Spheromak questions and issues for the FESAC Toroidal Alternates Concept Community Input Meeting in Dallas:

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RESPONSES IN ITALICS

1. The ITER-era goal for the spheromak should be more specific, and there are concerns that it may be too ambitious. We know from experiments on other concepts (tokamak and stellarator) that, following long-pulse current drive development and achievement of good confinement, extensive studies were required to resolve physics issues before experiments at the PE level. Given the present lack of a spheromak current drive that is demonstrated to be compatible with good confinement, can you craft a goal that recognizes this need? The result might be something like: "Conduct experiments and simulations that demonstrate current drive compatible with stability and good energy confinement, enabling successful fusion-plasma experiments at the PoP level followed by construction and initial operation of a PE-level experiment within 20 years."

A goal that embraces both confinement and current drive issues is:

"Conduct experiments and simulations that demonstrate good confinement and determine means for current drive compatible with stability and good energy confinement, enabling successful fusion-plasma experiments at the PoP level followed by construction and initial operation of a PE-level experiment within 20 years."

2. Your §4.3.5 calls for the PE in 7-10 years, which appears too ambitious and inconsistent with your goal. Did you mean PoP on the shorter time scale?

Given results from experiments that address confinement and current drive issues, we should be able to begin the design *of a performance extension device in the next decade. The design phase should be a national endeavor and draw on the expertise of many in the field, not just within the spheromak camp, but also within the broader program (particularly from the rfp and tokamak communities). We have outlined a time-line for addressing scientific issues (shown in table 1), that presents the scientific issues that were outlined in table 3 of our written contribution. The design work for the PE will need to occur in parallel with the POP - level experiments (results from simulation and experiments will naturally feed information into this).*

It is worth mentioning that to perform the development of the concept in series through CE and POP facilities could push out the PE experiment design phase out beyond the next 15 years. A compromise would be to build advanced CE level experiments with the most likely successful current drive schemes that are also able to address POP-level confinement issues. This development would proceed much like the MST rfp model in which confinement issues were gradually addressed and the device evolved to a POP-level device.

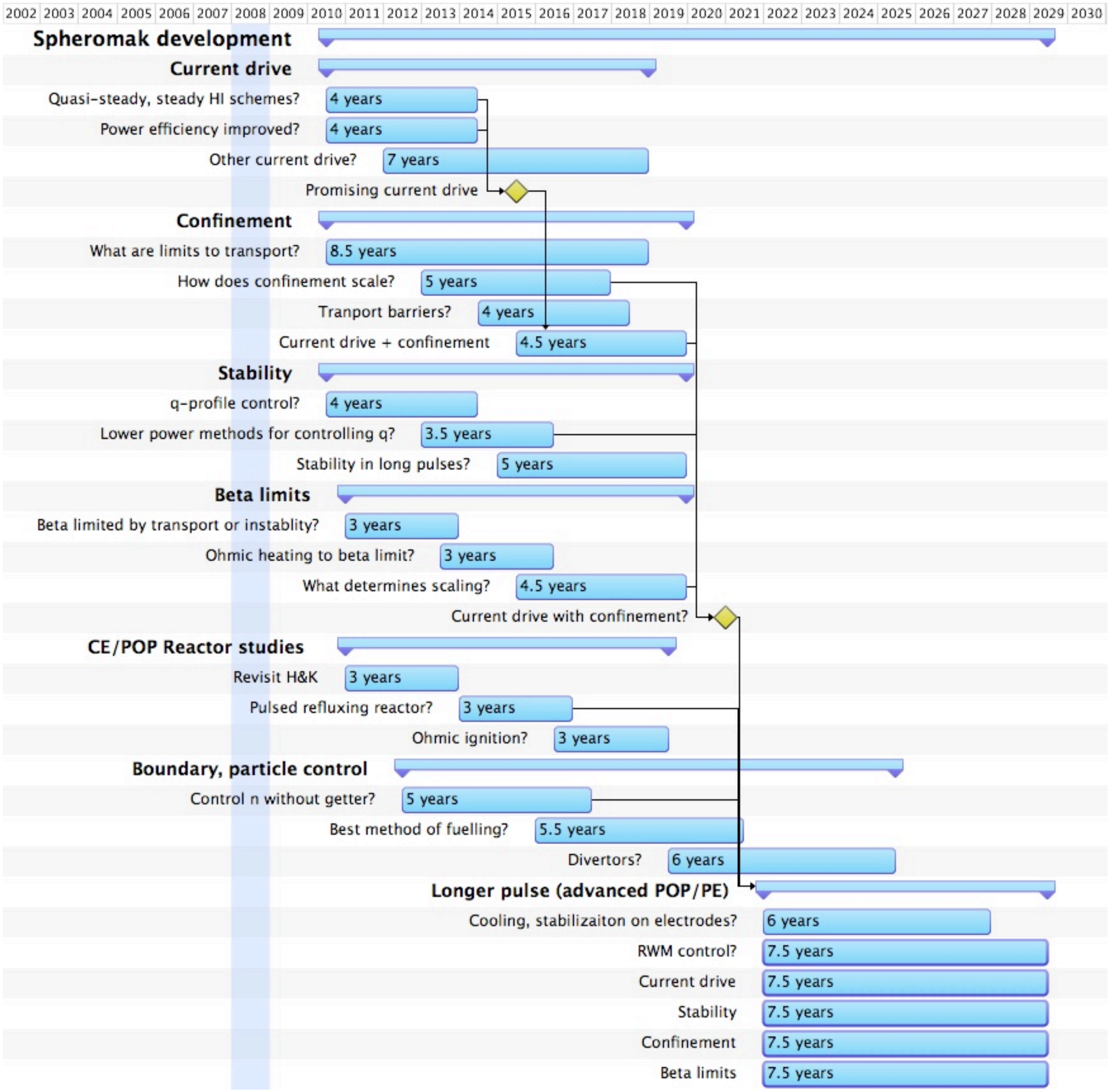
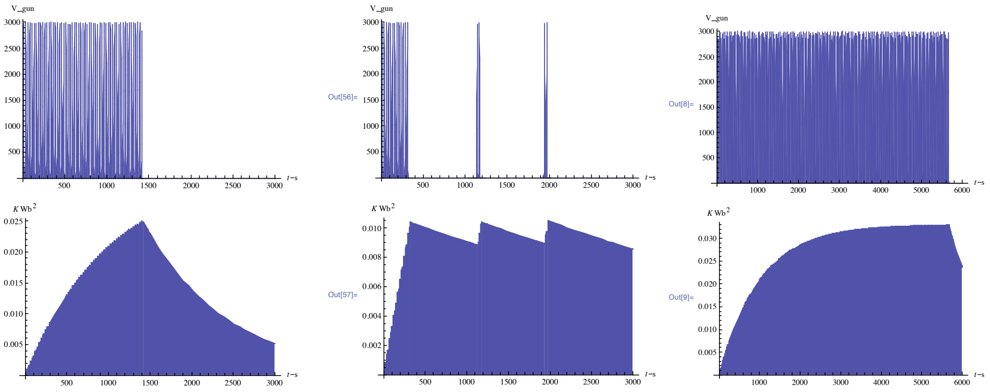


Table 1. Approximate (straw-man) scientific-issue time-line at the CE and POP level of exploration leading to longer pulses (and a PE level experiment).

While many of these issues are shown in series – our table from section 4 outlined that some issues would need to be explored at every level of development -



Pulsed Pulsed reflux Steady state

Figure 1. Three scenarios for exploring current drive and sustainment by injection of magnetic helicity. Shown are the voltages traces expected for pulsed operation and the resulting spheromak evolution for pulsed, refluxing, and steady-state sustainment.

3. Is it true that confinement compatible and efficient current drive requires success in at least one of the three scenarios: a) Achievement of helicity current drive at sufficiently low magnetic fluctuation levels that energy is well confined; b) Development of non-helicity current drive techniques; or c) Demonstration that a pulsed technique such as "refluxing" works well enough to be of interest for an eventual reactor?

The community agrees with this assessment. While states of high confinement have been produced in experiment, they have not occurred in sustained conditions. The primary challenges for each of the three scenarios are:

a. Do the MHD fluctuations (including resistive, two-fluid, and kinetic effects) that lead to relaxation allow confinement to scale favorably to reactor-grade plasmas?

a. Can we identify and demonstrate other forms of non-inductive non-helicity current drive that sustain the spheromak state without driving relaxation fluctuations?

a. Is it possible to optimize pulsed helicity current drive such that the cycle-averaged confinement scales to an economical reactor concept?

If so, experiments on these at a CE level should be identified as the highest priority.

The early years of our scientific timeline reflect these challenges; however, it is also important to understand the confinement properties of the spheromak configuration in optimal conditions (independent of the question of how the state is maintained).

To what extent can these [current drive scenarios] be explored by simulations?

Anticipating continuing improvement in numerical algorithms and computer hardware, laboratory validated simulations will make substantial contributions:

a. *Helicity current drive studies will include scaling of dynamo and fluctuation levels with resistive MHD and two-fluid modeling. Simulations with integrated transport modeling can examine whether confinement and current multiplication improves due to either fluctuation scaling with S-value (Lundquist number) or energy-flux limitations from kinetic effects.*
a. *For non-helicity current drive, MHD and two-fluid simulations can be used to optimize current profiles for macroscopic stability. 3D Taylor-state computations can be used for guidance in nonsymmetric configurations.*
a. *MHD and two-fluid simulations of pulsed operation will investigate macroscopic stability during transients such as 'refluxing' and compression. They can also be used to help assess the quality of magnetic topology and confinement during refluxing and the extent to which it affects overall cycle efficiency.*

Modeling of edge-plasma/wall interaction including particle neutral deposition, particle recycling, and ionization will be important for predicting performance of new designs for each of the three scenarios.

What and how much can be learned from the results of RFP research?

RFP research is extremely valuable to spheromak research:

- *RFP experiments and simulations have already scaled magnetic relaxation beyond what has been achieved in spheromaks—by more than an order of magnitude in terms of Lundquist number. The confinement in 'standard-RFP' experiments has direct implications for scaling helicity-injection current drive.*
    - *An important distinction, however, is that high-performance RFPs have very little magnetic flux penetrating the wall.*
    - *The reversed-shear in gun and flux-core spheromaks may provide other benefits that are not readily accessible to the RFP.*
- *The importance of profile control, for example PPCD in RFPs and optimized decay in spheromaks, applies to both. Each configuration has achieved its relatively high confinement state when magnetic stochasticity is reduced. With relatively weak magnetic fields and $q<1$, research of non-standard profile-control methods for the RFP may also apply to the spheromak.*

How will you examine the validity, efficiency, and compatibility of such methods?

- *Current amplification is important for helicity injection and pulsed operation. The ratio of toroidal plasma current to source current must increase beyond the order unity values achieved in present experiments to above order ten.*
- *Formation efficiency (configuration energy/input energy) needs to meet or exceed the H-K criterion of 10%.*
- *Sustainment efficiency (core Ohmic dissipation/power input) >10% is important for Ohmically heated designs.*

Predictions of validated numerical simulations will increase confidence in prospects for any of the three scenarios.

4. The scientific goals should stress measurement of basic stability and confinement properties in quasi-steady discharges (that is, pulse length >> all characteristic times for MHD, transport, current profile relaxation, etc. and of course many transit times or Alfvén times). The required dimensionless parameters should be based on the best current assessment of relevant physics not arbitrary dimensioned quantities.

Dimensionless physical parameters are explained and given for: current drive, sustainment, confinement, beta-limits, and stability. This clarification is given also in response to question 6.

Current amplification, $A_I = I_{tor}/I_{gun}$

- *The limiting spheromak magnetic field from e.g. pulsed injection is determined from the pulse repetition rate, 1/T, and the spheromak decay rate τ_K, set by resistive losses. Using the helicity balance equation:*

  $$dK/dt = 2\psi_g V_g - K/\tau_K$$

  the limiting helicity content can be found. Defining the helicity input from each pulse ΔK_g, and assuming constant τ_K, the limiting helicity content is given by:

  $$K_\infty = \Delta K_g \{1 - \exp(-T/\tau_K)\}^{-1}$$

  e.g. with T=300μs and τ_K=1000μs, one would expect $K_\infty = 3.8\Delta K_g$, so this means that a 'dissipation limit' can be exceeded either by shortening the time between pulses, or increasing the dissipation time: $\tau_K / T >> 1$, $\tau_K = \tau_K [W_B]$ (i.e. plasma gets hot during injection and varies as a function of the magnetic energy)
- *An engineering limit is encountered that provides a hard constraint on current amplifications, namely to avoid melting electrodes in larger devices.*
- *Reconnection needs to be able to occur so that the injected plasma can add helicity to the system (a basic condition of relaxation): $\tau_{Reconnection} < \tau_{injection} << \tau_{pulse}$ (i.e. the reconnection time is short compared with the period of injection, and is far shorter than the pulse length)*
- *The efficiency of coupling current into the spheromak is determined by the ratio of resistive dissipation in the cold edge over the circulating current (Hagenson and Krakowski made this observation requiring for A_I>10 for a* steady-state *reactor).*

Plasma Current, I_{tor}

- *Given a beta of a few percent, then the field (hence current) needed to obtain high temperatures is given by:*

  $$T_e(eV) = \frac{\beta(\%) B_p^2(T)}{2\mu_0 n_e(m^{-3})}$$

  $$B_p(T) = c_1 I_{gun}(A)$$

  so, for a CE level device, ~100eV temperatures would be expected with I< 1MA (with ß~5%, and few percent, and unity), for a POP, 5MA would allow access to keV regimes.

Electron Temperature, T_e

- *For a CE level device, pulses are short, and it is not expected that temperatures will be much greater than a few 100's of eV.*
- *Temperatures in the keV range will be required for the POP, and enable S-sclaing to be assessed over a wider range than is currently possible.*

Stability

- *Kruskal-Shafranov condition must be met for the n=1 column mode to be stabilized (requiring q<1 everywhere).*
- *The island width is usually expressed as:*

  $$W_{mn} = \left(\frac{L_S r_{mn}}{m} \frac{\delta B_r}{B} \right)^{1/2}$$

  where the shear-length $L_S = Rq/rq'$ *, and the radius of the rational surface is* r_{mn}*. Considering the 2/4 mode at a radius of* r_{mn}*~0.1m, a shear length of ~1m and fluctuation level of around 5%, an island could have a width~5cm and connect edge to core. It is therefore necessary for ~B/B ~< 5% to avoid stochasticity.*
- *In order to control and understand heating, the current profile needs to remain fixed for a period greater than the heating time, where the heating time is:*

  $$\tau_{heat}(s) = \frac{en}{c}\frac{2}{5}T^{5/2}(eV)$$

- *where* $c = 5.2 \times 10^{-5} Z_{eff} \, l \lambda l J^2 \Delta V$*, so a means for understanding heating would be to hold the q-profile constant for ~3*τ_{heat} *(or ~3*τ_E*).*

Beta, ß

- *Mercier stability requires for a shear in the q-profile, produced either by current profile control or plasma shaping.*
- *In CE level concepts, the profile is not controlled and so a Mercier limit of a few percent is expected.*
- *In larger devices, we expect to exceed this limit by shaping and q-profile control, so the beta limit condition would be for beta ~* $ß_{mercier}$ *in CE, and better in subsequent devices.*

Energy confinement time, τ_E

- *energy confinement scales roughly in proportion to the minor radius, and empirically,* τ_E *scales inversely with perturbation amplitude and temperature (S-scaling).*
- *An explicit comparison with the confinement times of similar sized devices with similar magnetic field strengths would be needed to assess* τ_E *(e.g. compare with tokamak L-mode scaling).*

Spheromak Metric	**General Physical Parameters**	**CE**	**POP**
Current amplification	τ_K / T > 1 $\tau_K = \tau_K [W_{\mathbf{B}}]$ $\tau_{Reconnection} < \tau_{injection} << \tau_{pulse}$	A_I ~3 implies that T ~ 300μs, and τ_K~1ms	A_I ~6 implies that T~300μs and τ_K~2ms
Current	$T_e(eV) = \dfrac{\beta(\%) B_p^2(T)}{2\mu_0 n_e(m^{-3})}$ $B_p(T) = c\, I_{gun}(A)$	<1MA to give few 100eV	~5MA to give >1keV
Temperature		Few 100s eV	>1keV
Stability	q<1 $<B_1>_{rms} / B_0$ $\tau_{heat}(s) = \dfrac{k}{c_3}\dfrac{2}{5}T^{5/2}(eV)$ $\tau_K > \tau_{heat}$	q<1 $<B_1>_{rms} / B_0 < 1\%$ $\tau_{heat} > \tau_{pulse}$ $\tau_K >> \tau_{heat}$	q<1 $<B_1>_{rms} / B_0 << 1\%$ dq(r)/dt= 0 for ~3τ_{heat}
Beta	Mercier Interchange		Control dq/dr
Energy confinement	$\tau_E \sim <B_1>_{rms} / B_0 \sim S^{\gamma}$ $\tau_E \sim \tau_{L\text{-}mode}$	τ_E ~ few 100 μs Favorable scaling with S and ~B/B	$\chi < 1 m^2/s$ $\tau_E \sim \tau_{L\text{-}mode}$ or better Clear S-scaling

Table 2. *Physical parameters for addressing spheromak metrics*

5. Scientific Roadmap: You have done an excellent job of describing the scientific goals, although more discussion of their physics basis would be useful to make them clearer. Less "sharp" is a scientific roadmap for reaching these goals, although much of the information is available, e.g. in Table 4-1. A scientific roadmap is recommended to pull these together and probably should have decision points (e.g. among the opportunities in §3-§4). What experimental and simulation work is needed in the near term?

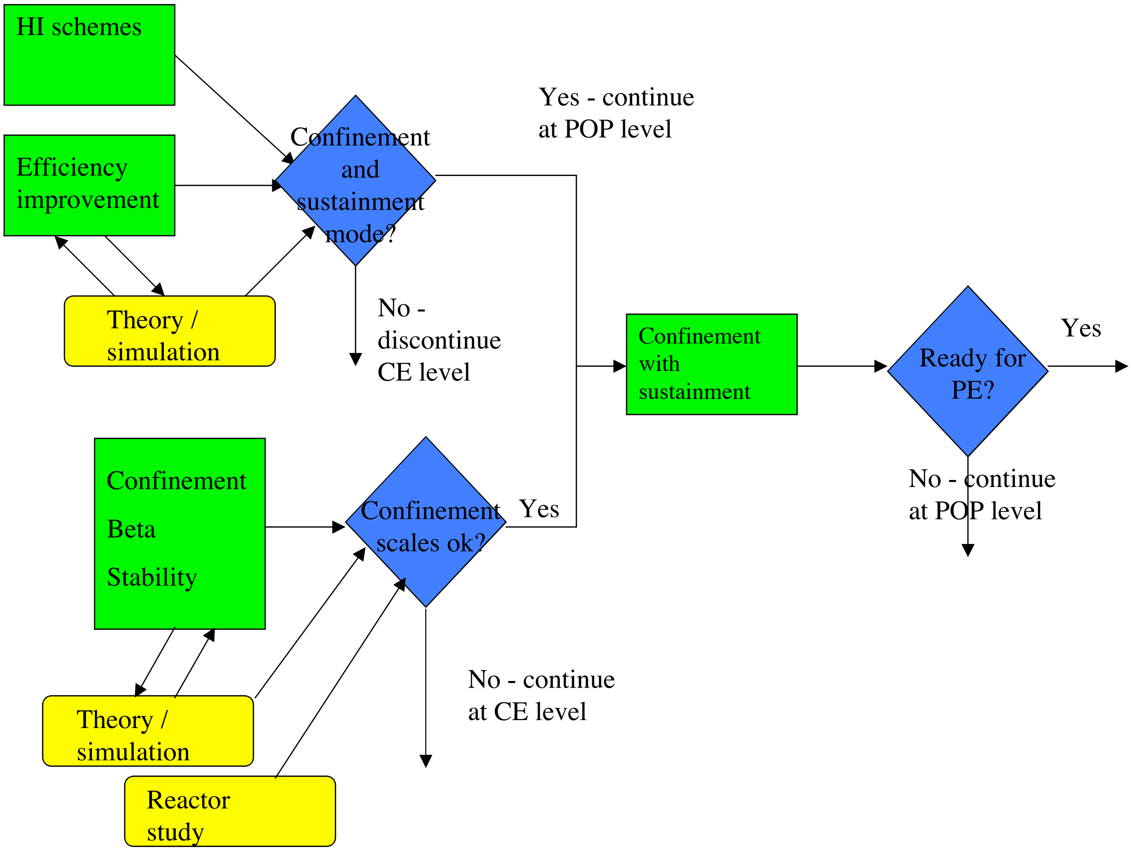


Figure 2. *Scientific R&D roadmap for the development of the spheromak concept through to PE level issues.*

In the near term, several parallel issues must be addressed both computationally and experimentally: – confinement issues overlap to a certain extent with current drive issues, particularly in the ability to produce large current amplification factors. Obtaining more control to produce stable plasmas is necessary to address both confinement and current drive, and allows beta limits to be addressed. Figure 2 shows the decision roadmap for CE and POP level issues – confinement issues are shown on the bottom branch, and current drive on the top branch, with a decision for integration when a clear path to high temperatures with sustainment is apparent.

There are numerous additional scientific goals which need to be met in the long term; these should be prioritized and worked into the scientific road map. Specifically:

6. Panel members were particularly complementary about Table 3.1. However, in general, the physics basis for reaching goals is not explained, nor are techniques outlined. A short table of desired target parameters would be useful.

Please see response to question 4 and table 2.

7. The basic spheromak equilibrium is force-free with β=0 and nearby MHD stable, finite pressure equilibria have been achieved with the use of close-fitting conducting walls. What is required for achieving high β?

The conventional emphasis on helicity injection and relaxation led to computations of force-free equilibria that have been used for MHD stability analysis, including estimates of beta where shear from the force-free equilibria is used in the Mercier condition. Experiments and simulations that have demonstrated relatively high confinement provide an important step toward high beta, but much more is needed at both the CE and PoP levels.

When and how should it be addressed?

Self-consistent stability analysis of finite-beta equilibria is needed for both hard limits associated with macroscopic ideal instabilities and soft limits associated with magnetic topology change (related to the confinement issue). Scaling with various shaping parameters and plasma parameters can be readily accomplished in linear computations. With the development of two-fluid simulation capability, we are now ready to consider important drift-stabilization effects that may help the spheromak maintain a self-organized state at beta-values beyond the Mercier limit. All simulation-related stability studies can proceed immediately with the exception of resistive-wall effects, which require further development. Experimentally, small CE-level experiments that produce high confinement states, even transiently, can explore ideal stability limits. However, long-pulse operation with sufficient separation of ideal and tearing time-scales is necessary to address non-ideal stability concerns. They are important for q<1 operation, because there is no curvature stabilization. Initial work in this area was conducted on SSPX, but a thorough investigation will need PoP-level performance.

8. Electrode-Wall interactions: With formation via electrodes, what is the situation on plasma impurity content? Is this formation method relevant for a fusion reactor? Will a technology development program be required?

Experience with SSPX shows that an electrode system will allow tokamak-like vacuum conditions, and low impurity content (very low radiated power) even with ~1MA injected current (not much more will be needed for POP/PE if current amplification can be increased). However, the power scaling for electrode systems needs to be *addressed - it is not possible to inject 30MA of current through electrodes, this is why current amplification is needed (in order to obtain large circulating currents from a low current source), and is hence a rather specific item in the development path.*

9. What issues will require a larger device, and when will it be appropriate to move to it?

In order to address issues relating to confinement scaling, a larger device would be needed. However, SSPX was already at the point of addressing many of the POP-level issues with a good diagnostic set, and so it may not be necessary to immediately go to a larger plasma. POP level issues entail understanding beta limits and limits to the confinement. A low cost extension could help address these issues. The MST model for the advancement has been to gradually evolve to POP issues. The SSPX device could be used for this purpose- it could be relocated and gradually upgraded to a POP facility, addressing many of the confinement and current drive issues that we outlined.

What should be done differently from SSPX for a next step experiment, aside from the addition of auxiliary heating and current drive for sustainment on the transport time scale?

Largely it would be good to have more control. Simply-connectedness could be traded for greater control and better confinement.

For a true POP-level confinement experiment, current profile control would be needed at a bear minimum - the tokamak does this very well with external coils. Benefits would include:

- *Reduction of field errors imposed by a distorted central column;*
- *Control of the q-profile: hold constant for a period that is long compared with the heating time;*
- *Control of the evolution of mode-rational surfaces would allow the exploration the most favorable operating regime - experience from SSPX suggested that the highest temperatures occurred when the q-profile spanned 2/3 to 4/5;*
- *Control of the magnetic shear to determine if Mercier sets the obtainable pressure.*
- *If toroidal mode evolution can be controlled, beta limits and confinement limits can also be addressed - independent heating would be instrumental in determining the confinement properties.*

Shaping would be important too - on SSPX it was possible to make a range of different configurations just by programming the vacuum field, so having some flexibility there would be important. Benefits would include:

- *maximize the plasma beta;*
- *control current paths.*
- *With longer pulses, resistive walls and feedback control will be needed, but much has been learned with copper first walls in other long-pulse devices.*

It is stated that a larger device at higher current and current amplification is needed, but little discussion of what this implies. At what point does efficiency become the leading issue?

Efficiency of coupling bank energy into the spheromak during formation needs to be addressed immediately. The requirement for stability in the spheromak during decay needs to be addressed immediately – Presently, current needs to be driven in the cold edge plasma in order to maintain stability during a controlled decay - the injected current only serves that purpose, which could be much more efficiently conducted by a copper rod, for example. If a rod provides more flexibility and control (without exciting the n=1 mode), it could be built in to CE or POP level devices somewhat straightforwardly (as was done for SPHEX). The connection and overlap with ST physics would also be good. For pulsed reflux experiments, we will need to be able to control the q-profile in the decay period.

One implication for a confinement experiment might be that we can produce an operating mode with 'reversed shear' over most of the volume. Reversed shear is considered important in the production of the internal transport barriers in tokamaks, and is considered an AT scenario (the Airies group consider the Reversed Shear tokamak separately). In the tokamak reversed shear usually covers only a small volume of the plasma. The implication therefore is that spheromak results could feed into advanced tokamak operating scenarios.

10. There is interest in generating similar parameter tables for all the concepts. This may be difficult for the spheromak given its stage of development, but it would be useful to fill out the attached table.

See table below.

Concept Key Parameters

Parameter	Present value[†]	ITER-era goal	Reactor Target
Confining Field[a] (T)	1.1	2.5	5 (wall value)
Plasma current[b] (MA)	1	20	47
Pulse length Δt (sec) and $\Delta t/\tau_E$	.01, 10	SS, QSS	SS, QSS
External sustainment/current drive type	CHI	SIHI, CHI, other	TBD
External sustainment/current drive power[c] (MW)	50 (P_{edge}) 5 (P_{ohm})	100	3 0 (60 @ η = 0.3)
Current drive efficiency (η)	0.1	0.2	0.6 (+1.5% on COE @ 0.3)
Major Radius[d] (m)	0.32	1.3	2
Minor Radius[d] (m)	0.18	1	1.5
Elongation (κ)	1.2	1.2	1.2
Central density n_e or $\langle n_e \rangle$ (m^{-3})	$2x10^{20}$	$2x10^{20}$	$2.3x10^{20}$
Central T_e or $\langle T_e \rangle$ (keV)	0.5	5	20
Central T_i or $\langle T_i \rangle$ (keV)	?	5	20
Central beta (% and β_N)	10, $\beta_N = 4$	20	20 (10% vol-ave)
Energy confinement time[d] (s) = U_{therm}/P_{in}, ($P_{in} = P_{ohm}$ or P_{edge})	.001 (P_{ohm}) .0001 (P_{edge})	0.043	0.43
Fusion power density $B\tau_E$ (T-s)	.001	0.1	2
Core electron transport[e] (χ_e m^2/s)	< 10	20	5 (a^2/τ_E)
Core ion transport[d] (χ_i m^2/s)	?	20	5 (a^2/τ_E)
$S_D = a / \rho_{Deut}$	42	175	260
$S_\alpha = a / \rho_\alpha$ ($E_\alpha \sim 2.5$ MeV)	0.2	8	37
Collisionality (ν^*) = a / λ_{mfp_e} ($\lambda_{mfp\_e} = V_{th,e} \times \tau_e$)	10^{-2}	10^{-3}	10^{-4}
Normalized pulse length (τ_p/τ_r)[f]	.01 (τ_p ~.01s) (τ_{res}~1s)	SS	SS
Normalized pulse length $(\tau_p /\tau_{Ti=Te})$[f]	50 (τ_p ~.01s) (τ_{eq}~200 us)	SS	SS
Estimated Fusion Power (MW)	0	0	3400
Estimated wall load[g] (MW/m^2) ($P_{conduction}+P_{rad}+P_{neutrals}+P_{neutron}$)	~ 1	~ 2-5 ?	20
Estimate divertor[g] (or injector anode+cathode) load (MW/m^2)	50	5	5

Table values based upon known or estimated values from present experiments, possible ITER-era targets based on extrapolation from present experiments, and estimated reactor conditions based on previous reactor studies or back-of-envelope style spreadsheet calculations. [†]Not simultaneous for all parameters
Definitions, formulary, and assumptions on a separate sheet.

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[a] peak on axis
[b] ohmic or driven or diamagnetic
[c] power to plasma needed to maintain configuration, magnetic field, or plasma current
[d] mean values if not axisymmetric
[e] measured or estimated from power balance, size, beta, or n_e, T_e, and T_i
[f] t_r ($t_{Ti=Te}$) is relevant time scale for configuration redistribution (temperature equilibration)
[g] For SSPX, A_{wall}~ 3 m^2, $A_{cathode}$=1.1m^2, A_{anode}=1.6m^2, P_{cond}~ P_{ohm} ~ 5 MW, P_{rad}~ 1.5 MW, P_{cx}~ 1 MW, $P_{neutrons}$= 0