Integrated Scenarios

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GENERAL ATOMICS

Outline

- **Introduction**
  - Integrated?
  - Scenarios?
- **Progress on experiments and modeling since Snowmass 2002**
- **Key issues remaining**
- **Related activities in the ITPA steady-state operation topical group**

What are “Integrated” Scenarios?

- **“Integrated” is redundant here, but emphasizes that the research involves combinations of the pieces discussed in previous talks – not “disintegrated”, “differentiated”, or “segregated” components**

- **Three areas of integration are under investigation by experiment and modeling:**
  - Compatibility in the core plasma of current and pressure profiles and the sources under burning plasma conditions
  - Compatibility of core burning plasma conditions with the boundary conditions imposed by open field lines intersecting a solid surface
  - Control of the operating point and the ability to access it

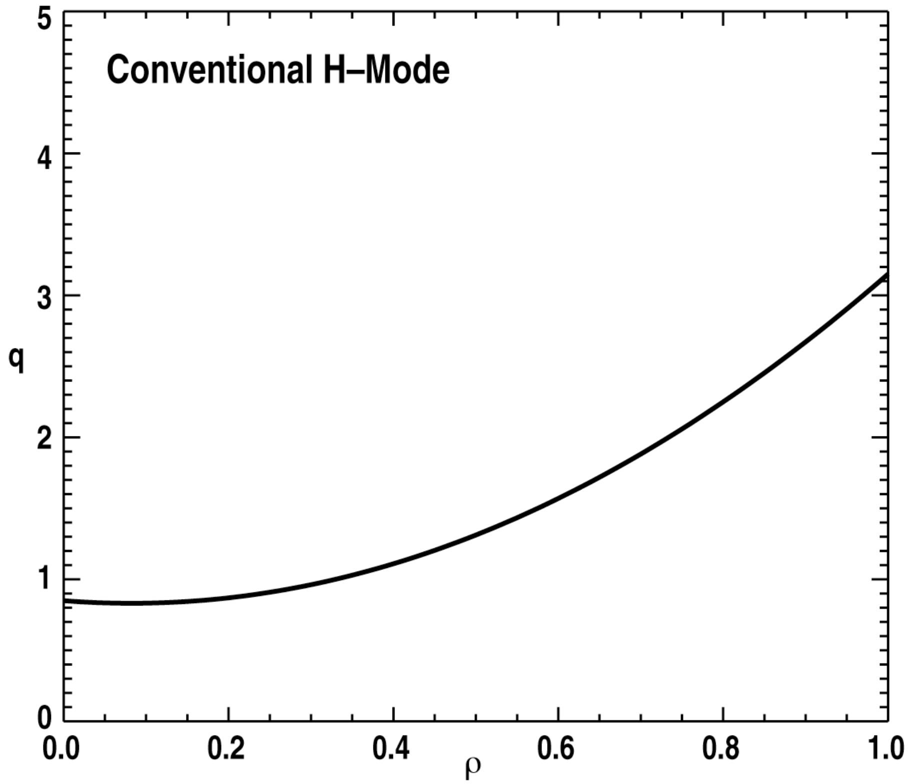
What "Scenarios" are Being Actively Investigated in Tokamaks?

- **Conventional H-mode (ITER baseline scenario)**
- **High-performance steady-state (ITER and beyond)**
- **Hybrid (ITER and perhaps nuclear test facility)**
- **Advanced inductive scenario (ITER?, Pulsed powerplant?)**

These scenarios are most easily characterized by their magnetic configuration

Conventional H-mode is the Baseline Scenario for ITER Burning Plasma Operation

ITER Goal: $Q \geq 10$ for $\geq 2\,\tau_R$



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Approach:

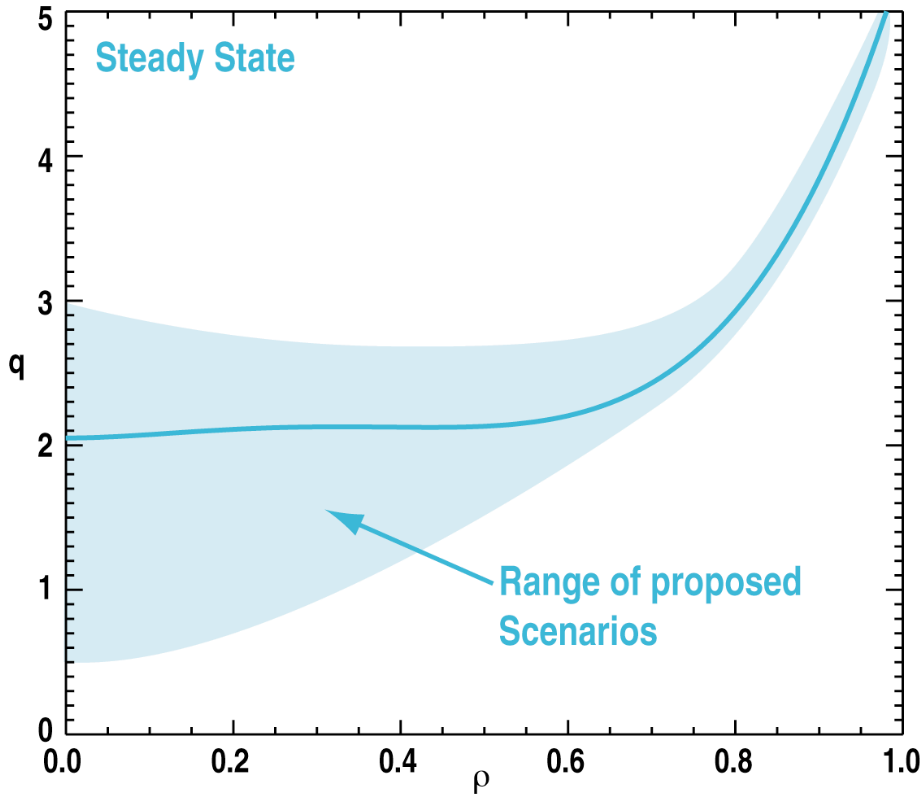
- Maximize gain through maximum current $\Rightarrow q_{95} = 3$
- Maximize macroscopic stability by operating well below ideal MHD limits for global modes $\Rightarrow \beta_N \leq 2$
- Maximize confinement through H-mode operation
- Minimize complexity by requiring only control of the boundary and scalar quantities

Limitations:

- Inherently pulsed
- Maximum magnetic energy configuration

Steady-State Scenario Opens the Potential for Continuous Burning Plasma Operation in a Tokamak

ITER Goal: Q ≥ 5 non-inductive



Approach:

- Minimize current to allow full non-inductive operation ⇒ $q_{95} = 5$
- Maximize fusion gain by operating near macroscopic stability limits for global modes ⇒ $\beta_N > 3$

Limitations:

- Active control may be required both for access to the operating point and maintaining it
- Upper limit on confinement quality set by current drive requirements

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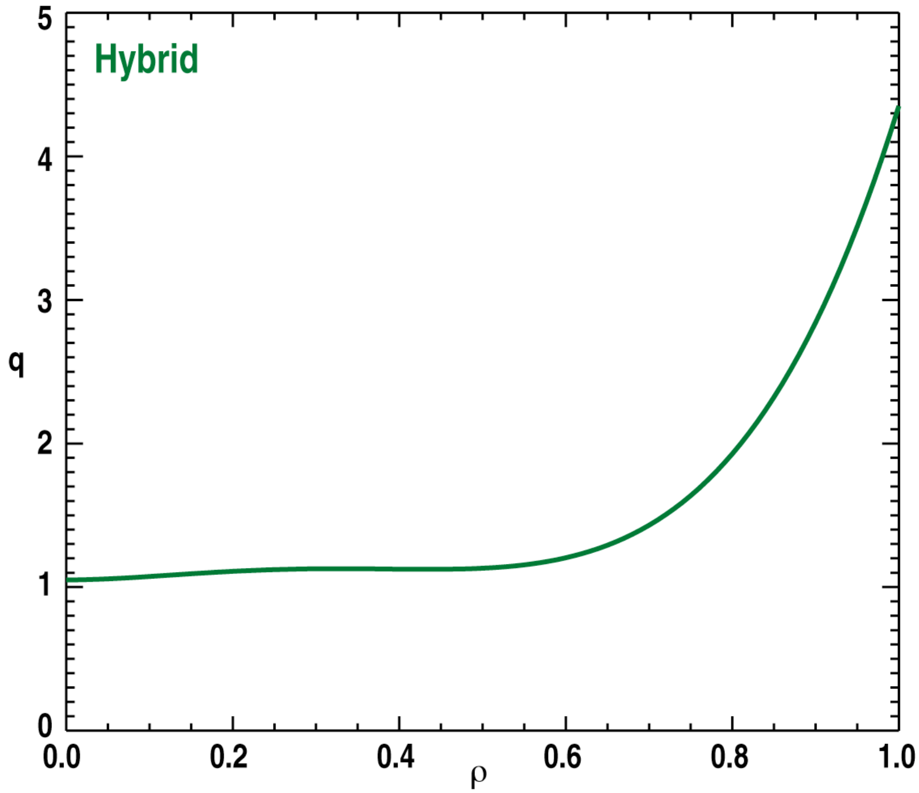
Hybrid Scenario for ITER Aims at Maximum Fluence in Pulsed Inductive Operation

ITER Potential: $P_{fus} \geq 400$ MW for 1 hour



Approach:

- **Maximize inductive pulse by reduction in current $\Rightarrow q_{95} = 4$**
- **Maximize fusion power by operating near macroscopic stability limits for global modes without rotation or active feedback $\Rightarrow \beta_N$ ~3**

Limitations:

- **Present candidate scenarios reach stationary conditions with essential contributions from non-ideal MHD instabilities**

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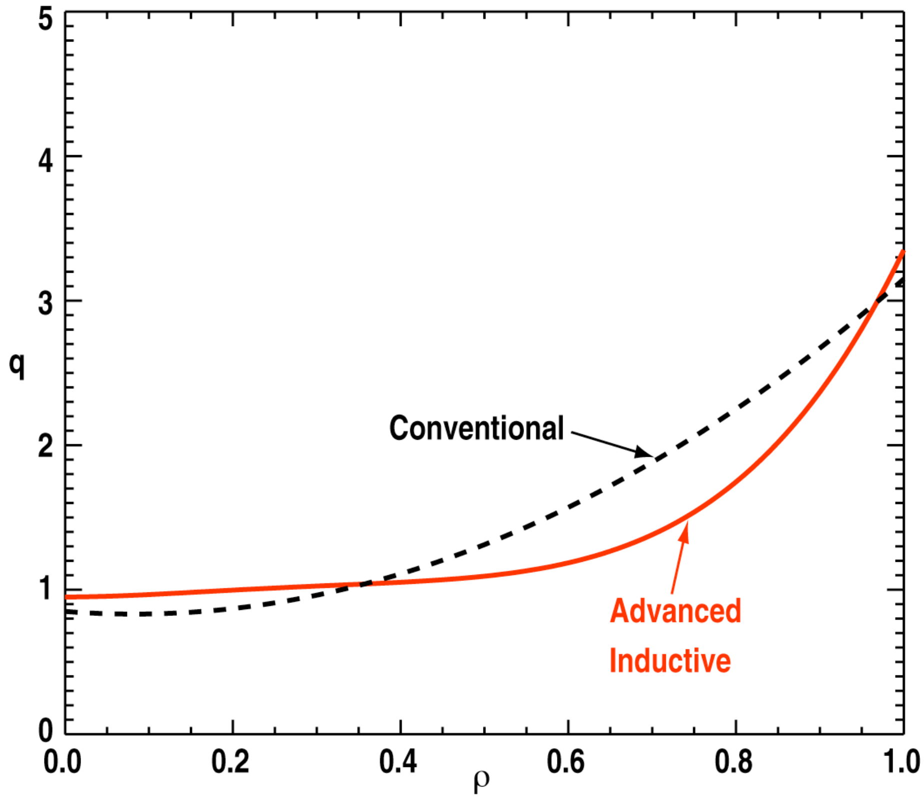
Advanced Inductive Scenario Aims for Maximum Fusion Power and Has Potential for Pulsed Ignition in ITER

ITER Potential: $P_{fus} \geq 700$ MW; Q > 50



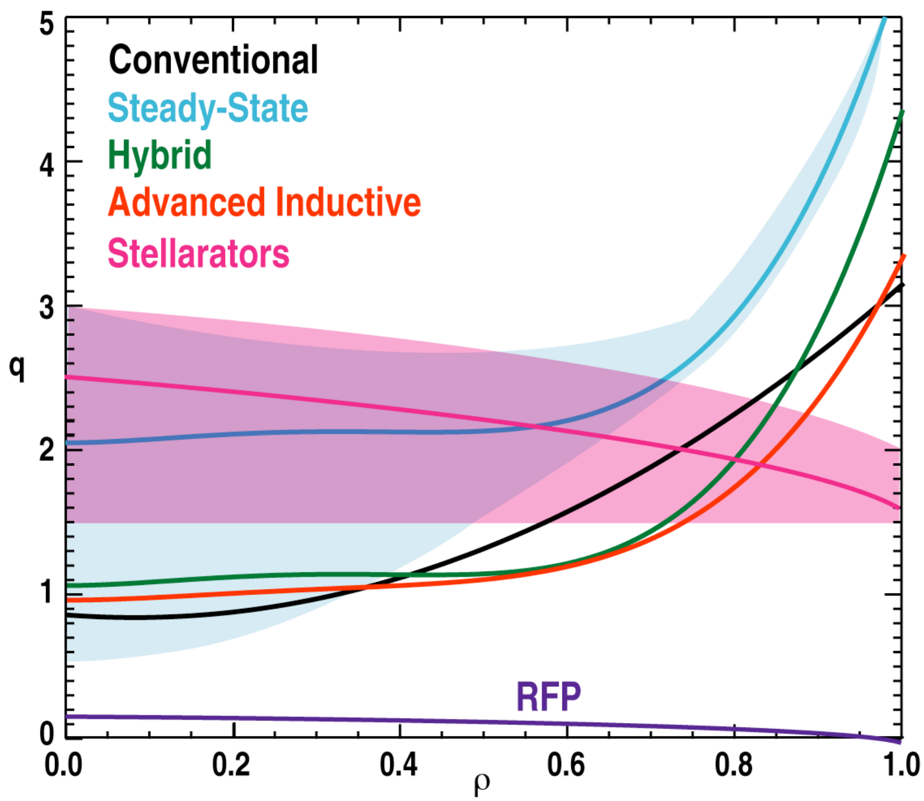
Approach:

- Maximize pressure by operation near the macroscopic stability limit to global modes without rotation or active feedback $\Rightarrow \beta_N \sim 3$
- Maximize gain by maximizing current $\Rightarrow q_{95} = 3$
- Minimize complexity by using only boundary and scalar control

Limitations:

- Maximum thermal and magnetic free energy

Characterization by Magnetic Configuration Shows the Natural Linkage to the Alternate Concepts



- Spherical torus uses similar q profiles but strong axisymmetric modification of the boundary to low aspect ratio
- RFP seeks optimum with q << 1 everywhere
- Classical stellarators add non-axisymmetry to gain steady state
- Optimized stellarators focus on quasi-2D configurations while maintaining steady-state and optimizing performance

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Progress in Conventional H-mode Integrated Scenario Experiments Since Snowmass 2002

Most of the integration work for this scenario was carried out in the 1990's, documented in the ITER Physics Basis, and exploited in formulating the present ITER design

Since Snowmass 2002:

- **Extensive work in the individual physics areas (see previous talks)**
- **Development of ELM mitigation/suppression techniques (pellet pacemaking, stochastic edge) – but not yet at ITER parameters**
- **Development of real-time tearing mode suppression/prevention – but not yet at ITER parameters**
- **Demonstration of density peaking in the absence of Ware pinch**
- **Burn control and α simulation experiments done with ICRH**

Progress in Conventional H-Mode Integrated Scenario Modeling Since Snowmass 2002

This was a major emphasis of Snowmass 2002. Since Snowmass 2002:

- **Extensive work in individual physics areas (see previous talks)**
- **Integration of H-mode pedestal models into modeling codes**
- **Integration of dynamical models for ELMs into modeling codes**

Progress in Steady-State Scenario Experiments Since Snowmass 2002

Prior to Snowmass 2002, several tokamaks had demonstrated transient high performance sufficient for a steady-state scenario. Some examples of high performance for several τ_E existed but under conditions not suitable for full non-inductive operation. Since Snowmass 2002

- **Demonstration of high performance at ~90% non-inductive for a resistive time**
- **Demonstration of full non-inductive with good alignment for $< \tau_R$**
- **Optimization of performance through variation of the q profile and boundary shape has begun**
- **Demonstration of full non-inductive high bootstrap fraction discharges ($f_{BS} > 0.8$) – but only at q_{95} ~10**

Progress in Steady-State Scenarios Modeling Since Snowmass 2002

Integrated scenario modeling before Snowmass 2002 focussed on self-consistent ITB solutions. Since Snowmass 2002:

- **Development of new algorithms to find stationary solutions**
- **Incorporation of more complex heat transport models and built-in stability analysis**
- **Automated scenario optimization through feedback including realistic actuator constraints**
- **Self-consistent ITER scenarios obtained with Q > 5, based on existing experimental discharges**

Progress in Hybrid and Advanced Inductive Scenario Experiments Since Snowmass 2002

Just before Snowmass 2002: first candidate discharges and ITER hybrid mission developed independently. Since Snowmass 2002:

- **Extensive mapping of existence domain**
- **Demonstration of stationary discharges with performance at or above that expected for Q = 10 in ITER**
- **Documentation of the essential role of non-ideal MHD in the stationary current profile**

Progress in Hybrid and Advanced Inductive Scenario Modeling Since Snowmass 2002

No work done before Snowmass 2002. Since Snowmass 2002:

- **Free boundary solutions for ITER performed to determine whether $q > 1$ at current flattop is possible**
- **Stationary phase simulations indicate parallel neoclassical theory does not explain the stationary current profiles**
- **Limitations of day-1 ITER heat-rejection system exposed**

Remaining Issues for ITER

	Experiment	Modeling
Conventional	Compatibility of ELM mitigation with good performance Burn control tests	Accurate L/H threshold model
Steady-State	Stationary existence proofs Confinement scaling Define profile control requirements	Free boundary calculations of formation scheme with ITER actuators Stability calculations with ITER 1st wall Impact of high q_{95} and low collisionality on divertor solution
Hybrid	Confinement scaling Burn control simulation near ignition	Modeling of non-ideal MHD Impact of higher q_{95} on divertor solution
All Scenarios		Pedestal model Particle transport model Simulations of control Transport of energetic particles due to instabilities

ITPA Steady State Operation Topical Group

The ITPA SSO group has four major areas of activity:

- **Coordination of advanced scenario experiments**
- **Integrated modeling of advanced scenarios (conventional scenario modeling shared by CDBM and Transport Physics group)**
- **Validation of heating and current drive actuator models (code-code, code – experiment benchmarks)**
- **Development of profile control methods**

Current US members:
T. Luce (GA) (US Lead)
P. Bonoli (MIT) (Co-lead)
C. Kessel (PPPL)
M. Murakami (ORNL)
R. Prater (GA)
C. Phillips (PPPL) (US Lead 2002–4)

International chairs:
G. Sips (IPP) (Chair)
S. Ide (JAEA) (Co-Chair)
C. Gormezano (ENEA) (Chair 2002–4)

Observations from ITPA Experience

- **One metric of the effectiveness of an organization is whether it produces useful output that would not be available without the organization. I believe the ITPA SSO group has done this, but the growth rate is about 2 years**
- **The key elements were:**
  - Effective leadership
  - Shared goals (does not require agreement in the way to reach them)
  - Consistent, active participation
- **US program is the clear leader in integrated scenario modeling and in advanced scenario development**
- **Close connection between experiment and modeling is essential**