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A vision for an experimental stellarator program in the U.S. that is a slingshot for a stellarator DT device

Oliver Schmitz

with input from and David T. Anderson, Aaron Bader,
Raymond J. Fonck, Chris C. Hegna, John S. Sarff, John C. Schmitt*

University of Wisconsin – Madison, Madison, WI, USA
*Auburn University, AL, USA, on assignment at UW Madison

I acknowledge very helpful discussions with

P. Helander, T. Klinger and R. Wolf – IPP Greifswald
D. Maurer and S. Knowlton – Auburn University

An invited report to the National Academy of Sciences, Engineering and Medicine panel on "A Strategic Plan for U.S. Burning Plasma", March 23 2018, video conference

Preface

The vision offered is based on reports on a *Stellarator Vision for the U.S. Fusion Program* which was generated in various community activities

- **Report of the National Stellarator Coordinating Committee NSCC**

  STELLCON report: ["**Stellarator Research Opportunities** – A report of the National Stellarator Coordinating Committee NSCC, various authors, 2017]

  Published as [D. Gates et al., "Stellarator Research Opportunities – A report of the National Stellarator Coordinating Committee, Journal of Fusion Energy **37** (2018) 1-44]

- **Presentations in community meetings in Madison and Austin in 2017**

  [D.T. Anderson et al., "The **Rationale for a Strong Stellarator Component** in the US FES Strategic Plan", U.S.MFRSD Madison Community Meeting, July, 2017]

  [C.C. Hegna et al., "Stellarator research: **Challenges and Opportunities**", U.S.MFRSD Madison Community Meeting, July, 2017]

  [D.A. Gates et al., "An **invigorated US domestic stellarator program** based on quasi-symmetry", U.S.MFRSD Madison Community Meeting, July, 2017]

- **A dedicated white paper submitted as input to this NAS study**

  [D.A. Gates, D.T. Anderson, C.C. Hegna, "**Quasi-symmetric Stellarators** as a Strategic Element in the US Fusion Energy Research Plan", 2018]

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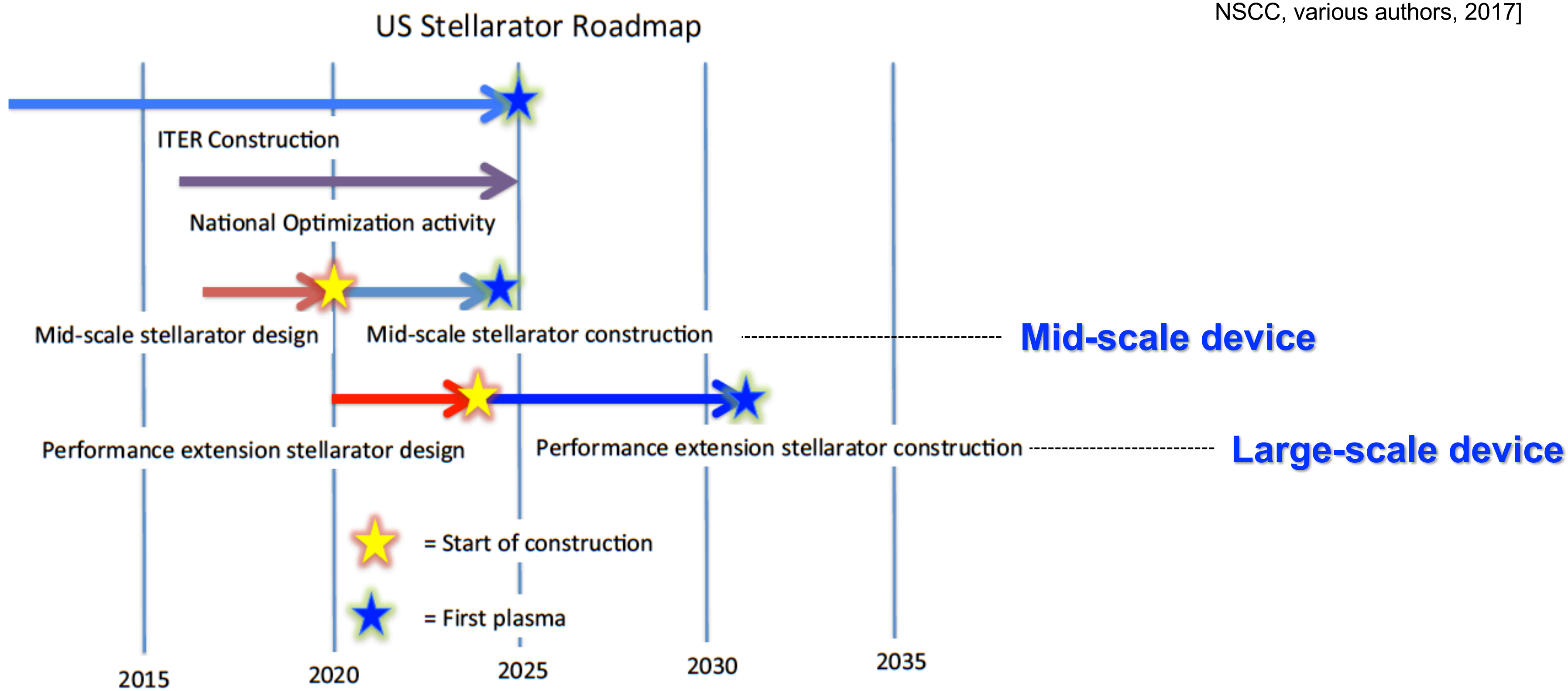
U.S. stellarator community consensus: a stepladder to a performance extension facility through an intermediate scale device

Taken from STELLCON report: ["Stellarator Research Opportunities – A report of the National Stellarator Coordinating Committee NSCC, various authors, 2017]



What is the goal for these devices and which choices should be made? This talk provides a vision!

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The proposal in a nutshell

Exploit our leading experience in Quasi-Helically Symmetric (QHS) stellarator research to engage into a rapid path to a DT stellarator concept.

Start design immediately

QHS device

Combine **neoclassical and turbulent transport optimization** with **flexible divertor test platform** and **custom fit PMI**

Steady state physics at W7-X

See talk by S. Lazerson

Sustained theory program to enable extrapolation

Enabling stellarator technology (A/M, HTSC)

Go to DT

Community process

Accelerate design effort

Command the risks

Leverage ITER knowledge

DT stellarator

A spectrum of DT & BPP science questions can be addressed

Stellarator as stable and efficient system will be made available as a new option

Such a bold approach based on the stellarator concept will be a slingshot for U.S. leadership to accelerate fusion energy.

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Outline

- **Stellarators: why?**
  Reasoning to consider stellarators as possible game changer

- **Stellarators: how?**
  Configuration aspects and prioritized research needs

- **Stellarators: what?**
  A concrete, one step initiative to a DT stellarator

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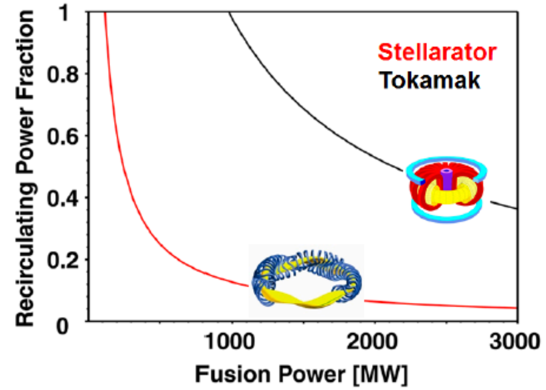
Energy efficiency: low recirculating power expected for stellarators

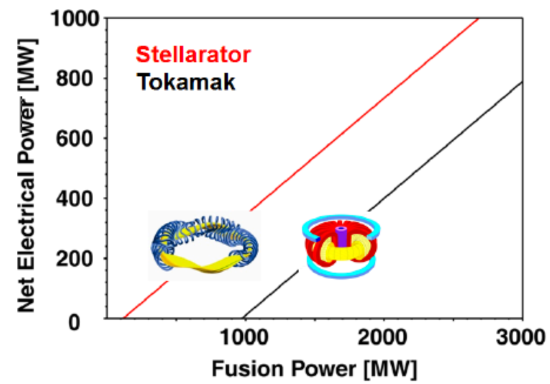
Pilot plant study comparing AT, ST and CT (Q-A) stellarator

	AT Pilot	ST Pilot	CS Pilot	
$A = R_0 / a$	4.0	1.7	4.5	
R_0 [m]	4.0	2.2	4.75	Similar size (Q-A stellarator)
B_T [T]	6.0	2.4	5.6	Fixed B at coil (14T)
I_P [MA]	7.7	20	2.1	
q_{95}	3.8	7.3	1.5	
f_{BS} or iota from BS	0.69	0.90	0.23	
$n_e / n_{Greenwald}$	1	0.7	-	
H_{98} or H_{ISS04}	1.22	1.35	1.75	
β_T [%]	4.8	39	6.9	
β_N	3.7	6.1	-	
P_{fus} [MW]	674	1016	529	Lowest fusion power
P_{aux} [MW]	79	50	12	
Q_{DT}	8.5	20.3	44	
Q_{eng}	1.0	1.0	2.5	
Net Electric [MW]	0	0	110	**Makes net electricity!**

[J.E. Menard et al., Nuclear Fusion **51** (2011) 103014]

DEMO study in the E.U.





[H. Zohm, "ITER-DEMO FPP: a Stepladder to Fusion Energy", Plasma Seminar, UW Madison (2017)]

[H. Zohm et al., Nuclear Fusion 57 (2017) 086002]

Efficient system with promise to be economically viable!

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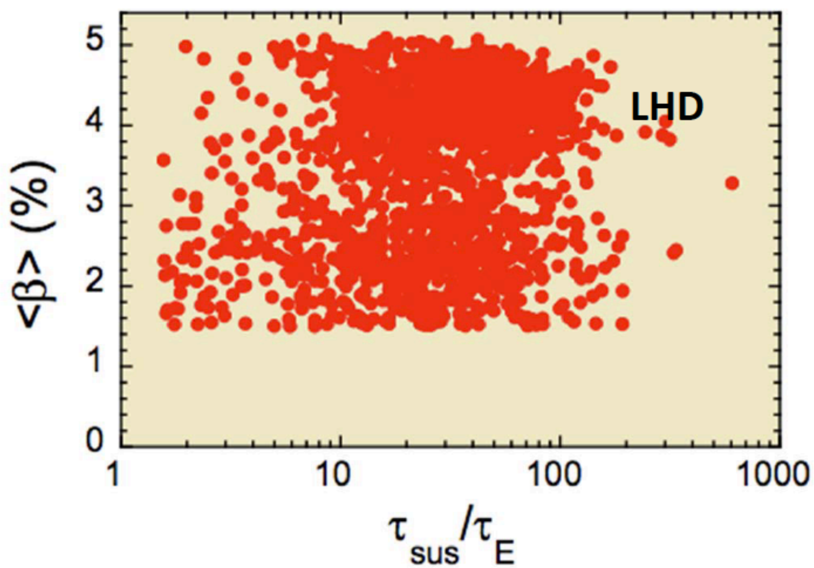
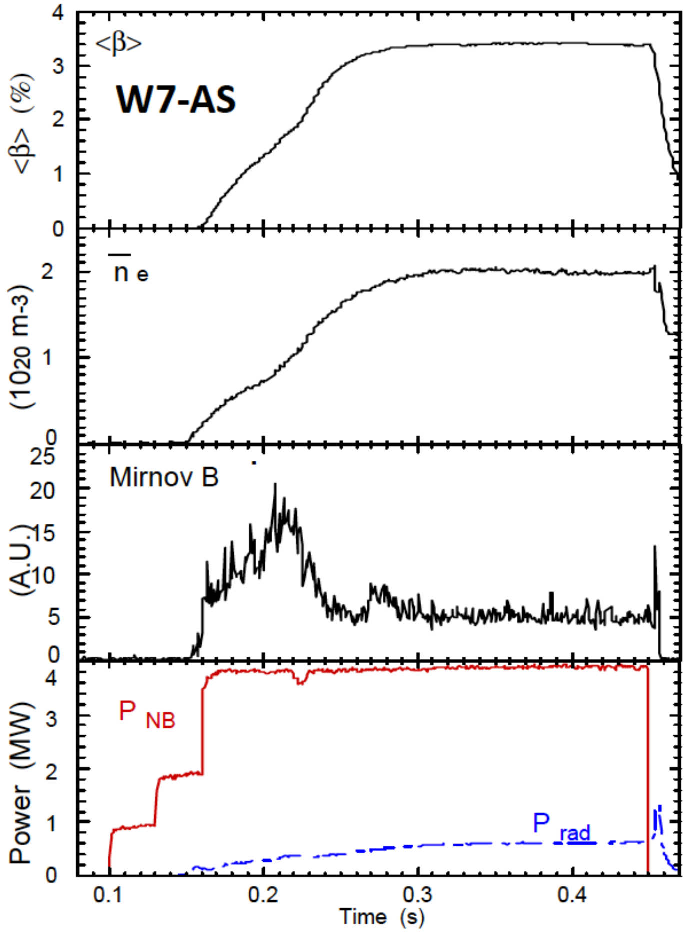
Shown to be free of current disruptions and MHD stable

No current disruptions observed



- **Discharge limited by power balance**
- **Runaway electron issue not present**

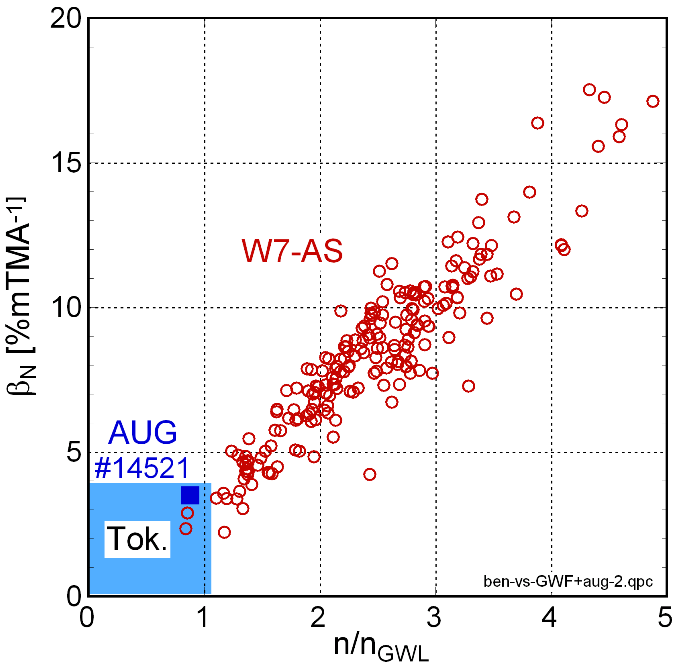
High-β, quiescent operation



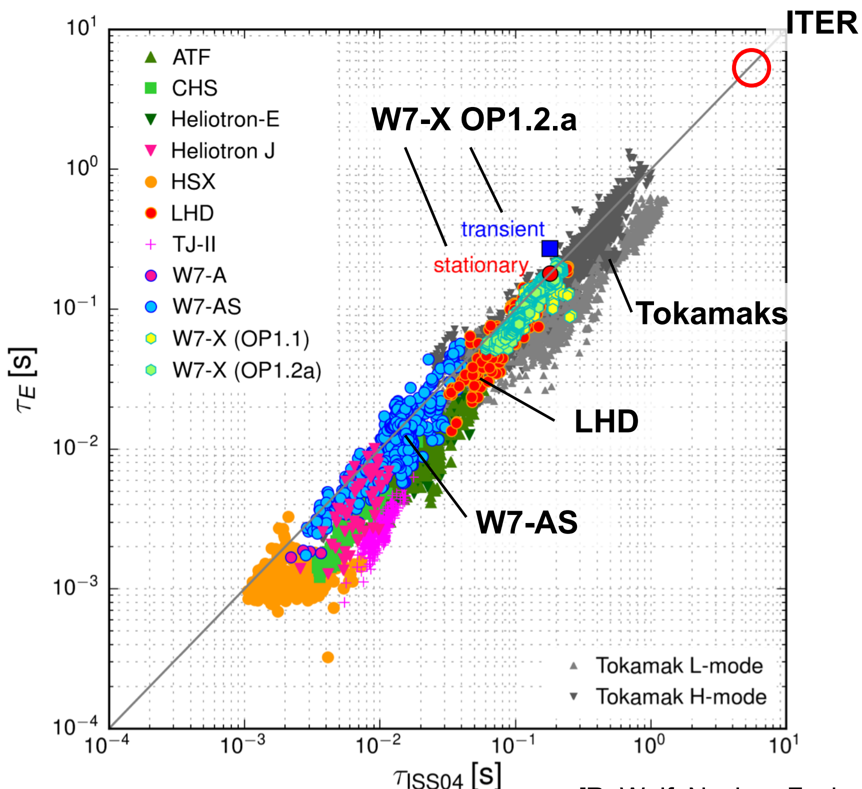
Stable system with promise to be a secure investment!

High density operation enables competitive performance

Stellarators are operated at high density



Performance of stellarators is approaching tokamak levels –
W7-X is on a very promising route



[R. Wolf, private communication]

[R. Wolf, Nuclear Fusion 57 (2017) 102020]

Reliable and high-gain system with promise for sufficient, steady state output.

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Recent success in stellarator research offers a new option for the U.S. to accelerate fusion energy development

Stellarators offer unique features for an economic power plant

Low recirculating power	⇔	energy efficiency
Steady state operation	⇔	system reliability
Free of current disruptions	⇔	investment security
MHD stable plasma operation	⇔	supply security
High density operation	⇔	maximize system gain/output

The next frontier is to realize a stellarator which demonstrates an integrated stellarator design: transport by design – divertor solution – custom fit PMI.

The proposal put forth a concrete idea that uses this challenge as research target.

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  Reasoning to consider stellarators as credible alternative

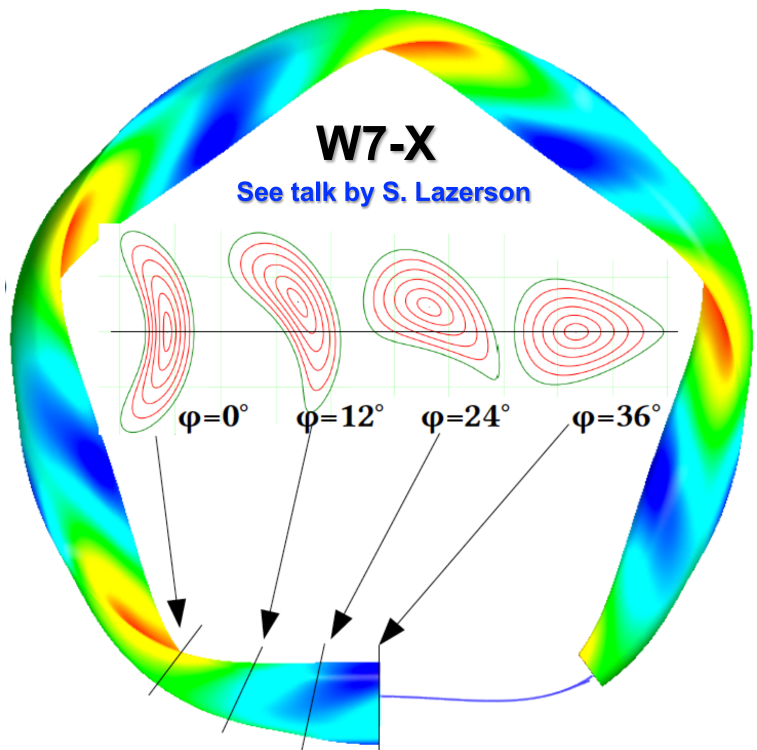
- **Stellarators: how?**
  Configuration aspects and prioritized research needs

- **Stellarators: what?**
  A concrete, one step initiative to a DT stellarator

Quasi-Symmetry is an U.S. invention which offers significant potential to further boost stellarator

Quasi-isodynamic (QI)

Good confinement (NC & FP) at nearly vanishing internal currents and significant mean flow damping

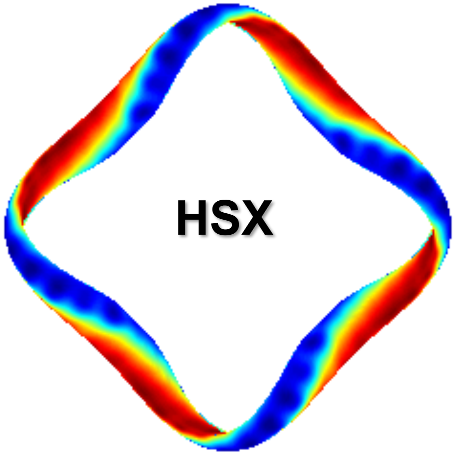


[J. Geiger et al., Wilhelm Hereaus Seminar, 2017, Bad Honnef]

Quasi-helical symmetric (QHS)

Good confinement (NC&FP) at moderate but finite internal currents with facilitated mean flows

[F.S. Anderson et al., Fusion Technology 27 (1995) 273]



Quasi-symmetric stellarator
optimization together with Quasi Axi-Symmetry (QAS)

Comparison between QI and QHS allows to assess advantages and role of flows and internal currents in stellarators for device performance

Fact chart optimization aspect – coarse grain (!!)

This is a coarse gain summary of the mean averaged cases made on these aspects in literature and discussions

Aspect	QAS	QHS	QI (W7-X, ongoing)
NC confinement	Expected to be good	**Demonstrated good (e- thermal)**	Expected to be good
FP confinement	Potential to be good	Potential to be good	Potential to be good
Internal currents	Expected high	**Demonstrated reduced**	**Initial evidence for low currents**
MHD stability	Open questions about MHD stability	High expected β limits (high ι_{eff})	β=6% target to get good performance
Turbulence optimization	Significant potential (e.g. Mynick PRL'10)	Significant potential (e.g. Hegna PoP'18)	Significant potential (e.g. Proll PPCF'16)
Facilitates flows	Expected	**Low flow damping demonstrated**	Not expected
Divertor solution	Non-resonant possible	Two candidates identified	**Island divertor**
Concept build and tested	**No**	**Yes**	**Yes (ongoing)**

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Decision in QS branch

- **Three main physics advantages for QHS (on this level)**
- **Only the QHS concept has been build and successfully explored (20 years, $30M)**

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Next frontiers (Turbulence optimization, Facilitates flows, Divertor solution)

Decision in QS branch

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- Only the QHS concept has been build and successfully explored (20 years, $30M)

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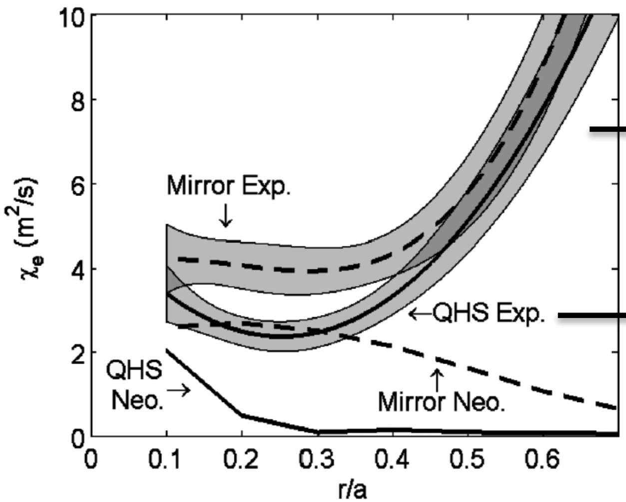
"Transport by design" is an exciting prospect for stellarators

- **Neoclassical electron thermal transport was reduced in HSX by design**



[J.M. Canik et al., Phys. Rev. Letters **98** (2007) 085002]

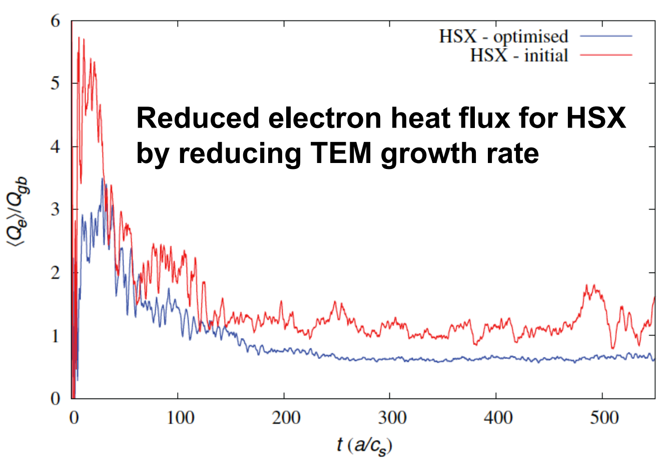
High heat flux towards plasma edge

QH reduces heat flux at mid-radius

$$Q_e = -n_e \chi_e \nabla T_e$$

Obviously: the underlying anomalous transport has to be the next target

- **Control the turbulence: next frontier to design for reduced turbulence levels**



[J.Proll et al., PPCF **58** (2016) 014006]

Optimization enabled by 3D gyro-kinetic codes

Non-linear ITG turbulence seems promising in QHS

Derivation of analytical metric for non-linear ITG turbulence saturation

[C.C. Hegna et al., Physics of Plasmas 25 (2018) 022511]

[P.W. Terry et al., Physics of Plasmas 25 (2018) 012308]

Such new metrics for turbulence optimization are being developed and tested

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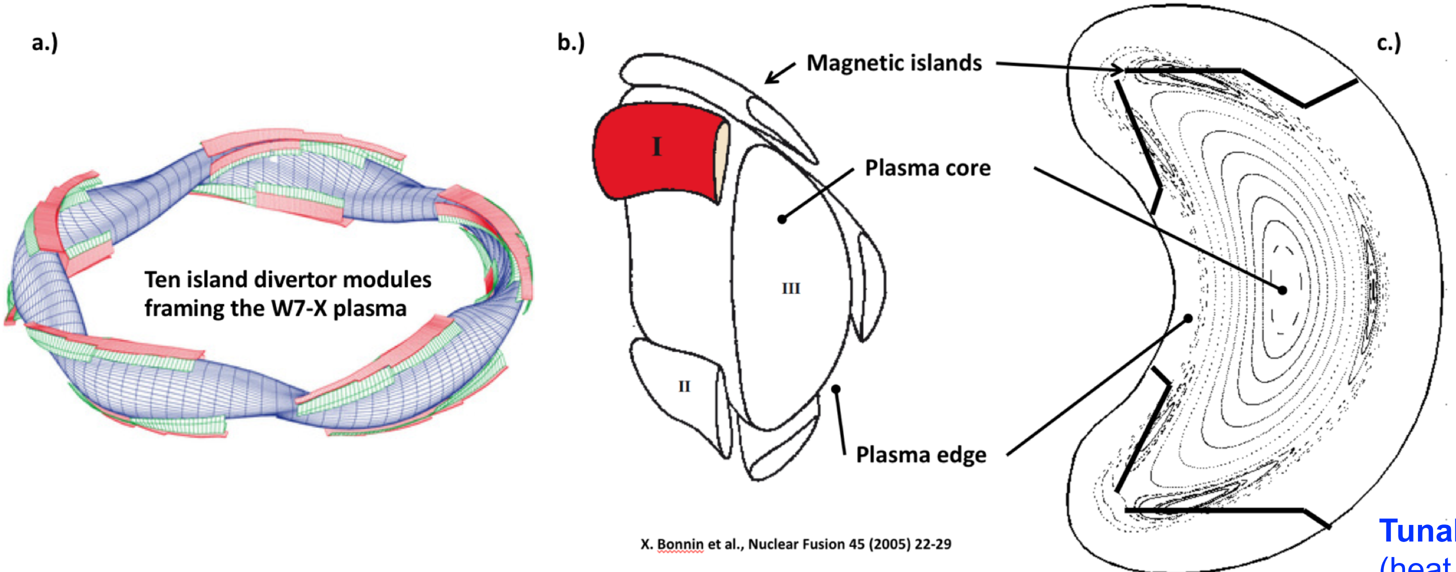
A flexible divertor test platform is needed to custom fit the divertor to the optimized plasma core

- **Island divertor** utilizes low order resonance in edge – equilibrium sensitivity

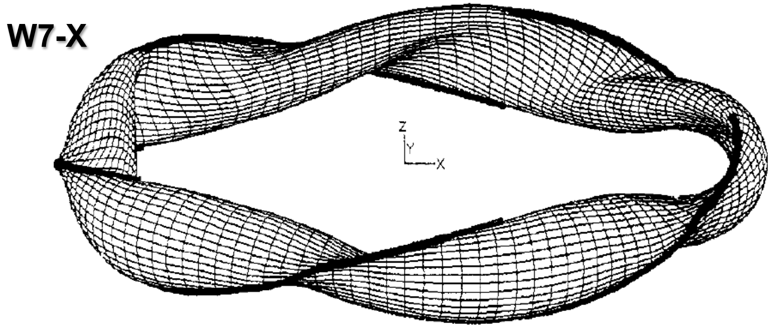


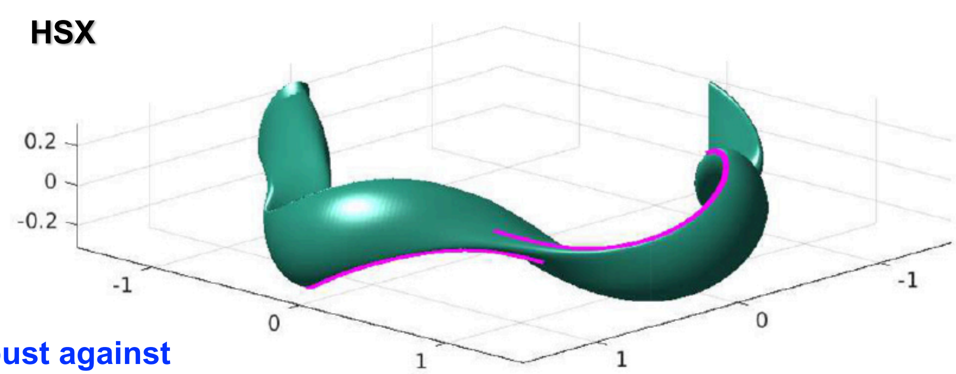
X. Bonnin et al., Nuclear Fusion 45 (2005) 22-29

Provided access to High Density H-mode at W7-AS

Tunable volume divertor (heat dissipation, exhaust)

- **Non-resonant divertor** utilizes sharp magnetic edges for robust divertor concept





Robust against equilibrium changes

[E. Strumberger et al., Nuclear Fusion 32 (1992) 737]

[A. Bader et al., Physics of Plasmas 24 (2016) 032506]

Outline

- **Stellarators: why?**
  Reasoning to consider stellarators as credible alternative

- **Stellarators: how?**
  Central research needs as background for a concrete initiative

- **Stellarators: what?**
  A concrete, one step initiative to a DT stellarator

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A medium-size QHS device is proposed as the intermediate step

QHS device

Combine **neoclassical and turbulent transport optimization** with **flexible divertor test platform** and **custom fit PMI**

The QHS device proposed will start from a firmly explored concept and is ready to take the next step.

Such a stepladder through a concept exploration (CE) phase is a mandate for device development.

The unique features of QHS are compelling - and they have been demonstrated in HSX

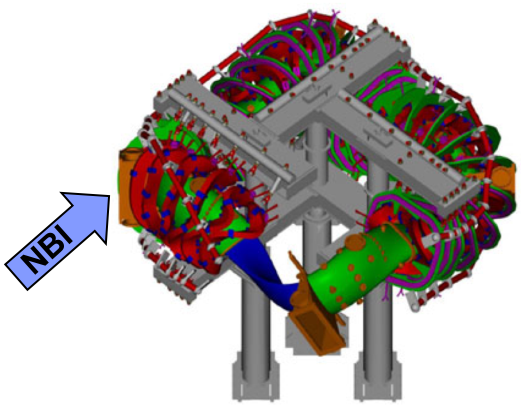
- **Constructed device matched the designed magnetic spectrum**
  [J.N. Talmadge et al., "Experimental determination of the magnetic field spectrum in HSX using passing particle orbits" Physics of Plasmas 12 (2001) 5165]
- **Improved neoclassical electron confinement in QHS**
  [J.M. Canik et al., "Experimental Demonstration of Improved Neoclassical Transport with Quasihelical Symmetry", Phys. Rev. Letters 98 (2007) 085002]
- **Reduced flow damping with QHS**
  [S.P. Gerhardt et al., Experimental Evidence of Reduced Plasma Flow Damping with Quasisymmetry, Phys. Rev. Letters 94 (2005) 015002]
- **Reduced Bootstrap and Pfirsch-Schlueter currents in QHS**
  [J.C.Schmitt et al., "Modeling, measurement and 3-D equilibrium reconstruction of the bootstrap current in HSX" Physics of Plasmas 21 (2014) 092518]
- **Good trapped particle confinement of high-E electrons in QHS**
  [D.T. Anderson et al, "Overview on recent results from HSX", Fusion Science and technology 50 (2006) 171-176]

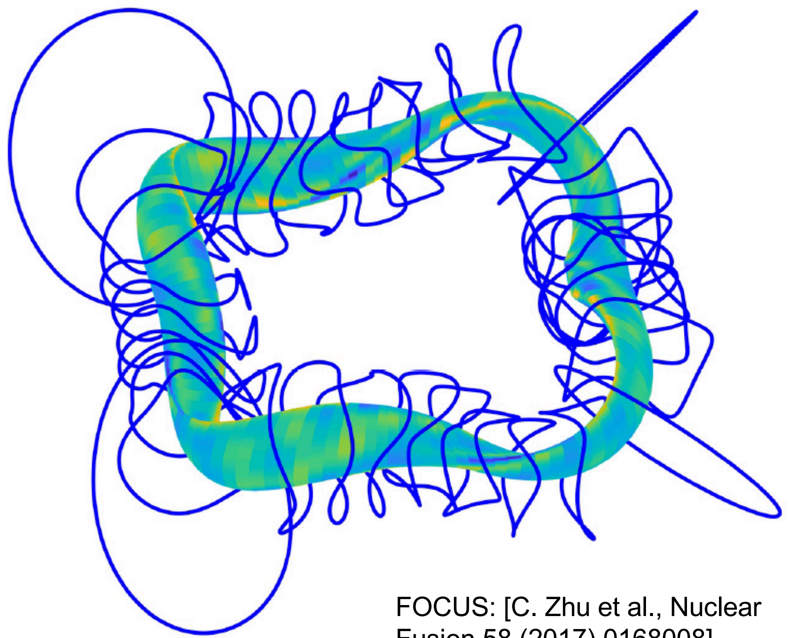
Clear goals were identified to complete the QHS qualification as candidate for a DT stellarator device

Goal 1: qualify electron and ion neoclassical transport

- **Complete validation of QHS neoclassical confinement performance requires hot ions (~0.5-1keV) with T_e ~ T_i at low collisionality**

  - **NBI route is versatile:** heating, flow drive, core fueling, fast particle physics
  - Requires sufficient space for tangential beam injection
  - Requires target plasma of ~ 5 x $10^{19}m^{-3}$ and low core neutral fraction





FOCUS: [C. Zhu et al., Nuclear Fusion 58 (2017) 0168008]

*collaboration PPPL

Larger corner coils needed for NBI injection

New coil design tools are being used!

This is an initial example and requires re-optimization of HSX.

But: HSX in its present size is too small
for beam absorption & full e-i coupling & low neutral density in core

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Goal 2: reduce turbulent transport through 3D shaping

- **A new non-linear metric for ITG driven turbulence was developed and is being tested against GENE modeling**

  [C.C. Hegna et al., "Theory of ITG turbulence saturation in stellarators: Identifying mechanisms to reduce turbulent transport", Physics of Plasmas 25 (2018) 022511]

- **Reduced flow damping in QHS is promising to reduced turbulence**

- **Other metrics are emerging and being tested**

Such metrics are being used in STELLOPT to optimize plasma equilibrium for reduced turbulence – an active field of research

- **Enables for the first time a perspective to design a magnetic confinement device with deliberate optimization for reduced turbulent transport**

- **Coupling to flow physics in QHS device offers unique fundamental science laboratory on link between turbulence and flows**

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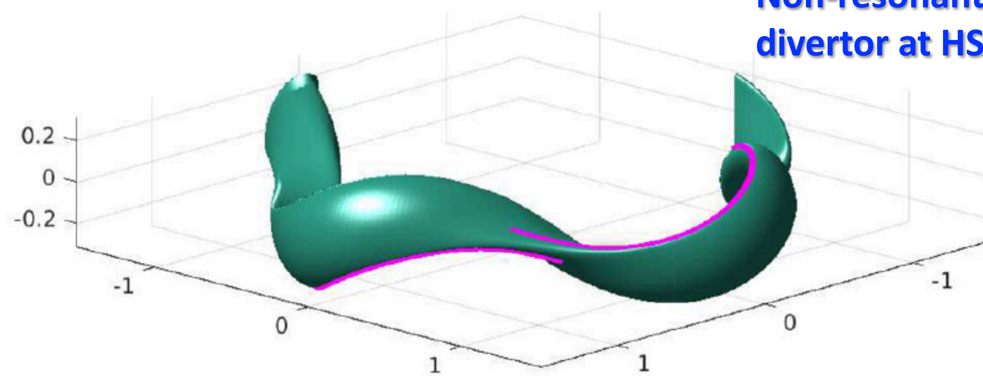
Goal 3: divertor test platform to generate integrated system

No existing stellarator has a flexible divertor qualification capacity

- **Island divertor:** attractive volume divertor with sensitivity to equilibrium
- **Non-resonant divertor:** focusing divertor but resilience against equilibrium effects

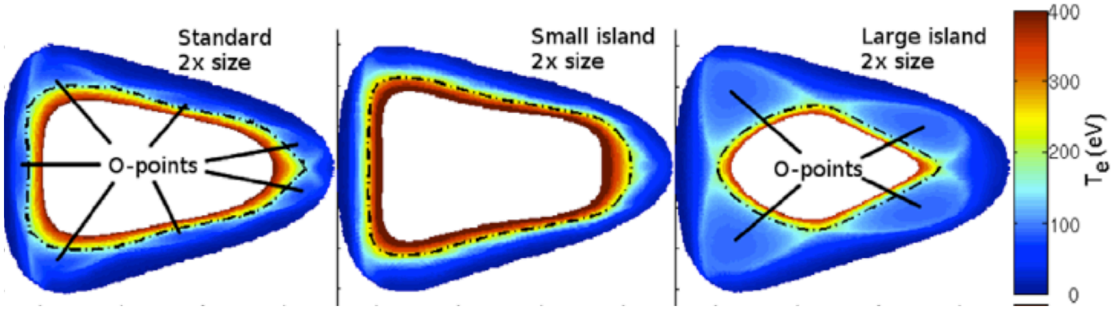
In QHS, both types of divertors are accessible

Non-resonant divertor at HSX



[A. Bader et al., Physics of Plasmas 24 (2017) 032506]

Flexible island divertor configurations at HSX



[A. Bader et al., Nuclear Fusion 53 (2013) 113036]

The divertor needs space, which makes it an integrated optimization challenge

Goal 4: custom fit a relevant plasma-wall interface to the divertor of choice

Assumptions: hot ion (ion root) T_i>0.5 keV plasma, opaque to neutrals (n_e> several $10^{19} m^{-3}$) at T_e > 1keV

- **It's not a choice, but a mandate to have a suitable PMI concept**

- **A stellarator on this level will be a top-notch PMI science facility in stellarator geometry – focus on anything but graphite! -**

$\Gamma > 10^{20}$ m^{-2} s^{-1}	**q_d > 3-5 MW m^{-2}**	**Realistic magnetic pre-sheath**

Inward impurity pinch in ion root can be addressed with realistic E_r

Hot ions give realistic sputtering conditions – not easily accessible in linear PMI facilities

- **Additive Manufacturing enables flexible first wall and divertor interface to custom fit PMI interface to optimized plasma core**

A focused concept for a new, mid-scale QHS stellarator in the U.S.

- Size: ~ HSX x 2
- Neoclassical and turbulent transport optimization
- NBI and ECH heating for high density (> 5 x 10^{19} m^{-3}) plasma at $T_e \sim T_i$ > 0.5-1keV
- Low core neutral content
- Increased room for divertor test platform
- Custom fit PMI and material test station for PMI studies

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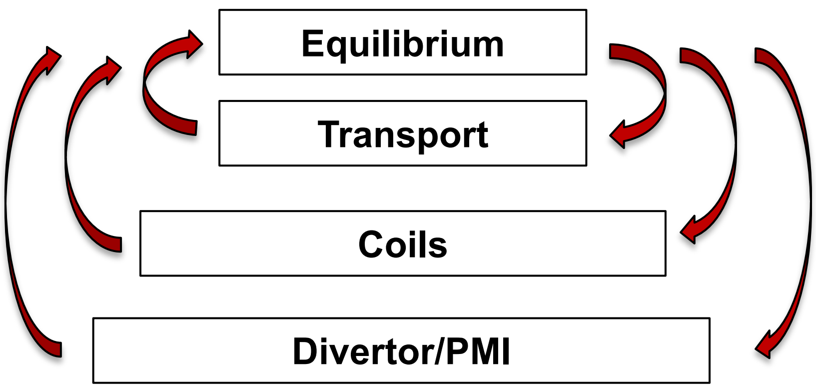
Where are we in the design process? Do we have the tools? Results?

Hierarchy of design loop



Tools used in STELLOPT*

*collaboration PPPL

VMEC *collaboration ORNL & Auburn U

NC & Turbulence & (FP) *collaboration NIFS

FOCUS/REGCOIL *collaboration PPPL & U Maryland

2-point model, analytical erosion model *collaboration IPP Greifswald & FZ Juelich

EMC3-EIRENE, GENE and other dedicated numerical tools are available for specific verification

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The necessary tools are at hand and they are being exercised addressing the central goals listed before

Coupling of new coil design tools and equilibrium optimization is working

REGCOIL solutions **pulls coils away** from HSX boundary

[M. Landreman et al., Nuclear Fusion 57 (2017) 046003]

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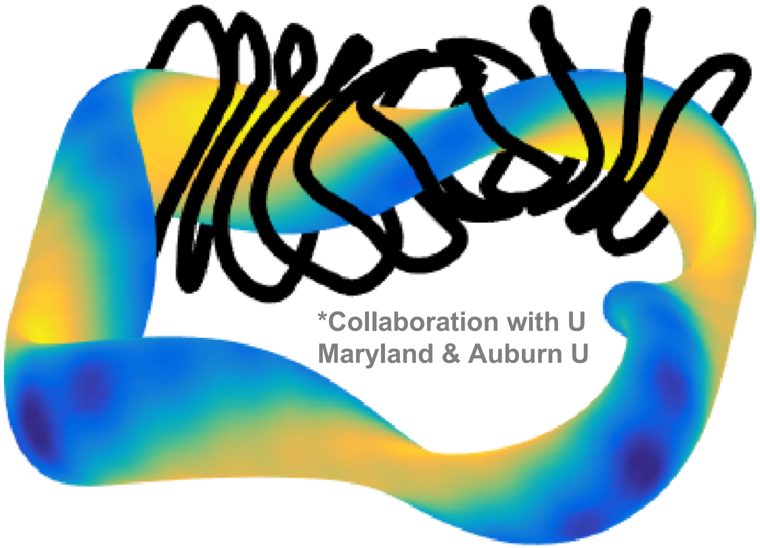

REGCOIL solutions **pulls coils away** from HSX boundary

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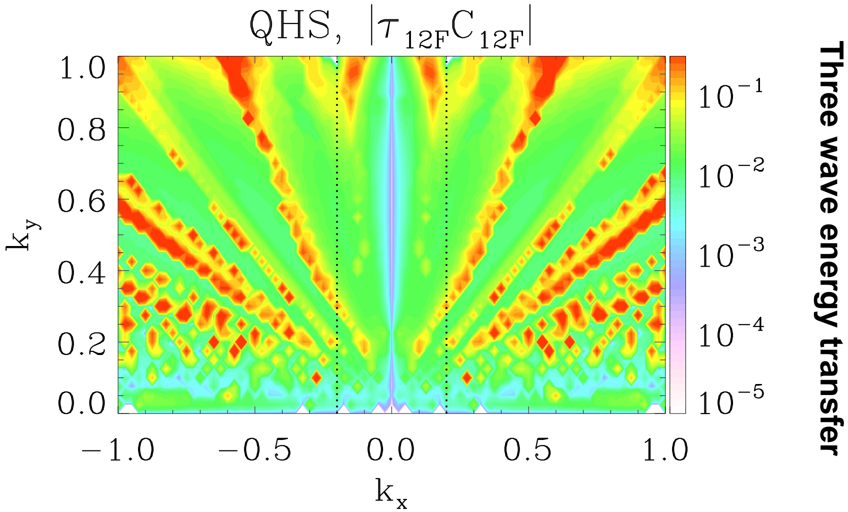
A new, non-linear 3D turbulence metric is being developed – *ongoing research*



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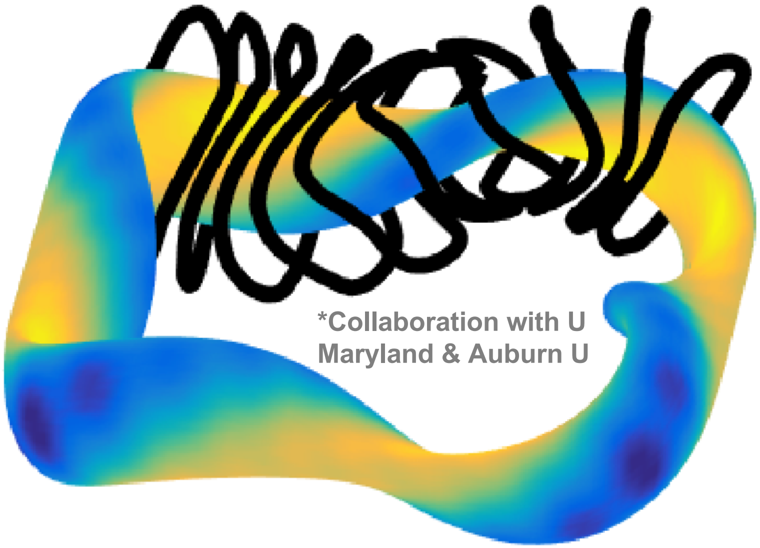

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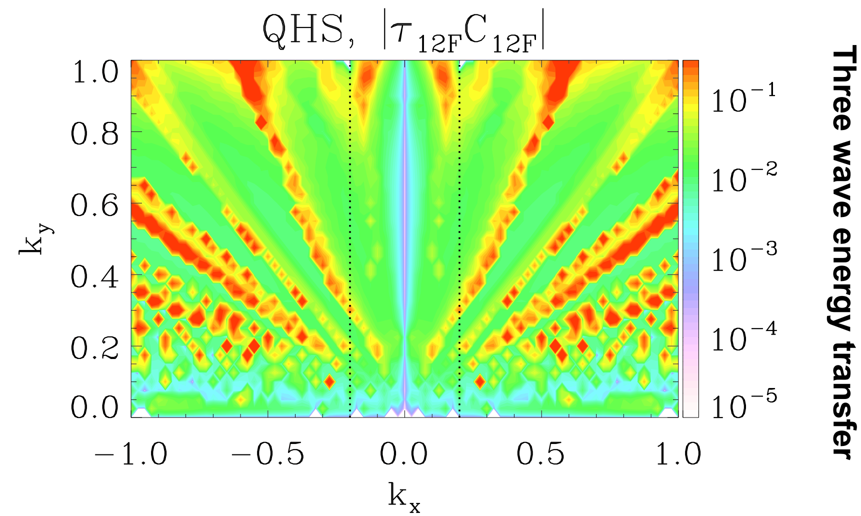
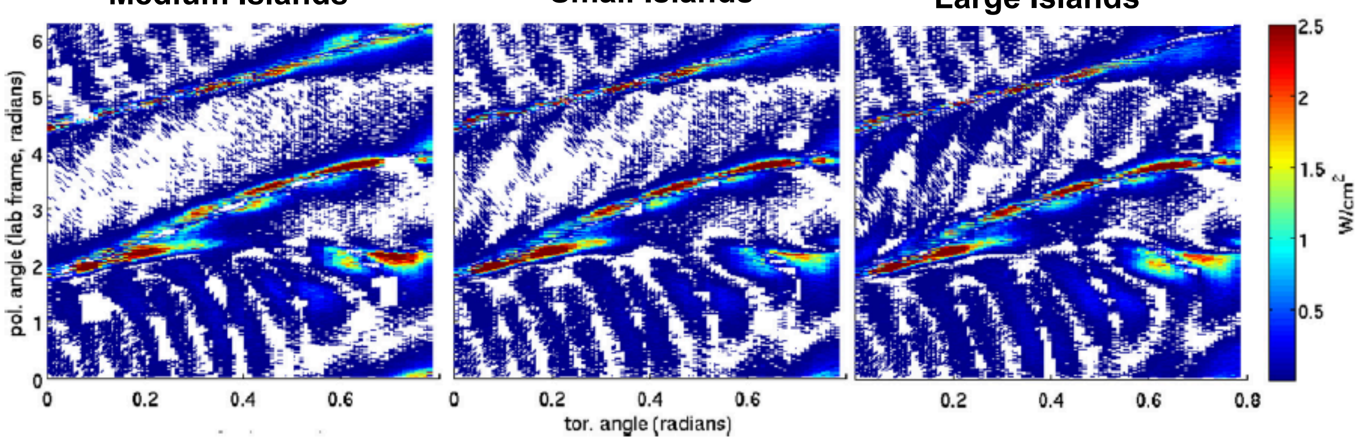


[C.C. Hegna et al., Physics of Plasmas 25 (2018) 022511]

EMC3-EIRENE predicts robust divertor strike lines at HSX

[A. Bader et al., Nuclear Fusion 53 (2013) 113036]



*Collaboration with IPP Greifswald

Such a device can be constructed and operated as a thrilling University based enterprise

- **Time line and cost estimate**

Design | Construct | Operate

today | 2 years | 6 years

Design: **$3M/a for 2 years**

Construction: **$10-25M/a for 4 years**

Operation: **~$10M/a**

- **Strategy considerations:**

- **Highly collaborative effort for design and construction**
- **Becomes USER FACILITY once completed** (single owner approach before accelerates)
- **Hosted by University makes it a thrilling enterprise for graduate student training**
- **Expertise across University(ies) is an asset for state of the art technology and engineering at high cost effectiveness**

Such a facility would be scientifically as well as from the implementation standpoint unique in the world!

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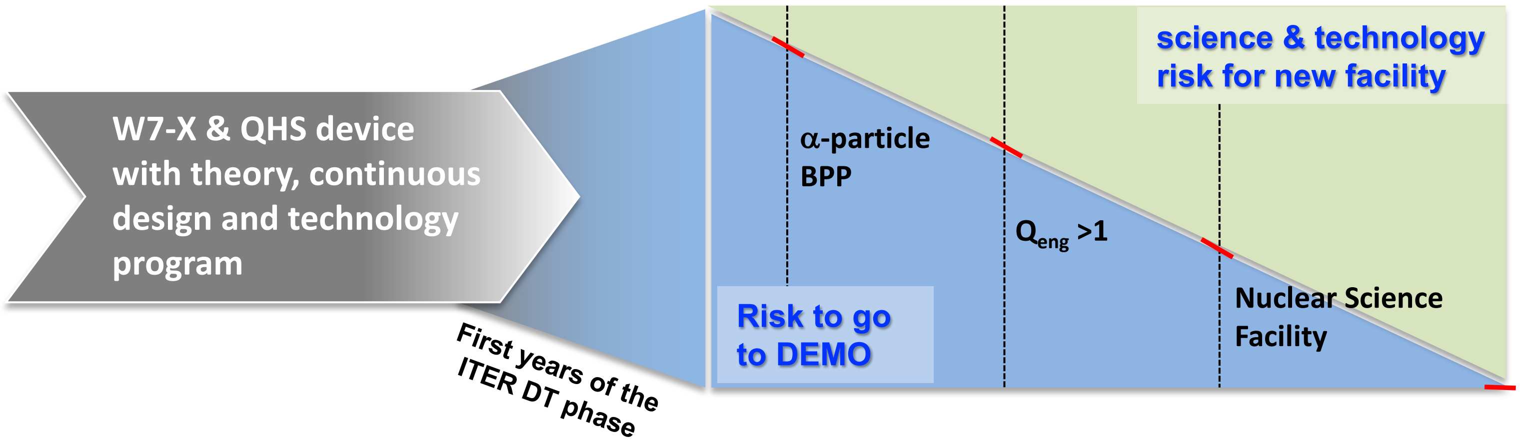
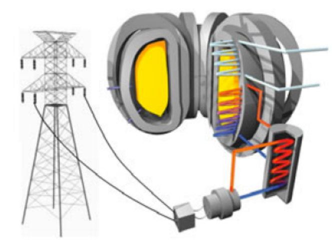
The DT stellarator perspective addresses a spectrum of needs for faster fusion energy development through design and operation security

Mission definition & risk assessment in community process

A spectrum of DT missions to reduce risk towards a demonstration power plant (DEMO)



First of a kind Power Plant



[J.E. Menard et al., Nuclear Fusion **51** (2011) 103014]

- **Initial design efforts support scalability of QHS to reactor levels**
  [SPP study led by UCSD, UCSD-ENG-004 (1997)]

The inherent features of the stellarator as reliable, steady state, high output system are transformational to provide a strong – maybe superior - candidate system for such facilities

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Summary of a concrete attempt to establish U.S. leadership at the frontier of the stellarator concept

Exploit our leading experience in QHS stellarator research to engage into a rapid path to a DT stellarator concept.

Start design immediately

Q-H device

Combine **neoclassical and turbulent transport optimization** with **flexible divertor test platform** and **custom fit PMI**

Steady state physics at W7-X

See talk by S. Lazerson

Sustained theory program to enable extrapolation

Enabling stellarator technology (A/M, HTSC)

Go to DT

Community process

Accelerate design effort

Command the risks

Leverage ITER knowledge

DT stellarator

A spectrum of DT & BPP science questions can be addressed

Stellarator as stable and efficient system will be made available as a new option

Such a bold approach based on the stellarator concept will be a slingshot for U.S. leadership to accelerate fusion energy.

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APPENDIX

Summary: concrete mission elements of QHS facility

Approach: **base facility on advantages of Q-H, which were demonstrated with the HSX device** ⇨ **QHS**

Goal 1: **qualify improved neoclassical transport with realistic ion temperature in Q-H**

Goal 2: **demonstrate for the first time "turbulence by design" approach in Q-H**

Goal 3: **Integrated divertor qualification for island and non-resonant divertor**

Goal 4: **custom fit PMI interface to divertor of choice using additive manufacturing**

Line of attack in a nutshell: size: ~ HSX x 2, Q-H, neoclassical and turbulent transport optimization, room for divertor, NBI, low neutrals in core, flexible wall interface + A/M
Parameters: ~5 s discharges, n_{sep}>5.0e^{19} m^{-3}, $T_{e,c}$~1-2keV, $T_{i,c}$~1keV

Not high priority guidance elements: MHD stability at high-β, extensive energetic particle studies, steady state aspects

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The long term goal must be a DT stellarator – a reasoning

(1) With the QHS device and the strong program at W7-X as well as experience from LHD, we must be able to make a significant step

This has to be the goal of this strategic initiative in a fusion energy context!

(2) Argument is: reduced control needs + significantly lower recirculating power make stellarator a more viable. This has to be shown by building a DT device faster!

(3) At the time, ITER will (hopefully) be operational, so additional BP physics starts to become available -> risk mitigation through leverage

(4) Tools used for QHS design and further development (sustained theory and design program!!) have to provide predictive capabilities

(5) Advances in A/M and magnetic design (SPARC) expected which will possibly aid stellarator design (high field magnets) and manufacture of 3D components
-> consider dedicated stellarator HTSC magnet and A/M component R&D effort