Pathway to Fusion Beyond ITER

By
Tony S. Taylor

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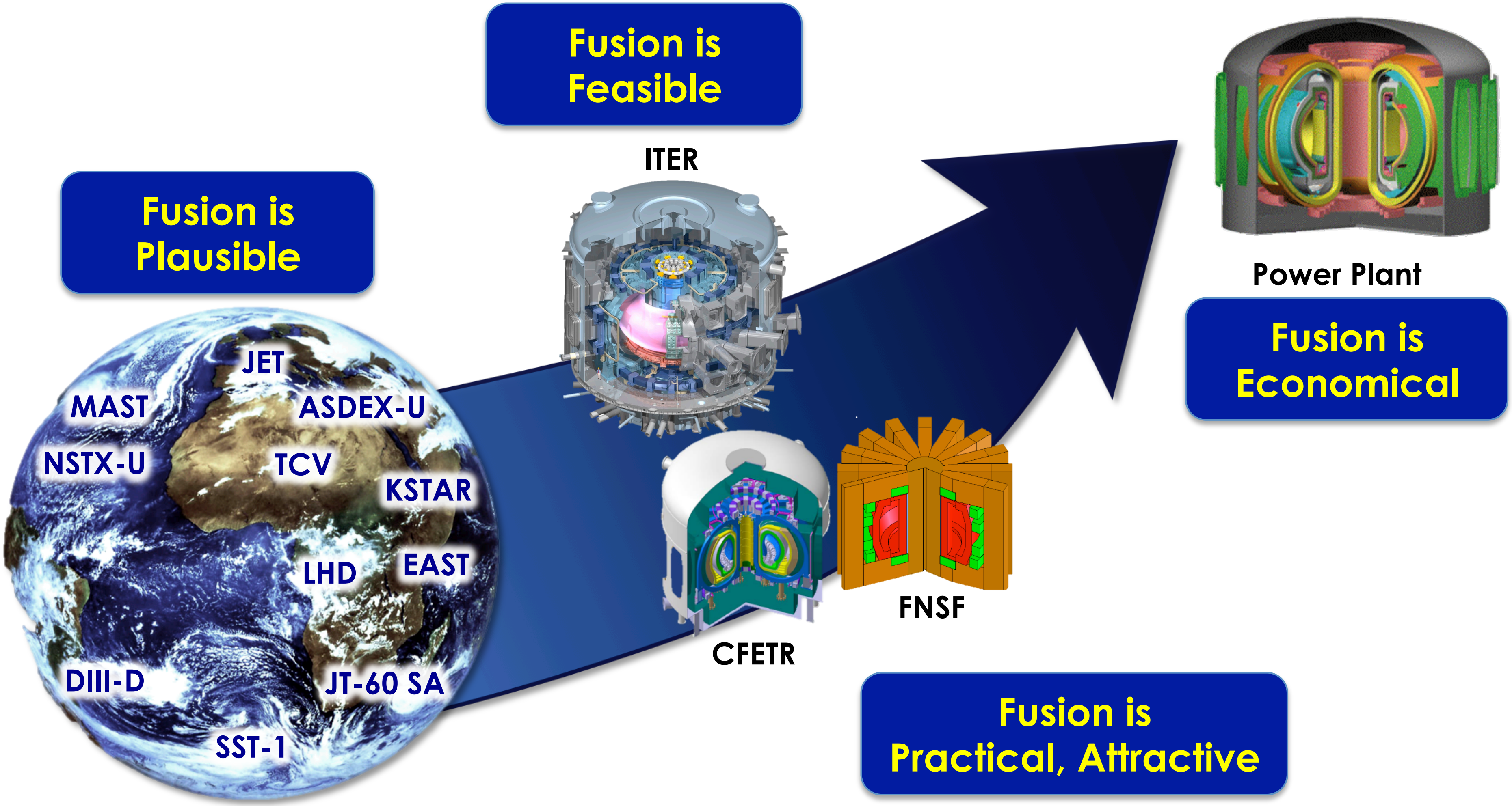
GENERAL ATOMICS

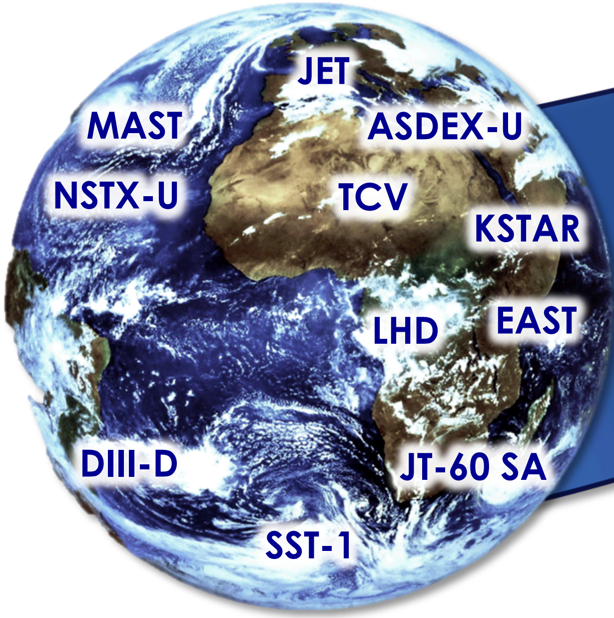
Path to Fusion Energy



Fusion Facilities of the World

Path to Fusion Energy

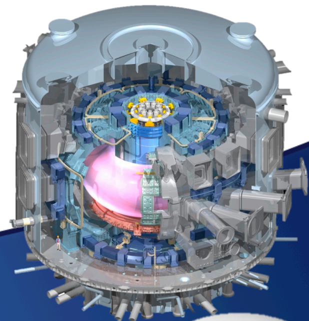
Scientific and Technical Basis

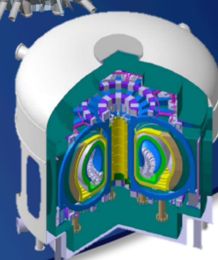


Fusion Facilities of the World

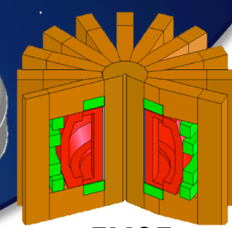
High Gain Burning Plasma Physics

ITER

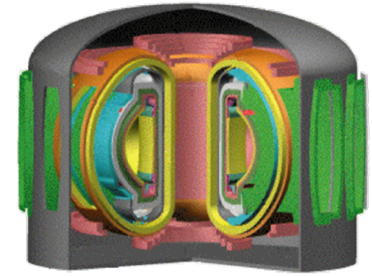




CFETR



FNSF



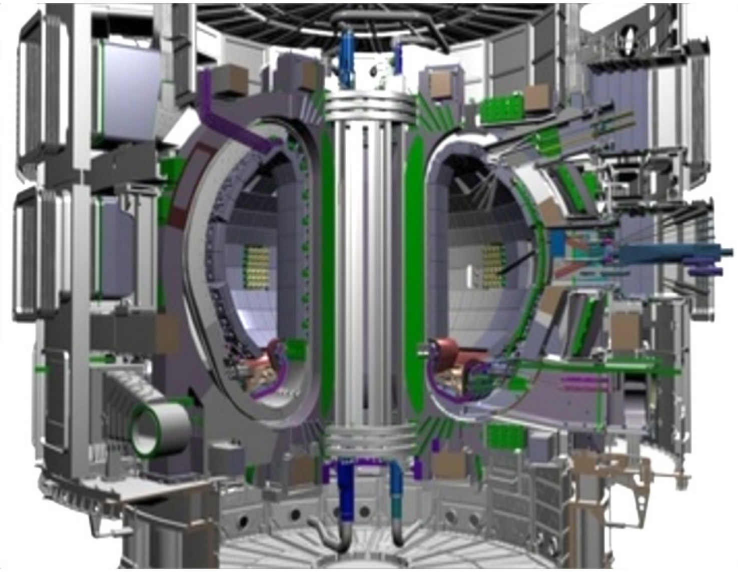
Power Plant

Electrical Energy Demonstration

- Breed its own Fuel
- Materials and components in extreme conditions
- High performance steady-state

ITER Is an Essential Element of the Path to Fusion Energy

- **Frontier fusion science in burning plasmas**
  - Self-heating, impacts profiles (heating + pressure + magnetic fields) → strong nonlinear complex behavior
  - Fast alpha population → unique and interesting instability physics
  - Extend transport and stability to physics to lower ρ^*
  - Grand challenge for theory and numerical modeling
- **Progress in fusion technologies**
  - Remote maintenance and handling
  - Test blankets for tritium breeding
  - Tritium processing systems
  - Hardened diagnostics
  - Large, high field superconducting magnets
  - High heat flux energy removal systems
  - Long pulse, high power density heating and current drive systems
  - Core fueling methods
  - Plasma current quench detection/remediation systems

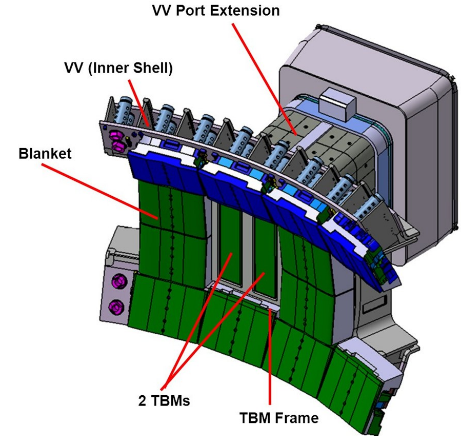


ITER

Tritium Self-Sufficiency is a Critical Issue for Fusion Energy

- **World's lithium reserves can meet global energy needs for >15,000 yrs at present rate of consumption**
- **Cost of tritium from present sources is prohibitive and supply is limited**
  - Tritium cost is approximately $100 M/kg
  - 1GW electric for 1 day requires ~ ½ kg of tritium
  - → 5 % short-fall = $0.1/kW-hr

ITER Test Blanket Module Port

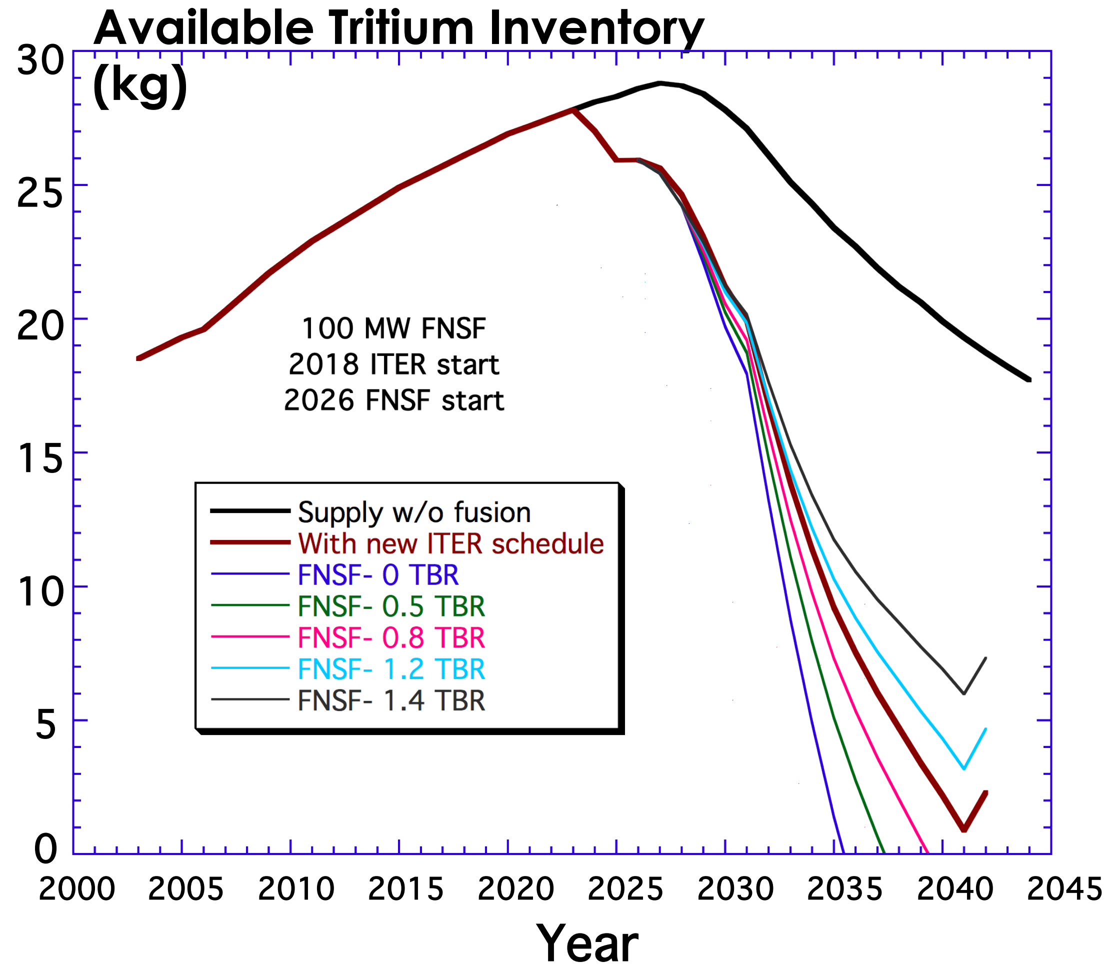


- **Challenges remain in development of blankets for power plants**
  - Produce sufficient tritium for the plant
  - Produce high quality heat → economical electricity production
  - Survive in harsh environment: neutron fluence, temperature, and magnetic loads
- **Blanket development and test facilities are needed**
- **FNSF/CFETR will validate tritium breeding and test components under fusion conditions**

Fusion Step Following ITER Must Consider the Tritium Supply for Fusion

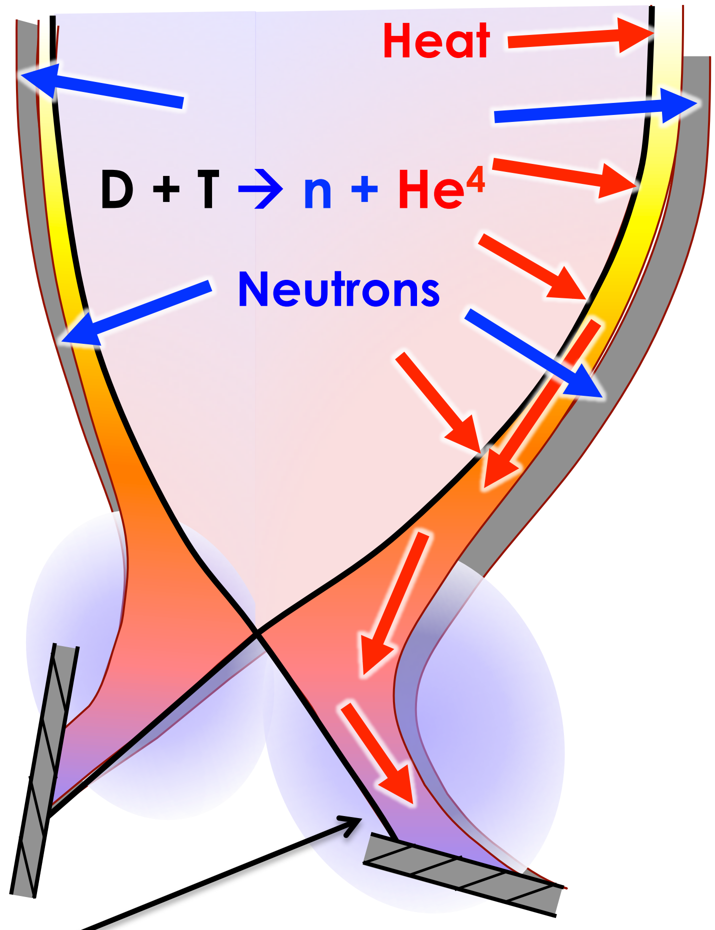
- **A 1000 MWe DEMO will burn 12 kg tritium per month**
- **Tritium inventory available following ITER is very low**
- **Next Step**
  → Must breed tritium very early
  → Must use little for start-up

[M.E. Sawan, TOFE (2010)]



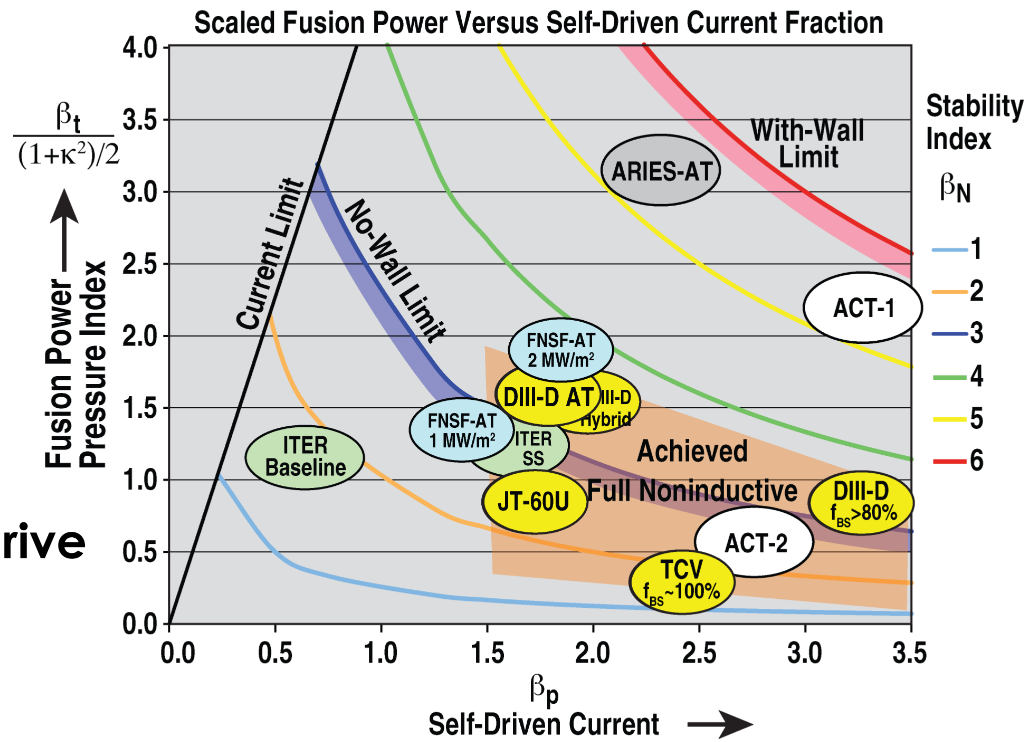
Fusion Reactor Creates Unique Challenge for Materials Due to Extreme Heat and Neutron Fluxes

- **Neutron penetrates deeply into chamber walls and has distinct effect on economics**
  - 2-3 GW volumetric heat source – 80%
  - Enables tritium breeding
  - Reduced lifetime $N_{lifetime}$ of walls due to high dpa (100 dpa → $N_{lifetime}$ ~ 5 years) → nuclear material test facilities needed
- **Surface heating of the divertor from plasma power flow can also limit lifetime**
  - Heat source is largely alpha particles – 20%
  - Peak heat fluxes near or above material limits for melting (~10 MW/m²) → material test facilities
  - Plasma solutions are likely needed to meet heat exhaust requirements → Can be addressed in today's experiments → Test in FNSF/CFETR



Attractive Economical Tokamak Solutions Lead to Both High Power Density and Steady State

- **Fusion power density increases with plasma pressure**
  $P_F \approx p^2 \approx \beta^2 B^4 \approx (\beta_N I_P B)^2$
- **Limits**
  - β limited by stability
  - I_P limited by stability and current drive scheme
  - B limited by mechanical forces
- **Steady state → external current drive**
  - Reduces cyclic thermal and and mechanical stresses
  - Increases duty cycle
  - Exploits higher self-driven current proportional to β_P or $(\beta_N \times q)$



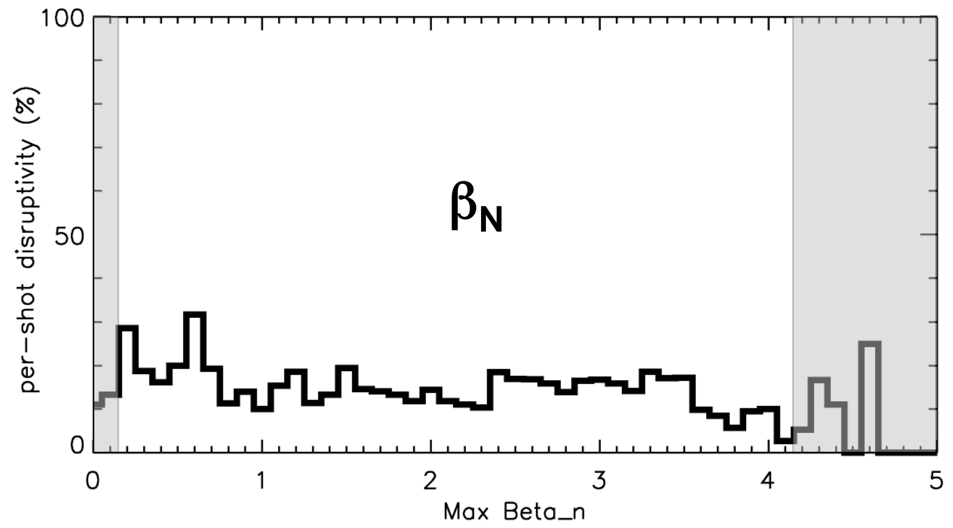
I_P = Plasma Current
B = Toroidal Field

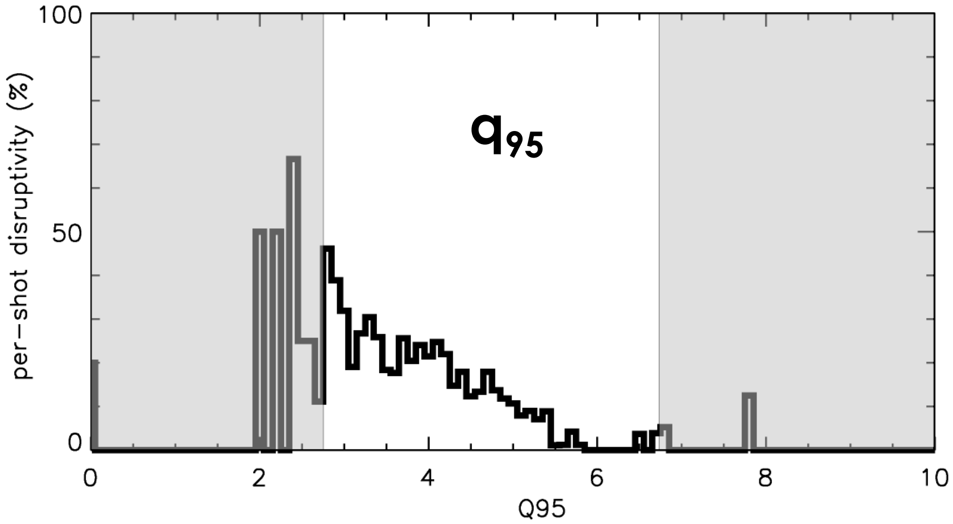
$$\beta = \frac{\text{Kinetic Pressure}}{\text{Magnetic Pressure}}$$

- **Range of experimentally demonstrated full noninductive discharges includes the operating regime of ITER-SS, FNSF-AT, and ACT-2 (revised ARIES-AT)**
- **FNSF will demonstrated integrated test of high power steady state**

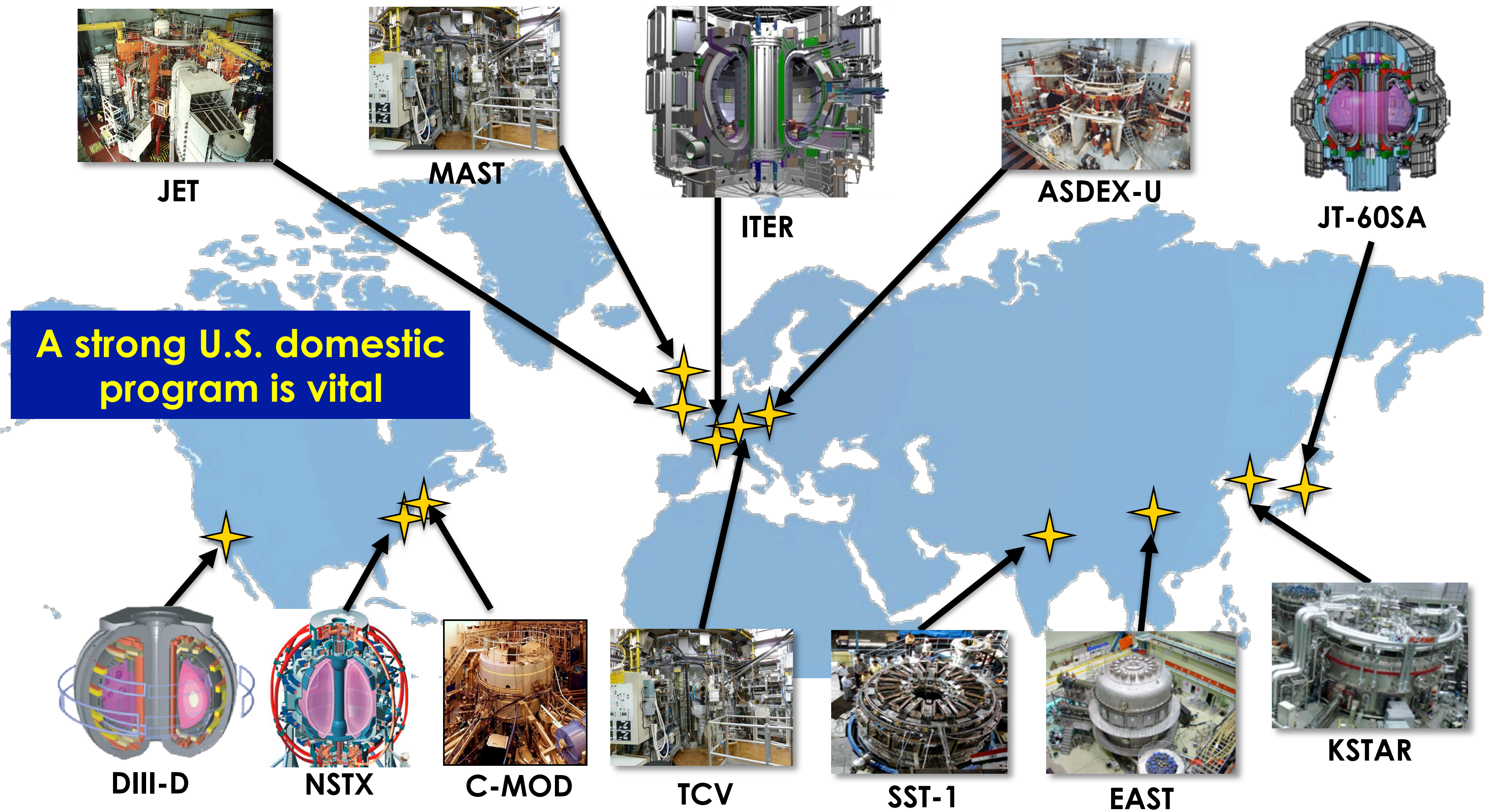
Steady-State Solution Regimes Exhibit Lower Risk to Disruptions

- **DIII-D disruption data base**
- **Disruption frequency does NOT increase with higher beta operation**
- **Disruption frequency decreases with higher q_{95}**
- **→ Stable operation for high noninductive fraction discharges**





The World Fusion Program Must Work Together to Prepare for ITER and the Future



Gifted and talented work force is required to support & exploit ITER

Summary Comments

- Fusion is an abundant energy source for the future of mankind
- ITER is an essential element of the path to fusion energy
- Challenges remain → can be addressed by blanket and nuclear/material test facilities, and FNSF/CFETR
- A strong U.S. domestic, and world, fusion programs are required to prepare for the future and make fusion energy a reality