Recent results from the SSPX spheromak, in which peak electron temperatures $T_e \sim 350\text{eV}$ were obtained, provide strong motivation for adding auxiliary heating to study energy transport and pressure limits. At $300\text{eV}$, 1.8MW of neutral beam injection (NBI) heating would match the ohmic heating in the core plasma to provide a known and controlled heat source for the first time in a spheromak. Neutral-beam heating will allow us to vary independently the heating power, plasma current, and confining field to study energy confinement scaling. In addition, the ability to increase the plasma pressure independent of the field will let us explore the physics of the beta limit. Looking further ahead, NBI will make possible deployment of beam-based core diagnostics such as charge-exchange recombination (for $T_e$, rotation, and $Z_{eff}$), beam emission spectroscopy (for density fluctuations), and motional Stark Effect (for internal field measurements). Historically, the application of NBI to fusion devices of all types (e.g. tokamaks, stellarators, and most recently, reversed field pinches) has increased the quality and scientific output of experiments significantly.

The addition of NBI would follow by about a year the commissioning of a new modular solid-state programmable capacitor bank late in CY2006. We plan to procure the beams from the Budker Institute in Russia. Preliminary modeling using the CORSICA code points to a favorable outcome with realistic neutral beam heating pulses.

This work performed under the auspices of the USDOE by LLNL under contract 7405-Eng-48.
Document reference: UCRL-PRES-218951
The Sustained Spheromak Physics Experiment (SSPX) is part of the DOE–OFES portfolio of Concept Exploration experiments

- First plasma: April ‘99.
- $2.42M annual budget ($2.27M in 07 budget)
- 6 FTEs
- Collaborations
  - Caltech, U. Wisconsin, U. Washington, FAMU, LANL
- Partner in NSF Frontier Science CMSO
- Since FY 2003:
  - 2 PhD graduates
  - 14 student interns
  - 20+ papers (4 PRLs)
  - 4+ invited talks
The SSPX spheromak is formed using coaxial helicity injection.

**Typical SSPX parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux conserver size: Radius × Height (m)</td>
<td>0.5×0.5</td>
</tr>
<tr>
<td>Radius of magnetic axis</td>
<td>0.31 m</td>
</tr>
<tr>
<td>Minor radius</td>
<td>0.17 m</td>
</tr>
<tr>
<td>Peak discharge current</td>
<td>450 kA</td>
</tr>
<tr>
<td>Toroidal current</td>
<td>600 kA</td>
</tr>
<tr>
<td>Peak toroidal field (T)</td>
<td>0.6</td>
</tr>
<tr>
<td>Edge poloidal field</td>
<td>0.35 T</td>
</tr>
<tr>
<td>Plasma duration</td>
<td>4.5 ms</td>
</tr>
<tr>
<td>Plasma density (m⁻³)</td>
<td>5×10¹⁹</td>
</tr>
<tr>
<td>Peak Te (eV)</td>
<td>350</td>
</tr>
</tbody>
</table>

1 m diameter
We are now installing a new programmable solid-state modular capacitor bank: higher current, longer pulses, multiple pulses.

Prototype module (1 of 30 required) tested successfully. Bank operational by end of January 2006.
Adding neutral beam heating to SSPX is a natural follow-on to recent positive experimental results.

- Continued optimization reduces transport and increases electron temperature from $T_e \sim 250\text{eV}$ to $\sim 350\text{eV}$.
- Decreasing plasma resistivity reduces ohmic heating so that auxiliary heating with beams can make a difference.
- In addition, now installing new capacitor bank to double the pulse length.
Core plasma thermal diffusivity in SSPX is comparable to that in present day tokamaks

- Power balance between ohmic heating and radial transport yields thermal diffusivity:
  \[ Q_\perp = \int n \chi \nabla T_e dS = P_{\text{ohmic}} = \int \eta j^2 dV \]
  \[ \eta = Z_{\text{eff}} T_e^{-3/2} \]
  \[ T_i = T_e \]

- Theory relating turbulent transport to magnetic fluctuations predicts \( \chi_e \propto S^{-\alpha} \), where Lundquist \# \( S \propto B T_e^{3/2} \).

- Experiment shows \( \chi_e \) falling with temperature; \( \chi_e < 10 \text{m}^2/\text{sec} \) at high temperature, comparable to tokamaks.

- Parameter variations challenging because \( P_{\text{ohmic}} \propto I_{\text{tor}} \), \( B \propto I_{\text{tor}} \), Density \( \propto I_{\text{tor}} \)

Neutral beam heating will transform quality of energy transport studies
- Independent heat input
- Heat pulse relaxation
- Fast ions to probe quality of magnetic flux surfaces
- Allows for improved diagnostics
SSPX renewal proposal includes neutral beam purchase. LLNL internal funding supports healthy NBI research program.

- 18 month, $800k contract delivers complete NBI heating system from Budker in FY08. Beams installed on MST and C-mod in US, GDT in Russia, and in Japan.
- Installation and operation of beams follows 2yrs of modular bank operation.
- Related physics research funded via a separate LDRD project.

Will be first application of external NBI heating to a spheromak.
Neutral beam injection allows us to attack fundamental plasma physics problems

FESAC panel report: Scientific Challenges, Opportunities, and Priorities for the US Fusion Energy Sciences Program
- How does magnetic field structure impact fusion plasma confinement?
- What limits the maximum pressure that can be achieved in laboratory plasmas?

Limiting plasma pressure in SSPX

\[ \frac{2\mu_0 n k T}{B^2} = \beta \]
\[ 2\mu_0 n k T = \beta B^2 \]

\[ Q_{\perp} = n\chi\nabla T = P_{\text{ohmic}} = RI^2 \]

\[ B \propto I \quad \frac{\chi n\hat{T}}{a} = RB^2 \]

Independent heating provides a control knob to vary the pressure separately from field.

Beam-ion orbits probe quality of internal magnetic fields, which can be related to internal turbulence.
Limiting $\beta_e$ observed - motivates drive for higher field and auxiliary heating for transport studies

\[
Q_\perp = n\chi \nabla T a = \eta j^2 V
\]
\[
n\chi \frac{T}{a} 4\pi^2 Ra = \eta j^2 2\pi^2 Ra^2
\]
\[
\frac{2n\chi T}{a^2} = \eta j^2
\]
\[
\chi = \frac{a^2 j^2 \eta}{2nT}
\quad \lambda = \mu_0 j / B \quad j = \lambda B / \mu_0
\]
\[
\chi = \frac{a^2 \lambda^2 B^2 \eta}{\mu_0 2\mu_0 nT} = \frac{a^2 \lambda^2 \eta}{\mu_0 \beta}
\]

Need external heat source to test
Preliminary studies predict increased plasma temperature and pressure in SSPX discharges with 1.5MW neutral beam heating. Simulation based on SSPX results predicts ion and electron heating (fixed transport). Results depend on fast-ion lifetime and electron transport. Higher temperatures may change turbulent transport and reconnection–nonlinear effects.
Outstanding issues for NBI physics design

1. What is optimum injection angle?
   — Normal to maximize penetration, ease of access
   — Tangential to provide current, minimize trapped population

2. Can beam injection affect the internal current profile and perhaps MHD modes?
   — So far we have considered only heating.

3. How will observed MHD modes affect fast-ion lifetime?
   — How to estimate?

4. What diagnostics are needed to meet physics objectives? (relative priority?)

5. What have we neglected?
Fast-ion orbit calculations for spheromaks

- Due to its low toroidal magnetic field relative to tokamaks and its tight aspect-ratio, the spheromak fast-ion orbits are somewhat exotic.

- We have developed a new module that constructs the fast-ion orbits in SSPX from which we calculate the fraction of time the particle spends in each poloidal flux sampling zone.

- We use NFREYA to obtain the point of injection and the particle’s injected velocity.

- The fast-ion distribution derived using Callen’s analytic “dragged-down distribution”.

- The particle density, current drive and power deposition are then determined.

- This method provides a fast calculation, compared with the more detailed Monte-Carlo calculation used in NBI modules such as NUBEAM.

- Initial results for SSPX show that a substantial fraction of the injected beam, of order 70%, is confined as fast ions and show that the electron temperature in the core can increase by a factor of two.

- Comparisons are made with analyses that have been generated by NUBEAM to provide a benchmark for our NBI module.
Calculations show a wide variety of orbits for SSPX equilibria

- First runs with new orbit-following module.
- Orbits likely to play a role in defining injection geometry and operating scenarios.
- Will help define requirements for fast-ion diagnostics.
Diagnostic plans for neutral beam experiments

- **Double-pulse Thomson**
  - Double-pulsed Q-switch gives $\Delta t \sim 100\mu\text{sec}$ (FY06 fluctuation measurements)
  - Adding second laser gives complete flexibility (proposed $100k$ to implement in FY06)

- **Soft X-ray cameras**
  - Hotter plasmas minimize line radiation
  - Provides $T_e$ profile and internal modes

- **Charge-exchange analyzer**
  - Florida A&M installing in FY06
  - Optimized for lower particle energies

- **Charge-exchange recombination spectroscopy**
  - Background light is key factor for feasibility ($T_e > 300\text{eV}$ greatly helps)
  - Collisionality a key factor for interpretability.
  - Single channel system proposed
  - Ion temperature and impurity concentration ($Z_{\text{eff}}$ for $P_{\text{OH}}$ calculation)
We have proposed a full and exciting research program for SSPX which builds on steadily increasing understanding and capability.

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<td>Q3 Q4</td>
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<td>Integrated confine exp (NBI &amp; MB)</td>
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- Hardware milestones
- Reports/papers
Addition of neutral beam injection heating to SSPX will significantly increase scientific capability to study confinement and beta limits in spheromaks.

Hotter plasmas \( (T_e > 300\text{eV}) \) provide suitable target plasma for adding modest (1.8MW) auxiliary heating to a spheromak.

LLNL internal funds are supporting physics design and preparation.

Planning to purchase beams from Budker Institute in Russia, with delivery scheduled for late FY07 or early FY08 (depends on funding).

Will provide a platform for significant diagnostic enhancements.

We welcome external collaborations, students, and post docs.