives orientation of $\mathbf{B}$.
- Orientation of $\mathbf{B}$ gives magnitude of $B_p$.
- $B_p(R)$ strongly determines $q(r)$ in equilibrium code fits using other known data such as external $\mathbf{B}$ fields and $p(r)$. 
JET Demonstrated the Technique of Early Heating to Freeze in a Hollow $q(r)$

- By heating during the current ramp, it is possible to maintain $q(o) \sim q(a) > q_{\text{min}}$ 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 $i_j$ associated with reversed shear.
Two Confinement Regimes are Observed in TFTR Reversed-Shear Plasmas

- 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 $q_{\text{min}} \sim 2$. 

\[ n_e(0) \times 10^{20} \text{ m}^{-3} \]

\[ P_{\text{NB}} = 24 \text{ MW} \]
\[ P_{\text{NB}} = 19 \text{ MW} \]
\[ P_{\text{co}}/P_{\text{NB}} = 0.48 \]
\[ P_{\text{co}}/P_{\text{NB}} = 0.63 \]

\( I_p = 1.6 \text{ MA} \)
\( B_T = 4.8 \text{ T} \)
\( R_0 = 2.6 \text{ m} \)
Plasma Parameters in TFTR
ERS Modes are Impressive

Zarnstorff, TFTR, Wednesday AM, 51A.02

- $P(o)/<P> \sim 8$, $P(o) = 4.6 \cdot 10^5$ Pa
- $n_e(o) = 1.2 \cdot 10^{20}$, $T_i(o) = 20$ keV, $T_e(o) = 8$ keV
- $H = 2.2$, $H^* = 4.2$; $\beta_N = 2.0$, $\beta_N^* = 3.8$, $f_{bs} = 0.75$
- $3.5 \cdot 10^{16}$ DD neutrons/sec at modest B and $P_{NB}$
- Small $v_\phi < 150$ km/sec due to balanced injection
  $\Rightarrow$ transport reduction not due to sheared toroidal flow
\( \chi_i \) & \( D_e \) 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 $T_\text{i}$ and $V_\phi$

in Reversed-Shear H-mode Plasmas

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

- $\beta_N$ up to 4 has been achieved in R/S ELM-free H-modes.
- Global confinement is $\sim$VH Mode $\sim$ 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

- $H \sim 2$, with high $\beta^*/\beta$
- $P(o)/\langle P \rangle = 5$, $n_e(o) = 6 \cdot 10^{19}$, $T_i(o) = 20$ keV, $T_e(o) = 5.5$ keV
- High DIII-D neutron rates $\sim 8 \cdot 10^{15}$/sec – at moderate $\beta$.
- 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, 812

• 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.
• 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.
• Observed $\beta$ 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 $\beta$ limit is inconsistent with wall at infinity, $\sim$ matches calculations for ideal wall at real wall location.
- Mode growth rates are $\sim$ consistent with “wall modes.”
- $q = 3$ surface is still rotating ($\sim 2$ kHz) as wall mode grows.
- NOVA-W calculations are in qualitative agreement, but suggest that $\sim 2$-3x higher rotation speed may be required for stability.
High values of $\beta_N$ are achieved by rapid initial formation.

Successful position control does not depend on shell location.

Disruptions are most often prevented if $dl_p/dt > 0$, 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-$\beta$ field-error induced “locked modes.”
  • DIII-D observation that $\beta$-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 $\beta$ / low $I_i$ studies with variable rotation.
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SS/AT Research Priorities

• Underlying science
  • Threshold physics of ERS.
  • Physics of fluctuation reduction.
  • Under what circumstances are $\chi_i$, $\chi_e$, 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, $\alpha$ channeling

• Shaping effects on performance
  • $\kappa$, $\delta$, $R/a$

• Integration with dispersive divertor operation
  • SND, DND, Edge L vs. ELM’ing H, vs. ELM-free H

• $\alpha$ physics
  • Stability, heating, burn control

• Wall stabilization
  • Rotation speed requirement, underlying mechanism

• Performance limits
  • $\beta_N^*, H^*, f_{bs} \rightarrow P_{fus}$
TPX would have been the Right Next Step in SS/AT Research

- Strong shaping and active current profile control.
- Divertor optimized for low recycling, strong pumping.
- Long pulse (1000 sec) $\gg \tau_{L/R}$, $\gg$ wall-equilibration time.
- Substantial plasma performance ($I_p R/a = 9$MA $\sim$ TFTR’s)
- DT capability to study $\alpha$ 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. $S \propto \frac{\tau_R}{\tau_A} \propto RBT^{3/2}n^{1/2}$
  • 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 $\alpha$-stability tests, $\alpha$-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

\[ I_p = 1.3 \text{ MA}, \quad B_t = 1.75 \text{T}, \quad \beta_N = 5.3, \quad f_{bs} = 0.69 \]
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 $\beta_N$. 
Shaping Effects are Important for the Steady-State Advanced Tokamak

• Experimental results to date point to higher $\beta_N$’s and higher $H$’s with strong shaping (especially triangularity).

• The higher current accessible with greater elongation and triangularity is favorable for $\beta_t$ and $\tau_E$ even at fixed $\beta_N$ and $H$.
  • The current accessible with $\kappa_{95} = 1.8$, $\delta_{95} = 0.5$ (TPX) is 40% higher than can be attained at $\kappa_{95} = 1.6$, $\delta_{95} = 0.24$ (ITER EDA), for fixed $R$, $a$, $B$.

• Theoretically, the highest performance wall-stabilized SS/AT modes need high $\delta$ to allow $q_{\text{min}}$ 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 $P_{\text{fus}} \sim 20$MW

- $\beta_N = 2$ ($\beta_N^* = 4$) 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 $\chi_e$, $\chi_i$ (with floor). $Z_{\text{eff}} = 1.5$. No $j(r)$ nor $p(r)$ control included.
- With $\alpha$ heating temperatures do not come into steady state. $Q(o) > 5$ when $Q(a) \sim 1$. Beam pulse $\sim 5$ seconds planned.
Alfvén Eigenmodes are Sensitive to $q(r)$

Fu, PPPL, 1995

- Instability drive increases as $q(0)$ 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

- 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 $\beta_p$, 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.