Spheromak Community Input to the FESAC Toroidal Alternates Panel

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1. Concept Description and Overall Vision

The spheromak is a toroidally symmetric confinement configuration distinguished from tokamaks by several attributes which offer a potential for significantly reduced reactor cost and size including: a simpler geometry, no material center post that could be damaged by energetic particles or radiation, and very high engineering beta. The simplicity and compactness of spheromaks makes construction relatively inexpensive and diagnostic implementation relatively easy. With comparable toroidal and poloidal fields and a low aspect ratio, their safety factor profile and hence stability physics is intermediate between that of low aspect ratio tokamaks and RFPs (Fig. 1). Because spheromaks involve self-organization, whereby poloidal and toroidal magnetic flux can convert from one to the other, they can be formed and sustained using a wide range of methods. This often involves fluctuations and turbulence, which impact energy confinement, so exploring how to sustain the configuration with sufficient energy confinement is a central theme of spheromak research. Advanced modeling tools have been benchmarked against experiment to provide moderate predictive capability with vigorous development ongoing.

2. Goal for the ITER era.

Over the next 20 years, a vigorous program should achieve sufficient understanding of spheromak science and technology to construct and have operating a pre-burning plasma experiment (PE-Level).

- The goal for spheromak research is derived from the advantages, current status, and the challenges facing the concept.
- If successful, the next step will be a cost effective burning plasma experiment that might be upgradeable to a Demo.
- If not successful in realizing a path to a reactor, we will apply our increased understanding of spheromak physics and technology to other fusion concepts such as the RFP, FRC, and tokamak as well as non-fusion-related plasma physics.

2.1 Spheromak advantages

- Simply connected geometry provides expanded options for addressing difficult reactor technology issues that may ultimately prove to be showstoppers for tokamaks.
  - Reactor studies [1, 2] show spheromaks can make an order of magnitude more economical reactor than a tokamak.
  - No material center post and no large, expensive toroidal field coils
    - Reduces blanket thickness and associated costs
  - Solenoidal field coils and open flux at the edge provide for a natural divertor to separate plasma particle loss heat load from areas of high neutron flux reducing total heat load to the first wall PFCs

        - Separating plasma heat loading to a remote divertor from neutron wall loading should allow smaller plasma facing surface area and independent optimization of wall/divertor systems.
        - Purely poloidal field at the wall allows easier pumping of liquid metals through blankets.
    - If success in all areas, provides for high engineering beta, high mass power density, possible ohmic ignition.
- Spheromak's unique characteristics contribute and connect to broader fusion science and technology community.
    - The concept explores toroidal confinement and stability in safety-factor regime between RFPs ($q < \sim 0.1$) and tokamaks ($q > 1$). (See Fig. 1).
    - Simple geometry and edge topology similar to FRC’s thus sharing many technological advantages.
    - Dominant physics theme of non-inductive current drive and startup applies to other fusion concepts.
        - Exploration of non-inductive CHI startup on NSTX [3].
        - Baseline startup for MAST [4] uses inductive formation technique developed on the S-1 spheromak [5] at PPPL. (Method still in use on MRX).
    - Benchmarking spheromak simulations against experimental data have made significant contributions to model validation (e.g. NIMROD).
    - Large pulse power and other systems make spheromaks a good test bed for plasma surface interaction studies.
- Spheromak physics has wide application beyond fusion: laboratory astrophysics & magnetic self-organization.
    - Overlap includes magnetic reconnection, ion heating, and turbulence; many researchers participate through the NSF/DOE CMSO [6].
    - Less constrained geometry is often easier to apply to astrophysical problems7 than toroidal boundaries.
        - Simple geometry also allows superior diagnostic access for laboratory experiments [8,9].

2.2 Status highlights

- Significant progress in performance has been achieved in smaller devices (e.g. SSPX [10]): $T_e \sim 0.5$ keV, $B_{tor} > 1$Tesla, $I_{plasma} \sim 1$MA, $n_e \sim 1\text{x}10^{20}\text{m}^{-3}$.
- Spheromaks can achieve good (but transient) core confinement approaching tokamak L-mode.
- Have achieved reasonable internal current profile control to avoid low-order mode rational surfaces by programming the initial flux distribution and discharge current. [11]
- Steady-state sustainment has been demonstrated both with electrodes [10,12,13,14] and inductively [15].
- Theory for steady inductive helicity injection current drive agrees with the measure profile and amplitude of the spheromak equilibrium produced [16].
- Have also demonstrated quasi-steady-state sustainment via repetitive cycles of pulsed build-up followed by partial decay [10].
- Ohmic heating to beta limit observed in some experiments [17,18] (i.e. CTX)

- Validated modeling tools have been developed - now providing moderate predictive capabilities [19,20,21,22,23]. [Many references are supplied to help clarify this imprecise statement.]

2.3 Issues that are particularly important, challenging, or unexplored

- Present methods of helicity injection have not shown good confinement when continuously driven in steady-state[10].
    - Relies on magnetic self-organization, plasma dynamo, magnetic reconnection and turbulence--all subjects of intense research even beyond MFE.
    - Can maintain magnetic field in steady state, but so far fluctuations are too large for good confinement.
    - Current drive saturates with unknown mechanism.
    - Multiplication of plasma current relative to the injector current is well-below reactor requirements.
- Confinement issues:
    - Unknown scaling versus size, magnetic field, plasma current, aux heating, Lundquist Number.
    - Confinement in the core near the magnetic axis is tokamak-like with low heat transport, but global confinement is dominated by large currents flowing on the edge.
        - Some modeling work [24,25] has looked at trying to reduce edge current while maintaining stability and internal current profile.
        - Extending the duration of good confinement will likely need further development in current profile control.
- Beta limit not well understood
    - Various pressure-driven modes observed, but not clear which will be important at higher S and longer discharge durations.
- Many other long-pulse issues are, as yet, unexplored
    - Would expect to need feedback control of RWM at some point.

2.4 Highest priority, near-term themes to advance goal of a spheromak burning plasma.

- Develop current drive that is compatible with good confinement.
    - Improve understanding of the coupling of the power source (coaxial and inductive) to the spheromak and how to sustain it with minimum perturbation to the axisymmetric configuration, optimizing both current-drive efficiency and confinement.
    - Explore alternate current sustainment methods
    - Explore pulsed reactor scenarios.
- Address spheromak physics issues at Te > 1 keV and larger size.
    - Understand confinement scaling.
    - Determine the beta-limiting processes in the spheromak plasma, and maximize the beta.

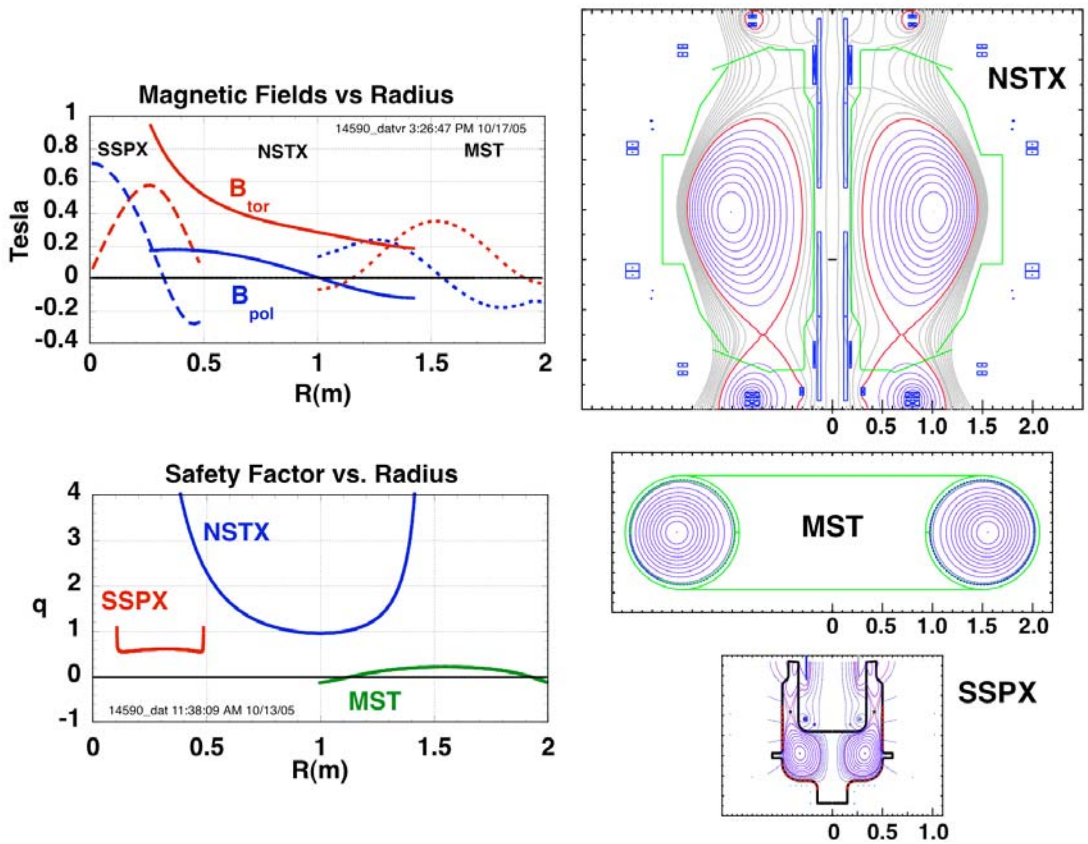

Figure 1. Magnetic fields, safety factor profile and relative size of the SSPX spheromak as compared to the NSTX spherical tokamak (ST) and the MST reversed-field-pinch (RFP).

3. Scientific and technical issues needed to reach goal.

3.1 KEY scientific and technical issues are summarized in Table 3.1.

Table 3.1 Scientific and technical questions to reach goal.

Physics Topic	Status	Issues	Questions
▪ Current drive / Sustainment	▪ Steady state or repetitively pulsed sustainment demonstrated with coaxial electrodes (~500kA). ▪ Steady State inductive CD demonstrated. (30kA toroidally averaged)	▪ Fluctuations/asymmetries are too large during steady-state for good confinement with either method. ▪ Efficiency of coupling external source to plasma needs to be improved. ▪ Current drive used on other concepts largely unstudied for spheromaks.	▪ Can we find a method or combination of methods that provides and optimizes both sustainment and confinement? ▪ Can power efficiency be improved? ▪ Are other current drive methods feasible? (NBI, RF, Bootstrap)
▪ Confinement	▪ Tokamak-like in the core (transiently), with current profile control. $\chi_e < 10$ m^2/s ▪ Global confinement set by large edge current (required for stability) ▪ Can maintain fluctuation amplitudes lower than 1% at the edge	▪ Scaling unknown (with size, current, aux heating, S) ▪ No independent control for heating, need aux heating to study. ▪ Global confinement dominated by power required to maintain current profile. (addressed under stability)	▪ How does confinement scale? ▪ What are limits to transport? What are the dominant causes of transport (e.g. overlap of mode-rational surfaces) ▪ Do transport barriers form in spheromaks? ▪
▪ Beta limits	▪ Limiting beta over wide range of parameters observed on SSPX. ▪ Evidence of ohmically heating to limit observed on some experiments. (CTX, SSPX) ▪ Mercier pressure limit exceeded transiently.	▪ Transport coupled to ohmic heating, therefore need aux heating (NBI?) to decouple for studying ▪ Ohmic power will diminish as Te increases. ▪ Classically, confinement should improve as Te increases	▪ Is beta limited by transport or by instability? ▪ At keV temperatures, do spheromaks ohmically heat to a beta limit or is auxiliary power required? ▪ How does it scale? (e.g. Troyon)
▪ Stability	▪ Demonstrated ideal stability to internal n=1, tilt and shift with current profile control and close-fitting conducting boundary. ▪ Toroidal and poloidal modes observed that correspond to low order mode-rational surfaces.	▪ Only done transiently using high power in edge, and for periods short compared to the heating time. ▪ More profile control needed to extend period of stability.	▪ Can q-profile be controlled in the spheromak for periods comparable to the heating time? ▪ Can existing techniques maintain stability when sustained for periods >> L/R decay time (of plasma currents or flux conserving wall)? ▪ Are there lower power methods of controlling the current profile?
▪ Boundary, particle control	▪ PFC condition critical to performance. ▪ Baking, discharge cleaning, Ti gettering produces regimes that are not dominated by radiation losses. ▪ -Refractory surfaces seem to be necessary.	▪ So far, Ti gettering required for good performance -will become less effective on longer pulse-lengths ▪ Will eventually need to develop refueling methods. (e.g. gas puff, small plasma injectors, pellets) ▪ Will eventually need to control recyling	▪ Are there means for controlling particle inventory without use of getter? ▪ What is the best method of refueling? ▪ Is a pumped diverter needed? What is best way to implement?
▪ Longer pulse	▪ Pulse lengths still < 10 ms ▪ Near power-loading limits on injector surfaces ▪ Stability maintained by wall diffusion time.	▪ Will need to increase pulse lengths and handle increased wall power. ▪ At some point will need to address RWM and feedback stabilization	▪ Can we design walls and electrodes that will take longer pulses? (active cooling, active stabilization required?) ▪ Are there other methods of controlling RWM (plasma rotation?)
▪ Burning plasma and Reactor Development	▪ Hagenson-Krakowski (1985) steady-state case study [1] ▪ Fowler (1998) pulsed reactor study [2]	▪ Much new knowledge accumulated since H-K ▪ Reactor with pulsed refluxing needs to be considered	▪ Is there new knowledge that motivates a revisiting of H-K? ▪ Can pulsed refluxing lead to an attractive reactor? ▪ Is confinement sufficient for ohmic ignition?

3.2 Discussion of the plasma parameters and conditions that would be needed to resolve these issues (e.g., collisionality, S, current drive efficiency, transport, and etc.)

Parameters are discussed here, both in terms of the plasma parameters needed to elucidate the issues and the parameters that need to be obtained in order to move the concept along the next level of development. The parameters are discussed by issue and further divided into CE, POP and PE categories. The parameters here relate to the definitions of CE, POP, and PE given in the 1999 FESAC Metrics documentation.

3.2.1 Current drive

Concept exploration:

- Show 0.1-1MA or credible path to >1MA plasma current;
- Show means for obtaining ratios of toroidal plasma current to source current (current amplification), A_I >3, increasing with Te and R;
- Formation efficiency: Energy config/Energy in, > 10% (H-K);
- Sustainment efficiency: Pohmic_core)/Pwall_plug > 10%;
- Ohmic dissipation ratio: (Closed flux dissipation)/(injector flux dissipation) ~> 1/5.

Proof of Principle

- Show ~1-10MA of circulating current, increased current amplification A_I >6;
- Maintain or increase formation, sustainment efficiencies at larger scale.

Performance extension

- Show ~10-20MA of circulating current, increased current amplification, A_I >10.
- Maintain or increase formation, sustainment efficiencies at larger scale.

3.2.2 Confinement

Concept Exploration

- Need T_e of > 100 eV in small (a < 0.5m) plasma to start looking at some confinement issues.
- Need T_e of few 100 eV or other evidence that radiation and charge-exchange not dominating the power balance.
- Need conditions that suppress stochastic fields and provide evidence of flux surfaces.

Proof of Principle

- Conditions to demonstrate scaling similar to tokamak L-mode (or better);
- Obtain Temperatures 1-5keV;
- Increase a by ~1.5 (above CE, SSPX) to nominally double τ_E and increase Te;
- Favorable τ_E scaling with Te, S;
- τ_E sufficiently large so that spheromak heats to beta limit;
- Collisionality regime for neutral beams;
- Suppress asymmetries to minimize island growth/size. (toroidal variation in |dB/B| < 1%).

Performance Extension

- Increase a to increase τ_E ~ heat to beta limit.
- Temperatures >5keV
- Understand microturbulence.

3.2.3 Beta limits

Concept Exploration

- General trends indicating beta limit behavior of <ß> ~ few %;
- Some specific instances of pressure limits (like observation of interchange, or Mercier stability analysis).

Proof of Principle

- Obtain $<ß>_{Vol}$ ~ 10%
- Understand effect of finite flux core, ($R_{wall}/2a$ > ~ 1.05 ?)
- Measured pressure limits, plasma parameters pushed to pressure limits (e.g. Mercier, Ballooning, or resistive interchange)
- Stability thresholds examined computationally and experimentally
- Scaling of pressure limit – geometrical effects (e.g. shaping) understood.

Performance extension

- Shaping to optimize volume average beta ~ 10%;
- More control for longer pulses.

3.2.4 Stability

Concept Exploration

- Tilt, shift ideally stable (i.e. with h/R < 1.6).
- Control of some current driven modes (e.g. n=1),
- Possible current profile control.

Proof of Principle

- Control of current- (or q-) profile to omit or preclude mode-rational surfaces;
- Hold profile between low-order mode rational surfaces (or control growth rate if cross them)
- Shaping to give increased stability to pressure-driven modes (possibly increasing shear);
- Investigate sheared flow (dv/dr~100km/s/meter) to produce transport barriers, increase stability to pressure-driven modes, and suppress RWM.

Performance Extension

- VF coils to support equilibrium along with flux conserver.
- Active feedback or other method to control RWM.
- Additional profile control and exploration of sheared-flow stabilization.

3.2.5 Particle control:

For all concepts levels there are similar needs to keep J/n > 10^{-14} A-m. (in order to avoid radiation-dominated discharges); (the limit might be similar in many regards to the Greenwald limit, electron streaming limits).

Proof of Principle

- Demonstrate divertor design.

Performance Extension

– Optimize divertor system.

3.2.6 Long pulses

Proof of Principle

– Means for providing stability with resistive walls for $t_{Pulse} > 100$ms

Performance Extension

– RWM stabilization;
– Active cooling of PFCs.
– Demonstrate active fueling and exhaust systems.

3.3 Status of research involving these issues.

Today, macroscopic ideal stability has been demonstrated. 500eV achieved by suppressing fluctuations. Low radiated power due to surface conditioning, q-profile evolution maintained in controlled decay by edge current drive, new methods of current drive have been explored. Full 3D resistive MHD simulations provide understanding on nearly all experimentally observed phenomena. Diagnostics are now sophisticated: approaching tokamak-like diagnostic set.

During the last 25 years several experiments have operated that gave important physical insight into the issues outlined above. In summary, the status of research is defined by the principal results from these experiments (approximately reverse-chronologically):

- The Sustained Spheromak Physics Experiment, **SSPX** (1999-2008): obtained 0.5keV temperatures with transient confinement approaching tokamak L-mode. Multi-pulsed formation and sustainment demonstrated.
- Helicity Injected Torus – Steady Inductive, **HIT-SI** (2003-): Have driven 30kA of plasma current in steady state inductively.
- Magnetic Reconnection Experiment, **MRX** (1995-). Fundamental physics studies of magnetic reconnection, spheromak merging, and the resistivity of current sheets. [26]
- Swarthmore Spheromak Experiment, **SSX** (1995-): extensive multi-probe surveys of the reconnection between two spheromaks. Studies include stability, ion heating, and flow.[27]
- **TS-3/4** (1986-): merging of spheromaks to form stronger field spheromaks, FRCs and other toroidal configurations. [28, 29]
- **CTIX** and other accelerators (1999-): acceleration of compact tori for tokamak fueling.
- **Caltech spheromak** (1999-): High speed cameras show jet-like expansion of plasma-filled flux tubes, extensive probe surveys reveal structure of the plasma during formation, and relevance to astrophysical jets. [30,31]
- Berkeley Compact Torus Experiment, **BCTX** (1995-1997): RF heating was applied to a decaying spheromak.

- The SPHeromak EXperiment, **SPHEX** (1989-1998), many internal probe surveys of a gun-driven plasma, determination of plasma structure when driven with n=1 mode; quasi-steady sustainment demonstrated, toroidal fields applied to a spheromak plasma – extended decays, higher total toroidal current.
- The Compact Torus Experiment, **CTX** (1978-1994), provided the first evidence that spheromaks could heat ohmically to a pressure limit and reach a few hundred eV temperatures. First demonstration of sustainment with CHI.
- Spheromak-1, **S1** (1985-1991) formed spheromaks inductively using a toroidal flux core. Many stability studies performed, together with research on relaxation phenomena and compression experiments with a passive stabilizer.
- FACT, Flux Amplification in a Compact Toroid, (Hyogo University, Japan). Studies of flux amplification with and without center rod in spherical geometry.

4. Facilities and gaps.

4.1 Issues and present devices able to address issues

The spheromak effort in the US consists of several small experiments and MHD code development. Related facilities are also listed.

4.1.1 Existing experimental facilities (all Concept Exploration or Basic Research)

- **HIT-SI --** experimental program investigates a concept to inductively drive current in bow-tie spheromak plasma. It uses two non-axisymmetric injectors to inject helicity at a constant rate with odd symmetry.
- **PBX** (new) – multipulsed startup experiment. Aims to show that by repetitive injection of plasma from a coaxial source, the energy density of a spheromak can be increased in a step-wise manner to achieve high current amplification.
- **SSX** - experimental program investigates the merging of counter-helicity spheromaks to form FRCs or spheromaks. The program investigates magnetic reconnection during the merging, and stability of the resulting plasma configuration.
- **SSPX** (shutdown, data analysis ongoing) T_e~0.5 keV, B_{tor} > 1Tesla, I_{plasma} ~ 1MA, n_e ~ $1x10^{20}m^{-3}$, achieved good (but transient) core confinement approaching tokamak L-mode. Achieved reasonable internal current profile control to avoid low-order mode rational surfaces by programming the initial flux distribution and discharge current.
- **Caltech** experiments - investigates the physics of spheromak formation by using a magnetized planar coaxial helicity source. The main issues being studied are topological evolution, helicity and mass injection, flows and stagnation, kink instabilities, flux amplification, relaxation and reconnection, and the generation of energetic particles.
- **MRX -** flexible experimental platform for inductive spheromak/FRC formation and merging of formed plasmas. Utilized for study of fundamental physics of magnetic reconnection and magnetic self-organization phenomena.
- **LANL – DRX** (internal funding, new) The Driven Relaxation Experiment [32] is a new experiment designed to explore power coupling efficiency (and possible resonances in that coupling) to maximize flux and current amplification while preserving stability. Key features include ability to vary aspect ratio (flux conserver length: diameter) and reaching very high gun lambda.

4.1.2 Theory and modeling

- Leading modeling tool is NIMROD. Spheromak modeling continuing at UW-Madison, UW, LLNL, Woodruff Scientific, Tech X, PSI center. The NIMROD team (http://nimrodteam.org) provides code development for a wide range of magnetized plasma applications.
- PSI center activities include developing codes, validating them against experiments and visualization for ICC program. Goal is to develop codes that can accurately predict the behavior of experiments before they are built.
- Analytic theory at LANL, LLNL, Woodruff Scientific, UW.

4.1.3 Related devices and relevant concepts

- ST- NSTX (CHI startup), PEGASUS (plasma injector startup)
- MAST (UKAEA) – (merging and compression for plasma startup)
- RFP – MST, (related confinement)
- FRC – TCS, PFRC (same topology)
- CT injectors (UC Davis, U. Saskatchewan)

4.2 Gaps

In section 3 we outlined the issues that need to be addressed in order to meet the goals discussed in section 2. It is clear that, while much progress has been made, all of the POP and PE issues remain to be addressed, and some of the CE issues warrant further exploration. We therefore outline here the issues by development level (CE, POP and PE). Implicit in this section are theory and modeling activities (described below in 4.3.3) to support the identified gaps. A summary of the issues by level can also be found in table 4.1.

Concept Exploration

- Current drive

  Show 0.1-1MA or credible path to >1MA *sustained* plasma current;
  Show means for obtaining ratios of toroidal plasma current to source current (current amplification), A_I >3, increasing with Te and R;
  Formation efficiency: Energy config / Energy in, > 10% (H-K);
  Sustainment efficiency: P(ohmic_core)/Pwall_plug > 10%;
  Ohmic dissipation ratio: (Closed flux dissipation)/(injector flux dissipation) ~> 1/5.
  Need Te > 100 eV in small (a < 0.5m) plasma in order to address current drive effects on confinement.

- Confinement

  On sustained device, need few 100 eV or other evidence that radiation and charge-exchange not dominating the power balance.
  On sustained device, need conditions that suppress stochastic fields and provide evidence of mode-rational surfaces.

- Stability

  Tilt, shift ideally stable (i.e. with h/R < 1.6).
  Control of some current driven modes (e.g. n=1),
  Possible current profile control.

- Particle Control
  - Keep $J/n > 10^{-14}$ A-m.
  - Explore advanced surface conditioning techniques such as lithium and boronization.

Proof of Principle

- Current Drive
  - Show ~1-10MA of circulating current, increased current amplification $A_I > 6$;
  - Maintain or increase formation, sustainment efficiencies at larger scale.
- Confinement
  - Conditions to demonstrate scaling similar to tokamak L-mode (or better);
  - Obtain Temperatures 1-5keV;
  - Increase *a* by ~1.5 (above CE, SSPX) to nominally double τ_E and increase Te;
  - Favorable τ_E scaling with Te, S;
  - τ_E sufficiently large so that spheromak heats to beta limit;
  - Collisionality regime for neutral beams;
  - Suppress asymmetries to minimize island growth/size. (toroidal variation in $|dB/B| < 1\%$).
- Beta limits
  - Obtain $\langle ß \rangle_{Vol} \sim 10\%$
  - Understand effect of finite flux core, ($R_{wall}/2a >\sim 1.05$?)
  - Measured pressure limits, plasma parameters pushed to pressure limits (e.g. Mercier, Ballooning, or resistive interchange)
- Stability
  - Stability thresholds examined computationally and experimentally
  - Scaling of pressure limit – geometrical effects (e.g. shaping) understood.
  - Control of current- (or q-) profile.
  - Hold profile between low-order mode rational surfaces (or control growth rate if cross them)
  - Shaping to give increased stability to pressure-driven modes (possibly increasing shear);
  - Investigate sheared flow (dv/dr~100km/s/meter) to produce transport barriers, increase stability to pressure-driven modes, and suppress RWM.
- Particle control
  - Keep $J/n > 10^{-14}$ A-m
  - Demonstrate divertor design.
  - Explore advanced surface conditioning techniques such as lithium and boronization.
- Long Pulses
  - Means for providing stability with resistive walls for $t_{Pulse} > 100$ms

Performance extension

- Current Drive
  - Show ~10-20MA of circulating current, increased current amplification, $A_I > 10$.
  - Maintain or increase formation, sustainment efficiencies at larger scale.
- Confinement
  - Increase *a* to increase τ_E ~ heat to beta limit.
  - Temperatures >5keV
- Beta limits
  - Shaping to optimize volume average beta ~ 10%;
  - More control for longer pulses.

- Stability
  - VF coils to support equilibrium along with flux conserver.
  - Active feedback or other method to control RWM.
  - Additional profile control and exploration of sheared-flow stabilization.
- Particle control
  - Keep J/n > 10^{-14} A-m.
  - Optimize divertor system.
- Long pulses
  - RWM stabilization;
  - Active cooling of PFCs.
  - Demonstrate active fueling and exhaust systems.

4.3 New programs and facilities needed to address gaps

New facilities and thrusts are needed for spheromak to make its goal during the ITER era.

The program needs and is ready to build the following facilities and programs to fill the gaps:

4.3.1 POP Level Facilities

- Platform to address confinement issues.
  - A spheromak demonstrating tokamak-like confinement and current profile control for a duration comparable to ~ 3 heating times (or energy confinement times).
    - Requires > ~1 keV temperatures to reach the collisionality and S needed for a confinement experiments.
    - Need a ~ 0.5 m. [~2 x SSPX] $T_e \sim a^2$ and a factor of two or more in Te is needed.
  - Initially single pulsed, upgradeable to a quasi-steady-state (i.e. pulsed-refluxing) when formation and controlled-decay powers/currents become acceptable.
  - Build spheromak with better/dynamic (i.e during the discharge) injector flux control.
  - Demonstrate heating to the beta limit at keV temperatures.
  - Aux. heating like NBI is needed for confinement studies.
- PoP level steady-state platform needs CE level demonstration discussed below.

4.3.2 CE Level Facilities

In parallel with PoP pulsed experiment, need to explore two current sustainment methods: pulsed-reflux and steady-state.

- Need flexible large-scale formation and sustainment experiments to develop and understand steady-state sustainment with good confinement.
  - Need spheromak a ~ 0.5 m [~ 2 x HIT-SI]. Size scaling is, as stated elsewhere, unknown but a factor of two is a reasonable first step based on other device experience.
    - To prevent neutral influx $na > 1\text{x}10^{19}\ \text{m}^{-2}$ is needed (presently $na = 0.5\text{x}10^{19}\text{m}^{-2}$)
    - Need larger $S \sim a^4$ (assuming $T_e \sim a^2$) to lower dissipation in order to give higher current amplification.
    - Possible upgrade to POP confinement device.
    - Rotation control and profile control.
- Need pulsed experiment to demonstrate pulsed reflux sustainment with good confinement.

- In addition, need new innovative efficient current drive experiments for spheromaks at the CE / Basic research level.
- Need experiments to explore reduction of ohmic power losses in the edge and open flux region. (e.g. replaceable rod down center, RF, runaway electrons carrying current)
- Need Facilities and computational effort to explore new spheromak geometries and current profiles.
    - This space is large and unexplored.

4.3.3 Theory and Computation

Need to strengthen the Theory/Computation effort in the following areas.

- Realistic edge plasma/material wall interaction modeling in 3D simulations.
- Realistic modeling of circuit coupling [22] to the plasma.
- Add two-fluid/Hall including atomic physics in 3D simulations.
    - Incorporate enough atomic physics to include breakdown in whole-device modeling.
- Model by direct numerical computation up to and including lower hybrid frequency. (Include higher frequency physics with transport parameters).
- Predictive *enough* to test experimental designs before they are built. Essential for the exploration and refinement of all promising device geometries with budget-limited research.

4.3.4 Reactor Study

- Need Aries-like reactor studies for pulsed, steady, and quasi-steady scenarios

4.3.5 PE Facility

- Need, in 7yrs to 10yrs from now, a facility to demonstrate a pre-burning-plasma class performance (5keV) with a steady-state or quasi-steady-state current drive method based on the results of the above effort.

4.3.6 Summary Table

The following table shows how existing and new facilities will address the questions under the various physic topics.

Table 4-1 Summary of Facilities to address physics topics and questions.

Physics Topic	Questions	MRX	Caltech	SSX	HIT-SI	PBX (constr.)	SSPX (Data only)	Upgraded CE's	POP Confinement	POP Steady-state	PE	Reactor
Current drive/sustainment	▪ Can we find a method or combination of methods that provides and optimizes both sustainment and confinement?	X	X	X	X	X-	X	X		X	X	
	▪ Can power efficiency be improved?				X-	X-		X		X		
	▪ Are other current drive methods feasible? (NBI, RF, Bootstrap)							X		X	X	
Confinement	▪ How does confinement scale?				X-	X-	X-	X	X	X	X	
	▪ What are limits to transport? What are the dominant causes of transport (e.g. overlap of mode-rational surfaces)						X-	X-	X+			
	▪ Do transport barriers form in spheromaks?							X	X+	X	X	
Beta limits	▪ Is beta limited by transport or by instability?							X	X+	X	X	
	▪ At keV temperatures, do spheromaks ohmically heat to a beta limit or is auxiliary power required?								X+		X	
	▪ How does it scale? (e.g. Troyon)				X-			X	X+		X	
Stability	▪ Can q-profile be controlled in the spheromak for periods comparable to the heating time?	X	X	X	X	X	X		X	X	X	
	▪ Can existing techniques maintain stability when sustained for periods >> L/R decay time (of plasma currents or flux conserving wall)?			X	X	X	X	X	X	X		
	▪ Are there lower power methods of controlling the current profile							X	X-	X-		
Boundary, particle control	▪ Are there means for controlling particle inventory without use of getter?	X	X	X	X	X	X	X	X	X	X	X
	▪ What is the best method of refueling?.							X	X	X		
	▪ Is a pumped diverter needed? What is best way to implement?							X-	X-	X	X	X
Longer pulse	▪ Can we design walls and electrodes that will take longer pulses? (active cooling, active stabilization required?)					X		X		X	X	X
	▪ Are there other methods of controlling RWM (plasma rotation?)							X		X	X	
Burning plasma/Reactor Development	▪ Is there new knowledge that motivates a revisiting of H-K?							X	X			X
	▪ Can pulsed refluxing lead to an attractive reactor?					X	X-		X			X
	▪ Is confinement sufficient for ohmic ignition								X-		X	

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