Question raised and discussed during L2-20141122:

Several big and tough questions were raised and briefly discussed during this lecture. They deserve thoughtful answers, which are provided below. Take a look. Do not hesitate to raise further questions if you have them. 彭元凯老师， 20141001

Elective homework suggested by lecturer:

选修的功课 20141201-1: Comparing with ITER, the technical objectives of CFETR include a range of fusion power instead of a range of Q value. Why?

Questions raised by students, and my answers:

1. **What simplifications can we expect to make fusion possible?**

   Answer: First, fusion energy is already judged to be possible. So, I would rephrase the question: **What simplifications can we expect to make fusion energy more readily achievable?**

   To provide a large-scale, sustainable energy supply, a new technology usually starts with complex combinations of many techniques from different, presently available, fields of science and technology (S&T). The new physics conditions so created usually engender new data and information in S&T. This in turn would provide possibility for improvements, via some form of breakthrough and in the direction of simplification.

   We can imaging even now a number of "what if" questions as part of answer to this question. To name a couple:

   a) What if the tokamak plasma $\tau\beta$ (confinement time × pressure / magnetic field pressure) can be increased two-fold? This would allow substantial reductions in magnetic field strength, plasma size, etc. of the fusion core. If this increase could be ten-fold, substantial aneutronic fusion burn (p-B^{11}) could be produced in a larger tokamak of practical size. This in turn would largely eliminate nuclear requirements of a tokamak fusion core, assuming that plasma heat and particle flux handling remained practical.

   b) What if materials are developed that can withstand two-fold increases in plasma particle fluence on divertor plate, and similar increases in energetic neutron fluence? How about materials to shield against neutrons and gamma rays two times more effectively than today's materials?

   Note that improvements to a more moderate degree than these would more likely be achieved in the near future. We plan to address this topic in L8 – "*Putting it all together: the box and thinking beyond*", scheduled for 2015.01.17.

2. **What if ITER could not achieve the goal of a Q value equaling 10?**

   Answer: Q value of 10 or larger is a technical objective for the ITER tokamak. I have added a slide to the L2 notes to help clarify the relationship between mission and technical objective. Please take a look at the updated lecture notes on the website. The idea there is that a technical objective can be updated without compromising the mission.

Let's say that someday the ITER experiment achieved Q=8, while Q=10 was to be expected. What would this mean? For sure we would re-examine the plasma assumptions and simulations up to that time and determine what had turned out to be different in what we measured. We would make corrections in various models to guide us to run the experiment differently and still obtain Q=10. For example, the variance could have been related to plasma-material issues at the divertor plate that injected more impurities into the plasma than previously simulated. Ways to go around this roadblock would be devised to reduce this impurity level, etc.

Another question would be: whether Q=8, with much improved understanding of the burning plasma in tokamak, would fail the mission of ITER, which is to "demonstrate the feasibility of fusion power"? The answer here will depend on the details of the situation.

Now, suppose that Q=2 turned out to be next to impossible to exceed, after extensive experimentation. In this case, would not such new information be of great importance? A rethinking of magnetic confinement fusion would become appropriate. By the way, the National Ignition Facility (NIF) in California recently has had the privilege of rethinking in a fundamental scientific way.

3. What is the biggest shortcoming of ITER from the view of technical issues?

Answer: First, let me clarify that the word "shortcoming" has a subjective designation. That is, a shortcoming depends on the purpose or condition assumed? It is not a shortcoming if all the engineering and technologies designed already and being implemented led to ITER mission success.

We are aware of criticisms of the ITER Project from the view of lower cost, faster schedule, or less technical complexity. Since ITER is a grand project and a grand experiment in scale and mission, it would be programmatically illogical to prejudge the outcome, once decisions have been made to proceed. The outcome of the ITER experiment can be better, worse, or just right relative to the present projections.

The world partners of ITER have committed to completing the ITER Project, and hopefully will continue to carry out the experiments fully. Logic suggests that at present we can not be a 100% sure of the outcome, until the experiments are properly built and completed. To say that the outcome were assured, positively or negatively, is to say that the experiment would not be necessary. By extension, that would be the same as saying that the project would not be necessary. I don't think anyone is at present capable to assure the outcome of ITER.

I would therefore suggest that the question be corrected to: **What are the**

biggest opportunities for improving ITER from the view of technical issues, within the framework of its design, cost and schedule? This, however, is also a big topic, to be left to future opportunities to address.

4. **What is the selection criteria for ITER diagnostics?**

   Answer: As promised, here is a big and important reference that addresses this question:

   - AJH Donne et al, *Nucl. Fusion* **47** (2007) S337.

5. **Which is the most important thing we can learn from ITER to design CFETR?**

   Answer: Many lessons can be identified from the ITER experience so far. Let me pick an example that has been largely overlooked.

   From a technical view point, the more complex the design and the cost/risk tradeoff, the more benefit can be derived from early, as detailed as required, design parameter space and design integration analysis and tradeoff calculations. As the project progresses in more detail and complexity, this effort would advance in sophistication to match and support all on-going project decisions and choices. Such decisions and choices are numerous at multiple levels of design hierarchy, which are in the nature of grand projects.

   The ITER Project has not earlier enjoyed the benefit of such a living "systems integration and tradeoff modeling platform". The computer aided design (CAD) and integration systems being implemented now is never too late to support the success of the ITER Project.

6. **What are your opinions about ITER?**

   Answer: I have the opinion that

   - The ITER Project is among the most important and timely grand projects for the world's sustainable energy future.
   - The cost and schedule extensions experienced by the project has its causes more in the earlier events during ITER project formation, than in the present efforts.
   - It is appropriate for such extensions be recognized and managed now than later, to maximize the chance for project success.
   - Commitment to complete the ITER Project may test the character of a partner nation and provide a peaceful opportunity for its beneficial evolution.
   - In time, these seeming problems will pale in significance compared to the benefits the project will accrue for the partners and the world, and for the R&D of fusion energy and other similar endeavors.

7. **What is your research on NSTX?**

   Answer: Since its start of project in 1997 and start of experimental operation in

2001, the National Spherical Torus Experiment (NSTX) become the second largest magnetic fusion experiment in the U.S., D-IIID remaining the largest. The NSTX research team has since carried out a full range of fusion plasma research, and accumulated thousands of referenced publications. This topic will require several lectures to adequately cover at a technically useful level. We will consider this option perhaps for a future lecture series.

8. **What's the most important or difficult (challenging) R&D regarding "refining neutron shield/heat conversion technology"? Is it about something like coupled multi-physics and thermal hydrodynamics?**

Answer: The power conversion, tritium breeding blanket of a fusion reactor is a unique example of coupled multi-physics subject of science and technology. It involves

- Multiple material phases (plasma, gas, liquid, solid, and even the energetic neutrons could be considered a different material phase from the plasma),
- Multiple energy levels (up to 14-MeV neutrons, order keV to order eV particles and ions including triton/tritium and alpha particle/helium, order 10^3 ^oK coolant and material, room temperature components connecting to these, etc.),
- Multiple layers of thermal hydrodynamics, which is a subject being analyzed for various blanket design concepts, including the ITER test blanket module,
- Multiple interaction physics (neutron-induced nuclear transmutation, neutron induced alteration to the atomic structures of solid materials, solid-liquid interface physics including corrosion chemistry, solid-plasma interface including ion and particle sputtering/erosion/redeposition, changing the material surface morphology (e.g., tungsten fuzz), energetic ion and particle induced under-the-surface material changes and damages, physics of tritium and helium permeation through materials in the presence of various material damages, barriers to permeation of tritium, accumulation of material damages and tritium retention in such materials, etc.),
- Multiple time scales (from Pico seconds for neutron-material lattice interactions, all the way to days and months for erosion and dust accumulation), and
- Multiple size scales (from atomic sizes, in angstroms, all the way to meters for a blanket module).

While most processes identified above have substantial information and experience base, simultaneity and colocation of several of these that mutually interact have little to none so far. This is to be expected, since a true fusion-nuclear environment is yet to be created regularly to provide opportunities for the physics of new interactions to manifest.

An exception to this situation would in part be the supercritical water (~300°C) cooled solid breeder blanket design, which enjoys an extensive thermal mechanical and thermal hydrodynamic database from the pressurized water-cooled fission nuclear reactors. Here the helium purged solid breeder channels still awaits tests in a reliable fusion nuclear environment, to collect database for possible use in a future fusion power plant.

It is fair to suggest that we will likely encounter surprises from R&D on this and other blanket concepts, when and if they are tested for the first time in a nuclear fusion environment.

This discussion serves to clarify further the meaning of the CFETR mission. It also points to the great potential for creativity and new discoveries.

9. **Why has the supercritical (300°C) water-cooled solid breeder blanket design been introduced for an ITER Test Blanket Module, in comparison with the helium cooled solid breeder blanket design?**

Answer: This is addressed in part by the answer to the preceding question. Let me provide a reference for further study by the interested.

- D Tsuru et al, *Nucl. Fusion* **49** (2009) 065024.