HSX Final Alignment, Assembly, and Initial Operation

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HSX Plasma Lab,
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HSX Support Collaborations

- **UW Madison**
  - Callen Hegna - theory
  - RFP group - Thomson Scattering, soft X ray diagnostic

- **UC Davis**
  - Domier and Luhmann - ECE Imaging

- **Princeton**
  - Park - Thomson Scattering
  - Takahashi - electron beam mapping

- **UCLA**
  - Brower and Peebles - 9 chord interferometer

- **Russian**
  - Likin - ECRH ray tracing/ECRH launcher
  - Karulin - ASTRA modeling code
  - Fedyanin - magnetics diagnostics

- **German**
  - Nuhrenberg and Merkel - HSX configuration and coil optimization

- **Japanese**
  - Takayama and Kitajima - HSX construction and single particle confinement experiment

- **Theory**
  - Cooper (Lausanne) - MHD Stability
  - Coronado (Mexico) - flows

- **ORNL**
  - Bigelow - ECRH gyrotron and transmission line
Talk Outline

• Introduction to HSX design
• Final fabrication, assembly and alignment of HSX components
• HSX first plasma
• Electron beam mapping of HSX magnetic surfaces
• The next phase of HSX
HSX Design Considerations

• HSX was designed with two major goals
  – provide an experimental test bed for a qhs device which could operate at relevant parameters
    • with accurately fabricated and positioned magnet coils
  – provide a flexible experiment
    • the magnetics can be altered to a more conventional stellarator-like configuration with transport implications
    • there is flexibility in the base qhs configuration in deepening the magnetic well and altering the MHD stability properties without significant qhs degradation
HSX has a Single Dominant Helical Component in the Magnetic Field Spectrum

Toroidal Curvature Virtually Nonexistent for A=8 Device

- Equivalent to Aspect Ratio 400 Device
- \( B = B_0 \left[ 1 - \epsilon_i \cos(N\phi-m\theta) \right] \) and \( \theta = \iota \phi \rightarrow \) equivalent to tokamak with \( \iota_{\text{eff}} = |N-m| \approx 3 \) or \( q_{\text{eff}} = 1/3 \)

Quasi-helically Symmetric (QHS) Configuration in HSX

- Neoclassical transport lower than comparable tokamak
- Direct orbit losses minimized
- Contours of constant \( \left| \frac{B}{G_e} \right| \) rotate about torus; high field side on outside at 1/2 field period as is good curvature region
- Pfirsch-Schlüter current is small (and helical)
  \( \implies \) high equilibrium beta (\( \langle \beta \rangle \approx 35 - 40 \% \))
  \( \implies \) robust to finite beta perturbations to spectrum
- Banana widths about 1/3 size in comparable tokamaks
- Bootstrap current reduces transform, magnitude about 1/3 comparable tokamak
- Neoclassical parallel viscosity small due to near-axis of symmetry
The HSX Stellarator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Radius</td>
<td>1.2 m</td>
</tr>
<tr>
<td>Average Plasma Minor Radius</td>
<td>0.15 m</td>
</tr>
<tr>
<td>Plasma Volume</td>
<td>~.44 m³</td>
</tr>
<tr>
<td>Number of Field Periods</td>
<td>4</td>
</tr>
<tr>
<td>Helical Axis Radius</td>
<td>20 cm</td>
</tr>
<tr>
<td>Rotational Transform</td>
<td></td>
</tr>
<tr>
<td>Axis</td>
<td>1.05</td>
</tr>
<tr>
<td>Edge</td>
<td>1.12</td>
</tr>
<tr>
<td>Number of Coils/period</td>
<td>12</td>
</tr>
<tr>
<td>Average Coil Radius</td>
<td>~ 30 cm</td>
</tr>
<tr>
<td>Number turns/coil</td>
<td>14</td>
</tr>
<tr>
<td>Coil Current</td>
<td>13.4 kA</td>
</tr>
<tr>
<td>Magnetic Field Strength (max)</td>
<td>1.37 T</td>
</tr>
<tr>
<td>Magnet Pulse Length (full field)</td>
<td>≤ 0.2 s</td>
</tr>
<tr>
<td>Auxiliary Coils (total)</td>
<td>48</td>
</tr>
</tbody>
</table>

Estimated Parameters with 28 GHz ECRH

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating Power (source)</td>
<td>200 kW</td>
</tr>
<tr>
<td>Power Density</td>
<td>.45 W/cm³</td>
</tr>
<tr>
<td>Density (cut-off)</td>
<td>1 x 10¹³ cm⁻³</td>
</tr>
<tr>
<td>T_e₀ (100 kW absorbed power - ASTRA)</td>
<td>~1 keV</td>
</tr>
<tr>
<td>τₑₑ (ASTRA)</td>
<td>2 - 4 ms</td>
</tr>
<tr>
<td>νₑₑ</td>
<td>≤ 0.1</td>
</tr>
</tbody>
</table>
Flexibility is obtained through the Auxiliary Coils

Auxiliary Currents:

```
+    +    +    -    -    -    -    +    +    +
MIRROR
-    -    -    -    -    -    -    -    -    -    WELL
```

Noncircular, planar auxiliary coils with 10% A-T of main coil set allow for independent control of transport and stability

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Auxiliary Current</th>
<th>Dominant Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>QHS</td>
<td>None</td>
<td>Best confinement</td>
</tr>
<tr>
<td>MIRROR</td>
<td>3 coils on either end opposite to coils in center</td>
<td>Transport similar to conventional stellarator</td>
</tr>
<tr>
<td>WELL</td>
<td>All aux currents oppose main coil current</td>
<td>Well depth and stability increases</td>
</tr>
</tbody>
</table>
Monte-Carlo Diffusion Coefficient

- Electron monoenergetic diffusion coefficient, assuming **NO** radial electric field
- Diffusion in **QHS** is 1-2 orders of magnitude less than conventional stellarator in low collisionality regime
- **MIRROR** mode increases transport back to level of conventional stellarator
- **WELL** configuration shows small degradation of neoclassical transport from QHS case
HSX Assembled
The HSX Device
Coil Module Assembly

- Each coil is initially aligned in a stainless steel support ring and pressure pads, which are epoxied to the coil, mount the coil into the ring
- An auxiliary coil is positioned and clamped on the support ring
- The castings are then fitted to the coil-ring assembly, and final match drilling of the ring to accept the splice plate bolts is performed
- Final measurement of the coil location via CMM provides for accurate coil assembly on the HSX superstructure (assembly to <1 mm at 6 reference points)
HSX Support Structure

- Modular interior box-beam support structure
  - 4 periods, each moves out for assembly and access
- Each coil support ring has a 3 point, multi-axis adjustable support
- External stiffening is supplied by the toroidal rig assembly for 1 Tesla operation
Vacuum Vessel Assembly

- Each piece was laser cut to the required length, and the port holes cut by laser to <0.5 mm accuracy
- The Metrecom (CMM (.1 mm accuracy over a 1 m radius sphere)) was used to accurately align the port tubes to the design orientation
- An alignment pointer located the port orientation correctly to the previous CMM setup while each port was welded to the vessel
Vacuum Vessel Assembly

- Each half-period section is made up of 2 separate pieces, with matching ends trimmed by laser cutting.
- These pieces are accurately (< 1mm) aligned in HSX space to form a full period section.
- The vacuum flange, which allows for period separation, is fitted to the section and accurately aligned.
- Re-measurement and alignment then permits the contours for box-port matching to be measured.
HSX First plasma at boxport

- 2.45 GHz rf - ~900 gauss
- < 1 kW power
- $2 \times 10^{-4}$ torr H$_2$
- > 30 Second duration
Magnetic Surface Mapping

• Rationale
  – Compare t profile to design
  – Check surfaces for islands/break-up
  – Compare the surface shape to calculated qhs predicted shape

• Method
  – Low energy electron gun (< 100 eV)
  – Highly transparent (95%) fluorescent mesh
  – View using sensitive (10^-5 lux) CCD camera
  – Capture images on video and frame-grab for later analysis
Beam Mapping Layout

- The electron gun assembly is almost 180° toroidally from the fluorescent mesh.
- The periscope optics is close to the mesh and views at 30° off perpendicular.
Electron Gun

- Can supply up to 2 mA of emission, but usually only 10’s of µA are required
- Electron acceleration energies up to 200 eV can be used
- Radially positionable via stepper control
- Rotary alignment of gun to field
- Situated ~180° from the fluorescent screen
Fluorescent Mesh

- 95% transparent mesh
  - 3 mm spaced wire, 0.2 mm diameter
- 22 reference LEDs on border for image reconstruction
- Viewed with periscope and sensitive CCD camera
Mirror Configuration Compared to QHS

MIRROR mode has similar transform to QHS with large increase in neoclassical transport

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Center Transform</th>
<th>Edge Transform</th>
</tr>
</thead>
<tbody>
<tr>
<td>QHS</td>
<td>1.05</td>
<td>1.12</td>
</tr>
<tr>
<td>MIRROR</td>
<td>1.07</td>
<td>1.16</td>
</tr>
<tr>
<td>WELL</td>
<td>1.17</td>
<td>1.26</td>
</tr>
</tbody>
</table>
Rotational transform calculation

- CCD camera image of 4 cm gun launch - preliminary
- 64 segment, 14 filament Biot-Savart field line following calculation
- Initial transform from ‘dot’ count to compare to experimental data
1 kG QHS e-beam

- Composite of 4 frames from frame-grabber
- No image restoration performed as yet
- Blue outer ‘dots’ are frame reference leds
- Dot poloidal progression provides transform information
1 kG QHS e-beam

- First ‘dot’ is from a half toroidal transit from the known gun radial launch position.
- Subsequent ‘dots’ make a complete toroidal transit, and 1+ poloidal transits.
- Number of ‘dots’ per $2\pi$ poloidally provide a measure of $\iota$. 

Reference leds
Rotational transform profile

- Iota-bar from 2 different methods of analysis
- Includes a scan at 1 kG and 100 gauss
- Comparison to electron transit information from Biot-Savart calculation
  - 14 filaments, 64 segments/filament, 48 coils
- Experiment is in agreement to < 1% with computed profile
HSX near-term plans

• Continue electron beam magnetic surface mapping
  – apply image restoration techniques to CCD images to permit comparison of surface shapes between experiment and calculation
  – further investigate magnetic configurations
    • Well
    • Mirror
• Single particle orbit experiments to test qhs confinement
• 0.5 T plasma operation at 2nd harmonic ECRH
HSX Magnetic Flexibility
Conclusions

• The HSX main assembly is complete
• 1st plasma at low field has been achieved
• Electron beam mapping of 1 kG magnetic field show well-formed surfaces, no measurable magnetic islands within the confinement region, and a transform profile in agreement to < 1% with calculation
• HSX is now up and running for physics experiments