HSX Final Alignment, Assembly, and Initial Operation

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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
- $B = B_0 [1 - \varepsilon_h \cos(N\phi - m\theta)]$ and $\theta = \iota\varphi \rightarrow$ equivalent to tokamak with $\iota_{eff} = |N - m\iota| \approx 3$ or $q_{eff} = 1/3$

Quasi-helically Symmetric (QHS) Configuration in HSX

- Neoclassical transport lower than comparable tokamak
- Direct orbit losses minimized
- Contours of constant $|B|$ 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)
  - $\Rightarrow$ high equilibrium beta ($\langle\beta\rangle \sim 35 - 40$ %)
  - $\Rightarrow$ 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

Major Radius	1.2 m
Average Plasma Minor Radius	0.15 m
Plasma Volume	~.44 m^3
Number of Field Periods	4
Helical Axis Radius	20 cm
Rotational Transform	
Axis	1.05
Edge	1.12
Number of Coils/period	12
Average Coil Radius	~ 30 cm
Number turns/coil	14
Coil Current	13.4 kA
Magnetic Field Strength (max)	1.37 T
Magnet Pulse Length (full field)	≤ 0.2 s
Auxiliary Coils (total)	48

Estimated Parameters with 28 GHz ECRH

Heating Power (source)	200 kW
Power Density	.45 W/cm^3
Density (cut-off)	1×10^{13} cm^{-3}
T_{eo} (100 kW absorbed power - ASTRA)	~1 keV
τ_E (ASTRA)	2 - 4 ms
υ_e^*	≤ 0.1

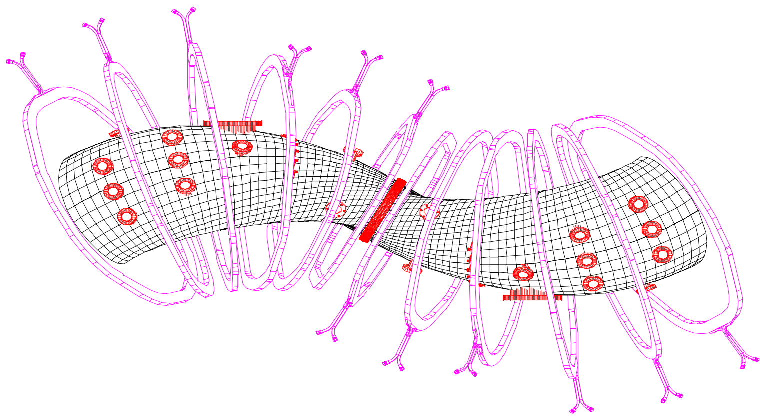
Flexibility is obtained through the Auxiliary Coils

Auxiliary Currents:

\+ + + - - - - - - + + +

MIRROR

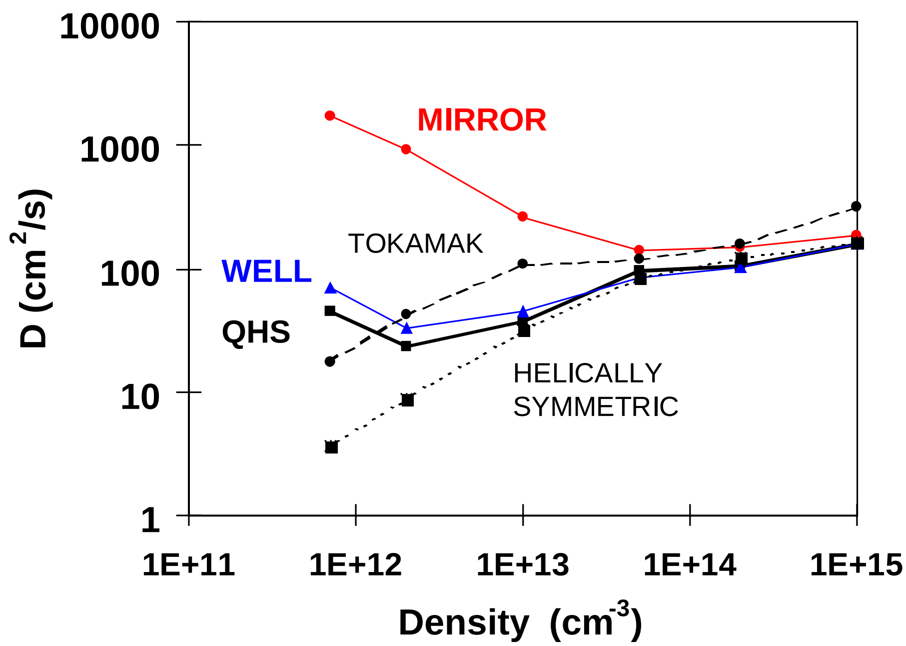
\- - - - - - - - - - - - WELL



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

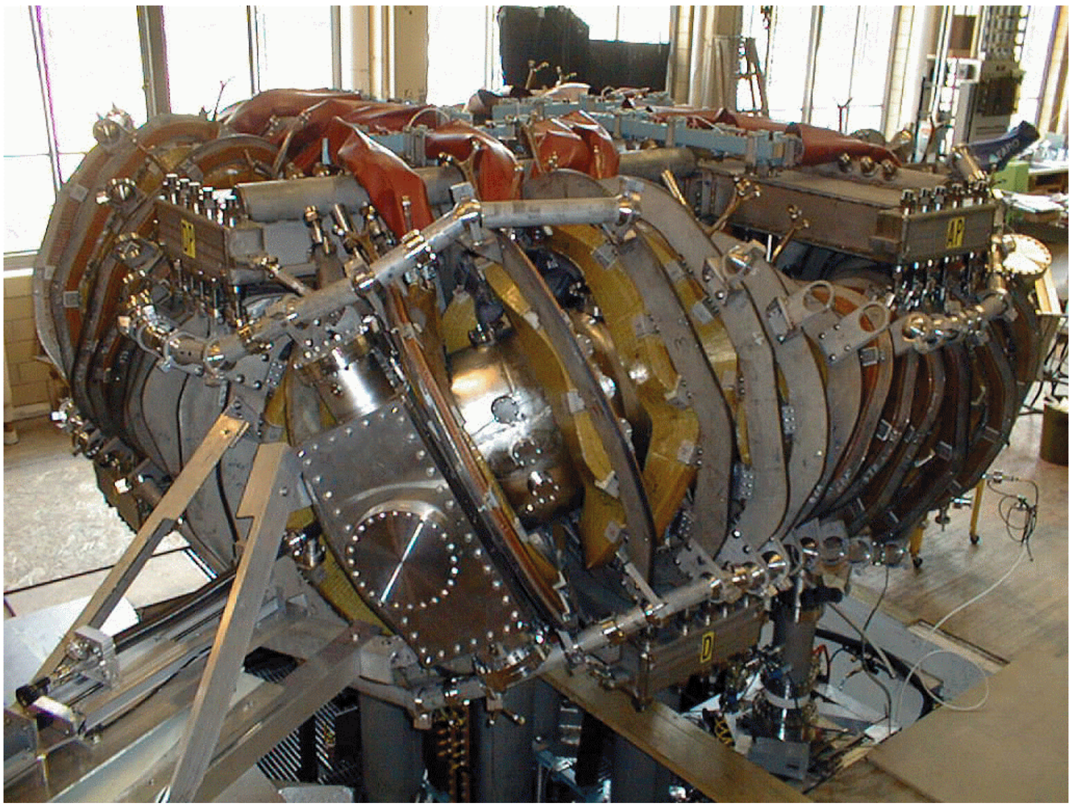
Configuration	Auxiliary Current	Dominant Feature
QHS	None	Best confinement
MIRROR	3 coils on either end opposite to coils in center	Transport similar to conventional stellarator
WELL	All aux currents oppose main coil current	Well depth and stability increases

Monte-Carlo Diffusion Coefficient

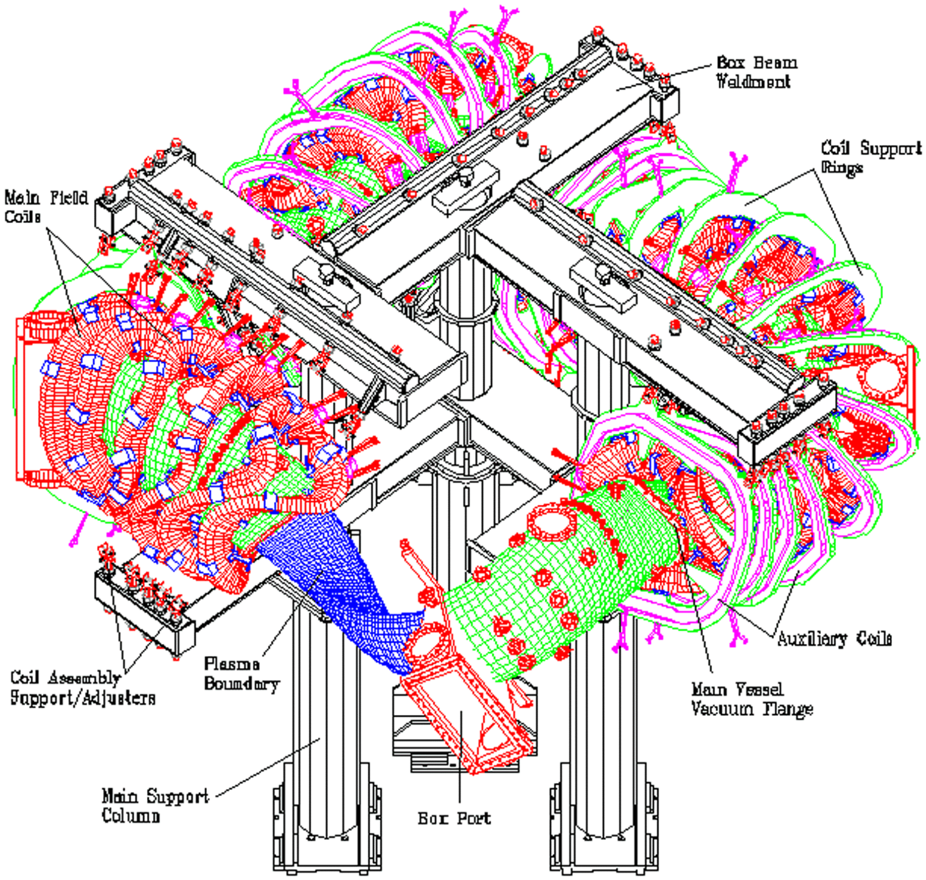


- Electron monoenergetic diffusion coefficient, assuming **NO** radial electric field
- Diffusion in **QHS** is 1-2 orders of magnitude less than conventional stellarator in low collisionality regime
- MIRROR mode increases transport back to level of conventional stellarator
- WELL configuration shows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

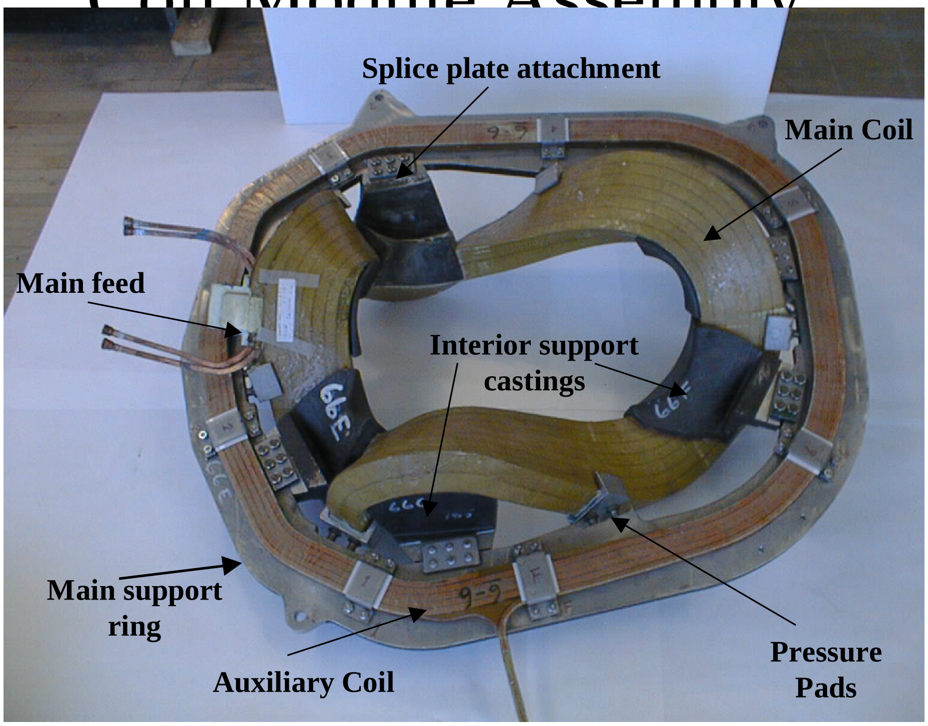
HSX Assembled



The HSX Device

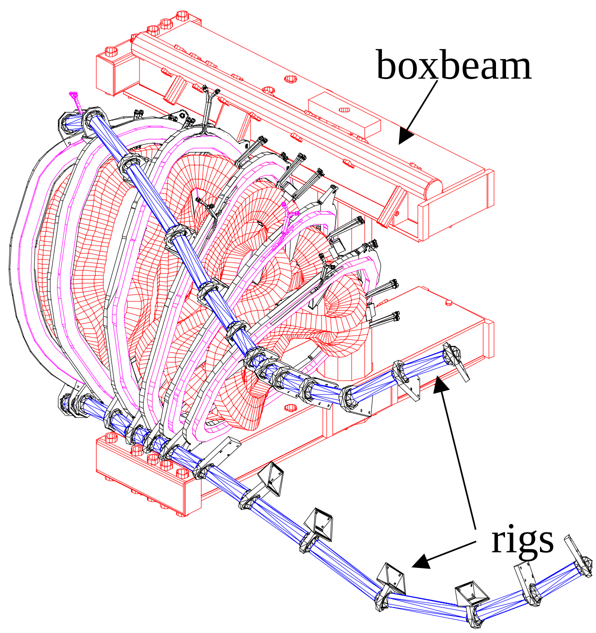


Coil Module Assembly



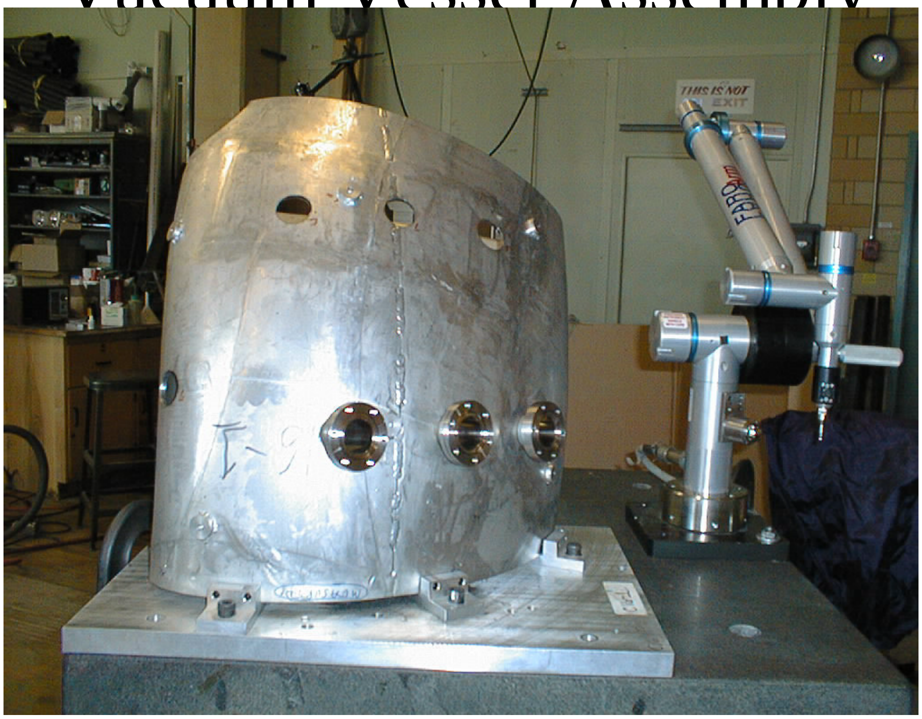
- Each coil is initially aligned in a stainless steel support ring and pressure pads, which are epoxied to the coil, mount the coil into the ring
- An auxiliary coil is positioned and clamped on the support ring
- The castings are then fitted to the coil-ring assembly, and final match drilling of the 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



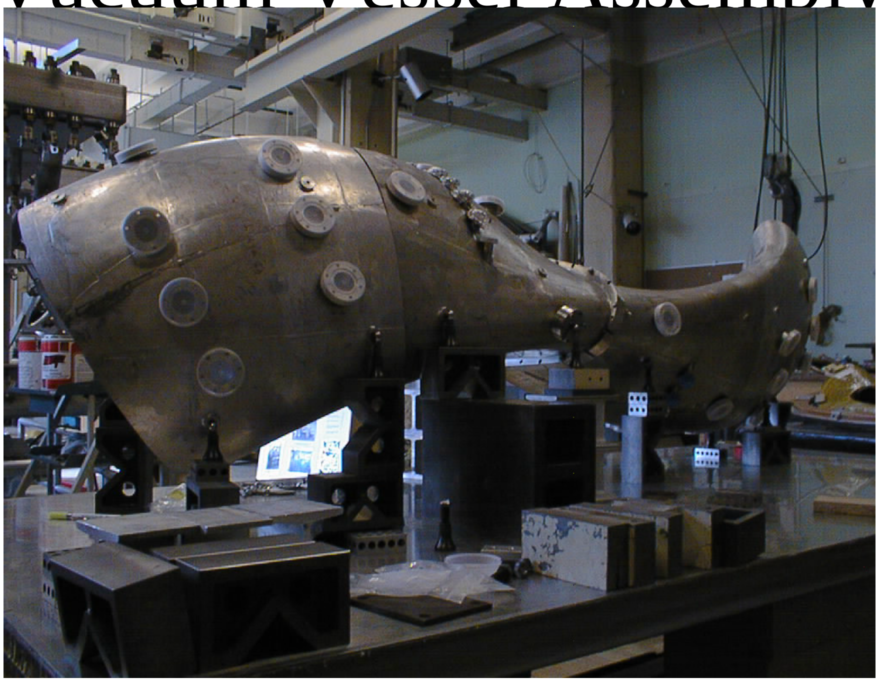
- Modular interior box-beam support structure
  - 4 periods, each moves out for assembly and access
- Each coil support ring has a 3 point, multi-axis adjustable support
- External stiffening is supplied by the toroidal rig assembly for 1 Tesla operation

Vacuum Vessel Assembly



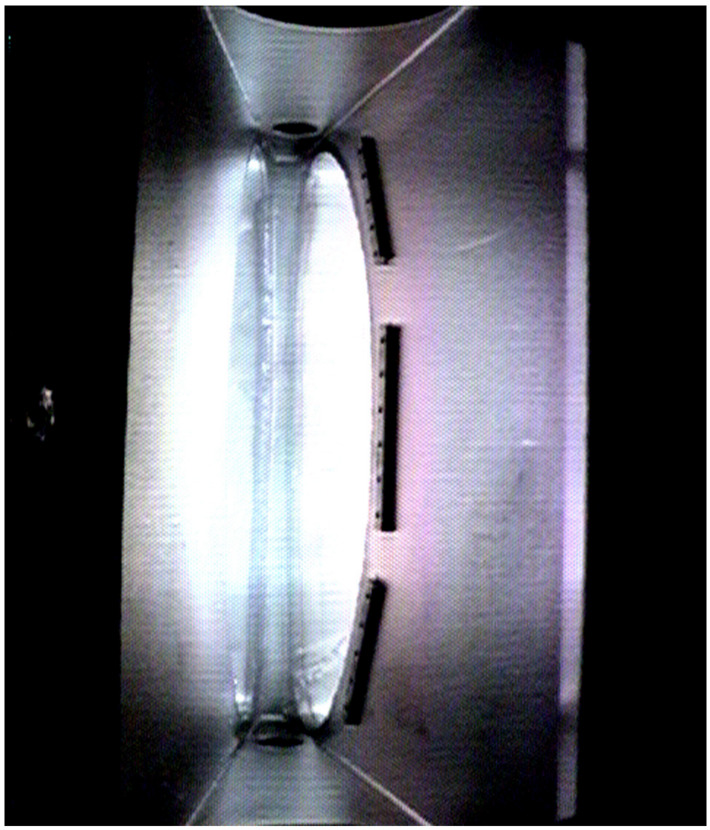
- Each piece was laser cut to the required length, and the port holes cut by laser to <0.5 mm accuracy
- The Metrecom (CMM (.1 mm accuracy over a 1 m radius sphere)) was used to accurately align the port tubes to the design orientation
- An alignment pointer located the port orientation correctly to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

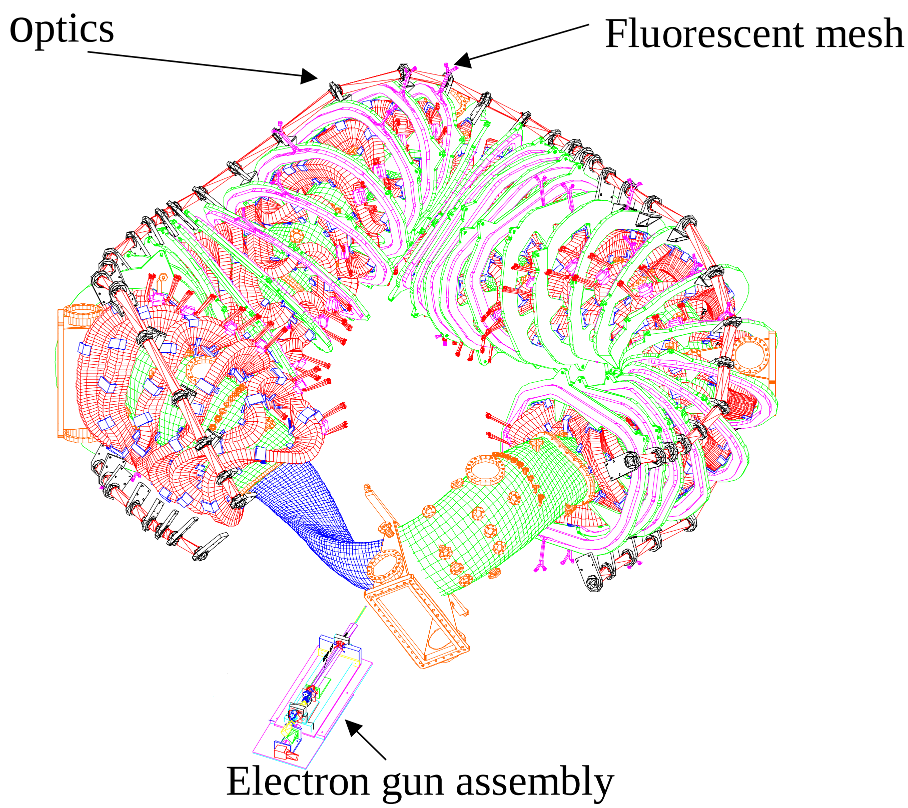


- 2.45 GHz rf - ~900 gauss
- < 1 kW power
- 2 * 10^{-4} torr H_2
- > 30 Second duration

Magnetic Surface Mapping

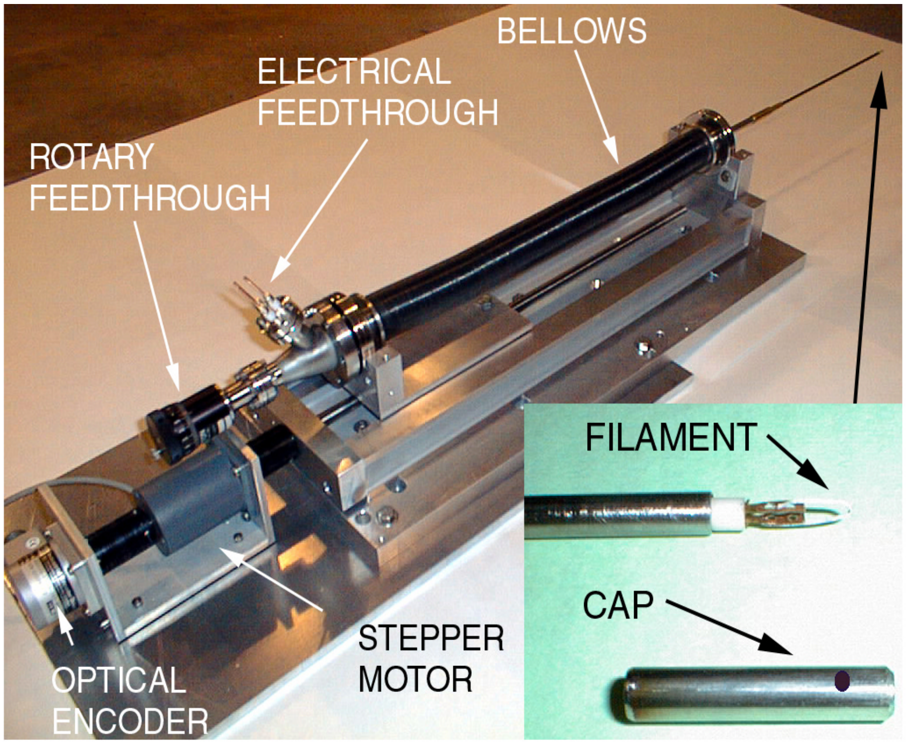
- Rationale
  - Compare ι profile to design
  - Check surfaces for islands/break-up
  - Compare the surface shape to calculated qhs predicted shape
- Method
  - Low energy electron gun (< 100 eV)
  - Highly transparent (95%) fluorescent mesh
  - View using sensitive (10^{-5} lux) CCD camera
  - Capture images on video and frame-grab for later analysis

Beam Mapping Layout



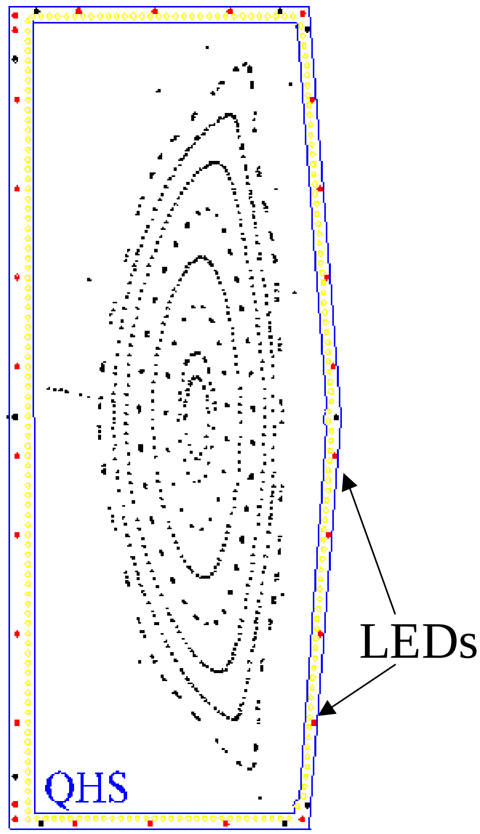
- The electron gun assembly is almost 180^o toroidally from the fluorescent mesh
- The periscope optics is close to the mesh and views at 30^o off perpendicular

Electron Gun



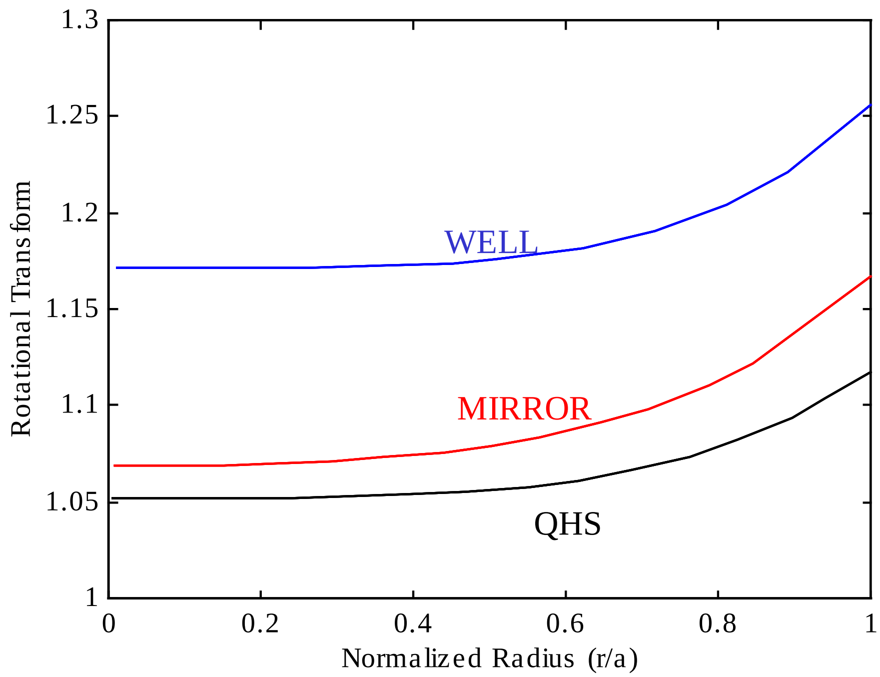
- Can supply up to 2 mA of emission, but usually only 10's of μA are required
- Electron acceleration energies up to 200 eV can be used
- Radially positionable via stepper control
- Rotary alignment of gun to field
- Situated ~180º from the fluorescent screen

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



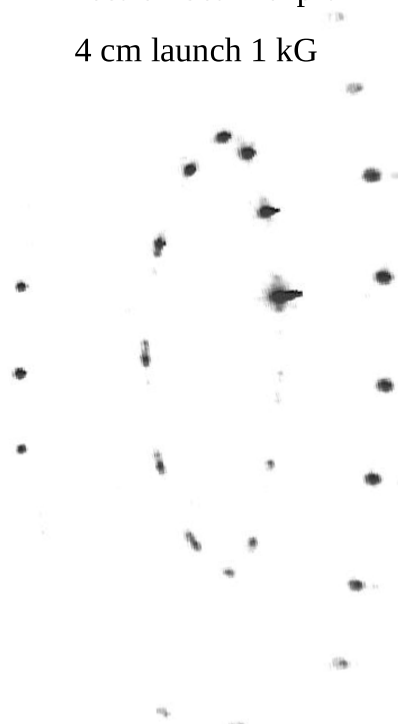
MIRROR mode has similar transform to **QHS** with large increase in neoclassical transport

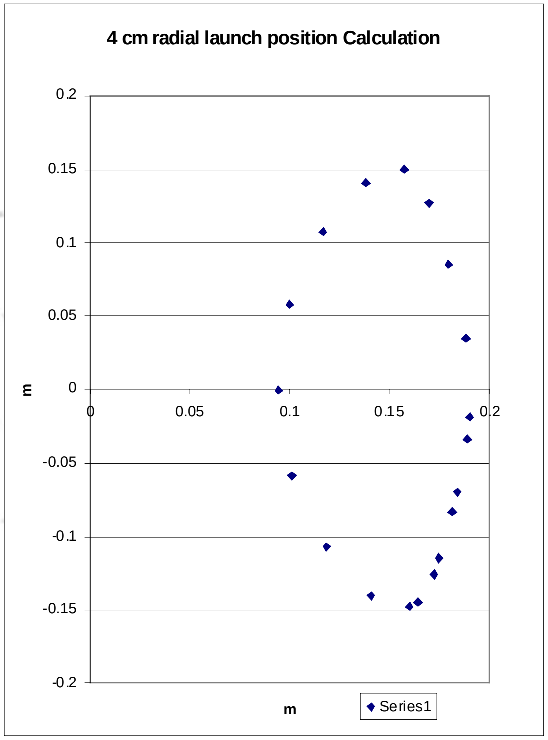
Configuration	Center Transform	Edge Transform
QHS	1.05	1.12
MIRROR	1.07	1.16
WELL	1.17	1.26

Rotational transform calculation

Electron beam exp't

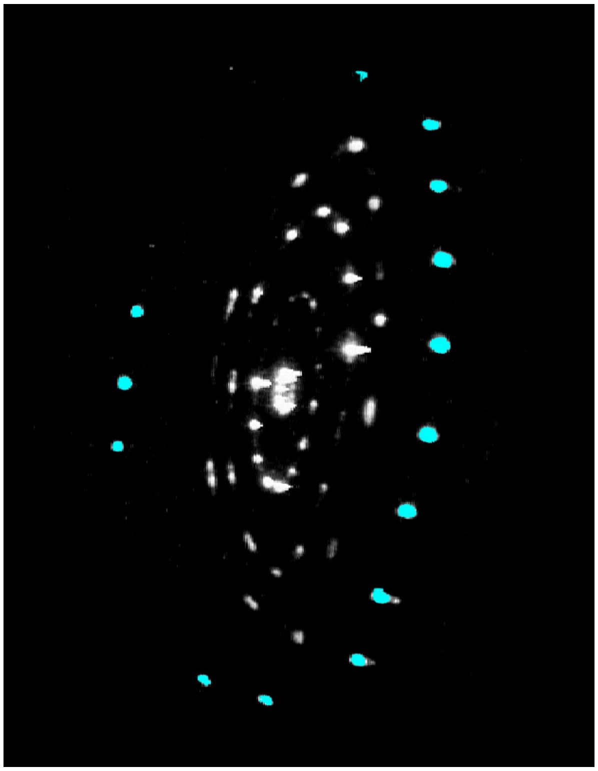
4 cm launch 1 kG





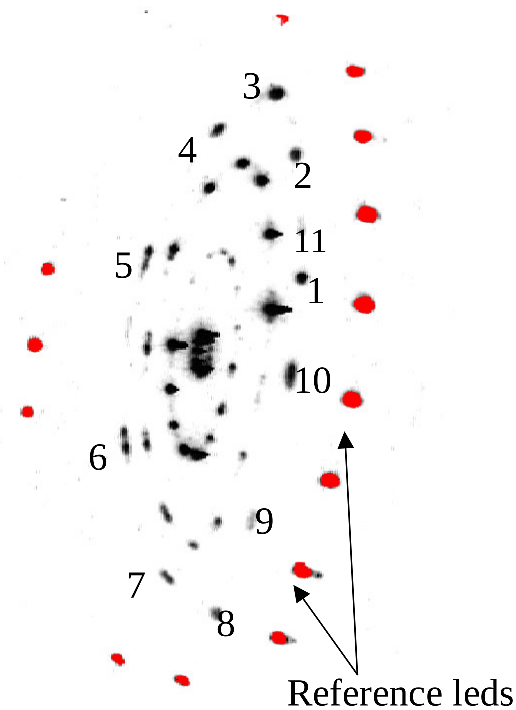
- CCD camera image of 4 cm gun launch - preliminary
- 64 segment, 14 filament Biot-Savart field line following calculation
- Initial transform from 'dot' count to compare to experimental data

1 kG QHS e-beam



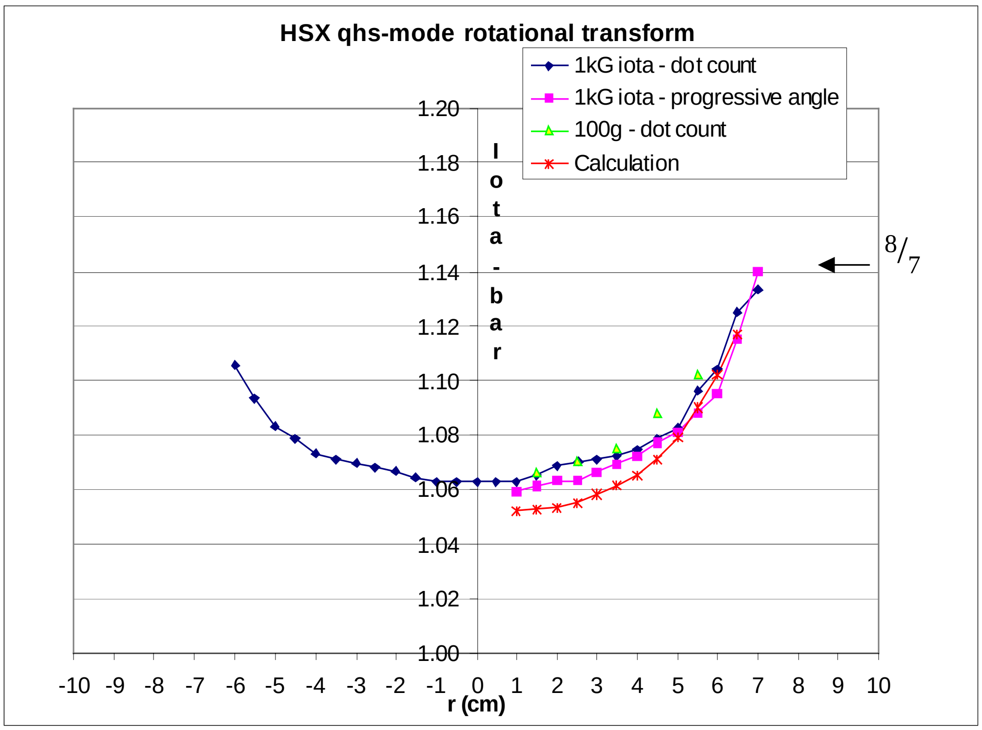
- Composite of 4 frames from frame-grabber
- No image restoration performed as yet
- Blue outer ‘dots’ are frame reference leds
- Dot poloidal progression provides transform information

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 2π poloidally provide a measure of ι

Rotational transform profile

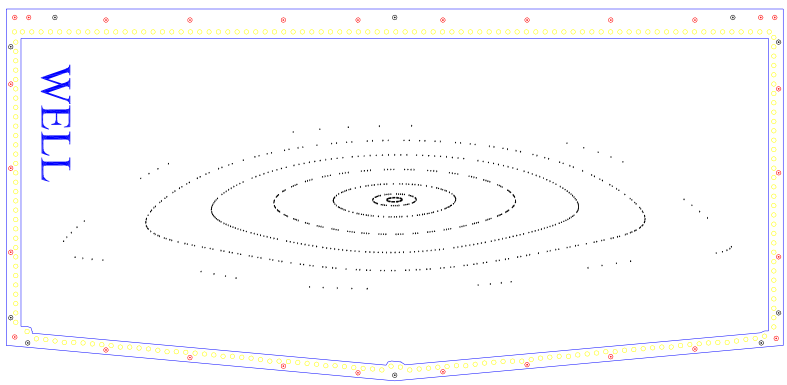


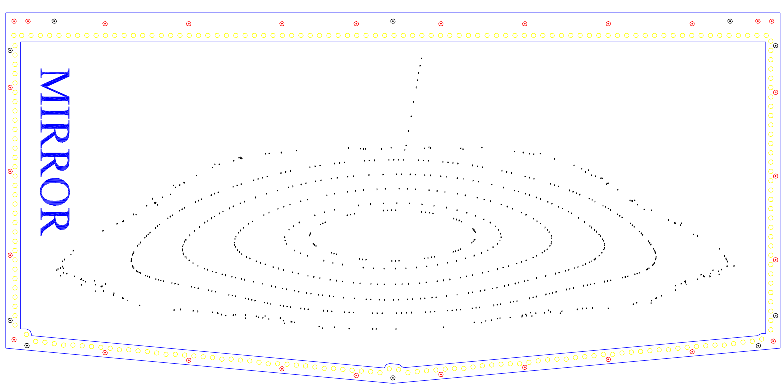
- Iota-bar from 2 different methods of analysis
- Includes a scan at 1 kG and 100 gauss
- Comparison to electron transit information from Biot-Savart calculation
  - 14 filaments, 64 segments/filament, 48 coils
- Experiment is in agreement to < 1% with computed profile

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