ITER Hybrid Scenarios

by
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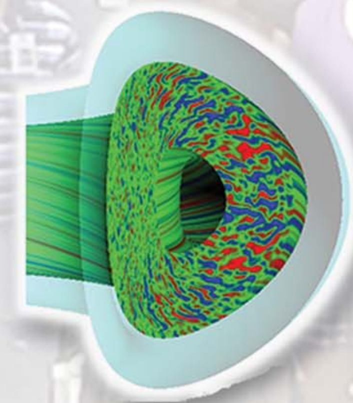
Presented to
DIII–D Program
Advisory Committee



January 31– February 2, 2006

Misssion and Long Term Goals of Thrust IT-2: ITER Hybrid Scenarios

- **Mission: Develop, assess, and qualify (to the extent possible) candidate high performance, pulsed tokamak scenarios for next-generation devices**

- **Long term goals**
  - Provide next generation devices with robust, reliable operating regimes that offer the potential of a substantial increase in performance over the conventional, sawtoothing, ELMy H-mode regime
  - Develop a detailed physics understanding of the processes that lead to improved performance
  - Convince the worldwide community to adopt the hybrid scenario as the new benchmark in pulsed tokamak performance

What is the Hybrid Scenrio?

- **Hybrid regime in DIII–D refers to long duration, high performance discharges that have favorable fusion and neutron fluence characteristics for ITER**
  - Typical parameters β_N ~2.8, H_{89P} ~2.5, q_{95} ~4
- **Hybrid scenario is distinct from the Advanced Tokamak scenario**
  - Inductively driven
  - Bootstrap current fractions of 35% to 50%
  - Fully penetrated current profile with q(0) ~1

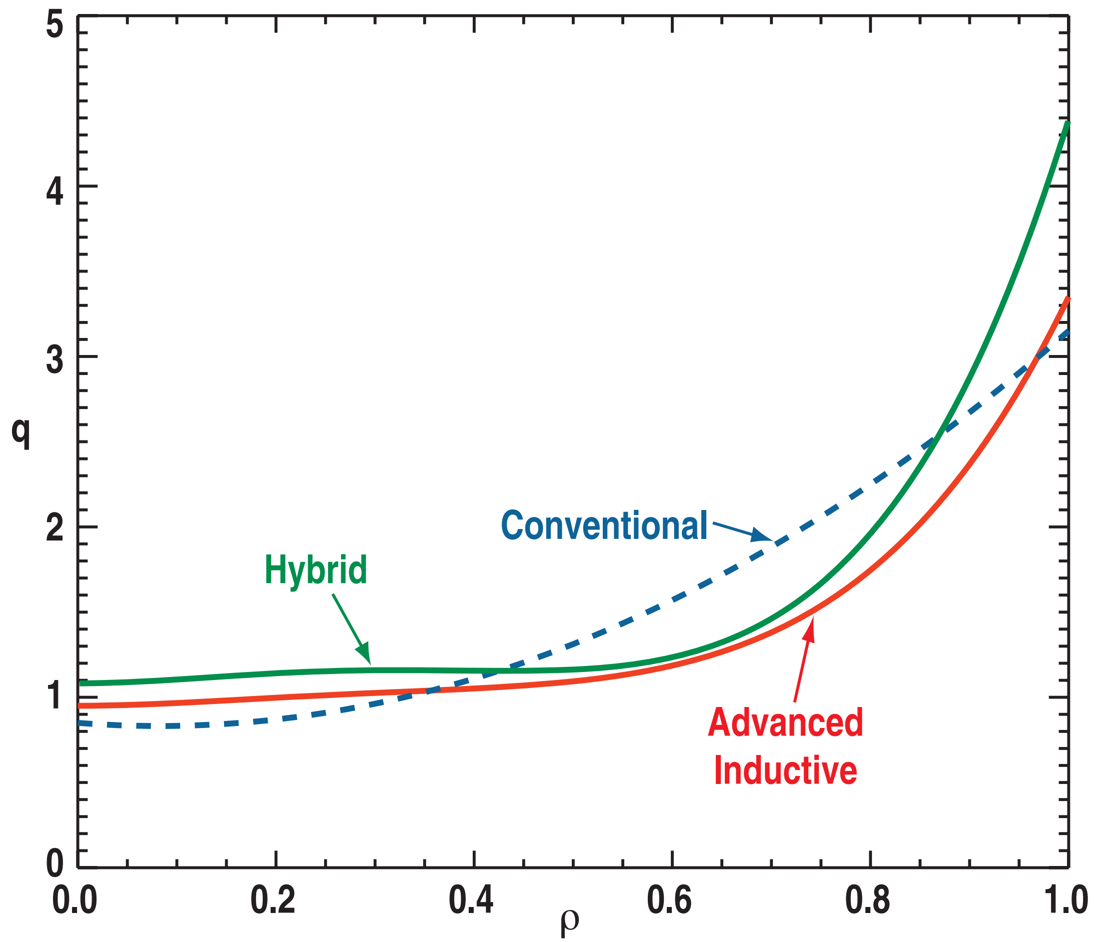
The Word "Hybrid" Serves Double Duty as a Specific Mode and as a General Term

- **The hybrid mode in ITER specifically calls for a high fusion performance plasma with reduced ohmic flux consumption, leading to an extension of the burn duration**
  - Volt-sec reduction comes from lower plasma current and substantial bootstrap current fraction
  - Provides the maximum neutron fluence per ITER pulse
  - Projection for ITER is Q≈10 for flat-top length of ~4000 s (q_{95}≈4)

- **The advanced inductive mode extends the hybrid regime to higher fusion gain by maximizing the plasma current, but with shorter burn duration**
  - Projection for ITER is Q≈40 for flat-top length of ~1500 s (q_{95}≈3)
  - These plasma have greater disruption risk owing to higher I_p

- **The "ITER Hybrid Scenarios" Thrust includes both of these modes of operation**

Improved Performance of Hybrid Scenarios is Due to Broader Current Profile Formed by Moderate Heating During I_p Ramp



- Central flat magnetic shear region forms spontaneously, no specific noninductive current drive profile is required
- This q profile is less susceptible to onset of 2/1 NTM, allowing higher β_N operation
- This q profile also has theoretically lower turbulent growth rate characteristics, allowing higher confinement

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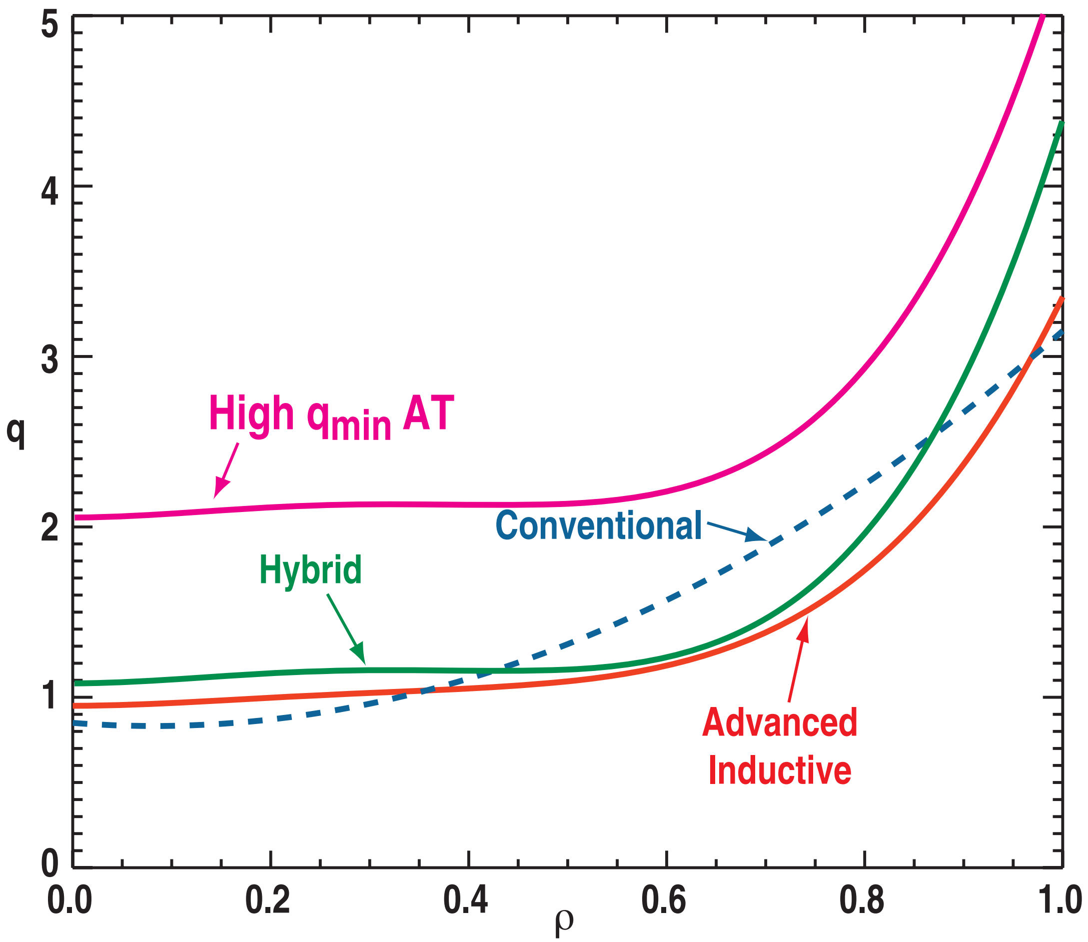

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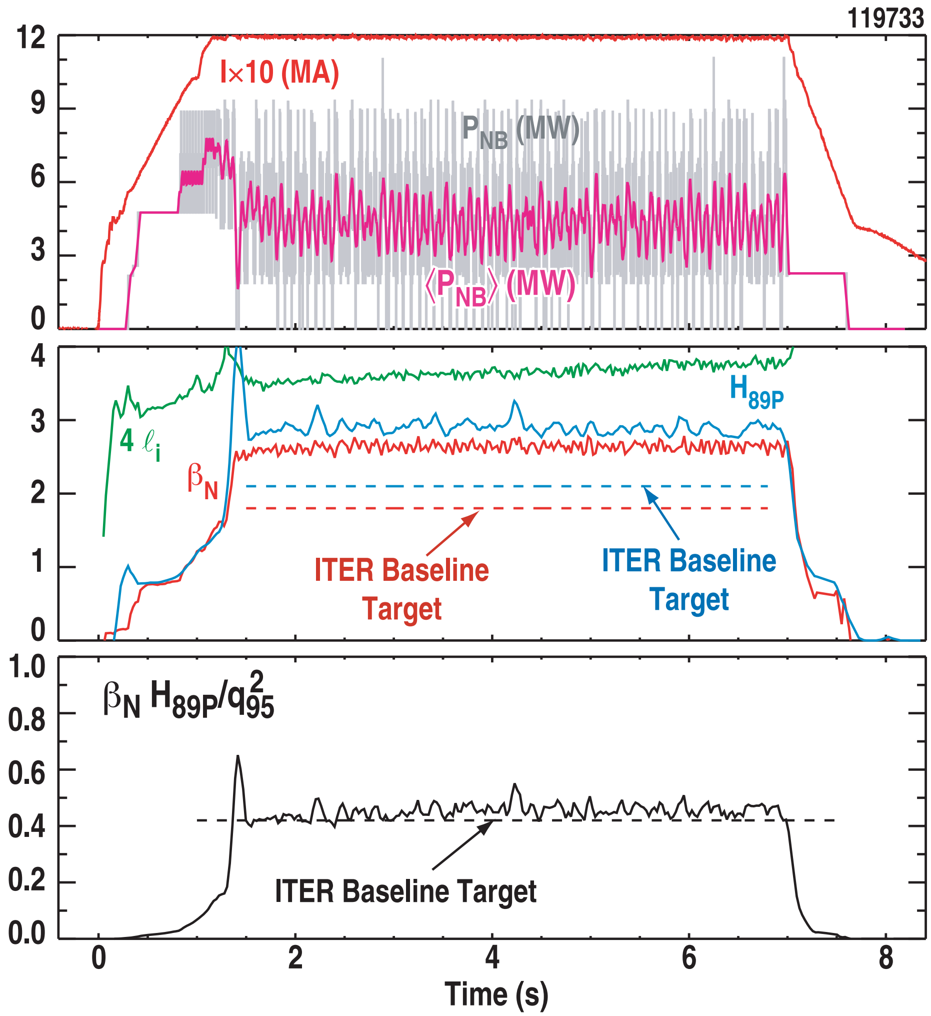
‘Hybrid’ Scenario Occupies Critical Strategic Position within Tokamak Scenario Portfolio

Conventional	Advanced Inductive	Hybrid	Advanced Tokamak
$\beta_N \approx 1.8$	$\beta_N \lesssim \beta_{N,no\text{-}wall}$	$\beta_N \approx \beta_{N,no\text{-}wall}$	$\beta_N \lesssim \beta_{N,ideal\text{-}wall}$
$q_{95} \approx 3$	$q_{95} \approx 3$	$q_{95} \gtrsim 4$	$q_{95} \approx 5$
$f_{BS} << 1$	$f_{BS} \sim 0.3$	$f_{BS} \sim 0.5$	$f_{BS} \sim 0.8$
$H_{89} \approx 2$	$H_{89} > 2$	$H_{89} > 2$	$H_{89} > 2$

Increasing Complexity/Payoff

Projection of Hybrid Scenario to ITER Indicates Possibility of Q = 10 Sustained for >1 Hour



Projection to ITER:

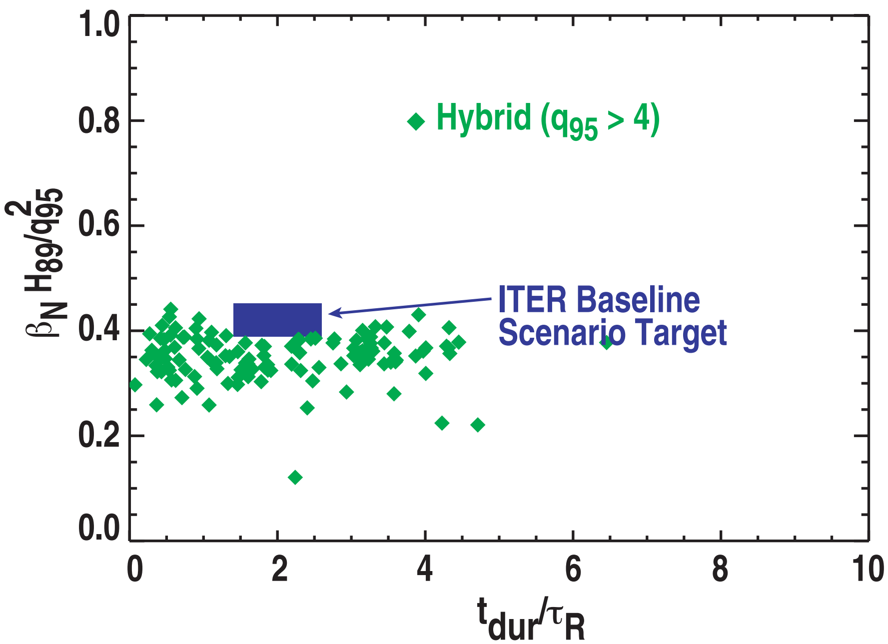
$\beta_N = 2.7$ $q_{95} = 4.4$ $n/n_G = 0.85$

$B = 5.3$ T $I = 10.8$ MA

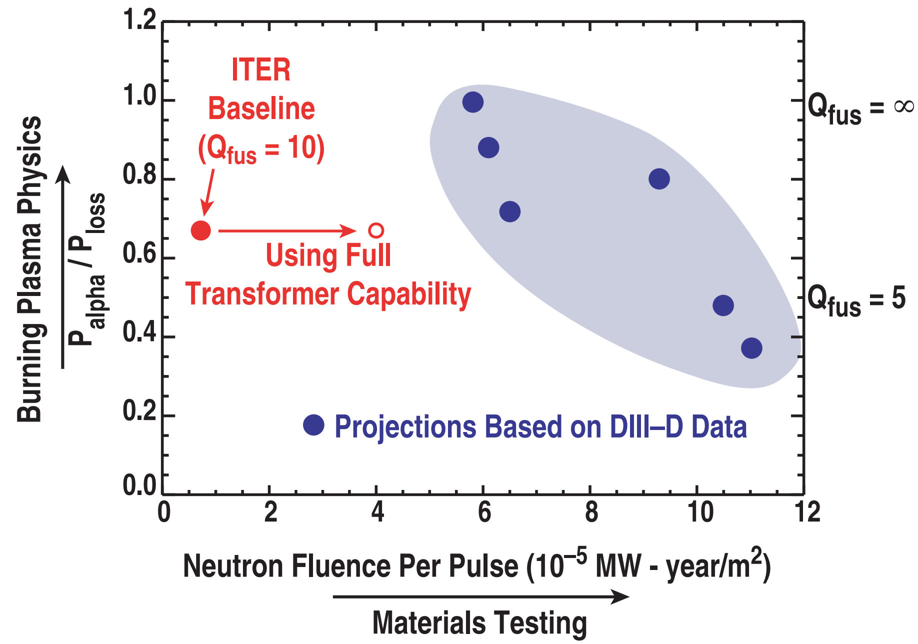
- **Hybrid scenario goal is maximum fusion energy (or neutron fluence) per inductive pulse**
- **DIII–D approach is reduced current and higher normalized pressure, up to no-wall pressure limit (~4 ℓ_i)**

Advanced Inductive and Hybrid Scenarios Offer the Potential of a Significantly Enhanced Research Program on ITER

- Performance at or above ITER baseline maintained in stationary conditions



- Projections of DIII-D data suggest expanded research opportunites in ITER



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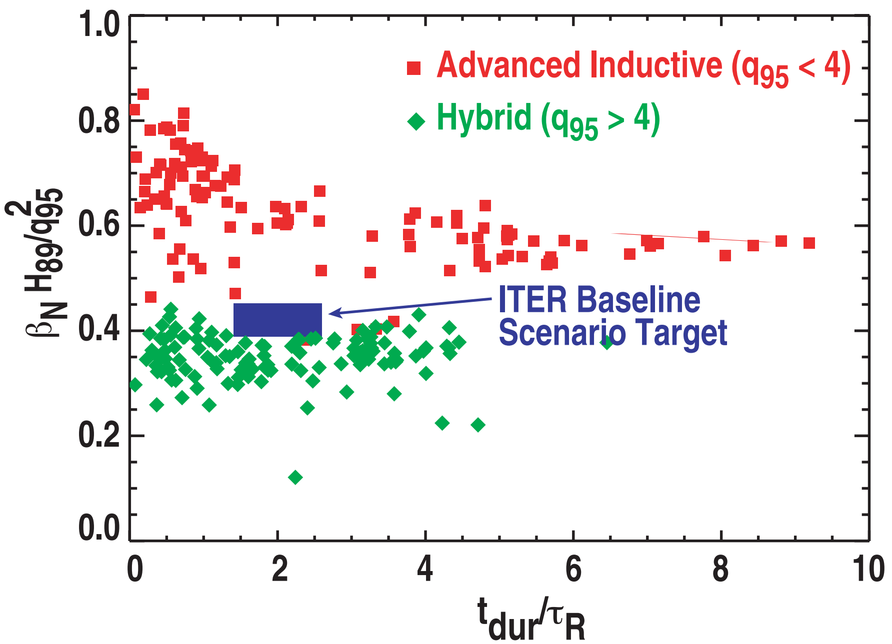

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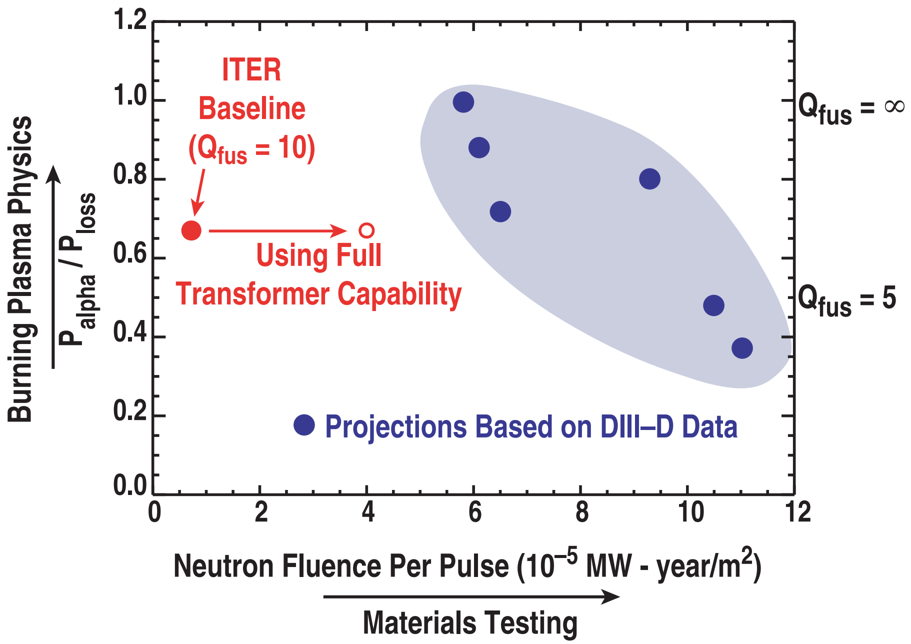

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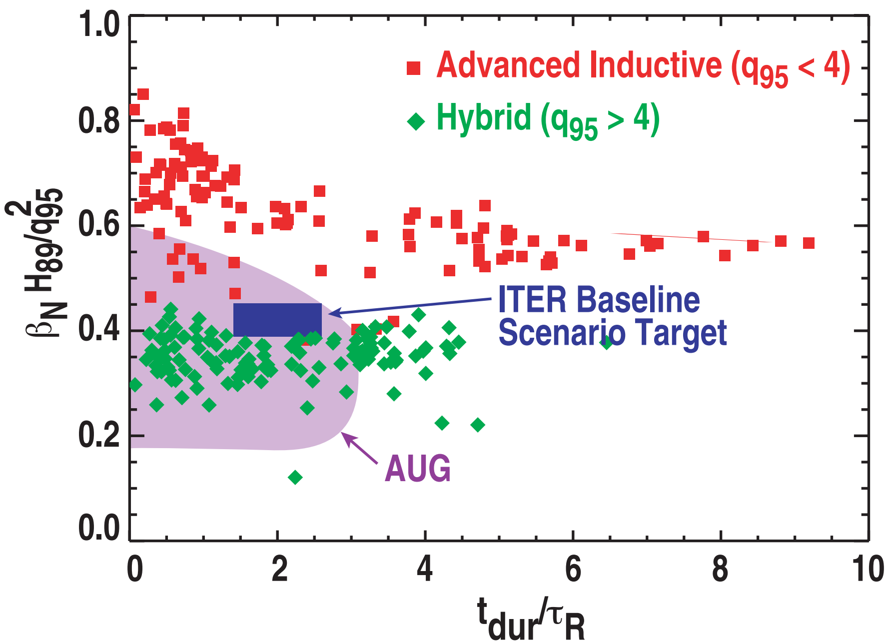

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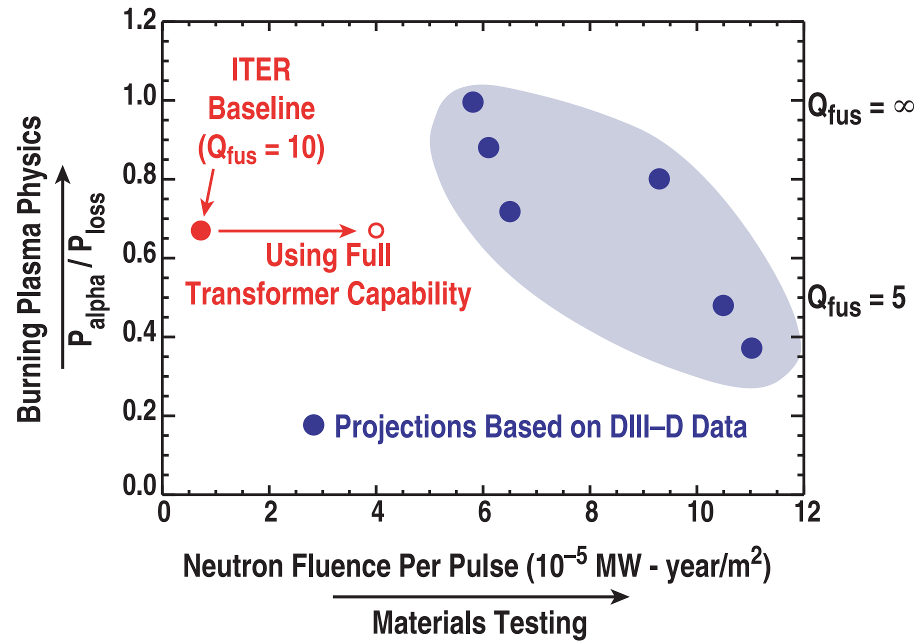

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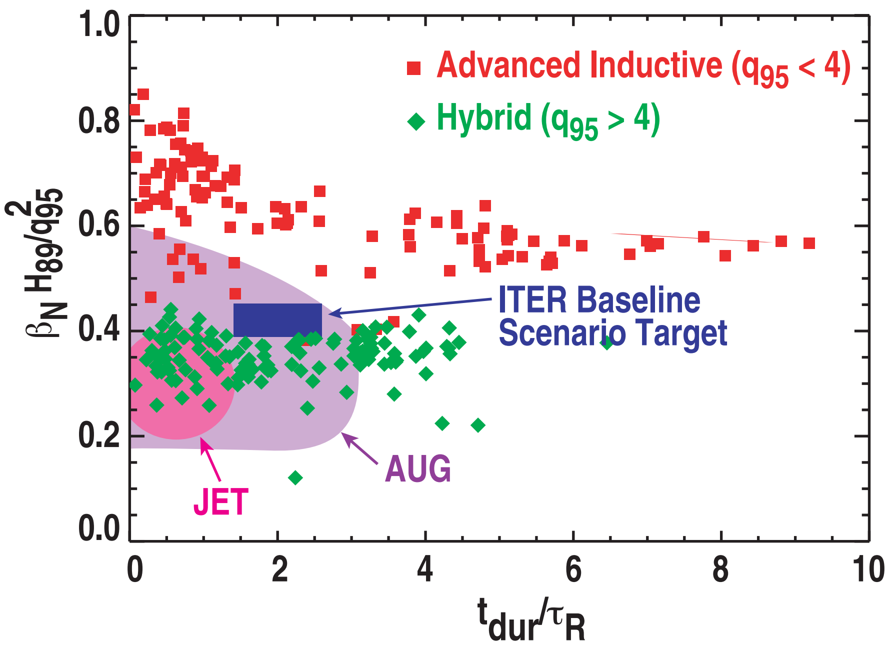

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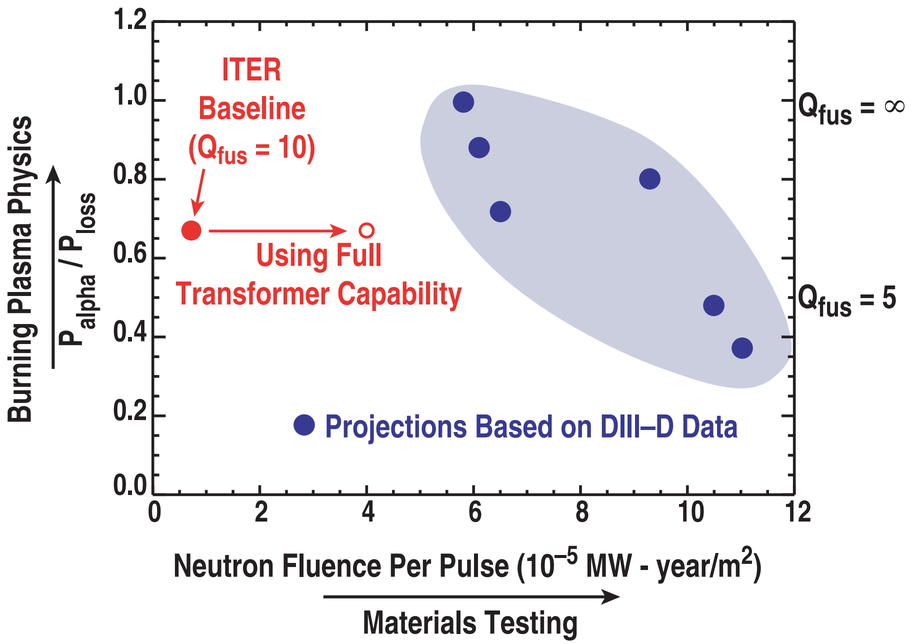
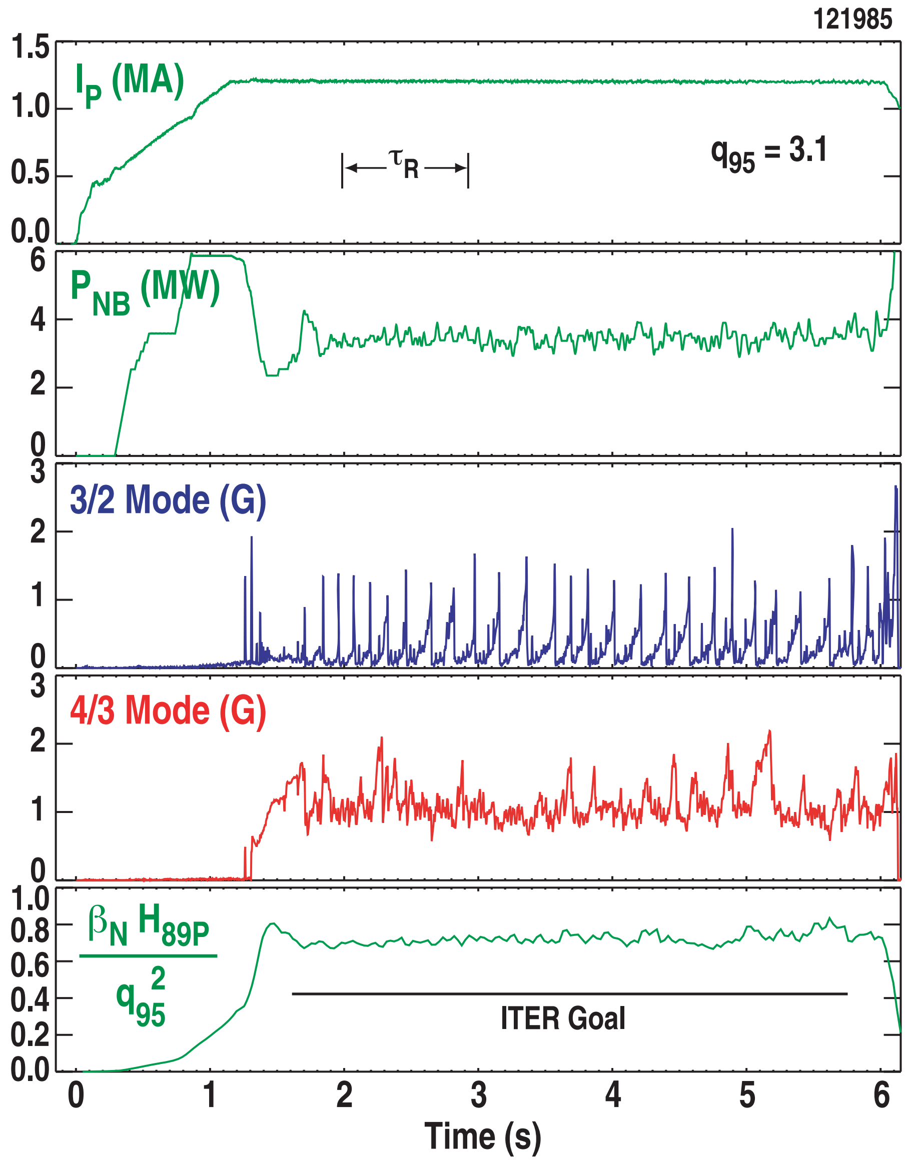
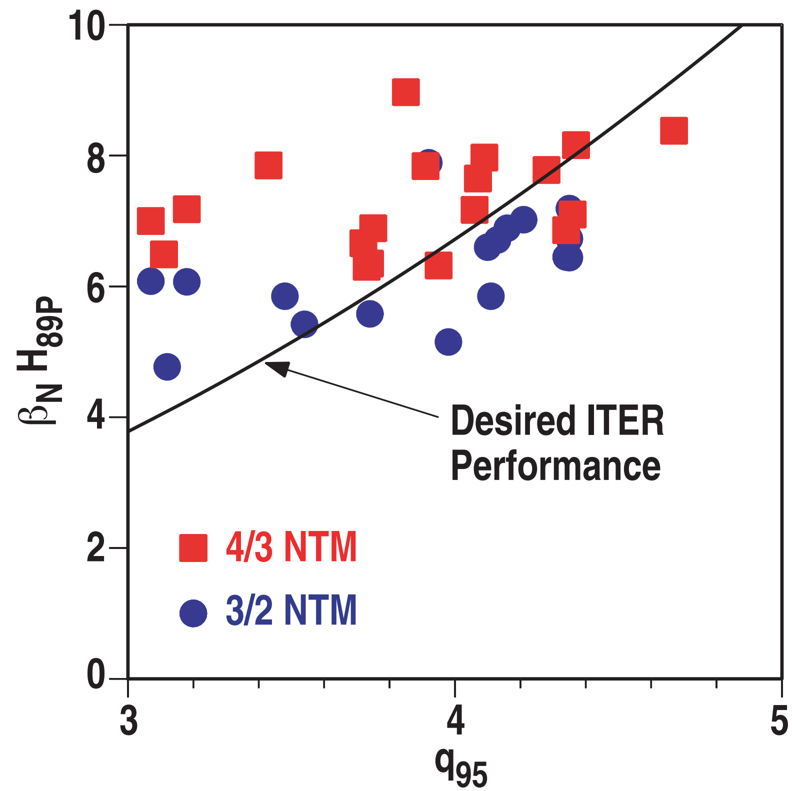


Advanced Inductive Discharges with Dominant 4/3 NTM Achieved Performance 70% Above Desired ITER Value

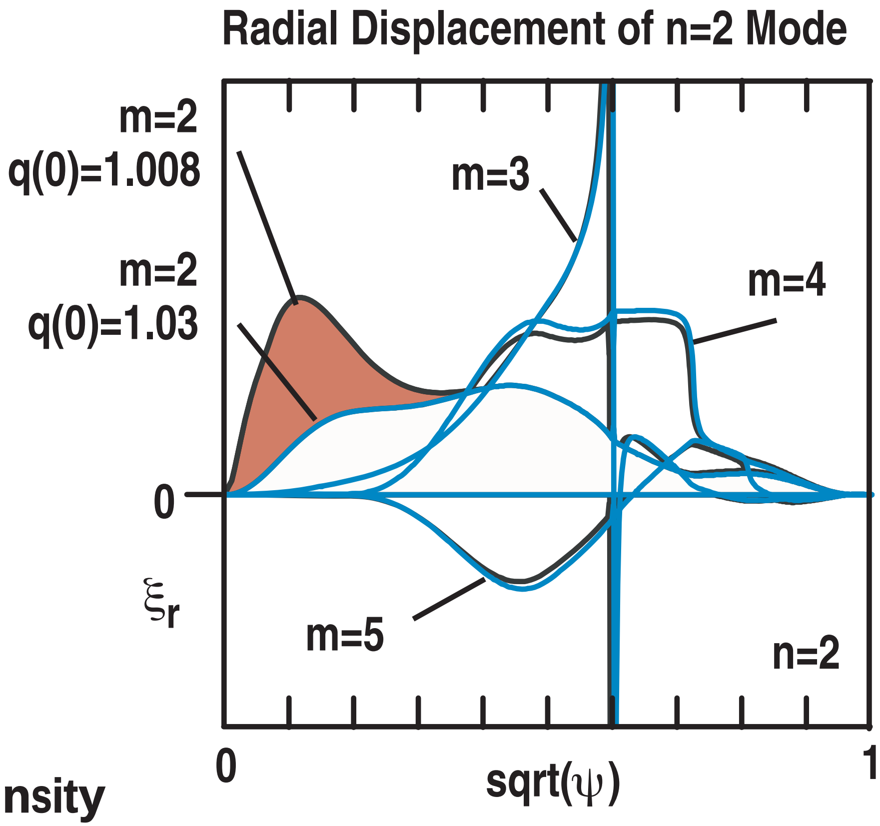




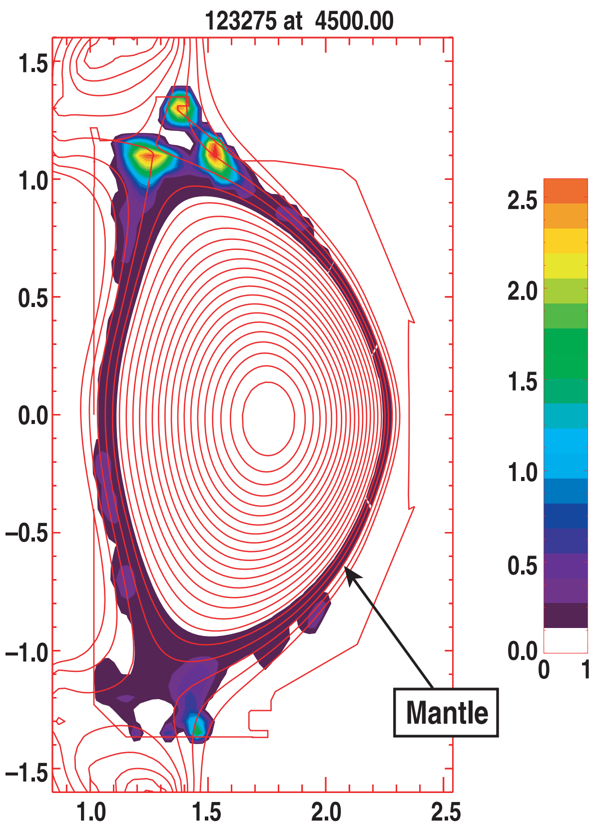
- Hybrid discharges equal or exceed ITER baseline performance over a large range of q_{95}, especially when 4/3 NTM is dominant

Theoretical Explanation for q(0) > 1 in Hybrids is Central Counter-Current Drive from Kinetic Alfvén Wave

- PEST3 linear calculation shows m = 2 amplitude near the axis rises rapidly when q(0) is reduced below 1.03
- The 2/2 component looks like a wave propagating in the counter-current direction (because of toroidal velocity shear)
- At Alfvén resonance, 2/2 component is converted to a kinetic Alfvén wave, which electron Landau damps near the axis yielding a counter-current density

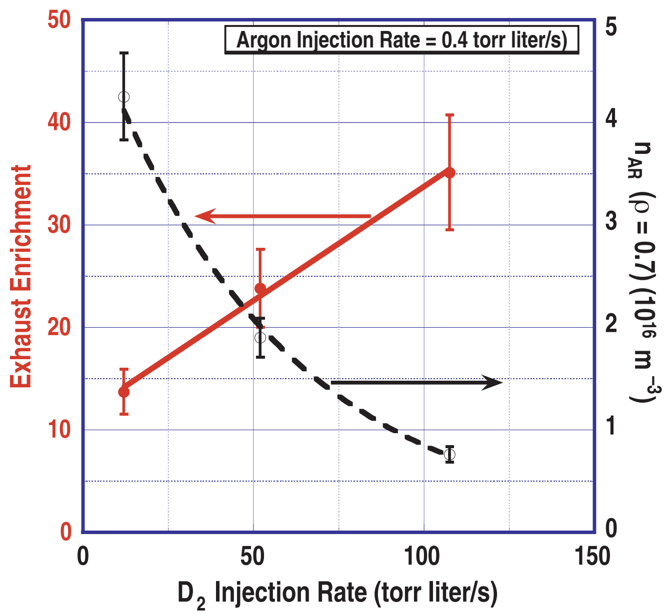


The Radiative Divertor was Successfully Applied to "Hybrid" Operation

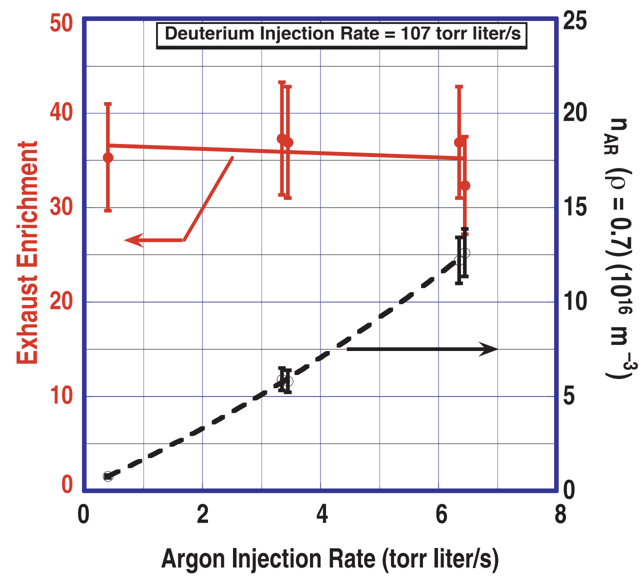


$P_{rad}/P_{tot} = 0.62$
$\beta_N = 2.5$
$H_{89P} = 2.0$

Enrichment ≡ $\frac{f_{exh}}{f_{core}}$



Enrichment of trace argon increased with Γ_{D2}



Enrichment was relatively insensitive to Γ_{AR}, with Γ_{D2} ~ constant

New Tools on DIII–D will Help Establish the Physics Basis for Hybrid Scenarios

Counter NB

EC

Lower Divertor

Transport

- What roles do rotation, T_e/T_i, magnetic shear play in good confinement?
- Do ELMs transport poloidal flux and raise q_o?
- Is the stationary q profile sensitive to the noninductive current profile?

Stability

- What is the role of NTMs in the hybrid scenario?
- Can the beta limit be raised by increasing ℓ_i (with pumped DND shape)?
- Can hybrid plasmas operate above no-wall stability limit with ECCD suppression of 2/1 NTM?

Pedestal/Divertor

- What is the effect of H-mode threshold on hybrid performance?
- What role does shape play on H-mode pedestal height and divertor heat load?
- Is a radiative divertor compatible with the hybrid scenario?

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Improved Diagnostics

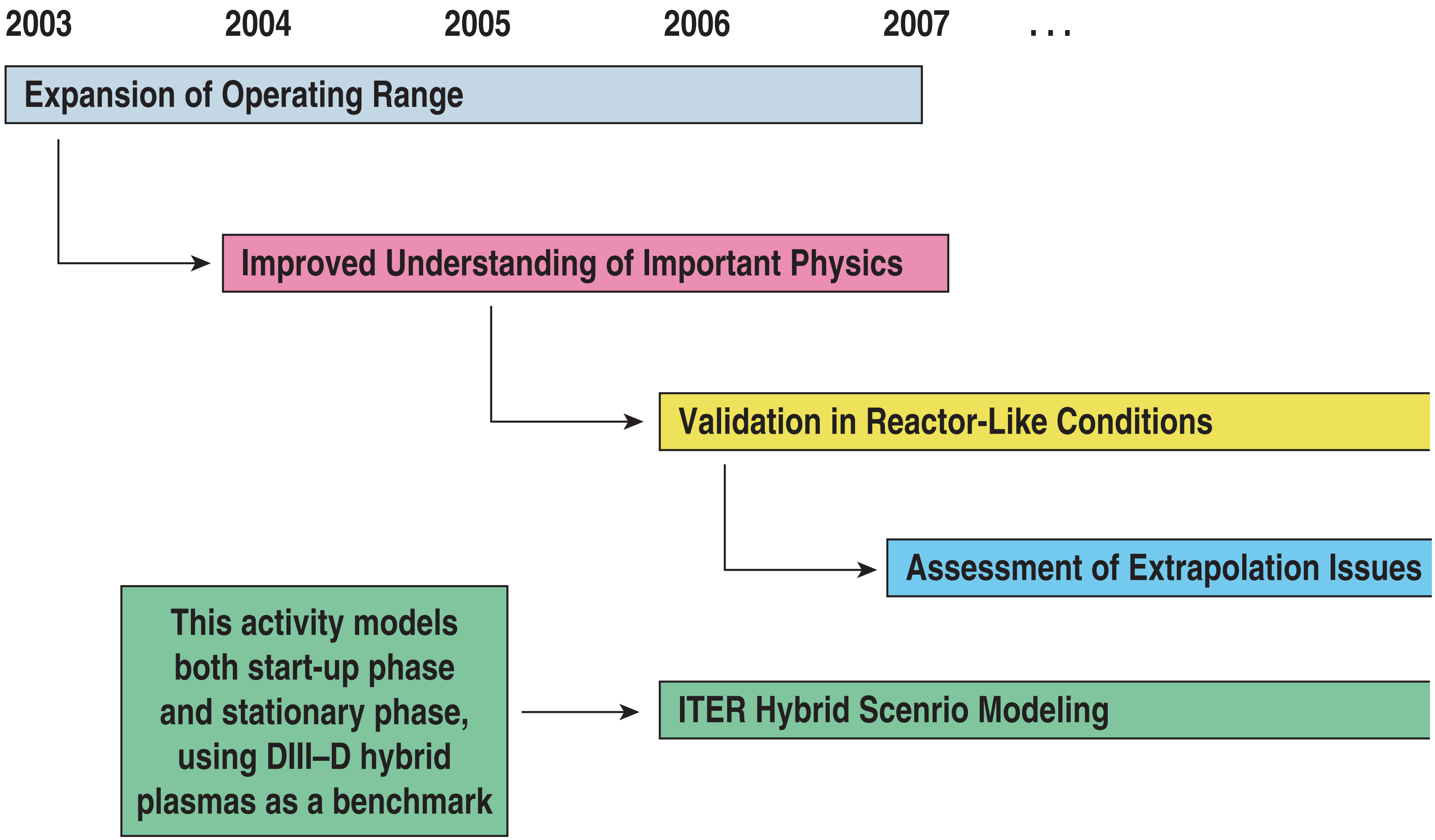
Many IEA/ITPA Joint Experiments Concern the Hybrid Regime

- **DIII–D program has expressed strong interest in participating in the following ITPA Joint Experiments**

  – 12 week plan:
  TP-3 "Determine transport dependence on T_i/T_e ratio with high confinement operation"
  TP-4.2 "Low momentum input operation effects on ExB shear and reduced transport"
  SSO-2.1 "Complete mapping of hybrid scenrio"
  SSO-2.2 "MHD effects on q-profile and confinement for hybrid scenarios"
  SSO-4 "Documentation of the edge pedestal in advanced scenarios"

  – 32 week plan:
  CDB-8 "ρ^* scaling along ITER relevant path at both high and low β"
  SSO-2.3 "ρ^* dependence on confinement, trasport, and stability in hybrid scenarios"
  SSO-3 "Real-time q-profile control in hybrid and steady-state scenarios"

Hybrid Scenario Development Time Line



Focus Area 1: Expansion of Operating Range

- **Motivation**
  - Hybrid plasmas at low B_T and high I_p can suffer from operating too close to the H-mode threshold (using previous pumped upper SND shape)
  - Extension to higher I_p and B_T is needed for ρ^* scaling studies, and increases the absolute performance of hybrids on DIII–D
  - Increase beta from β_N ~3 to β_N ~4 to improve fusion performance

- **Considerations**
  - Need to develop lower SND shape for IEA/ITPA joint experiments with JET and AUG (and to emulate the ITER shape)

Plan for Expansion of Operating Range

- **12 Week Experimental Plan**
  - Hybrid development in lower SND shape (0.5 day)
    - Should improve hybrid operation when close to H-mode threshold
  - Hybrid performance at high I_p and B_T (0.5 day)
    - Extend hybrid regime to 1.6 MA and 2.1 T (q95 ≈ 3), and optimize performance (plasma shape, error field correction, density etc.)
- **32 Week Experimental Plan**
  - High I_p and B_T continued (1 day)
    - Contains small ρ^* case for future ρ^* scaling experiments
  - Increasing the beta limit (2 days)
    - Increase no-wall stability limit using high ℓ_i approach
    - Exceed no-wall beta limit using ECCD to stabilize 2/1 NTM

Focus Area 2: Improved Understanding of Important Physics

- **Motivation**
  - One of the primary distinguishing aspects of the hybrid regime is the sustainment of a stationary current profile with q_{min} >1. This allows operation without sawteeth and triggering of 2/1 NTM at high β_N values
  - While the presence of the 3/2 NTM correlates with q_{min} > 1, its role is not clear. It may act to pump poloidal flux outwards, or drive central counter-current drive via the kinetic Alfvén wave, or redistribute the neutral beam current drive profile. This process needs to be understood to project this regime to ITER
  - A second distinguishing aspect of the hybrid regime is the remarkably high confinement factors achieved. Is this related to the H-mode pedestal height?

Plan for Improved Understanding of Important Physics

- **12 Week Experimental Plan**
  - MHD effects (1 day)
    - See if driven kinetic Alfven waves drive central counter current to maintain q_{min} >1
    - Determine if tearing modes are redistributing neutral beam ions
    - Study coupling of ELMs to tearing modes and the effect on the q-profile
- **32 Week Experimental Plan**
  - MHD effects continued (1 day)
    - Compare dominant 4/3 NTM hybrids with dominant 3/2 NTM hybrids
  - Role of H-mode pedestal (1 day)
    - Compare with AUG using both hybrid and conventional H-mode plasmas

Focus Area 3: Validation in Reactor-Like Conditions

- **Motivation**
  - To date, hybrid regime in DIII–D has been obtained with $T_i > T_e$ and high toroidal rotation, which are plasma conditions quite different from those expected in ITER
  - Because both of these effects can improve confinement, it is important to assess $T_i \approx T_e$ and low rotation conditions to be able to extrapolate to ITER with more confidence

Plan for Validation in Reactor-Like Conditions

- **12 Week Experimental Plan**
  - Expanding hybrid scenario to low rotation plasmas (2 days)
    - Includes studying ExB shear effects, NBCD effects, ELM effects (QH-mode)
    - Substitute counter beams for co beams during flat-top
    - Investigate balanced NBI start up of hybrid scenario
  - Dependence on T_i/T_e at low collisionality (1 days)
    - Use 3rd harmonic ECH at low B_T to minimize NBI power (shot #121985 used only 3.5 MW of NBI)
- **32 Week Experimental Plan**
  - Dependence on T_i/T_e continued (2 days)
    - 6 gyrotron experiments at higher B_T (2nd hamonic ECH)
    - 1 day is integrated long pulse experiment with low rotation and high $\beta_N H/q_{95}^2$

Focus Area 4: Assessment of Extrapolation Issues

- **12 Week Experimental Plan**
  - none
- **32 Week Experimental Plan**
  - ρ^* scaling of transport (1.5 days)
    - Joint experiment with JET to extend range of ρ^* scan
    - Also study ρ^* dependence of beta limits
  - Divertor and ELM solutions (0.5 day)
    - ELM suppression with I-coil
    - Radiative divertor in ELM-free hybrid
    - Combine with 0.5 day from thrust IT-1

Summary of 12 Week Experimental Plan for Thrust IT-2 in Priority Order

– Validation in reactor-like conditions
  - Low rotation plasmas ✓ — 2 days
  - Dependence on T_i=T_e ✓ — 1 day

– Expansion of operating range
  - Development of lower SND shape — 0.5 day
  - Higher I_p and B_T ✓ — 0.5 day

– Improved understanding of important physics
  - MHD effects ✓ — 1 day = 5 days total

(✓ means ITPA Joint Experiment)

Summary of Additional Experiments for 32 Week Plan for Thrust IT-2

– Improved understanding of important physics
  - Role of H–mode pedestal ✓ — 1 day
  - MHD effects continued ✓ — 1 day
– Validation in reactor-like conditions
  - Dependence on T_i/T_e continued ✓ — 2 days
– Expansion of operating range
  - High Ip and BT continued ✓ — 1 day
  - Increasing the beta limit — 2 days
– Assessment of extrapolation issues
  - ρ^* scaling of transport ✓ — 1.5 days
  - Divertor and ELM solutions — 0.5 day = 9 days total

(✓ means ITPA Joint Experiment)

Summary of ITER Contributions for Thrust IT-2

- **Provide ITER with a robust, reliable operating regime that has substantially increased performance over the conventional, sawtoothing, ELMy H-mode regime**
  - Validation of improved confinement and sawteeth-free operation in low rotating plasmas with $T_i \approx T_e$
  - ρ^* extrapolation of transport and beta limits in hybrid plasmas to burning plasma experiments
  - Modeling of expected q profile and transport for hybrid plasmas in ITER based on DIII–D physics understanding
  - Compatibility between hybrid H-mode pedestal and ITER ELM solution/radiative divertor