Spheromak research in the ITER era

By

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To

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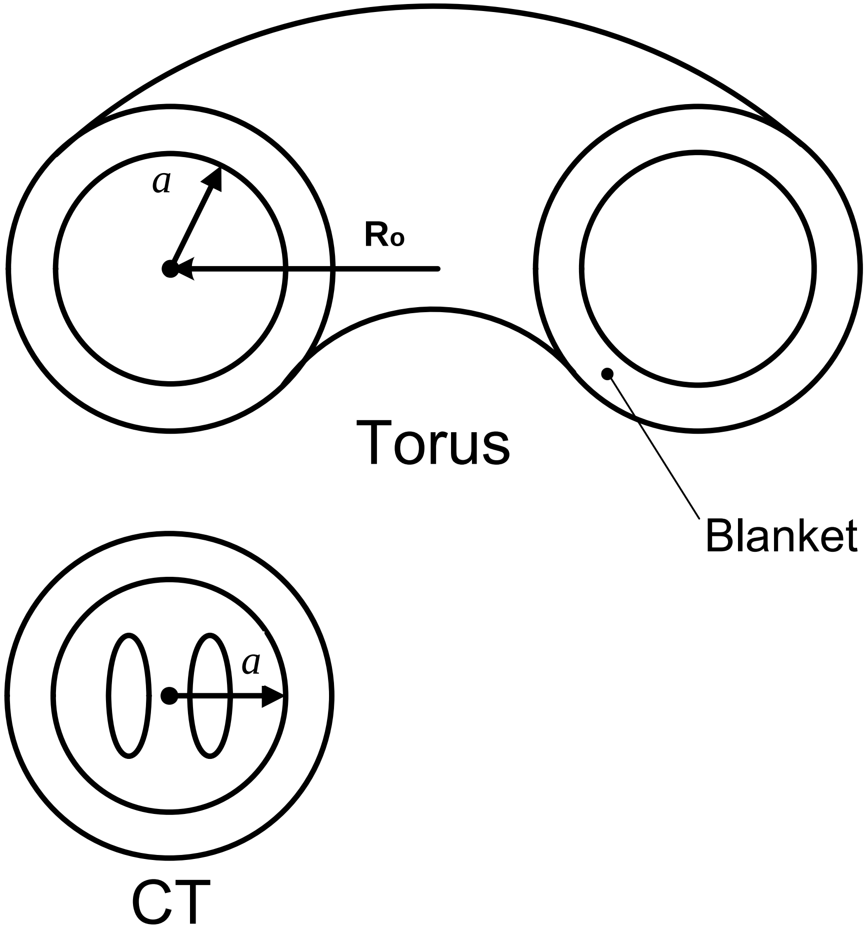
Outline

- Motivation
- Goal
- Questions
- Summary

The spheromak is a toroidal confinement device with the material center stack removed leading to very large reactor advantages.



- The optimum size of a reactor has: *a* a little larger than the thickness of the blanket, shield and coil where *a* is the smallest characteristic size. (C. Baker)
  - Area ratio ≅ 6
  - Vol. ratio ≅ 10
- Reduces capital cost by a factor of 10 compared to tokamak [Hagenson R. L. and Krakowski R. A., Fusion Technol. **8**,1606 (1985).]
- Spheromaks has been pursued by leaders in fusion research:
  - Harold Furth
  - Marshal Rosenbluth
  - Kin Fowler

Spheromak research has made good progress with very limited budgets

- Significant progress in performance has been achieved in smaller devices (e.g. SSPX): Te~0.5 keV, B_{tor} > 1Tesla, I_p ~ 1MA, n_e ~ $1x10^{20}$m-3.
- Spheromaks can achieve good (but transient) core confinement approaching tokamak L-mode.
- SSPX has achieved reasonable internal current profile control to avoid low-order mode rational surfaces by programming the initial flux distribution and discharge current.
- Steady-state sustainment by helicity injection has been demonstrated both with electrodes and inductively.
- Theory for steady inductive helicity injection current drive agrees with the measure profile and amplitude of the spheromak equilibrium produced. (i.e. HIT-SI)
- Quasi-steady-state sustainment via repetitive cycles of pulsed build-up followed by partial decay has been achieved.
- Ohmic heating to beta limit was observed in CTX during decay with zero injector current and flux.
- Validated modeling tools have been developed - now providing moderate predictive capabilities (i.e.NIMROD)

1. 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?

Goal: ***"Conduct experiments and simulations that demonstrate good confinement and determine means for current drive compatible with stability and good energy confinement. This will enable successful experiments at the PoP level followed by construction and initial operation of a PE-level experiment within 20 years."***

- 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.

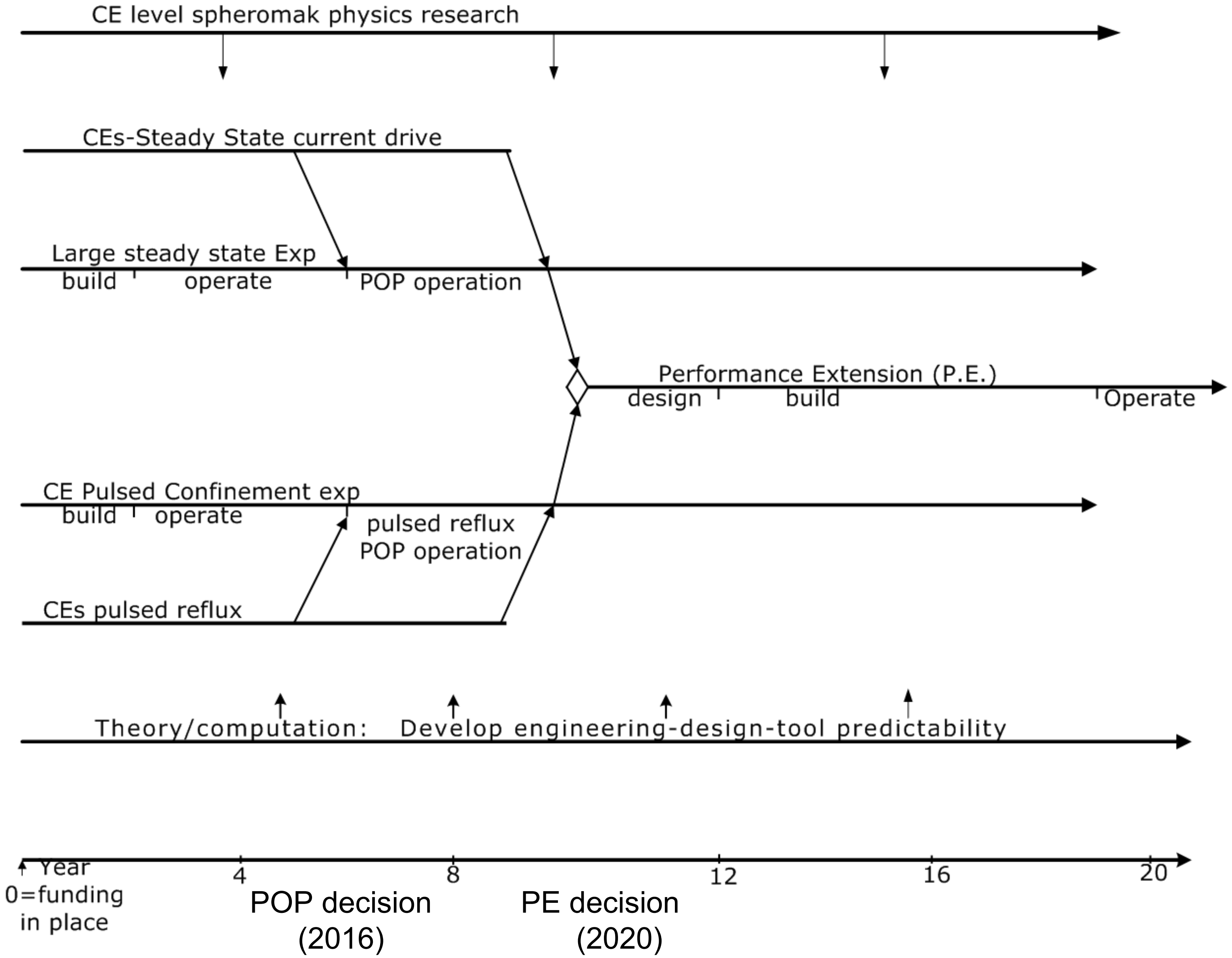
2. Your plan calls for the PE in 7-10 years, which appears too ambitious and inconsistent with your goal. Did you mean PoP on the shorter time scale?

- Begin now designing and building two CE experiment that can each grow into POP experiments and begin now designing and building smaller supporting CE experiments.

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 what we are thinking. This is done with two lines of attack in parallel with at least one of three scenarios successful.
  - Develop steady-state current drive that is compatible with good confinement (both core and global) either by helicity injection (large CE) **or** some other method. (The holy grail of fusion research.)
  - Develop pulsed refluxing followed by good confinement in controlled decay. (quasi-steady-state)
    - Need methods to make long periods of relaxation free decay (using low power) and short periods of refluxing (using acceptable power and current).
    - Need to assess cyclic fatigue and other pulsed reactor issues in a reactor study.

Timeline of Spheromak Research in ITER ERA (Aggressive Funding)[3][2][5]



CE level spheromak physics research

CEs-Steady State current drive

Large steady state Exp
build
operate
POP operation

Performance Extension (P.E.)
design
build
Operate

CE Pulsed Confinement exp
build
operate
pulsed reflux
POP operation

CEs pulsed reflux

Theory/computation: Develop engineering-design-tool predictability

Year
0=funding
in place
4
8
12
16
20

POP decision
(2016)

PE decision
(2020)

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

- All lines are essential if we are to succeed in the time proposed.
- Highest priority are the large steady state CE and the CE confinement experiment.
- The risk is much higher without the supporting CE experiments

3 cont. 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.
- 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.

3. Cont- 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. Solutions found for RFP might apply to spheromak
- Dominant RFP physics theme of non-inductive current drive and startup applies to the spheromak.

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

Answer with 6

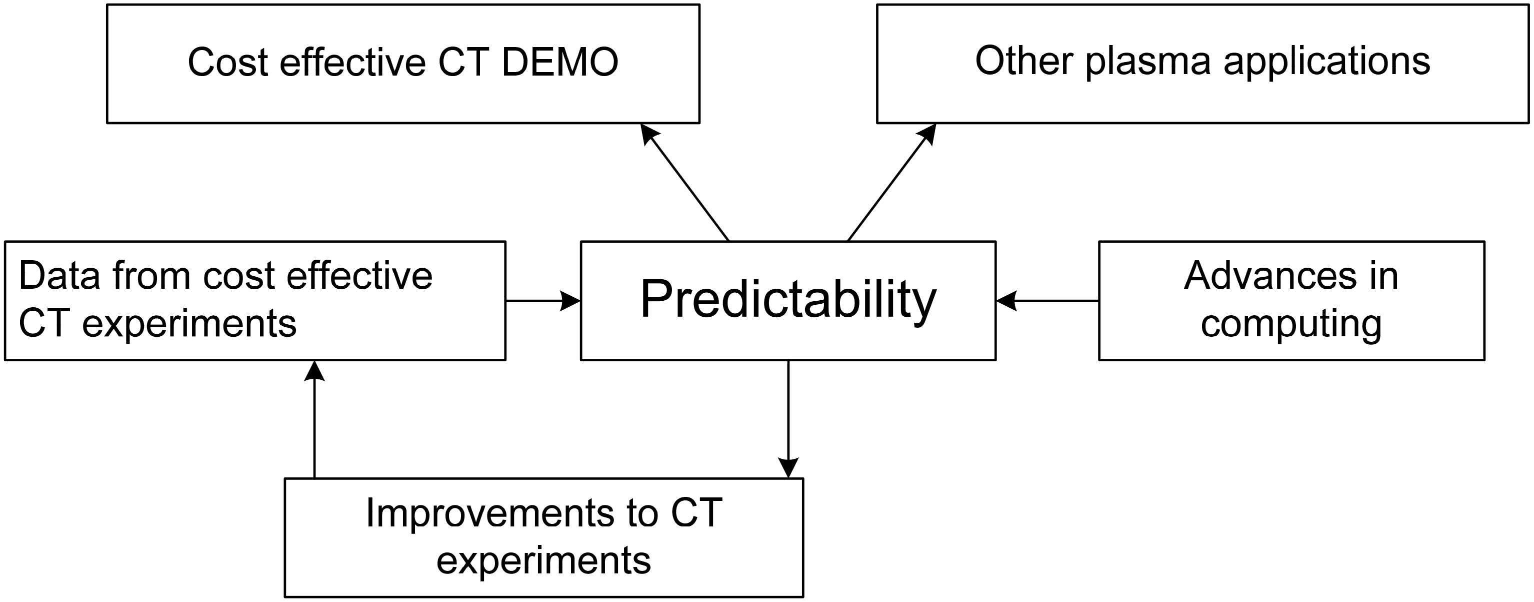
4. The required dimensionless parameters should be based on the best current assessment of relevant physics not arbitrary dimensioned quantities.

Several physical parameters are needed for an experiment to address the gaps at different levels

- 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 needed so that parallel transport is much larger than crossfield.
  - 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.
  - Cannot be too high or the drift-parameter limit will be exceeded, causing anomalous resistivity.

Table will be given after 6.

5. A scientific roadmap is recommended to pull these together and probably should have decision points



Cost effective CT DEMO

Other plasma applications

Data from cost effective CT experiments

Predictability

Advances in computing

Improvements to CT experiments

- A knowledge-led strategy, where computer models become engineering design tool, and the timeline constitutes a Roadmap.

Key go or no-go decisions for POP(2016) and PE(2020)

Physics Topic	Questions	Time range to address	Yes required in 2016 For next step	Pos. 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, flux conserver)?	**10-29**		**X**	
	▪Are there lower power methods of controlling the current profile?	**12-29**	X	**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**

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5.cont- What experimental and simulation work is needed in the near term?

- Near term experimental needs are described elsewhere
- Advances in Theory and Computation are central to achieving the goal and Theory/Computation effort needs to be strengthen in the following areas:
  - Model by direct numerical computation up to and including lower hybrid frequency.
    - Include higher frequency physics with transport parameters.
    - Add two-fluid/Hall physics in 3D simulations (available very soon).
  - Realistic edge plasma/material wall interaction modeling in 3D simulations.
  - Realistic modeling of circuit coupling to the plasma.
  - Incorporate enough atomic physics to include breakdown in whole-device modeling.
  - Predictive *enough* to test engineering designs before they are built. Essential for the exploration and refinement of all promising device geometries with budget-limited research.

6. (&5,3.)The physics basis for reaching goals, metrics

- 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%
  - 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

Parameters needed to study physics and to achieve success at the level given.[4] [6] [3]

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
I_p (MA)	0.1-1	1-10	10-20
Power eff.	0.1, 0.2	0.1, 0.2	0.1, 0.2
beta	0.1	0.1	0.1

7. What is required for achieving high β?

- Various pressure-driven modes are observed, but not clear which will be important at higher S and longer discharge durations. Mercier limit should apply since spheromak is shear stabilized.
- Mercier beta-limit can be increased with boundary shape (bowtie) and/or profile optimization (current peak off axis), which increase shear.
  - 10% beta limit is quite possible.
  - Experiments tend to exceed Mercier because the growth rate is a very slowly increasing function of beta at the instability threshold.
- Ohmic power will diminish as T_e increases.
- Classically, confinement should improve as T_e increases
  - Classically: $\beta \sim \lambda a$ (λ is inverse magnetic scale length)
  - Exceeding beta limit on a small warm experiment bodes well for ohmic ignition in a reactor.
  - However, classical confinement/heating is questionable and study is needed.
- We do not know if confinement is limited by beta-limit or beta is limited by confinement. (Aux. heating is needed to resolve this.)

7.cont- When and how should beta be addressed?

- Beta should be addressed now. High beta allows experiment to achieve high temperatures at low magnetic field without exceeding the drift-parameter limit.
- For steady state need to:
  - Shape the boundary (e.g. bowtie shaped)
  - Drive a mode whose dynamo drive results in correct profile (Need more accurate modeling of dynamo to develop this.)
  - Use additional current-drive methods for profile-control. (NBI, RF, bootstrap)
- For pulsed refluxing:
  - Use all of the above plus pulsed reprofiling. (e.g. Refluxing might re-establish off-axis current peak.)

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?

- Experimentally impurities from electrode material is not a problem at low wall loading.
- Electrode formation and sustainment are reactor relevent because the natural divertor geometry allows the area of the electrodes to be optimized too handle the surface loading.
- In the H-K spheromak reactor study, electrode wall loading (5MWm^{-2}) is less demanding than Aries AT diverter loading (14MWm^{-2}).
  - Technology should be in place before spheromak needs it because it will be developed for tokamak divertors.

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

- A flexible large-scale formation and sustainment experiments to develop and understand steady-state sustainment with good confinement is needed now.
  - Need spheromak a ~ 0.5 m [~ 2 x HIT-SI].
    - To prevent neutral influx *na* > 2×10^{19} m^{-2} is needed (presently *na* = $0.5 \times 10^{19} m^{-2}$)
    - To lower dissipation in order to give higher current amplification. Need larger $S \sim a^5$- (assuming $T_e \sim a^2$)
  - Upgradable to POP confinement device when ready.
  - Large enough for NBI rotation and profile control.

9.cont- 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?

- Platform to address confinement issues is needed now
  - 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 T_e is needed.
  - Initially single pulsed. Upgrade to a quasi-steady-state POP (i.e. pulsed-refluxing) when formation and controlled-decay powers and currents become acceptable.
- Different from SSPX:
  - Build spheromak with better/dynamic (i.e during the discharge) injector flux control.
  - Optimize helicity injector for higher flux amplification
  - Test double null diverter (Was the best configuration on HIT-II.)
  - Test more bowtie-like shape

10. can you give a table of desired target 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**	12	**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})	**$2x10^{20}$**	**$2x10^{20}$**	**$2.3x10^{20}$**
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-avg)**
Energy confinement time[d] (s) = U_{therm}/P_{in}, ($P_{in} = P_{ohm}$ or P_{edge})	**.001 (P_{ohm})** **.0001**	**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**	**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)**	**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[i] (MW/m^2) ($P_{conduction}+P_{rad}+P_{neutrals}+P_{neutron}$)	**~ 1**	**~ 2 - 5 ?**	**20**
Estimate divertor (or injector anode+cathode) loading (MW/m^2)	**50**	**5**	**5**

Notes

[a] peak on axis

[b] ohmic or driven or diamagnetic

[c] mean values if not axisymmetric

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

[d] measured or estimated from power balance, size, beta, or n_e, T_e, and T_i

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

[*] use either a or R as appropriate not simultaneous.

[i] 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

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.

Summary

- The spheromak is a CT with $B_{tor} \sim B_{pol}$ having ideal MHD stable equilibria at high beta (10%).
- A spheromak fusion reactor might be an order of magnitude more cost effective
- Considerable progress has been made
- A much stronger effort in spheromak research is needed for it to become a serious backup for the ITER-based fusion reactor.
- Developing computational engineering design tools will greatly facilitate progress towards a spheromak reactor.