ITER Fuelling and Glow Discharge Cleaning System Overview

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Abstract

The ITER Fuelling and Wall Conditioning (FWC) System consists of 4 major sub-systems: the Gas Injection System (GIS), Pellet Injection System (PIS), Disruption Mitigation System (DMS) and Glow Discharge Cleaning System (GDC).

The conceptual design of the GIS has been completed succeeding to engineering and detailed system design phases. The Fusion Power Shutdown System operation scheme and its interface with the Central Safety and Interlock Systems are studied. The engineering R&D of key elements of PIS is ongoing at the United States Domestic Agency in parallel with the conceptual design. Due to design evolution of in-vessel coil feeder, the PIS has been relocated to avoid crash while maintaining 120 degree toroidal uniformity at divertor level. The preliminary physics requirements for DMS has been defined its location is finalized; 3 diagnostics upper ports and 1 equatorial diagnostics port plug. The GDC has been relocated from divertor level to upper and equatorial level and detached from the in-vessel viewing system. This allows the fixed anode design and solves vulnerability issues associated with movable anode with flexible hose.

This paper summarizes the progress and perspectives of ITER FWC system development and design.

1. Introduction

The ITER Fuelling and Wall Conditioning (FWC) System consists of 4 major sub-systems: the Gas Injection System (GIS), Pellet Injection System (PIS), Disruption Mitigation System (DMS) and Glow Discharge Cleaning System (GDC).

Each Sub-system provides the following functions.

(1) Gas Injection System

− Injection of fuel gases for plasma density control and fuel replenishment for helium removal.
− Injection of impurity gases for radiative cooling enhancement, divertor detachment control and controlled discharge termination.
− Injection of minority species to improve coupling of radio frequency heating waves with the plasma.
− Provision of an emergency fusion power shutdown as a safety function.
− Supply of H₂ or D₂ gases to the heating and diagnostic Neutral Beam (NB) injectors.
− Supply of fuelling gases (D₂, H₂ & T₂) and impurity gases (N₂, Ar, or Ne) to the PIS.
− Supply of gases for wall conditioning.

(2) Pellet Injection System

− Injection of hydrogen isotope ice pellets for plasma density control.
− Injection of impurity ice pellets into the plasma for studies of impurity transport and possible radiative cooling enhancement at the edge.
− Provision of pellet injection into the edge plasma for control of Edge Localized Modes (ELMs).

(3) Disruption Mitigation System
− Rapid injection of a massive number of particles into the vacuum vessel to mitigate excessive thermal and electromagnetic loads and suppression of runaway electrons.

(4) Glow Discharge Cleaning System
− Reduction and control of impurity and hydrogenic fuel out-gassing from plasma-facing components and possible contribution to in-vessel tritium inventory control.

2. System Requirements and Configuration

Since the previous report on the status of the ITER FWC system [1], a significant effort has been invested in finding the best possible compromise for the distribution of the various entry points for the various systems. For example, the GDC and DMS must compete for precious space/volume in the various port plugs which are already highly occupied by other systems (e.g. diagnostics). Figure 1 shows the configuration finally adopted and which is now expected to be stable through the process of port plug procurement.

The PIS has been relocated from divertor port No.6, 12 and 18 to 4, 10 and 16 to avoid a crash with in-vessel coil feeders while maintaining toroidal uniformity.

In addition to the plasma fuelling parameters and impurity gas injection for radiative cooling and divertor detachment control [1], the physics requirements on DMS have tentatively defined for its conceptual design. Detail will be presented in the following section. Number of the system and their locations are determined to avoid localized radiative heat load to the vicinity of injection points, which may exceed acceptable heat load on the first wall and lead local melting.

The GDC has been relocated to upper and equatorial levels and fully integrated in the diagnostics port plugs.

Each sub-system consists of the following.

(1) Gas Injection System
− Upper port level: 4 gas valve boxes (GVB)
– Divertor port level: 6 GVBs distributed toroidally with 60° of separation, and 6 PIS fuelling GVBs.
– Dedicated manifold for fuel supply to the heating and diagnostic NB injectors.

(2) Pellet Injection System

– Three divertor ports are allocated. Each port is equipped with a PIS cask which can accommodate 2 injectors.
– Two injectors will be installed for the beginning of machine operations.
– Six injectors will be available for the start of DT plasma operation.

(3) Disruption Mitigation System

– Three locations at upper port level are allocated for Thermal (and electromagnetic load) Mitigation system (TM) and 1 equatorial port for both TM and Runaway Electron suppression (RE) systems.

(4) Glow Discharge Cleaning System

– Total of 7 GDC electrodes will be integrated in 3 diagnostics upper port plugs (UPP) and 4 diagnostics equatorial port plugs (EPP).

3. System Design and Development

3.1 Gas Injection System

The GIS Conceptual Design Review (CDR) was successfully completed in 2011 and is now in the preliminary design phase. Procurement of the system will be performed by the Chinese Domestic Agency (CN-DA). The GIS consists principally of the Gas Fuelling System (GFS), Gas Delivery System (GDS) and Fusion Power Shutdown System (FPSS). The GFS consists of GVBs at 4 of the upper ports and 6 divertor ports, with additional GVBs on the GDS fuelling manifold for the PIS (the GVB is illustrated in Figure 2).

The GFS provides vessel pre-fill and early gas feed during plasma initiation and current ramp-up, steady state gas supply for non-active plasmas (e.g. hydrogen and helium), injection of extrinsic impurities and fuel atoms for divertor plasma seeding and detachment control and adjustment of the main scrape-off layer plasma density.

The GDS provides hydrogenic fuel and impurity gases for pellet production and propellant gas for pellet acceleration. These gases are provided through dedicated GVBs, which have almost the same configuration as those used for the GFS. It also provides H\textsubscript{2} and/or D\textsubscript{2} gases for heating and diagnostic NB injectors.

![Flow diagram in GFS GVB with FPSS](image-url)
The FPSS provides safety plasma shutdown in the case of an ex-vessel Loss of Coolant Accident (LOCA) and has 100% redundancy. It is fully integrated into 2 GVBs at upper port level and consists of a 1 liter reservoir and safety isolation valves as shown in Figure 2. The reservoir is filled with 30 kPa·m³ of neon gas, which will be injected within 3 sec by a trigger signal from the Central Safety System (CSS). Once the FPSS is triggered, disruption is usually generated, which might damage the in-vessel components. Therefore, it is set up in this way that CSS shall provide the information to ITER interlock system to actuate the DMS to avoid additional damages to the ITER components. It should be noted that this mitigation is not a safety operation. The further detailed study of the FPSS concept, including numerical analysis of gas injection response and its operational logic and sequence, is on-going as a part of the preliminary engineering of the GIS [2].

The GFS is now exploring possible use of a digital dosing valve as one of the viable solution for gas puffing, which has excellent repeatability and stability in throughput control, and is robust against the high gamma radiation dose and magnetic field in the port cells. This valve consists of flow nozzles with different sizes and on-off valves, and can provide step-wise flow control throughout the required flow regime.

### 3.2 Pellet Injection System

During operation in high power H-modes, plasma simulations suggest that gas puffing from the edge in ITER will be inefficient for core fuelling [3]. Pellet injection, which is capable of injecting fuel particles into the confined plasma, is thus expected to be mandatory for core fuelling. The PIS provides core plasma density control using high field side (HFS) injection and is being designed to provide ELM pacing via low field side (LFS) pellet introduction. Maximum pellet injection speeds of 300 ms⁻¹ are expected to be possible with the current HFS and LFS flight tube configuration. To improve the pellet fuelling efficiency, an elevated injection point near the HFS machine mid-plane in addition to the lower position is now being explored as shown in Figure 3.

An engineering R&D program is now on-going at the United States Domestic Agency (US-DA) to develop and demonstrate the key technologies necessary for the ITER pellet injector, namely a twin screw extruder, pneumatic gas gun pellet accelerator, fuel recirculation, propellant gas recovery and recirculation and flight tube selector as shown in Figure 4. A prototype one-fifth ITER scale, twin-screw extruder has been designed and built at the Oak Ridge National Laboratory (ORNL) which produces a continuous deuterium (D₂) extrudate as the material source for the fuelling and ELM pacing pellets [4]. A propellant recirculate prototype is now being built and tested at ORNL.
Recently an ITER-like LFS pellet injection line has been installed on DIII-D near the X-point, shown in Figure 3, in addition to the LFS injector installed on the machine mid-plane. The experimental results have successfully demonstrated that LFS high frequency pellets at 60 Hz from both of the mid-plane and X-point injection trigger ELMs and significantly reduce the heat load to the divertor. Reduced high-Z and lower Z impurities have been also observed in the plasma core and edge during the ELM pacing phase [5].

3.3 Disruption Mitigation System

ITER plasmas will operate at very high stored energy and plasma current. It is mandatory for machine protection that the enormous thermal and electromagnetic loads and runaway electrons, which will be generated during disruptions of such plasma, be reliably and effectively mitigated. Physics studies to define the requirements for the DMS are currently running in parallel with a detailed engineering assessment of candidate systems [6]. A Shattered Pellet Injection (SPI) with pipe gun injector [7, 8] and Massive Gas Injection (MGI), based on a high pressure gas cartridge concept [9], have been developed. Figure 5 shows another scheme of MGI DMS, which employs a flush valve concept for rapid delivery of particles [10]. The ITER Organization (IO), together with the US-DA, is planning an R&D program to develop and demonstrate SPI and MGI DMS techniques, including the development of synchronized injection from multiple locations.
There is a limitation imposed by the ITER vacuum pumping system on the quantity of gases which can be introduced by DMS. The limit is determined for each candidate gas species (see Table 1) by the vacuum system design and operation, and additionally for deuterium by the safety requirement that the accumulated quantity of D$_2$ in torus cryopumps not exceed the deflagration limit.

The US DA has organized a Disruption Mitigation Workshop in March 2012 to develop the scope and work plan for the ITER DMS procurement with participants from US, EU and the IO. Three options, based on compatibility with the ITER DMS schedule and accumulated technology basis, were selected for near term development plan. ITER will proceed with MGI, SPI and beryllium shell cartridge DMS options through the preliminary engineering phase. In parallel with the system design, prototype development is planned for final selection of the ITER DMS.

Each UPP accommodates 1 TM DMS with both a TM and RE DMS being housed in EPP 1. As shown Figure 6, a 200 mm diameter cylindrical space has been allocated at the bottom of the UPP for installation of the TM DMS. This has the least impact on diagnostics housed within the port. In the EPP, which, like the UPP consists of separate “drawers”, a single entire drawer will be dedicated the TM and RE DMS. A port cell integration study is running in parallel with port plug integration to allocate necessary utilities and port plug feed-throughs, even though the DMS designs are only at the conceptual design stage. This is unavoidable given the short delays set by port plug procurement.

### 3.4 Glow Discharge Cleaning System

The GDC CDR, held in 2011, identified key vulnerabilities associated with the requirements for flexible water feeds and technical challenges associated with the original movable electrode concept which was sharing lower divertor port space with the in-vessel viewing system (IVVS). As a result, it has now been decided to relocate the GDC electrodes to EPP or UPP (see Figure 1) and integration studies are nearing completion at ITER. A new, flat electrode design (in contrast to the cylindrical electrode design presented at the 2011 CDR) similar to the concept which has been used successfully in several tokamaks is now being considered and would be installed as part of the diagnostic first wall (DFW) as shown Figure 6. Three UPPs and 4 EPPs are allocated for the new GDC electrode installation to ensure as much toroidal uniformity as possible in the glow plasma.

However, GDC electrodes installed in the DFW face new challenges. In particular, they cannot be retracted, and will face the plasma at all times, even if the DFW is sufficiently recessed behind the first wall so as to avoid all direct contact with plasma flowing along field lines. Space is also extremely limited in the crowded port plugs. The system must be reliable,
compact, ensure neutron shielding, be water cooled, and capable of the application of bias voltages up to ~1.5 kV.

The IO is now working with CEA/IRFM to test experimentally the proposed electrode geometries and to benchmark GDC plasma measurements made in a test chamber against simulations using a hybrid fluid/kinetic plasma code developed at the Univ. of Toulouse, France. Once benchmarked, the simulations will be used to assess the glow plasma uniformity to be expected on ITER for the GDC electrode number and location. Meanwhile the experimental tests will assess the breakdown efficiency and heat loading of the proposed electrode concept, including the effects of recess behind a first wall surface.

The CN-DA is also performing GDC bench tests with their facility, in which pressure in the chamber is controlled to simulate the ITER condition.

Due to unavailability of diagnostics port plugs for the first plasma (only 1 diagnostic EPP with GDC electrode will be installed during the initial machine assembly phase), temporary GDC electrodes are mandatory to condition the bare stainless steel Vacuum Vessel (VV) surfaces. The total surface area in this case (~1600 m$^2$), is much larger than for the case when the blanket and divertor will be installed (~800 m$^2$), requiring a larger number of electrodes than the 7 units to be installed in the final system (Section 2). Ten GDC electrodes in total are being proposed for the first plasma: 1 permanent electrode on the EPP and 9 temporary electrodes. Six temporary electrodes will be placed at the vicinity of allocated port plugs; 3 at upper port region and 3 at equatorial port region. A further 3 temporary electrodes will be installed at the bottom of VV separated toroidally by 120°. As shown in Figure 7, these temporary electrodes will be fixed on the VV inner wall using blanket module flexible support structures.

4. Summary and Concluding Remarks

The GIS entered the preliminary engineering phase under the responsibility of CN-DA to develop detail design of the system and preliminary assembly scheme. An engineering R&D and conceptual design of PIS is on-going aiming its CDR in March 2013. Integrating the developed PIS key elements to demonstrate the feasibility of ITER scale PIS is planned in 2013 onward; PIS design will be finalized taking this result into account. The requirements and allocation of DMS have been finalized to develop the system concepts. The several viable solutions will be reviewed at the DMS CDR, which is planned in December 2012. Final selection of DMS option will take place during succeeding engineering phase, taking in the engineering and physics R&D results (Engineering R&D will start in 2014). A fixed and flat GDC electrode detached from the IVVS, in contrast to the movable and cylindrical electrode
presented at the 2011 CDR has been employed as the ITER baseline. This new design together
with the additional scope of temporary electrode design will be presented to the CDR in
November 2012.

Following the GIS, the PIS, DMS and GDC will move ahead to the succeeding engineering
phase in 2013 under the responsibility of the CN and US-DA. The IO will support the DAs
with respect to the system integration, interface control, assembly and commissioning planning.

Acknowledgement

The authors would like to thank members from ITER Organization and Domestic Agencies for
the useful discussion and support of this work. The authors express special thanks to Drs.
Y.H. Kim and M. Glugla for continuous support and encouragement for the conceptual
engineering of ITER fuelling system.

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER
Organization.

Reference