The Helically Symmetric Experiment

- Combination of toroidal and helical curvature in a stellarator is bad for confinement of trapped particles

- In HSX, the toroidal curvature is reduced $\Rightarrow$ Equivalent to an aspect ratio of 400 in a device with A ~ 8.

  - Quasihelical $\Rightarrow$ Although 3-D, there is a symmetry in the magnitude of B : $B = B_0\left[1 - \varepsilon_h \cos\left(N\phi - m\theta\right)\right]$

  - In a straight field line coordinate system $\theta = \iota\phi$

$$B = B_0\left[1 - \varepsilon_h \cos\left(N - m\iota\right)\phi\right]$$

$\Rightarrow$ Equivalent to a tokamak with transform given by $N - m\iota$.

  - In HSX: N = 4, m=1 and $\iota \sim 1$ the effective transform is approximately 3.

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

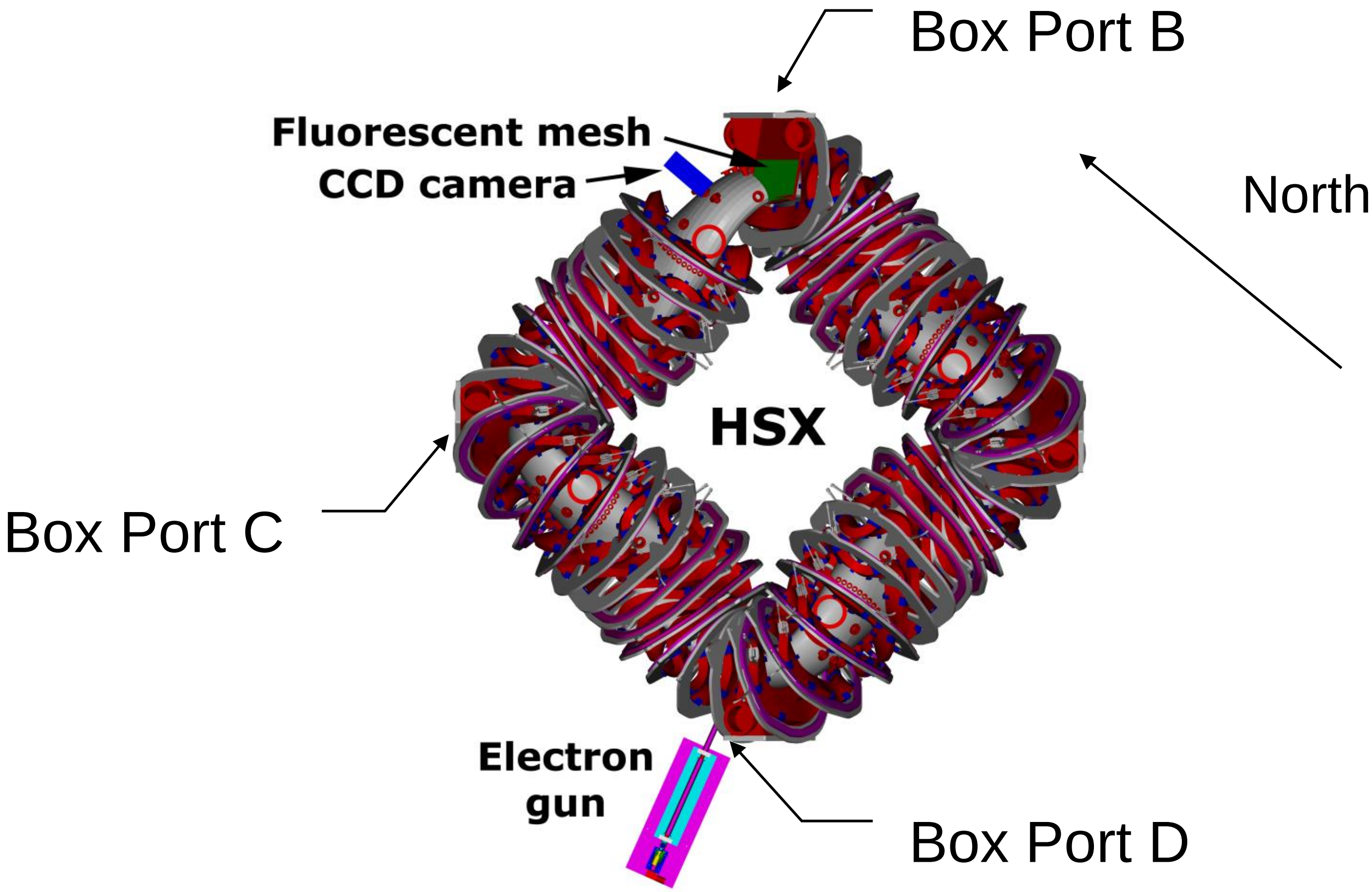
- Low Neoclassical Transport
  - Small deviations from magnetic surfaces, small banana widths
  - Minimal direct loss particles, reduction in '$1/\upsilon$' transport, very small neoclassical thermal conductivity

- 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

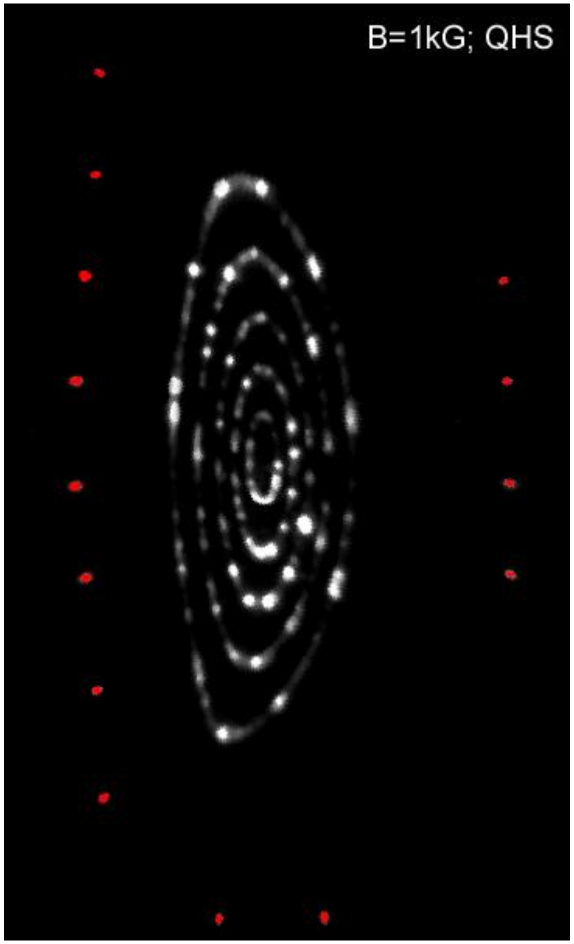
- Lower anomalous transport ?
  - L-2 experimental results $\chi_{e,anom} \propto 1/\iota$

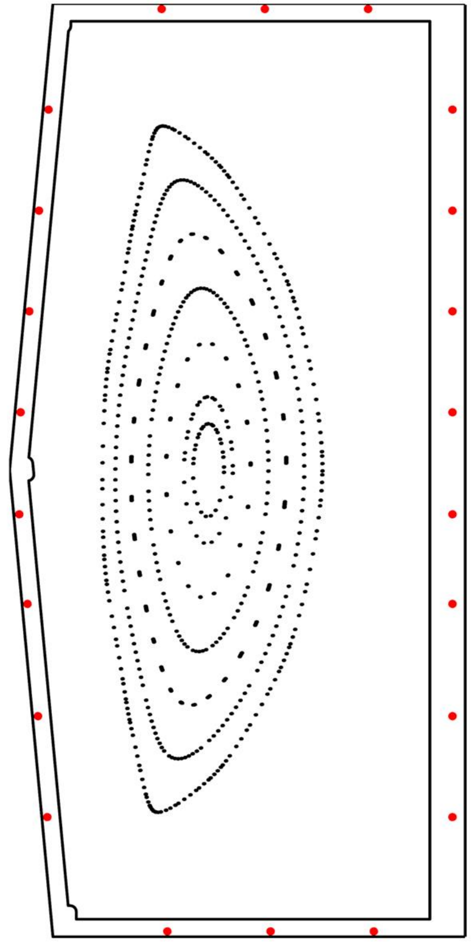
Surface Mapping and Drift Orbits at 3 Ports



- Fluorescent mesh located at three different box ports, spaced 90^0 apart; electron gun was held at fixed position toroidally.

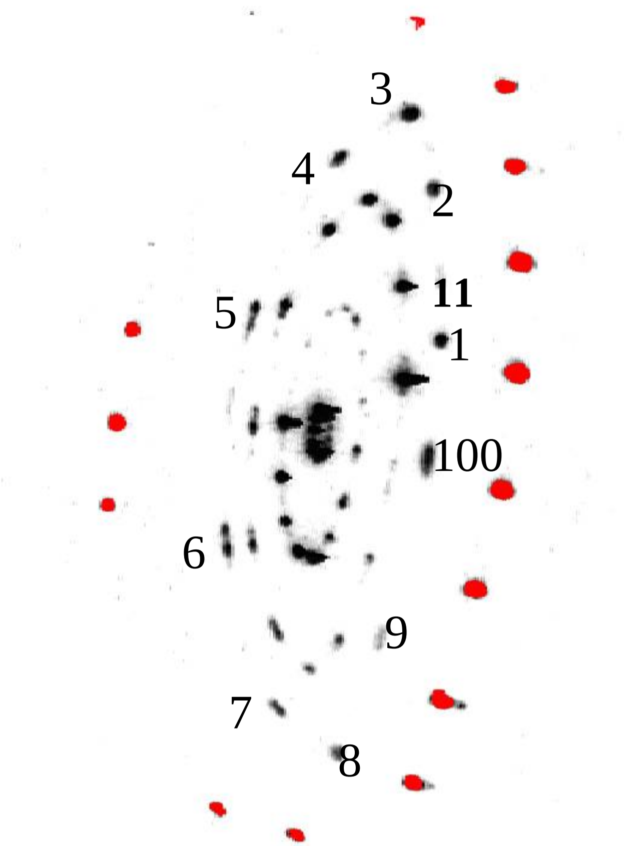
Experimental and Calculated Magnetic Surfaces

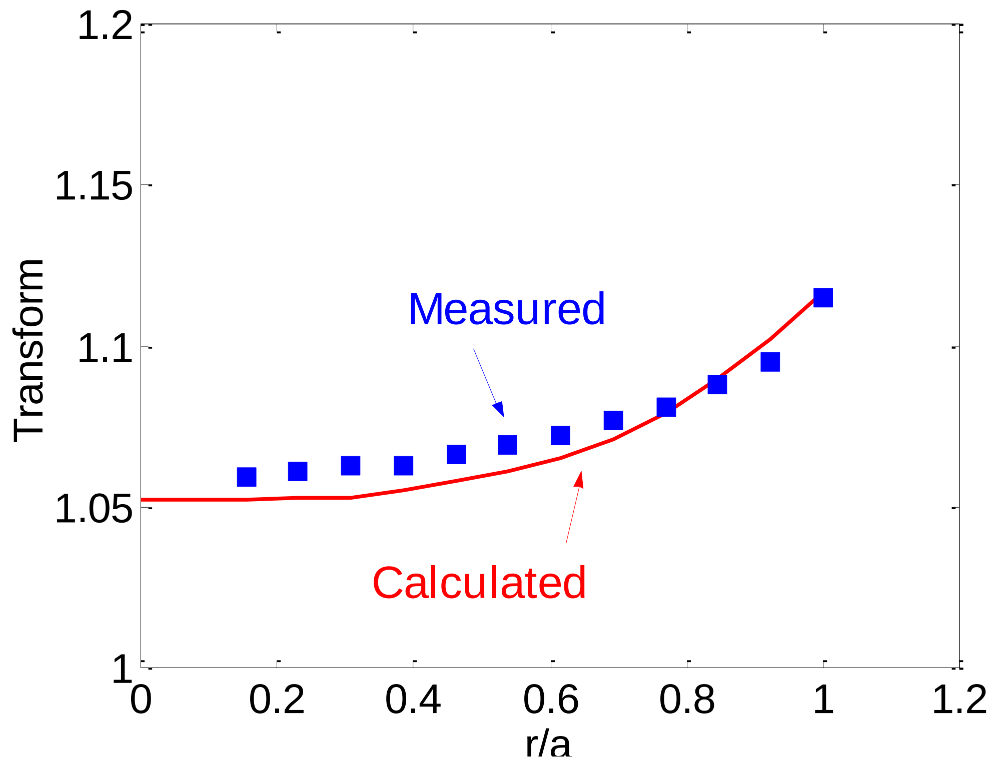




Rotational Transform

- Experimental rotational transform agrees with calculated values to within 1%





How Can We Confirm Quasihelical Nature of HSX?

- HSX is the first stellarator constructed to have a specific magnetic field spectrum $\Rightarrow$ quasihelically symmetric field has low neoclassical transport

- World-wide effort now to construct stellarators with other properties: quasi-axisymmetric, quasi-omnigeneous, improved stability properties etc.

- Desirable to find method for advanced stellarators to confirm expected magnetic field spectrum.

- Goal for HSX is two-fold:

    - Confirm absence of toroidal curvature.
    - Demonstrate that drift excursions from flux surface are very small due to very high effective transform

Guiding Center Equations for Passing Particles

For particles with $v_\perp = 0$ and a magnetic configuration with no toroidal current, the guiding center equations in Boozer coordinates are given by the following set of equations:

$$B_0 r \frac{dr}{dt} = -\frac{Mv_\parallel^{\,2}}{eB}\frac{dB}{d\theta},$$

$$\frac{d\theta}{dt} = \frac{\iota B v_\parallel}{g} + \frac{Mv_\parallel^{\,2}}{eB}\frac{1}{B_0 r}\frac{dB}{dr}, \qquad (1)$$

$$\frac{d\phi}{dt} = \frac{B v_\parallel}{g}.$$

M = particle mass

$v_\parallel$ = parallel velocity

g = poloidal current outside a flux surface

r = flux surface variable given by $r = (\psi/\pi B_0)^{1/2}$

(ψ is the toroidal flux and B_0 is the field at the magnetic axis).

Passing Particle Orbits Contain Information about m $\neq$ 0 Spectral Components of B

- In Boozer straight field line coordinate system magnetic spectrum given by

$$\frac{B}{B_0} = \sum_{n,m} b_{nm} \cos(n\phi - m\theta)$$

where n = toroidal mode number, m = poloidal mode number

- For small orbit shifts from flux surface, assume b_{nm} and ι do not depend on the radial flux coordinate. Also ignore dB/dr term:

$$r^2 = r_0^2 + \frac{2Mv_\parallel g}{eB_0^2} \sum b_{nm} \frac{m}{n - m\iota} \left[\cos(n\phi - m\theta) - a_{nm}\right] \qquad (2)$$

$a_{nm} = \cos(n\phi_0 - m\theta_0)$ to satisfy initial conditions, $r = r_0$, $\theta = \theta_0$, $\phi = \phi_0$

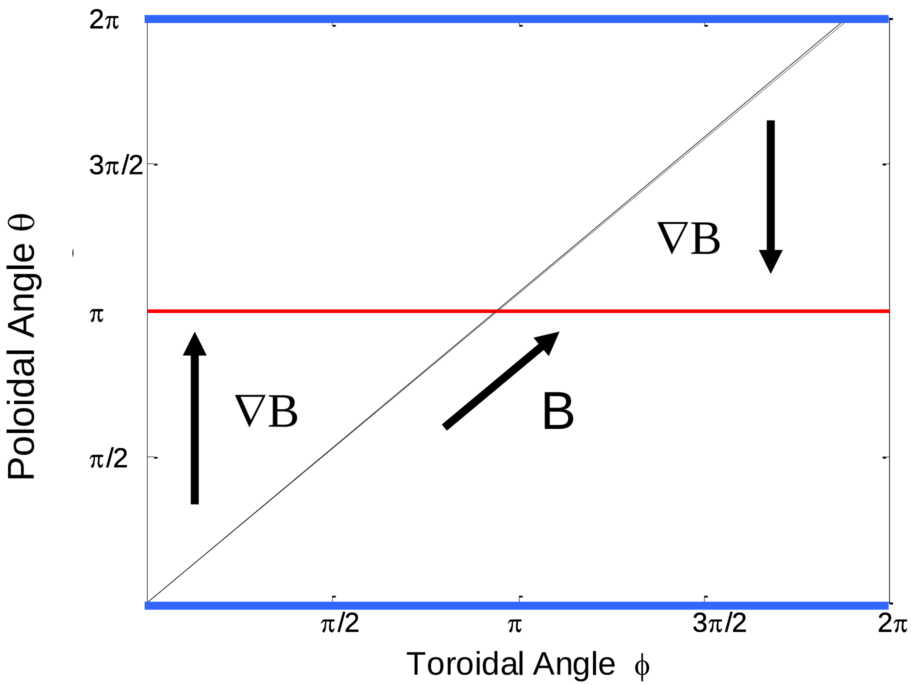
Drifts are Smaller in HSX Than a Tokamak

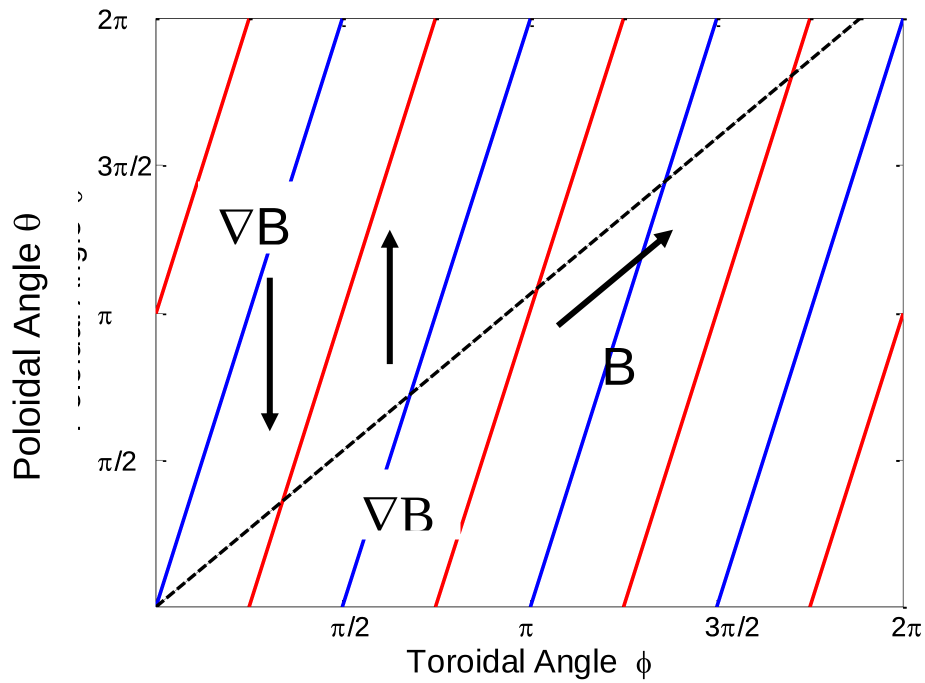
Tokamak with n=0, m=1

$$\delta r \propto -\frac{b_{01}}{\iota}[\cos\theta - a_{01}]$$

HSX with n =4, m=1

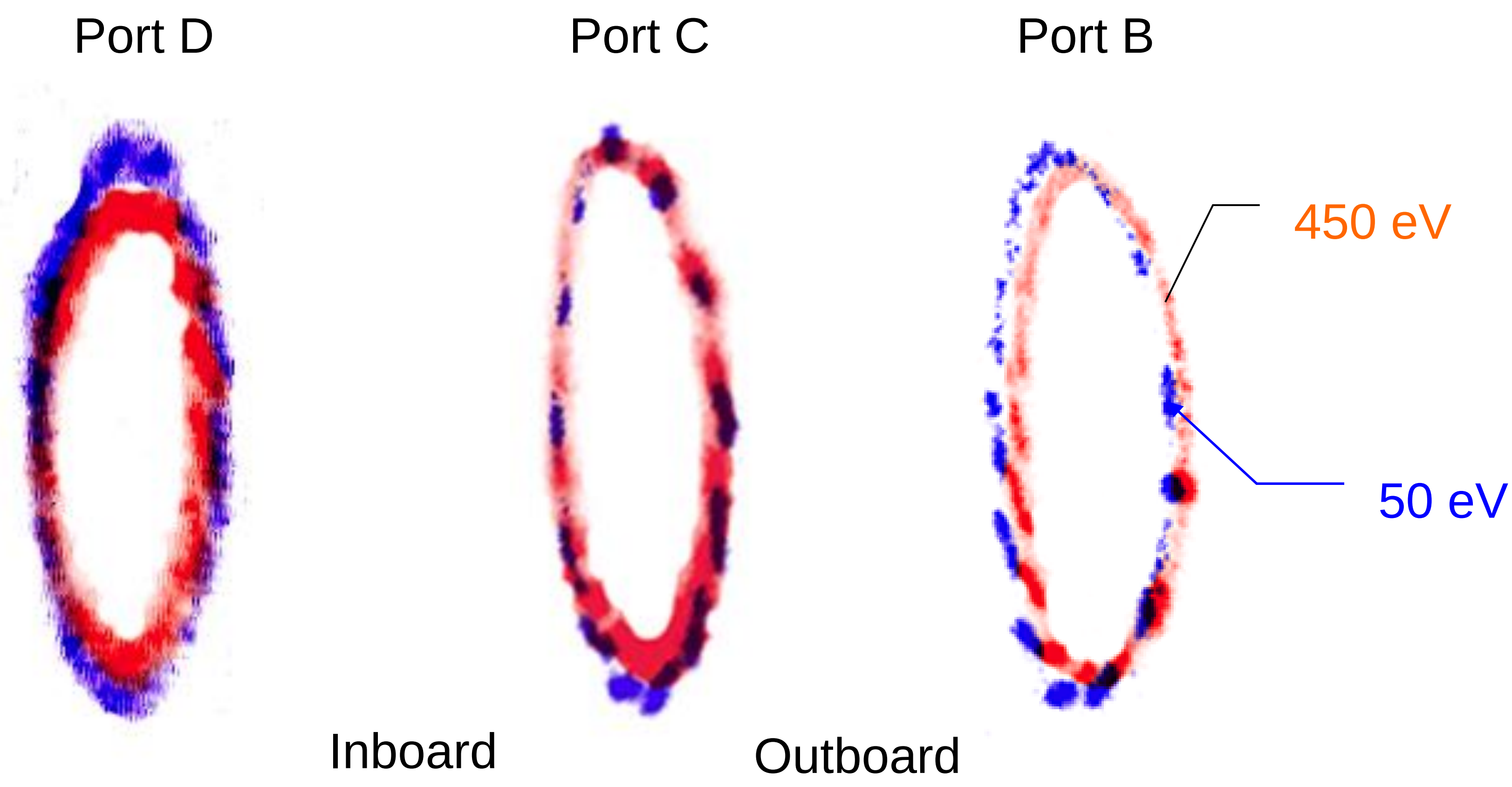
$$\delta r \propto \frac{b_{41}}{4-\iota}[\cos(4\phi-\theta) - a_{41}]$$





- Drift of a particle in HSX is in opposite direction to a tokamak if both particles are started at $\phi = 0$.

Passing Orbits at 3 Box Ports



- Comparison of high energy orbits (450 eV) to low energy (50 eV) at 3 box ports separated by 90^0 in the toroidal direction.
- Port D is almost at the same location as the electron gun.

The Boozer Coordinate System

- To determine the magnetic field spectrum from the high energy orbits the data must be mapped to the Boozer coordinate system [1].

- In the Boozer representation for a curl-free field,

$$B = \nabla \psi \times \nabla \theta_0 \quad \text{contravariant representation}$$
$$B = \nabla \chi \quad \text{covariant representation}$$

A point in space is located by the coordinate ψ a flux surface label, θ_0 an angle which labels the field line and $\chi = \int B dl$ which is related to distance along field line.

- The Boozer poloidal and toroidal angle are then given by,

$$\chi = g(\psi)\phi + I(\psi)\theta,$$
$$\theta_0 = \theta - \iota\phi.$$

where I(ψ) is the toroidal current inside a surface $\Rightarrow$ 0 for HSX.

[1] Boozer, A.H., Phys. Fluids 23 (1980) 904.

Mapping to Boozer Space

- The low-energy electrons map out the Boozer space:

  - ϕ**:** A numerical calculation shows that for HSX, $\phi = \frac{1}{g}\int Bdl$ is within a few degrees of the cylindrical angle ϕ_L, therefore we use this as the Boozer toroidal angle.

  - θ: The rotational transform $\iota(\psi)$ is calculated based on the data. Identify N successive passes on a surface, then $\iota_N = \Delta\theta_L / \Delta\phi_L$ where $\Delta\theta_L$ and $\Delta\phi_L$ are the total poloidal and toroidal angle the beam has traversed in lab frame. $\iota(\psi) = \iota_N$ as N is extrapolated to ∞. For each successive pass, $\theta = \iota\phi$ determines the Boozer poloidal angle.

  - r: Instead of the toroidal flux, where $r = (\psi/\pi B_0)^{1/2}$, $r = (A/\pi B_0)^{1/2}$ we use the area enclosed by the flux surface at 1 toroidal location. This same value is used for all the surfaces at other ports that correspond to the same gun location.

Neural Network is used to Generalize the Mapping

- Data from 4 surfaces generated by the low-energy electrons, about 13 points on each surface, are used to develop a map between x,y coordinates of fluorescent mesh and the Boozer coordinates ψ and θ (lab coordinate used for ϕ).

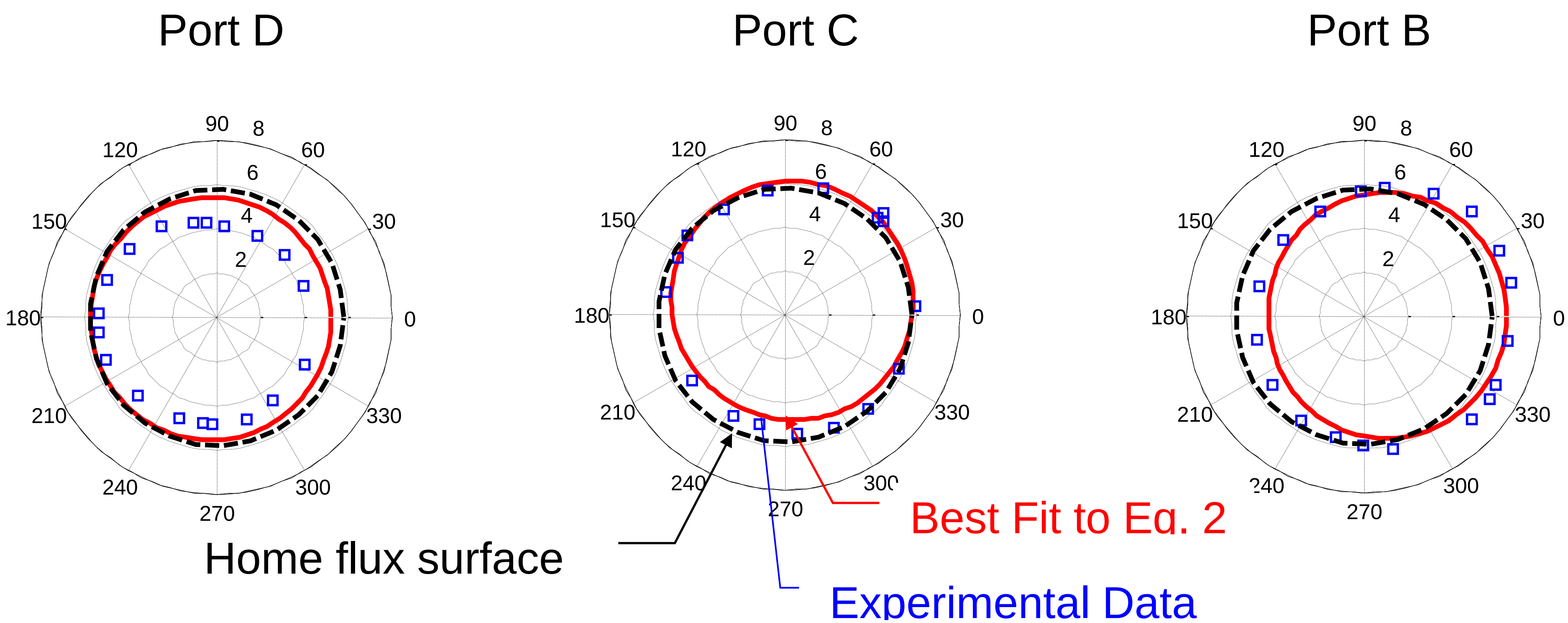
- To overcome difficulty in mapping across jump at $0/2\pi$ interface, outboard side of surface mapped from $-\pi$ to π, inboard side mapped from 0 to 2π.

- A neural network is then trained in the coordinate transformation. Network is standard multilayer perceptron with 1 hidden layer [2].

- A set of 2 surfaces is used to test the neural network and verify that the mapping has not been over fitted.

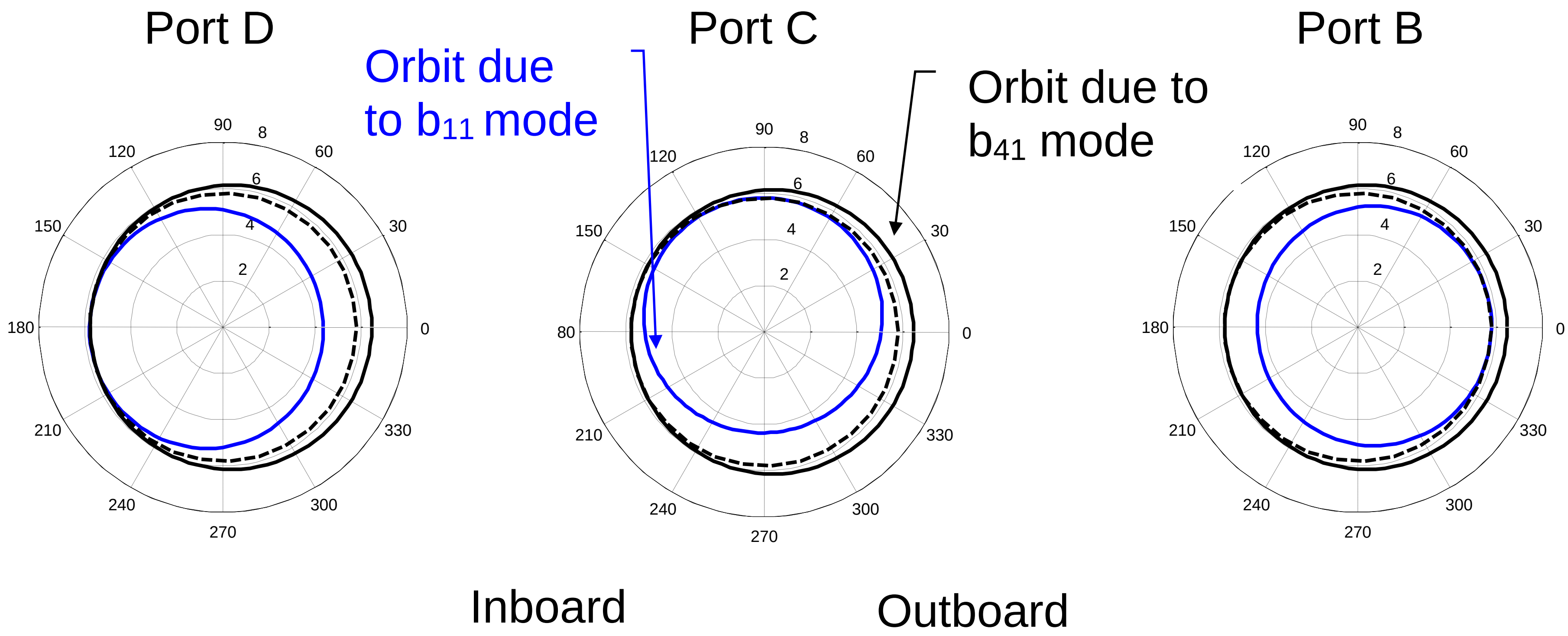
[2] Neural Network Toolbox, distributed by The Math Works Inc., Natick, MA.

Transformed Data and Best Fit



- High-energy orbit is transformed to Boozer coordinates with the neural network.
- Simultaneous linear equations yield $b_{41} = -0.051$ and $b_{11} = 0.0023$.

Sum of Two Spectral Components Determine Orbit



- Due to symmetric placement of fluorescent mesh, the orbit due to the b_{41} term is the same for all 3 box ports. Orbit due to b_{11} term rotates by 90^0 from D to C and C to B.
- At Port B, the orbits due to b_{11} and b_{41} are out of phase so that shift on outboard is due to b_{41} and shift on inboard side is due to b_{11}.

Extrapolation of Boozer Mapping for Zero Energy Particle and Comparison to Numerical Calculation

- Experimental results are an underestimate of the spectral components because of finite energy of particles used for mapping to Boozer coordinates. Correcting home flux surface for zero energy particle, rather than 50 eV, yields $b_{41} = -0.077$ and $b_{11} = 0.0034$

- At nominal 1 T magnetic field, all symmetry-breaking terms are less than 1% at the plasma edge. At 90 gauss, model earth's field [3] perturbs quasihelical spectrum.

- Agreement with data does not reflect errors in the measurements. Phase of b_{11} mode off by 45^0 compared to data.

Mode Numbers (n,m)	Amplitude
(4,1)	-0.07262
(3,0)	0.02524
(4,0)	-0.01182
(1,1)	0.003559
(4,2)	-0.002754

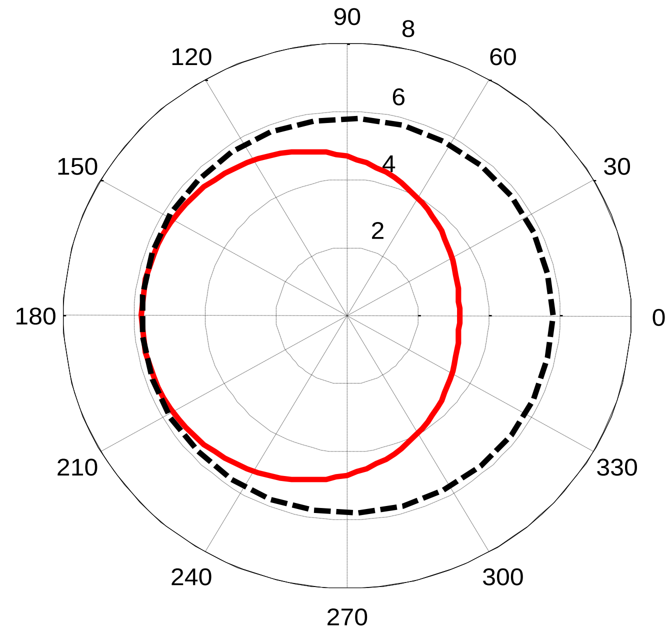
- This technique cannot be used to observe (3,0) and (4,0) modes.

[3] Geomagix, written by John Quinn of the US Geological Survey, distributed by Interpex Limited of Golden, Colorado, USA., http://geomag.usgs.gov/Freeware/geomagix.htm.

Conclusions

- Placement of the fluorescent mesh in 3 ports located 90^0 apart does not allow for unambiguous measurement of toroidal curvature b_{01}.

- However, data does not show standard toroidal curvature that exists in other devices (low field on outboard side). Passing particle with only toroidal curvature would be shifted interior to home flux surface on outboard side (b_{01} = -0.051 for figure to right), contrary to data at Port B



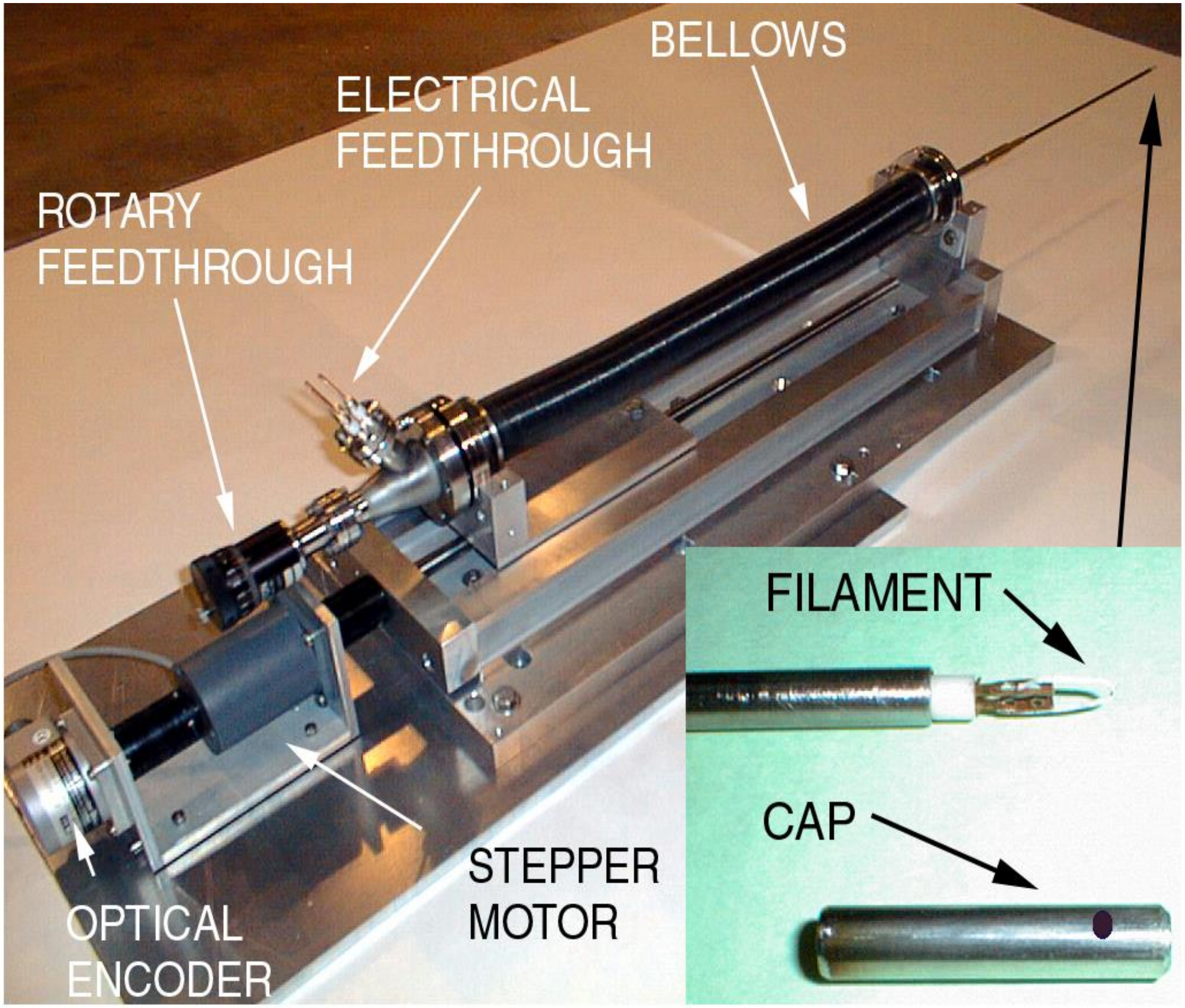
- Displacement of orbit due to b_{41} mode is about 3 times smaller compared to b_{01} term because of $n - m\iota$ factor.

- First demonstration of transport-optimized properties of quasihelical stellarator

Abstract

HSX is a toroidal quasihelically-symmetric stellarator with negligibly small toroidal curvature. Vacuum magnetic surfaces at 1 kG are measured using low-energy electron beams that strike a fluorescent mesh. The images are recorded with a CCD camera and show no observable evidence of island structures inside the separatrix. The experimental determination of the rotational transform agrees with numerical calculations to within 1%. A simple analytic expression is derived in Boozer coordinates to relate the drift orbits of passing particles to the magnetic field spectrum. This expression is used to analyze images of high-energy electron orbits in HSX, using a neural network to map the lab coordinate system into Boozer coordinates. At very low magnetic field strengths (90 G) where the b_{11} component due to the earth's field is not ignorable, this spectral component and the dominant helical term b_{41} can be experimentally determined. The data does not show the magnitude and direction of the orbit shift that would be expected from the standard toroidal curvature term that exists in other toroidal devices. The results also confirm for the first time that quasihelical stellarators have a large effective transform that is responsible for small drifts of particles off a flux surface.

Electron Gun



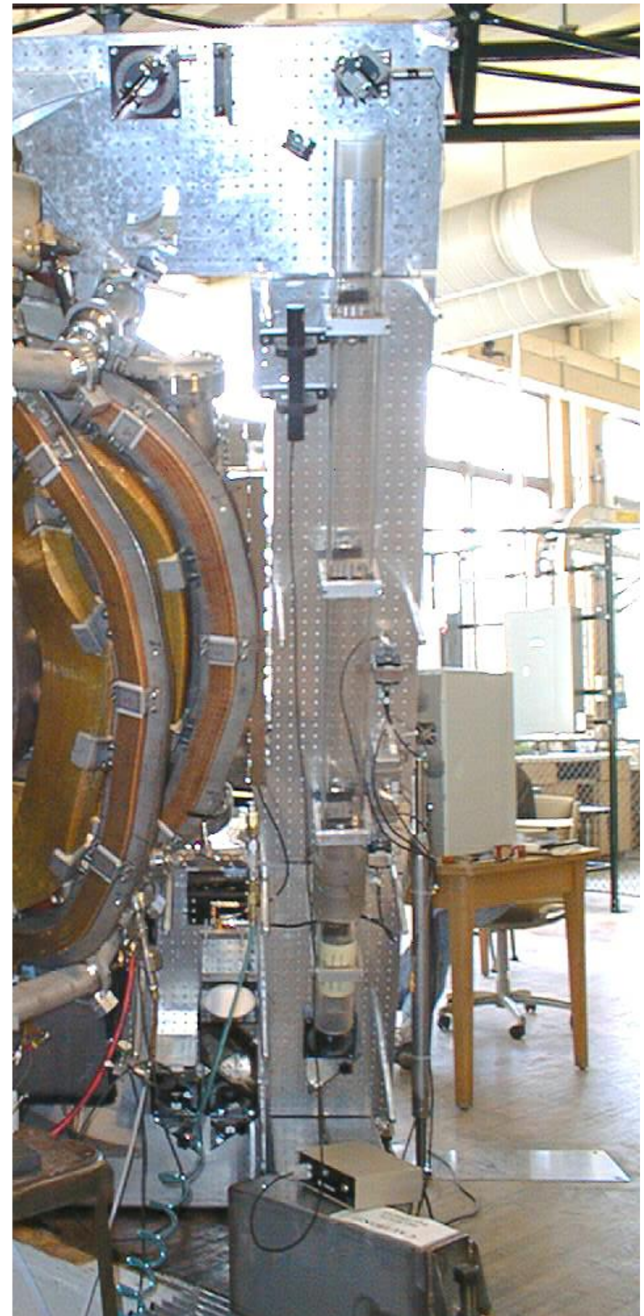
Diagnostics

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

- **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**
- **Single channel ECE system for B=0.5T operation (in progress) (UC-Davis)**
- **2-D ECEI system for B= 1.0T operation to be implemented by UC-Davis**



Near-Term Experimental Program

- Heat electrons with ECRH to collisionless regime with 28 GHz gyrotron. In this regime, neoclassical transport in HSX is vastly improved over conventional stellarators.
  - Does T_e or τ_e improve with quasihelical symmetry?

- Use auxiliary coil set to break symmetry. Direct orbit losses and neoclassical electron thermal conductivity both increase dramatically.
  - Does the ECH breakdown time change with symmetry present due to improved confinement of trapped particles?
  - Do soft X-ray profiles and energy spectra show changes with B-field variation and magnetic field spectrum?
  - How does the density profile change? Are hollow density profiles, usually observed in stellarators during ECH, due to off-diagonal terms ($\Gamma \propto \nabla T_e$) or direct orbit losses?

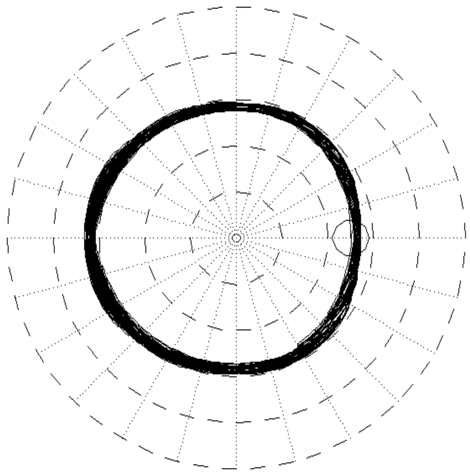
- Vary viscous damping rates by manipulating magnetic field spectrum and measuring plasma flows and electric fields.
  - Does small flow damping in helical direction improve prospects for decreasing anomalous transport?

Summary

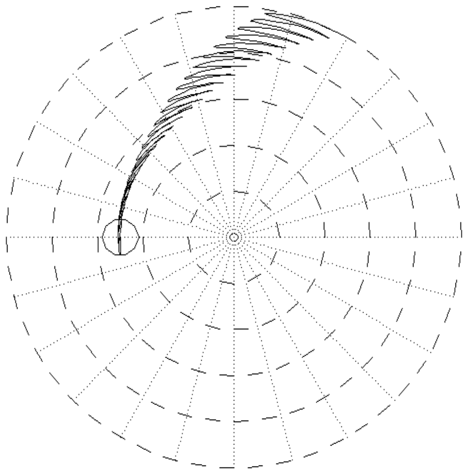
- Magnetic surfaces have been mapped in HSX showing no evidence of islands.
- Rotational transform within 1% of design value.
- A method has been developed to measure m $\neq$ 0 spectral content of the magnetic field. Drift due to toroidal curvature is not observed.
- The predicted $n - m\iota$ reduction in drifts off flux surfaces has been observed.
- First plasma achieved using 28 GHz gyrotron. Experimental focus now turns to whether quasihelical symmetry improves confinement in stellarators.

Control of Direct Orbit Losses with Magnetic Symmetry

Trapped Particle in HSX is well-confined

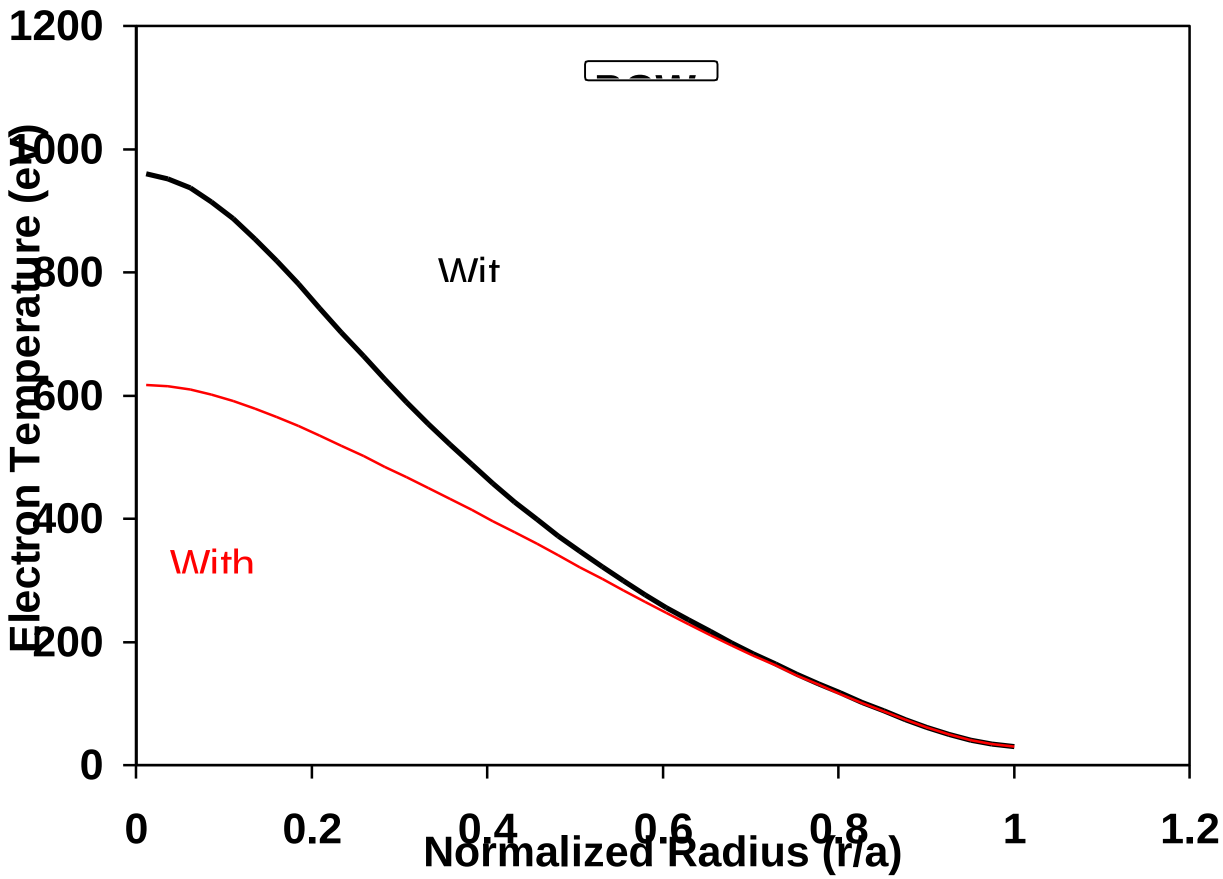


Particle is lost when symmetry is broken



- 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.

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.

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)	1.25 T
Magnet Pulse Length (full field)	$\leq$ 0.2 s
Auxiliary Coils (total)	48

28 GHz gyrotron	200 kW
Power Density	.45 W/cm^3
Density (cut-off)	1×10^{13} cm^{-3}
T_{eo} (100 kW absorbed)	1000 eV
τ_E	2-5 ms
υ_e^*	$\leq$ 0.1