# Needs for Stellarator Research in Fusion Energy Development

Presented by D. A. Gates
Representing the National Stellarator Coordinating Committee
at the USBPO webinar
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# Stellarators provide solutions for fusion energy

- Steady-state, disruption free reactor concept with minimal power requirements for sustainment
- Steady-state (~30 min) operation in W7-X will validate understanding of confinement in 3D systems
- Given recent advances in optimization a renewed US stellarator program is timely.
  – The US leads the world in development of quasi-symmetric stellarators

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# Advances in stellarator optimization have created enormous opportunities for advancing fusion energy

- Stellarators can be optimized for:
  - Neoclassical confinement
  - Ideal MHD Stability
  - Turbulent transport
  - Divertor performance
  - Energetic particle confinement and transport
- Important research topics for stellarators include
  - MHD/High Beta Quasi-Symmetric Stellarators
  - Plasma material interaction (PMI) issues in 3-D fusion systems
  - Impurity transport and accumulation
  - Power Plant Issues
  - Stellarator Coil Simplification
- Programmatic needs and Priorities
  - Analytic theory for stellarators
  - Code development and computation
  - Stellarator technology development
  - Issues best addressed experimentally on international facilities
  - Major challenges and opportunities can be addressed in a U.S stellarator initiative engaging domestic experiments

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# Neoclassical losses in classical stellarators

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# Neoclassical optimization strategy

- For trapped orbits, the action integral is conserved,

$$J = \int m v_{\|} dl = mv \int_{B(l)<E/\mu} \sqrt{1 - \frac{\mu B}{E}}\, dl$$

and the cross-field drift can be expressed in terms of it:

 – If $$\mathbf{B} = \nabla\psi \times \nabla\alpha$$

 then the distance drifted during one bounce is

$$\Delta\psi = \int \dot{\mathbf{R}} \cdot \nabla\psi dt = \frac{1}{e}\left(\frac{\partial J}{\partial \alpha}\right)_{E,\mu}$$

- Recipe for confinement: make J the same for all field lines on the same magnetic surface.

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# Trajectories in an optimized stellarator

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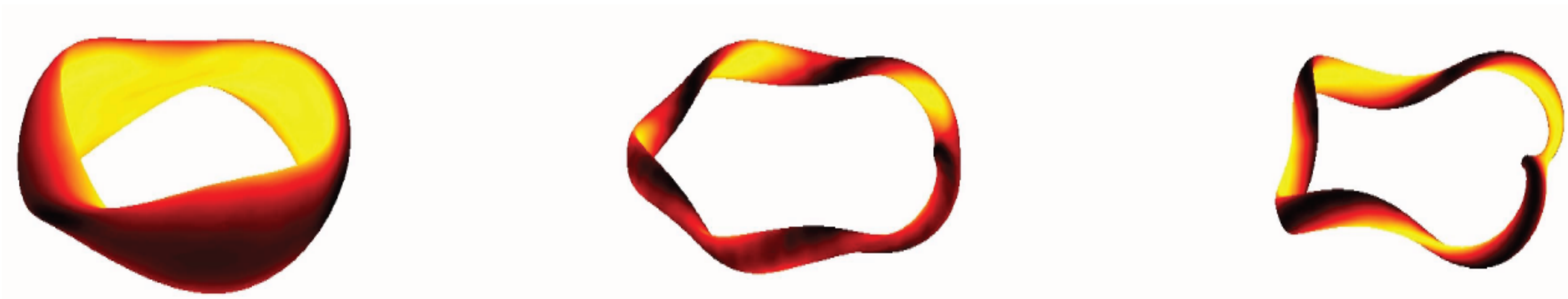
# Neoclassically Optimized Configurations

- Three types of neoclassical optimization
- US has substantial expertise in quasi-symmetry



Quasi-axisymmetry (QA)
NCSX

Bootstrap current increases transform
Bootstrap current is large
Can be designed at lower aspect ratio

Quasi-omnigeneity (QO)
W7-X

Bootstrap current can be made to cancel ~0
High aspect ratio

Quasi-helical symmetry (QH)
HSX

Bootstrap current reduces transform
Bootstrap current is lower than QA
High aspect ratio

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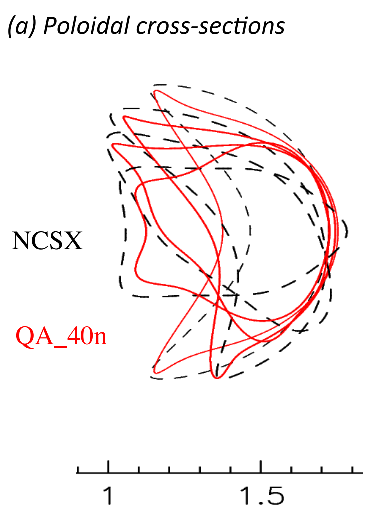
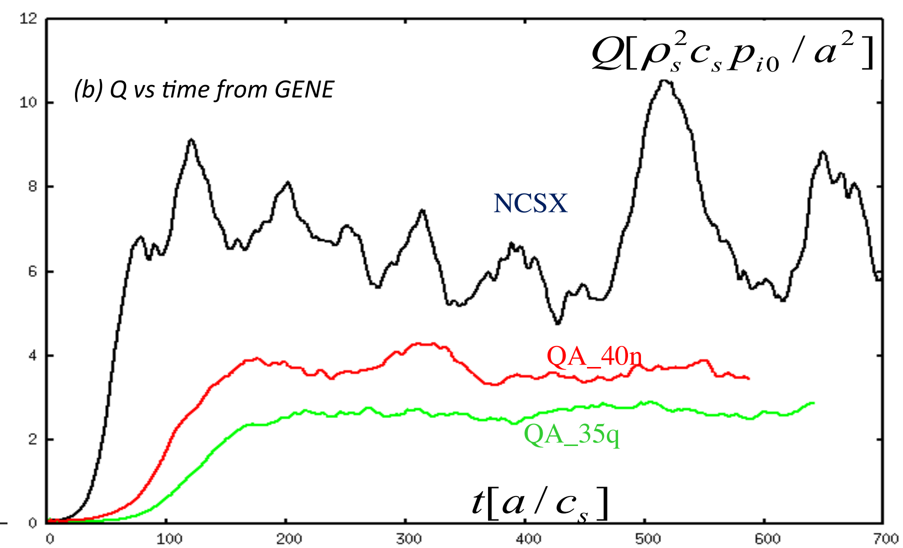
# Turbulent transport optimization has been demonstrated numerically

- Turbulence depends on shaping – shaping provides the opportunity to reduce turbulent transport
- Using STELLOPT and GENE, configurations were found with reduced turbulent transport

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H. Mynick, N. Pomphrey, P. Xanthopoulos, *Phys. Rev. Letters* **105**, 095004 (2010).

# Research needs for turbulence optimization

- Further work on proxy methods may enable further optimization
  - New schemes aimed at optimizing non-linear saturation mechanisms are promising
- Exascale computing could enable full turbulence optimization for the first time
- Success in this area holds out the promise of a substantial gain in energy confinement

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# Stellarator divertor systems offer unique opportunities and design flexibility

- A divertor system must facilitate power and particle exhaust with acceptable component lifetime and enable pumping of neutral particles
- Stellarator divertor systems
  - **Helical** (e.g., LHD). Continuous with structure reflecting helical coils. Stochastic edge with localized fluxes
  - **Island** (e.g., W7-X). Edge island chain intersected by divertor plates. Requires fixed edge transform. Natural extension of tokamak poloidal divertor.
  - **Intrinsic**. Intercept field lines that tend to exit in natural "troughs". Can exhibit resiliency to plasma beta, current evolution.
- Advantages
  - **Naturally diverting field** without extra coils
  - **Long connection length**: larger parallel temperature drop, increased effect of cross-field transport; impurity screening in islands
  - **Configuration flexibility**: possibility to optimize divertor structure and edge transport along with other targets (core transport, coil design)
  - **Lack of hard density limit** allows for high-density operation

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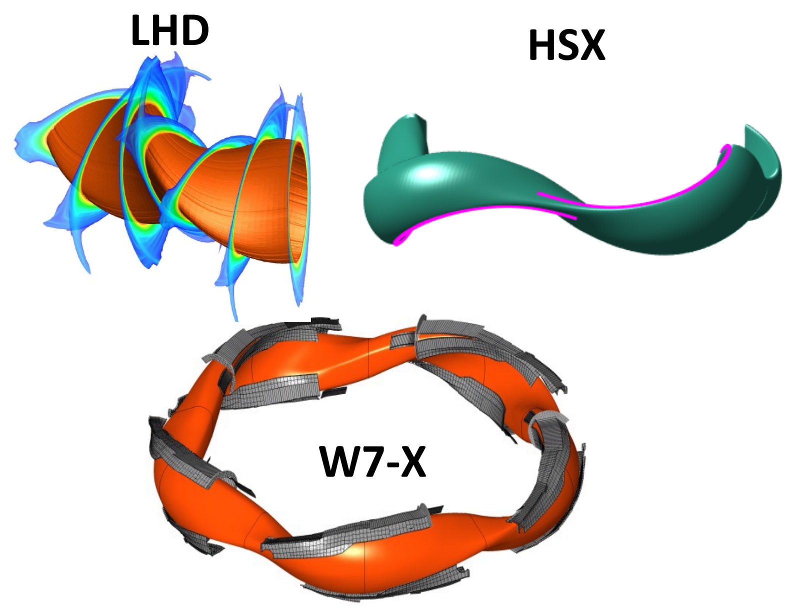


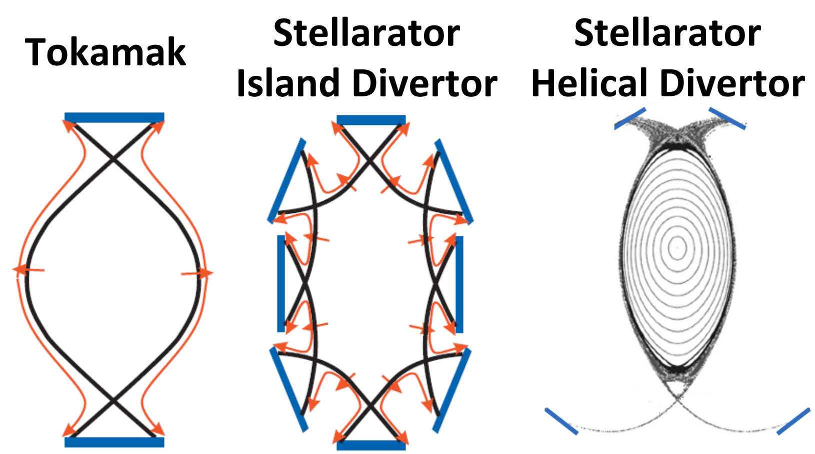


Figures c.o. M. Kobayashi, A. Bader, Y. Feng

# W7-X collaboration and targeted domestic research can provide rapid advancement

Active research areas

- Access to high confinement regimes
- Achievement of high recycling regime and detachment
- Heat flux width scaling
- Robustness of divertor to $\beta$, $I_p$. Necessity of active control scenarios.

Targeted research areas with appropriate investment

**1) Testing of divertor concepts**

- Explore basic divertor concepts, edge physics and materials on existing domestic devices
- Leverage W7-X collaboration to test island divertor physics and integrated core-edge operatio
- Design and construct medium scale device to explore simultaneous optimization of core transport and divertor/edge physics

**2) Model validation and advancement**

- Validate state of the art 3D edge code EMC3-EIRENE on W7-X
- Develop of a new world-leading 3D edge transport simulation capability that includes important effects neglected in EMC3-EIRENE (kinetic corrections, cross-field drifts and stable access to detachment)

**3) Divertor optimization algorithms to automate design process**

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# Stellarators readily provide access to high flux conditions for advancement of **PMI** materials and technology

- Access to **high density plasmas** in stellarators enables significant **heat and particle fluxes** on **quasi-stationary time scales**

**Example W7-X :** $\Gamma=10^{20}$-$10^{22}$ $m^2/s$ q=10-20 $MW/m^2$ $t_{disch}$ <30 minutes

**Hot ions** ➡ **Magnetic pre-sheath with realistic sputtering conditions**

**Stellarators are an excellent concept for relevant PMI research and test facilities combined with toroidal magnetic confinement**

- Inward directed **neoclassical impurity pinch** makes **coupling between the core plasma and PMI** a **critical integration challenge**

**Demonstration of viable stellarator performance mandates an <u>integrated approach</u> with a realistic plasma material interface**

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**Grand challenge:** testing the integration of a reactor relevant wall interface (divertor and main chamber) with performance of an optimized stellarator

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- Research on plasma material interaction is a young field in stellarator research and mandates dedicated attention

**Material choice:** **ITER: Be** **Reactor:** **Fission steels, ceramics, custom surface, liquids**

➡ **Studying these choices as well as new, transformational concepts in a stellarator facility in an integrated fashion is not available in the world wide fusion program**

**Geometry:** **ITER: Chamfering** **Reactor:** **Advanced manufacturing enables new approaches which are not exploited**

➡ **Technology advances provide new approaches to 3-D shape main chamber wall which can be an asset for progress on stellarator wall and divertor design.**

**Wall conditions:** **Hot wall (e.g. W7-X, OP2: 350C+) transits to desorbing state which is unexplored w.r.t density control and impurity production to date**

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**Differences and similarities to tokamak PMI need to be assessed and pursued if beneficial**

# Fast particle orbit losses require optimization in a stellarator

- Stellarators can improve EP confinement through
  - Quasi-Symmetry (B constant in helical or toroidal path)
  - Quasi-Isodynamic (poloidally closed B contours)
  - Quasi-Omnigeneity (minimize J variation on flux surface for given range of pitch angles)
- QS & QI configurations have better confinement properties than QO configurations, but challenges remain for all configurations
  - Lost energetic particles may damage plasma facing components
  - Perpendicular NBI in W7-X may lead to significant particle losses
  - Proximity of coils to plasma leads to modular coil ripple and significant EP losses
  - Research needs: Further reduce EP losses by optimizing coil/plasma distance<br>Protect PFC where needed

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# Opportunities exist for avoiding EP driven instabilities in stellarators

- Stellarators can experience fast ion driven instabilities similar to those seen in tokamaks (Alfvén, GAM, fishbone, etc.)
  - In some tokamak regimes these can lead to 40 – 60% loss of fast ions
- Stellarators offer new possibilities for suppressing EP instabilities
  - Use 3D fields and shaping to influence Alfvén gaps and damping
  - Control of rotational transform profile
  - High density operation: lowers slowing-down time => lower fast ion energy density

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# Understanding how finite $\beta$ affects 3D MHD equilibrium is complex

- A distinguishing feature of 3D equilibria is a generally a rich mix of topology --- good surfaces, islands, magnetic stochasticity
- Conventional model for estimating $\beta$-limit comes from MHD equilibrium
  - Large Shafranov shift deforms flux surfaces --- produces islands and stochasticity via Pfirsch-Schluter induced resonant **B**.
  - Quantitative calculations made with 3D equilibrium tools that allow for islands --- HINT, PIES, SIESTA, SPEC
  - Several effects outside of ideal MHD can affect magnetic topology evolution
    - Neoclassical physics (bootstrap currents)
    - Flow physics (island healing via plasma flows)
    - Finite parallel transport in the edge (pressure gradients along magnetic fields)

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# MHD Stability Issues in Stellarators

- The external rotational transform provides an important centering force on stellarator plasmas --- plasma induced displacements are countered by the interaction of plasma currents with vacuum **B** field.
- MHD instabilities are generally not a major impediment to stellarator operation
  - Low-current stellarators do not experience major disruptions
  - Stellarators have exceeded predictions of pressure driven MHD stability boundaries - weak degradation of confinement w/o disruption
  - Stellarators are not subject to Greenwald level density limits

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# Open questions in MHD/high beta motivate research opportunities

- Open questions include:
  - How accurately can we predict 3D MHD equilibrium properties?
  - Do MHD equilibrium considerations determine beta limits?
  - Can 3D equilibrium tools that allow for islands be incorporated in optimization studies and routinely used to analyze experiments?
  - What extended MHD physics needs to accounted for to accurately predict magnetic field topology?
  - Can we reliably operate high-beta, high bootstrap fraction QS stellarator without deleterious instabilities?
  - Can non-linear MHD calculations explain the ability for stellarators to exceed predicted linear stability limits

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# Impurity transport is an active research topic

- Neoclassical theory predicts accumulation of impurities in reactor relevant conditions
  - Neoclassical flux:

$$\Gamma_a = \sum_b \left[ -\frac{c_1^{ab} n_b'}{n_b} + \frac{c_1^{ab} q_b E_r}{T_b} - \frac{c_2^{ab} T_b'}{T_b} \right]$$

    - For impurities the $E_r$ term often dominates
- Some operating regimes show little/no impurity accumulation
  - What's needed to determine/enhance access to these regimes?

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# Research needs for stellarator impurity transport

- Can quasisymmetry offer a pathway to tokamak-like impurity screening in a stellarator?
- Can gyrokinetic simulations with impurities show impurity outflux and aid in possible solutions?
- Can the in-surface variation of the electrostatic potential produce an outward impurity flux?

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# Stellarators have both challenges and advantages as power plants

- Most of the power plant issues for stellarators are in common with tokamaks
- There are several special considerations
  - 3D divertor design/alignment requires special tools (an issue for tokamaks w/ RMPs too)
  - Non-planar superconducting coil design and fabrication is a young field that presents engineering challenges
  - Stellarators don't have to be designed to survive disruptions
  - Wider design space for stellarators because of no density limit and no current drive need
- Design of a stellarator with a viable high-availability maintenance scheme is a current area of study

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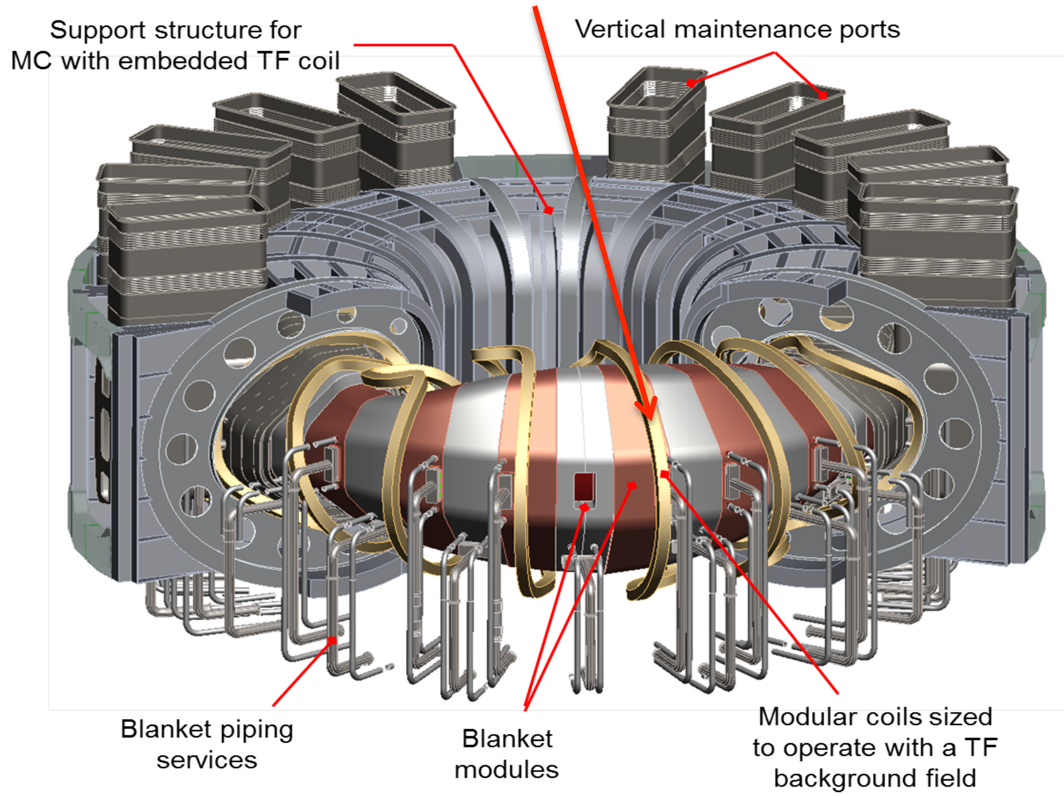
# Many new techniques for coil design

- COILOPT++ (Breslau)
  Coils represented as splines rather than as Fourier series
  - Has been used to design a device with clear access for maintenance
  - Technique facilitates any set of spatial constraints
- FOCUS (Zhu, Hudson)
  No winding surface specified
- REGCOIL (Landreman)
  Uses properly truncated Fourier method

Cutaway view of accessible stellarator – straight outer legs

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# New design ideas hold promise for better stellarator coils

- How much simpler can we make coils while maintaining stellarator advantages?
- How does coil complexity depend on plasma shape?
- Can we use shape flexibility to decrease coil complexity?
  - New ideas on efficiency of coils can contribute
- Can advanced manufacturing techniques make 3D coil systems more tractable?

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# Analytic theory plays a foundational role in advancing the stellarator

- The stellarator concept has been uniquely impacted by analytic theory
  - Concept improvement emanates from optimization schemes employing a set of metrics from analytic theory
  - The primary classification of modern stellarator design (QS, QO, QI, …) are theoretical constructs developed for improving neoclassical transport --- These optimization schemes dominate present day stellarator design as embodied by HSX, W7X, NCSX, …

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# Analytic theory is needed to further optimization schemes

- How can 3D shaping can be used to optimize turbulent transport?--- linear micro-instabilities, zonal flow physics, turbulent saturation
- Do 3D MHD equilibrium properties require physics beyond ideal MHD? --- rotation, neoclassical physics, anisotropic transport physics
- How much 3D shaping is required to prevent disruptions?
- Can QS optimization alone be used to control impurity flux?
- How close to QS is good enough? --- for flow damping physics, impurities, energetic ions, …
- Are there simple metrics for divertor physics can be included in stellarator optimization?
- How do modify field structure to minimize energetic particle losses?
- Can we develop theoretical models for understanding tolerances that impact fabrication and coil assembly costs?
- Can we formulate an approach that simultaneously addresses plasma physics and coil needs in optimization schemes?

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# Computation is required for improved stellarator design

- Stellarator research has long relied on simulation to enhance design concepts
  - The designer can control plasma properties through the 3D fields – minimal self-organization
  - Extensive effort to build predictive capability in 'problem areas' (e.g., neoclassical transport, MHD stability)
  - Tools integrated into optimization suite (e.g., STELLOPT) to produce configurations with favorable properties (design problems out of the system)
- Significant investment in stellarator simulation is needed to advance the state of the art
  - Broad need for resources to study problems using existing capabilities
  - Specific areas where code development is needed
  - Advanced simulation tools should be incorporated into re-invigorated optimization effort

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# Needs and priorities in code development and computation

- A concerted effort to minimize fast particle losses in QS stellarators is required to ensure adequate confinement
- The advent of stellarator gyrokinetic codes presents a unique opportunity for improving the confinement even further in optimized stellarators
- The development of a new modern 3D edge physics code will aid in stellarator divertor design
- A 3D equilibrium code that handles islands and stochastic regions, including flow shielding of rational surfaces and viscous toque on magnetic islands could clarify pressure limits
- A fully 3D extended MHD code development activity may relax some stability constraints broadening the available stellarator design space
- An integrated optimization program will be the basis for an invigorated US experimental program

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# Stellarators can obviate many technology issues

**Stellarators provide opportunities to reduce technology challenges: no central solenoid, H&CD, disruption mitigation, or in-vessel coils, simpler control.**

- 3D geometry is the main general challenge for stellarators, affecting multiple subsystems, construction, and maintenance.

**Other magnetic fusion technology issues and R&D requirements are largely the same for tokamaks and stellarators.**

- Material choices for magnets, tritium breeding and handling, divertors, PFCs, diagnostic are mostly indifferent to the configuration choice.

**Optimizing engineering together with the physics in an integrated design process is a general need for stellarators.**

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# Stellarator Subsystems: Opportunities to meet 3D challenges

**Magnets**

- New advances in integrated (i.e. plasma and coils) optimization lead to simpler geometries.
- High-$T_c$ coils: potential for higher current densities, jointed coils

**Plasma exhaust**

- Newly available resources for long-pulse divertor research: W7-X, LHD.
- Advanced manufacturing: potential to resolve complex engineering issues, e.g., fabrication, cooling.

**Blankets**

- New advances in 3D analysis fidelity, e.g. coupling of CAD models with 3D neutronics codes

**Assembly and maintenance**

- New machine configuration designs provide access for large-sector installation and removal of in-vessel systems.

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# Available Resources to Advance Stellarator Science Through International Collaboration

**Wendelstein 7-X (Germany)**

- Large machine w/optimized configuration, island divertor, superconducting magnets, international team.
- U.S. team collaboration in divertors, boundary physics / control, field errors, core transport, fluctuations, scenarios continue to strengthen.
- Emerging opportunities in steady-state PMI, energetic particle physics, steady-state fueling.

**Large Helical Device (Japan)**

- Large machine w/ superconducting magnets, mature heating and diagnostics, diverse & experienced team.
- Long-standing U.S. PI-driven collaborations in helium exhaust, divertors, core transport, equilibrium physics, and energetic particle physics continue. NIFS initiative offers travel support to encourage growth.
- Emerging opportunities for new physics with start of deuterium operation and closed helical divertor. Complements W7-X.

**Stellarator Coordinated Working Group Meetings (CWGM)**

- The "Stellarator ITPA"- important forum to coordinate international stellarator research.

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# U.S. Partnership in W7-X: Working at the Forefront of Stellarator Research

**U.S. Agenda for OP1.2 (2017-2018): Control of high-performance 3D plasmas.**

- Can we control the W7-X island divertor to:
  - Keep heat exhaust uniform on high heat-flux surfaces
  - Maintain plasma purity
  - Protect sensitive components
- How well can we control the 3D equilibrium from start-up thru high-β steady-state?
- What turbulent process governs transport in a neoclassically optimized stellarator with hot ions?
- **→ Preparing for steady-state (30 min.) operation in OP2.**
- Steady-state pellet fueling (collaboration with IPP and NIFS)
- Long-pulse PMI: impurity transport, helium exhaust, future transition to metal walls.

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# New domestic experiments required for continued US fusion impact

**Influence and impact.**

- Fusion *needs* innovation to succeed. A clear path to a practical steady-state fusion system does not yet exist; tokamaks and W7-X are insufficient.
- Scale and scope:  Convincing tests requires a program comparable to others of the leadership class:  W7-X, JT60-SA, JET/ASDEX-U…
- Timely decisions are required to have impact on the future of fusion

**New facilities at a range of scales are required to deliver impactful conclusions.**

- A new mid-scale experiment to deepen pioneering US exploration of quasi-symmetric confinement.
- A follow-on flagship experiment testing integrated challenges in reactor-scale3D  plasmas.
- CE scale experiments on focused issues on fundamental 3D physics, new materials and technology are possible

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# Explore Key Issues of Quasi-symmetry with a New Medium-scale Experiment

- HSX has demonstrated benefit of quasi-symmetry in low-density, hot-electron plasmas
- Opportunity to extend successful program to examine quasi-symmetry with relevant divertor and PMI in more fusion relevant regimes
  - Hot thermal ions; low $\nu^*_i$
  - Higher density operation
  - Good core confinement coupled with robust edge control
  - Good energetic ion confinement
- Any facility should consider critical issues that **cannot** be addressed in W7-X
  - Improved trapped particle confinement over broad pitch angle space (unlike QO approach)
  - Low flow damping
  - High residual zonal flows
  - High effective transform (for QH)
- Defer high $\beta$ and long-pulse issues to flagship experiment

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# US expertise in quasi-symmetry presents an opportunity for world leadership

**Mission Need: Integrated test of these innovations in a leadership-class experiment.**

**Likely characteristics**

- Optimized, quasi-symmetric core configuration
- Optimized divertor configuration
- Engineering-optimized coils
- Well-diagnosed, national facility

**A concept design study is the next step to determine requirements in the context of a national initiative.**

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# Community Process has Identified Program Priorities

1. **Aggressively pursue collaborations on the international superconducting devices**
   - W7X - Long pulse, high $\beta$, island divertor and PMI, fueling
   - LHD – D-D campaign, high $\beta$, helical divertor
2. **Develop a conceptual design for a next-step mid-size US facility to extend quasisymmetry studies into hot ion regime**
   - Focus on benefits of flows and symmetries which <u>cannot</u> be investigated on the large international facilities
   - Define the minimum scope, needs and capabilities of such a system
3. **Position the US to build a world leadership-scale experiment beyond W7X**

**Utilize existing devices, as appropriate, in addressing STELLCON issues and in support of items 1 and 2.**

**Theory and computation are a necessary component of all three elements to form an effective program**

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