A Pilot Plant:
The Fastest Path to
Net Electricity from Fusion

ARIES Team Meeting

Rob Goldston

December 15, 2009

Fusion Development Needs to Move Faster

Situation

- **Need to demonstrate the practicality of fusion soon.**
- **ITER's earliest-case first plasma is in 2018**
- **Earliest-case Q = 10, 300 – 500 seconds in 2028.**
  - **500 MW x 400 seconds = 200,000 MJ/pulse.**
  - **Designed for 25% duty factor for 12 days ⇒ 10^7 MJ/day**
- **NIF success (100MJ/day) could launch IFE technology development**
  - **Synergy between MFE and IFE technology development very desirable.**
- ***ITER success could launch a fusion facility to produce electricity!***

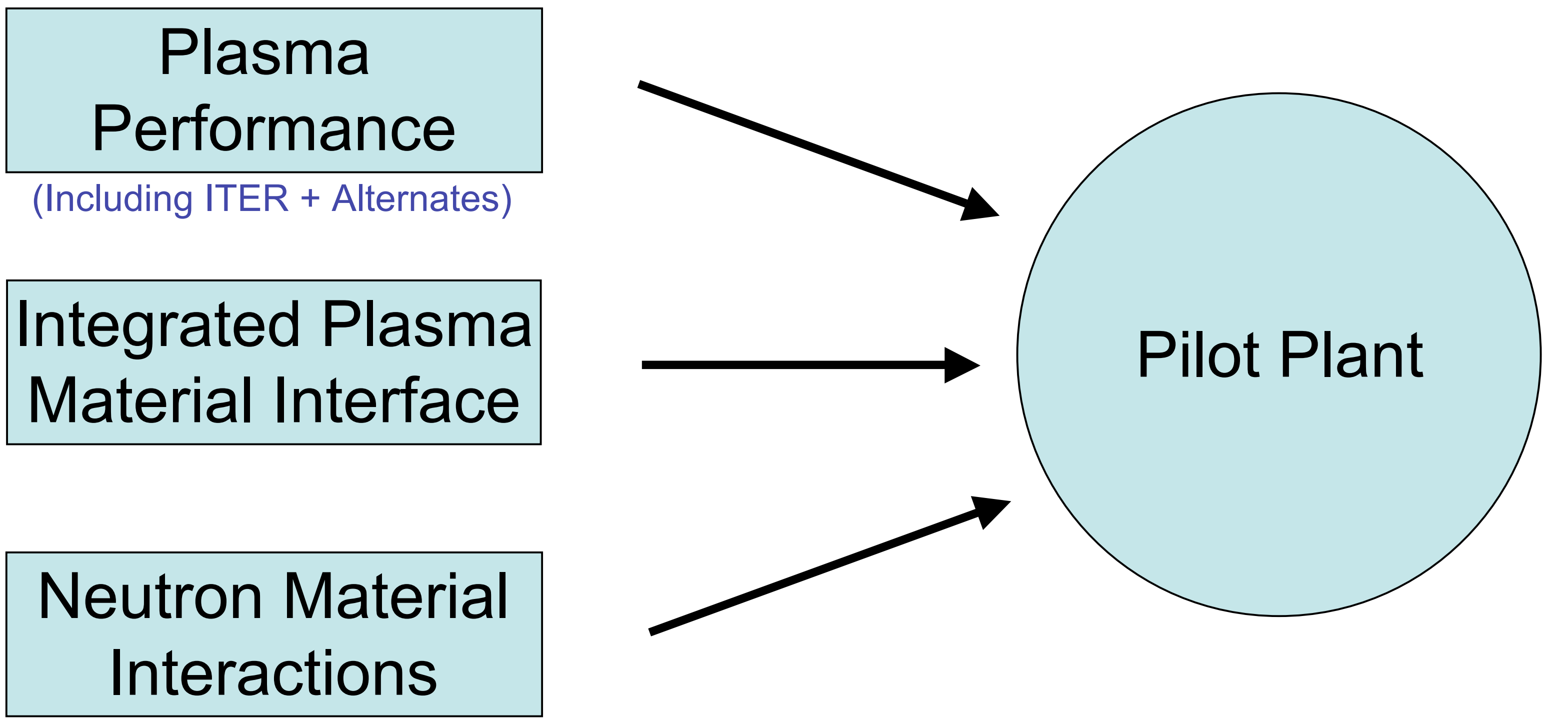
Implications

⇒ **Building a Component Test Facility and *<u>then</u>* building Demo to produce net electricity may not be the fastest path.**

⇒ **Consider construction of the minimum device to make *<u>net electricity</u>***

- $Q_{eng} > 1 \equiv$ "Pilot Plant", making net electricity.
- Pilot Plant would also perform the component testing mission.
- It should prototype power plant maintenance approach.
- *Next step: public-private partnership on a commercial-scale power plant.*

Three Key Science Needs for a Technically Sound MFE Pilot Plant Design



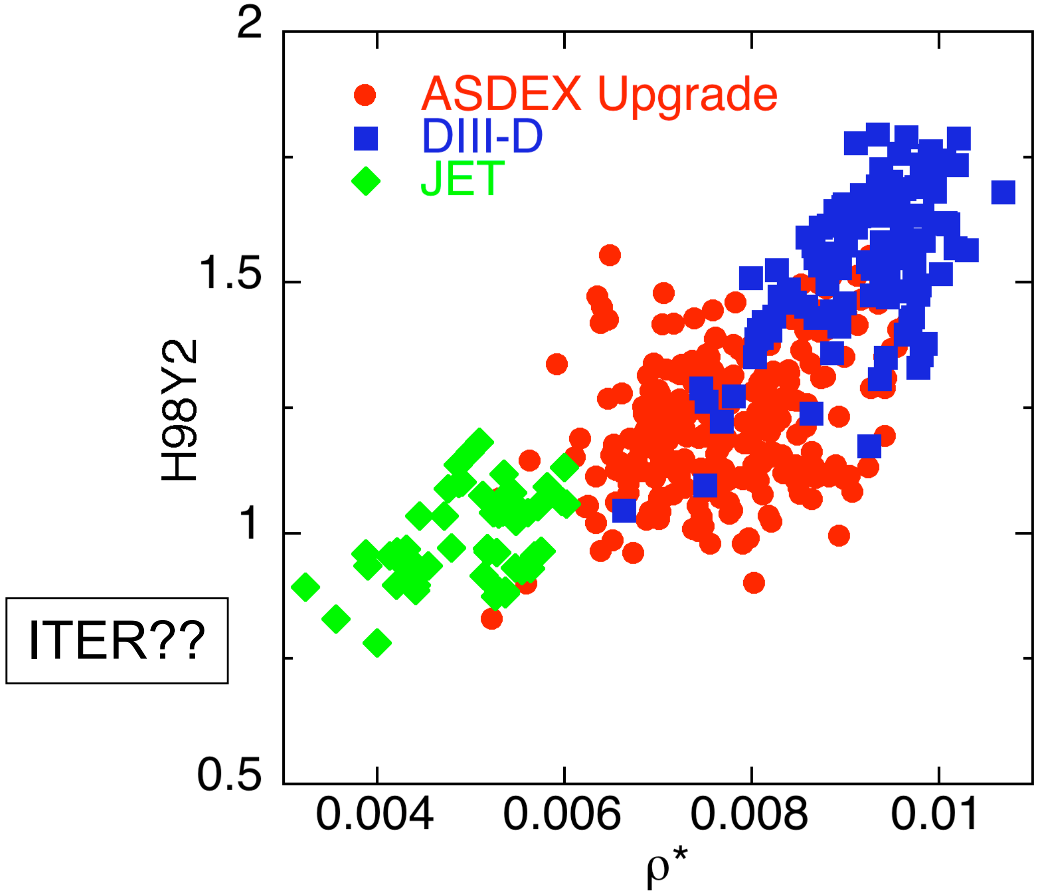
Themes from FESAC Priorities, Gaps and Opportunities Report
(ReNeW Themes 1, 2 & 5 included in Plasma Performance)

What Science is Needed for a Technically Sound MFE Pilot Plant Design? (1)

Plasma Performance

- ***A strong physics program is needed for CTF, PP or Demo.***
- **Scaling of confinement, operating limits and sustainment in non-inductive plasmas**
- **Confinement scaling to relevant ρ^* and ν_*, low rotation**
- **Alpha heating physics**
- **Scaling information at low A**
    - Low A provides an alternate maintenance approach
- **Scaling information for stellarators**
    - Stellarators most credible for disruption avoidance, sustainment with low recirculating power
- **Are there faster/better/cheaper alternatives?**
    - ICCs

Example: Confinement Scaling to ITER Long-Pulse "Hybrid" Mode Uncertain



Latest matched DIII-D + JET results look better on these axes, but still do not give needed favorable "Gyro-Bohm" scaling of Bτ. Projection to CTF, Pilot Plant or Demo is not settled.

What Science is Needed for a Technically Sound MFE Pilot Plant Design? (2)

Integrated Plasma-Materials Interface

- ***A strong PFC technology program is needed for CTF, PP or Demo.***
- **High heat and particle flux and fluence**
  - What divertor designs work at needed power & duty factor?
  - What materials work at needed power & duty factor?
- **Tritium retention**
  - How to remove tritium in continuous operation?
  - All plasma-facing components (PFCs) must operate very hot.
- **Dust production**
  - How to remove dust in continuous operation?
- **Practical experience with high-pressure He-cooled PFCs**
- **Practical experience with liquid metal PFCs**
- ***Effects of ELMs and high-energy disruptions***
  - *Major issue for blanket / first wall survival in tokamaks & STs.*

Significant synergy with many IFE concepts.

Pilot Plant PMI Challenges Similar to PMI Challenges Projected for CTF

- **Heat flux, pulse length, duty factor for Pilot Plant (PP) ~ CTF**
  - CTF: 2x ITER's heat flux — Demo: 4x ITER's heat flux
  - CTF: 2 week pulses — Demo: Few month pulses
  - CTF: 30% duty factor — Demo: up to ~70% duty factor
- **Real-time dust removal, tritium inventory control and component lifetime issues are challenging due to CTF, PP & Demo missions**
  - Must remove dust and tritium in real time: CTF, PP, Demo
  - Need to demonstrate PFC solution that allows long periods of high power operation between change-outs, including off-normal events: CTF, PP, Demo
  - ITER with few % duty factor, plans to change out divertors after ~ 0.08 full-power years – at much lower power density.
- **Many solutions used on ITER are not CTF, PP or Demo relevant.**
  - Beryllium first wall
  - Stainless-steel vacuum vessel
  - Water cooled ~200C PFCs
  - Intermittent dust collection and tritium clean-up

CTF, PP or Demo: All Would Need New PMI Solutions.

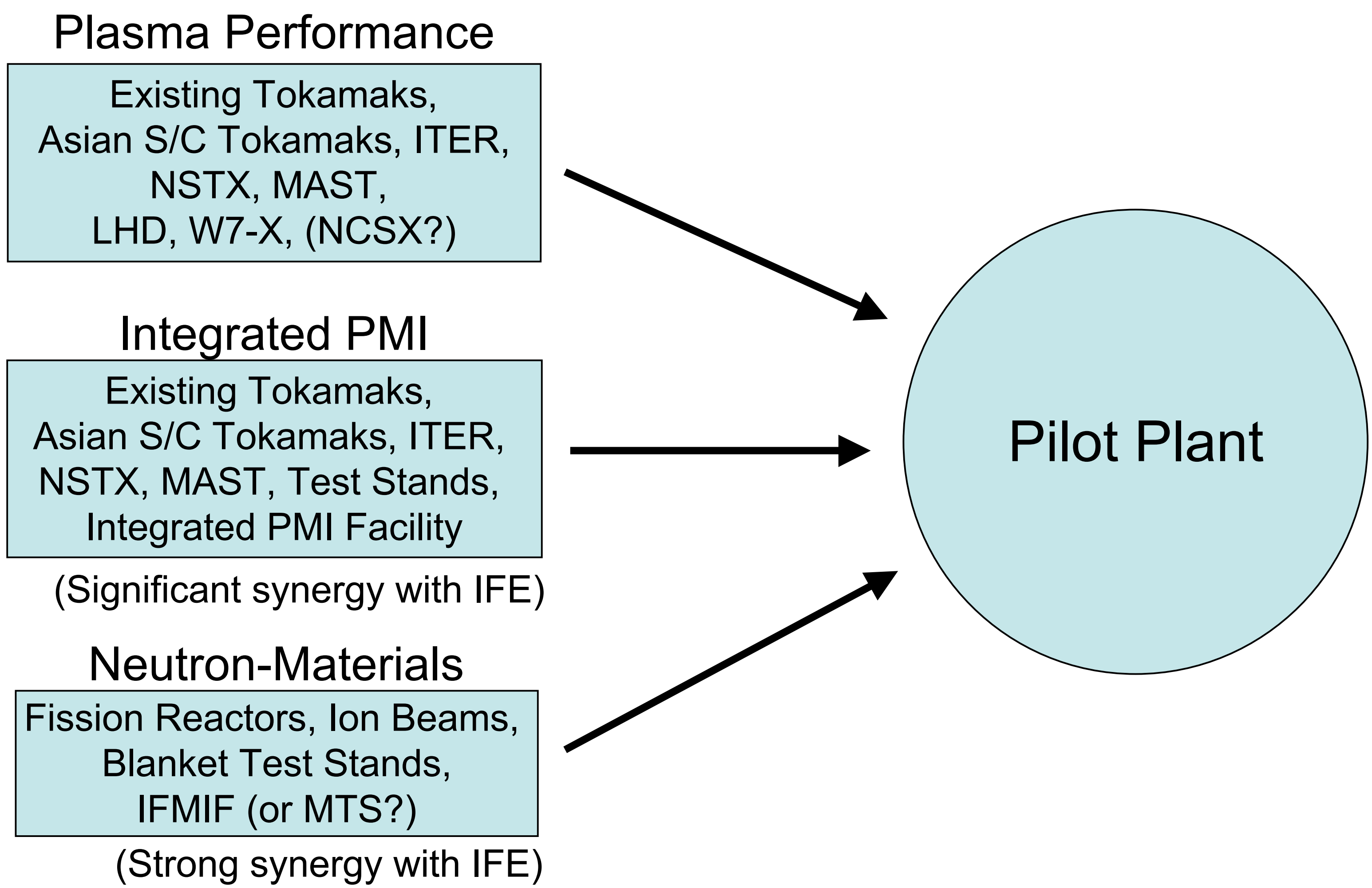
What Science is Needed for a Technically Sound MFE Pilot Plant Design ? (3)

- ***A strong blanket technology program is required for CTF, PP or Demo.***
- **Design of CTF, PP or Demo would be informed by a powerful point neutron source such as IFMIF (or MTS?). For example:**
  - Vacuum vessel design depends on properties of hot main blankets: electrical conduction paths, structural integrity, size, services (coolant, T purge fluid).
  - Hot main blanket design depends on material properties w/14 MeV neutrons.
  - Same logic holds for many other components, *e.g.,* divertors, antennas.
  - Point neutron source needed to develop materials for test blankets.
- **Tritium breeding uncertainties can be mitigated by Li isotopic mix.**
  - Tritium cycle can be confirmed in Pilot Plant.
- **ReNeW on this topic:**

A later possibility might be to include a provision for materials irradiation capabilities as part of a large-scale nuclear facility such as the proposed Fusion Nuclear Science Facility. However, it must be emphasized that bulk material property data from a fusion relevant neutron source would inform the design, construction and licensing of such facilities.

A point neutron source has high synergy with many IFE concepts.

Facilities to Contribute to a Technically Sound MFE Pilot Plant Design



Roles of Major Facilities

- **Plasma Performance**
  - ITER for ρ^* scaling, α–particle heating
  - Existing tokamaks, Asian S/C tokamaks for AT pilot plant option
  - NSTX, MAST at relevant β and ν_* for low aspect ratio pilot plant option
  - LHD, W7-X, (NCSX?) at relevant β and ν_* for stellarator pilot plant option
- **Integrated Plasma-Material Interface**
  - Existing tokamaks, Asian S/C tokamaks, NSTX-U, MAST, test stands, for initial tests of new PFC geometries and materials.
  - Long-pulse, hot walls, high-heat-flux DD confinement facility for integrated power and particle handling studies. Develops solutions for divertor lifetime, tritium retention, dust clean-up, long-pulse disruption avoidance.
  - *ITER for effects of high-energy ELMs and disruptions.*
- **Neutron Material Interactions**
  - Fission reactors, ion beams to sieve candidate materials.
  - Blanket test stands to develop required technologies.
  - IFMIF (or MTS?) with correct He/dpa to investigate materials physics at high fluence; qualify materials to be used in PP design, then test blankets.

Is a Pilot Plant Smaller than a Demo?

- Assume conservatively that recirculating power, P_{rec}, is constant from Pilot Plant (PP) to Demo
- Assume recirculating fraction in Demo is 20%; $Q_{eng} = 5$
- Assume Pilot Plant $Q_{eng} = 1.2$
- $P_{e,gross,Demo} = 5\ P_{rec}$; $P_{e,gross,PP} = 1.2\ P_{rec}$
- $P_{e,gross,PP} = 0.24\ P_{e,gross,Demo}$
- Assume Demo-level B & $\beta \Rightarrow R^3 \propto P_{fus} \propto P_{e,gross}$

  Assume adequate confinement
- $P_{fus,PP} = 0.24\ P_{fus,Demo}$; $R_{PP} = 0.62\ R_{demo}$; $R^2_{PP} = 0.38\ R^2_{demo}$
- Neutron wall loading in Pilot Plant = 0.62 Demo neutron wall loading

Obviously there are other factors (*e.g.,* neutron m.f.p.).
On the other hand P_{rec} = constant is conservative.
Initial looks at Tokamak, ST, Stellarator support $R_{PP} \sim 0.6\ R_{Demo}$

Spreadsheet Pilot Plants Assuming High Confinement are Encouraging

- **Tokamak**
  - R/a = 4.0m/1.0m, B_0 = 6T, I_p = 8MA
  - H_H = 1.5, P_{fus} = 520MW, Q_p = 10, Q_{eng} ~ 1
- **ST**
  - R/a = 1.5m/0.9m, B_0 = 2.2T, I_p = 15 MA
  - H_H = 1.7, P_{fus} = 500MW, Q_p = 25, Q_{eng} ~ 1
- **Stellarator**
  - R/<a> = 4.5m/1.0m, B_0 = 5.7T
  - H_{ISS04} = 2, P_{fus} = 470MW, Q_p = 40, Q_{eng} ~ 4

These spreadsheet analyses are only very first looks. Engineering scaled simply from ARIES studies.

Much More Analysis is Required

- **What would an MFE Pilot Plant look like?**
  - Advanced Tokamak (Superconducting for $Q_{eng} > 1$)
  - Spherical Torus (Most readily maintained configuration)
  - Stellarator (Lowest recirculating power, no disruptions)

  Any design should prototype power plant maintenance approach.
  This also points to superconducting coils for AT.

- **What near-term program of Modeling, Test Stand R&D, New Facilities is necessary to support a Pilot Plant?**
  - Plasma performance
  - Integrated plasma material interface
  - Neutron interactive materials

A Pilot Plant is an Exciting Goal

- **We can explain it to our sponsors and the public**
  - We have a plan to make net electricity soon.
  - This will put fusion "on the map" as an energy option.
  - The step after this would be public-private partnership on a full commercial-scale power plant.
- **It would culminate the key FESAC Themes**
  - Creating Predictable High-Performance Steady-State Plasmas
  - Taming the Plasma-Material Interface
  - Harnessing Fusion Power
- **ARIES + Fusion Community Pilot Plant Study?**
  - What would a tokamak, ST or stellarator Pilot Plant look like?
    - Lifetime fluence, maintenance approach, cost
    - It should be designed to drive fusion R&D in the right directions
  - What supporting program is needed for a technically sound design?
  - A similar IFE Pilot Plant study should be carried out in parallel.