The Stellarator Option for FNSFs

M.C. Zarnstorff

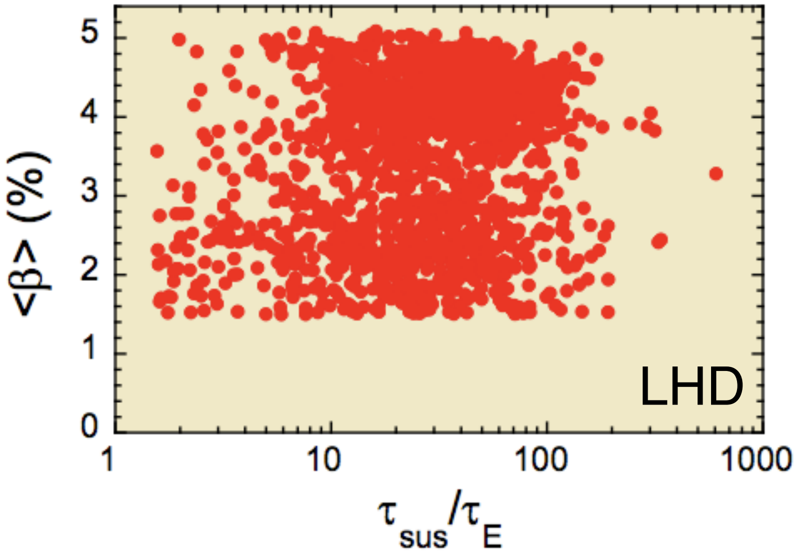
Princeton Plasma Physics Laboratory

Fusion Power Associates Annual Meeting

2 December 2010

Motivation: Stellarators Reduce Risks for FNSF

- Plasma configuration sustained by coils
  – Don't require steady-state neutral beams and RF-launchers in burning environment
- Steady-state high-beta plasmas already demonstrated
- Robust confinement: no disruptions, can avoid edge instabilities (ELMs)
  – Allows thin first wall for breeding
  – No need for conducting wall in blanket
  ⇒ Increase TBR & reduce wall complexity



Motivation: Stellarators Reduce Risks (2)

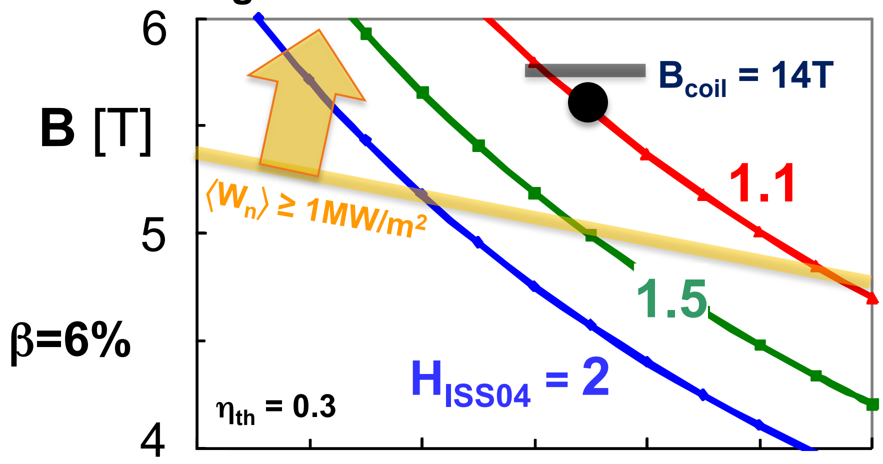
- Don’t need instability or profile feedback control
  - Reduce need for diagnostics, feedback actuators in burning environment.
  - Higher reliability

But:

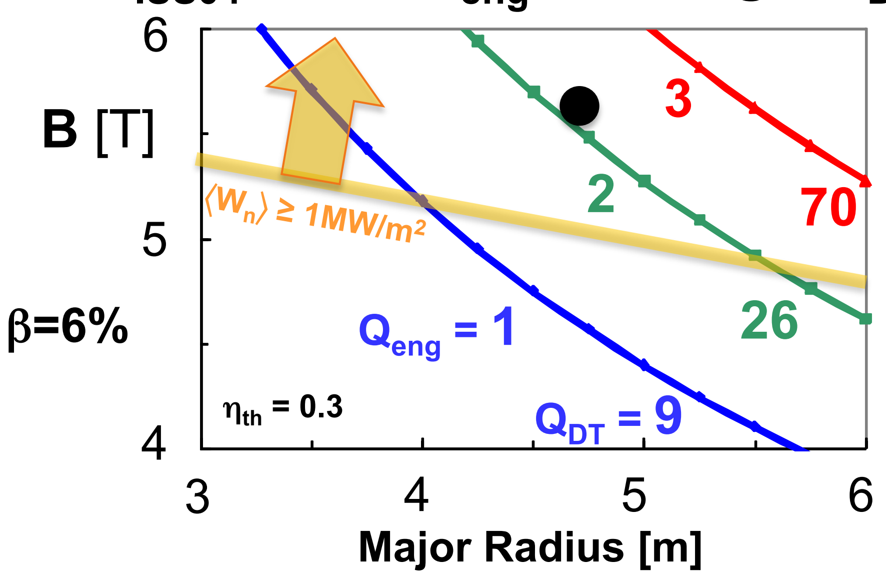
- Higher coil complexity.
- Smaller database of optimized experiments

Stellarator Pilot Plant can Operate Q_{eng} > 1 with L-mode Confinement.

Q_{eng}=1.1 contours vs H_{ISS04}



H_{ISS04}=2 → Q_{eng}=2-3, high Q_{DT}

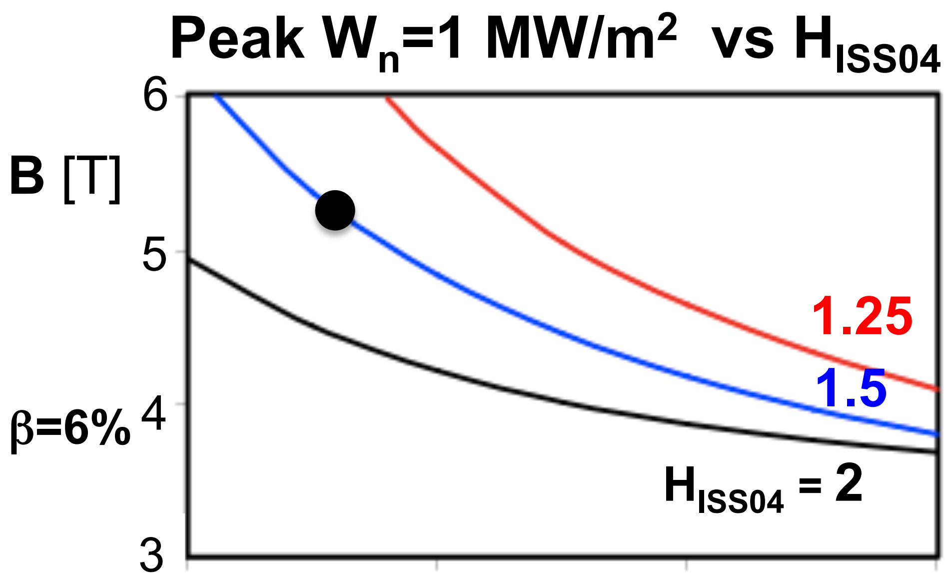


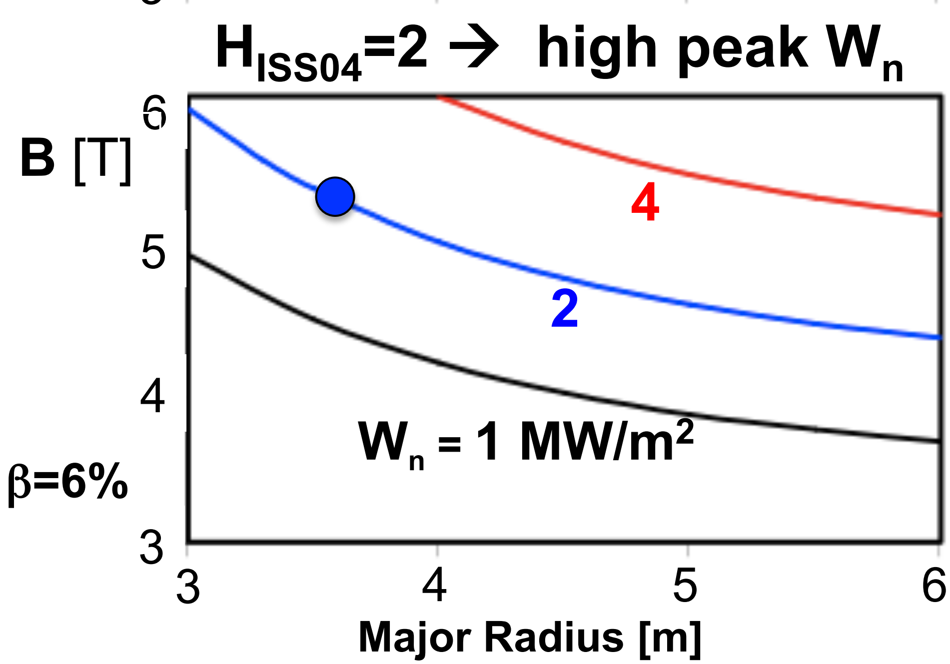
● **Pilot design point**

- A = 4.5 = 4.75m / 1.05m
- B_T = 5.6T, I_P = 1.7MA (BS)
- Avg. W_n = 1.2-2 MW/m^2
- Peak W_n = 2.4-4 MW/m^2

- H_{ISS04} an L-mode scaling, Comparable to $H_{ITER97P}$
- Q_{eng} > 1 with H_{ISS04}~ 1. Due to low recirculating power.
- Flux sufficient for blanket testing
- Expect higher H, gives higher Q_{eng}, provides margin & reliability.
- Can operate Q_{eng} >1 at low fusion power ~ 100 MW.

Stellarator CTFs Available at Reduced Size



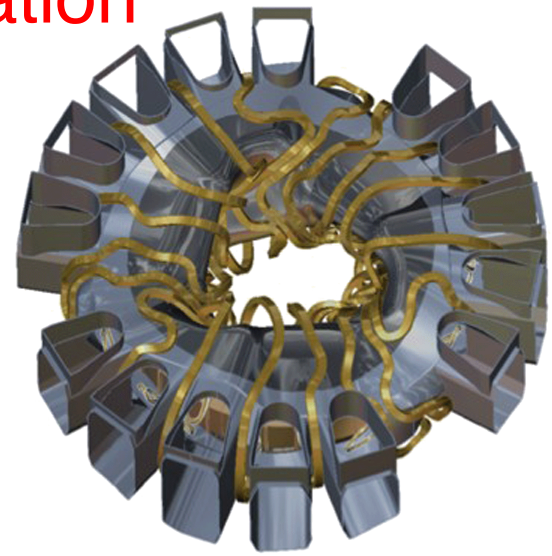


- H_{ISS04} =1.5 attained on non-optimized stellarators
- Could allow CTF with R=3.5m, <a> = 0.77m, B_T=5.4T P_{fus} = 72MW
- H-mode confinement H=2 gives Peak W_n=2 MW/m^2, P_{fus}=144 MW
- Optimal size depends on blanket thickness and magnet technology.
- W7X will give data on low-ripple, optimized stellarator confinement. But, not at low aspect ratio, nor QA ⇒ need experiment to validate calc.

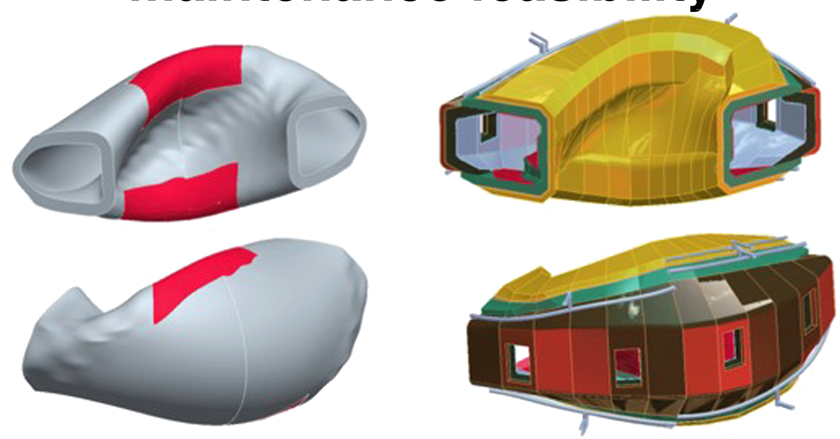
Engineering Improvements for High Availability And Simplification

Starting from ARIES-CS:

- Reduce the number of internal components (from ~200 modules in ARIES-CS to 50-70), by increasing size.
- Widen inter-coil openings on the outboard side; straighten the outboard legs.
  - Maintenance between coils.
- Simplify the in-vessel blanket-shield geometry: 3D→2D shapes where possible.



Modified ARIES CS to improve maintenance feasibility



ARIES-CS blanket **HTS wf/bkt/shld**

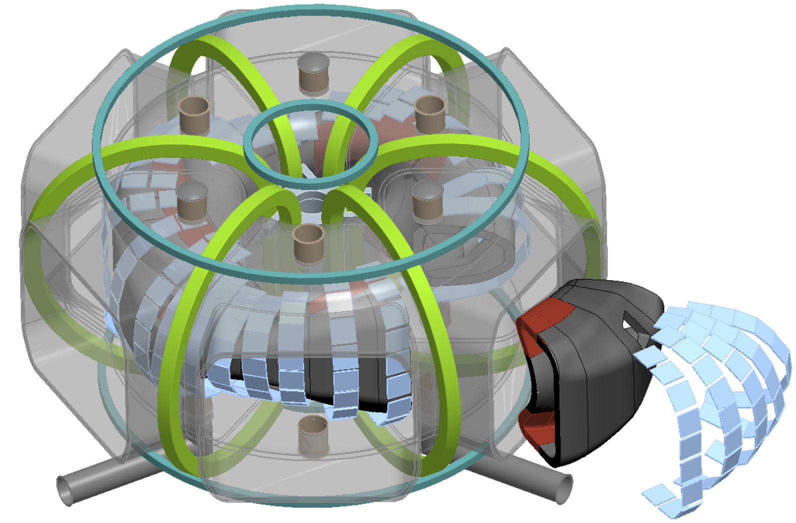
Simplify Coils using
Passive High-Temp. Superconducting Materials

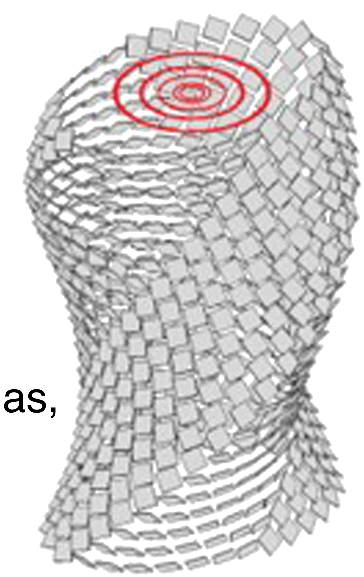
HTS materials offer new design options

- Available in bulk tiles; Good properties at temperatures >30 K.
- Tiles on modular shell structure act as diamagnets, shaping background toroidal field.
- Direct magnetic calculations for tile arrays verify shaping and iota for linear and toroidal geometries

Optimize tilt & overlap next.

ARIES CS using HTS tiles for shaping.





L. Bromberg,
M. Zarnstorff, *et al.*
TOFE-19, Las Vegas, Nov. 2010

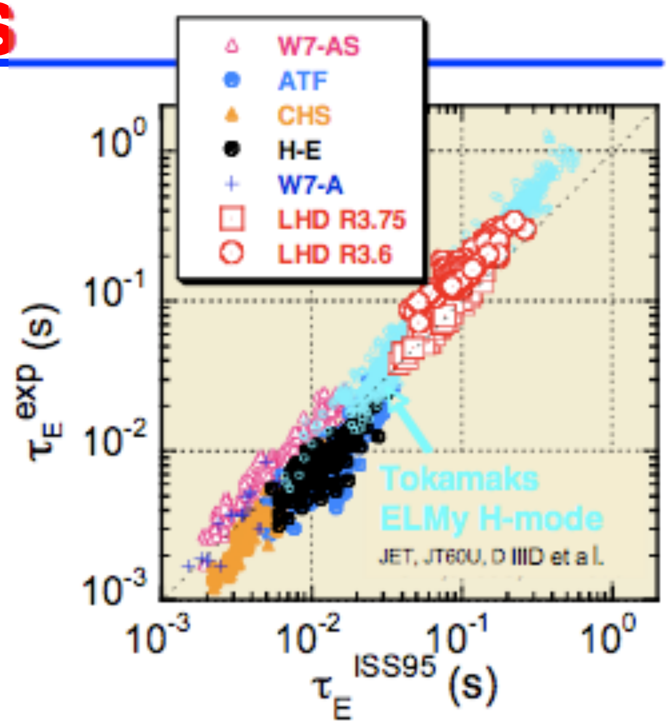
Summary

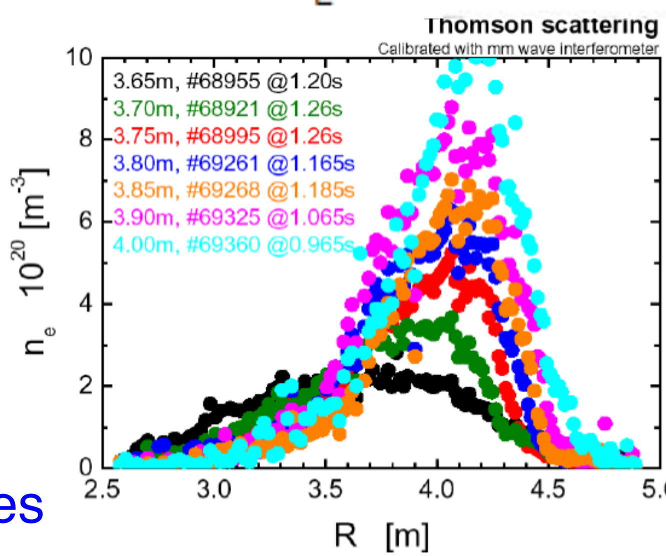
- Stellarators can reduce the risks to advance magnetic fusion
  - Steady-state, disruption free, high beta demonstrated
  - No need for steady-state NBI, in-vessel RF launchers in burning environment
  - Reduce/eliminate need for feedback, diagnostics, actuators in burning environment
- Compact stellarator project to conservative FNSFs
  - Pilot plants, even with L-mode confinement; R=4.75 m
  - CTFs, $R \geq 3.5$ m
- Strategies to simplify stellarator engineering progressing
- Need to validate optimized, compact stellarator characteristics in moderate scale experiments.

Supplemental

Stellarators are Achieving Outstanding Results

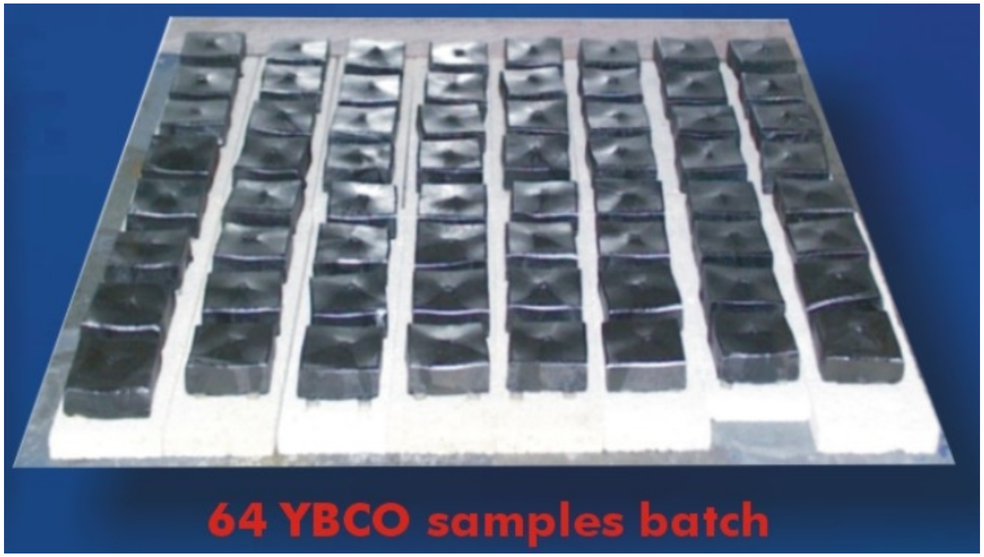
- Quiescent high beta plasmas, limited by heating power & confinement
  - LHD $\beta = 5.2\%$ transiently; 4.8% sustained
  - W7AS $\beta > 3.2\%$ for 120 τ_E
- τ_E similar to ELMy H-mode
- Improved confinement with quasi-symmetry
  - HSX finds reduced transport of momentum, particles, and heat with quasi-symmetry.
- Very high density operation, limited only by heating power, without confinement degradation
  - Up to 5 x equivalent Greenwald density (W7AS)
  - LHD $n_e(0)$ up to 10^{21} m^{-3} at B=2.7T !
- Importance of divertors to control recycling
- Steady state: LHD pulse lengths up to 55 minutes



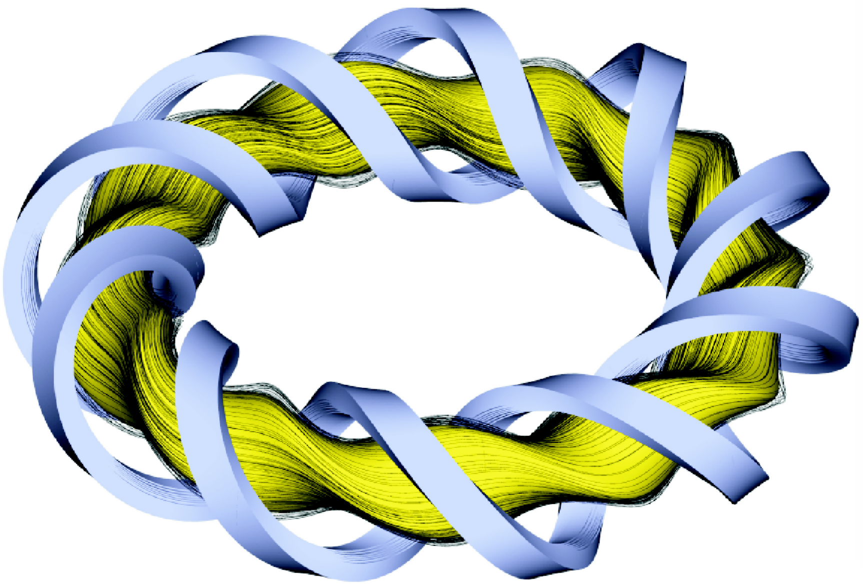


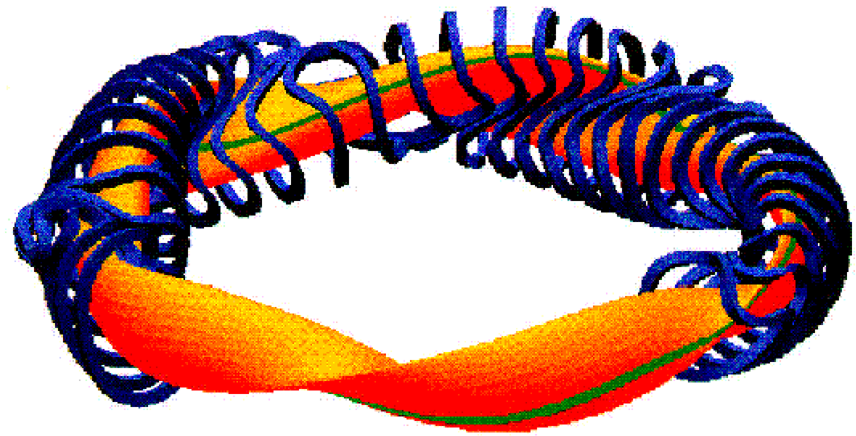
Passive 3D shaping: Diamagnetic Tiles

- Idea: use bulk high temperature superconducting tiles as diamagnets to shape magnetic field
- Commercially available, up to 25 cm diameter
- Position and orient tiles to produce desired field shape, reacting to field from simple coils.



Large International Superconducting Stellarators



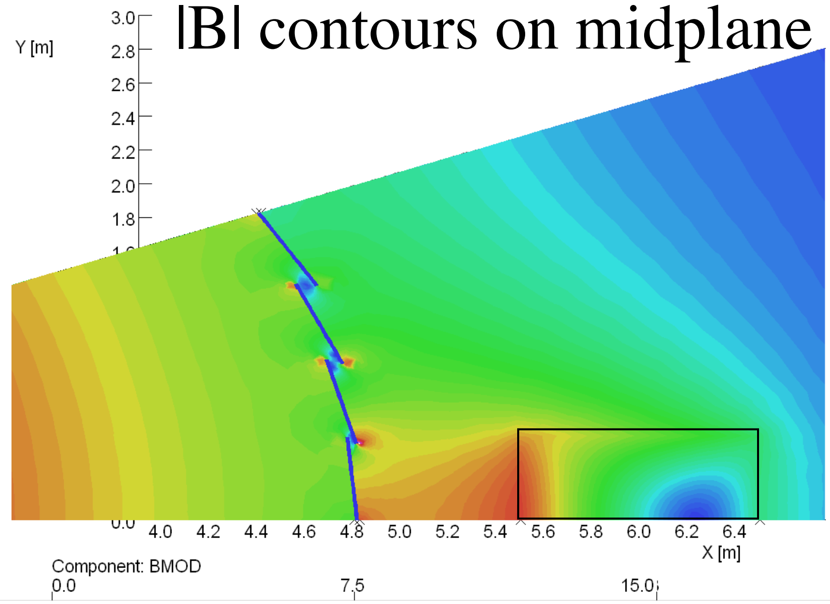


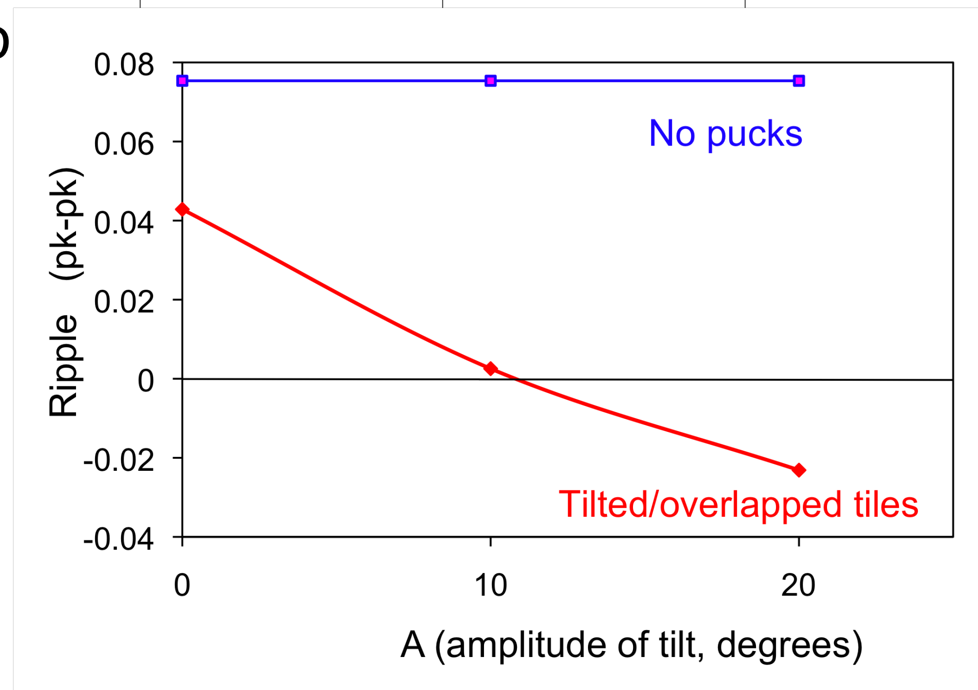
- **Large Helical Device (Japan)**
  - Non-symmetric
  - A = 6-7, R=3.9 m, B=3T
- **Wendelstein 7-X (Germany)**
  - QP optimized design
  - A = 11, R=5.4 m, B=3T

- Focused on steady state, including power handling. LHD has achieved 54-minute pulses.
- Optimized for other properties than quasi-symmetry ⇒ flows strongly damped
- Not compact. Extrapolate to larger fusion systems than favored in U.S.
- Neither can directly build on or inform tokamak understanding.

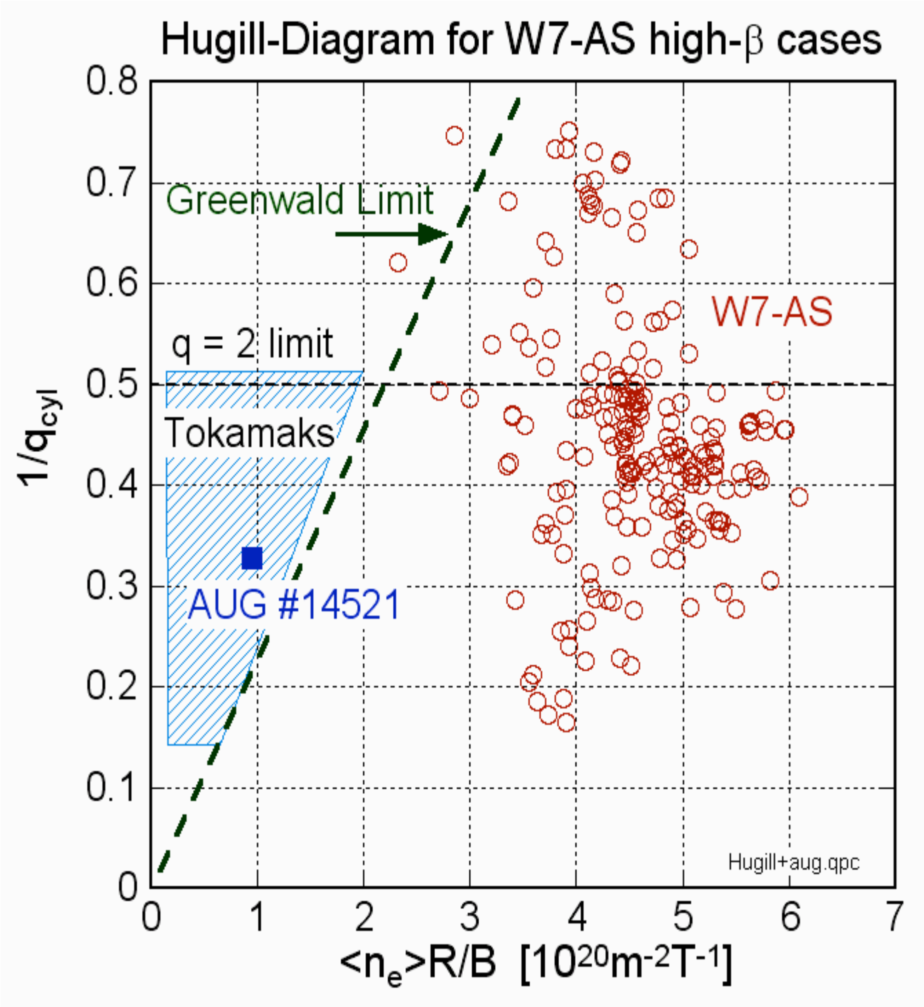
Trial Problem: Eliminate TF Ripple For 8-coil TF

- Simple geometry
  - 8 TF-coils at R=6m axisymmetric
  - Use HTS tiles at R=4.8m to eliminate ripple at R≤4m
- Tilt tiles so that they interact with toroidal field
- Can zero or reverse ripple Magnitude of |B| change similar to need for stellarator





Stellarator Operating Range is much larger than for Tokamaks

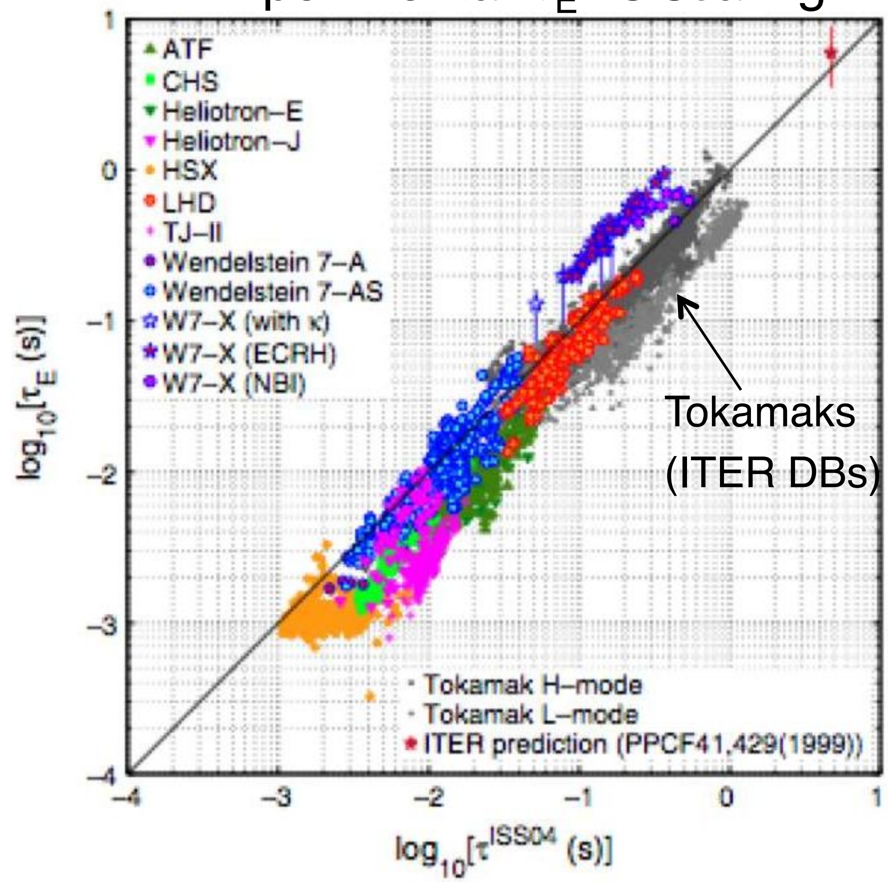


- Using equivalent toroidal current that produces same edge iota in Greenwald evaluation.
- LHD $n_{e0} = 10^{21}$ m^{-3} at B = 2.7 T
  3-5 X Greenwald limit
- No disruptions.
  Limits are not due to MHD instabilities.
- High density favorable:
  - Lower plasma edge temperature, Eases edge design
  - Reduces energetic particle instability drive

Stellarator Energy Confinement Similar to Tokamaks

- Stellarator τ_E similar to ELMy H-mode
- T_i = 6.8 keV without impurity accumulation (LHD)
- Discharge duration ~ 1 hr with P ~ 0.6 MW, limited by PWI

Experimental τ_E vs scaling



ARIES-CS: a Competitive, Attractive Reactor

Reference parameters for baseline:

NCSX-like: 3 periods

$\langle R \rangle = 7.75$ m

$\langle a \rangle = 1.72$ m

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

$\langle T \rangle = 6.6$ keV

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

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

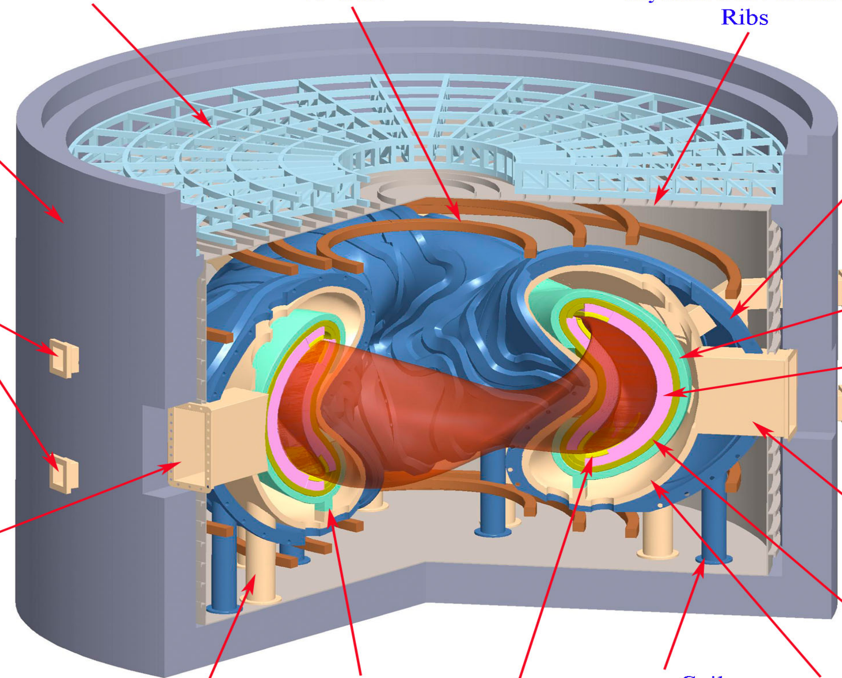
H(ISS04) = 1.1

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

P(fusion) = 2.364 GW

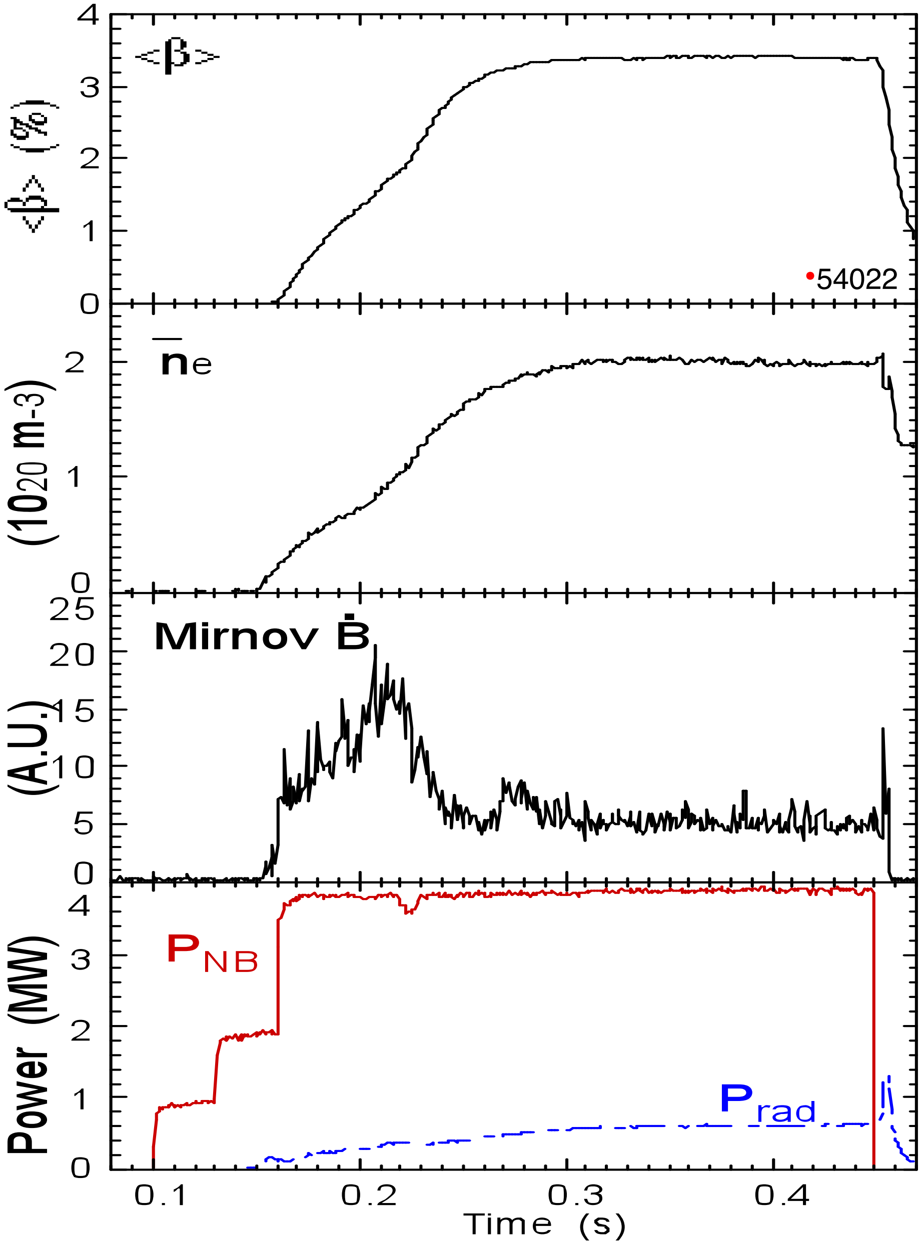
P(electric) = 1 GW

Ignited



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

•⟨β⟩ ≈ 3.4 % : Quiescent, Quasi-stationary



- B = 0.9 T, $iota_{vac} \approx 0.5$
- Almost quiescent high- β phase, MHD-activity in early medium-β phase
- In general, β not limited by any detected MHD-activity.
- $I_P = 0$, but there can be local currents
- Peak β~8%
- Similar plasmas with B = 0.9 – 1.1 T, either NBI-alone, or combined NBI + OXB ECH.
- Much higher than predicted linear stability β limit ~ 2%