US stellarator program: Response to TAP questions

J. H. Harris

For the US stellarator community

FESAC-Toroidal Alternates Panel

30 June 2008

Contributions from:

Auburn University

Columbia University

New York University

Oak Ridge National Laboratory

Princeton Plasma Physics Laboratory

University of Wisconsin

Goal of stellarator confinement research

Ignited ($P_{ext} \approx 0$), steady-state, non-disruptive toroidal fusion reactor

- Common physics base with tokamak, but confinement principally with external helical fields.
- Specification of configuration determines physics properties. Theory —magnetics, MHD equil/stability, transport—plays leading and unifying role.
- Full 3-D geometry makes major demands on physics/engineering optimization, design, and fabrication well in advance of operation.

  “ . . . harder to build, easier to operate . . .”

Unique features of US stellarator program

- Quasi-symmetry: performance advantages, connection w/ tokamak
- Compactness:
  - Near term: less expensive experiments
  - Long term: more accessible reactor—unit size, capital investment
- *Quest for “simplicity”*

Stellarators address with Greenwald Panel Template

Predictable, high-performance steady-state plasmas

- Equilibrium from external fields ⇒ no disruptions, avoids ELMs
- Quiescent high-beta plasmas with confinement similar to tokamaks
- Good alpha particle confinement in optimized (e.g., quasi-sym.) configurations
- No need for current drive, rotation drive, or profile control systems in reactor.
- Very high density operation reduces fast-ion instability drive
- Strong coupling between theory, design, & experiment ⇒ predictability
- Variety of coil schemes to realize desirable magnetic configurations

Taming the plasma material interface

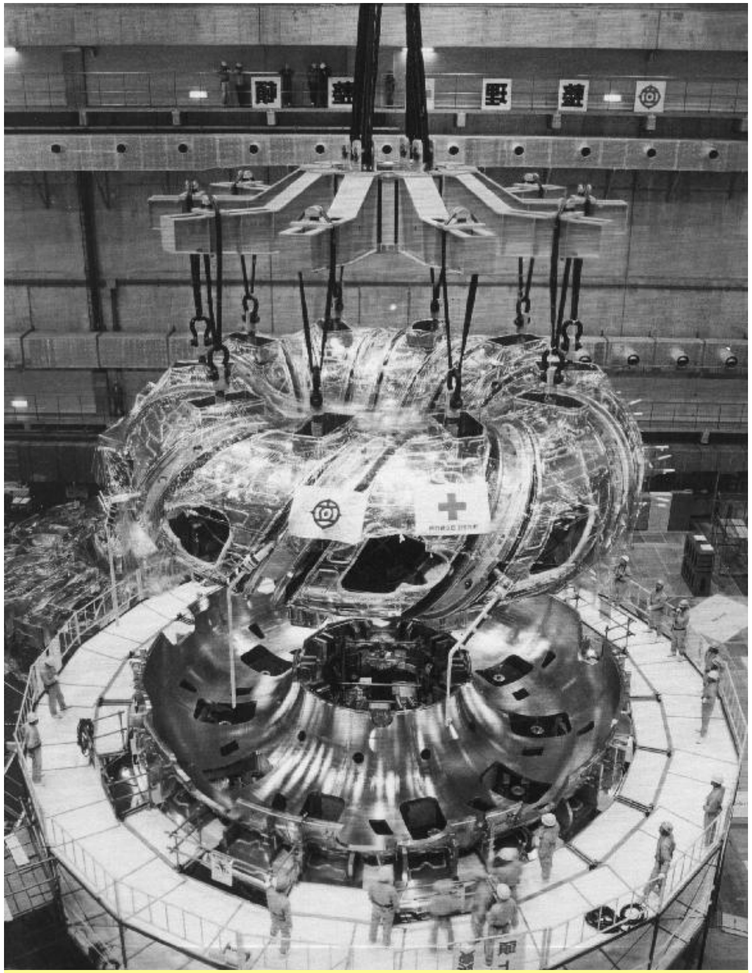
- 3-D divertor (islands, stochastic field lines)
- Very high density operation leads to easier plasma solutions for divertor
- No disruptions, avoids ELMs

Harnessing fusion power

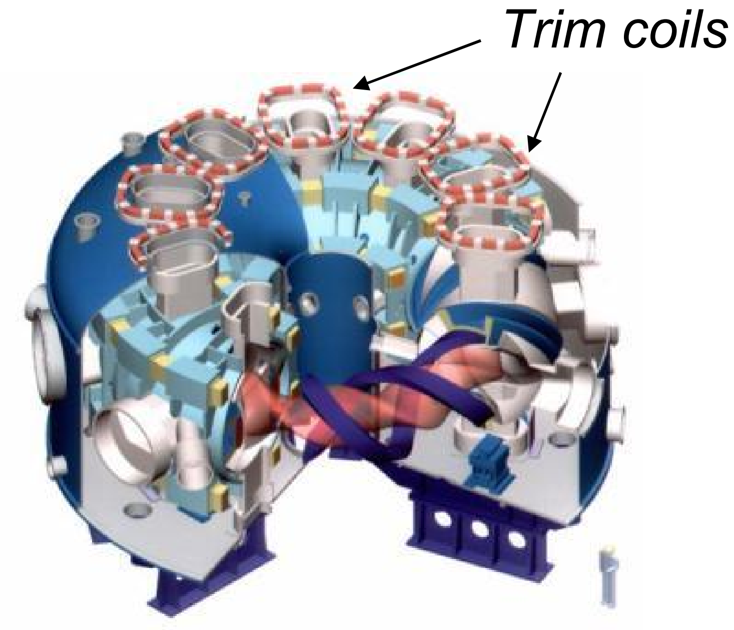
- Fully ignited operation: turn off external power
- High power density (similar to ARIES-RS and –AT)
- Not limited by macroscopic instabilities

Large stellarators have been successfully built and operated

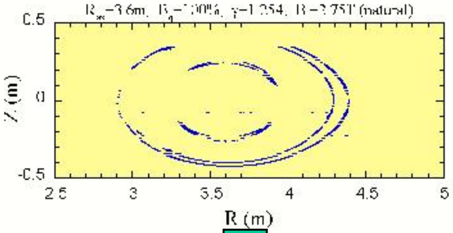
Large Helical Device (LHD), Japan (1997)



R = 3.9 m, a = 0.6 m, B = 4 T
superconducting coils
1500 tonnes

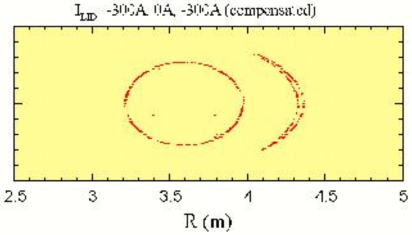


e-beam mapping results



trim coils

tune q = 1, 2 islands

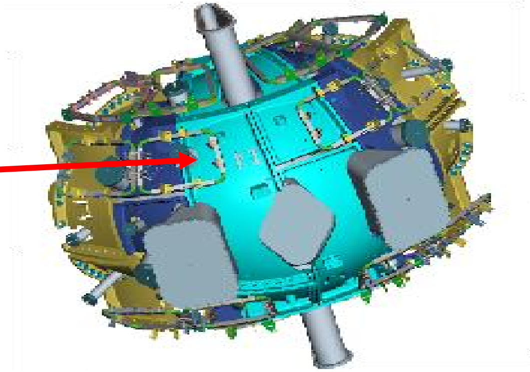


NCSX: modular coil fabrication & assembly required extensive innovation & development of 3-D techniques

- All 18 NCSX modular coils fabricated to req’d ±0.5 mm tolerance. Machining of coil forms required development of tools, process control,& load balancing between multiple machines.

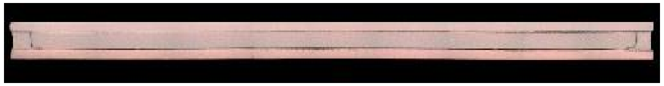
- Coil-to-coil joining required resolution of complex interface issues (forces, insulation, permeability tolerances, clearances) & joining techniques (bolts, shims, welds & custom tooling). Substantial delays incurred as design challenges resolved. Evolution in metrology from laser trackers to photogrammetry.

- Development of optimal programming for array of 48 planar trim coils will permit relaxation of tolerances. Will be tested on CTH torsatron (Auburn).

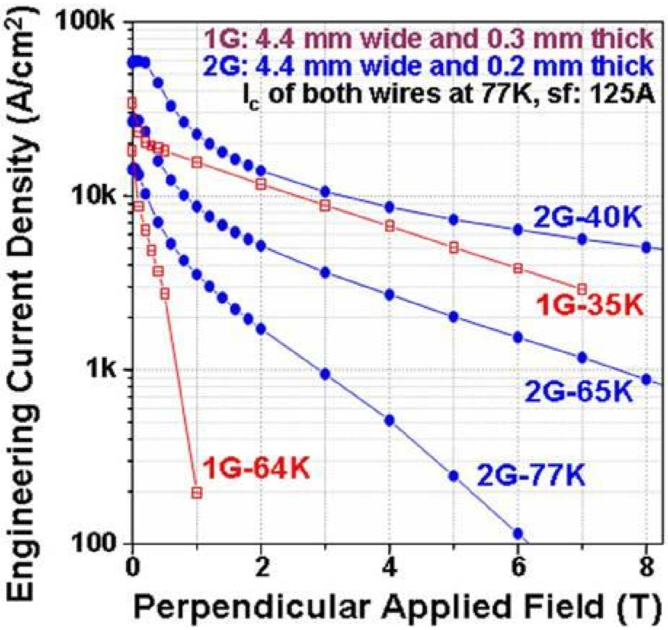


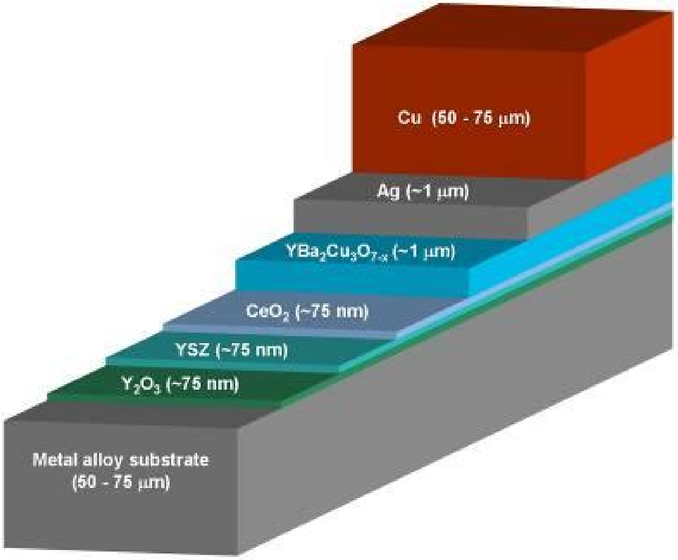
High temperature superconductors for stellarator coils?

- ***"2nd Generation": YBCO on metal tapes***



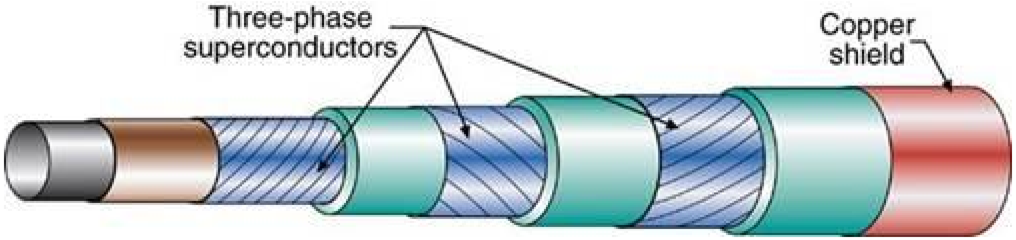
- ***Enabling properties for operation at liquid nitrogen temperatures***
- ***Early development, shorter lengths (~few 100 meters)***
- ***Cost goal 10-30 $/kA-m***





American Superconductor

HTS 3-phase power cable project suggests path for coil development



Ultera™
A Southwire / nkt cables Joint Venture

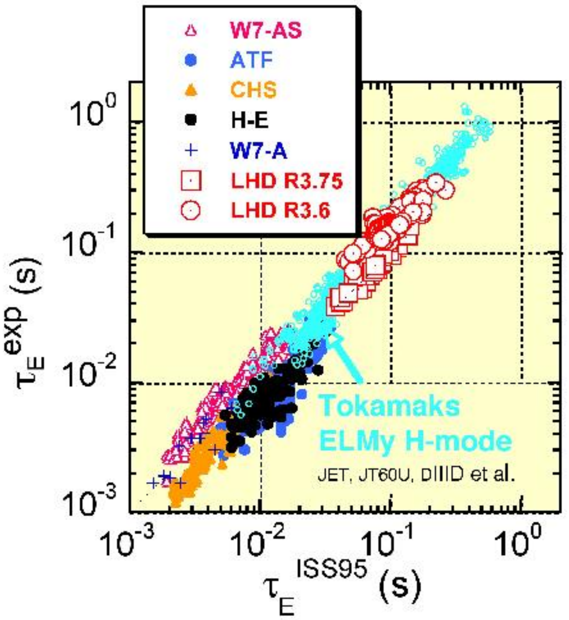
- **Tri-axial design is most compact HTS cable concept:**
  - Minimizes use of HTS tape
  - Requires minimum surface area for cryostat-lower heat load
  - Patent pending by ORNL/Southwire
  - Bend radii of tape ~ 2-3 cm
- **Basis for modular stellarator coil development?**
  - High current density very favorable for stellarator *(transform)*
  - Wind non-planar test coil with stainless tape (w/out HTS layer)
  - Thin tape may result in less springback, greater precision
  - Further development paced by declines in superconductor cost

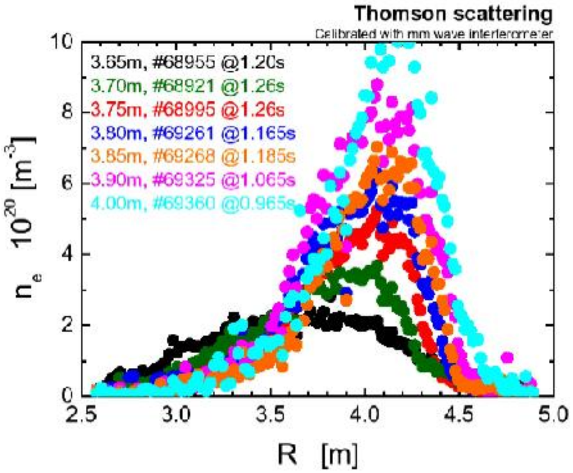
Current-carrying stellarator plasmas stabililized by external ι
Operation with large bootstrap currents $\Rightarrow$ principal goal of NCSX

- *Stellarators built since 1980 (Heliotron-E, ATF, CHS, W7AS, TJ-II, LHD)*
  Seldom used/use OH, and bootstrap currents were/are small.
- *Earlier devices (W7A, L-2, etc) with OH: R/a =10-20, I_{oh} < 20 kA.*
  Confinement minima when (OH + ext) iota profile $\Rightarrow$ low shear on resonance
  Transient MHD activity at edge rationals as current rises, but no disruption
- *W7A did low β exp'ts at tokamak-stellarator boundary:*
  Very low $\iota \sim 0.05$ obviates need for VF control
  Avoided disruptions with $\iota > 0.14 \Rightarrow$ shift of ∇J away from $q = 2$
- *W7AS showed mitigation of deliberate $q = 2$ disruption by external transform*
  Recovery possible if heating continues
- *W7X optimized to have low bootstrap current in nominal target configuration.*
- *NCSX is first stellarator designed to use substantial current (≤150 kA) to provide ≤50% of the total rotational transform.* Simulations of discharge evolution show that with control of 3-D boundary shape (via control of modular coil currents), stable plasmas with $\beta > 4\%$ can be be obtained with bootstrap fraction ~25%. This extrapolates to ARIES-CS reactor scenario

Stellarators are achieving outstanding results

- Quiescent high beta plasmas, limited by heating power & confinement
  - LHD β = 5.2% transiently; 4.8% sustained
  - W7AS β > 3.2% for 120 τ_E
- τ_E similar to ELMy H-mode
- Improved confinement with quasi-symmetry
  - HSX finds reduced transport of momentum, particles, and heat with quasi-symmetric config.
- Very high density operation, limited only by heating power, without confinement degradation
  - Up to 5x equivalent Greenwald density (W7AS)
  - LHD $n_e(0) \sim 10^{21}$ m^{-3} at B=2.7T !
  - Importance of divertors to control recycling
- Steady state: LHD ~0.7 MW pulse lengths ~1 hr





US compact stellarator research program is developing basis for attractive reactor concepts, e.g. ARIES-CS

Ref. baseline parameters:

NCSX-like (QA): 3 periods

$\langle R \rangle = 7.75$ m

$\langle R \rangle / \langle a \rangle \sim 4.5$

$\langle a \rangle = 1.72$ m

$\langle n \rangle = 4.0 \times 10^{20}$ m^{-3}

$\langle T \rangle = 6.6$ keV

$\langle B \rangle_{axis} = 5.7$ T

$\langle \beta \rangle = 6.4\%$

H(ISS04) = 1.1

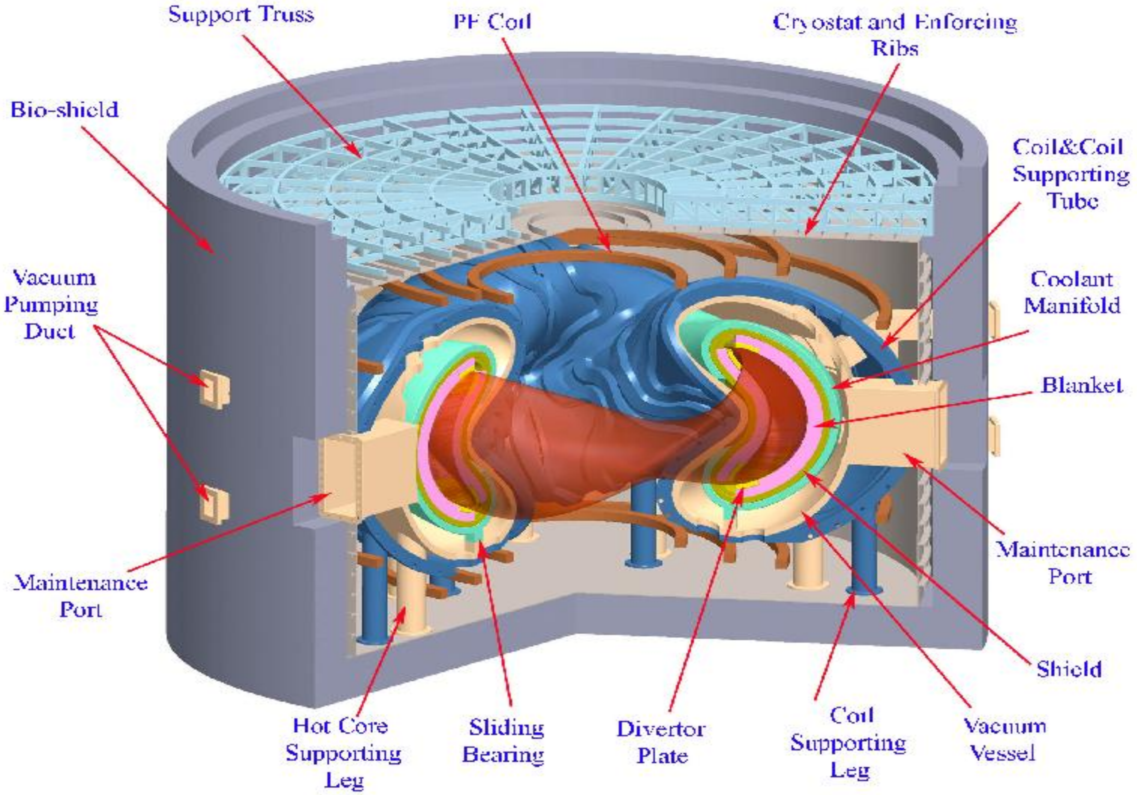
$I_{plasma} = 3.5$ MA (bootstrap)

25% of rotational transform

P(fusion) = 2.364 GW

P(electric) = 1 GW

Fully ignited ($P_{ext} = 0$)



Aries-	-I	-RS	-CS	-AT	-CS
Blanket			LiPb/FS	LiPb/SiC	LiPb/SiC
COE(92)	99.7	75.8	61.3	47.5	48.

alpha loss ≈ 5% ⇒ divertor heat load ~ 5-18 MW/m^2

(core radiation fraction ~75% as in ARIES tokamaks)

Is there a shortcut from ITER to a Stellarator Demo?

- Validated models of plasma/system performance & demonstrated solutions to key problems are a pre-requisite to DEMO. The close relationship between stellarators and tokamaks may allow for some acceleration of this process.

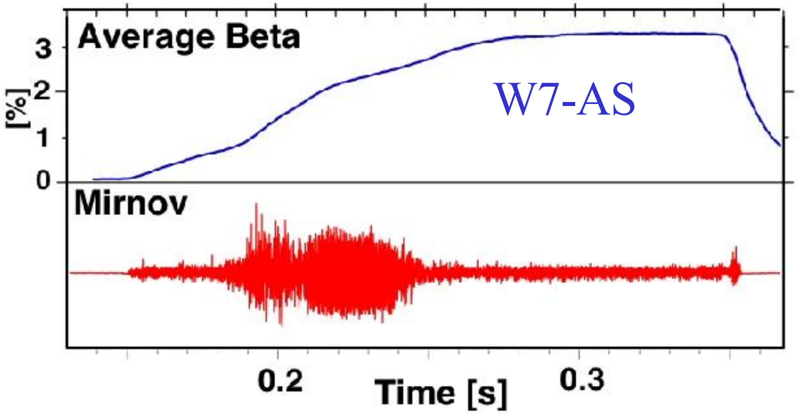
- DT experiments on ITER will test
  - ρ^* dependency;
  - the effect of the α particles on plasma stability;
  - effect of α-loss on PFCs;
  - effect of α-heating on plasma profiles & operating limits.

- Understanding of α effects from ITER can be tested on stellarators using isotope & fast-particle studies. External magnetic configuration makes stellarators less sensitive to profiles than tokamaks.

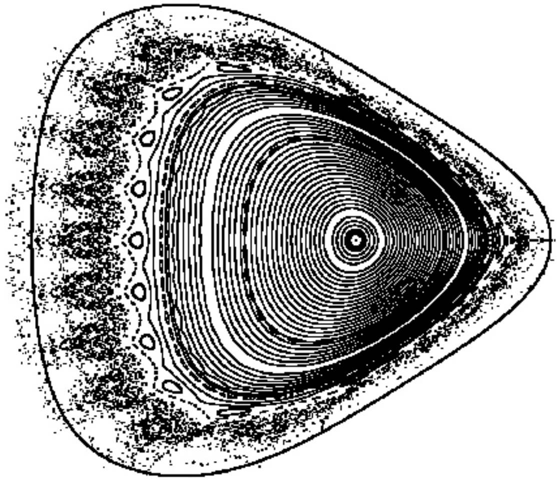
- Quasi-symmetric stellarators are particularly attractive in this regard.

High-β: equilibrium limits rather than stability?

- Resistive modes seen at finite β stellarators. With exception of Heliotron-E (ι = 1 on magnetic hill ⇒ sawtooth) these do not lead to disruption. No sign of ballooning yet (up to β ≈ 5% in LHD).



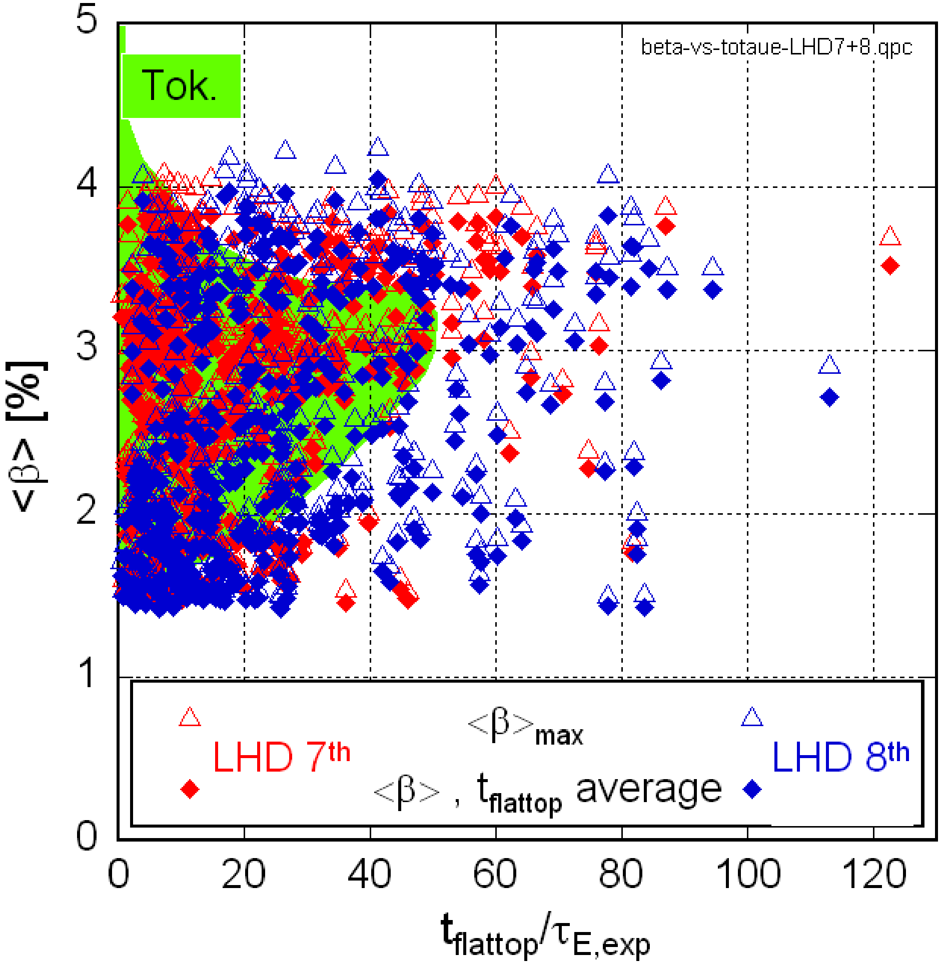
- Equilibrium reconstruction analysis indicates loss of 35% of minor radius surface break-up as β increases. Trim coils can improve flux surfaces.



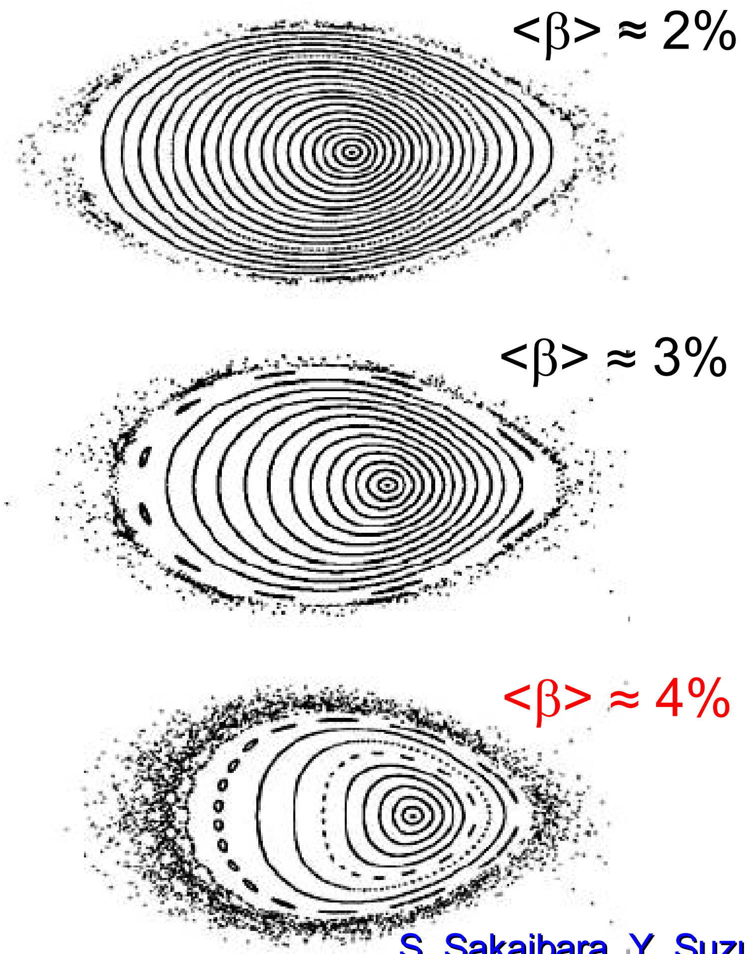
⟨β⟩ = 2.7%

LHD: evidence of high-β equilibrium deterioration

LHD: <β> vs.normalized flattop time



HINT-Analysis for LHD

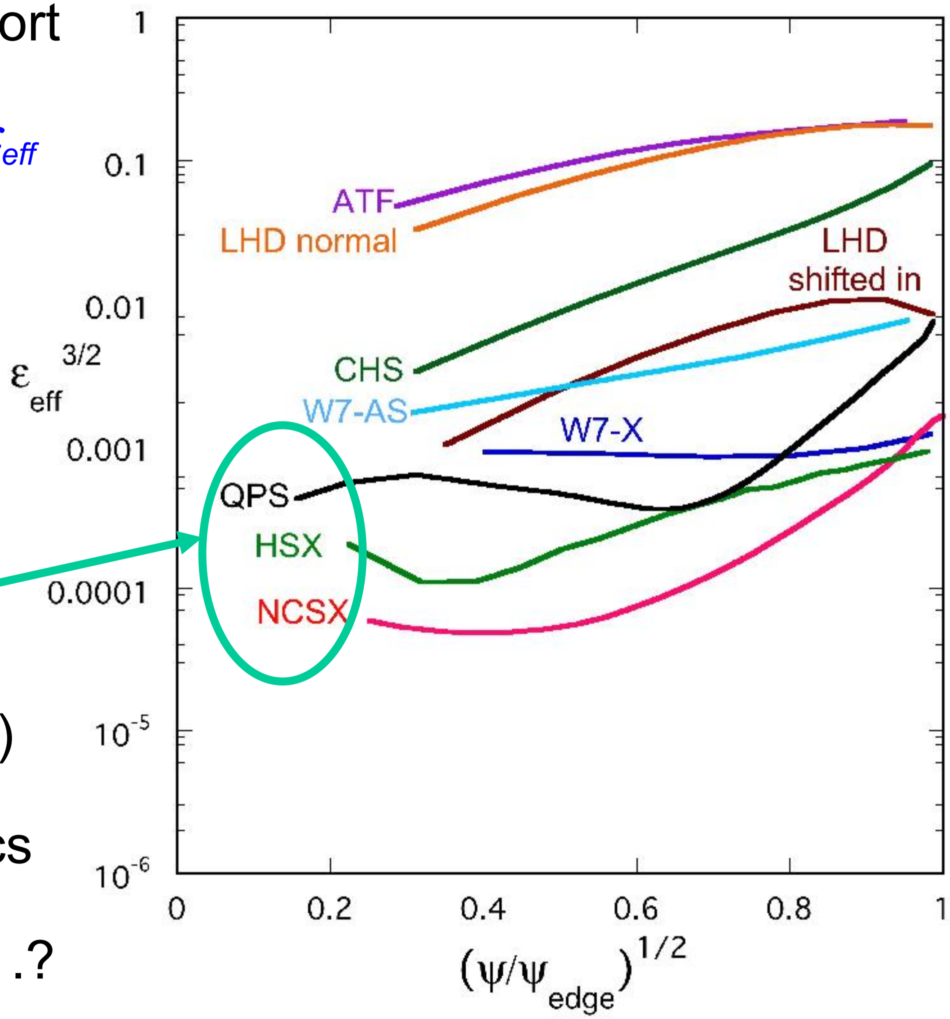


S. Sakaibara, Y. Suzuki

- LHD is low collisionality (W7-AS is high collisionality)
- No disruptions.
- Density collapse at high Shafranov shift for some configurations/profiles

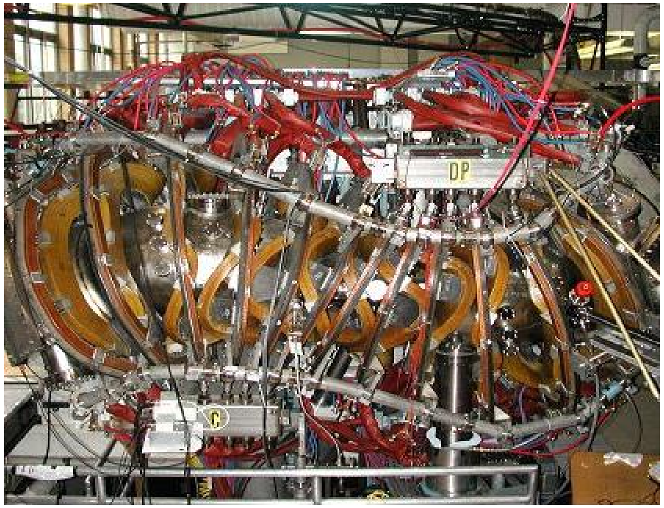
Configuration optimization has produced compact "quasi-symmetric" stellarators

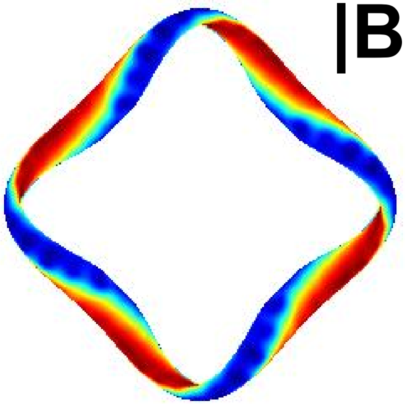
- Helical field ripple from stellarator coils enhances neoclassical transport losses. Configuration optimization that minimizes the *effective ripple* ε_{eff} along one coordinate produces "quasi-symmetric" configurations which can be built at low R/a: *compact stellarators*.
- US-developed configurations use:
  - quasi-axisymmetry (NCSX);
  - quasi-helical symmetry (HSX);
  - quasi-poloidal symmetry (QPS).
- Global confinement studies (ISS04) suggest that anomalous transport may also decrease with ε_{eff} . Physics under study (theory, LHD, HSX). Sheared flows, trapped particles . . .?



HSX: Helically Symmetric Experiment

Major Radius	1.2 m
Minor Radius	0.12 m
Number of Field Periods	4
Coils per Field Period	12
Rotational Transform	1.05 -1.12
Magnetic Field	1.0 T
ECH Power	<100 kW 28 GHz



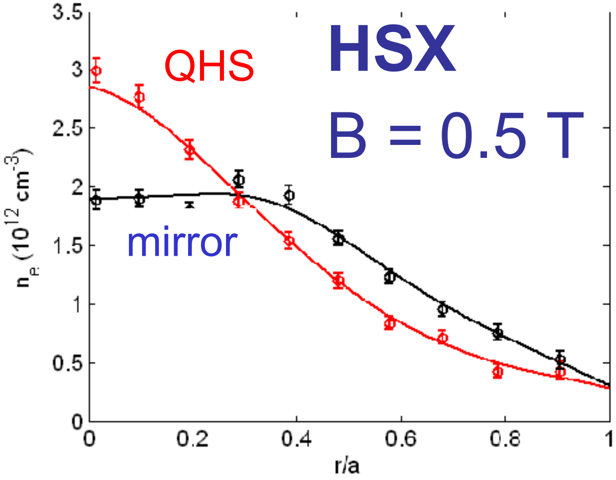


Can spoil symmetry
by changing coil currents:
= *"mirror configuration"*

quasi-helical symmetry

In 2nd harmonic ECH plasmas, quasi-symmetry reduces core transport and *may* also reduce core turbulence

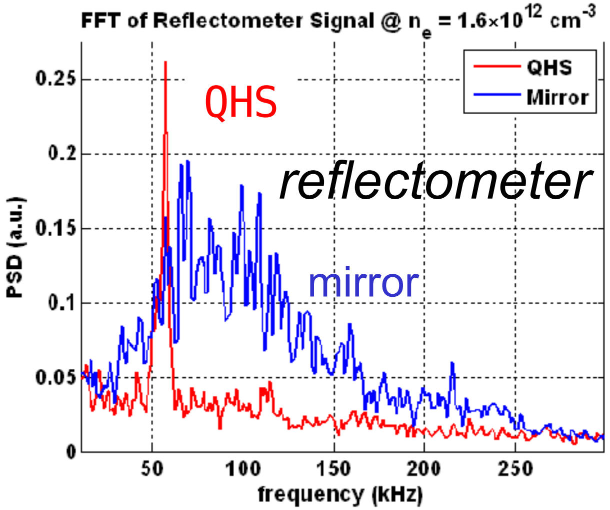
Particles



Peaked density profiles in QHS

➔ Reduced thermo-diffusion

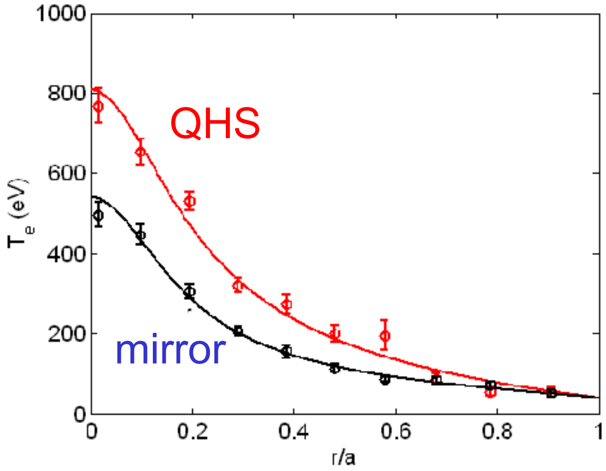
Turbulence **NEW!**



⇒ *Lower ñ in QHS*

Increased E x B flow shear?

Heat

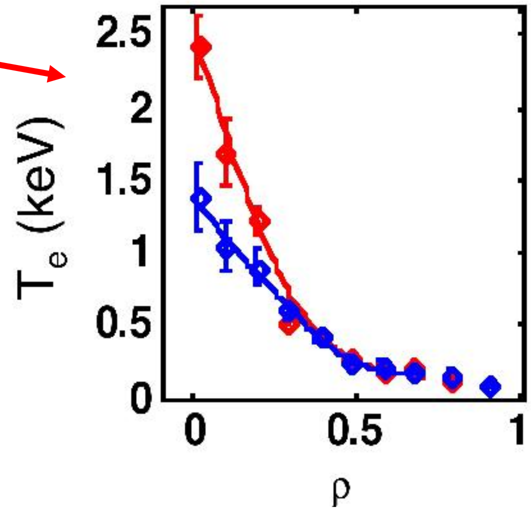


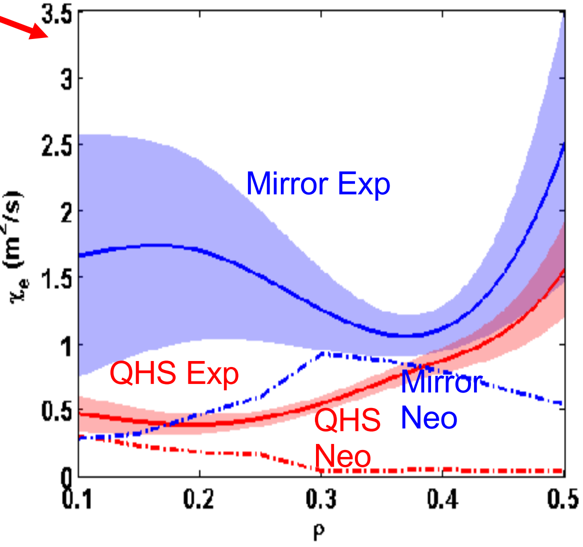
Higher T_e in QHS w/ same P_{abs}

➔Lower χ_e consistent with neoclassical theory

Does quasi-symmetry reduce anomalous core transport in HSX?

- Fundamental ECH at B=1.0 T $\Rightarrow$ T_e (0) ~ 2.5 keV. Further increase in ECH power underway.
- Initial transport analysis (ambipolar estimate for E_r) $\Rightarrow$ core anomalous transport reduced with quasi-symmetry as compared to mirror?
- Need E_r measurements. CHERS being installed. Heavy ion beam probe being developed with Interscience.
- *Does reduced zonal flow damping with quasi-symmetry or $E \times B$ shear lead to reduction of turbulence & anomalous transport?*
- Connect with ISS04 confinement scaling with ripple (ε_{eff}), turbulence & zonal flow exp'ts in LHD, CHS.
- *Priority topic for stellarator development.*





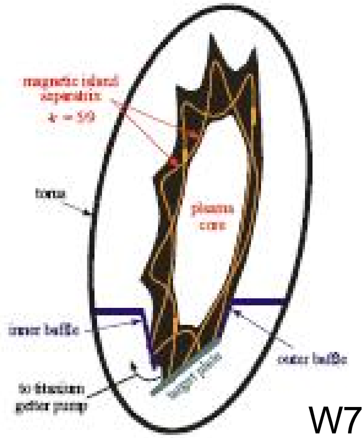
Divertors and impurities

- 3-D divertor physics is being pursued vigorously in the W7AS/W7X (island divertor) and LHD (both island & helical divertors) programs with strong mutual collaboration.

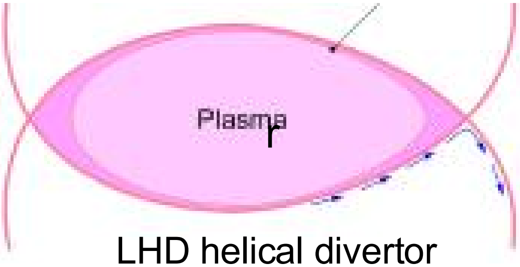
- Divertors already effective in accessing improved confinement regimes of record high density in two different ways:
    - High-power H (HDH) mode in W7AS with impurity, neutral screening from island divertor; detachment with strong radiation from island regions.
    - Super Dense Core (SDC) mode in LHD with highly peaked n(r): low-recycling divertor and repeating pellet injection

- Effective 3-D fluid modeling (EMC3); also applied to tokamaks.

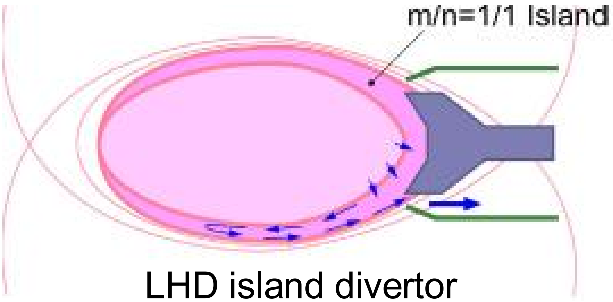
- Both LHD, W7X committed to steady-state operation, however at modest P/R ~ 1-3 for immediate future. ARIES-CS: P/R ~60.



W7AS



LHD helical divertor



LHD island divertor

Stellarator configuration improvement

- **Expand scope of optimization used to design NCSX & QPS**
  Additional physics considerations (examples):
  - Relax MHD stability constraints (e.g., ballooning)
  - Impact of departures from quasi-symmetry
  - Trapped & energetic particle instabilities, sheared flow
  - Perturbed flux surfaces (see next slide)
  - Divertor geometry

  Additional engineering considerations (examples):
  - Limitations on coil distortions & addition of trim coils
  - Coil curvature, clamping requirements
  - Clearance between components
  - Maximum B field, current density

- **Employ new optimization tools** developed in other domains.

- **Possible targets:** lower coil distortion, lower divertor flux, larger coil aperture, larger engineering β, etc.

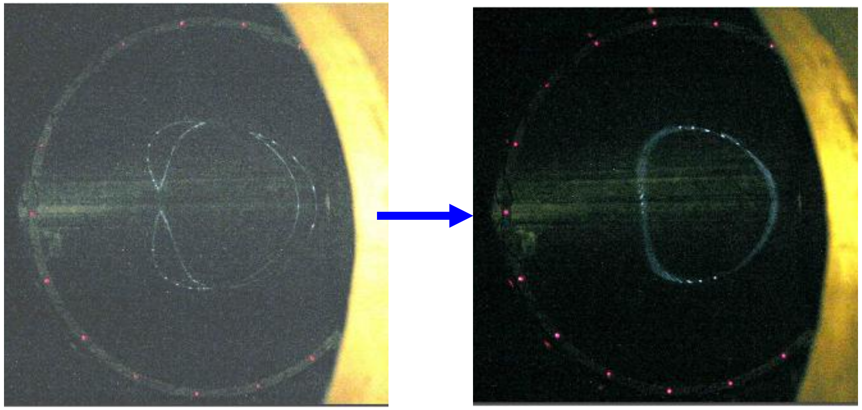
New developments in 3-D equilibrium calculation will contribute to “real world” stellarator & tokamak optimization

- **Multiple, complementary approaches**
  - NYU: incipient island detection (Garabedian)
  - PPPL/Greifswald: STELLOPT & PIES reconstruct experimental equilibria (Reiman et al)
  - Auburn/ORNL/PPPL/GA: V3FIT magnetic equilibrium reconstruction; comparison w/ expt's (Hanson et al)
  - ORNL: SIESTA code extends VMEC to islands (Hirshman/Sanchez)
  - Columbia/PPPL/Greifswald: IPEC computes perturbed equilibrium incl. plasma response, tested in experiments (Park et al).
  - PPPL: Optimal compensation of multiple helicity vacuum field errors using expanded set of simple trim coils (Brooks)
- **Outcomes**
  - Minimization of perturbations in configuration optimization
  - Trim coil method for optimization of experiment *after* construction
  - Extension to ELM, disruption avoidance in tokamaks. Effects of ferromagnetic blanket modules.
  - Improved structure for 3-D edge plasma modelling (stell. + tok.)

CTH explores magnetic island effects in current-carrying compact stellarators

Vacuum configuration studies

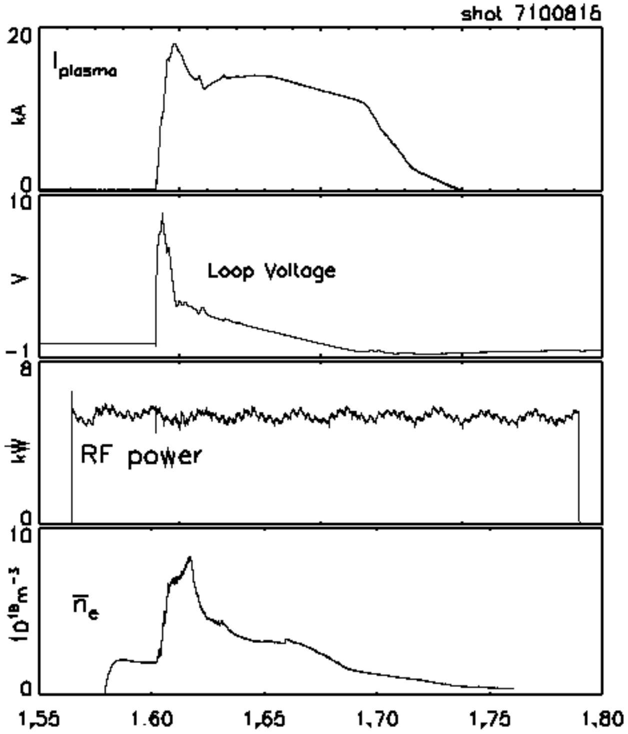
Measurement & control of deliberately induced
m = 3/n = 1 island (operation at B < 0.03 T)

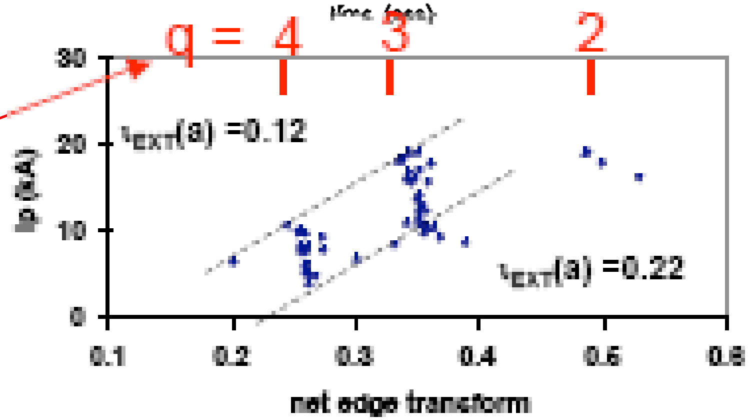


- *e-beam maps flux surface on fluorescent screen*
- *Use trim coils to null, enhance, or rotate island.*
- *Extend to multiple island compensation with 15 trim coils using Brooks optimization from NCSX.*
- *Look for plasma effects before/after*

Transient instability bursts linked with passage through rational edge transform values

Plasma behavior





Compact Stellarator Roadmap for the ITER Era

Goal

- Be able to reliably evaluate the operating characteristics, costs, and risks of a DEMO based on the quasi-symmetric (QS) compact stellarator.

QS Stellarator Knowledge Needed

- Physics: At least, a PoP test of a QS stellarator to answer key questions affecting design and operation, for example:
  - What is the beta limit and what sets the limit?
  - What levels of external transform and bootstrap current are compatible with disruption-free operation?
  - Are enhanced confinement regimes similar to tokamaks? How does confinement scale?
  - What are the roles of MHD and energetic-ion instabilities?
  - What divertor and edge control solutions are compatible with good core performance?

  These are the same goals as for the original CS PoP program approved in 2001.

- Engineering: Sufficient understanding to be able to estimate DEMO construction and operating costs. Issues specific to stellarators:
  - Manufacturability of the coils and associated structures.
  - Maintainability.

Roadmap to a Compact Stellarator PoP Decision - 1

- The loss of the PoP program to address the science of compact stellarators leaves a gap in the FES program. The TAP should identify this gap.
  - Community workshops will address how best to fill the gaps.
  - A CS PoP program plan will be one of the workshop outcomes.

Criteria for a decision to reinstate a CS PoP program:

- Are the goals and scientific basis for the new program supported by the world stellarator data base?
- If the predicted reactor benefits of CS are validated, are there likely to be practical engineering embodiments? For what range of physics outcomes?
- Are the engineering problems encountered on NCSX and W-7X understood? What are the lessons learned that will preclude the recurrence of such problems in future stellarators? What assurances are there that a proposed PoP experiment can be constructed within a predictable cost and schedule?

Roadmap to a Compact Stellarator PoP Decision - 2

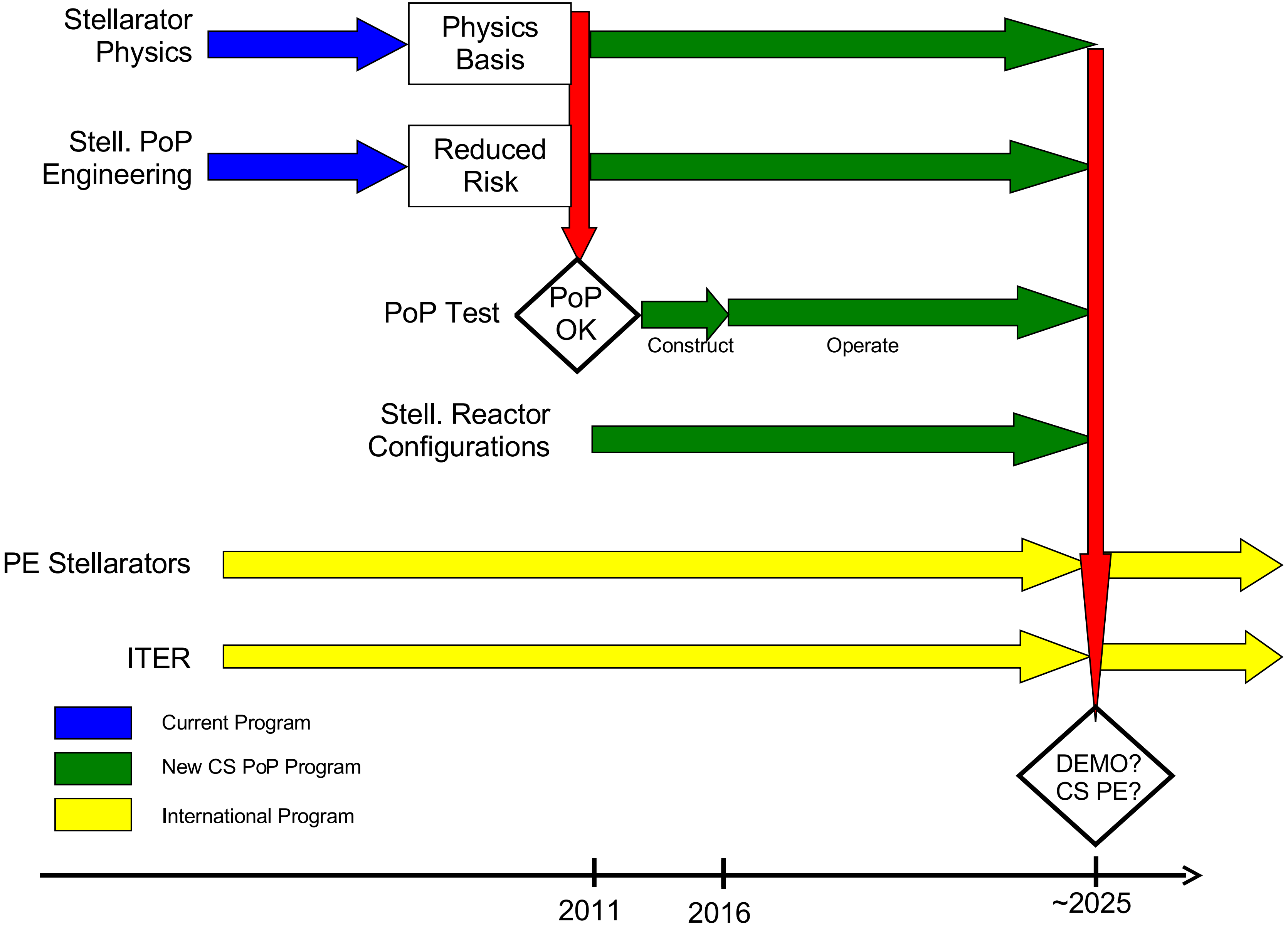
Program Elements:

- **Stellarator physics R&D** addressing key CS physics issues and utilizing existing CE experiments, theory, and collaboration on international stellarators.
  Goal for PoP decision point: updated physics basis for PoP program.

- **CS reactor configuration improvement studies** addressing issues raised by ARIES-CS study- simpler coils, divertors, high peak heat fluxes, manufacturability, maintenance, etc. Sensitivity to PoP physics outcomes.
  Goal for PoP decision point: A plausible engineering embodiment for a CS reactor and demonstrated progress in improving the vision.

- **Stellarator PoP engineering R&D** addressing construction risks, and utilizing NCSX equipment and data.
  Goal for PoP decision point: A design and implementation plan for a proposed PoP experiment. Sufficient technical basis to show that the project can be carried all the way through to completion within an acceptable level of risk.

Compact Stellarator Roadmap



Stellarator Physics

Physics Basis

Stell. PoP Engineering

Reduced Risk

PoP Test

PoP OK

Construct

Operate

Stell. Reactor Configurations

PE Stellarators

ITER

DEMO? CS PE?

2011

2016

~2025

🟦 Current Program

🟩 New CS PoP Program

🟨 International Program