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Sustained Spheromak Physics Experiment, SSPX

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Abstract

The Sustained Spheromak Physics Experiment is proposed for experimental studies of spheromak confinement issues in a controlled way: in steady state relative to the confinement timescale and at low collisionality. Experiments in a flux conserver will provide data on transport in the presence of resistive modes in shear-stabilized systems and establish operating regimes which pave the way for true steady-state experiments with the equilibrium field supplied by external coils.

The proposal is based on analysis[1,2] of past experiments, including the achievement of $T_e = 400$ eV in a decaying spheromak in CTX. Electrostatic helicity injection from a coaxial "gun" into a shaped flux conserver will form and sustain the plasma for several milliseconds. The flux conserver minimizes fluxline intersection with the walls and provides MHD stability. Improvements from previous experiments include modern wall conditioning (especially boronization), a divertor for density and impurity control, and a bias magnetic flux for configurational flexibility. The bias flux will provide innovative experimental opportunities, including testing helicity drive on the large-radius plasma boundary. Diagnostics include Thomson scattering for T_e measurements and ultra-short pulse reflectrometry to measure density and magnetic field profiles and turbulence.

We expect to operate at T_e of several hundred eV, allowing improved understanding of energy and current transport due to resistive MHD turbulence during sustained operation. This will provide an exciting advance in spheromak physics and a firm basis for future experiments in the fusion regime.

Background and Significance

Motivation and scientific issues

The spheromak represents the extreme use of shear stabilization to confine plasmas, and the simplest possible toroidal reactor by virtue of maximal use of intrinsic plasma properties for confinement with minimal external control. Two confinement issues of special concern for spheromaks are resistive modes (current-driven tearing modes and pressure-driven resistive interchange modes) and the requirement of a flux conserver to stabilize the tilt and shift modes, which in turn imposes different boundary conditions for edge physics. A third issue, ideal MHD stability at interesting values of beta, may not be very restrictive for spheromaks according to calculations. Experimental results in the CTX and subsequent theoretical work offer hope for a favorable resolution of all three issues.

The goal of the SSPX is to provide an experimental environment in which spheromak confinement issues can be studied in a controlled way, namely in steady state relative to transport timescales, and in the low collisionality regime relevant to fusion plasmas. The initial work proposed here, using the flux conserver to establish equilibrium, will pave the way for future steady-state experiments in which the equilibrium field is supplied by external coils, and will provide data on resistive modes in shear-stabilized systems complementary to ongoing studies in RFPs.

Of the two key confinement issues – tilt/shift stabilization and resistive modes – it is the resistive modes that are the most fundamental concern for energy confinement in a spheromak sustained through helicity injection. Achieving steady-state in SSPX by edge helicity injection should reduce the spatial variation of $\mathbf{j}\cdot\mathbf{B}/B^2$, and thus the amplitude of current-driven modes, relative to induction-driven systems in which current is peaked on the magnetic axis and decreases in the cold plasma edge. There are several potentially stabilizing effects present in spheromaks which may limit the growth of islands, including neoclassical currents (which are stabilizing for tearing in spheromaks) and the currents driven by the dynamo itself which act to limit island growth. A reduction in current-driven turbulence will allow the study of pressure-driven resistive modes thought to limit beta in spheromaks, but which must have been relatively benign in order that CTX achieve the temperatures reached in that device. Thus, studies of resistive MHD modes in spheromaks could contribute to the general body of knowledge important to all toroidal devices as well as potentially lead to the understanding necessary to carry the spheromak into the fusion regime.

Two key diagnostics for the plasma interior are a conventional Thomson scattering system and a new diagnostic, Ultra Short-Pulse Reflectrometry (USPR), to observe island growth and behavior in the core of the spheromak. USPR complements conventional diagnostics (such as edge magnetic probes and xrays) for studying these modes, providing important data to understand the coupling between magnetic fluctuations and energy losses. It will also provide density and magnetic field profile data, important to the spheromak plasma's evolution.

Several innovations for spheromak research will be applied to advance the experimental goals, including a divertor to control density and impurities, the use of a bias flux to provide increased flexibility in the magnetic configuration, and modern vacuum and wall techniques to ensure that the plasma is not dominated by atomic and radiation effects. Application of these new features to the experiment will be described in the physics design section.

These studies could be extended to include external control of current-profiles, pioneered in tokamaks and RFPs, as an additional experimental control to turn on and off current driven modes in competition with pressure-driven modes or as an alternative means of enhancing spheromak performance. Our initial plans, however, are focused on the need to develop understanding of the transport mechanisms in a sustained spheromak with current driven by helicity injected at the edge, with the goal of applying this knowledge to limiting energy losses while balancing the current dissipated in the hot spheromak core by the helicity-driven dynamo. Opportunities or need for current drive will be reassessed as the experiment progresses.

Finally, the study of tilt/shift modes in SSPX will provide data on the practical issue of wall stabilization without a toroidal field supplied by external coils. This looks ahead to future experiments in which SSPX will provide a testbed for studies of feedback stabilization on the resistive wall time. According to our estimates, the power required to stabilize spheromaks by feedback is substantially less than that required to maintain a stabilizing toroidal field with copper conductors (as in the spherical torus), and the quantity of material exposed to neutrons and related nuclear engineering issues are no worst, perhaps better, in the spheromak than other devices.

Status of experimental and theoretical knowledge.

Interest in the spheromak was generated in the late 70s with a ground-breaking paper by Rosenbluth and Bussac[3] concerning MHD equilibrium and stability of the device. The spheromak is a toroidal magnetic configuration with helical field lines lying on closed surfaces as in the tokamak. The basic geometry has evolved from the ideal one of Rosenbluth and Bussac, and now typically involves a flux "hole" along the axis of symmetry. Examples of this are described later in the proposal as part of the detailed physics design.

Five different methods for forming the spheromak have been proposed and tested: an inductive flux-core scheme,[4] a theta/z-pinch,[5] a magnetized coaxial gun,[6,7] a conical z-pinch,[8] and a kinked z-pinch.[9] Jarboe[10] has reviewed the experimental results and physics in detail. Experiments based on each of these concepts successfully demonstrated spheromak formation, although the best performance in confinement and electron temperature were eventually achieved in gun-produced spheromaks formed in flux-conserving shells: electron temperature = 400 eV, peak magnetic field = 3 T, toroidal magnetic current = 1 MA, helicity decay time = 2 ms, and global energy decay time = 0.2 ms.[11]

The magnetized coaxial plasma gun technique was pioneered at LLNL and LANL in the late 70s and early 80s with the BETA-II and CTX experiments. Plasma flowing from the coaxial gun discharge entrains poloidal magnetic field generated by solenoidal coils. The plasma and fields flow into a formation region where the spheromak is established following magnetic reconnection. Early work showed that spheromaks could readily by formed by this technique, although the discharges were radiation dominated from large quantities of low-Z impurities, with electron temperatures in the 10 eV range.[12] It was also demonstrated that a close fitting, oblate, flux-conserving shell was needed to suppress tilt and shift instabilities.[13,14,15] The ability of the coaxial gun to form the spheromak within a flux conserver[16] is a major advantage of this technique and may account for why it proved the most successful. (On the L/R time of the shell these modes become resistive-wall instabilities, so feedback techniques similar to those for vertical control in tokamaks will likely be required in future long-pulse experiments.)

Spheromak research progressed rapidly, in part because of the existence of MHD theory and the Taylor minimum energy principle[17,18] which provided a theoretical basis for the work. A key result of the early spheromak experiments was the validation of the Taylor theory. Taylor applied relaxation concepts to reversed field pinch discharges, concepts originally put forward by L. Woltjer[19] for astrophysical plasmas and later by Wells[20] to explain early compact toroid results. Spheromaks such as BETA-II were shown to exhibit "flux amplification" and other phenomena, as do RFPs, that could not be explained by the usual models[12] but were in quantitative agreement with Taylor's theory. Experiments on S-1 at PPPL explicitly demonstrated[21] the transformation of poloidal to toroidal flux during the relaxation towards the Taylor state. The role of magnetic helicity[17,22] was demonstrated,[23] which led to long-pulse build up and sustainment of the spheromak over many resistive decay times.[24] More recently, the SPHEX experiment at Manchester made probe measurements[25] which demonstrate that kinking of the current column along the geometric axis of a sustained spheromak drives a dynamo inside the separatrix. The helicity is then transported throughout the plasma volume by a lower level of magnetic turbulence.

Spheromak confinement experiments at LLNL were terminated in 1982, although experiments on related compact tori continued for other purposes. At LANL, the CTX experiment confinement studies led to improved plasma parameters. LANL developed the slow (100-1000 microsecond) formation technique,[24] which was subsequently employed on compact tori at LLNL to produce cleaner discharges. Through a sequence of improvements in plasma-facing surfaces, flux-conserver designs to minimize losses on open field lines at the plasma edge, discharge cleaning, and titanium gettering, the plasma purity and lifetime on CTX were improved. Flattops of almost 6 ms[26] and total duration of nearly 10 ms[24] were achieved by balancing the ohmic decay with continuous helicity injection from the gun. In experiments on a large (0.61 m radius) flux conserver, 200 eV electron temperatures were reached after injection ended.[27] A smaller flux conserver (0.28 m radius) reached a field of 3 T, electron density of 5×10^{20} m^{-3}, electron temperature of 400 eV, ion temperature of 1 keV, and a global confinement parameter $n\tau =$ 1.8×10^{16} m^{-3} sec.[28] Fowler later argued that the core confinement was larger by perhaps as much as an order of magnitude.[2,29]

The CTX parameters were limited by the onset of an interchange instability when the central beta reached ~ 20%, although the global beta was only a few percent. Theoretical calculations[30,31,32] indicate that correct shaping of the flux conserver, especially with a flux hole along the geometric axis, and with shaping of the current profile in the confinement region can increase the magnetic shear of the spheromak equilibrium, leading to global β-limits of 10% or more. (Proper flux conserver shaping is also required to stabilize the tilt and shift modes.[3,33])

In these decaying plasmas (with open, "mesh" flux conservers) the energy confinement was limited by losses in the cold edge plasma.[34] The lack of neutral-particle control at the spheromak edge, coupled to the constraints in the spheromak MHD equilibrium evolution, led to a global loop voltage (and thus global confinement decay rates) dominated by ohmic plasma currents driven along the outer flux surfaces where the resistivity was very high due to electron-neutral collisions.[34] Plasma energy losses were dominated by charge exchange, particle transport, and the drive for the current along open-field lines in the edge. Indeed, until the last series of experiments in solid flux conservers, the edge included a significant volume of open magnetic field lines, so that these losses were very large. In experiments on the CTX large flux conserver, the global time was improved by careful magnetic design. These solid flux conserver experiments were funded to achieve high temperature, low resistivity, and relatively long magnetic lifetimes suitable for explosive compression.[35]

Further details and references can be found in several review articles.[10,36,37,38] A recent report[39] reviewed the theoretical status of MHD equilibria, MHD stability, the spheromak dynamo, and the edge plasma. The critical information missing from previous experiments is the energy confinement time (and transport) in the core of decaying plasma and in sustained plasmas, as well as the role of resistive modes in energy confinement. Fowler developed a model[2,29] based on the Rechester-Rosenbluth thermal conductivity with tearing modes carrying helicity into the spheromak core. Extrapolation to reactors is promising in that it predicts good confinement at the low level of turbulence needed to balance resistive current dissipation in the core at high electron temperatures. The model also predicts that ohmic ignition of a reactor is possible. Experimental evidence for this hypothesis was examined in considerable detail by Hooper, et al.,[1] who concluded that it was well supported by experiments in decaying plasmas but that there is insufficient data to support it in spheromaks sustained by helicity injection.

Fusion power plant prospects

The spheromak is potentially an attractive reactor, in large measure because of the lack of a central column to generate a vacuum toroidal field and/or inductive electric field. An economic analysis by Hagenson and Krakowski[40] was very encouraging, subject to large extrapolations of confinement and other physics parameters. Ohmic ignition may be possible,[41,42] eliminating the need for auxiliary heating. A recent study[43] showed that a plasma configuration with a divertor is possible; see Fig. 1. This geometry has a separatrix for control of the current flow around the plasma and a divertor for power, particle, and impurity control. The possibility of a high mass power density and other reactor advantages are also of interest.

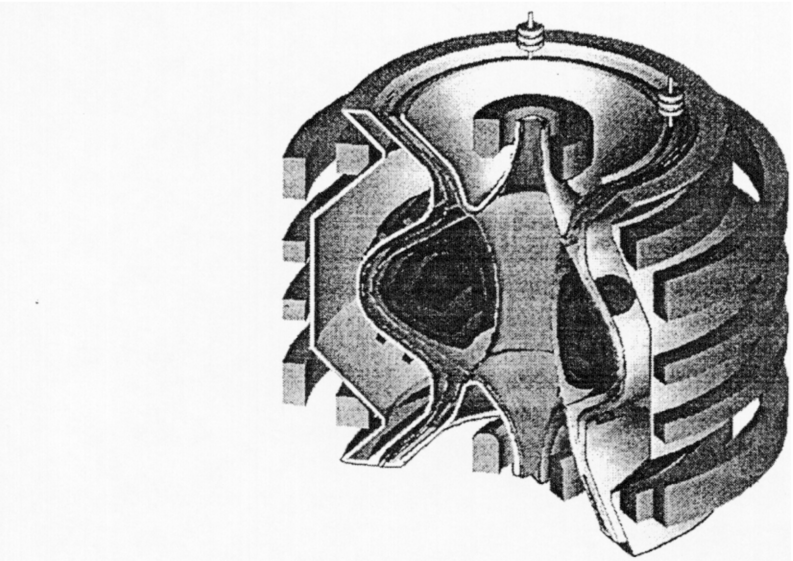

Fig. 1. Conceptual design of a spheromak reactor, showing the plasma and vertical-field coils. The helicity injector is on the top and a divertor on the bottom. Feedback stabilization of the tilt and shift modes is assumed in the concept.

The spheromak geometry also opens opportunities for innovations in the reactor design, including possible liquid lithium walls[44] or a liquid Li-Na/K boiling pot[45] as shown in Fig. 2. In all cases, further study awaits better knowledge of the confinement in a sustained plasma so that more realistic dimensions, magnetic fields, and other parameters can be determined.

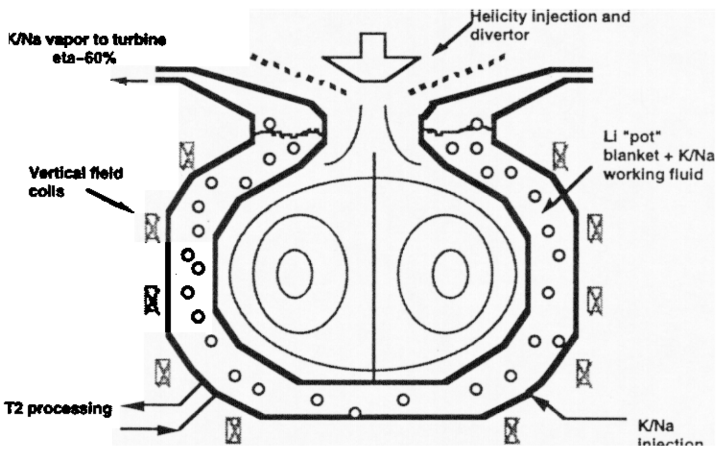

Fig. 2. Conceptual design of a pot-boiler reactor. The Na/K boils from a liquid-Li pot and drives a combined cycle with possible efficiencies of 60%. A major issue is ensuring a sufficiently large heat transfer rate from the first wall to the liquid lithium.

Preliminary Studies

LLNL internal funding

Support to explore spheromak physics and its experimental implications was provided at a fractional FTE level in FY 1995 and FY 1996 by the LLNL Laboratory Directed Research and Development (LDRD) Program. Funding from DOE-OFE in FY 1996 was used to review results from previous experiments and to apply modeling codes to the spheromak. We did a preliminary design of the spheromak flux conserver shape and evaluated consequences for a spheromak experiment. The modeling included modifying the CORSICA[46] system of codes for application to the spheromak; studying the MHD equilibrium, including a separatrix and currents on external, open flux surfaces; modeling transport using CORSICA; and examining the beta limits of the designs of interest. A "white paper" review of theoretical issues[39] was prepared to define issues and guide the design in the areas of MHD equilibria and stability, the spheromak dynamo, and edge physics. Results from these efforts are reflected in the design presented below.

In FY97, LDRD funds in the amount of $750k were provided address the critical physics issues necessary to evaluate the feasibility of the spheromak as an alternative choice to the tokamak. A proposal has been submitted to continue these studies in FY98 with the expectation that they would continue in future years. OFES provided $600k in March for design and construction of an experimental facility with the understanding that any future funding is contingent on the OFES review process. This proposal is in response to OFES' request for a review of our spheromak program. We are requesting $1500k per year from OFES to continue construction and to operate the facility.

Detailed physics design of the spheromak has been undertaken by the principle investigator and several members of the LLNL theory group. General Atomics has contributed MHD stability analysis. A group of LANL physicists (who worked on CTX) has reviewed the preliminary design and presented detailed comments and suggestions, most of which have being incorporated in the design. A team has been assembled to do detailed engineering design and preparation for construction. Cleaning out of the facility previously used by a previous experiment ("RACE") has commenced. Vacuum and power system designs have been initiated. Detailed design and construction plans are presented later in this proposal.

Several collaborations have been initiated. We have a graduate student from U.C. Berkeley working on a reactor study, and plan for an additional student this summer to work on a diagnostic. We have reached agreement with the plasma diagnostics group at U.C. Davis to construct the USPR reflectrometer diagnostic and to provide a student to apply it to the experiment. We are having discussions with U. Washington for a student to construct and measure magnetic fields with the Transient Internal Probe presently used there on the HIT tokamak experiment. We have also had discussions with the U. Wisconsin MST group about a collaboration to apply some of their transport diagnostics to the edge plasma in SSPX.

Implementing the scientific goals in the experiment

The scientific goals of SSPX have been described in the introductory section. Helicity injection drives a magnetic dynamo which breaks the axisymmetric magnetic flux surfaces, allowing energy leakage from the core. One way of viewing the process is to consider magnetic island growth and saturation due to a variety of processes, resulting in a description for the island width, w:

$$\frac{dw}{dt} = C\frac{\eta}{\mu_0}\left[\Delta' + 4.6\frac{D_R + D_{NC}}{w} + \ldots - \mathcal{D}_{dyn}\right] \qquad (1)$$

where C is a constant of order unity, η the resistivity, Δ' the Rutherford parameter describing the free-energy due to the current gradient, D_R the resistive interchange parameter, and D_{NC} the neoclassical interchange parameter. We have added to the neoclassical description[47] a nonlinear term, $-\mathcal{D}_{dyn}$ resulting from current flow generated by the dynamo; full specification of this term includes the balance with the resistive current decay needed to sustain the equilibrium. A spheromak differs from the tokamak in that D_R is destabilizing and D_{NC} stabilizing; the opposite is true in the tokamak. Description of the final state will require a consistent solution with all the terms, including processes such as finite-Larmour radius stabilization indicated by the dots in the above equation.

Good energy confinement in the presence of a dynamo driving the plasma current is a critical issue for the spheromak, closely related to the saturated island size and possible chaotic fieldlines resulting from overlap of islands. Recent results indicate that in RFPs deviations of the current profile from the Taylor state generate instabilities that open field lines sufficiently to destroy confinement. An important parameter is λ, constant in the Taylor state, where:

$$\lambda = \mu_0 \mathbf{j} \cdot \mathbf{B}/B^2 \qquad (2)$$

In the ohmically-driven RFP, λ is peaked on the magnetic axis where the resistivity is smallest; the decay of helicity is on the cold edge so that there is a strong gradient in λ from the axis to the edge. The result is a strong drive for the resistive tearing modes resulting in highly chaotic magnetic fieldlines in the core. Adding edge current drive to flatten the λ-profile reduces the turbulence and significantly improves energy confinement.[48] In the edge-driven spheromak λ is peaked on the edge, with a minimum in the core where the resistivity is low.[49,50] The resultant reduction in the required helicity transport should allow a lower gradient in λ than in the RFP.

Other differences such as the relatively low aspect ratio of the spheromak, make a direct extrapolation from the RFP difficult. Indeed, the opportunity to explore and compare the physics of the dynamo and helicity in the spheromak and the RFP is likely to lead to a better understanding of the fundamental physics underlying them and natural dynamos.

Achieving the scientific goal of providing an experimental environment in which spheromak confinement issues can be studied in a controlled way will require establishing a sustained plasma for times long compared with the time for the plasma turbulence to develop, and with good control of the magnetic geometry, a low impurity contamination, etc. The electron mean-free-path should exceed plasma dimensions, so we need $T_e > 0.1$ keV. The tearing mode linear growth rate must be short compared to discharge times; at a wave number k it is $0.5(ka)^{2/5}(\Delta' a)^{4/5}/(\tau_H^{2/5}\tau_R^{3/5})$, where τ_H is the Alfvén time and τ_H the resistive time of the plasma.[51] At $n = 10^{20}$ m^{-3}, $B = 1$ T, $a = 0.25$ m, and $T_e = 0.4$ keV, $\tau_H^{2/5}\tau_R^{3/5} \approx 1$ ms; islands small compared with the plasma radius grow rapidly compared with this into the nonlinear regime where Eq. (1) applies. ("Seed" current sheets from the startup may initiate the growth at sizes already in the nonlinear regime.) In any event, we expect the lower limit on the necessary discharge pulselength to be about 1-2 ms. It follows that this physics can be studied on a timescale short compared with the L/R time of the flux conserver (wall), so that the issues of transferring the equilibrium to external coils and feedback control of low-m modes can be postponed to the final stages of the present experimental program.

An additional experimental requirement which follows from these considerations is that the power system be easily reconfigured to match time scales associated with the achieved temperatures, thus optimizing power system efficiencies. In SSPX the sustainment system is a pulse-forming network (PFN) which is being designed to allow shaping of the discharge wave form to best match the pulselength and power requirements of the discharge.

Diagnostics must also be selected to address the physics issues. In addition to the standard diagnostics (magnetic wall probes, x-ray arrays, Thomson scattering) we will be installing an ultra-short-pulse reflectrometer (USPR), developed by the U.C. Davis plasma diagnostics team, which will operate with both O- and X-modes, providing both density and magnetic field measurements. LLNL has collaborated with this group to develop the theory and inversion techniques. We find that the technique is sensitive to islands and turbulence in the plasma; details are in a later section.

Although the beta can be quite high in principle, experimental limits are poorly understood. Assuming success in achieving reasonable temperatures, the opportunity to compare with expected beta limits will provide further understanding of the physics. Thus, the SSPX experimental objectives include evaluating the beta limits of the spheromak and comparing these with theoretical predictions including the effects of current profiles. The magnetic-field measuring capabilities of the USPR will contribute here to provide information in the plasma core where wall magnetic probes are insensitive.

Physics design

Spheromak design. The most successful approach of reaching high electron temperature in a spheromak has been to inject helicity from a Marshall gun into a flux conserver. Sustainment has been demonstrated, although only for relatively collisional plasmas. Consequently, the starting point for the spheromak design is similar to the final CTX experiment, with a large diameter injector closely coupled to the flux conserver. We discuss physics design issues in this section, expanding on those discussed in Ref. 1. Important differences with CTX include:

- All corners are rounded to minimize the effects of magnetic flux diffusion into the wall. For a nominal 2 ms discharge duration, the skin depth in copper is ~ 8 mm, so it is important that the radius of curvature of the wall be everywhere large compared to this. Generally, the radius of curvature will be maximized, subject to the other constraints on the geometry, to minimize the effects of open fieldlines near the wall. CORSICA has the capability of quantifying the effects of fieldline diffusion and will be applied to the geometry before the final design is frozen.
- A divertor has been added for density and particle control. The configuration chosen has the divertor on the geometric axis on the (grounded) end of the flux conserver opposite the gun, and includes a coil to generate a local x-point.

The MHD equilibrium and flux conserver design are shown in Fig. 3. The ideal MHD stability to low *n,m* modes has been verified by the GATO code; studies on the sensitivity of the design to the detailed shape, divertor dimensions, and assumptions about the equilibrium are continuing so as to ensure that the stability is as robust as possible and at as high a beta as possible.

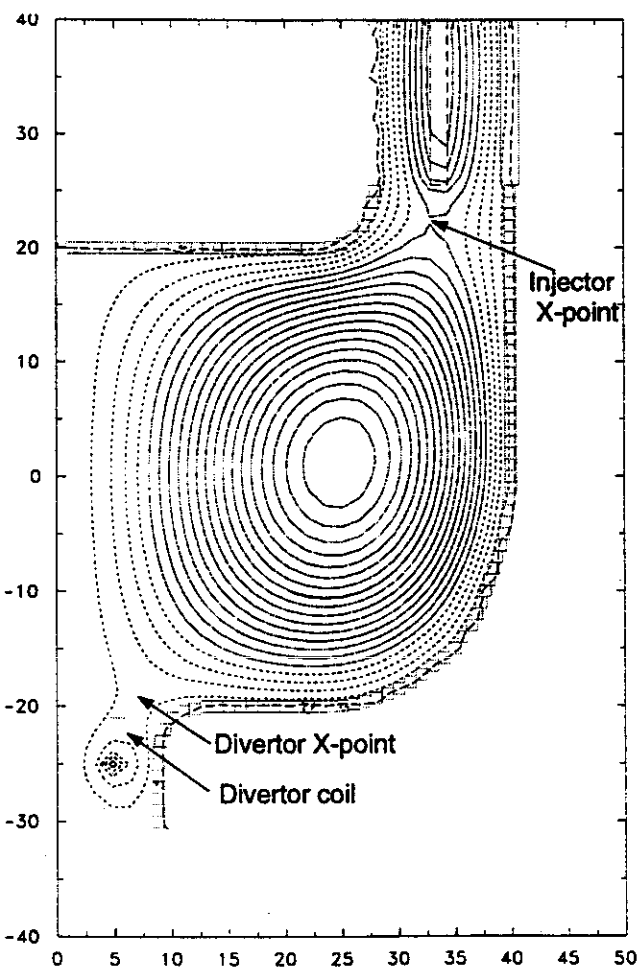

Fig. 3. MHD equilibrium and flux conserver design. In the experiment the flux conserver will be constructed separately from the injector to permit changes in the configuration. The helicity injector has been modeled by two solenoidal coils together with current flow in the private flux region. The walls are represented by multiple coils with the boundary condition that the magnetic flux be zero at the coils. The current in the divertor coil can be varied to change the location of the divertor x-point and thus the amount of diverted flux. The divertor opens into a large vacuum vessel to provide pumping for the duration of the pulsed experiment. Not shown on the design is a slot on the midplane of the flux conserver to allow for diagnostic access. The operational goal will be to control density and impurities by diverting a flux layer close to the wall while minimizing the effects of energy losses on open field lines.

Bias magnetic flux. To increase flexibility and control of the fieldline structure external to the separatrix, a bias magnetic flux (~ 10% of the total poloidal flux) will be available. This flux allows several options, shown in Fig. 4; detailed stability analysis of these configurations has not yet been done. Options in the figure include operation with some or all of the discharge current flowing only along the geometric axis or outside the plasma, and of having a magnetic boundary layer ("pillow") along the outside wall to protect it from plasma bombardment. By placing an electrode (cathode) in the divertor the injection current can be carried predominately on fieldlines on the large major radius side of the separatrix. This would have the effect of eliminating (or greatly reducing) the toroidal magnetic field on the separatrix, thus allowing the safety factor to drop to zero there rather than having a logarithmic divergence as it does in the tokamak. In the spheromak, the divergence reduces the magnetic shear and thus the predicted beta limit; if further calculations are promising, it would be interesting to test the ability of the outside drive to couple helicity into the confinement volume without a toroidal magnetic field on the separatrix. Presumably the coupling would be by higher order modes than the $n=1$ which is found when there is current through the flux hole about the geometric axis.

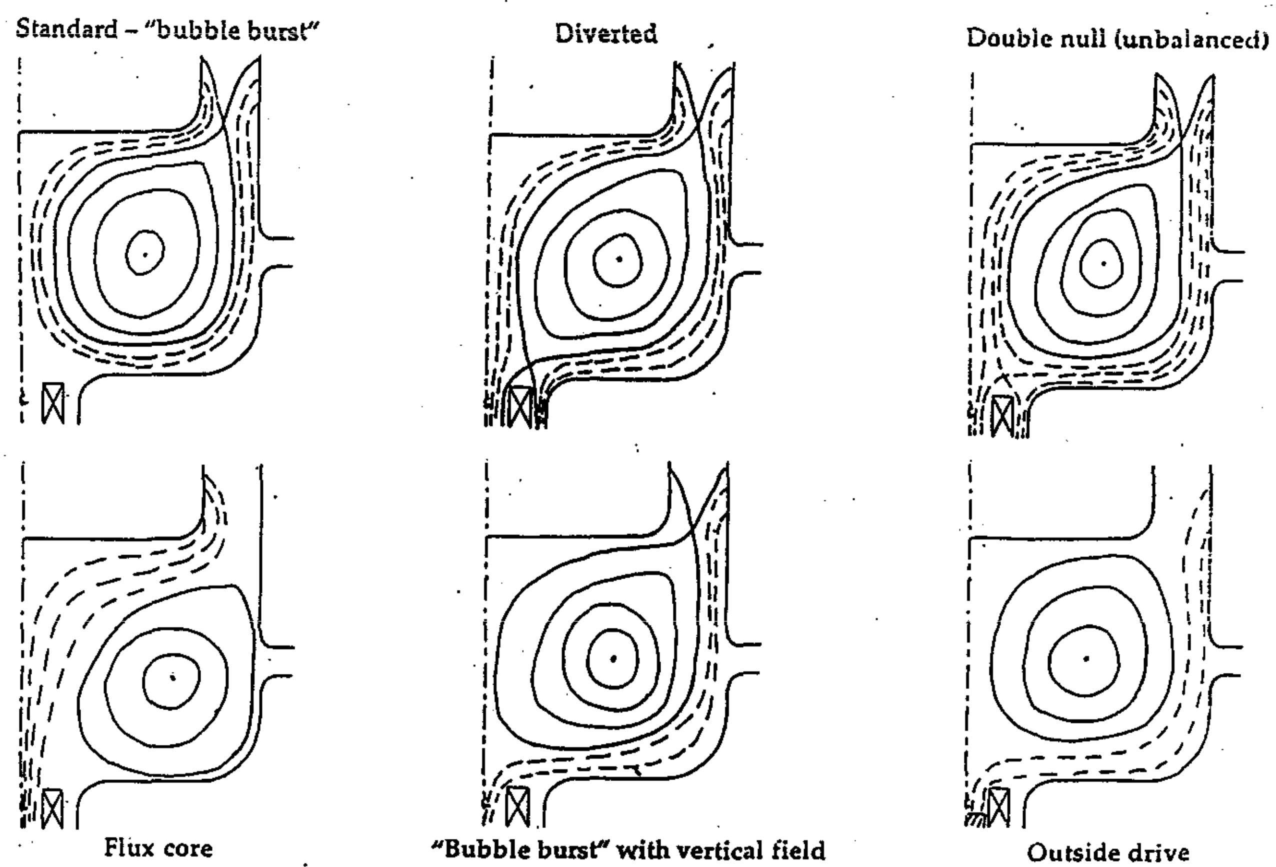

Fig. 4. Bias flux options.[52]

The bias flux will be generated by coils outside the flux conserver, as shown in Fig. 5. The coil locations and currents are chosen to match the fieldlines to the flux conserver shape so that no open field lines will pass through the flux conserver wall. (Previous experiments using a bias flux in a flux mesh conserver[53] found improvements - slower decay times - even without this constraint.) In operation, these coils will be energized long enough before the discharge that the

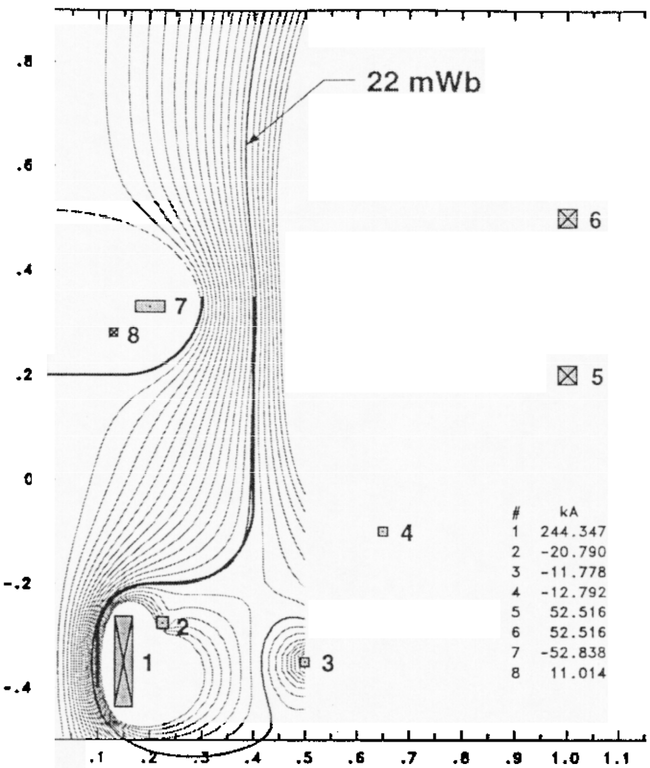

Fig. 5. Bias field coils to provide a flux of 22 mWb inside the flux conserver. The coil sizes are chosen to absorb the ohmic heat inertially for 2-3 s during the discharge. Coils 5 and 6 are placed outside the vacuum vessel. Coils 2 and 7 are in the helicity injector, and are integrated into the gun poloidal flux system (not shown).

eddy currents in the walls will die away. They will also be used in studying the transition from an equilibrium supported by currents in the flux conserver to one supported by external fields, although to minimize costs they will not be sized to permit steady state operation.

Discharge startup and plasma size. The discharge initiation requires supplying sufficient energy from the capacitor bank to generate the spheromak magnetic field, about 2 T (peak) in the design. (This corresponds to 1 MA discharge current.) Because this phase will have different power and impedance requirements than the sustaining phase, an "initiation" capacitor bank is planned with the sustainment provided by a pulse-forming network. The available energy in the initiation bank is required to be sufficiently large that the field reaches an appreciable fraction of the final field and that the electron temperature be sufficiently large (> 100 eV) that the plasma is "burned-out." These conditions translate into requirements on total energy for the initiation bank, including the initiation efficiency which we take to be 15-20%.[16]

A major constraint on operation is the value of I/N, where I is the discharge current and N the areal density ($\pi a^2 n$); the experiment is designed for $n \sim 10^{20}$ m^{-3}. Spheromaks have operated in the range 1×10^{-14} A-m $< I/N < 30\times10^{-14}$ A-m, although the extremes of this range are probably difficult to reach. The 0.4 m radius flux conserver used in the modeling shown in the figures above is predicted to reach $B > 0.7$ T using an existing 250 kJ bank. Discharge buildup modeling[1] using this bank and a conservative confinement time predict $T_e > 300$ eV at the end of the buildup phase.

Increasing the radius of the flux conserver from 0.4 to 0.5 m would have several advantages: reducing the surface-to-volume ratio, thus reducing the effects of the walls; reducing the differential diffusion of magnetic fieldlines into the walls; and decreasing the ratio of edge current density to plasma density. However, it will require increasing the size of the initiation capacitor bank by a factor of two and may have impacts on the design of the helicity injector. The costs and other trade-offs of this option are being evaluated before a decision is made.

Vacuum and wall conditioning. The high-quality operation proposed will require careful attention to vacuum and wall conditions, so we plan to apply the lessons learned from tokamak operation. The experiment design specifications include a base pressure of 10^{-8} torr and the ability to bake out the spheromak flux conserver at 250 C or above. All copper surfaces will be coated with tungsten (vacuum sprayed) to eliminate the large sputtering associated with copper. Discharge cleaning will be done routinely before operation. Boron will be applied to getter oxygen and to provide a low-Z surface facing the plasma.

Helicity injector. The helicity injector ("gun") is perhaps the most critical component of the experiment, as it is potentially a source of impurities. Instabilities in the arc discharge can degrade the spheromak plasma, and arcing or other high voltage problems can cause major operational difficulties. In the long term, a development program will be needed if electrostatic helicity injection is used for long-pulse experiments. For SSPX, we plan incremental improvements to the standard gun.

The existing analysis[16] of the injector is based on plasma flow through a magnetic nozzle at the exit to the gun. In the absence of downstream pressure, the resulting flow is at the Alfvén speed. This model is probably a good description of the physics during the initiation stage of the discharge, but once the spheromak is established there will be appreciable back pressure and the plasma flow will become much smaller. This is the likely reason why the particle balance during steady state operation implies an order-of-magnitude less flow than the model. The injection of helicity from the gun is $2\Phi_g V_g$, with Φ_g the gun flux and V_g the voltage, and thus does not require the large flow. The consequence for the gun design is that the vacuum magnetic flux should be designed without a mirror at the injector-spheromak interface. Furthermore, the cathode current is supplied predominately by the ion saturation current from the plasma, so optimum operation should require as uniform a magnetic flux through the cathode as possible. Modeling of the gun and its bias magnetic field is being done for a uniform flux up to 40 mWb at a cathode current density sufficiently high to overcome the threshold λ in the gun, and a total current such that in the gun $\lambda_g \sim 2\lambda_{spheromak}$.

Diagnostics

The diagnostic plan is described in the construction, cost, and schedule section. Included are a range of "standard" diagnostics, including machine operations, interferometry, magnetic loops, bolometry, etc. The electron temperature will be measured by Thomson scattering.

Previous experiments have obtained good measurements of magnetic fields and magnetic field fluctuations using wall loops. However, loops are not sensitive to the field profile in the plasma core, essential to understanding the magnetic dynamo which drives the plasma current. We plan to supplement these field measurements with ultra-short pulse reflectometry. Electromagnetic waves reflected from the plasma and cyclotron cutoffs in the plasma allow us to measure the density and magnetic field. This method uses group-velocity delays and thus escapes phase problems often associated with interference in standard reflectometry. Sensitivity to wall reflections is also reduced significantly. Modeling of this process has been done as part of an LLNL LDRD Exploratory Research project for application to both SSPX and the DIII-D tokamak at General Atomics. Robust procedures for inverting the data to yield the profiles of interest have been found and demonstrated to be insensitive to noise.[54]

The technique can also be used to diagnose islands and turbulence. Shown in Fig. 6 is a comparison of the reflection delays of reflections from a plasma without and with a flat step in the density profile. As shown, the step has a clear signature in the time delay of the reflected wave. Optimal inversion procedures are being evaluated. A high repetition rate (200 kHz) for the pulses is planned to provide the time resolution required for the measurement.

Coupling between the O- and X-modes is sensitive to shear in the magnetic field.[55,56] We intend to examine the use of this effect to extend reflectometry beyond measurements of density and magnetic field strength profiles.

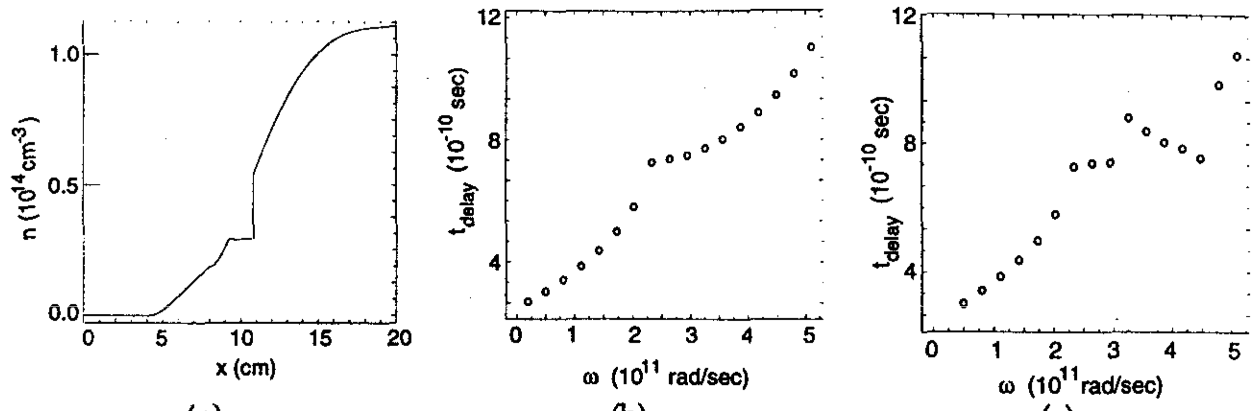

Figure 6. Reflectrometry simulation (O-mode). (a) Density profile including a flat step model of an island. (b) Delay times vs. frequency for the profile without the flat region. The slope change arises from the change in density profile modeled at the separatrix. (b) Delay times vs. frequency for the profile with the flat region.

We plan to fund the U.C. Davis plasma diagnostics group to construct the diagnostic for SSPX and to provide a graduate student to operate it. The technique will be tested on the Gamma-10 tandem mirror at Tsukuba, Japan this summer as part of the base research program of the Davis group. Results from this test will be used in the detailed design of the SSPX system.

We also expect to collaborate with the MST group at U. Wisconsin to use their techniques to correlate magnetic fluctuations with transport in the edge plasma of SSPX. Comparison of the RFP and spheromak plasmas should add insight into the common physics.

Research Plan and Methods

Overview

Our goal is to complete construction and take the first discharge in the Spring, 1998. The first stage of diagnostics ("startup") will be completed soon thereafter. The effort through the end of FY 1998 will focus on bringing the plasma into operation with well-defined magnetic geometry and a low impurity level. We will then initiate confinement experiments, with particular emphasis on magnetic turbulence and island growth. Preparation for this initial operation will include detailed modeling to provide a benchmark for the anticipated characteristics and preparation of software tools to permit a rapid, initial analysis of the data. Success in the initial operation of the experiment will require learning how to program the plasma initiation, including discharge characteristics and gas injection. Once in operation, the major effort will be directed to the evaluation of results, improved measurements, etc.

Additional diagnostic construction will bring new diagnostics to bear throughout FY 1999 to address the studies of confinement, of reaching $T_e \sim 400$ eV, and of determining the beta limits. The USPR will be used extensively to study magnetic islands and turbulence. Following these studies we will replace the flux conserver with a resistive wall to study the transition to externally supported equilibria. There are significant uncertainties in projecting that far ahead; the present goal is in FY 2000.

Startup.

Several important issues will be addressed during this initial stage in the second half of FY 1998 and possibly carrying over into FY 1999 if needed:

Density and particle control. The current from the helicity injector (gun) is generated by discharge processes in the vicinity of the injector cathode. These processes are closely coupled to the plasma density there, which in turn is the source of the plasma in the spheromak. Operation of the injector at low gas flow (and thus low plasma density) is thus essential to control of the density in the confined plasma. The process of understanding how to optimize the injector operation will require parameter scans and diagnostic measurements.

Divertors have never been used before in spheromaks. Tuning of the divertor magnet, which controls the magnetic flux and configuration near the divertor, will require experimental studies.

Impurities. A major effort has been made to design a system which will minimize the impurities in the confined plasma. Spectroscopic measurements will be essential to evaluate the success of this control. If significant impurities are present, they will be identified so that the source can be located and corrective measures taken.

Magnetic geometry. Magnetic probes will be installed on the inside wall of the flux conserver. Modeling of the MHD equilibrium predicts the probe signals; comparison with the measurement provides a determination of the extent to which the experiment agrees with the expected results. In addition, Rogowski coils, e.g. on the conducting jumpers across the diagnostic slot, will be used to determine the wall currents.

Startup scenario optimization. The details of the startup timing and rate of initial helicity injection can have major effects on the steady-state part of the discharge. If the startup is too fast, the initial generation of the magnetic field will be inefficient as strong magnetic fluctuations and non-uniform currents can generate large amounts of impurities which will cause residual problems in the steady-state part of the discharge. If too slow, impurities will not be burned out, and the required high electron temperature not achieved. Determining the correct profile for gun voltage, current, and gas injection during the startup will require testing various timing options, varying the rate of application of current to the injector, etc.

Sustainment and energy confinement.

Once the techniques are determined to establish and maintain a clean, well behaved discharge, the experimental effort will move into initial energy confinement experiments. The diagnostics on the experiment will be improved over this period; however, resource availability will probably delay the use of Thomson scattering to measure electron temperature, T_e, until FY 1999. An initial, semi-quantitative measure of the temperature will be given by soft x-ray emission and atomic spectroscopy.

During FY 1998-2000 additional staff and graduate students will be brought into the program to work on diagnostics and the physics of the spheromak. Funds for this increase in staff are included in the budget presented below.

Accurate evaluation of the core confinement time is difficult. A "zeroth order" evaluation is the central electron temperature; $T_e > 200$ eV demonstrates that effective pathlengths for electron losses in the presence of turbulence are much longer than those achieved in mirror experiments, so that fieldlines are closed in that sense. At the next "order" conservative estimates of the core heating will be required. This will be done by a combination of measurements and modeling using the CORSICA or other codes; we anticipate that iteration between experiment and modeling will be required to converge on believable results.

Construction, cost, and schedule

Construction and initial operation (FY 1998)

The physics design section discussed specific design details, including innovations to previous spheromaks. Here we discuss the implementation of this design: the facility, milestones, the schedule, and an overview of the budget. The SSPX program goals for FY 1998 are:

- Complete construction of SSPX (April 1998).
- Initial discharge and debugging (April 1998).
- Establish a sustained plasma for times short compared with the L/R time of the flux conserver, with good control of magnetic geometry, impurities, etc. (Sept. 1998).
- Initiate studies of energy confinement and magnetic fluctuations associated with the dynamo (Sept. 1998).
- Begin extension of diagnostics for confinement studies (Sept. 1998).

The FY 1998 milestones associated with these goals are listed below; for completeness milestones for FY 1997 are included.

Milestones for FY 1997-98

Milestone	Date
1. National workshop to fix physics design	March, 1997 (completed)
2. Remove old vacuum vessel, cleanup facility	July, 1997
3. Complete detailed physics design of flux conserver and helicity injector	June, 1997
4. Complete engineering designs of flux conserver and helicity injector	October, 1997
5. Install vacuum vessel, mechanical hardware	October, 1997
6. Install PFN	December, 1997
7. Complete construction of flux conserver	January, 1997
8. Complete construction of helicity injector	January, 1997
9. Install data acquisition system	March, 1998
10. Condition PFN	March, 1998
11. First discharge with machine diagnostics	April, 1998
12. Complete installation of startup diagnostics	August, 1998
13. Start Phase II (sustainment) diagnostics	September, 1998
14. Install bias field coils	September, 1998

Facility.

The SSPX facility is modified from the RACE facility at LLNL. There are several major subsystems:

Vacuum system. SSPX will utilize an existing (nearly) all hardseal vacuum vessel to achieve the vacuum (10^{-8} torr) required for the spheromak operation. The existing chamber will be shortened in length to allow installation into the existing facility, and installed vertically. Figure 7 shows the tank with the spheromak flux conserver and gun installed. With this vessel, an initial estimate of the pump-out time for the expected plasma gas load is much less than the anticipated

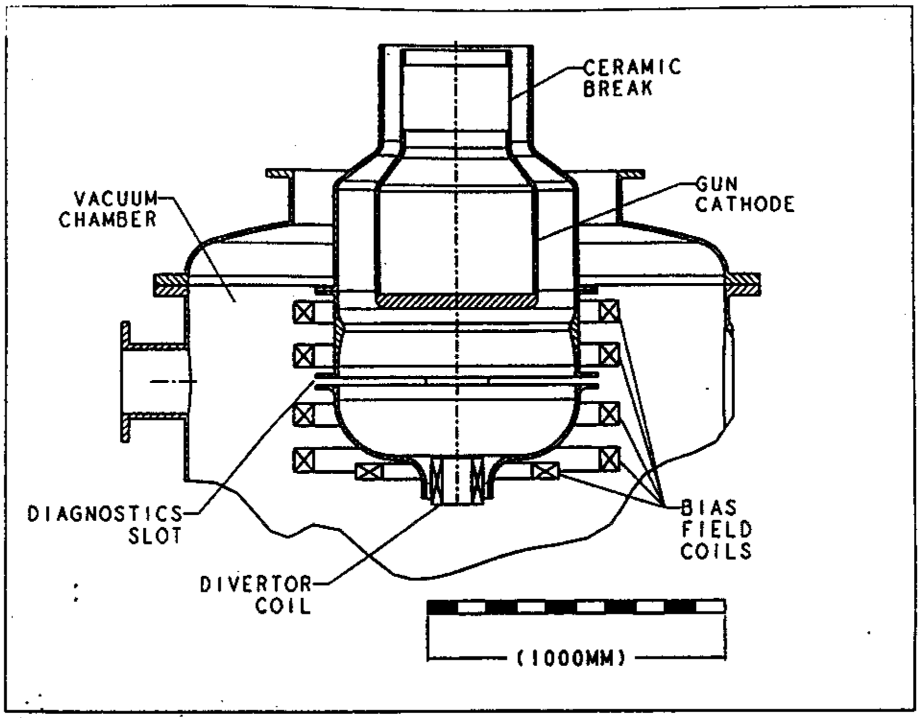

Fig. 7. Spheromak placed in new vacuum vessel, showing the helicity injector (gun), flux conserver, and divertor and bias coils.

time between shots (<15 minutes). The pump-out time was calculated assuming "baked" vacuum components, a lumped vacuum volume of ~7500 liters, a H_2 gas load of 100 T-l/sec for 10 ms, and a pumping speed of 1000 l/s.

To obtain clean high-vacuum conditions for SSPX, the vacuum pumping system must consist of oil-free components. We plan to reduce the cost significantly from an all new system by using existing equipment at LLNL to the extent possible.

Other high vacuum techniques planned for the experiment include a moderate (150 C) bake of the vacuum vessel, a high temperature (> 250 C) bake of the gun/flux conserver, plasma discharge cleaning, tungsten coating of plasma-facing walls, and boronization as used in modern tokamaks.

Power systems. The power system is shown in Fig. 8. Analysis indicates that the use of modern, metallized electrode capacitors provides a compact and reliable system at reasonable cost.

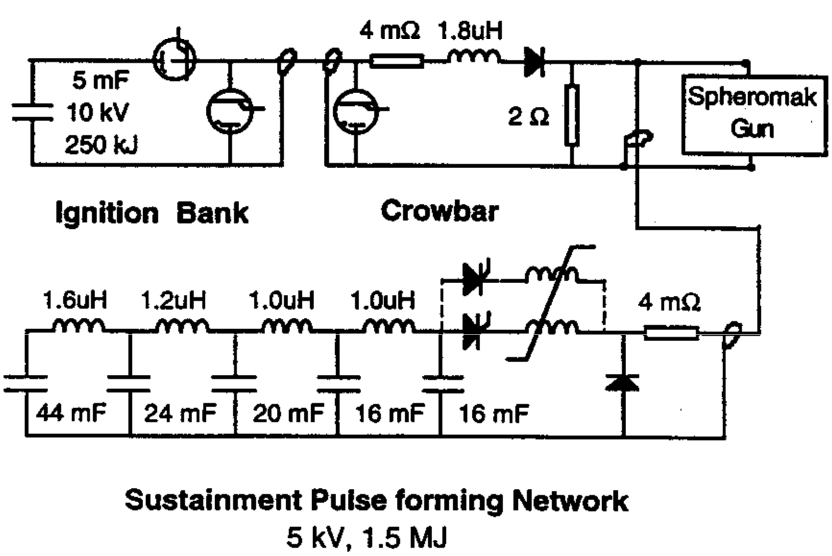

Fig. 8. Electrical schematic.

Diagnostics Plan

As diagnostics will be implemented throughout the life of the experiment, the proposed list is separated from the annual plans. The plan is divided into three phases for convenience, although differing development times and changes in emphasis will undoubtedly change the timing with which diagnostics are implemented. Several possible collaborations are noted which are being discussed with universities or other laboratories. Not included in the list are specific diagnostics for studying the transition to external coils. Also not included because of resource limitations are additional diagnostics of interest such as charge-exchange, neutron measurements, and a diagnostic neutral beam.

System	*Comments*
Startup Diagnostics	
Machine Gas pressure (slow and fast)	Need both slow measurements for vacuum and fast measurements for tracking particles
Gun Voltage and Current	
Density Interferometer (multi-cord)	CO_2 uses UC Davis/LANL equipment Possible collab. UC Davis, LANL
Electron temperature Soft xrays	Simple diagnostic (diodes w/filters)
Magnetic field Wall probes	Need to be designed into flux conserver, several
Impurities Spectroscopy (VUV)	Needed to understand any impurity problems, Visible and UV. Possible collab. U. Wisc. (MST), LANL
Radiated Power Bolometer array	Power balance; quality of operation, simple array
Energetic electrons (Hard) xrays	NaI crystal and PM tube
Wall currents Rogowski loops	Includes currents to divertor, currents through the wall
Ionization, recycling H-alpha	Measurements at several places desirable. Possible collab. LANL
Edge plasma (n, T_e, j) Camera	Locate at divertor, diagnostic slot? Important for operations
Sustainment Diagnostics	
Gun Diagnostics to evaluate and understand operation	Light, H-alpha, UV, other
Density Reflectrometer (O-mode, ultra short pulse)	Anticipate installation in two stages: Initial stage to test approach at minimum cost followed by full system. Collab. with UC Davis
Magnetic field (includes fluctuations) Reflectrometry (combined O- and X-mode) Transient Internal Probe (TIP)	See density. Collaboration with UC Davis "Snapshot" for calibrating other systems. Collab. with U. Washington
Edge plasma (n, T_e, j) Probes (Langmuir) Probes (Rogowski)	n, T_e j

System	*Comments*
Energy confinement	
Density Thomson Scattering	See electron temperature
Electron temperature Thomson scattering	Options: Rebuild MTX (ruby, single pulse, single location); new multiple pulse, location
Ion temperature Spectroscopy (impurities)	Could use LLNL instruments and/or collab. MST.
Transport Transport (correlation) probes	Compare results with RFPs. Use instruments similar to MST in near-edge plasma. Collab. U. Wisc.
Dynamo Dynamo electric field	Used on SPHEX; works in near-edge plasma

The baseline Thomson scattering is a single pulse system used on the MTX tokamak. We will be exploring the possibility of a multi-pulse, multi-point system, but we may not be able to afford it without a budget increment above that in this proposal.

Construction schedule. A project schedule has been prepared and is shown in Fig. 9. Note that the schedule is predicated both on the LDRD funding of the complementary studies and on proposed OFES funding.

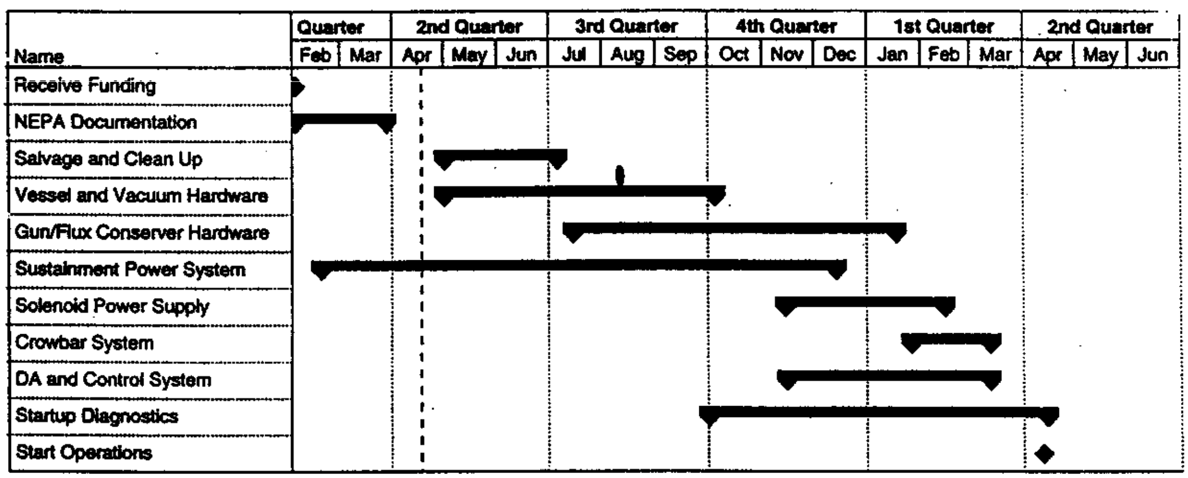

Fig. 9. Construction schedule

Budget summary

Detailed cost schedules for the integrated projects can be provided on request. The DOE-OFES effort in FY98 is addressed to completion of the experiment and to the initial operations. In FY99-FY00 the funding will include operations of the experiment and further diagnostic development. Additional experimental physics staff, including postdocs and students will be brought into the experiment.

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