A new strategic plan to accelerate fusion energy development is urgently needed
The plan must be credible, attractive and realistic

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With much appreciation to the many scientists and engineers I have worked with over decades!

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A credible and realistic pathway to DEMO/Pilot must seriously address the Fusion Nuclear Science and Technology (FNST) development as the most formidable challenge on the way to fusion energy

FNST is the **science**, **engineering**, **technology** and **materials** for the fusion nuclear components that generate, control and utilize neutrons, energetic particles & tritium

The primary FNST components are those from the edge of the plasma to the inner surface of the TF coils – these form the Reactor "Core" and often called the "in-vessel components":

1- **Blanket** (including integrated first wall)

2- Plasma Interactive & High Heat Flux components (divertor, rf antennas, etc.)

3- Vacuum Vessel and shield components

Other FNST systems include: - Tritium Fuel Cycle, - Instrumentation & Control, - Remote Maintenance components, and- Heat Transport system

Current Situation in the World Fusion Energy programs

Reasons for Optimism

Recent Events:

- positive plasma energy balance obtained in inertial fusion
- a stable plasma was maintained for ~ 1000 S in China Tokamak EAST
- a plasma energy turnover > 1 GJ achieved in the W7X Stellarator
- enormous interest in fusion energy from industry and private investors
- much increased interest of governments in fusion: e.g.
  - USA fusion energy international strategy announced at COP28
  - Europe is evaluating new strategy to accelerate fusion energy
  - ASIPP in China received funding and license to construct BEST and operate by Dec 2027. Construction and R&D programs are ongoing

Current Situation in the World Fusion Energy programs

Reasons for Concern and Caution

- Long delays in ITER
- ITER has nearly eliminated the Nuclear Mission. It focuses now only on DT burning Plasma physics and plasma support technology
- The TBM program in ITER has been reduced to “symbolic testing”
- Many international technology assessment studies concluded that the tritium breeding blanket is at a very low TRL. No blanket has ever been built or tested. There is an urgent need to qualify blankets in the fusion nuclear environment, which can be obtained only in a DT plasma-based nuclear facility
- The world has failed to implement proposals from 30 years ago to build a 14 MeV Volumetric Neutron Source (VNS) in which testing and qualification of blanket can be performed
- Major design and R&D DEMO studies (e.g. EU DEMO) have concluded that using the first stage of DEMO operation for qualification of breeding blanket is nearly impossible, and at best is very expensive and takes very long time
- No definitive solution has been identified yet for maintaining the blanket and other in-vessel components

Principal Challenging FNST issues identified in comprehensive international studies as most essential to address in defining a credible pathway

1. Lack of External T Supply to provide the large **T Startup Inventory** required for any major fusion facility
2. Technology and physics Uncertainties in achieving **Tritium Self-Sufficiency**
3. RAMI (Reliability/Availability/Maintainability/Inspectability)
    - **RAMI** is the Achilles' Heel issue for fusion
4. Complex and new **Multiple/synergistic Effects** and Interactions Phenomena
    - These phenomena cannot be synthesized from "separate effects" experiments or modelling
5. **Nuclear Heating in a large volume with steep gradients**

Issues 2, 3, 4, and 5 can be adequately addressed only in the fusion nuclear environment of a DT plasma-based facility

Issues 1 and 2 mandate that the DT plasma-based facility must be **small** fusion power (< 100 MW). So, it cannot be Pilot or DEMO

Issue 3 requires very aggressive RAMI program and indicates that it is hard to predict the time in which reliability growth will be sufficient to proceed to Pilot/DEMO plant

Reliability/Availability/Maintainability/Inspectability (RAMI)

Detailed Analyses show: **RAMI is a serious challenge that has major impact on engineering feasibility and economics**: anticipated MTBF is hours/days (required is years), and MTTR is 3-4 months (required is days), and availability is very low < 5%

Fundamental reasons:

- Location of Blanket/FW/Divertor inside* the vacuum vessel:

  → ***low fault tolerance*** → ***short MTBF*** because many failures (e.g. coolant leak) require immediate shutdown, also no redundancy possible.

  → ***long MTTR*** because repair & replacement require breaking "vacuum seal" and many connects/disconnects, and many operations in the limited access space of tokamaks, stellerators, and other "toroidal/closed" configurations

  ** The decision to put the blanket inside the vacuum vessel is necessary to protect the vacuum vessel, which must be robust and cannot be in high radiation/temperature/stress state facing the plasma.*

- Large surface area of the first wall results in high failure rate for a given unit failure rate per unit length of piping, welds, and joints → ***short MTBF***

Contrast this to fission reactors:

- Can continue operation with ~ 2% of fuel rods with failures (MTBF ~ years)
- An entire fuel bundle can be replaced in ~ 2 days (MTTR ~ 2 days).
- Fission reactors have been able to achieve 90% availability

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Tritium Issues Dictate the fusion power of the next DT Device must be small (<100 MW)

- **With ITER DT start in 2036, there will be no external non-fusion supply of tritium left to provide T Startup inventory for any major DT Fusion facility beyond ITER. The tritium we had at the beginning of ITER design has already decayed!**
- The tritium consumption in fusion systems is huge: 55.8 kg per 1000 MW fusion power per full power year. This means that a device like DEMO with 2000 MW Fusion Power (~500 MWe) would consume: 112 kg/year; 0.31 kg/day. For a Pilot Plant with 1000 MW Fusion Power (200 MWe), tritium consumption is 56 kg/year; 0.15 kg/day
- The Required Startup T inventory will be 14 kg for DEMO and 7 kg for Pilot Plant
- **There are very large uncertainties in achieving T self-sufficiency in early DT devices** due to uncertainties in system definition (e.g. amount of structure, presence of stabilizing coils, etc.),plasma burn up , fuelling efficiency, etc.
- **The issue of RAMI and expected low availability in early devices will have a huge impact on the potential to achieve T self-sufficiency.**

  Reason**:** During device downtime, T production in the blanket is interrupted while T loss by radioactive decay continues, inexorably

- **Therefore, the next DT device like VNS should have small fusion power (< 100 MW)**

Accelerating Fusion Development will be realized only from a credible plan. There is no credible plan if it does not seriously address FNST- this requires constructing and operating VNS parallel to (or earlier than) ITER

Comprehensive international technical assessments and evaluation studies over the past 30 years show that:

1. A credible pathway must start with a DT plasma-based device that has low fusion power (<100 MW to minimize requirements for external T supply), in which we can learn behavior of Blanket/FW/Divertor in the fusion nuclear environment, discover and understand multiple/synergistic-effects phenomena, quantify the potential to attain T self-sufficiency; and understand failure modes, rates, effects (RAMI).
   - ➢ **This first DT fusion device is often called VNS.** It should have small size (R ~ 2-3 m), low fusion power (< 100 MW), ~ 0.5 MW/m^2 NWL on ~10 m^2 test area. Only inside the vacuum vessel (Blanket / FW/divertor) need to be prototypical. Plasma should be highly driven, Q ~ 1-3 with plasma burn > 200s (should be based on current plasma physics)

2. Results and experience from this first DT device will tell us much about the viability of current concepts, and whether we need another one or more devices for reliability growth and other physics and technology improvements; and possibly produce excess tritium to supply the required Start up inventory for DEMO/Pilot.

There are also important benefits of implementing a technology program centered around a key development facility like the VNS. These include:

- Forcing function to concept engineering developments (nuclear performance, reliability growth, Remote Maintenance)
- Provides additional experience in design, construction and licensing of a nuclear fusion device
- Provides focus and guidance to realign interests of private investors (most of which are biased towards developing primarily magnets), towards programmatic priorities
- Keeps industry, private Investors, and governments interest high
- Provides a powerful incentive to attract and form a new generation of engineers and scientists

VNS should have two sequential stages to establish Scientific AND Engineering Feasibility

Stage I: Scientific Feasibility

Objectives:

- Discover and understand new synergistic phenomena
- Establish scientific feasibility of basic functions under prompt responses and under the impact of rapid material property changes in early life
- Show that tritium self-sufficiency can be attained

Requirements:

- Fluence: ~ 0.3 MW-y/m^2
- NWL ~ 0.35 MW/m^2
- Plasma Burn > 200 s
- Sub-modules, modules

Stage II: Engineering Feasibility

Objectives:

- Show that blankets/PFC/materials can satisfy basic functions & performance, up to 10 to 20% of MTBF and of lifetime
- Show basic feasibility: obtained MTBF is at least 10% of required MTBF, and MTTR is no longer than 10 times the required MTTR.

Requirements:

- Fluence: ~ 1 - 3 MW-y/m^2
- NWL : ~ 0.35 – 0.5 MW/m^2
- Plasma burn : steady-state or long burn time/short dwell time
- Achieve periods of continuous operation (COT) of ~ 1-2 weeks

Primary Recommendations

- Build VNS soon, parallel to ITER and in advance of the DEMO/Pilot final design.
- Select a version of VNS that can make it near term (operation parallel to ITER). Make it small volume, low fusion power, with small requirements for external T supply, simplest, most reliable, driven plasma with current physics basis to enable the FNST mission.
- Initiate immediately a study to investigate the options for the design of VNS. Several design options were proposed in previous studies. But recent advances in superconducting magnets and identification of high heat load on the divertor are examples of tradeoffs to be considered in selecting the design of VNS
- Strengthen the current program of development and testing of blankets and PFC in non-fusion facilities (laboratory facilities and fission reactors) as well as modelling/simulations to enable building the breeding blanket modules for testing in VNS.
- An intensive program on RAMI is needed. For example, a non-fusion facility is required now to develop and qualify tools and procedures for the remote replacement of the breeding blanket in DT fusion devices. In parallel, components to be used in the remote handling devices of DEMO/Pilot will have to be qualified for operation in a representative fusion nuclear environment such as VNS.

Note: **Important effort is ongoing in Europe to investigate a viable VNS option (ref. Gianfranco Federici Nuclear Fusion 63 (2023) 125002 (18pp)). See also Gianfranco Federici presentation at the 2022 FPA.**

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Thank you!