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Conceptual study of Indian Fusion Power Plant

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Abstract

The baseline conceptual study of Indian Fusion Power Plant (IFPP) is being focused on to achieve the electric power without any aggressive physics and engineering assumptions. As the research and development progresses, it will be possible to improve the baseline design for achieving power plant with greater efficiency. A system design code with considerations from engineering and physics issues has been developed and used to design the IFPP with normal/advanced tokamak configurations. Equilibrium and stability of these configurations has been analyzed. The requirement of heating and current drive systems to provide steady state operation has been computed. The requirement in fusion technology development for making the design economically more attractive has been identified.

1. Introduction

The energy requirement in India is expected to grow by almost 10 to 13 times of present requirement in next 100 years. The most of this energy has to be produced with Coal and Gas. This can lead to enhancement of carbon emission by almost five times [1]. It is essential to have an alternative energy source which is safe and free from pollution. The electricity production through fusion reactor is the promising source which makes the environment safe and free from pollution.

The study [1] has also revealed that the fusion power plant has to be realized by 2050 so that it can reduce the carbon emission considerably and also makes an impact on the long-term Indian energy scenario. It is calculated that the power generated through fusion will be about 70 GWe by 2100. Hence, it is essential to achieve a fusion power plant by 2050 and the cost of electricity should be comparable with other sources.

A system code with physics and engineering constraints has been developed and validated by applying it to existing tokamak devices. The base line design of Indian Fusion Power Plant (IFPP) has been constructed. The requirements from various sub-systems for this base line design have been identified.

Section 2 describes the design objectives and the physics and engineering constraints needed to describe the reactor. The physics model and its validity has been described in Section 3. Section 4 discuses the base line design of IFPP. The fusion technology requirement for this design and the R&D for improving this design have been discussed in Section 5.

2. Design objectives

The fusion power plant should produce 1 GWe net electric power. The life time of the power plant should be 40 years so that even if the machine availability is just 60 %, it can be operated for 25 Full Power Years (FPY). The materials to be used in the fusion rector should have low activation and hence environment safety can be maintained. The base line configuration of IFPP should be conservative and any incremental improvement in design will enhance the performance. The existing and well proven technologies should be considered. The available materials should be considered for making reactor components and the development of new materials will improve the design further.

The fusion gain (Q) depends directly on energy confinement time, operational plasma density (n), normalized plasma pressure, and the conducted power through separatrix. The geometrical dependence comes through the constraints like allowable maximum magnetic field at the Toroidal Field (TF) conductor, maximum heat load on the divertor plate, and the neutron load on the First Wall (FW) and blanket so that damage is minimum but breeding is maximum.

3. System model

The ignition condition along with energy confinement scaling lead to an expression [2] which depends on plasma current, plasma density, aspect ratio, confinement enhancement factor H_H and the fusion gain Q. The required fusion power along with Q gives the external input power. From the ignition condition, one can obtain all the geometrical factors of reactor as well as various plasma parameters like plasma current, density, etc. With these parameters, using power balance one can self-consistently find the plasma temperature. The calculated fusion power at this temperature should be compared with the required fusion power, and is iterated till it matches the required fusion power output. Fig. 1 shows the flow chart of this model.

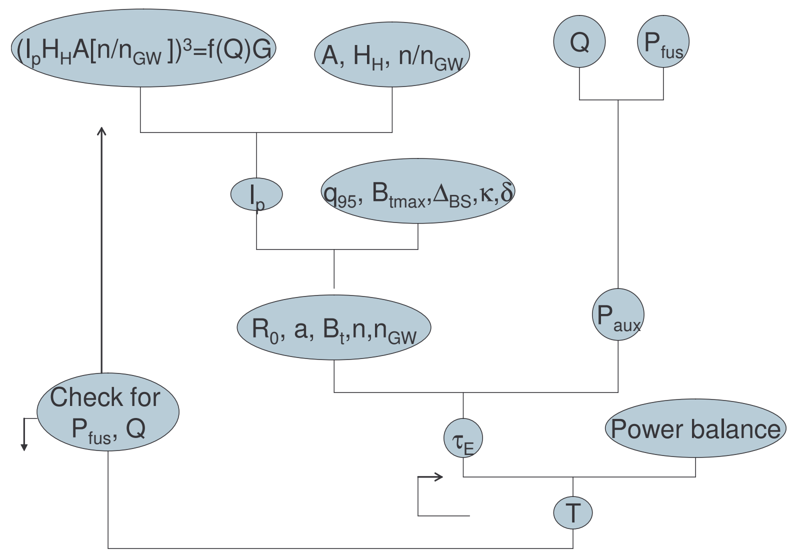

Fig. 1 shows the flow chart of physics model

Plasma Parameters	ITER-FEAT	Model prediction
R_0	6.2	6.13
A	2.0	1.98
B_t (T)	5.3	5.4
I_p(MA)	15.0	15.1
P_{loss}/P_{LH}	2.5	2.1
P_{fusion} (MW)	500	500
P_{aux}(MW)	50	50
$<n_{20}>$	1.1	1.1
<T> keV	8.9	8.9
β_N	2.0	1.9

Table 1 shows the comparison of model prediction for ITER – FEAT

This physics model has been applied to ITER [2], JET D-T shot [2] and ITER-FEAT [3] to predict the various device parameters like major, minor radius, fusion power and so on. The Table – 1 shows the comparison of model prediction with parameters mentioned in Ref. 3 for ITER-FEAT.

4. IFPP – baseline design

This model has been applied to construct the baseline design of IFPP. As it is mentioned earlier, conservative design has been considered. The bootstrap fraction is considered 25 % and 50 %. One would like to increase this fraction to make the reactor design attractive. The safety factor at the 95 % flux surface is taken to be 3 and 3.8 respectively and the confinement enhancement factor is little higher than 1 for the high

Plasma Parameters	IFPP – baseline design	IFPP – baseline design
R_0	7.7	7.7
A	2.6	2.6
A	3.0	3.0
B_t (T)	6.0	6.0
I_p(MA)	21.4	17.8
f_{bs} (%)	25	50
P_{loss}(MW)	522	720
P_{fusion} (MW)	2500	3300
P_{aux}(MW)	83	110
Q	30	30
n/n_{GW}	0.93	0.93
<T> keV	15.5	21.5
β_N	2.3	3.3

Table – 2 shows the various plasma parameters for the baseline design of IFPP

bootstrap fraction (50 %) case. The maximum magnetic field at the conductor is taken to be 12 T which means the conductor material is Nb_3Sn. The elongation and triangularity is taken as 1.7 and 0.24 for the 95% flux surface. The aspect ratio is 3 and the fusion gain is taken as 30 for both the cases. Table -2 shows the various plasma parameters for the baseline design of IFPP. The requirements of various sub-systems for this baseline design have been analyzed.

a. MHD equilibrium and stability

The MHD equilibrium of this baseline configuration is constructed with fixed-boundary code JSOLVER [4] and has been analyzed for ideal MHD instability with PEST2 [5]. This analysis has shown that these configurations are stable against ideal modes. Fig. 2 shows the MHD equilibrium with various profiles and Fig. 3 shows the equilibrium used for stability analysis.

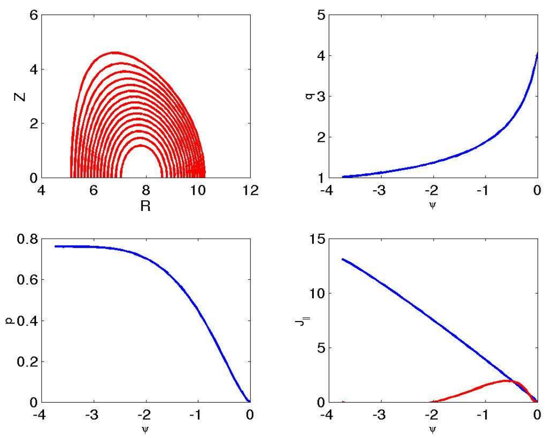

Fig. 2 shows the MHD equilibrium with profiles of various plasma parameters

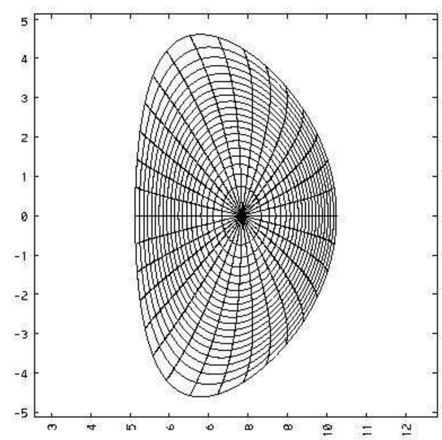

Fig. 3 shows the MHD equilibrium used in ideal MHD stability code PEST2

b. Auxiliary power system

The auxiliary power requirement has been split into two categories as NBI and RF systems. NBI is mainly to drive the required plasma current where as RF is needed to provide additional heating, off-axis current drive, assist the startup and suppression of neoclassical tearing modes in advanced configurations. It has been identified that 80 MW of NBI can sustain the plasma current in steady state while 30 MW of ICRH can provide additional heating. The systems like LHCD and ECRH will have capability to provide 20 MW each. Hence the total power available from auxiliary power system will be around 150 MW [6].

c. Magnet system

The TF coil will have D-shape where the width of D is about 11.4 m and the height is about 12.4 m. The engineering current density is about 25 A/mm^2 and the current carrying width is 0.6 m in radial direction and about 1.1 m in toroidal direction. There will be 16 – 18 TF modules depending upon the port requirement. The conductor is Nb_3Sn and the cryo requirement for this will be around 20 kW@ 4.2 K. The electro-magnetic stress is expected to be 750 MPa and the support structures should with stand around 1000 MPa. This requires additional 0.4 m in the inner bore region. The Ohmic coil conductor is also considered as Nb_3Sn. The mean radius of this coil is about 1.9 m and the radial thickness is about 1.4 m. This can provide more than 100 V-s and can sustain the required plasma current [7].

d. Divertor system

The heat removing capability of divertor is a crucial issue for reactor size machines. The option of having double null can reduce the heat load on divertor by a factor of 2. It is very difficult to produce perfect double null plasma since the system errors tend to make it as single null plasma. It is important to quantify the asymmetry produced by these errors and if the asymmetry is small enough, one can have a double null configuration. In our design, both single and double null cases are presently considered and a detailed estimate will be carried out to choose either of them. With SOL thickness of 10 mm at the mid plane, flux expansion about five times at the strike point, and an inclination angle of 20 ^{o}, the estimate of heat load on divertor for single null case is about 10 to 15 MW/m^2 and for double null case, this will be 5 to 8 MW/m^2[8].

e. Blanket system

The blanket concept considered for IFPP is Lead – Lithium cooled Ceramic Breeder (LLCB). A number of Pb-Li and ceramic breeder (CB) sections are stacked together alternately in the radial direction. The structural material occupies about 30 % of the blanket unit while Pb-Li occupies 40 % and CB occupies 30 %. Helium is used as the purge gas in the ceramic breeder. The blanket thickness at the in board side is 0.85 m and at the out board side, it will be about 1.14 m. Each blanket module is expected to be in size of 2 m x 2 m x 1.2 m. The breeding zone considered for this study is 75 % of the total surface area (for single null this can be higher). The expected tritium breeding ratio is around 1.1, the power gain is 1.2 and the thermal efficiency is 0.3 [9].

The first wall material is Tungsten on LAFMS and the divertor is helium cooled tungsten. The CB material is Li_2TiO_3, neutron multiplier is Pb, structural material is LAFMS, coolant is Pb-Li, reflector is graphite, and shielding material is WC and SS [10].

5. Fusion Technology Development

The development in fusion technologies such as divertor, blanket, magnets and power conversion systems will be crucial in making the reactor attractive for commercial purpose. Any development in these areas will directly translate into reducing the cost of electricity produced by the fusion power plant. It is expected to have a strong Research and Development (R&D) program to improve these technologies in coming 25 years.

There are few crucial areas in magnet system to be considered for this. The development of high T_c superconductor so that cooling requirement can be considerably reduced. The dependence of fusion power goes as fourth power of toroidal field and hence any increase in this direction will give considerable amount of reduction in the system cost. The development of conductors whose maximum operational magnetic field can be more than 12 T (for Nb_3Al, it is about 18 T) will be very important. Such high magnetic field may allow the reduction of inner bore area and there by it can reduce the system size.

The development of special materials to take high heat load more than 20 MW/m^2 will be attractive for the power plant. The double null case can enhance the heat load capability with the existing technology but one has to prove the realization of this configuration for reactor size machine. The modification of magnetic geometry near the divertor plate will spread the heat load over a longer poloidal region. This needs an internal coil to be placed near the divertor and operated in steady state. The feasibility of such configuration has to be explored.

The development of special materials for blanket to sustain higher operational temperature, neutron damage, etc. will make thermal efficiency better and reduce the cost of electricity. The innovative blanket concepts are also useful for maximizing the availability of the reactor.

6. Conclusion

The baseline design of IFPP has been constructed and analyzed for various sub systems requirements. The approximate cost estimation of electricity shows that the unit price of electricity will be comparable or little higher than other commercially available schemes. This can provide safe and pollution free power for centuries to come. The detailed studies and optimization of this configuration will be carried out in future.

7. References

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