

# Thrust 18: Achieve High Performance Toroidal Confinement Using Minimal Externally Applied Magnetic Field

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Optimizing wrt  $B$ -external is motivated by potentially high payoff for reactor engineering and by plasma science.

- Smaller external magnets reduce engineering challenges and costs.
- Greater Ohmic heating reduces auxiliary system requirements.
- Compact toroids (cylindrical vessels) avoid accessibility problems and increase divertor flexibility.
- Research on several configurations improves plasma science knowledge base.
- Low  $B$ -external configurations help connect fusion to space and astrophysical plasma science.

## Findings of the Toroidal Alternates Panel guide selection of key scientific issues.

- Understand confinement and stability of low- $q$  configurations at high  $S$ , small  $\rho^*$ .
- Develop efficient current sustainment.
- Integrate approaches for sustainment, confinement, and boundary control

## Distinct advantages motivate work on three configurations: RFP, spheromak, and FRC.

- Reversed field pinch--toroidal vessel, paramagnetic, moderately high beta
  - large magnetic shear
  - nonlinear macroscopic stability
- Spheromak--cylindrical vessel, moderately high beta
  - moderately large and reversed shear possible
  - solenoid-free formation
- Field reversed configuration--cylindrical vessel, diamagnetic, resilient to translation
  - highest possible beta
  - leading candidate for advanced fuels

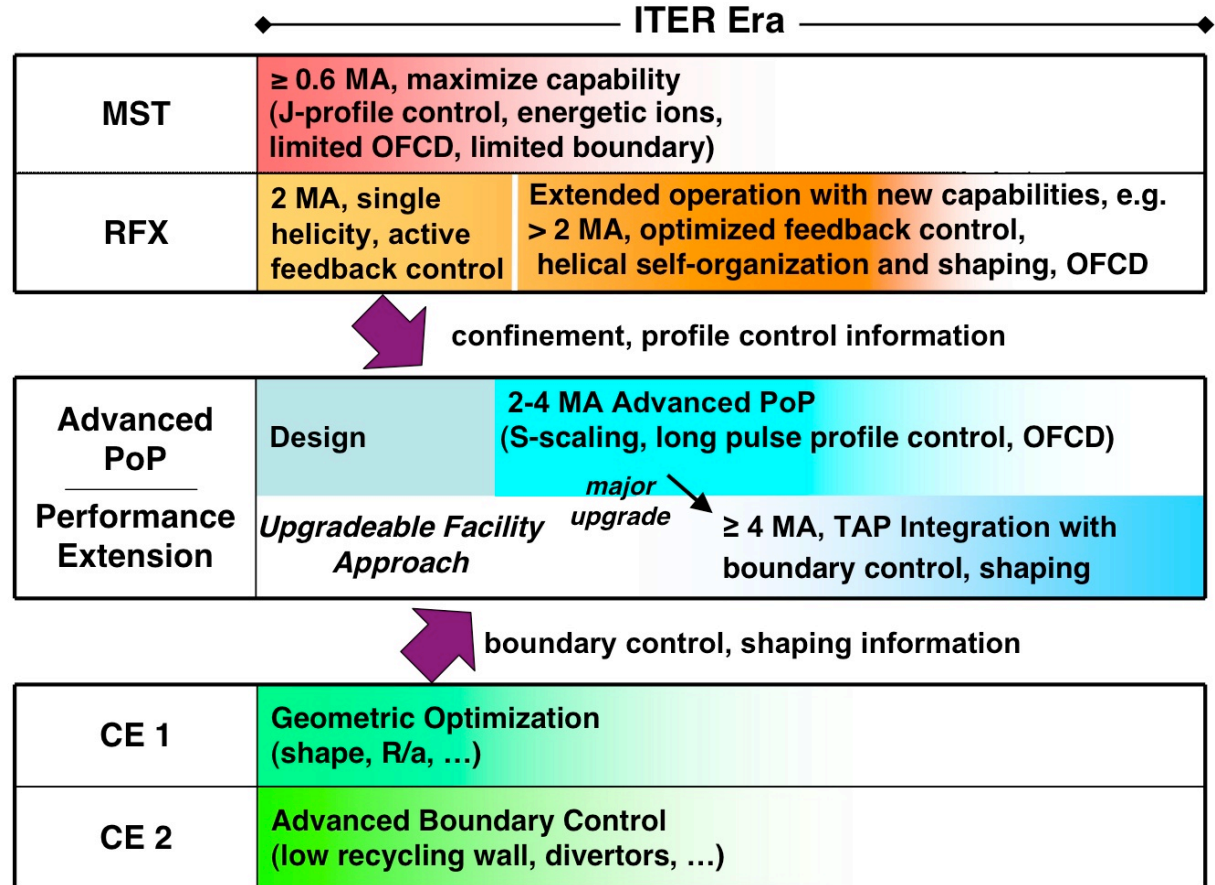
## Elements of the thrust are the activities that are needed for all three configurations.

- **Facility upgrade and construction**--maximize existing capabilities for scaling  $S$  and  $\rho^*$  but move to higher performance when justified.
- **Theory and simulation**--explore nonlinear effects on scaling and use as predictive tools to optimize and design.
- **Diagnostic development**--low- $B$  and turbulence measurements with integrated analysis are essential.
- **Development and application of control tools**--benefits of profile control are proven; expanded use and development of NBI and RF are needed.
- **Development for low-recycling walls**--low-field configurations are sensitive to edge conditions and are well suited to poloidal liquid metal flows.
- **System studies**--updates using modern engineering and plasma science information will quantify low  $B$ -external benefits.

# Readiness and scale of effort for the RFP: extending confinement scaling is central.

- Build upon confinement improvement and  $T_i, T_e > 1$  keV via transient control, active control of multiple external modes, and progress in single helicity.

- Upgrade power supplies, diagnostics, and profile control in existing experiments.
- Develop divertor and boundary control.
- Optimize geometry and shaping.
- With information from 1-3, proceed to upgradeable facility to confirm  $S, \rho^*$  scaling and integration.



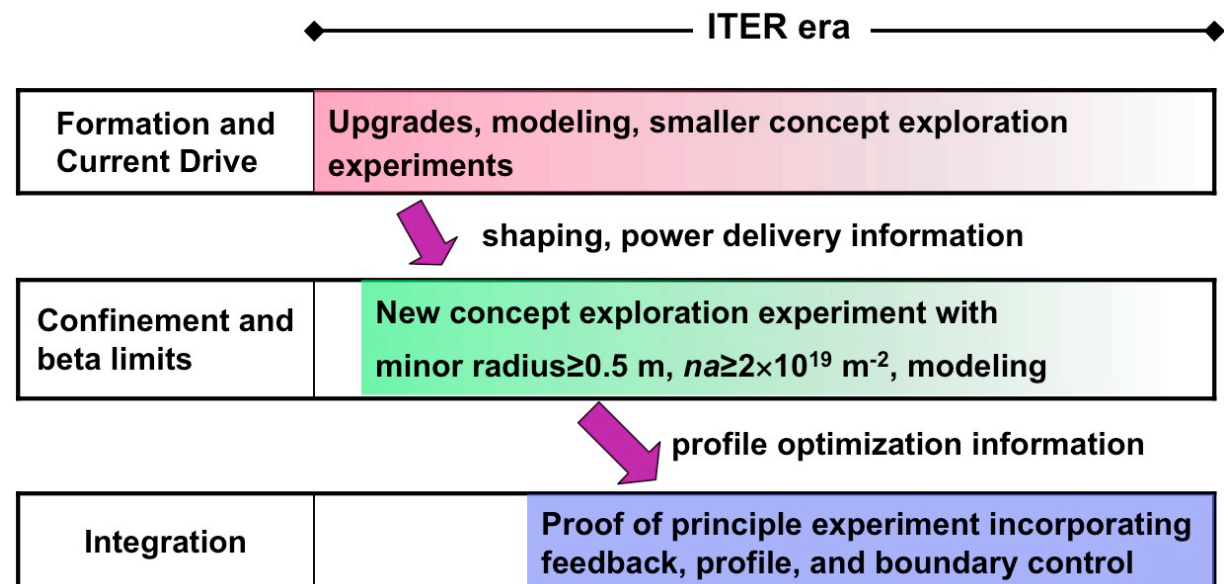
# Readiness and scale for the spheromak: concept development and scaling information are needed.

- $T_e$  up to 0.5 keV and estimated core 10 ms  $\tau_E$  during controlled decay demonstrate potential, but concept development is needed to avoid edge losses.

1. Upgrade of existing facilities and new innovative CE experiments will address current drive.

2. With positive results from 1 and from modeling, a larger CE experiment will study confinement scaling and beta limits.

3. RWM control will be developed and integrated at a PoP step.



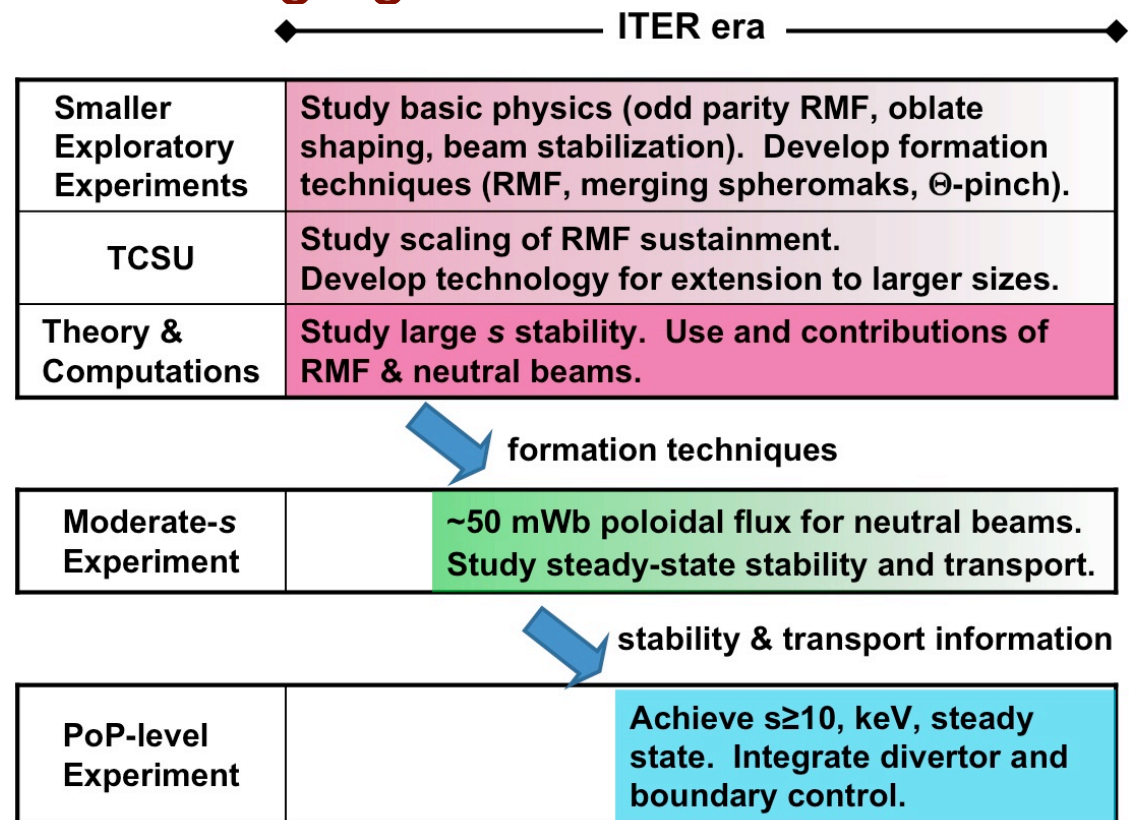
# Readiness and scale for the FRC: work focuses on scaling of kinetic effects.

- Recent results on RMF and merging spheromak formation, current drive, and theoretical understanding of kinetic effects are encouraging.

1. Upgrades to trap more magnetic flux will confine ions near 10 keV.

2. Based on 1, develop a new facility for large thermal- $s$  ( $=1/\rho^*$ ). Explore transport and current drive with minority energetic ions.

3. With favorable results from 1 & 2, construct PoP integration facility.



## Integration of elements provides the scientific and technological basis for fusion power at low $B$ -external.

- Configurations cover a space of parameters.
  - Paramagnetic to diamagnetic
  - Varying degrees of magnetic shear
  - Moderate to large beta
- Common activities will foster greater collaboration.
  - Diagnostic development for low- $B$
  - Technology for profile control
  - Technology for boundary control
  - Simulations integrating time-dependent  $\mathbf{B}$  and kinetics
- System studies quantify advantages and opportunities.

## Other scientific benefits extend to other fusion and plasma research areas.

- RFP and spheromak studies have ties to space, solar, and astrophysical plasmas.
  - Dynamo and magnetic self-organization
  - Magnetic reconnection and ion heating
  - Collimation and stability in astrophysical jets
- Kinetically dominated FRCs have application beyond MFE.
  - Magneto-inertial fusion
  - plasma thrusters

# **This effort will contribute to and benefit from other fusion research thrusts.**

- **Three-dimensional field shaping may improve confinement. (Thrust 17)**
- **Aspect-ratio optimization may enhance bootstrap current and influence mode coupling. (Thrust 16)**
- **Integrated data analysis and turbulence & fast-ion diagnostics are critical for ITER and predictive modeling. (Thrusts 1 and 6)**
- **Predictive modeling will be more reliable if it is validated on a broad range of configurations. (Thrust 6)**
- **Low-recycling wall technology is generally important for power and particle handling. (Thrust 11)**
- **Non-inductive current drive methods will benefit ST operation. (Thrust 16)**
- **CT injection may be useful for fueling and rotation in large machines. (Thrust 13)**

## Summary of ReNeW Thrust 18

- Optimizing  $B$ -external thrust represents high potential payoff activities for fusion.
- Elements of the thrust are largely common areas in diagnostics, technology, modeling, and systems.
- Readiness and scale of effort are configuration-specific, and development paths address the most critical needs.
- As a whole, the activities develop the scientific and technological basis for fusion power at low  $B$ -external.
- Activities are well connected to other areas of plasma science, in addition to other thrusts.