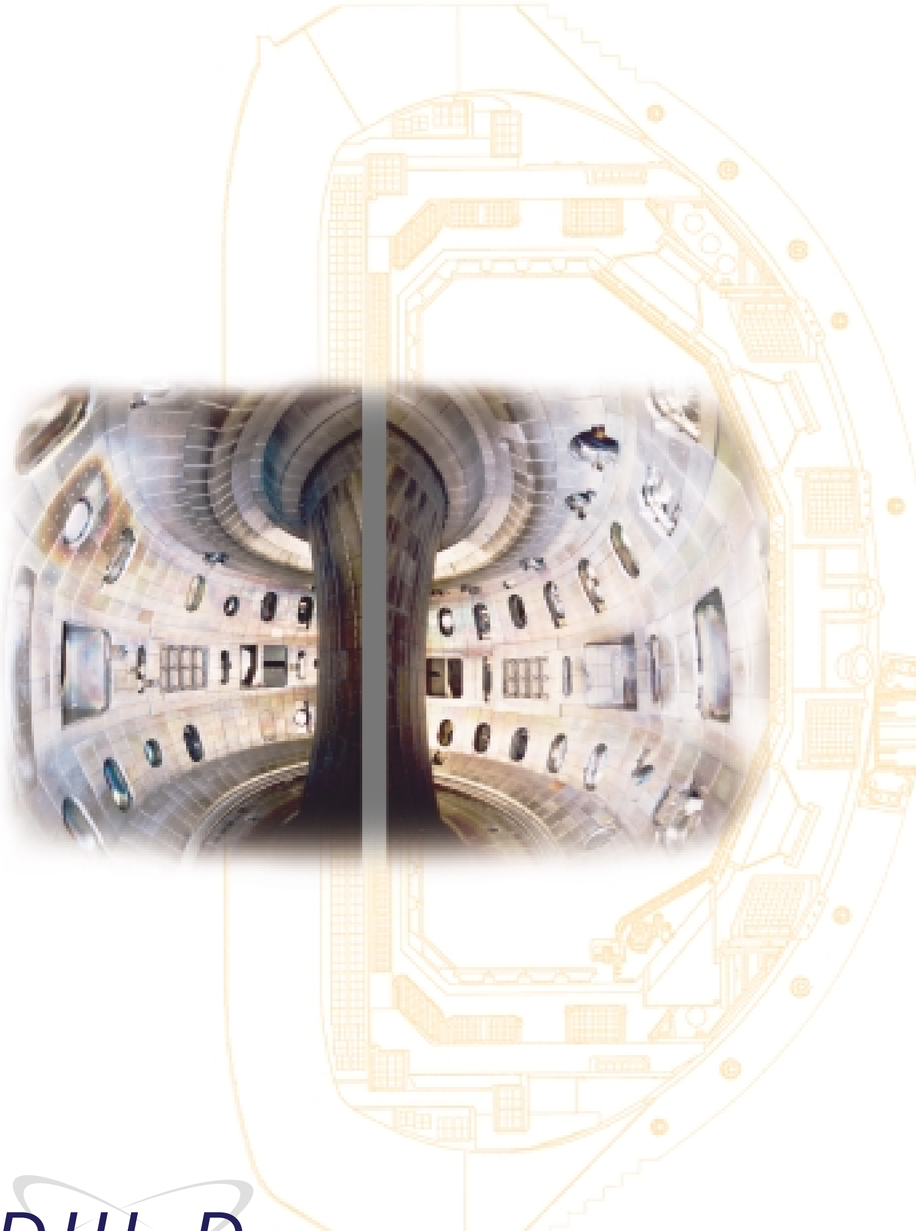
# Optimization of the Tokamak Concept



by
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GENERAL ATOMICS

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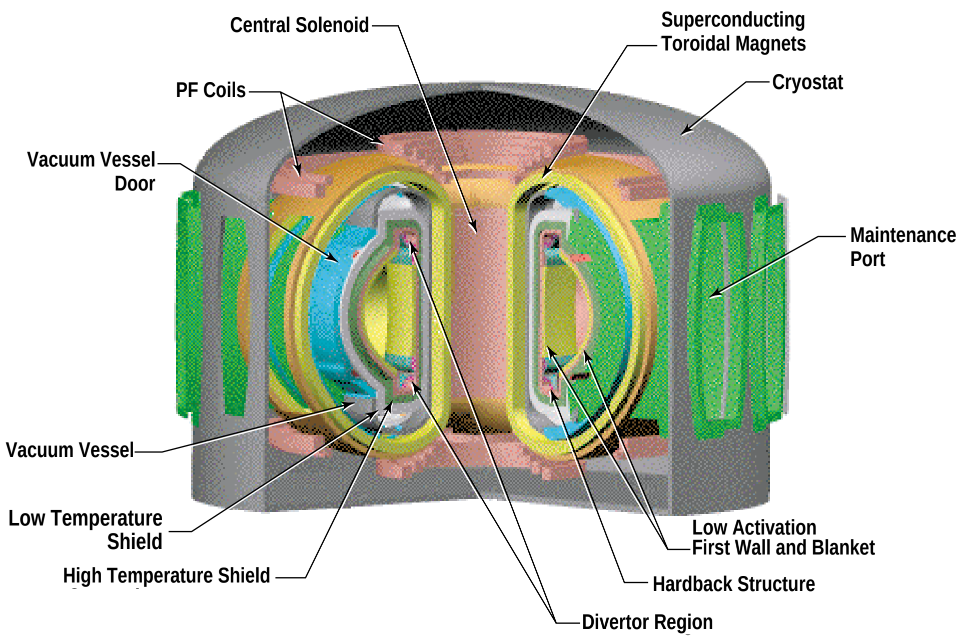
# OPTIMIZATION OF THE TOKAMAK CONCEPT LEADS TO AN ATTRACTIVE FUSION POWER PLANT

- **Attractive features**
  - Improved power cycle
  - Improved economics
  - Reduced size

    *Higher pressure, reduced heat loss*

| | Conventional | Optimized |
|---|---|---|
| Power cycle | Pulsed | Steady-state |
| COE ¢/kWhr | ~13 | ~7 |
| Major radius (m) | 8 | 5 |

- **The U.S. ARIES system study**




- **Optimization of the tokamak concept is known as the Advanced Tokamak program**

# THE GOAL OF THE ADVANCED TOKAMAK PROGRAM IS TO OPTIMIZE THE TOKAMAK CONCEPT FOR ATTRACTIVE FUSION ENERGY PRODUCTION

## — Discovering the Ultimate Potential of the Tokamak —

**Key Elements**

- **Steady state**
  - High self-generated bootstrap current
- **Compact (smaller)**
  - Improved confinement (reduced heat loss)

    Fusion Ignition Requirement

    $$3\times10^{21}\ \mathrm{m^{-3}\ keV\ s} < n\,T_i\,\tau \propto (H\,\underbrace{a\,B\,\kappa}_{\text{Size}})^2$$

    $$H = \tau_E/\tau_E^{conv}$$
- **High power density**
  - Improved stability

    $$P_{Fus} \propto (n\,T)^2\,\mathrm{Vol} \propto \beta^2 B^4\ \mathrm{Vol} \qquad \beta = \frac{2\,\mu_o\,\langle P\rangle}{B^2}$$

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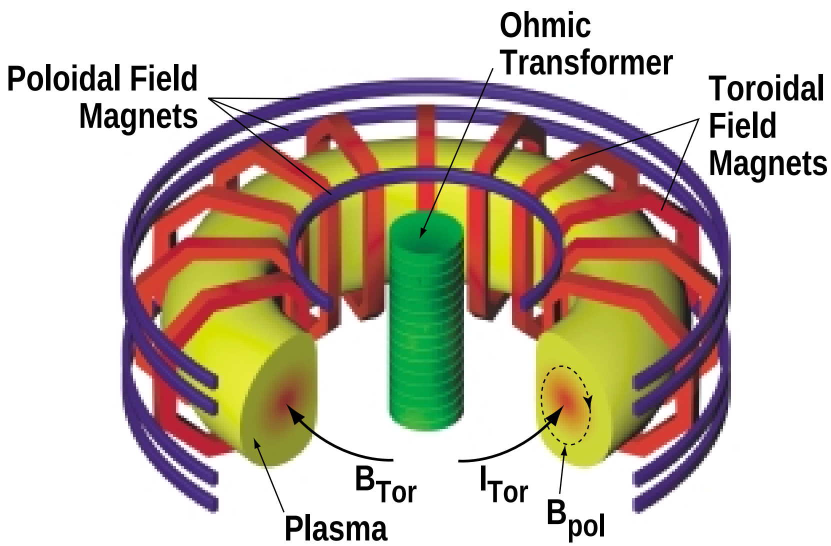
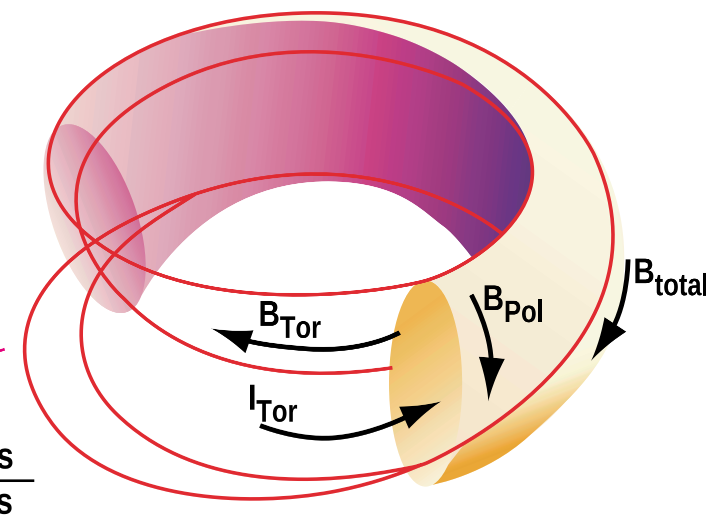
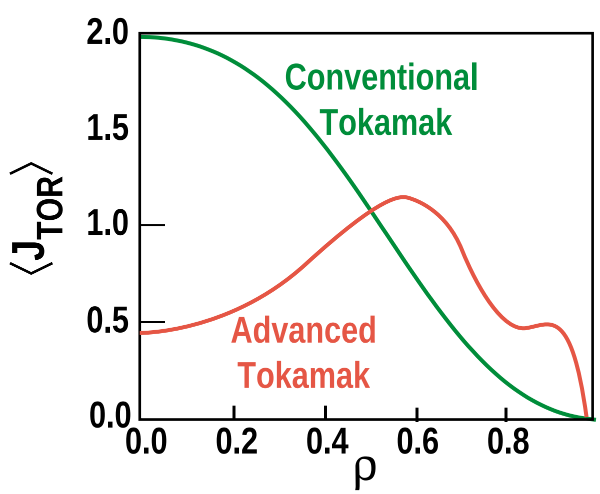
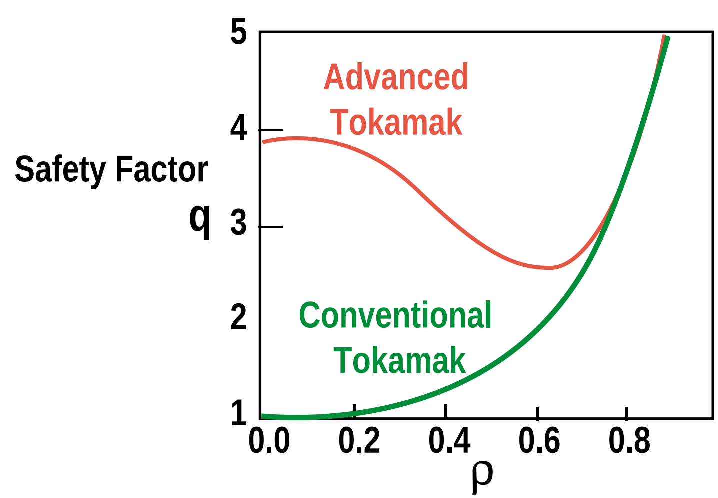
# THE CONFINING MAGNETIC FIELD IN A TOKAMAK IS PRODUCED BY CURRENTS IN EXTERNAL COILS PLUS A CURRENT IN THE PLASMA




$$q = \frac{\#\text{Tor Circuits}}{\#\text{Pol Circuits}}$$

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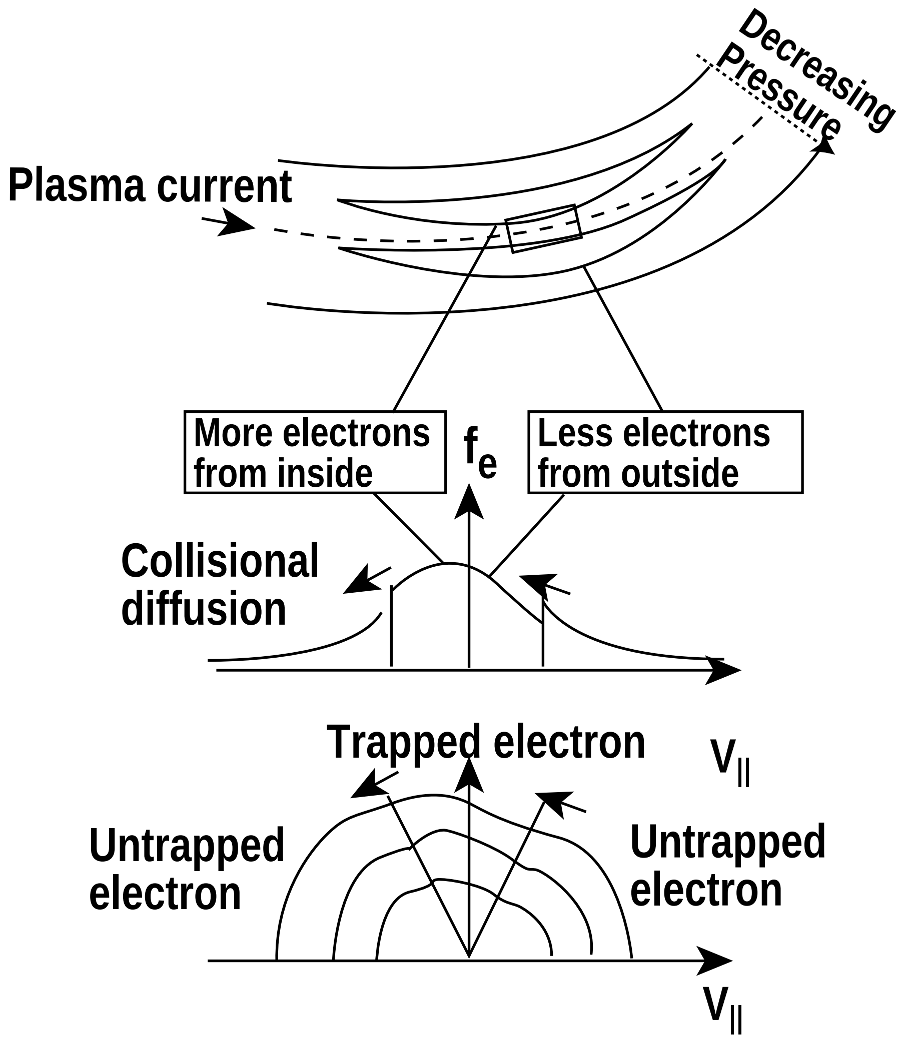
# THE PLASMA'S SELF-GENERATED BOOTSTRAP CURRENT IS THE BASIS FOR MODERN APPROACHES TO STEADY-STATE OPERATION

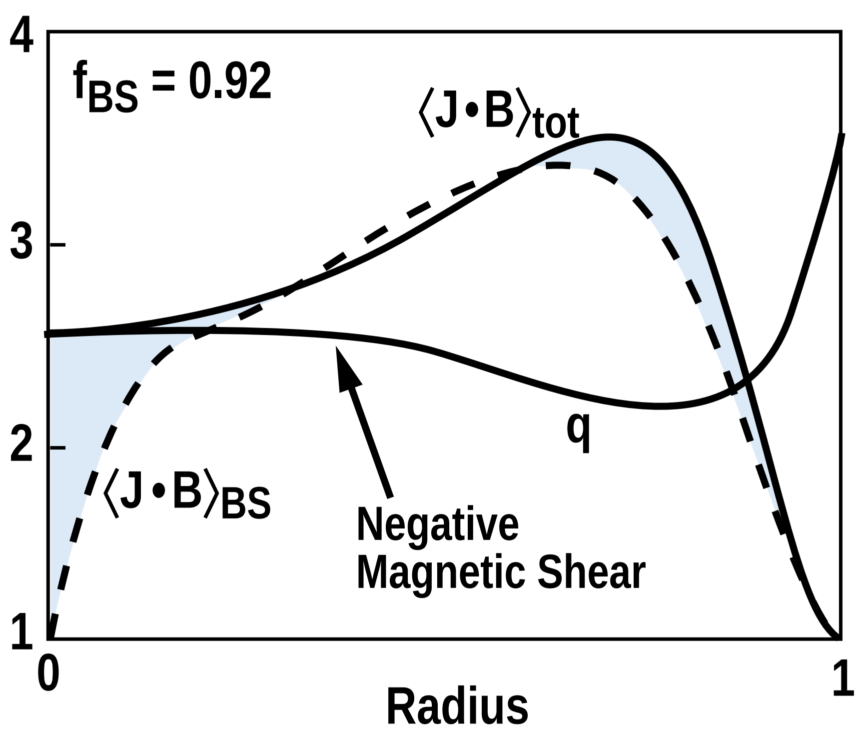



(Kikuchi, PPCF 37 (1995))

- Result of conservation of momentum in toroidal geometry (neoclassical transport theory)
- $J_{BS} \propto$ local pressure gradient
- $I_{BS}/I_{TOT} \propto \sqrt{a/R}\,\beta_{POL}$
  $\propto \sqrt{R/a}\;q\,\beta_N$
- High bootstrap current is essential for steady state

$$Q_{SS} = \frac{P_{Fus}}{P_{CD}} \propto \frac{P_{Fus}}{1/\gamma_{CD}\left(I_{TOT} - I_{BS}\right)}$$

# SIMULATIONS PREDICT SELF-CONSISTENT EQUILIBRIA WITH NEARLY 100% BOOTSTRAP




→ Steady state with low recirculating power

- Off-axis current drive to supply missing current
  - Provided by high power microwaves in DIII–D
- Other benefits of negative central shear profile
  - Reduced transport, improved confinement
  - Improved stability to central unstable MHD modes
    - ★ Ballooning
    - ★ Tearing modes
    - ★ Sawteeth

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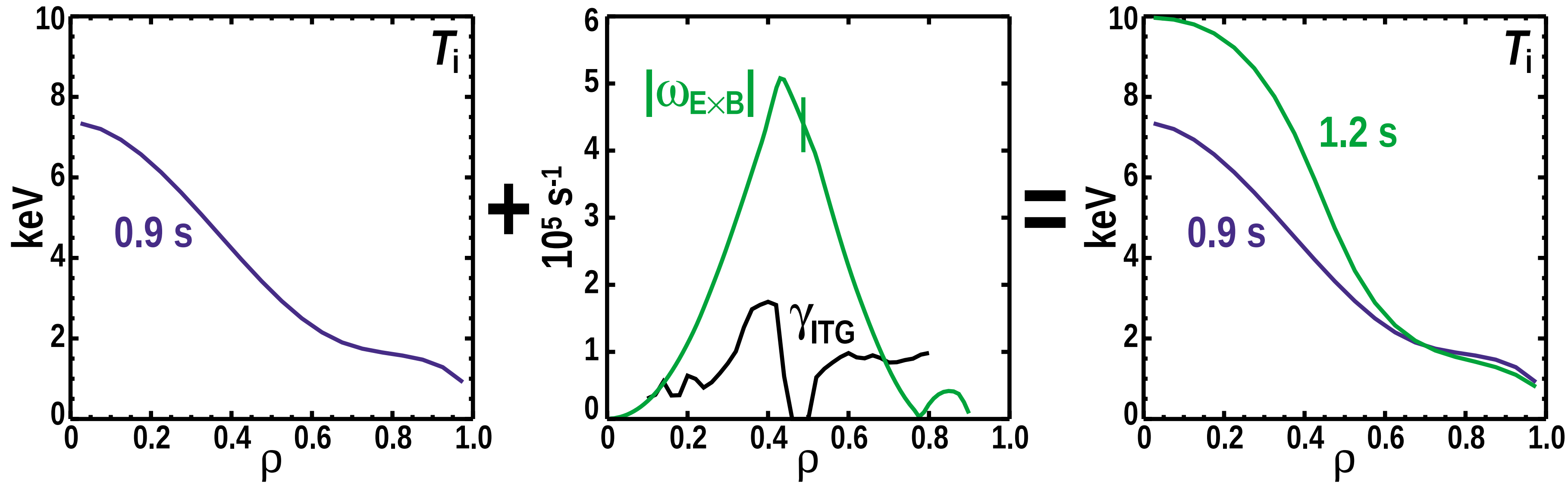
# NEGATIVE CENTRAL SHEAR AND SHEARED E×B FLOW LEAD TO IMPROVED CORE CONFINEMENT

- Key physics
  - Measured turbulence reduction is consistent with theoretical prediction
    - ★ E×B shearing rate exceeds maximum growth rate of ion temperature gradient mode
  - Negative magnetic shear contributes to reduced $\gamma_{ITG}$
- Similar reduction is often observed in other transport channels

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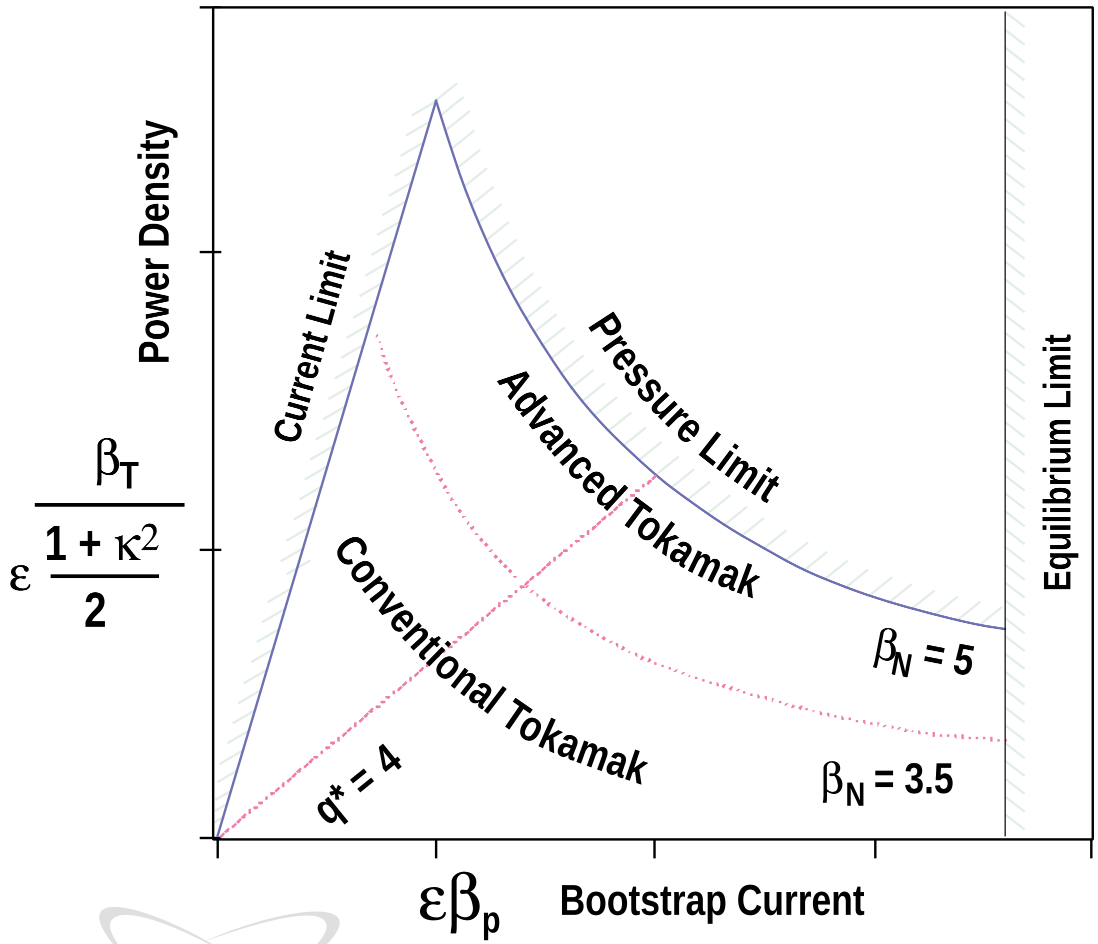
# A COMPACT STEADY STATE TOKAMAK REQUIRES OPERATION AT HIGH $\beta_N$

$$Q_{ss} = \frac{P_{fus}}{P_{CD}} \propto \frac{\gamma_{cur}}{nq} \quad \frac{\varepsilon_{eff} \quad \beta_N^2}{(1 - \xi \sqrt{A}\, q\, \beta_N)} \quad B^3 a\kappa$$



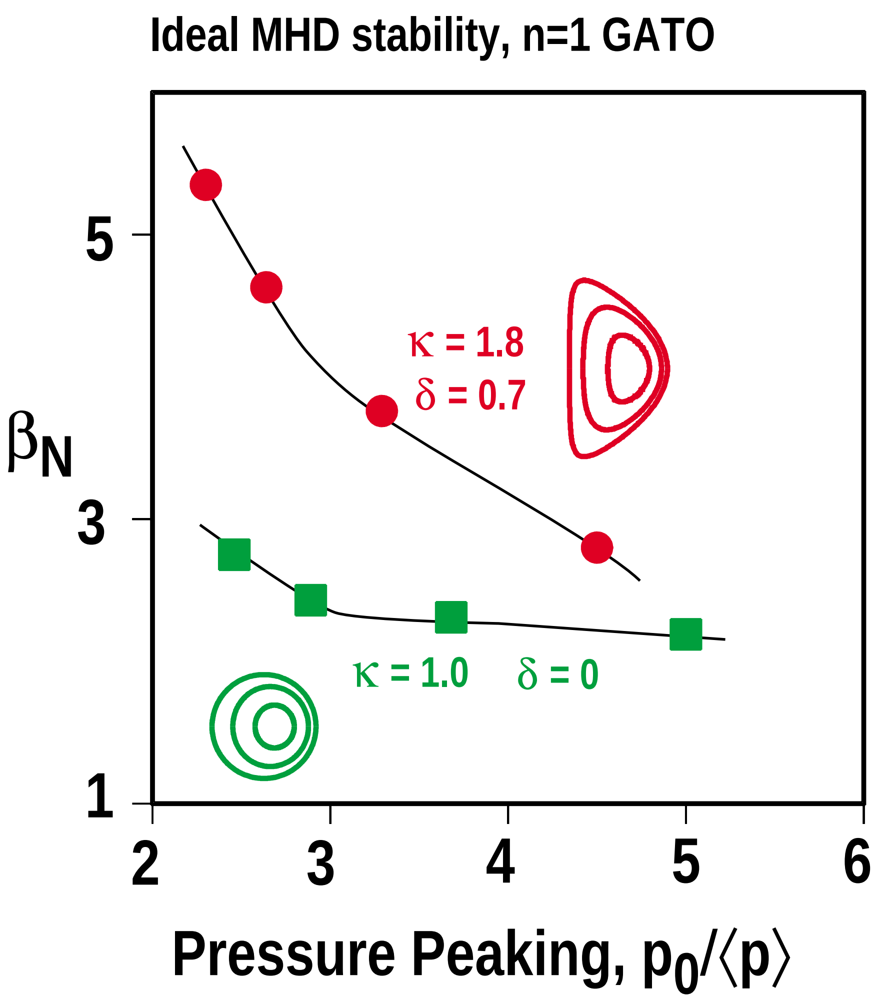

- High power density $\Rightarrow$ high $\beta_T$
- Large bootstrap fraction $\Rightarrow$ high $\beta_p$
- Steady state $\Rightarrow$ high $\beta_N$

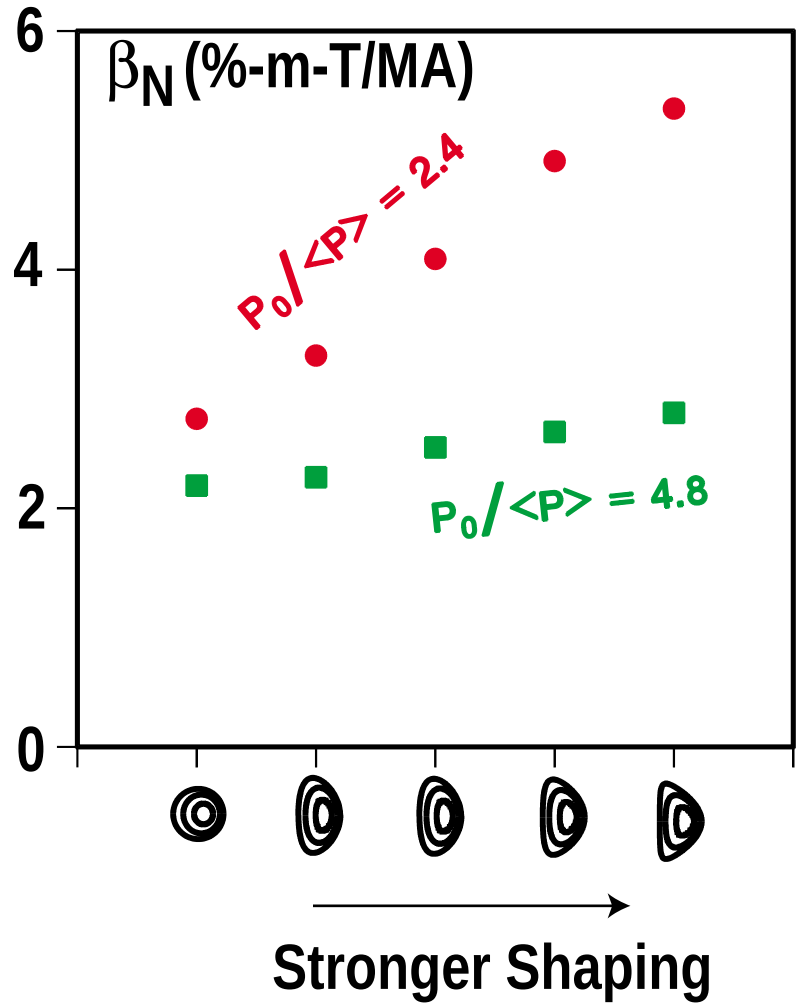
  $\beta_N \propto$ power density $\times$ bootstrap current

$$\beta_T\, \beta_p \propto \left(\frac{1+\kappa^2}{2}\right) \beta_N^2$$

$$\beta_N^2 = \beta_T / (I/aB)$$

# BROAD PRESSURE PROFILE AND STRONG SHAPING REQUIRED FOR HIGH BETA

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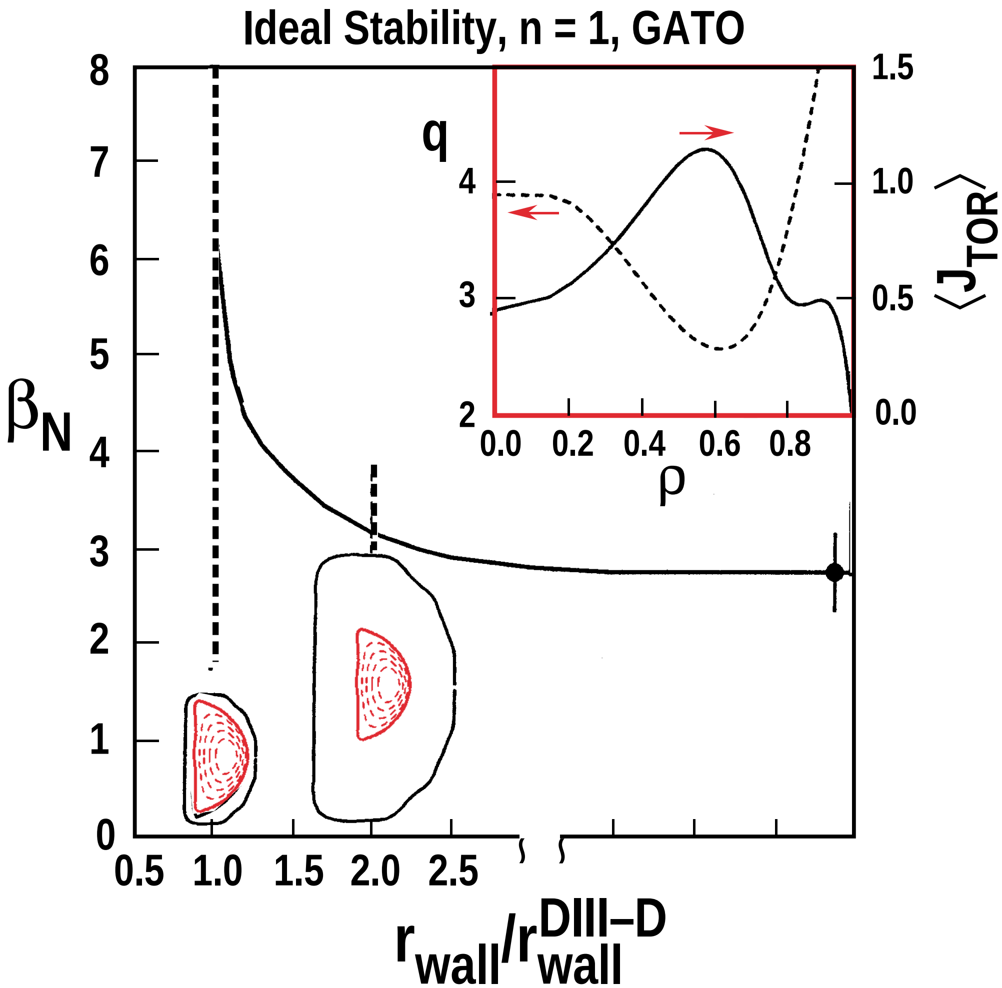
# WALL STABILIZATION GREATLY IMPROVES ACHIEVABLE STABLE BETA




- $\beta_T \ \beta_p = 25 \left(\frac{1+\kappa^2}{2}\right)\left(\frac{\beta_N}{100}\right)^2$
  - $f_{BS} = C_{BS}\ \varepsilon^{1/2}\ \beta_p$
  - $P_{FUS} \propto \beta_T^2\ B_T^4$
- $\beta_N \equiv \beta_T/(I/aB)$
- $\beta_N$ ~ 6 with wall stabilization
- $\beta_N$ ~ 3 without wall stabilization

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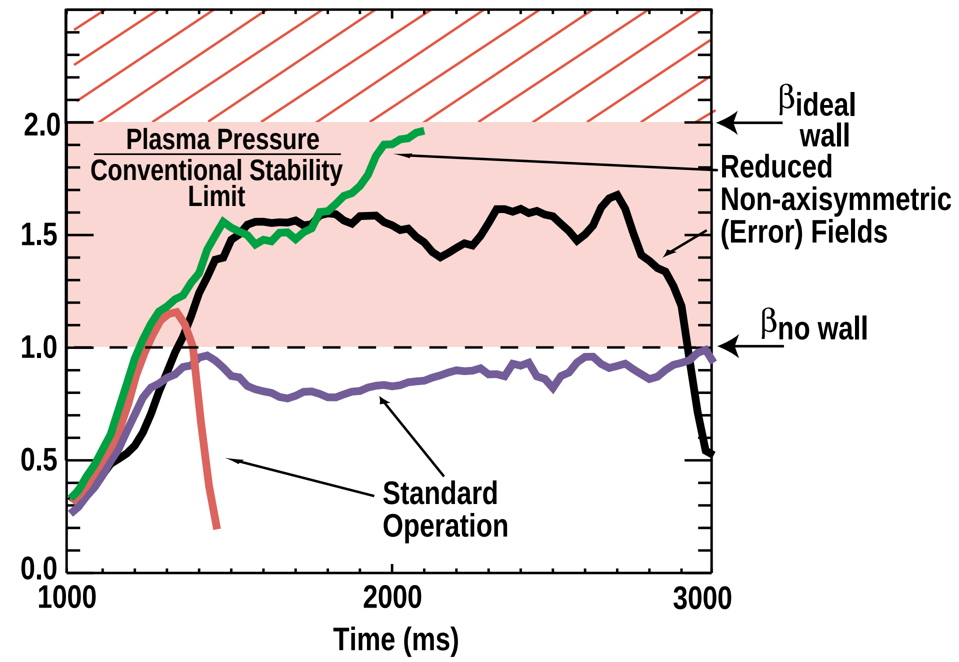
# RESISTIVE WALL MODE STABILIZED BY ROTATION AND ACTIVE FEEDBACK ON DIII–D

## KEY RESULT

- Plasma pressure is stably maintained above the conventional pressure limit
  - Up to a factor of two
  - Up to ideal wall limit




## KEY PHYSICS

- Resistive wall mode is stabilized by plasma rotation in agreement with theory
- Identification of "error field amplification" as mechanism for rotation slowdown as predicted by theory
- Reduction of non-axisymmetric error field → continued rotation → stable to high pressure

⇒ Non-axisymmetric stabilization coils calculated to provide stable operation near the ideal wall limit with or without rotation

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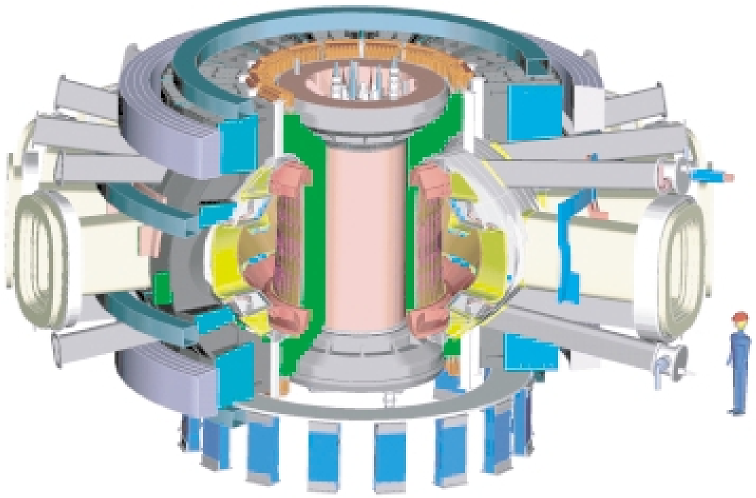
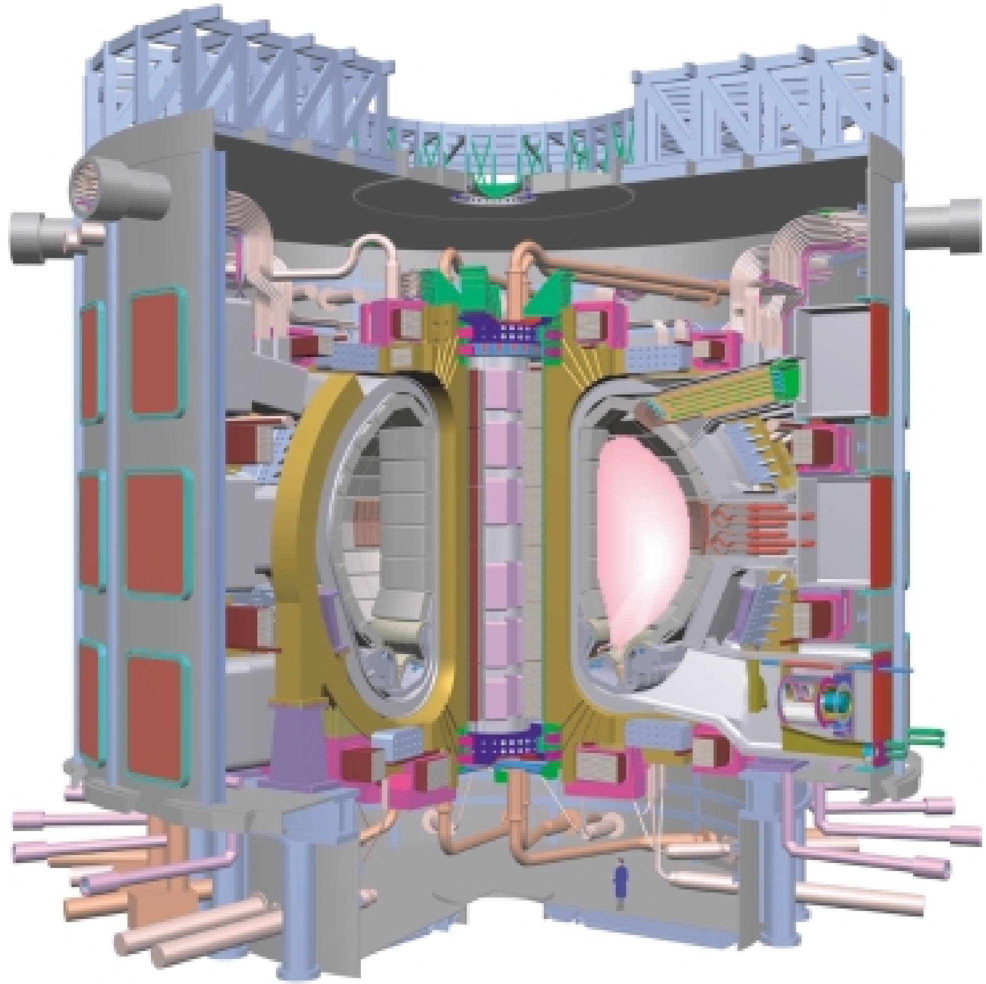
# THE NEXT FRONTIER IS ADVANCED TOKAMAK PHYSICS IN THE SELF-HEATED BURNING PLASMA REGIME

- Strong nonlinear coupling amongst fusion alpha particles, pressure driven current, turbulent transport, MHD stability and boundary behavior



FIRE



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