Expectations
for Steady-State MFE

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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

• DIIIID : extensive shape optimization. DN, $\kappa \sim 1.9$, $\delta \sim 0.6$, $\zeta \sim -0.25$

• 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 $H_{89} = \tau_E / \text{ITER-89P}$ or $H_{98} = \tau_E / \text{ITER-98(y,2)}$

(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

- JT-60U Hybrid sustained for 16 $\tau_R$
- All three regimes sustained to $\sim 3 \tau_R$ or longer, stationary.
- Bootstrap current fractions differ systematically

Hybrid $f_{\text{boot}} < 0.5$; Weak reversal $f_{\text{boot}} \sim 0.6$; Strong rev. $f_{\text{boot}} > 0.7$
Limiting process similar on All Experiments

- High bootstrap, strong reversed shear: $\beta_N$ 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

<table>
<thead>
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<th>Hybrid</th>
<th>Weak Rever</th>
<th>Strong Rever</th>
<th>Slim CS</th>
<th>CREST</th>
<th>EU AB</th>
<th>EU C</th>
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<td>JT-60 U</td>
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<td>q\textsubscript{95}</td>
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<td>6.3</td>
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<td>1.5</td>
<td>1.8</td>
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<td>2.8</td>
<td>3.7</td>
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<td>5.5</td>
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<tr>
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<td>0.14</td>
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<td>f\textsubscript{bootstrap}</td>
<td>~0.4</td>
<td>0.65</td>
<td>0.75</td>
<td>0.77</td>
<td>0.83</td>
<td>0.45</td>
<td>0.63</td>
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<tr>
<td>(n / n_{GW})</td>
<td>0.4</td>
<td>0.5</td>
<td></td>
<td>0.98</td>
<td>1.3</td>
<td>1.2</td>
<td>1.5</td>
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- Need to iterate designs using more realistic parameters
H&CD efficiency for DEMO:

assumptions vs reality (IV)

- **DEMO assumptions:**
  \[ \eta_{WP} \cdot \gamma_{CD} = 0.24 - 0.27 \]

- **Negative NBI**
  \[ \eta_{WP} \cdot \gamma_{CD} \approx 0.12 - 0.14 \]

- **ECCD**
  \[ \eta_{WP} \cdot \gamma_{CD} \approx 0.08 \]

- **ICRF**
  \[ \eta_{WP} \cdot \gamma_{CD} \approx [0.18 - 0.24] \cdot f_{\text{coupled}} \]
  (where \( f_{\text{coupled}} \) = fraction of generator power coupled at edge of plasma \( \approx 0.4 \) max H-mode – note no experiment has ever coupled >12MW ICRF power into an H-mode) \( \approx 0.07 - 0.095 \) for H-mode

- **Lower Hybrid CD**
  \[ \eta_{WP} \cdot \gamma_{CD} \approx [0.15 - 0.18] \cdot f_{\text{coupled}} \]
  (LH klystrons are \( \approx 50\% \) efficient – again \( f_{\text{coupled}} \) 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**
Vary $\beta_N$ between 2 and 5 and $f_{CD}$ between 0 (ohmic) and 0.3 and assume conventional technology ($\eta_{CD}f_{coup}=0.25$, $\eta_{TD}=0.3$, $P_{BOP}=50$ 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 $\beta_N=3$, $P_{el,net}=350$ MW), but pulse length is nowhere near the target!

Even $P_{fus}=3$ GW ($\beta_N=4.2$, $f_{CD}=0.2$, $f_{rec}=0.33$) only gives $\tau_{pulse}\approx 3$ hrs
Stellarators: High-\(\beta\) Steady State, without Disruptions

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

What sets \(\beta\)-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-\(\beta\), Quasi-Isodynamic

- \(R/\langle a \rangle = 11\), \(R = 5.4\) m
  Superconducting coils

  Operation starting in 2014 / 2015

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

- MHD Stable for \(\beta = 5\%\)

- Designed for good flux surfaces to \(\beta \sim 5\%\). Shaping optimized to minimize Shafranov-shift and bootstrap current.
3D Tokamak Shaping Gives Stellarator Stability with Tokamak-like Confinement

- NCSX: 3 periods, $R/\langle a \rangle = 4.4$, $\langle \kappa \rangle \sim 1.8$, $\langle \delta \rangle \sim 1$

- 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 $\sim$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 $\beta$ or bootstrap current.

Need experiment to validate modeling predictions for 3D shaping.

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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-\(\beta\), 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?