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) ITER 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

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

Background

ReNeW Study (2009)  FNSP Assessment CK (2011)
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

Path to fusion demonstration: scientific thrusts a la ReNeW

Ed Synakowski, UFA talk, APS-DPP 2012
All Road Map exercises start with where you are today, and where do you want to be at the end

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>
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<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>
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<tr>
<td>$\beta_N / \beta_{tot}(%)$</td>
<td>5.6/8.2</td>
<td>2.6/3.8</td>
<td>-/6.4</td>
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<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>
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<tr>
<td>$&lt;\Gamma_n&gt; MWm^{-2}$</td>
<td>2.5</td>
<td>1.5</td>
<td>2.6</td>
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</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
TRLs express increasing levels of integration and relevance to final product.
## ITER + FNSF => Advanced Tokamak Demo Pathway

### Mission 1  Create Fusion Power Source

**Technical Readiness Level**

<table>
<thead>
<tr>
<th></th>
<th>Concept Development</th>
<th>Proof of Principle</th>
<th>Proof of Performance</th>
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<tr>
<td></td>
<td>1</td>
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<tr>
<td>Attain Burning Plasma Performance</td>
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<td>ITER</td>
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<td>Ba5/4, n\textsubscript{T}, T, Q\textsubscript{DT}</td>
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<td>Now</td>
<td>DEMO</td>
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<tr>
<td>Control High Performance Burning Plasma</td>
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<td>Now</td>
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</tr>
<tr>
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<td>Support Pgm</td>
<td>Now</td>
<td>DEMO</td>
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<td>Sustain Magnetic Configuration</td>
<td>AT</td>
<td>Now</td>
<td>Support Program</td>
</tr>
<tr>
<td>f\textsubscript{CD}, P\textsubscript{CD}/P\textsubscript{heating}, \cdots</td>
<td>ST</td>
<td>Now</td>
<td>FNSF</td>
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<tr>
<td>Sustain Fusion Fuel Mix and Stable Burn</td>
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<td>Now</td>
<td>ITER</td>
</tr>
<tr>
<td>n\textsubscript{0}(0)n\textsubscript{T}(0)/n\textsubscript{e}(0)\textsuperscript{2}, Pop.Con stable, \tau \text{long}</td>
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<td>Now</td>
<td>DEMO</td>
</tr>
<tr>
<td>Attain High Performance Burning Plasma</td>
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<td>Now</td>
<td>FNSF</td>
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<tr>
<td>Compatible with Plasma Exhaust</td>
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<td>Now</td>
<td>ITER</td>
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<tr>
<td>T\textsubscript{pedr}, n\textsubscript{pedr}, fuel dilution, P\textsubscript{core-rad}</td>
<td></td>
<td>Now</td>
<td>FNSF</td>
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</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?

More Work Needed here

- Need to review
- Compare with EU
- NAS IFE
- DOE TRL Guidelines
- Describe reqmts for each TRL with issues, milestones

**Support Facilities**

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

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
ITER + FNSF => AT DEMO Pathway (Logic)

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<th>2010</th>
<th>2020</th>
<th>2030</th>
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</table>

Legend:
- ◇ Milestone
- ♦ Decision Point
- ★ Goal

- Create Fusion Power Source
- Tame Plasma Wall Interface
- Harness Fusion Power
- Materials for Fusion Power
- Economic Attractiveness

- ITER Initiate Construction
- FNSF Initiate CDA
- DEMO Initiate CDA
- DEMO Initiate EDA
- DEMO Initiate Construction
- DEMO OPS Electricity From Fusion
### ITER + QS-Stell Program => Stellarator DEMO Pathway (Logic)

<table>
<thead>
<tr>
<th>Year</th>
<th>2000</th>
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<th>2020</th>
<th>2030</th>
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<td>Initiate Operation</td>
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**Legend**
- ◇ Milestone
- ■ Decision Point
- ★ Goal

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

2000  | 2010  | 2020  | 2030  | 2040
--- | --- | --- | --- | ---
C-Mod, DIII-D, ASDEX-U, JET | NSTX-U, MAST-U | EAST, KSTAR | WEST |

**Adv Tokamak Pathway**

AT or ST for FNSF?

AT OK for Demo Basis?

**PMI Facilities**

OK for FNSF?

**Blanket Facilities**

**Materials Facilities**

QS Stellarator Pathway

**LHD**

Stellarator Base Program

**QS Stellarator Pathway**

QTSE

W7-X

**QS Stellarator Pathway**

QSS  OK for BP or PP Basis?

**Stellarator NS**

**DEMO**

**DT**

**Non-DT**
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