Three-dimensional toroidal plasma confinement

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Ongoing work at:

Auburn University

Columbia University

Massachusetts Institute of Technology

New York University

University of Wisconsin

Kyoto University

Los Alamos National Laboratory

Oak Ridge National Laboratory

Princeton Plasma Physics Laboratory

General Atomics

National Institute of Fusion Science (Japan)

Max-Planck Institut für Plasmaphysik

Topics

Why does 3D confinement matter?

- Flux surfaces
- Stellarators
- Tokamaks are 3D, too!
- Boundary between physics/engineering

Dealing with geometry: inside the plasma

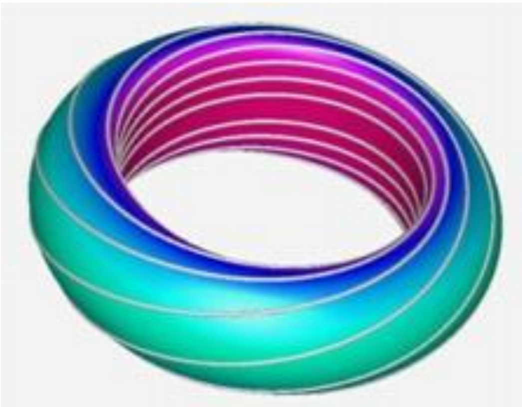
- The stellarator toolkit
- Imperfect flux surfaces

Dealing with geometry: outside the plasma

- Divertors

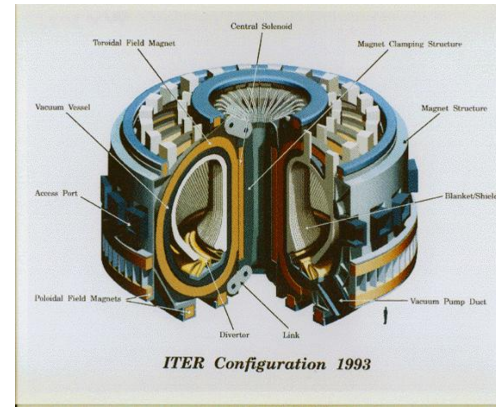
Realizing 3D confining fields

Toroidal-helical magnetic fields for confinement produce closed pressure (“flux”) surfaces



TOKAMAK

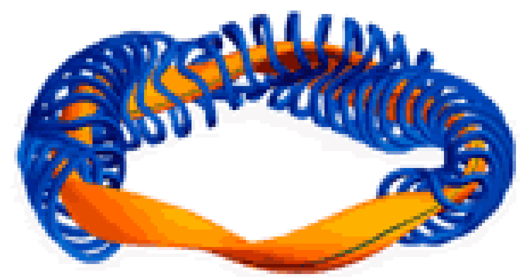
Symmetric geometry
Large plasma current:
Stability, sustainment?



ITER (France)

STELLARATOR

Complex 3D geometry
Zero-to-low current
Inherently steady-state

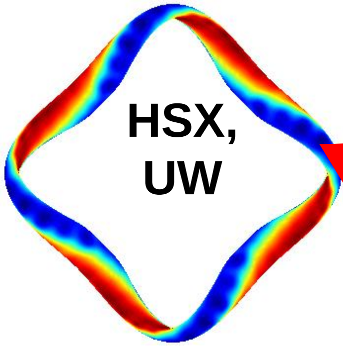


W7-X (Germany)

Reality is three-dimensional . . .

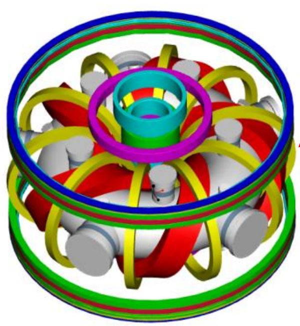
Tools: International experiments + theory/computation

Developed original for stellarator design/optimization
Verification/validation via multiple codes & experiments



Quasi-symmetrical

CTH, Auburn



External helical fields
+ plasma current

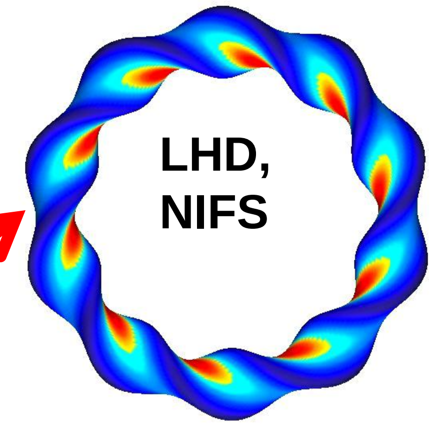
⇒ **3D equilibrium:**
- VMEC: flux surf + free bound.
- PIES: islands + free bound.
- HINT2: islands + free bound.
- SIESTA: islands (ext'd VMEC)
- V3FIT: experimental reconstruction
- IPEC: perturbed equil. (2D→3D)

3D stability:
- TERPSICHORE
- PIXIE3D
- M3D
- COBRA
- CAS3D
- STELLGAP/AE3D

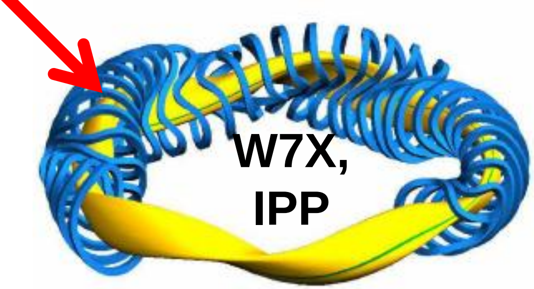
3D transport:
- DKES: transp. coefficients
- PENTA: flows
- GENE: turbulent transport

Integrated optimization
- STELLOPT
- NSTAB

Plasma edge/divertor
- EMC3



Superconducting
Heliotron



Superconducting
Quasi-omnigenous

How to find and represent 3D equilibria

1983-91: Garabedian, Betancourt, & Bauer, NYU (**BETA**);
Hirshman, Whitson, Lee, van Rij, Merkel ORNL/IPP (**VMEC**)

Variational calculation of 3D MHD equilibrium using the energy

$$W = \int \left(\frac{|\vec{B}|^2}{2\mu_0} + \frac{p}{\gamma - 1} \right) d^3x$$

Steepest descent to find minima

Compact Fourier representation of flux surfaces (VMEC representation)

$$R = \sum R_{mn}(s) \cos(m\theta - n\varphi)$$

$$Z = \sum Z_{mn}(s) \sin(m\theta - n\varphi)$$

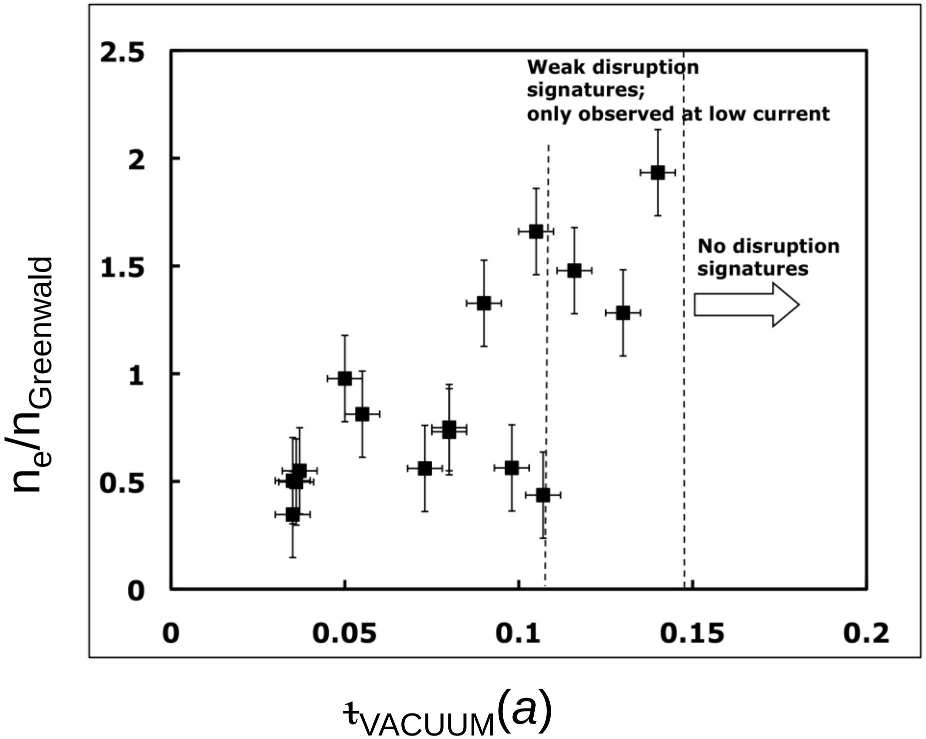
Rapid, portable 3D equilibria for (stellarators, tokamaks, RFPs) for configuration design, optimization and experimental analysis.

Codes to handle islated equilibria have followed (PIES, HINT, SIESTA)

CTH: disruption suppression with stellarator field

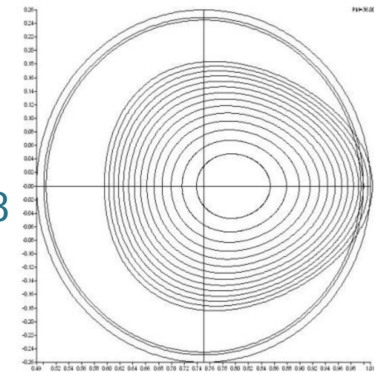
V3FIT: VMEC reconstruction using magnetic measurements

Density-driven disruptions suppressed with increasing stellarator transform; No disruptions for $\iota_{VACUUM}(a) \geq 0.15$

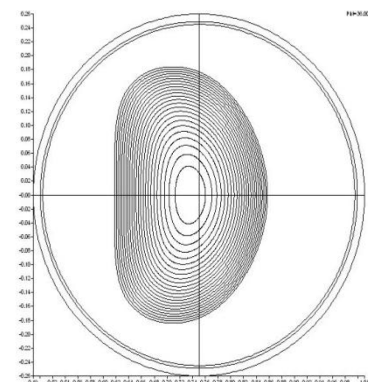


Experimentally reconstructed flux surfaces **before** (upper) and **after** (lower) disruption => maintenance of equilibrium

I_p = 40 kA
$\iota(a)$ = 0.48



I_p = 0
$\iota(a)$ = 0.1

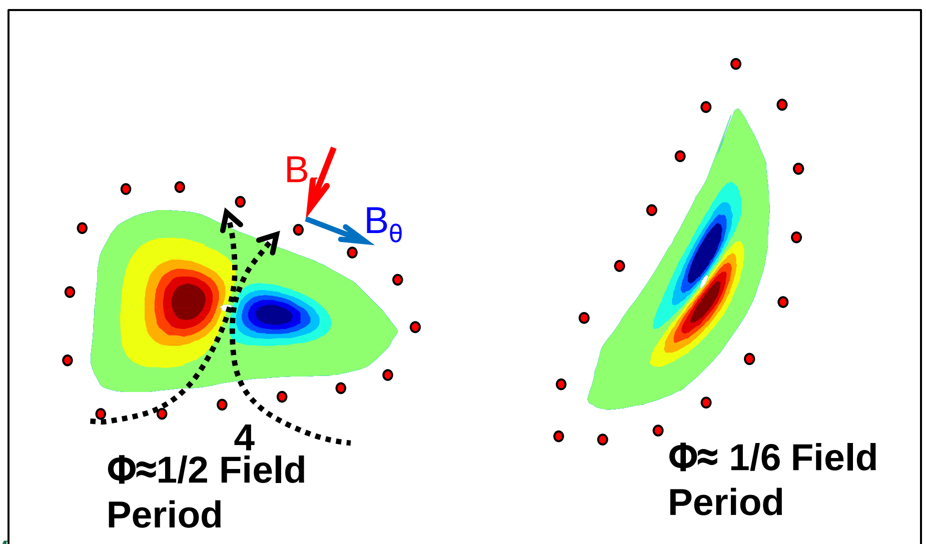


V3FIT being configured for LHD (ORNL/Auburn/NIFS)

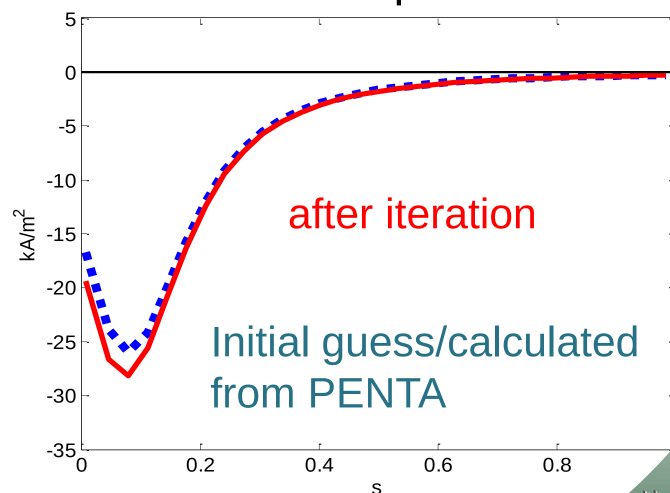
HSX: V3FIT used to measure Pfirsch-Schlüter & bootstrap currents

- HSX low β ECH plasmas have only pressure-driven currents
  - Pfirsch-Schlüter (PS): ***helical*** dipole current (no toroidal curvature!)
  - Bootstrap (BS): net toroidal current
- V3FIT (Auburn + ORNL + PPPL+ GA) is used with time series of poloidal and radial magnetic field distribution to determine distributions of PS and BS currents
- Essential for ECCD control of bootstrap current and divertor in W7X
  - Importance of bootstrap dependence on E_r

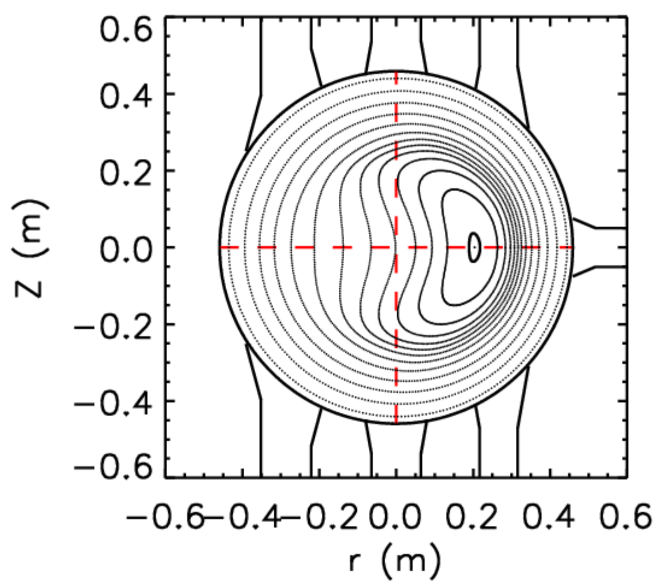
Pfirsch-Schlüter

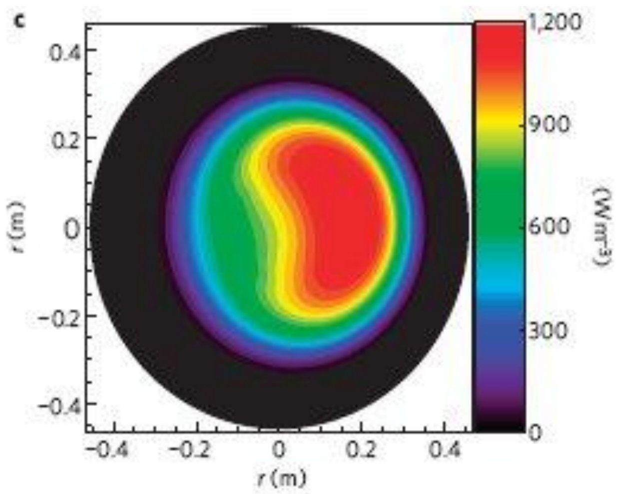


Bootstrap

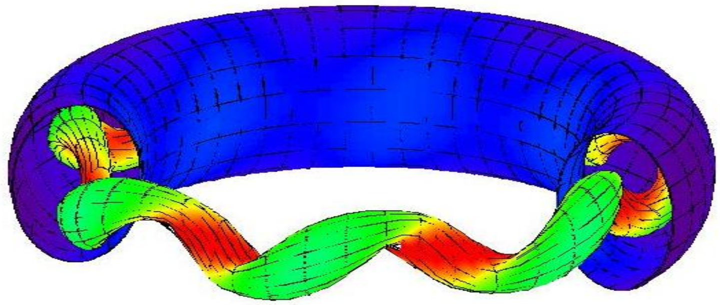


Self-organized helical states in RFP: RFX





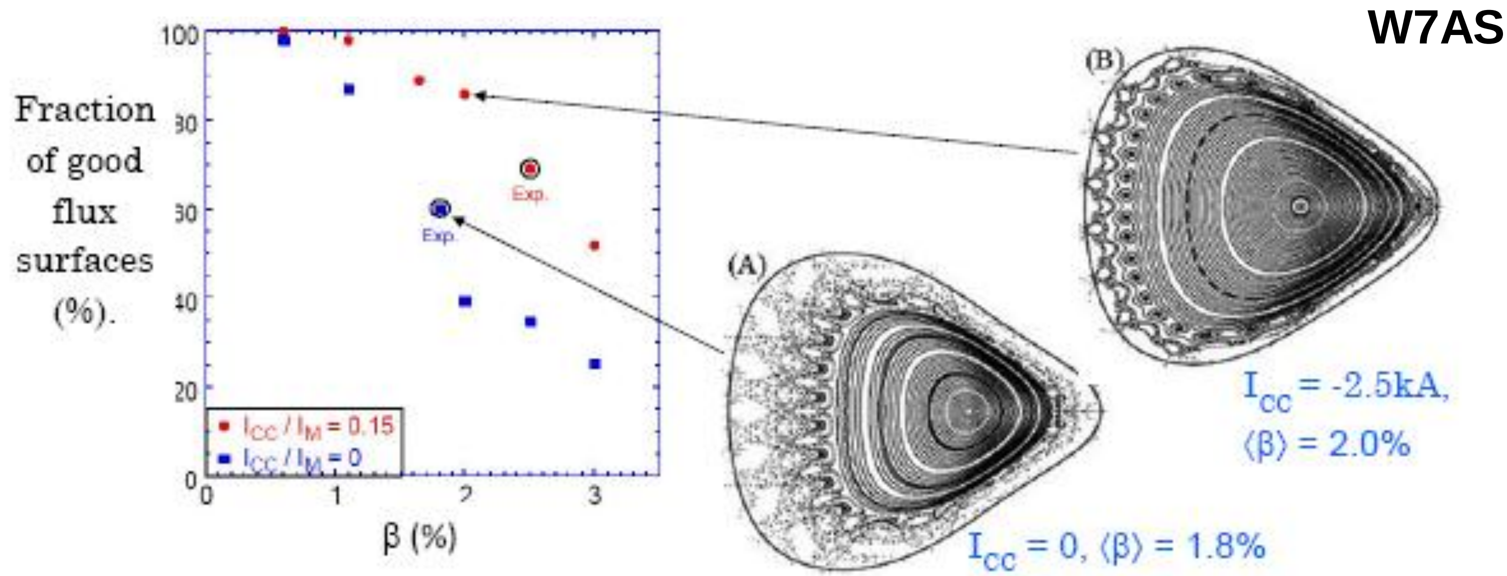
Flux surfaces fit experimental data for both axisymmetric & helical configurations



- Transition 2D → 3D
- VMEC equilibrium → access to all 3D physics
- TERPSICHORE: MHD stability
- DKES + PENTA: transport, flows
- SIESTA: islands

Consorzio RFX, ORNL, PPPL, Auburn, Columbia, CRPP-Lausanne

W7AS: equilibrium reconstruction shows that magnetic islands can appear at high β



- PIES + STELLOPT fits synthetic diagnostics to experimental data for reconstruction.
- Trim coils improve finite-β flux surfaces in code and experiment
- Now being applied to LHD.
- Future: extend reconstruction w/islands to LHD, tokamaks, W7-X with improvements the PIES, SIESTA, and HINT2 codes.

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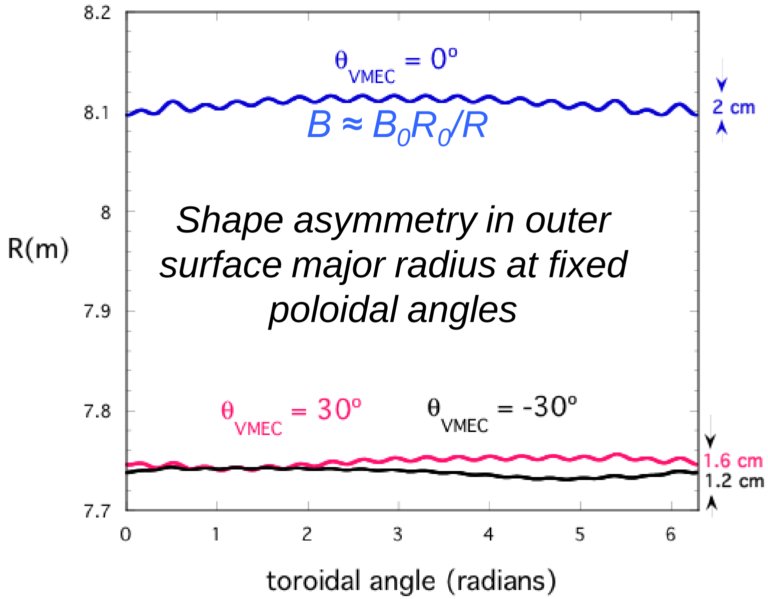
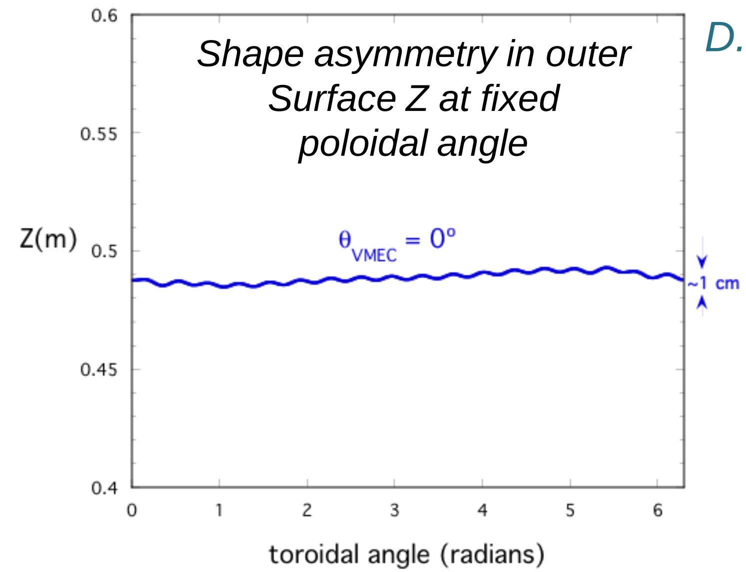
Analysis of a realistic ITER with ferritic materials requires stellarator physics tools

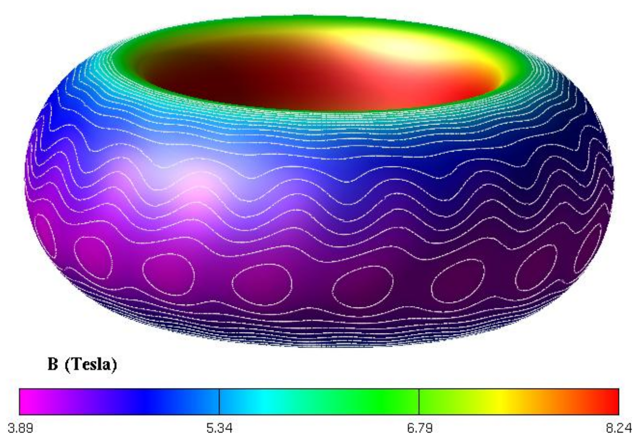
D. Spong

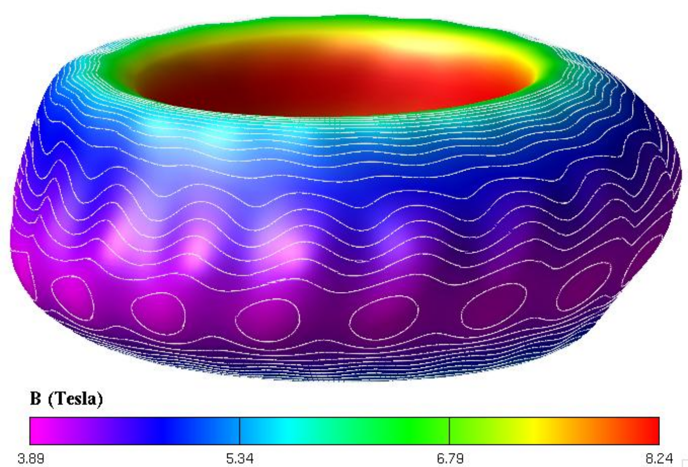


Correct VMEC outer surface shape

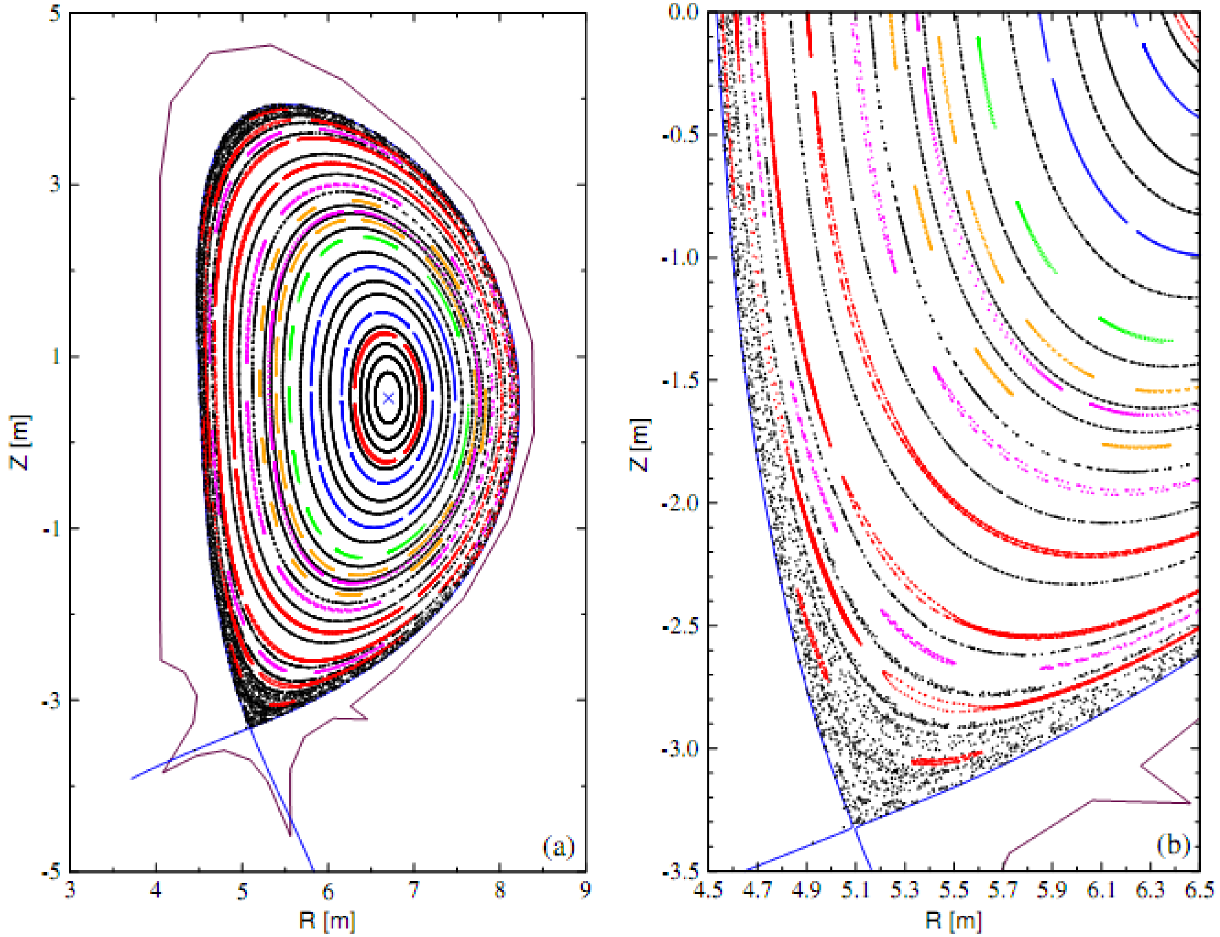


Non-symmetric shape terms artificially enhanced ×50





Error fields can break surfaces and form islands
EX: Effect of ferritic blanket on ITER

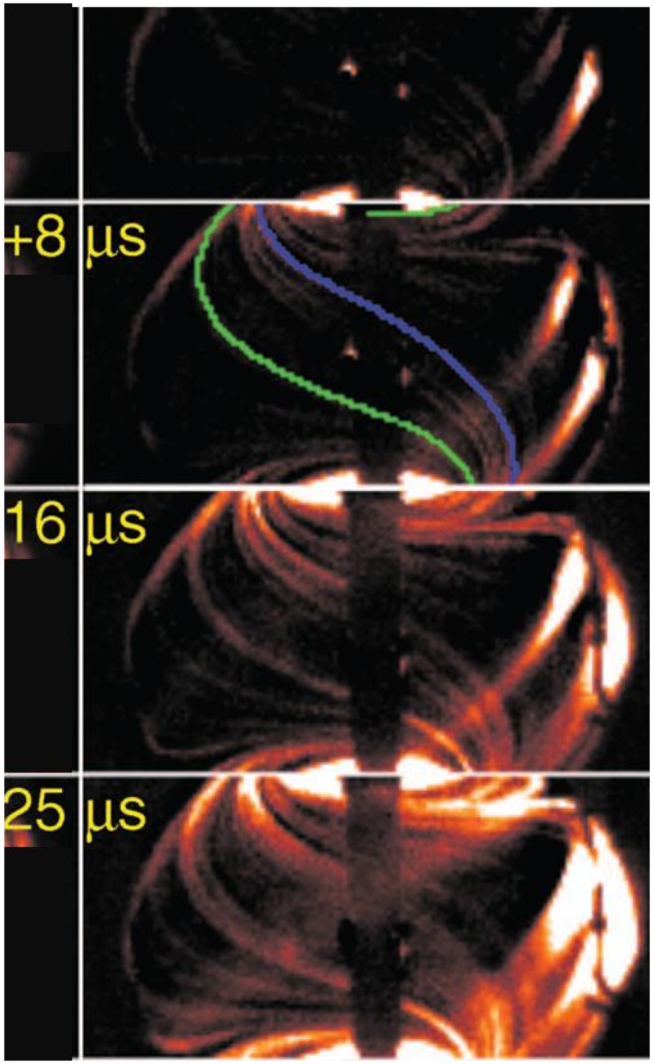


B-field: VMEC + error field (not fully self-consistent)

E. Strumberger et al

Edge Localized Modes make tokamaks very 3D

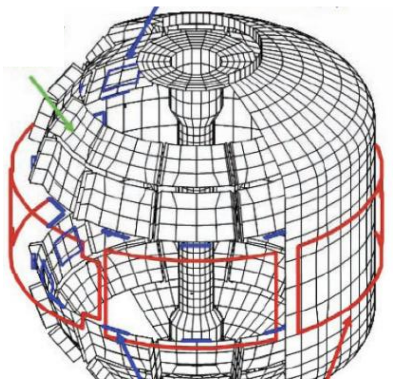
NSTX visual imaging
Maqueda, Maingi, et al,
Phys. Plasmas 16, 056117 (2009)



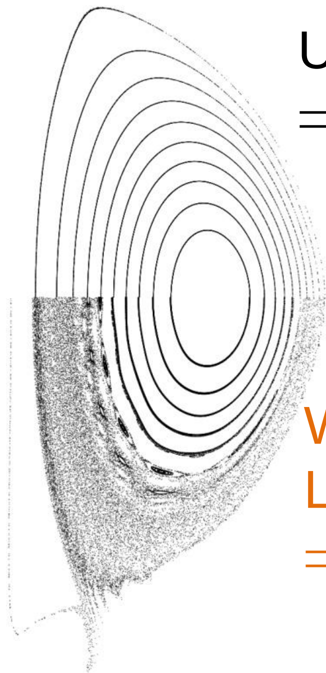
3-D fields control ELMs in tokamaks

NSTX with Li conditioning

*J. M. Canik et al, PRL **104**, 045001 (2010)*

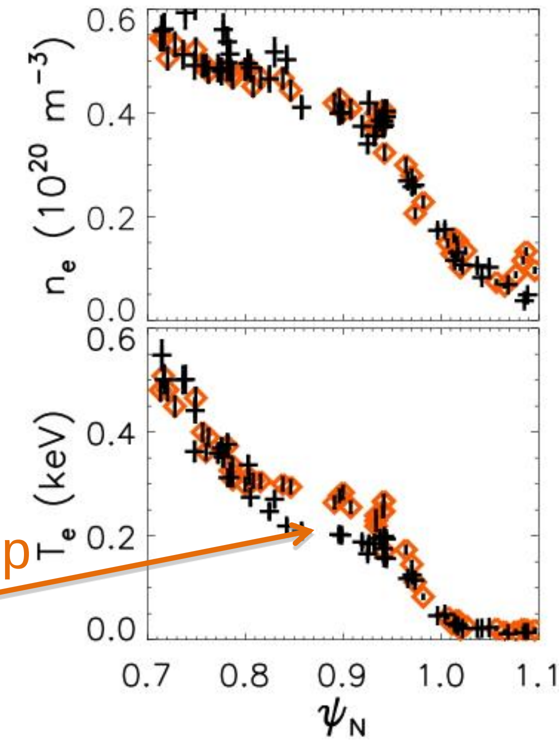


Resonant Magnetic Perturbation Coils



Unperturbed
⇒ no ELMs

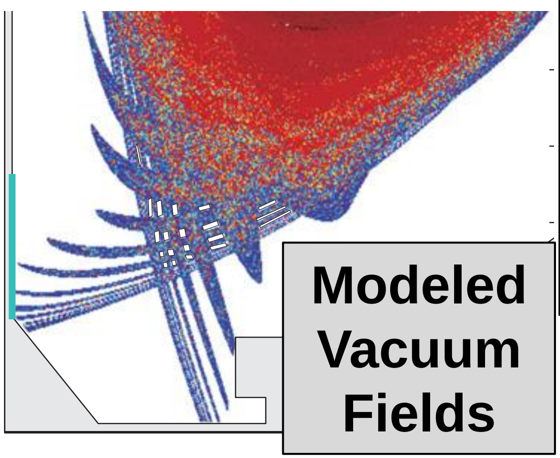
With RMP coils
Local *increase* in p
⇒ ELMs

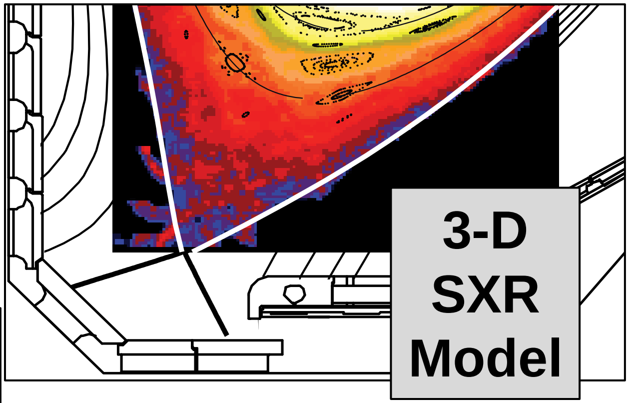


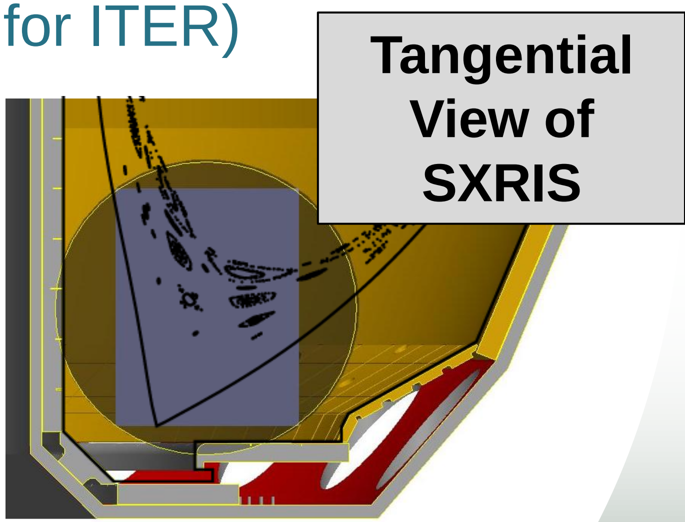
- Compare with DIII-D (no lithium) which yields opposite result:
  Addition of RMP (asymmetric in *m*) *decreases* p & *stabilizes* ELMs
- Transport, fueling, divertor contact?
- How to extrapolate RMP coil design to ITER?
- What is actual width of stochastic layer including plasma response?

DIII-D (new): soft X-ray imaging + 3D equilibrium to determine stochastic layer width needed for ELM suppression by RMP

- Tangential soft-X ray camera images flux surface shapes
- Compare plasma images with RMP-ON and RMP-OFF:
  - Image processing ↔ 3D equilibria (HINT2, SIESTA, PIES)
  - β, flow effects can amplify or attenuate plasma response
- Layer width needed for ELM suppression→RMP amplitude →RMP coil design requirements (e.g, for ITER)



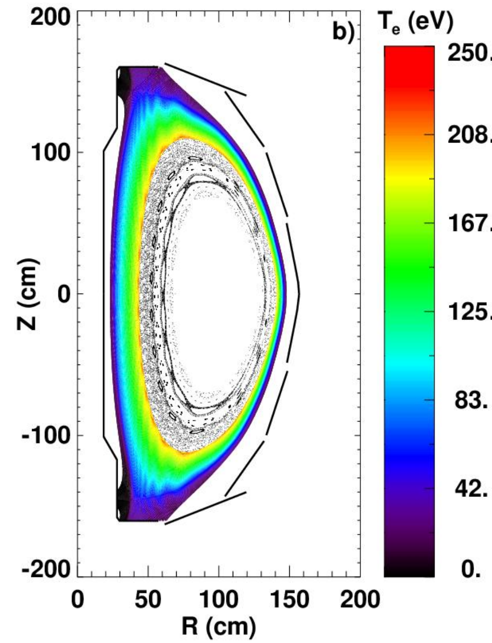


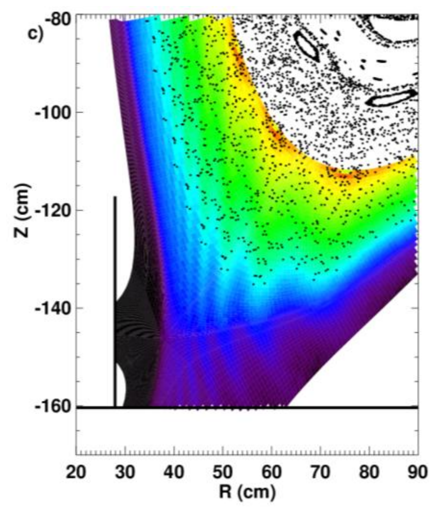


ORNL + GA + NIFS (LHD)

3D tokamak edge modeling: EMC3-Eirene

- Developed at IPP-Greifswald for stellarator divertor design; here applied to NSTX with RMP
- Coupled 3D fluid (EMC3) and 3D kinetic neutral and recycling (Eirene) code.
  - Classical parallel transport with prescribed anomalous cross-field coefficients .
  - Computation grid is 'field-aligned', to speed calculations (but grid development is time consuming)
- Includes transport of ion & electron energy, particles, and parallel momentum in 3D magnetic fields.



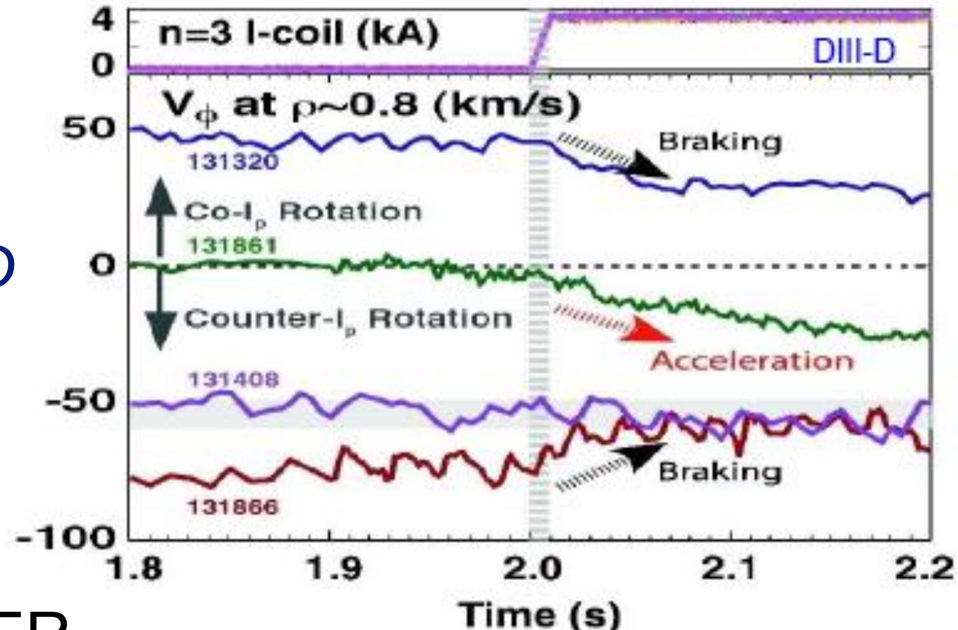


J. Lore, J. Canik (ORNL), Y. Feng (IPP)

Application of stellarator theory → breakthrough in understanding tokamak locked modes

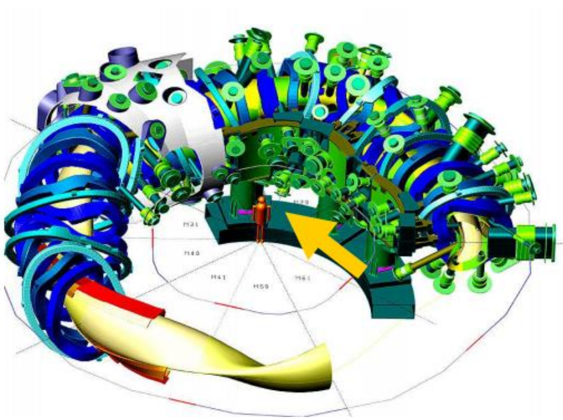
- In non-axisymmetric perturbation of tokamak, non-resonant modes have important effect on rotation.
- Stellarator neoclassical theory gives effect of non-resonant modes.

Evidence for predicted offset rotation confirmed on DIII-D (Garofalo et al, PRL 2008)

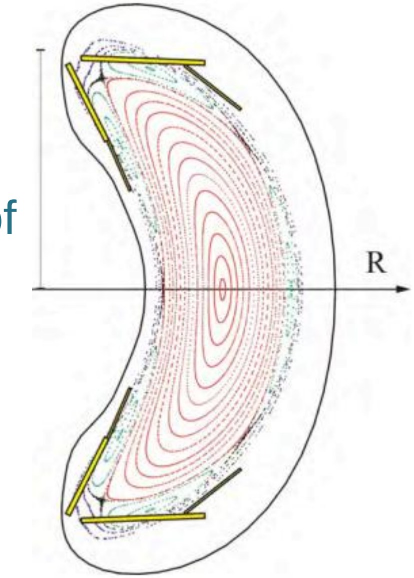


- Applied 3D fields affect rotation →potential tool for ITER

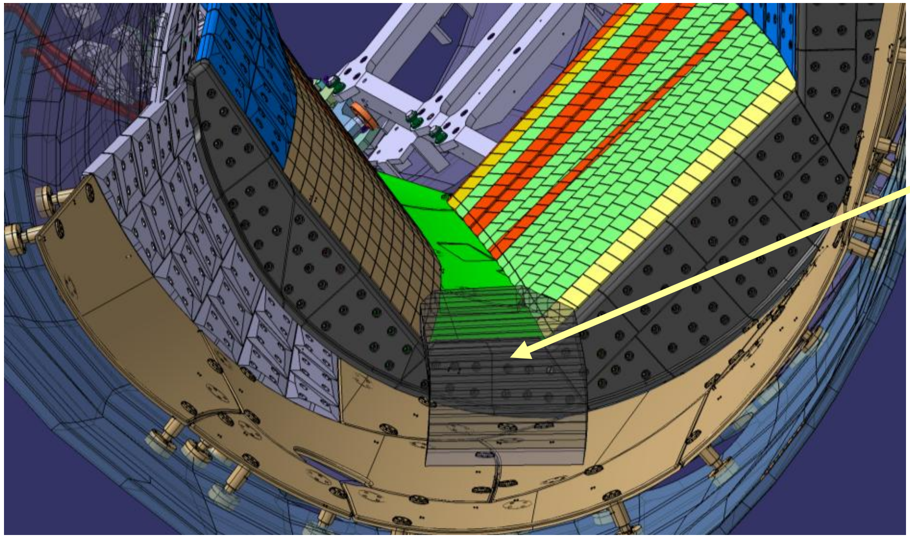
W7-X island divertor: 3D flux concentration



Cross-section of island divertor: physics view



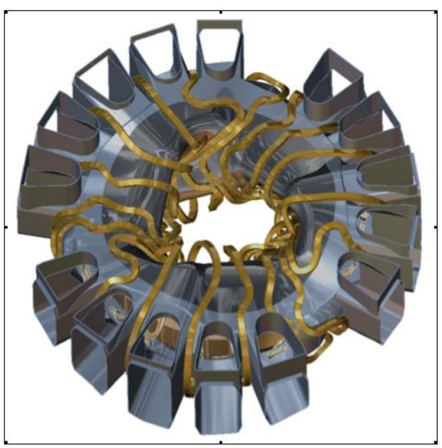
One sector of island divertor: engineering view



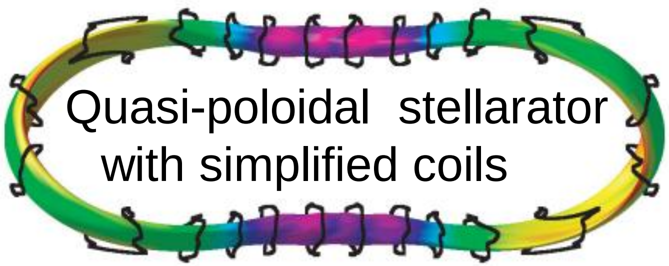
Divertor scraper element:
Transient during β evolution
Max. flux > 10 MW/m^2, 30 s
ITER monoblock technology
IPP/ORNL, under design

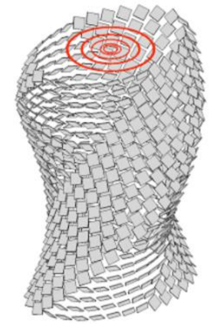
Improved realization of 3D toroidal configurations

- Incremental investments in optimization (physics/engineering) have consistently produced improvements in the stellarator reactor vision
- Ex: MHH (study) → HSX → (NCSX) → ARIES-CS (reactor concept)
- Issues: *maintainability; field realization*: less deformed coils;
  How much precision in construction really required?

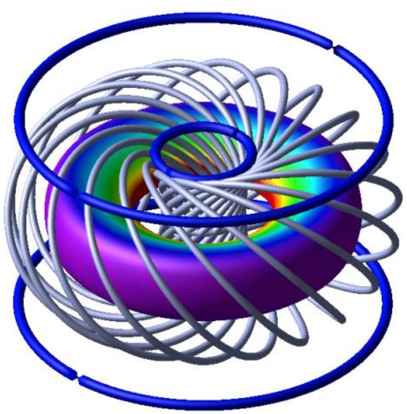


ARIES-CS mod
Improved access

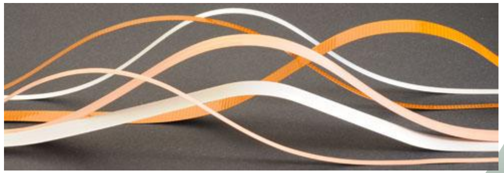




HTS tiles



Helically-
assisted
tokamak



HTS tape

Conclusions

- The geometrical challenges of stellarators have inspired the development of advanced 3D concepts and computational tools for describing configurations of closed flux surfaces. These techniques have revolutionized the design of stellarator devices.
- The major goals for new work in this area are:
  - Development of efficient methods for treating equilibria with broken magnetic surfaces.
  - Validated 3D modeling of the plasma edge and divertor.
  - Application of 3D techniques to experimental analysis and control in real-world conditions
- Overlap between stellarator and tokamak research is developing rapidly, and this synergy can accelerate progress toward advanced configuration designs and operational techniques.