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Conceptual design of the JT-60SA pellet launching system

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A conceptual design for a pellet injection system will be worked out, capable to support key missions of the new tokamak device JT-60SA. For exploitations in view of ITER and to resolve key physics and engineering issues for DEMO, several tasks were assigned to this system. Physics investigations aim at operation at high density in ITER and DEMO relevant plasma regime above Greenwald density, power exhaust techniques with radiation layers, particle balance studies, and ELM control and mitigation. The postulated engineering requirement is to quantify pellet actuation on electron density for application within the advanced real-time control scheme by controlling density gradients. Our intended pellet system comprises three major components: pellet source, accelerator and guiding system. The guiding system must be installed inside the torus vessel already under construction, hence still possible launch geometry were pursued first. Three different options have been identified: inboard, outboard and top launch. The first one is most promising with respect to fuelling performance but will impose pellet speed restrictions to about 470 m/s for adequate pellet sizes. Both others offer headroom for significantly higher injection speed but under less favourable physics boundary conditions. In order to evaluate expected performances for all relevant plasma scenarios, detailed modelling efforts for every launch geometry option have been made. For a suitable pellet source covering all requirements, several options are at hand including commercial providers. For the accelerator, the high speed option up to about 4000 m/s could be covered by a multi stage gas gun. Single stage gas guns and centrifuges can cover the speed range up to about 1000 m/s for the basic work load since both fulfil the requirements for pellet size and speed. Due to a higher speed precision resulting in less timing jitter, a centrifuge would be better suited for control requirements.

Keywords: Tokamak, Pellet fuelling, Launcher technology, JT-60SA

1. Introduction

JT-60SA [1] is a project with the mission to contribute to early realization of fusion energy by supporting the exploitation of ITER and by resolving key physics and engineering issues for DEMO reactors. The device has been designed in order to satisfy all of the central research needs for ITER and DEMO. In particular, the most important goal is to decide the practically acceptable DEMO plasma design including reliable plasma control schemes suitable for a power plant.

Using superconducting toroidal and poloidal field coils, the device is capable of confining break-even-equivalent class high-temperature deuterium plasmas lasting for a duration of typically 100 s, longer than the time scales characterizing key plasma processes, such as current diffusion and particle recycling. It has been designed to realize a wide range of diverted plasma equilibrium configurations, covering a high plasma shaping factor ($S = q_{95}I_p/[a_0B_t] \sim 7$) and low aspect ratio ($A\sim2.5$) with a sufficient inductive plasma current flattop duration. The maximum plasma current is 5.5 MA. JT-60SA should also pursue fully non-inductive steady-state operation with high values of the plasma pressure exceeding the no-wall ideal MHD stability limit. The experiments should explore ITER and DEMO-relevant plasma regimes in terms of non-dimensional plasma parameters at high densities in the range of $1\text{x}10^{20}$ m^{-3}.

The JT-60SA research strategy aims to explore a couple of relevant scenarios, comprising such with a high integrated economically attractive performance, calling for operation at a Greenwald fraction at or even above unity. Gas fuelling is not very suitable to achieve this since usually severe performance degradation takes place when approaching the Greenwald density. However, injection of cryogenic solid pellets formed from fuel turned out a powerful tool for this task [2]. Hence, the project necessitates a suitable pellet injection system. Beside the basic fuelling tasks it is expected to cover also the capability for controlling ELMs, applications for particle balance studies in the scrape off layer and the divertor and for investigation on power exhaust by developing radiation layers. In addition to these physics oriented investigations, the pellet system must enable engineering functions of the actuator “pellet injection” on electron density and ELMs. Actuation has to be quantified in an initial open loop phase to prepare closed-loop control experiments for density gradient control within the advanced real-time control scheme.

A conceptual design for the JT-60SA pellet injection system will be worked out in the time period 2015-2017, taking into account the status of the torus vessel assembly. Within a feasibility study an approach has to be established with minimized risks but covering all requirements stated in research plan. A tentative solution is presented here. It is composed from a baseline device

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covering all the essential operational needs but yielding also the option for potential extensions and upgrades.

2. Basic considerations

Aiming on the development of a conventional pellet system, it is clear such an injector will be composed from three main components:

Pellet source delivering solid fuel with the right size to the accelerating unit, formed from gas in the reservoir. This can be done as batch process or in steady state.

Pellet accelerator section receives pellet from the source or cuts pellet with the required size from an ice ribbon provided and accelerates it to the pre-selected speed. Several options of different complexity are available offering different operational parameter ranges.

Pellet guiding system provides pellet transport to the desired launch position at the plasma boundary. If required by guiding tubes, in case direct access is possible via free flight.

Since pellet production, acceleration and injection is a serial process, any limitation on the performance at any step results in an according restriction of the accessible operational system parameters. Hence, the conceptual design has to avoid any bottlenecks. In addition, every main component has to achieve a high reliability as the system reliability is the product of the sub systems values and a single weak link would spoil the reliability of the entire system.

Another determining factor for the design is the interplay between technical pellet parameters and the complex physics underlying ablation and deposition of pellet particles in hot plasmas. It is a well-known fact that, in the inhomogeneous field of a tokamak, injection from the magnetic high field side can show much better performance with respect to pellet penetration and fuelling efficiency than low field side injection [3]. However, high field side injection from the vessel inboard is technically more complex. It requires pellet transfer through a guiding tube likely to impose a limit on the maximum achievable injection speed. On the other hand, low field side injection usually performed from the torus outboard side mostly allows for free flight injection making full use of the accelerators speed range.

For the optimization of a pellet system, all the key parameters which can be adjusted during design and eventually during operation have to be considered. These actuation parameters are:

- Pellet material

- Pellet mass m_P [atoms] and shape

- Pellet rate f_P [Hz] (times m_P it determines the pellet particle flux Γ_P [at/s]). During operation, f_P will be most likely the main actuation parameter for control purposes.

- Pellet speed [m/s]

- Pellet launching location/geometry

3. Launch site options and related pellet parameters

In principle, all the key parameters of the pellet system can be freely chosen, provided the parameter set is self-consistent and covered by the present state of technology. However, finally pellets have to be launched into the plasma and hence need access through the torus vessel. This unavoidable boundary condition can impose limits on the accessible parameter range, thus the initial step of the study was to identify possible access solutions. The result is shown in figure 1, displaying a poloidal cross section of JT-60SA with three launch options compatible with the construction and layout of vacuum vessel and surrounding components. For two of them, the injection from the outboard side or from the machine top, direct access through vessel ports enables in principle for free flight straight injection. The outboard pellet trajectory intersects closely spaced flux surfaces almost perpendicular, representing in principle the most favourable case with respect to pellet penetration. For the desired inboard launch, an elaborate guiding tube system has to be designed and installed. Besides the expected limitation of the pellet speed, the tube geometry enforces a pellet trajectory declined by 70 degrees with respect to the horizontal plane.

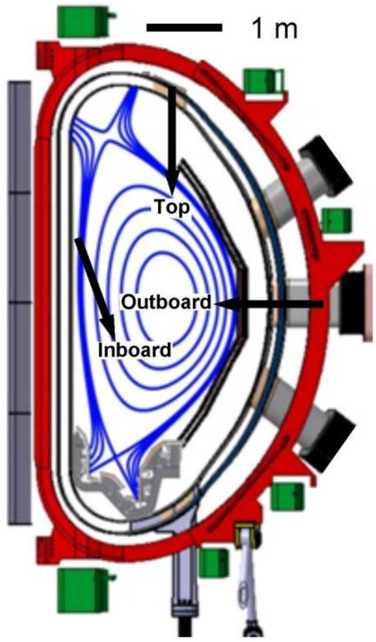

Fig. 1. Poloidal cross section of JT-60SA with the three launch trajectories considered. Injection from the outboard and top can be achieved in free flight, for inboard launch the guiding system shown in figure 2 has to be employed.

In order to grant a reliable cover of the inboard launch option, guiding tube systems have been worked out for different sectors of the torus. Primarily, this is to provide redundancy for such a vulnerable tube system. Furthermore, since available sectors have a somewhat different make, resulting variants map out the possible construction-conditioned leeway. A typical design drawing, worked out for installation in sector P7, is presented in figure 2. The challenging character of this solution employing many tube bends is evident.

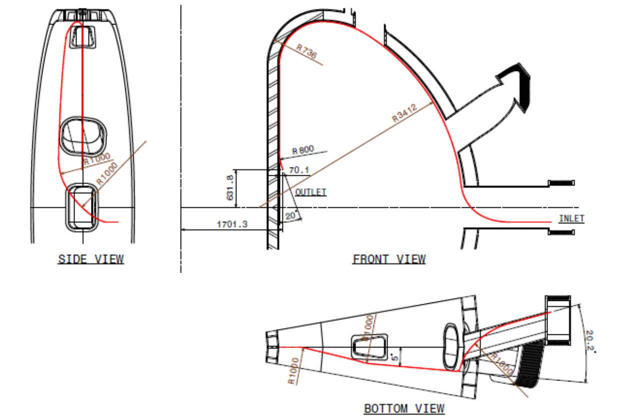

Fig. 2. Guiding tube geometry installed inside the JT-60SA vessel for pellet transfer to the inboard. Multiple bends of the guiding tube are expected to impose a strict limit to the maximum injection speed.

For comparison of the three different injection options, a proper modelling of the different cases is needed. Therefore, according reasonable input plasma and pellet parameters must be provided. 6 reference plasma scenarios (details in [1]) were considered, relevance ranking assigning top priority to high density base line plasmas (#3). As pellet material, deuterium (D) was assumed, foreseen as major plasma and hence fuel species once the "Initial Research phase II" is entered. Operation with hydrogen (H) plasma during the preceding "Initial Research phase I" will require H pellets. The system design is envisaged to cover this need, however without optimization for this species. For the pellet size and shape, a pretty precise request is stated already in the research plan. Cylindrical pellets with both diameter and length L = 2.4 mm are envisaged. It is estimated such pellets with $m_P = 6.5 \times 10^{20}$ D atoms can yield the necessary fuelling particle flux to achieve the target core density in scenario #3 at a rate of 13 Hz. For other reference scenarios, sufficient fuelling is expected already at f_P of about 10 Hz. To provide some operational headroom, the system is challenged to provide f_P = 20 Hz for fuelling needs. For ELM pacing applications, this capacity has to be extended up to 60 Hz. For the modelling, f_P is a parameter yet disregarded. Evaluation of the fuelling performance is based on the impact of a single pellet; no full self-consistent modelling has been performed at this stage. However, considering the pellet impact in various scenarios provides information on how durable a potential solution is under changing plasma conditions. Besides the reference case, also the option of applying "oversized" pellets with $m_P = 4 \times 10^{21}$ D atoms was analysed in order to sound out how larger pellets could help to improve the fuelling efficiency. For the pellet ELM pacing it appears most likely a reduced pellet mass would be desirable to avoid unwanted fuelling side effects. However, since a sound modelling of pellet induced ELM triggering still lacks a reliable physics description, this adaption at best should be done in situ employing a system providing sufficient flexibility. To complete the parameter sets, information about the achievable pellet speeds for the different configurations is needed. For outboard launch, the maximum speed is due to the accelerator unit potential. Taking here the technical potential of a double stage gas gun, a range from 2000 to 4000 m/s can be assumed, depending on the demand on reliability and f_P [4]. It is understood a technical system capable to cover requirements would require still some R&D for development. For the inboard guiding tube solution, in a first step the effective bend radius R_{eff} for any considered solution was estimated, yielding typical values of about 0.4 m. The maximum transfer speed is calculated using the empirical "AUG calibrated" relation [5]

$$v_c = 36.4 \left[\frac{m}{s}\right] \sqrt{\frac{R_{eff}}{L}}$$

yielding 470 m/s for L = 2.4 mm. To sound out if a more tight speed restriction would deteriorate the inboard fuelling performance significantly, a safer low speed option with 200 m/s was also considered. For top launch, no dedicated technical solution is yet worked out. Here, 470 and 2000 m/s are assumed, bordering the range of reasonably possible set ups.

4. Modelling of pellet ablation and deposition

With the parameter set derived as discussed, a modelling effort was made using the currently most advanced tool, the HPI2 code. The code is valid for any magnetic and plasma configurations - computes the pellet ablation taking into account thermal ions and electrons and the supra thermal ions generated by the plasma heating systems [6]. The drift model is based on the compensation of the cloud polarization by parallel currents [7]. Essential result obtained from the modelling highlighting the fuelling performance of all considered cases is presented in figure 3. It displays the deposition depths of pellet carried particles with dots representing the location of the maxima and bars the deposition profile extension until 0.1 times of this value. As well, according fuelling efficiencies are shown.

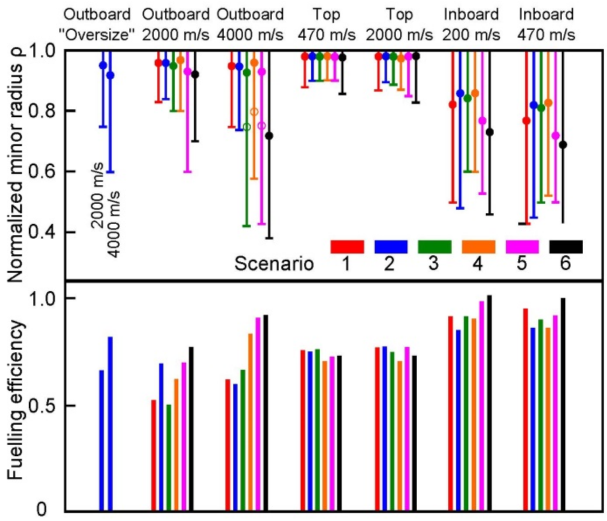

Fig. 3. Upper: Particle deposition depths calculated for different pellet launch sites and speeds for every considered target scenario. Dots represent the maxima of the deposition profile (open dots: secondary maxima); bars the deposition profile extension until 0.1 times the peak value. Lower: According fuelling efficiencies (Deposited particles/m_P).

It is clearly visible that the injection configuration is most important for the pellet fuelling characteristics and inboard launch provides the best suitable solution despite its speed restriction and the unfavourable trajectory with respect to the flux tube geometry. Both other configurations cause already significant instant losses, resulting in a fuelling efficiently considerably below unity. Strikingly, this hold for any scenario considered, thus forming a well settled base for qualifying the expected fuelling performance even in cases where plasma parameters are established in a controlled way. The only exception is outboard launch at very high speed using “oversize” pellets. Here, penetration is deep enough for a significant part of the material to be deposited inside the q = 2 surface (typically located at $\rho \approx 0.82$), blocking the outward drift. Top launch is not favourable in any case. The speed sensitivity for inboard launch is modest, hence more severe speed restrictions than assumed would not really cause major performance losses. Main conclusions derived from modelling are:

- Inboard launch is the prime choice; good performance can be expected even in case of a rather low pellet speed has to be used to grant successful delivery.

- Very high speed outboard launch could yield a possibility for sophisticated investigations on pellet and particle transport physics and foster technology R&D.

5. Tentative system layout

Taking into account all the results obtained so far, a tentative system lay out was elaborated as described in the following. For the basic system, pure inboard launch is suggested. To produce the required pellets, a steady state extruder should be employed alike the type developed for the JET HFPI [8]. It has the capability to produce ice rods with different diameter and length; hence it offers flexibility for adapting pellet size and mass. The cooling power has to be sufficient for operation with H, control capabilities to ensure operation in D as well. Further on, the mechanical capabilities should be laid out allowing ice doping by radiator or plasma enhancement gases. For the accelerator unit, a stop cylinder centrifuge appears most suitable. There are designs at hand allowing integration of several steady state extruders into one centrifuge, enabling for pellet rates up 100 Hz and accordingly high particle fluxes [9]. Since in a centrifuge the acceleration force is not mass dependent, this would enable for the use of doped pellets or mass adaptation for pacing as well. High speed precision, resulting in little scatter of pellet flight times [10], yields very regular and well predictable pellet sequences arriving in the plasma. Thus, controlled operation relying on precise actuation is fostered. Requirements with respect to repetition rate, pellet particle flux and control can be well covered by an accordingly laid out system. Using a stop cylinder with sufficiently large diameter and an acceleration arm with adapted length, the centrifuge speed range can even be optimised for covering the maximum potential of the pellet transfer system. Introducing minor modifications, the centrifuge based system could also be employed for outboard launch, e.g. for pacing or fuelling studies using pellet speeds up to about 1000 m/s.

Optionally, a dedicated system is suggested for high speed outboard launch, covering the potential for an injection of different pellet species (eventually also doped ones) at a speed significantly beyond 2000 m/s. Such a system has to be at a least double staged gas gun. As such systems at present only provide quite low repetition rates, additional R&D to improve the situation would be needed. Such efforts could turn out also very beneficial for a DEMO type pellet system.

6. Summary and Outlook

A basic pellet launching system is proposed capable to cover all requirements expressed in the JT-60SA research program. It should grant all needs for fuelling purposed and is especially well suited for control applications. Modelling efforts indicate, in agreement with experimental findings, pellet parameters suitable for fuelling are also convenient for pacing purposes [10]. Hence, this system likely is adequate for pacing applications as well and could reduce the pellet mass in order to minimize unwanted fuelling side effects. Finally, its flexibility could allow injection via other launch sites as well. Modelling performed in order to find out which option can be expected to yield the best fuelling performance has been done, yet for single pellets. However, the result showing HFS injection is the best approach for any scenario**;** indicate the chosen solution will be the optimum one also for an entire fuelling sequence.

An analysis still to be performed is about the impact of the pellet created perturbation on plasma stability. It is well possible strong local profile modifications can result in instabilities. For example, sufficient large pellets have been found to trigger NTMs [11] deteriorating the confinement. Usually, such effects do show threshold behaviour and have to be taken into account for optimisation as well.

Acknowledgments

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