Plans for Increasing the Magnetic Field and Plasma Temperature in the SSPX Spheromak

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Summary

• Good confinement (low core transport) is obtained with controlled decay.

• Peak temperatures of ~250eV observed when magnetic fluctuations are small (< 1%).

• SSPX discharge database points to importance of increasing the magnetic field and especially the current amplification factor ($A_I = I_{toroidal}/I_{gun}$) or $B_{pol}/I_{gun}$.

• Very slow formation and double-formation-pulse discharges yield the highest magnetic fields in SSPX.

• Magnetic field evolution during formation suggests that higher efficiency ($B/I_{gun}$) would be achieved with longer formation pulses.

• We plan to install a new small-radius injector in SSPX which should increase the helicity input and the resulting spheromak magnetic field

• We also plan to install a modular capacitor bank for flexible current programming
SSPX cross-section and operating parameters

Typical SSPX parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux conserver RxH (m)</td>
<td>0.5x0.5</td>
</tr>
<tr>
<td>Radius of mag axis (m)</td>
<td>0.31</td>
</tr>
<tr>
<td>Minor radius (m)</td>
<td>0.23</td>
</tr>
<tr>
<td>Discharge current (kA)</td>
<td>200</td>
</tr>
<tr>
<td>Toroidal current (kA)</td>
<td>400</td>
</tr>
<tr>
<td>Edge poloidal field (T)</td>
<td>0.2</td>
</tr>
<tr>
<td>Pulse length (msec)</td>
<td>3.5</td>
</tr>
<tr>
<td>Electron Temperature (eV)</td>
<td>20-200</td>
</tr>
<tr>
<td>Ion Temperature (eV)</td>
<td>?-600</td>
</tr>
<tr>
<td>Lundquist number, S</td>
<td>10^5</td>
</tr>
<tr>
<td>Fluctuations (kHz)</td>
<td>20</td>
</tr>
<tr>
<td>Plasma density (m^-3)</td>
<td>5x10^{19}</td>
</tr>
</tbody>
</table>

High electron temperatures and low core transport are observed when fluctuations are low

- Peak electron temperature now approach 250eV
- Temperature climbs as fluctuations decrease
- Focus over last year:
  - Quality of flux surfaces (n=1 perturbation coil)
  - Density control
  - Isotope effects
Initial current pulse determines the peak field: best confinement observed during controlled ramp down

- Short high-current formation pulse sets the peak field
- Sustaining edge current maintains overall stability
- Asymmetric modes evolve during ramp down
  - General decrease in overall mode amplitude
  - Particular modes come and go during ramp down
- Highest $Te$ when total amplitude is lowest
Higher magnetic field and lower plasma density allow operation at higher plasma temperature in SSPX

- Upgrades directed towards increasing the magnetic field
  - New gun to test helicity injection physics
  - Modular bank for current control and better efficiency

- Major new diagnostic planned for energy confinement studies
  - Charge exchange analyzer
  - Collaboration with Florida A&M University

- A new small-radius coaxial injector has been designed: increased voltage and helicity injection.

- Plans are being developed to convert the present bank to a multi-pulse modular design to increase peak current and coupling efficiency.
Design parameters for a next-step spheromak are sensitive to density control and current amplification

- Target 1 keV spheromak plasma. What are the device requirements?
- Transport scaling sets device size (minor radius).
- Beta limit and density scaling determine field and toroidal current.
- Field generation efficiency \( \left( \frac{B_p}{I_{\text{gun}}} \right) \) sets bank and injector requirements.

\[
\begin{align*}
T (eV) & \quad B (T) \\
0 & \quad 0.25 & \quad 0.50 \\
0 & \quad 0.254 & \quad 0.38 \\
B = k \cdot I_{\text{gun}} & \quad 0.36 & \quad 0.75 \\
\text{Helicity balance} & \quad 0.254 & \quad 0.38
\end{align*}
\]
Double-pulse and very slow formation discharges obtain higher magnetic field per unit current than fast formation.

- Standard fast formation followed by sustainment yields maximum $B/I_{gun} \approx 0.65 \text{T/MA}$.
- Slow–start formation has steadily growing $B$ with $B/I_{gun} = 0.75 \text{T/MA}$.
- Double-pulse also produces highest fields of $0.78 \text{T/MA}$.
- What physics is involved in determining $B/I_{gun}$ ratio?
- Why is $B_{max} \approx B_{gun}$ for these regimes?
I-V Trajectories show time-dependent efficiency of field generation

- Data compares three reference discharge scenarios
  - Standard fast formation followed by sustainment
  - Very slow formation using sustainment bank only
  - Double formation pulse on top of sustainment pulse

- Standard formation pulse is clearly too short to achieve maximum field.
- Double pulse seems to recover trajectory of the first pulse.
- After formation pulse, all sustainment bank shots on same trajectory.
Field is still building when formation bank current peaks and begins decaying: higher B/I if pulse were extended.

- Running longer formation pulses should produce higher fields
  - Assume constant efficiency during pulse
  - Assume fixed energy decay time (no heating during pulse)
Slow–start formation steadily builds helicity content

- Injector current is maintained just above threshold ($\lambda_g \geq \lambda_{sph}$). No large initial formation pulse.
- Helicity content increases with or without coherent $n=1$ oscillations.
- Buildup limited by pulse length.
- High source voltage with large fluctuations.

Poor correlation between field and voltage fluctuations suggests fine-scale turbulence.
Multiple pulses yield higher fields and larger confined volumes: NIMROD and experiment

- Higher order (asymmetric) field components decay first.
- Multiple pulses build the field in a stepwise manner.
- Double-pulse experiment successfully builds the field: NIMROD also suggests pulse length may play a role.
- Density control remains an issue: $n_e \propto I_p$ or ?

Russian translation:
A multi-pulse modular capacitor bank may allow buildup to higher fields and temperatures.

- Assume same efficiency for each pulse
- Assume that resistive decay time remains constant.
The modular bank would provide programmable control of the current waveform and improve energy coupling

- Physics Design is complete for a 10-module bank upgrade.
- Estimated about $350k total cost.
- Proposed to test a single module late in FY04, do full conversion in FY05.
- Anticipation of flat budgets at present level drives us to explore alternatives
  - Add only another “formation” type pulse
  - Use students for preliminary design starting this summer
  - Procure hardware late in FY05
  - Would extend present multi-pulse buildup to three pulses

Modification of bank will provide three important conditions:
- Better control of operation near threshold (Operation near threshold produces lowest fluctuations and highest Te)
- Multiple pulse experiments.
- A way to increase total pulse length incrementally.
We are ready to procure a new small-radius gun for SSPX

- Competing models predict same or 2x higher fields.
- Final design review completed last fall.
- Estimated cost to complete is about 200k$.
- Staff reduction allows fabrication this year even though budget is down
  - 1 tech, 0.5 scientists
  - 2 retirees
- Installation in early FY05.

\[
\frac{dK}{dt} = \frac{-K}{\tau_K} + 2\Phi_{inj} V_{inj} \\
V_{inj} \propto \log\left(\frac{R_o}{R_i}\right)
\]
Injector probes help improve understanding of helicity balance for field generation

- First measurements of current and field distribution inside the coaxial source.
- Significant asymmetries can be observed: $\lambda$ is not constant inside the injector.
- Even so, helicity balance can be obtained using spatial integrals.
Best high temperature discharges are near the observed low-density limit

- Observed low density operational limit at $0.5 \times 10^{14}$ corresponds to $0.1 v_e$ for $<T_e> \sim 100$eV plasma.

- Greenwald density limit computed using spheromak toroidal current computed from MHD equilibrium:

$$n_{GW}(10^{14} \text{ cm}^{-3}) = \frac{I_{tor}(MA)}{\pi a^2(m)}$$
High current density implies strong recycling at electrodes which may inhibit low-density operation

- Previous spheromak experiments found density rising with gun current.

- Possible explanations included:
  - Mass flow associated with helicity injection (C. Barnes–CTX)
  - Fueling by fast ions from central column (M. Rusbridge – SPHEX)

- Strong electrode recycling needed to sustain the central column current:
  - \(250\text{kA}, \pi a^2=450\text{cm}^2 \rightarrow 560\text{A/cm}^2\) vs. \(35\text{A/cm}^2 \at \ 5\times10^{13}\text{cm}^{-3}, 30\text{eV}\)

- Three experiments explored relationship between \(I_g\) and \(n_e\) in SSPX:
  1. Scan injector current at fixed magnetic flux (\(\lambda_{\text{gun}}\) increases)
  2. Scan injector current and flux at fixed \(\lambda_{\text{gun}} = I_{\text{gun}}/\phi_{\text{gun}}\)
  3. Change vacuum flux configuration (threshold & current path)
Density rises with current in each experiment

Scan at constant $\lambda_{\text{gun}}/\lambda_{\text{FC}}$ shows rising density, as do scans with increasing $I_{\text{gun}}$ at constant flux (increasing $\lambda_{\text{gun}}$).
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