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Fusion for Sustainable World Development

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This document is the transcription for the keynote talk at the 26th IAEA Fusion Energy Conference held at Kyoto (Kyoto International Conference Center) on 17 - 22 October, 2016.

1. Prologue

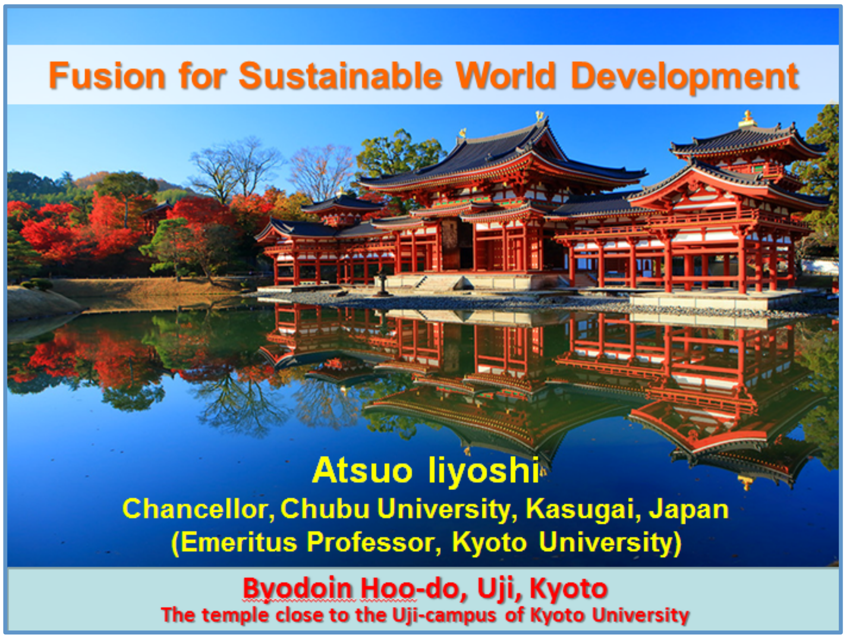

Figure 1 Cover page (Byodoin Hoo-do)

I will give a talk, entitled "Fusion for Sustainable World Development" for the 26th IAEA Fusion Energy Conference.

There is a famous temple, Byodoin temple (Fig. 1), one of the world heritages selected by UNESCO. This temple was built in the 11th century to help people dream of the heaven and is located nearby Kyoto University Uji Campus. By the way, Uji is a city adjacent south to Kyoto. The main hall, Hoo-do, was named after a legendary bird, "Phoenix", two statues of which are sitting at the top of the roof. This bird is believed to get burned to revive, a fortitude spirit, something that I think we need for fusion energy development.

With that, let me go over the outline of my talk.

First, I will talk about the pioneering fusion research at Kyoto University with myself dedicated to it.

The Fusion Energy Conferences have been held in Japan three times before, one in Tokyo in 1974, one in Kyoto in 1986 and another one in Yokohama in 1998. In particular, I will mention the one in Yokohama.

Then, I make some comments on the present status of world fusion research, of course, including ITER. After that, I will mention some of the outstanding technical issues.

In addition, I would like to say a few words about the possible contribution of fusion research to sustainable world development, sharing with you some of the spin-off products out of fusion research.

Finally, I will make a brief summary and mention my perspective of future fusion research.

2. Pioneering fusion research at Kyoto University, leading to Large Helical Device

When I was younger back in around 1965, I participated in the C-Stellarator experiments at Princeton Plasma Physics Laboratory. By the way, as you all know, the stellarator concept was developed by Dr. L. Spitzer. After that, I joined the Heliotron research at Kyoto University. Some photos are shown in Fig. 2. Shown in the photo together with myself are Prof. K. Uo, who invented the Heliotron concept, and also Prof. O. Motojima, who later became the Director General of ITER.

Based on all the knowledge from the Heliotron experiments, the Large Helical Device (LHD) was built and I happened to be in charge of this project as the first Director General of NIFS (National Institute for Fusion Science). What you see in Fig. 2 (bottom right) is actually one of the most memorable photos of mine, taken after the successful first plasma discharge, showing all the staff people together with Prof. O. Motojima and myself.

The machine construction went very well and the first plasma was produced on schedule, owing to the efforts by all the colleagues you can see in this photo. I remember proudly giving a talk about LHD at the IAEA conference in Yokohama.

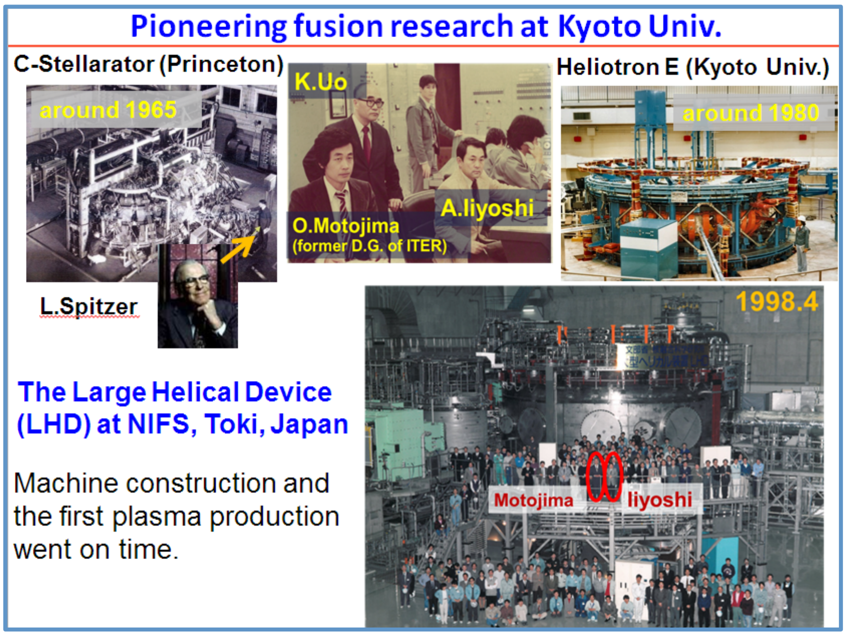

Figure 2 Memorable pictures related to my career as a fusion scientist (above: from left to right, C-Stellarator (Princeton Plasma Physics Laboratory, around 1965) along with a picture of Prof. L. Spitzer), the control room and the machine itself of Heliotron E (Kyoto University, around 1980) and, bottom right, the group photo after the successful first plasma in LHD (April, 1998).

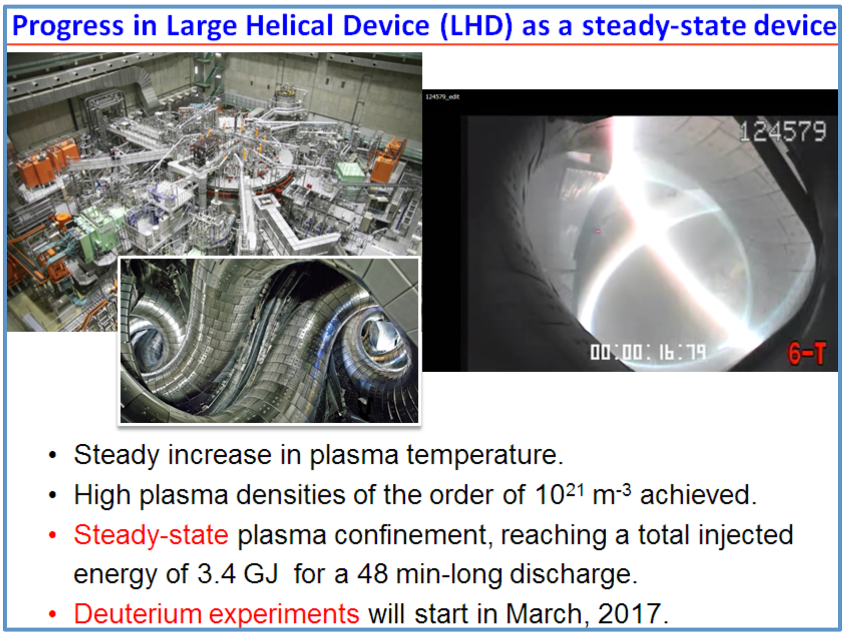

Figure 3 Progress in LHD: machine overview, recent interior view and the snapshot of a discharge.

LHD has made steady progress in plasma temperature, and also has achieved a high density of the order of 10^{21} m^{-3}. In particular, steady-state plasma confinement has been demonstrated, reaching a total injected energy of 3.4 GJ for a long pulse discharge of 48 minutes. LHD will start deuterium experiments in coming March 2017, entering a new phase of research for even more improved plasma confinement.

Last time IAEA Fusion Energy Conference held in Japan was in Yokohama, just after the D-T burning experiments in TFTR and JET. Meanwhile, ITER-EDA was approaching a critical stage, for reducing the cost of the construction. Also, helical systems research entered a new era of large-device experiments, producing the first plasma in LHD.

3. Comments on the world fusion research, including ITER

One of the greatest achievements with large tokamaks is the demonstration of controlled fusion by the D-T reaction. Perhaps, this is the most significant achievement since Bhabha's statement at the Atoms for Peace conference in 1955, predicting "fusion energy will be liberated in a controlled manner within the next two decades". I respect all the efforts made over these 4 decades.

In 1994, TFTR demonstrated the generation of fusion power of more than 10 MW, as shown in Fig. 4 (left), and in 1997 JET recorded 16.1 MW of fusion power, nearly a power breakeven [1]. Meanwhile, JT-60U demonstrated the confinement, equivalent to D-T power breakeven. In JET, another D-T burning campaign is planned for 2018, under the conditions similar to those for ITER, which would hopefully outperform all the earlier D-T experimental data. Shown on the right side of Fig. 4 is the confinement performance progress, based on the fusion triple product database for tokamaks as well as those for helical systems plotted against year, nicely obeying Moore's law but only up to 2000.

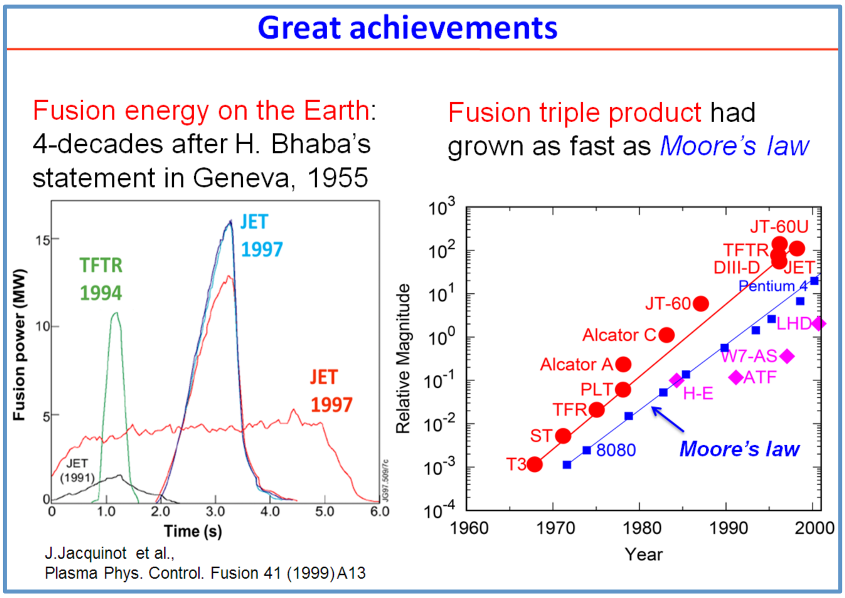

Figure 4 Great achievements in fusion research: (left) demonstration of the generation of fusion power in TFTR and JET [1], and (right) the evolution of fusion triple product in tokamaks and helical systems.

The construction of ITER is in progress as you can see in Fig. 5. The ITER council officially announced that the first plasma production will be in December 2025. This means that D-T burning experiments will be conducted even further in the future.

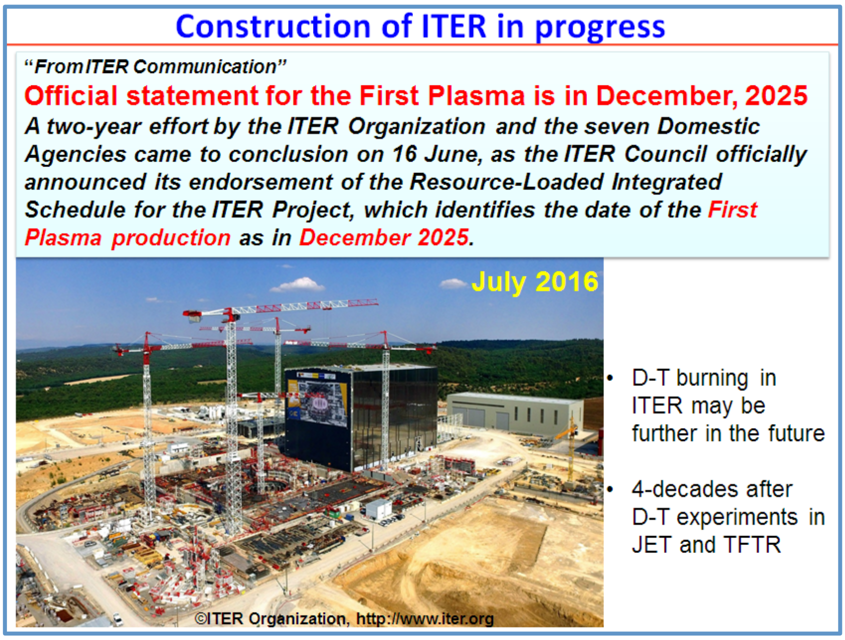

Figure 5 Official statement on the first plasma in ITER (quoted from ITER Communication) and the picture of the construction site as of July 2016.

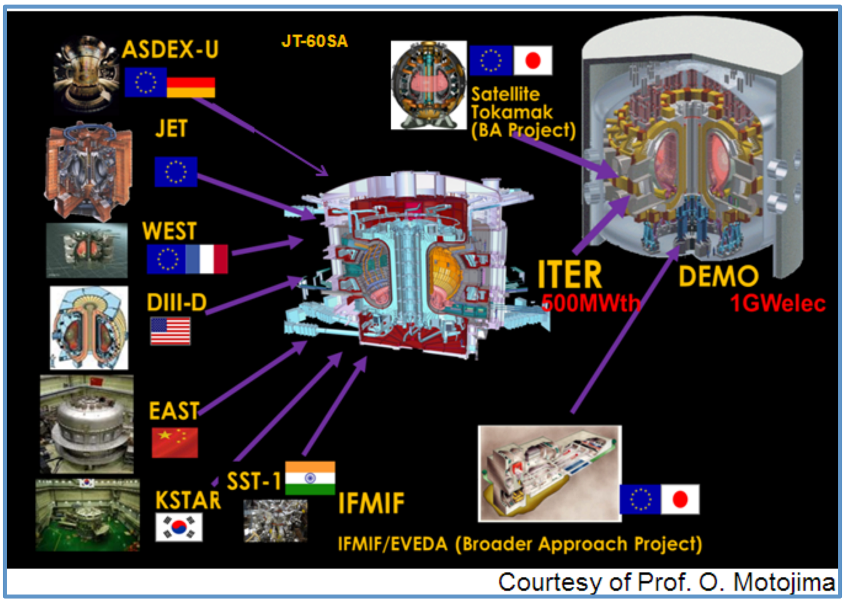

Figure 6 More efforts are necessary to resolve outstanding technical issues, intended to speed up the ITER construction and successful operation. Courtesy of Prof. O. Motojima.

The delay in ITER project schedule and the increase in construction cost needs to be recognized very seriously. So, as shown in Fig. 6, the fusion community needs to make more efforts together to resolve outstanding technical issues, intended to speed up the ITER construction and experiment schedule, obtain a fundamental understanding for the D-T burning experiments in ITER, and appeal to gain more public support for fusion. In return to the large investment, the development of fusion energy needs to be understood by public as one of the few pathways to enable sustainable world development.

Next, I would like to share with you some of the outstanding technical issues. The following is just a list of those issues that come to my mind; disruption, edge localized mode (ELM), confinement physics, divertor, power and particle handling, impurity control, materials development based on IFMIF and fusion neutron test facility, test blanket module design and development, and decommissioning. Needless to say, resolutions of these issues are crucial for the success of ITER.

Of course, a great deal of effort has already been made to resolve some of these outstanding technical issues, more specifically, ELM control by the use of a non-symmetric perturbation magnetic field in DIII-D and many other tokamaks, tungsten wall experiments in JET and ASDEX-U based on the prediction that tungsten will be used as the wall material in ITER and DEMO, WEST and JT-60SA will soon be coming on line, and EAST and KSTAR are taking a leading role in the development of steady state plasma control. Growing activities in Asia have been playing a crucial role in fusion research, and this will be true for the next couple of decades.

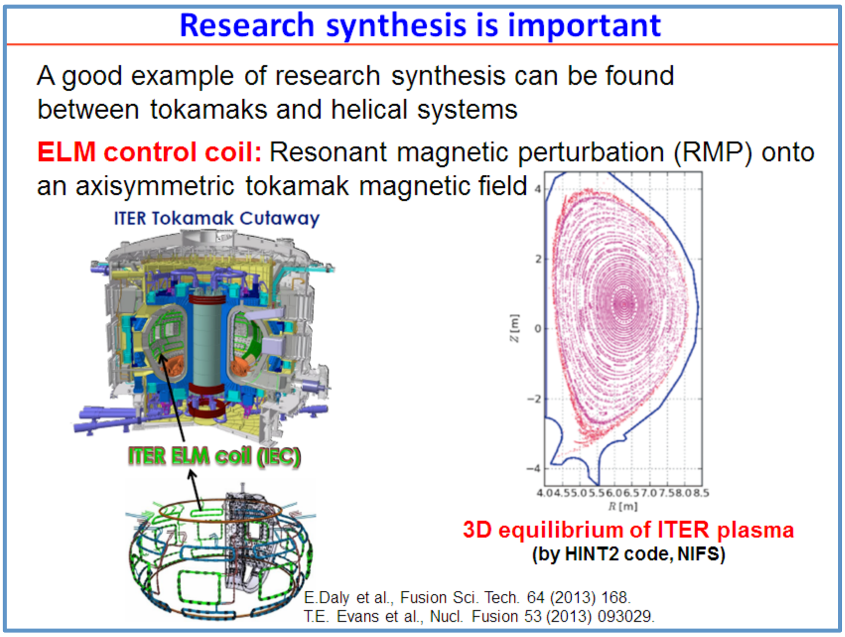

Figure 7 Research synthesis is important to resolve some of outstanding technical issues. A good example, research synthesis between tokamaks and helical systems on RMP for ELM control, is shown.

To change the subject here, I would like to talk about "research synthesis" and its importance. A good example can be found in the approach taken for ELM control, that is, resonant magnetic perturbation (RMP) is applied on the axisymmetric tokamak magnetic field [2,3], as shown in Fig. 7. This may be something one would call research synthesis between the tokamak and helical systems. The 3D equilibrium code, developed for helical systems, has been applied to investigate the effect of an RMP field for stochastization of peripheral region of ITER magnetic field [4], to mitigate heat and particle fluxes to the wall and divertor.

JT-60SA is expected to resolve outstanding technical issues for ITER. JT-60SA is coming up for the first plasma production in 2019 as described in Fig. 8, in order to support and compliment ITER and also to train young generation scientists.

Now, let me share with you some of the recent highlight events in fusion research. One of them is the first plasma production in Wendelstein 7-X, a stellerator in Germany just as large as LHD. A successful helium plasma production on December 10 in 2015 was great news not only to the Heliotron-Stellarator community but also for the entire magnetic fusion community. And, on February 3, 2016, the German Chancellor Angela Merkel pushed the button to switch on the first hydrogen plasma in W7-X as shown in Fig. 9. Nested magnetic surfaces were confirmed, and high electron temperature plasmas were successfully produced in its first campaign. I would like to congratulate the entire W7-X group on their success.

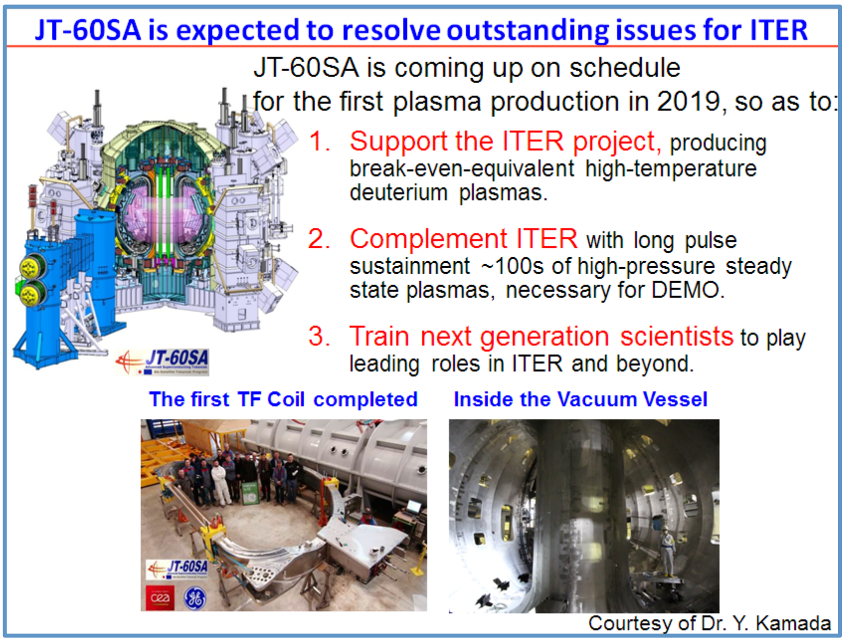

Figure 8 JT-60SA is coming up for the first plasma production in 2019. Photos are those provided in June 2016. Courtesy of Dr. Y. Kamada.

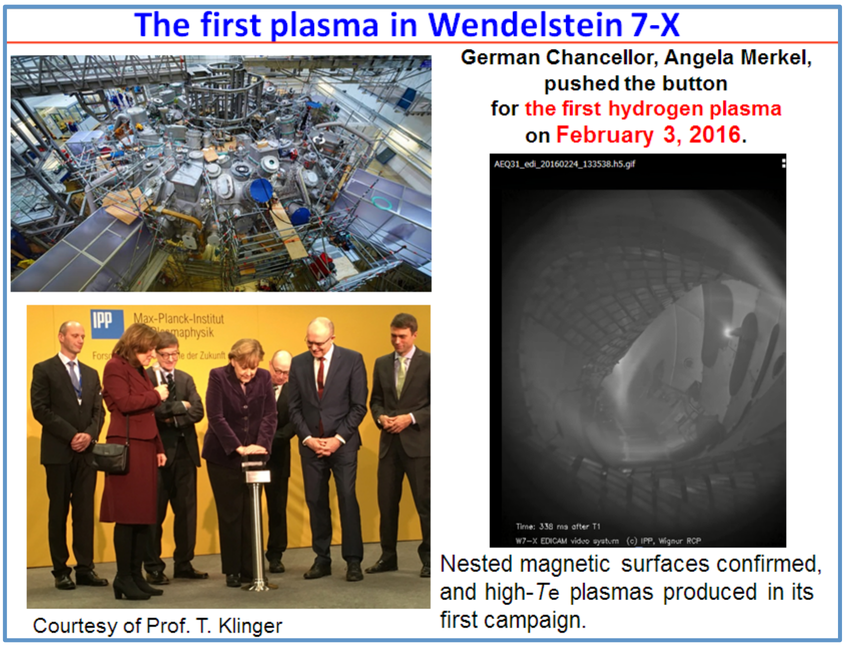

Figure 9 Plasma operations in Wendelstein 7-X has started (machine overview just before the completion of construction, the ceremony of the first hydrogen plasma production and the snapshot of a discharge). Courtesy of Prof. T. Klinger.

Turning to the subjects related to inertial fusion, we should never forget the other side of world fusion research conducted by the institutions shown in Fig. 10. With the operation of NIF at Livermore, a large amount of laser energy input for pellet implosions has been achieved towards D-T ignition. A great deal of progress on the understanding of implosion physics has also been obtained, demonstrating improved implosion efficiencies for D-T burning.

Figure 10　World centers for high power laser research, leading the inertial fusion research. Courtesy of Prof. H. Azechi.

4. Contribution by fusion research to sustainable world development

Now, I would like to change the gear to start talking about spin-off technologies from fusion research, which I hope would be regarded as a contribution to sustainable world development, in return to the large investment to the fusion research. More specifically, let me talk about the application of fusion neutrons and superconducting magnet technologies as remarkable innovations.

As opposed to the way that fusion neutrons are utilized by IFMIF and fusion neutron test facility, the application of fusion neutrons to the transmutation of long-lived fission products (LLFP) is a spin-off idea that should be tried out, perhaps to help clean up LLFPs. Nuclear radiation hazard has been pointed out as a critical issue, particularly since Fukushima Accident. To resolve this socio-technical issue, we have proposed that a D-T fusion reactor be used as a neutron source for that purpose.

One good innovative example is shown in Fig. 11: an LLFP element ^{107}Pd, which is a beta emitter, can be transmuted into stable element of ^{106}Pd by a (n, 2n) reaction. Importantly, the cross section for this reaction is known to maximize at energies around 14 MeV. This is why D-T fusion neutrons can best be applied. Interestingly, ^{107}Pd can also be transmuted into stable ^{108}Pd by a neutron capture reaction with 2.45 MeV D-D neutrons. A similar trend has been found for other LLFP elements including Cs, Se, and Zr.

The estimated effective half-life time in years of LLFP, taking ^{107}Pd as an example, is examined. We find that for a neutron flux of 10^{19} neutrons/(m^2s), the effective life time would be of the order of 10 years, as opposed to 6.5 million years for the beta-decay reaction. This analysis has been done using PHITS code for a shell geometry containing a point neutron source. We are also planning to conduct feasibility-check experiments to generate hot ions in the perpendicular direction in a magnetic mirror configuration with RF heating, and also the concept of muon-catalyzed fusion will be implemented.

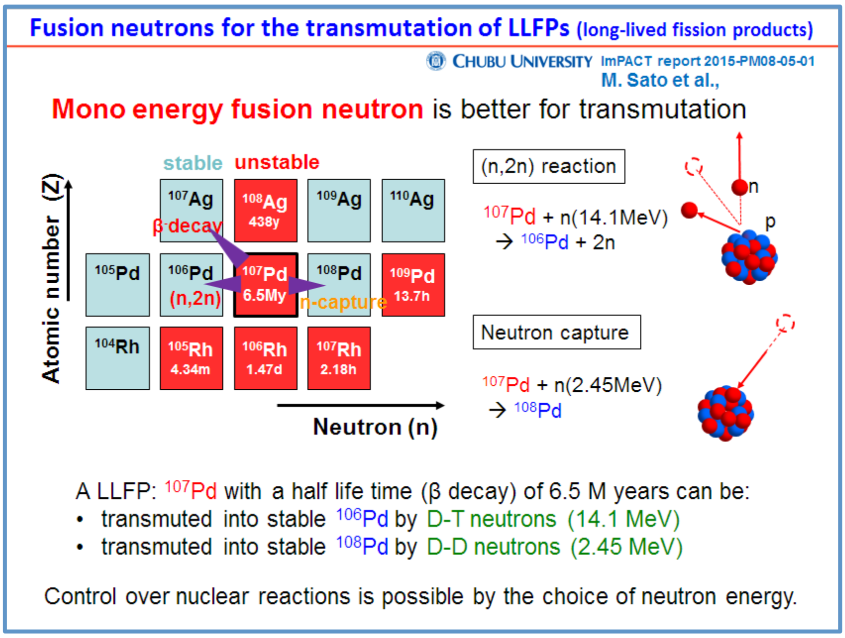

Figure 11 Innovative application of fusion neutrons for the transmutation of long-lived fission products (LLFPs), proposed in Ref. [5]. Courtesy of Prof. M. Sato.

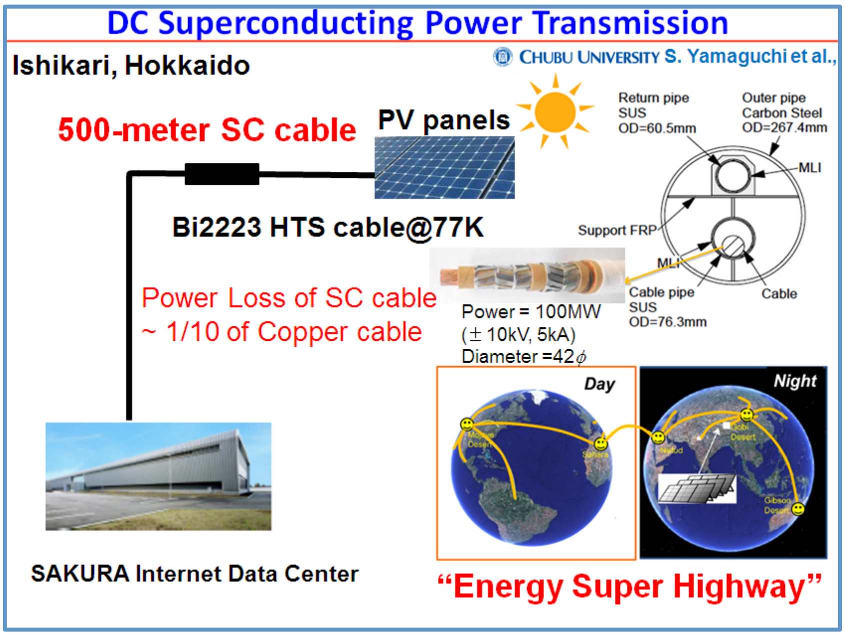

Figure 12 DC superconducting power transmission system has been setup and tested in Ishikari, Hokkaido. Its extension would be global "energy super highway". Courtesy of Prof. S. Yamaguchi.

The second result of spin-off technologies is the application of superconductors for long-distance power transmission. We have proposed a concept of DC power transmission, employing high-temperature superconducting cables made by Bi2223, cooled by liquid nitrogen. The advantages are: minimal loss of energy, environment-friendly, cost-effective, long-distance transmission, and high security.

Based on the experimental data taken so far, a 500-meter superconducting cable setup was built in 2015 in Ishikari, Hokkaido, connecting the internet data center and the Photo Voltaic panel system with a power output of 300 kW, as schematically shown in Fig. 12. The measured power loss has been found to be 10 % of normal copper conductor.

Extending this superconductor application, we hope to bring about "energy super highway", connecting point-to-point worldwide, something one might compare to the internet often referred to as "information super highway".

5. Conclusions

Now, let me conclude my talk. I am quite happy to find that fusion research has reached a level of technical maturity to build ITER for long-pulse D-T burning experiments, which, however, doesn't mean everything is understood for the development of fusion energy. Worldwide competitive and collaborative network research is becoming more and more important for the success of fusion research. Looking to the fusion triple products anticipated by the LHD deuterium experiment, and those by ITER, regardless of the confinement scheme, one finds that research synthesis may be an important process to come up with new ideas to resolve outstanding technical issues.

I would like to encourage next-generation researchers to challenge all the existing technical difficulties for fusion energy. In return to the large investment, the contribution to sustainable world development by fusion research is extremely important in gaining the public support. I sincerely hope that this IAEA Fusion Energy Conference will provide us with an opportunity to bring about new ideas for revitalizing fusion research.
I wish each and every one of you here and in the world a great success in the future.

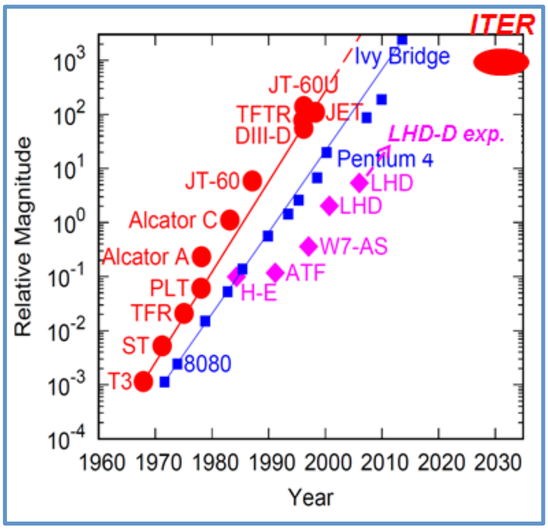

Figure 13 Expected evolution of fusion triple product (the trend in the LHD deuterium experiment is shown by an arrow, and the expectation for D-T operation in ITER are added on the previous evolution shown in Fig. 4 (right)).

Acknowledgements

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