Measurements of Magnetic Surfaces and Particle Orbits in HSX

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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 ⇒ Equivalent to an aspect ratio of 400 in a device with A ~ 8.

  - Quasihelical ⇒ Although 3-D, there is a symmetry in the magnitude of B : $B = B_0\left[1 - e_h \cos\left(Nf - mq\right)\right]$

  - In a straight field line coordinate system $q = \bar{\iota} f$

$$B = B_0\left[1 - e_h \cos\left(N - m\bar{\iota}\right)f\right]$$

  ⇒ Equivalent to a tokamak with transform given by $N - m\bar{\iota}$.

  - In HSX: N = 4, m=1 and $\bar{\iota} \sim 1$ 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 '$1/u$' transport, very small neoclassical thermal conductivity

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

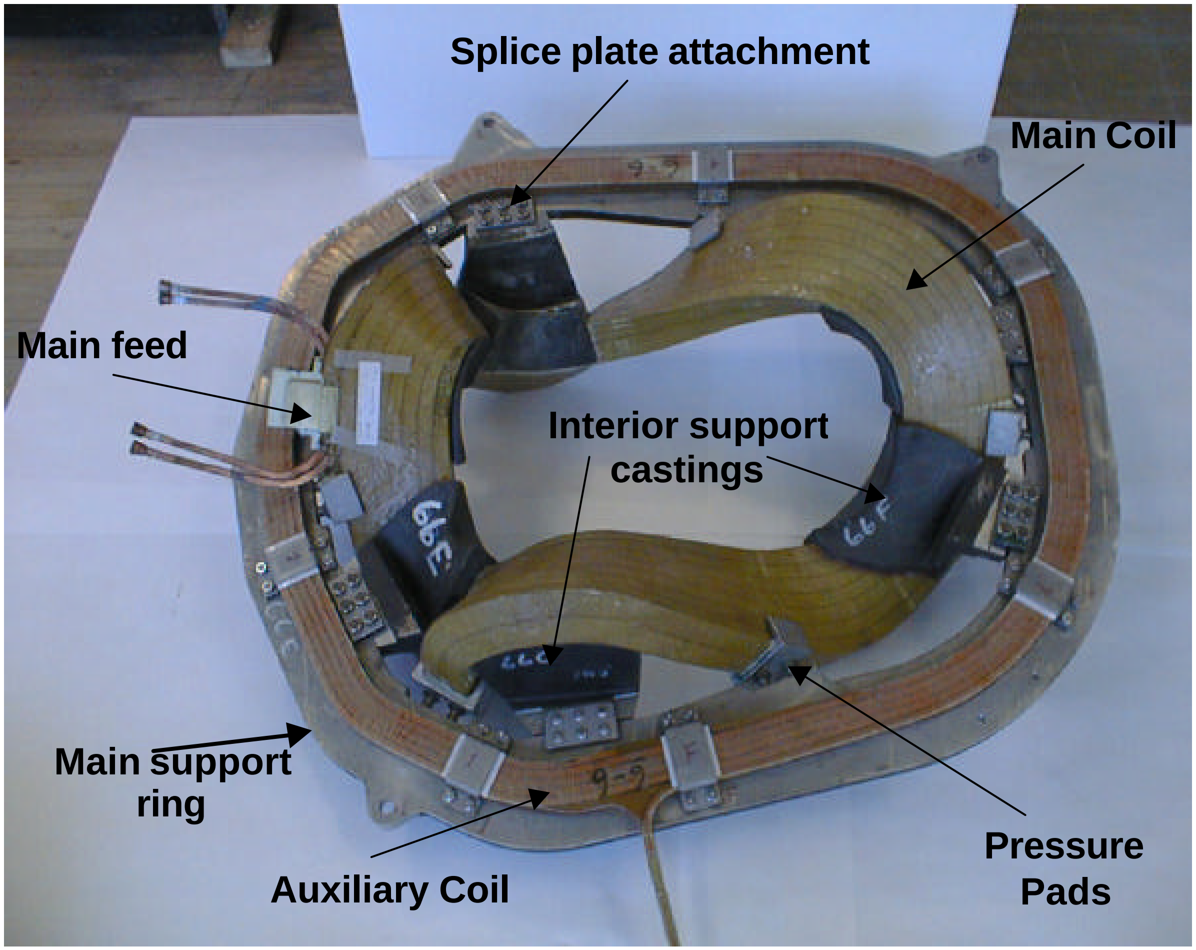
- Low parallel viscosity in the direction of symmetry
  - Possibility of high E x B shear to reduce turbulence

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

Near-Term Experimental Program

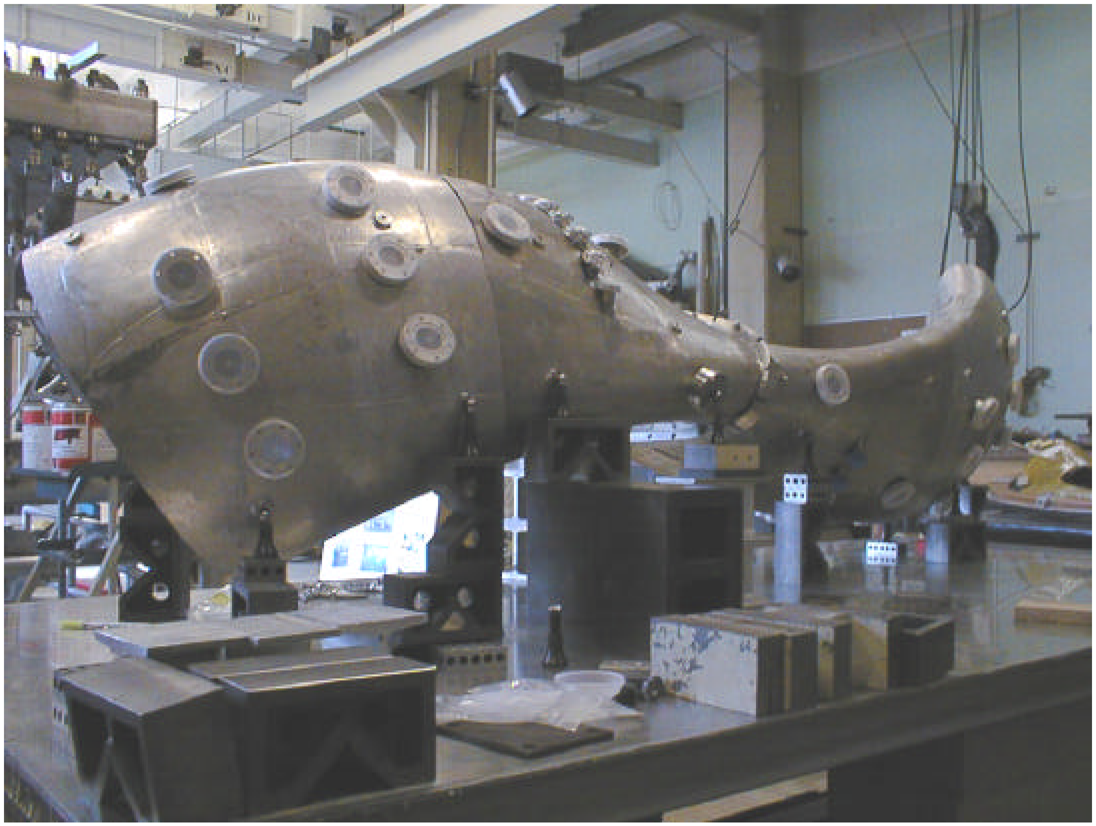
- Explore drift orbits of passing and trapped particles
- Heat electrons with ECRH to collisionless regime (28 GHz gyrotron)
- Use auxiliary coil set to break symmetry
- Vary viscous damping rates by manipulating magnetic field spectrum and measuring plasma flows and electric fields
- Measure Pfirsch-Schlüter and bootstrap currents

Quasi-Helical Field in HSX Produced by 48 Modular Coils

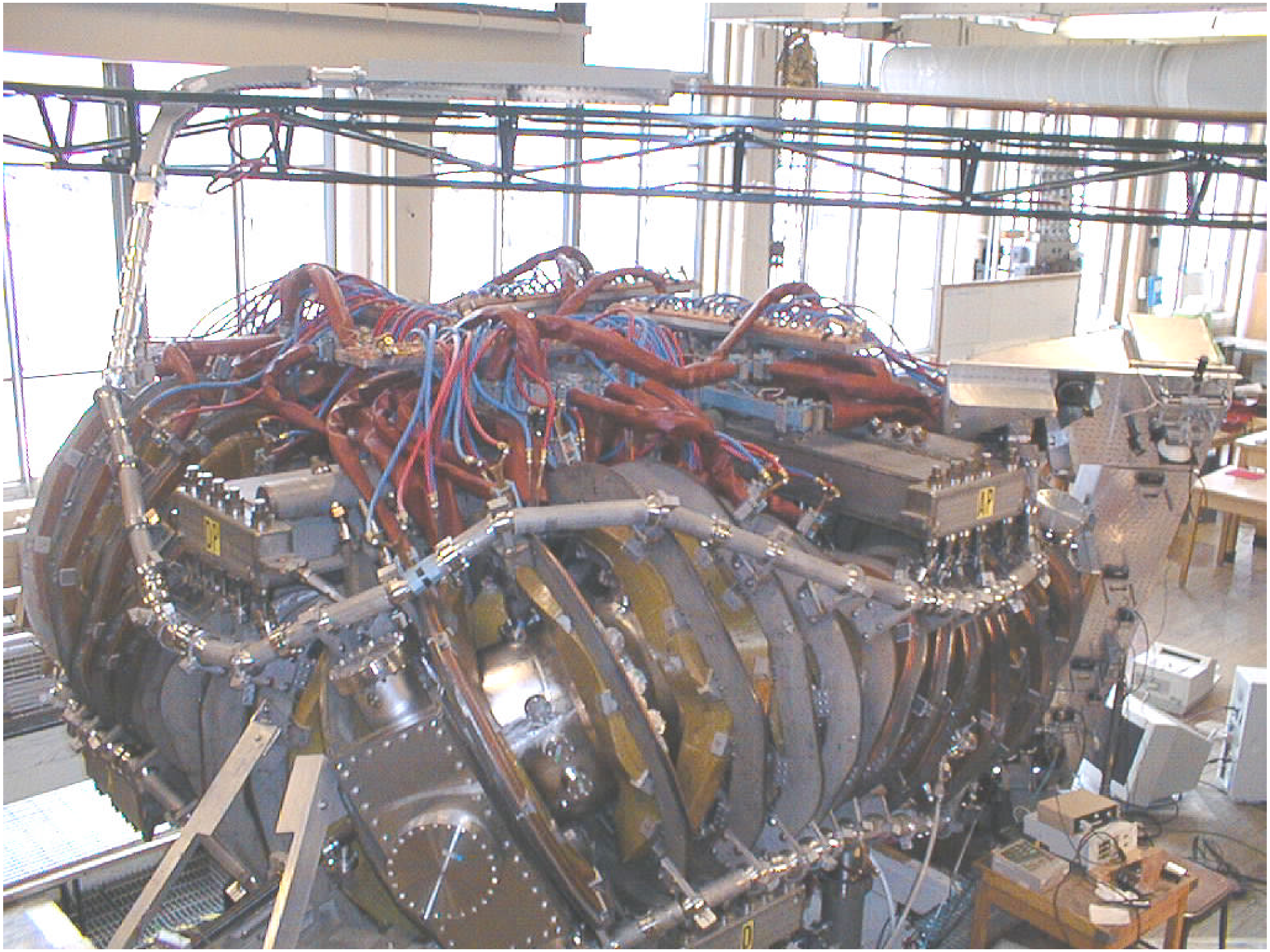


- 6 different types of main coils
- Auxiliary coils mounted with modular coils to support ring
- All the coils were built in the HSX Laboratory

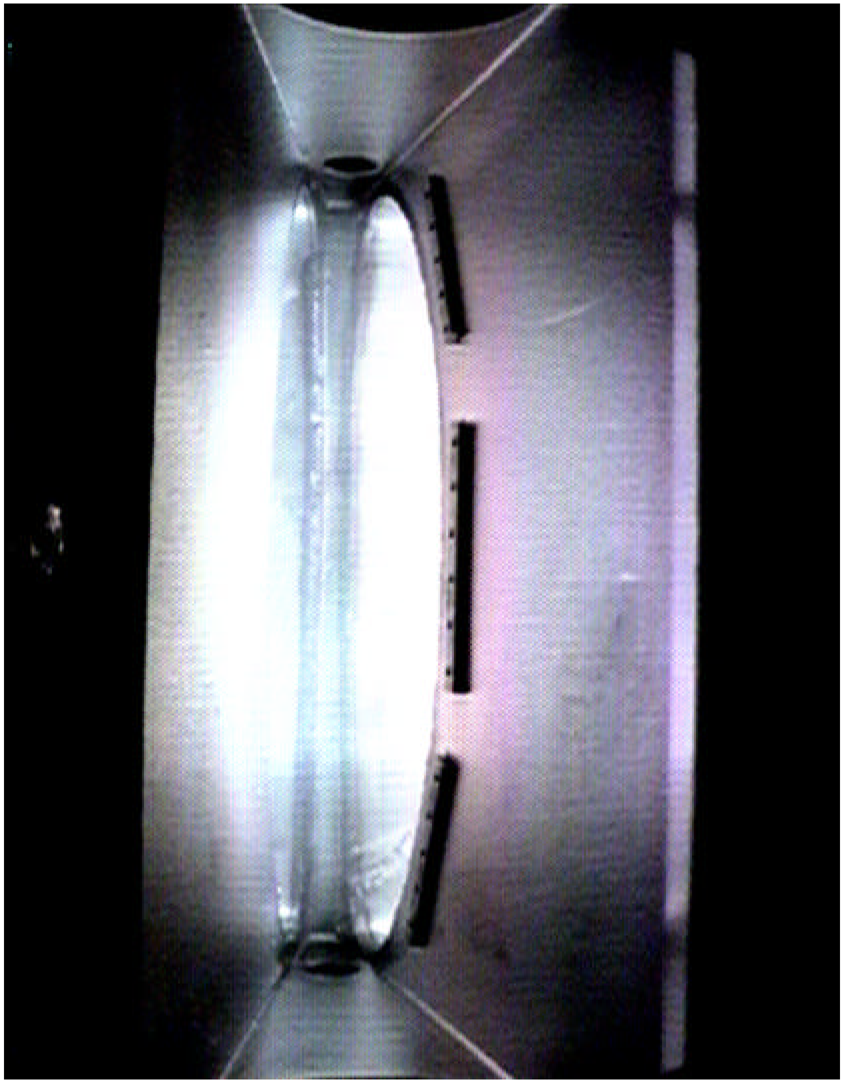
Helical Vacuum Chamber Has the Same Shape as the Plasma



- Four identical sections make up 4 field-period device
- Joint flanges at middle allow field periods to be pulled apart for access to interior
- Explosive forming used to fabricate vessel sections

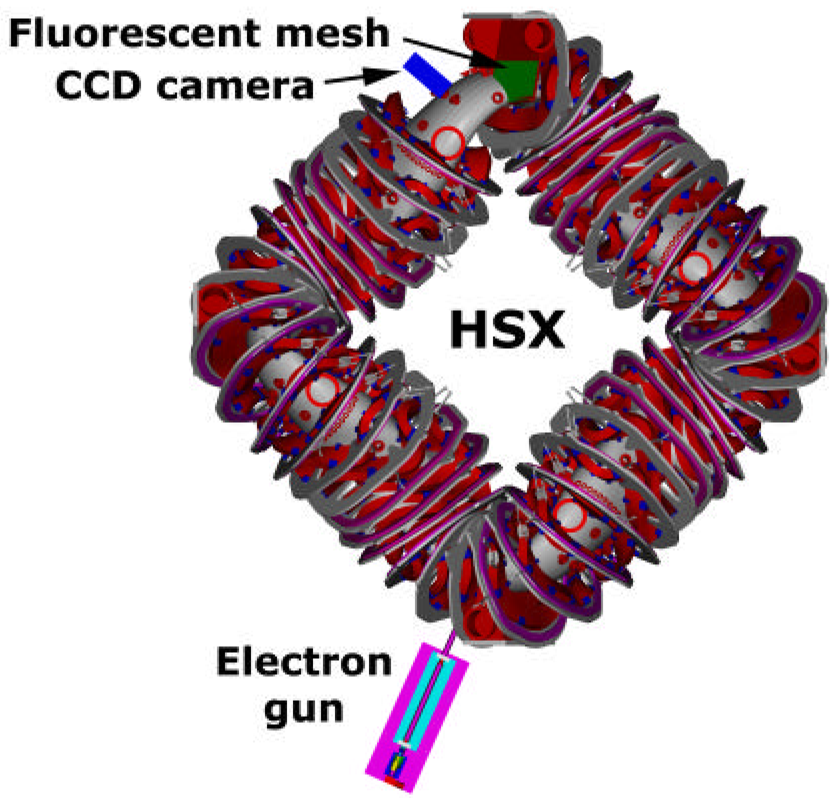


HSX First Plasma!



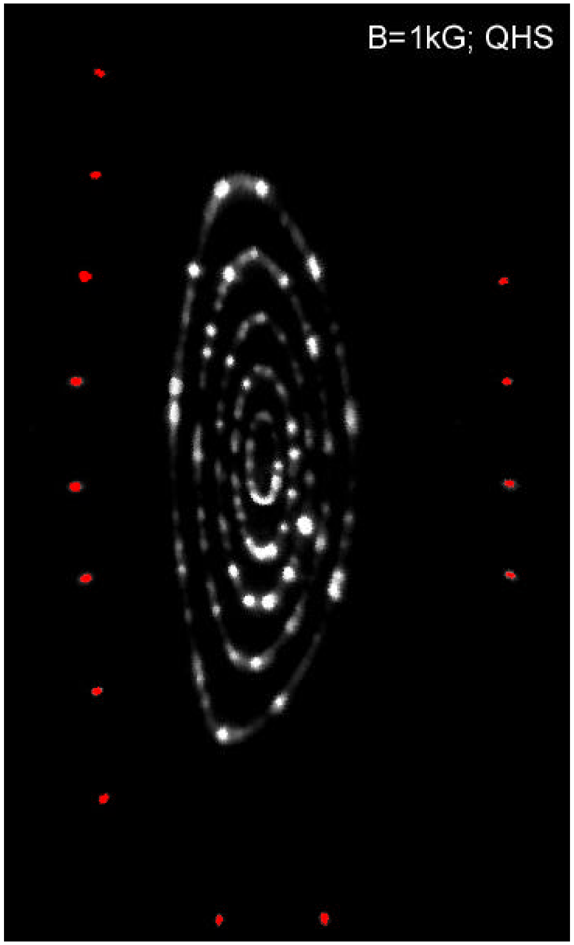
- 2.45 GHz source at B ~ 900 gauss
- Power ~ 1 kW
- 30 second duration
- August 31 1999

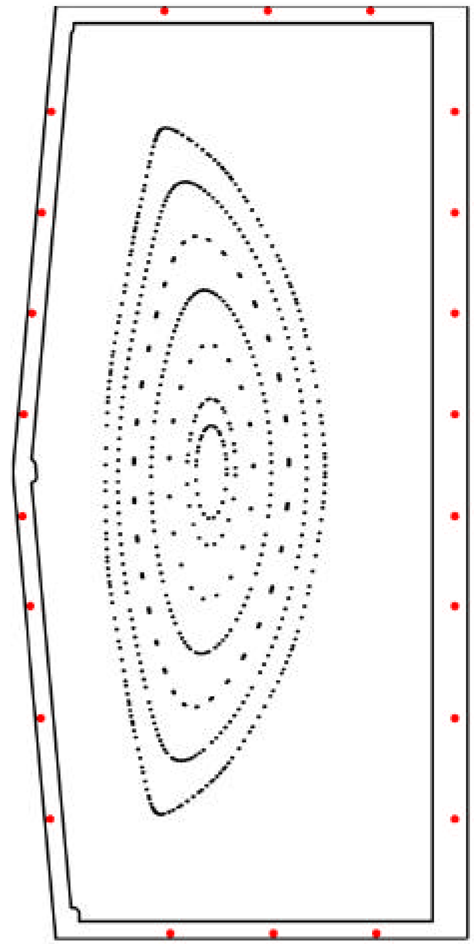
Magnetic Surface Mapping in HSX



- Low energy electron beam launched in steady-state 1 kG field
- Beam intercepts 95% transparent fluorescent mesh
- Periscope Optics close to mesh views image at 30^0 angle off perpendicular
- CCD camera views image and data is recorded

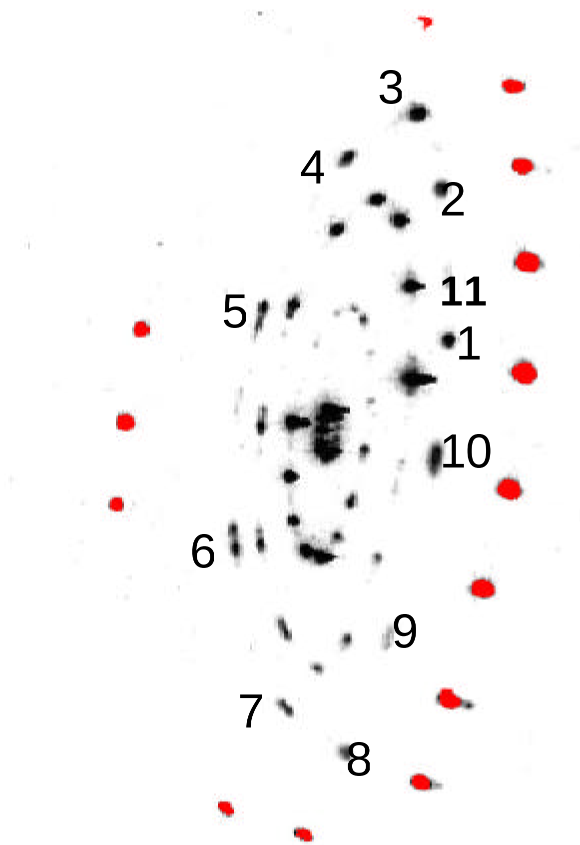
Experimental and Calculated Magnetic Surfaces

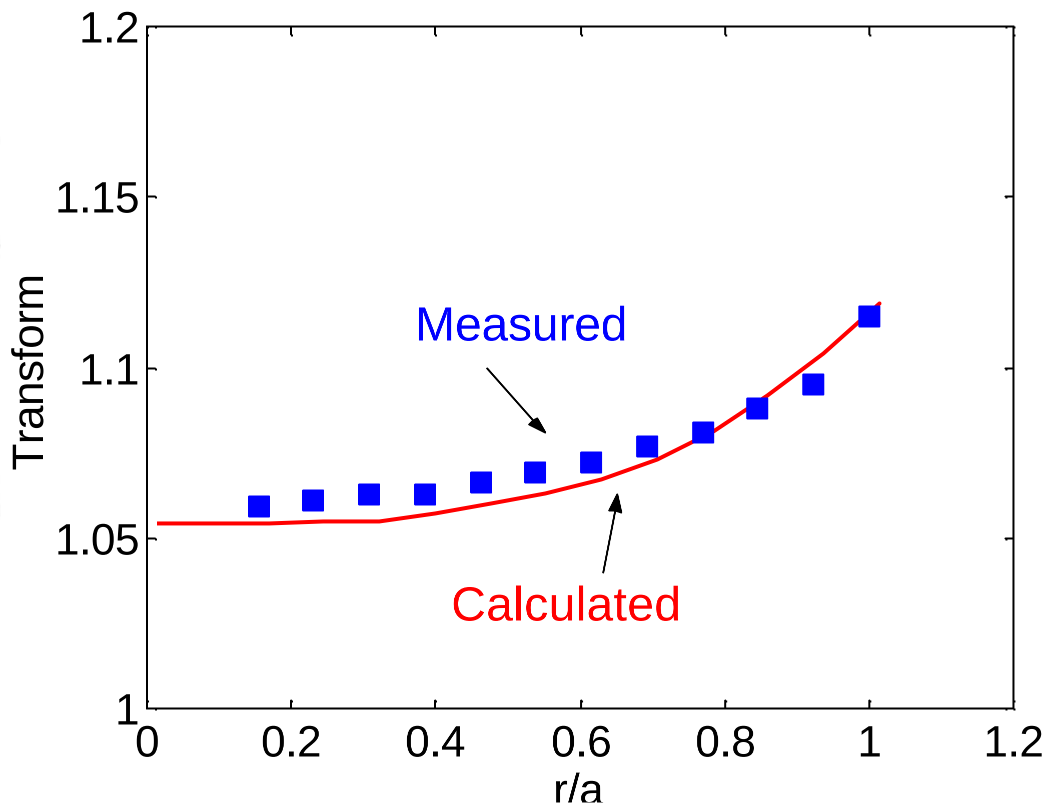




Rotational Transform

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





What Can We Learn About the Magnetic Field Spectrum by Analyzing Passing Particle Orbits?

- HSX is a quasihelical stellarator with a dominant [4,1] helical component in the magnetic field spectrum ⇒ No toroidal curvature

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

- In straight field line coordinate system (Boozer), the drift of a passing particle from a flux surface is given by:

$$dr = \frac{Mv_{\parallel} g}{reB_0{}^2} \sum_{n,m} b_{nm} \frac{m}{n - m\iota\!\!\!-} ([\cos(nf - mq] + a_{nm})$$

- m = 0 modes don’t contribute to the drift!

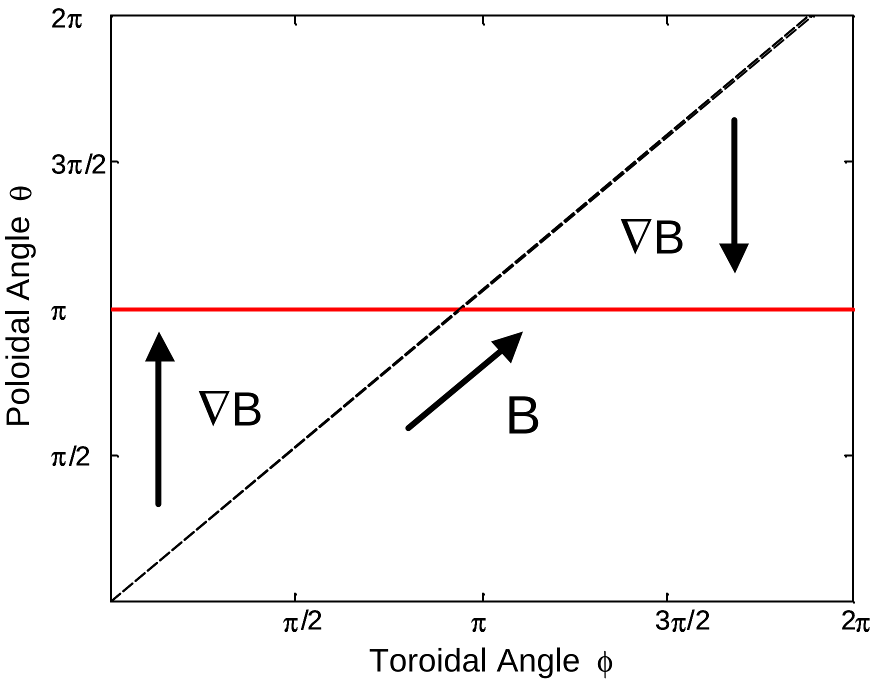
Drifts are Smaller in HSX Than a Tokamak

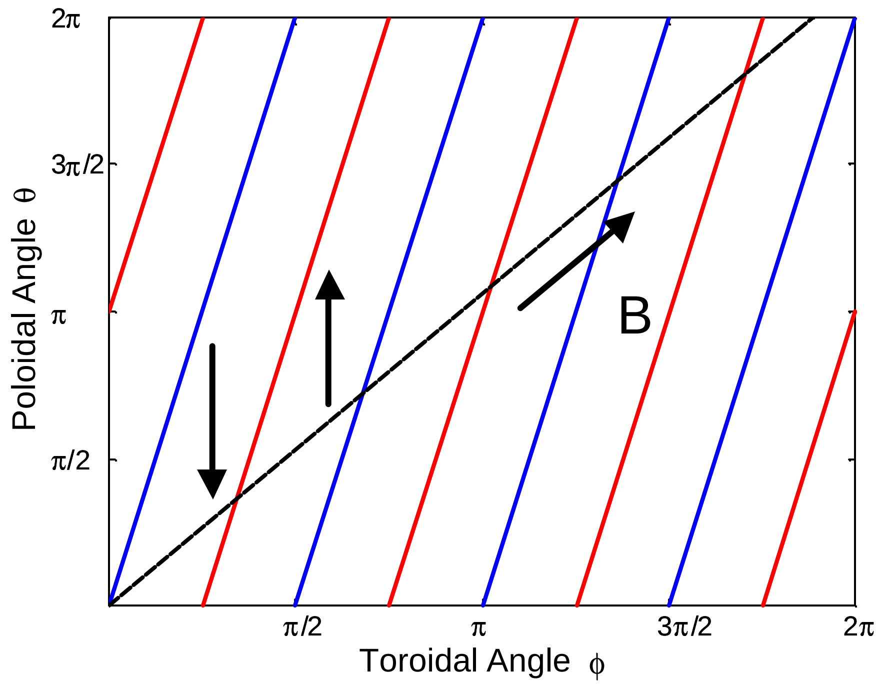
Tokamak with n=0, m=1

$$dr \propto -\frac{b_{01}}{\iota}[\cos q + a_{01}]$$

HSX with n =4, m=1

$$dr \propto \frac{b_{41}}{4-\iota}[\cos(4f - q) + a_{41}]$$





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

Drift Orbit Measurements Require Low Field

- The shift due to the dominant helical mode is very small $\Rightarrow$ very low magnetic field or high energy particles are needed

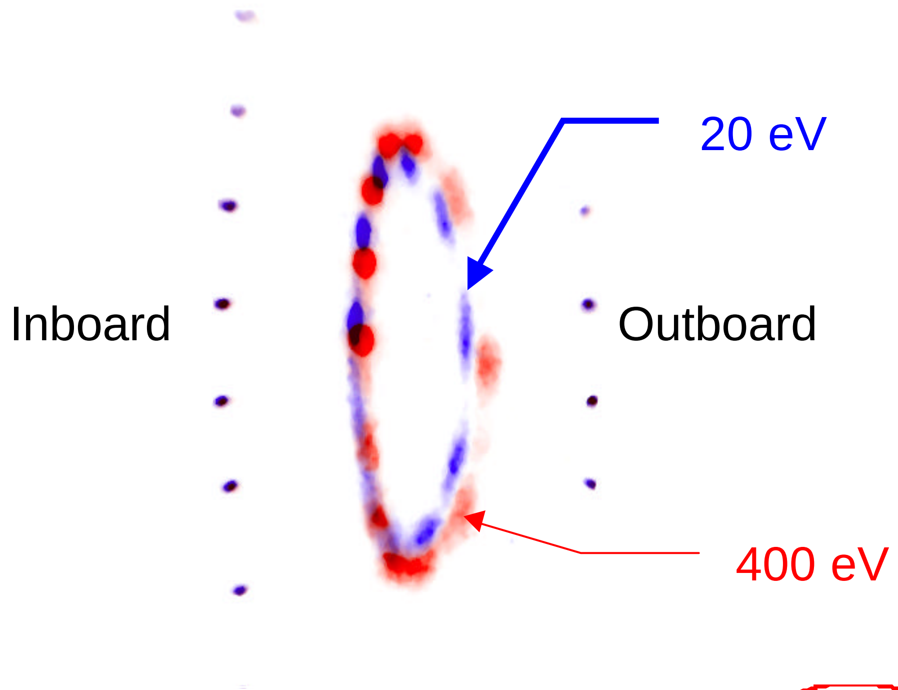
- At low field, the earth's magnetic field is important:
  $\Rightarrow$Ignorable at higher magnetic fields

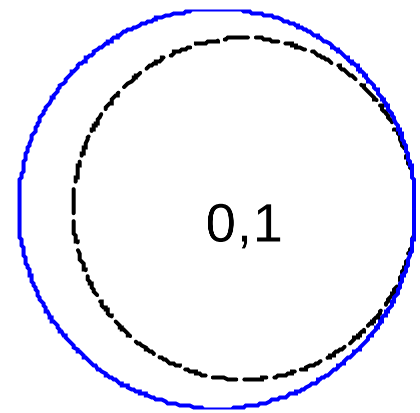
B = 60 gauss

Mode Numbers	Amplitude
4,1	5.3%
3,0	3.8
4,0	1.9
1,1	0.37

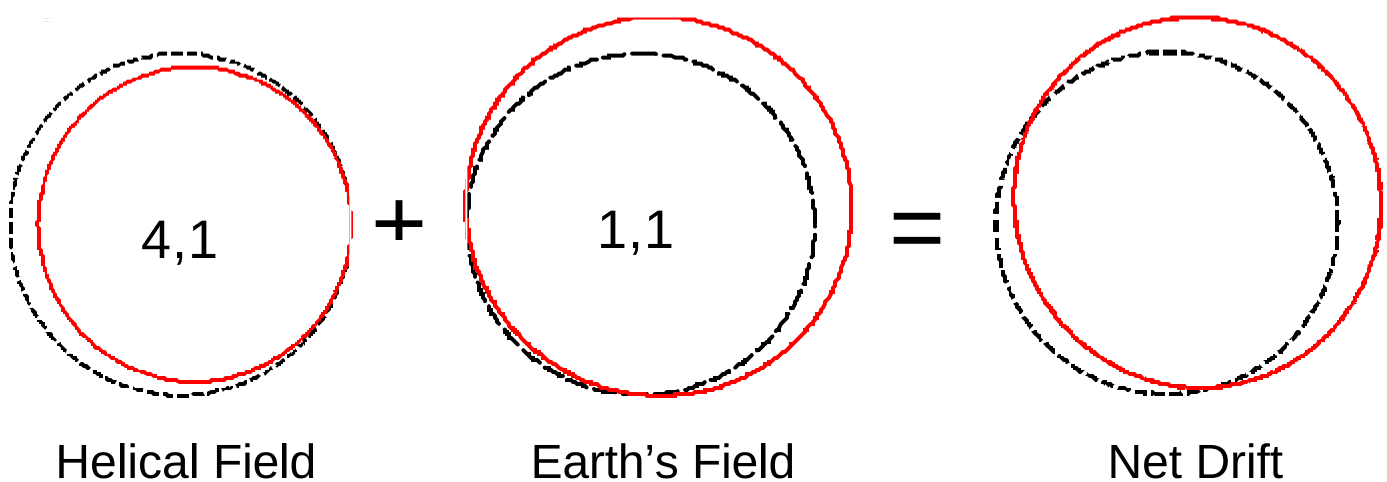
- $dr \propto \dfrac{m}{n - m\iota\!\!\!-}$ $\Rightarrow$ m = 0 terms don't contribute
  $\Rightarrow$ large drift for [1,1] mode when $\iota\!\!\!- \geq 1$

Drift Caused by Helical Field and Earth's Field



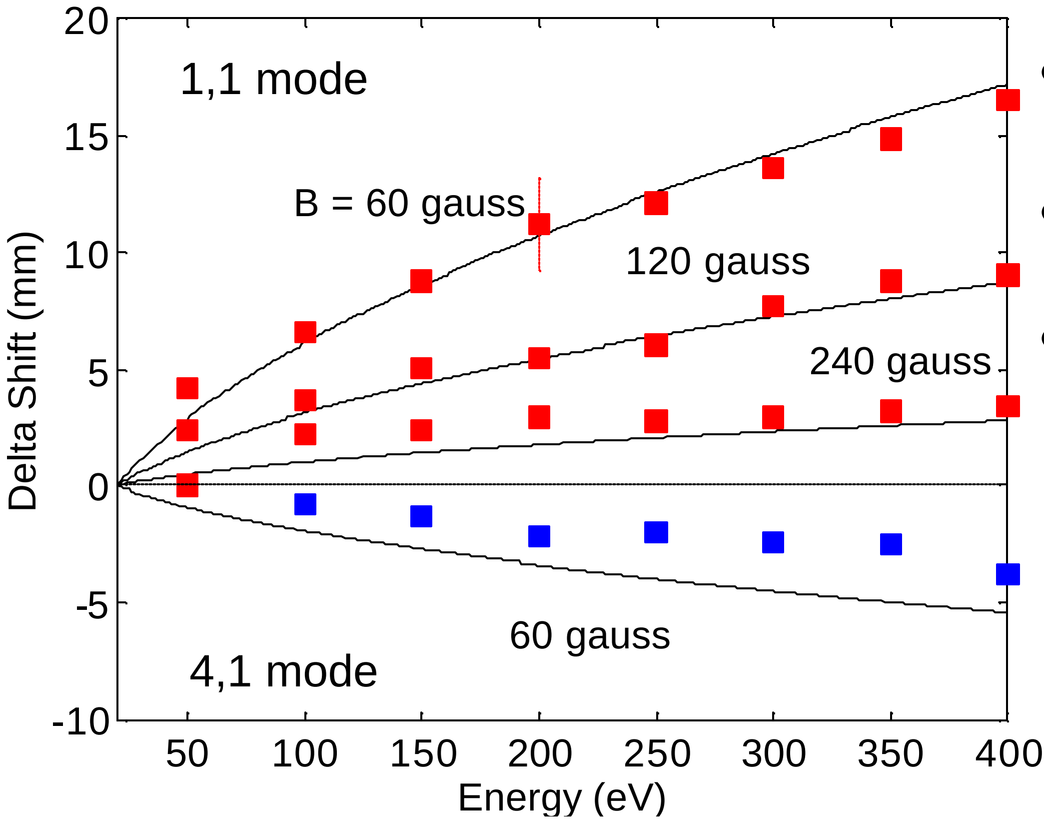


The direction of the drift is not explained by toroidal curvature



Initial Results

Comparison of the orbit shift to 20 eV reference case



- Drift ~ $\sqrt{Energy}$
- Drift ~ $1/B^2$ for earth's field
- Sign of drift for [4,1] mode consistent with small toroidal curvature

Summary

- Measured surfaces and rotational transform agree well with calculated values.

- Analysis of passing particle orbits can provide information about the magnetic field spectrum. The results indicate:
  - $\Rightarrow$ Toroidal curvature in HSX is small
  - $\Rightarrow$ Particle drift in the quasihelical field is very small.
  - $\Rightarrow$ Earth's field is important only at very low field

Coming up …..

- More with passing particles

- Trapped particle orbits $\Rightarrow$ Confirm whether trapped particles are confined better in quasihelical field than conventional stellarator

- Second harmonic ECH at 0.5 T with 28 GHz gyrotron