Framework for a Road Map to Magnetic Fusion Energy

Status Report

Dale Meade
for MFPL Working Group

APS-DPP UFA Meeting
Denver, CO.
November 11, 2013
Why Work on a Fusion Roadmap Now?

• To demonstrate that there are realistic technical paths to a Magnetic Fusion DEMO
  - essential to convince others that fusion is worth supporting even if the funding is
    not yet available to follow an aggressive path

• To update previous studies, and develop some initial views on the relative attributes
  of various paths.

• This exercise is not to down select !!

• In difficult of times, it is even more important to have a plan to make progress
  - Be ready when external conditions change – R. Conn, Snowmass 1999
  - That was the case in the mid 1970s, and the US MFE was able to exploit the change.
Magnetic Fusion Program Leaders (MFPL) Initiative

**Magnetic Fusion Program Leaders:** S. Prager, PPPL; T. Taylor, GA; N. Sauthoff, USIPO; M. Porkolab, MIT; P. Ferguson, ORNL; R. Fonck, U.Wisc; D. Brennan, UFA.

**Goal:** Develop and assess three aggressive technically feasible, but constrained, paths for the US Fusion Program to support or motivate a commitment to DEMO on the timescale of ITER $Q \approx 10$ experiments (nominally 2028).

**Task:** Building on previous Fusion Community workshops and studies, assess the technical readiness and risks associated with proceeding aggressively along three potential paths:

1) ITE plus Fusion Nuclear Science Facility leading to a Tokamak DEMO
2) ITER directly to a Tokamak DEMO (possibly staged)
3) ITER plus additional facilities leading to a QS - Stellarator DEMO

Each of these paths will include major aspects of a broad supporting research program.

**Process:**
1. A core group (10) has been formed
2. Solicit review from a large (30) group of technical experts and external advisors
# Road Map Study Group

## Members

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
</tr>
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<tbody>
<tr>
<td>Dale Meade</td>
<td>Chair</td>
</tr>
<tr>
<td>Steve Zinkle</td>
<td>Materials</td>
</tr>
<tr>
<td>Chuck Kessel</td>
<td>Power Plant Studies, FNSPA</td>
</tr>
<tr>
<td>Andrea Garofalo</td>
<td>Toroidal Physics</td>
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<tr>
<td>Neil Morley</td>
<td>Blanket Technology</td>
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<tr>
<td>Jerry Navratil</td>
<td>University Experimental Perspective</td>
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<tr>
<td>Hutch Neilson</td>
<td>3-D Toroidal, Road Map Studies</td>
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<td>Dave Hill</td>
<td>Toroidal Alternates</td>
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<tr>
<td>Dave Rasmussen</td>
<td>Enabling Technology, ITER</td>
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<tr>
<td>Bruce Lipschultz/Dennis Whyte</td>
<td>Plasma Wall Interactions</td>
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<tr>
<td></td>
<td>Reactor Innovations</td>
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## Background

<table>
<thead>
<tr>
<th>Report</th>
<th>Year</th>
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<tbody>
<tr>
<td>FESAC 35 Yr RJG</td>
<td>2003</td>
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<tr>
<td>ReNeW Study</td>
<td>2009</td>
</tr>
<tr>
<td>FESAC Materials SZ</td>
<td>2012</td>
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<td>FESAC Priorities RR</td>
<td>2013</td>
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<td>EU Road Map/Annex</td>
<td>2013</td>
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<td>FESAC Opportunity MG</td>
<td>2007</td>
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<td>FNSP Assessment CK</td>
<td>2011</td>
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<td>FESAC Int Collab DM</td>
<td>2012</td>
</tr>
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<td>FESAC Facilities JS</td>
<td>2013</td>
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<tr>
<td>China CFETR Plan</td>
<td>2013</td>
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</table>
What I have argued for in the Administration regarding fusion per se: two major thrusts need to be pursued to demonstrate practical fusion power on a relevant time scale.
Today – the scientific basis for MFE is very strong but incomplete

- Detailed understanding and predictive capability for plasma equilibrium, MHD stability, energetic particles, etc. Improving understanding of plasma material interactions,.......

- Fusion energy production demonstrated 7.5-22 MJ/pulse, >1.5 GJ fusion energy total, alpha heating and alpha dynamics confirmed, fusion gain $Q \sim 1$

- MFE has initiated, and is solving the challenges of building world’s 1st reactor-scale fusion facility that will establish burning plasma physics, and demonstrate fusion gain $Q \approx 10$, 500 MW, 200 GJ/pulse and fusion technologies.

- Ongoing research program is addressing technical issues to ensure ITER’s success

- What additional issues need to be resolved for fusion power? - look back from the Fusion Demo.
ARIES Studies Identified General Characteristics of Magnetic Fusion Demonstration Plants

<table>
<thead>
<tr>
<th></th>
<th>ARIES-ACT1</th>
<th>ARIES-ACT2</th>
<th>ARIES-CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>R(m)</td>
<td>6.25</td>
<td>9.75</td>
<td>7.75</td>
</tr>
<tr>
<td>B(T) / B_{max-coil}(T)</td>
<td>6.0/10.6</td>
<td>8.75/14.4</td>
<td>5.7/15.1</td>
</tr>
<tr>
<td>(\beta_N/\beta_{tot}) %</td>
<td>5.6/6.5</td>
<td>2.6/1.7</td>
<td>-/6.4</td>
</tr>
<tr>
<td>P_{Fusion} (MW)</td>
<td>1813</td>
<td>2637</td>
<td>2440</td>
</tr>
<tr>
<td>f_{bs} (%)</td>
<td>91</td>
<td>77</td>
<td>~25</td>
</tr>
<tr>
<td>(&lt;\Gamma_n&gt;) MWm^{-2}</td>
<td>2.5</td>
<td>1.5</td>
<td>2.6</td>
</tr>
</tbody>
</table>

All steady-state at 1,000 MW$_E$
Major Mission Elements on the Path to an MFE Power Plant

Mission 1. Create Fusion Power Source

Mission 2. Tame the Plasma Wall Interface

Mission 3. Harness the Power of Fusion

Mission 4. Develop Materials for Fusion Energy

Mission 5. Establish the Economic Attractiveness, and Environmental Benefits of Fusion Energy

- Restatement of Greenwald Panel and ReNeW themes
- Each Mission has ~ five sub-missions
Technical Readiness Levels

Readiness levels can identify R&D gaps between the present status and any level of achievement.

<table>
<thead>
<tr>
<th>Issues, components or systems encompassing the key challenges</th>
<th>Readiness level</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Item 1</td>
<td></td>
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<tr>
<td>Item 2</td>
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<tr>
<td>Item 3</td>
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<tr>
<td>Etc.</td>
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TRLs express increasing levels of integration and relevance to final product.
## ITER + FNSF => Advanced Tokamak Demo Pathway

### Mission 1  Create Fusion Power Source

<table>
<thead>
<tr>
<th>Technical Readiness Level</th>
<th>Concept Development</th>
<th>Proof of Principle</th>
<th>Proof of Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Attain Burning Plasma Performance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_{\mu}/4$, $n_T$, $T_e$, $Q_{DT}$</td>
<td>Now</td>
<td>ITER</td>
<td>DEMO Power Plant</td>
</tr>
<tr>
<td>Control High Performance Burning Plasma</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_n$, $n_T$, disruptivity, $\tau_{\text{controlled}}$, $P_{\text{loss}}/P_{\text{heat}}$</td>
<td>Now</td>
<td>Support Pgm</td>
<td>ITER</td>
</tr>
<tr>
<td>Sustain Magnetic Configuration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_{\text{CD}}$, $P_{\text{CD}}/P_{\text{heat}}$, ... $\tau_{\text{sustained}}/\tau_{\text{CR}}$, etc</td>
<td>AT</td>
<td>Now</td>
<td>Support Pgm</td>
</tr>
<tr>
<td>ST</td>
<td>Now</td>
<td>Support Program</td>
<td>FNSF</td>
</tr>
<tr>
<td>Sustain Fusion Fuel Mix and Stable Burn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n_0(0)n_\tau(0)/n_\nu(0)^2$, Pop.Con stable, $\tau$ long</td>
<td>Now</td>
<td>ITER</td>
<td>DEMO Power Plant</td>
</tr>
<tr>
<td>FNSF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attain High Performance Burning Plasma</td>
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<td></td>
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<tr>
<td>Compatible with Plasma Exhaust</td>
<td></td>
<td></td>
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<tr>
<td>$P_{\text{pedr}}$, $P_{\text{pedr}}$, fuel dilution, $P_{\text{core-rad}}$</td>
<td>Now</td>
<td>Support Pgm</td>
<td>ITER</td>
</tr>
</tbody>
</table>

**Major Issues**
- Can AT be sustained in DEMO relevant mode with low disruptivity?
- Does QSS confinement extend to BP regime?
- Can high performance be sustained in either with DEMO relevant PFCs?
- Can fuel mix be sustained in either?

**Support Facilities**
- Existing DD tokamaks (domestic and foreign)
- Upgrades to existing facilities
- New Facilities

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**Note: this is linked to an active Excel spreadsheet**

Double click to open spreadsheet
Mission 1: Create Fusion Power Source (AT DEMO Pathway)

- **Attain high burning plasma performance**
  TRL 4: Q~1 achieved in DT experiments in TFTR/JET & extended with DT in JET 2015 with a Be wall

- **Control high performance burning:**
  TRL 3: Q~1 DT experiments in TFTR/JET see self-heating
  TRL 4: DIII-D ECH dominated ITER baseline experiments
  JET DT experiments on TAE transport in Q~1 DT plasmas with Be walls

- **Sustain fusion fuel mix and stable burn:**
  TRL 5: NBI Tritium fueling in TFTR/JET & cryo pellet injection technology

- **Sustain magnetic configuration-AT Configuration:**
  TRL 4: Bootstrap current widely observed; non-inductive sustained plasmas observed on JT-60U & DIII-D using NBI-CD/LHCD/ECCD
  TRL 5: DIII-D/K-STAR/JT-60SA observation of ≥80% bootstrap sustained plasma
  EAST/K-STAR/WEST observation of RF & bootstrap sustained SS plasma

- **Sustain magnetic configuration-ST Configuration:**
  TRL 3: Bootstrap current observed in NSTX; CHI demonstrated non-inductive current drive
  TRL 4: NSTX-U demonstrate non-inductive start-up and sustainment extrapolable to FNSF-AT

- **Attain high burning plasma performance compatible with plasma exhaust:**
  TRL 3: JET/DIII-D/ASDEX-U demonstration of detached divertor operation
  TRL 4: JET/DIII-D/K-STAR demonstration of detached divertor in SS AT ITER like plasma
  TRL 4: NSTX-U demonstration of advanced divertor operation in FNSF-ST like plasma
  TRL 5: Test stand validation of long lifetime divertor PMI material
## DEMOOPS Phase II Results

<table>
<thead>
<tr>
<th>Create Fusion Power Source</th>
<th>2000</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tame Plasma Wall Interface</td>
<td></td>
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<tr>
<td>Harness Fusion Power</td>
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<tr>
<td>Materials for Fusion Power</td>
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<tr>
<td>Economic Attractiveness</td>
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**Timeline**

- **2000**: ITER Basis
- **2010**: TRL=4
  - FNSF CDA
  - FNSI EDA
  - FNSF Const
  - DEMO CDA
  - DEMO EDA
  - DEMO Const
- **2020**: TRL=4
  - TRL=5
  - 7.5?
- **2030**: TRL=2
  - TRL=3
  - 7.5?
- **2040**: TRL=2
  - TRL=3
  - 7.5?

**Legend**

- ◇ Milestone
- ♦ Decision Point
- ★ Goal

**Initiation**

- **ITER**: Initiate Construction
- **FNSF**: Initiate CDA
- **DEMO**: Initiate Construction

**Operation**

- **DEMO**: Initiate EDA
- **ITER**: Initiate Operation

**Economic Attractiveness**

- **DEMO Const**: Gain~10 500 MW
- **DEMO Pathway (Logic)**
ITER + QS-Stell Program => Stellarator DEMO Pathway (Logic)

Legend:
- Milestone
- Decision Point
- Goal

Stell-NS = Stellarator Next Step
NS Mission Options:
- Burning Plasma (BP)
- Pilot Plant (PP)
Facilities for US Magnetic Fusion Program Road Map

- **C-Mod, DIII-D, ASDEX-U, JET**
- **NSTX-U, MAST-U**
- **EAST, KSTAR**
- **WEST**
- **JT60-SA**
- **ITER**
- **AT or ST for FNSF?**
- **AT OK for Demo Basis?**
- **PMI Facilities**
- **Blanket Facilities**
- **Materials Facilities**
- **QS Stellarator Pathway**
- **QSSE**
- **W7-X**
- **LHD**
- **Stellarator Base Program**
- **Adv Tokamak Pathway**
- **Demonstration**
- **Stellarator NS**
- **QS Stellarator Pathway**
- **QSSE**
- **W7-X**
- **LHD**
- **Stellarator Base Program**
- **DT**
- **Non-DT**

- **2000**
- **2010**
- **2020**
- **2030**
- **2040**

- **OK for FNSF?**
- **OK for Demo Basis?**

- **AT or ST FNSF?**
- **AT or ST Demo Basis?**

- **Demo Basis?**
- **BP or PP Basis?**
Next Steps for Road Map Activity

• Complete draft framework for each path forward:
  - Review critical issues
    - TRL assessments
    - Milestones
    - Decision points
  - Review aggressiveness of the schedule (More or less)
  - Compare relative technical gaps and risks
  - Resource needs (more than hardware)

• Seek input and review by technical experts and the fusion community

• Continue working with international groups that are developing Road Maps for their National Programs (e.g., 2nd IAEA DEMO Programme Workshop, Dec 16-20, 2013)

Comments – to the working group or me  dmeade@pppl.gov

These slides will be posted on FIRE  http://fire.pppl.gov