Initial Experimental Program Plan for HSX

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The Helically Symmetric Experiment (HSX) is the principal experimental element in the present US Stellarator Program, starting operation in summer 1999. The quasi-helically symmetric fields in HSX should provide good neoclassical confinement of single particles with minimal direct loss orbits and low flow damping in the direction of near-symmetry. First plasmas will be produced by up to 2 kW of 2.45 GHz ECH, which is primarily used for vacuum vessel wall conditioning. The first experimental campaign will measure the attained magnetic field structure by electron beam mapping techniques. A key capability needed for the experimental program is the flexibility of the magnetic configuration introduced by a set of auxiliary coils to vary the magnetic field spectrum. The addition of a toroidal mirror mode in the spectrum increases neoclassical transport and flow damping to the level of a conventional stellarator. Some control over the rotational transform profile is also available through the auxiliary coils. Surfaces in these modes of operation will also be mapped to demonstrate this flexibility in the device.

This set of investigations will be followed immediately by operation at B=0.5 T with 2nd harmonic ECH (28 GHz-200kW). Pfirsch-Schluter current measurements to ascertain their predicted helical structure and their magnitude reduction by the factor $|N-m\iota|$ will also serve to elucidate the attained magnetic field structure. With soft x-ray measurements we will examine the confinement of deeply-trapped energetic electrons produced by the 2nd harmonic ECH as a function of magnetic field spectrum and heating locations. Other early investigations on trapped-particle and neoclassical confinement will look at the ECH breakdown process and the diffusion of electron or ion populations through a neutral gas background as a function of the magnetic field spectrum.

A single-channel radiometer is being installed in collaboration with UC-Davis to provide initial T_e measurements and to serve as a basis for development of a full ECE imaging (ECEI) system to be implemented when HSX later moves to B=1.0 T operation. The full ECEI array will provide 2-D electron temperature profiles as well as measurements of T_e fluctuations. Initial density profile data will be obtained from a 9-chord, 274 GHz interferometer system developed and installed by UCLA. Profile measurements will be augmented later by a 10-channel Nd:YAG filter-polychrometer Thomson system based on the GA DIII-D divertor Thomson system. This diagnostic set, with flux loops and spectrometers, permits early investigation of key issues: energetic particle confinement, hollow vs. peaked density profiles, plasma rotation and electric fields.

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Optimization can improve neoclassical confinement at low collisionalities to tokamak levels, or better

Quasi-symmetry – A symmetry direction in |B|

$|B| \sim B_0 + \Sigma\, b_{mn} \cos(m\theta - n\phi)$; single dominant b_{mn}

Neoclassical transport analogous to tokamak with:

$\iota_{eff} \Rightarrow |n - m\iota|$

HSX is quasi-helically symmetric: n=4, m=1, ι~1

HSX has an effective rotational transform of 3 !
Reduced anomalous transport with ISS95 scaling

High Effective Transform and Quasi-Helical Symmetry Lead to Unique Properties

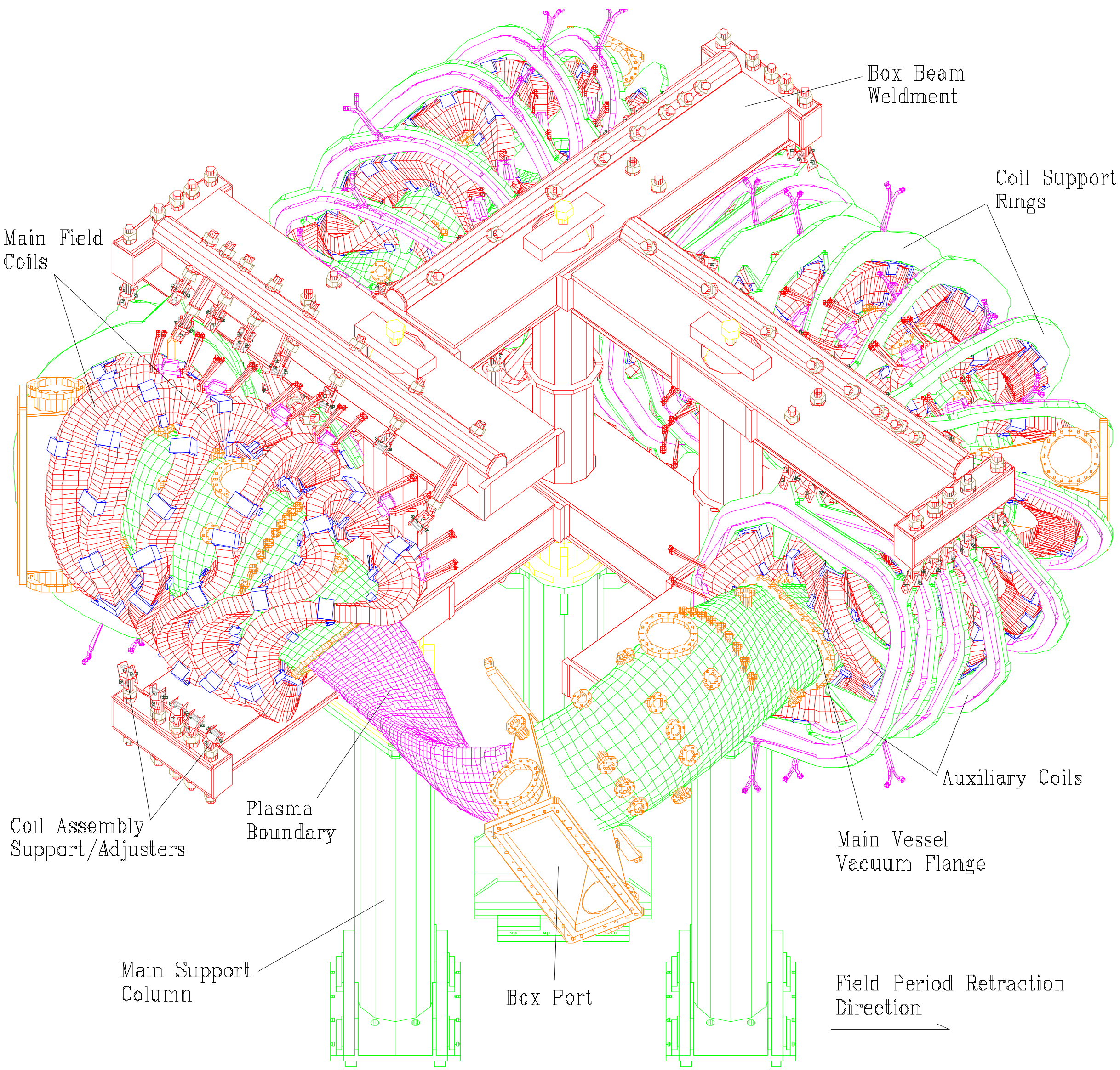
- Low Neoclassical Transport
  - Small deviations from magnetic surfaces, small banana widths
  - Minimal direct loss particles, reduction in '$1/\nu$' transport, very small neoclassical thermal conductivity

- Plasma Currents are Small
  - Small Pfirsch-Schlüter and bootstrap currents
  - Robust magnetic surfaces, high equilibrium beta limit

- Low parallel viscosity in the direction of symmetry
  - Possibility of high E x B shear to reduce turbulence

- Lower anomalous transport ? L-2 experimental results $\chi_{e,anom} \propto 1/\iota$

Cut-away Drawing of HSX



$R = 1.2$ m
$\langle a_p \rangle = 0.15$ m
$B_{max} = 1.25$ T
4 Field Periods
$1.05 < \iota < 1.12$

Toroidal curvature like conventional stellarator with R/a > 400

Auxiliary coils provide flexibility in transform, well and spectrum

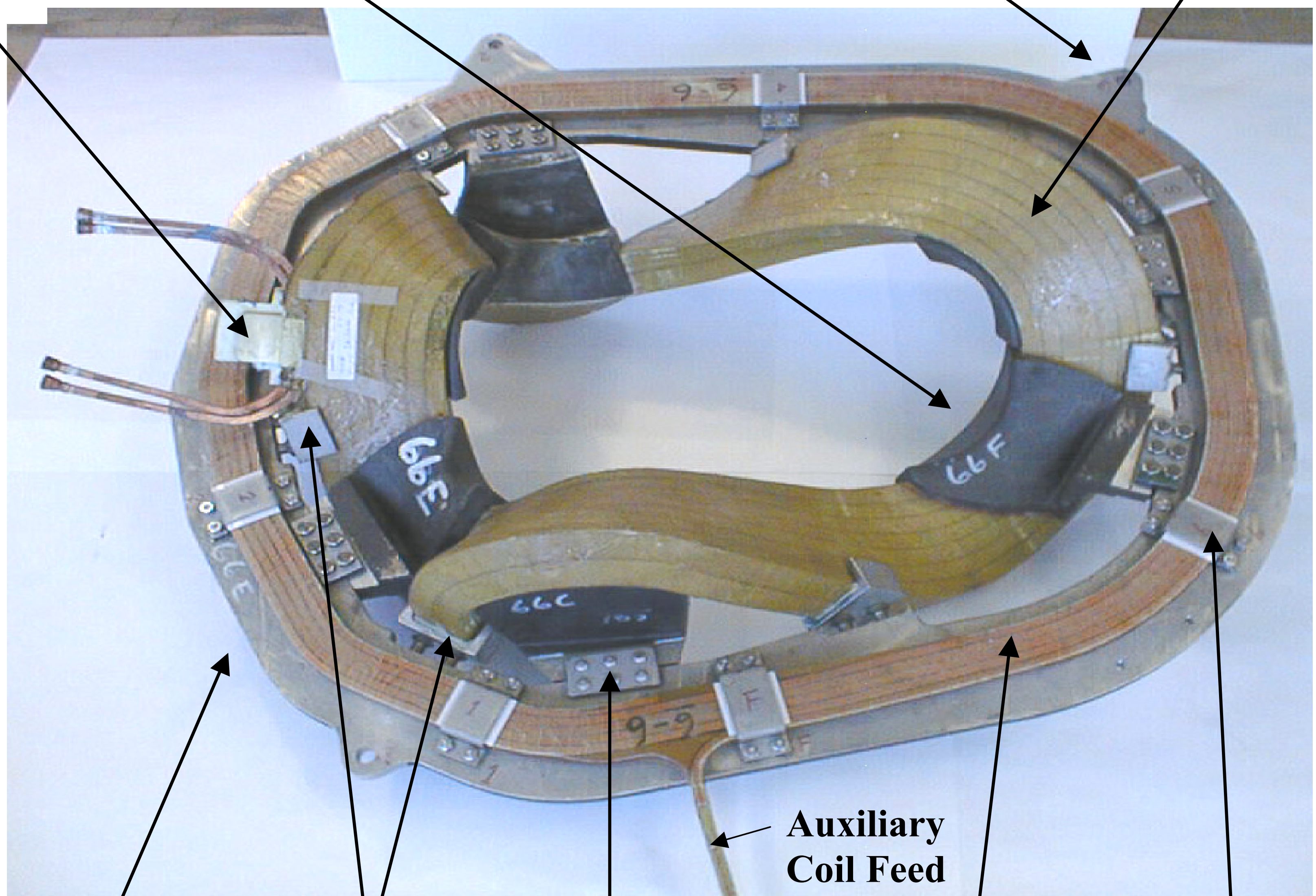
The HSX Device

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)	1.25 T
Magnet Pulse Length (full field)	≤ 0.2 s
Auxiliary Coils (total)	48

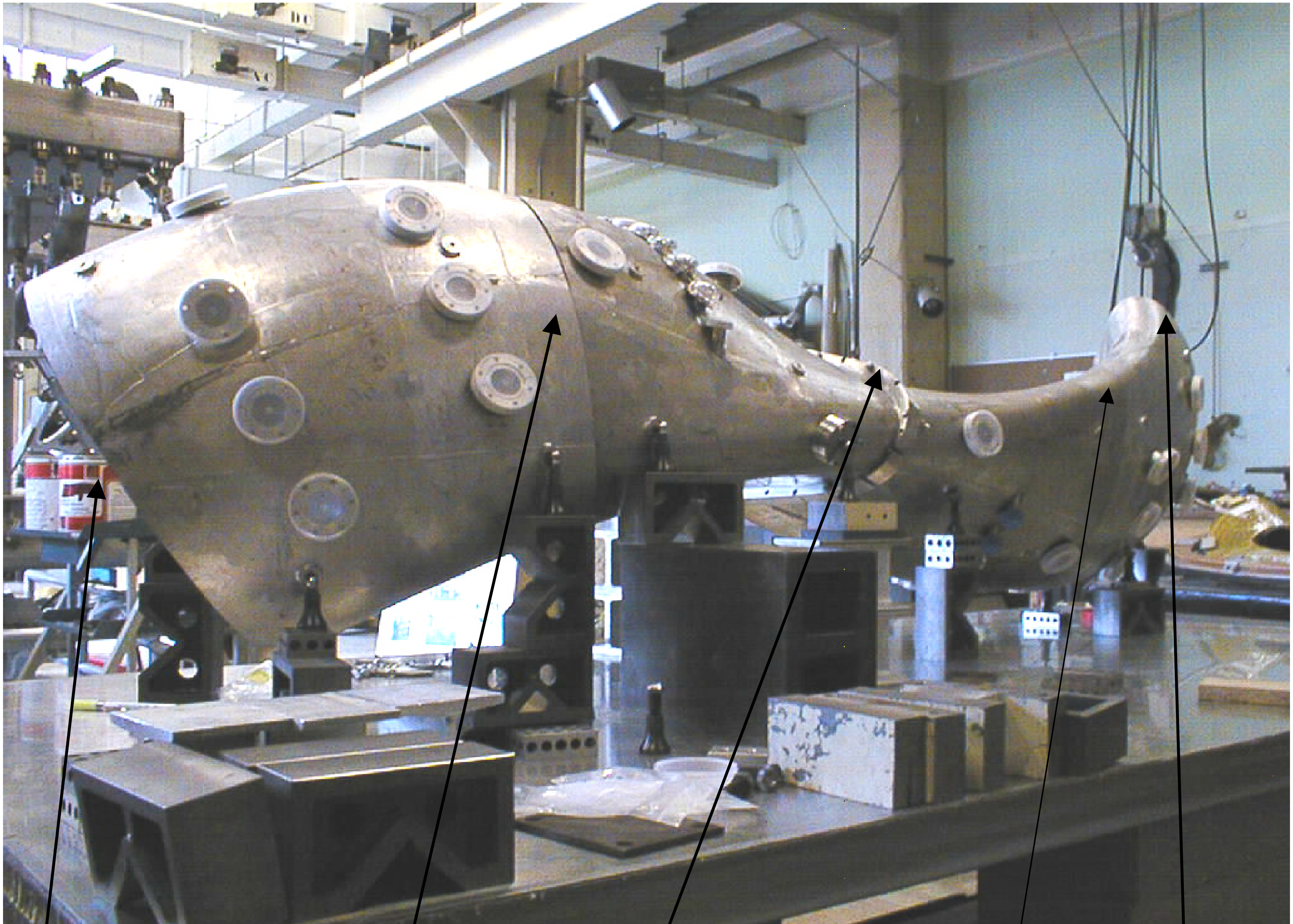
Estimated Parameters with 28 GHz ECH

Heating Power (source)	200 kW
Power Density	.45 W/cm^3
Density (cut-off)	1×10^{13} cm^{-3}
T_{eo} (LHD scaling, 100 kW)	700 eV
τ_E (LHD scaling)	2 ms
υ_e^*	≤ 0.1

Main and Auxiliary HSX Coil Module in Supporting Assembly

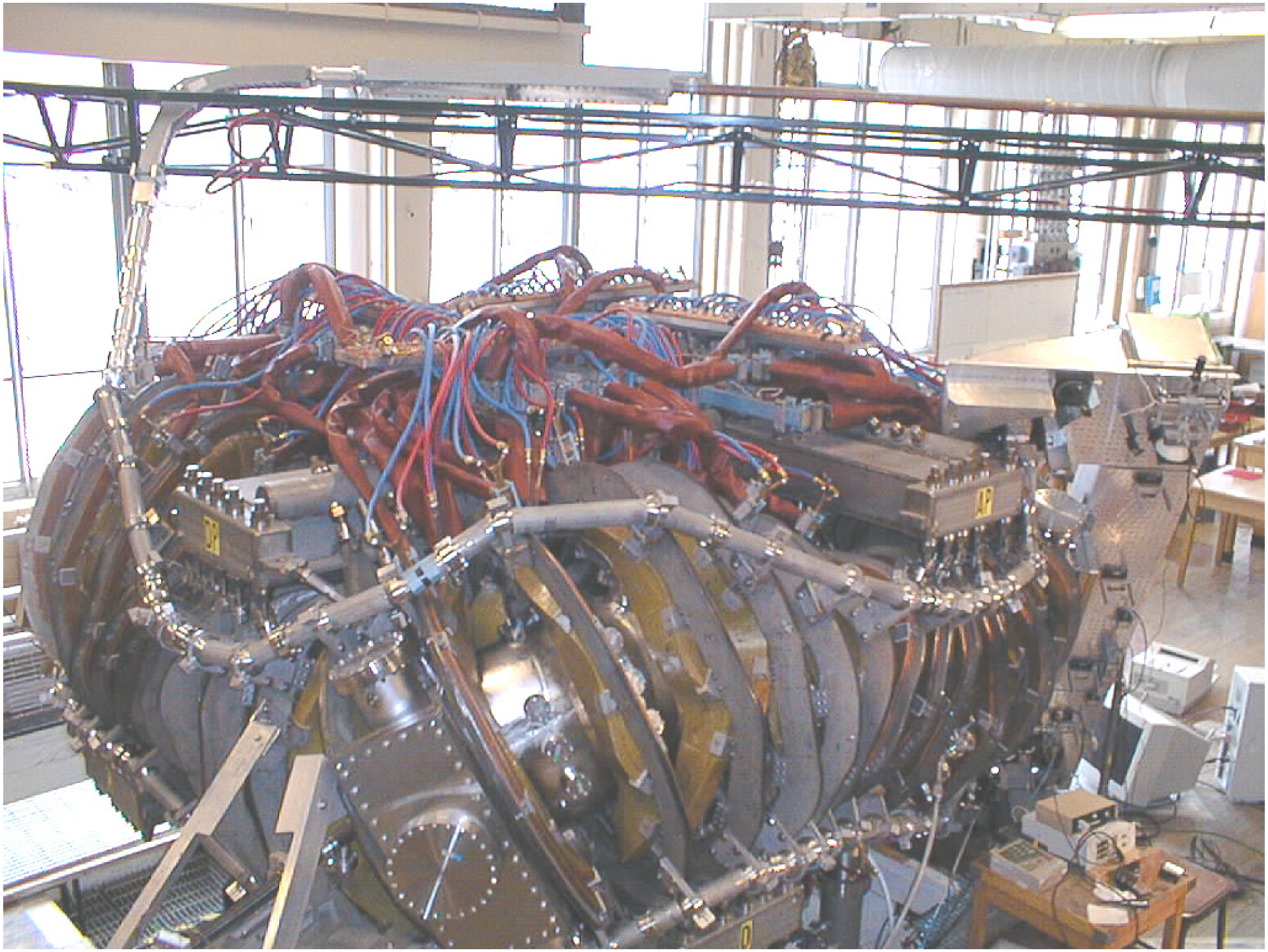


One Field-Period of HSX Vacuum Vessel Fit-up for Welding

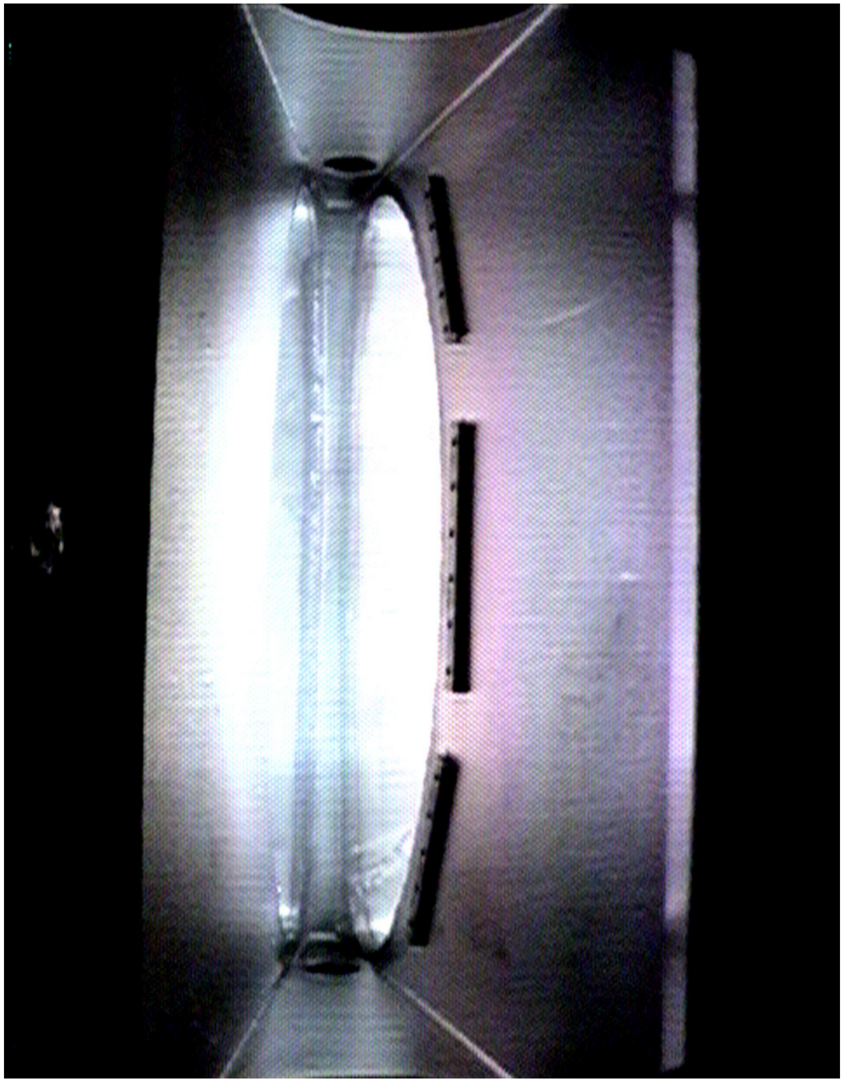


Boxport End #1 | Section Joint | Joint Flanges | Section Joint | Boxport End #2

HSX Has Begun Experimental Operations

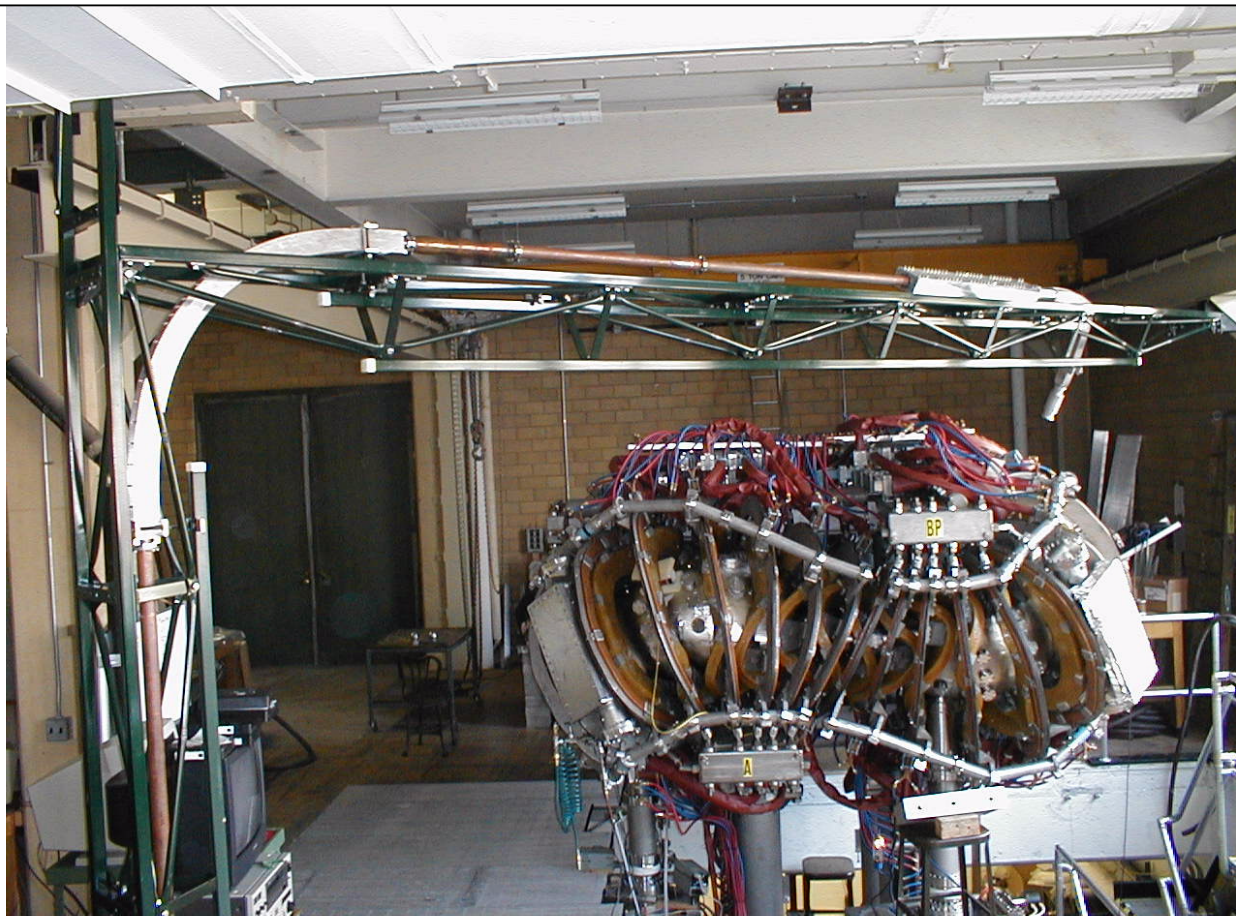


First Plasma in HSX



- August 31, 1999
- 2.45 GHz ECH; 840 G and 1 kW power level
- >30 s duration

28 GHz Transmission Line/Mode Converter Installation Nearly Complete



- Details of transmission line in poster by Shafii
- Launching/focusing mirror and window to be installed at next venting; cold test system
- Gyrotron power supplies all operational
- Gyrotron has been installed in socket; beginning conditioning and power testing into dummy load

Physics Goals of the HSX Program

- Immediate goals are to explore the multiple advantageous confinement characteristics of quasi-helical symmetry

  - No toroidal curvature
  - High effective transform
  - Small particle drifts and banana widths
  - Minimal direct loss orbits
  - Low neoclassical transport
  - Small parallel currents
  - Low parallel viscous damping in symmetry direction

- The program will move towards understanding the physics of and possible routes to enhanced confinement regimes in stellarators

  - Reduced anomalous transport from Lackner-Gottardi scaling; high effective transform in HSX (3)
  - Low parallel viscosity permitting larger ExB shear for reducing fluctuation levels
  - Introduction of shear through controlling the ambipolarity constraint

- Longer range plans include physics of stability and beta limits; upgrade power for electron heating (minimizing FLR stabilization)

The HSX experimental program focuses on improvements of electron transport through quasi-helical symmetry

Utilize 28 GHz ECH (200 kW) to put electrons into low collisionality regime; ECH system discussed in poster by Shafii

Second harmonic heating at B=0.5T to generate hot tail electrons for energetic particle confinement studies

Fundamental heating at B=1.0T to study bulk confinement and reduced electron thermal conductivity with QHS

Auxiliary coils provide the flexibility to alter the magnetic field spectrum between QHS and fully 3-D for comparison

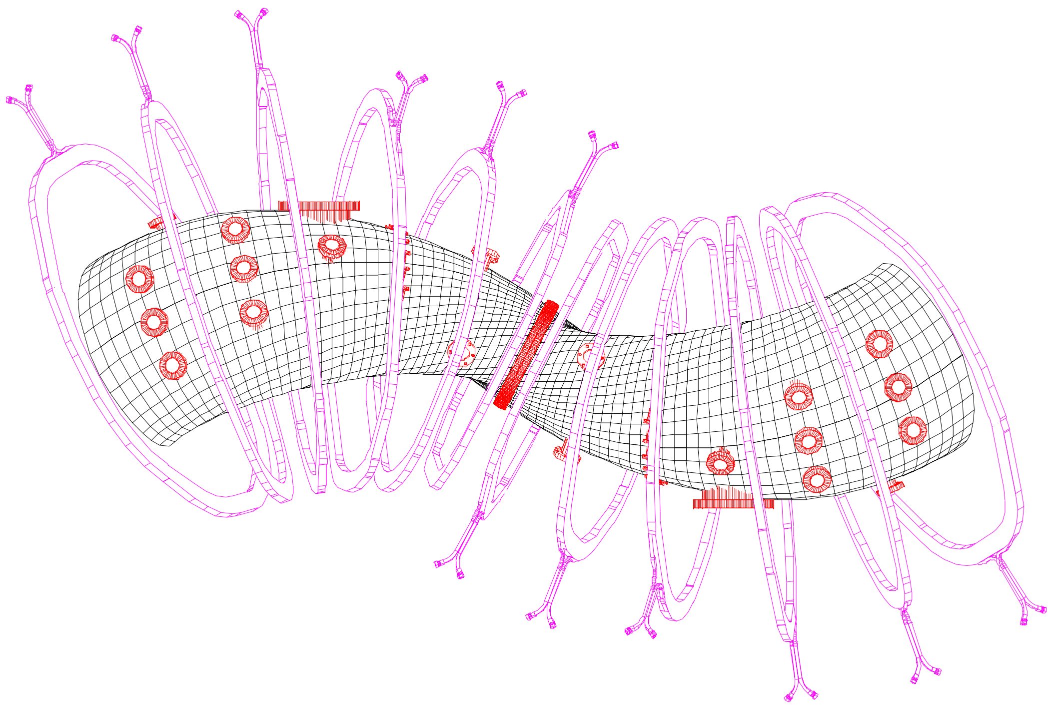
AUXILIARY COILS CAN ALTER MAGNETIC CONFIGURATION

Auxiliary Currents:

+ + + - - - - - - + + + MIRROR

- - - - - - - - - - - - WELL

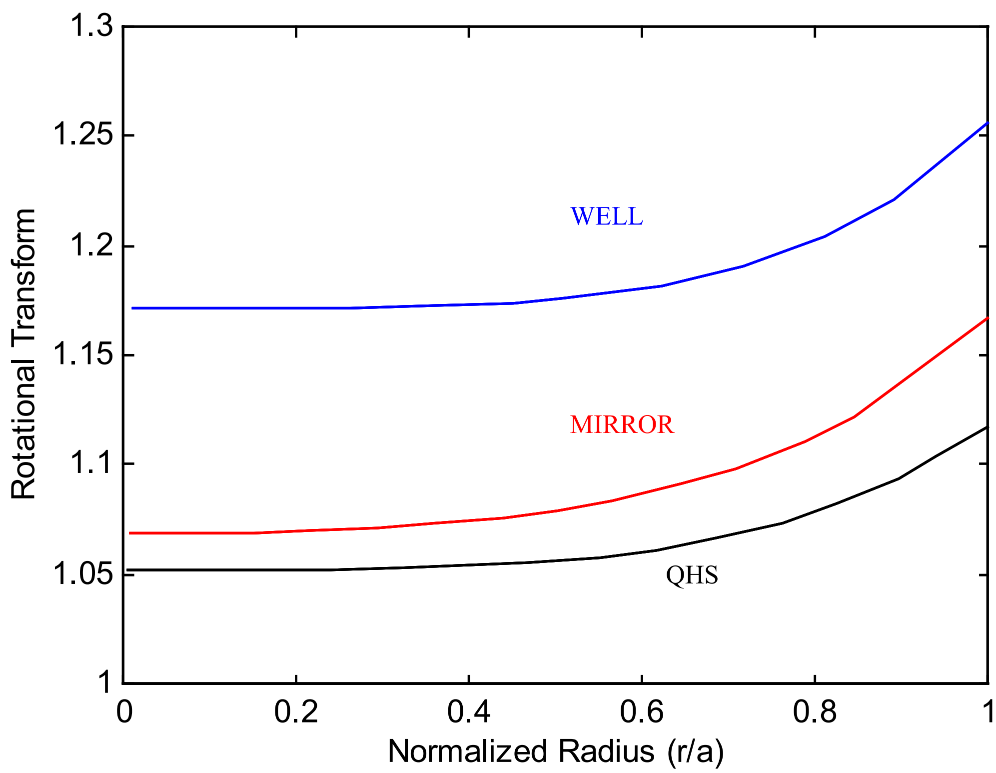
- Noncircular, planar auxiliary coils with 10% A-T of main coil set allow for independent control of transport and stability



Configuration	Auxiliary Current	Dominant Feature
QHS	None	Best transport
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

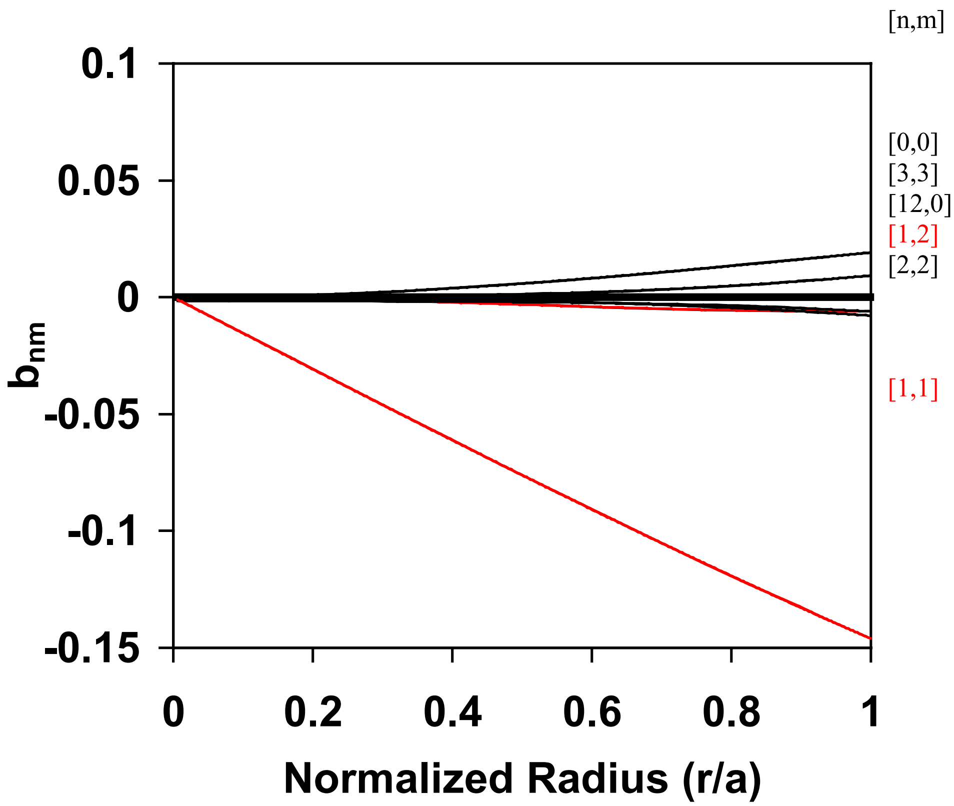
ROTATIONAL TRANSFORM IN MIRROR IS CLOSE TO QHS

- 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

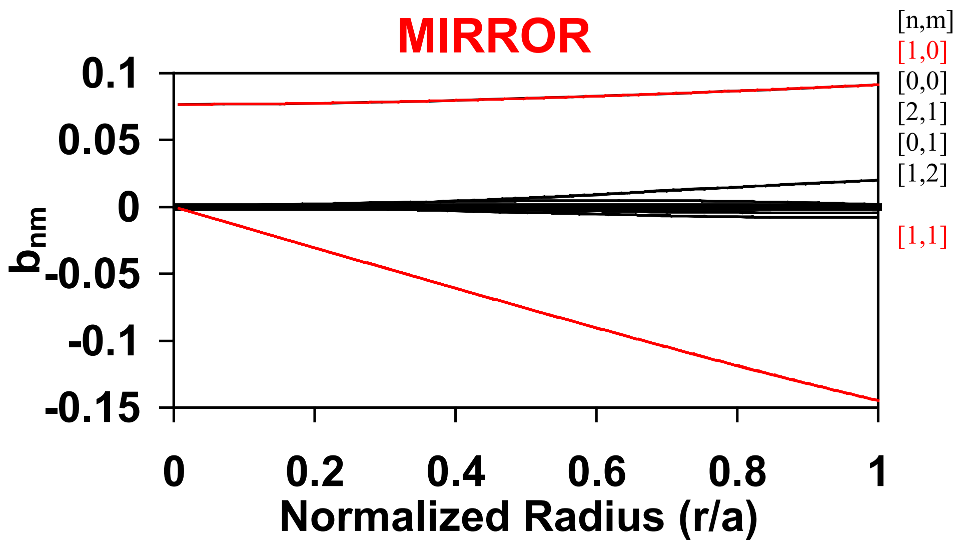
MAGNETIC FIELD SPECTRUM FOR QHS CONFIGURATION

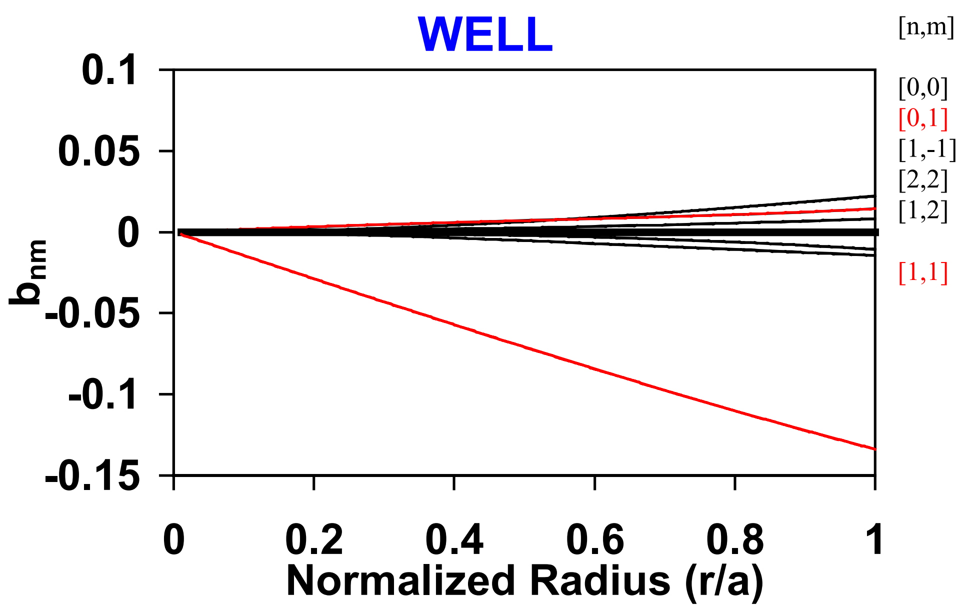


- Spectrum based on finite-size coil model
- Magnetic field spectrum given by: $\frac{B}{B_0} = \sum_{n,m} b_{nm} \cos(n\phi - m\theta)$,

  n = toroidal mode number in one field period
- Largest symmetry-breaking term is the [1,2] mode

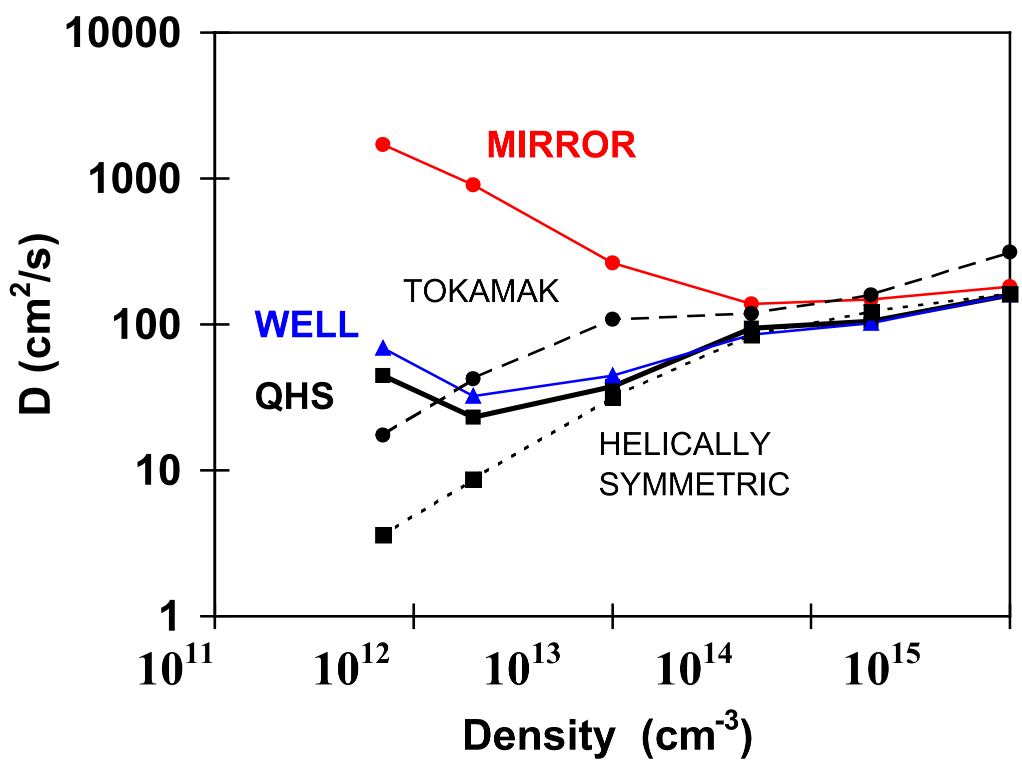
SPECTRUM WITH AUXILIARY COILS





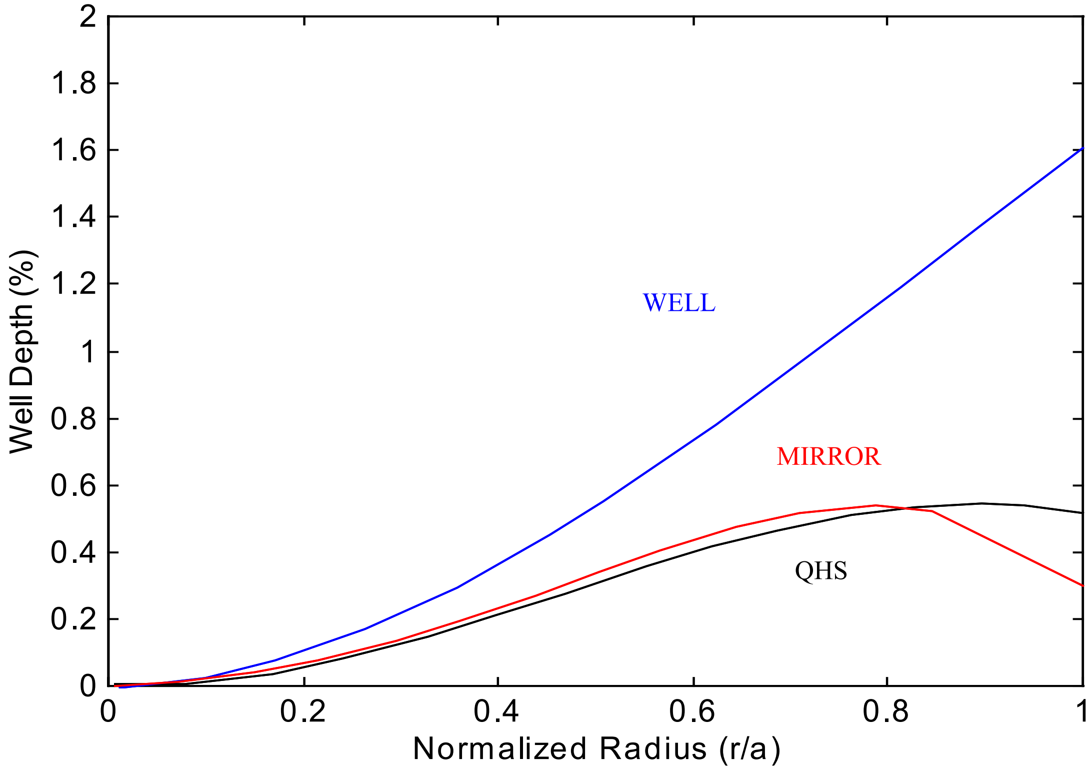
- Toroidal mirror mode [1,0] increases neoclassical transport for MIRROR
- Toroidal curvature mode [0,1] dominant symmetry- breaking component in WELL configuration

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

MAGNETIC WELL DEPTH



- **QHS** and MIRROR configurations have similar well depths (~.5%), with slight hill at edge

- WELL case has maximum well depth of 1.6% at plasma edge

SUMMARY OF STABILITY CALCULATIONS

- $\langle\beta\rangle$ limit for three configurations:

	MERCIER	BALLOONING
QHS	0.4%	0.7%
MIRROR	0.3%	0.6%
WELL	1.3%	1.7%

- **QHS** and MIRROR configurations have similar stability limits, with vastly different transport properties

- Significant increase in stability limit for WELL configuration compared to **QHS** with only marginal degradation of transport

The HSX Experimental Program

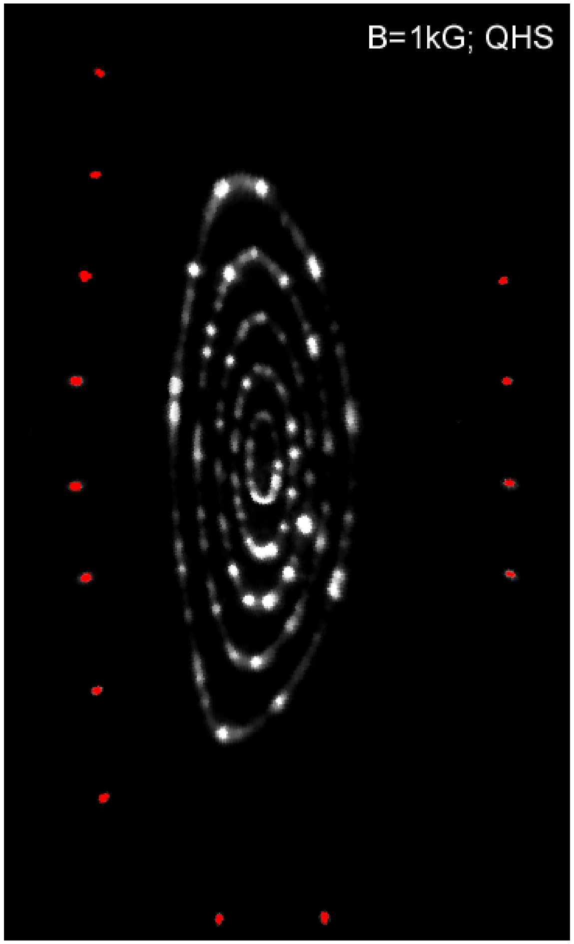
- **Electron beam mapping of the magnetic surface structure**

  -Search for evidence of unexpected island structure in the QHS configuration

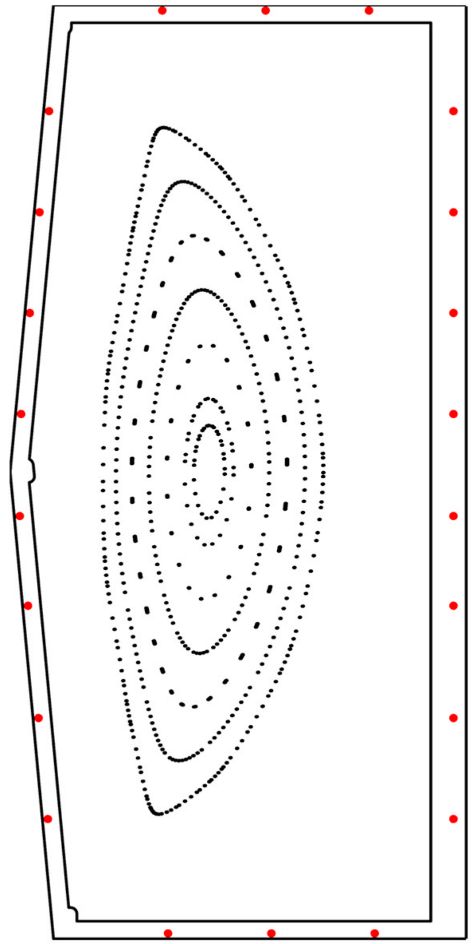
  -Map surfaces and transform profile for alternate configurations in HSX; especially Well and Mirror modes

  -Effects of materials-induced errors

Electron Beam Mapping of the Magnetic Surfaces in HSX



Calculated Surfaces



- **No evidence of island structures**
- **Rotational transform profile agrees with modeling to within 1%**

Measurement of reduced neoclassical transport: Drift surfaces, diffusion coefficient and parallel currents

-Measure reduced drifts of high-energy passing electrons with CCD

-Measure diffusion of electron or ion population in neutral gas; vary collisionality and look for evidence of $1/\nu$ regime in Mirror mode/reduced transport in QHS

-Measure Pfirsch-Schluter current with mini-Rogowski; verify helical nature and reduce magnitude by $| N - m\iota |$

Reduction of Direct Loss Orbits with Helical Symmetry

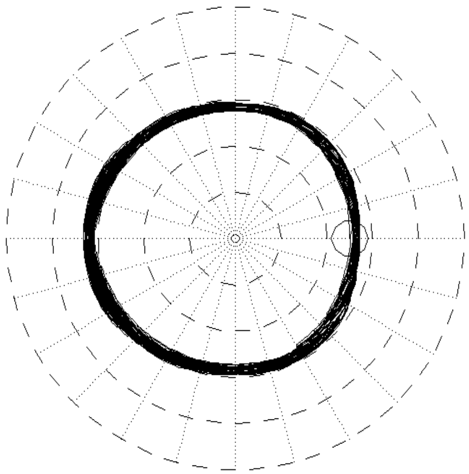
- **Measure confinement of injected high pitch angle electrons and dependence on magnetic geometry (Tohoku collaboration)**

- **Compare ECH plasma breakdown between QHS and mirror modes to look for significant increase in breakdown electron confinement**

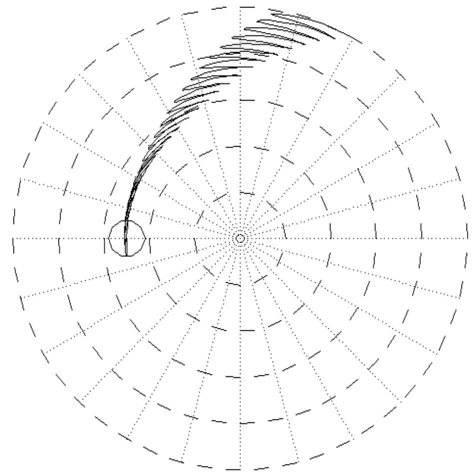
- **Measure dependence of S-X profile on the magnetic field strength for the QHS/Mirror modes of operation**

Control of Direct Orbit Losses with Magnetic Symmetry

Trapped Particle in HSX is well-confined



Particle is lost when symmetry is broken

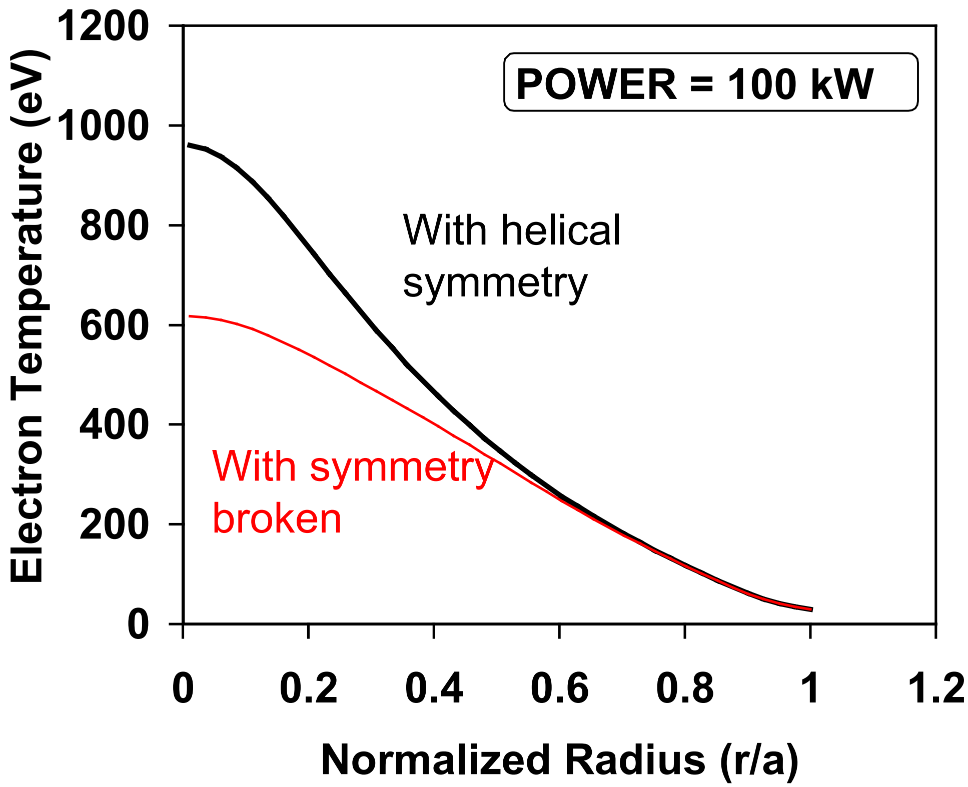


- **Particle confinement and direct orbit losses will be investigated in HSX with single particles and during ECH**
- **Auxiliary coils will be used to destroy helical symmetry and increase direct orbit losses to level of conventional stellarator**

Variation of Neoclassical Electron Thermal Conductivity

- **Increase to B=1.0T to provide sufficient confinement to push through to low collisionality regime**
- **Measure central electron temperature with and without auxiliary coils. Initial measurements using central point Thomson scattering and UC-Davis radiometer; implement full diagnostic set for profile information/power balance**
- **Begin assessment of anomalous transport levels for comparison with ISS95 and Lackner-Gotardi scaling**

Reduction of Neoclassical Transport



- Electron thermal conductivity modeled as a sum of neoclassical and anomalous
- Reduction of neoclassical thermal conductivity by 2-3 orders of magnitude due to helical symmetry should produce observable changes in the electron temperature profile

Radial Electric Field Measurements and Physics of Improved Confinement Modes

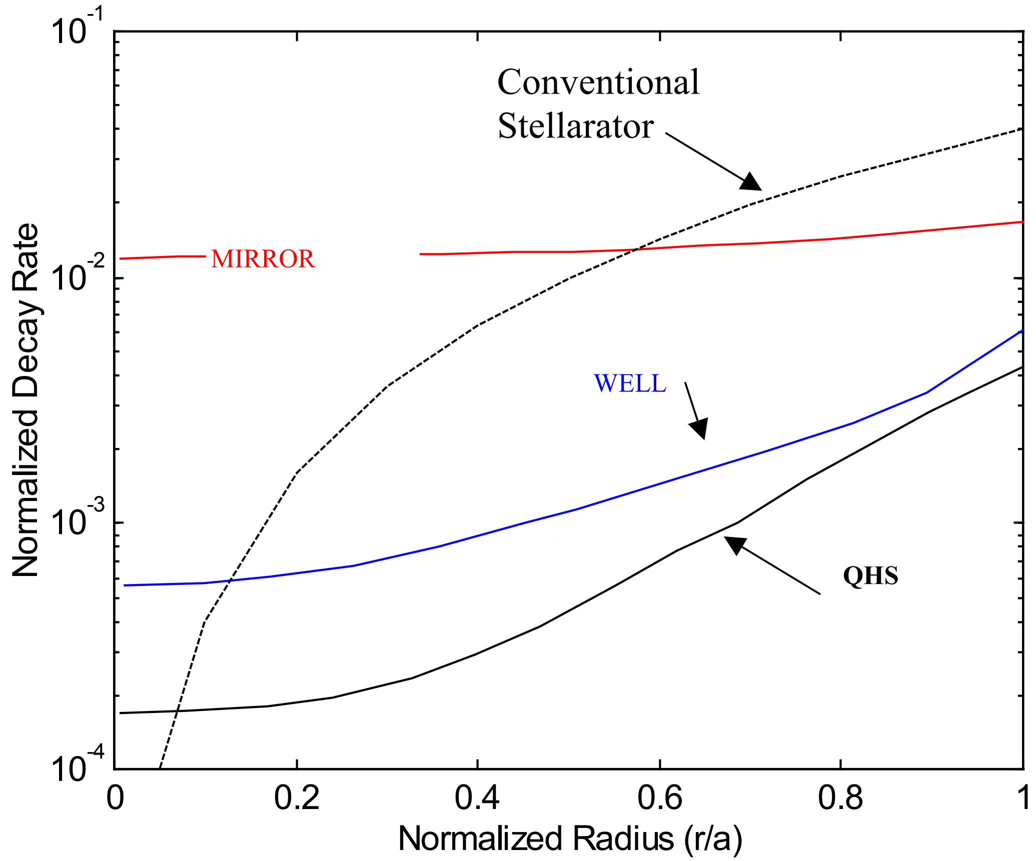
-Measure poloidal flow velocity in HSX as a function of minor radius (within limits of C-V detection)

-Examine poloidal flow as a function of spectrum and rotational transform; viscous damping

-Investigate appropriate models of electric field calculation for inclusion in ASTRA transport modeling

-Determine appropriate parameters of CHERS system for further detailed experiments

Comparison of Flow Damping Rates



- **Viscosity calculated in plateau regime**
- **QHS has smallest decay rate because of near axis of symmetry in helical direction**

Fluctuation-induced Transport in a Geometry with Only Helical Curvature

-Measure potential and density fluctuation in moderate parameter plasma using Langmuir probes; correlate mode numbers with transform and comparison to drift-wave models

-Examine fluctuation-induced transport as a function of location of good and bad curvature and magnetic well depth

-As B increased to 1.0T need to rely increasingly on nonintrusive diagnostics (collaborations)

Diagnostics

5-chord interferometer system (UCLA) installed and operational; will expand to 9-chord with new higher-power source

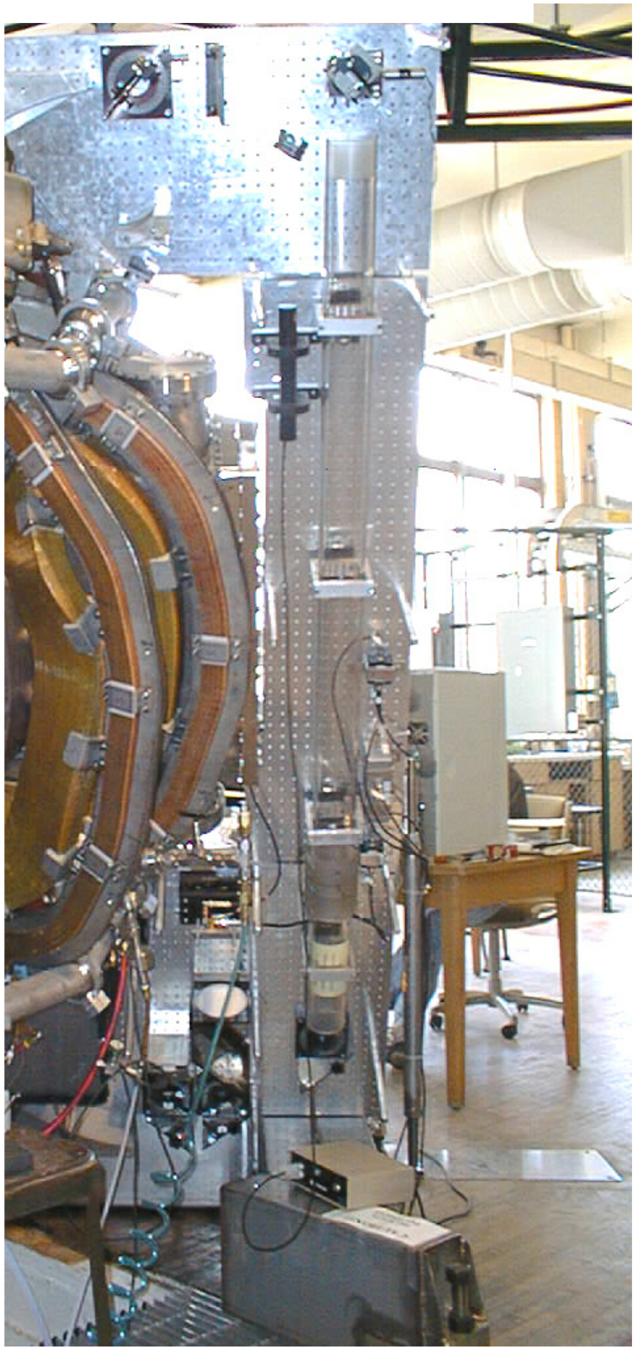
=>

Ready to Install at next major vent:

- **Single channel ECE system for B=0.5T operation (UC-Davis)**
- **Bolometer**
- **Diamagnetic loop**
- **H-α monitors**
- **1-m spectrometer**
- **T_{eo} S-X**
- **S-X array**

Under development:

- **10 channel Nd:YAG filter polychromator Thomson system (MST,GA); operational status next fiscal year**
- **2-D ECEI system for B= 1.0T operation to be implemented by UC-Davis**



Thomson Scattering System; Based on GA divertor Thomson System

-Commercial Nd:YAG based with 4 channel filter polychrometer detectors

-Central electron temperatures to 2 keV; ability to resolve <50 eV

-Electron densities 2 x 10^{12} cm^{-3} to ~1 x 10^{13} cm^{-3}

-Full frontal area of boxport available for collection optics

-Laser purchase order has been let; GA is fabricating 10 polychrometers; deliveries starting late fall 1999

The Role of HSX in the National (and World) Stellarator Program

- HSX will be the first experimental test of highly-optimized stellarators designed to reduce neoclassical transport to very low levels

- Through its flexibility, HSX can elucidate the level to which neoclassical transport should be lowered at the expense of other constraints for future stellarator design efforts

- HSX is the only device under construction or design which possesses a high effective rotational transform, | N – m□ | ~ 3

  - Small equilibrium currents
  - Small banana widths of high-energy trapped particles
  - Lower neoclassical and anomalous transport as predicted by scaling laws

- HSX can span the space between having a large plasma flow in the direction of symmetry contribute to the radial electric field or a non-intrinsically ambipolar field with broken symmetry for quenching anomalous transport

HSX is a unique device in the world-wide program for providing critical physics results key to evaluation of the stellarator concept

HSX Has Reached Operational Status!

Core Device Assembly Complete

- First discharge cleaning plasma produced August 31, 1999 with 1 kW 2.45 GHz ECH
- Magnetic surface mapping experiments have begun; rotational transform agreement to ~1%; no islands

Device commissioning and installation of diagnostics in progress for physics program

- Magnets tested with MG to 2 kG; going to B=0.5 T
- Gyrotron in socket; transmission line near complete

HSX is the First of a New Generation of Advanced Stellarators