

Optimizing the Magnetic Configuration

Theme 5 Overview and Research Requirements

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On behalf of Theme 5 Members



Theme 5 originates from the FESAC Toroidal Alternates Panel (TAP)

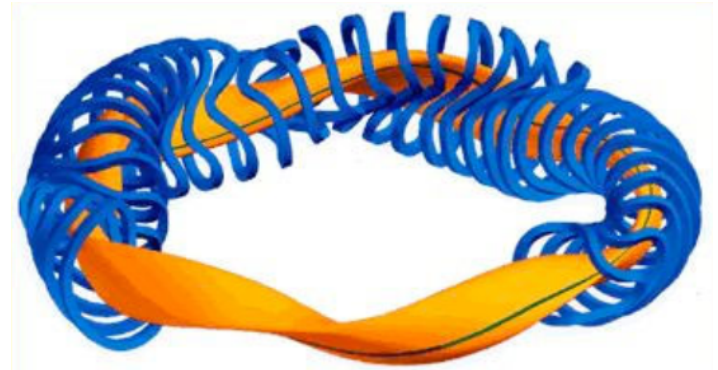
- Five toroidal alternates were examined by TAP, with focus on goals for the ITER era
 - Stellarator
 - Spherical Torus (ST)
 - Reversed Field Pinch (RFP)
 - Compact Torus (CT):
 - Field Reversed Configuration (FRC)
 - Spheromak
- Toroidal alternates also appear in FESAC Priorities, Gaps, and Opportunities (Greenwald report)
 - PGO is basis for the organizational structure in Themes 1 to 4
 - Examined research gaps to DEMO
 - Most issues in PGO generic to all magnetic configurations

Theme 5 organization and membership

- **Chairs:** John Sarff, Michael Zarnstorff, Sam Barish (OFES Champion)
- **Stellarator Panel**
David Anderson, Jeff Freidberg, Jeff Harris, Chris Hegna, Steve Knowlton, Mike Mauel, Allan Reiman, Andrew Ware, Harold Weitzner
- **Spherical Torus Panel**
Steve Sabbagh, Nikolai Gorelenkov, Chris Hegna, Dick Majeski, Jon Menard, Martin Peng, Aaron Sontag, Vlad Soukhanovskii, Dan Stutman
- **Reversed Field Pinch Panel**
Hantao Ji, Brett Chapman, Daniel Den Hartog, Gennady Fiksel, Piero Martin, Farrokh Najmabadi, Stewart Prager, Carl Sovinec
- **Compact Torus Panel (FRC and Spheromak)**
Bick Hooper, Elena Belova, Mike Brown, Sam Cohen, Alan Hoffman, Scott Hsu, Tom Intrator, Tom Jarboe, Richard Milroy, Mike Schaeffer, Carl Sovinec, Xianzhu Tang, Simon Woodruff, Masaaki Yamada

Stellarator: Goal and Accomplishments

- **TAP ITER-era goal:** Develop and validate the scientific understanding necessary to assess the feasibility of a burning plasma experiment based on the quasi-symmetric (QS) stellarator
- **Accomplishments**
 - Many stellarator devices have been successfully built and operated.
 - Energy confinement similar to tokamaks; H-mode and transport barriers observed.
 - A volume averaged beta of $\langle\beta\rangle > 5\%$; disruptions are not observed.
 - Near steady-state operation with record energy throughput for toroidal plasmas.
 - Density limit set by radiative power balance, far above an equivalent Greenwald limit; exceeding the density limit results in a relatively slow radiative collapse.
 - Quasisymmetric fields shown experimentally to reduce low-collisionality neoclassical transport.
 - 3D fields shown in tokamaks to control ELM's and provide neoclassical rotation drive.



Stellarator: Research Requirements

- Simpler coil systems with reduced fabrication risk and cost
 - Optimize physics and engineering metrics; use trim coils; assess coil topologies and technologies
- Integrated high performance of quasi-symmetric configurations
 - Experiments achieving low collisionality & high beta; compatible divertor
- Predictive capability including full 3D equilibrium effects
 - Merge 3D equilibrium with major physics codes; magnetic islands and stochasticity physics
- Power handling consistent with optimized quasi-symmetric configurations
 - Exploit higher density operation; improve modeling for 3D peaking effects
- Operational limits for density and beta
 - Assess level of bootstrap current that affects limits
- Impurity and fusion ash accumulation
 - Assess with quasi-symmetry; collaboration with LHD & W7-X studies; integrated modeling
- Anomalous transport reduction with quasi-symmetric shaping
 - Experiments achieving high ion temperature and strong zonal flows

Stellarator: Research Requirements (2)

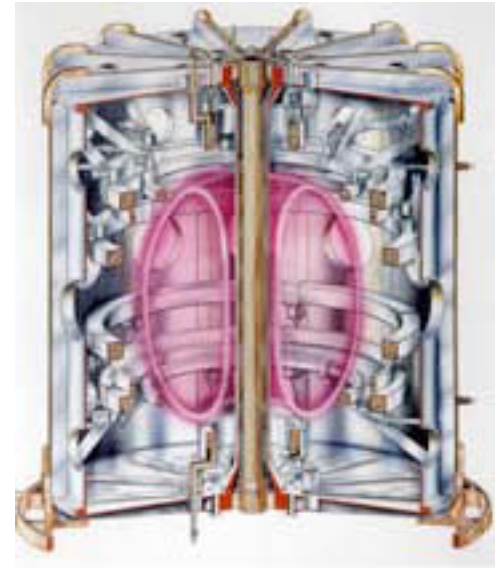
- Energetic particle instabilities
 - Assess possibility for high density mitigation of energetic particle instabilities
- Disruptions
 - Experiments with varying plasma current at stability limits
- ELM-free high performance
 - 3D-capable theory & modeling to understand edge pedestal behavior
- Profile sensitivity of operational limits
 - Profile control for quasi-symmetric configurations with large bootstrap
- Superconducting stellarator coils
 - High temperature superconductors (HTS) and flux shaping components

Spherical Torus: Goal and Accomplishments

- **TAP ITER-era goal:** Establish the ST knowledge base to be ready to construct a low aspect-ratio fusion component test facility that provides high heat flux, neutron flux, and duty factor needed to inform the design of a demo. fusion power plant
(*Note: research requirements in ReNeW extend to ST-based reactor*)

- **Accomplishments**

- Up to 160kA of non-inductive startup using coaxial and point-source helicity injection.
- Handoff of non-solenoidal startup to inductive drive.
- Sustainment of CTF-level $\langle\beta_T\rangle=15\text{-}20\%$ for 3-4 resistive diffusion times, with a majority of non-inductive current.
- Access to $\langle\beta_T\rangle=40\%$, controlled above the no-wall limit.
- Lithium divertor increases energy confinement, mitigates NTMs and ELMs, enables $\beta_N=7.2$
- Active control of $n = 1$ resistive wall modes and $n = 3$ error fields decreases disruption probability for long-pulse discharges.
- Strong dependence of confinement on B_T unlike high R/a . Measured short wavelength turbulence consistent with ETG theory.
- Experimental and theoretical connection established between fast particle loss and toroidal Alfvén eigenmode avalanches, providing understanding with $V_{\text{fast}}/V_{\text{Alfvén}} \gg 1$.



Spherical Torus: Research Requirements

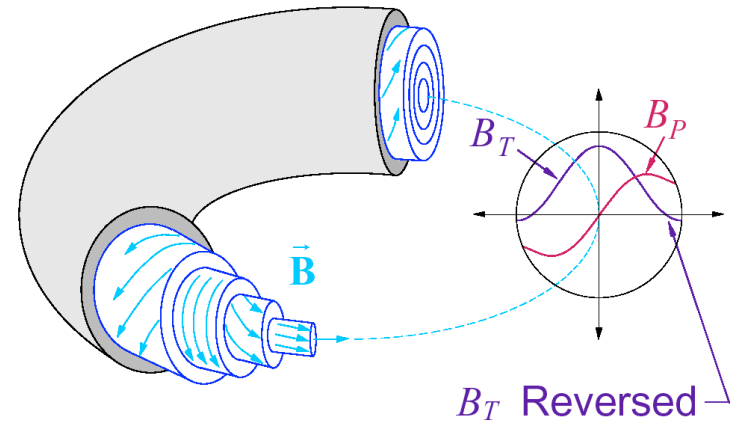
- Non-inductive plasma initiation and ramp-up of the current
 - Electrode and/or RF current formation; NBI and/or RF current ramp-up
- Plasma-material interface for high heat flux in the low R/a limit
 - Advanced divertors, liquid metal wall; integrated power and particle control; comprehensive scrape-off layer physics models & codes
- Energy transport mechanisms and scaling, and dependence on R/a
 - Extend experiments to low collisionality and low rotation input regimes; high and low- k ES and EM turbulence measurements
- Stability and steady-state control at high beta with low disruptivity
 - Non-axisymmetric coils (RWM, ELM, error fields); improved models and diagnostics for energetic particle effects; localized current drive for NTMs
- Technological development to support unique ST challenges
 - Normally-conducting, radiation-tolerant magnets; continuous NBI
- Integration of the elements
 - Demonstrate sustained high beta performance to meet ITER era goal; 2X to 4X increase in B_T field and plasma current

Reversed Field Pinch: Goal and Accomplishments

- **TAP ITER-era goal:** Establish the basis for a burning plasma experiment by developing an attractive self-consistent integrated scenario: favorable confinement in a sustained high beta plasma with resistive wall stabilization

- **Accomplishments**

- 10-fold increase in energy confinement using transient current profile control.
- Spontaneous helical equilibrium at high I_p , with improved confinement.
- Simultaneous $T_e \sim 2$ keV and $T_i \sim 1$ keV in Ohmic heated plasmas. Energetic ions and electrons are well-confined.
- High beta plasmas produced (up to 26%) that exceed Mercier and pressure-driven MHD tearing theoretical limits. No fast disruptive behavior observed.
- Active feedback stabilization of multiple resistive wall modes. Discharge lengths up to 0.5 s (>10 RWM growth times).
- 10% current drive by Oscillating Field Current Drive demonstrated.
- The physics of magnetic self-organization has been advanced, with strong connections to plasma astrophysics.

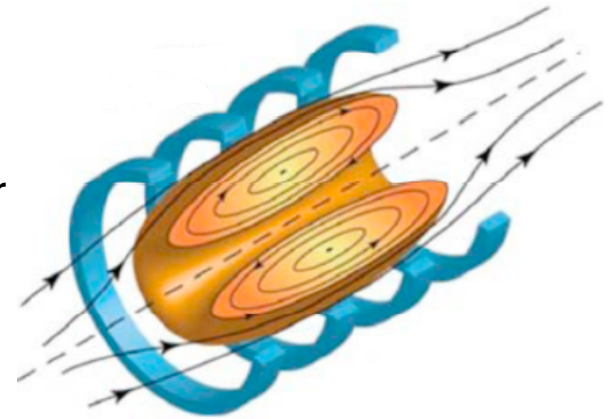


Reversed Field Pinch: Research Requirements

- Understand transport mechanisms and confinement scaling
 - Extend to higher Lundquist number, S , and lower ρ^* ; gyro-kinetics at low q
- Efficient sustainment of the plasma current
 - Test AC helicity injection at high S ; evaluate bootstrap at low R/a
- Integration of current sustainment and improved confinement
 - Plasma models and codes with two-fluid capability and transport physics
- Develop boundary control suited to low toroidal field geometry
 - Poloidal/toroidal divertors; liquid walls; radiative core; impact on stability
- Energetic particle effects
 - NBI for super-Alfvenic ions; adapt codes like TRANSP and NOVA
- Determine beta-limiting mechanisms
 - Auxiliary heating, with pulse length sufficient for thermalization
- Active control of MHD instabilities
 - Optimized feedback; extend for 3D shaping to optimize single-helicity state
- Self-consistent reactor scenarios
 - Demonstrate integration with plasma performance meeting ITER era goal

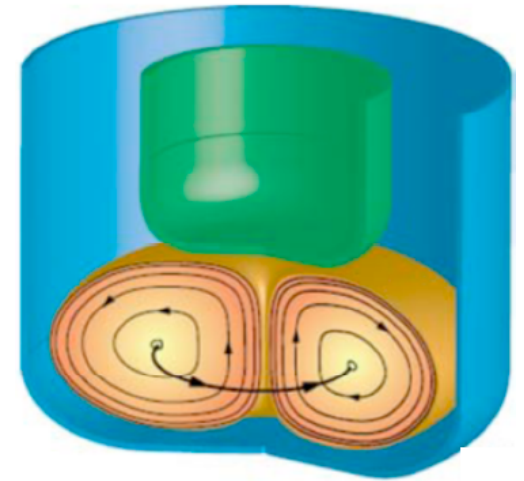
Compact Torus: Goal and Accomplishments (FRC)

- **TAP ITER-era goal:** Demonstrate that a compact toroid (CT) with simply connected vessel can achieve stable, sustained or long-pulse plasmas at kilovolt temperatures, with favorable confinement scaling to proceed to a pre-burning CT plasma experiment
- **FRC Accomplishments**
 - FRCs produced and sustained with low-MW input power in well-conditioned experiments, with $(T_e + T_i) > 200$ eV
 - Wall conditioning controls recycling
 - Transport in FRCs that are formed and sustained by rotating magnetic fields found to have central resistivity ~ 5 times less than the average, edge-dominated values.
 - Successful formation and inductive sustainment of oblate FRCs stable to the $n=1$ tilt mode, and with improved stability to higher- n modes in the MHD regime by using external field shaping.
 - Hybrid fluid-PIC numerical simulations demonstrate oblate FRC stabilization using a combination of close-fitting conducting shell and energetic ions (NBI injection).



Compact Torus: Goal and Accomplishments (Spheromak)

- **TAP ITER-era goal:** Demonstrate that a compact toroid (CT) with simply connected vessel can achieve stable, sustained or long-pulse plasmas at kilovolt temperatures, with favorable confinement scaling to proceed to a pre-burning CT plasma experiment
- **Spheromak Accomplishments**
 - Steady-state inductive helicity injection formation demonstrated, with $B_T \sim 1\text{T}$, $I_p \sim 1\text{MA}$, $n \sim 1 \times 10^{20} \text{ m}^{-3}$, $T_e = 0.5 \text{ keV}$, and (transient) core electron energy confinement \sim tokamak L-mode.
 - Good agreement between whole-device, resistive MHD simulations (NIMROD) and experiment (SSPX).
 - Steady-state inductive helicity injection formation demonstrated ($I_{\text{tor}} \leq 34 \text{ kA}$, $I_{\text{tor}}/I_{\text{inj}} \leq 2$, $j/n \leq 10^{-14} \text{ Am}$) in good agreement with theory
 - New experiments exploring innovative buildup and sustainment techniques have started operation. (PBX, LANL-DRX).
 - Basic science investigations on the high-speed dynamics of helicity injection.



FRC: Research Requirements

- Stability at large s (the ratio of plasma radius to ion gyroradius)
 - Experimental capability at low collisionality and enough B to confine NBI fast ions; 3D hybrid MHD+kinetic codes
- Understand transport mechanisms
 - Mutli-point equilibrium profile diagnostics; non-invasive measurements of fluctuations associated with diamagnetic current drift
- Current drive and sustainment
 - Test rotating magnetic field (RMF) current drive; NBI injection for both fueling and current drive
- Fast particle effects
 - Theory for fast ion coupling to magnetosonic and other modes, and non-Maxwellian effects
- Heating to high temperature
 - Experimental capability for current drive, stability, and sustainment at ITER era goal performance

Spheromak: Research Requirements

- Sustainment and confinement
 - Well-diagnosed experiment with flexible power systems to assess improved helicity injection methods and non steady-state scenarios
- Plasma formation with improved efficiency
 - Modeling of formation and ramp-up scenarios; experimental verification
- Transport mechanisms
 - Diagnostic capability for equilibrium and turbulence measurements
- Beta limits
 - Auxiliary heating, and plasma shaping capability
- Particle balance and density control
 - Advanced boundary control techniques
- Fast particle effect on current drive, stability, and confinement
 - Theory and modeling for low q ; NBI source of fast ions
- Resistive wall mode control
 - Thin-shell experiment with active control or rotational stabilization
- Technology for long pulse operation

Toroidal alternates in Research Thrusts

- What is the best way to cast important questions involving the alternates:
 - Specific to each magnetic configuration?
 - More compelling organized around general scientific questions?
- Each configuration offers particular strengths for fusion development. Each requires a self-consistent and unique set of solutions to general scientific issues, e.g., confinement, stability, sustainment, controlled boundary interface, etc.
- Research on multiple magnetic configurations collectively advances and validates our understanding of fusion plasma science and technology
- Both of these perspectives are compelling, both are needed, and clearly not fully separable

Thrusts 16-18 advance configuration optimization

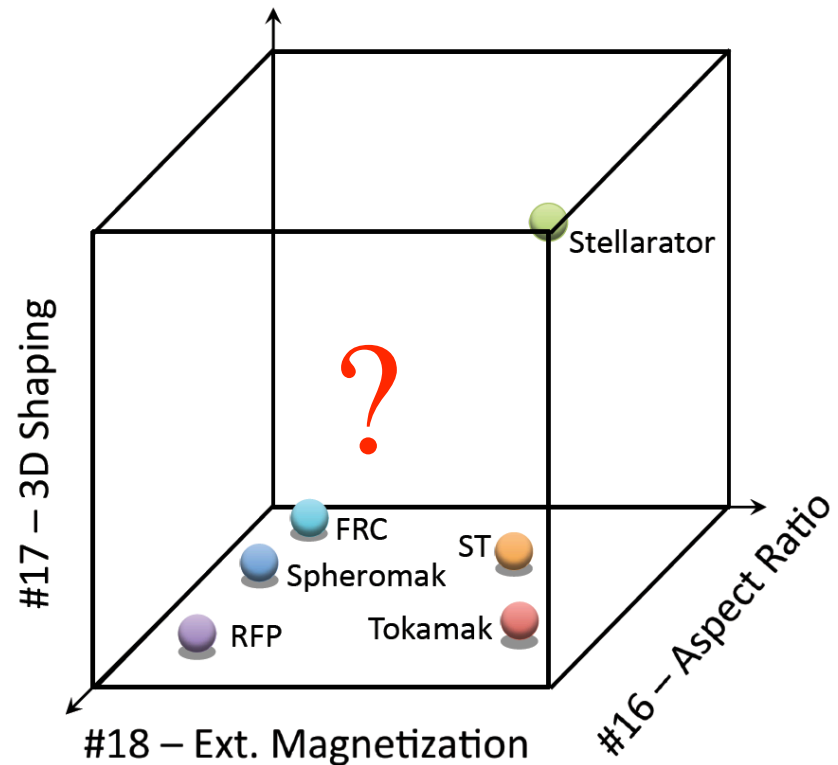
16. Demonstrate and understand sustained high beta plasma confinement at reduced aspect ratio
17. Optimize steady-state, disruption-free plasma confinement using 3D magnetic shaping, emphasizing quasi-symmetry principles
18. Achieve high performance plasma confinement using minimal externally applied magnetic field

Thrusts 16-18 advance configuration optimization

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18. Achieve high performance plasma confinement using minimal externally applied magnetic field

“spots” represent typical or historical view of the configurations

optimized configurations exist in this space, likely in the void



Connections to ReNeW Thrusts

- All thrusts advance alternates (and the tokamak of course)
- Alternates are major contributors to most thrusts
- #16-18 are primary thrusts for configuration optimization
- Strive for predictive capability in all configurations, thrust #6
- Capitalize on generic issues for boundary control, esp. #11
- Options for mitigating transient events, #2

3 = addresses primary research need(s); configuration is a primary contributor

2 = addresses significant research need; configuration is a major contributor

1 = configuration is a potential contributor and/or benefactor of thrust

Research Thrust	Stell.	ST	RFP	CT
1. Develop Capable and Reliable Measurement Techniques for Understanding and Controlling Burning Plasmas	2	2	2	1
2. Control transient events in burning plasmas	3	2	1	1
3. Understand how the presence of alpha particles in burning plasmas will change plasma behavior	1	2	1	1
4. Develop and qualify operational scenarios for achieving ITER burning plasma objectives	1	2	1	1
5. Develop and Demonstrate the Enabling Science and Technology For Controlling and Sustaining Fusion Plasmas	2	2	2	1
6. Develop Predictive Models for Fusion Plasmas, Supported by Theory and Challenged with Detailed Experimental Measurements	3	3	3	3
7. Develop High-temperature Superconductors and Other Magnet Innovations to Advance Fusion Research	2	2	1	1
8. Understand and explore the highly integrated dynamics of self-sustained plasmas dominated by alpha heating	2	2	1	1
9. Unfolding the Physics of the Boundary Layer Plasma	2	2	1	1
10. Understanding and Developing PMI Science and Technology	1	2	1	1
11. Innovations for Improved Power and Particle Handling	2	3	2	2
12. Demonstrate an integrated solution for plasma-material interfaces compatible with sustainment and control of an attractive core plasma	2	2	1	1
13. Establish the Underlying Science and Innovative Technology Needed for Fusion Power Extraction and Fuel Sustainability	1	1	1	1
14. Materials Science and Technology Needed to Harness Fusion Power	1	1	1	1
15. Create Integrated Models and Designs for Attractive Fusion Power Systems	1	2	1	1
16. Demonstrate and Understand High-Beta Toroidal Confinement at Reduced Aspect Ratio	2	3	2	3
17. Optimize Steady-State Disruption-free Toroidal Confinement, Emphasizing Quasi-Symmetry Principles	3	2	2	2
18. Achieve High Performance Toroidal Confinement Using Minimal Externally Applied Magnetic Field	1	1	3	3

Again, many thanks to...

- Theme members
- Panel leaders
- Thrust lead authors