Expectations for Steady-State MFE

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Fusion Power Associates Meeting

15 December2011

U.S. DEPARTMENT OF ENERGY | Office of Science

PPPL

Outline

To have a timely impact, pathway to fusion energy needs to

- build upon our substantial knowledge base
- address outstanding Issues and Risks,

- Plasma Issues for steady-state DEMOs
- Steady-state tokamaks
- Steady-state stellarators
- Summary

Lots of Challenges for a Fusion Energy System

ReNeW, FESAC studies:

- Steady-state, high-performance, robust plasma confinement

- Divertor exhaust loads, PFCs

  Materials & technology in a nuclear environment

  Current drive

- ITER issues continue: ELMs & Disruptions
  - Worse in DEMO: more energy, higher forces
  - PFC armor must be much thinner to achieve TBR > 1

Disruptions and ELMs must be reliably eliminated

Substantial advances in Steady-State Tokamak Regimes

- Lots of significant work by AUG, DIII-D, JET, JT-60U in part to prepare for ITER

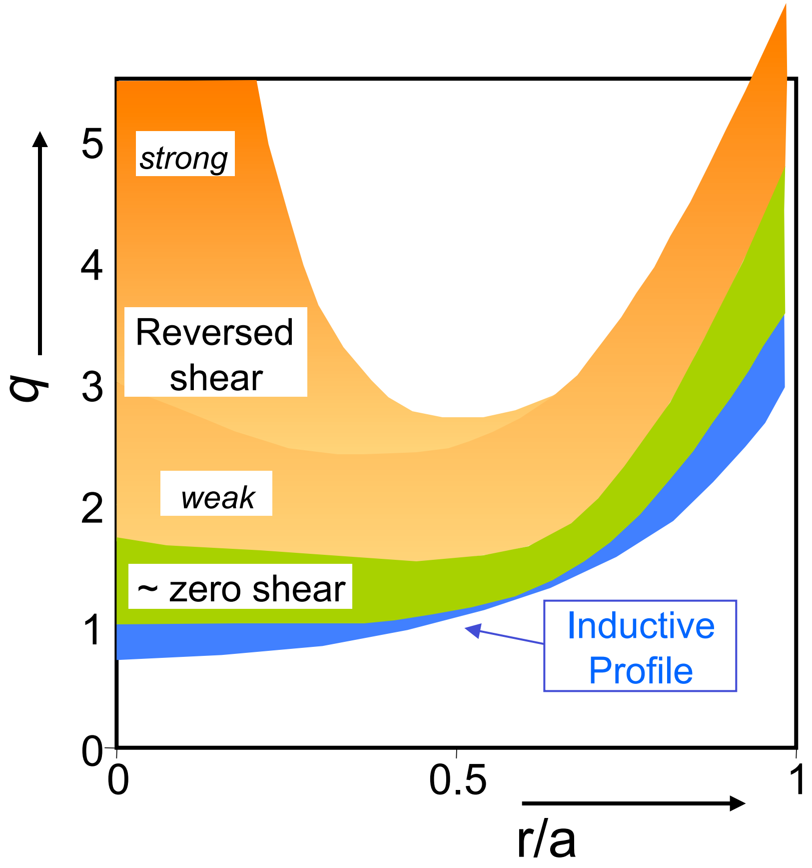
- 100% Non-inductive plasmas achieved in all three strategies ~ stationary for at least ~3 relaxation times for the current profile

- DIIID : extensive shape optimization. DN, κ~1.9, δ~0.6, ζ~ -0.25
- JT-60U : extended to almost 30 sec.
- DIII-D, JT-60U, NSTX : above the no-wall limit

Will use $G = \beta_N H / q_{95}^2$ as a dimensionless metric for $nT\tau \sim Q$
using either $H_{89} = \tau_E$ / ITER-89P or $H_{98} = \tau_E$ / ITER-98(y,2)

(see Sipps 2005, Luce 2005, Luce 2011 for summaries)

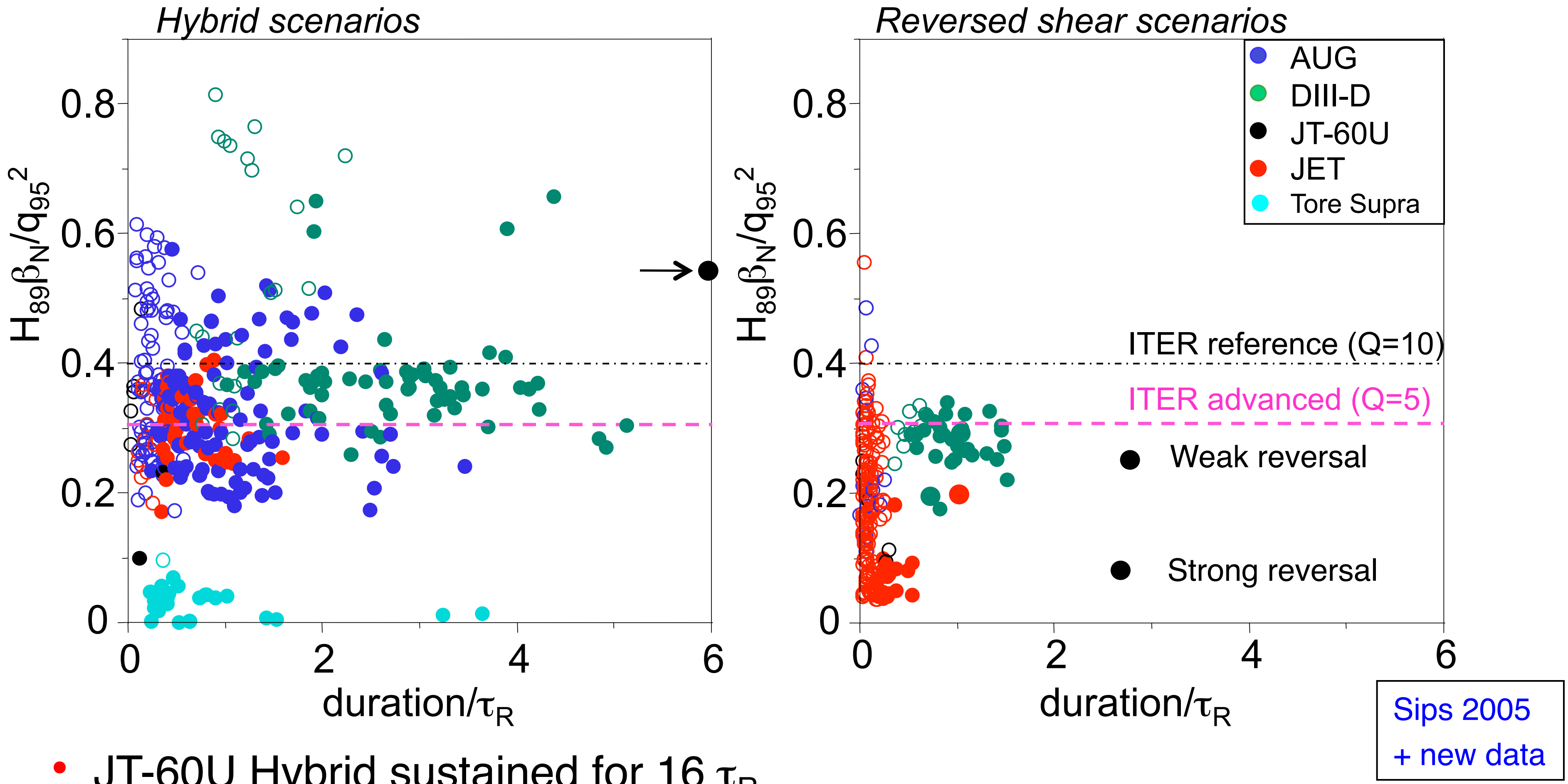
Steady-state tokamak: how much bootstrap?



- Need to maintain current / q-profile without inductive current
- Highest Q with maximum self-generated bootstrap current
- Large bootstrap current makes hollow profile, changes transport and plasma stability.

Three Advanced Tokamak strategies: ~zero core shear
weak reversed shear
strong reversed shear

Similar Landscape on All Experiments



Sips 2005
+ new data

- JT-60U Hybrid sustained for 16 τ_R
- All three regimes sustained to ~ 3 τ_R or longer, stationary.
- Bootstrap current fractions differ systematically

Hybrid $f_{boot} < 0.5$; Weak reversal $f_{boot} \sim 0.6$; Strong rev. $f_{boot} > 0.7$

Limiting process similar on All Experiments

- High bootstrap, strong reversed shear: β_N limited by strong ITBs
  produces extremely fast disruptions, often without precursors

- Weak reversed shear is a strategy to avoid ITBs
  limited by when they occur

- Hybrid and Weak shear reversal limited by external kinks / Wall modes
  & tearing modes

Reactor Designs are Not Consistent with Sustained AT Characteristics

	Hybrid	**Weak Rever**	**Strong Rever**	**Slim CS**	**CREST**	**EU AB**	**EU C**	**Aries-AT**
	DIII-D	DIII-D	JT-60 U		Weak rev			Weak rev
q_{95}	3.3	6.3	8.3	5.4	4.3	3.0	4.3	3.2
H_{98}	1.5	1.5	1.8	1.3	1.3	1.2	1.3	1.7
β_N	2.8	3.7	1.7	4.3	5.5	3.5	4	5.4
G_{98}	0.38	0.14	0.044	0.19	0.39	0.47	0.28	0.90
$f_{bootstrap}$	~0.4	0.65	0.75	0.77	0.83	0.45	0.63	0.91
n / n_{GW}	0.4	0.5		0.98	1.3	1.2	1.5	0.9

- Need to iterate designs using more realistic parameters

H&CD efficiency for DEMO:

assumptions vs reality (IV)

- DEMO assumptions:

  $\eta_{WP}\bullet\gamma_{CD} = 0.24 - 0.27$
- Negative NBI $\eta_{WP}\bullet\gamma_{CD} \sim 0.12 - 0.14$
- ECCD $\eta_{WP}\bullet\gamma_{CD} \sim 0.08$
- ICRF $\eta_{WP}\bullet\gamma_{CD} \sim [0.18 - 0.24] \bullet f_{coupled}$

  (where $f_{coupled}$ = fraction of generator power coupled at edge of plasma ~ 0.4 max H-mode – note no experiment has ever coupled >12MW ICRF power into an H-mode) ~0.07 – 0.095 for H-mode
- Lower Hybrid CD $\eta_{WP}\bullet\gamma_{CD} \sim [0.15 - 0.18] \bullet f_{coupled}$

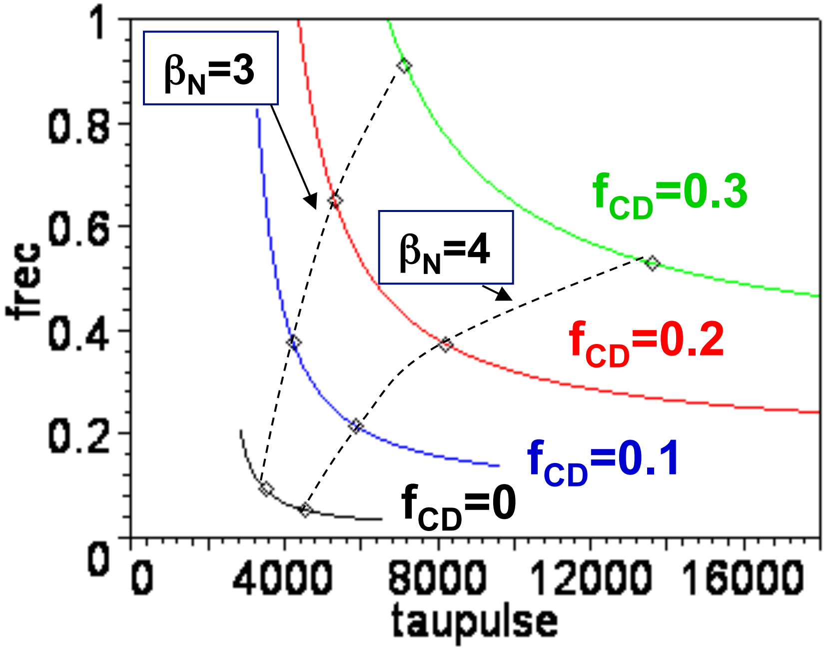
  (LH klystrons are ~ 50% efficient – again $f_{coupled}$ is fraction of generator power coupled by grill to plasma – note, no experiment has ever coupled more than 4MW LH power into an H-mode)
- With these levels the installed CD powers on PPCS power plants go up considerably

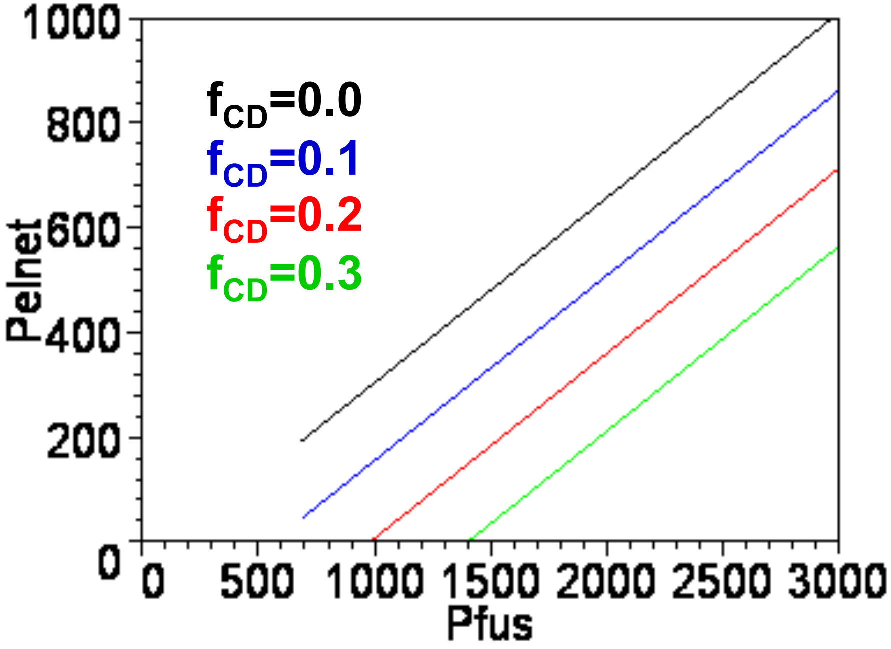
Duration limited by CD-efficiency & Beta

ITER-like case with R_0=7.5 m

H. Zohm

Vary β_N between 2 and 5 and f_{CD} between 0 (ohmic) and 0.3 and assume conventional technology ($\eta_{CD}\ f_{coupl}=0.25$, $\eta_{TD}=0.3$, P_{BOP}=50 MW, $\eta_{BOP}=0$)



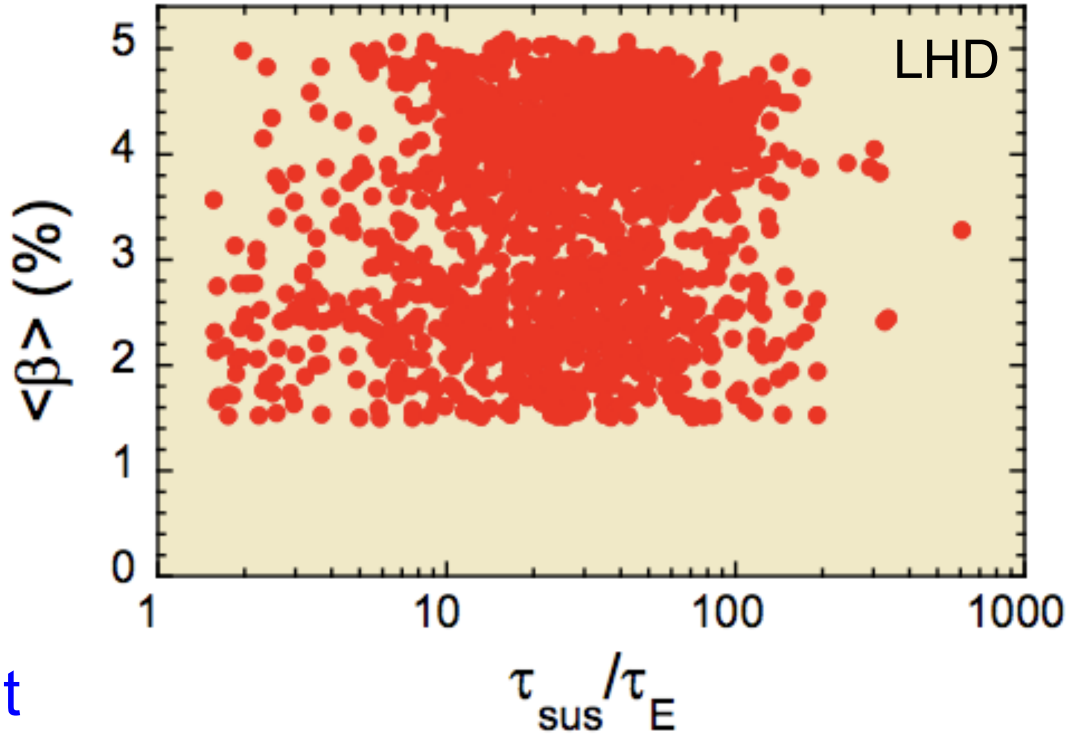


Acceptable $f_{rec} < 0.4$ and significant $P_{el,net}$ can be fulfilled relatively easily (e.g with f_{CD}=0.1 and β_N=3, $P_{el,net}$=350 MW), but pulse length is nowhere near the target!

Even P_{fus}=3 GW (β_N=4.2, f_{CD}=0.2, f_{rec}=0.33) only gives $\tau_{pulse} \approx$ 3 hrs

Stellarators: High-β Steady State, without Disruptions

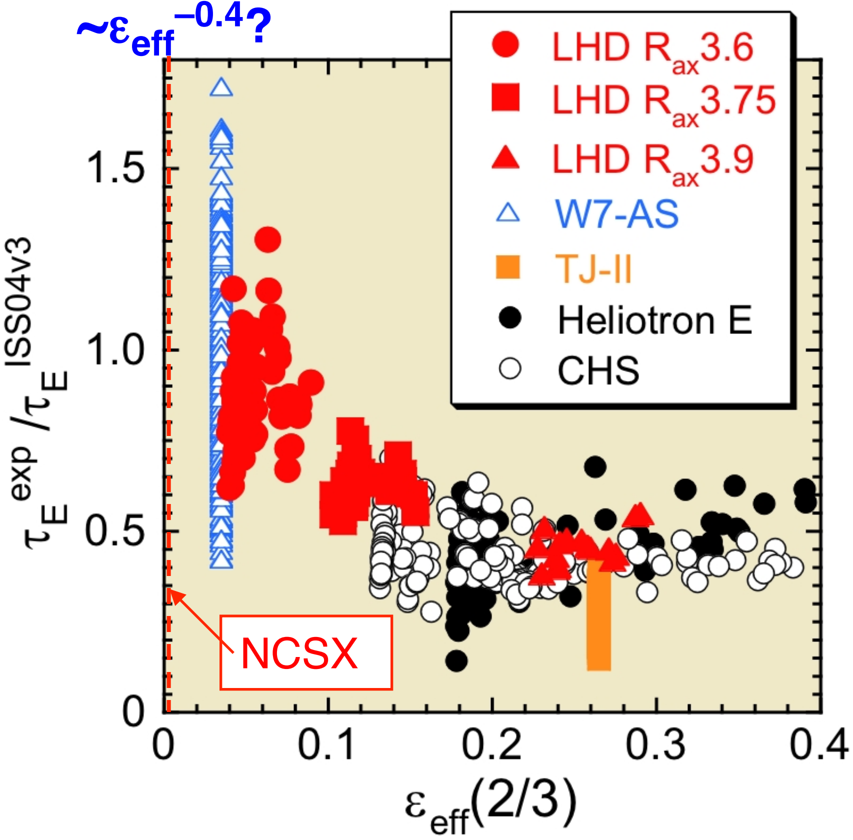
- Equilibrium maintained by coils, from 3d shaping
- β =5.4% (LHD) and β=3.4% (W 7-AS) without *any* disruptions.
- Soft limit is observed, due to saturation in confinement

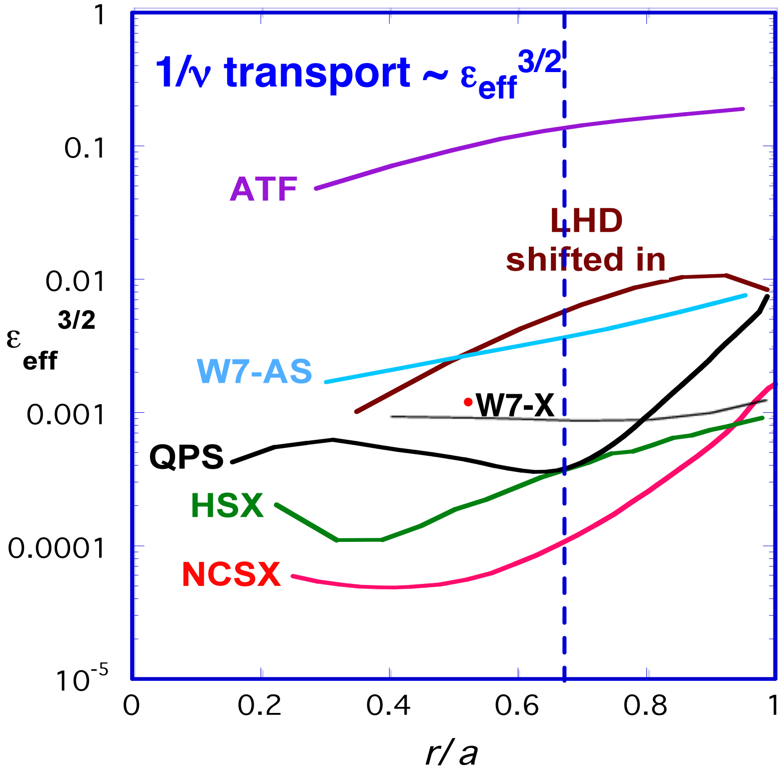


- Density limit >> Greenwald-equivalent, without disruptions

What sets β-limit? May be due to onset of stochastic B field. Can be improved by design (W7-X, NCSX).

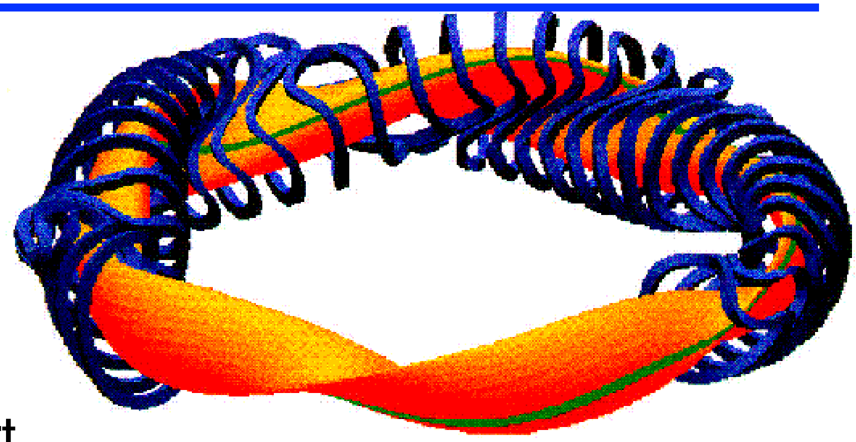
Low Ripple Gives Good Confinement





- Experimental confinement time shows dependence on ripple magnitude. Analysis: Anomalous transport in addition to 3D-neoclassical.
- Confinement magnitude similar to tokamak ELMy H-mode
- H(ISS04) up to 1.5 obtained at low ripple
- H(ISS04) = 1.1 adequate for reactor, simultaneous with high beta.

W 7-X Optimized for High-β, Quasi-Isodynamic



- R/⟨a⟩=11, R=5.4 m
  Superconducting coils

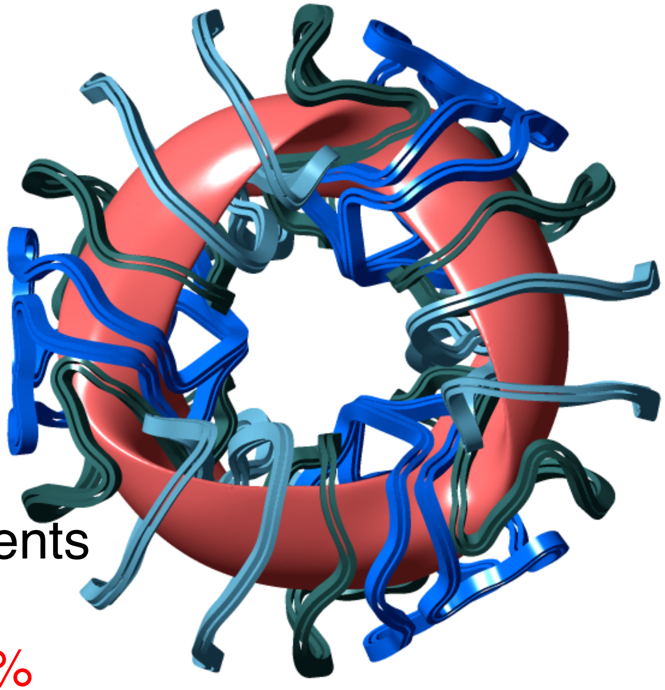
  Operation starting in 2014 / 2015

- Quasi-isodynamic: neoclassical transport minimized by minimizing drift-orbit widths.

- MHD Stable for β = 5%

- Designed for good flux surfaces to β~5%. Shaping optimized to minimize Shafranov-shift and bootstrap current.

3D Tokamak Shaping Gives Stellarator Stability with Tokamak-like Confinement



- NCSX: 3 periods, $R/\langle a\rangle=4.4$, $\langle\kappa\rangle\sim1.8$, $\langle\delta\rangle\sim1$

- Quasi-axisymmetric: tokamak with 3D shaping
  ripple-induced thermal transport insignificant.
  Build on ITER results.

- Passively MHD stable at $\beta=4.1\%$ to kink, ballooning, vertical, Mercier, NTM
  Stable for at least $\beta > 6.5\%$ by adjusting coil currents

- Designed to keep ~perfect flux surfaces to $\beta=4.1\%$
  2-fluid calculations indicate it may continue to $\beta > 7\%$

- Passive disruption stability: equilibrium maintained even with total loss of β or bootstrap current

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Need experiment to validate modeling predictions for 3D shaping

Issues for Stellarators

Sustained high-beta, robust confinement already achieved.

US Assessment (ReNeW & FESAC):

1. Simplify coil designs *(US design studies)*
   Simplify maintenance strategies for blanket
2. Demonstrate integrated high performance: high-β, low collisionality *(W7X)*
3. Confinement predictability *(LHD, W7X)*
4. Effective 3D divertor design *(LHD, W7X)*

Summary

- Substantial advances in last 10 yrs. in understanding steady-state tokamaks and stellarators.
- AT experiments have achieved 100% non-inductive sustainment in three q-profiles, with varying amounts of bootstrap current. Very similar characteristics across all experiments.
- AT steady-state performance levels and CD efficiencies are lower than assumed in reactor designs. Disruptions are challenging at high bootstrap fraction.
- Reactor design groups should assess realistic performance, combined with realistic current drive efficiencies.

Summary (2)

- Steady-state, high-beta plasmas already demonstrated using 3D shaping. No CD needed: minimizes recirculating power required.
- Robust confinement: no disruptions, can avoid edge instabilities (ELMs)
- Simplify & reduce auxiliary technology needs
  - Don't require steady-state neutral beams and RF-launchers in burning environment
  - Minimize need for diagnostics & feedback in nuclear env.
- Need to simplify coil engineering, maintainability.
- Need to demonstrate integrated performance, incl. divertor. How to best build on ITER?