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

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."**

How about *"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?**

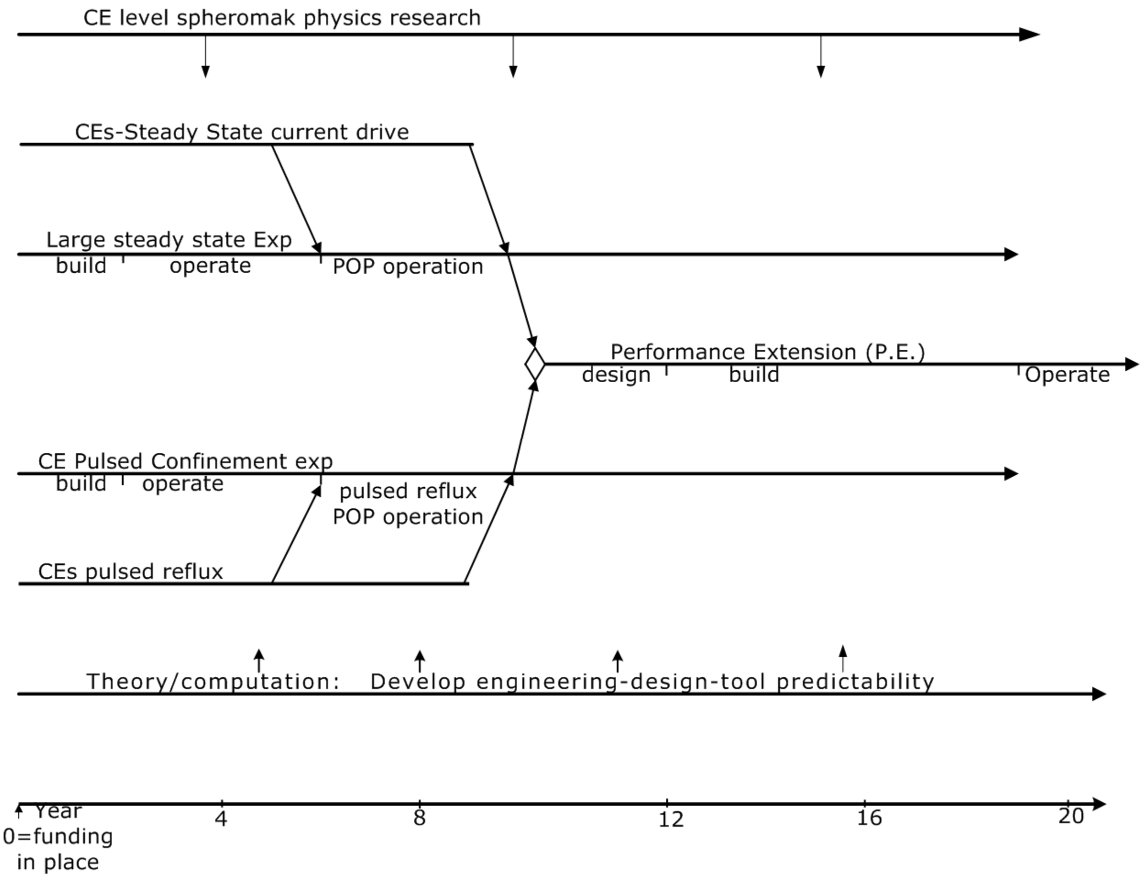
Begin design of PE in 10 yrs. Begin now to design and building of pulsed confinement CE and a pulsed-refuxing CE experiment, which lead to a pulsed refluxed quasi-steady state PoP. Begin now design and building of a large (with NBI) steady-state experiment and other steady-state-methods CE experiments, which lead to a steady-state PoP. PE decision point between methods in 10 years. See timeline figure below.

3. **Is it true that confinement-compatible and efficient current drive requires success in at least one of 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?**

Yes, that is now the plan, See time lines below

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

Yes, All of these types of experiments at the CE level plus the pulsed need to be done with high priority. Highest priority are the large steady state CE and the CE confinement experiment.



Time line of spheromak research in the ITER era (aggressive funding)

To what extent can these be explored via simulations?

- Present 3D resistive MHD codes and Taylor state calculations can act as guidance. However, Resistive MHD might be too conservative, predicting lower temperatures and higher fluctuation than observed, while Taylor is too optimistic about relaxation and does not tell us about confinement. To resistive MHD we need to add additional dynamo mechanisms like two-fluid effects. The codes are not sufficient to be used as engineering design tools at this point. However, I anticipate that in the not to distance future their predictability will reach that level. In addition to higher frequency physics we need to develop self consistent boundary conditions. By self-consistent boundary conditions we mean: Calculate plasma particle influx from recycling and wall heating models. Calculate neutral deposition from neutral penetration, and ionization models. Calculate currents to the wall from sheath impedances and possibly arcing models. Calculate the electric field and magnetic field boundary conditions by self-consistently solving the 2D surface pattern consistent with the imposed voltages and currents from the power supply circuits, sheath physics (for conducting boundaries), and plasma particle influx. The self-consistent velocity BC should come out of this calculation. Of course, this all needs to be done while validating results against experiments.

- In the more near term, 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.
  b. 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.
  c. 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.

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

RFP research is extremely valuable to spheromak research:

- The RFP can be used to validate codes in the PoP regime with physics similar to the spheromak.
- RFP experiments show the importance of profile control, to keep fluctuations low, for good confinement.
- RFP has similar need of efficient steady-state current drive with good confinement

- Dominant physics theme of non-inductive current drive and startup applies to the RFP.

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

We defined five metrics:

- Current amplification: the ratios of toroidal plasma current to source current (A_I), which must increase with progress.
- 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
- Plasma current $I_{p.}$

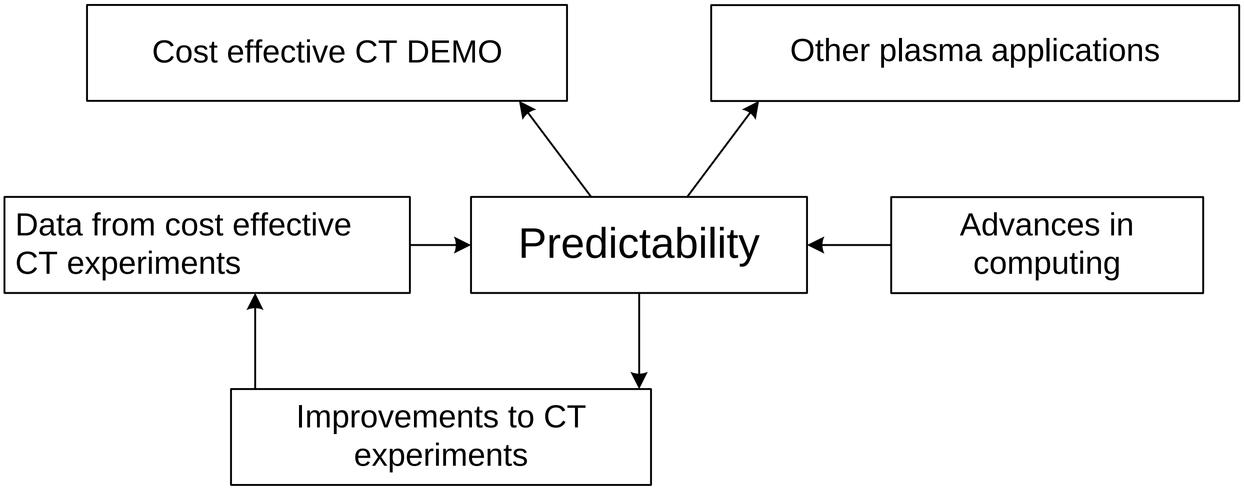
4. **The scientific goals should stress measurement of basic stability and confinement properties in quasi-steady discharges (that is, pulse length >> all characteristic times for MHD, transport, current profile relaxation, etc. and of course many transit times or Alfvén times). The required dimensionless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

We gave required parameter, while they are all based on dimensionless parameters, some are traditionally given dimensionally. The parameters are na, T, S, j/n, and beta. (I have added $\omega\tau$.) High na is needed for stopping neutral penetration into the plasma and is compared to the effective crossection for stopping neutrals (~ 10^{-19}m^2). High temperature is need so that crossfield transport is larger than parallel. The dimensionless physics is $\chi_{parll} / \chi_{perp}$ (~ T^3). About 100eV is needed to show some cross-field confinement. We also need to approach reactor temperature conditions. The Lundquist number S (= $\tau_{L/R}/\tau_{Alf}$) needs to be high to separate the Alfven, reconnection, and resistive-diffusion time scales. The nature of relaxation depends on the value of S which increases towards a reactor. High j/n is needed to be safe with respect to the Greenwald limit which is not well understood but a good guess is that j/n needs to be high enough so the Ohmic heating exceeds radiation in the edge. However, it cannot be too high or the drift-parameter limit will be exceeded causing high anomalous resistivity. Beta needs to be high for a cost effective reactor and for an experiment to achieve high temperatures at low magnetic field without exceeding the drift-parameter limit.

Parameter (units)	CE	PoP	PE
na (m^2)	2×10^{19}	6×10^{19}	10^{20}
T (eV)	100	1000	5000
S	10^5	3×10^6	10^8
j/n (Am)	10^{-14}	10^{-14}	10^{-14}
A_i	3	6	10
$\frac{\text{Core Pow}}{\text{Plug Pow}}$	0.1	0.1	0.1
I_p (MA)	0.1-1	1-10	10-20
beta	0.1	0.1	0.1

Parameters needed to study physics and to achieve success at the level given.

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?**



This strategy used in conjunction with the time line and previous table 4 constitutes a Roadmap. To help we include a table for the range of time that each question is addressed and decision points.

Physics Topic	Questions	Time range to address	Yes required in 2016 For next step	Ans. required in 2020 For next step	PE question beyond 2029)
Current drive/sustainment	▪ Can we find a method or combination of methods that provides and optimizes both sustainment and confinement?	10-30	X	X	X
	▪ Can power efficiency be improved?	10-29	X	X	
	▪ Are other current drive methods feasible? (NBI, RF, Bootstrap)	10-30			X
Confinement	▪ How does confinement scale?	10-30		X	X
	▪ What are limits to transport? What are the dominant causes of transport (e.g. overlap of mode-rational surfaces)	10-29		X	X
	▪ Do transport barriers form in spheromaks?	12-30			X
Beta limits	▪ Is beta limited by transport or by instability?	12-30			X
	▪ At keV temperatures, do spheromaks ohmically heat to a beta limit or is auxiliary power required?	12-30		X	X
	▪ How does it scale? (e.g. Troyon)	10-30			X
Stability	▪ Can q-profile be controlled in the spheromak for periods comparable to the heating time?	10-30	X	X	X
	▪ Can existing techniques maintain stability when sustained for periods >> L/R decay time (of plasma currents or flux conserving wall)?	10-29		**Steady-State**	
	▪ Are there lower power methods of controlling the current profile?	12-29		X	
Boundary, particle control	▪ Are there means for controlling particle inventory without use of getter?	10-30		X	X
	▪ What is the best method of refueling?.	16-30			X
	▪ Is a pumped diverter needed? What is best way to implement?	16-30		X	X
Longer pulse	▪ Can we design walls and electrodes that will take longer pulses? (active cooling, active stabilization required?)	10-30			X
	▪ Are there other methods of controlling RWM (plasma rotation?)	16-30		X	X
Burning plasma/Reactor Development	▪ Is there new knowledge that motivates a revisiting of H-K?	16-30		X	
	▪ Can pulsed refluxing lead to an attractive reactor?	10-30	X		
	▪ Is confinement sufficient for ohmic ignition	10-30		X	X

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**.
   - High current amplification A_i (ratios of toroidal plasma current to source current) is necessary to limit the demands on the injector and limit the power consumed on injector flux.
   - High plasma current I_p is necessary for confining a high pressure plasma.
   - High current drive efficiency is needed for cost effective experiments and the reactor. The efficiencies needed for all levels of experiments in the ITER era are given below. (BPX will need an increase.)
     - 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) ~> 20%.
- Beta needs to be high for a cost effective reactor and for an experiment to achieve high temperatures at low magnetic field without exceeding the drift-parameter limit.
- Confinement high enough for Ohmic heating to the beta limit is a goal at all levels

See table with 4 for values needed at the different levels.

7. **The basic spheromak equilibrium is force-free with $\beta=0$ 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?**

This will be discussed with respect to the Mercier beta limits. Because the spheromak is shear stabilized Mercier accurately describes its beta limits. However, the growth rate is a very slowly increasing function of beta at the instability threshold and, at low temperatures, Ohmic dissipation can stabilize the mode and/or Ohmic heating can overcome the losses due to the weak instability. Therefore, the beta of colder spheromaks tends to be higher then hotter ones of the same shape and the betas exceed the Mercier limit. This soft beta limit is difficult to distinguish from poor confinement. The beta-limit of a simple tuna-can flux conserver is very low because of low shear.

There are two way to raise the beta one is by changing the shape of the boundary and the other is optimizing the current profile. Both methods increase the shear by increasing the change in q across the profile. The q at the axis of symmetry is given by $\lambda(0)\, L/4\pi$ and at the magnetic axis by $2/\lambda(\psi_o)b$ (assuming the flux surfaces have circular poloidal cross sections at the magnetic axis) where $\lambda(0)$ and $\lambda(\psi_o)$ are $\mu_o j/B$ at the symmetry axis and the magnetic axis respectively and q is the safety factor. L is the length of the plasma at the symmetry axis and b is the radius of the magnetic axis. For a stable spheromak low q at the symmetry axis and high q at the magnetic axis gives the largest variation of q and hence the highest shear and beta. These considerations have led to the "bow tie" geometry (for low L and low edge q) sustained by helicity injection at the edge (for a hollow current profile and low $\lambda(\psi_o)$ and a high magnetic-axis q). The bow-tie spheromak equilibrium that has a linear $\lambda(\psi_o)$ profile which is marginally stable to the n=1 has a Mercier beta-limit of about 10%. Having both $\lambda(0)$ and $\lambda(\psi_o)$ low can also give high shear but $\lambda(\psi)$ in between has to be high so that the spheromak fits in the flux conserver.

When and how should it be addressed?

We should consider beta now and even in designs at the CE level. HIT-SI is designed with a bowtie shape for beta reasons. (The beta-limit of a Taylor-tuna-can spheromak is an uninteresting 1%). It might be possible to achieve a more optimal current profile while refluxing the spheromak. Refluxing the spheromak will produce a hollow current profile. Follow refluxing with a rapid shut-off of the edge current should give such a profile. (It has been speculated that CTX achieved such profiles.)

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?**

Impurities from electrode material are not a problem experimentally unless you over heat the electrodes. The CT diverter advantage should make this electrode-wall interactions problems quite solvable because the area for taking the electrode power is a free parameter. The H-K spheromak design has only 5MW/m^2 of power on the electrodes. (Aries AT has 14MW/m^2 on the diverter plates.) It is quite possible that the technology developed for tokamak diverters will be more than adequate for spheromak electrodes. However, electrodes would probably not operate in a detached-divertor mode.

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

To minimize the risk in meeting our goal two larger devices should be built ASAP, one to develop steady-state sustainment and one to study spheromak confinement using pulsed formation and controlled decay. Current amplification is an issue now! The larger size is needed for the steady-state experiment so that na will be large enough for density control needed to get j/n high enough to achieve 100 eV temperatures so S will be large enough to allow relaxation to produce large current and flux amplification. Once this is achieved the experiment will be upgraded to a PoP steady-state confinement experiment. The larger-size pulsed confinement experiment at the CE level, upgradable to a POP, is needed to get to the keV temperature needed for confinement studies. The experiment will be designed for studying confinement during controlled decay. The decay time is much longer than the confinement time so this is quit possible. Dynamic control of the injector flux and current during the controlled decay should allow controlled decay at much lower injector currents. (CTX achieved 400eV with zero external current.) SSPX required a large amount of controlled decay current because it could not remove the formation flux for the decay and it had to keep the edge lambda up.

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.**

For today we use SSPX values and for reactor we use H-K, for the ITER-era we use the PE level even though the PE will barely operate.

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[‡] (MW)	50 (P_{edge}) 5 (P_{ohm})	100	30 (60 @ η = 0.3)
Current drive efficiency (η)	0.1	0.2	0.6 (+1.5% on COE @ 0.3)
Major Radius[c] (m)	.32	1.3	2
Minor Radius[c] (m)	.18	1	1.5
Elongation (κ)	1.2	1.2	1.2
Central density n_e or $\langle n_e \rangle$ (m^{-3})	$2\text{x}10^{20}$	$2\text{x}10^{20}$	$2.3\text{x}10^{20}$
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) = Utherm/Pin, (Pin = Pohm or Pedge)	.001 (Pohm) .0001 (Pedge)	0.043	0.43
Fusion power density $B\tau_E$ (T-s)	.001	.1	2
Core electron transport[d] (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)
$S_D = a / \rho_D$	42 ($L^* = a$)	175	260
$S_\alpha = a / \rho_\alpha$ ($E_\alpha \sim 2.5$ MeV)	0.2	8	37
Collisionality (ν_*) = a / λ_{mfp_e} ($\lambda_{mfp\_e} = V_{th,e}{*}\ \tau_e$)	10^{-2}	10^{-3}	10^{-4}
Normalized pulse length (τ/τ_r)[#]	.01 (τ~.01s) (τ_{res}~1s)	SS	SS
Normalized pulse length ($\tau/\tau_{Ti=Te}$)[#]	50 (τ~.01s) (τ_{eq}~200 us)	SS	SS
Estimated Fusion Power (MW)	0	0	3400
Estimated wall loading (MW/m^2)	0	0	20
Estimated plasma exhaust power (MW/m^2)	40	5	5

[a] peak on axis [b] ohmic or driven or diamagnetic [c] mean values if not axisymmetric

[‡] power to plasma needed to maintain configuration, magnetic field, or plasma current

[d] measured or estimated from power balance, size, beta, or ne, Te, and Ti

[#] τ_r ($\tau_{Ti=Te}$) is relevant time scale for configuration redistribution (temperature equilibration)

[*] use either a or R as appropriate [†] indicate if not simultaneous

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.

Please provide definitions, formulary, or assumptions on a separate sheet.