Fusion research programme in India

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Abstract. The fusion energy research program of India is summarized in the context of energy needs and scenario of tokamak advancements on domestic and international fronts. In particular, the various technologies that will lead us to ultimately build a fusion power reactor are identified along with the steps being taken for their indigenous development.

Keywords. Fusion; plasma physics; tokamak; ITER.

1. Introduction

India is a rapidly growing economy and a fast growth is expected in the industrial and transportation infrastructure. Naturally, the energy requirements are set to ramp up at high values and the question of supply becomes a very important one. India needs to increase its current power production of 207 GW (Ministry of Power 2012) by almost a factor of 5–6 to reach the world average. Given that the major share of our production comes from thermal (65%, dominated by coal), about 20% from hydro and about 10% from renewables, the immediate ‘gap-filling’ measures are likely to further the exploitation of the above sources.

Exactly 20 years ago (30 Sept. 1992) a case for fusion power need for the developing world was made (Kaw 1992). India’s per capita electricity consumption then was 250 kWh (16.7%) in comparison to the World which was 1500 kWh. In 2008, these figures were 432 kWh (17.8%) of the world average, 2429 kWh (Grover 2008), a shade better than its 18 year older value. In comparison, the per capita consumption in China has made spectacular rise and almost equals world average today.

We have been growing painfully slowly. In the 11th plan, our capacity-addition was less than (50 GW) compared to targeted 78 GW (Planning Commission 2012). Although India ranks among the leading consumers (viz. USA, China, Russia and Japan) in terms of total figures, the fact that distinguishes us from the rest is the extraordinary gap between our needs and supply and the fact that we have growing dependence on imports. Energy drives everything, economy, social well-being, health and in essence, quality of everything. We have little option but to use every possible resource to increase the power generation immediately. However, there is also an urgent need to think about developing those technologies which will enable us to utilize the vast

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resources that are available in the country. This is because it is clear that conventional resources cannot fulfill our long-term needs, even when they are stretched to their maximum practicable limits. Currently fission reactors contribute about 4% of our present capacity, but they are expected to play an important role in the coming decades by increasing their share.

Our strength and independence lies in our own resources. Utilizing the thorium resources in the long run is a part of DAE's vision. Nuclear fusion now enjoys an important place in this vision. Apart from fusion-power, there are important applications of energetic neutrons from fusion reaction in the interim period. We must therefore develop this technology for our own energy security and multifarious applications.

1.1 Nuclear fusion

It is the process, which has kept the sun and other stars burning brilliantly for billions of years. In the quest for star-fire in the laboratory, one tries to duplicate in the laboratory, the same nuclear fusion reaction albeit with different reactants: that is between the two nuclei of hydrogen isotopes (deuterium and tritium).

Thermonuclear fusion occurs when the D and T ions in hot and dense plasma undergo a chance collision in which the nuclei come so close together that the fusion reaction takes place. This can happen only at high enough energies so that the matter is in plasma state. In a reactor, neutrons come out as fast projectiles but can be trapped in a blanket surrounding the reactor core, producing heat, which can be used to generate steam and produce electricity using conventional turbines.

1.2 Fusion as a future energy source

The motivation for developing fusion as an energy source lies in its possible large scale contribution in the second-half of this century, with a virtually inexhaustible fuel supply, attractive safety characteristics and an acceptable environmental impact.

The excellent energy multiplication factor (~ 500 , per reaction) allows one to have a net gain in power, in spite of the fact that only about 0.1 % of the fuel in the reactor actually gets consumed. The neutron can be trapped by a 'blanket' surrounding the plasma core and made to react with a lithium containing material in order to re-generate the 'lost' triton. With the D available from the ample sea-water and T-generated within the reactor-blanket, an interesting fuel-economics results, especially when one notes that barely a gram of gaseous fuel is within the reactor at any given time (e.g., the input and exhaust approximately same at 30 milligrams/sec of D or T for a 1000 m^3 volume). For a full-power-year burn, one needs about 30 kg of tritium for consumption, but when the complete fuel-cycle is considered the required inventory on-site is much reduced as fuel extraction and re-injection time is of the order of days. The key features of the fusion power are: wide availability (including lithium ores, in fact a very interesting geological distribution when compared to oil (Clarke & Harben 2009; Camille *et al* 2012), less volume of fuel to handle, less complexity, significantly low radioactive waste, passive safety (the reaction stops automatically when the temperature is lowered) and practically inexhaustible fuel supply. These features are so tremendously attractive that they remain a strong driver for exploring fusion energy source in spite of its well-known criticism over expected delay in realization.

There were many different configuration proposed to confine the plasma effectively and tried world-wide. The most successful amongst them is the so called 'tokamak' (a magnetic bottle to

Figure 1. Growth of fusion triple product.

hold the hot and dense plasma). It is a torus shaped vessel in which the toroidal magnetic field (B_T) is produced by the toroidal-field coils and a poloidal magnetic field (B_θ) by a superposition of poloidal-field coils as well as a current (I_p) flowing within the plasma itself.

Simply stated, for achieving economical fusion power we must confine hot and dense plasma for a long enough time. The tokamaks have registered a faster progress in the ‘fusion-triple-product’ $nT\tau$ (the product of density, temperature and energy confinement time) when compared to Moore’s law! See figure 1 (also shown in figure 1 on the same scale are factors in growth of speed of computers and energies of accelerators). The output fusion power (P_f) must at least equal the losses if we are to achieve the break even. Scientists have studied the problem of confinement, transport and turbulence for many years now and have come up with solutions to be implemented in the next step devices like ITER (International Tokamak Experimental Reactor) so that fusion can be achieved on a desired scale.

At present, only two devices (which were planned for carrying out D-T fusion) have produced fusion power. The first one, TFTR, was in 1994 at Princeton Plasma Physics Lab, USA, which generated 10.7 MW and the second was in 1997 when JET, in UK generated 16 MW. But that was the last big device built around late 80s and opportunities to take the next step were continuously missed.

A good part of the delay in realizing fusion power needs to be linked to this spectacular ‘dithering’ of 30 years (ITER started construction only 2010). The sharp reminder (Kaw 1992) about 20 years ago notwithstanding.

Exhaustive overview of need and role of fusion energy in the context of global energy scenario was given by Chen (2010).

1.3 Other uses of fusion and plasma

Like any other science/technology, plasma science/fusion technology is not without its spin-off benefits. A very large number of people around the world have been working on plasma and its applications for almost 40 years. In terms of returns to society, the vital role of plasma-based technologies in etching processes and revolutionizing the field of electronic circuit miniaturization and enabling compact high-speed computing is well-known. It is already a multi-billion dollar industry. A great many of plasma applications flow from the fact that it is a very

reactive medium, due to high particle energies and sensitive to electromagnetic fields. Processing of mineral ores, improving hardness of surfaces for improved wear-and-tear and bio-medical waste incineration are some of the fast growing industries.

There are three important applications of fusion in the fission area. First, some of the long-lived nuclear waste from fission reactors can be treated with an intense neutron source to improve its management by transmuting it to short-lived waste. Second, it will be possible to convert fertile material like thorium to uranium (U^{233}) and third, it is possible to conceive a sub-critical fission reactor (thorium) which uses fusion neutrons as a driver. These potential applications in the interim period can justify investment in fusion technology development. As an example, a study at MIT (Freidberg & Kadak 2009) suggests that a 500 MW-thermal fusion reactor can be used to produce 5500 kg of U^{233} and 20 kg of T per year from a thorium–lithium blanket, which in turn, can support two 800 MWe LWRs. There are many studies like this, considering various scenarios of a combination of fusion and fission reactors.

To make a self-contained, high-power fusion reactor successful it is necessary to find solutions for handling high heat-flux and develop materials which can withstand the neutron-induced radiation damage (measured in ‘dpa’, i.e., displacements per atom). The developments in these areas and also in very large sized magnets and associated cryogenics could very well impact other fields of our life like space research, mass transportation, medical research and a number of others.

2. Fusion research

2.1 Overview of worldwide activities

World has witnessed a large effort in plasma and fusion research in pursuit of the dream of making fusion-power a reality. Initially, there were a number of options that were being explored to confine the plasma and also to heat it to high temperatures. One of them is the magnetic confinement scheme in which plasma is confined by magnetic forces. In this scheme, there are two leading devices, one which has the confining field produced entirely by external coils and the other (tokamak) in which there is a contribution from both, internal as well as external currents. Tokamak, the most successful fusion device, was invented in the late 50s in Russia, but started making spectacular experimental progress only in the 70s. During the 80s, some of the most important developments were made in understanding the nature of transport, improving impurity control and starting new larger-scale tokamaks. The next decade saw the improvement in confinement time and introduction of superconducting magnets to support long-pulse operation. Key developments in heating, exhaust and current drive took place. In 2-Nov-1994, the TFTR (Tokamak Fusion Test Reactor) tokamak at Princeton NJ, USA established a record by producing about 10 MW of fusion power. It had accomplished its mission and was shutdown subsequently. Later in 1997, the D-shaped plasma in the Joint European Torus (JET) in UK produced a fusion power of about 17 MW. It was designed to reach high temperatures (45 keV or about half a billion degree) and demonstrate good power exhaust efficiency. This was achieved by using a magnetic divertor to redirect the plasma-flame towards specially designed target plates, away from the reactor-core. At present, it is contributing to the novel database on tungsten-based materials for handling extreme heat flux. A number of other tokamaks also contributed to an in-depth understanding of turbulence (ADITYA, India; Alcator C-MOD, TEXT, USA; COMPASS-D, UK) and to novel methods of controlling the edge-plasma region (TEXTOR, Germany). Some tokamaks (e.g., ASDEX in Germany, JT-60 in Japan, DIII-D and C-MOD in the US, HT-7 in China) have

done various experiments to push boundaries of performance for a few parameters in isolation. These have demonstrated that, with optimized profiles improved performance is possible for (a) higher fusion gain, (b) controlled plasma-wall interactions and (c) stable long-pulse operation (up to a minute). All these devices have a limitation of being ‘pulsed’ in nature due to current being driven by transformer action. It was already foreseen that RF waves can impart their energy to the electrons under certain conditions for driving current.

To overcome this limitation, there was a need to demonstrate steady-state current drive (by launching EM waves of about a few GHz in the plasma), steady-state heat removal and usage of superconducting instead of copper magnets. TORE SUPRA, the French tokamak and TRIAM-1M, the Japanese tokamak have taken the pulse length from a few minutes to a few hours and have brought out the truly long-term thermal behaviour of the integrated tokamak and auxiliary systems.

The EAST tokamak in China and KSTAR tokamak in S. Korea have produced results of current interest. Like the Indian Steady State Superconducting Tokamak (SST-1), the above devices have key features of future reactor in that all three have *all* magnets as superconducting, have a steady-state current drive and heat and particle exhaust which will allow a long pulse operation.

Computer simulations and modelling of fusion plasmas have made enormous progress in the past decade and have added to our understanding of complex physical phenomena such as turbulence driven transport and have also enabled us to make quantitative predictions for many of the experimental situations. It has added confidence to the design of new devices.

2.2 Fusion research in India

During early 1970s theoretical and experimental studies in plasma physics to understand space plasma phenomena was initiated in the Physical Research Laboratory (PRL), Ahmedabad. In the early days the experiments were conducted for understanding a variety of nonlinear plasma phenomena with linear and toroidal devices. The theory activities spanned fields like turbulence, transport, basic plasma physics, nonlinear dynamics, astrophysical plasmas, quark-gluon plasma, etc. In 1982, the Department of Science and Technology identified the magnetic confinement fusion research as a high priority thrust area and initiated ‘Plasma Physics Program’ (PPP) in PRL. In PPP, emphasis grew on study of phenomena in toroidal devices and developing insights into the confinement and transport phenomena. The BETA device (Basic Experiments on Toroidal Assembly) was designed and built.

In 1986, PPP transformed into a major program, when it separated as the DST-funded Institute for Plasma Research (IPR) at Gandhinagar. A major achievement of IPR has been the indigenous design, fabrication and erection of the tokamak ADITYA (see figure 2) (major radius 0.75 m, minor radius 0.25 m). ADITYA was commissioned in September 1989 and has already generated scientific results on turbulent processes in tokamaks, which are of considerable interest to the international community. It earned a name for itself in discovering ‘intermittency’ or ‘blobby’ nature of complex transport mechanism and underpinning short-term coherent structure formation in otherwise turbulent plasma. In addition, a number of fusion technologies such as large volume UHV (ultra-high vacuum) systems, large pulsed electromagnets, pulsed power systems, sophisticated plasma diagnostics, plasma surface-cleaning methods, RF (radio-frequency) heating systems in the MHz range have been indigenously developed. Apart from ADITYA, India also has a smaller tokamak, purchased as a complete system from TOSHIBA Ltd. of Japan which has been set-up at the Saha Institute of Nuclear Physics, Kolkata (SINP). It has produced very interesting results of interest to turbulence and dynamo mechanism.

Figure 2. ADITYA Tokamak.

Next major program at the Institute for Plasma Research has been to construct a Steady State Superconducting Tokamak (SST-1) by mix of import and indigenous development (see figure 3). The aim of this experiment is to (i) generate the essential database particularly for understanding the interaction between the plasma and the wall of tokamak in long pulse steady-state discharges and (ii) develop various fusion relevant technologies. SST-1 has a major radius of 1.1 m and a minor radius of 0.2 m, elongation of 1.7 and triangularity of 0.4–0.7, toroidal field of 3 T and a plasma current of 220 kA. In this machine, a typical plasma discharge will be of 1000 s. Auxiliary heating and current drive will be carried out using Lower Hybrid Current Drive mechanism (GHz waves) and heating by Ion Cyclotron Resonance Heating (ICRH) and Neutral Beam Injection (NBI). The auxiliary heating systems are necessary as the conventional ohmic heating is not efficient at high temperatures. Most of the subsystems of SST-1 have been fabricated,

Figure 3. SST-1 Tokamak.

assembled and individually tested before final assembly. The basic machine itself has now been re-assembled after a setback on the magnet systems during its first commissioning. Cool-down trials of the toroidal field magnets have been successful and integrated tests of all systems are now planned in 2012.

It is worth noting that the above programs have led to a significant knowledge and capability addition to various Indian industries.

2.3 Technology development projects

India joined the ITER consortium on 5-Dec-2005 with an aim to accelerate the gap-closure between indigenous technology and that which is required to build a DEMO reactor.

Indigenous development of fusion technologies was started in XI Plan for magnet, divertor and cryopumping areas. In collaboration with Atomic Fuels Division, IPR has achieved the milestone of making the superconducting strands, making a cable-in-conduit conductor and making a magnet from the same. The point to note is that during the SST-1 tokamak (1997–98) we had bought the conductor from Hitachi. Now it is possible to make it ourselves. In the area of divertor, we have been able to make small scale samples of tungsten-mounted on copper blocks (collaboration with NFTDC Hyderabad) and subject them to extreme heat fluxes (5 MW/m^2). Here, we will be able to break free from the limitation of 0.5 MW/m^2 as is present in SST-1. In the area of cryopumping, we have been able to complete the design and R&D on materials and start making of prototype cryopumps. Notable developments have been made on heating and current-drive technologies in terms of increasing their performance parameters. Collaborative development of new systems like ion-source for negative neutral beam using cesium has also been started.

2.4 About ITER

ITER (see figure 4) is the world's first fusion reactor experiment which will lead to a first ever exploration of physics of burning plasmas, charting a new territory in the science and technology of fusion. It will usher a strong development of enabling technologies for ensuring success of future fusion-power reactors. The seven Parties which are contributing to ITER are China, EU,

Figure 4. ITER Tokamak.

India, Japan, Korea, Russia and the US. ITER-India is the domestic agency for executing India's share of in-kind procurements for the ITER Project, being hosted by EU (5/11th share of construction). India's share is 1/11th (like other five partners). The knowledge generated from the experiments will be shared equally by all the ITER-members.

By the time site (Cadarache, France) was finalized (after negotiations between EU and Japan) on 28-Jun-2005, US, China and South Korea had already joined as full partners. India joined in December 2005 and the Joint ITER Agreement (JIA) was signed soon after, between the seven partners. An International Organization (IO) was created to take the formal 'ownership' of the nuclear facility with its own Governing Council to manage the project at site and begin construction. Staff at IO is contributed according to the share of construction by the seven Parties. All seven Domestic Agencies (DA) have now been created (by the respective Parties) to manage their own in-kind supply. The previous baseline for ITER was defined in 2001; it was redefined in 2010 after extensive design reviews, latest results from tokamak research and incorporating site-specific safety/regulatory requirements.

Currently, ITER is under construction. The tokamak complex has started the civil works. The whole structure is on anti-seismic bearing (ASB) pads to reduce the accelerations due to an earthquake if it occurs. The last of the 493 ASBs was installed recently and construction of this and other building will begin soon. Several contracts for ITER procurements are getting signed by respective Domestic Agencies and this pace will continue for a few years. Actual activities for assembly are likely to begin in 2019 as components arrive on site.

3. Future plan

3.1 Aiming for DEMO

The construction and operation of the SST-1 machine will give enough insight into plasma wall interactions under long pulse conditions. Many key technology areas such as superconducting magnets, control systems, heating and current drive systems, and cryogenics will also be tested in the process. However, there will still be considerable knowledge and technological gap to be covered before electricity producing fusion reactor can be built. IPR's vision is to build a demonstration fusion power reactor (DEMO) which produces electricity. Considering the estimated efficiency of power conversion from fusion to thermal (0.5) and from thermal to electrical (0.4), a fusion reactor of 1 GWf needs to be targeted initially so that a net electrical output of about 200 MWe. Improvements are very likely in the meanwhile in conversion efficiency.

3.2 R&D plans for technology gaps

After the operation and experimentation on SST-1 machine, and contribution to the construction of ITER, focus will be on the following:

- (i) Continue to participate in ITER into the operation phase and contribute to achieve energy yield factor of 10. The scientific outcome will be included in the design of the next reactor, which will produce continuous fusion power.
- (ii) Continue research on SST-1 on finer aspects of control and physics issues.
- (iii) Development of technologies:
 - Large superconducting magnets (GJ class), Cryogenics (plants of tens of kW capacity at LHe temperature).

- Non-inductive Current Drive (5 GHz) and Heating systems (tens of MW), Neutral Beam Heating system (beams of order MV).
- Large vacuum components, Fusion Fuel Cycle and Tritium systems.
- Materials and technologies for blanket and divertor, irradiation and other test facility development.
- Diagnostics and reactor control systems.
- Safety systems, remote handling and hot cell.

3.3 HR and R&D infrastructure development

IPR has also launched the technology-seeding program for creating centers of excellence in the Indian Universities. It is managed by the Board of Research for Fusion Science and Technology (BFRST). This program has received an overwhelming response and is the key to develop various centers of excellence in the long run with an eye on human resource development.

IPR has currently about 500 employees, from about 50 in 1985. In addition, there is a dedicated ITER-India group (about 100 scientists/engineers) which is working exclusively for 'in-kind' deliveries to ITER. There are new facilities being built in IPR for RF and beam technologies, labs for magnets, divertor and blanket research and development. Test facilities for high heat flux, liquid metal loops and high pressure helium loop are being created. In the 12th plan, a number of new technology projects are being launched which will further these developments and start new projects on fusion reactor design, fusion materials, remote handling, etc. These activities will continue to 13th and 14th plan so that we carry out extensive testing and

Figure 5. From ADITYA to DEMO.

validation of the indigenously developed systems. IPR is looking forward to a combination of these unique facilities and basic sciences to grant researchers a cutting-edge set of tools to attack important problems.

4. Conclusion

In conclusion, an overview of India's program for fusion research has been presented in the context of energy scenario, latest developments in the world and our own analysis of knowledge gaps. The pictorial summary of how our projects will lead us to the goal is shown in figure 5.

Acknowledgements

The authors thank various project managers and division heads for road-mapping discussions.

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