Worldwide Timelines for Fusion Energy

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The development of practical fusion power systems takes decades to bring fusion from the current conceptual design phase to market penetration. Since the beginning of fusion development, nations with strong fusion programs have been developing long-term plans and schedules with the end goal of operating fusion power plants in 50 years. So far, this has been a sliding scale vision and it is still uncertain when exactly fusion will contribute to the commercial energy mix, perhaps in a few decades if the social and political climate creates a demand for fusion energy maintained with strong governmental support, realistic funding, and international collaboration between the U.S., Europe, Japan, Korea, and China.

In his PVMC document titled "Thoughts on Mission and Values," M. Greenwald (MIT) stated "A critical set of choices for our strategy must involve which elements to take on ourselves and which can be better to achieve through international collaboration based on evolving fusion developments." In this regard, it is necessary to show how our roadmap fits into the larger international picture. This report outlines the projected worldwide roadmaps to fusion energy for the U.S., Europe, Japan, Korea, and China. Even though numerous worldwide roadmaps and plans have been developed in recent decades [1-9], the schedule for placing a fusion power plant on the grid is still uncertain. The main reasons are the recent delay in ITER schedule, the unreadiness of structural materials along with many fusion technologies, and/or the lack of funding for necessary R&D programs. At the present time, all countries are revising their roadmaps primarily because the delay in ITER.

There is a wide agreement between international fusion communities that a demonstration plant (DEMO) is the last step necessary to reduce the technical and programmatic risk associated with the first commercial power plant. Beyond ITER, multiple small-scale facilities and significant fusion technologies remain to be developed to bridge the large gap between existing fusion experiments and DEMO operation. In the U.S., design teams proposed the two-machine pathway, shown in Fig. 1, where the first machine would be a Fusion Nuclear Science Facility (FNSF) (based on tokamak (US-I pathway) [10], spherical tokamak (US-II pathway) [11], or stellarator [12]) followed by a DEMO which is envisioned to be identical in content (i.e., same confinement concept, materials and technologies), but varying in performance level (such as fusion power and availability). In this approach, more advanced physics and technical stepping-stones remain to be developed and validated before building a DEMO that should mimic advanced U.S. power plants designed by the ARIES and PPPL teams. The potential benefit for the ST-FNSF is the cost – in particular the smaller ST-FNSF design is cheaper/faster to build than a tokamak. Just recently, the NAS working group for Strategic Approach-1 suggested proceeding *now* toward DEMO using present physics and technology to achieve fusion energy in the next several decades (US-III pathway), hoping the U.S. energy market will accelerate the development of fusion in the near future with a substantial increase in funding and governmental support.

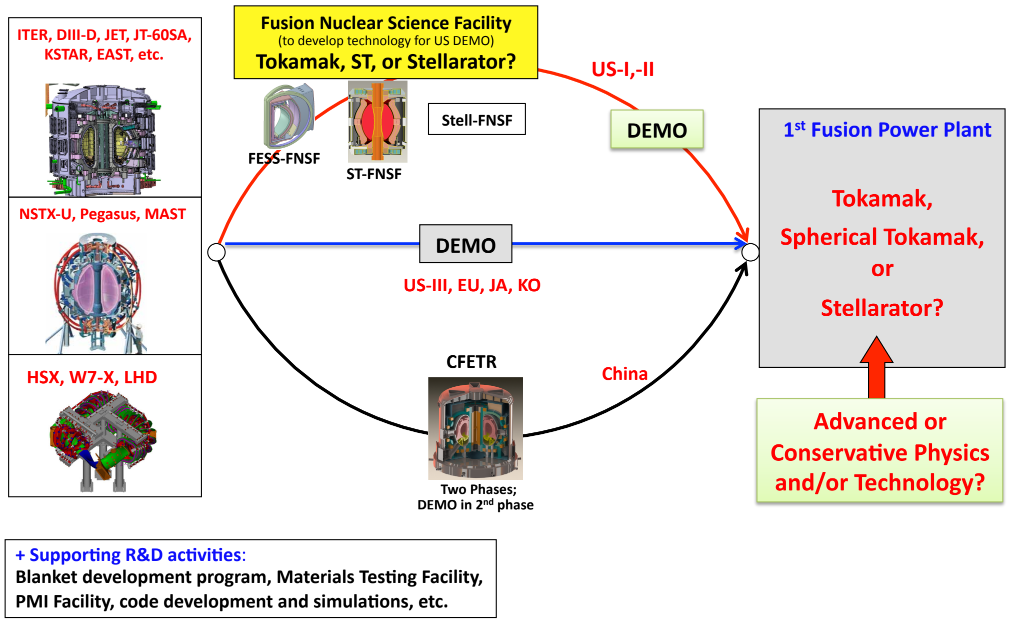

Figure 1. Worldwide pathways from experimental facilities to first fusion power plants.

Figure 2 displays the current projection of the timelines for DEMO and first commercial power plant that might be built in the U.S. and other countries whose fusion programs are explicitly energy-oriented. Note that these timelines adopted different approaches, depending on the degree of assumed technology readiness, the extent of physics and technology extrapolation beyond ITER, and the desired economic competitiveness of power plants [13]. As Figure 2 illustrates, all countries projected operating DEMOs in 30-40 years, targeting power production from DEMO in the 2045-2055 timeframe:

- Korea suggests a scenario for a multi-phase operation [5], where Phase-I starting in 2042 would have an FNSF-type mission and the following Phase-II would rebuild the facility to be a true DEMO by replacing all in-vessel components [14] to produce a net electric power of 600 MW in the early 2050s. The first-of-a-kind power plant will start operating in 2060.
- The European roadmap is currently under complete revision and the new version will be available in the spring of 2018. At the present time, the EU DEMO [7] is in a pre-conceptual design phase. Major decisions will be made during the 2020s, followed by detailed DEMO design, hoping the 2035-2045

ITER D-T phase will confirm these decisions. The EU DEMO could operate around 2050.

- The Japanese roadmap toward DEMO is also under revision. Because of delays in ITER, it seems risky for Japan to define the fusion schedule beyond 2035. Nevertheless, Japan is currently defining the timetable for the essential R&D activities [8] needed before building the DEMO. The fusion energy will be ready in Japan for commercialization in the middle of this century.
- The China Fusion Engineering Test Reactor (CFETR) is the next device in the roadmap for the realization of fusion energy in China [9]. The machine will operate in two phases: Phase-I with steady-state operation of CFETR with modest 200 MW of fusion power; Phase-II aims at DEMO validation with a fusion power over 1 GW. The CFETR components of Phase-I will be upgraded and rebuilt to a larger size device for the DEMO of Phase-II.

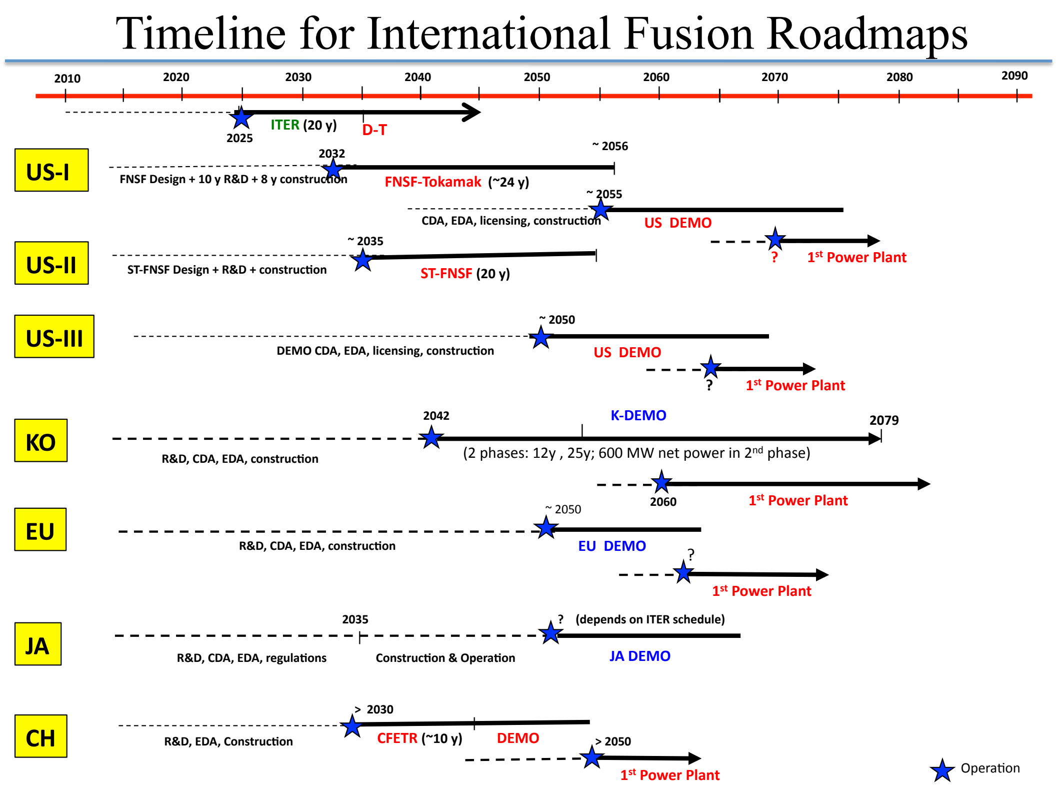

Figure 2. Projection of DEMO and first power plant operation.

In summary, all approaches are targeting the same goal of operating a DEMO during the 2045-2055 timeframe. The most optimistic projection is by China, followed by Korea, Europe, Japan, and the U.S. These approaches differ in the level of risk (two-step approach or single DEMO machine) and the degree of extrapolation beyond ITER (near-term or more advanced physics and technology for DEMO and/or power plant). The pressing questions are: What are the necessary steps to move the roadmap to a higher level of confidence on the performance toward the end goal of a fusion power plant? Are the ambitious plans consistent with the current status and rate of progress in fusion R&D? Is there convincing evidence of government commitment and spending at the levels necessary to dramatically accelerate progress in closing the large gaps in materials, technology, and magnetic confinement science?

Aside from the schedule and prominent strategic approach, the U.S. should invest upfront in R&D programs that could lead to more attractive DEMO/power plant, possibly through higher magnetic field (from high-temperature superconducting magnets), some advances in divertors and plasma confinement, higher temperature blankets and ODS structural alloys, and advanced manufacturing techniques (such as additive manufacturing and nano-fabrication) [15], otherwise the end-product will be too large, expensive, unattractive, and probably won't ever get built in the U.S.

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