Cryogenics for the fusion devices: An overview of heating, fueling, exhaust and fuel separation systems

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The exponentially increasing power consumption of the world requires a tremendously large source of power production, nuclear fusion has the potential to meet this requirement. Among various possible nuclear fusion reactions, deuterium-tritium (D-T) reaction has emerged as the most favorable reaction. Energy production by the D-T reaction has been demonstrated in the Tokamak Fusion Test Reactor (TFTR) and Joint European Torus (JET) fusion devices based on the magnetic confinement. The scientific breakeven, i.e. produced fusion power exceeding the input power, is aimed to be demonstrated in the International Thermonuclear Experimental Reactor (ITER) and SPARC fusion devices currently in construction. The toroidal devices based on the magnetic confinement are of two types, i.e., tokamaks and stellarators, having 2D and 3D the magnetic geometries respectively. Optimized stellarator Wendelstein 7-X (W7-X) [1], in operation since 2015, has successfully completed the sixth plasma campaign, i.e. OP2.3 in 2025, preparations are being made for the next campaign.

Though the first fusion devices began operation towards the end of 1950s (e.g., T-1 tokamak), as the development progressed towards the steady state, high power operation, after about two decades cryogenics stepped in. Towards the end of 1970s, fusion devices were in operation with the superconducting toroidal field magnets (e.g., T-7 tokamak) and the electron cyclotron resonance heating gyrotrons with superconducting solenoids (e.g., Axially Symmetric Divertor Experiment (ASDEX)). Around the same time, cryogenically frozen H/D pellets were developed to fuel the plasma [2] (e.g., ASDEX [3]). Cryogenics was also used for the large cryo-vacuum pumps, for achieving high levels of vacuum in the plasma vessel, neutral beam injection (NBI) heating boxes (e.g., JET) and exhaust improvements. Developments are currently taking place for the separation of H, D, T and He from the exhaust gas mixtures in the fuel cycle system, using cryogenic fuel separation techniques [4].

In W7-X, ECRH is the main heating system for the long plasma pulse operation, there are, eleven pieces of MW-class gyrotrons generating a microwave frequency of 140 GHz to deliver up to 8.5 MW power to the plasma. Each gyrotron is equipped with three superconducting solenoids immerged in liquid He bath, generating a magnetic field of about 5.6 T [5]. The continuous pellet fuelling system is used to inject frozen H pellets (disc of diameter/height ca. 2-3 mm) at a frequency of 10 Hz from the outboard low field side with a speed of 200-800 m/s to fuel the plasma [6]. Cooling of H is done using the closed-cycle Gifford McMahon cryo-coolers. Ten cryo-vacuum pumps are installed within the plasma vessel located behind the divertor to improve the gas exhaust, helping for a better plasma density control and reduction of gas recycling from the plasma-facing wall. The cryo pumps are cooled with supercritical helium at ca. 4 K, thermal shield is cooled with liquid nitrogen at ca. 80 K [7].

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