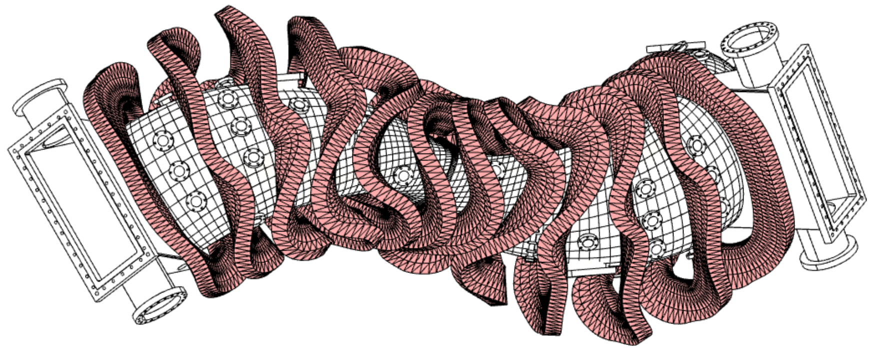
The HSX Stellarator

B. Geiger and the HSX team

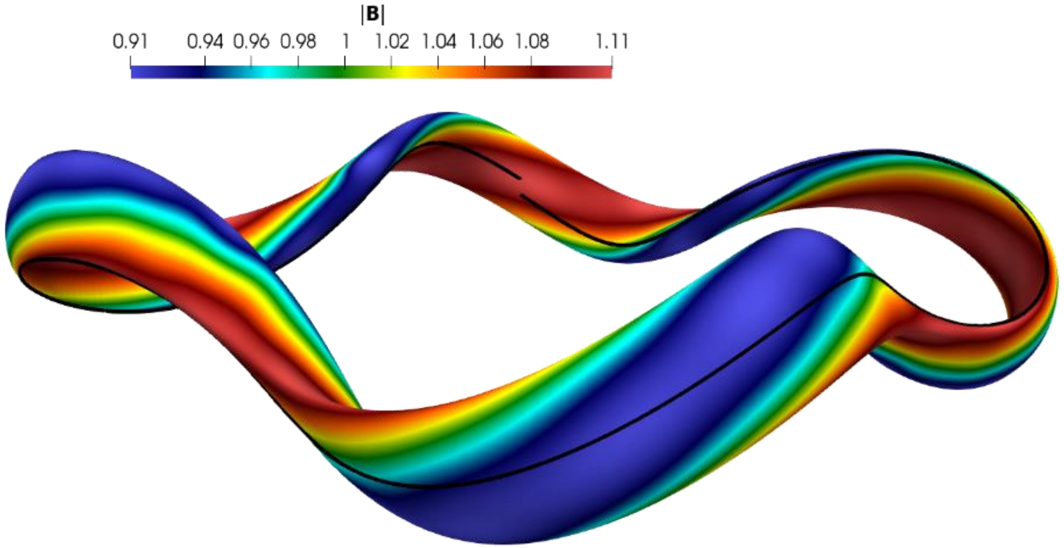


Department of Nuclear Engineering & Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

This work was funded the Department of Energy (DoE) under grant number DE-FG02-93ER54222

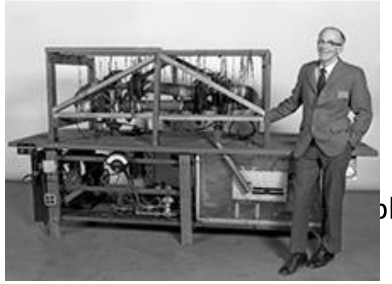
Outline

- History of HSX
- Design and construction
- Results until 2020
- Plasma restart in 2023
- Next Steps and Upgrades
- Summary

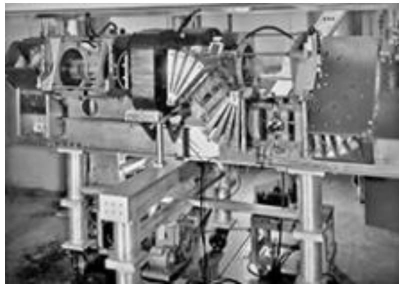


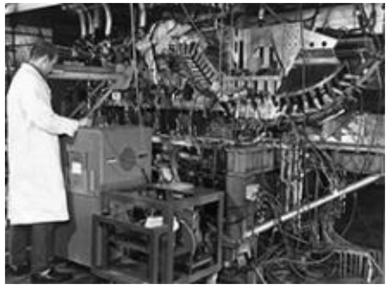
Stellarator experiments in the US

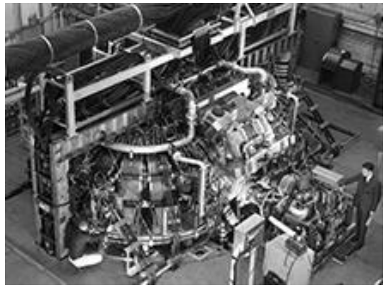
HSX
Helically Symmetric eXperiment


Model A (1953)

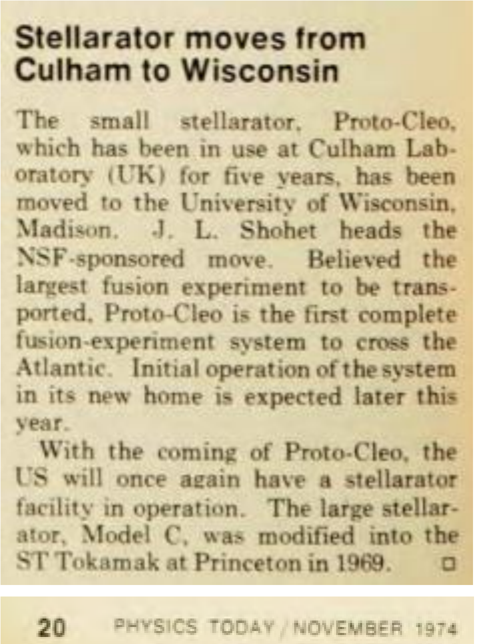

B-65 (1957)


B-2 (1958)


Model B-3 (1958)


Model C (1962)

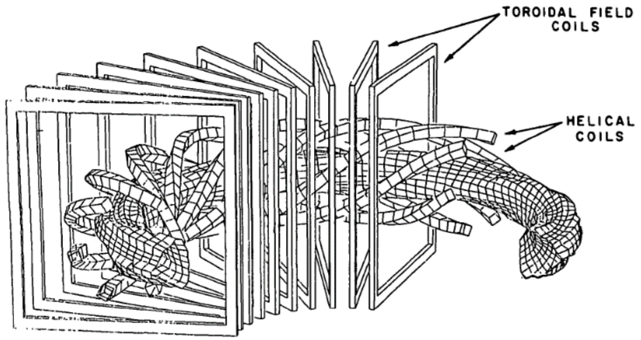
1969
Model C Stellarator has been modified to a tokamak
1974
Prof. L. Shohet brings Proto-Cleo Stellarator from Culham (UK) to Madison
→ Start of the torsatron/stellarator laboratory


Stellarator moves from Culham to Wisconsin

The small stellarator, Proto-Cleo, which has been in use at Culham Laboratory (UK) for five years, has been moved to the University of Wisconsin, Madison. J. L. Shohet heads the NSF-sponsored move. Believed the largest fusion experiment to be transported, Proto-Cleo is the first complete fusion-experiment system to cross the Atlantic. Initial operation of the system in its new home is expected later this year.

With the coming of Proto-Cleo, the US will once again have a stellarator facility in operation. The large stellarator, Model C, was modified into the ST Tokamak at Princeton in 1969. □

20 PHYSICS TODAY / NOVEMBER 1974



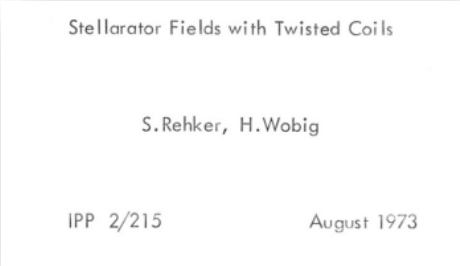
R = 40 cm
a = 3.9 cm
B = 0.3 T

DJ. HOFFMAN, J.N. TALMADGE, J.L. SHOHET, NUCLEAR FUSION, Vol.21, No.10 (1981)

Interchangeable Modular Stellarator

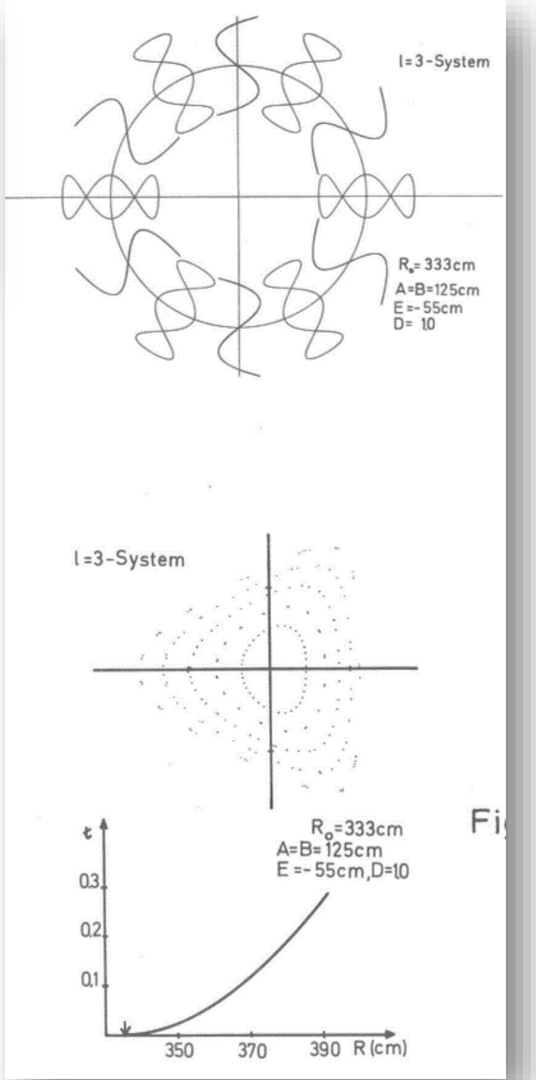
1973
Rehker and Wobig at IPP Garching develop the idea of using modular 3D-shaped coils

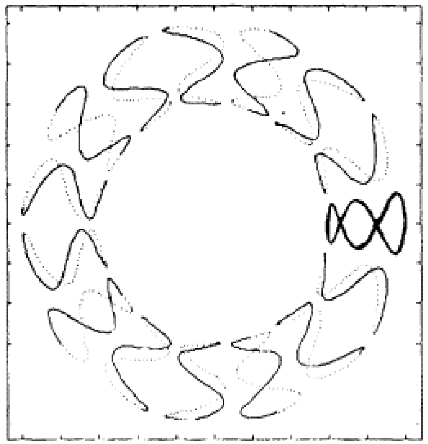
1981
Design and construction of the Interchangeable Modular Stellarator (IMS) at UW Madison

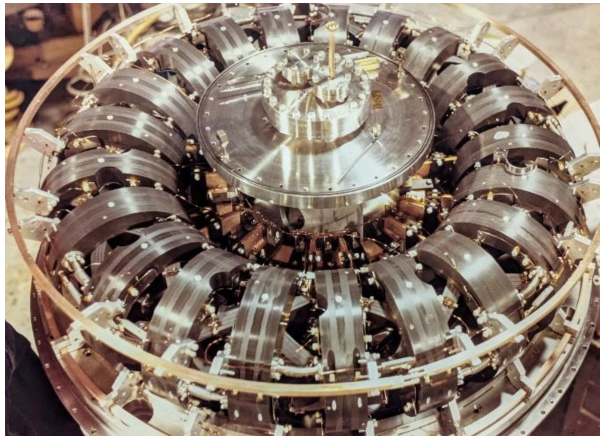

Stellarator Fields with Twisted Coils

S.Rehker, H.Wobig

IPP 2/215 August 1973







D.T. Anderson, IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. PS-9, NO. 4, DECEMBER 1981

https://pure.mpg.de/rest/items/item_2133171/component/file_2133170/content

Quasi Helically Symmetric Stellarators

HSX
Helically Symmetric eXperiment

1986
Garching scientists J. Nührenberg and R. Zille publish a paper on HELIcal Axis Advanced Stellarators (HELIAS)

1988
Nührenberg and Zille use their framework to show the existence quasi-helically-symmetric stellarators

Volume 129, number 2 PHYSICS LETTERS A 9 May 1988

QUASI-HELICALLY SYMMETRIC TOROIDAL STELLARATORS

J. NÜHRENBERG and R. ZILLE
Max-Planck-Institut für Plasmaphysik, IPP-EURATOM Association, D-8046 Garching near München, FRG

Received 30 December 1987; revised manuscript received 19 February 1988; accepted for publication 9 March 1988
Communicated by R.C. Davidson

It is computationally shown that there are toroidal stellarators whose magnetic field strength is helically symmetric in magnetic coordinates. Accordingly, these stellarators, without collisions, strictly confine guiding centre orbits.

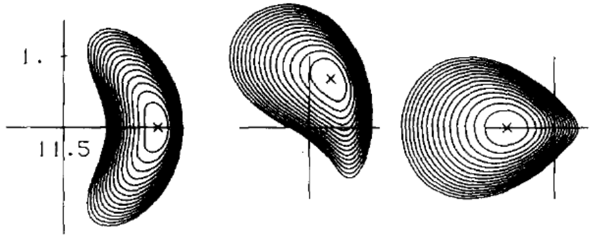


Fig. 1. Flux surface cross sections at $V = 0, \pi/2, \pi$ of a Helias

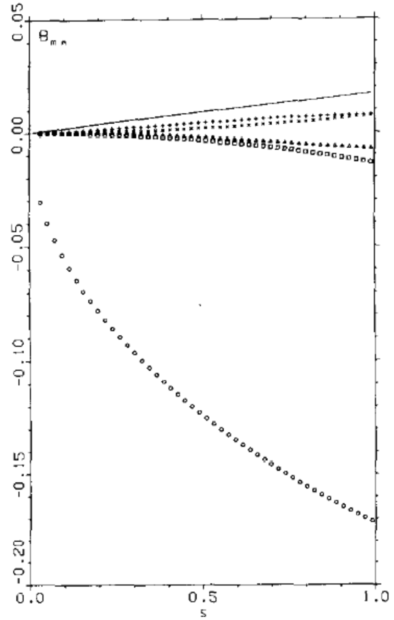
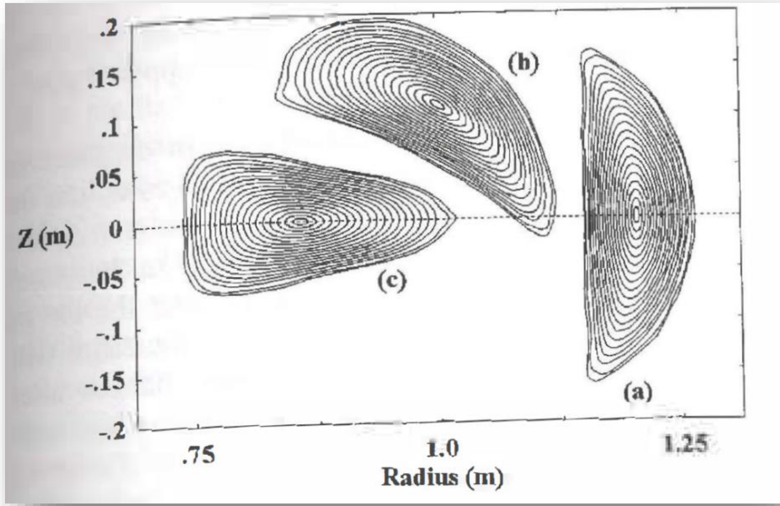


Fig. 2. Fourier coefficients $B_{m,n}$ versus normalized flux surface label s; —: $[B_{0,0} - B_{0,0}(s=0)]$, ○: $B_{1,-1}$, □: $B_{3,-2}$, △: $B_{2,-3}$, ×: $B_{4,-3}$, +: $B_{2,-1}$.

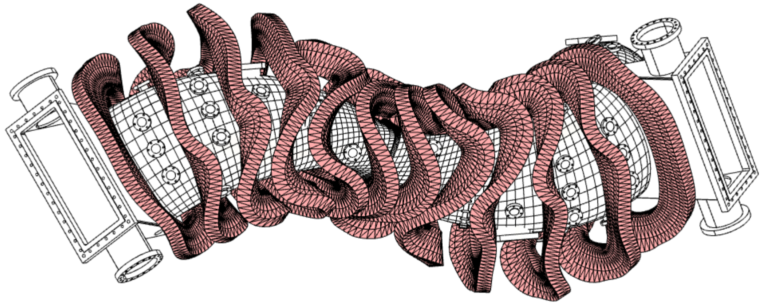
Physics design phase of HSX

- Future PI of HSX -- David Anderson -- travels to Germany to design HSX together with Jürgen Nührenberg and his team
- 3D coils designed by the NESCOIL code package developed at IPP Garching
(P. Merkel, Nucl. Fusion 27, 1987)
- Equilibrium found with:
  - Good quasi-symmetry
  - MHD stability (magnetic well)
  - High rotational transform (~1)



F. Anderson, Transactions of Fusion Technology, 1995

- Initial design of HSX has been made in Garching using the same tools and metrics as used for W7-X
→ HSX can be seen as the small sibling of W7-X
- Funding proposal got accepted in 1993
with a budget of $5M for 5 years
(final budget will be $7.5 M for 8 years)



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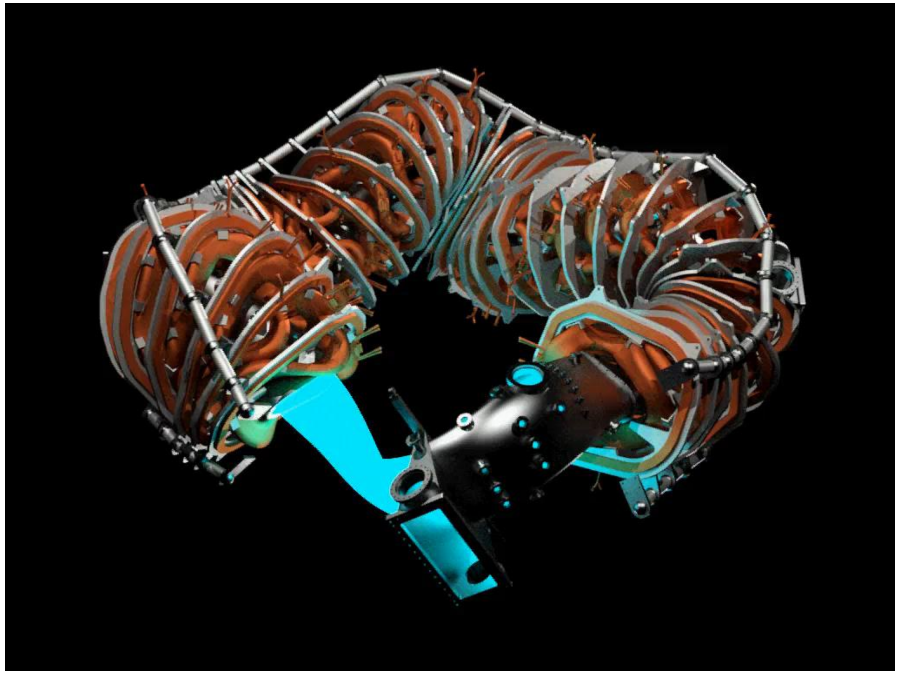
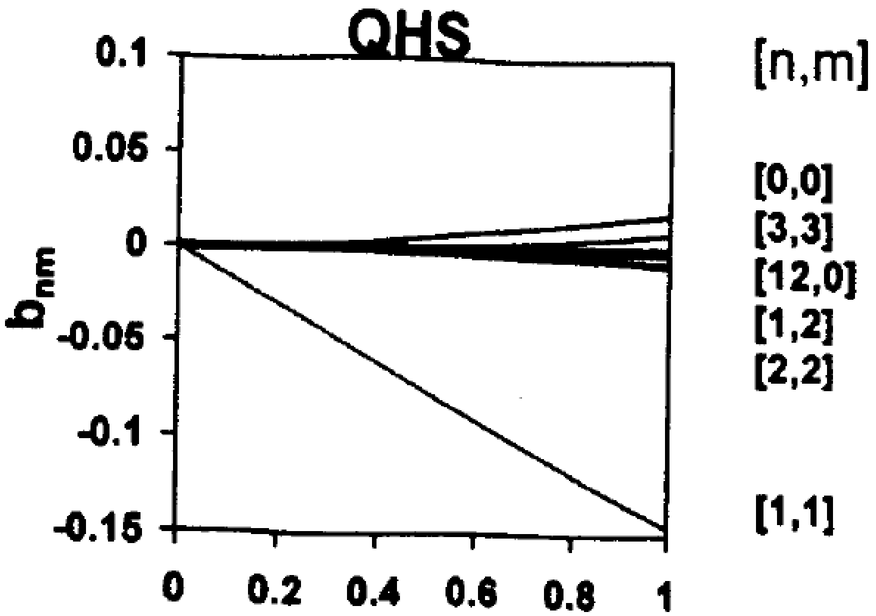


Magnetic field structure

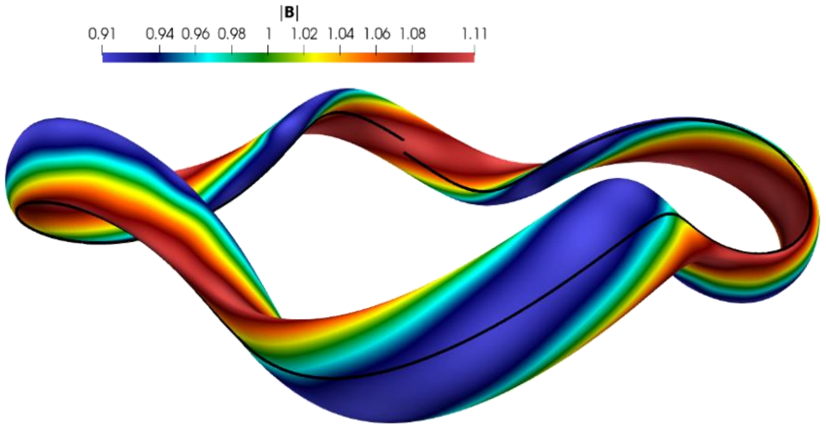
- Quasi quasi-symmetric magnetic field structure:
  - n=4, m=1 is dominant but other modes are present

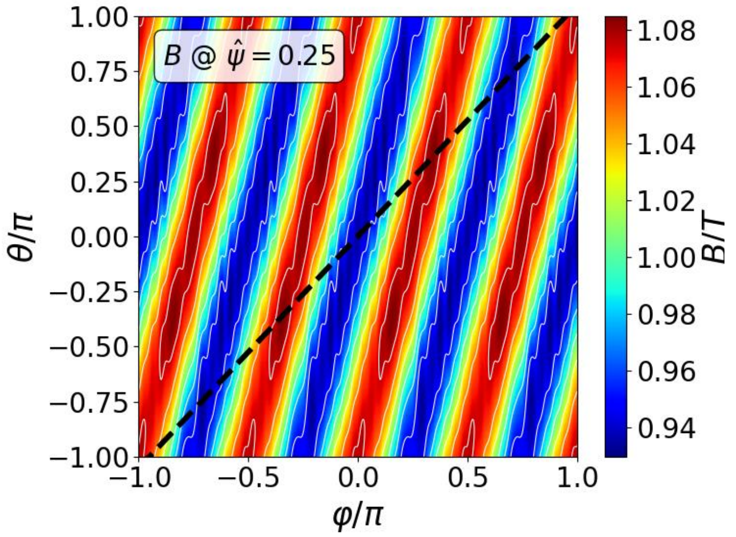
$$B = B_0\left(1 - \sum b_{nm}\cos(n\varphi - m\theta)\right)$$

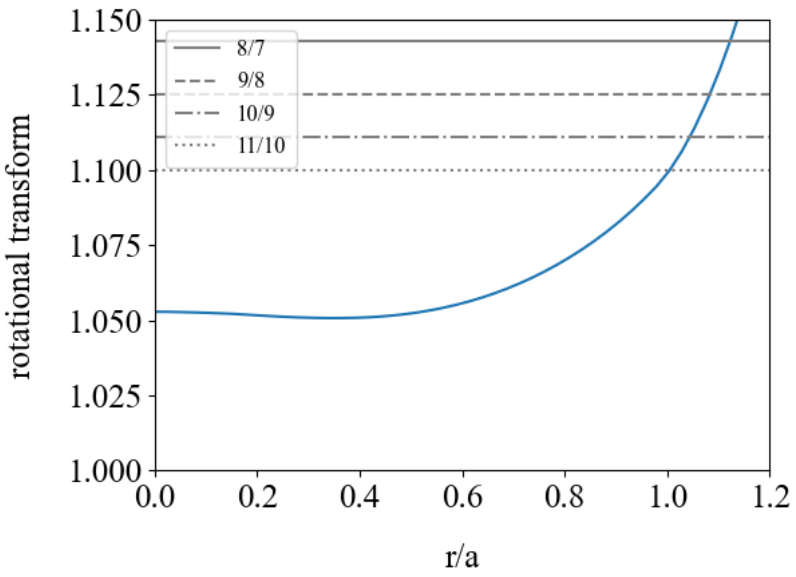
- High rotational transform with low shear



D.T. Anderson et al, J. Plasma Fusion Res. SERIES, Vol.I (1998)

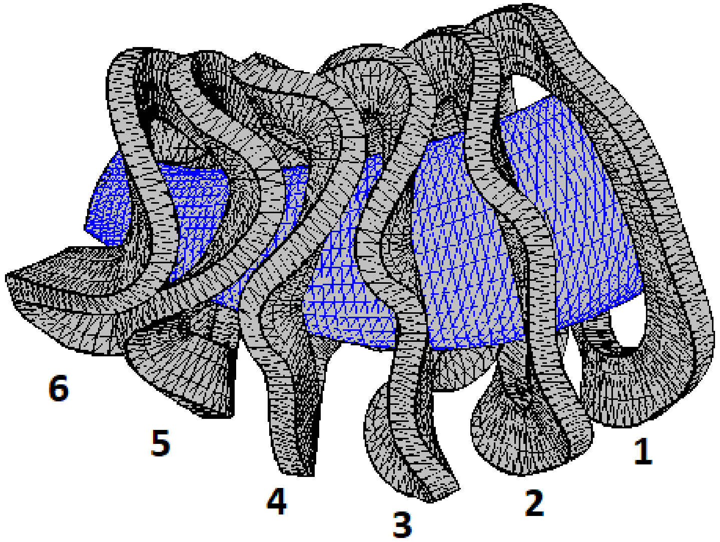


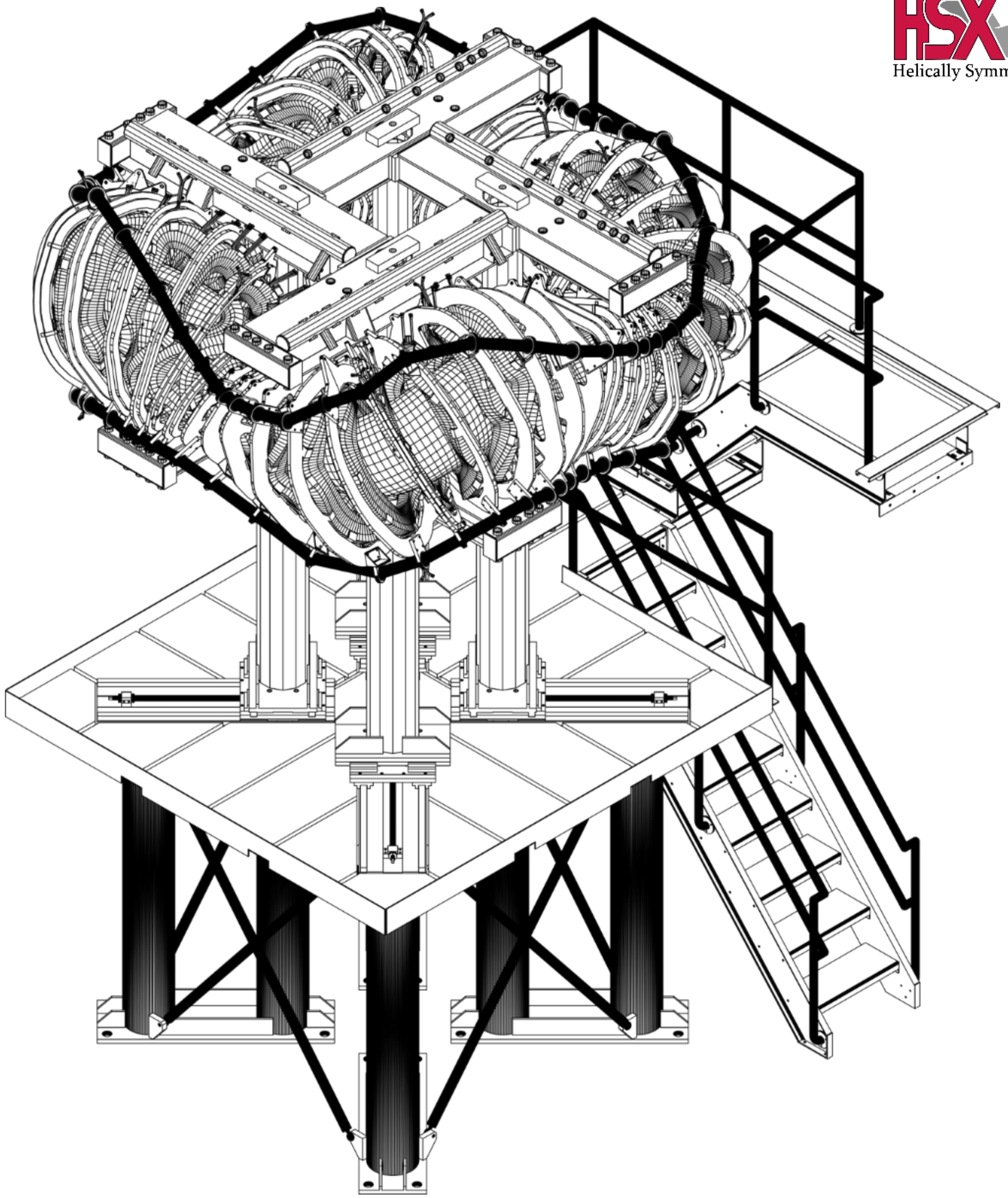




HSX engineering design

- R= 1.2 m, a = 12 cm
- 4 periods
- 48 coils 3D shaped coils, 6 unique coil types
- Engineering design performed at UW Madison with help of the Physical Sciences Lab (PSL)

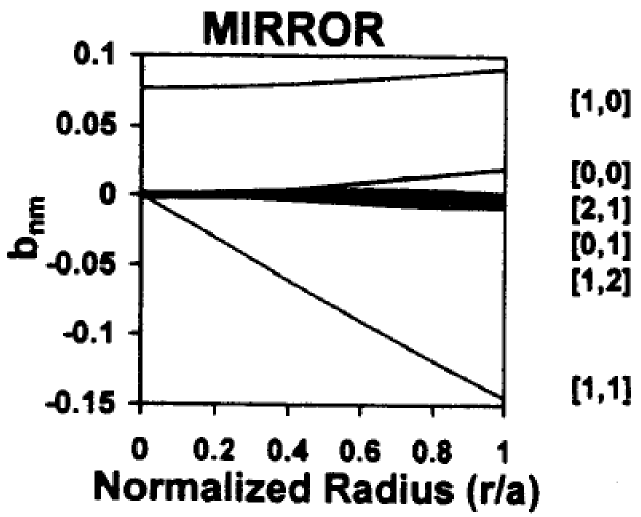




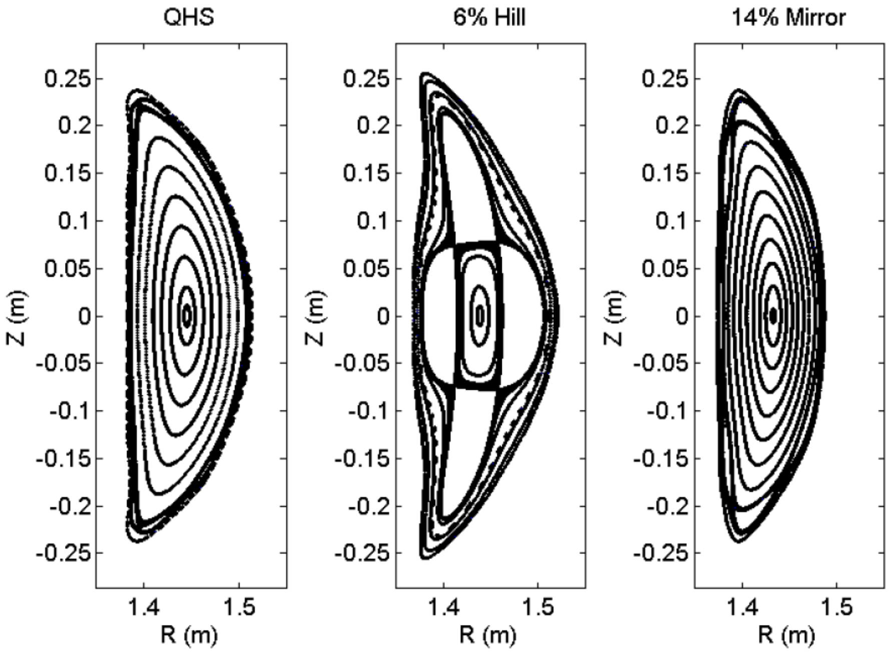
HSX
Helically Symmetric eXperiment

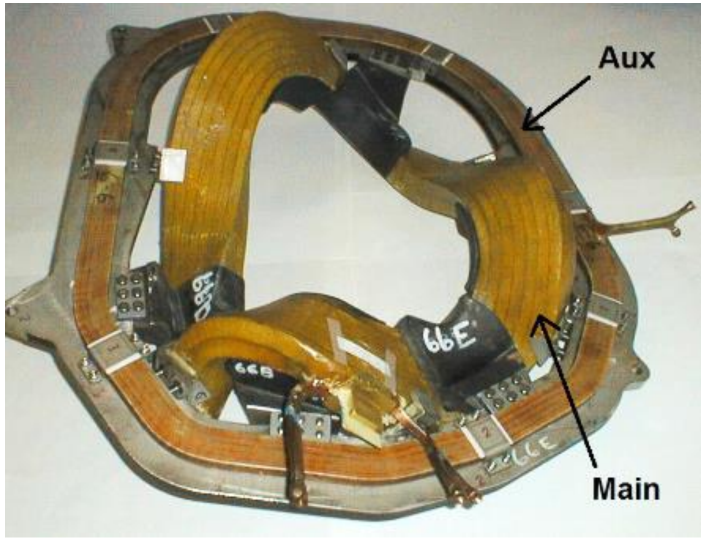
Coil support rings and auxiliary coils

- 3D coils supported by planar support rings
- Additional "auxiliary coils" mounted on support rings. Auxiliary coils allow one to modify the quasi-helically-symmetric (QHS) magnetic field structure



D.T. Anderson et al, J. Plasma Fusion Res. SERIES, Vol.l (1998)

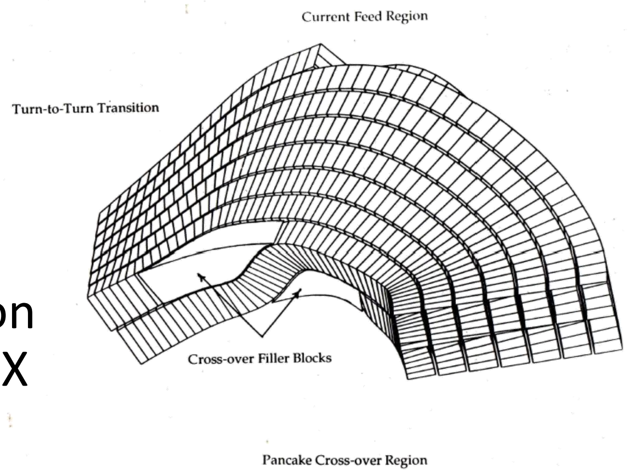


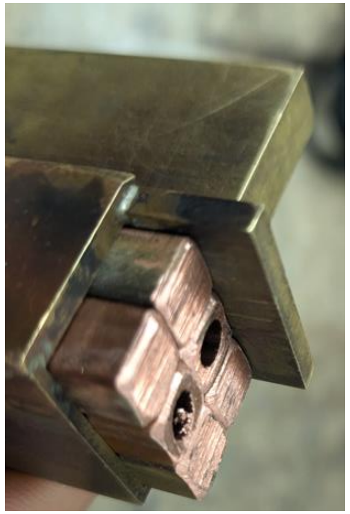


S. Gerhart, PhD thesis

HSX coil manufacturing

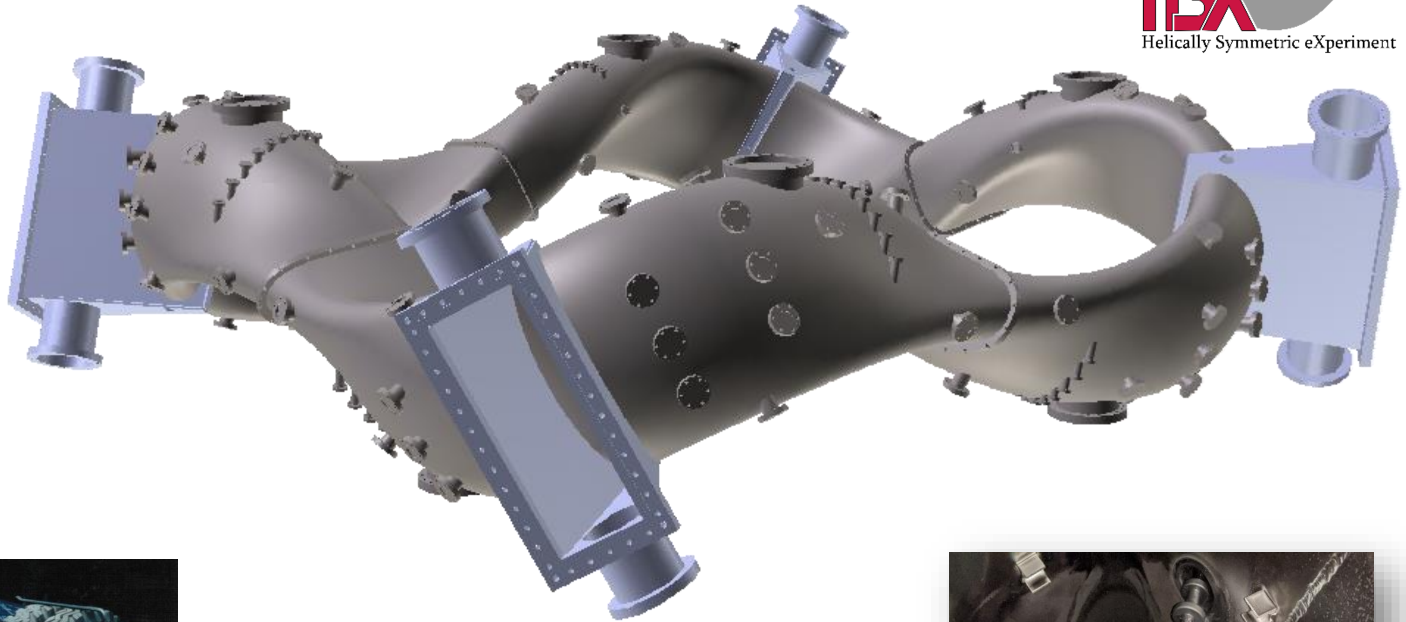
- 3D shaped main copper coils
  - 14 windings, double pancake
  - Each winding consist of six 8x8 mm^2 conductors
- Due to coil vendor bankruptcy, coil production was delayed and finally performed by the HSX team

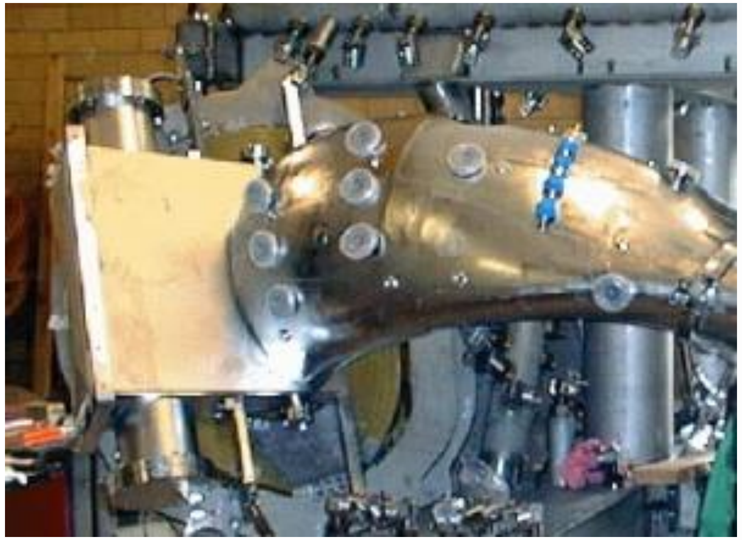




HSX vacuum vessel

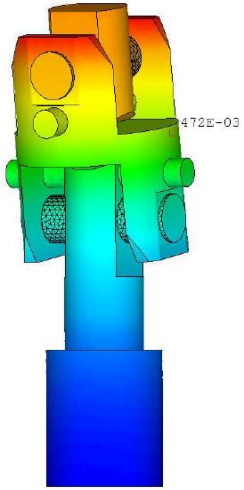
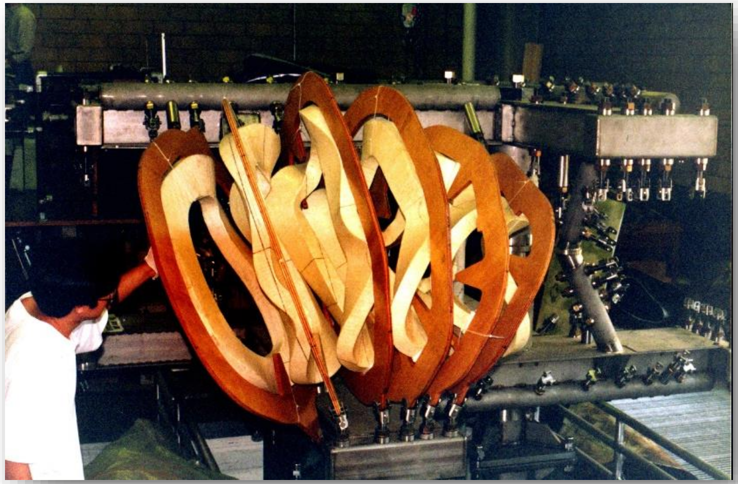
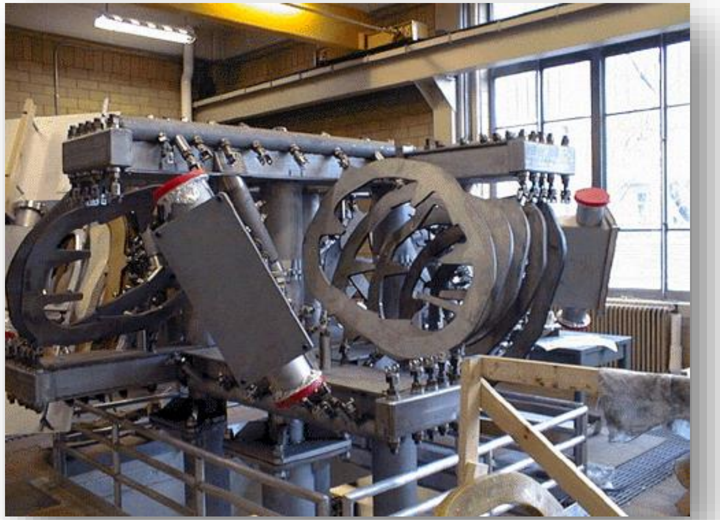
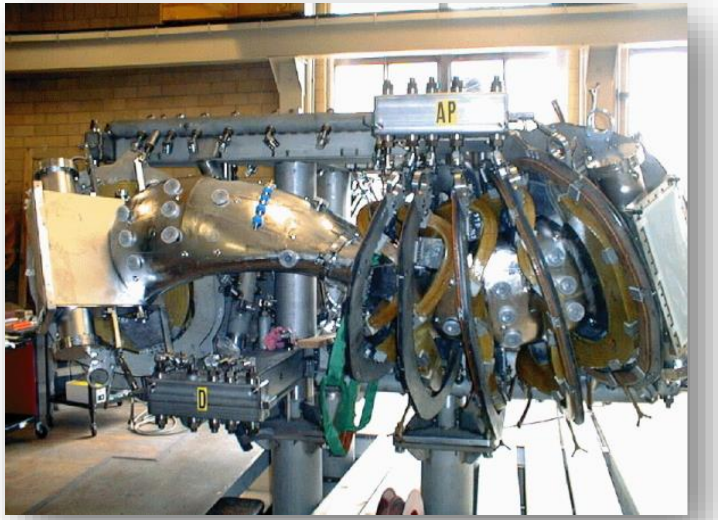
- 316-steel vessel manufactured by explosive forming





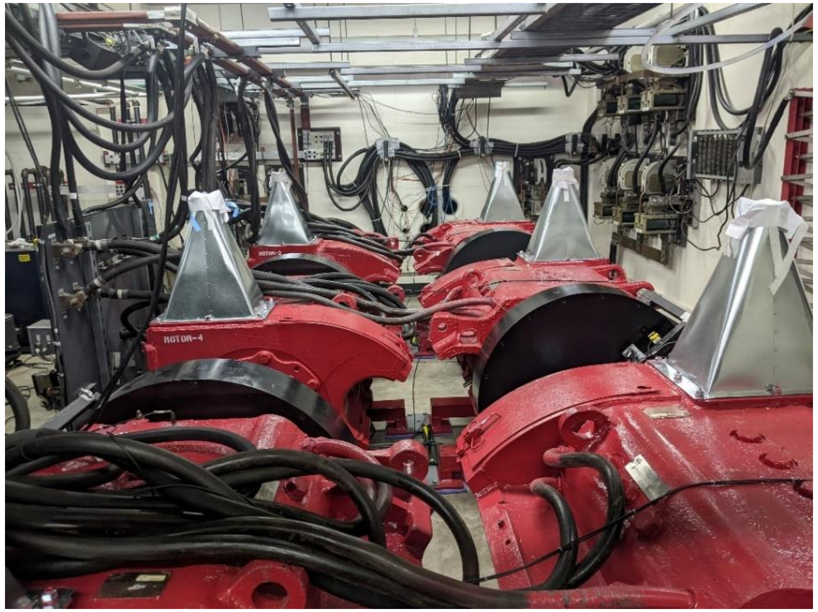
Assembly

- Start of assembly 1996
- Adjuster rods used to position the coils
- Max forces < 38kN
- 2 mm tolerances

Power supply for the magnetic field coils

- 1 kV, 10.8 kA required for standard 1T operation
- 18 flywheel generators can provide ~15 MW of power for 1 s



Plasma heating by 28 GHz ECRH

- 28 GHz gyrotron delivering 100 kW of heating power for 50 ms
- 20% – 30 % absorption (20-30 kW heating power)

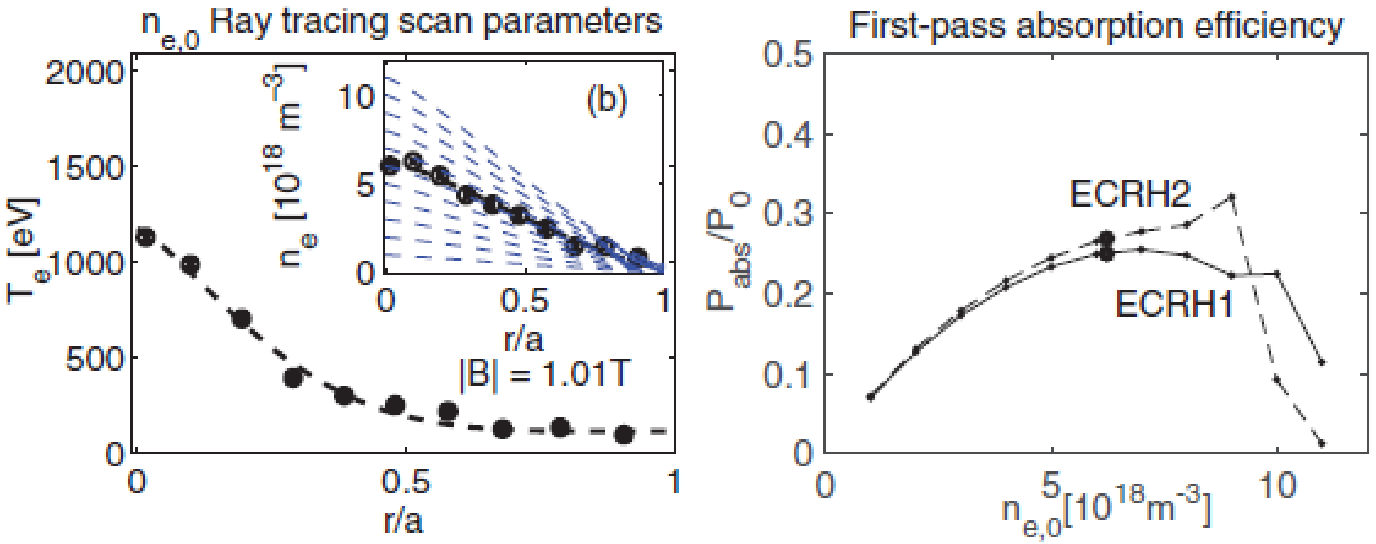
Cut-off densities for the k^{th} harmonic:

$$n_{cut-off}^{O-mode} = 9.65 \times 10^{18} k^2 B^2$$
$$n_{cut-off}^{X-mode} = 9.65 \times 10^{18} k(k-1) B^2$$

B=1T O1-mode → ~9.6 x10^{18} /m^3

B=0.5T X2-mode → ~4.8 x10^{19} /m^3

H. Zohm et al, FUSION SCIENCE AND TECHNOLOGY VOL. 52 AUG. 2007



G.M. Weir, Nucl. Fusion 55 (2015)

Start of operations after 6 years

- Field line mapping in 1999
- First 28 GHz ECRH plasma in 2001

8/31/1999 HSX First Plasma. 850 Gauss, 2 kW 2.45 GHz ECRH.


Wisconsin State Journal

WEDNESDAY, MARCH 28, 2007

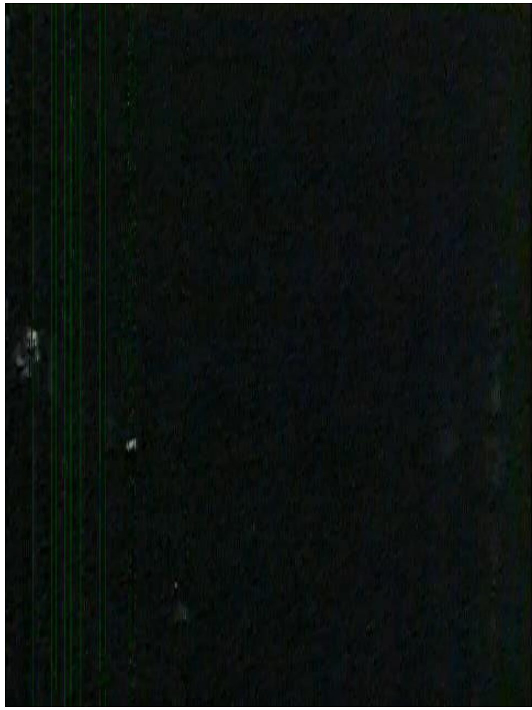
UW'S FUSION GUYS

A FIRST FOR FUSION

David Anderson
The electrical and computer engineering professor leads the team that made the recent breakthrough in fusion research.

Joe Talmadge
A co-investigator on the stellarator has invested nearly 17 years in the project and helped build it from the ground up.

Fusion



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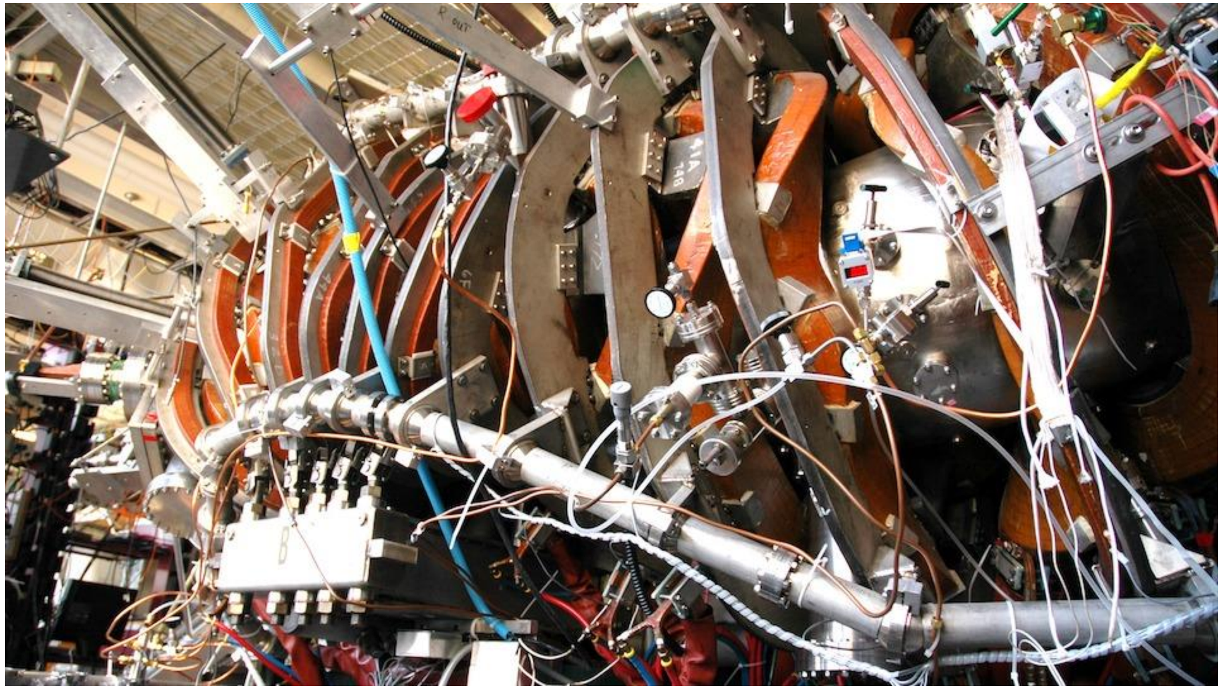
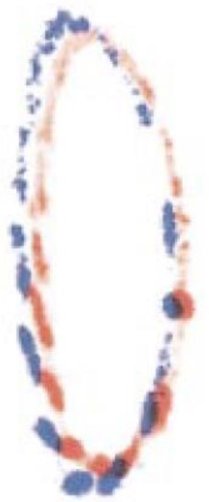
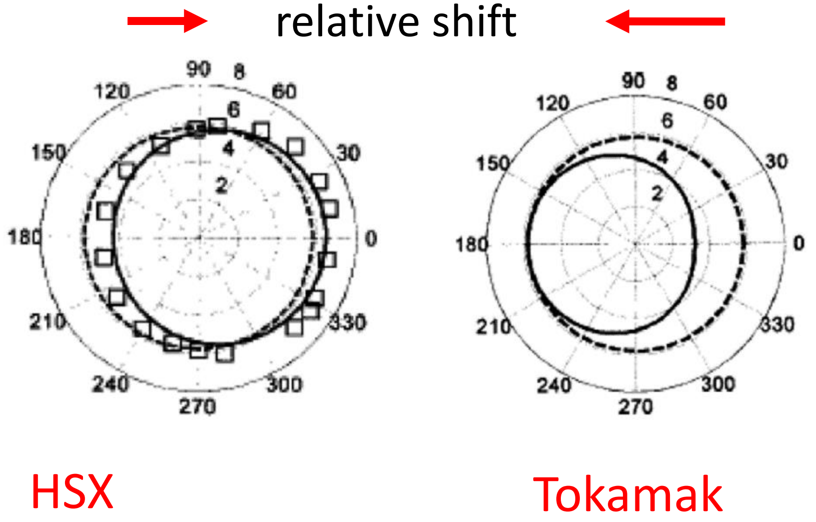


Neoclassical optimization demonstrated in 2001

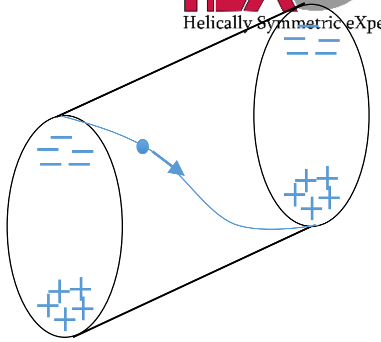
Electron beam experiments demonstrate that "drift orbits" of high energy passing electrons (450 eV ,red) are shifted in the direction opposite to what is expected in presence of toroidal curvature.

→ This demonstrates NC optimization



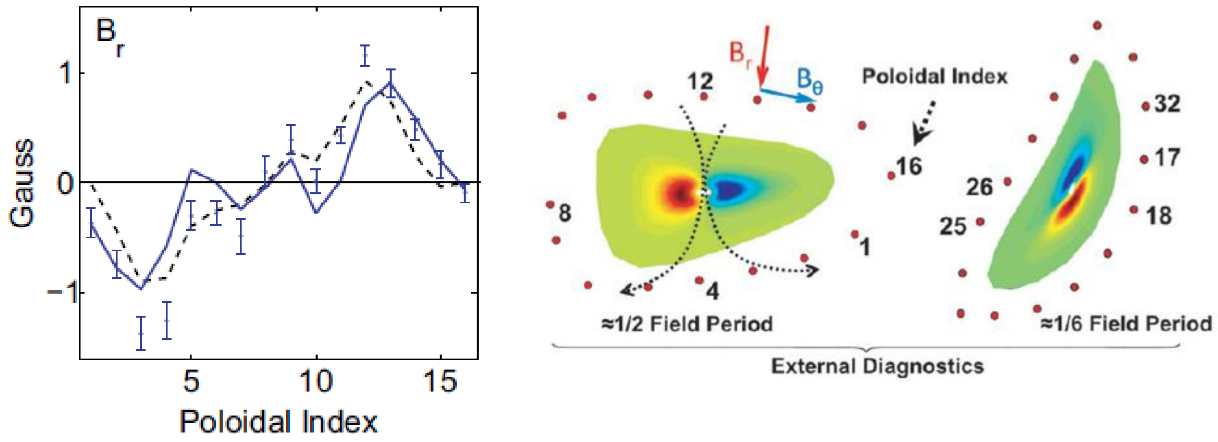


J. N. Talmadge, Physics of Plasmas **8**, 5165 (2001);



Neo-classical drifts cause a charge separation which will be balanced by Pfirsch Schluter currents.

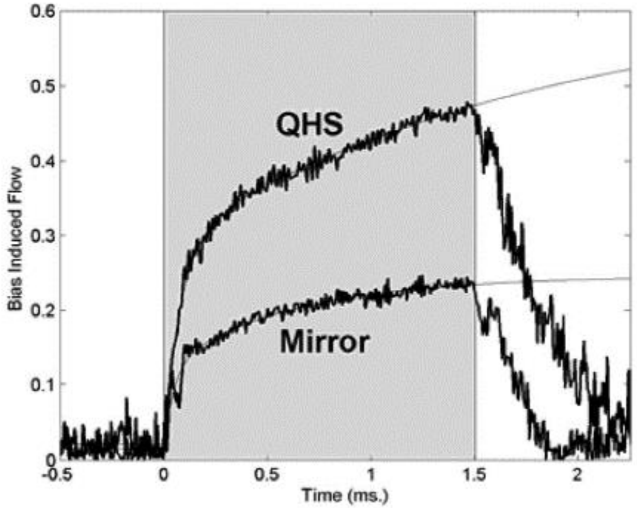
Pfirsch Schluter currents are weak which demonstrates neo-classical optimization!



J. C. Schmitt, Nucl. Fusion 53 (2013) 082001

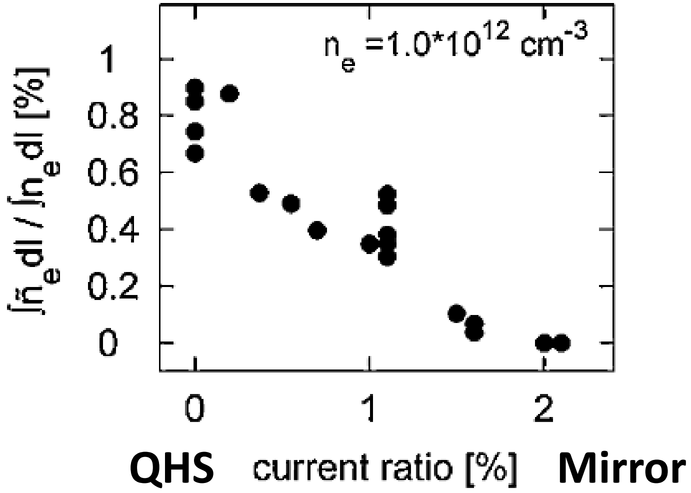
Auxiliary coils allow studies of the QHS optimization

- Successful demonstration of reduced flow damping when comparing QHS and mirror configurations.



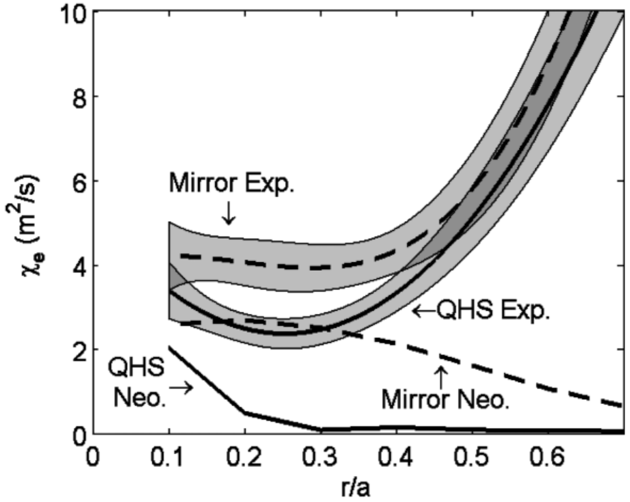
S. P. Gerhardt, PRL94,015002 (2005)

- ECRH-driven fast electrons excite Alfven waves that are only present in QHS (good energetic electron confinement)



C. B. Deng, PRL103,025003 (2009)

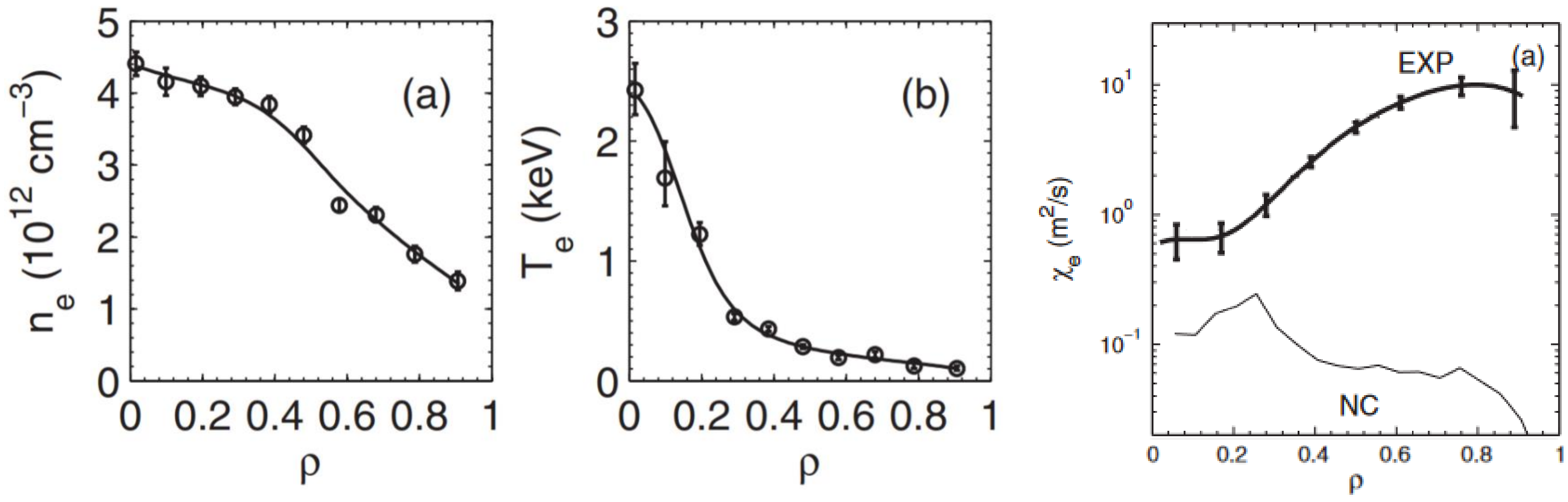
- Power balance analysis shows agreement with neoclassical modelling in the core plasma



J. M. Canik et al, PRL (2007)

Strong Anomalous Transport for r/a>0.3

- Temperature profiles are typically flat outside of r/a=0.3
- Significant levels of anomalous heat transport observed!
- Explained by turbulence driven by Trapped Electron Mode (TEMs) instabilities



W. Guttenfelder et al. 2008 PRL **101**, 215002

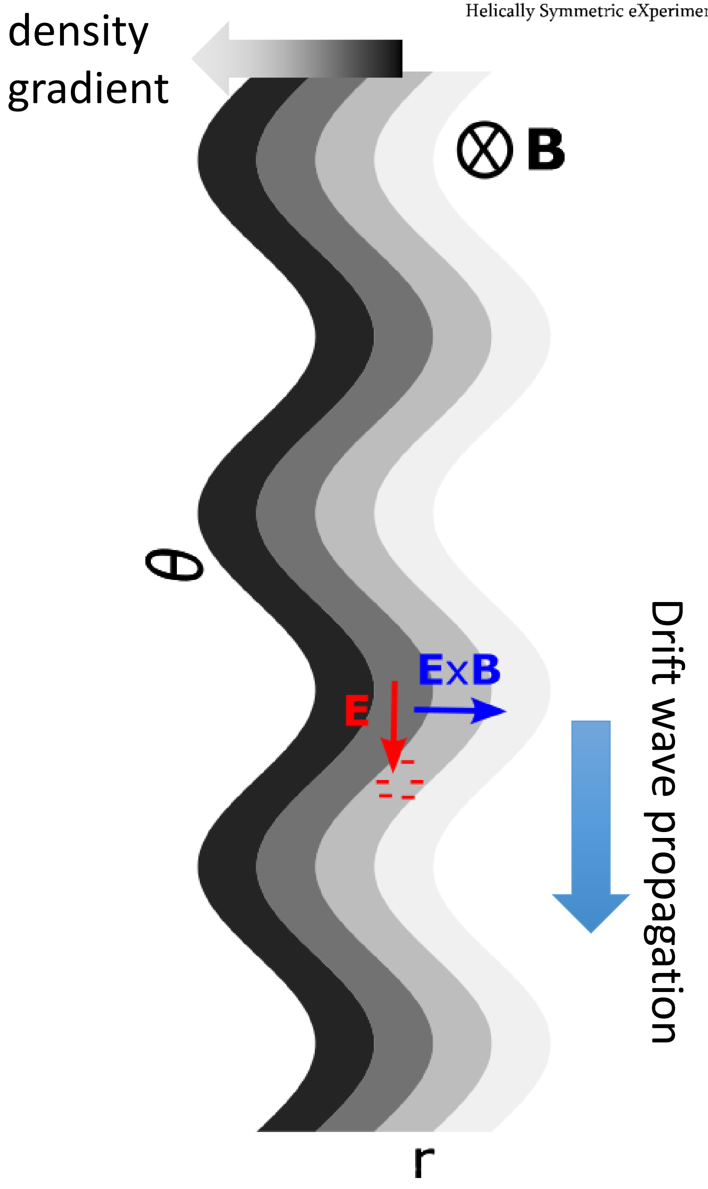
Background on Trapped Electron Modes

Simple picture of drift waves

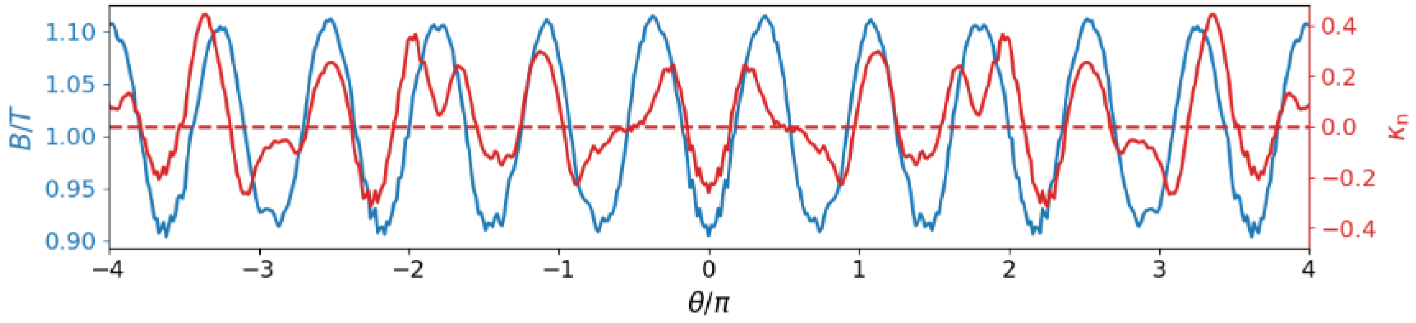
- Adiabatic electron response in presence of a perturbation provides an electric field. The resulting **ExB** drift "only" contributes to the propagation of the wave.
- No growth / radial transport ($\tilde{E}$ *and* $\tilde{n}$ *are not in phase*)

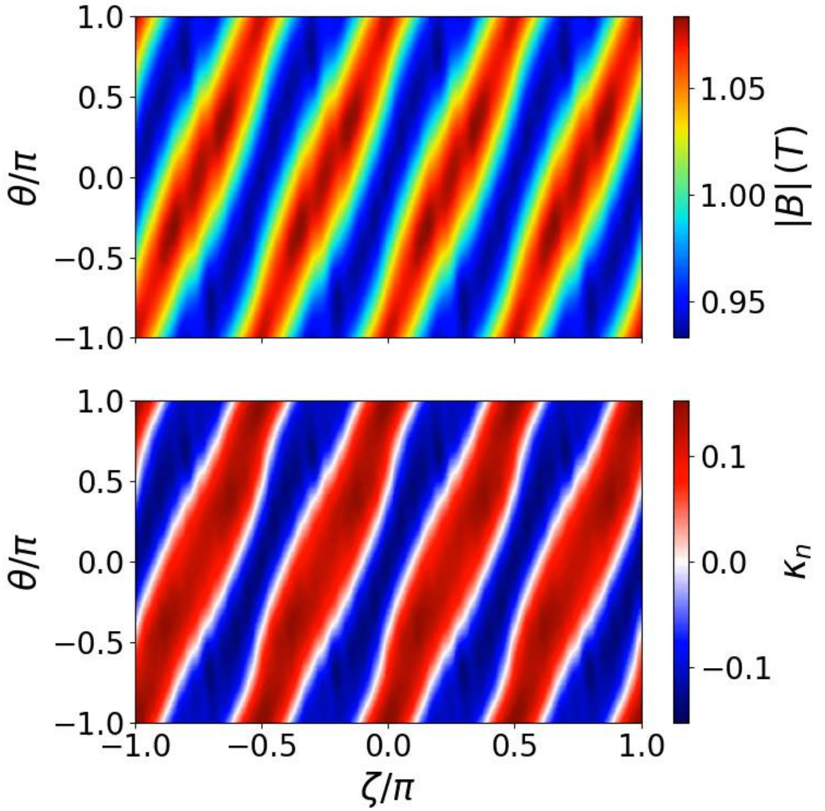
Trapped Electron Mode (TEM)

- Kinetic response of trapped particle (drift) causes an electric field whose **ExB** drift can amplify the wave.



Good overlap of magnetic wells with bad curvature





- Trapped Electron Mode (TEMs) are excited when the electron precession goes in the same direction as the drift wave
- Trapped particles are located in magnetic wells (low field regions)
- In HSX, magnetic wells overlap with regions of bad (neg.) curvature

$same\ direction$ $\kappa_n < 0$ → bad curvature

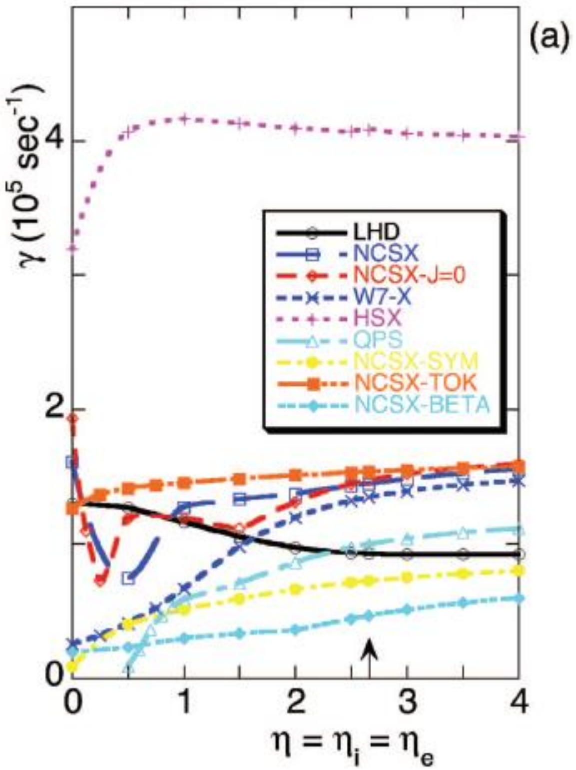
$opposite\ direction$ $\kappa_n > 0$ → good curvature

HSX is linearly unstable against TEMs (and ITG modes)!

- HSX has the largest growth rates for TEM (low η) and ITG modes (high η) of all stellarators

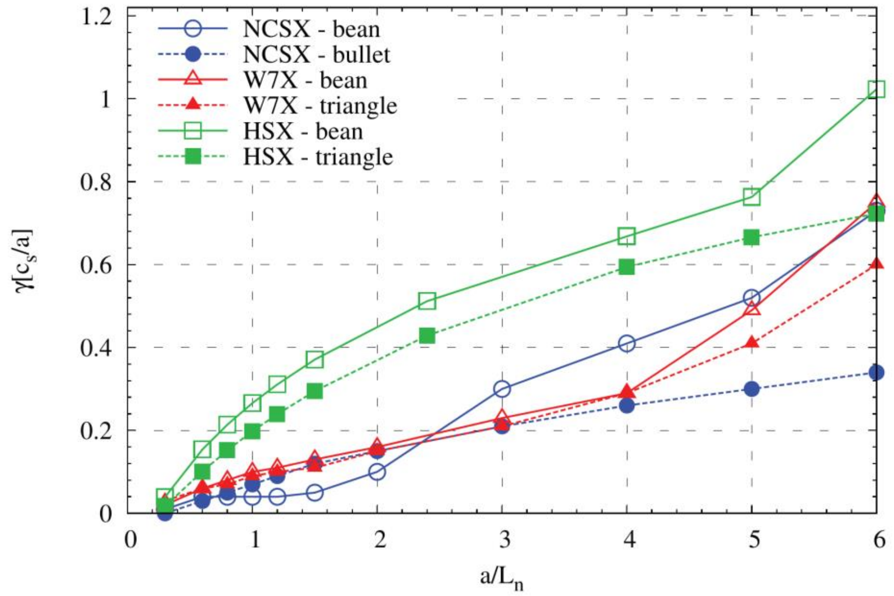
- Larger TEM growth rates in HSX than in W7-X!

- Linear growth rates and non-linear heat fluxes increase with the density gradient

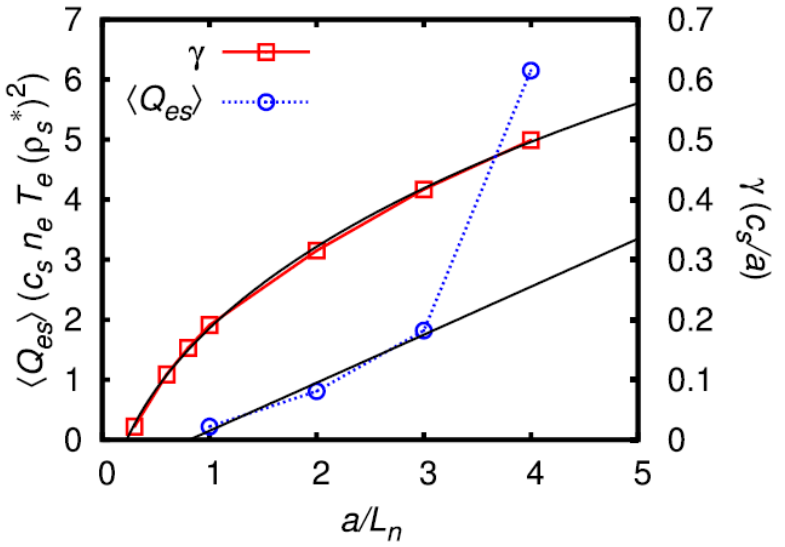


Rewoldt, Ku, and Tang Phys. Plasmas **12**, 2005

$$\eta = \frac{\nabla T/T}{\nabla n/n}$$



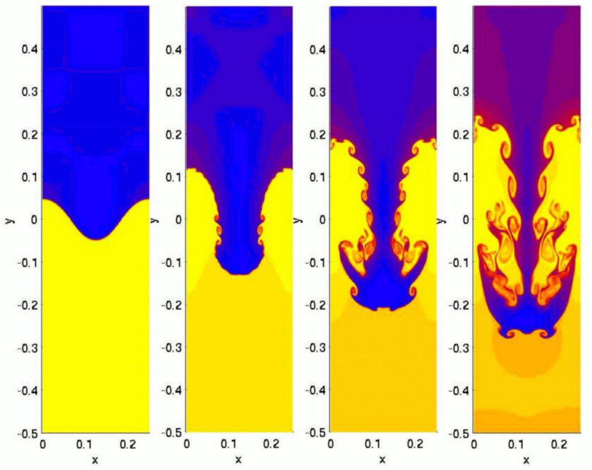
J. Proll et al PPCF **58** (2015)



B. Faber et al Phys. Plasmas 22, 072305 (2015)

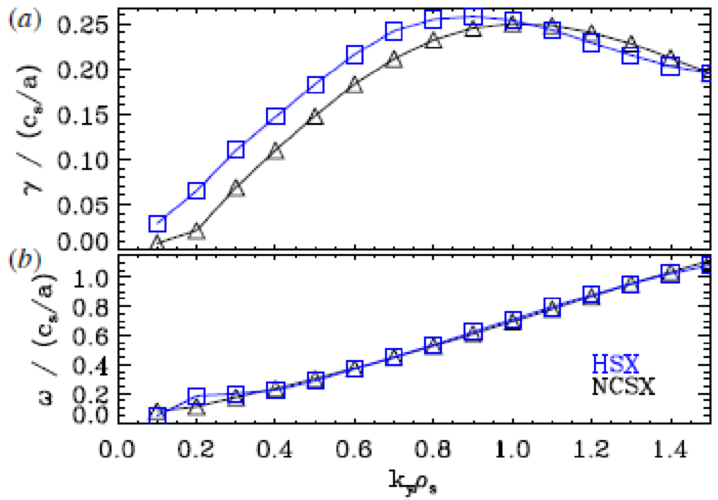
Non-linear physics are important when studying turbulent transport

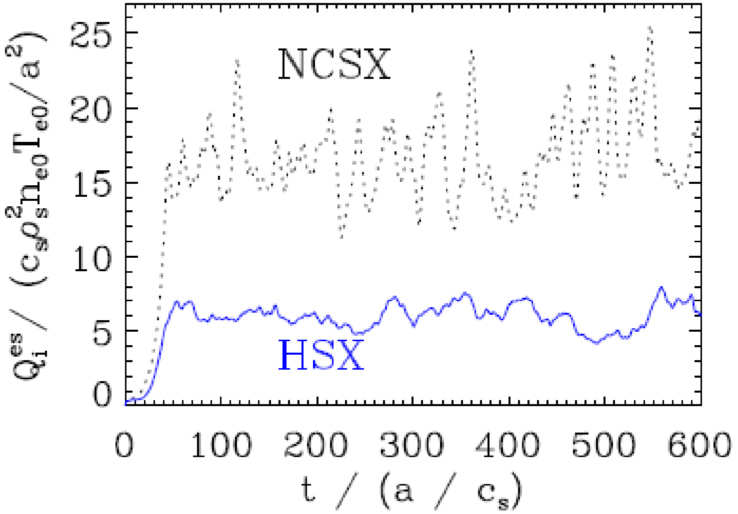
- Linear ITG growth rates are predicted to be larger in HSX than in NCSX, However, the non-linear heat fluxes are smaller in HSX!



Rayleigh Taylor instability present when a dense fluid is above a lighter one

Secondary Kelvin-Helmholtz (KH) instability (velocity shear) limits growth of primary Rayleigh-Taylor instability





I. J. McKinney, J. Plasma Phys. (2019), vol. 85, 905850503

Outline

- History of HSX
- Design and construction
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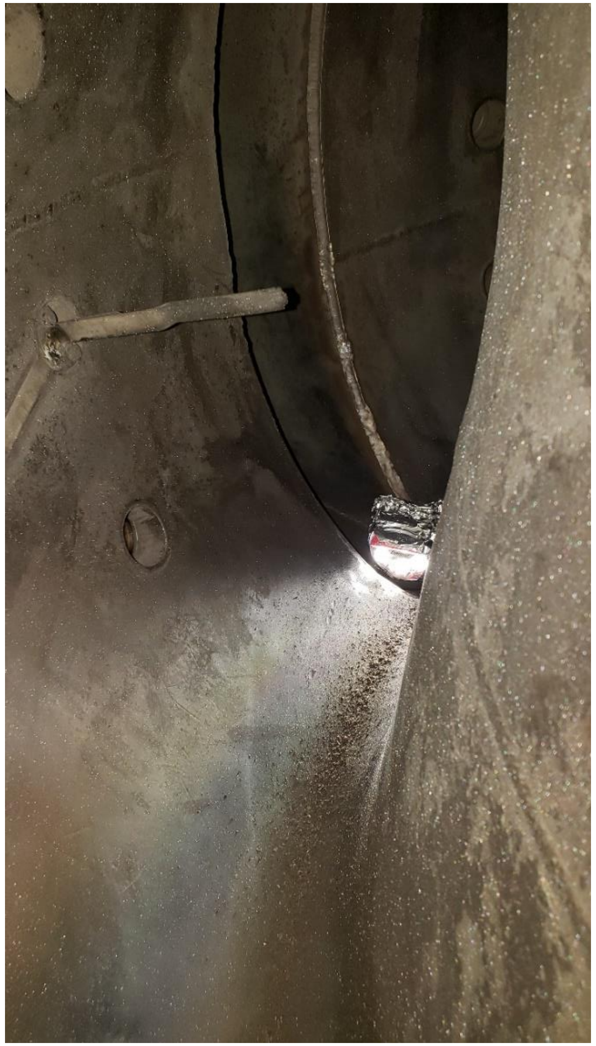
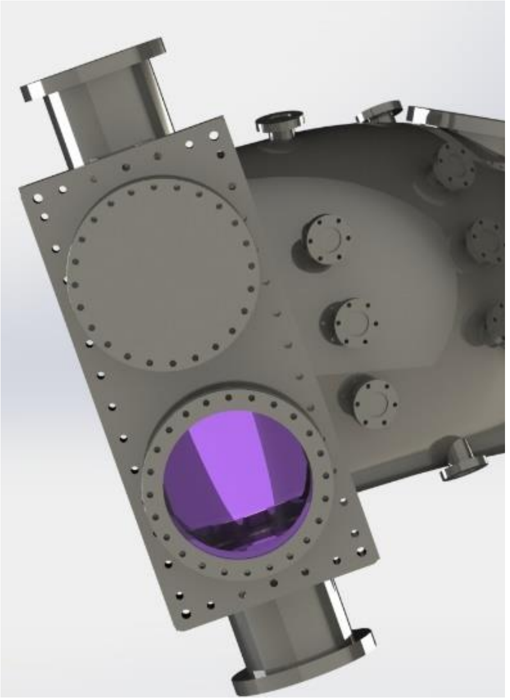
First wall conditioning

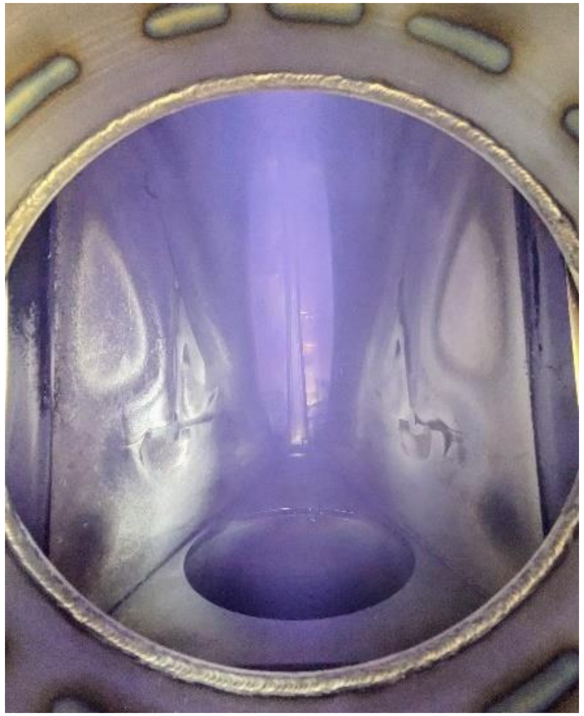
- Significant amount of dust and debris found inside of HSX after 20 years of operation
- Cleaning with a rotary brush and vacuum cleaner performed



Baking and glow discharge cleaning system

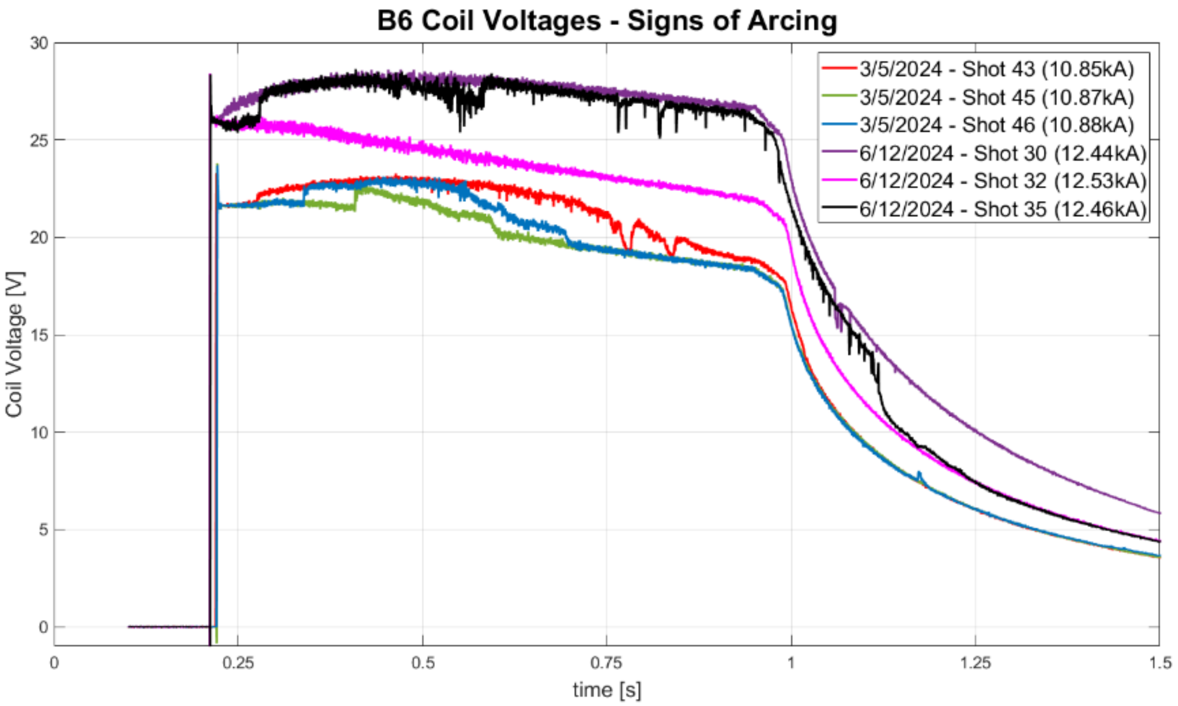
- Baking of the vessel at 50 degC routinely performed
- Glow discharge cleaning using Ar and He plasmas
- Excellent vacuum conditions obtained (~2×10^{-8} torr)





Coil arcing problems

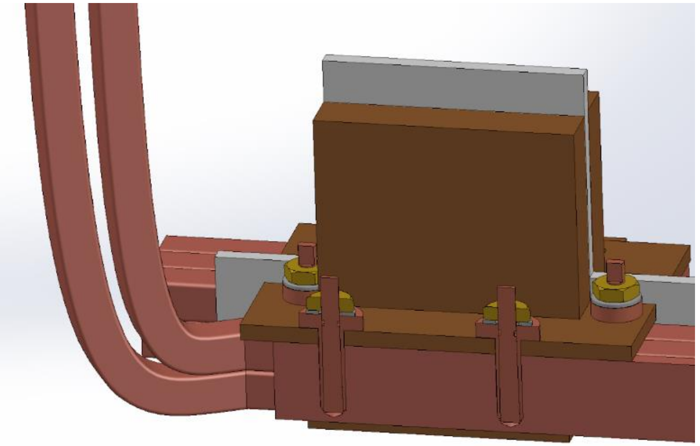
- Coil feeds (brass cages) have poor connection to the set of six copper conductors.
- Arcing and jumps in voltage across the coil is observed
- Burn marks at the coil feeds and on the coil identified

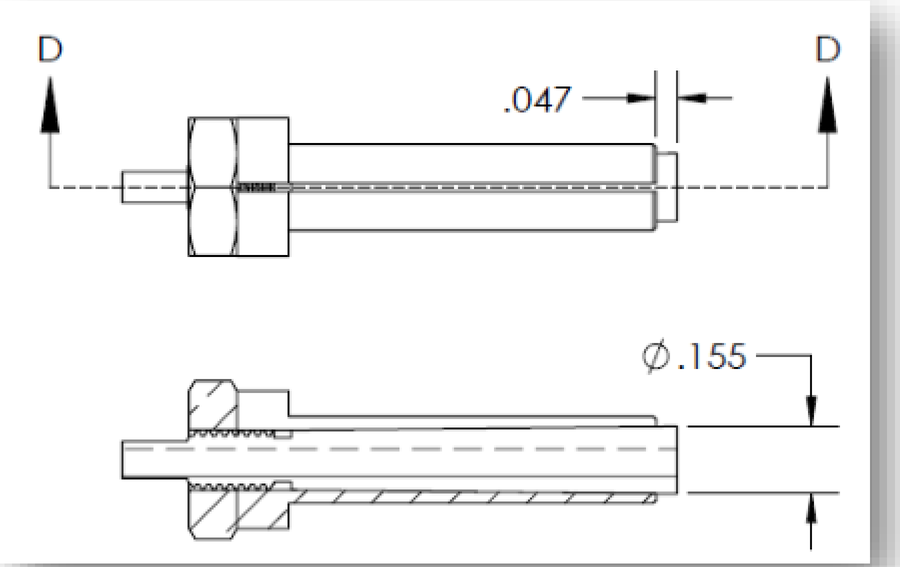


Coil feed repair using "expansion sleeves"

Helically Symmetric eXperiment

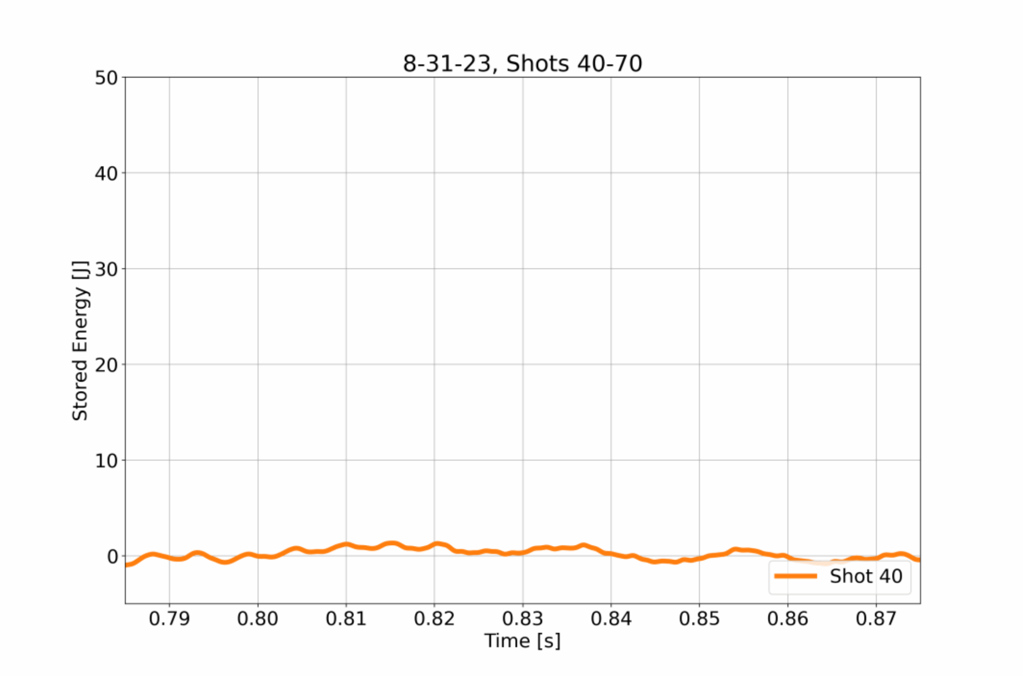
- Expansion sleeves designed that improve connection between brass feed and the copper conductors
- "Sleeves" successfully installed and fix the problem.





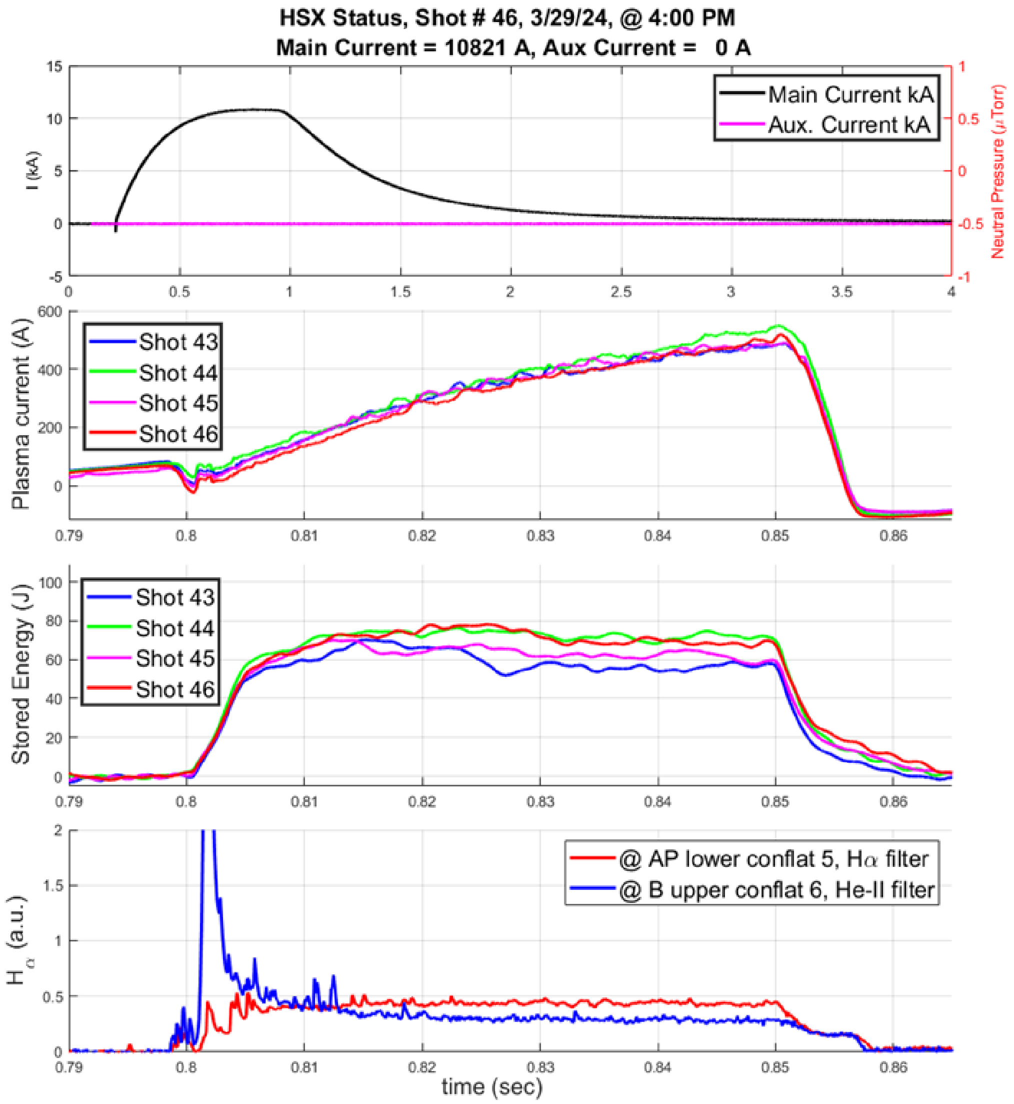
HSX has resumed plasma operations

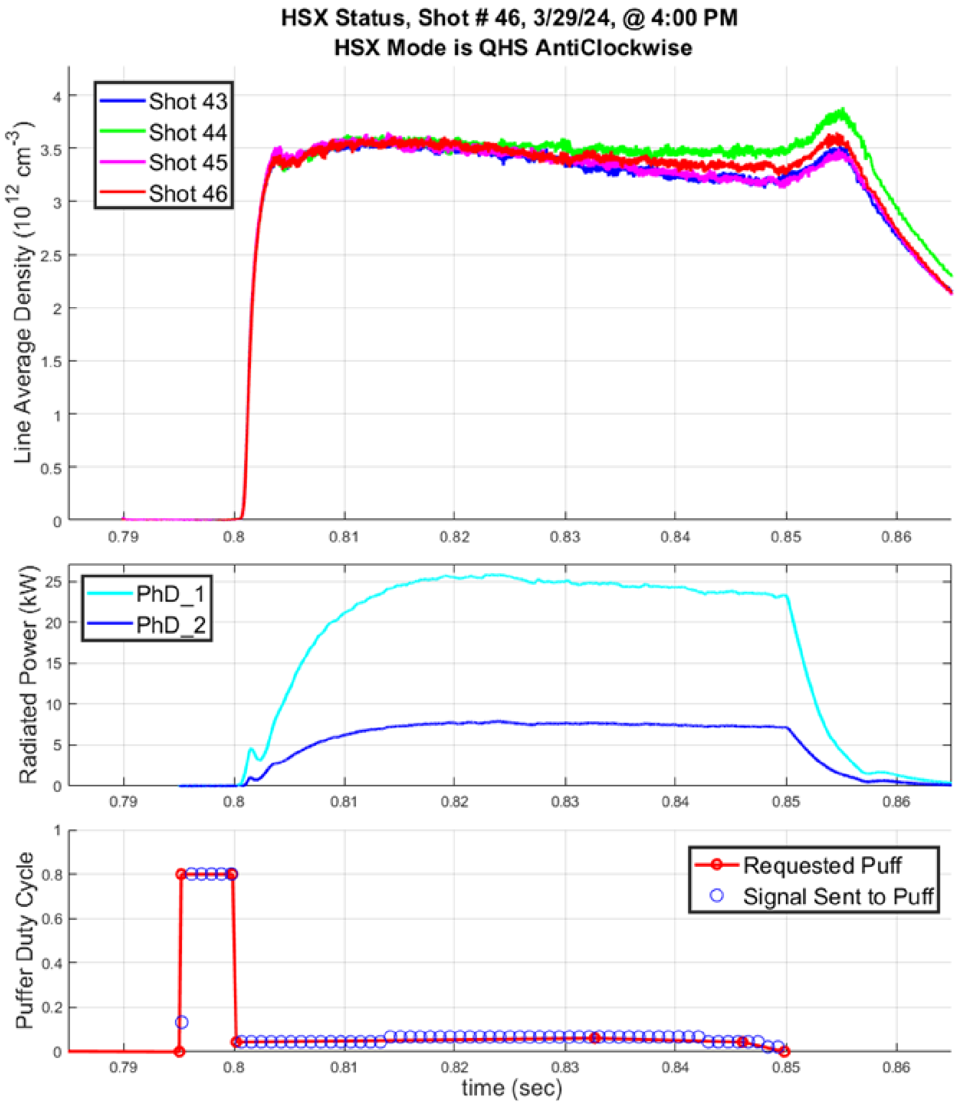
- Start of plasma operation in August 2023
- First shots show uncontrolled density rise due to outgassing
- Plasma conditions improve from shot-to-shot without need of boronization



Courtesy Patrick O'Neill

Stable, reproducible plasmas routinely produced

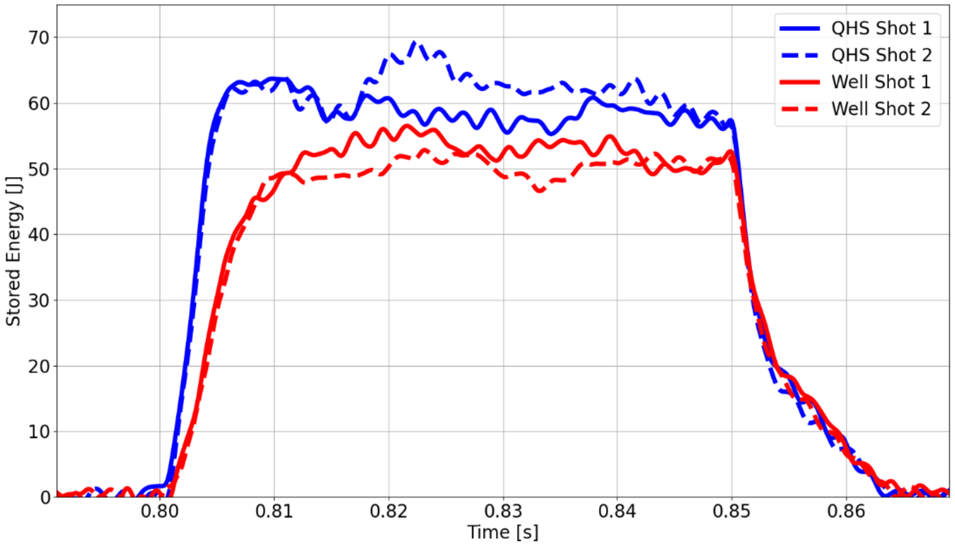


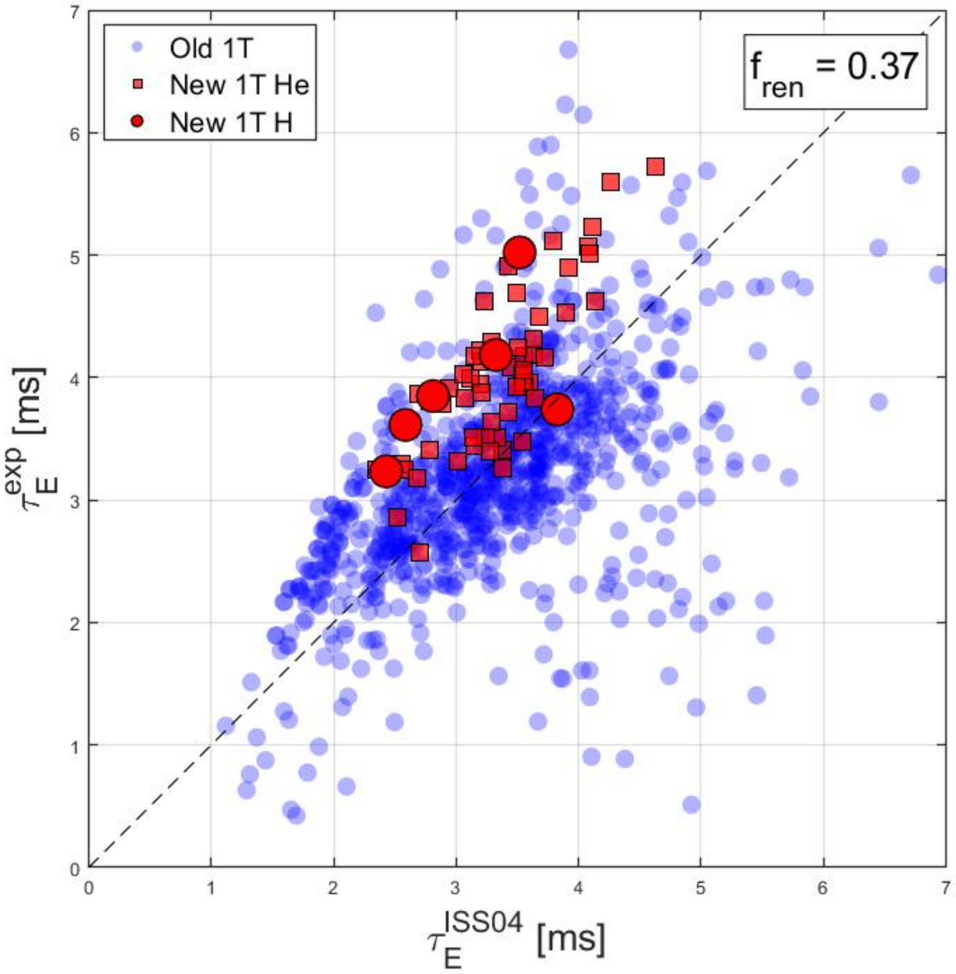


Confinement times commensurate with previous high-performance discharges

- Energy confinement time determined based on the decay of the stored energy shortly after ECRH turn-off
- Comparison based on ISS04 scaling suggests confinement improvement by about 20%

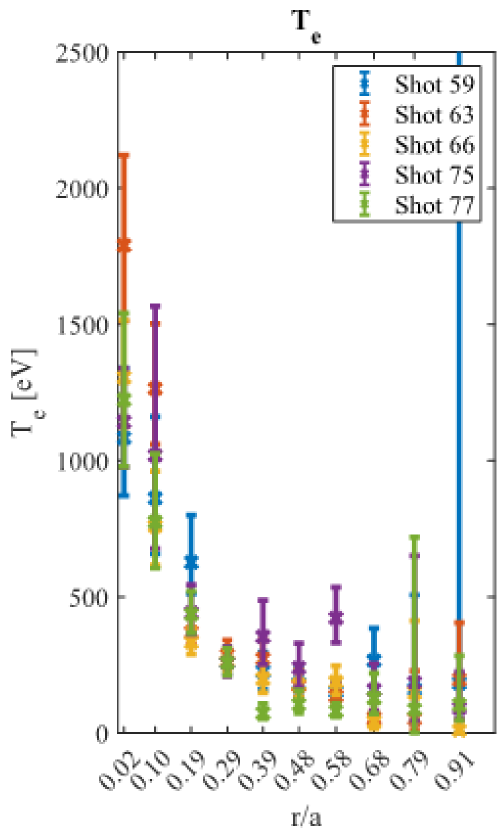
$$\tau_{ISS04} = 0.134 \cdot f_{ren} R^{0.64} a^{2.28} n^{0.54} B^{0.84} \iota_{2/3}^{0.41} P^{-0.64}$$

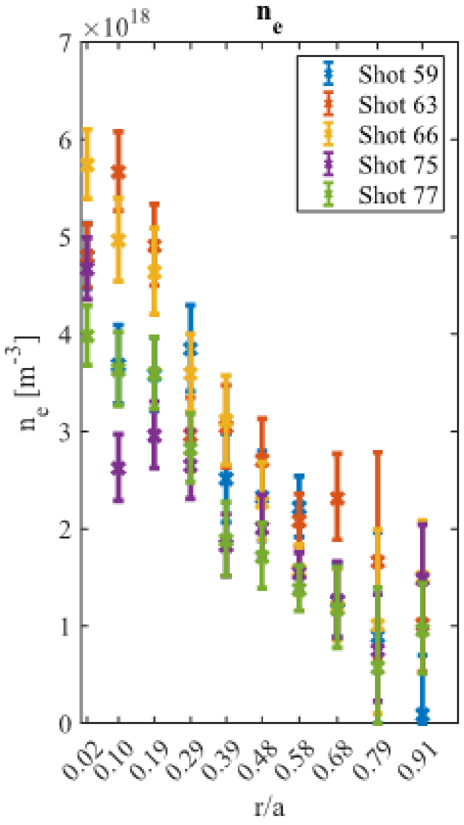




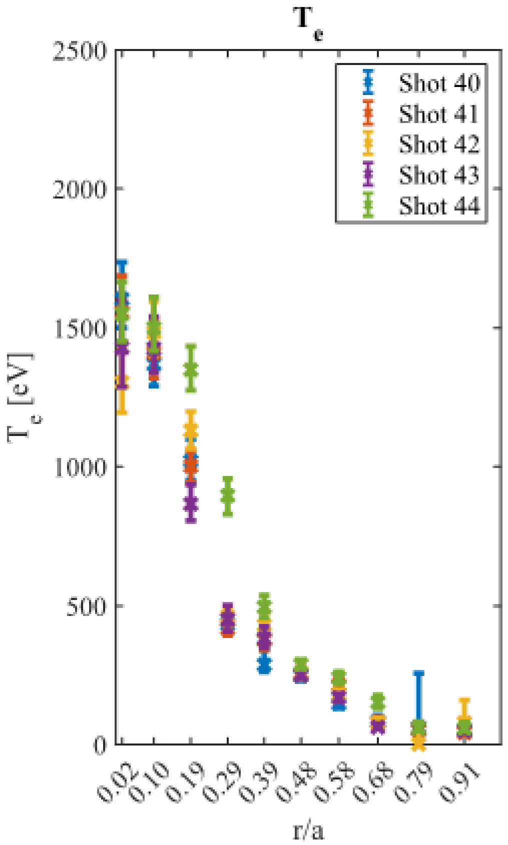
Profiles suggest higher performance after "wall reset"

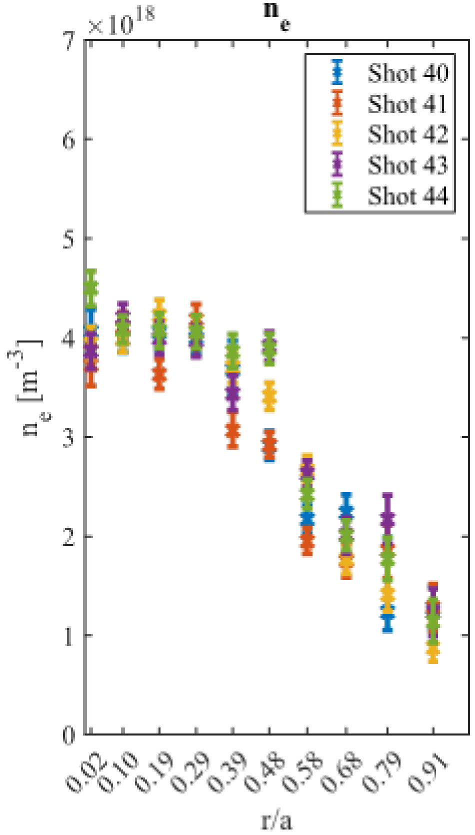
Data from 2024-03-29: He plasmas, 1 T QHS, 50 kW, Shots 40 – 44





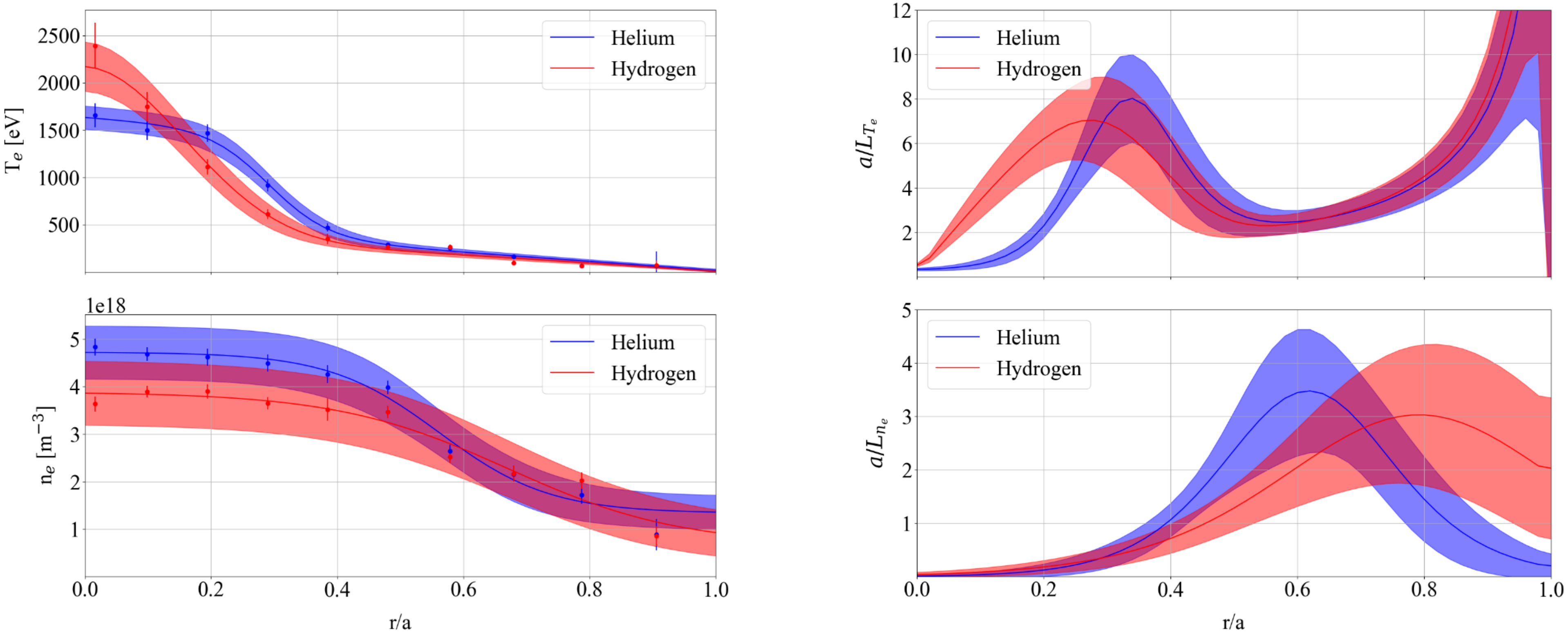
QI





- Temperature peaking starts further out during new experiments

Experiments in Hydrogen and Helium

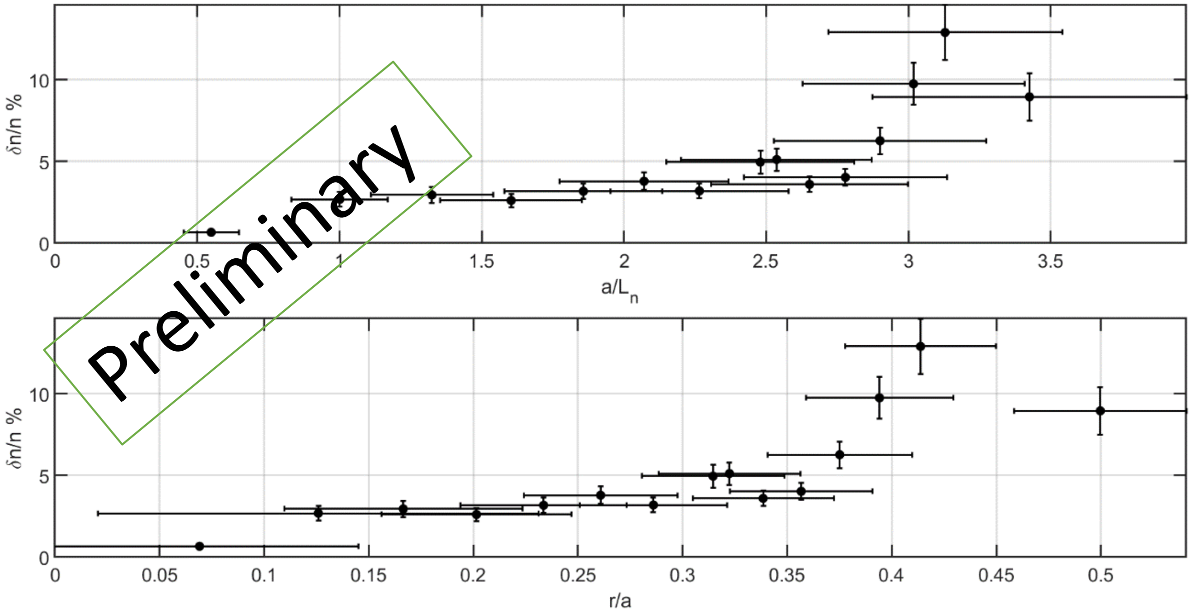


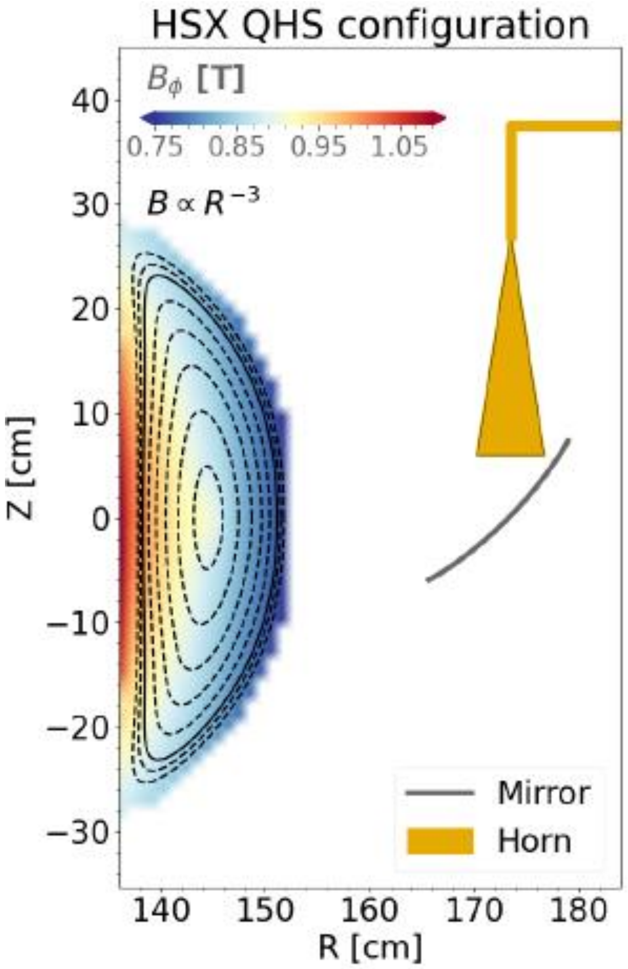
- Helium is much easier to control (reduced outgassing from the walls)
- Changes in the density and temperature gradient length suggest different transport mechanisms

→ Additional experiments and gyrokinetic modelling is ongoing

Density fluctuation levels scale with the density gradient

- O-mode, perpendicular incidence reflectometer
- Sensitive to densities in the range
  $2.8 - 8 \times 10^{18}\mathrm{m}^{-3}$
- Initial results suggest that density fluctuations increase with the density gradient, **but** detailed ray tracing and full-wave models needed

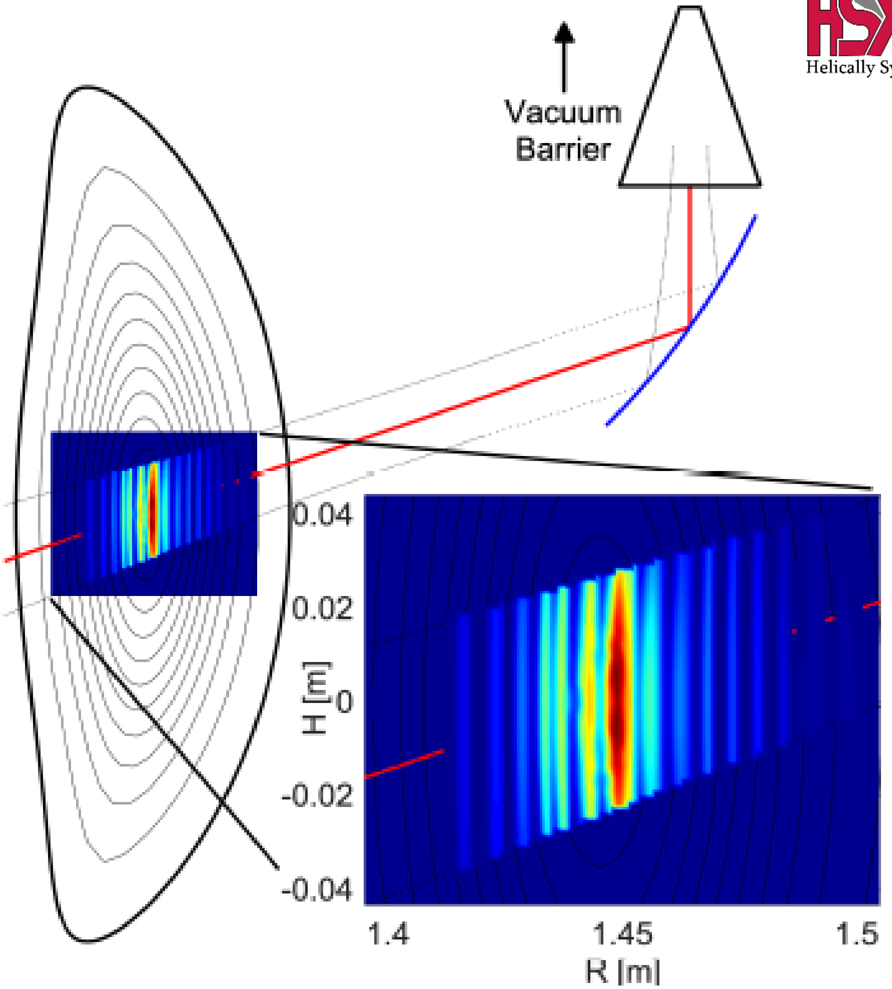


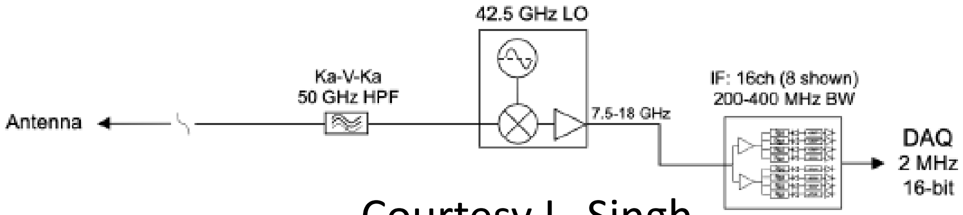


Courtesy H. Hillebrecht, X. Han

CECE diagnostic of HSX

- 16 channel system that covers the low- and high-field side
- Correlation of adjacent channels used to isolate temperature fluctuations from thermal plasma noise
- Multi-pass scattering of the radiation allows analysis of T_e fluctuation in optically thin plasmas on the high field side

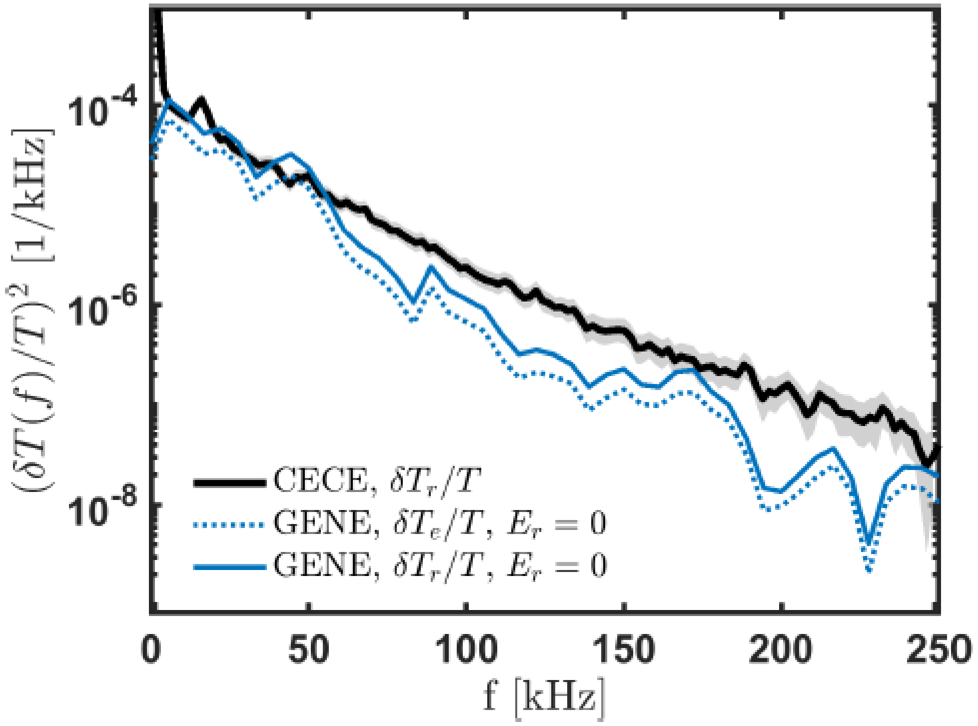


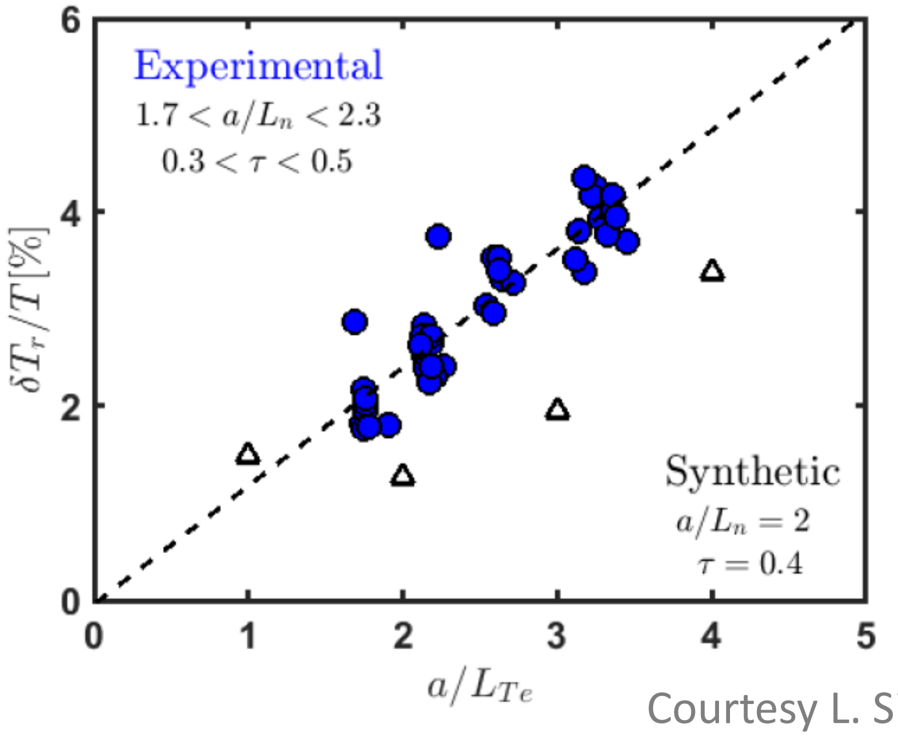


Courtesy L. Singh

Observed Temperature fluctuations scale with a/L_{Te}

- CECE system sensitive to $k_y\rho_s < 0.5$
  → observation of fluctuations points towards TEM
- Observed frequency spectra and a/L_{Te} dependence on fluctuation levels roughly agrees with synthetic data based on non-linear gyrokinetic modeling results by GENE





Courtesy L. Singh

Outline

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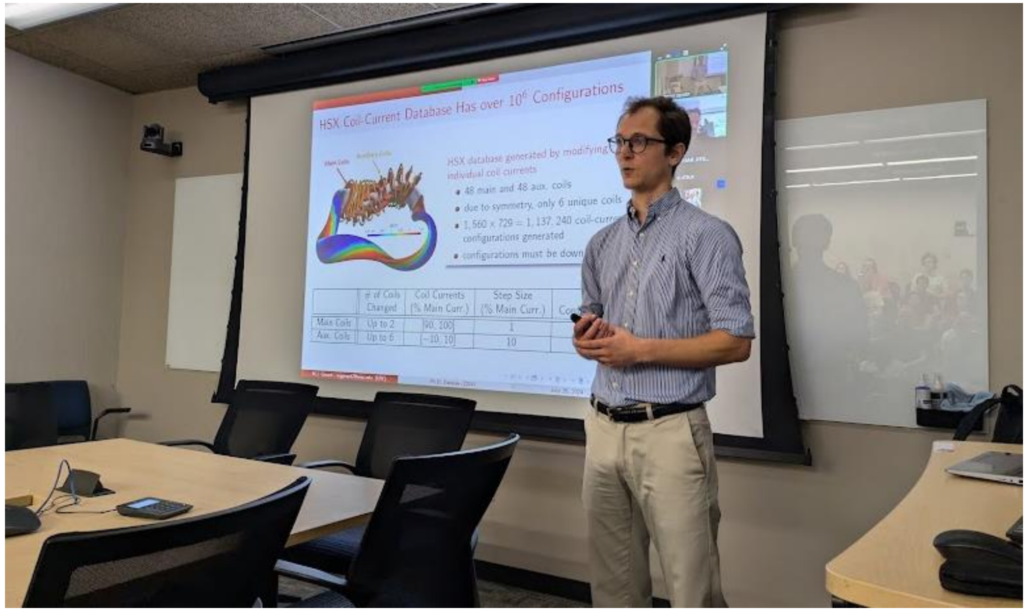
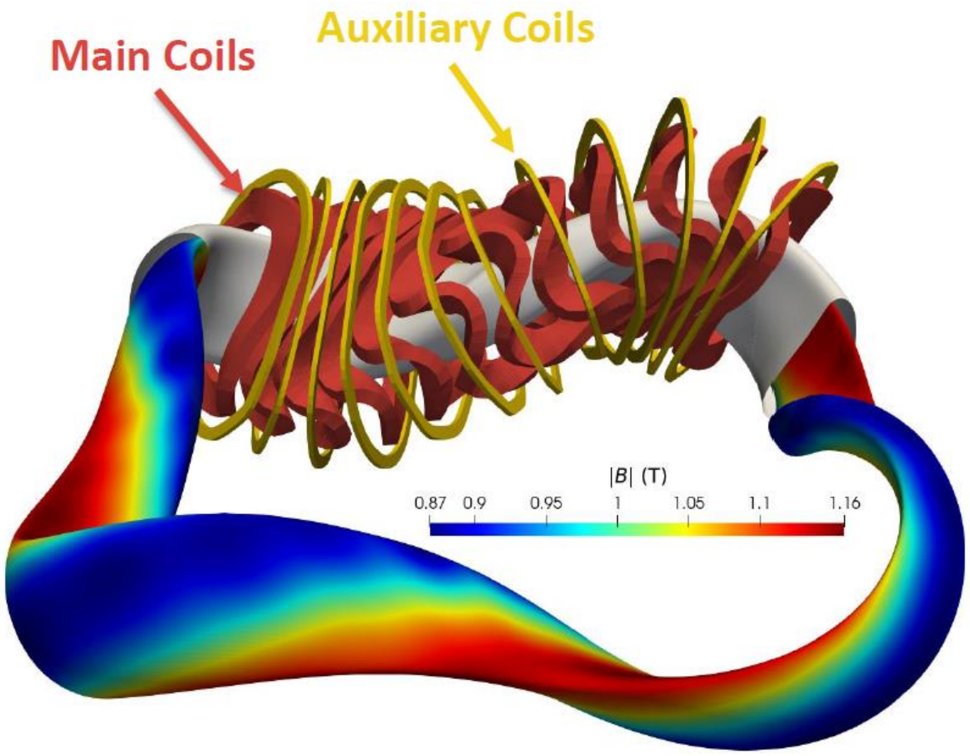


HSX coil-current database has over 10^6 configurations



- Potential for TEM optimization investigated with coil-current database
  - 48 main and auxiliary coils, but only 6 unique coil shapes
  - Coil currents varied to generate different equilibria
  - VMEC, NEO and Boozer mode spectra computed for 1,137,240 configurations

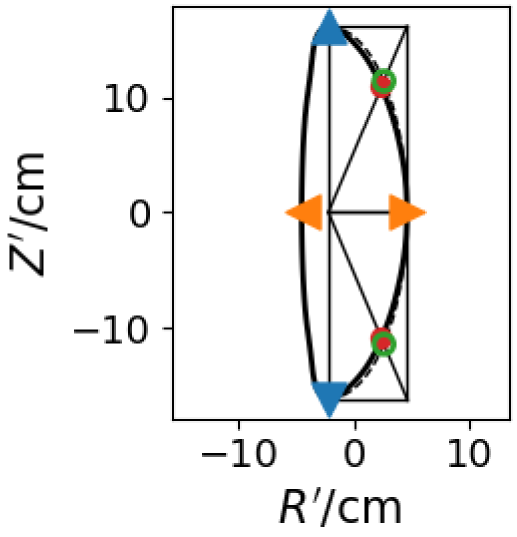
M.J. Gerard *et al* 2023 *Nucl. Fusion* **63** 056004

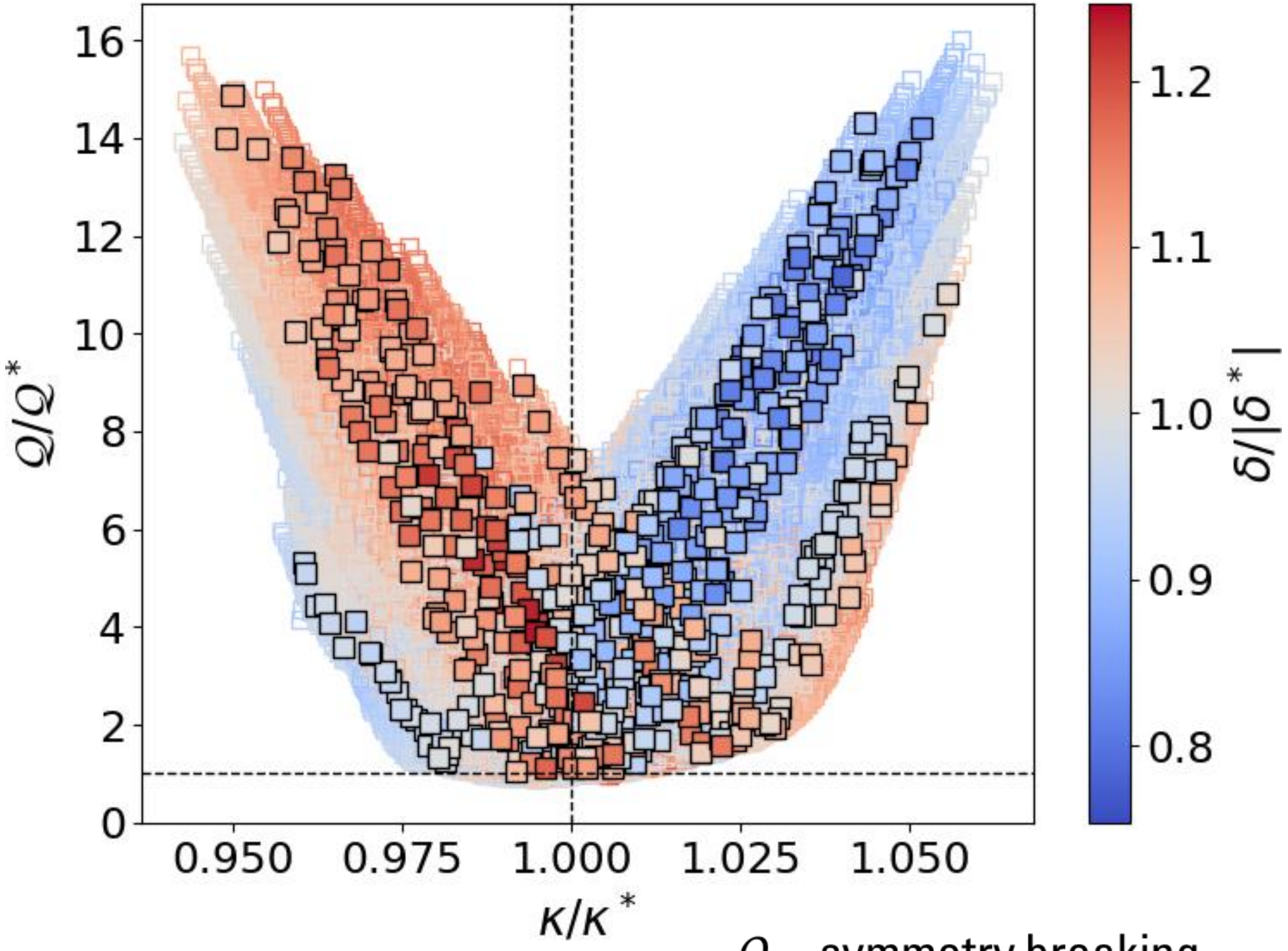
Flux-surface shaping parameters sort configuration space

- Shaping parameters adapted from tokamak applications[1]

[1]T.C. Luce, PPCF, 55 095009 (2013)

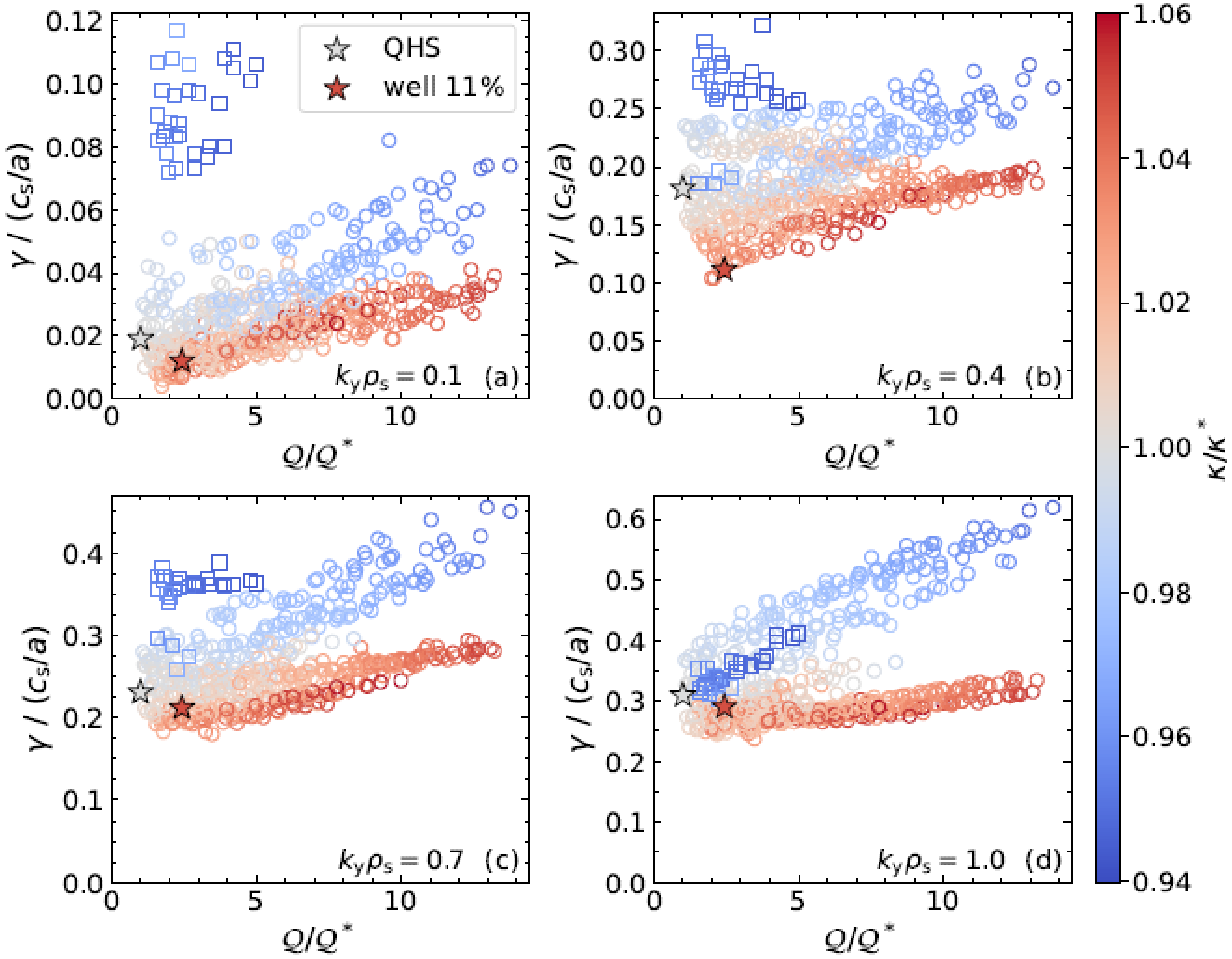
- Parameters defined by flux surface extrema points

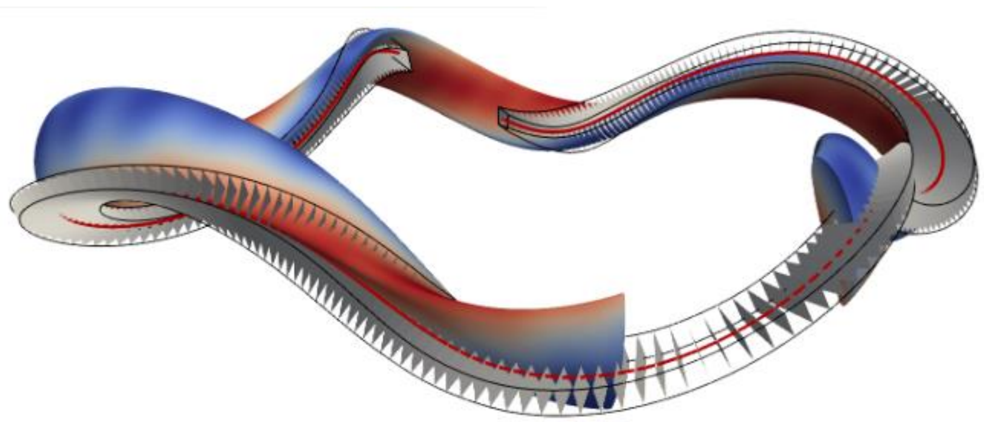




Q – symmetry breaking
κ – elongation

GENE calculation of linear growth rates





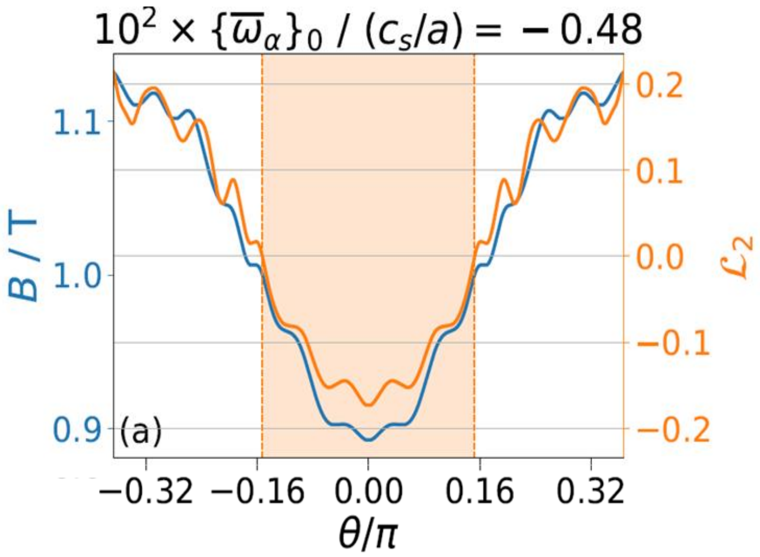
- Growth rates reduce with increasing elongation
- Breaking quasihelical symmetry increases growth rates

Q – symmetry breaking
κ – elongation

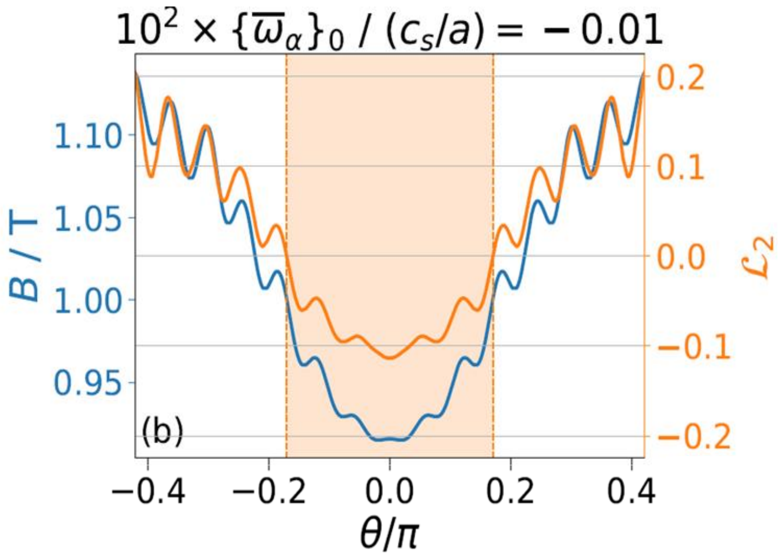
M.J. Gerard et al. *Phys. Plasmas* **31**, 052501 (2024)

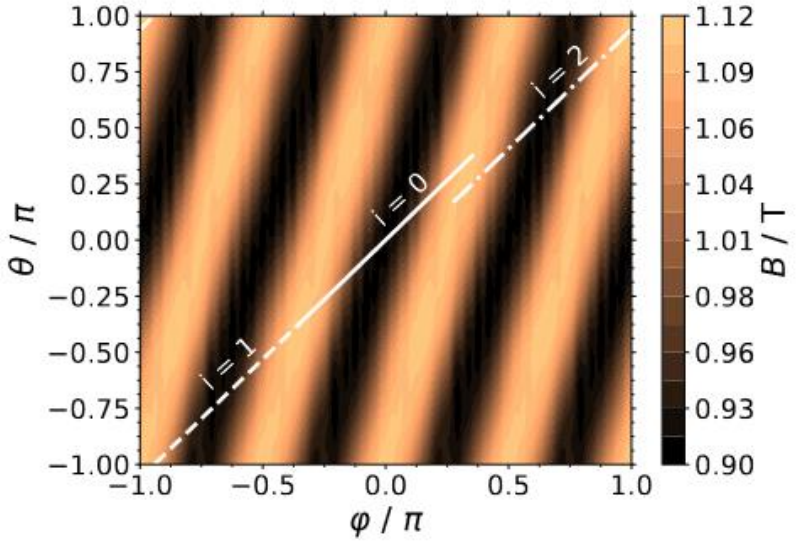
Elongation flattens magnetic trapping well

Low elongation



High elongation



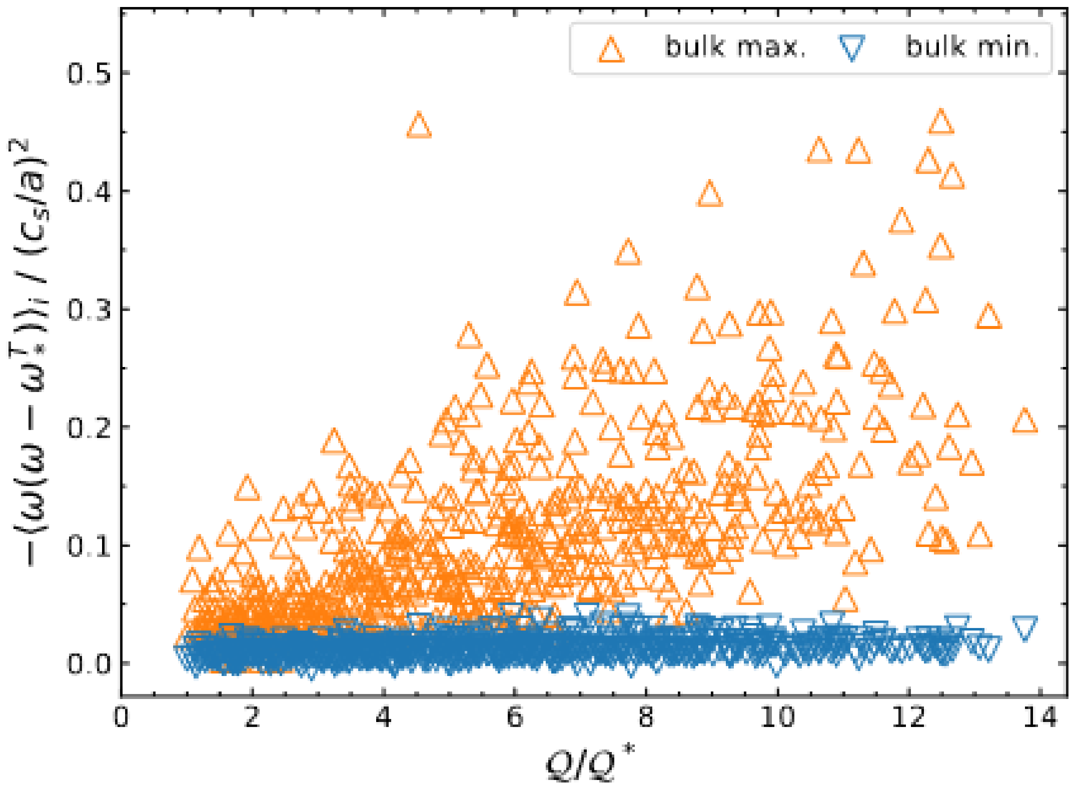


$\mathcal{L}_2$– curvature

Higher elongation excites more symmetry-conserving boozer modes which flatten the helical well
→ Less deeply trapped particles in the region of negative curvature

M.J. Gerard et al. *Phys. Plasmas* **31**, 052501 (2024)

QH symmetry reduces variance across trapping wells



$\langle\omega(\omega-\omega_*^T)\rangle$ – velocity-space-averaged TEM resonance operator

M.J. Gerard et al. *Phys. Plasmas* **31**, (2024)

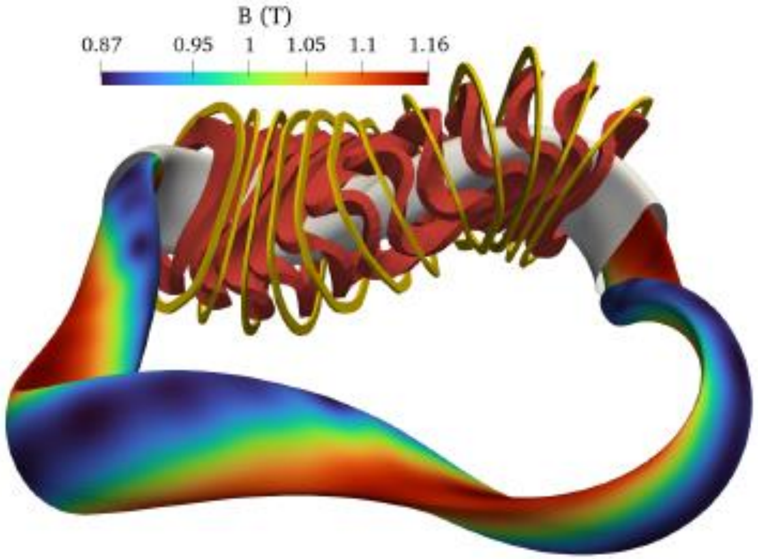
Energy transfer described by:

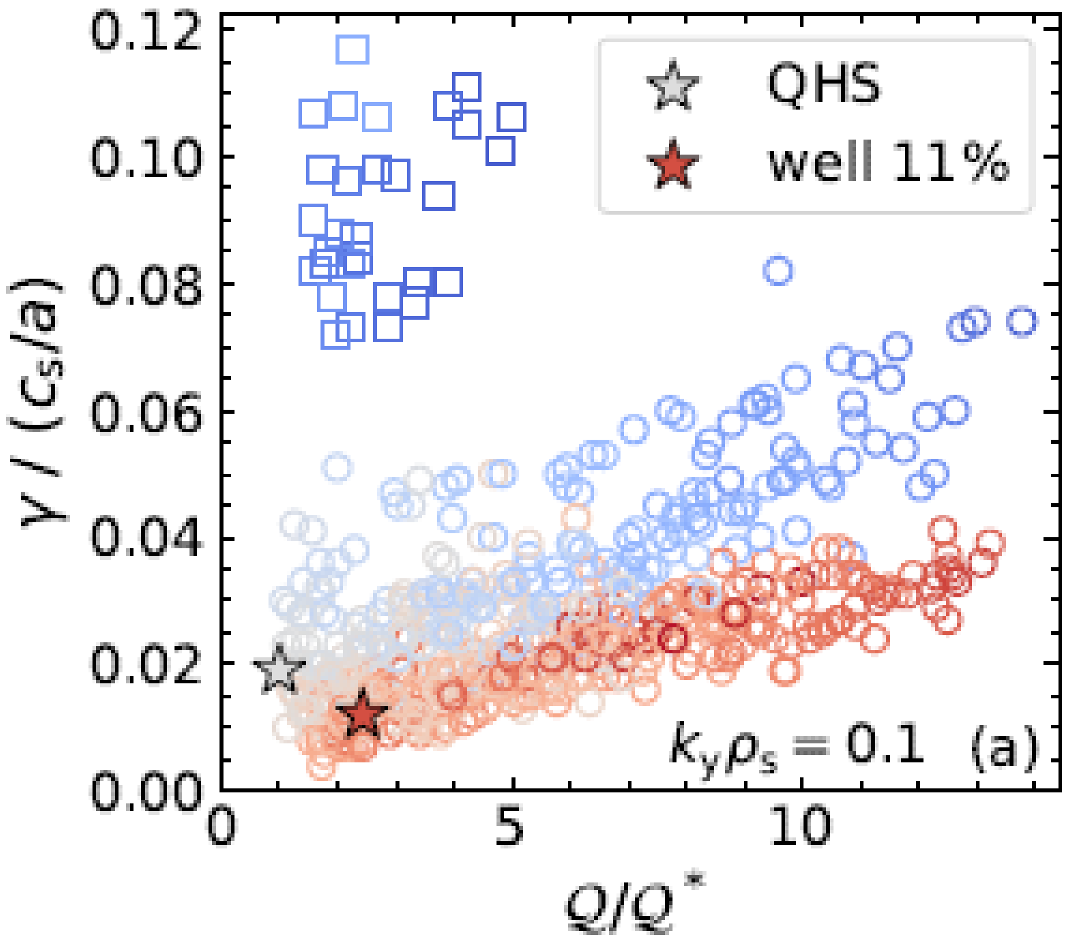
$$P_e = \frac{\pi e^2}{T_{e0}} \int_{-\infty}^{\infty} \frac{d\ell}{B} \int_{-\infty}^{\infty} \omega\left(\omega - \omega_{*e}^T\right)\delta\left(\omega - \overline{\omega}_{de}\right)|\overline{\Phi}|^2 f_{e0}\, d^3v$$

- Breaking QH symmetry results in highly resonant trapping wells

Easy-to-implement at HSX: "Well" configuration

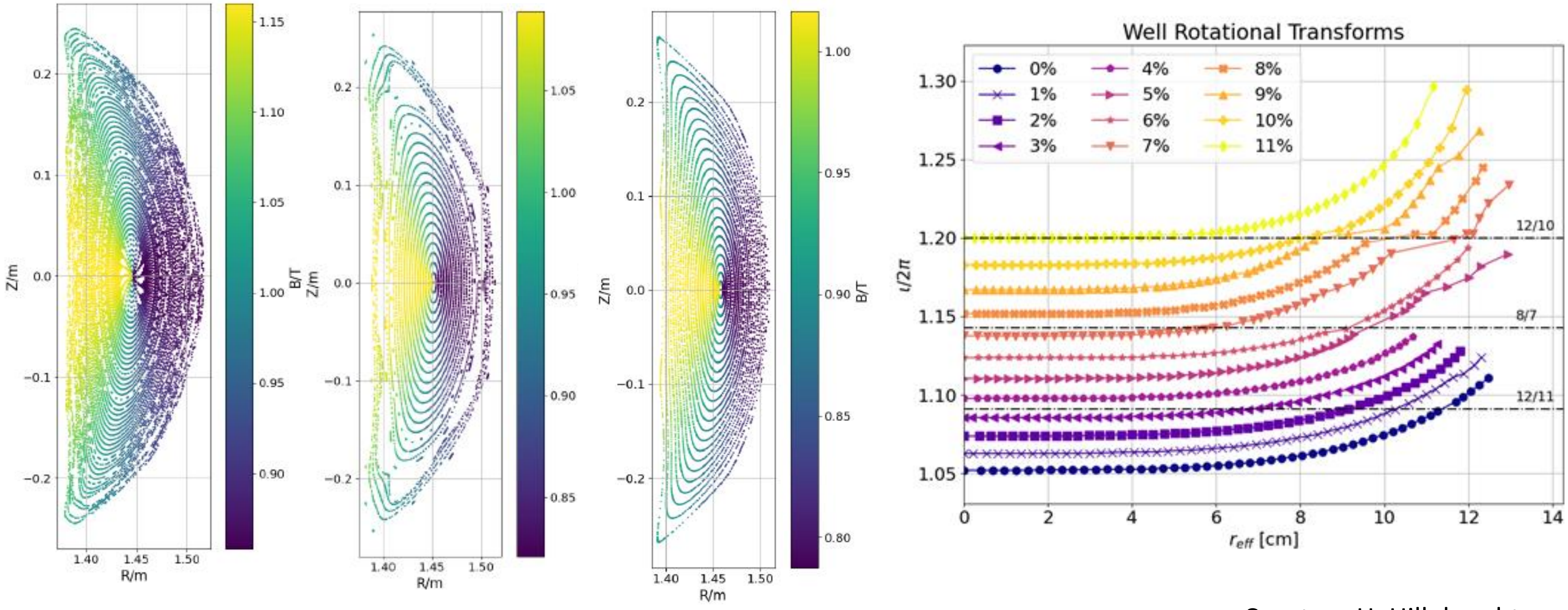
- Well configuration is obtained by operating all planar auxiliary coils in the direction opposite to the main 3D field coils.
- Well configuration offers enhanced elongation, good quasi-symmetry and reduced growth rates





Well configurations exist without major islands

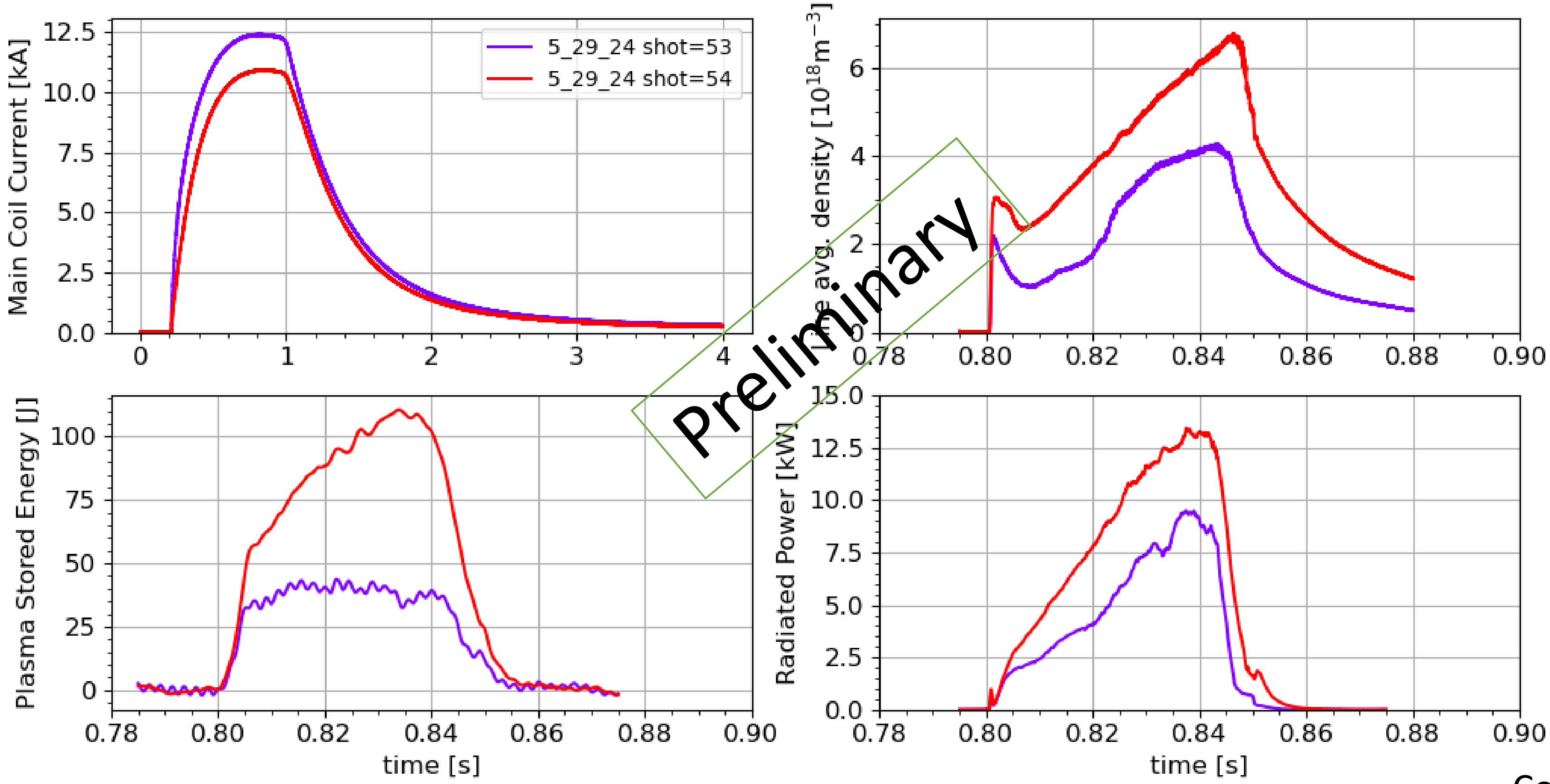
- Rotational transform increases with the well percentage
- Large 8/7 islands are avoided for configurations > 7%



Courtesy H. Hillebrecht

Preliminary comparison QHS vs 11% well

- First 1T Experiments in the 11% well configuration performed
- Successful plasma operation demonstrated but difficult to gain density control
- Plasma stored energy well below the stored energy obtained during QHS plasmas



Courtesy H. Hillebrecht

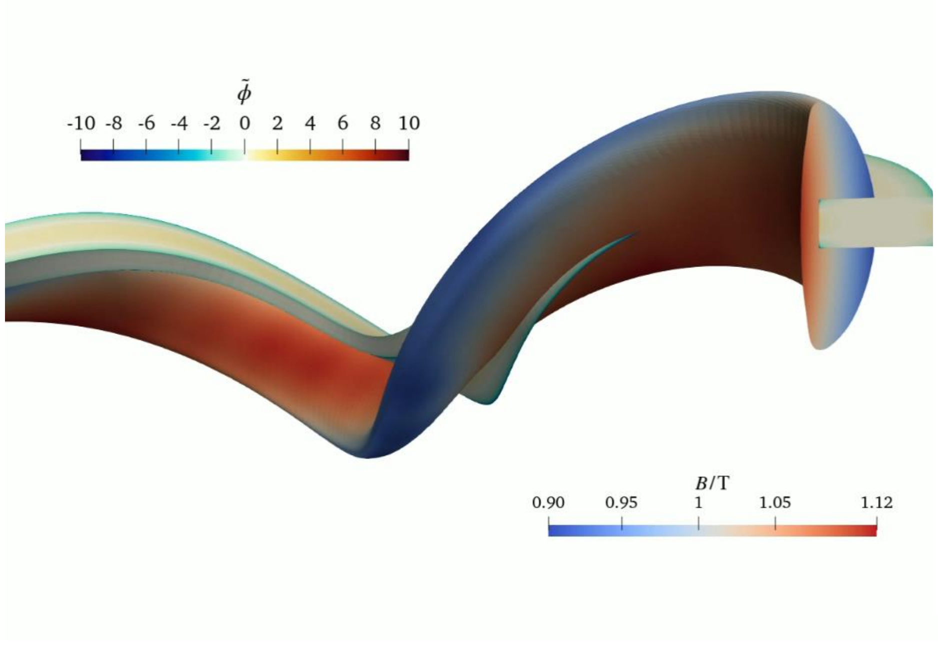
Non-linear simulations show opposite trend

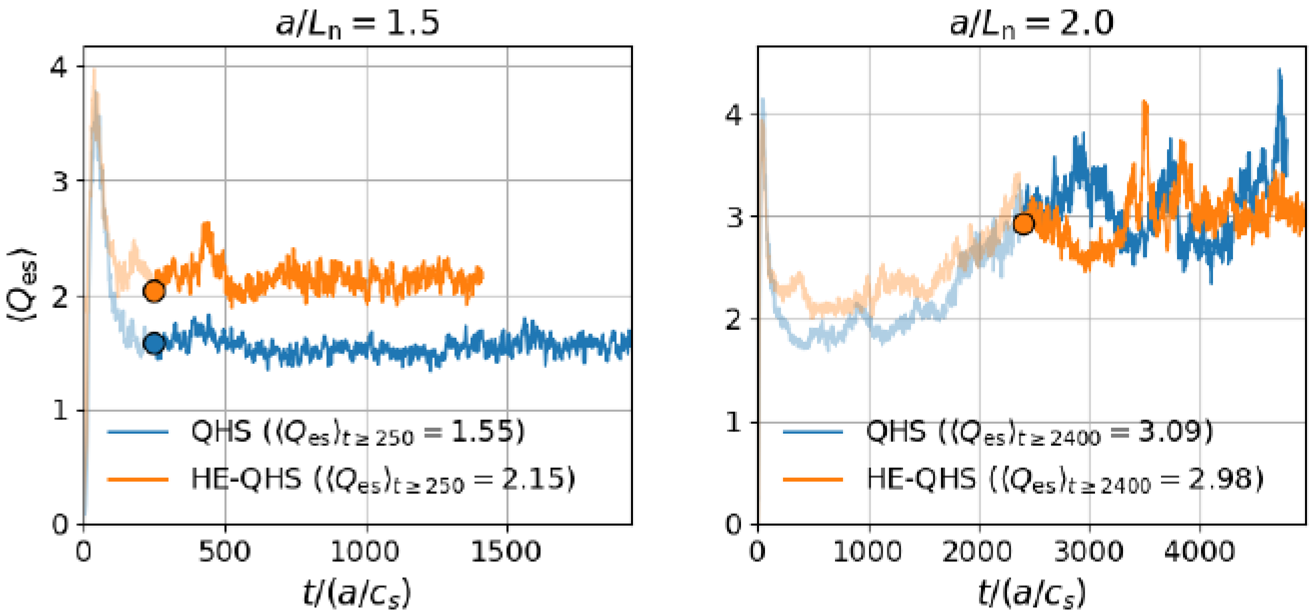
- Simulations performed for QHS and an elongated configuration (HE-QHS)
- Higher heat flux in the elongated configuration

	a/L_n	a/L_T
Ions	2	0
Electrons	1.5-2.5	2

$\beta = 5 \times 10^{-4}$ $\quad \nu = 0$

$T_\mathrm{i}/T_\mathrm{e} = 0.2$ $\quad \hat{\psi} = 0.5$



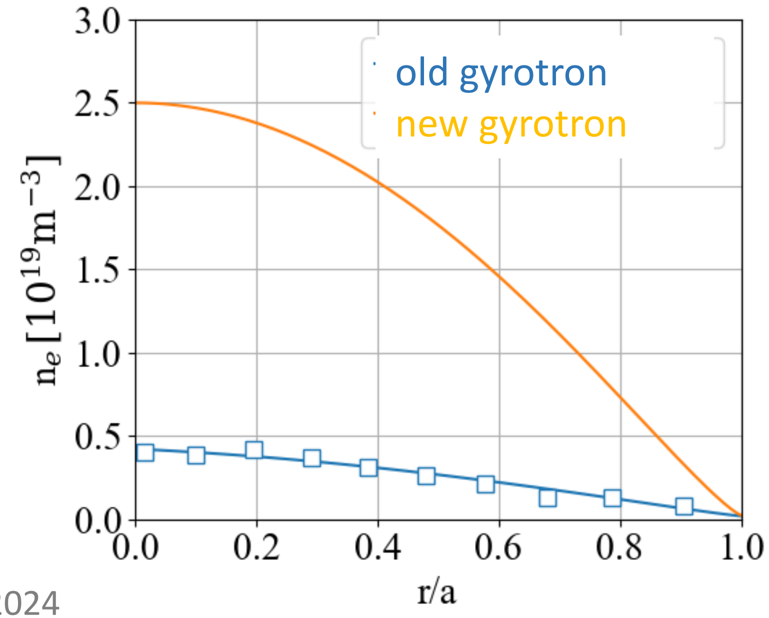


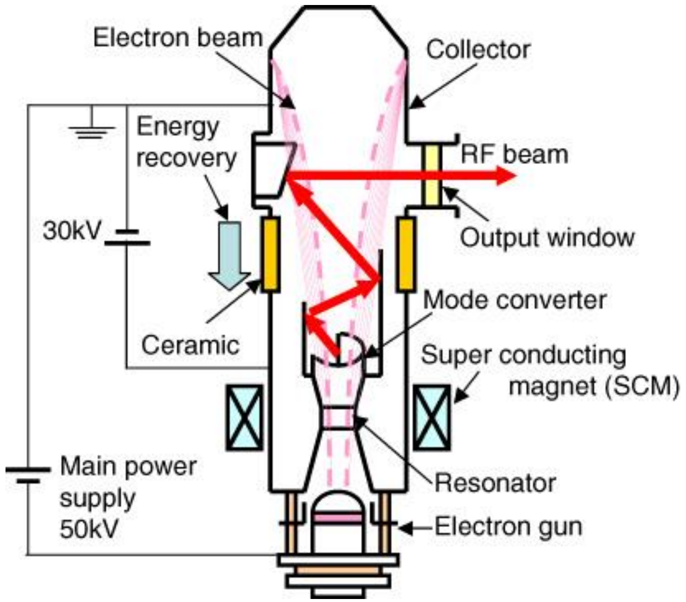
Courtesy M. J. Gerard

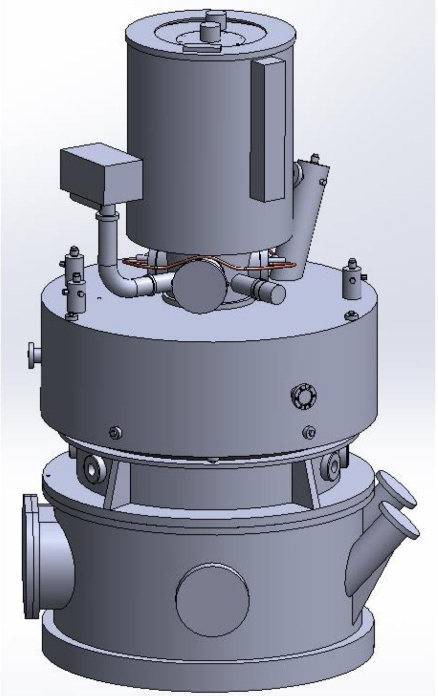
New ECRH system

70 GHz gyrotron (X2 mode, 1.25T):

- Donated by IPP Greifswald
- Offers 500 kW of power for 2s (aim: 300 kW, 0.1 s)
- 2.7T superconducting magnet
- Allows plasma operation at **3.0 x10^{19} /m^3**



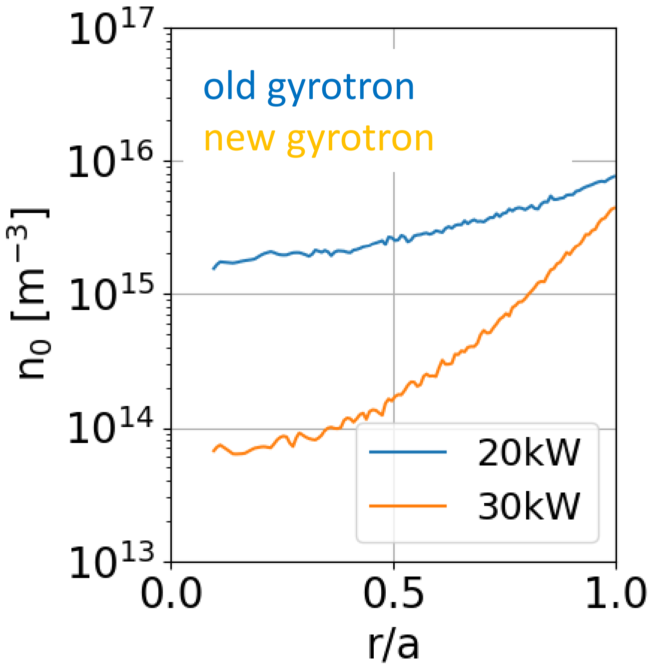


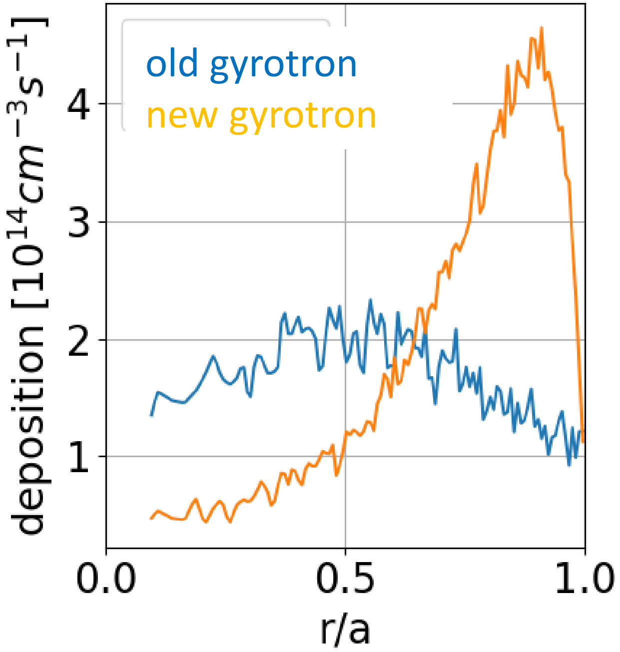


Benefits of higher density operation in HSX

- Neutral density reduced during high-density operation (shorter ionization length):
  - Reduced level of charge exchange losses
  - Reduced damping of plasma flows

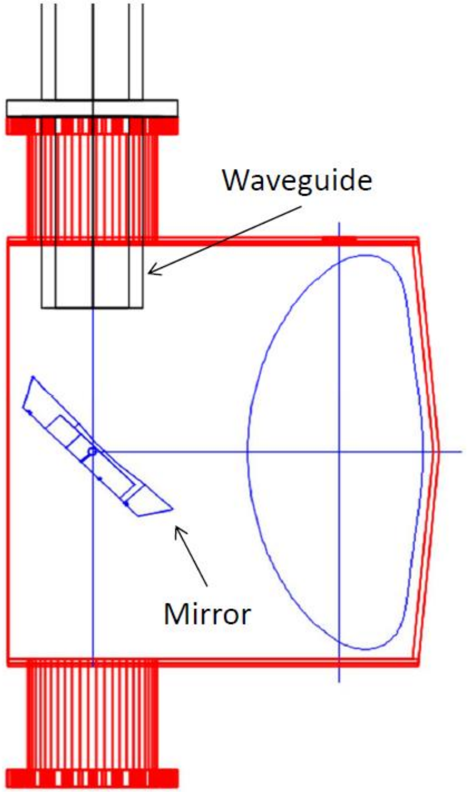
- Deposition profile shifted outwards
- Modified density profile shape expected at high-density operation (due to changed fueling profile)
- Modification of TEM growth rates

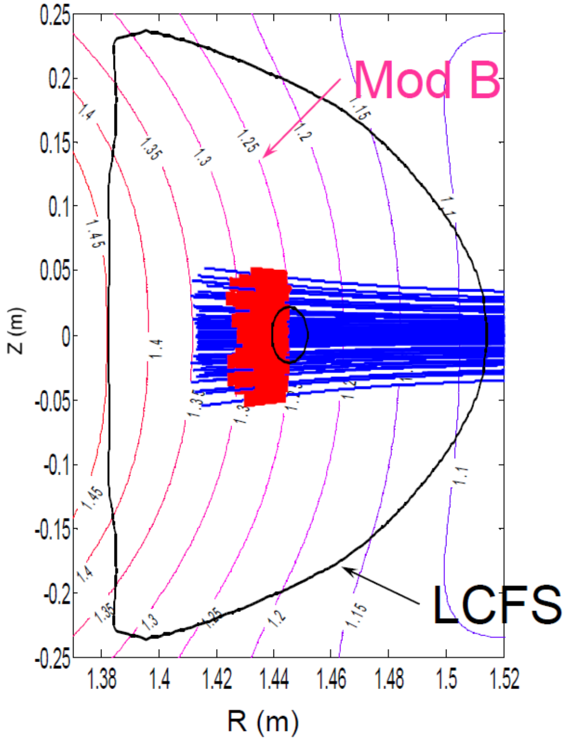


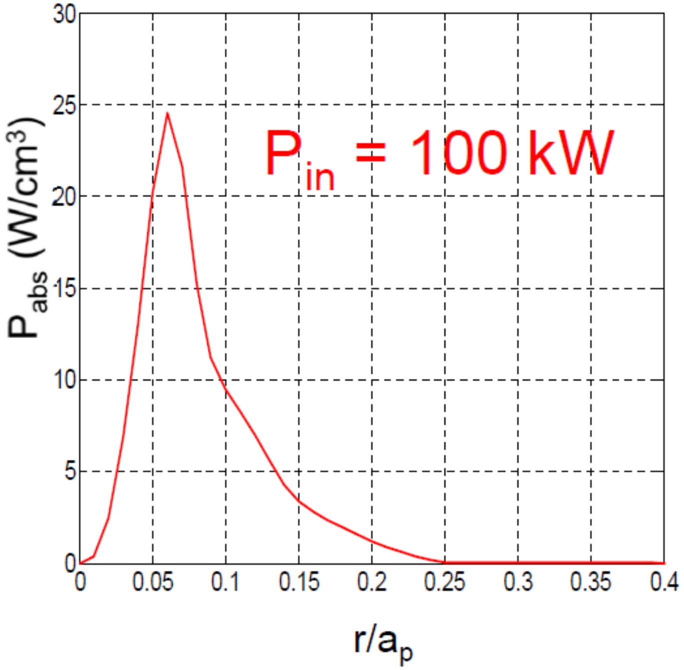


HSX-Upgrade plasmas will have ~100% ECRH absorption

ECRH Ray tracing results show that X2 heating will be absorbed very well considering higher densities.
→ Much more heating power will become available
→ Better localization of the power deposition profile



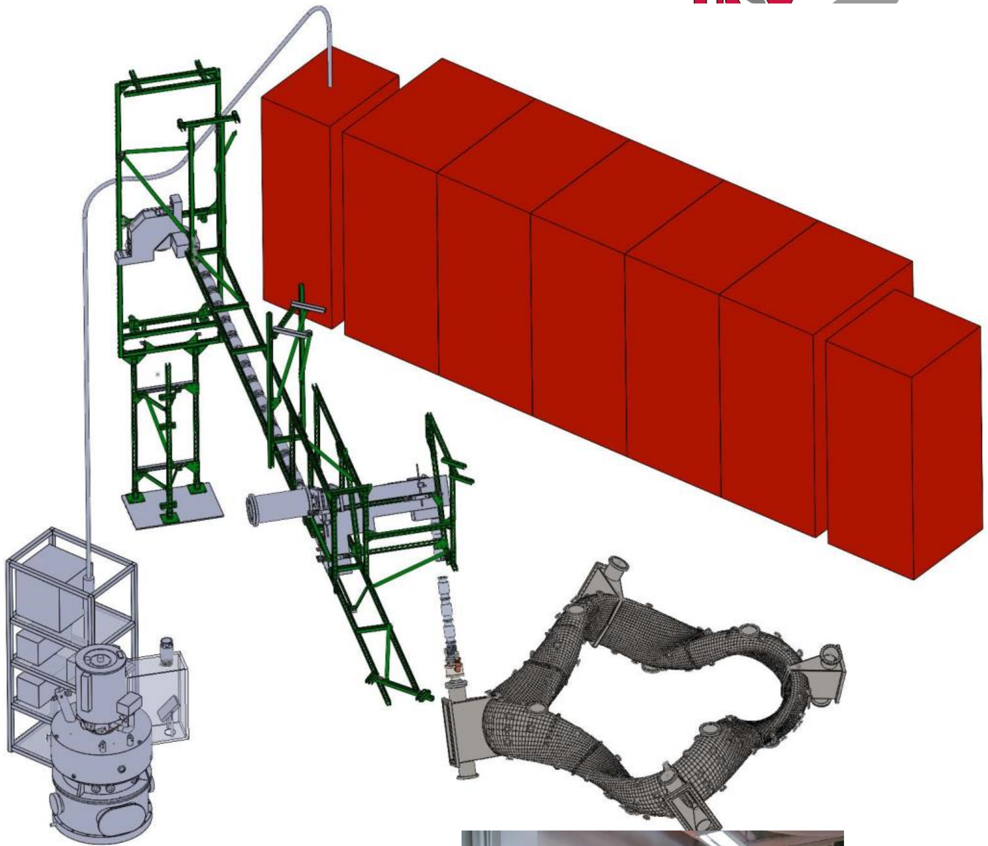


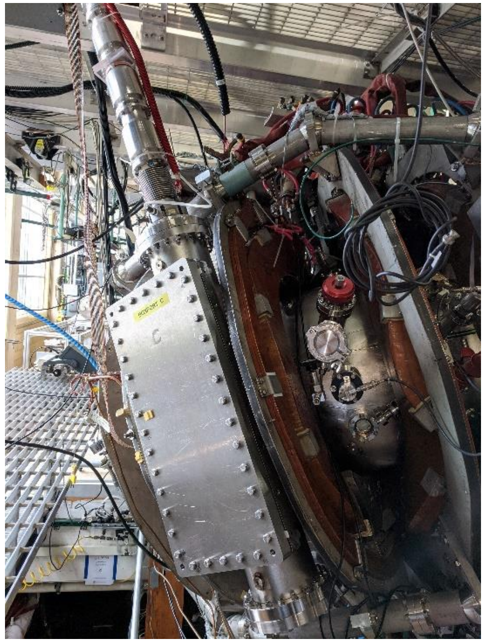


New Transmission Line

70 GHz radiation requires a new transmission line and launcher

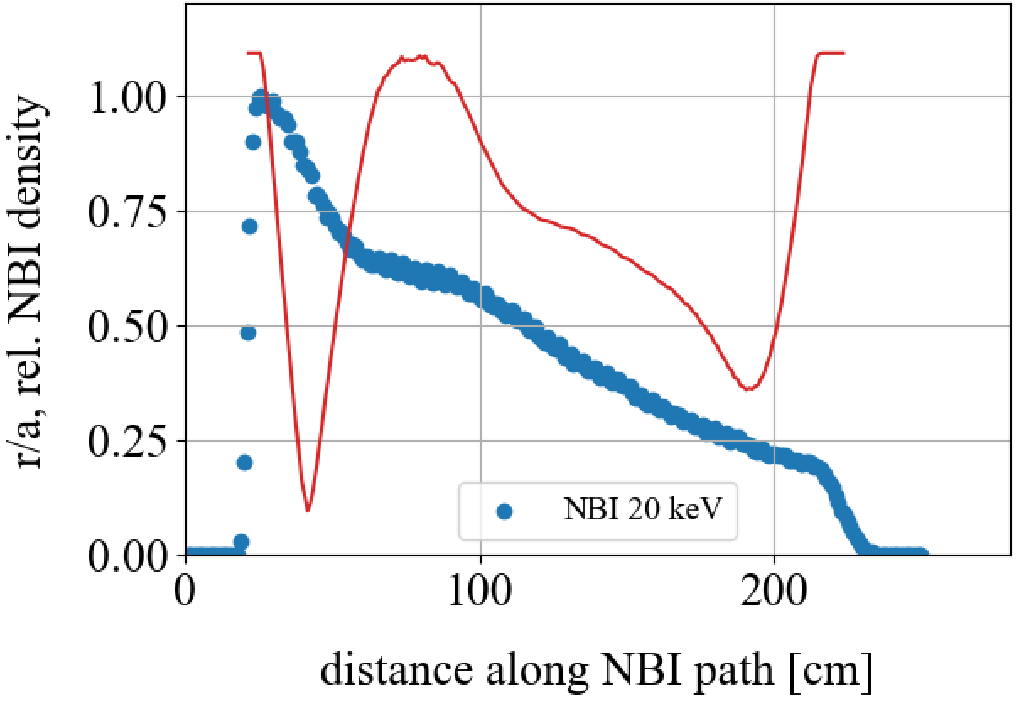
- Transmission line components received from IPP Greifswald, design completed and to be installed
- New mirror has been designed and manufactured and is currently being installed

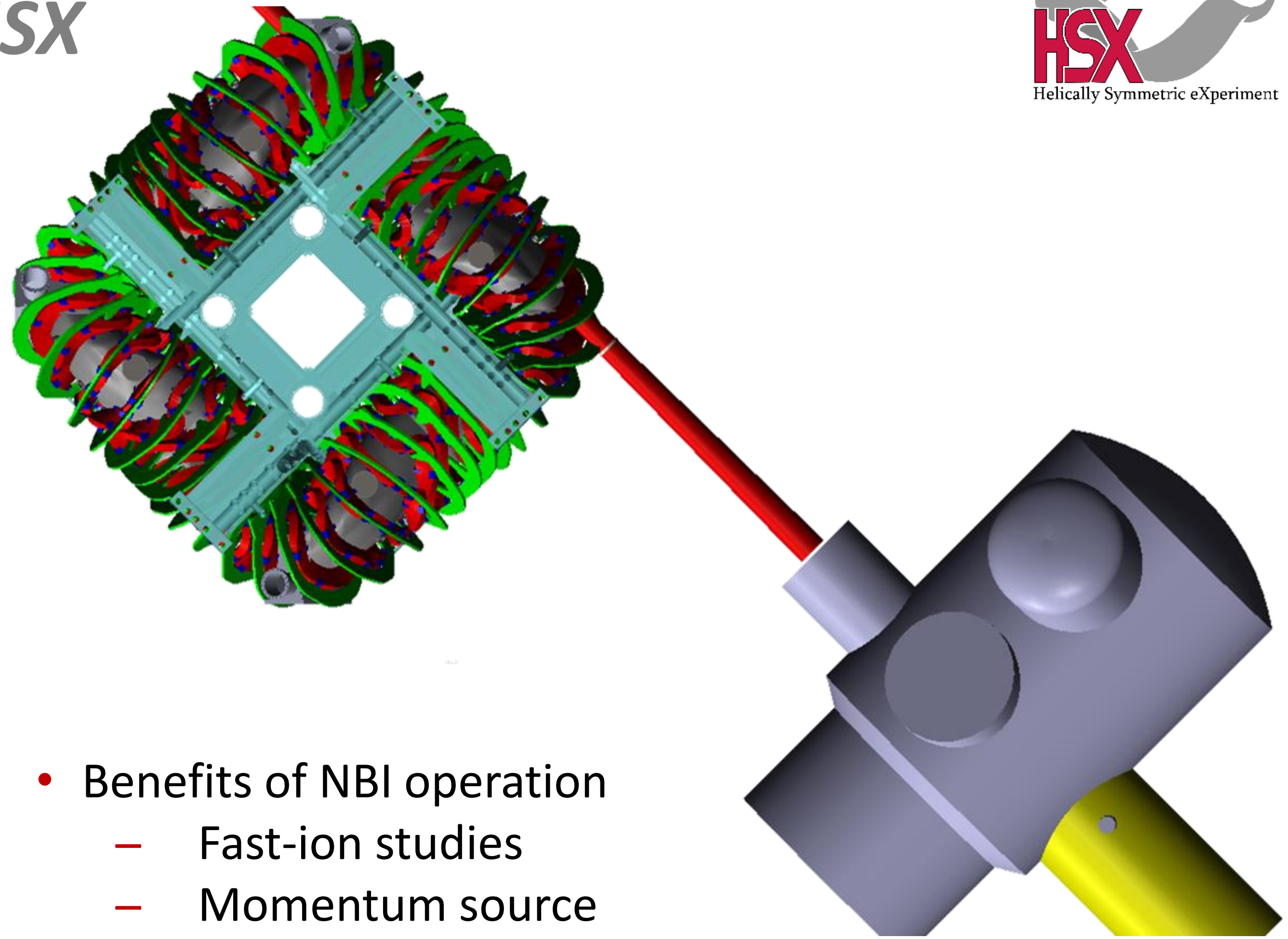




Neutral beam injection for HSX

- High density operation provides a target plasma for NBI
- Tangential geometry found that allows for good beam absorption of a 20 keV beam: only ~20% shine-through





- Benefits of NBI operation
  - Fast-ion studies
  - Momentum source
  - ~ 200 eV ion temperatures predicted

Work on NBI installation to be started late 2024

Helically Symmetric eXperiment

Outline

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Summary

- HSX is the worlds only quasi helically symmetric stellarator experiment operated at UW Madison since 2001
- The experiment contributes with studies of:
  - Neoclassical transport and flows
  - Turbulence optimization
  - Diagnostic development
- New 70 GHz ECRH is being installed
- Installation of a heating neutral beam is planned