THE DIII–D ADVANCED TOKAMAK PROGRAM

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GENERAL ATOMICS

045-99/TST

OUTLINE

- Introduction
  - What is an advanced tokamak
  - DIII–D AT program goals

- Steady state and high β_N

- Principal AT scenarios

- DIII–D AT program elements
  - ITB physics
  - Profile control [J(r)]
  - Stability limits and pressure profile
  - Edge stability
  - Neoclassical tearing modes
  - Wall stabilization

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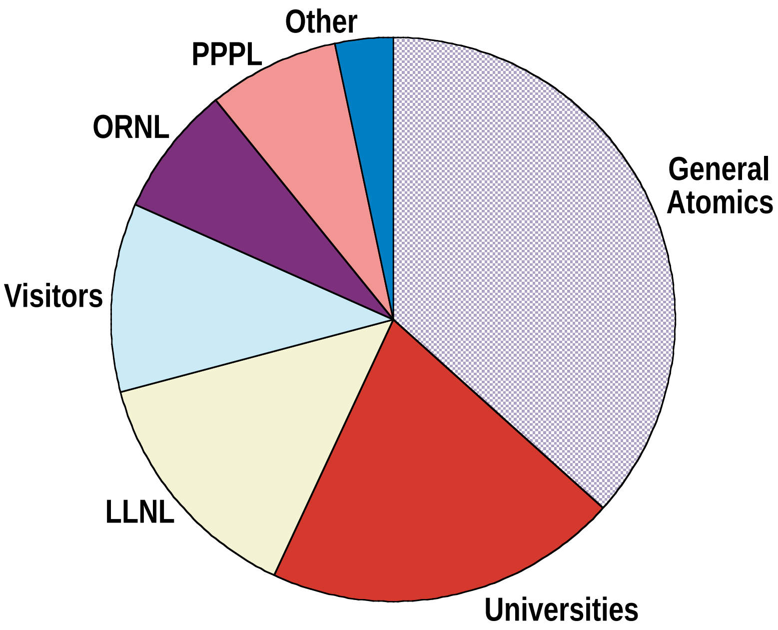
DIII–D — A NATIONAL FUSION RESEARCH PROGRAM

1999 DIII–D National Physics Team (93 FTE)



- Collaborations with 50 institutions — 300 users

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WHAT IS AN ADVANCED TOKAMAK

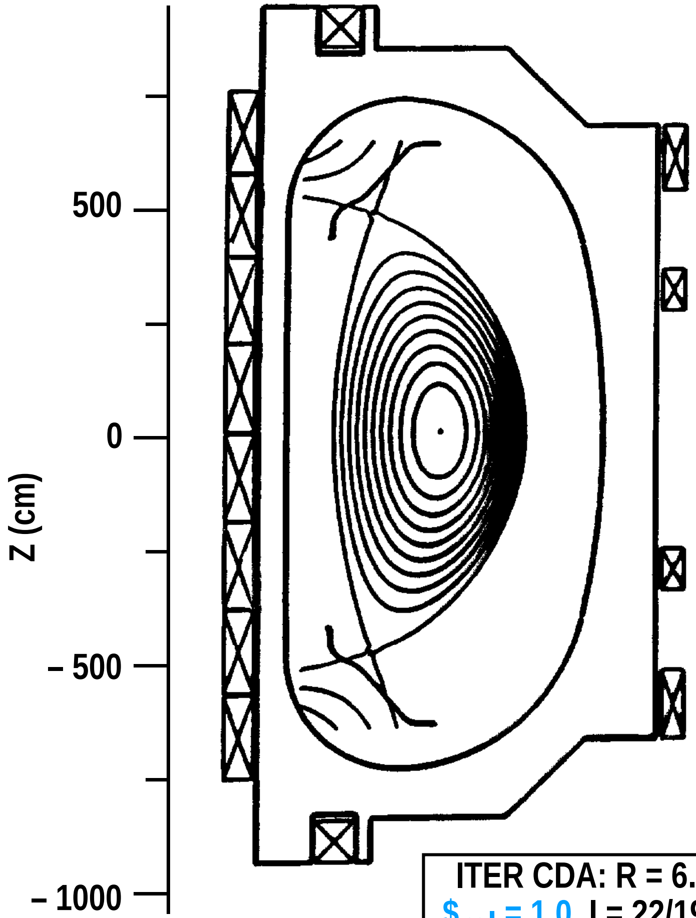
"Improvement of the tokamak concept towards higher performance and steady-state operation through profile modification and control, plasma shape, and MHD stabilization"

- **Goal: concept improvement**
  - – **High performance**
    - ★ **High β**
    - ★ **High τ_E**
  - – **Steady state**

- **How, techniques**
  - – **Profile control**
  - – **Shape**
  - – **MHD stabilization**

IMPROVED CONFINEMENT AND STABILITY LIMITS LEAD TO MORE COMPACT POWER PLANT DESIGNS

CONVENTIONAL TOKAMAK

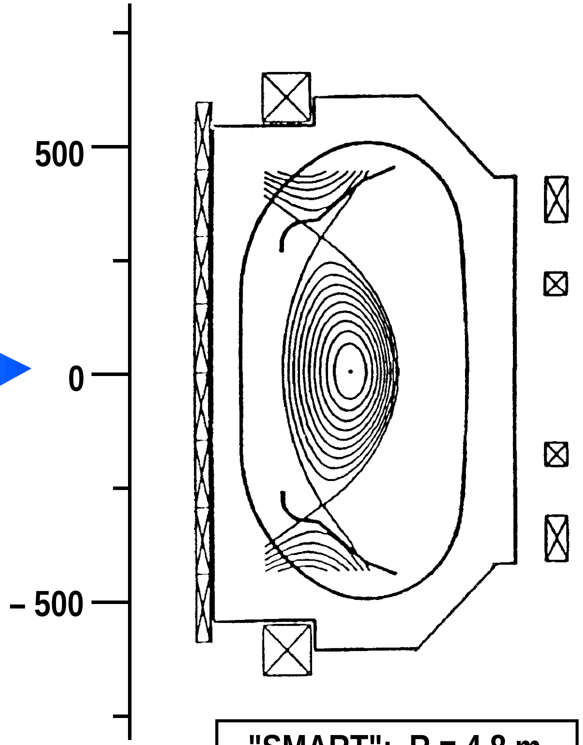


ITER CDA: R = 6.0 m,
$\$_{rel} = 1.0$, I = 22/19 MA,
$Q_{ss} = 4$

$\beta \uparrow$ 50% $\beta \sim 4.5\ I/aB$

$\tau \uparrow$ 80% $\tau \sim 3.6\ \tau_{ITER-89P}$

ADVANCED TOKAMAK



"SMART": R = 4.8 m,
$\$_{rel} = 0.59$, I = 10/7 MA,
$Q_{ss} = 27$

(Perkins, LLNL, 1993)

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ADVANCED TOKAMAK APPROACH RELIES ON MODIFICATION OF PROFILES

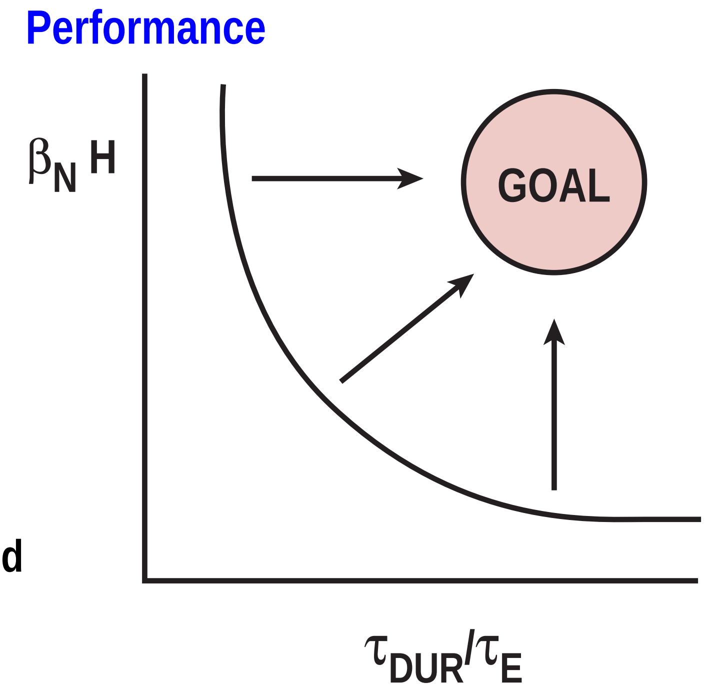
	"Conventional Tokamak"	Advanced Physics Approach
	Global parameters (0–D)	Internal profiles (1–D, 2–D)
Confinement:	$1 < H < 2$ Increase I_p ● Larger size, or ● Large B	$2 < H < 4$ ● Shape, $\delta, \kappa, \varepsilon, \ldots$ ● Plasma rotation → sheared $(E \times B)$ ● Current density ● Pressure $p_o / \langle p \rangle, \beta_p$ ● Density profile control, edge control
Stability:	$2\ I/aB \le \beta \le 3\ I/aB$ ● Limited power/A ● Increase I_p, lower q	$3\ I/aB \le \beta \le 6\ I/aB$ ● Shape ● Plasma rotation, wall stabilization ● Current density, $\ell_i, q_o, < J(a) >$ ● Pressure $p_o / < p >, p'(a)$
Current Drive:	Inductive ● Pulsed reactor	RF "smart" current drive bootstrap ● Steady-state
Disruptions:	High I_p → low q → increased risk of disruptions	Lower I_p — higher q → reduced force Disruption avoidance – "maintain" stable profiles Disruption control — local heating and current drive, passive and active mode control

⇒ Advanced Tokamak achieves same performance at lower I_p

THE MISSION OF THE DIII–D PROGRAM IS

- To establish scientific basis for the optimization of the tokamak approach to fusion energy production
  - The DIII–D Program's primary focus is the Advanced Tokamak that seeks to find the ultimate potential of the tokamak as a magnetic confinement system

- Strategy:
  - Demonstrate improvements separately, then simultaneously
  - Develop solid scientific understanding and predictive capability
    - ★ Diagnostics
    - ★ Theory/modeling
    - ★ Require strong coupling of theory and experiment
  - Develop control scenarios and tools based on scientific understanding
  - Increase performance and duration



⇒ Steady State

THE DIII–D ADVANCED TOKAMAK PROGRAM SEEKS TO EXPLORE THE ULTIMATE POTENTIAL OF THE TOKAMAK

Performance

- High confinement enhancement factor, $H \rightarrow 4$
- High β, $\beta_N \rightarrow 6$

Duration, Steady State

- Non-inductively driven, $E_\phi(\rho) \rightarrow 0$
  - High bootstrap fraction

Heat Removal and Particle Control

- High volume recombination and radiated power fraction
- Low core impurity content

Simultaneously
Integrated

Approach: Active Control of Profiles

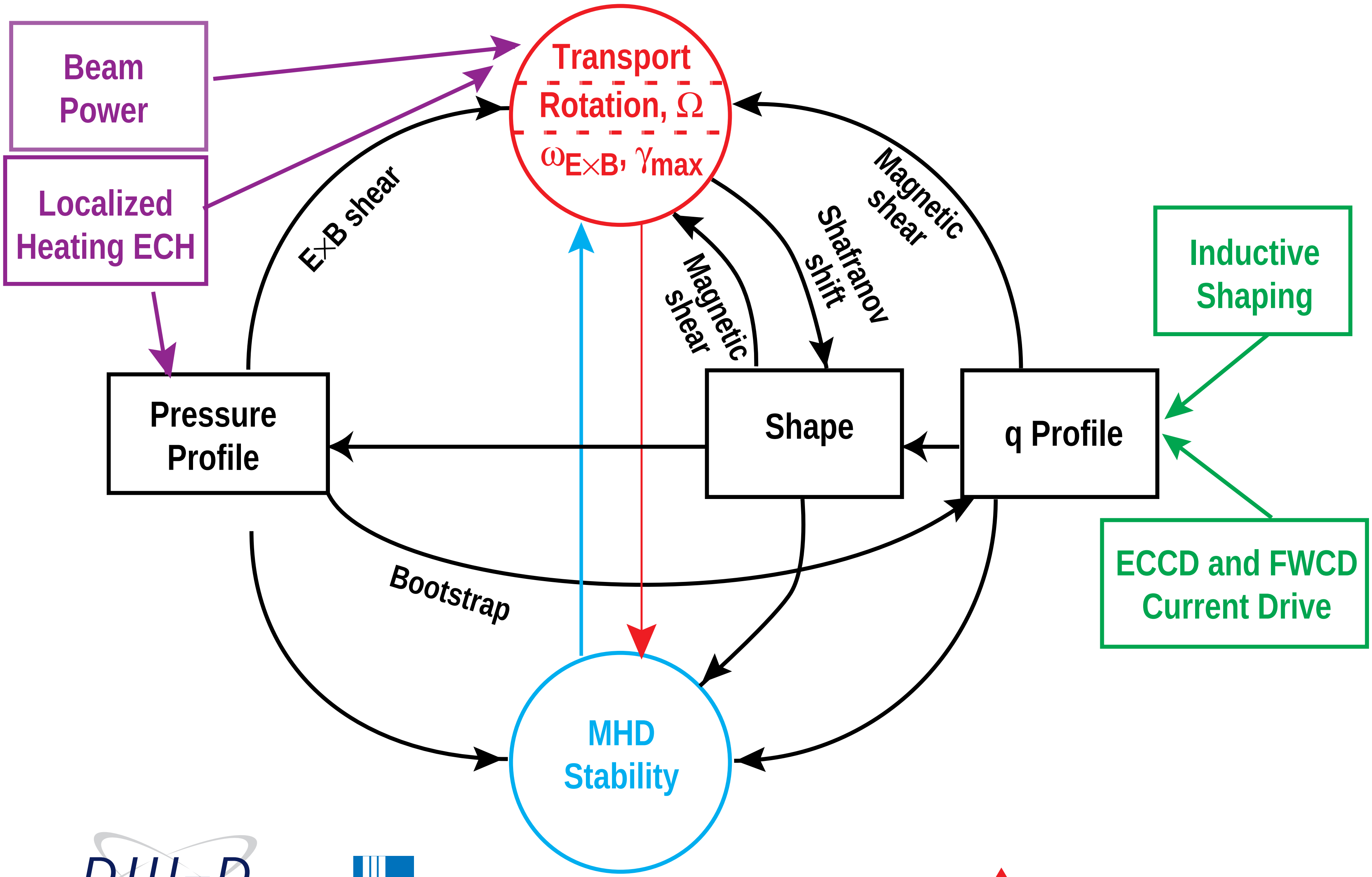
- Plasma shape
- Current density profile
  - ⇒ Localized current drive
- Pressure profile
  - ⇒ Localized heating for ITB
  - ⇒ $\Omega_{E\times B}$, poloidal rotation with RF
- Rotation profile, $E\times B$
- Density profile
- Radiation, impurity, profile
- Recombination, fueling source

ADVANCED TOKAMAK PROGRAM DEMANDS NEW RESEARCH PARADIGM

- Details of profiles are important
  - $q(\rho)$; $P'(\rho)$; $\Omega(\rho)$ or $\omega_{E\times B}$; $P(a)$, $J(a)$; turbulence, $\tilde{n}(\rho)$, $\tilde{T}(\rho)$
  - Geometry is important, plasma shape, divertor shape; interaction with profiles
  - Inherently 1 and 2 dimensional
  - Requires new profile diagnostics
  - Requires new analysis approaches, new analysis tools
- Self-consistency and simultaneity increase complexity
  - Strong, nonlinear interaction of many elements
    - ★ Current profile → transport → pressure profile → current profile
    - ★ Heating deposition → pressure profile → $\omega_{E\times B}$ → transport → pressure profile → current profile
    - ★ Strong coupling between pressure profile, plasma shape, wall stabilization and stability limit
    - ★ Divertor → SOL → pedestal → edge stability and core transport
  - Synergism among different physics must be fully explored
  - Demands more integrated experimental research program
  - Requires new analysis code capabilities — more “integrated” codes
- Fundamental physics theories are required to understand, lead the experiments, and provide predictive capability
  - Strong coupling between theory, modeling, and experiment

⇒ Increased challenge ⇒ exciting

THE CHALLENGE OF SELF-CONSISTENT PROFILES



Beam Power

Localized Heating ECH

Transport

Rotation, Ω

$\omega_{E\times B}$, γ_{max}

E×B shear

Magnetic shear

Shafranov shift

Magnetic shear

Inductive Shaping

Pressure Profile

Shape

q Profile

Bootstrap

ECCD and FWCD Current Drive

MHD Stability

FIGURES OF MERIT

Confinement enhancement	$H = \tau_E / \tau_E^{ITER-89P}$
Normalized beta	$\beta_N = \dfrac{B_T}{(I/aB)}$
Bootstrap fraction	$f_{BS} \propto \xi \sqrt{A}\, q\, \beta_N$
Fusion gain	$\dfrac{P_{fus}}{P_{loss}} \propto nT\,\tau \propto \beta_N\, H I^1\, B^3 \propto \dfrac{\beta_N\, H}{q^2}$
Steady state Q	$\dfrac{P_{fus}}{P_{CD}} \propto \dfrac{\gamma_{cur}\, \varepsilon_{eff}\, \beta_N\, B^3}{n\, q\, (1 - \xi \sqrt{A}\, q\beta_N)}$
Bootstrap alignment (Politzer)	$f_{align} = 1 - \dfrac{\int dv\, \frac{n_e}{T}\, \mathrm{abs}\,(J - J_{BS})}{\int dv\, \frac{n_e}{T}\, \mathrm{abs}\,(J)}$
Duration	$\tau_{DUR}/\tau_E \;; \qquad \tau_{DUR}/\tau_{CR}$

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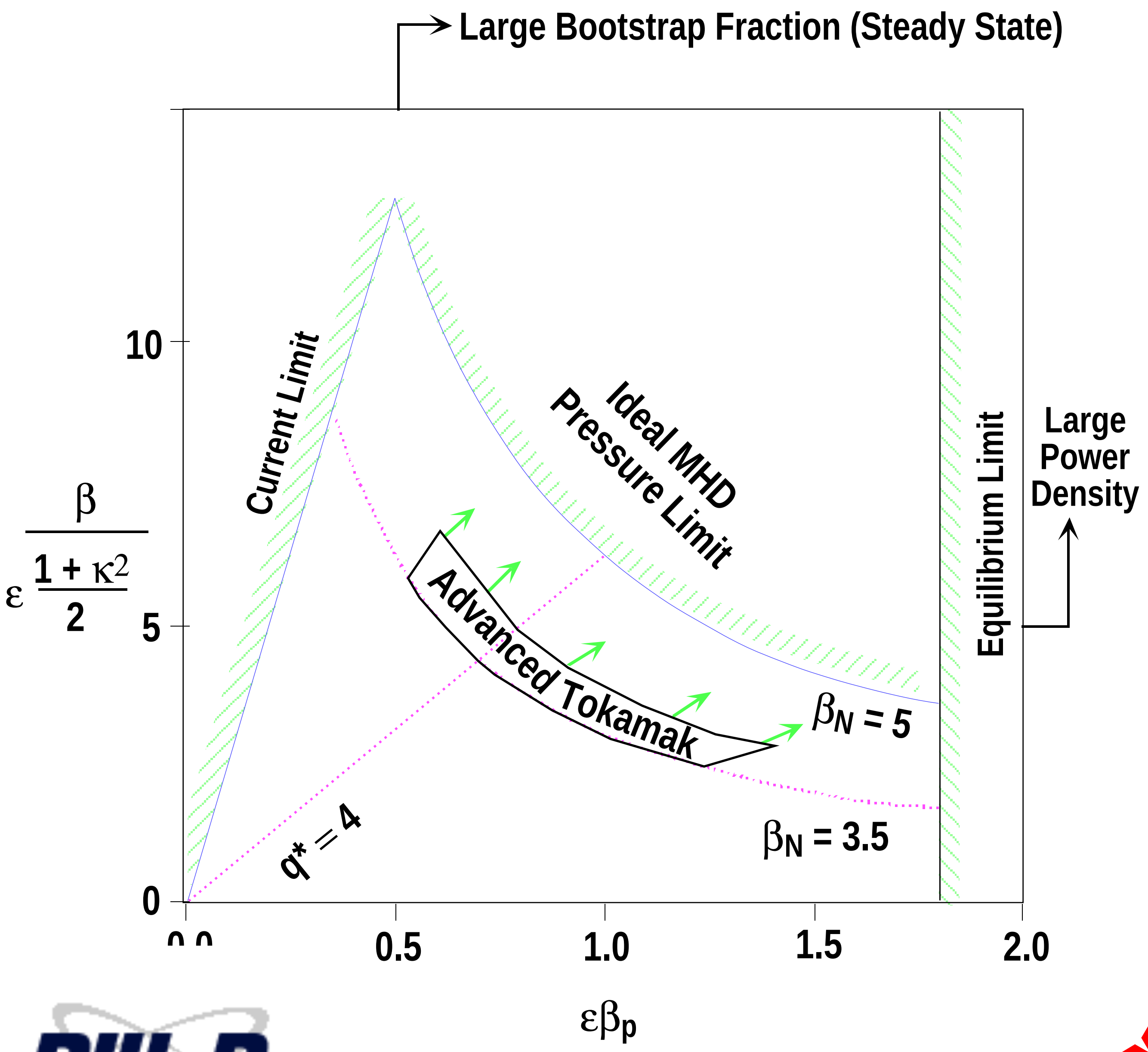
A COMPACT STEADY-STATE TOKAMAK REQUIRES OPERATION AT HIGH β_N



- High power density
  $\Rightarrow$ high β_T
- Steady state
  $\Rightarrow$ high I_B/I_p
  $\Rightarrow$ high β_p
- High β_T + high β_p
  $\Rightarrow$ high β_N

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

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

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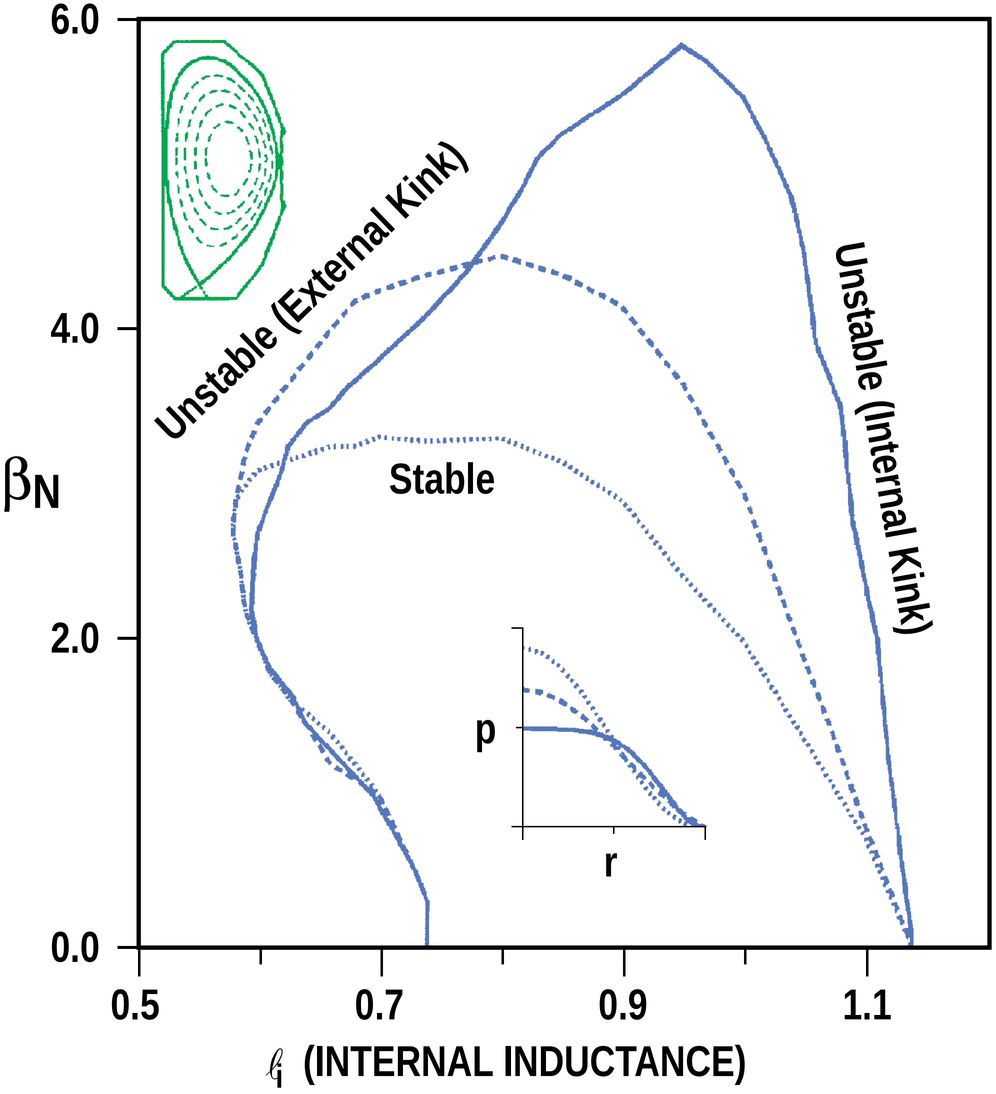
MODELING INDICATES PROFILE OPTIMIZATION AS A WAY TO INCREASE THE BETA LIMIT



(J.R. Ferron, Phys. Fluids B, 1990)

- **Beta limit sensitive to**
  - Current profile
  - Pressure profile
- **Inductively driven current constrains allowable current profiles (and possibly pressure profiles)**
- **Strong heating, fueling, current drive alters the constraints**
- **Implies two time scales**
  - Pressure profile relaxation → τ_E
  - Current profile relaxation

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HIGH PERFORMANCE DURATION IS A RELEVANT FIGURE OF MERIT

- Profiles impact the stability limit
  - Pressure profile
  - Current density profile

⇒ Two obvious time scales of interest to develop physics basis

- Pressure profile relaxation, τ_E
  - ★ Required to demonstraate self-consistency between transport, pressure profile, and stability limit
- Current profile relaxation, τ_{CR}

$$\tau_{CR} \sim 1\,4 a^2 K \frac{T_e^{3/2}}{Z_{eff}}$$

  - ★ Required to demonstraate self-consistency between pressure profile, current density profile, and stability limit

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THE DIII–D AT PROGRAM BALANCE — FOCUS

- The DIII–D program aims to develop the best possible operational scenario for fusion energy production
  - — Many opportunities to make improvements
  - — Many complex interdependencies ⇒ many possible advanced tokamak solutions

- A key to our approach to research.
  Maintain research attitude that is open to
  - — Evolving and improving knowledge base
  - — Innovations
  - — New discoveries
  - ⇒ Device flexibility
  - ⇒ Diagnostic capabilities
  - ⇒ Control capabilities

BUT,

- Focus sufficiently to test specific scenarios
  - — Indicated by the theory
  - — Identified potential for high performance + steady state
  - — Consistent with limited resources

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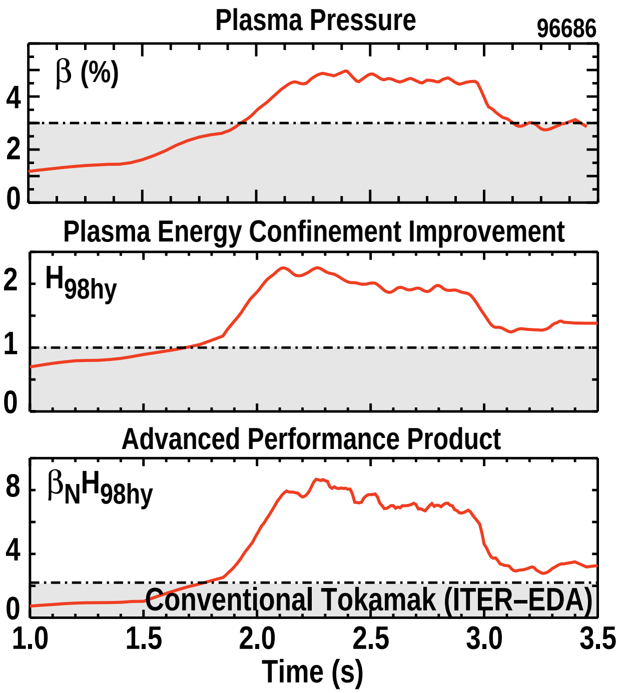
DIII–D 1998 RESEARCH HAS EXTENDED TOKAMAK PERFORMANCE AND DURATION



Plasma Parameters

I_p = 1.6 mega-amperes

B = 2 Tesla

q_{95} = 4.4

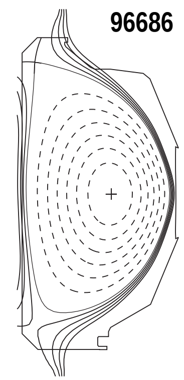
$T_i(0)$ = 10 keV

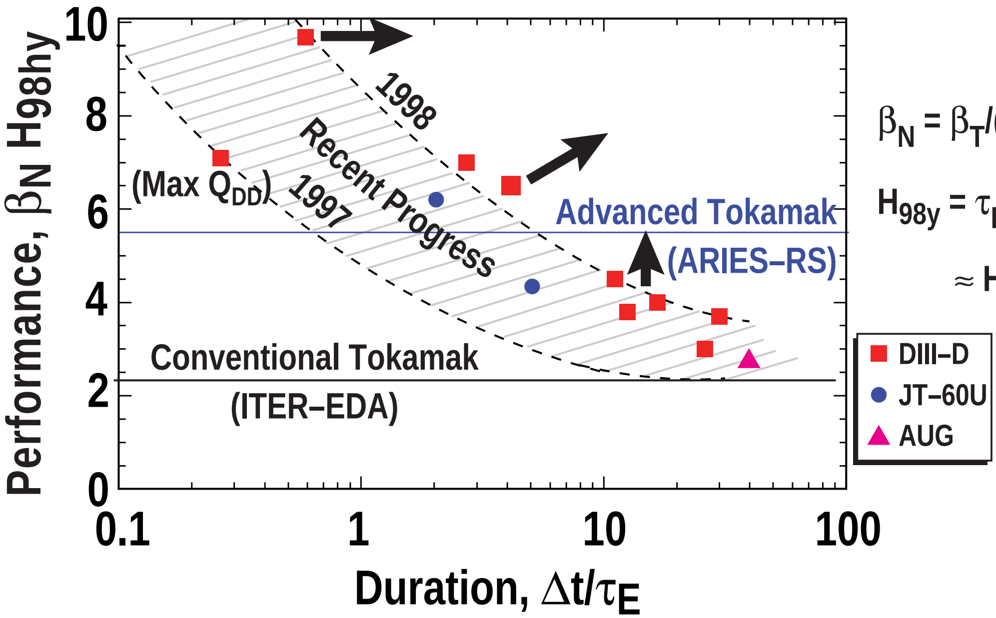
$T_e(0)$ = 6 keV

$n_e = 6.5 \times 10^{19}$ m^{-3}

τ_E = 0.21 seconds

DIII–D Plasma Shape





$\beta_N = \beta_T/(I/AB)$

$H_{98y} = \tau_E/\tau_E^{ITER98y}$

$\approx H_{89P}/1.7$

- AT duration limited by neoclassical tearing mode

WE HAVE IDENTIFIED FOUR ADVANCED TOKAMAK SCENARIOS THAT HAVE POTENTIAL FOR IMPROVED PERFORMANCE

- Negative central magnetic shear
- High internal inductance
- Radiative improved modes
  - Consistent with high ℓ_i
- GyroBohm scaling of ELMing H–mode to improved confinement
  - ρ_* scaling to ignition gives H > 3
  - Requires improvement of the β-limit (NTM)

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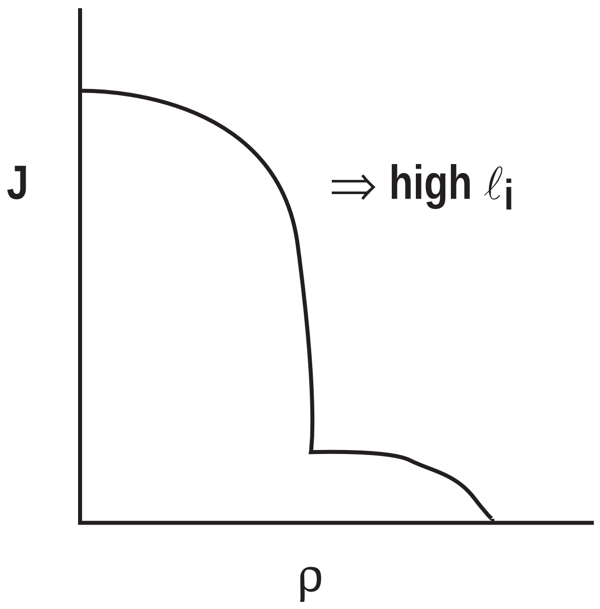
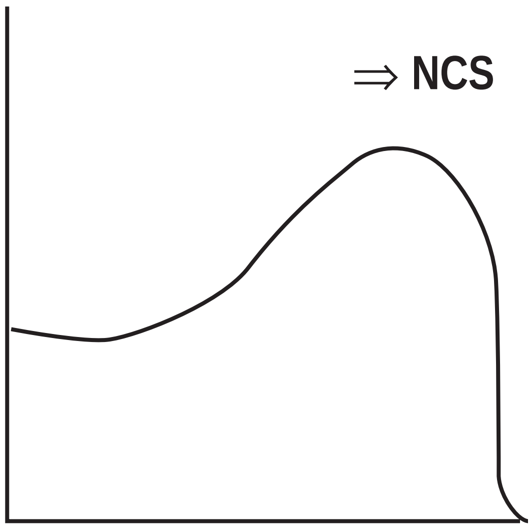
STEADY STATE CONSIDERATIONS ALSO LEAD TO TWO "NATURAL" CURRENT PROFILES

$$Q_{ss} = \frac{P_{fus}}{P_{CD}} \propto \frac{\gamma_{cur} P_{fus}}{nRI_{CD}} \propto \frac{\gamma_{cur} P_{fus}}{nRI\,(1 - J_{BS})}$$

High current drive



High bootstrap



IMPROVED PERFORMANCE CONSIDERATIONS LEAD TO THE IDENTIFICATION OF TWO AT SCENARIOS BASED ON THE CURRENT PROFILE

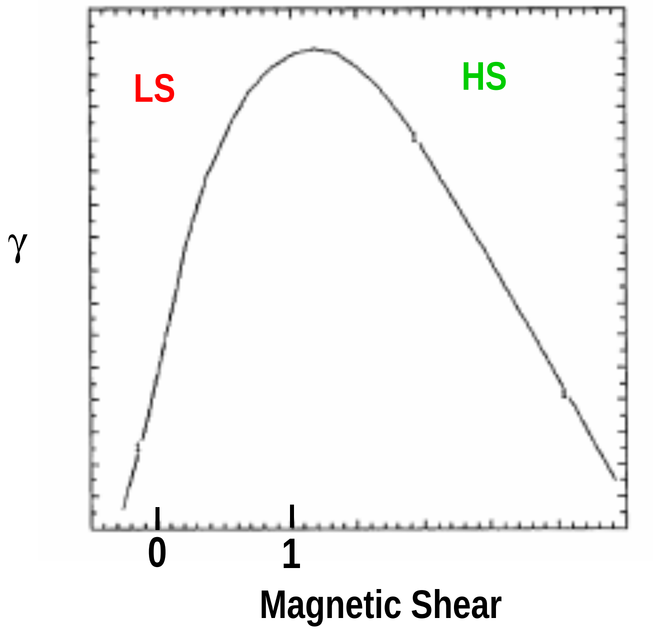
- High ℓ_i — high magnetic shear (HS) in the outer region of the plasma
- Negative central magnetic shear → low or negative shear (LS) in the plasma core

- **Motivated by theoretical considerations**

Both low magnetic shear (LS) and high shear (HS) are favorable for:

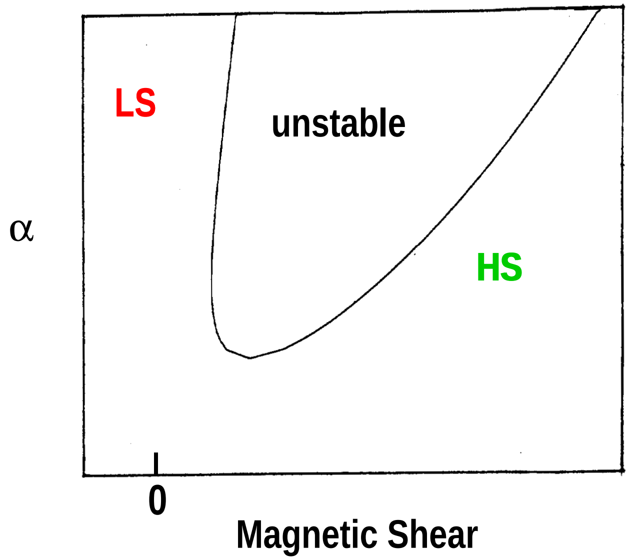
Reduced turbulence and Reduced transport

Growth rate of trapped particle modes

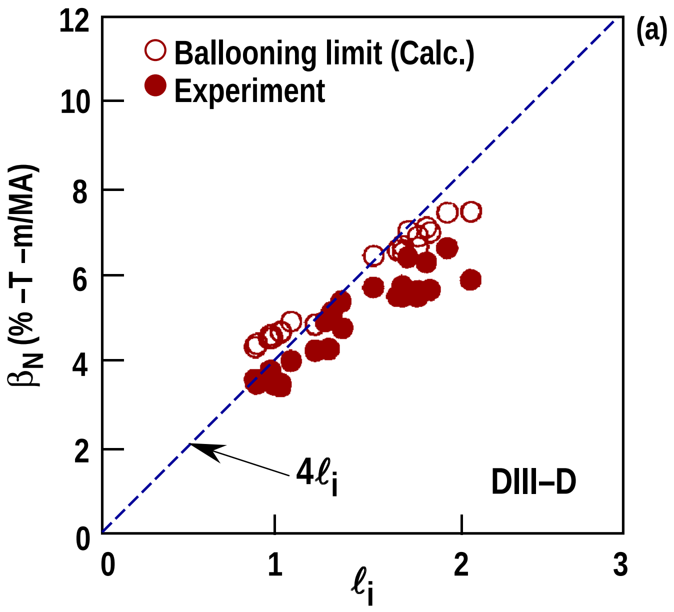


Higher Beta

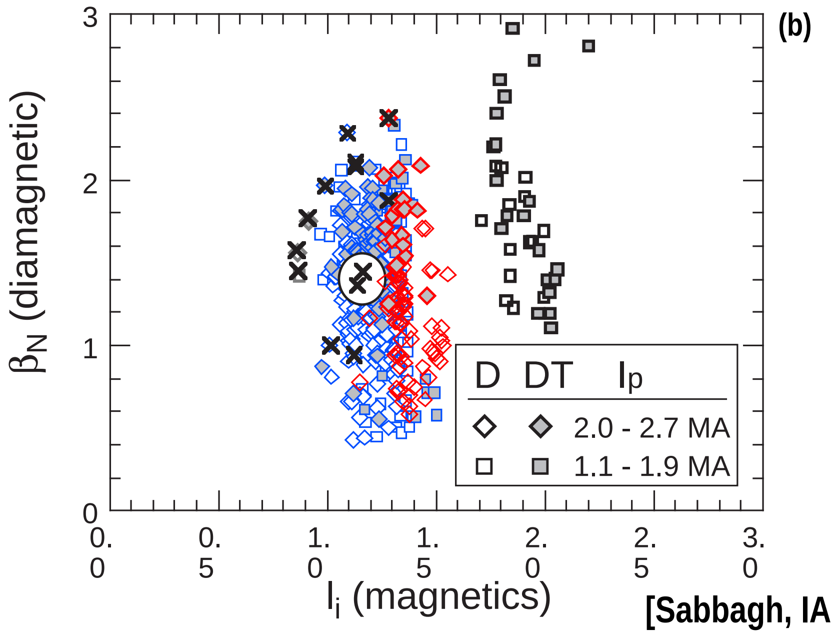
High n ballooning stability diagram



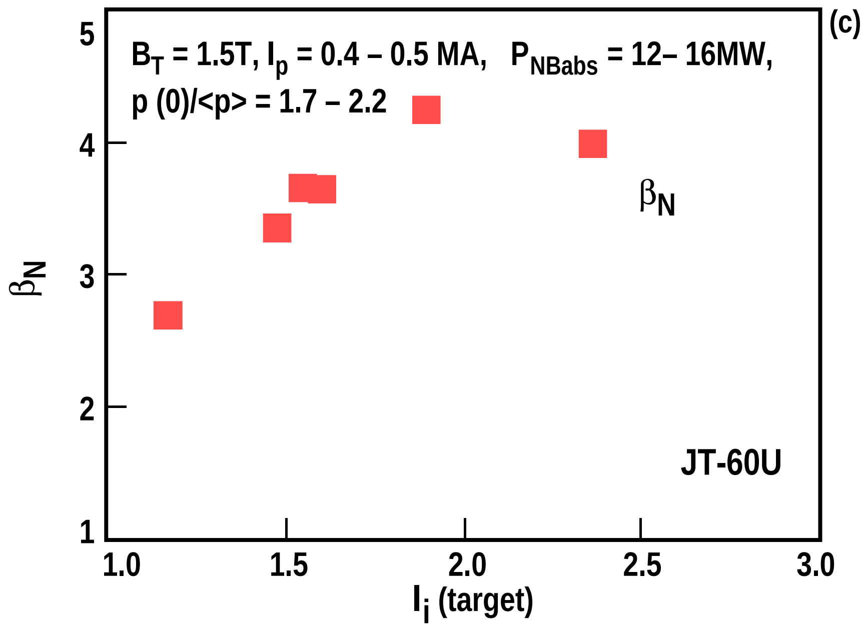
β_N INCREASES WITH INTERNAL INDUCTANCE, ℓ_i



[Ferron, Phys. Fluids B5, 2534, (1993)]



[Sabbagh, IAEA, Montreal, F1-CN-64/AP2-17]



[Kamada, Nucl. Fusion 34, 1603, (1994)]

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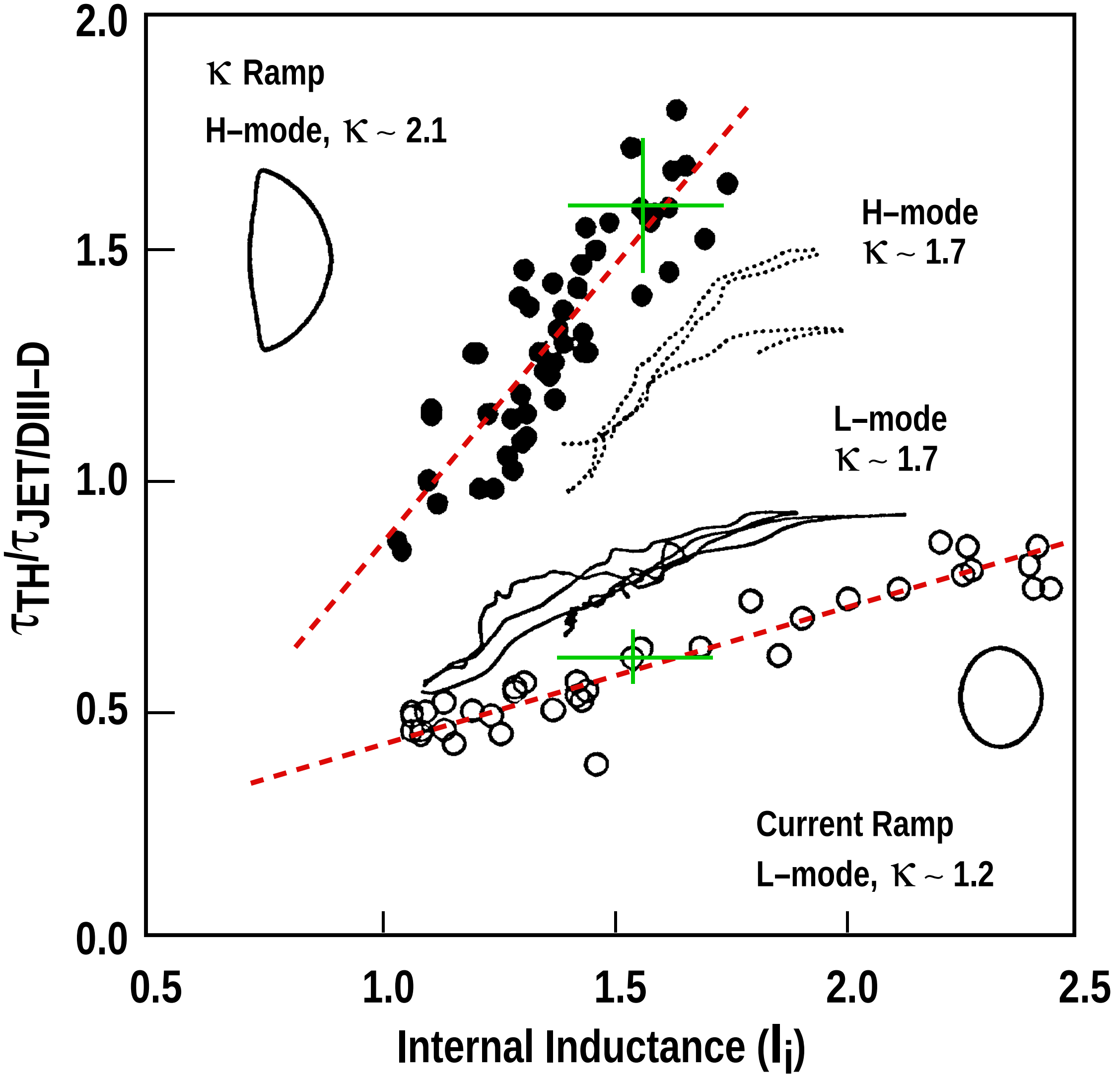
ENERGY CONFINEMENT INCREASES WITH PEAKING OF CURRENT DENSITY PROFILE



Ferron, Phys. Fluids B 5, 2534 (1993)

- $\tau_{JET/DIII-D} = 0.106\, P_L^{-0.46}\, I^{1.03}\, R^{1.48}$
- Confinement improvement with l_i observed in many experiments
  - TFTR [Zarnstorff, Phys. Fluid B 3, 2338, (1991)]
  - JET [Christiansen, Proc. 19th EPS Conf., Innsbruck, Austria, Vol. I, p. 13. (1992)]
  - Tore Supra [Hoang, ibid, p. 27]
  - JT–60U [Kamada,Nucl. Fusion 34 1605, (1994)]
- TFTR has obtained high fusion power in high l_i discharges (Sabbagh, IAEA, Montreal, F1-CN-64/AP2-17):
  - P_{Fus} = 8.7 MW
  - ℓ_i = 1.4
  - I_p / B_T = 2.0 MA, 4.8 T

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INCREASING H AND β_N WITH ℓ_i SUGGEST AN ATTRACTIVE ADVANCED TOKAMAK SCENARIO

Advantages

- Ease of central current drive
- High β_N, high H observed on many experiments
- No power threshold
- Compatibility with ELMing H–mode, radiative I–mode

Limitation

- Alignment of bootstrap current:

High ℓ_i

⇒ Low edge J, high $\hat{S}_n$

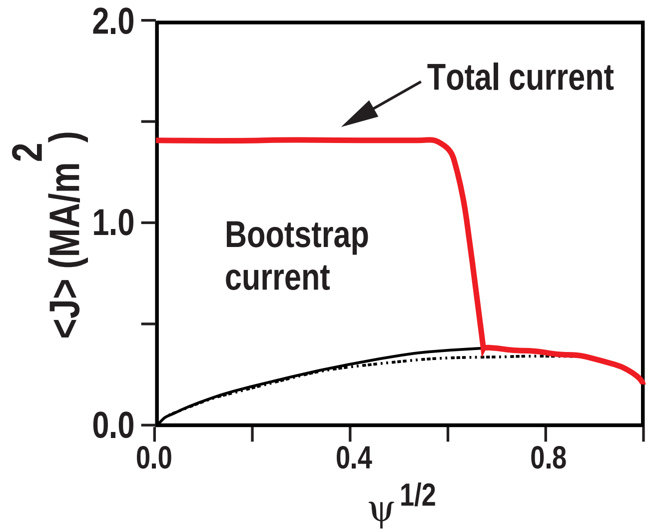
⇒ Reduced edge transport

⇒ High edge p'

⇒ High edge bootstrap

★ High edge J

Challenge: Self-Consistent High β, High ℓ_i Scenario



$q_o = 1.05$

$\ell_i = 1.2$

$q_{95} \sim 8$

$I_{BS}/I_p \sim 50\%–60\%$

$\beta_N \sim 4$

H ~ 2–3

⇒ ⇒ ⇒

with sawtooth stabilization

$q_o = 0.55$

$\ell_i = 1.4–1.6$

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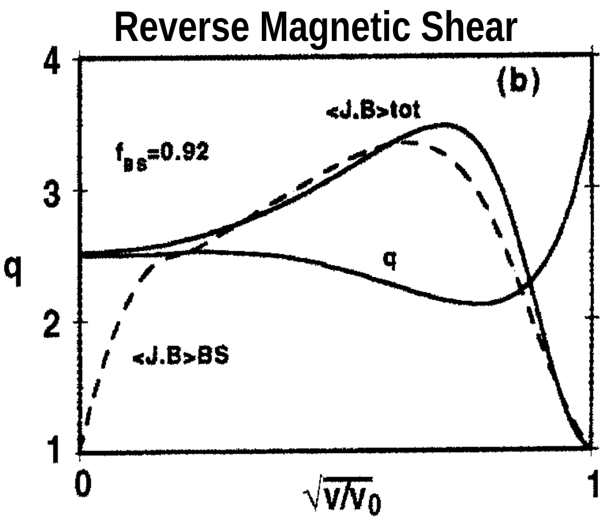
NEGATIVE CENTRAL MAGNETIC SHEAR (NCS) SCENARIO IS BEING PURSUED BY DIII–D AS STEADY-STATE HIGH PERFORMANCE ADVANCED TOKAMAK (AT) SCENARIO

- Reduced current drive requirements with aligned bootstrap is predicted
  - Ozeki et al., Nucl. Fusion 33, 1025 (1993)
  - Kessel, Phys. Rev. Lett. 72, 1212 (1994)
  - Manickam, Phys. Plasma 1, 1601 (1994)
  - Turnbull, Phys. Rev. Lett. 74, 718 (1995)
- Improved performance observed experimentally
  - Reduced core transport observed in a number of experiments
  - Highest performance in DIII–D is in NCS with H–mode edge
- Great progress in understanding the ion transport in internal transport barriers
  - $\omega_{E\times B} > \gamma_{LIN}$
  - $\chi \sim \chi_{Neo}$ $\quad 0 < \rho < 1$
- Challenges remain in understanding electron thermal transport



- Current profile control and transport barrier control is needed to increase duration
- Broad pressure profiles and wall stabilization are needed for improved stability

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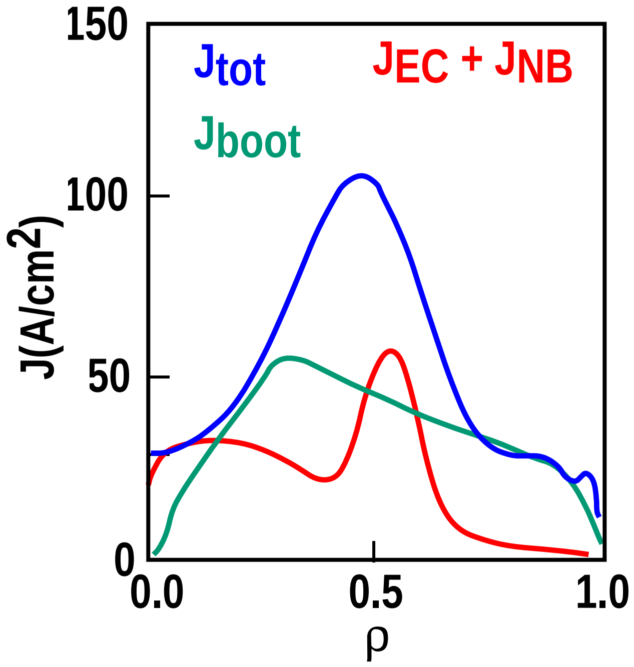
SELF-CONSISTENT SIMULATIONS INDICATE DESIRED CURRENT DENSITY PROFILE CAN BE OBTAINED WITH OFF-AXIS ECCD

— Extended duration —

$\beta_N = 4$, H = 2.8

$I_p = 1.0$ MA, $\overline{n}_e = 3.2 \times 10^{19}$

$P_{EC} = 2.3$ MW, $I_{EC} = 0.15$ MA

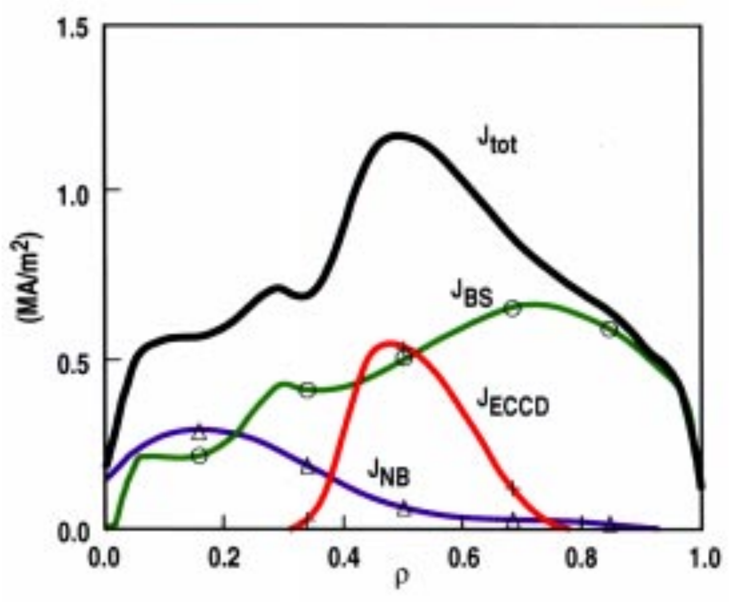


— Fully penetrated profiles —

$\beta_N = 5.7$, H = 3.6

$I_p = 1.6$ MA, $\overline{n}_e = 5.7 \times 10^{19}$

$P_{EC} = 7$ MW, $I_{EC} = 0.32$ MA



KEY CHALLENGE FOR NCS SCENARIO

⇒ Consistency of resulting pressure profile in discharges with transport barriers with stability at high beta

Steep pressure gradients at ITB or at the boundary can lead to instability at low beta

⇒ Develop scenarios that have "naturally" favorable profiles

- Requires fundamental understanding of ITB, and stability boundaries
- Magnetic shear has an input

or

⇒ Develop transport barrier control techniques

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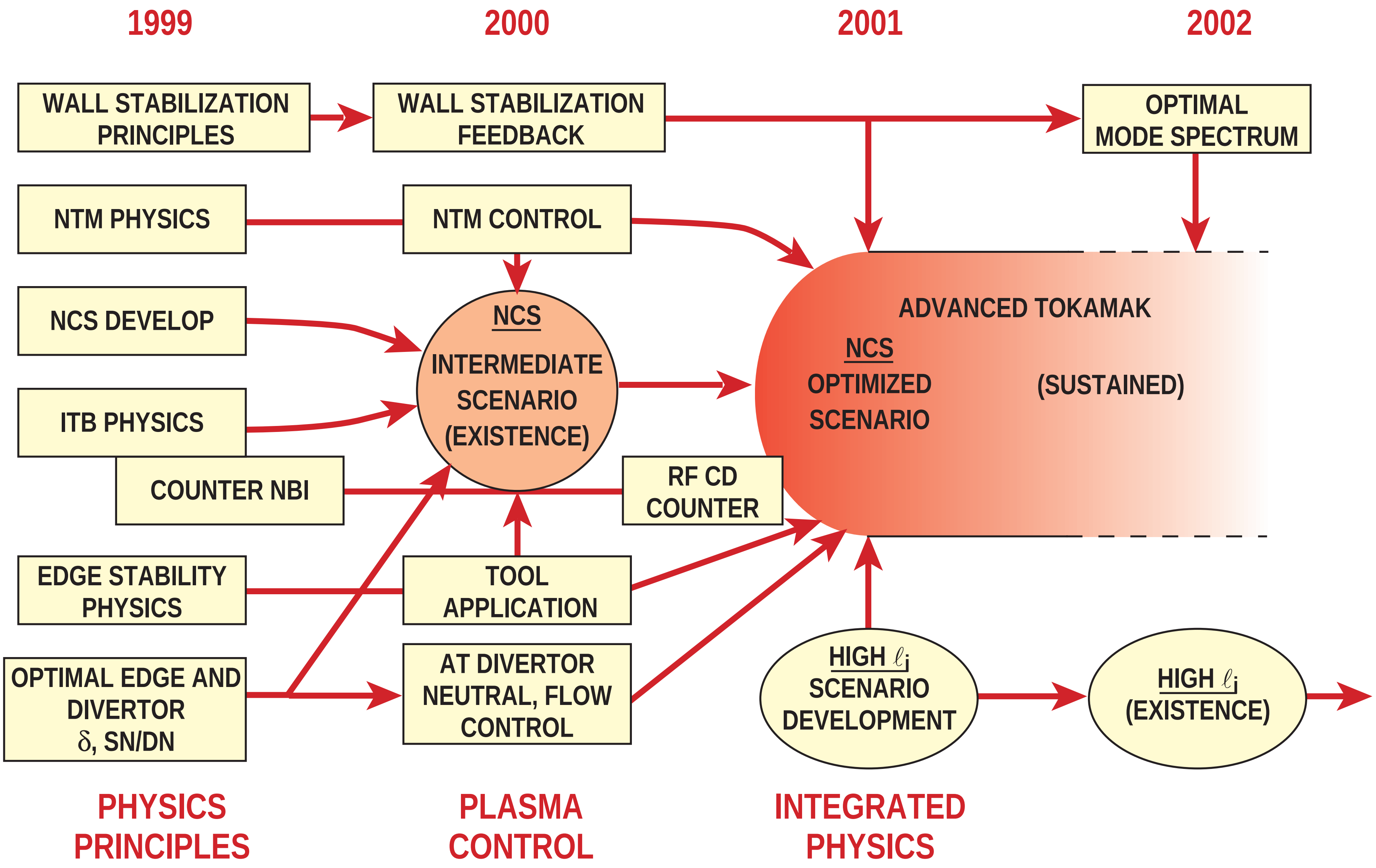
PHYSICS UNDERSTANDING DRIVES DIII–D AT RESEARCH PLAN



1999

2000

2001

2002

WALL STABILIZATION PRINCIPLES

WALL STABILIZATION FEEDBACK

OPTIMAL MODE SPECTRUM

NTM PHYSICS

NTM CONTROL

NCS DEVELOP

ITB PHYSICS

COUNTER NBI

NCS

INTERMEDIATE SCENARIO (EXISTENCE)

ADVANCED TOKAMAK

NCS

OPTIMIZED SCENARIO

(SUSTAINED)

RF CD COUNTER

EDGE STABILITY PHYSICS

TOOL APPLICATION

OPTIMAL EDGE AND DIVERTOR δ, SN/DN

AT DIVERTOR NEUTRAL, FLOW CONTROL

HIGH ℓ_i

SCENARIO DEVELOPMENT

HIGH ℓ_i

(EXISTENCE)

PHYSICS PRINCIPLES

PLASMA CONTROL

INTEGRATED PHYSICS

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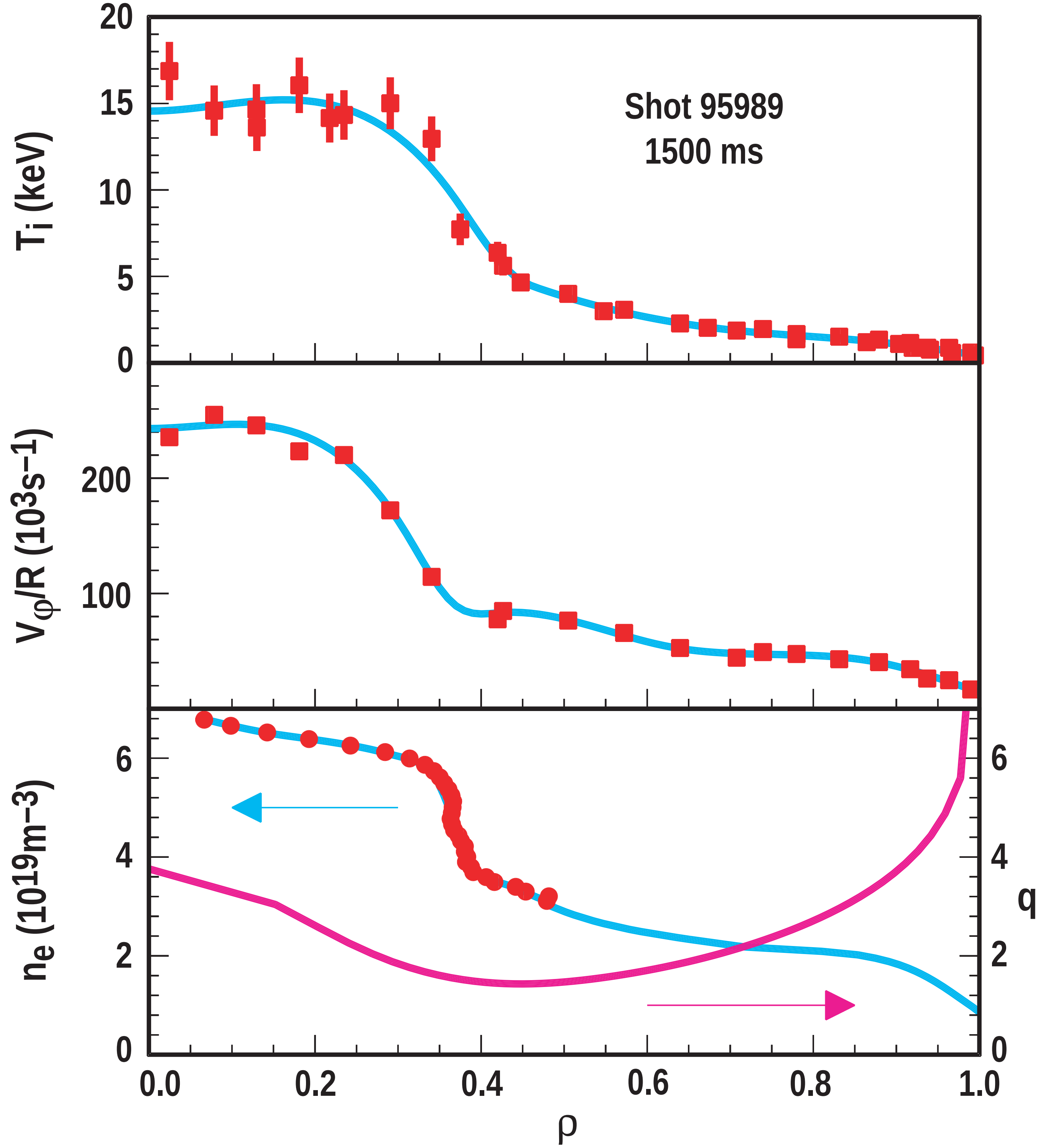
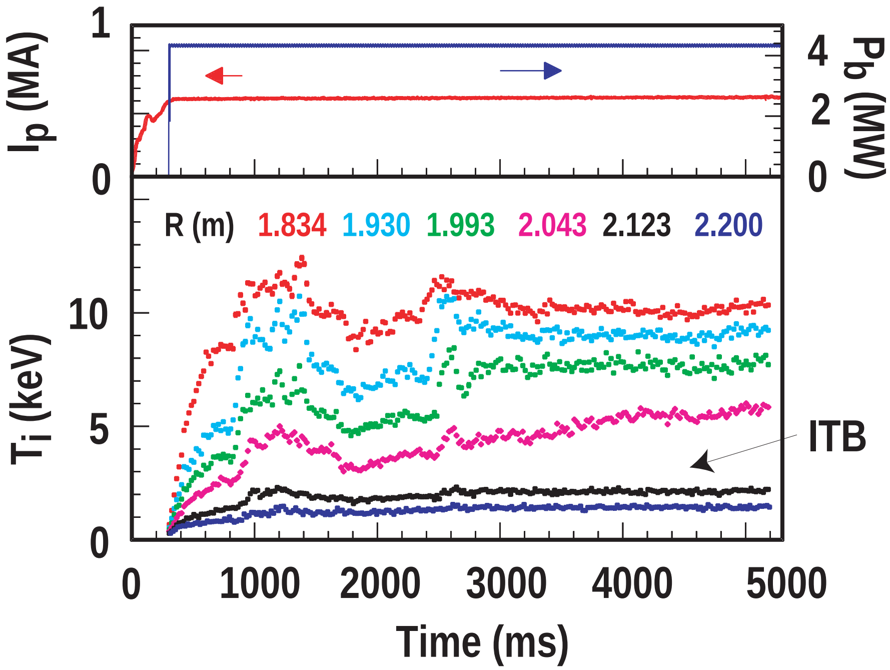
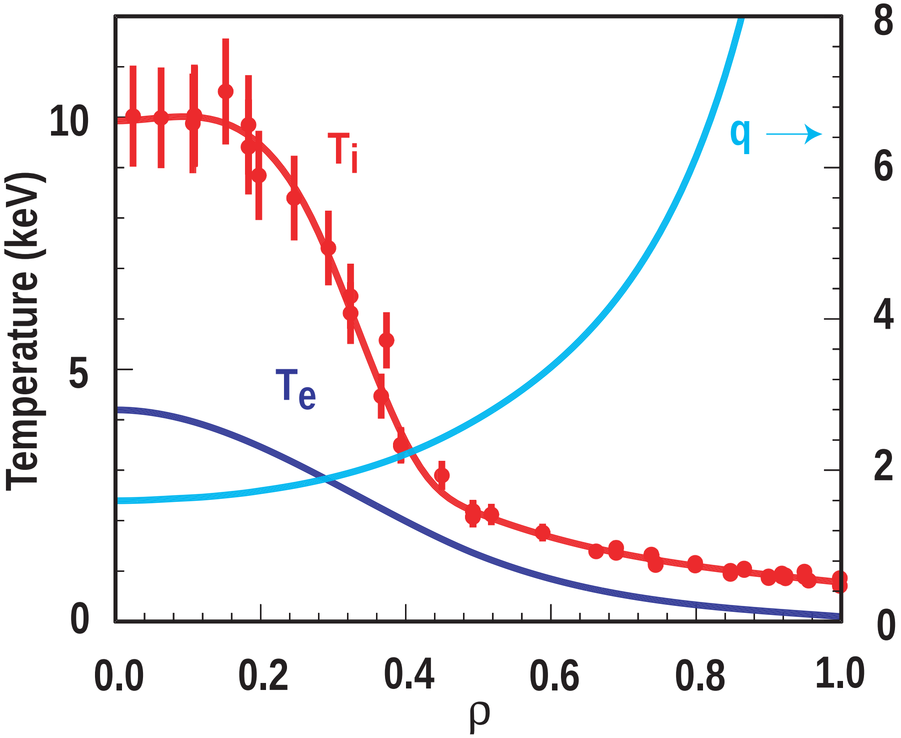
STEEPEST CORE GRADIENTS FORM IN SHOTS WITH NEGATIVE MAGNETIC SHEAR



INTERNAL TRANSPORT BARRIER (ITB) HAS BEEN SUSTAINED FOR ~5 s IN DIII–D L–MODE DISCHARGES

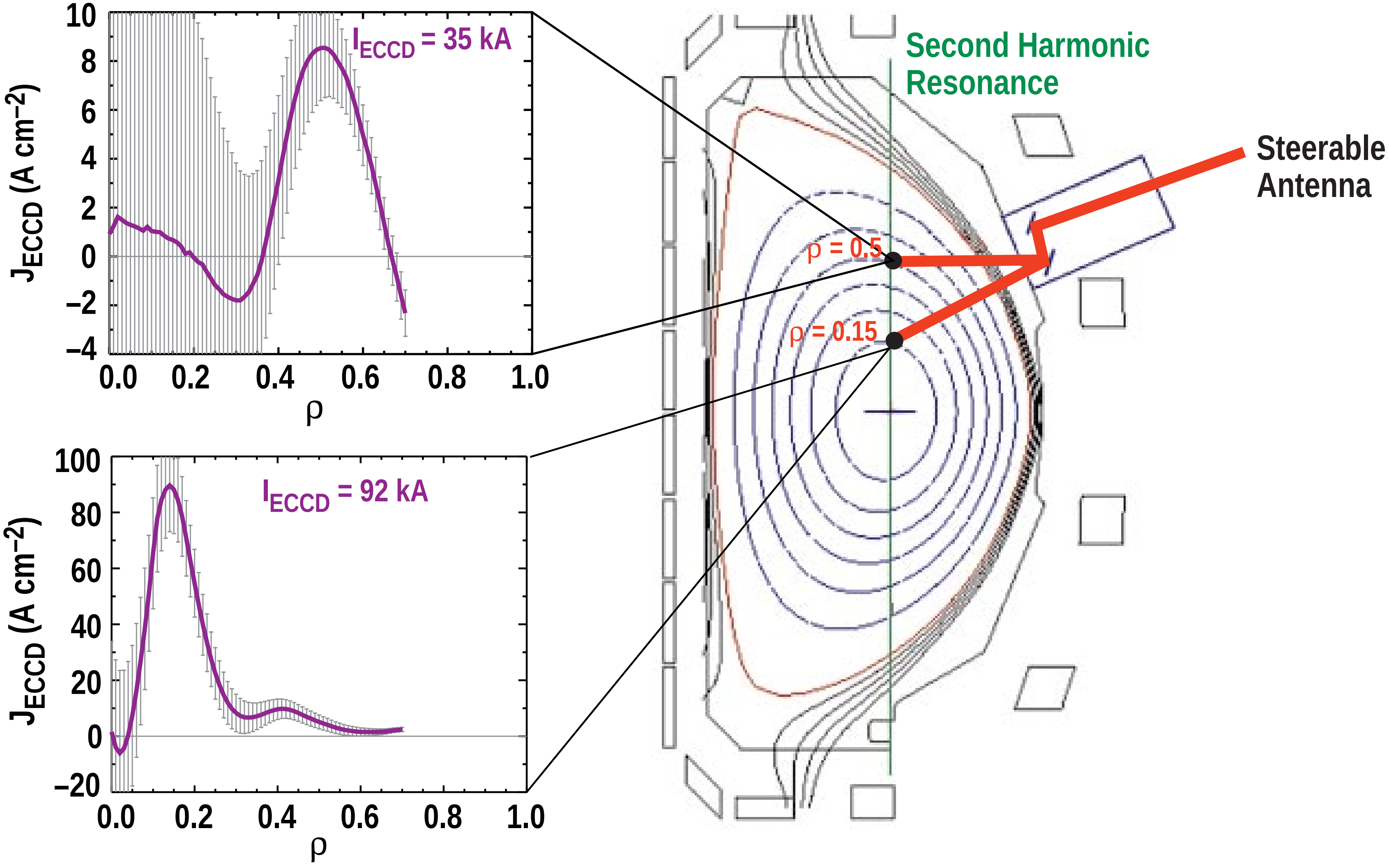
- Fully penetrated current, profile with weak central magnetic shear and q > 1
- BES shows suppression of turbulence $\rho \lesssim 0.4$
- Key to long-pulse ITB is sustainment of the current profile





IAEA-F-CN-69 EX5/6 Synakowski

MICROWAVE ELECTRON CYCLOTRON HEATING PROVIDES LOCALIZED CURRENT DRIVE



DIII–D
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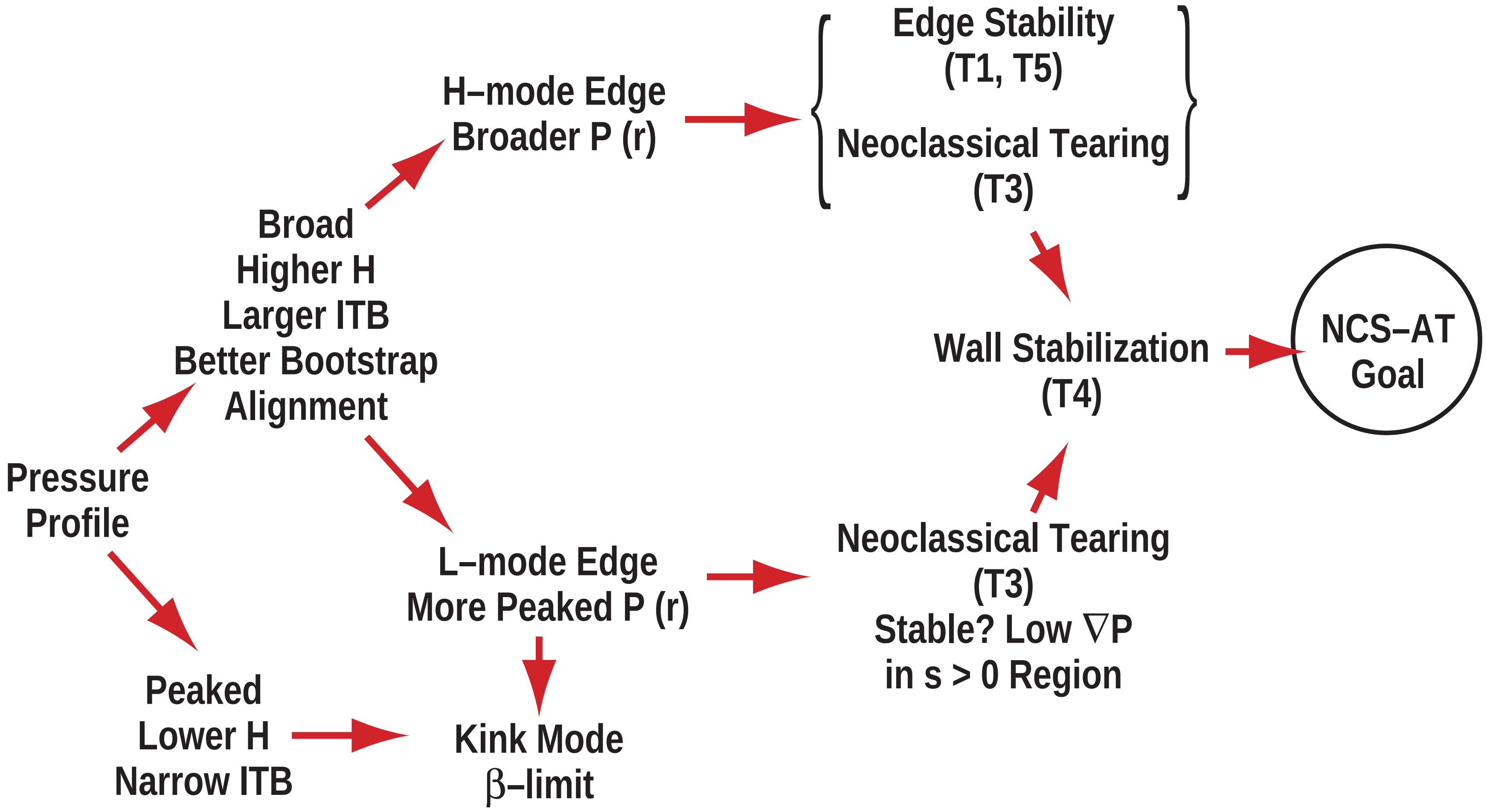
NCS DISCHARGES CAN BE FURTHER CATEGORIZED BY THE EDGE CONDITION

	L–Mode Edge	ELMing H–Mode Edge	ELM-Free H–Mode Edge
Advantages	● Low p' edge ● Large SOL ● Neoclassical transport in core ● Good beam penetration	● Steady-state edge ● ELMs purge impurities ● Cryopump can control density	● Highest $\beta_N H$ product ● Neoclassical χ_i over entire radius ● Better bootstrap alingment ● High performance even with $T_i \sim T_e$
Present Limitations/Status	● H ~ 2.3, β_N ~ 2.3 ● Low beta limit ● Misaligned bootstrap current ● Small core volume ● Control of q_{min}	● H ~ 2.4, β_N ~ 2.8 ● Difficult to establish ITB ● Type I ELM perturbations are too large ● Neoclassical tearing modes	● Little control over edge density, p' and J_{bs} ⇒ peeling modes ● Carbon impurity accumulation at edge ● Pump ineffective for density control
Research Effort/Directions	● Expand radius of q_{min} ● Control core p' using RF ● Use ECH to slow current diffusion	● Reduce edge 2nd stability access and ELM size by varying shape (squareness) ● Sustain ELMing H–mode during I_p ramp for additional profile control	● Change edge collisionality to reduce J_{bs} ● Trigger ELMs prior to X-event (Global MHD event) using pellets or other?

THE PATH TO THE NCS–AT GOAL LEADS THROUGH MANY STABILITY ISSUES



Pressure
Profile

Broad
Higher H
Larger ITB
Better Bootstrap
Alignment

H–mode Edge
Broader P (r)

Edge Stability
(T1, T5)

Neoclassical Tearing
(T3)

Wall Stabilization
(T4)

NCS–AT
Goal

Peaked
Lower H
Narrow ITB

L–mode Edge
More Peaked P (r)

Kink Mode
β–limit

Neoclassical Tearing
(T3)
Stable? Low ∇P
in s > 0 Region

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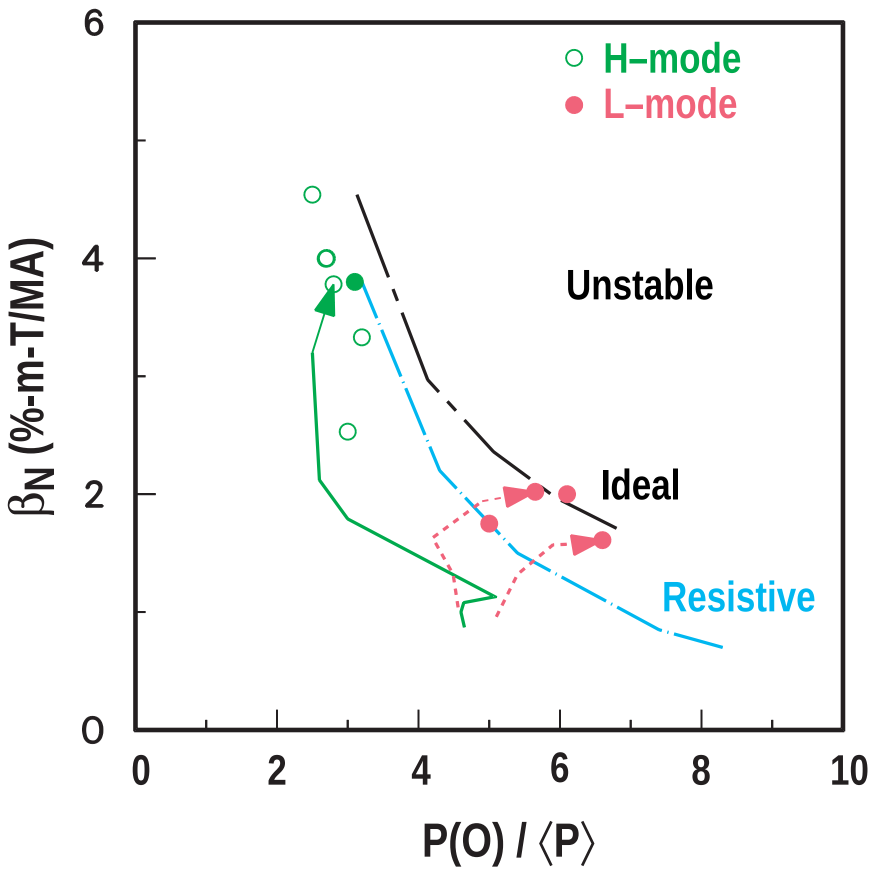
EXPERIMENTAL β LIMITS CONSISTENT WITH CALCULATED DEPENDENCE ON $p_o/\langle p\rangle$

- DIII–D high $p_o/\langle p\rangle$ ~ 6.0 (L–mode):
  $\beta_N \lesssim 2.5$
  - Limited by fast n = 1 disruption
- TFTR high $p_o/\langle p\rangle$ ~ 6.0 (ERS–mode):
  $\beta_N \lesssim 2$
  - Limited by fast n = 1 disruption
- DIII–D low $p_o/\langle p\rangle$ ~ 1.5 (H–mode):
  $\beta_N \lesssim 4$
  - No disruption
    limited by ELM-like activity from
    finite edge pressure gradients



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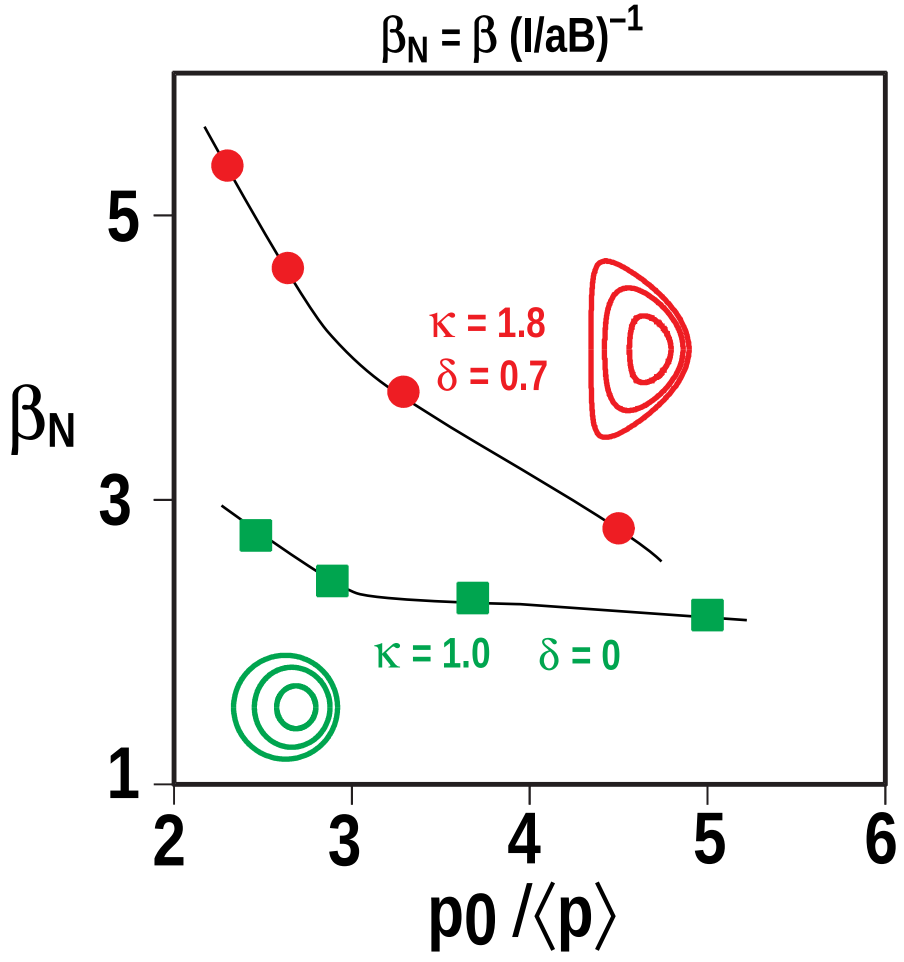
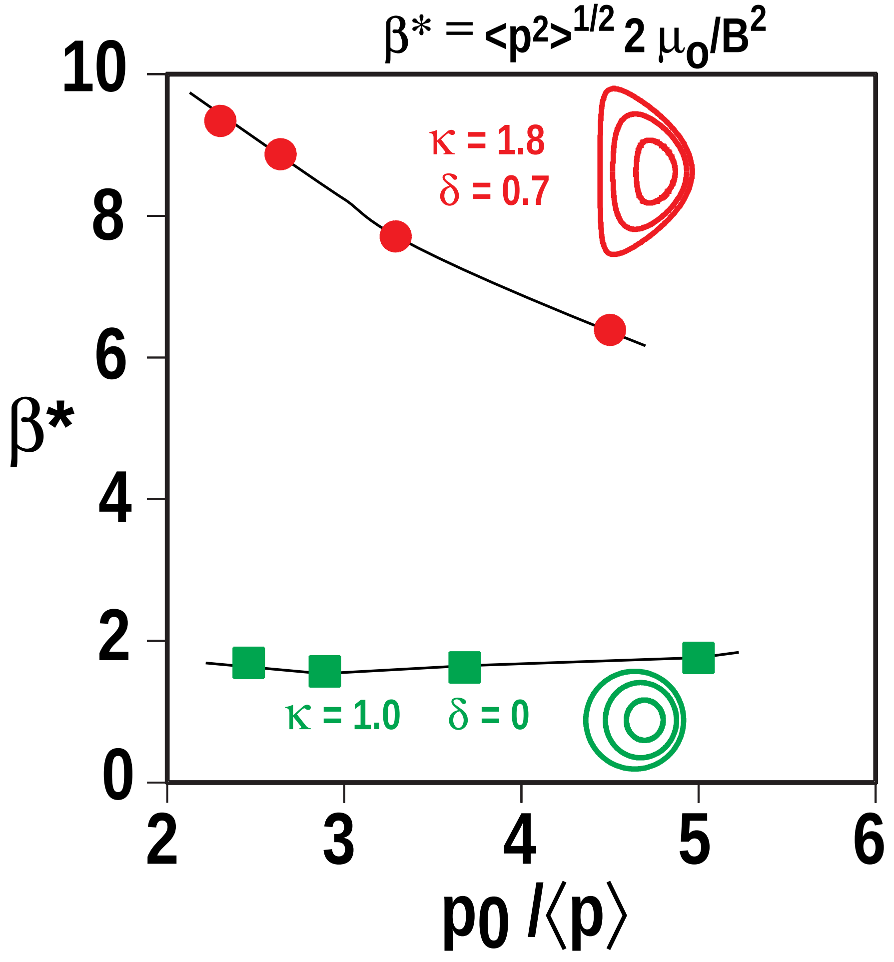
HIGH BETA REQUIRES BOTH BROAD PRESSURE AND STRONG SHAPING

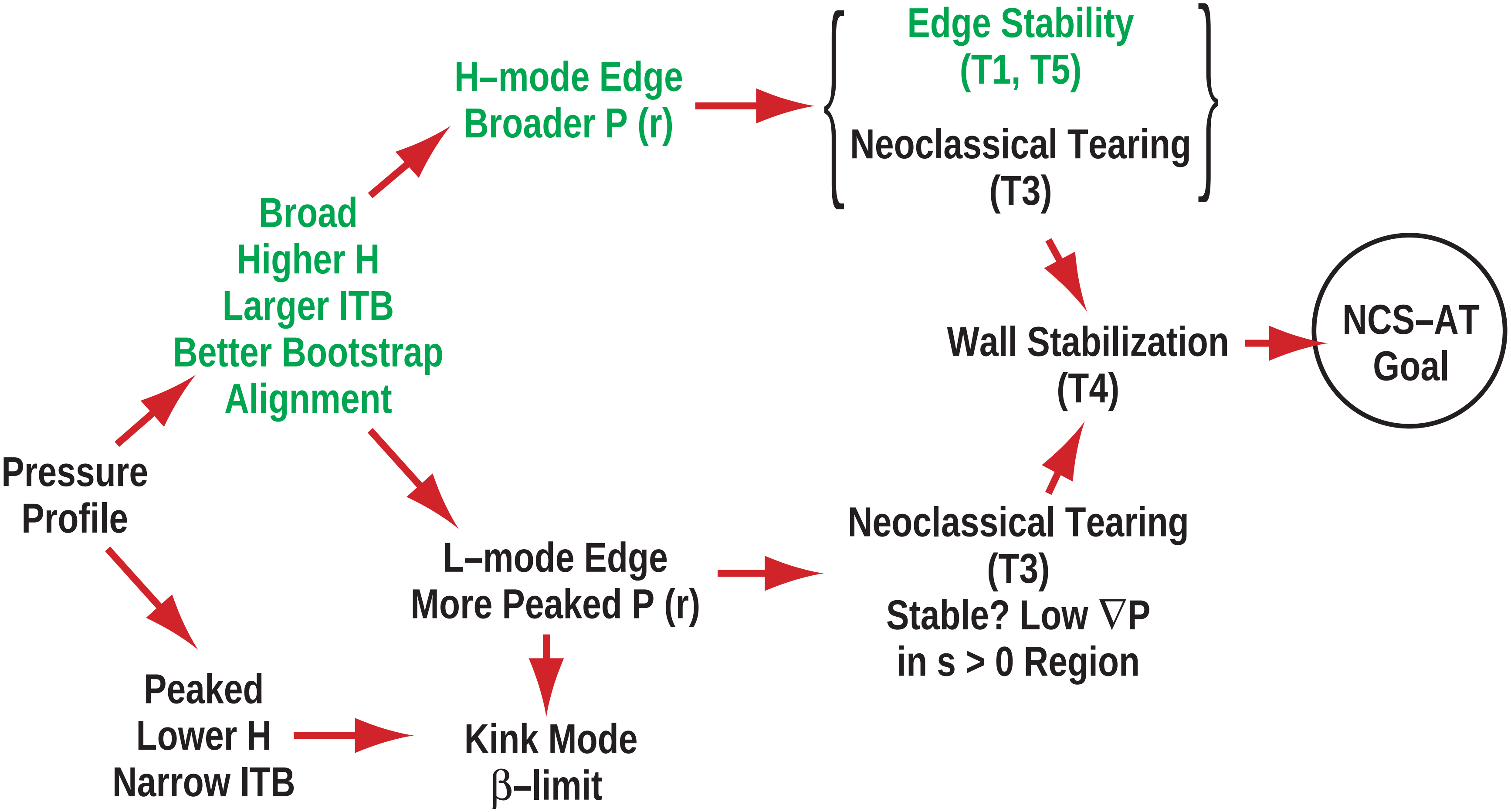
- Calculated ideal $n = 1$ stability limit, wall at $r/a = 1.5$
- Fixed q profile: $q_0 = 3.9$, $q_{min} = 2.1$, $q_{95} = 5.1$





[A. Turnbull, IAEA 1996]

THE PATH TO THE NCS–AT GOAL LEADS THROUGH MANY STABILITY ISSUES



Pressure
Profile

Broad
Higher H
Larger ITB
Better Bootstrap
Alignment

H–mode Edge
Broader P (r)

Edge Stability
(T1, T5)

Neoclassical Tearing
(T3)

Wall Stabilization
(T4)

NCS–AT
Goal

Peaked
Lower H
Narrow ITB

L–mode Edge
More Peaked P (r)

Kink Mode
β–limit

Neoclassical Tearing
(T3)
Stable? Low ∇P
in s > 0 Region

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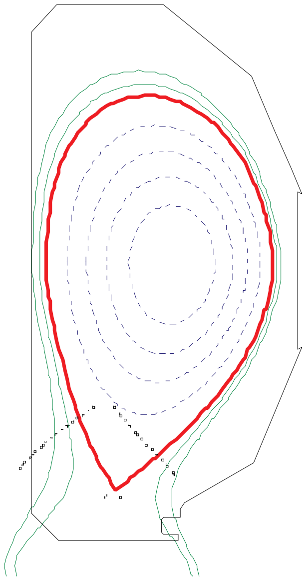
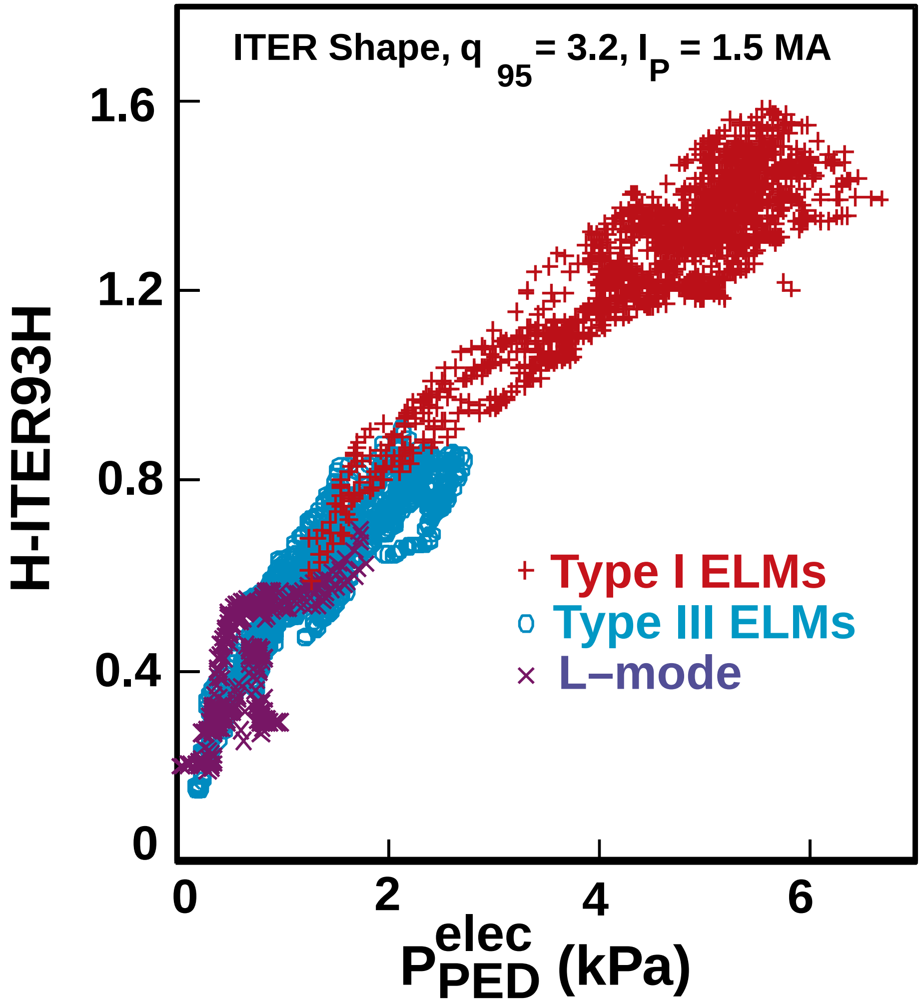
ENERGY CONFINEMENT TIME INCREASES WITH THE PEDESTAL PRESSURE IN DIII–D ELMing H–MODES



ITER SHAPE
(fixed)
$\delta = 0.24$
$\kappa = 1.75$
$\varepsilon = 0.34$



- For fixed shape $H \propto \beta_{PED}^{1/2}$
- "Stiff" transport models predict τ_E increasing with P_{PED}

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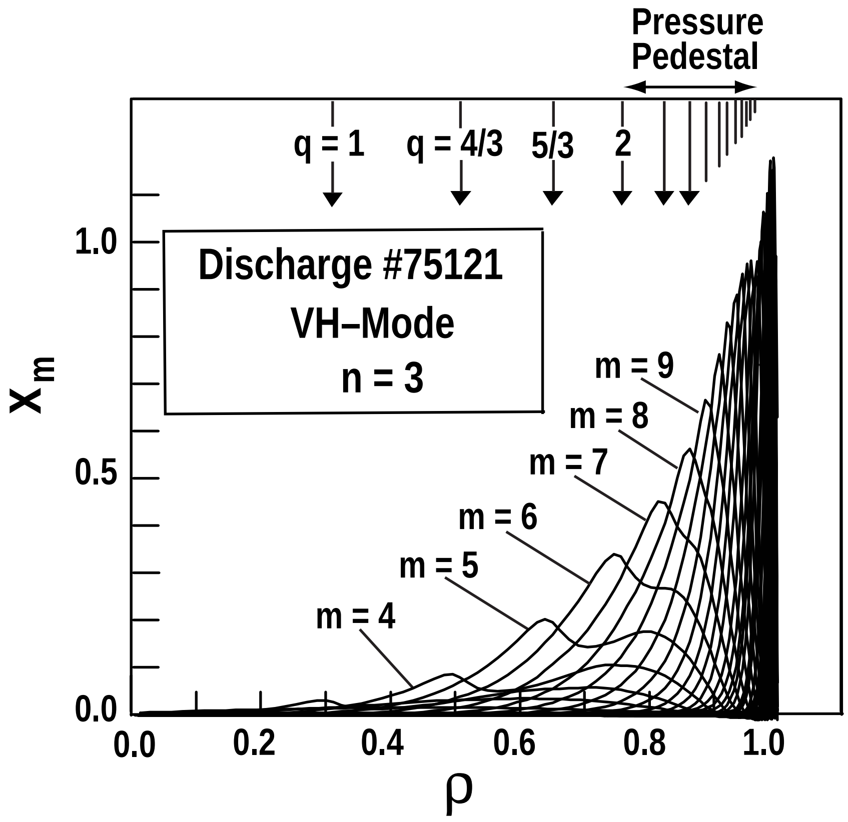
GENERAL ATOMICS

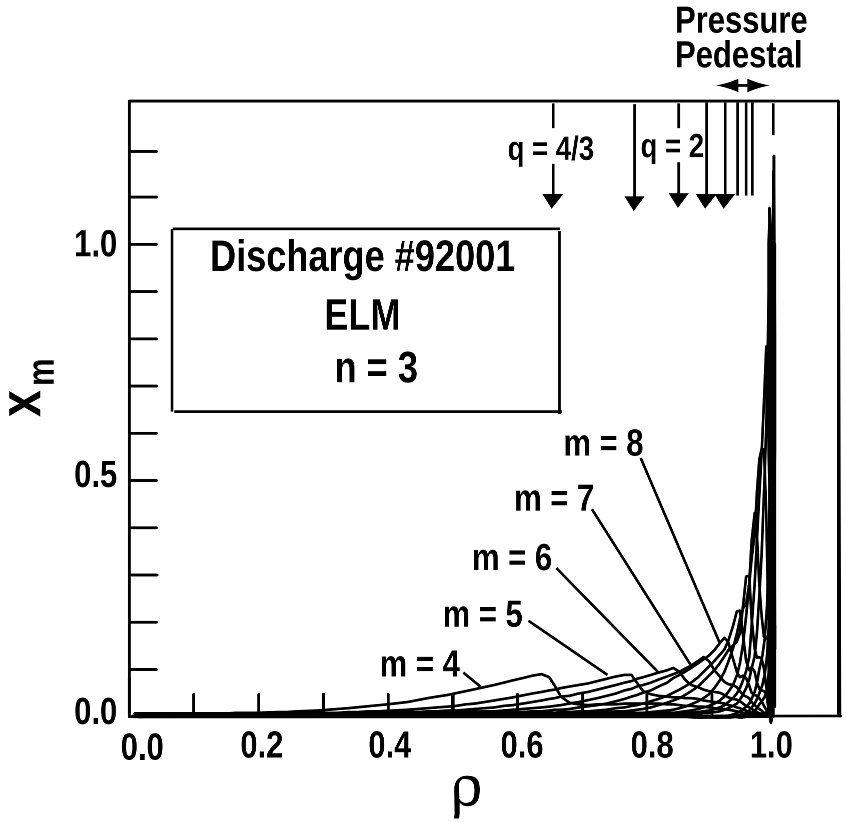
WIDTH OF THE EDGE MODE IS LARGER WITH A LARGER PRESSURE PEDESTAL

GATO CALCULATIONS

- VH–mode ($\beta_N = 3$): termination



- H–mode ($\beta_N = 2$): ELM



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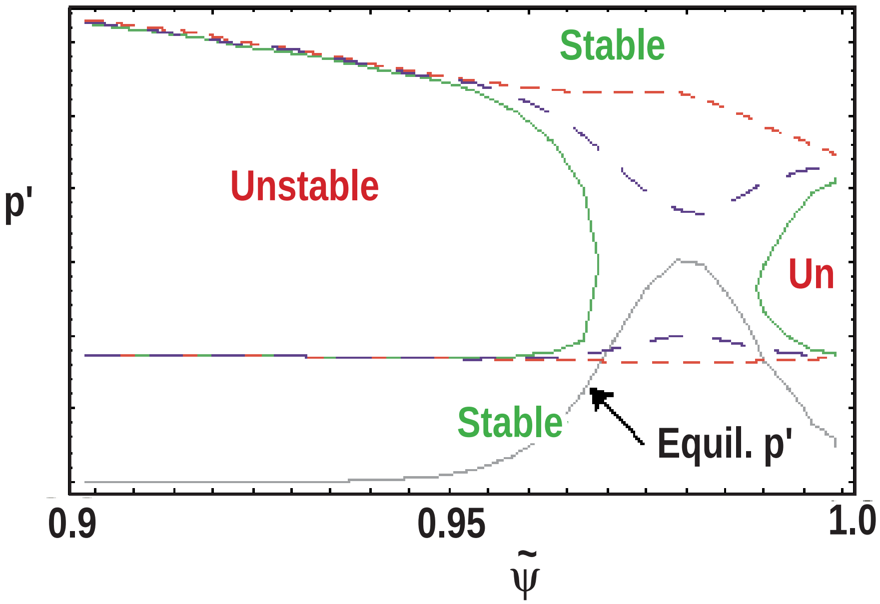
EMERGING EDGE STABILITY PICTURE SUGGESTS NEED TO REGULATE THE EDGE BOOTSTRAP CURRENT AND/OR THE EDGE PRESSURE GRADIENT TO EXTEND THE DURATION OF AT MODES (T1)

- Need ELMs to provide density and impurity control
- But, most of our high performance discharges are terminated by an ELM that **couples** to low–n modes, causing a drop in plasma confinement



Reference Equilibrium:
$\kappa = 1.8$, $\delta = 0.3$, A = 170/65, $\psi_{ped} = 0.98$, $\psi_{wid} = 0.0125$, $q_{95} = 3.5$, and $q_{axis} = 1.1$

- Pressure gradient and bootstrap current work in a positive feedback loop until second stability limit is reached

- Need to regulate the edge ∇P and or J_{BS} either through changes in transport or stability
- Reducing the edge current should, in general, be the favorable path since this will reduce the kink-like (low–n) character of the edge instability
- Techniques: shaping, impurity radiation, fueling, edge ECH

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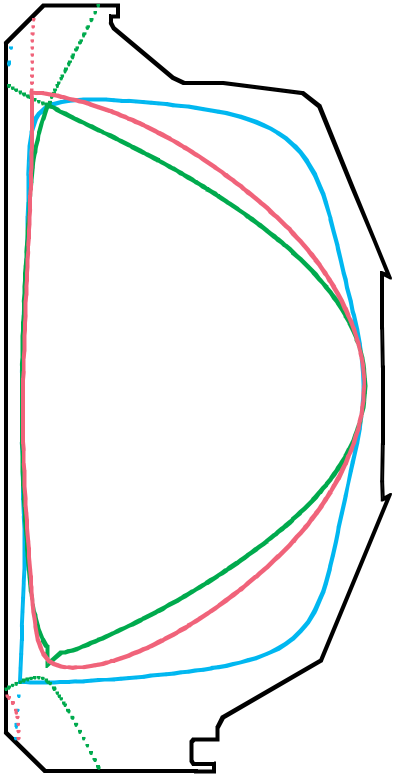
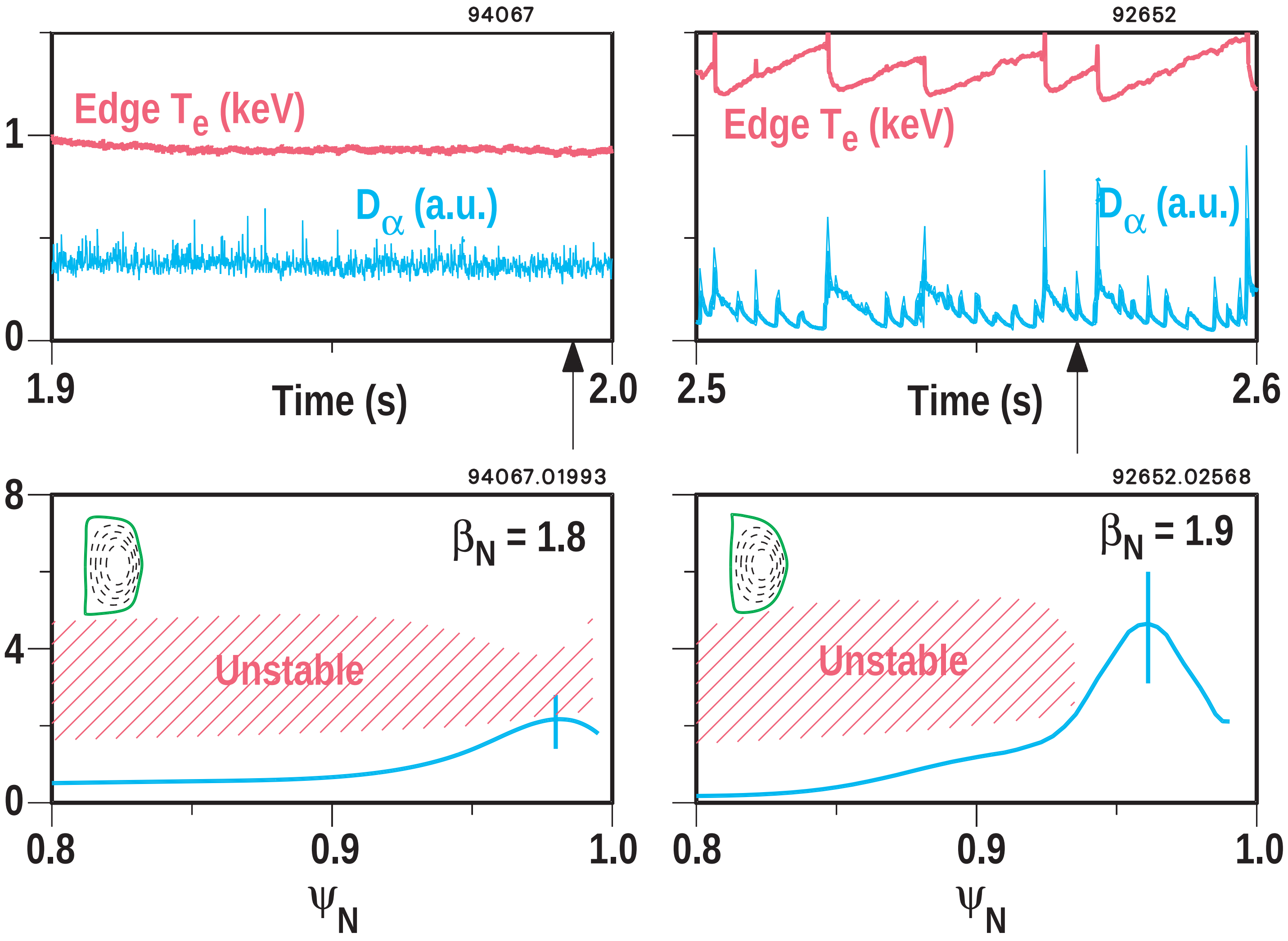
SHAPING: HIGH AND LOW SQUARENESS ELIMINATES SECOND STABLE ACCESS AND HAS A LARGE IMPACT ON ELMs

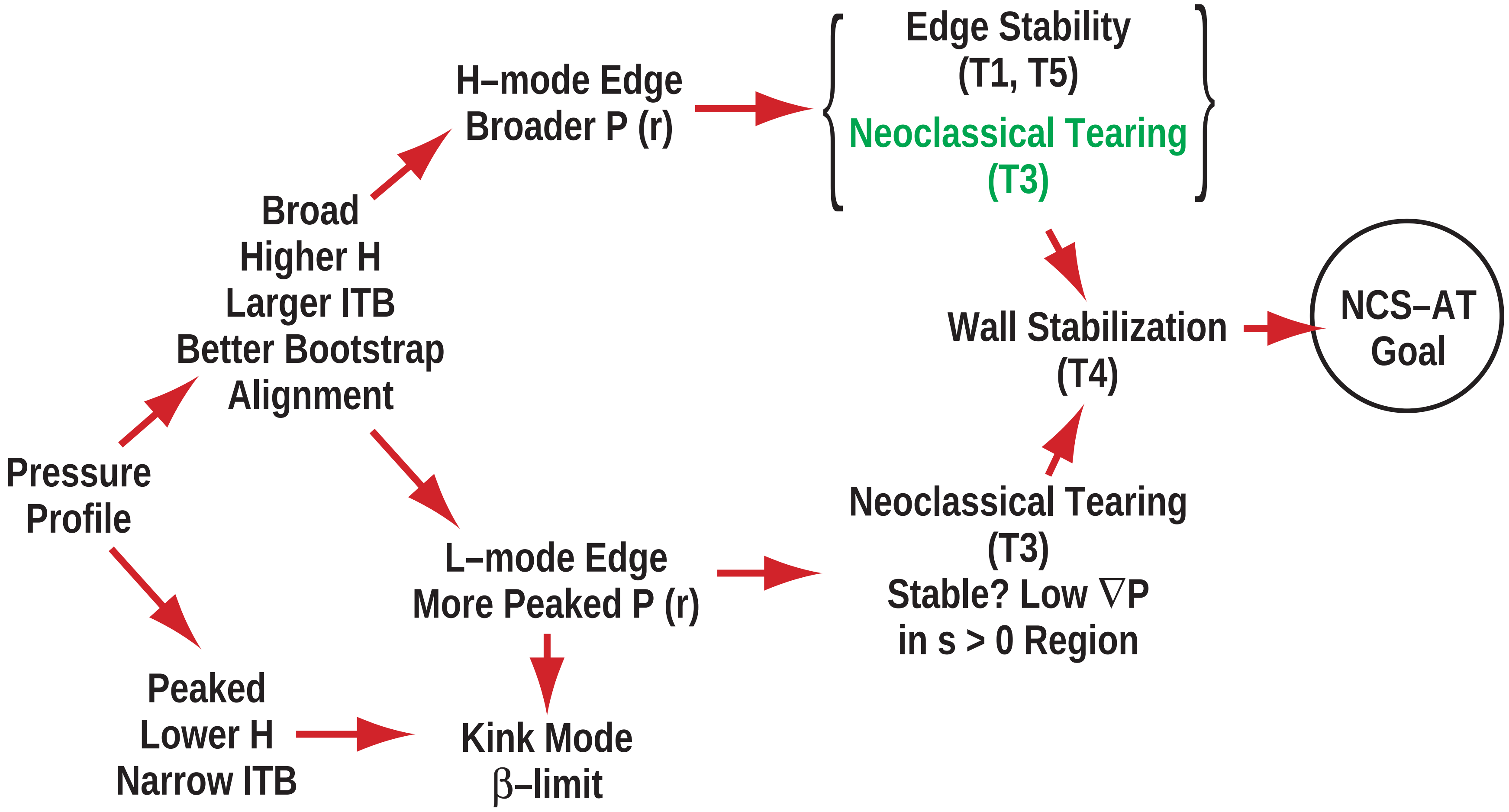




No second regime access
small ELMs

Second regime access
large ELMs

THE PATH TO THE NCS–AT GOAL LEADS THROUGH MANY STABILITY ISSUES



Pressure
Profile

Broad
Higher H
Larger ITB
Better Bootstrap
Alignment

Peaked
Lower H
Narrow ITB

H–mode Edge
Broader P (r)

L–mode Edge
More Peaked P (r)

Kink Mode
β–limit

Edge Stability
(T1, T5)
Neoclassical Tearing
(T3)

Neoclassical Tearing
(T3)
Stable? Low ∇P
in s > 0 Region

Wall Stabilization
(T4)

NCS–AT
Goal

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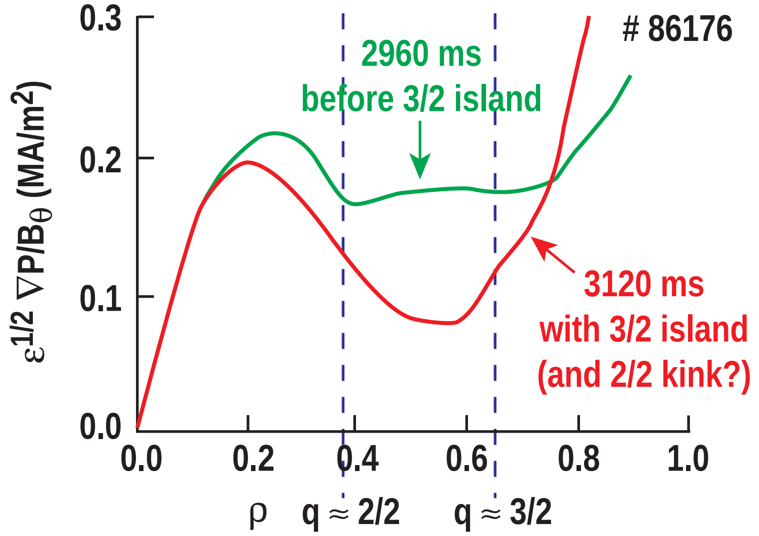
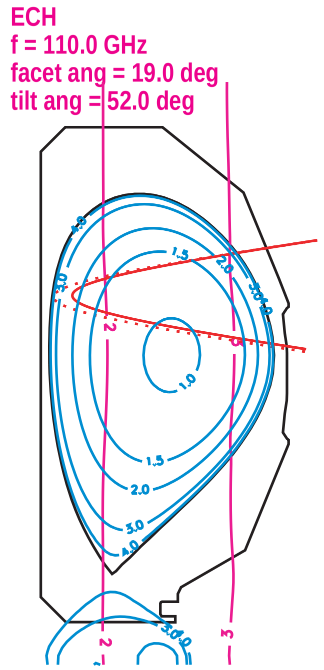
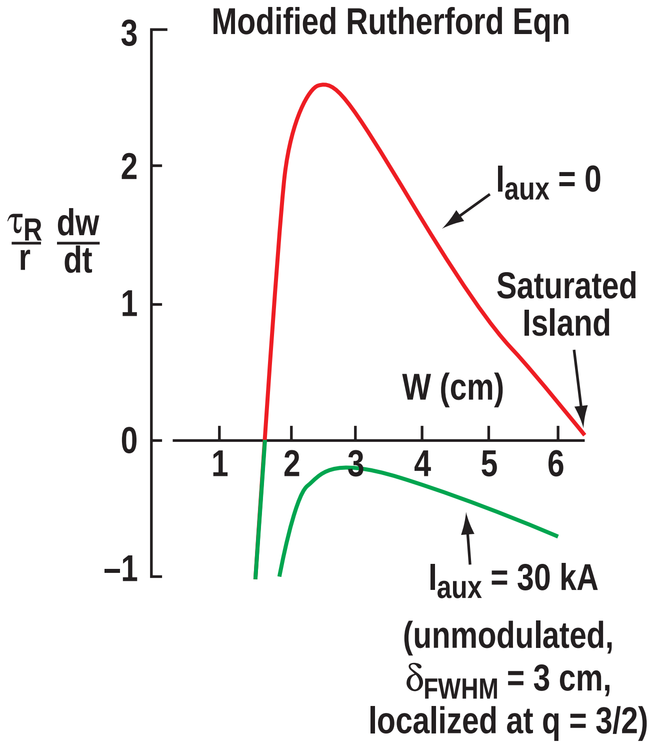
FUTURE WORK: RADIALLY LOCALIZED OFF–AXIS ECCD FOR SUPPRESSION OF NEOCLASSICAL TEARING MODES

- **MOTIVATION – Expected beta limit for ITER-like discharge**
  - Island sustained by “missing” bootstrap current in O–PT



- **GOAL – Replace “missing” bootstrap current (Hegna, Callen, Zohm)**
  - Suppress island size or make vanish





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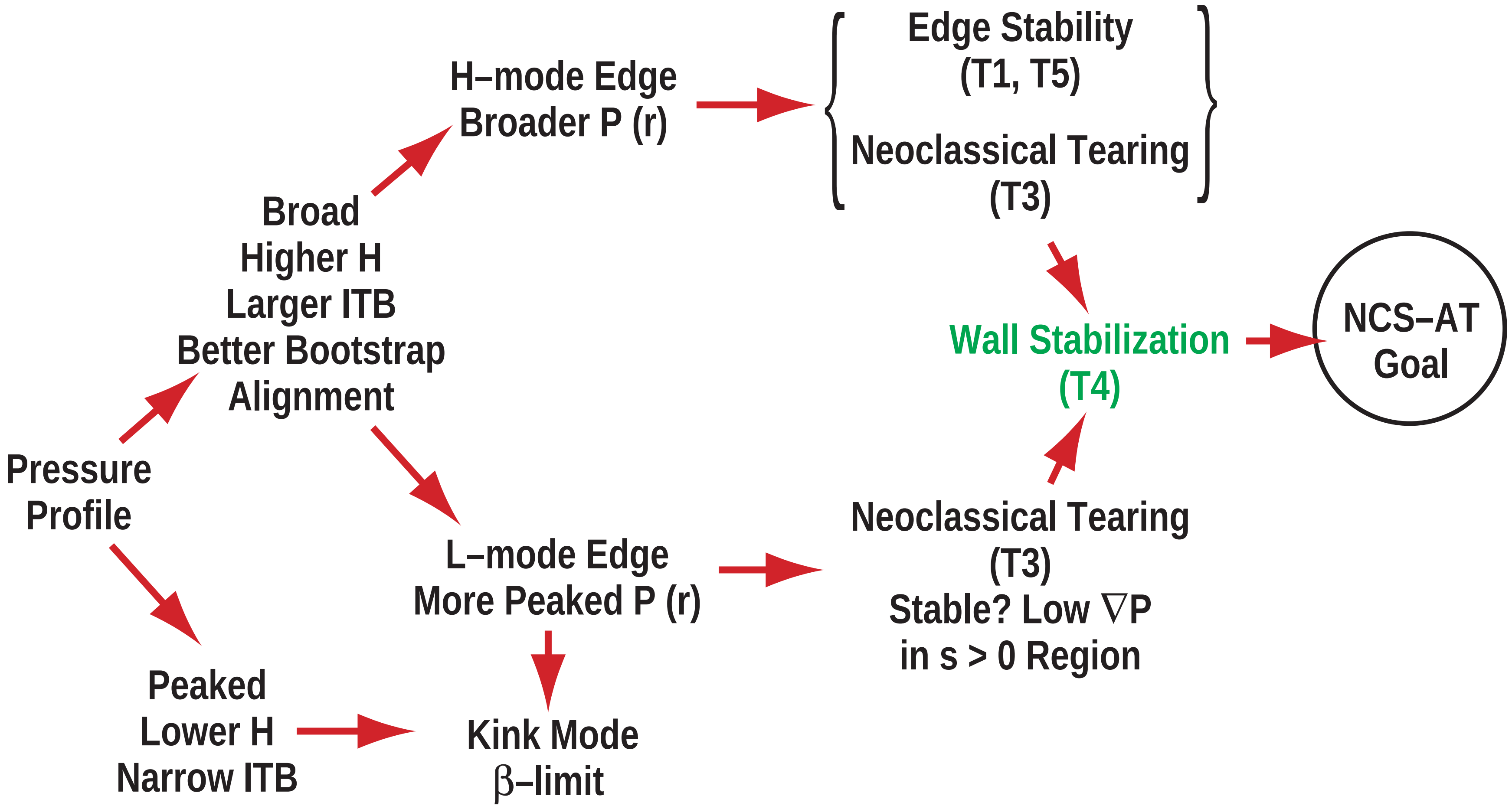
THE PATH TO THE NCS–AT GOAL LEADS THROUGH MANY STABILITY ISSUES



Pressure
Profile

Broad
Higher H
Larger ITB
Better Bootstrap
Alignment

Peaked
Lower H
Narrow ITB

H–mode Edge
Broader P (r)

L–mode Edge
More Peaked P (r)

Kink Mode
β–limit

Edge Stability
(T1, T5)

Neoclassical Tearing
(T3)

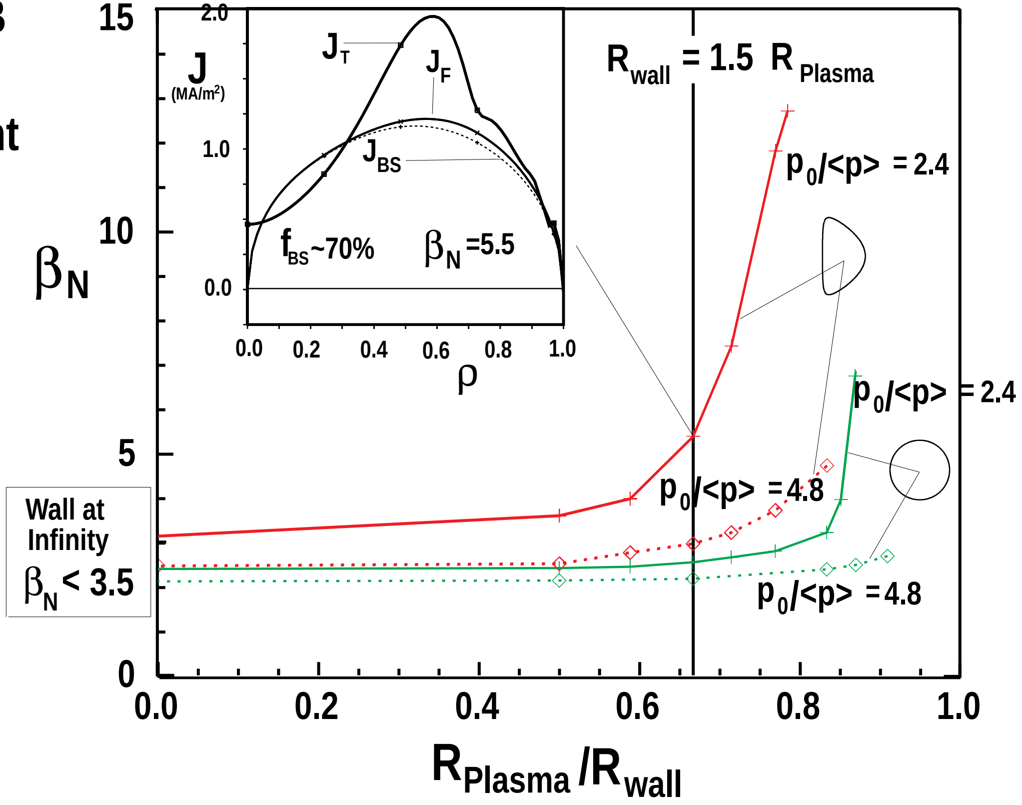
Neoclassical Tearing
(T3)
Stable? Low ∇P
in $s > 0$ Region

Wall Stabilization
(T4)

NCS–AT
Goal

WALL STABILIZATION IS CRUCIAL FOR ADVANCED TOKAMAK OPERATION

- AT operation with
  - High normalized beta, $\beta_N = \beta/I/aB$
  - Large bootstrap current fraction
  - Good bootstrap current alignment
- Requires plasmas with
  - Broad pressure profile
  - Broad current profile
- Such plasmas have
  - Low β_N stability limit to n = 1 external kink without a wall
  - Significantly higher limit with a conducting wall



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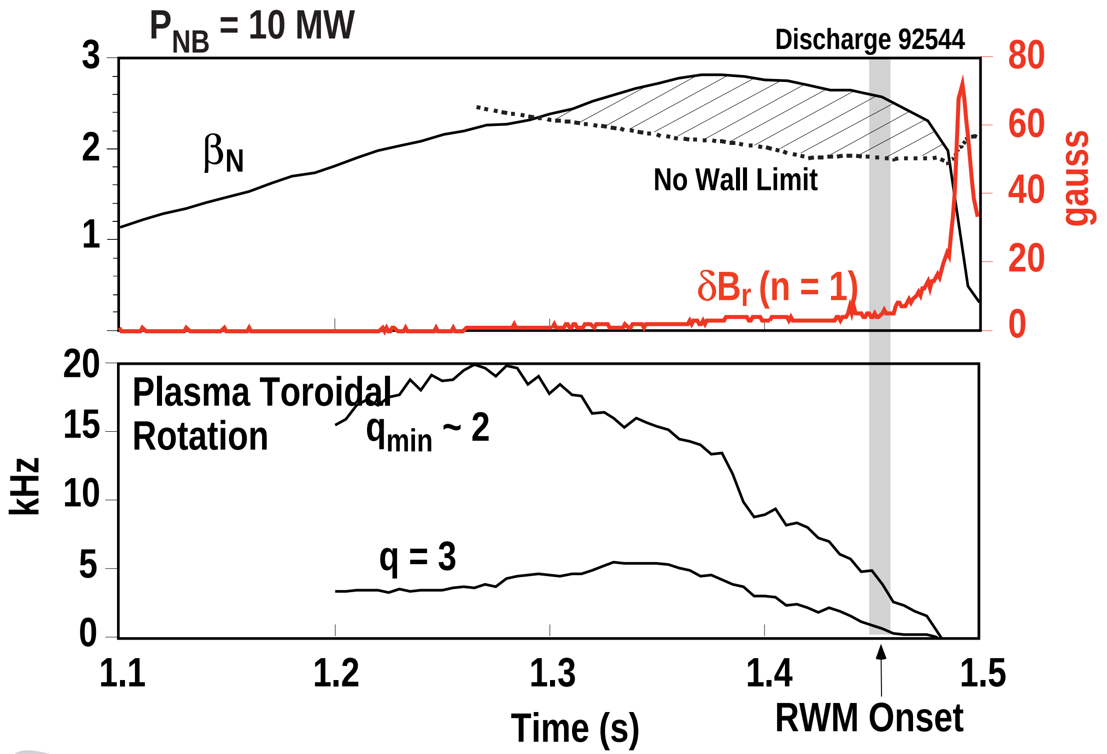
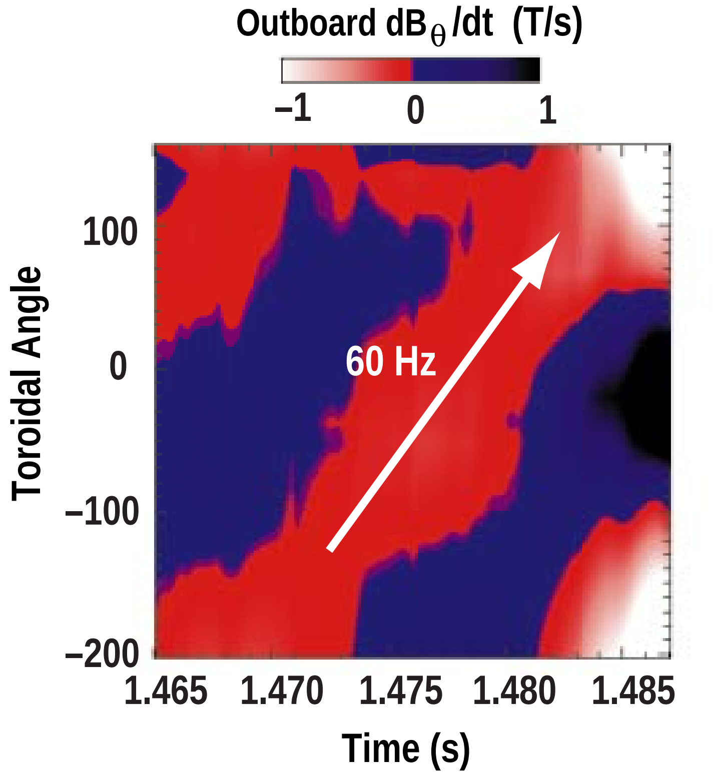
IDEAL KINK MODE STABILIZED BY ROTATION AND RESISTIVE WALL ABOVE NO-WALL β_N LIMIT FOR > 30 τ_{wall}

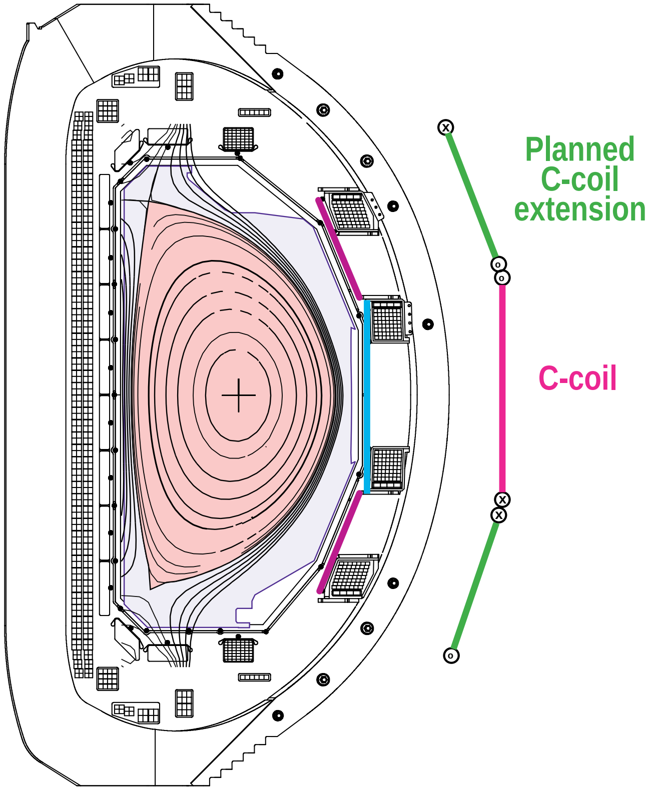
- Wall stabilization sustained with β_N up to $1.4 \times \beta_N^{no\text{-}wall}$
- Plasma rotation slows as β_N exceeds the no-wall limit
- Resistive wall mode grows when rotation drops below a critical value

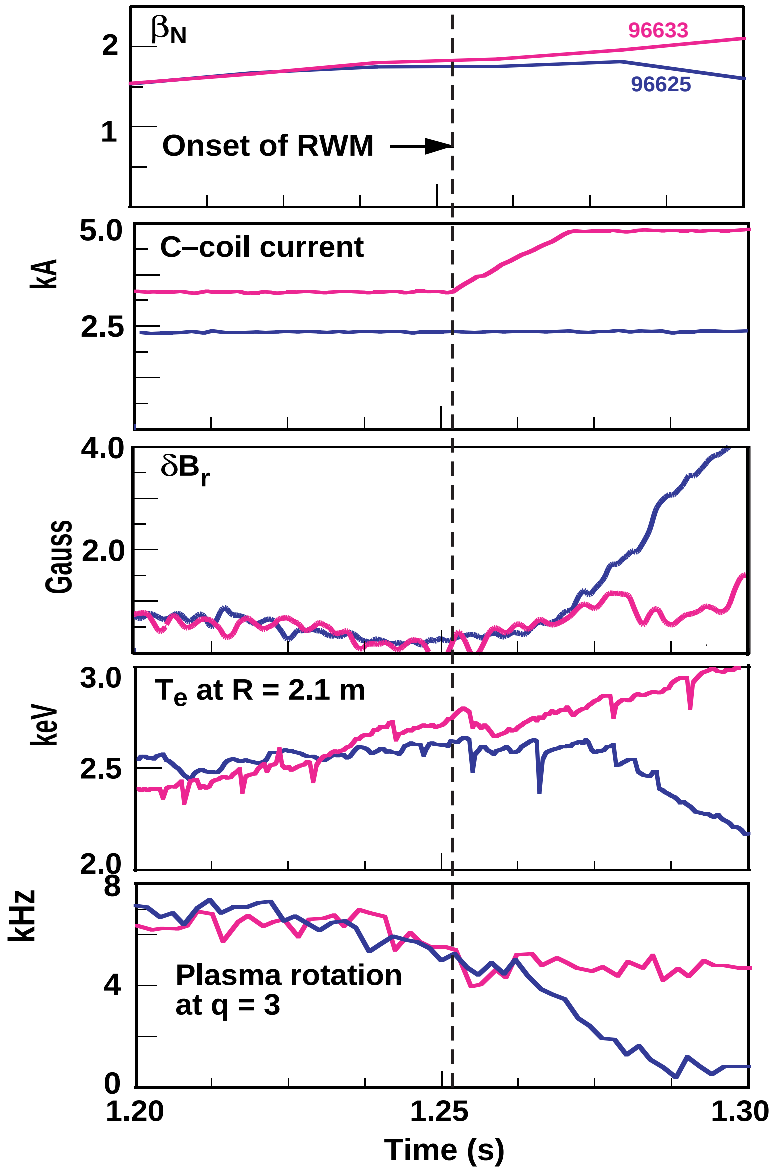




RESISTIVE WALL MODE (RWM) IS SUPPRESSED (~30 ms) BY OPEN-LOOP ACTIVE CONTROL

- Near stationary RWM is reproducibly obtained
- Feed-forward static n = 1 field is preprogrammed at RWM onset, with phase opposing the mode





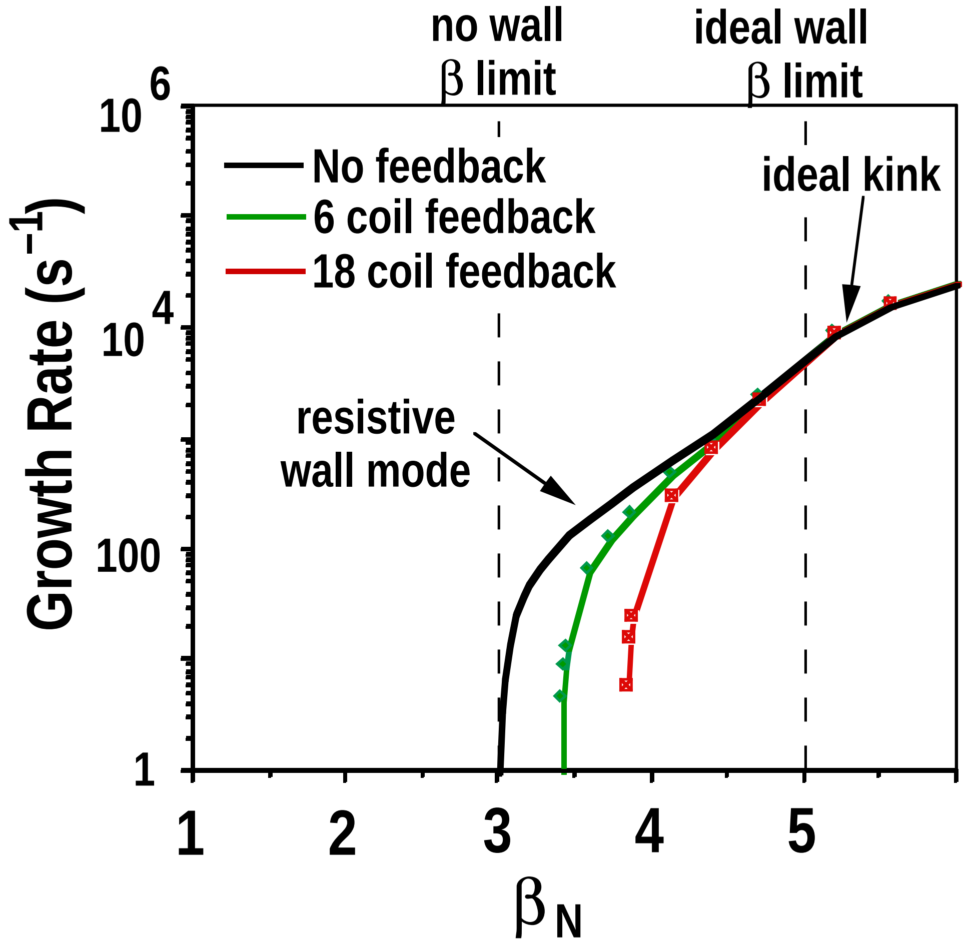
- This result is encouraging for active feedback

VALEN 3D FEEDBACK CONTROL MODEL PREDICTS IMPROVED β LIMIT IN DIII–D

- Existing 6 coil set can increase RWM stability limit to $\beta_N \sim 3.4$

- Extended 18 coil set can increase RWM stability limit to $\beta_N \sim 3.8$ (not optimized design)

- Gain in fusion power at fixed bootstrap fraction = $\left(\frac{3.8}{3.0}\right)^4 = 2.6$!



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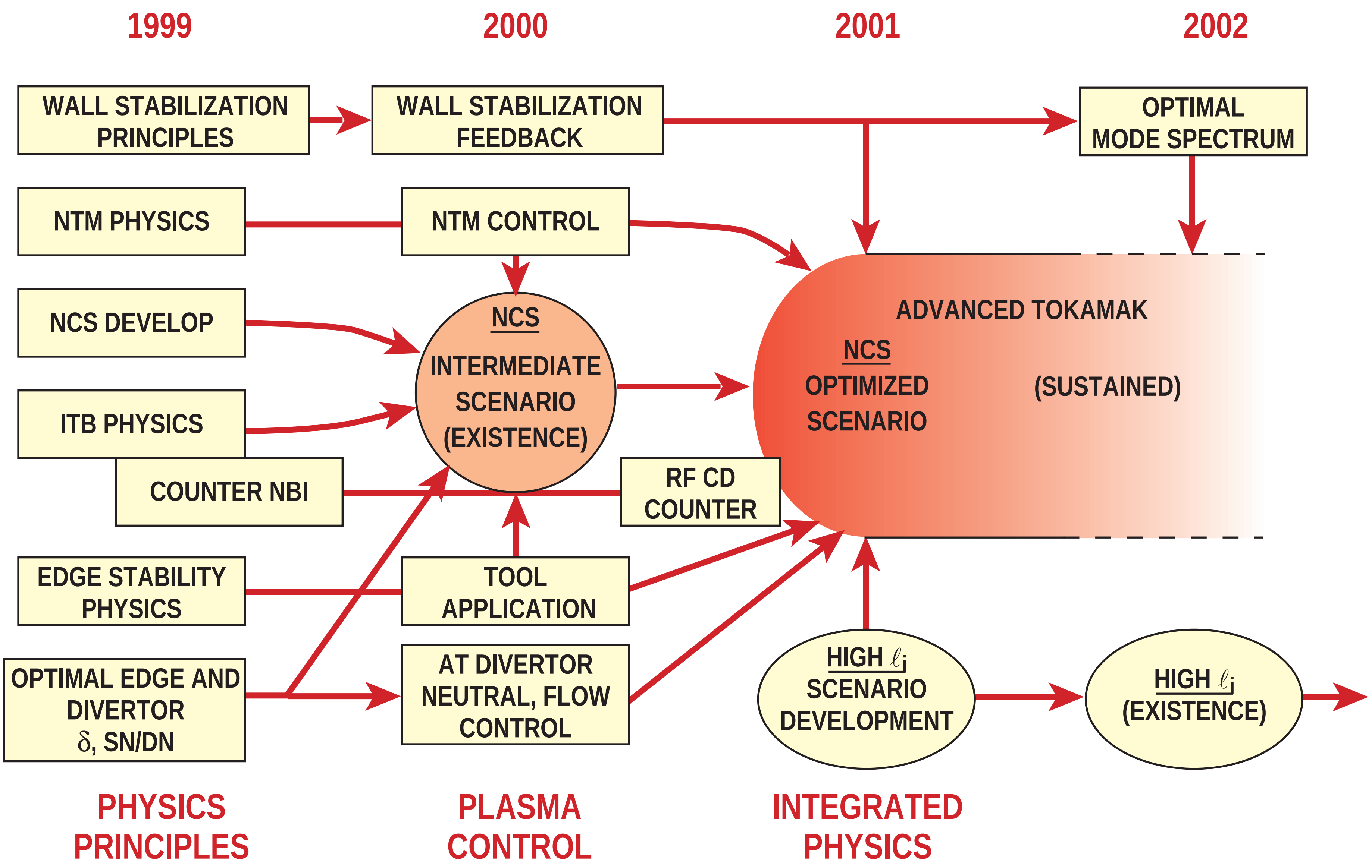
PHYSICS UNDERSTANDING DRIVES DIII–D AT RESEARCH PLAN



1999

2000

2001

2002

WALL STABILIZATION PRINCIPLES

WALL STABILIZATION FEEDBACK

OPTIMAL MODE SPECTRUM

NTM PHYSICS

NTM CONTROL

NCS DEVELOP

ITB PHYSICS

COUNTER NBI

<u>NCS</u>
INTERMEDIATE SCENARIO (EXISTENCE)

RF CD COUNTER

ADVANCED TOKAMAK

<u>NCS</u>
OPTIMIZED SCENARIO

(SUSTAINED)

EDGE STABILITY PHYSICS

TOOL APPLICATION

OPTIMAL EDGE AND DIVERTOR
δ, SN/DN

AT DIVERTOR NEUTRAL, FLOW CONTROL

<u>HIGH ℓ_i</u>
SCENARIO DEVELOPMENT

<u>HIGH ℓ_i</u>
(EXISTENCE)

PHYSICS PRINCIPLES

PLASMA CONTROL

INTEGRATED PHYSICS

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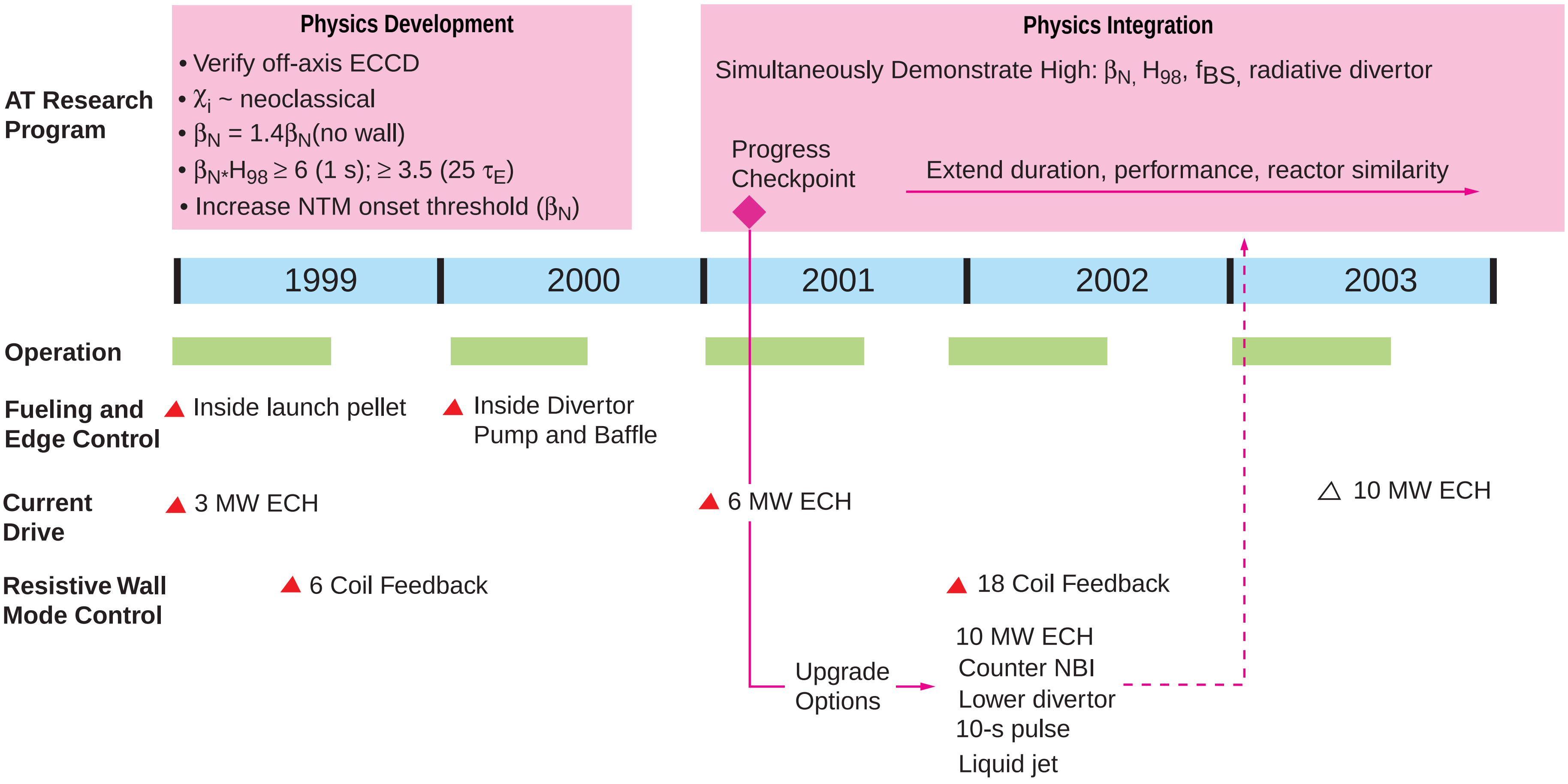
DIII–D ADVANCED TOKAMAK 5–YEAR RESEARCH PLAN



AT Research Program

Physics Development

- Verify off-axis ECCD
- χ_i ~ neoclassical
- $\beta_N = 1.4\beta_N$(no wall)
- $\beta_{N}*H_{98} \geq 6$ (1 s); ≥ 3.5 (25 τ_E)
- Increase NTM onset threshold (β_N)

Physics Integration

Simultaneously Demonstrate High: β_N, H_{98}, f_{BS}, radiative divertor

Progress Checkpoint

Extend duration, performance, reactor similarity

1999 | 2000 | 2001 | 2002 | 2003

Operation

Fueling and Edge Control

▲ Inside launch pellet

▲ Inside Divertor Pump and Baffle

Current Drive

▲ 3 MW ECH

▲ 6 MW ECH

△ 10 MW ECH

Resistive Wall Mode Control

▲ 6 Coil Feedback

▲ 18 Coil Feedback

Upgrade Options →

10 MW ECH
Counter NBI
Lower divertor
10-s pulse
Liquid jet

- **Hardware upgrades with new diagnostics in 1999–2000 supports a two-phase AT physics development and integration plan**
- **An initial test of AT integration with a progress checkpoint in 2001 will evaluate upgrade options to extend AT integration**

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DIII–D AT PROGRAM: REMAINING CHALLENGES AND OPPORTUNITIES

- Understand transport barrier dynamics; broaden pressure profiles
  - Develop ITB control as needed
- Implement methods to sustain hollow current profiles and high bootstrap fractions
- Deepen the physics understanding of neoclassical tearing modes; avoid or stabilize
- Confirm our edge stability physics picture; find a compromise
- Understand the physics of wall stabilization; implement feedback

WHAT DO WE HAVE TO GAIN?

- An understanding of the ultimate potential of the tokamak as a magnetic confinement system
- Greatly increased fusion power output
- Much improved prospects for steady-state