Questions & discussion during L3-20141206, and my answers

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The question raised by me:

选修的功课 **20141212-1: The world built more than 200 fission R&D facilities during the 1950-60's to establish the technical basis for the first successful fission demonstration power plant. For example, the U.S. Shippingport demonstration power plant started construction in 1967 with an initial goal of delivering ~300MW electricity. In 3 years it delivered 60MW electricity during the first year before shutdown for improvements. In comparison with this fission R&D experience, under what conditions would the ITER and a CFETR successfully establish the technical basis for a first successful fusion demonstration power plant (DEMO) to follow?

Hint: Look up information on "Idaho Reactor Testing Station" and "Shippingport" on the web.

Questions raised by students:

1. **How to rotate the plasma in the chamber in the picture of slide 8?**

   Answer: Since the toroidal plasma is immersed in magnetic field, the plasma would rotate by charging up to also carry a radial electric field ($\boldsymbol{E_r}$). The plasma would locally move according to $\boldsymbol{v} = \boldsymbol{E_r} \times \boldsymbol{B}$, where $\boldsymbol{v}$ is the plasma velocity. Since $\boldsymbol{v}$ is perpendicular to both $\boldsymbol{B}$ and $\boldsymbol{E_r}$, it can only be in the poloidal direction on a magnetic flux surface. That is, it rotates around in the poloidal direction, as shown in the slide. This process is similar in nature to an electric motor, which moves by crossing $\boldsymbol{B}$ with a current-carrying wire.

2. **Could you explain how we charge the plasma? (in slide 8, to make plasma rotation happen)**

   Answer: The plasma would charge up electrically if there is a preferential loss of electrons or ions. This would cause the plasma to contain more ions or electrons, respectively, leading to a non-zero electric potential relative to the surrounding component, such as the vacuum vessel. This is a rather universal phenomenon for plasmas over a wide range of parameters in temperature, density, magnetic field, etc.

   Preferential loss can be caused by several methods. One popular method is to heat he electrons or the ions more in the plasma by means of applying radiofrequency waves that are absorbed more by the electrons or the ions.

3. **If we put coils on the wall to stabilize the plasma, would there be some force on the wall when the coils try to push the kink back? (slide 8)**

   Answer: Yes, there would be the kinetic and the electromagnetic forces. The kinetic force refers to the force applied by the plasma pushing against a conducting wall, which is proportional to the inertia of the plasma. In ITER, the total plasma mass would be of the order of 1 gram, causing only a tiny force.

By far the primary force results from the electromagnetic interaction between the current in the plasma, as it moves against a near-by conducting wall, and the electromagnetically induced eddy current in the wall. If a current loop mounted on the wall is to apply proactively a countering current in assisting the eddy current, this force would be enhanced.

4. **What's the width of the pedestal in the picture of slide 7? Is the width of pedestal constant or it can be changed in different machines?**

Answer: The pedestal width of the START plasma was ~1cm. I personally think the pedestal widths of H-mode tokamak plasmas are not likely to be constant under all plasma conditions in different devices. In addition, the physics processes involved in determining the width and height of pedestals have been proposed and compared with data. A good example of such studies is provided below.

- PB Snyder et al, *Phys. Plasmas* **16** (2009) 056118.

A key conclusion of this work is that the pedestal width, in fractions of normalized plasma poloidal flux, can vary from 0.03 to 0.11 under a range of plasma conditions.

A comment I would offer of this complex topic is that the issue of near sonic poloidal plasma flows, already indicated in some measurements (see in the reference below), is yet to be included in the consideration. Such flows have been known to strongly affect the equilibrium (force balance) and stability of the pedestal plasma. In turn, this would affect the stability properties, which was the basis of the Snyder work, possibly making the different conclusions.

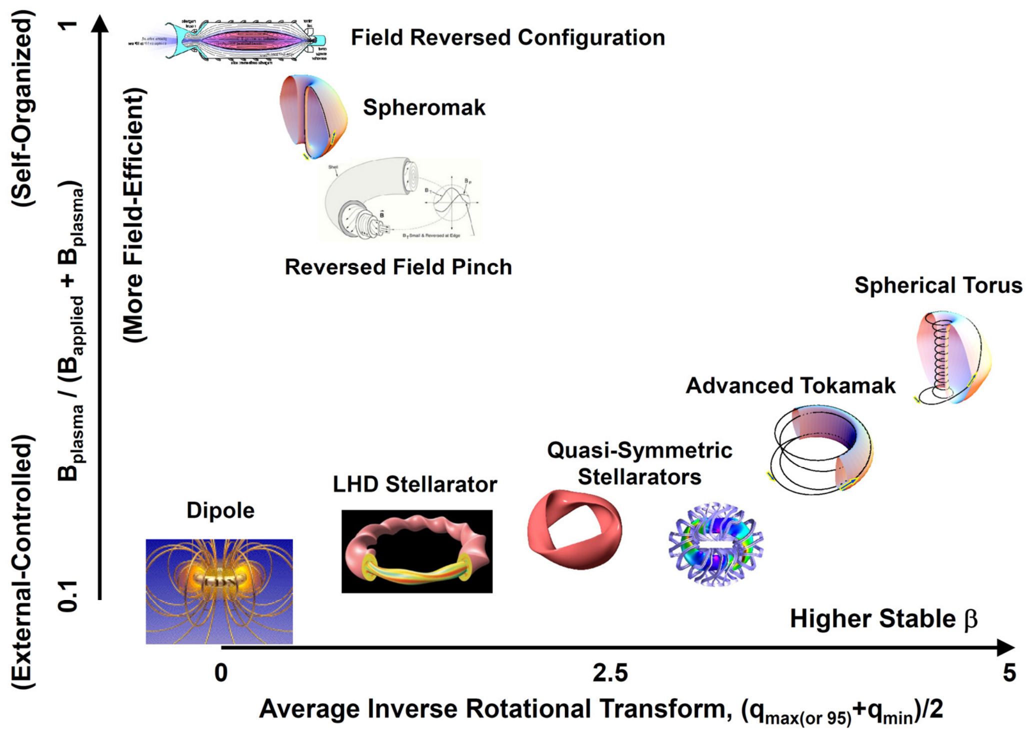
- TE Evans et al, *Nature Phys.* **2** (2006) 419.

5. **What are the advantages and disadvantages of tokamak compared with other kind of fusion facilities, like the stellarator and the inertial confinement fusion facility?**

Answer: This is a complex question with complex answers that may require several lectures to cover the details with balance. Since L3 covers $\beta\tau_E$ and its effects on design, let's look at these two parameters. For the Stellarator,

- The figure below shows several magnetic confinement configurations in the space of plasma self-generated vs. externally applied magnetic field, and the mean safety factor. The vertical axis indicates the efficiency in utilizing the externally applied magnetic field, which exerts control over the plasma shape and position. The horizontal axis is the so-called "safety factor" q, which roughly indicates the plasma stability at high plasma β.
- In a schematic way, the figure shows that the LHD stellarator, compared to the tokamak, has a lower stable β and a lower efficiency in utilizing the externally applied magnetic field. This implies that the stellarator power

plant, with the remaining physics and technology assumptions being the same, would likely require a larger fusion core than a tokamak power plant.



- If the device is large, it is likely that τ_E becomes large, such as the projected τ_E~6s for ITER. Slide 24 of L3 suggests that, to raise the performance of toroidal magnetic fusion devices, β and τ_E should be raised together in a relatively narrow band. So, it may turn out that τ_E would become more than needed in future tokamak or stellarator power plants. However, to limit the power consumption by the magnets in very large devices, superconducting magnets become required.
- Turning to inertial fusion, thanks to 冯竟超 and 徐国梁 for providing the following link, which reports the latest progress in early 2014 by NIF to achieve the condition of Q ~ 1. This is about a factor of 10 increase in Q over the condition obtained during 2012, and a factor of 10 below what is required for ignition.

  http://www.natureasia.com/zh-cn/nature/highlights/52065/.
- Since the confinement, ignition, engineering, technology mechanisms and requirements for inertial fusion are different from those for tokamak fusion, I am not sure how to compare these two approaches of fusion energy. It is nevertheless likely that either approach will require an extensive R&D in power conversion technologies to enable a power plant.

6. What is the meaning of 'IPB(y, 2)' in slide 4? Are the data all from H-mode?

Answer: Yes, the data are all from the H-mode. During the time, from the late 1990's to the late 2000's, the International Tokamak Physics Activities (ITPA) was organized to allow the U.S. researchers to participate in ITER-related discussions and analysis and modeling work. A tokamak physics databases was collected and organized to help refine the plasma physics assumptions needed by the ITER design. One of such a database was for the energy confinement time. The "IPB(y,2)" confinement time scaling relationship was one among many options under discussion in ITPA. After much debate among the participants, this scaling relationship was adopted as an confinement time assumptions to help determine major ITER design parameters.

7. What is the meaning of 'safety factor (95% flux)' in the table of slide 17?

Answer: Here 95%flux refers to the percentage of total poloidal magnetic flux contained within the last closed flux surface (plasma boundary). That is, this moves to the flux surface that is 5% from the plasma boundary. This is a scheme to simplify the calculation of the safety factor of a tokamak plasma that is bounded by a divertor "x-point", which appears at the plasma boundary when you look at the poloidal flux plots of the plasma cross section.