ReNeW Theme 5 Report

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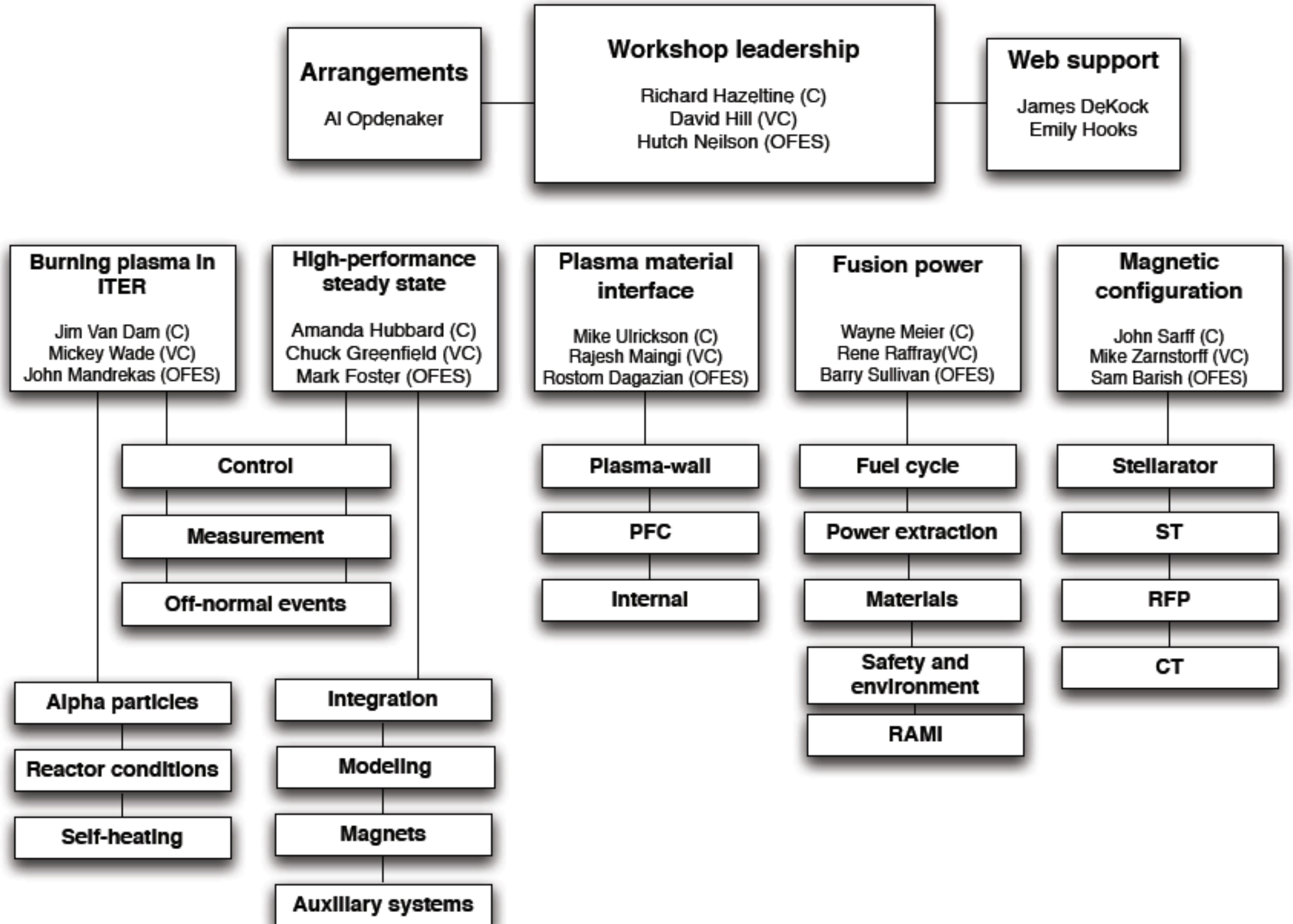
Theme 5 structure originates from the FESAC Toroidal Alternates Panel (TAP)

- Five toroidal alternates were examined by TAP, with focus on the “ITER era” (next 20 years)
  - 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: Towards a Long-Range Strategic Plan for Magnetic Fusion Energy” (Greenwald report)
  - Basis for the organizational structure in ReNeW Themes 1 to 4
  - Examined research gaps to DEMO
  - Many issues generic to all magnetic configurations

Theme 5 is organized by magnetic configuration



Theme 5 organization

John Sarff (UWisc), Theme Chair
Mike Zarnstorff (PPPL), Theme Vice Chair
Sam Barish, OFES Champion

Panel Chairs

Stellartor:	Dave Anderson (UWisc)
ST :	Steve Sabbagh (CU)
RFP :	Hantao Ji (PPPL)
CT :	Bick Hooper (LLNL)

Cross-configuration Task Force (internal organization to Theme 5)

	Mike Zarnstorff, chair
Stellartor:	Jeff Freidberg (MIT), Jeff Harris (ORNL)
ST :	Jon Menard (PPPL), Steve Sabbagh (CU)
RFP :	Brett Chapman (UWisc), Carl Sovinec (UWisc)
CT :	Richard Milroy (UWash), Mike Schaeffer (GA)
	+ Panel Chairs

Theme 5 Workshop

- March 16-19, at PPPL
- 43 white papers submitted
- All talks available at workshop website: http://www.pppl.gov/conferences/ReNeW/T5Workshop
- Affirmed scientific issues identified by TAP
- Proposed 3 main research thrusts

Following slides:

ITER era goals and issues → ReNeW research needs

Stellarator

- **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

- Tier 1 issues
  - **Simpler coil systems**: Can we find ways to reduce the fabrication risk of optimized high performance stellarators?
  - **Integrated high performance**: Can improvements observed in smaller experiments be carried over to a high performance level device and what are its required attributes?
  - **Predictive capability**: Can a predictive capability for quasi-symmetric systems be developed by building upon the work in the tokamak program coupled with a smaller experimental database?
  - **Power handling**: Can a divertor solutions be found for a 3D stellarator system compatible with quasi-symmetry?
- Tier 2 issues
  - **Operational limits**: What sets the operational limits on density and beta in quasi-symmetric stellartors?
  - **Impurity and fusion ash accumulation**: What determines impurity accumulation in stellarators ans what are the design implications?
  - **Anomalous transport reduction**: Can quasi-symmetry and optimized 3D shaping reduce turbulent transport and increase confinement?

Stellarator

- Tier 3 issues
  - **Disruptions**: how much bootstrap current allowed before disruption-like effects appear
  - **Profile sensitivity of operational limits**: can QS stellatrators operate with high performance without detailed profile control
  - **Superconducting stellarator coils**: can high Tc conductors be used

Spherical Torus

- **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

- Tier 1 issues
  - **Start-up and ramp-up**: Is it possible to start-up and ramp-up the plasma current to multi-MA levels using non-inductive current drive with minimal or no central solenoid?
  - **First wall heat flux**: What strategies can be employed for handling normal and off-normal heat flux consistent with core and scrape-off-layer operating conditions?
  - **Electron transport**: What governs electron transport at low-aspect ratio and low collisionality?
  - **Magnets**: Can we develop reliable center post magnets and current feeds to operate reliably under substantial fluence of fusion neutrons?
- Tier 2 issues
  - **Integration**: demonstrate integrated high-performance scenarios
  - **Disruptions**: avoidance and mitigation for reliable continuous operation
  - **RF heating/CD**: efficient heating and/or CD at MA-level in overdense plasmas
  - **3D fields**: control error fields, ELMS and RWM using far-away 3D coils
  - **Ion-scale transport**: predictive understanding of ExB shear and suppression of ion-scale turbulence and transport
  - **Fast-particle instabilities**: impact of super-Alfvenic ion driven instabilities on NBI heating, current drive, and torque at low-R/a

Spherical Torus

- Tier 3 issues
  - **NTMs**: avoidance of NTM in rotating plasmas near no-wall beta limit.
  - **Continuous NBI systems**: Continuous operation of positive or negative-ion energetic neutral beam systems

Reversed Field Pinch

- **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

- Tier 1 issues
  - Identify transport mechanisms and establish confinement scaling
  - Current sustainment
  - Integration of current sustainment and improved confinement
- Tier 2 issues
  - Plasma boundary interactions
  - Energetic particle effects
  - Determine beta-limiting mechanisms
- Tier 3 issues
  - Self-consistent reactor scenarios
  - Optimization of RWM control for a fusion environment

Compact Torus: Spheromak and Field-Reversed Config.

- ITER-era goal: “Demonstrate that a compact torid (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”

- Tier 1 FRC
  - Achieve global stability at large s in low collisionality, keV-range, steady-state
- Tier 2 FRC
  - Achieve efficient current drive and sustain the FRC configuration with good confinement
  - Reduce transport
- Tier 3 FRC
  - What are the effects of fast particles on current drive, stability and confinement
  - Demonstrate efficient heating methods (RMF, NBI, and compression) to increase the temperature to near burning-plasma conditions

Compact Torus: Spheromak and Field-Reversed Config.

- Tier 1 Spheromak
  - Achieve efficient time-average current drive simultaneously with good confinement
  - Develop an efficient formation technique to achieve fusion-relevant spheromak magnetic fields
- Tier 2 Spheromak
  - Determine underlying transport mechanisms and confinement scaling in low collisionality spheromak plasmas
  - Understand beta-limiting mechanisms
  - Understand particle balance and control of plasma density and impurities
- Tier 3 Spheromak
  - Evaluate the effect of fast particles on current drive, stability, and confinement
  - Demonstrate resistive wall mode control
  - Develop the technology for long pulse operation

Special challenge for research thrusts in Theme 5

- 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 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

- Each of these perspectives is compelling, each is needed, and clearly not fully separable

Proposed Research Thrusts from Theme 5

1. Demonstrate and understand sustained high beta plasma confinement at reduced aspect ratio

2. Optimize steady-state, disruption-free plasma confinement using 3D magnetic shaping, emphasizing quasi-symmetry principles

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

Demonstrate and understand sustained high beta plasma confinement at reduced aspect ratio

- Develop plasma start-up and ramp-up innovations with low transformer flux
- Demonstrate and understand a viable plasma-material interface at high heat flux, high temperature, and low density
- Understand electron and ion confinement in high beta, low collisionality ST plasmas
- Achieve and understand integrated, continuous high beta, low collisionality, broad current profile ST plasmas
- Develop normally-conducting radiation-tolerant magnets
- Deploy liquid metals, in particular liquid lithium, as plasma-facing components in the ST to solve PMI challenges and for stability and confinement enhancements
- Understand confinement and stability in compact tori with order-unity beta and with vanishingly small linked poloidal flux outside the last closed flux surface to attain unity aspect ratio
- Evaluate RFP stability and confinement with maximum pressure-driven “bootstrap” current at high beta and low aspect ratio

ST core elements

Optimize steady-state, disruption-free plas. conf. using 3D magnetic shaping, emphasizing quasi-symmetry principles

- Improve the design and construction of 3D coils through a combination of advanced engineering and physics optimization
- Demonstrate and understand the advantages of quasi-symmetry to attain high performance in stellarator confinement (e.g., high beta and low collisionality)
- Develop predictive capability for toroidal confinement that covers 3D shaping, building on and in collaboration with axisymmetric tokamaks and other magnetic configurations.
- Establish advanced divertor designs compatible with quasi-symmetric 3D shaping that can handle the necessary power exhaust and control neutral particle/impurity influx
- Identify and understand expanded operational boundaries using 3D shaping to avoid disruptions and other transient events; what is the physics of soft beta limits in stellarators and how much plasma current is permissible while avoiding the Greenwald limit, disruptions, and profile stiffness?
- Understand neoclassical and turbulent transport physics for controlling impurity transport and helium expulsion in quasi-symmetric stellarator configurations
- Predict and confirm the thresholds for fast ion losses with respect to the breaking of quasi-symmetry as well as through nonlinear kinetic interaction.

Stellarator core elements

Optimize steady-state, disruption-free plas. conf. using 3D magnetic shaping, emphasizing quasi-symmetry principles

- Apply varying degree of 3D shaping to a broad range of magnetic configurations to achieve specific benefits from 3D control tools and analysis techniques
- Develop innovative approaches to the production of the 3D fields required for optimized stellarator confinement and non-axisymmetric shaping of tokamaks and other magnetic configurations. This element spans the physics basis of efficient and flexible trim coils to the explorations of novel HTS steady-state configurations
- Understand improved RFP confinement using 3D shaping, by optimizing spontaneous single-helicity magnetic self-organization, or by application of non-axisymmetric field

Achieve high performance plasma confinement using minimal externally applied magnetic field

- Understand transport mechanisms and confinement scaling for inductively sustained RFP plasmas at high Lundquist number, with and without magnetic self-organization
- Test and understand steady-state current sustainment using AC magnetic helicity injection and its impact on confinement at high Lundquist number
- Establish divertor configurations and other advanced boundary control in axisymmetric plasmas with weak toroidal magnetic field
- Demonstrate high performance RFP plasmas, sustained using efficient current drive, with control of the plasma-material interface, and robust active feedback stabilization of resistive wall modes
- Study FRC stability for a wide range of the *s* parameter, the ratio of plasma radius to the Larmor radius
- Understand the integrated impacts of FRC physics in the fusion plasma, high-beta regime using NBI or RF, addressing transport, current drive, fast particles, heating and other important physics

RFP core elements

FRC core elements

Achieve high performance plasma confinement using minimal externally applied magnetic field

- Demonstrate spheromak formation and sustainment compatible with good confinement
- Understand the integrated impacts of spheromak physics in the fusion-plasma regime, including transport, beta limits, and particle balance and density control
- Develop modeling capability that will predict the synergy and scaling of macroscopic dynamics and transport when testing current drive and beta limits in low-*q* configurations such as the RFP and spheromak

Spheromak core elements

Role of system studies in toroidal alternate research.

- System studies are appearing in research needs discussion, especially for the lesser developed concepts (spheromak, FRC, RFP) that have not been examined in depth for a while.

- Potential fusion advantages associated with low field, high beta, compactness, etc. are often cited. Quantitatively, how much impact do these factors impart on the attractiveness of a fusion power plant?

- The advantages of various configurations may appear primarily as simplified assemblies or "lower" technology, e.g., non-linked coils, Ohmic heating to ignition, non superconducting magnets, etc. These could greatly impact RAMI

- Can/should ARIES have an ongoing broader set of system study activities that inform and guide toroidal alternate research? Full fledge system studies would no doubt be beneficial, but limited scope studies could have high impact in helping define attractive pathways and setting physics research priorities.